Reuse of Treated Municipal Wastewater in Drylands: A Multi-Sector Optimization Analysis

Final Report

Presented to New Mexico Water Resources Research Institute

In Partial Fulfilment of the Completion of the Award of Student Water Research Grants, 2022-2023

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September 2023.

Abstract

The increasing population and need for water in drylands, along with climate change, are exerting extra pressure on freshwater resources. In this study, we develop a multi-sector optimization model at the regional level to explore the economic implications of treated municipal wastewater (TMW) reuse in drylands, using the Middle Rio Grande Basin (MRGB) in New Mexico as a case study. We first develop a theoretical optimization model of TMW reuse across urban, environmental, and agricultural sectors in drylands and then apply the model to the MRGB to identify the optimal allocation of TMW across the three sectors in the basin. We use nonmarket evaluation to estimate the value of water in each sector and use the estimates as inputs to our multi-sector optimization model. Results show that the environmental sector has the highest marginal economic value of water at $1,625/AF, followed by the urban sector at $209/AF and the agricultural sector at $32.08/AF. This suggest that, in the MRGB, TMW reuse should be prioritized for the environmental sector, followed by the urban sector and then the agricultural sector. It further suggests that obtaining information on the economic value of water in different sectors across a region is critical for the optimal allocation of scarce water resources in the region.

Keywords: Wastewater; Reuse; Agriculture; Environment; Urban.
JEL Classification Codes: Q25, Q57

1 INTRODUCTION

Drylands, usually defined as regions with an aridity index (i.e., the ratio of annual precipitation to annual potential evapotranspiration) below 0.65, cover 41% of the global land surface and are home to 38% of the global population (Lu et al., 2018). It consists of different sectors actively competing for limited water resources. The main sectors are agriculture, urban and environmental sectors. The United States Geological Survey (USGS) data reveals that agriculture accounted for 42 percent of the U.S. total freshwater withdrawals in 2015. This water use percentage is much higher in drylands. In New Mexico US, 72% of freshwater withdrawals are for agriculture (USGS, 2015; Dieter, 2018). In Central Asia, annual water withdrawal by agriculture is as high as 93%, and 85% in Northern Africa (Ghahremaninejad et al., 2021). In addition to climate change, the increasing demand for freshwater in drylands by agriculture leaves less freshwater resources for other sectors. The rising demand for limited water resources and the changing climate patterns poses the risk of water scarcity, aridity, and land degradation in the drylands (Castle et al. 2014; Ward et al. 2019).

Freshwater sources in drylands regions of the world often experience seasonal periods of extremely low flow conditions (Medeiros and Maltchik, 1999; McMahon and Finlayson, 2003; Oliva-Paterna et al., 2003). The fluctuation is a characteristic of dryland streams, which have associated environmental, ecological, and societal values. Seasonal variation has posed threats to endangered species and hydrologic connectivity (Jaeger et al., 2014). Hydrologic connectivity, which is the upstream-downstream longitudinal connection of surface water, is recognized as the main driver of freshwater ecosystem structure and function (Bunn et al., 2006; Larned et al., 2009). Hydrologic connectivity is considered fundamental to the survival and persistence of endangered species in drylands (Stanley, et al., 1997; Magoulick and Kobza, 2003). Natural perennial streamflow in the American Southwest has already declined or disappeared completely over the last two centuries (Jaeger et al., 2014), and future temperature warming and altered climate regimes are predicted to further increase aridity and reduce streamflow (Seager et al., 2013). This growing concern is likely to lead to river dryness, aquatic habitat loss and fragmentation, and loss of ecosystems that depend on river flows.

In 2008, urban areas covered about 2% of drylands (Koohafkan and Stewart, 2008), and in 2016, 33% of big cities (including New Delhi, Mexico City, and Cairo) are in drylands. As populations grow, there will be more demand for water for municipal uses including irrigation of green spaces. Ghahremaninejad et al., (2021) note that annual water withdrawal for municipal uses is averaged at 5.3% in Central Asia and 9.0% in Northern Africa. In urban drylands of North America, 59-67% of residential water consumption is used for urban irrigation (Milesi et al., 2009). Urban green spaces provide important ecosystem services to residents.

Urban areas are relatively water resilient because they have the potential advantage of relying on municipal wastewater reuse and desalination for urban water demand (Jain and Jain, 2020). They also have better infrastructure and technology for efficient water consumption (Mahjabin et al., 2018). Despite these, urban areas in drylands face desertification, degradation, and salination. Burell et al., (2020) note that between 1982 and 2015, 15% of drylands turned into deserts by over-exploitation and anthropogenic climatic changes. Identifying and using alternative water sources in drylands is essential for maintaining urban green spaces.

The limited water resources in drylands have led to over-reliance on freshwater sources-surface water and groundwater. For example, the city of Albuquerque in the US over-relied on groundwater due to the dryness of its major river (the Rio Grande River), which led to rapidly depleting groundwater resources in the 1990s. In 2008, an inter-basin water transfer project was completed to divert water from headwater streams to mitigate the river dryness, reduce over-reliance on the over-depleted aquifer, and support water use in the city. Despite the diversion project and other water conservation efforts in the local Middle Rio Grande Basin (MRGB), prolonged droughts and climate change have the potential to reduce snowpack, increase temperatures, and create earlier mountain snow thaws, which all reduce water supplies (Townsend and Gutzler, 2020; Samimi et al., 2020). This suggests that conflicts among water user sectors over water scarcity will increase as the temporal distribution keeps changing. Understanding the implications of these hydroclimatic changes is necessary for alternative water source planning and management in drylands, including the MRGB.

Treated municipal wastewater (TMW) has been reused in the United States since the early 1960s (Asano, 2007). The end uses of TMW can be agricultural irrigation (Toze, 2006), urban irrigation (Fabregat, et al., 2002), aquaculture (Umble and Ketchum, 1997), groundwater recharge (Fournier, et al., 2016), direct potable reuse (Leverenz, et al., 2011) and direct discharge into water bodies (Brooks, et al., 2006; McEneff, et al., 2014). Various studies have explored wastewater reuse in agricultural, urban, and environmental sectors independently. Dinar and Yaron (1986); Dinar et al. (1986); Hussain *et al.* (2001); Winpenny et al. (2010); Kanyoka and Eshtawl (2012) investigate the reuse of treated municipal wastewater for agricultural purposes. The studies find that the use of TMW increases agricultural production. Rahman et al., (2016) and Candela et al., (2007) find that the reuse of TMW could help improve water security and help supply nutrients to golf courses and urban green spaces. The studies caution that the unregulated use of TMW for urban irrigation can pose threats to public health, soil health, and groundwater quality.

Globally, the discharge of TMW to water bodies is becoming more common as urban populations grow. Rivers are among the most altered ecosystems in the world (Hamdhani, et al., 2020). For almost two centuries, large-scale human use of rivers has resulted in poor water quality and ecological degradation in these systems (Vorosmarty et al., 2010). While treated municipal wastewater provides potential use for river ecosystems, there are concerns about the quality of disposed wastewater to rivers (Vaughan and Ormerod, 2012). Rivers receiving TMW are generally called effluent-fed depending on the ratio of effluent-to-natural streamflow (Hamdhani, et al., 2020). Although water quality issues in the effluent-fed river have received much research attention, little to no attention has been dedicated to the use of TMW for additional environmental flow and its economics. According to Brisbane Declaration (2007) environmental flows are the quantity, quality, and timing of water flows required to maintain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems. Apart from using TMW for additional environmental flow, it can serve to enhance baseflow or restore flows to streams or rivers that have dried due to climate change or anthropogenic water withdrawals (Halaburka et al., 2013; Luthy et al., 2015).

