rate of 1 cm/h and a 7-day application/10-day drying cycle. All four organic amendments tested with the synthetic secondary effluent were effective in completely removing nitrate (10 mg/L as NO_3^-N) from the feed solution as negligible amounts of nitrate were detected in the effluents from all four experimental soil columns. On the other hand, minimal reduction in nitrate concentration was observed in the control column. These results suggest that RIBs with substrate amendments may be a viable option for enhancing the removal of nitrate in RIB systems.

After the efficient removal of nitrate in the synthetic effluent by the substrate-amended soil columns, the "real" secondary effluent from a local nitrifying wastewater treatment plant (Water Farm 1) was pumped into the same soil columns to compare the rate and extent of denitrification to that of synthetic effluent. Again, all four organic amendments tested were effective in completely removing nitrate from the "real" secondary effluent as negligible amounts of nitrate were detected in the effluents from all four experimental soil columns. Analysis of nitrate levels at the sampling ports along the height of the columns, indicated that the majority of nitrate in the feed solution was removed within the first 30 cm of the soil columns. This result suggests that the selected hydraulic loading rate is overly conservative and that the columns may be able to treat nitrified effluents at much higher loading rates. In addition, the soil columns were effective in removing phosphate from the synthetic influent.

When the same column experiments were repeated under winter conditions (10^{o}C and 5^{o}C), the nitrate removal efficiency in all columns decreased due to decreased microbial activity at lower temperatures. Nevertheless, substantial nitrate removal rates (greater than 50%) were observed in columns amended with solid organics (wood chips and compost materials) even after 1-year of operation. Nitrate removal efficiency at 5^{o}C was improved to over 95% when the wood chips and compost columns were replaced with fresh materials. The laboratory study clearly demonstrated that a properly designed RI system offers the possibility of cost-effective tertiary treatment for the reduction of nutrient loading to down-stream surface water bodies.

In Phase II of the RIBs evaluation project for Middletown, Smith et al. (2015) conducted a field study over a two-year period. The study included a pilot-scale RIB system, which consisted of four test basins (25 by 60 feet) that were constructed in the buffer areas of an existing spray irrigation field. The test basins contained 0, 10, 20, or 30% by volume of finely graded woodchips in the top 1-foot of soil, which provided an external carbon source. Three woodchip-amended laboratory columns were also operated to simulate the RIBs and act as a model for predicting carbon depletion in the field. Between May 2013 and March 2015, lagoon effluent was loaded into the basins in volumes of 7,10052,500 gallons per day for 1-9 days, with resting periods (no loading) of 5-13 days. Suction lysimeters were installed at 3 feet and 6 feet below the surface for the collection of soil pore water samples following infiltration. After initial flushing effects, the system was shown to remove significant amounts of nitrate, with the highest removal ($\geq$50%) observed in the basin amended with 30% woodchips. Improved performance was observed for increased sampling depth and increased woodchip volume. The short (1-2 day) loading plan was shown to be superior to the extended (9 day) loading. During winter tests, the 6-foot samples continued to show substantial treatment, while some operational concerns were raised due to excessive ice buildup. The column study predicted a woodchip lifespan of at least 2.5 years.

Based on the findings of this study, the recommendations for operation of the woodchip-amended RIB system are as follows:

- Addition of 30% woodchips by volume in the soil surface. Increased amounts of woodchips in the soil were shown to support a higher denitrification capacity in both the RIB soils and the laboratory columns.

- Use of one-day loading cycle rather than extended loading schedule. The one-day loading cycles performed equally well or better than the extended loading schedule (tested during Phase-2). The shorter loading cycles may be easier for maintenance and operation.
- Design and construction of RIB facilities should address operation in freezing conditions. In the operation of the pilot RIBs during freezing conditions layers of ice that form during loading would attach to and interfere with the proper operation of the lysimeter and RIB inlet structure. Future designs should be modified to avoid these situations.
- Replenishment of woodchips every 2 years. The column studies suggested that bioavailable material from the woodchips may become limiting after roughly 2.5 years of scheduled operation. This estimate may be conservative, and woodchip depletion may be slower in the field system.

