Formalizing the Santa Fe Water Bank

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Abstract

Water users depend on institutional flexibility to efficiently allocate water in legally constrained and overallocated basins. Adaptive market-based mechanisms such as water banking proffer flexibility and fairness, but often face practical challenges fueled by empirical and institutional uncertainties. The Santa Fe Water Bank is a case in point. The City of Santa Fe transfers agricultural water rights from the Middle Rio Grande to its municipal Water Bank for sustainable development. Combined uncertainties in this process can obscure latent changes in water balance and foster misunderstanding, potentially provoking transfer protests. This study develops a formal model clarifying the interrelated institutional and hydrological processes in Santa Fe Water Bank transfers. The model then incorporates OpenET remote sensing to examine how established transfer conditions, which are contingent on an administrative constant representing consumptive use, influence regional water balance. Results demonstrate that current practices leave the potential for considerable changes in water availability, and that potential errors in administrative consumptive use can augment or diminish these changes. The overarching purpose is to show that lingering uncertainties hamper the institutional flexibility and intended outcomes of water transfer mechanisms. The study underscores the importance of considering formal models and new empirical tools in adaptive management strategies and provides a framework for addressing consumptive use uncertainty in Santa Fe Water Bank transfers.

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Glossary

Actual Evapotranspiration (ET_a):
The actual amount of water transpired by plants and evaporated from soil and plant surfaces, often estimated using remote sensing data like OpenET.

Blaney-Criddle:
A method for estimating potential evapotranspiration based on crop coefficients, average monthly air temperature, and daylight hours.

Conceptual Model:
A representation outlining key components and relationships within a system, guiding understanding, analysis, and decision-making.

Conjunctive Management:
A management approach ensuring that surface water depletions caused by groundwater pumping do not impair existing water rights or other state and environmental obligations.

Consumptive Use (CU):
Generally, the portion of water withdrawn that is not returned to the source, including evaporation, ET, and water incorporated into products. In our study it refers to on-farm and irrigation derived crop consumptive use.

Effective Precipitation (P_e):
The process of using observed and measured data to estimate values or parameters in a study, contrasting theoretical or simplified assumptions.

Empirical Estimation:
The process of using observed and measured data to estimate values or parameters in a study, contrasting theoretical or simplified assumptions.

Epistemic Uncertainty:
Uncertainty in knowledge due to incomplete understanding or information about a system, often identified in scientific studies for further investigation.

Hydrological Processes:
Natural processes governing the movement and distribution of water, including captured flow, induced recharge, seepage losses, and wasteway flows, impacting the fate of retired water and its re-entry into the Rio Grande.

Instream Storage:
The annual volume of retired water kept in the Rio Grande by terminating agricultural diversions, nullifying depletions caused by BWF pumping. This stored water represents a functional reserve for the Water Bank but is subject to local hydrology and management practices.

Knowledge Commons:
A shared resource of information maintained by a community, emphasizing collective understanding and collaboration, particularly in decision-making.

Transfer:
In water management refers to moving water rights from one user to another, often through legal or administrative processes. Can include place of use, point of diversion, purpose of use, or ownership.

Mass Balance Conceptual Model:
A conceptual framework used to organize transfer processes into clearly defined constituent parts, classify corresponding types of uncertainty, and describe their logical interactions. Mathematical relationships within this model help generate outputs and uncover processes and scale dependencies in water transfer systems.

Remote Sensing:
Techniques using sensors on satellites or aircraft to capture data on environmental variables related to ET.

Relative Balance:
A concept comparing ideal transfer conditions with actual consumptive use, understanding discrepancies and potential impacts on water flow.

River Depletions:
Reductions in river flows caused by groundwater pumping, requiring offset measures to maintain water balance and comply with regulatory requirements.

Soil Water Balance:
A method for estimating effective precipitation by assessing soil moisture recharge, runoff, and evaporation.

Supply-Limited Consumptive Use:
Consumptive use restricted by water availability, often due to irrigation limitations or water rights shortages.

Theoretical Consumptive (CU_0):
The administratively assigned constant to all water right transfers in the Middle Rio Grande. Represents on-farm crop consumptive use.

Water Banks:
Institutions facilitating the temporary holding (or retaining) of water rights – and theoretically connected to some system storage, and then the transfer of those water rights to improve market efficiency and reduce transaction costs.

Water Management:
Operations and strategies for sustainable water use, distribution, and quality, including monitoring, infrastructure maintenance, and risk management.

Water Markets:
Economic mechanisms involving pricing and trading for reallocating water resources, enhancing efficiency and social welfare.

Water Offset:
A mechanism requiring offsets new demands on the water system by purchasing Middle Rio Grande (MRG) water rights for transfer into the Buckman Wellfield (BWF) permit. This process aims to balance new water demands from construction projects with available water supply, ensuring sustainable development practices.

Water Planning:
Developing strategies and policies to address future water needs, emphasizing foresight, community involvement, and preparation for challenges like climate change.

Water Right Transfers:
The legal process of transferring water rights between users, ensuring fair and equitable water distribution.

Quantity Terms

BWF Depletion (D_{RG})
Depletion-outflow at the BWF.
Modeled annually for Rio Grande depletion offsets by the OSE.

Consumptive Use Error (ε_{cu})
Measures the difference between theoretical and actual consumptive use.
Equation: $CU_a - CU_0 = \varepsilon_{cu}$

Actual Consumptive (CU_a)
Represents the actual consumptive use estimate based on OpenET.
Equation: $CU_a = ET_a - P_e$ (in ft)

Actual CU Volume (w_a)
Represents the actual consumptive use volume.
Equation: $(ET_a - P_e) \cdot acres$ in af

Actual Evapotranspiration (ET_a)
Actual evapotranspiration estimate based on OpenET.

Theoretical Consumptive (CU_0)
Represents the theoretical consumptive use constant.
Value: 2.1 (in ft)

Relative Balance ($\boldsymbol{\delta}$)
Represents the steady-state balance between BWF depletions and total retired water volume.
Equation: $\delta = \frac{D_{RG}}{W}$

Retired Consumptive Use ($\boldsymbol{w}$)
Water rights retained in the river system as in-stream storage.

System Change in River Flow ($\Delta \boldsymbol{Q_{river}}$)
Net change in river flow past San Marcial.

Total Retired Consumptive Use ($\boldsymbol{W}$)
Represents the total volume of retired water in the Bank.
Represents the sum of all retired water rights in the Bank.

Total Rio Grande Inflow ($\boldsymbol{Q_{in}}$)
Represents all system inflows including instream flow and diversion flows.

Total Rio Grande Outflow ($\boldsymbol{Q_{out}}$)
Represents all depletion-outflows including consumptive use and BWF depletion.

Transfer:
Administrative switch between Phase I and Phase II marking a scenario change.
Result: Flow change ΔQ_{river}

Water Balance Equation:
Equation: $Q_{in} - Q_{out} = \Delta Q_{river}$

Theoretical CU Volume ($\boldsymbol{w_0}$)
Represents the theoretical consumptive use volume.
Equation: $2.1 \cdot acres$ in af

Introduction

Water right transfers in the Middle Rio Grande face many obstacles. The practical value of transferring the use of water from one place or purpose to another is well understood. But water scarcity and climate change elicit a sense of unease over transfers, in particular who it is they serve, and how others may be harmed. Resource distribution can become adversarial, especially in the tiered system of western water law. Being able to reliably transfer water within legally rigid – and arguably outdated – allocation regimes, requires indirect and sometimes novel strategies. Among these strategies, water banks have gained traction as a mechanism for facilitating water reallocation and potentially offering broadening community involvement in the planning and management of water resources. Distributing a dwindling common-pool resource in a harmonious way requires mutual understanding of the resource and the distributive processes involved. And yet, the implementation of water bank is often beset by uncertainties. The Santa Fe Water Bank (City Bank or the Bank) exemplifies the difficulties involved in balancing water right transfers and sustainability in the absence of knowledge.

The Santa Fe Water Bank is an adaptive management strategy serving dual purposes. On one hand, it is an administrative market-based mechanism to enhance the reallocative flexibility of water right transfers in a fully allocated basin. This allows the City to sustainably increase the supply allocated to new development in accordance with State water law. On the other hand, the Water Bank is a physical hydrologic entity; a *pool* of retired agricultural water (*consumptive use*), retained downstream in exchange for water depleted upstream for City development. As groundwater pumping upstream near Santa Fe induces depletion in the Rio Grande, it is mitigated by the total volume of water rights transferred into the Bank, and therefore retained in the downstream system. The new depletion triggered by City pumping effectively swaps positions with the former depletion attributed to crop consumptive use, theoretically resulting in a net-zero effect in overall water balance.

This dual administrative and theoretically ideal transfer strategy aims to preserve regional hydrologic equilibrium, and thereby enhance the Bank's reallocative flexibility while complying with State conjunctive management policy. But the transfer process is fraught with epistemic challenges stemming from empirical and institutional uncertainties. The legally transferred volume is based on an administrative constant representing on-farm consumptive. This is a theoretical volume in the sense that it is not an empirical measure of the farm's historical consumption. Potential errors inherent in the theoretical constant can propagate through multiple transfers, leading to uncertainties in the total-system impacts of the Water Bank. These uncertainties not only result in unquantified changes in local and regional water balances, but also impede the Water Bank's flexibility by generating opposition from stakeholders concerned about the reliability of the Bank's operations.