In this study, we develop a multi-sector optimization model at the regional level to explore the economic implications of TMW reuse in drylands, using the MRGB in New Mexico as a case study. Specifically, we first develop a theoretical optimization model of TMW reuse across urban, environmental, and agricultural sectors in drylands; then we apply the model to the MRGB and identify the optimal allocation of TMW across the three sectors in the MRGB. Our results suggest that, in the MRGB, TMW should be prioritized for the environmental sector (i.e., to provide additional environmental flow to the Rio Grande River), followed by the urban sector and then the agricultural sector. It further suggests that obtaining information on the economic value of water in different sectors across a region is critical for the optimal allocation of scarce water resources in the region.

This study contributes to the literature on the economics of TMW reuse in the following ways. First, it is the first study that researches extensively into the economics of TMW reuse in drylands by modeling three main water user sectors (agricultural, urban, and environmental) simultaneously. Second, this is the first economic analysis including a case study that considers the agricultural sector as a nutrient sink (which reduces nutrient pollution) as opposed to a nutrient source (which increases nutrient pollution). Last, this study presents empirical examples of nonmarket evaluation methods that can be used to estimate the marginal economic value of water in different sectors in dryland water basins.

2 THEORETICAL MODEL

2.1 Conceptual Framework

Water is generally considered by economists as a public good. This means that water is owned by the public but administered by the government for the benefit of the public. The government has the responsibility to manage and regulate the use of water resources to ensure their sustainability and equitable access and allocation. This also applies to TMW, which could be further considered as a public resource because of its treatment and management by public utilities and agencies that are typically funded by public taxes and funds. This means that the treatment, use, and management of TMW are made in the best interests of the public.

The goal of TMW reuse is to maximize social welfare, thus a social planning approach is appropriate. This is because it provides a framework for evaluating economic decisions and their potential impacts on society. Furthermore, we use this approach because it investigates the collective preference of society instead of individuals or firms. The approach captures externalities and market failures and promotes the optimal allocation of TMW. In order to determine the optimal level of TMW allocation, we introduce the concept of marginal net benefit into our model. This helps us identify the level of TMW allocation that maximizes net social benefits by comparing the additional benefit and cost of a unit (in this case per acre-feet) use of TMW across different sectors.

We construct a theoretical model that investigates the optimal allocation of TMW across urban, agricultural, and environmental sectors in drylands. Figure 1 displays the modeling framework. The model is a simplified representation of a region that comprises economic decision-makers, and the effects of their decisions on residents' welfare and the environment. This is represented in independent but connected sub-models- urban, agricultural, and environmental sub-models.

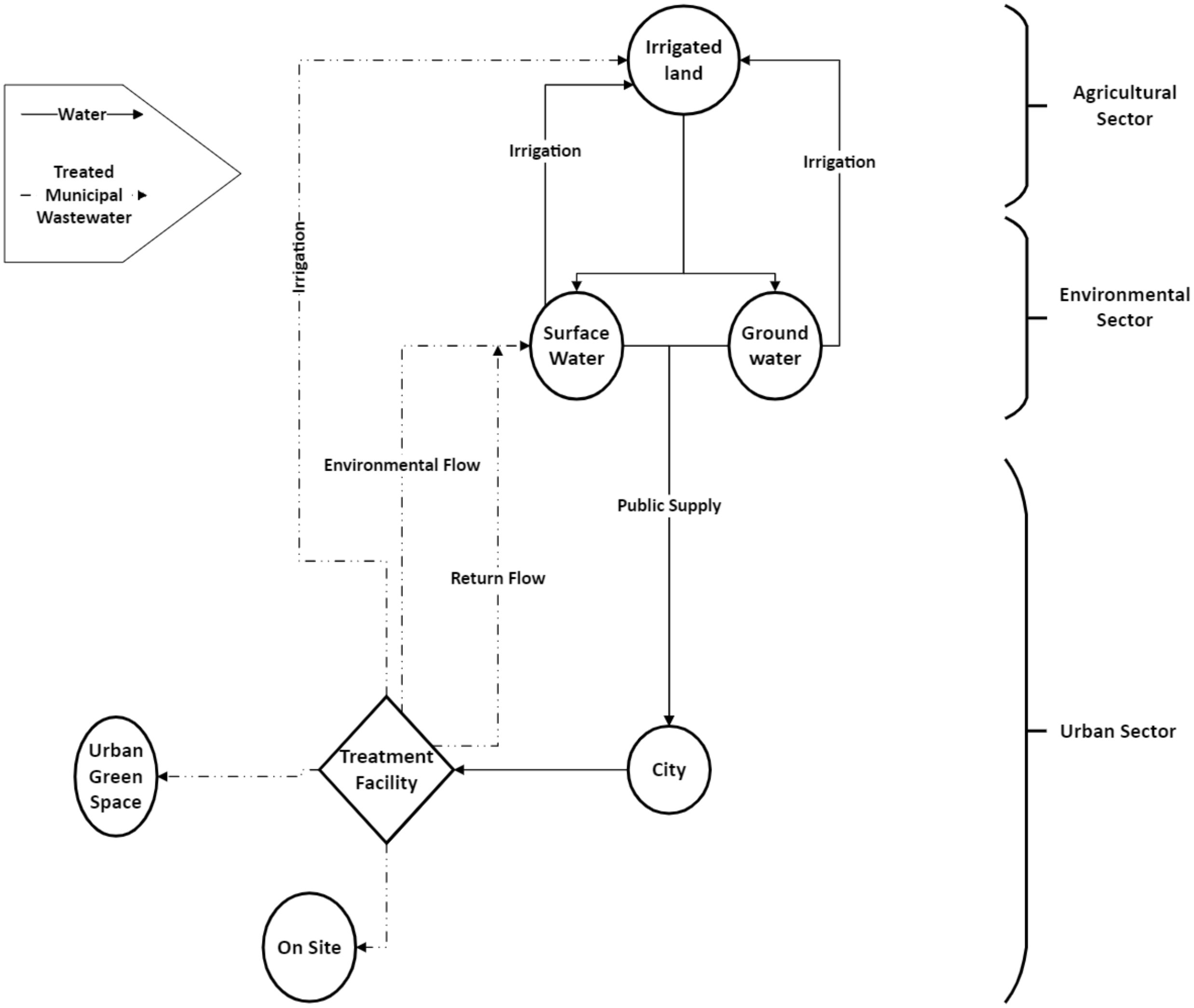

Figure 1: Conceptual Framework

In the urban sector, a share of freshwater (surface water and groundwater) consumed by the residents is passed to a wastewater treatment facility as sewage. The wastewater treatment facility chooses the quality of municipal wastewater to produce as effluent. The effluent can then be reused for on-site usage, urban and/or agricultural irrigation, emitted as or disposed of safely into a waterway as return flow and/or environmental flow. Return flow refers to non-consumptive water (i.e., diverted water not consumed) that can be reused (King, 2008). The water could be from surface water (e.g., rivers) or aquifer systems, but it is not consumed and can be used or recaptured by the local hydrologic system. Return flow to the river helps to support the river ecosystem, riparian systems, and downstream users.

In semi-arid regions such as the western United States including New Mexico, there is water allocation and water rights between shared upstream and downstream users. Water rights define the way a right holder can use water and the relationships between the right holder and others who may have rights or be impacted by that use (Matthews, 2013). Water rights must be considered when water is reallocated. For example, a municipal water user that returns water back to the surface water source can receive return flow credits. These are credits to the water user when a percentage of the total diversion of surface water has been applied to beneficial use pursuant to a water right or permit and returned to the same surface water stream from which it was appropriated (Office of the State Engineer, 2013).

The environmental sector mainly consists of freshwater sources which are surface water and groundwater, and their interactions with other sectors. Surface runoff and percolation are inflows into the freshwater. A major inflow to surface water is TMW, which can be used as return flows and/or additional environmental flows. Return flows help meet regional requirements for downstream water users. Environmental flow reflects the quantity, quality, and timing of water flows required to maintain surface water. This protects endangered aquatic species freshwater, and estuarine/riparian ecosystems, and supports humans, and all that depend on these ecosystems.