In 2019 Middletown started the process of building nine rapid infiltration basins. Each one of the RIBs will allow the town to dispose of 275,000 gallons of treated wastewater once a week and will help the town keep up with its growth. The total cost of the project is about $2.5 million. It includes a $2.2 million nitrogen removal system that will bring the nitrogen levels down to 10 mg/l before the water goes back into the aquifers and water table. One of the biggest reasons the town opted for the basins is the ability to dispose of wastewater year-round in them.,

Mapping Spray Irrigation Sites: Ritter et al. (2012b) mapped the soils in Delaware for potential spray irrigation sites. They used the criteria of Williams (2006), USDA-NRCS (2012), and DNREC (2004) for mapping potential sites (Table 1). These factors were used to determine not only suitability for spray irrigation, but also area requirements and maximum hydraulic loading rates. Williams and NRCS criteria are similar to each other, however, the minimum K, slope, and depth to seasonal high water are slightly different from those in the DNREC guidelines. Both sets of criteria were the bases for identifying areas that would likely be suitable for spray irrigation.

One of the first processing steps was to select from all soil map units those units that may be suitable for spray irrigation. One set of soil units was identified from the NRCS classification of somewhat limited for slow rate application of wastewater. Similarly, the DNREC suitability criteria for soils were then used to select from all soil map units those NRCS soil map units meeting the DNREC criteria. These results were the basis for all the following processing steps.

Site area requirements were estimated from wastewater flow, typical loading rates, and required setbacks. Following discussions with the Clean Water Advisory Council (CWAC), a 50 acre parcel size, which could potentially accommodate a 200,000 to 350,000 gpd facility, was used to screen parcels. This flow rate is similar to the design capacity of many of the treatment facilities recently built and being planned in the State. Additional area is needed for treatment plants and storage facilities, as well as required setbacks from those facilities. The area requirements for treatment and storage facilities are, of course, dependent on the capacity

Costs for SBRs, membrane bioreactors, biological nutrient removal (BNRs) and spray irrigation were developed for wastewater flows of 0.5, 1.0, 2.0, 5.0 and 15.0 mgd. Capital costs are presented in Table 2. In calculating capital and operation and maintenance costs for the different systems cost data was obtained from various sources. All published cost data was updated to 2019 costs using the Engineering New Record (ENR) construction cost index. Spray irrigation construction costs were calculated by the following equations taken from the EPA

Wastewater Technology fact sheet on Slow Rate Land Application (EPA, 2002).

$$C = 1.71 \text{ x } Q^{0.999}$$

where C = Capital costs, $

Q = Flow rate, MGD

The capital costs include 75 days of storage, center pivot irrigation and transmission pipe distances of up to 2 mile, but not land costs.

Table 1. Comparative Chart Showing Factors Limiting Spray Irrigation Of Treated Wastewater.

Limiting Factor	Williams	DNREC	USDA
Soil Type			
Texture	Medium textured – loamy		
Permeability (vertical)	Moderate or more (.06 – 2.0 in/hr)[1]	Moderately slow or more (.02 to 0.6 in/hr)	> .06 in/hr
Slope			
Row crops	< 12%	< 7%	< 12%
Forage crops	< 12%	< 15%	< 12%
Forests	< 20%	< 30%	< 12%
State Regulated Buffering Distances			
Property boundaries		150 ft	
Perennial lakes or streams		100 ft	2 ft
Channelized,intermittent watercourse		50 ft	
Depth to seasonal high water table		5 ft[2]	
Wetlands		Case-by-case	
State Strategy (Investment Level)			
Level 1	120 gal/day/capita		
Level 2	100 gal/day/capita		
Level 3	75 gal/day/capita		
Storage Capacity			
	45 to 60 days		45 days
Application Rates			
	2.5 in/week	2.5 in/week	
Area Requirements			
		120 – 300 acres[3]	

Costs for BNR systems were calculated by the following equations that were developed for the Chesapeake Bay (Chesapeake Bay Program, 2002):

a. Capital Costs = ((1061.7 x Q) + 205.83) x1000
b. Capital Costs = ((866.49 x Q) + 627.19) x 1000

$$Q = \text{Flow rate, MGD}$$

Costs for SBRs and MBRs were obtained from Costwater (2011)