Conceptual Model

To address these challenges, our study pursued a comprehensive approach by formalizing a mass balance conceptual model. The transfer model builds upon previous research and integrates elements influencing transfer impacts into well-defined mathematical relationships. It encompasses factors such as consumptive use, system interdependencies, and management rules, thereby offering a structured framework for understanding the interactions between these elements and their collective impact on water balance. Different types of uncertainties involved were discussed and categorized to identify areas where understanding is lacking and for guiding further research efforts within the structured framework. By organizing uncertainties and characterizing their influence on transfer outcomes, the model can address and mitigate potential sources of error and ambiguity. The model was also intended to demonstrate how formalized approaches allow the disentanglement of complexities inherent in water transfers, providing stakeholders with a clearer understanding of the factors driving transfer impacts and facilitating informed decision-making in water management. The model focuses on two key metrics, *Relative Balance* and *Consumptive Use Error*.

Relative Balance

The transfer model involves the concept of *relative balance*. This is a metric we created to quantify the impact of pumping depletions relative to the total cumulative effect of retiring water rights. It becomes relevant when pumping depletions on the Rio Grande are not equal to the volume of transferred water rights in the Bank. This difference can be expressed as a ratio on a total system scale, and locally under certain conditions. Relative balance was motivated by a desire to reconcile incongruities in flow changes due to different levels of scale and the different depletion metrics used between transfer locations. This enabled multi-scale quantification of alterations in Rio Grande flow triggered by water right transfers. Thus, we were better able to describe stream augmentation and depletion effects that are generally overlooked when discussing Santa Fe Water Bank transfers.

Actual Evapotranspiration

The study focused especially on the role of evapotranspiration (ET), highlighting the discrepancy between the legally assigned *Theoretical Consumptive Use* applied in water right transfers, and the empirically estimated *Actual Consumptive Use* obtained from OpenET remote sensing data. Theoretical crop consumptive use is a simplification of farm consumptive losses due to crop evapotranspiration. It is set at 2.1 acre feet per acre and applied to all agricultural water right transfers in the Middle Rio Grande.[1] While this constant serves as an administrative convenience, its divergence from empirical estimates of actual crop consumptive use raises the possibility of significant errors between legally transferred depletions and historically accurate depletions, further amplifying cumulative changes in Rio Grande flow due to transfers. For example: ignoring other factors, if *Actual Consumptive Use* exceeds *Theoretical Consumptive Use*, the retired volume will exceed the legally transferred and subsequently depleted volume, indicating an increase in flow from pre-transfer conditions. Conversely, if *Actual Consumptive Use* is less than *Theoretical Consumptive Use*, the transfer leads to increased water usage in the basin.

Transfer Possibility I:

$$\begin{aligned} &If\ transferred\ depletion > actual\ depletion \\ &\Rightarrow new\ consumption > old\ consumption \\ &\Rightarrow increased\ depletion \end{aligned}$$

Transfer Possibility II:

$$\begin{aligned} &If\ transferred\ depletion < actual\ depletion \\ &\Rightarrow new\ consumption < old\ consumption \\ &\Rightarrow decreased\ depletion \end{aligned}$$

The above scenarios are a simplification of transfers that do not account for the collective effects of relative balance. Their purpose here is to demonstrate the reasoning behind comparing theoretical and actual consumptive use. The current practice does not consider relative balance and practically assumes equality between actual and theoretical values. Combining consumptive use errors with relative balance potentially amplifies net changes in Rio Grande Flow and opens the door to substantial cumulative changes. We therefore sought to express these two relationships as outputs in the transfer model – the two relationships being:

1. *Relative balance (Under ideal transfer conditions and then with actual consumptive use)*
2. *Differences between Theoretical and Actual Consumptive Use*

These two relationships and their numerical representations formed the basis of analysis in our study. OpenET was used to compare theoretical consumptive use with empirical estimates to gauge potential errors and produce uncertainty boundaries.

Knowledge Commons

The complexity of conditions in Water Bank transfers warrants a formalized approach. Alteration of the established hydrology is a central issue in water transfer negotiations and decision making. The ability to harness surplus flows or anticipate increased deficits holds significant value, particularly if those actions are backed by confidence in shared knowledge. Failure to accurately characterize and quantify transfer effects not only impacts hydrology, but also misses an opportunity to establish mutual understanding among stakeholders. Ultimately, it may exacerbate future conflicts and undermine the effectiveness and integrity of water banking as an adaptive management strategy. Therefore, the transfer model was also intended to provide a systematic way of comprehending Santa Fe Water Bank transfers and – within reasonable bounds, offer a means to reduce some epistemic uncertainties. We viewed this as part of a wider goal of expanding collective knowledge around Water Bank transfers to improve collaborative decision-making and stewardship of Middle Rio Grande water. The idea being that knowledge itself is a shared resource, with information collectively created, maintained, and used by a community of individuals.[2] We believe that by formalizing a conceptual model of the Water Bank, we can beneficially contribute information to the commons, by making its ideas publicly available for critique and discussion.

Planning and Practice

It is worth discussing the terms *planning* and *management*. In general, Water management encompasses day-to-day operations and long-term strategies ensuring the sustainable use, distribution, and quality of water resources. This includes activities like monitoring water quality, maintaining infrastructure, regulating water usage, implementing conservation practices, and managing water-related risks such as floods and droughts. The focus is on executing and maintaining systems. Water planning, on the other hand, is a subset of water management focused on the future. It involves developing strategies and policies to address future water needs and challenges. There is greater emphasis on integrative community systems and involvement, creating policies for sustainable use, and preparing for potential issues such as climate change impacts or population growth. The terms *planning*, *administration*, and *management* are interchangeable in our study for the most part. However, when *planning* is used it generally confers emphasis on foresight, preparation, and designing frameworks to guide future water management practices.

Applicability

Although real-world data informed the study and empirical improvements were attempted, it remains a hypothetical exercise. This is partly because of the vast complexities and constituent uncertainties involved in Middle Rio Grande hydrology. However, the study's objectives do not necessitate a complete and thoroughly calibrated quantification of all its constituent parts. Non-negligible areas of uncertainty, such as effective precipitation, are not adequately explored. And until such areas receive further attention, this study serves as a useful guide at best. Investigation into each underlying uncertainty is undoubtedly important, and it is hoped that this study provides a platform for such endeavors. But that is a long and iterative process of scientific improvement, in which this study is just a contributing part.

The primary aim was not to predict outcomes with pinpoint accuracy, but to reduce uncertainty among system relationships while providing empirical estimation of a crucial parameter. Thus, the study aspired primarily to achieve a valid conceptual model of Water Bank transfers, and secondarily to strengthen the cogency of that model by using an empirical estimate of consumptive use. Results are intended to provide a template for further research and a framework for assessing and negotiating Santa Fe Water Bank transfers. In its most basic sense, this study is a call for improved methods in water right transfers, so that watershed communities and the Santa Fe Water Bank can peaceably coexist.

Part I: Background

Challenges of Water Management

Water availability is a growing concern for municipalities across the arid west.[1] Demand typically exceeds supply, and this difference will likely increase due to climate change.[2] Hydrologic basins are often overallocated and closed to development of new water rights. Furthermore, cities must usually grapple with junior rights status for much of their supply portfolio, as a large fraction of existing water rights are bound up by senior agricultural users.[3] In response to these challenges, municipalities have increasingly adopted alternative management strategies to reallocate water from the agricultural sector, with water banking emerging as a popular mechanism.[4] Water banking's appeal lies in its flexibility to transfer water within closed, unadjudicated basins, facilitated by legal efficiency and market fairness for the parties involved.[5] But despite its potential as an adaptive transfer mechanism, the full scope of water banking's fairness and effectiveness across sectors and hydrogeologic boundaries remains subject to debate and scrutiny.[6] While legal and voluntary among participants, third parties may perceive transfers as jeopardizing existing water rights or public welfare. Concerns may escalate to legal protests, resulting in costly and prolonged antagonisms that undermine the merits of water banking as an adaptive and efficient transfer mechanism.[7]

Dissenting opinions regarding water banking and transfers typically revolve around alterations to the existing water balance. While this is a legitimate basis of concern, it doesn't fully capture the broader entanglement of issues at hand. Conflicts over scarcity are often amplified by historical, social, and environmental deprivations related to water access.[3] Legal claims for a particular use of water, when unambiguous, may not reflect common pool values or even the true market value. Moreover, determining which use holds a broader moral claim—beyond the legal strictures of western water code—is perhaps an impossible task. The inclusion of a public welfare clause in several state water codes opens the door for such deliberation, but employing public welfare as a proactive tool for water reallocation has little precedence in New Mexico. In the political arena, traditional use of resources often holds persuasive power. But traditional water use can encompass varied meanings across New Mexico's diverse and deeply rooted communities, with progressive ideas either conflicting with or complementing traditional practices depending on evolving circumstances. Given the historical context, a certain level of stakeholder scrutiny, or even suspicion, regarding water transfers should be anticipated.

And yet, amidst the competing demands and cultural and environmental concerns surrounding water right transfers, there is a general acknowledgment that historical allocation systems cannot remain fixed in perpetuity – that evolving values and hydrologic realities demand some flexibility and stakeholder input in the allocation of water.[8] To this end it is prudent to recognize that the various strands of disagreement all stem from a fundamental issue of quantity, often entailing relatively small amounts. Quantifying and transferring water rights in an increasingly constrained and politically sensitive landscape leaves little room for error and highlights the importance of establishing shared terms of discourse that alleviate uncertainty. Miscommunication and obscured judgement hamper the achievement of mutually beneficial agreements, potentially undermining valuable trust and cooperation among stakeholders over time. This is where conceptual models of system processes and accurate empirical assessments take on a pivotal role. By establishing common understanding of the quantitative impacts of transfers, conceptual models and reliable empirical methods help navigate the complexities, becoming immensely valuable in threading the many needles of demand.

