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Perspectives on Innovative Approaches in Agriculture to Managing Water Scarcity in the Middle Rio Grande Basin

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Abstract: Water planning and governance strategies must adapt to challenges associated with population growth, climate change, and projected water shortages. In the Western United States, agriculture is the dominant water use, and agricultural water users are being asked to conserve or share their water with other uses. Managing scarce water supplies at the local level often involves creative solutions, many of which are not well documented, especially in the agricultural sector. It is therefore critical to understand ideas to manage scarce water resources from the perspective of agricultural water users and those who work with them. In our research, we used interviews to explore how agricultural water users are managing increasing water scarcity in the Middle Rio Grande basin of central New Mexico and what enables or prevents them from taking innovative action to manage water scarcity. We hypothesized that we would find undocumented water use innovations born out of water users' responses to lower and more variable water availability in recent years. We primarily recruited interviewees through snowball sampling, with a total of 42 (47%) agricultural water users, decision makers, and non-profit leaders influencing agricultural water governance in the basin accepting our invitation to participate. Our approximately one-hour, semi-structured and open-ended interviews explored agricultural water users' lived experiences with water governance and opportunities to manage water scarcity. The interviews were recorded, transcribed, coded, and analyzed using HyperRESEARCH software (version 4.5.4). Our results did not support our hypothesis. Instead, we found that agricultural water users struggled to implement well-known innovations amid the pressures of water scarcity, supply uncertainty, administrative complexity, and constraints on their time, labor, and money. Water users and decision makers were mutually interested in implementing innovations in crop choice, flexibility in water storage, use, and management, stricter enforcement of water use efficiency, and access to more efficient irrigation equipment. However, high costs, a lack of knowledge, education, and training, and challenges related to water distribution and scheduling prevented agricultural water users from accessing these and other innovations. Recommendations include incentive-based policies to promote agricultural water use innovations that require high initial costs, improved water accounting at the basin and regional levels to promote flexible and reliable access to agricultural water, targeted education and outreach programming on alternative irrigation methods and cropping patterns, and improved access to irrigation scheduling information to support agricultural water users in planning for water scarcity.

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1. Introduction

Shortages and competing demands for water are global problems. According to the 2014 World Economic Forum [1], "Water security is one of the most tangible and fastest-growing social, political and economic challenges faced today", and a "fast-unfolding environmental crisis" (p. 6). A global shortfall between the supply and demand for water of 40% is expected by 2030 [1,2], with the highest demand coming from agriculture [3,4]. In global croplands specifically, water scarcity is expected to increase in more than 3% of crop areas by 2050, with up to 21% increases in some regions [4]. Local to regional entities around the globe are grappling with water planning strategies [5], elevating the discussion of water scarcity innovations and solutions to the international level.

The state of New Mexico in the United States (USA) shares concerns around competing demands for increasingly scarce water supplies. While the people of the Rio Grande have irrigated agricultural land in what is now central New Mexico since time immemorial [6], more recent agricultural practices in New Mexico's Middle Rio Grande basin are adapting to an increasingly scarce water supply due to long-term drought and climate change [7]. As supply is decreasing, demand is increasing because of increasing evapotranspiration [7], population growth [8], and legal obligations to provide water for endangered species [8]. Agriculture is the largest water use by sector in the Rio Grande basin [9].

This reflects a larger trend in the Western USA, where agriculture is both the dominant use and under increasing pressure from a number of competing demands of growing populations [10], species concerns [11], and a changing climate [12]. How agricultural communities adapt to climate change and related stresses is a major focus and concern in both the USA and globally [13–15]. In the context of irrigated agriculture specifically, water supplies and associated infrastructure are facing unprecedented challenges related to increasing water scarcity.

The Rio Grande's main water source is spring runoff from mountain snowmelt in northern New Mexico and southern Colorado [16]. Across the globe, 3.5 billion people are reliant on snow-fed rivers to sustain farms and communities [17,18]. Understanding how social and physical systems are changing as less water is available in the Rio Grande can prove useful to other arid and snow-dependent basins facing similar challenges under climate change.

Given the constraints on water resources created by increasing water scarcity and water policy, agricultural water users will inevitably face a future with less water and, in New Mexico, are already experiencing reduced water deliveries [19,20]. As such, agricultural water users face pressure to reduce water use, conserve water, and/or share it with other users. Legal, social, and cultural barriers can make these actions difficult to pursue without the risk of loss of access to water and threats to rural livelihoods and communities [21]. Since agriculture is the dominant water user in the Western USA [22], it is critical to understand ideas to manage scarce water resources from the perspective of agricultural water users and those who work with them.

Various water management actions (e.g., agricultural water conservation and efficiency, water transfer, and shared carry-over storage) and barriers to these actions have been studied in Western USA regions like the Upper Rio Grande basin [23–25], while several other studies [26,27] have examined regional decision-making support systems for irrigation in the Middle Rio Grande basin. However, these did not assess existing agricultural water use and governance innovations in the region, especially within the Middle Rio

Grande of central New Mexico. In this paper, we ask the following: How are agricultural water users managing increasing water scarcity within the Middle Rio Grande, and what factors enable or hinder the adoption of innovative water management practices in the Middle Rio Grande basin? We hypothesized that we would find undocumented water use innovations born out of water users' responses to lower and more variable water availability in recent years. To answer our questions and address our hypothesis, we interviewed farmers and other agricultural water users, decision makers, and non-governmental leaders influencing agricultural water governance in New Mexico's Middle Rio Grande basin. The interviews explored agricultural water users' lived experiences with water governance and opportunities to manage water scarcity. Given the limited published information about innovations in agricultural water use in New Mexico's Middle Rio Grande, the results of this paper will be useful in New Mexico and other places with similar water governance structures and/or water scarcity challenges.

This paper starts with a brief background to provide key concepts and constraints within the study area. It then describes our methods for recruiting, interviewing, and data analysis. Our results and discussion focus on the ability of agricultural water users to pursue innovative actions to manage water scarcity along with the barriers to such actions. We conclude with recommendations for policy change that could help optimize the use of scarce water resources.

2. Background

2.1. The Greater Rio Grande

The Rio Grande is the 20th longest river in the world, the 5th longest in North America, and defines the international boundary between the USA and Mexico. It flows 3051 km across 3700 m of elevation change through a series of structural basins of the Rio Grande rift, from its headwaters in the southern Rocky Mountains to its outlet at the Gulf of Mexico.

The Rio Grande is a critical source of water supply for Mexico, the USA states of Colorado, New Mexico, and Texas, and the sovereign nations of the Navajo Nation and six Native American communities (the Pueblos of Kewa, Cochiti, San Felipe, Santa Ana, Sandia, and Isleta), serving more than 6 million people, 8000 km^2 (800,000 hectares or 2 million acres) of agricultural land, and numerous diverse ecosystems across its basin. Starting in the San Luis mountains of Colorado, the river flows 3000 km (1896 miles) through Alamosa, Colorado, Albuquerque and Las Cruces, New Mexico, El Paso, Laredo, and Brownsville, Texas, and Ciudad Juárez, Nuevo Laredo, Reynosa, Matamoros, and Ojinaga in Mexico [28].

2.2. Study Area and Water Users

New Mexico's Middle Rio Grande basin, hereafter Middle Rio Grande, includes portions of the watershed in the Sandoval, Bernalillo, Valencia, and Socorro counties and roughly aligns with the Middle Rio Grande Conservancy District's (MRGCD's) jurisdiction (Figure 1). Geologically, this area is contained within the Middle Rio Grande structural basin of the Rio Grande rift, which is the largest and oldest of the rift's three major basins, and contains deep (4407 to 6592 m) alluvial sediments of sand and silt, with lesser amounts of clay and gravel [29]. This alluvial fill supports the Santa Fe Group aquifer system, which provides groundwater resources to the region. Participants self-identified as working in or with users in the Middle Rio Grande at the beginning of each interview. Figure 1 displays the boundaries of the MRGCD across the four counties mentioned.

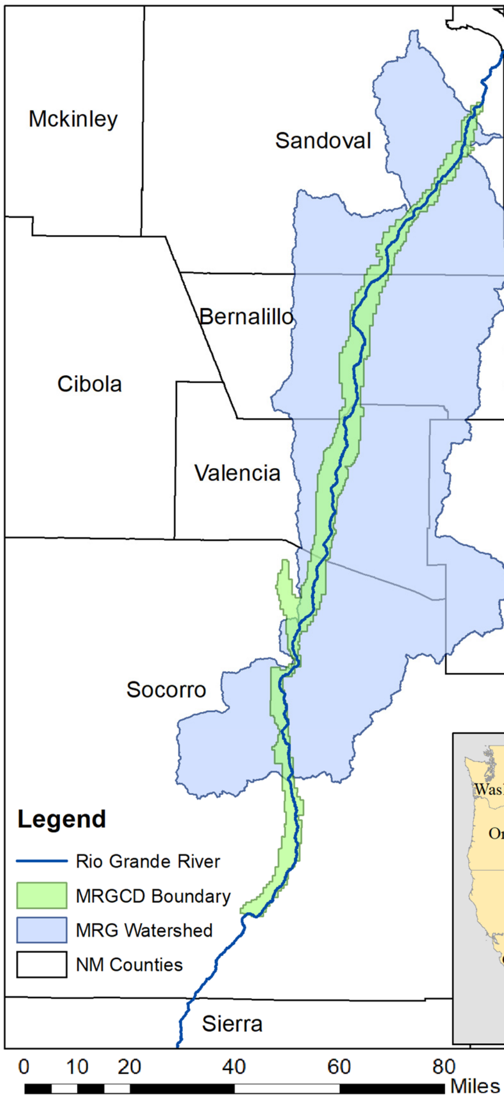

Figure 1. A map of the Middle Rio Grande (MRG) watershed and Middle Rio Grande Conservancy District (MRGCD) jurisdictional boundary in Sandoval, Bernalillo, Valencia, and Socorro counties in central New Mexico (NM).

The Middle Rio Grande is mostly semi-arid desert, receiving an annual mean of less than 250 mm (10 inches) of precipitation [29]. Most agriculture in each county is situated along or close to the Rio Grande [30]. Irrigated agriculture was the largest water use category in the basin, accounting for 75% of total withdrawals in 2015 [9]. The public supply for municipalities is the second largest use, at 17%, as shown in Figure 2.