Table 2. Capital Costs For Different Wastewater Treatment Systems

System	0.5 MGD	1.0 MGD	2.0 MGD	5.0 MGD	15.0 MGD
Spray Irrigation	$1,300,000	$2,596,000	$3,3930,000	$12,8800,000	$38,884,000
SBR	$1,575,000	$3,151,000	$5.313,000	$13,225,000	NA
BNR	$1,177,000	$2.024.000	$3.772.000	$10,025,000	$21,735,000
MBR	$6,869,000	$11,145,000	$19,457,000	$40,496,000	$79,222,000

MARYLAND

Wastewater reuse in Maryland started in the 1940s. Beginning in the 1940s, millions of gallons of treated water from Baltimore City's Back River wastewater treatment plant were diverted daily to the Bethlehem Steel plant to be reused for industrial purposes before being discharged into the Patapsco River. The three dominant types of reuse in Maryland today are for irrigation (55%), cooling water (34%) and groundwater recharge (13%) (MDE, 2019a).

In 2013 there were 33 spray irrigation sites in Maryland. The locations of the spray irrigation sites are shown in Figure 1 (Tien, 2013). Of the 33 systems, 9 are on golf courses and 24 systems on agricultural irrigation of crops or grass. The largest permitted spray irrigation system in Maryland is for 0.75 MGD. The second largest permitted system is for 0.70 MGD. There are 9 spray irrigation systems with design flow rates of 0.20 MGD.

The largest spray irrigation system is in Berlin, Maryland. The town of Berlin in 2009 received $12 million dollars in grants and low-interest loans from the USDA Recovery Act to renovate and update the Berlin wastewater treatment plant. The upgrades included an SBR for nutrient removal. In the upgraded plant the treated effluent is then pumped by pipeline to a spray irrigation site on Purnell Crossing Road in Libertytown, Maryland where it is used to water trees and crops. The town brought a second spray irrigation site in Newark that went online in 2013, which eliminated the need for dumping treated effluent into the coastal bays. The second site cost an additional $6 million.

More recently the Worton-Butlertown plant in Kent County was upgraded to an advanced wastewater treatment plant. The existing lagoon treatment system was upgraded to a 0.25 MGD MBR treatment system capable of generating high quality effluent with concentrations of total nitrogen at, or less than, 4.8 mg/L and total phosphorous concentrations of 0.3 mg/L or less. The treatment process begins with a 2 mm fine screening process. The screened wastewater is then pumped to a modified 4-stage Bardenpho® process and then passes through ultra-filtration membranes, which separate solids from treated water. The treated water then passes through UV disinfection. During the upgrade the Maryland Department of Environment encouraged the County to look for a farm where the wastewater could be applied to crops. As a result, a 10,000 ft of 10-inch PVC force main between the WWTP site and Piccadilly Farm. Treated wastewater is applied to corn and soybeans by five center-pivot irrigation units on 75.5 ac of farmland. The total cost of the wastewater plants upgrades and irrigation infrastructure was $25 million (MDE, 2019b).