While water planners are cognizant of the knowledge gaps involved in water right transfers, developing a process to address them is a difficult task. In addition to the social intricacies just described, other circumstances are worth considering. First, the sheer complexity of hydrologic fluxes compounded by human systems creates a formidable challenge. This is especially evident in the Middle Rio Grande, where efforts to develop a high resolution water budget have spanned multiple decades and careers, and remain incomplete.[9] On top of this, agencies are budgetarily constrained by the priorities of changing state legislatures.[10] Rule systems tend towards institutional inertia and are slow to change, preserving conformity with the state's historically senior and dominant appropriator, agriculture.[3] Convincing these major users of the need or value in replacing established traditional practices in favor of new and potentially threatening accounting mechanisms is understandably met with resistance. Thus, there is a tendency for regulatory frameworks to support the status quo and to be resistant to significant changes that might challenge established norms and interests.

Data availability and record management can also prove to be a challenge. The complicated process of transferring water rights, involving multiple parties and co-applicants, occasional partial transfers of rights, fragmentation of original allocations into sub-rights across multiple owners, and scattered or incomplete water right records, renders both current and retroactive analysis of water right transfers cumbersome and time-consuming. Transfer documents often comprise numerous paper files or PDFs that require meticulous examination to comprehensively characterize transfer history, let alone the associated spatial and volumetric quantities involved. Considering all the challenges it's no surprise that epistemic uncertainty lingers on, baked in as a perfunctory part of a very complicated process, despite the availability of new techniques aimed at mitigating it.

Reducing epistemic uncertainty in key areas of water use allows for a more holistic knowledge of the long-term hydrologic effects of management choices. It enables anticipation of surpluses and shortages, meeting interstate demands, fulfilling environmental obligations, and averting conflicts. Yet while this improved comprehension is essential, it is not solely adequate for successful management. Converting knowledge into meaningful outcomes demands robust institutional mechanisms that effectively translate empirical insights into practical rules that are adhered to.[5] Successful management is defined here as the optimal and sustainable distribution of water within feasible legal, hydrological, and socio-environmental constraints. Maintaining this delicate balance necessitates mechanisms whose structure and functionality meet high expectations. There is no single formula for the type of arrangement that can achieve these desired outcomes. But it is reasonable to assume that for any such mechanism to be successful, it must consist of rules that are easy to engage with, reliably trusted, and capable of being implemented and enforced.

Market or exchange-based approaches emphasize the ease of engagement piece, but such mechanisms are nested within a broader extra-market web of agencies and socio-environmental forces. For market or exchange strategies to be successful they must be integrated within this web, wherein both management agencies and the public draw upon scientific understanding and principles of public welfare for guidance. In other words, beyond mere efficiency in the transfer process, it is imperative that all stakeholders have confidence in the epistemic claims guiding oversight, as well as a belief that the rules align with broader norms and are complied with. These factors are essential and must work together for adaptive strategies to fulfill their intended purpose. This is a topic that we shall return to later when discussing the implications of study results.

Water Markets & Banking

In the 20th century, the southwest experienced a remarkable advancement in the ability to access and store previously inaccessible water.[3] Large reservoir projects backed up rivers and dampened their cyclical variability. Surpluses in spring snowmelt could be captured to avoid late season shortages, providing uniform supplies year-round. Irrigation districts created diversion networks and flood control systems capable of transporting water across great distances.[3,4] Innovations in pumping technology provided a new frontier in groundwater, capable of tapping deep into confined aquifers to reach ancient sources. Large commercial farms and cities grew in places previously impossible.[3] This so-called *reclamation* of the west happened in less than a century of increased water supply.[3,4]

For a time, confidence in the ability to meet growing demand through new supply became an informal management ethos.[3,5] Despite early cracks in the narrative, economic growth was guided by a spirit of supply-side water management.[5,6] This was especially true of major urban centers. Unlike the agricultural sector, whose forbearer's staked out legal claims to water in the early supply-limited days of Prior Appropriation, southwestern cities were relatively new to the scene.[3] Although cities existed in the early west, they had not yet become the large economic and development engines we see today.[3] And without having secured water rights in these early times, cities increasingly relied, and grew enormously, on the assumption of continuous supply.[4,5]

The 20th century increases in water supplies, which permitted the rapid growth of southwestern cities, industry, and large-scale agriculture, fostered a general perspective of water management oriented to increasing supply.[5] But this attitude has been forced to shift in recent decades.[5] Natural hydrologic sources have been fully squeezed, and both surface and groundwater systems are now either exhausted or overdrawn.[3] But population growth, and now climate change, have become dominant forces in outstripping supply even further.[5] Water managers have gradually begun to reorient management efforts around existing, rather than new supplies, emphasizing the redistribution of water along with conservation and use efficiency.[5] This new approach encompasses what's known as water demand management, which focuses on strategies and policies aimed at influencing the patterns and levels of water usage to achieve efficient and sustainable water consumption.[7] This involves measures to reduce water wastage, promote conservation practices, optimize water use in various sectors, encourage behavioral changes among water users, and, importantly increasing flexibility for water reallocation.[7]

The ability to reallocate existing water uses can be interpreted as a type of demand optimization, particularly regarding the transference of water to higher valued sectors.[5,7] Modern expectations, practices, and legal constraints are more easily met when new supplies are available. When they aren't available, and demand persists, water management faces a zero-sum scenario: new allocations cease, and water development commences entirely through reallocation.[3] Thus, new water use in one place requires the termination of water use in another. This is presently the case for much of New Mexico, including the MRG basin.[3] Addressing this situation necessarily requires demand-oriented management, as a technically intricate re-allocative balancing act.[5] In New Mexico, water reallocations occur either through judicial or market processes, or both, often intertwined.[3] This necessitates developing comprehensive policies, strategies, and detailed plans that align with environmental, economic, sociocultural considerations.[3,5]

Transfers

Because reallocation entails transforming a water right's type of use, location, or ownership, water transfers become an implicit feature of reallocation demand management strategy.[5,8] As one might expect, transfers are function of supply limitation, requiring the trading of water in lieu of generating new supplies. In water-scarce regions and overallocated basins typical of the southwest, transfers play a complex role in broader sociopolitical legal battels and adjudications. They are however, the primary unit through which exchange of water can take place in closed basins.[3] The Western Governors Association & Western States Water Council adopt the definition of a water transfer as:

"…a voluntary agreement that results in a temporary or permanent change in the type, time, or place of use of water and or a water right. Water transfers can be local or distant; they can be a sale, lease, or donation; and they can move water among agricultural, municipal, industrial, and environmental uses."[9]

Water transfers accommodate a broad range of potential reasons for moving water use from one regime to another. In arid states, transfer and the ability to reallocate is generally the only option for rearranging pre-existing water right hierarchies to reflect new societal values, competing at times with the foundational tenets of Prior Appropriation.[3,4] Interpreting transfer statutes through a traditionalist lens can limit the range of options for things like in-stream flows or public welfare. Progressive or not, transfers exchange the legal currency of water rights, and water banks are specifically designed to improve their functionality and flexibility.[4,5]

Water Markets

The complexities of demand management along with its transactional nature has prompted planners and administrators to view solutions through a lens of economic theory. Afterall, the general features of the problems are analogous. This has led to the adoption of economic instruments and incentive mechanisms, such as water pricing and water markets, for systematically reallocating water.[5] The reliance on economic theory is predicated on markets being efficient mechanisms for allocating scarce resources. This familiar refrain works well within a theoretical framework in which certain conditions are met, such as perfect competition, the absence of externalities, and no transaction costs – conditions which in the real world are rarely met.[7]

Nevertheless, water markets offer a compatible environment for working with existing norms and institutions. And they have been shown to improve measures of water use efficiency and social welfare efficacy in some contexts involving resource scarcity and reallocation.[7] Water markets encompass a variety of institutions that facilitate voluntary water exchanges between users, and they can take different forms based on legal status, the types of rights traded, and the parties involved.[7] Markets may involve direct negotiations between private buyers and sellers, sometimes with intermediaries or brokers. Water rights might be traded permanently or temporarily, and exchanges could occur through formal or informal arrangements.[7]

Water Banks

Water banks exist within the general context of water markets but operate in a more institutionalized context, with an administrative agency acting as an essential intermediary in the trading of water rights. Unlike typical market transactions in which buyers and sellers interact directly, water banks involve agents who are not water users themselves, providing a structured and regulated mechanism for reallocating among water users. Therefore, a water bank is a market mechanism in which a public or private administrative agency necessarily acts as an intermediary in the transfer of water rights.[7]

Water banks are designed to manage water efficiently by facilitating temporary and permanent transfers of water rights, thereby responding to both cyclical and structural changes in water availability.[7] They aim to reduce transaction costs and improve market efficiency by enabling interested parties to lease or sell their water rights. Water banks can be organized either publicly, by government agencies with expertise in water management, or privately, and by non-profit organizations.[7] There can be exchanges of various types of rights, including permanent, temporary, and option contracts, serving different purposes such as reallocating resources, addressing environmental concerns, and managing risks related to water availability.

Management strategies vary between active and passive approaches: active water banks take a proactive role in buying and selling water rights to achieve market balance, while passive water banks act as intermediaries, facilitating transactions between buyers and sellers without actively participating in market operations.[7] The storage of water within a bank also varies. Some banks may involve actual physical storage of water deposits, as in an aquifer or reservoirs, while others may be purely institutional, focusing on legal and accounting mechanisms for exchanging water rights rather than physical water storage. This latter approach, is sometimes called *paper exchange*, and tends to operate in larger regional accounting systems with limited water availability.[5] In fact, water banks should not be conflated with the commonly used term water banking. Although they often overlap, that latter term is more exclusively to the simple physical process of storing water for future use. This is a common feature of water banks, but not necessary.[5] In our study, we argue the Santa Fe Water Bank practices a novel form of physical storage, and in that sense can be said to practice water banking.