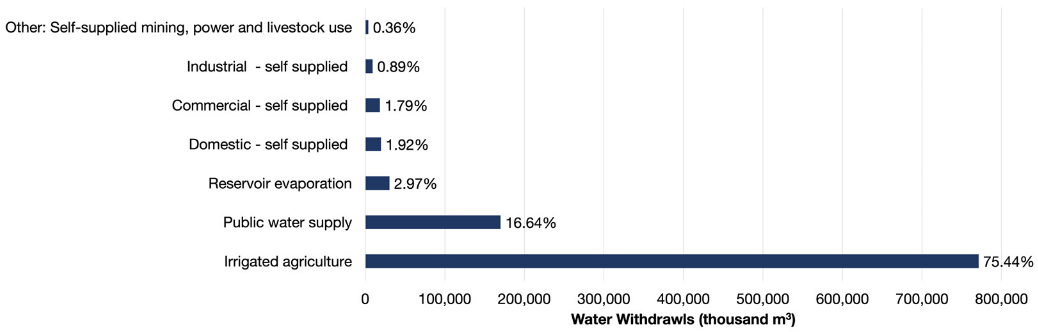

Figure 2. Total annual water withdrawals in four Middle Rio Grande counties (Sandoval, Bernalillo, Valencia, and Socorro) in 2015 [9].

2.3. Agricultural Water Use

The Middle Rio Grande grows a mix of agricultural products, including cattle for meat and dairy production, hay, horses, and vegetables (Table 1 [31]). Alfalfa is a forage crop commonly used in hay [32]. Hay is the primary plant crop by area in all counties (Figure 3 [31]) and the primary crop by sales value in the three counties except Sandoval, where more sales come from vegetable crops (Figure 4 [31]). Due to the arid climate, producers use irrigation to grow most crops. Figure 5 shows that most counties either use only surface water or a combination of surface water and groundwater to irrigate [9]. The proportion of groundwater or surface water used for irrigation varies seasonally depending on drought conditions, with a greater reliance on groundwater in drought years [7]. Socorro County contains larger agricultural operations compared to the three northern counties (Figure 6 [31]), which operate at a net loss (i.e., negative net farm income) at a county-wide scale [31]. Throughout the Middle Rio Grande, some users farm not with the intention to turn a profit, but for lifestyle, pleasure, and cultural tradition [33].

Table 1. Farm characteristics of the four Middle Rio Grande counties, data from USDA (2019).

County	Number of Farms	Land in Farms (Hectares)	Average Farm Size (Hectares)	Net Cash Farm Income (USD)	Most Valuable Commodities
Bernalillo	1248	89,635.9	71.6	−4,776,000	Other crops and hay * and milk from cows
Sandoval	1007	317,162.1	314.8	−513	Cattle and calves, vegetables, and other crops and hay *
Socorro	658	369,266.3	561.3	11,067	Milk from cows and other crops and hay *
Valencia	1360	209,506.8	154.2	−3516	Other crops and hay * and milk from cows, cattle, and calves

* other crops and hay data are for the total market value of all crops not categorized into one of the prelisted crop sales categories in the USDA Census of Agriculture and include hay sales. This category includes crops such as grass seed, hay and grass silage, haylage, greenchop, hemp grown in the open, hops, maple syrup, mint for oil, peanuts, sugarcane, and sugar beets.

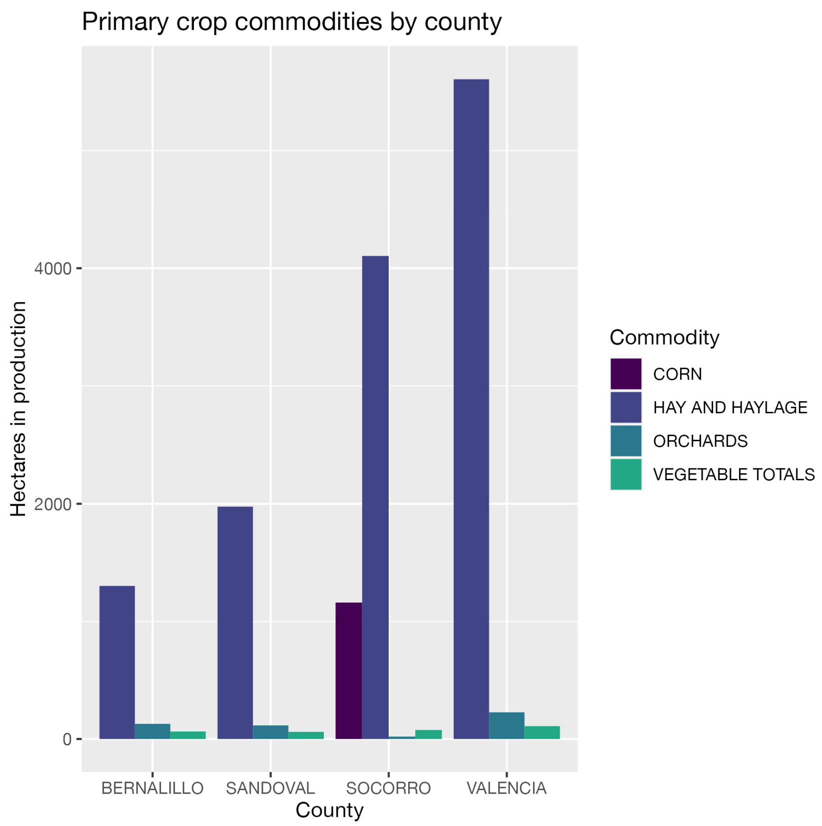

Figure 3. Predominant crops for each Middle Rio Grande county in terms of hectares in production for the four Middle Rio Grande counties [31].

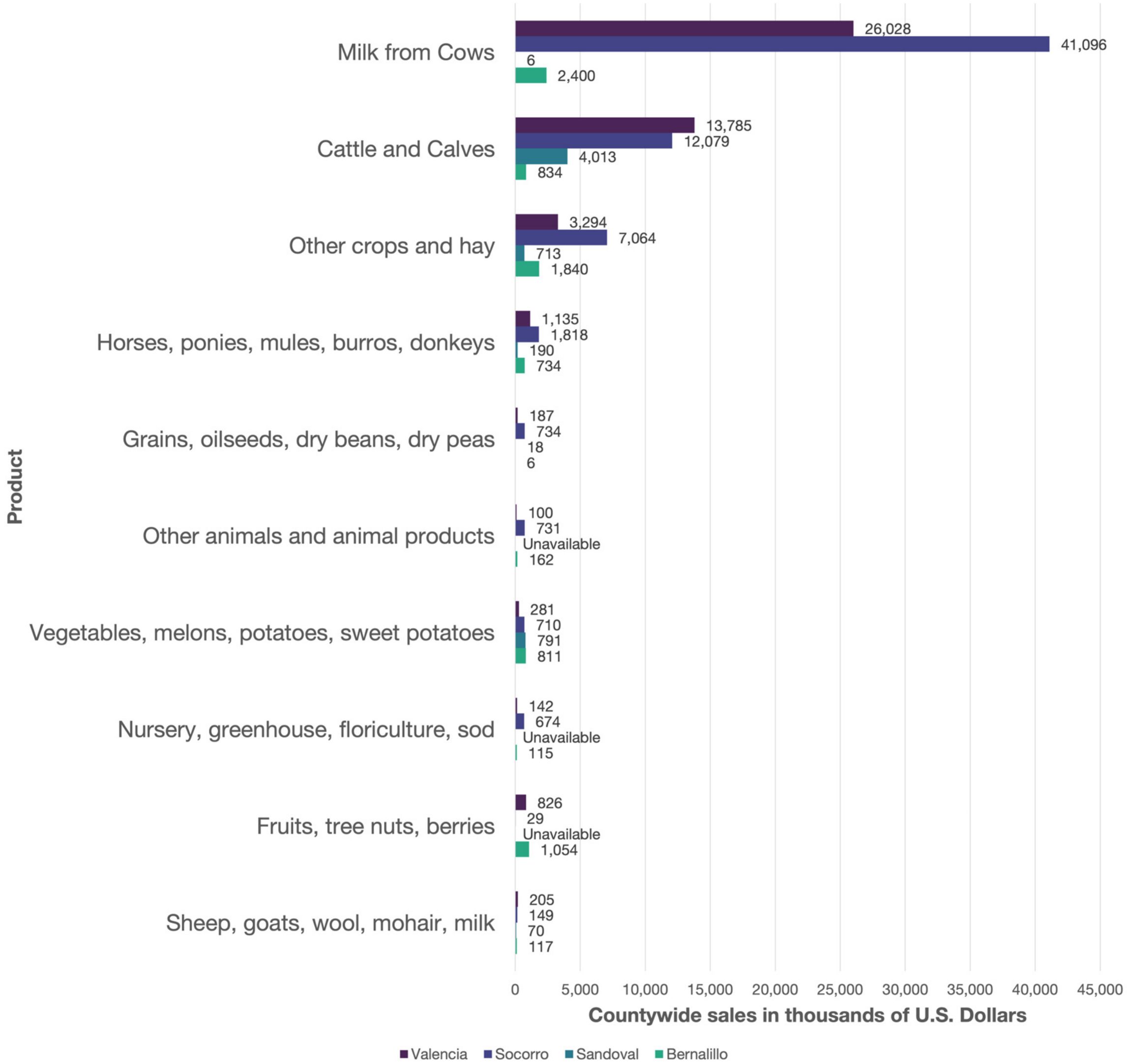

Figure 4. Value of agricultural crops in the Middle Rio Grande valley [31]. Some values are unavailable for Sandoval County to avoid disclosing data for individual operations.

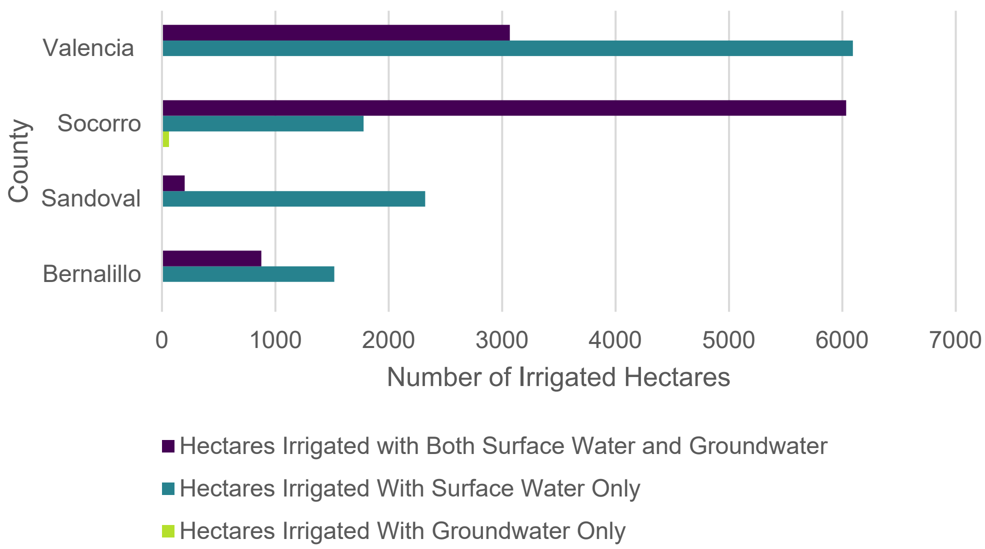

Figure 5. Land irrigated by water source for Middle Rio Grande counties [9].