In the agricultural sector, farmers can choose water sources (freshwater and treated municipal wastewater), and sources of additional nitrogen supply (treated municipal wastewater and inorganic fertilizers) to maximize their net farm income. The three sub-models are linked to optimizing the net social benefits of the reuse of municipal wastewater across different sectors.

2.2 Agricultural Sector Submodel

The agricultural sector uses water, fertilizer, and other basic inputs for crop production. The main source of water available for the sector is freshwater. The bulk of water used for irrigation, especially in the dry regions, is from freshwater sources. The potential use of treated municipal wastewater by the sector will help to reduce the pressure on freshwater and fertilizer costs. The agricultural sector submodel demonstrates the choice of inputs to maximize benefits in the sector. The freshwater sources are categorized into surface water (s) and groundwater (g).

Therefore, water from h sources is given as $h = [s, g]$.

Total water applied to crop i (AF/year-acre) is given as:

$$W^i = \sum_{h=1}^{H} w_h^i \tag{1}$$

The amount of water s that is delivered to farmland is subject to the water budget/released and conveyance loss. Water budget is the total required water for irrigation in the irrigation season. Equation 2 mathematically defines the surface water delivered ω. Where ϖ is the water released into the irrigation channels and ρ is the irrigation system conveyance efficiency ranging from 0 to 1. We use ϖ as a proxy for water budget because we understand that in various dryland regions, the water budget is not always equal to the water released into the channels.

$$\omega = \varpi\rho \tag{2}$$

Crop i also needs nitrogen[1] for growth and development, therefore, the total nitrogen N^i to crop i is given as:

$$N^i = F^i + \sum_{h=1}^{H} N_h w_h^i \tag{3}$$

F^i is the inorganic nitrogen fertilizer applied to crop i, $N_h w_h^i$ is the total amount of N in each water source w_h applied to crop i, and N_h is the nitrogen concentration in w_h.

Crop yield is dependent on two key inputs, which are total water applied W^i and total nitrogen applied N^i. We explore the Mitscherlich-Baule production equation in (4) for our crop yield production function.

$$Y^i = \beta_1 \left(1 - exp\left(-\beta_2(\beta_3 + N^i)\right)\right)\left(1 - exp\left(-\beta_4(\beta_5 + W^i)\right)\right) \tag{4}$$

The yield Y^i of crop i is measured in tons per acre. β_1 is the maximum yield when neither nitrogen nor water is a limiting factor, β_3 is the residual level of N in the soil prior to fertilization, β_5 is the residual water content in the soil prior to irrigation, $\beta_{2,}$ and β_4 are the regression coefficients.

The farmers maximize their net farm income subject to the water availability constraint by choosing an optimal portfolio of water sources w_h^i and inorganic nitrogen fertilizer F^i, as shown in equation (5). We denote e_h as the cost of water source h ($/acre/year), P^i as the market price of

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[1] In our model, we use nitrogen as the main nutrient in the agricultural sector. The model works for any other single nutrient.

harvested crop i (\$/ton), and P_f as the price of N fertilizer (\$/lb). The total net farm income is calculated by subtracting costs (labor and management cost C^i, operating cost M^i, fertilizer cost $P_f F^i$, and irrigation cost $e_h w_h^i$) from the revenue $P^i Y^i$ over the total area of cultivation A^i.

$$Max_{w_h^i, F^i} \pi^{ag} = \sum_{i=1}^{I} \left(P^i Y^i - C^i - M^i - P_f F^i - \sum_{h=1}^{H} e_h w_h^i \right) A^i \tag{5}$$

subject to

$$\sum_{i=1}^{I} w_s^i A^i \leq \omega$$

We then derive from the model the shadow value of water (i.e., the marginal economic value of water) in the agricultural sector.

2.3 Environmental Submodel

Another possible use of TMW is for release into a river for environmental purposes and shepherded downstream (protected from diversions) in what is referred to as instream flows or environmental flows. River flows serve environmental and human uses. The flows and uses are threatened by adverse climatic conditions especially in the dry/summer season of the year (Brooks et al., 2006). Thus, the release of TMW into the river provides an additional environmental flow to protect river endangered species, ecosystems and enhance river connectivity. Such use might have some combination of nonmarket economic values; these could include both use values (e.g., recreational use either directly in or adjacent to the river) and nonuse values (e.g., for the protection of an endangered species, in what are referred to as "existence values"). If both use and nonuse values are present, then annual household willingness to pay (WTP) for these publicly provided goods must be estimated with stated preference approaches such as the contingent valuation (CV) method.

The additional benefit associated with additional environmental flows in the river is expressed as a willingness to pay θ for environmental flow E. θ is the benefits of E which can be determined by estimating the willingness to pay to protect the minimum instream flow using CV and it is measured in \$/Acre-feet**.** θ is the maximum amount the sector is willing to offer to the treatment facility for E. E is the environmental flow which is a low-quality municipal wastewater[2]. The total benefit to the sector is θE.

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[2] Note that low-quality TMW is adheres acceptable water quality in the region.

2.4 Urban Sector Submodel

As one possible use of TMW from the treatment facility, the model requires an estimate of the value of such water to households and residents in the provision of urban green space, as a publicly provided good. For urban green space, such values would typically be considered nonmarket use values from recreationally visiting or living proximally to green amenities. Within the battery of economic valuation techniques for producing estimates of willingness to pay, both stated preference approaches (such as the survey-based contingent valuation method) and revealed preference approaches (such as the hedonic pricing method (HPM) can be used (Champ et al., 2017). In the absence of an original valuation study, transferring a value estimate (point or range) from a prior study or meta-analysis (known as "benefits transfer") (Rosenberger and Loomis, 2017) are usually used to bridge the data gap in the study. Boyle and Bergstrom (1992) define benefit transfer as "the transfer of existing estimates of non-market values to a new study which is different from the study for which the values were originally estimated". This is a common practice in environmental studies, and we employ the benefit transfer for the valuation of TMW in the provision and maintenance of urban green space.

The WTP per household for urban green spaces such as parks has been extensively studied across the United States and elsewhere (Bishop, 1992; Bowker and Diychuck, 1994; Fleischer and Tsur, 2000; Willis and Whitby, 1985; Tyrvainen, 2001; Kwak et al., 2003; Jim and Chen, 2006; Lindsay and Knapp, 1999; Tajima, 2003; Bolitzer and Netusil, 2000). However, in places or regions where such studies have not been identified benefits transfer approaches must be relied upon. These can include: (i) transferring a point estimate or value range from a closely applicable study; (ii) transferring a benefit function (e.g., $WTP = f(X\beta)$ where X represents the explanatory variables and β the corresponding estimated coefficients) from a closely applicable study, and then calibrating the function (the X values) to our setting; and (iii) calibrating the WTP function from a meta-analysis of prior related analyses (e.g., from CV and HPM studies).

The urban planner aims to maximize the benefits derived from the consumption of urban green spaces by the residents. Thus, the willingness to pay of urban residents (WTP_{urb}) for establishing and maintaining the urban green space needs to be estimated. The total benefit (TB) of using TMW for irrigation of urban green spaces is $TB = WTP_{urb}\, X_{urb}$. Where X_{urb} is the treated municipal wastewater from the treatment facility for irrigation of urban green space.