A central objective common to all water banks is the creation of a long-term strategic reserve.[5] The bank achieves this by enhancing flexibility for water transfers rather than increasing supply. Consequently, the success of a water bank as an adaptive mechanism for reallocating water is contingent on its ability to improve transfer flexibility. As we have discussed, there are numerous impairments to flexibility that water banks contend with. Perhaps the most daunting is a lack of shared knowledge about the specific water being traded as a common pool resource.

Evapotranspiration and Consumptive Use

Evapotranspiration (ET) is the process by which water moves from the earth to the atmosphere through the combination of plant transpiration and evaporation.[10] ET is a crucial consideration in water management, indicating water demand for crop growth and constituting a significant outflow parameter in the hydrologic budget.[10] When water changes from liquid into vapor and enters the atmosphere, it is practically irretrievable. Thus, ET represents a loss or depletion from the local hydrologic system to atmospheric demand.[11] Technically speaking ET, is a process and not a quantity. But it is often described volumetrically, indicating the volume of water transferred through ET over some unit of time. Due to its pivotal role in agricultural water loss, ET is often equated with consumptive use as the primary driver of depletion. While this is generally true, casually equating these terms can cause confusion.

Consumptive use is a broad term encompassing various types of water loss or depletion.[3,10] In urban areas, it includes evaporation from industrial processes and evapotranspiration from parks and lawns. In agriculture, consumptive use primarily refers to depletion associated with crop ET, but even here the term can have varied meanings.[3] It is sometimes interpreted as any part of a withdrawal that doesn't return to the system or point of diversion.[3] This could describe several types of depletion, of which crop ET is only one.[3] Furthermore, in agriculture, *consumptive* typically denotes the portion of withdrawal intentionally or beneficially supporting crop growth i.e., water consumed in the act of fulfilling intended plant metabolic and soil moisture needs.[4] This understanding of consumptive use – often referred to as the *duty* of water – contrasts with non-crop depletions, such as surface evaporation from spills or open channels, which are inadvertent and do not directly support crop growth. These *incidental* losses are sometimes classified separately from consumptive use.[10]

Another distinction between consumptive use and ET is the specification of a source or system relating withdrawals to returns. ET is a biophysical process independent of notions about where a volume of water comes from or belongs. The *system* involved in defining consumptive use entails such an abstraction. The perception of what constitutes a loss or depletion depends on the scale and context within which it's observed. What might be considered a loss at the farm level could be nullified or even beneficial on a larger scale, such as district-level deep percolation and groundwater recharge.[3,4] As a matter of mass balance, terms like loss, depletion, surplus, and augmentation are relative to the boundaries of the system described, and system boundaries are to a degree arbitrary. This issue has become a salient point of contention in Santa Fe Water Bank transfers. To minimize confusion, this study will specify system boundaries when clarification is needed.

Even more complexity is possible if crop consumptive use consists of multiple sources. ET does not distinguish between the origins of the water being depleted. The water transported to the atmosphere might have come from surface irrigation diverted from a nearby stream, or perhaps from vadose zone capillary action, or pulled up from the water table by roots, or from rainfall infiltration into the rootzone.[11] Managers might think it important to make such a distinction, at which point it becomes necessary to differentiate those parts of crop ET which come from different sources. Fully delineating these sources may necessitate the development of a comprehensive soil moisture model, meticulous tracking of delivery flows and precipitation events, or better aquifer characterization and understanding of local hydraulic conductivity. The partitioning of ET into its constituent processes of evaporation and transpiration could be required if characterization of supply source is of utmost importance.[12]

Supply source further entails the idea of *supply-limited* consumptive use. Consumptive use calculation often relies on empirical models which assume *well-watered* crop conditions. This approach is generally used to quantify the irrigation water requirement. This is the quantity of water required from an irrigation source, in addition to precipitation and other sources, to grow a reference crop under optimal conditions.[10] Both the reference crop and the well-watered conditions are idealizations necessary for calibrating empirical models, representing experimentally controlled circumstances not ordinarily found in the field. Well-watered conditions refer to optimal moisture levels in soil, typically achieved through sufficient irrigation or natural rainfall, ensuring that plants have access to an abundant water supply.[10] These conditions represent an ideal scenario where crops receive adequate water to meet their growth and transpiration needs without experiencing water stress.[10] This condition serves as a reference point for calculating the maximum potential water consumption by crops under favorable circumstances. It allows for a baseline assessment of water requirements, facilitating comparisons with actual water usage.

Well-watered conditions are often associated with a reference crop, which serves as a standard for calculating water requirements.[10] The reference crop is typically a type of vegetation, such as grass or alfalfa, that is grown under optimal conditions with ample water supply. The reference crop's water consumption under these conditions is used as a benchmark to estimate the *Potential ET* rate ET_p, which reflects the amount of water that *could* evaporate and transpire from the reference crop and the surrounding soil surface.[10] When well-watered conditions are assumed, it means that the crop is receiving a full supply of water to meet its needs – that the crop is not experiencing any water stress or deficit, and its water requirements are fully met throughout its growth cycle. This assumption allows for the estimation of consumptive use under optimal conditions, where water availability is not a limiting factor for plant growth and development.[10] It provides a reference point for calculating a Potential ET rate that models can then use an upper bound of water consumption for a given crop species.

In reality, agricultural fields experience varying degrees of water availability due to factors such as soil type, irrigation practices, climate conditions, and land topography. Particularly in the arid west, a significant impediment to crop cultivation arises from the reduction or cessation of irrigation water.[10] These supply limitations are usually a direct result of intentional fallowing or water right shortage.[10] Such actions are typical responses to broader climate related reductions in watershed supply like drought and early snowmelt runoff, further compounded by management constraints and water right seniority.[3,10]

Supply limitation is an important consideration when assessing hydrological impacts of on-farm consumptive use.[10] Idealized crop ET values based solely on non-observational records might assume a constant interannual fulfillment of the legal water right, overlooking the seasonal variability limiting the actual volume supplied to the crop.[10] The difference between supply limited crop ET and potential crop ET applied uniformly over time can be substantial, especially if a farm has many total or partial non-irrigation seasons in its historical record. Factoring in supply limitation as part of potential crop ET can be done, but it requires access to irrigative records unique to the farm or other ways of assessing irrigation history. When assessing transfer viability, the OSE tries to establish whether farm irrigation has been present and continuous relative to the legal standards of beneficial use, but the focus and methods of these assessments leave a high degree of uncertainty in the magnitude and frequency of supply limitation.[1]

Consumptive use clearly demands rigorous description. Much of the study borrows from terminology and approaches established in the multi-year report *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin* (UCRB Report).[10] This was a three-phase study involving multiple research organizations and local, state, and federal agencies, beginning in 2013 and ending in 2021. The aim of the report was to investigate and compare different approaches for estimating agricultural consumptive use and to develop a comprehensive estimation methodology for managers based on the current state of science.[10] Member states in the Upper Colorado River Commission (UCRC) adopted through resolution the recommended methods and procedures outlined in the report for estimating agricultural water usage across the Upper Basin.[10] UCRC staff were instructed to collaborate with states and the Bureau of Reclamation to monitor and enhance the accuracy of estimating Upper Basin agricultural water use, accounting for advancements in scientific understanding and methodological developments.[10] The resolution considered such factors as the accuracy and consistency of methods, alignment with current scientific knowledge, cost-effectiveness, and ability to provide timely information.[10] The UCRB Report therefore provided a useful template for the current study and is referred to throughout.

Accurately quantifying crop ET and its constituent sources quickly becomes an empirical challenge, demanding fine spatial and temporal data resolution, sophisticated modeling techniques, and nuanced understanding of many processes. Such perfect research conditions seldom manifest, and managers must at some point determine a cutoff as to what level of certainty is sufficient for meeting their goals. Within reasonable bounds, this study sought to isolate water sources for crop ET to irrigative applications alone. This interpretation emphasizes the management and legal objectives associated with maintaining water balance based on crop irrigation requirements delivered from a point of diversion. Construing the withdrawal source in this way accords with goals of water rights transfers in the Middle Rio Grande and the agricultural construct of the *duty* of water. We emphasize *actual* ET, as this denotes the use of empirical estimation methods, as opposed to a uniformly applied administrative constant CU_0. We therefore define actual crop consumptive use CU_a as follows:

Actual Crop Consumptive Use (CU_a):
The estimated depletion volume of evapotranspiration due to crop growth and originating exclusively from supply-limited surface irrigative diversions.

This represents the part of a surface water right that is depleted from the system due to crop beneficial use, and therefore constitutes an empirical analog of the administrative portion legally transferred. Effort was made to tackle some of the many complexities contained in this definition. For instance, *Effective Precipitation* deductions were used to address non-irrigative soil moisture and precipitation sources. These efforts are described in greater detail later in the study. In the UCRB Report, *Crop Irrigative Requirement* CU_{irr} is used to specify supply limited crop ET derived exclusively from irrigative applications.[10] This is the same definition of consumptive use emphasized in our study. However, the notation CU_a was used in place of CU_{irr}, as this was more consistent with other notion used in the study and emphasized the role of *actual* as opposed the *theoretical* consumptive use constant CU_0.