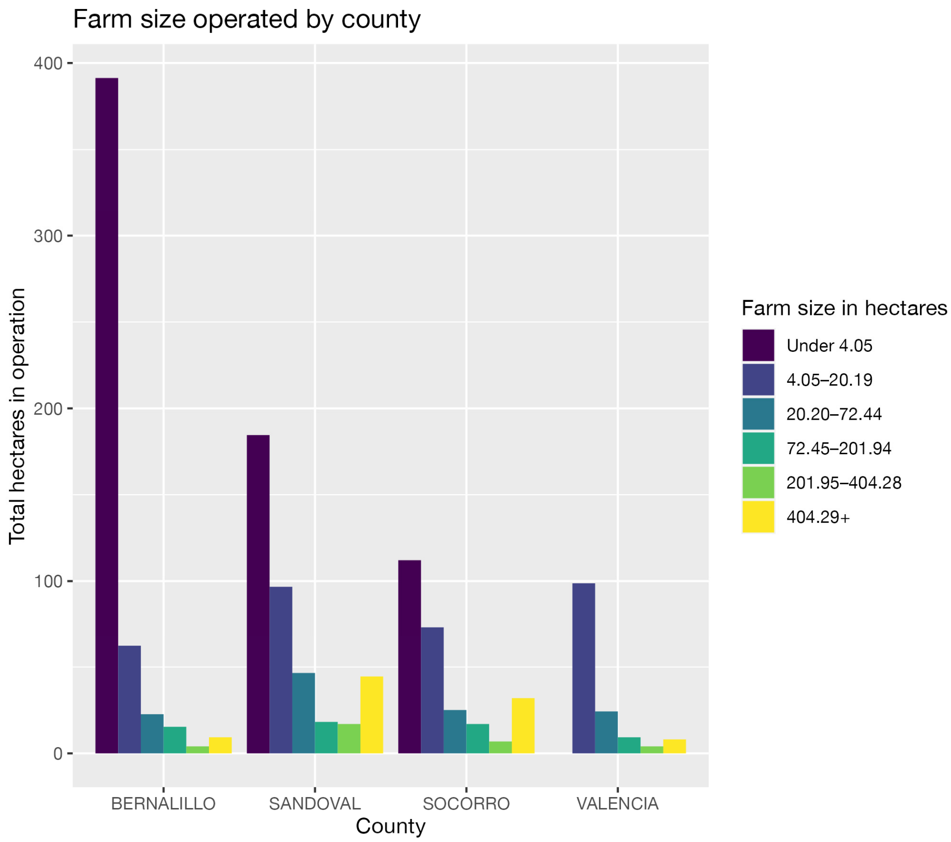

Figure 6. Number of hectares in operation by farm size for the four Middle Rio Grande counties [31].

Water for agriculture in the Middle Rio Grande is primarily managed and delivered by the MRGCD, which was created in 1925 by the state legislature [6]. The MRGCD includes four divisions from north to south, each using a system of ditches, acequias, canals, laterals, and drains as infrastructure to manage and deliver water [34]. More recently, in addition to water delivered to farms, MRGCD has also allocated water for habitat and species conservation. Instream flows in the basin occur by way of agreements between the MRGCD, Reclamation, and the USA Fish and Wildlife Service to comply with Endangered Species Act protections for the Rio Grande Silvery Minnow (*Hybognathus amarus*), a federally endangered species [35]. These deliveries sustain flows for habitats in critical times of the year [36].

2.4. Urbanization and Water Allocation in the Middle Rio Grande

The MRGCD has seen and continues to see urbanization and the transition of rural and agricultural lands into urban and suburban development, reducing the amount of land in agricultural production. This has caused physical and social changes in the district [37]. Between 1982 and 2011, 25.9 million cubic meters (21,000 acre-feet) of water were transferred in the Middle Rio Grande, with most transfers moving agricultural water rights to the cities of Albuquerque, Rio Rancho, and Santa Fe [38]. MRGCD owns most post-1930s water rights in the basin and nearly all major irrigation conveyance infrastructure in the Middle Rio Grande [39], and it creates the irrigation schedules for users.

New Mexico's state constitution recognizes prior appropriation, but the state has historically allocated water using alternatives to priority administration [40], adopting a form of water governance that hybridizes Pueblo, Hispano, and American institutions to allocate water [39]. Pueblo rights for the six Middle Rio Grande Pueblos mean that they receive water preferentially over all other MRGCD lands [41]. Except for Pueblo water, MRGCD administers water in times of scarcity using shortage sharing, distributing water equally to users based on irrigated area, similar to irrigation districts elsewhere [41]. Though New Mexico grants priority to water rights with use pre-dating the state's 1907 Constitution over rights permitted after that date, in times of scarcity, water for these rights is also delivered via shortage sharing and has not historically been administered by priority [42,43]. Under New Mexico statutes, water users forfeit their water rights after four years of non-use and one year after the state engineer gives them notice of non-use, a principle often called "use it or lose it". Today, there are exceptions for water users who temporarily stop using water as part of a state-approved conservation program [44,45].

2.5. Water Obligations Outside of New Mexico, Interbasin Transfers, and Tribal Rights

Two major agreements obligate New Mexico to deliver water to Texas and Mexico downstream. The Rio Grande Compact divides Rio Grande water between Colorado, New Mexico, and Texas annually based on how much water is in the river [46]. An international treaty between the United States and Mexico, the 1906 Convention, requires the United States to deliver 740 million cubic meters (599,929 acre-feet) of water per year to Mexico, with proportional reductions to this obligation in drought years [47].

The basin is unique in that it also benefits from additional water from the Upper Colorado River Compact via an interbasin transfer of water at the San Juan–Chama Diversion Project. The MRGCD is a major recipient of water under the San Juan–Chama Project, receiving a projected 26 million cubic meters (20,900 acre-feet) annually, or approximately 24% of the overall amount delivered [48]. Tribal agreements with the six Native American communities in the Middle Rio Grande also shape the distribution of water in the basin [40]. Based on prior agreements, the six Middle Rio Grande Pueblo communities are recognized as having "Prior and Paramount" rights to water [6].

3. Materials and Methods

3.1. Developing the Interview Questions

The idea for this project developed among faculty at the University of New Mexico in 2021 as discussions increased in intensity among New Mexico water professionals about the need for water reuse, municipal conservation, and other innovations/solutions to drought and future water scarcity in the state. Largely absent from these public discussions were solutions and innovations that might be happening or are possible in the agricultural sector, even though this sector is responsible for a large share of the water use in the state. Based on faculty knowledge from the local news, state water conferences, and interactions with other water professionals, the team developed a set of interview questions to better understand any possible solutions and innovations related to agricultural water use.

The research team pretested the interview questions on experts in Middle Rio Grande water management and agricultural water use to ensure that essential topics were covered, questions would make sense to both decision makers and agricultural water users, and interviews could be conducted in about 30–60 min [49]. The team conducted six pretests, which was sufficient to ensure that all the issues with the questions were addressed and that the topics were on point [50]. The pretests revealed that two sets of interview questions would be needed. They also provided necessary information related to the inner workings of the MRGCD and its shortage-sharing approach to water management, information that was critical to crafting meaningful and relevant interview questions. The research team revised the interview questions based on pretest feedback and finalized two sets of 10 open-ended questions (Appendix A). One set of interview questions aimed to understand the perspective of agricultural water users, and the other targeted the perspectives of water managers and individuals with influence on water governance, such as representatives from water-related nonprofit organizations. Questions considered water use, how decisions related to water use are made, innovations participants would like to make to address water scarcity, and innovations already occurring to address increasing water scarcity. In this study, we defined innovations as informal or formal, new, unconventional, or experimental actions that agricultural water users were performing to make scarce water supplies go farther. The innovations of interest could already be occurring on an agricultural water user's farm or in their community. We also asked about innovations used in other places that users felt could be useful in their area. This study was approved by the Institutional Review Board of the University of New Mexico (protocol #18721, approved with effective date of 5 January 2022).

3.2. Recruiting Participants

Researchers recruited participants at local farmers' markets via flyers posted at local feed stores, from contact information on market and farm websites, and at public meetings that agricultural water users were likely to attend. However, since water use can be a sensitive subject, most participants were recruited via snowball sampling because it can help establish trust between interviewers and participants [51]. With snowball sampling, participants were asked if there was anyone else researchers should speak to, and participants connected researchers to other potential participants in this way. This method allowed researchers to build some degree of trust with potential participants by virtue of the researchers' relationships with the people who already participated in interviews.

Within the time and resource constraints of this project, the researchers exhausted the recruitment options described to contact and invite 89 people to participate. Of the 89 who were invited, 42 (47%) agreed to participate in a total of 39 semi-structured research interviews (three interviews included two participants each). Researchers were satisfied with this number of interviewees given the sensitive nature of the topic, as well as the time and resource constraints of the project. Individuals were eligible to participate if they were over age 18 and fell into one of the following categories: (1) Agricultural water users, such as farmers, ranchers, irrigators, and dairy operators who use water to grow crops and/or livestock. (2) Decision makers (e.g., water managers within the local, state, or federal government) who make decisions directly related to water governance (e.g., issues of water allocation, quality, and use) and individuals who influence water governance in the region without directly managing water in a governmental role (e.g., water lawyers and persons working for non-governmental organizations focused on agriculture or environmental conservation). This group is referred to as decision makers in this study, although it includes participants who do not directly manage water.

Seventeen (17) interviews were conducted with agricultural water users, eighteen (18) interviews were completed with decision makers, and four interviews were conducted with participants who fit into both categories.