2.5 The Social Planner

The social planner aims to maximize the net social benefits of the TMW reuse across the urban, agricultural, and environmental sectors. Many publicly owned treatment facilities are not allowed to make positive profits, especially in the United States. Thus, the social planner aims to maximize the social net benefit (not profits) of reusing TMW across different sectors. The planner chooses optimal allocation of TMW for urban irrigation X_{urb}, agricultural irrigation X_{ag}, and environmental flows E while observing the constraints. The net social benefit is defined as the total benefit derived from using TMW across different sectors minus the cost of producing TMW. This is mathematically defined in equation (6).

$$Max_{u,j;\, X_{ag},j;V_j\, E}\, B^{social} = \sum_{j=1}^{J} (X_{urb,j} WTP_{urb} + X_{ag,j}\lambda) + \theta E - k_n \sum_{j=1}^{J} V_j n_j \tag{6}$$

subject to

$$\sum_{j=1}^{J} V_j \leq \overline{T}$$

$$X_{urb,1} + X_{ag,1} + X_{on} \leq V_1$$

$$X_{ag,2} + X_r + E \leq V_2$$

$$X_{urb,2} = 0$$

$$X_r \geq \overline{R}$$

$$V_2 N_{v_2} \leq\ L$$

The treatment facility can send high-quality municipal wastewater for urban and agricultural irrigation, and on-site uses. Low-quality municipal wastewater can be sent for agricultural irrigation, river return flow and environmental flow. Due to environmental restrictions, low-quality municipal wastewater cannot be used for urban irrigation. Therefore, we categorize TMW j into two sub-categories based on water quality[3], high-quality j_1 and low-quality j_2. λ is the shadow value from the agricultural submodel, demonstrating the value of water in the agricultural sector. L is maximum allowed nitrogen pollution in effluent as stated in discharge permit to the treatment facility, $X_r N_r \leq\ L$. N_{v_2} is the nitrogen concentration in return flow to the

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[3] In our model, we categorize water quality based on the nitrogen content in the treated municipal wastewater.

low-quality effluent, k_n is the unit cost of N removal, n_j is the amount of nitrogen reduction, and V_j is the volume of TMW. $\overline{T}$ is the influent, total water that flow into the treatment facility for treatment. $\overline{R}$ is the return flow requirement. The social planner maximizes the social net benefits from the treatment facility by choosing the quantity and quality of municipal wastewater to produce and send for urban irrigation, agricultural irrigation, river flow, environmental flow and on-site usage. The volume of municipal wastewater produced should be less than or equal to the influent. The nutrient load in the low-quality TMW should not be more than the allowable load in the region. Return flow should be greater than or equal to the requirement.

3 CASE STUDY and DATA

3.1 Middle Rio Grande Basin

Our study area is the Middle Rio Grande (MRG) Basin. This is a purposeful selection because of its climatic composition and its proximity to the research institution The MRG basin is within the Rio Grande Valley extending from about Cochiti Lake downstream to about San Acacia. It covers approximately 3,060 square miles in central New Mexico, encompassing parts of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola Counties, and includes a ground-water basin composed of the Santa Fe Group aquifer system (USGS, 2005). The climate over most of the basin is semiarid. MRG basin is the most densely populated region in New Mexico and contains more than half of New Mexico’s population, most of whom live in the cities and towns of Albuquerque, Santa Fe, Rio Rancho, Belen, and Socorro. This suggests that a lot of urban activities go on in the basin. Most of Bernalillo, Sandoval, Valencia, Socorro counties fall within the Middle Rio Grande. There are four reservoirs in the basin, they are Nambe, Cochiti, Jemez and Galisteo reservoirs (Office of the State Engineer, 2023). The basin has agricultural activities and it is dedicated to protecting the endangered silvery minnows and southwester willow flycatcher. Currently (2023) the source of public water supply is freshwater (surface water and groundwater).

The surface water is Rio Grande River and through the San Juan Chama project, which get water from the Colorado river.. The San Juan Chama project provides the city of Albuquerque with 20,900 acre-feet of water annually. This project has helped to reduce restrictions on the use of TMW by the Albuquerque Water Authority. Another source of water in the basin is groundwater from the aquifers.

3.2 Agricultural sector

The major crops cultivated by acreage in the MRGB are alfalfa, small grain hay, corn and wheat. The maximum yields of these crops are in Lauriautt *et al.,* (2020), Scott *et al.,* (2019), and Marsalis *et al*., (2020). Their results are consistent with NM Agricultural Statistics report 2018 - 2020, United State Department of Agriculture (USDA) annual report and the New Mexico State University (NMSU) enterprise budgets (2018 and 2019). The water and nitrogen requirements per acre are from NMSU published enterprise budgets (2020), Scott *et al.,* (2019), and Marsalis *et al*., (2020). The initial soil water content prior to irrigation was gotten from the OpenET software package. The software package is an online publicly available water management tool that uses data from Landsat, Sentinel-2, GOES, and other satellites; weather station networks and models; and field boundary and crop type datasets. Marsalis *et al*., (2020) provides the initial soil nitrogen before fertilization.

United States Geology Survey (USGS) provides historical water data on the water budgets. Water budget is averaged over 2018 to 2020. The administrative charge for surface water for agricultural irrigation in the basin is $43.83 per acre per year and it is gotten MRGCD’s website. Ward (2014) estimates the price of groundwater pumping per acre-foot to be $90 (in 2013 $ value) (approximately $102 per acre-foot in $2020). The prices of crop yields at farmgate are averages from the 2018- 2020 NM Agricultural Statistics. The cost of labor and management, operating costs, and the price of inorganic nitrogen fertilizer (in $/lb) are gotten from NMSU published enterprise budgets (2018-2019). Fixed costs, land rents, loan serving costs and payment are not included in the model because most of the farmers own their lands, loan payments and fixed costs vary across the basin.

The total acreage for the cultivation of the crops are provided by CropScape. CropScape is a web-based interactive map visualization, dissemination, and querying system for U.S. cropland, which is developed within the USDA's National Agricultural Statistics Service (NASS).

In all the sectors, the dollar values are in 2020-dollar values to account for inflation. The data we have is the best acre-crop-level detailed data we can get for the basin.

Table 1: Detailed data description and source for the Agricultural Submodel.

Variables	Unit	Value	Source
Maximum Crop yield			
Alfalfa	ton/acre	5.97	Lauriautt *et al.*, (2020)
Small grain hay	ton/acre	2.7	Marsalis *et al.*, (2020)
Corn	ton/acre	4.45	Marsalis *et al.*, (2020)
Wheat	ton/acre	1.2	Scott et al., (2019)
Water requirements			
Alfalfa	Ac-in	45 – 60	NMSU enterprise budgets (2020)
Small grain hay	Ac-in	28.67 - 47.0	Marsalis *et al.*, (2020)
Corn	Ac-in	21.3 – 41.0	Marsalis *et al.*, (2020)
Wheat	Ac-in	11.3	Scott et al., (2019)
Nitrogen requirements			
Alfalfa	lb/ac	0	Lauriautt *et al.*, (2020)
Small grain hay	lb/ac	68 – 175	Marsalis *et al.*, (2020)

Corn	lb/ac	288	Marsalis *et al*., (2020)
Wheat	lb/ac	70- 147	Scott et al., (2019)
Initial soil moisture	in	0.5- 3.0	OpenET - https://explore.etdata.org/custom#15/35.0854/-106.6595
Initial soil nitrogen	lb/ac	13.2 - 21.0	Marsalis *et al*., (2020)
Water budget	Ac-ft/year	269,829	USGS, 2015 water report
Prices of harvested crops			
Alfalfa	$/ton	223 – 240	2018 - 2020 NM Annual Bulletin
Small grain hay	$/ton	170 - 215	2018 - 2020 NM Annual Bulletin
Corn	$/bu	3.9 – 4.4	2018 - 2020 NM Annual Bulletin
Wheat	$/bu	4.5 – 5	2018 - 2020 NM Annual Bulletin
Price of N fertilizer	$/lb	0.42 – 0.53	NMSU published enterprise budgets (2018-2019)
Cost of labor			
Alfalfa	$/acre	133.74	NMSU enterprise budgets (2018-2019)
Small grain hay	$/acre	112.52	NMSU enterprise budgets (2018-2019)
Corn	$/acre	79.02	NMSU enterprise budgets (2018-2019)
Wheat	$/acre	54.55	NMSU enterprise budgets (2018-2019)
Operating cost			
Alfalfa	$/acre	311.1	NMSU enterprise budgets (2018-2019)
Small grain hay	$/acre	364.41	NMSU enterprise budgets (2018-2019)
Corn	$/acre	367.52	NMSU enterprise budgets (2018-2019)