Common Approaches for Assessing Consumptive Use

Early methods for estimating crop consumptive use relied on empirical models.[3] These models generalized evapotranspiration based on observational relationships between plant and soil conditions and meteorological factors like temperature and daylight hours. They produced *Potential ET* values, referring to idealized well-watered conditions of specific reference crops.[10] While allowing generality of use absent technology and data, these models rely on broad-based assumptions which limit their precision and accuracy. They are useful relative to management goals, especially when data is lacking – but confidence in their values is limited compared with some modern approaches. In more recent decades, the use of improved technology and data allows for greater certainty among estimates but come with implementation costs or lack validation in their respective areas of application. In some cases, a combination of multiple methods is required.[10]

Assigned Constants:

One way of attributing a value to a collection of phenomena is to simply assign it a constant. Ideally, there are assumptions involved which make the attribution involved relevant. Assigned constants may not be terribly inaccurate if the underlying assumptions hold mostly true. But if they do not incorporate empirical data in measuring a particular instance of a phenomenon, such as an actual ET rate, then they are not really an empirical measure. Rather, they are estimates of a statistical mean based on assumptions. A statistic can be a valuable tool when little else is known, but its value is highly dependent on how well underlying conditions are aggregated and characterized.

The New Mexico State Engineer has established a set of constants for allowable diversion and consumptive use in transfers from irrigated lands within the Middle Rio Grande basin. The allowable consumptive use is set at 2.1 acre-feet per acre, while the allowable farm diversion stands at 3.0 acre-feet per acre.[1] This quantity is based on an on-farm consumptive irrigation requirement of 2.1 acre-feet per acre and includes a reasonable allowance for losses.[1] However, the measurement and accounting of MRGCD diversions is complicated by wide ranging practices and conditions a high degree of spatial and hydrologic heterogeneity, which casts doubt on the uniform application of assumptions beyond the tract scale. That being said, the CU_0 theoretical constant is surprisingly, but unreliably, accurate in many cases. We were unable to verify the origins of the 2.1 value, but assume that it is based on 20th century reference crop.[1]

Modified Blaney Criddle:

Modified Blaney-Criddle is a method used to estimate potential evapotranspiration. This method is particularly popular in situations where only limited meteorological data is available, such as in regions with sparse weather station networks or historical data gaps. It operates on a monthly time scale and requires only two primary inputs: average monthly air temperature and daylight hours.[10] The method is based on empirical relationships between air temperature, daylight hours, and ET_p, derived from historical observations. By utilizing these relationships, Modified Blaney-Criddle provides a relatively simple yet practical way to estimate ET_p, making it accessible and widely used, especially in agricultural and water resource management contexts.[10]

However, despite its simplicity and ease of application, Modified Blaney-Criddle has certain limitations. Studies have shown that it tends to underestimate reference ET, particularly in arid climates where factors such as wind speed, humidity, and solar radiation play significant roles in evapotranspiration.[10] Therefore, while Modified Blaney-Criddle remains a valuable tool, especially in data-constrained situations, users should be mindful of its inherent limitations and consider alternative methods for more accurate ET estimations, especially in regions with specific climatic conditions.

Penman-Monteith:

The Penman-Monteith method is a more sophisticated crop coefficient approach than the Modified Blaney-Criddle method and requires a broader set of meteorological variables.[10] These variables typically include air temperature, humidity, wind speed, solar radiation, and atmospheric pressure. By incorporating these factors, the Penman-Monteith method accounts for the various physical processes involved in evapotranspiration, such as evaporation from the soil surface and transpiration from plant leaves, as well as the influence of weather conditions on these processes.

The Penman-Monteith equation calculates reference ET based on the principles of energy balance and mass transfer, considering both energy and water fluxes at the land surface. This makes it particularly suitable for diverse climatic conditions and land surface types, as it can capture the complex interactions between environmental factors and vegetation characteristics. While the Penman-Monteith method is more complex and computationally intensive compared to simpler methods like Modified Blaney-Criddle, it offers greater accuracy and reliability, especially in regions with variable climates or when detailed meteorological data is available.[10] As a result, it is widely used in hydrology, agriculture, and water resource management for various applications, including irrigation scheduling, drought monitoring, and water balance assessments. Like the Blaney-Criddle however, Penman-Monteith method empirically models ET_p as opposed to being a direct measure of ET flux.

Eddie Covariance Flux Towers:

Eddy covariance flux towers are instrumental in directly measuring Actual Evapotranspiration (ET_a) rates in the field.[13] These towers are equipped with sophisticated instruments that continuously monitor the exchange of water vapor, heat, and carbon dioxide between the land surface and the atmosphere. The principle behind eddy covariance is based on turbulent fluctuations in the air flow above the surface, which carry information about these exchanges.[13] Towers contain a fast-response sensor that measures fluctuations in vertical wind speed and the concentration of water vapor.[13] By analyzing these fluctuations over time, scientists can calculate the flux of water vapor, which represents the rate of evapotranspiration from the land surface. This flux measurement is typically expressed in units of mass per unit area per unit time. Eddy covariance flux towers are located in various ecosystems, including forests, grasslands, croplands, wetlands, and urban areas, to capture the diverse processes driving evapotranspiration.[13] These towers provide continuous, high-frequency data measurements of

ET, as well as the responses of ecosystems to environmental changes such as rainfall, temperature, and vegetation dynamics.

Flux towers are widely regarded as the gold standard of ET measurement and are used as benchmarks for calibrating other models and bounding measurement uncertainty.[13] One drawback of eddy covariance towers, however, is their limited spatial coverage. While they provide highly accurate and detailed measurements of evapotranspiration at specific locations, their reach is confined to the immediate vicinity of the tower. This means that extrapolating ET measurements from a single tower to larger spatial scales can be challenging, especially in heterogeneous landscapes where ET rates may vary significantly over short distances.[13] Additionally, setting up and maintaining eddy covariance towers can be resource-intensive and costly. These towers require careful calibration and quality control procedures to ensure the accuracy and reliability of the data collected. Moreover, they are typically fixed in place, making it difficult to capture ET dynamics across diverse land cover types or in regions with complex terrain.

Remote Sensing:

Developments in areal technology have led to the use of remote sensing techniques for measuring ET.[10] Remote sensing utilizes sensors on satellites, aircraft, or ground-based platforms to capture electromagnetic radiation reflected or emitted by the Earth's surface and atmosphere. This data provides insights into environmental features and processes. Passive sensors detect natural radiation, while active sensors emit radiation for measurement.[14] Remote sensing data aids in environmental monitoring, resource management, and scientific research through spectral analysis and image processing techniques.

Remote sensing is capable of measuring ET_a indirectly using environmental variables related to the surface energy balance. These variables include land surface temperature, vegetation indices (such as NDVI), albedo, and emissivity. By combining this data with meteorological information and surface characteristics, models can estimate ET_a over large areas. While this indirect measure constitutes a very close estimate of ET_a (as opposed to ET_p) it is not as accurate as flux towers and must be augmented by reference crop data during cloudy periods or non-overpass days.[13] Furthermore, the newest models involving remotes sensing are still in the process of being validated by researchers and agencies – OpenET may be an exception that is now widely embraced.[10] Because of this, remote sensing is becoming recognized as a superior estimate of ET as compared to crop coefficient models, with the caveat that they still require caution and careful examination of existing conditions for proper use.

Soil Water Balance and Effective Precipitation:

The methods described are only the most common approaches available to researchers and managers, but they are methods specific to ET. All of them must be combined with other methodologies to capture aspects of supply source and limitation to meaningfully characterize consumptive use in water right transfers. A crucial consideration is the delineation of local water balance contributions to crop ET coming from non-irrigative sources. To this end soil moisture balance methods are used to estimate Effective Precipitation P_e.[15]

The Soil Water Balance method for P_e estimation relies on the principles of hydrology and soil science to assess how much of the precipitation effectively contributes to soil moisture recharge and plant growth.[15] This method considers factors such as soil type, vegetation cover, slope, and land use to estimate the portion of precipitation that infiltrates the soil and replenishes soil moisture, as well as the portion that runs off or evaporates.[15] The method calculates the difference between precipitation input and losses from runoff, evaporation, and deep percolation. The remaining portion of precipitation, which contributes to soil moisture recharge and potential plant uptake, is considered the effective precipitation.[15]

To calculate effective precipitation, the method requires information about precipitation amounts, soil characteristics (such as texture, depth, and available water capacity), vegetation type and density, land slope, and land management practices (such as irrigation or tillage).[15] These parameters are used in equations and models to estimate the water balance components and determine the effective precipitation amount. By quantifying the portion of precipitation that effectively recharges soil moisture and supports plant growth, soil balance methods can help quantify crop irrigative requirements.[15] Additionally, it can be integrated with other hydrological models and remote sensing techniques to improve accuracy and spatial resolution in effective precipitation estimation.[10] Methods for soil moisture balance estimation vary from field measurement using probes, to empirical models. The latter are more commonly used for larger spatial scales given the many variables involved. Some models are extremely well developed but require many data inputs. In our study, the Soil Conservation Service (SCS) was used due to a lack of available data.[10]

The SCS method is a widely used empirical approach for estimating direct runoff from rainfall events.[10] Developed by the United States Department of Agriculture for predicting runoff in watersheds. The SCS method is based on the concept of curve numbers, which are empirical parameters representing the hydrological characteristics of a watershed.[10] The curve number reflects the soil type, land use, land cover, antecedent soil moisture conditions, and hydrological soil group. These factors collectively influence the infiltration capacity of the soil and the amount of rainfall that becomes runoff. Effective precipitation is then derived as the complementary portion of precipitation which penetrates the root zone, where it can contribute to consumptive use. This quantity is then subtracted from ET.[10]

The method can be used in a crude sense by assuming soil characteristics as regional statistical values – in the Middle Rio Grande for instance, the soil depth factor is generally construed as 3 inches.[16] but it can also be integrated into more sophisticated modeling if quality data is available. Our study assumed regional statistical values and in conjunction with real-time precipitation data obtained from OpenET. Despite its widespread use, the SCS method has limitations, particularly in regions with highly variable soil and land cover conditions.[15] Additionally, its reliance on curve numbers derived from empirical relationships may lead to uncertainties in runoff estimation, especially in areas with limited data availability or significant land use changes. However, with appropriate calibration and validation, the SCS method remains a valuable tool for hydrological analysis and watershed management.