3.3. Interviews and Analysis

Interviews took place between March and September 2022. Two researchers conducted interviews by phone, via the video conferencing platform Zoom, and in person, based on the interviewee's preference. The researchers conducted the first five interviews together to establish a consistent approach and conducted the remaining interviews individually. Most interviews took 45–60 min, but the length ranged from 23 min to 2 h. Participants were asked to create a descriptor for themselves that identified them anonymously. For example, in place of a participant's name, they might have chosen to be identified as "Middle Rio Grande farmer" or "irrigator". Interview results were anonymized by using these descriptors in place of participants' names, removing references to neighboring farms and retracting information identifying their specific position of employment or farm.

Researchers recorded all interviews using a digital audio recorder. This recording generated an initial transcript using Sonix AI, a service that uses artificial intelligence to transcribe audio. A research team member then listened to and corrected the software-generated transcript to create an accurate transcript for analysis. Another team member reviewed the transcript once more to remove identifying information and verify accuracy before uploading it to qualitative analysis software. Two researchers then coded the finalized transcripts in HyperRESEARCH (version 4.5.4), a qualitative data analysis software. An initial codebook was developed by the research team after approximately 30 interviews were completed. The codebook was revised, and individual codes were adjusted as the study progressed. A final codebook was established in March 2023, including detailed descriptions of code applications (Appendix B). To ensure reliability between the two coders, each interview was coded twice: after initial coding by one researcher, the second researcher reviewed coded interviews with the finalized codebook. Disagreements in code application were highlighted and discussed until all codes were agreed upon by both coders in a method similar to "negotiated agreement" described by others [52].

Once researchers coded the transcripts, we selected codes related to responding to water scarcity for further analysis. This coded text, which was related to specific innovations, barriers to innovation, and enabling factors for innovation, was coded a second time, this time identifying innovations that participants wanted to pursue, innovations they disapproved of, and innovations that have been or are being implemented. Innovations that participants disapproved of were not further considered because there was limited consensus on which innovations were undesirable. This second round of coding more specifically focused on where participants discussed barriers and enabling factors alongside their perspectives on these innovations. For codes related to the ability to implement innovations, the number of interviews where a code was used was summed up to understand how often innovations were mentioned by participants and identify the most frequently discussed innovations.

4. Results

4.1. What Innovations Were of Interest to Participants?

A goal of this study was to discover undocumented water use innovations in the Middle Rio Grande. We found that in many cases, the "innovations" that water users implemented, such as drip irrigation and leveling fields, have been used in the basin in the past decade and earlier, but irrigators now have more urgent interest in implementing them due to increasing water scarcity. The innovations that participants most frequently described implementing were switching to different crops, utilizing more efficient equipment, water banking and markets (including a formal "pay-to-fallow" program through the MRGCD), the cooperative management of water, and efforts to improve soil health and moisture (Table 2). Regarding desired innovations not currently practiced, participants described a desire to grow different crops, to utilize groundwater, for additional flexibility in water storage, use, and management, and for the increased enforcement of water use efficiency (Table 3). The most common barriers to implementing innovations included the risk and capital required to make changes, a lack of knowledge, education, and training to implement desired changes, challenges related to a distribution schedule that does not supply water at appropriate times for a given crop, and a cultural practice that maintains the status quo (Table 4). Water users and decision makers discussed these topics with variable frequency (Tables 2–4). Below, we report patterns related to each major theme in more detail, with illustrative quotes and added context where needed to understand interview results.

Table 2. Number of interviews in which participants described implementing desired innovations.

Innovation Code	Total Interviews	Irrigator Interviews	Interviews with Participants Who Are Both Decision Maker and Irrigator	Decision Maker Interviews
crop choices	21	11	4	6
more efficient irrigation equipment—drip irrigation, sprinklers, microsprinklers, etc.	19	9	2	8
water banking, leasing, and markets	18	4	3	11
farm and water cooperatives	17	7	2	8
related to soil health and moisture	17	8	3	6
cost-share programs, tax incentives, and grants/loans for ranchers and farmers	16	4	4	8
leveling/grading	15	7	1	7
using/building wells to ensure supply when needed	15	10	2	3
other innovations in MRG	14	8	1	5
reducing leak lining/concrete ditches and piping	14	6	3	5
better data, research and information about population growth, development, climate, and water supply and use	13	2	0	11
use of Indigenous, permaculture, dry farming, and inter/cover cropping techniques	13	6	2	5
flexibility in water storage and use; management necessary to adapt to climate change and local needs	11	3	1	7

Table 3. Number of interviews in which participants described desired innovations not in practice.

Code	Total Interviews	Irrigator Interviews	Interviews with Participants Who Are Both Decision Maker and Irrigator	Decision Maker Interviews
crop choices	21	9	2	10
using/building wells to ensure supply when needed	15	9	3	3
flexibility in water storage and use; management necessary to adapt to climate change and local needs	14	4	3	7
stricter enforcement of water use efficiency	14	4	3	7
innovations elsewhere	14	4	1	9
better data, research and information about population growth, development, climate, and water supply and use	13	3	1	9
more efficient irrigation equipment—drip irrigation, sprinklers, microsprinklers, etc.	13	5	1	7
other innovations in MRG	13	7	1	5
lack of, gaining, or sharing knowledge/education/training	13	6	2	5
related to soil health and moisture	12	6	2	4
cost-share programs, tax incentives, and grants/loans for ranchers and farmers	10	2	3	5
water banking, leasing, and markets	10	3	1	6

Table 4. Number of interviews in which participants described barriers to innovation.

Barrier Code	Total Interviews	Irrigator Interviews	Interviews with Participants Who Are Both Decision Maker and Irrigator	Decision Maker Interviews
innovation requires access to capital/resources, risk, new tools, equipment, and changing land	35	15	4	16
lack of, gaining, or sharing knowledge/education/training	26	9	3	14
current water distribution schedule does not work for desired crop	25	16	3	6
cultural practice prevents innovation	23	7	1	15
need more time/labor or innovation reduced time/labor needed	21	9	3	9
market challenges in changing crops	18	6	3	9

Table 4. *Cont.*

Barrier Code	Total Interviews	Irrigator Interviews	Interviews with Participants Who Are Both Decision Maker and Irrigator	Decision Maker Interviews
bureaucracy moves too slow	12	3	1	8
lack of capacity to go after funding	9	2	3	4
forward contracts, subsidies, and crop insurance	2	0	1	1

4.2. Crop Changes

Given that a change in crops was both the most implemented and most desired innovation, further analysis focused on barriers and enabling factors that impact a producer's ability to make different crop choices.

Producers who made crop changes described these shifts in their cropping decisions:

- Growing spring, fall, or winter crops (such as garlic and winter oats) in place of the summer growing season. This practice could also be used as part of a plan to fallow a portion of their farmed land.
- Shifting from alfalfa to drought-resistant grasses, such as fescue, blue grama, Sudan grass, and teff grass.
- Adopting more drought-tolerant specialty crops, such as drought-tolerant varieties of eggplant and cucumbers, tepary beans, and Chinese dates.

Agricultural water users and decision makers described some changes they would like to see implemented that currently do not seem feasible:

- Shifting to grain crops consumed by humans, such as barley or quinoa.
- Implementing new equipment or infrastructure to support more efficient irrigation of vegetable and specialty crops in rows as an alternative to flooding forage crops.
- Encouraging Pueblos, who hold the most senior water rights, to grow food crops for human consumption.
- Implementation of regionally appropriate agroforestry and other practices to provide shade and wind breaks for farmland.

Interviewees described how agricultural producers face barriers related to financial capital, infrastructure, and access to water that prevent them from implementing the above changes. Most participants described the capital required and the financial risk involved in changing crops as a barrier to pursuing desired actions. For example, new equipment may be needed to irrigate or harvest a new crop, adding to the expense of a transition. Wells may improve access to water, but they are both bureaucratically and financially intensive to pursue. Further, investing time, labor, and money into alternative crops during times of decreased water availability was seen as a risky endeavor, since insufficient or ill-timed irrigation water could reduce or eliminate crop yields.

4.3. Marketing Other Crops

Some specialty crops require less water, but there is not currently a market for them, making agricultural water users reluctant to experiment with growing them. Water users growing specialty crops explained a need to build consumer awareness about crops that shoppers may not be familiar with. A restoration practitioner explained that they had to work to develop consumer knowledge of the local crops that they were producing:

> *Chefs, you know, local producers, value added producers, farmers market, you know, that all just takes a different look, because things look different, right? "Oh, I want my green bean". Well, here's something different and it can be utilized very similarly. Same with a lot of our native squash varieties, corn as well, being . . . The landrace varieties being*

much quicker to mature and utilizing much less irrigation than maybe a normal hybrid, sweet, or dent corn. So, I think there's a lot of crop choices that we can change.

4.4. Equipment and Labor

Changing irrigation practices or crop type can increase the amount of labor and production costs required to grow crops. This creates a tradeoff between high production costs and higher-value specialty crops. This can serve as a barrier to adopting new strategies, as explained by a water manager and irrigator:

> *I myself would change to a specialty crop, but the harvest equipment changes your cost. . .Your tractor implement changes are going to have to be done. Your water needs. It's . . . It's a change. It's definitely a labor intensive . . . Specialty crops are labor intensive. They have to be furrowed crop versus flood irrigation—just flood it, whatever, you're done—but a specialty crop has to be cultivated routinely for weeds, and it has to be watched, and it's more labor.*

After a labor-intensive investment in installing drip irrigation or automatic check gates and flumes, some participants described the payoff of less time and labor required to complete an irrigation. Others described drip irrigation as a burden, working to install and remove drip tape seasonally, protecting drip tape from damage from farm implements, and managing clogs. Agricultural water users also described the investment of time needed to learn about the crops and irrigation practices that they are not familiar with. Participants suggested that peer-to-peer information sharing may support the implementation of innovations in the basin and could reduce the time investment needed for other irrigators in the area. While the example quote below is from a basin water manager, both decision makers and water users identified peer-to-peer information sharing as a mechanism to learn about innovative approaches:

> *You don't know what you don't know, that you can do something different. And so, I think, sometimes it takes somebody to set the example in certain communities. Somebody that's willing to kind of go out and think outside the box or try something different and set that example and show that it's not . . . that these other methods of irrigating or whatever can be done, they can be productive, and that, you know, you can still make money doing it.*

Multiple agricultural water users described learning or sharing information about new techniques with their neighbors. A small urban farmer who utilizes no-till practices described teaching others about the method by hosting informal visits to the farm. A Lemitar horse hay farmer described transitioning from siphon tubes to an underground pipe after seeing it work well on a neighboring farm. The transition reduced the time and amount of labor needed to irrigate, which was particularly helpful for overnight irrigations, reduced damages to the ditch, and allowed for continuous irrigation even when water levels in the ditch changed. One decision maker suggested that experimenting with innovations on even a small portion of a water user's acreage could build confidence in new approaches and, if successful, spread among neighboring farms.