Wheat	$/acre	365.13	NMSU enterprise budgets (2018-2019)
Area cultivated			CropScape- https://nassgeodata.gmu.edu/CropScape/
Alfalfa	Acres	18534	CropScape
Small grain hay	Acres	3907	CropScape
Corn	Acres	4177	CropScape
Wheat	Acres	571	CropScape
Administrative charge of surface water	$/ acre/year	43.83	MRGCD’s website
Price of groundwater	$/ acre/year	102	Ward (2014), pg. 120
Conveyance efficiency	%	0.65	USGS Data

3.3 Environmental Sector

In the specific case of the highly engineered Rio Grande running through the Middle Rio Grande (MRG) Valley, the focus of environmental flow provisions has been on the protection of a particular endangered fish. The silvery minnow (*Hybognathus amarus*) was the most abundant fish in the Rio Grande and Pecos River occupying approximately 3,800 river km (2400 mi) in New Mexico and Texas to the Gulf of Mexico (Bestgen and Platania, 1991). *H. amarus* was formally listed as an endangered fish species in 1994 under the US Endangered Species Act and is now found only in the Middle Rio Grande (MRG) (USFWS, 1994). Critical habitat was designated for silvery minnow in 1999 (USFWS, 1999), with revisions published February 19, 2003 (USFWS, 2003). It is now found in the Middle Rio Grande, a 280 km (174 mi) river stretch that runs from Cochiti Dam to the headwaters of Elephant Butte Reservoir. This is 7% of its former range, and its split by three dams into four reaches[4]. Magaña (2012) notes *H. amarus* is confined to about 3.7% of its former range between Angostura diversion dam and south of San Acacia dam, a distance of 141 km (88 mi). In the revised recovery plan, the US Fish and Wildlife Service (USFWS, 2010) reassessed the pressures or threats to the species that can threaten its continued existence in the MRG. These are dewatering and water diversion, water impoundment, river modification, water pollutants, disease, predation and competition, and loss of genetic diversity.

There have been ongoing efforts to improve fish passages and habitat restoration. In the 2003 biological opinion (BiOp)[5], the FWS concluded that it is important to address river drying through targeted flows, fish passages, habitat restoration, and increased channel capacity. In 2013, FWS developed Hydrobiological Objectives (HO) to address the extremely low silvery minnow in MRG. Hydrobiological Objectives consist of possible water management plans for silvery minnow production and survival. The 2016 BiOp provides additional conservation measures for the silvery minnow to the HO. The measures are restoration of river connectivity; big habitat restoration and enhancement; and conservation storage of water. Platania et al., (2019) recommend river connectivity to ensure the recovery of Silvery minnow.

River flows are an important factor in determining river fish survival (Dudley et al., 2016). Archdeacon (2016) notes that high flows during spring significantly increase silvery minnow population, and low flows during summer negatively affect the population significantly. Platania and Dudley (2007) and Archdeacon and Diver-Franssen (2020) confirm that extremely low-flows result in near-complete spawning and recruitment failure of Rio Grande silvery minnow. The Rio Grande Silvery Minnow Population Monitoring Program (Silvery Minnow PMP) uses a statistical

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[4] A reach is that part of a river extending downstream from a given point for which the reach is named to the river's next significant physical feature.

[5] A Biological Opinion is the document the FWS issues that states FWS' opinion as to whether federal action is likely to jeopardize the continued existence of listed species or result in the destruction or adverse modification of critical habitat.

model to monitor the status and trends of Silvery minnow. The model is used to determine the Silvery minnow density from the catch-per-unit effort (CPUE) data (Atkins, 2016). The densities of Silvery minnow have been unstable which calls for salvage activities and augmentation when estimated densities are below 0.1 (Archdeacon et al., 2016).

According to 2001 BiOp issued by FWS on June 29, 2001, the Silvery minnow requires a steady minimum river flow of at least 50 cubic feet per second (cfs)[6] over the San Acacia Diversion Dam in the San Acacia reach of the Rio Grande (USFWS, 2001, p. 10)[7]. Dudley and Platania (2011) did an extensive study on the hydraulic factors that affect Silvery minnow production and survival from 1993-1997 and 1999-2010. The main factors are the number of days with flows and the amount of flows. The results show that Silvery minnow densities are negative affected by flows with less than 200 cfs and 100 cfs in the respective periods, measured at the San Marcial gage. While there are significant increases in the Silvery minnow densities when flows are greater than 2,000 cfs and 3,000 cfs at the respective periods[8], measured at the Albuquerque gage.

The 2016 BiOp seeks to effect actions targeted at the Silvery minnow and its critical habitat. River restoration and conservation storage capacity are two of the actions[9]. The reuse of treated wastewater can help to achieve the objectives.

ABCWUA produces a daily flow of 75.6 cfs (approximately 150 acre-feet per day). The water is currently reused, but not for providing additional environmental flow in the basin. The USGS flow readings at the Albuquerque gate station shows that minimum flows for some days during the summer months are not met in recent years (see figures 2 - 4 in the Appendix).

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[6] 1 cfs = 0.028321 m^3/s)

[7] June 2001 biological opinion established 50 cfs minimum flow requirement at the San Acacia reach from July 1 to October 31.

[8] The results can be found on page 5 and 19 of Dudley and Platania (2011).

[9] Details of the planned actions can be found on Pg 76, 2016 BiOp.

Many studies have investigated the value of protecting minimum river flows for endangered fish species (e.g., Silvery minnow) and downstream users (Berrens, 1996; Ward and Booker, 2006). The CV method has been used to investigate the nonmarket benefits of protecting minimum instream flows[10].

In an initial CV study for New Mexico, Berrens et al., (1996) use a February 1995 survey to estimate the WTP of New Mexico residents to protect minimum instream flows both in their state more broadly and for the MRG specifically. Their estimates show that households have a mean annual WTP of $29 ($50 in $2020 value) per household per year to protect the Silvery minnow in MRG and $90 ($155 in $2020 value) per household per year to protect all the 11 endangered fish species in NM.[11]

Following from the original CV study on the provision of instream flows to protect the silvery minnow, various methodological follow-up CV survey and experimental studies (e.g., testing temporal reliability etc.) have included: Berrens et al., (1998)[12]; Bohara et al. (1998) Berrens et al., (2000)[13]; and Berrens et al. (2002). These studies provide estimates of per median household WTP to provide instream flows in the MRG to help protect the silvery minnow. Most recently, Berrens and Grijalva (2021) then further reviewed a set of meta-analyses (which included the silvery minnow studies), for facilitating the benefit transfer of annual household WTP for endangered species preservation (in the US and internationally). They also calibrated these functions to calculate estimates for the annual household WTP to provide instream flows in the

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[10] Protection of instream flows involves the protection of river ecosystem, fish species and the riparian habitat.

[11] We calculate 95% CI for Berrens et al (1996) estimates. The mean WTP to protect Silvery minnow lies between $42 -$37 per household annually. The mean WTP to protect all 11 endangered species in NM lies between $78-$101 per household annually.

[12] The conditional mean WTP is $94 (95% CI of $76–116) ($161 with 95% CI of $130-$199 in $2020 value). The marginal mean WTP's are $80 (95% CI of $62–97) ($154 with 95% CI of $119 -$187 in $2020 value) for those who voted YES to protect minimum instream flow and −$6 (95% CI of −$14– -$2) (-11 with 95% CI of -$24- -$3.4 in $2020 value) for those who voted NO, respectively. The study uses February 1995 and February 1996 surveys. The WTPs are $2020 value per household per year.

[13] Median annual household values for conditional WTP are approximately $25 ($42.73 in $2020 value) for protecting minimum instream flows in the Middle Rio Grande (specifically targeted to protect the endangered silvery minnow), and approximately $55 ($94.4 in $2020 value) for protecting instream flows on four major New Mexico rivers (with 11 endangered fish species).