OpenET: Satellite-Based Actual Evapotranspiration

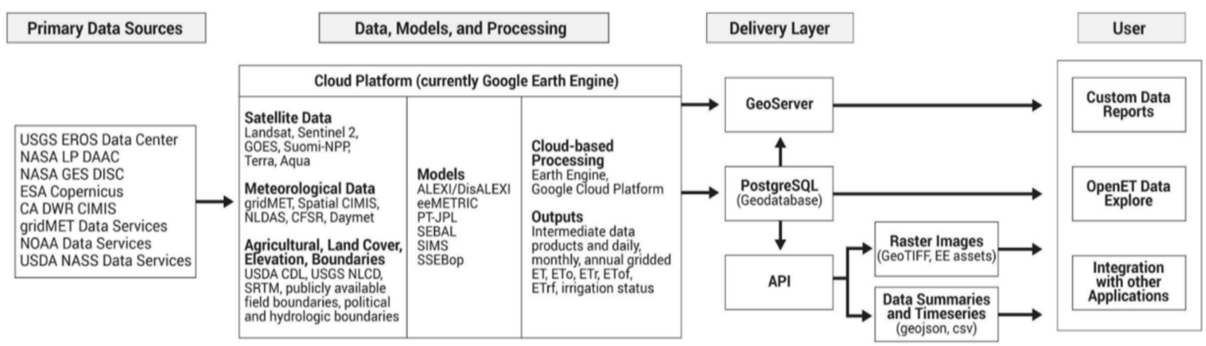
OpenET was launched in 2020 as a collaborative initiative involving multiple government agencies, research institutions, and technology companies.[17] Its primary aim is to provide accurate estimates of actual evapotranspiration ET_a at useful spatial-temporal scales using satellite remote sensing data. This information can then be used to address issues in water management, including irrigation optimization, drought monitoring, and sustainable water allocation. The OpenET platform offers online access and provides a comprehensive interface for querying large datasets through the OpenET API, developed in collaboration with Google Earth Engine (fig.1).[17]

The OpenET Platform

The OpenET platform integrates satellite data, weather information, and modeling techniques to provide a comprehensive integration of variables. These datasets are especially useful for estimating on-farm ET_a in the Middle Rio Grande.[17] The ET_a data consist of raster imagery at spatial resolutions of 30 meters per pixel, providing resolution suitable for farm-scale estimations.[17] Timesteps are daily or monthly but can be rolled into annual as well. Although the website interface is useful for quick access, obtaining data through the API provides access to longer time-series and a greater range of platform variables, such as NDVI or alfalfa reference ET. Other variables, such as weather data, have varying degrees of spatial-temporal resolution.[17]

Figure 1

Open ET Data Platform



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OpenET relies primarily on satellite data, with the Landsat program serving as its primary data source.[17] Landsat provides long-term, continuous observations of the Earth's land surface, offering both optical and thermal imagery used to estimate ET_a. In addition to Landsat, OpenET integrates data from other satellite missions, including GOES, Sentinel-2, Suomi NPP, Terra, and Aqua.[17] These additional satellite datasets, along with weather station measurements, are incorporated to enhance the accuracy of ET assessments.[17]

Weather data on the platform include meteorological variables such as solar radiation, air temperature, humidity, wind speed, and precipitation.[17] Weather station measurements across different regions are assimilated to produce spatially distributed or gridded weather datasets. Weather datasets then provide comprehensive information on atmospheric conditions, allowing for a more precise calculation of reference ET and ET_a values.[17] The most prominent weather dataset in OpenET is gridMET at an approximately 4 km spatial resolution.[13]

Model Ensemble of Surface Energy Balance

The platform has the important ability to combine outputs from multiple models. These models use various algorithms and methodologies to generate a wide range of ET estimates.[17] Individual models exhibit unique biases or inaccuracies due to differences in physics, assumptions, and input data. The ensemble option is therefore helpful for combining model outputs into an ensemble average to mitigate model discrepancies.[13] Ensemble averaging is a well-established practice in climate science and hydrology for improving estimation accuracy.[13]

The satellite-driven models rely on the surface energy balance to analyze the interaction between Earth's surface and the atmosphere.[13] They utilize incoming solar radiation as the primary energy source, which drives processes like surface evaporation and vegetation transpiration.[14] By measuring solar radiation in different spectral bands and surface reflectance, satellites estimate incoming radiation and the energy absorbed by different land cover types. As the surface heats up, it transfers heat to the air above, affecting temperature and humidity in the atmospheric boundary. Evapotranspiration, representing latent heat exchange, occurs as water evaporates and transpires. These heat fluxes are what the satellites capture for modeling ET_a in the surface energy balance.[14] Therefore, OpenET estimations are not truly direct measures of evaporative flux, such as Eddie Covariance measures, but they are close empirical proxies. Other model inputs include surface temperature, vegetation indices, land cover, and meteorological variables assist.[14]

Ancillary Data and Interpolation

The OpenET methodology still requires ancillary crop and environmental datasets provided by various agencies and organizations to enhance its estimation of evapotranspiration.[14] Table 1 provides an example of ancillary data types and sources.

Table 1: Example of OpenET Ancillary Data and Data Sources[14]	
USDA	Crop Type and Crop Characteristics
USDA	Soil Characteristics
USGS	Digital Elevation Models
USGS	Land Use Classifications
State and Local Agencies	Crop Type Data
State and Local Agencies	Active Irrigated Lands Datasets
USDA, State, Local, Research Groups	Manually Digitized Agricultural Field Boundaries

There are several reasons for including the ancillary data. For one, they support the characterization and interpretation of model outputs by providing information about land cover, soil types, and agricultural practices.[14] In this way the datasets contribute to a more comprehensive understanding of the underlying environmental conditions. But most importantly, in scenarios where satellite data have gaps between overpass days, the inclusion of ancillary crop data helps fill these voids by integrating on-ground information.[14] Satellite passes occur every eight days, resulting in cyclical data gaps in the estimated ET_a between each pass.[14] This necessitates reverting to the calculation of crop reference ET for the intervening periods without direct data. The ancillary data is dynamically integrated with weather data and other satellite programs to linearly interpolate ET_a estimates for the missing days.[14] See Appendix I for further details.

Accuracy and Acceptance of OpenET

A recent 2024 study *Assessing the Accuracy of OpenET Satellite-based Evapotranspiration Data to Support Water Resource and Land Management Applications* evaluated the performance of OpenET data using Eddy Flux Towers for various Köppen-Geiger climate regions.[13] Two of these regions and pertinent crop ET conditions were relevant for our study. The results of the 2024 analysis provided Mean Absolute Error and Mean Bias Error values that we incorporated, allowing the creation of uncertainty ranges and bias correction based on the overlapping conditions between the two studies. While not constituting an ideal comparison for quantifying empirical error bounds, we were at the very least able to posit a method for doing so.

Other studies have investigated OpenET, and it is gradually becoming embraced by water planners and administrators. The methodology has been accepted by the UCRC as offering an improvement in consumptive use estimation for the Upper Basin member states.[11] However, OpenET cannot be used without caution. Appropriate use of remotely sensed data requires critical assessment of various factors in combination with additional methodology. To the extent possible, this study adopted methods outlined in a recent publication commissioned by the UCRC, including necessary adjustments for effective precipitation.[11]

Geography Middle Rio Grande

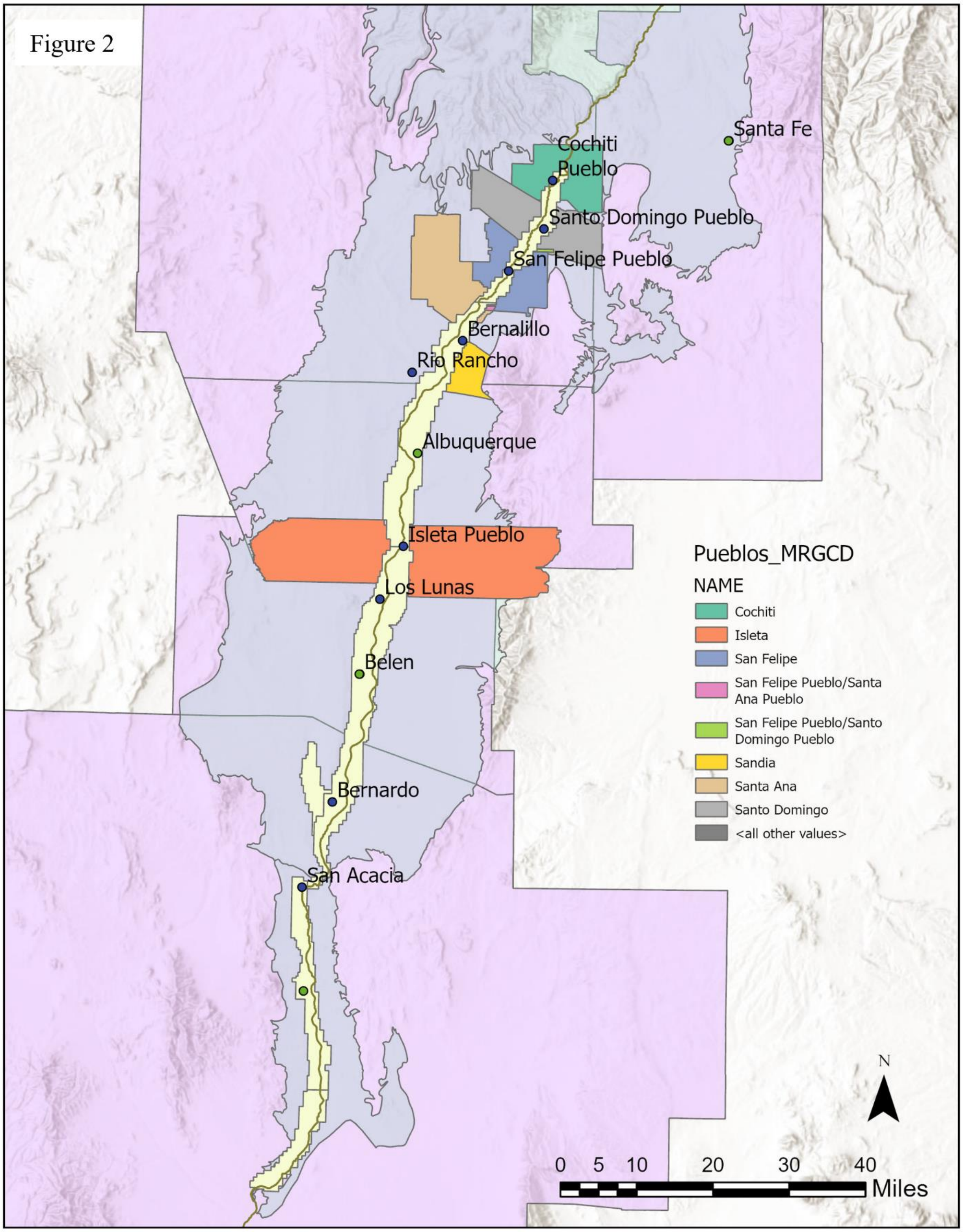
The Middle Rio Grande (MRG) is a section of the Rio Grande basin in central New Mexico. The region is generally located between Cochiti Reservoir in the north and Elephant Butte Reservoir in the south.[3] Its western boundaries are shaped by the Rio Puerco watershed and geological uplifts, while its eastern edge is defined by the Sandia, Manzano, and Los Pinos Mountains.[18] The Rio Grande flows through the MRG from north to south along an alluvial valley floor formed by the Rio Grande Rift.[18]