Those who saw a reduction in labor after making on-farm changes were able to invest financial resources in new equipment. This is important because growing alternative crops may require different tractor implements and attachments, fertilizer and other inputs, irrigation infrastructure, and hoop houses. An inability to cover these costs can limit agricultural water users' ability to experiment with new practices, making it easier to continue growing what they already have the equipment to grow. A quote from a livestock grower illustrates how the purchase of equipment for a particular crop can commit an irrigator to that crop:

Say you've got a $250,000 [hay] cutter, which, you know, is a self-propelled cutter. That, new, will cost you $250,000. Okay, so that's more than what the average price of a home now will purchase, so you've already made that investment. You are going to try to continue farming as you can. . .You've got this huge capital investment, and so if you change your mind about what you're doing for a living, now you've got a huge capital investment that you'll liquidate for pennies on the dollar. So, coming and going, getting in and out, changing what you're cropping, all these things cost money.

Similarly, irrigators growing alfalfa described access to storage and new equipment as reasons why they could not manage to grow corn, too:

Well, I started with alfalfa because it was easier, you know, working and stuff. . .And so, we've got the hay cutter, the bailers. And then we were going to try to do corn. But you need to have—if you can't get rid of it, you have to have storage or you're going to lose your [crop], you know, if it's not stored right. And then you have to get a combine or hire somebody. Not very many people around here have combines.

A lack of access to needed equipment also challenges any temporary fallowing of agricultural land, whether formally through a pay-to-fallow program or informally as a farm management decision. Water users described the time and labor challenges of removing weeds from land after a season of fallowing. Multiple participants described the cost to rent or purchase the heavy equipment needed to bring a fallowed field back into production as a barrier to implementing fallowing.

4.5. Cost-Share Programs

Cost-share programs exist to support some innovative actions that improve the delivery of water to crops, such as efficiency-increasing projects to line ditches, upgrade turnouts, and level fields. These programs require an investment of time to learn about requirements and complete the application to receive funding. However, funding is not guaranteed, and a rejected application can leave agricultural users feeling like the process was a wasted effort. In some cases, the financial support offered is not substantial enough to make the project feasible or worthwhile for water users. A water manager and irrigator discussed these problems from the perspective of water users:

They don't want to enter the government system to get assistance because they see it as a long, drawn-out process to get there. It takes time to get on programs to do that, and a lot of times they're turned down, and they don't want to do it. It's just cost and time and effort. But in order to do [efficiencies], you have to do that. It's hard work. It's hard labor, increasing your efficiency and keeping it there.

4.6. Access to Water

Some participants described both water availability and the timing of the availability as critical to whether they could adopt alternative crops, since aspects of MRGCD's water delivery schedule impact what water users are able to grow. The district does not guarantee the number or frequency of irrigation deliveries each year [53]. When the demand for water exceeds supply, the MRGCD delivers irrigation water in a systematic rotation between areas, canals, and water users with a goal of "equitable and efficient distribution" of irrigation water, according to a MRGCD staff member. Irrigation intervals vary with supply, demand, and efficiency under rotational scheduling [54]. At the local scale, users often do not receive an advanced warning of when water will be delivered to them, and some water users face difficulty in being ready to receive water at a moment's notice. MRGCD policies state both that irrigators should contact the district to schedule irrigations about a week in advance but also that water users are expected to be able to receive water 24/7 [41]. One

Middle Rio Grande water user described calling to schedule irrigations a week in advance as recommended by MRGCD and being told they can irrigate that day:

> *I say, "I don't want to irrigate right now. I didn't plan on it". [They say,] "Well, you can irrigate right now. I don't know when you can irrigate at another time".*

This makes it difficult to plan crop types and schedule planting or to project crop yields. With the water delivery schedule becoming increasingly unreliable for users, agricultural water users expressed a desire for a more advanced warning of when they would receive water. A small urban farmer said they wished they could choose a window in which to receive water since irrigation is limited to only a few waterings per year:

> *I wish I had more control over—if I was only going to get one irrigation on the acequia this year, if I was only going to get two—when those would happen. Right now, it's kind of at the whim of whenever they want to give it to us, and we just have to be ready. But if I knew I only had one, let's just say I would really make it count, if I could choose ahead of time...They're kind of telling us it's going to be kind of like a surprise at this point, you know? Which means if I want to seed something, or if I want to seed something drought tolerant to at least cover the soil, I just kind of have to go with faith and luck that I happen to plant it at the right time. Or I might miss the window completely if they call sooner, and they're like, "Surprise! You get it today, and this is your only one!"*

The predictability of irrigation deliveries also suffered in 2022 because the El Vado reservoir, the only upstream reservoir used to store snowmelt runoff for irrigation, could not store water due to maintenance [55]. Without this stored water, users were reliant on monsoonal precipitation contributions to streamflow for late-season irrigation. A MRGCD staff member explained that this makes it difficult to give users advanced notice of when irrigation water will be delivered, as rain events swell the Rio Grande and require irrigators to divert and deliver water on short notice.

Agricultural water users also wanted more transparency about who is receiving water deliveries and when. MRGCD maintains internal logs of disputes and tracks who watered and when, but, at the time of these interviews, these logs were not publicly accessible online (since writing, the MRGCD adopted a system which shows volumetric flow through its lateral ditches, see [56]). Reclamation and MRGCD maintain web-based schematics of flow in MRGCD ditches [41,57]. While these schematics displaying where water is in MRGCD's system are publicly available, they can be difficult for users to interpret, as a Middle Rio Grande water user explained:

> *I look at the water diagrams the MRGCD has, as far as how much water is in the ditches. But, you know, those are not user friendly. They have all these acronyms for identifying what the various canals are and drains are. And I can't make heads or tails of what...what it all means to know where is the water or where it isn't. And they could certainly make that a lot more user-friendly so we could actually figure out, you know...Is there water in the Highline? Or how far down has it come? Or is it all up on the Isleta reservation?*

While water users may not be able to access official information related to who is supposed to be using water in the Middle Rio Grande system, they notice when neighbors are taking water out of turn or using too much water. Some participants expressed frustration when they felt neighbors received water more frequently than they did or that their neighbor was using water inefficiently, as expressed by this livestock grower:

> *I see these guys that...They irrigate their grass every couple of weeks or so, you know. And I'm precluded from doing it but once a month...There's no, there's no quantification of what they did. So, like I said, I think there's nothing like bookkeeping, you know, and accounting to keep people honest. And that's not really happening in a trustworthy way.*

A Middle Rio Grande staff member said that the MRGCD plans to shift from recording water use using paper logs to a mobile platform "to have that information more readily available", which may make progress to address these concerns and build trust among users. They added that technology could enhance the process of water ordering, scheduling, and delivery.

A lack of available water and an inability to control the timing of irrigations have caused some users to stop growing vegetable crops, which require more frequent, shallow waterings than alfalfa and pasture grasses [58]. Many producers who did not have access to groundwater expressed an interest in shifting from surface water irrigation to groundwater or in supplementing surface water with groundwater. Utilizing groundwater provided agricultural water users with better certainty that they would be able to water crops when needed. The use of groundwater also enabled producers to use more efficient irrigation equipment. Several participants discussed how drip irrigation operates best when using water without significant sediment, which can clog drip emitters, and a small amount of water pressure [59], making drip irrigation more feasible with pumped groundwater than the sediment-filled surface waters of the Rio Grande.

However, groundwater is not accessible to everyone. To drill a well, users must supply surface water to reduce the impact that groundwater pumping has on hydrologically connected surface water [60]. In New Mexico, senior water rights holders can transfer their surface water diversion to a groundwater diversion from an aquifer hydrologically connected to the surface water from which they previously diverted. Applications from more junior water rights holders for the same type of transfer may be denied as they are likely to impair more senior water rights [61]. Transferring a water right from surface to groundwater requires users to enter a bureaucratically intensive administrative review process with the Office of the State Engineer (OSE), which as of 2021 takes an average of 8–10 months to complete [62]. Further, if users do not already own a pre-1907 water right, they face competition and high costs to purchase these rights. In 2007, 1233 m^3 (1 acre-foot) of water in the Middle Rio Grande was estimated to cost USD 20,000 to 35,000 [63]. This cost limits groundwater access to those who have inherited or are able to purchase pre-1907 water rights, as this agricultural water user, who had access to wells, explained:

> *With drip irrigation, you have to use—for all practical purposes—well water. One of the biggest strengths that we have is nobody has an ability to drill a well unless they go out and buy a pre-1907 water right, and you're competing against the city of Albuquerque, the city of Rio Rancho, city of Los Lunas. . .I'd say the water today is about $18,000 an acre-foot, and buy three acre-feet of water, hell, that's $54,000. You can't come out. . .These farmers don't have that type of money. So, a lot of the technology is based around pumping water. So those things are pretty astronomically unfeasible here.*

Wells are costly to drill and have continuous operational costs to power and maintain a pump. As a reference point, a hydrogeologist familiar with the area said wells would likely be drilled at a depth of 91 to 366 m (300 to 1200 feet) with costs ranging from USD 3281 to 4922 per meter (USD 1000 to 1500 per foot) of depth. This creates a range of costs from USD 300,000 to 1,800,000 to drill, test, and install a pump in a well [64]. Power supplies and pipelines would require additional costs. Those interested in using groundwater must weigh the cost of diesel, propane, or electricity used to pump a well with the benefits of increased crop yields and a reliable water supply.

5. Discussion

Our results did not support our hypothesis that we would uncover unique and undocumented water use innovations that have arisen out of agricultural water users' adaptation to changing conditions. Rather, we found that agricultural water users were struggling to implement well-known "innovations" under the intense pressures of recent water scarcity and supply uncertainties, complex administrative processes, and constraints on their time, labor, and money. These results are indicative of the complex challenges and opportunities for water management innovation in the Middle Rio Grande basin and other agricultural areas faced with water scarcity. Like many regions globally, our study region faces increasing pressure to optimize water use while balancing the needs of various water users, particularly agricultural users. While there are several promising areas for innovation—including crop diversification, flexible water storage solutions, improved irrigation efficiency, and enhanced water use enforcement—these opportunities come with significant implementation challenges. Cost barriers, technical requirements, and potential unintended consequences must be carefully considered. This section highlights five key points based on the findings and compares them to findings from similar research from other regions. These five points are critical to developing sustainable water management strategies that can address both individual water users' needs and broader regional water conservation goals.