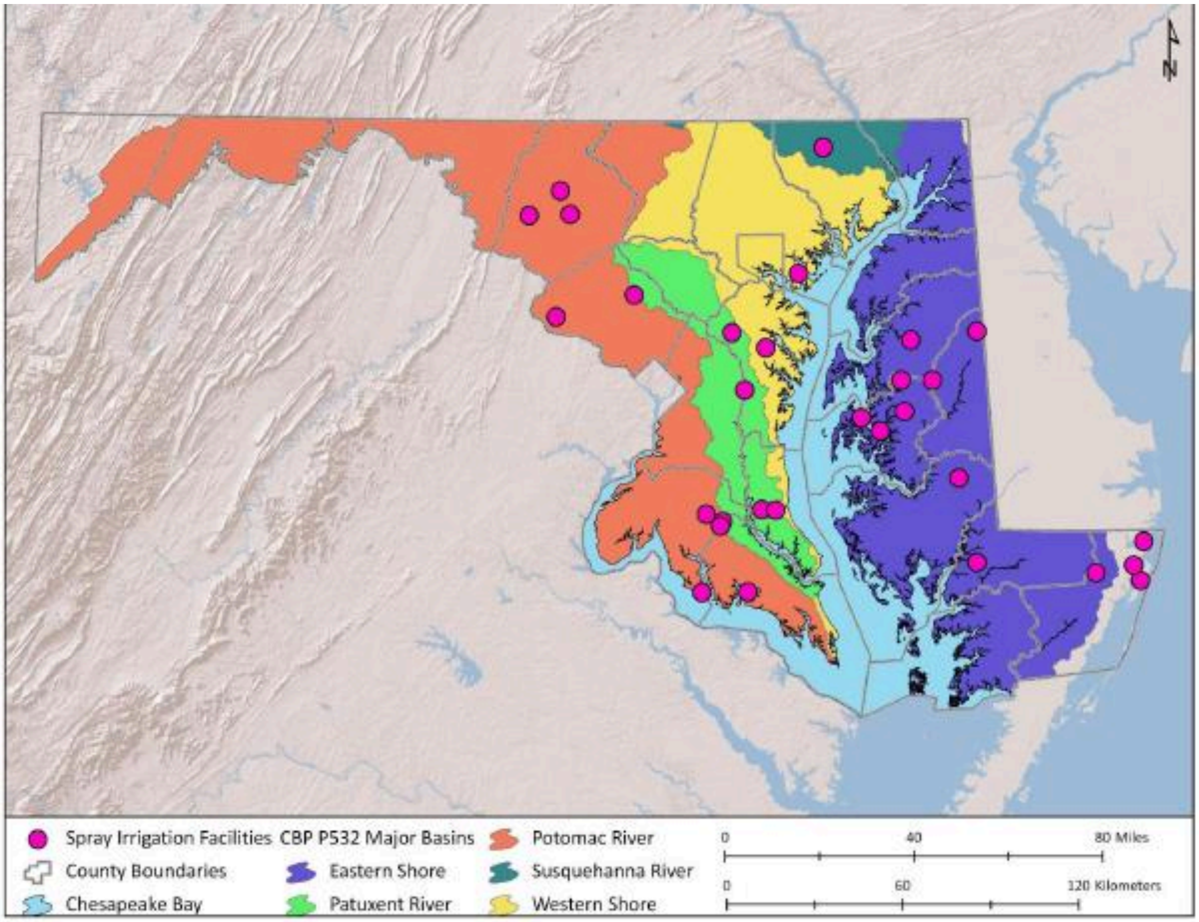

Figure 1. Location Of Land Application Sites In Maryland

Maryland Wastewater Reuse Guidelines: The Maryland guidelines for land application of wastewater were last updated in 2010 (MDE, 2010). For slow rate irrigation there are three classes of wastewater as shown in Table 3. Soils suitable for slow rate irrigation must have a minimum of 4 ft depth to groundwater or bedrock except on the Eastern Shore where a 2 ft depth to groundwater is required. Soils may vary from clay loam to sandy loam with a permeability of from moderately slow to moderately rapid. A maximum slope of 15% for cultivated land and 25% for non-cultivated land is allow. A minimum storage of 60 days is required for all facilities that generate wastewater for the entire year. Buffer zones required are as follows:

- Class I wastewater effluent requires a 200 ft buffer from spray areas to property lines, roads and waterways and a 500 ft buffer for residential properties and parks.
- Class II effluent requires 25 ft buffers from property lines, roads and streams
- Class III rewires buffers of 100 ft potable wells and water intakes

Groundwater quality land application permits requirements are as follows:
Nitrates -10 mg/l
Nitrites – 1.0 mg/l

Total N – 10 mg/l
Fecal coliform – no detection
Chlorides – 250 mg/l
Total dissolved solids – 500 mg/l
The frequency of groundwater monitoring is on case by case basis.

Table 3. Categories Of Effluent For Slow Rate Irrigation

Parameter	Class I	Class II	Class III
BOD	70	10	10
TSS (mg/l monthly average) Or Turbidity in NTU	90	10	Turbidity 2 NTU
Fecal Coliform (MPN/100 ml) monthly geometric mean	200	3	2
pH	6.5 – 8.5	6.5 – 8.5	6.5 – 8.5

Challenges For Wastewater Spray Irrigation: Some of the challenges for land application of wastewater by spray irrigation water reuse include:

- Some years parts of the region may get over 60 in of rainfall. Treatment systems with lagoons have an excessive amount of water to dispose of.
- Farming operations on the site.
- Soil conditions on the site.
- Extensive maintenance of irrigation hardware.
- Delaware and Maryland are a water rich area, so it may be difficult to consider wastewater recycling.
- Sometimes wastewater recycling in only considered in drought conditions.