MRG to protect the silvery minnow. Berrens and Grijalva (2021)[14] found the mean WTP of households in $2022 to be $26.7 with 95% CI of $9.8-$72 per household per year. Taken together, and accounting for inflation, this leaves us with 2020 $ values for WTP to protect minimum instream flow and endangered species in MRG to range from $37.62 to $72 per household annually.

To help provide a conservative estimate for current use in aggregating WTP, we apply the annual household WTP estimate to the proportion of the surveyed population that expressed a positive WTP; and then apply this to the number of households in the Albuquerque metropolitan statistical area.

To calculate the aggregate total economic value (TEV) we use the annual WTP per household and the total number of households in Albuquerque.[15] According to the 2020 US Census, there were 236,191 households in Albuquerque. Berrens et al., (1996), the first comprehensive WTP study of New Mexico households to protect minimum instream flow estimate that 71% of the surveyed population has positive WTP to protect Silvery minnow by protecting minimum instream flows in the MRG[16]. Taking a conservative approach of assuming that 29% of the population has no WTP to protect minimum instream flows in the MRG, we then generalize that 71% is plausible for our study. This yields about 165,334 households. With an annual WTP per household of $37.62 to $72, the annual total benefit of maintaining the minimum flow in the MRG is $6,219,854 to $ 11,904,026[17].

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[14] Berrens and Grijalva (2021) did meta-analyses on WTP to protect endangered species while exploring Richardson and Loomis's (2009) and Subroy et al.'s (2019) estimated WTPs.

[15] This is a conservative estimate as Albuquerque is the main city in the MRG basin..

[16] 85% of the survey population has predicted positive WTP to protect the 11 endangered species in New Mexico.

[17] We multiply the 165,334households by the WTP per household.

We use USGS data from the Albuquerque gage for 2020 (see Appendix) to calculate the amount of water needed to maintain minimum flows from July 1 to October 31[18]. With the findings of Dudley and Platania (2011), and the mean discharge of 208 cfs (413 Acre-feet per day)[19], a total of 2,792 cfs (5,537 acre-feet per day) is required to protect Silvery minnow in the MRG[20]. Using the annual TEV divided by 5,537 acre-feet of water represents an annual TEV value of water for a minimum instream flow of approximately $1,100 to $2,150 per acre-foot per household. Though the amount of treated wastewater being reused is minimal, it can help to restore river connectivity and conservation storage measures.

Table 2: Environmental Sector Data

Variables	Unit	Value	Source
Maximum N load allowed	lb/yr	950,700	US EPA Pollutant loading website
Nitrogen concentration:			
Surface water	Mg of N/l	6.8	Mortensen et al., (2016)
Groundwater	Mg of N/l	15	Puckett et al., (2011)
Marginal value of water	$/Acre-feet/year	1,100 -2,150	Estimated from Berrens et al., (1996) and other literature

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[18] These are the summer months and most studies have referenced the months as the basis of their analyses.

[19] Conversion link can be found here, https://waterrights.utah.gov/automm/cfs2af.asp

[20] Dudley and Platania (2011) on page vi and 2016 BiOp (page 8, 78) require river flows between 100 cfs and 3,000 cfs at the Albuquerque gage for the survival of Silvery minnow.

3.4 Urban sector

There are studies that have investigated the value of urban greenspace in the US, but we have not identified any study specific to the Albuquerque Metropolitan Statistical area or MRGB. Therefore, we rely on benefits transfer, but caution must be taken when transferring their benefits. These studies use CV and HPM to evaluate the WTP of residents and visitors to establish and conserve urban greenspace in the US (Vaughan, 1981; Hofe et al., 2007; Bolitzer and Netusil 2000; Anderson and West, 2006; Palmquist and Fulcher, 2006; Linsay and Knapp, 1999). Due to the wide range of studies estimates, and to increase the power and precision of the nonmarket value for greenspace, we rely on meta-analysis for the transfer of benefits. In deciding the most suitable meta-analysis study to adopt, we follow the recommendation of Rosenberger and Loomis (2017)[21]. A notable meta-analysis study is by Brander and Koetse (2011) who estimate nonmarket values of urban greenspace across different regions (Europe, Asia, and North America). They use both CV and HPM to estimate the nonmarket value of greenspace across the regions and find regional effects in their estimates. The US states' estimates are not statistically different from zero[22], thus we transfer the point estimate of the CV model from Brander and Koetse (2011).[23] Rosenberger and Loomis (2017) describe five criteria for choosing the most appropriate benefit transfer approach. "*A point estimate transfer may be preferred when the available study site estimates closely match the policy site on (1) the good being valued, including quantity and quality, activity type, resource attributes (e.g., water clarity), or species of interest; (2) the geographic area being evaluated; (3) the affected population and its characteristics; (4) the welfare measure (e.g., property rights assignments, WTP); and (5) the valuation methods used in the study site*

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[21] Table 11.1 in Rosenberger and J.B. Loomis presents the steps in conducting a point estimate value transfer.

[22] Brander and Koetse (2011), figure 1 on page 2767.

[23] We do not use the HPM because it is not well suited for our model and that the dependent variable is measured in percentage change in house prices due to the closeness to open space.

application are conceptually, theoretically, and empirically sound." The point estimate from Brander and Koetse (2011) meets the criteria.

Though estimates from CV and HMP may differ for various reasons, there is no good theoretical justification for the differences (Brander and Koetse, 2011). Woodward and Wui (2001) find that HP studies in their meta-analyses have statistically significantly higher estimates than CV studies. Whereas Ghermandi et al., (2010) find no statistical difference in the estimates from the methods. Our choice of CV estimates is based on, first, we want to determine the value for land use planning related to the establishment and conservation of urban green space. Second, CV measures annual WTP values, while HP generally measures static percentage changes in property values. Third, CV can estimate the use and non-use of environmental services that are not responsive to the view of the locations of recipients and resources.[24] While HP captures the value of environmental services that are connected to housing location relative to the location of the resource under consideration. Fourth, the unit of the dependent variable of the CV model in Brander and Koetse (2011) is more suited to our model than the unit of the dependent variable of the HPM in their analysis.

The value of greenspace with 'average'[25] characteristics is approximately 900 US$/acre/year[26] (Brander and Koetse, 2011) with 95% confidence intervals (CI)[27] of $690/acre/year to $1157/acre/year. The standardized unit- US$/acre/year is more convenient to benefit transfer than US$/acre/household or /per visit. It helps to solve the difficulty in identifying

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[24] We are interested in the value the city residents place on greenspace irrespective of their location in the city.

[25] "Average characteristics correspond to the average area (9918 ha), GDP per capita (20,542 US$), and population density (218/km^2) in the meta-data; and the omitted categories of the dummy variables included in the meta regression, namely forests, environmental/agricultural services, other payment vehicles, and open-ended elicitation format"

[26] The estimate in Brander and Koetse (2011) is 1550 US$/ha/year in 2003-dollar prices. We accounted for inflation and converted the value to 2020 $ and US/acre/year. 2.47 acres = 1 hectare. All dollar values are converted to $2020 value using the Consumers Price Index.

[27] We calculate the CI from the data presented in Brander and Koetse (2011).

the size of the population that has WTP for greenspace in the transfer exercise (Brander and Koetse, 2011).

The Albuquerque Water Authority currently uses 1119 acre-feet of treated municipal wastewater at the Puerto Del Sol reservoir for irrigation purposes in the southeastern (SE) part of the city of Albuquerque. An acre of greenspace in an arid region uses approximately 4.3 acre-feet of water annually[28]. This shows that the Albuquerque water authority will be able to irrigate 257 acres of green space with the available treated wastewater. According to Small (2015), the available treated wastewater will irrigate half of the neighborhood parks or all unclassified parks in Albuquerque for a year.[29] With the information about the annual WTP of greenspace and the amount of water needed by an acre of greenspace, we calculate the WTP for TMW. The WTP for TMW to be used for the establishment and conservation of urban greenspace in the MRGB is 209 US$/acre-feet/year within the range of approximately 160 to 270 US$/acre-feet/year[30].