5.1. Areas of Opportunity for Innovation

Areas where water users' and decision makers' goals align present the best starting points for innovation in the basin. According to the innovation frequency counts in this study, these areas involve the following: (1) crop choice (2) flexibility in water storage, use, and management, (3) stricter enforcement of water use efficiency, and (4) access to more efficient irrigation equipment. However, the cost of some of these changes can be high. The amount of time required to learn about and adopt new approaches and labor and equipment needed to grow alternative crops or implement more efficient irrigation is cost prohibitive for many agricultural water users. Cost-share programs for farmers currently present challenges for some farmers, and not all water users are aware of the funding opportunities available to them. Many agricultural water users who do not have wells are interested in incorporating groundwater, or a means of water storage, into their irrigation regimes, but costs or legal requirements related to using groundwater or storing water are a barrier. Similar cost barriers are reported for water users in agricultural regions in Australia [65], Europe [66,67], and Southern Africa [68]. While specifics vary regionally, the complexity of navigating cost-share programs and regulations is a common additional barrier reported by water users across studies.

5.2. Improving Access to Information in the Middle Rio Grande

Existing information displaying where water is in MRGCD's system is confusing to many users. A provision of data about water deliveries to users would serve to improve transparency and might address water users' concerns about equity and transparency, but only if this information is presented in an accessible format.

Both agricultural water users and decision makers mentioned informal information sharing between farmers as a mechanism to impart expertise and implement new practices. Farmer communication networks have similarly been identified as a key mechanism for the spread of innovations in agricultural practices and water management in the Western USA and globally [68–70]. Supporting farmers in sharing information and experience with other farmers may help users learn about and adopt innovative approaches.

5.3. Building Flexibility into Irrigation Scheduling

Irrigation schedules in the Middle Rio Grande are set with a goal of delivering water proportional to the amount of land served. This does not consider the needs of specific crops and soil moisture conditions. Scheduling tied to soil moisture and a plant's specific irrigation requirements might allow for more efficient water use in the Middle Rio Grande basin. A study of pecan fields in El Paso County, Texas, which is downstream of the study area, examined the effect of different irrigation schedules [71]. Irrigation scheduling based on soil moisture was found to decrease the frequency and volume of irrigation water applied without decreasing crop yield compared to an irrigation schedule based on a farmer's intuition or counting the number of days since the previous irrigation. However, shifting to scheduling in these ways may only apply to perennial crops and may not meet management goals to allocate water proportional to the amount of land irrigated.

Some innovations that participants expressed interest in—storage options that would provide water on demand or the use of groundwater for irrigation—provide more control of when they have access to water. Many water users were either already using well water to supplement surface water irrigation from the MRGCD or expressed a desire to use well water, largely because it would enable them to have water based on crop needs and allow the use of drip irrigation. However, operating and maintaining existing wells and pursuing water rights is an expensive and time- and labor-intensive endeavor. Storage, whether on farms in tanks or ponds, or as seasonal carry-over storage in regional reservoirs, may provide the same benefit as allowing water users to water based on crop needs. On-farm water storage has been shown to be a feasible intervention to prevent crop failure in semi-arid areas in sub-Saharan Africa [72] and could provide similar benefits here. Such storage could also reduce MRGCD's difficulty in providing notice that water users will receive water when supply is low or less predictable, which has been the case more often in recent years. Implementing a fair mechanism to deliver stored water on demand may require more complex accounting of water use than currently exists in the basin. The MRGCD is moving toward a more robust, digital system of tracking water use and deliveries in the district, which may support these innovations. In other regions around the world, modernizing water distribution and delivery systems has been shown to make numerous innovations more feasible, including allowing on-demand irrigation, in-network water storage, the conjunctive management of surface and groundwater resources, and a better evaluation of seepage losses and other inefficiencies [73].

Although administration by priority has not historically occurred on a broad scale in the MRGCD, many participants still value the institution of prior appropriation. Owning pre-1907 water rights—the most senior water rights after Pueblo Prior and Paramount water rights—allows water users to shift from surface water to groundwater as an irrigation source. However, the prior appropriation legacy of "use it or lose it" [43] may lead water users to take water when they do not need it.

5.4. Who Can Adopt Alternative Crops and Who Cannot?

The intersection of the barriers above plays a role in a producer's ability to pursue innovations, in particular, the adoption of alternative crops and the more efficient irrigation equipment that supports them. While alfalfa hay is the dominant crop in the basin, producers expressed interest in other forage crops, specialty crops, and vegetables. Those who can invest (1) time in learning about alternative crops and practices, (2) money in equipment and labor (their own or someone else's), and (3) in wells and/or efficient irrigation infrastructure are able to pursue these changes. These barriers to adoption reflect those expressed by farmers globally [74]. One way to address some of these barriers may be the cooperative sharing of equipment needed to change crops or bring a fallowed field back into production. One such example of this was described [75], where dairy producers formed a collective and pooled their investment into new equipment to be shared. Broadly, close partnerships between governments, research institutions, and producers are a proven way to accelerate the development of new markets and overcome production challenges in regions across the world [74].

Vegetables and specialty crops offer a higher value per unit of water compared to pastureland [76]. However, hay crops in the basin sustain the valley's livestock industry and make up the bulk of agricultural sales in the four Middle Rio Grande counties (Figure 4). In addition to the barriers farmers face in adopting vegetable and specialty crops, the combination of an established market, longstanding tradition, already-owned equipment, and the flexibility of alfalfa hay to generate some income in drought years may encourage growers to continue producing alfalfa. Interestingly, while Sandoval County had more land in hay production than any other crop, the county's vegetables have the highest sales value of any crop. It is the only county of the four included in the study area where vegetables make up more sales than hay. If there is a societal or individual desire to adopt more vegetable and specialty crops in the Middle Rio Grande, it may be valuable to examine why and how this is occurring in Sandoval County.

5.5. Negative Impacts of Innovations: The Efficiency Paradox, Groundwater Depletion, and Rio Grande Compact Compliance

The consideration of any action to support innovation should include possible negative or unintended consequences of the action. While more efficient irrigation can improve on-farm productivity, many studies have found that such irrigation practices can increase overall water use [77–81]. Irrigation that applies water at optimal times close to the plant root can increase a crop's consumptive water use and crop yield while reducing runoff and percolation to aquifers. This provides a higher income per unit of land, which benefits individual water users, but the increased overall consumptive use and reduced runoff may have a negative regional impact of reduced return flow and percolation to aquifers [81]. Previous research in Kansas [80] found that implementing efficient irrigation equipment led farmers to adopt more water-intensive crops and increased groundwater depletion. This increase in water use under more efficient practices has been coined the irrigation efficiency paradox [78]. The paradox is that while one might assume that efficient irrigation methods would use less water for crops and leave more water for municipalities, the environment, and other users, studies have shown that it usually does not increase water availability at the basin scale. This is because the water lost from less efficient irrigation practices is recovered to the system for reuse through runoff and groundwater recharge, while there is minimal water lost or recovered when efficient methods are used, with the crops consuming most of the water applied [78]. Table 5 [81] shows a comparison of crop consumptive use and yields using drip and flood irrigation in New Mexico's Lower Rio Grande basin. We see that for every crop type studied, crop water use and yield are higher, but water loss to deep percolation is zero when drip irrigation is used.

As surface water becomes scarcer, surface water irrigators are increasingly seeking groundwater. Historically, New Mexico agricultural water users with wells could rely on aquifers as a rechargeable "water battery", using groundwater in drought years and surface water in wet years. In a changing climate, these periods of recharge and recovery will occur less often, resulting in a decline in the amount of groundwater available [7]. In addition to reduced water availability, lower water tables can increase salinity concentration in shallow groundwater, which stresses agricultural and riparian vegetation [24]. A loss of groundwater also drives desertification and a loss of vegetation, which can contribute to positive feedback loops that further warm the climate and contribute to increasing water scarcity [7,82]. As one conservation practitioner put it, "It's critical for [agricultural water users] to keep the farming community vibrant and alive because it's really part of our culture and a part of our valley, but also, if you lose the farms, you're going to lose the river".

If implemented, the practice of storing water on farms could change the pattern of return flow in the Middle Rio Grande, and without adequate measurement and accounting, could exacerbate problems of real or perceived inequities in water deliveries. Changes to local and regional storage practices could also impact New Mexico's compliance with the Rio Grande Compact. The practices of changing storage regimes, more efficient irrigation practices, and an increased reliance on groundwater must be considered holistically to account for any negative or unintended effects.

Table 5. Water demand and yield of select crops in the Lower Rio Grande, modified from [81].

Crop	Water Applied * (m^3 per Hectare per Year)		Evapotranspiration (m^3 per Hectare per Year)		Deep Percolation (m^3 per Hectare per Year)		Crop Price	Yield Quantity	Yield Quantity per Hectare	
	Flood	**Drip**	**Flood**	**Drip**	**Flood**	**Drip**	**USD per Unit**	**Yield Units**	**Drip**	**Flood**
Alfalfa	15,239.96	8229.58	6705.58	8229.58	8839.18	0.00	130.00	Tons	3.24	4.05
Spring lettuce	7619.98	4267.19	3352.79	4267.19	4267.19	0.00	5.84	Cartons	192.23	240.30
Fall lettuce	10,058.38	5486.39	4267.19	5486.39	5791.19	0.00	6.23	Cartons	202.34	252.93
Fall onions	14,325.57	7619.98	6095.99	7619.98	8229.58	0.00	6.63	Sacks	485.62	607.03
Midseason onions	12,191.97	8839.18	7010.38	8839.18	5181.59	0.00	6.38	Sacks	273.16	341.47
Spring onions	14,630.37	10,363.18	8229.58	10,363.18	6095.99	0.00	6.43	Sacks	333.87	417.35
Grain sorghum	6095.99	3352.79	2743.19	3352.79	3352.79	0.00	3.70	Hundredweight	16.19	20.23
Green chile	14,020.77	7619.98	6095.99	7619.98	7924.78	0.00	285.00	Tons	4.45	5.58
Red chile	15,239.96	8229.58	6705.58	8229.58	8839.18	0.00	0.72	Pounds	1416.40	1770.50
Pecans	18,287.96	9753.58	7924.78	9753.58	10,363.18	0.00	2.28	Pounds	468.67	585.86

* compared to flood irrigation, crop water use (evapotranspiration) and yields increase using drip irrigation for all crop types. Total water applied is approximately equal to the sum of the amount of water used by the crop and lost to deep percolation.