In terms of hydrogeology, the MRG overlies the Albuquerque Basin within the broader Santa Fe Group aquifer system – neighboring basins within this group are the Espanola (north) and Socorro Basin (south).[18] The areal extent of the MRG is approximately 2,900 square miles with a longitudinal extent of approximately 160 miles. Elevation within the basin ranges from 4,700 to 6,200 ft. Its climate is characterized as semiarid rangeland with a mean annual precipitation of 8.7 inches.[18] The *Köpen-Geiger* climate classification system (KG) is added to this study for specifying conditions relevant for evapotranspiration.[13] Under the KG system, the MRG can be characterized as a combination of the climate zones *Cold and Hot Semi-Arid Steppe* and *Hot and Cold Desert*.[13] Both surface and groundwater are used throughout the basin, but the Rio Grande is the principal source for irrigated agriculture. Alfalfa production, turf grass, and riparian forest are the primary modes of evapotranspirative loss, which is concentrated along the roughly 4.5-mile-wide inner valley flood plain.[18]

The MRG contains many administrative and political subdivisions, each representing some or all of the many diverse communities found there.[3] It is the ancestral home for six tribal nations and contains the state's largest urban centers of Albuquerque and Rio Rancho (fig.2).[3] Various forms of agriculture are practiced in the MRG, ranging from traditional acequia systems to urban agriculture and large-scale mechanized farming.[3] Many small to mid-sized communities cluster along the valley floor near the river, some are old acequia communities going back to the Spanish colonial period.[3] The four counties which it spans account for nearly half of the State's total population and contain many of its most important economic sectors and political arenas.[3] The MRG is symbolized by its beloved riparian cottonwood forest, colloquially known as the *Bosque*, which is present to varying degrees along most reaches of the river.[3] These riparian ecosystems evolved under predevelopment flood regimes and are considered threatened today, along with several federally listed endangered species.[19]

The Middle Rio Grande Basin

Figure 2



The Middle Rio Grande Conservancy District (MRGCD)

The Middle Rio Grande Conservancy District (MRGCD) plays a central role in water operations, planning, and management in the Middle Rio Grande basin. The District was formed in 1925 for various purposes like flood control, drainage, and delivering irrigation water.[3] The MRGCD wields authority over the majority of MRG surface water.[20] The District represents multiple communities and jurisdictions throughout the valley, including the six MRG Pueblos. In 1927 the MRGCD was granted power by the state legislature to execute infrastructure projects aimed at flood control, water storage, and improving regional habitability, as well as bolstering agricultural economy. However, these endeavors, such as canal construction and bank stabilization, gradually altered the river flood plain and surrounding hydrology, introducing new development and environmental alterations on top of new allocation practices.[20]

MRGCD water policy initiated the growth trajectory of the region's economy as well as opening a path for extensive urbanized land use.[20] As irrigated agriculture distributed water outward from the river's main stem, it created a verdant region within the arid landscape – a coveted attraction for urban development.[20] This oasis effect elevated land values, catalyzing the gentrification and subsequent residential subdivision of valley farms, inevitably encroaching upon the MRGCD irrigation system.[20] Furthermore, MRGCD ditches and diversion works inadvertently began to recharge the alluvial aquifer.[20] This unintended consequence fueled growth-oriented urban planning endeavors across the area.[20] Consequently, the very irrigation network designed to preserve nonurban land and agricultural water use has paradoxically fueled the urban expansion now conflicting with its agricultural objectives.[20]

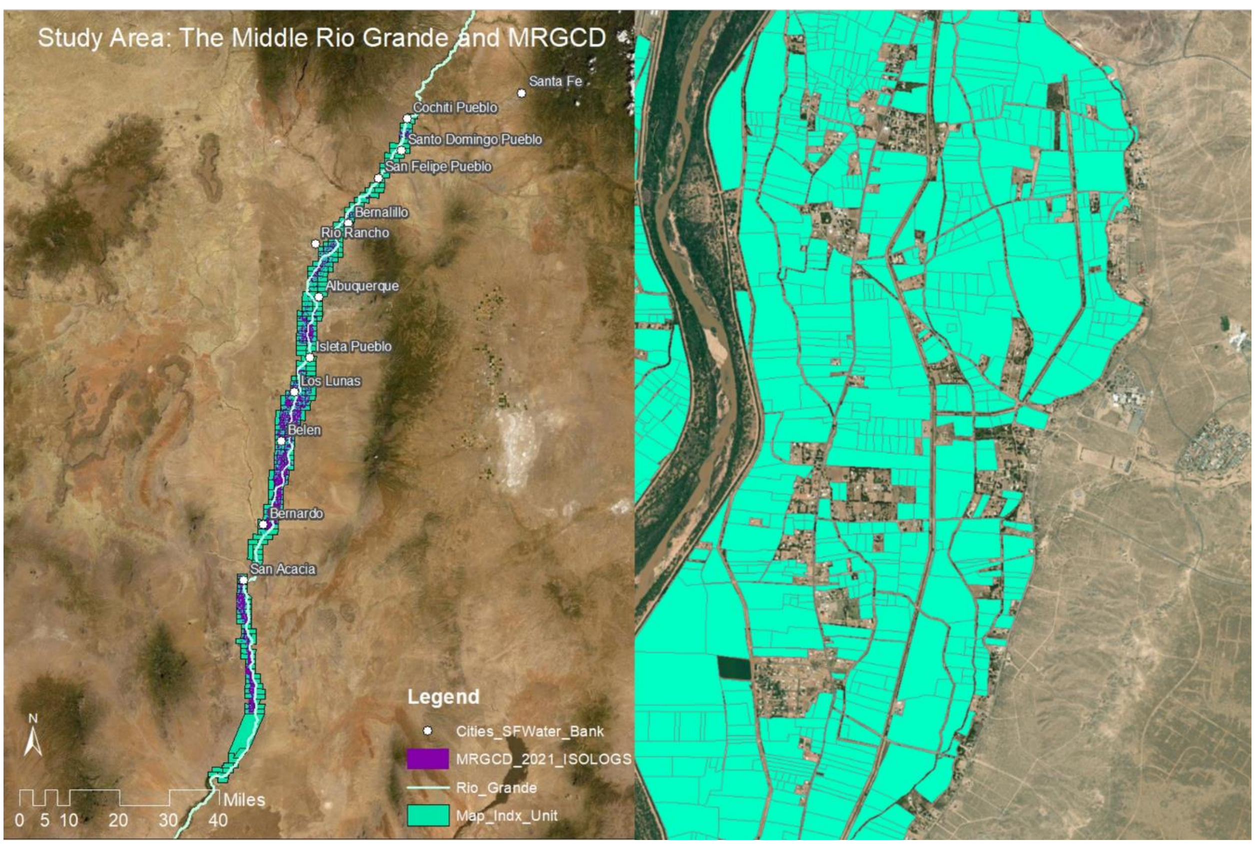
There are seven distinct categories of legally recognized water rights within the District.[1] These encompass pre-1907 individual water rights, permits issued between 1907 and 1927, MRGCD surface water rights awaiting quantification, Pueblo water rights with Prior and Paramount seniority, pre-1956 and permitted groundwater rights, San Juan-Chama water rights, and storage rights for El Vado Reservoir.[1] The MRGCD also manages its own water bank, established by the Board of Directors, to promote efficient transfers between MRGCD farmers while keeping water supplies within the District.[21] It allows irrigators to lease additional water during periods of sufficient supply.[21] However, when water supply is inadequate for all lands, the

Water Bank may prioritize allocations, curtailing leases, or ensuring equitable distribution through shortage sharing.[21]