Table 3: Urban Sector Data

Urban submodel			
Variables	Unit	Value	Source
Influent	MGal/day	48	2021 SWRP Effluent and Reuse Flows
Marginal cost of nitrogen removal	$/ton	269	SWRP Internal report
The nonmarket value for water	$/ acre/year	209	Estimated from Brander and Koetse (2011) and other literature

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[28] Keeping vital turf healthy in parks requires one inch of water per week during the summer season. One inch per week equates to about 27,000 gallons of water used per acre (https://www.sanjoseca.gov/home/showpublisheddocument/9669/636656930550200000). We converted 27,000 gallons per week for 52 weeks (assuming it uses a constant water efficiency throughout the year) to 4.30 acre-feet per year.

[29] Table 1 on page 28 in Small (2015) gives the counts and acreage of Albuquerque parks. Neighborhood parks have an acreage of 407 acres and park-all others with an acreage of 217 acres.

[30] The value of greenspace $900/acre/year divided by 4.3 acre-feet required to irrigate a greenspace per year gives $209/acre-feet/year.

River flow requirement	Acre-feet/year	51949	Water Authority Annual Report
High Quality Municipal wastewater	Mg of N/l	4.5	SWRP re-use system 2021 annual reports
Low Quality Municipal wastewater (High N)	Mg of N/l	7.9	Mortensen et al., (2016)

The model is coded in General Algebraic Modelling System (GAMS) and solved with the continuous nonlinear programming CONOPT solver.

4. RESULTS AND DISCUSSIONS

4.1 Agricultural Sector

We estimate the model by maximizing the objective function while considering all the constraints. Four major crops- alfalfa, small grain hay, corn, and wheat in MRGB are used in the optimization model. The sources of irrigation are surface water and groundwater.

Table 4 shows that baseline results of the agricultural sector are validated. The total water used-up in the basin is 175,389 Acre-feet. The agricultural sector makes a net benefit of $19 million from the production and sales of alfalfa, small grain hay, corn, and wheat. Note that capital costs such as land and infrastructure, and loan repayments are not included in the analysis. United States Department of Agriculture (USDA) reports show that over the past two decades the net farm income has been negative in the basin. This is because farming in the basin is mostly hobby farming, that is, farming is not for profit maximization. But farming in Socorro and Valencia counties is for commercial and profit purposes. Crop-county-level data is rare for the basin, but we have access to and use data from Socorro and Valencia counties. The optimization model estimates the value of water in the sector to be $32.08 per acre-foot, which is more than $14.45 per acre-foot water service charge the farmers currently pay in the irrigation district. Our result is close to Ward and Michelsen (2002) who estimate the average value of water in the agricultural sector in the basin at $36 ($53 in 2020 dollar) per acre-foot per year.

Table 4: Baseline Results and Model Validation.

Variables	**Units**	**Optimal**	**Reference**	**Reference source**
Irrigation				
Water applied:				
Surface water				
Alfalfa	ac-in/acre	54.5	45 – 60	NMSU enterprise budgets (2020)
Small Grain Hay	ac-in/acre	39.0	28.67 - 47.0	Marsalis *et al*., (2020)
Corn	ac-in/acre	37.0	21.3 – 41.0	Marsalis *et al*., (2020)
Wheat	ac-in/acre	13.9	14.3 – 17.5	Scott et al., (2019)
Groundwater				
Alfalfa	ac-in/acre	0.0		
Small Grain Hay	ac-in/acre	0.0		
Corn	ac-in/acre	0.0		
Wheat	ac-in/acre	0.0		
Inorganic Nitrogen fertilizer applied				
Alfalfa	lb/ac	0	0	Lauriautt *et al.*, (2020)
Small Grain Hay	lb/ac	173.0	68 – 175	Marsalis *et al*., (2020)
Corn	lb/ac	227.3	288	Marsalis *et al*., (2020)
Wheat	lb/ac	103.8	70- 147	Scott et al., (2019)
Yield				
Alfalfa	ton/ac	5.7	5.97	Lauriautt *et al.*, (2020)
Small Grain Hay	ton/ac	2.2	2.7	Marsalis *et al*., (2020)
Corn	ton/ac	4.1	4.45	Marsalis *et al*., (2020)
Wheat	ton/ac	1.0	1.2	Scott et al., (2019)

Total Agricultural Water Used	AF/year	175,389		
Value of water	$/AF/year	32.08	14.45; 36	MRGCD Website; Ward &Michelsen (2002, pg. 442).
Agricultural benefit	million dollars	19	17.19[31]	2018 - 2020 NM Agricultural Statistics, USDA

Figure 2 shows that Alfalfa production accounts for about 77% of the water applied and wheat production for 1% of the water applied in the basin. Furthermore, alfalfa has a share of 76% of the total nitrogen used in the basin, corn has a share of 12%, small grain hay has 11%, and wheat is 1% of the total nitrogen used in the basin. No additional inorganic N is applied to Alfalfa. The source of N to Alfalfa is the N in the surface water.

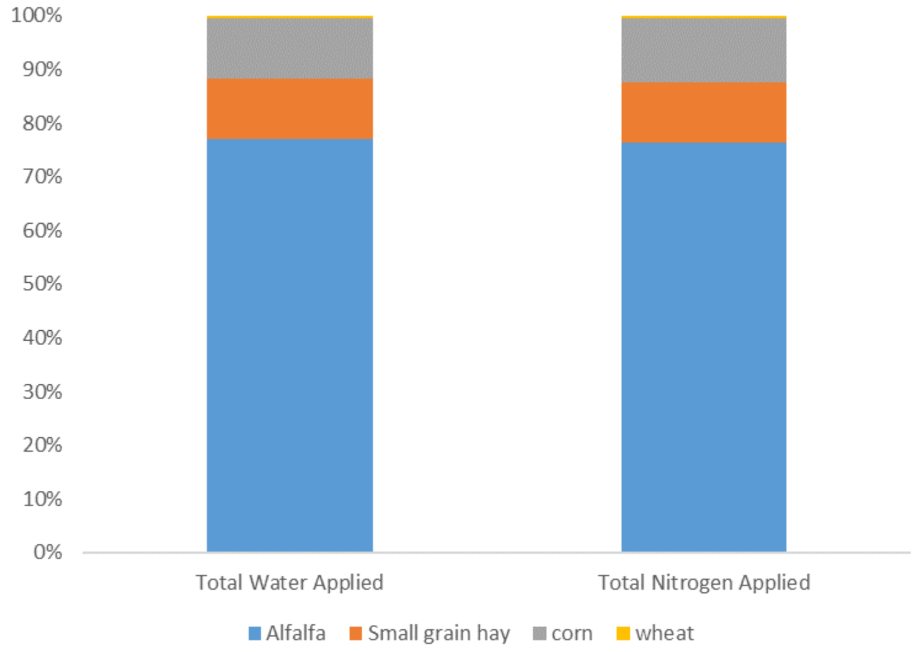

Figure 2: Percentage of total water and nitrogen applied per crop.

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[31] The estimate is calculated from USDA annual report, pages 11 and 12. Page 11 gives farm income indicators including expenses, revenue, and net farm income. Page 12 gives county-based farm revenue. This enables us to calculate the net benefit.

Figure 3 shows the agricultural net benefit per crop per acre. Alfalfa cultivation in the basin gives per acre net income of $691. Though, the agricultural net benefit in the basin is expected to be negative because agriculture in the basin is for hobby-not for commercial purpose, the model net benefit for Alfalfa and Corn are positive, and wheat and small grain hay have negative net benefit per acre..