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Colorado River Basin Governance, Decision Making, and Alternative Approaches

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ABSTRACT

The Colorado River Basin supports agricultural, municipal, industrial, and environmental uses in seven states in the United States and in Mexico. This highly overallocated basin faces significant challenges in managing water and environmental resources under a complex set of compacts, federal laws, court decisions, decrees, contracts, and regulatory guidelines know collectively as the “Law of the River”. This paper highlights several key physical and institutional challenges facing the basin and summarizes the existing institutional processes in place for governance and decision making. The discussion encourages a more holistic approach to management of the Colorado River by integrating management and decision-making from the current program-specific management approach.

INTRODUCTION AND PURPOSE

The Colorado River Basin stretches across seven states and into Mexico and plays a critical role in the social and economic well-being for millions of people and provides extensive environmental benefits. Over 40 million people in the United States rely on the Colorado River and its tributaries to provide agricultural and municipal water supplies. Approximately 5.5 million acres within the United States and nearly 500,000 acres within Mexico are irrigated using Colorado River water (Reclamation, 2012). As one of the most overallocated and highly managed rivers in the United States, the Colorado River faces significant challenges from a growing population and a changing climate. Management of these challenges occurs through a well-established group of binational, federal, state and local agencies. This paper summarizes some of the key challenges facing the basin today and the programs and institutions in place to manage these challenges.

CHALLENGES FACING MANAGEMENT OF THE COLORADO RIVER BASIN

This section introduces several of the key long-term management challenges within the Colorado River Basin. Water supply is under pressure in many areas of the Basin, particularly in the lower basin which has been using its full apportionment for years and has benefitted from unused supplies from the upper basin. A historic drought in the 21st century has further stressed supplies while population has exploded in the American Southwest. There are a number of environmental challenges in the Basin particularly for flows into Mexico from the border to the Colorado River Delta with the Sea of Cortez. The Salton Sea in California has experienced significant reductions in inflows directly related to management decisions required to keep California within its 4.4 million acre-feet allocation. And there is an increasing expectation that tribal and non-governmental organizations should have a larger say in the management of the Colorado River.

Climate change and severed sustained drought

The 2000-2018 period has proven to be the driest extended period on the Colorado River since 1906 with an average annual natural flow at Lee Ferry of 12.4 million acre-feet (Kuhn and Fleck, 2019). This is significantly lower than the long-term 1906-2017 annual average flow of 14.8 million acre-feet, and far below the combined total of 17.5 million acre-feet allocated to water users in the United States and Mexico. These dry conditions led to development of the 2007 Interim Guidelines and 2019 Drought Contingency Plans to find ways of balancing water supplies and demands in the Basin between Lakes Powell and Mead. The Colorado River Basin Water Supply and Demand Study (Reclamation, 2012) considered possible future changes in climate variability and trends from global circulation models, which indicate significant warming trends across the Basin with the median increase in average annual temperature of approximately 4 degrees Fahrenheit by 2055. The global circulation models do not show a significant trend in precipitation. However, the dry conditions experienced over the last two decades have raised questions about the long-term reliability of the Basin even with the measures prescribed in the Drought Contingency Plans.

Population growth

According to the United States Census Bureau, for every decade between 1950 and 2010 the population growth rate in the Desert Southwest (portions of California, Arizona, New Mexico and Texas), was at least twice as great as that for the United States as a whole (https://www.census.gov/library/stories/2019/02/fast-growth-in-desert-southwest-continues.html). Much of this growth has occurred within the Colorado River Basin and areas served by Colorado River water. According to the 2012 Basin Study, the population within the areas receiving Colorado River water was approximately 40 million people in the seven basin states. By 2060, the population is expected to increase to 62 million people under the Current Projected Scenario.