5.6. Study Limitations and Future Research

With 39 interviews, this study does not represent the perspectives of every agricultural water user and decision maker in the Middle Rio Grande. As discussed in the Methods Section, snowball sampling was used due to the sensitivity of the subject matter in an effort to build trust by proxy between interviewers and participants. Snowball sampling may have introduced some selection bias into the study; in speaking to participants who were part of the same network, participants may have been more likely to hold similar opinions about water use in the basin compared to a random sample. Additional research surveying a random sample of agricultural water users and decision makers might have improved the representativeness of our sample but was outside of the scope of this study due to time and resource constraints and the desire to collect in-depth information via individual interviews. The results of this work could inform survey questions mailed to a larger number of agricultural water users to gain a more representative sample.

Also, we had some challenges scheduling interviews in the irrigation season. Interviews took place, in large part, in the spring and summer—the peak of the growing and irrigation season. Contacting agricultural water users outside of the growing season, between October and February, might have yielded higher participation and a more representative sample.

In future research, new questionnaires could be designed to collect more comprehensive data from a large random sample of agricultural water users in the water basin, and more in-depth analyses could be conducted to explore the mechanisms of agricultural water use adaptations.

6. Conclusions

As water scarcity is expected to increase in the Rio Grande basin, agricultural water users will need to innovate and adapt to sustain agricultural production in the Middle Rio Grande basin. Water users and decision makers are mutually interested in implementing innovations in crop choice, flexibility in water storage, use, and management, stricter enforcement of water use efficiency, and access to more efficient irrigation equipment. Prohibitive costs prevent agricultural water users from accessing innovations such as more efficient irrigation equipment, planting and harvesting equipment needed to experiment with new cropping and watering patterns, groundwater wells, or water storage, which would provide more reliable access to water.

Improving access to information could support agricultural water users in planning for increasing water scarcity and increase decision makers' understanding of water use. Some desired innovations, such as more efficient irrigation equipment and an incorporation of more groundwater in irrigation regimes, could have negative consequences for regional water management, which should be considered as users increasingly seek these changes. A more advanced warning of when agricultural users can expect irrigation water and modifications to the irrigation schedule may represent an opportunity to innovate irrigation regimes in the MRGCD. Small-scale local or individual storage or changes to regional storage may provide benefits in granting flexible and reliable access to water. While the current methods of accounting for water use are likely not robust enough to support this change in a fair way, improved water accounting could make this possible.

Based on the findings, three major policy implications are proposed. First, incentive-based or financially motivating public policies including grants and low-interest loans are highly recommended for incentivizing agricultural water use innovations that require prohibitive initial costs. Specifically, policymakers can provide low-interest loans or grants for new equipment and infrastructure (e.g., grants for the purchase of more efficient irrigation equipment, planting and harvesting equipment needed for new cropping or watering patterns, well drilling, and onsite water storage infrastructure) and provide incentives for new cropping patterns (e.g., small grants for seed purchases and farm-to-school programs for crop sales). Second, improving water accounting toward holistic water management at the basin and regional level can provide benefits in granting flexible and reliable access to agricultural water. Lastly, policymakers can also develop targeted education and outreach programs on alternative irrigation methods and cropping patterns (e.g., fostering awareness of grant opportunities and technical assistance to agricultural water users for how to apply for grants).

With increasing water scarcity in the basin, nearly any action one water user takes impacts others. This occurs at multiple scales, from the impact one neighbor has on another, to the impact New Mexico's water use has on water users in Texas and Mexico. Scarcity under climate change is increasing competition for water resources in the Middle Rio Grande. As agriculture is the largest water use sector in the basin, agricultural water users will continue to face societal pressure to conserve water and financial pressure to sell water rights. Sustaining water for agriculture supports not only agricultural water users and those who buy their crops but also New Mexico's tradition and cultural heritage, green landscapes, and habitat. It is therefore in the interests of agricultural water users, the public, and ecosystems to ensure New Mexico's agriculture can adapt and survive amid the threats of increasing water scarcity.

The results here have implications for the American West and other arid regions throughout the world. The struggle to implement known water conservation innovations reflects a common pattern throughout Western states and arid regions worldwide, as agricultural users face similar pressures from climate change, increasing water scarcity, and competing demands from urban and environmental sectors [83]. The identified barriers are systemic issues affecting agricultural water users across these systems. The "irrigation efficiency paradox" presents a significant challenge, complicating policy approaches that promote technology-based solutions, while the policy recommendations—financial incentives, improved water accounting, and education programs—offer a template that could benefit agricultural adaptation strategies across Western states and other regions facing similar water governance challenges [83,84].

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Appendix A

This appendix contains interview questions asked of agricultural water users and decision makers.

Appendix A.1. Interview Questions for Agricultural Water Users

Interviewees, please note that we are focused on the following:

- The Middle Rio Grande basin,
- Water that is permitted for agricultural use, and
- Innovations that help NM address issues like water scarcity, water quality, and maximizing beneficial use of water for people and the environment.

1. Tell me about your background and experience with water use. Where do you get your water?
2. Why are you growing what you are growing? What would you like to grow that you're not, and what are the barriers?
3. What water use decisions do you feel like you have control over? Is there some option you wish you had as a water user that could help you innovate to make scarce supplies go farther?

4. What tradeoffs and priorities are you considering when you are making your water use decisions, especially when water is most limited?

5. Within what time frame (e.g., 1 year, 5 years, 10 years, longer) are you making your decisions related to water use and farming (e.g., how many acres to grow crops on, what crops to grow, timing of crops grown, how much water to irrigate, what irrigation methods to use, when to stop irrigating)?

Note: The next several questions use the word "innovations". By this we mean informal or formal, new, or unconventional or experimental things you are doing to make scarce water supplies go farther.

6. Are there any innovations or changes you're involved with regarding your use of irrigation water? Why?

7. Are there any collaborations or agreements that agricultural users in your community are involved in to manage water usage among many users? (This can be formal or informal). What challenges do they aim to address?

8. What are some of the innovations related to agricultural water use beyond your community or region that you think may be useful here?

9. How do you see your future as an agricultural water user in the Middle Rio Grande basin? What sort of challenges do you think there will be in getting the water needed to continue irrigating for either yourself or future generations?

10. In practice, what is your experience with how water is (or has been) allocated among agricultural water users in the Middle Rio Grande basin? Are there major differences in how this is meant to happen on paper versus how it actually happens in practice?

11. Is there anything else you'd like to share related to the future of water allocation and use in the Middle Rio Grande basin?

Appendix A.2. Interview Questions for Decision Makers

Interviewees, please note that we are focused on the following:

- The Middle Rio Grande basin,
- Water that is permitted for agricultural use, and
- Innovations that help NM address issues like water scarcity, water quality, and maximizing beneficial use of water for people and the environment.

1. Could you say a few words about your background and experience related to agricultural water management or use in the Middle Rio Grande basin?

2. What tradeoffs and priorities are you considering when thinking about water resources management decisions, especially when water is most limited?

3. Within what time horizon are you thinking about water resources management?

4. Are there collaborations related to water allocation, management, or use that are (or have been) occurring and among whom? (The collaborations could be in any format, e.g., formal, informal, or emerging, and could be at any scale, e.g., farm field, acequia association, watershed, etc.).

5. Including and beyond collaborations, what are some of the innovations related to agricultural water use that you see occurring and what challenges do they aim to address?

6. Is there anything that agricultural water users could be doing that they aren't to make better use of scarce water supplies? This can include measures taken individually, collectively, formally, or informally.

7. Why do you think the users aren't making these changes?

8. Related to water management, allocation, and use, are there models or innovations in use elsewhere that the Middle Rio Grande basin could benefit from experimenting with?

9. In practice, what is your experience with how water is (or has been) allocated among agricultural water users in the Middle Rio Grande basin? Are there major differences in how this is meant to happen on paper versus how it actually happens in practice?

10. What do you think will be the difficult choices related to water and agriculture in the Middle Rio Grande basin in the next 1–2 generations?

11. Is there anything else you'd like to share related to the future of water management, allocation, and use in the Middle Rio Grande basin?

Appendix B

This appendix contains the codebook used in this study. Managerial codes were used to track participant characteristics, collaborations, and conflicts in the basin. We did not write descriptions for managerial codes. Bold text indicates codebook categories.

Table A1. Study codebook and code descriptions.

Code	Description
Anticipation of climate change impacts	
decreasing water supply	Used when participant describes experiencing or having experienced a decrease in their water supply or when participant describes an outlook/speaks of a future with less water.
increase in catastrophic wildfire	Used when participant refers to effects of wildfires and/or increase in wildfires.
planning for uncertain water future	Used when participant describes a desire to act in anticipation of a decrease in water supply or describes the actions taken in preparation.
Barriers to innovation; economic/financial	
forward contracts; subsidies and crop insurance	Used when participant mentions forward contracts, agricultural subsidies, and/or crop insurance.
lack of capacity to go after funding	Used when participant describes experiencing/having experienced an inability to apply for available funding, maintain eligibility for funding, or access resources due to any of the following: lack of awareness of existence of available funding, lack of time to apply for funding, or lack of how to apply for funding.
market challenges in changing crops	Used when participant describes a lack of a market to sell their agricultural product, as well as difficulties related to transportation to market, access to processing facilities, and creation of value-added products.
need more time/labor	Used when participant describes an inability to meet their labor needs such as necessary work/tasks that need to be accomplished on their land.
Barriers to innovation; farming/tech	
cultural practice prevents innovation	Used when participant describes a lack of innovative activities occurring in favor of using cultural, traditional, and/or habitual methods.
current water distribution schedule does not work for desired crop	Used when participant describes an inability to grow desired crop(s) due to few or irregularly occurring waterings.
innovation requires access to capital/resources; risk; new tools; equipment; changing land	Used when participant describes innovations requiring the following: access to financial capital, any associated riskiness, or the need to purchase/that they purchased new tools or equipment.
lack of knowledge/education/training	Used when participant describes how a lack of knowledge/education/training has inhibited agricultural water users from innovating or how innovations require new knowledge/education/training. Includes a desire to better understand their farm, such as appropriate crops and soil type.
Barriers to innovation; legal/policy	
bureaucracy moves too slow	Used when participant describes an individual's lack of desire or inability to innovate due to slow-moving government processes such as application turnaround time, slow responses to inquiries, difficulty reaching the appropriate entity to respond to problems, etc.
Concern	
agencies do not enforce rules	Used when participant describes agencies not fulfilling their duties, such as not applying penalties for violating rules
competition with other users	Used when participant describes water as a limited resource being divided amongst many users, perceived difficulties in meeting demand of competing users and the idea of a "zero sum game" between users.
effects of land conversion	Used when participant describes how a change in where water is used and how water is used affects land/environment such as impact of urbanization, conversion of agricultural land, riparian habitat, or green belt.
idea that other ag areas are too different from MRG, that their innovation cannot be applied here	Used when participant states that innovations or practices from regions outside the Middle Rio Grande will not work here due to topography, geology, climate, institutions, etc.