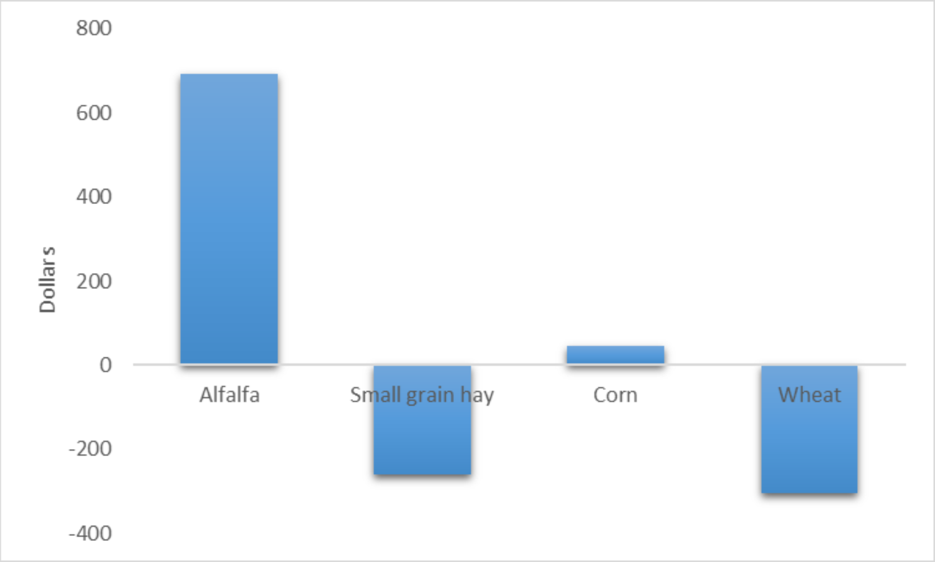

Figure 3: Agricultural net benefit per crop per acre.

4.2 Social Planner

Table 5 shows the optimal allocation of TMW from the social planner's perspective. The result demonstrates that 95% of TMW is used as the required return flow to fulfill the Rio Grande compact. The state of New Mexico is in water debt of the state of Texas, thus the reason for the continuous high percentage of TMW being used as return flow. When the debt is paid in full, the Albuquerque water authority has the liberty to reallocate TMW for social benefit maximization. Three percent (3%) of TMW is used for on-site uses such as plant generation and recycling purposes. The environmental sector gets 2% of TMW for additional environmental flow.

The urban and agricultural sectors have zero allocation from the TMW. The residents value the environmental sector more, with a value of $1,625 per acre-foot of water, as compared to the urban sector which contains green spaces that give recreational and health benefits.

Table 5: Social Planner Results

Variables	Units	Optimal	Reference	Reference source
Production of treated wastewater				
High quality	ac-ft	2711		
Low quality	ac-ft	51949		
Allocation of treated wastewater				
urban irrigation	ac-ft/yr	0	1119	SWRP 2021 Annual Report
Agriculture	ac-ft/yr	0	0	SWRP 2021 Annual Report
Return flow	ac-ft/yr	51949	51941.1	SWRP 2021 Annual Report
Environmental flow	Ac-ft/yr	1119	0	SWRP 2021 Annual Report
On-site	Ac-ft/yr	1592	1592.04	SWRP 2021 Annual Report
Net Benefit	dollars	1, 222,348	430,440	ABCWUA Financial Report, 2021, pages 28&29[32].

The social net benefit of reusing TMW is $1.22 million, which is much higher than the $0.43 million revenue from the current sales of TMW in the basin. This further confirms the importance of evaluation study to allocating resources. If the social planner or non-governmental agency is willing to buy TMW at a nonmarket value, the residents and the society benefit more. There is a need for further research to compare the policy implications of buying additional environmental flow from the agricultural sector and from TMW from the Albuquerque Water Authority.

The model results show the allocation of treated municipal wastewater among different water sectors based on the non-market value of water in each sector. Though the results show that TMW is used for additional environmental flow and none for urban green spaces and agriculture, this is not currently the situation in the basin.. Currently (2023), The Albuquerque

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[32] Table 2 states $1.36 million as net benefit (loss) before capital contributions. On page 29, wastewater system accounts for 31.85% of revenue.

Water Authority reuses 2% (1.5 cfs) of treated wastewater for urban irrigation of urban green spaces[33]. This is because the market price ($678/acre-feet) of treated wastewater for urban green space is greater than its nonmarket value ($209/acre-feet), and no one is buying TMW for additional environmental flow.

Another reason why all the TMW is not sent for additional environmental flow in the basin is that not all the water used for public supply comes from the Rio Grande and groundwater. The Albuquerque Water Authority, therefore, plans to sell more TMW at the malls and commercial centers in addition to the continued uses for urban green space irrigation.

In the hot and dry summer sessions, it is difficult to meet the minimum environmental flow requirements (25 cfs). Water agencies and the government encourage or incentivize water users to leave more water in the river or use less water. The Middle Rio Grande Conservancy District implements the Environmental Water Leasing Program. The program incentivizes farmers who fallow their farmland during the growing season. The participating farmers get $425 per acre[34] ($141.7 per acre-feet per year[35]) each. The saved water (that is water not withdrawn for agricultural production) is left in the river and shepherded downstream for additional environmental flow.

5. CONCLUSION

This study focuses on the economics of TMW reuse in drylands. Literature has explored the reuse of treated municipal wastewater for urban, agricultural purposes, and environmental purposes independently. In this paper, we develop a theoretical framework that explores the reuse of TMW across the urban, agricultural, and environmental sectors simultaneously in dry regions. The sectors are interconnected but independent submodels. Data for the case study are obtained from various sources within the Middle Rio Grande Basin, the New Mexico state, and other regions using the benefit transfer mechanism. We use nonmarket evaluation to estimate the value of water in each sector and use the estimates as inputs to our multi-sector optimization model. The results show that the environmental sector has the highest marginal economic value of water at

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[33] 95% of the treated wastewater goes to the Rio Grande River. This is to fulfill the Rio Grande Compact and to pay water debit to Texas. 3% is reused at the Southside Water Reclamation Plant (SWRP) for industrial purposes. 2% is reused at the Puerto Del Sol Reservoir for urban irrigation. A total of 5% of the treated wastewater is reused. When the debt is fully paid, we expect Water Authority to fully have control of the treated wastewater for reuse in the urban, environmental and agricultural sectors.

[34] To learn more about the program, here is the link, https://www.mrgcd.com/water-leasing-program/

[35] The conversion is based on the USGS data and data from the State Engineer's office stating that the adjudicated consumptive-use water rights is an average of 3 acre-foot of water per acre in the basin (Rio Grande Foundation, 2022). $425 acre/$3 acre-feet per acre gives $141.67 acre-feet.

$1,625/AF, followed by the urban sector at $209/AF and the agricultural sector at $32.08/AF. As a result, in addition to 95% of TMW effluents discharged to surface water as required return flows and 3% used on-site for the wastewater treatment operation, the modeling results suggest all remaining TMW be allocated to the environmental sector to maximize social welfare.

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Budget

Funding organization: NM WRRI
Project Period: 06/01/2022 to 05/31/2023

Cost Category	Total	Justification	Status
Salaries, Wages, and Fringe Benefits			
- Student PI	$2,000	Tosin Olofinsao, an Economics Ph.D. student. He is the student PI and will work for 20 hours a week during the Fall semester intersession of FY 2022. Dec 19, 2022 - Jan 13, 2023.	Funded
- Student PI	$2,500	Tosin Olofinsao, an Economics Ph.D. student. He is the student PI and will work for 20 hours a week during the Spring semester FY 2022. April 1 – May 31, 2023.	Funded
- Fringe benefit and banner tax	$305.18	Fringe benefits for Student PI are based on a 1% rate = $45 https://osp.unm.edu/resources/fringeratesfy22.pdf	Funded
Total Salaries, Wages & fringe benefits	$4,805.18		
Non-Salary			
Travel	$194.82	Travel to a professional meeting by the Student PI. Annual New Mexico Water Conference in Fall 2022 at Las Cruses = $194.92	Funded
Materials and Supplies	$2,500	GAMS Licensing and solvers: $2,500 https://www.gams.com/sales/pricing_academic/	Funded
Total travel costs, materials, and supplies	$2,694.82		
Total budget	$7,500		