Sustainable Salton Sea management

The Salton Sea is California's largest lake. Thirty-five miles long and fifteen miles wide, the desert lake extends from the Coachella Valley into the Imperial Valley. Though saltier than the ocean, the sea supports an abundance of fish, a food source for millions of migratory birds on the Pacific Flyway. Much of the area within and adjacent to the Sea is below sea level and geologic information suggests a long history of periodic inundation from the shifting delta of the Colorado River or from infrequent storm events (CNRA, 2018). The current Sea was formed in 1905 after an irrigation canal inlet gate failed, allowing the Colorado River to flow unimpeded for 18 months into what is now the Salton Sea. Today, inflows to the Sea are primarily maintained from agricultural runoff in the area and flows from the New and Alamo Rivers originating in Mexico.

Over the last several decades inflows and water levels at the Salton Sea have declined because of climate fluctuations, agricultural conservation measures, cropping practices, and reduced inflows from Mexico (CNRA, 2018). The need for California to maintain its Colorado River water use within its 4.4 million acre-feet allocation, and the 2000-2018 drought experienced in the Colorado River Basin, has encouraged water managers to implement water transfers and water conservation measures such as land fallowing and reuse of agricultural return flows that have reduced inflows to the Sea (QSA, 2003). As the Sea level has declined, salinity concentrations have increased with negative impacts to the fisheries and birds that prey on them. Declining water levels have also exposed Sea floor areas creating dust emissions that worsen air quality for the 650,000 residents in nearby communities and potentially affects millions more residents across Southern California.

Management of endangered species and habitat

The Colorado River serves as a significant source of water for recreational and environmental resources in the Basin States. The riverine corridor and associated historical floodplain compose a significant portion of the remaining aquatic, marsh, and riparian habitat that is vital to many different resident and migratory species including many bird and native fish species that have been listed as endangered under the Federal Endangered Species Act (Reclamation, 2004b). In 1995, U.S. Department of the Interior agencies; water, power, and wildlife resources agencies from Arizona, California, and Nevada; Native American tribes; environmental interests; and recreational interests agreed to form a partnership to develop and implement a long-term endangered species compliance and management program for the historical floodplain of the Lower Colorado River. The Lower Colorado River Multi-Species Conservation Program (LCR MSCP) is a 50-year program to conserve at least 27 species along the lower Colorado River from Lake Mead to the Southerly International Boundary with Mexico (Reclamation, 2004a).

Management of the Colorado River Delta

Since the early 1990's, there has been a long diplomatic and programmatic record through the United States and Mexican Sections of the International Boundary and Water Commission of seeking ways of enhancing the environmental conditions of the Colorado River from the United States Mexico border to the Colorado River Delta at the Sea of Cortez (https://www.ibwc.gov/home.html). Minute No. 306, signed in December 2000, proposed to create a conceptual framework for studies and recommendations concerning the riparian and estuarine ecology of the Colorado River in its limitrophe section and associated delta. Minute No. 319, signed in November 2012, committed the United States to providing funding to support environmental enhancement of riparian areas of the Colorado River, including its delta. The United States and Mexico also committed to conducting a binational cooperative pilot program to generate a pulse flow benefitting the riparian ecosystem and the Colorado River Delta. A pulse flow of approximately 105,000 acre-feet was delivered over an eight-week period that began on March 23, 2014 and ended on May 18, 2014. Peak flows were released early in this period to simulate a spring flood. The United States and Mexico formed the Binational Environmental Work Group to support longer term efforts to create, maintain, and monitor new habitat and provide flows to improve environmental conditions in the Delta as described in Minute No. 323 signed on September 2017.

Stakeholder inclusion

According to the 2012 Colorado River Basin Water Supply and Demand Study, over 40 million people in the United States rely on the Colorado River and its tributaries to provide municipal water supplies. Approximately 5.5 million acres within the United States and nearly 500,000 acres within Mexico are irrigated using Colorado River water. There are 29 federally recognized tribes that depend on the river (Reclamation, 2018). The river supports numerous national wildlife refuges, national recreation areas, and national parks. Hydropower facilities along the river produce abundant power providing much of the Southwest with carbon-free energy.

A key challenge in the Colorado River Basin has been developing a forum to include robust stakeholder outreach and education as part of the decision-making process. Currently, most