Table A1. *Cont.*

Code	Description
other concern	Used when participant describes a concern that is not listed here. Use annotation to specify.
overuse of groundwater and aquifer sustainability	Used when participant describes aquifer in Middle Rio Grande valley as a limited resource and expresses concern over an increase of depth to water table.
perspectives on water quality	Used when participant mentions water quality, including references to pollution, salinity, trash, or sediment
thoughts/perspectives on compact compliance	Used when participant mentions compacts.
will young farmers want to stick around/young people leaving farming	Used when participant mentions next generation of agricultural water users, or the risks associated with going into the farming business.
Economic and financial incentives and innovations	
cost-share programs; tax incentives; grants/loans for ranchers and farmers	Used when participant mentions cost-share programs, tax incentives, and grants/loans for agricultural water users.
Farmer decision making	
financial incentive to sell water right	Used when participant mentions financial incentives to sell water right including sale to other producers, municipalities, water bank.
makes decision to plant/not plant based on water availability	Used when participant describes inability to plant crops due to water availability.
making choices now to try to benefit future generations/family later	Used when participant describes making decisions that will offer their family/future generations more opportunity.
prioritize creating/protecting habitat	Used when participant describes activity, they have done that creates habitat or provides ecosystem services.
prioritize high-value crops	Used when a participant describes preference for crops with high economic value.
prioritize long-term crops	Used when participant describes planting longer term crops.
Farming/tech innovations in use	
crop choices	Used when participant mentions crop choices such as decision making when choosing crops, action, or desire to switch crops
farm and water cooperatives	Used when participant describes need for formation of farm/water coops, or participation in farm/water coops such as acequia associations.
leveling/grading	Used when participant mentions leveling/grading to increase irrigation efficiency.
more efficient irrigation equipment—drip irrigation, sprinklers, microsprinklers, etc.	Used when participant mentions use of drip, sprinkler systems, or any other system for disseminating water across their crops more efficiently.
re-using water/crops on farms for multiple purposes	Used when participant intentionally uses resources for multiple purposes or re-uses resources or agricultural byproducts on their farm.
reducing leak lining/concrete ditches; piping	Used when participant mentions lining waterways or using piping to increase efficiency.
reducing or recapturing evapotranspiration using greenhouses; shade structures	Used when participant describes increasing moisture in immediate atmosphere by creating shade or using greenhouses.
related to soil health and moisture	Used when participant mentions soil health and/or soil moisture.
telemetries flume; automated gates	Used when participant mentions telemetrized flumes or automatic gates.
use of Indigenous, permaculture, dry farming, and inter/cover cropping techniques	Used when participant mentions Indigenous farming techniques, permaculture, dry farming, intercropping, cover cropping, and mulching.
use of solar, wind, and micro hydropower in ag production	Used when participant mentions solar power, wind power, or micro hydropower.
using/building wells to ensure supply when needed	Used when participant mentions building wells in anticipation of a lack of water needed to grow crops or refers to the use of a well for such an occasion.
Farming/tech wish list	
implementing aerial/aquifer mapping technologies for land management	Used when participant mentions the use or future use of aerial/aquifer mapping.
improve transparency in water availability, requests, and deliveries	Used when participant refers to the accessibility of information concerning water supply, water requests, and water deliveries.
metering all water users' wells and surface water	Used when participant refers to their desire for water managers to meter all water users.
transparency in grant/funding decisions	Used when participant mentions desire for transparency in grant/funding decisions.
treating low-quality water to create new freshwater supplies	Used when participant refers to the desire for treatment of low-quality water to add to supply such as produced water, etc.
water storage on farm	Used when participant describes desire for water storage on their farm, such as tanks, ponds, etc., including a need to store or pressurize water to utilize more efficient methods.
Legal/policy innovations in use	
creation of land easements	Used when participant mentions land easements.
water banking, leasing, and markets	Used when participant mentions water banks, water leases, and water markets, including pay-to-fallow programs.
Legal/policy innovations wish list	
better data, research and information about population growth, development, climate, and water supply and use	Used when participant mentions need for better data, more research and information about climate change and population growth, and the state of water supplies and how they are used.

Table A1. *Cont.*

Code	Description
flexibility in water storage, use, and management necessary to adapt to climate change and local needs	Used when participant states desire for more flexibility in water storage, water use, and improvement in water management to adapt to climate change and resident needs.
stricter enforcement of water use efficiency	Used when participant expresses a desire for stricter enforcement of water use efficiency or laments the lack of efficiency by another water user.
Other innovations and barriers	
innovations elsewhere	Used to identify innovations occurring outside the Middle Rio Grande region, including elsewhere in New Mexico, the US, and the world. Description of innovation and location in annotation.
other barriers	Used when participant describes a barrier not included in our "barriers. . ." lists.
other innovations in MRG	Used to identify innovations occurring inside the Middle Rio Grande region. Description of innovation in annotation.
Preserve culture/lifestyle	
perspectives on ag in NM	Used when participant describes the future of agriculture in New Mexico.
perspectives on green belt	Used when participant describes the greening of the Middle Rio Grande region as a result of agriculture in the area or the loss of green belt.
preserve traditions	Used when participant mentions the preservation of traditions and culture, or the historical aspects of water use, and irrigation used in the MRG.
the land will continue to be farmed whether by family or someone else	Used when participant expresses that agricultural land will continue to be farmed by future generations.
Priority administration; P&P rights; adjudication of water rights	
cost and risk of transferring a water right	Used when participant refers to the cost and riskiness involved in transferring, buying, or selling a water right.
MRGCD is delegated administration authority	Used when participant states that MRGCD is the administrator of water in the Middle Rio Grande region and tasked with allocations among other responsibilities.
Prior and Paramount water rights; Winters decision	Used when participant refers to Prior and Paramount water rights of the Winters decision.
prior appropriation or the use-it-or-lose-it principle prevent innovation or conservation	Used when participant expresses that the prior appropriation doctrine or elements of prior appropriation, such as use it or lose it, hinder innovation or conservation in some way.
thoughts about adjudication	Used when participant mentions adjudication.
water code/water law in conflict with shortage sharing already in practice	Used when participant describes shortage sharing that is currently occurring being in conflict with prior appropriation as outlined in water code/water law.
Protecting species and habitats	
farmers competing with water for environment	Used when participant describes competition between agricultural water use and water being used for the environment.
managing invasive species	Used when participant mentions invasive species or agricultural weeds.
using ag water rights for ecosystem restoration	Used when participant refers to the transfer of water rights from agriculture to instream use or habitat creation.
Reform traditional farming	
thoughts about growing food for humans	Used when participant mentions growing food for human consumption.
Secondary analysis codes	
Desired innovation not in practice	Used when participant describes an innovation they would like to see used on farms or within the region.
Implemented innovation	Used when participant describes implementing an innovation.
Undesirable innovation	Used when participant describes an innovation they disapproved of or do not want to see used on a farm or within the region.
Things participants dislike in current mgmt. of Middle Rio Grande water	
difficulty meeting MRGCD irrigation rate	Used when participant describes difficulty meeting MRGCD irrigation rate on their own farm or someone else's.
feelings of inequity with water delivery, allocation, etc.	Used when participant describes inequitable water deliveries, allocation of water, etc.
infrastructure problems negatively impact water supply	Used when participant refers to infrastructure negatively impacting water supply locally (such as on-farm or within public or private ditches) or regionally (such as reservoirs and storage).
MRGCD is getting worse	Used when participant describes MRGCD as an entity worsening its productivity or practices.
officials are not farmers; therefore, they do not understand farmers' needs	Used when participant refers to government/agency representatives not being agricultural water users and therefore not understanding their needs.
Things participants like in current system	
building community around shared food/water	Used when participant describes interacting with other community members as a result of their agricultural activities, or the idea that shared water supports building community.

Table A1. *Cont.*

Code	Description
flood irrigating from ditch creates recharge and return flow	Used when participant mentions that flood irrigation increases flow to groundwater.
MRGCD is getting better	Used when participant describes MRGCD as an entity improving its operations or activities.
Water as a communal resource	
cheating or illegal use	Used when participant describes agricultural water users taking water when it is not their turn or using more than their share.
opinions about water and shortage sharing	Used when participant mentions water/shortage sharing.
Collaboration tags (managerial codes)	
collab—with businesses/industry	
collab—with fed gov	
collab—with higher ed/extension	
collab—with landowners	
collab—with local gov municipalities; counties; soil and water districts	
collab—with MRGCD	
collab—with NGOs/non-profits	
collab—with state gov	
collab—with tribes	
formal collab	
informal collab	
Conflict tags (managerial codes)	
conflict—with businesses/industry	
conflict—with fed gov	
conflict—with higher ed/extension	
conflict—with landowners	
conflict—with local gov municipalities; counties; soil and water districts	
conflict—With MRGCD	
conflict—with NGOs/non-profits	
conflict—With outsiders	
conflict—with state gov	
conflict—with tribes	
Farm size (managerial codes)	
Large 100+ acres	
Medium 10–100 acres	
Small less than 10 acres	
Reliance on farm income (managerial codes)	
farm is main income	
farm is supplemental or not income	
Time horizon (managerial codes)	
0–1 year	
11–20 years	
2–5 years	
21–50 years	
6–10 years	
more than 50 years	
Water source (managerial codes)	
acequia	
domestic well	
Rio Grande surface right	
stored water that is illegal to use	
transferred surface right to GW right supplemental well	
well	
well that cannot be used	
What are they growing (managerial codes)	
alfalfa	
livestock—dairy	

Table A1. *Cont.*

Code	Description
livestock—meat	
non-alfalfa hay; pasture; or silage	
orchard—fruit and nuts	
other	
row crops—vegetables and fruit chile; melons; tomato	
turf grass/lawn	

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