The District spans the full extent of the MRG from Cochiti Reservoir to San Marcial above Elephant Butte (fig3). It is subdivided into the four main divisions: Cochiti, Albuquerque, Belen, and Socorro, in a north-to-south direction respectively. These four subdivisions are separated and distinguished by their main diversion points, which send irrigation water out laterally into the fields via a network of ditch conveyances.[1] Most agriculture is practiced at the northern and southern extremities of its range (primarily southern), owing to the increased urban density of the Albuquerque metropolitan area in the Districts center.[1] In the northern reaches agriculture are characterized by smaller and more densely clustered farms, many of which occur on pueblo land.[1] South MRGCD agriculture is more extensive and large-scale, constituting the major agricultural interests of the District.[1]

The Middle Rio Grande Conservancy District

Figure 3



MRGCD diversion networks and management practices create an intricate and highly complicated hydrological system that has become entangled with multiple urban and environmental values, making it concentrated region of management complexity.[1] The full extent of this complexity was not explored in our study. However, we did address some of the local spatial scale dependencies associated with these networks in relation to the locations of retired water rights. The MRGCD irrigative season from March through October was also used as a time series for consumptive use analysis.[1]

City of Santa Fe Water

Santa Fe's water resources and infrastructure are a publicly owned and managed extension of City of Santa Fe municipal government. Implementation of the water system's daily and long-range requirements is carried out primarily by the City Water Division, which operates under the broader Public Utilities Department.[22] While the Water Division is composed of technical professionals with decision making authority, decisions affecting the City's overarching water planning goals are integrated with the City's democratic processes and ultimately guided by civic values and approval.[22] This accountability to both local citizens and broader regional communities, combined with the City's multiple water sources, creates significant institutional complexity to City water management and requires technical expertise, meticulous planning, and collaboration among multiple groups and agencies.[23]

Production Sources

City water comes from four distinct but interrelated hydrologic systems.[22] Of the four sources, two are surface water systems and two are groundwater systems (fig4). Surface water is sourced from the Santa Fe River and San Juan Chama Project water diverted from the Colorado Basin. Groundwater is sourced from multiple wells within the City limits, collectively referred to as the City Wellfield, as well as from 13 regional wells situated between the City and the Rio Grande, known as the Buckman Wellfield.[22] Together, these sources provide drinking water to thes City's population of approximately 88,000 residents, as well as providing some supply for Santa Fe County through negotiated agreements. Currently, the City produces approximately 8,800 afy from all sources to meet demand. However, only an approximate 4,700 afy of the water produced is used consumptivley. The remaining 4,100 afy returns to the lower Sante Fe river as treated effluent from the Paseo Real Water Treatment Plant.[22]

City of Sante Fe Sources of Water Supply

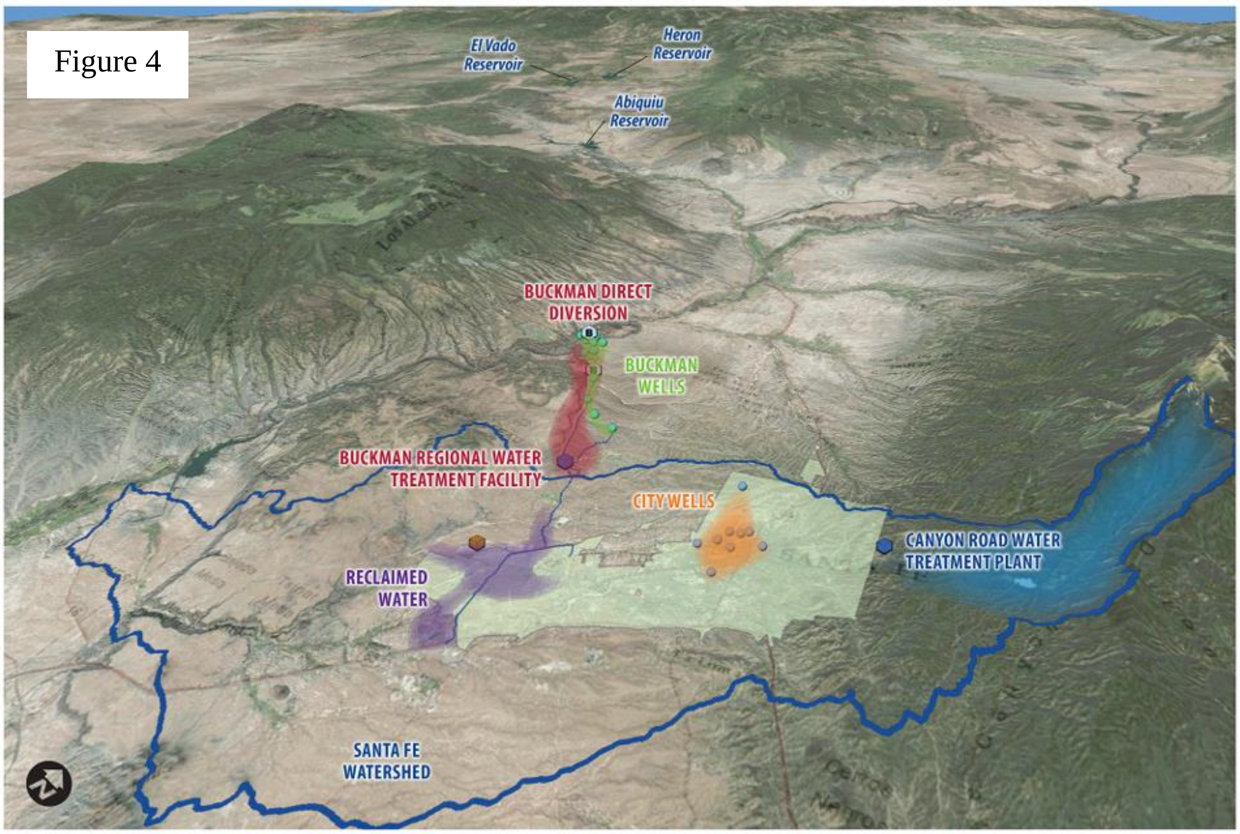


Figure 4

Production from the four sources is prioritized in accordance with resilience and sustainability strategies implemented by the Santa Fe Water Division. Generally, the City places higher importance on conserving groundwater systems. As a result, groundwater is utilized as a last resort, primarily complementing surface water supplies. This approach is based on the understanding that aquifers recharge slowly over time and are essentially finite in the short term. Therefore, Santa Fe adopts a management strategy focused on ensuring the long-term sustainability of its aquifers and their role as storage reserves to mitigate potential supply disruptions like wildfires or droughts.[22] Interestingly, the City does not divert any native Rio Grande surface flows. Instead, the City diverts non-native San Juan Chama water using the Rio Grande as a conveyance, but these are not counted as Rio Grande surface diversions.[22]

The Santa Fe River

The Santa Fe River is typically the first source for production.[22] It originates as snowmelt in the southern Sangre de Cristo Mountains immediately northeast of the City. The upper watershed is approximately 17,000 acres and contributes most of the basins recharge and runoff.[22] The Santa Fe River is impounded at two small storage sites in the lower watershed: McClure and Nichols Reservoirs. Water diverted from these reservoirs is first treated at the Canyon Road Water Treatment Plant, then diverted through the City's supply distribution system. Some water is bypassed for local acequias and to support the City’s Living River Project.[22]

Despite being a hydrologic tributary of the Rio Grande, the Santa Fe River's flow seldom reaches its historical confluence near Cochiti Lake. Instead, treated effluent from the plant is returned to the River’s natural channel at that location, which allows the river to remain above ground temporarily.[23] Over the course of decades, this effluent has contributed substantially to groundwater recharge in the lower watershed, allowing the establishment of riparian ecosystems and surface flows for local small-scale farms.[24] The ephemeral nature of the Santa Fe River, along with storage constraints outlined in Article VII of the Rio Grande Compact, motivate its use as the first source for City withdrawal and consumption.[22]

The Buckman Direct Diversion (BDD) & San Juan Chama (SJC)

The Buckman Direct Diversion (BDD) is the second production source for the City.[22] The BDD is an infrastructure project delivering an annual supply of San Juan Chama (SJC) contract water conveyed in the Rio Grande.[22] SJC contract water forms a signficant portion of the City’s supply portfolio, about half of the City’s annual demand.[22] As it’s name suggests, the BDD is a conduit for carrying SJC water directly to the City. Technically speaking it is not itself a source, but rather a tool for delivering water from the actual source, which are three San Juan River tributaries in the Colorado Basin.[22] SJC water is diverted through the Continental Divide to the Rio Grande Basin and stored in a series of federal reservoirs via the Rio Chama, and ultimately is released into the Rio Grande. The Rio Grande then acts carriage for SJC water, moving it downstream to the BDD diversion structure, where it is pumped to the City.[22] Prior to BDD’s construction in 2011, the City had no conveyance system for its SJC allocation.[22] Diversion was carried out indirectly by groundwater pumping near the Rio Grande. Depletions in stream flow would then be offset by realeasing SJC water from storage into the river. Since SJC water is not native Rio Grande flow, it is not subject to Article VII restrictions of the Rio Grande compact.[22] This fortuitous exception makes SJC water increadibly important for the City, providing a wide range of strategic flexibility when compact conditions are in place.[22]

The City's SJC water right is legally designated as 5,230 afy.[22] However, this allocation fluctuates based on annual variations in the total *firm yield* allocation of 96,000 afy shared annually among other SJC contractors.[22] In years of limited supply, each contractor's legal allocation will be shorted in proportion with the overall deficit.[25] Although SJC water has thus far provided a vital and reliable source of supply, there is some uncertainty regarding long range climatological impairments and its legal priority in the broader conflicts of the Upper and Lower Colorado Basins.[23] Replenishment of seasonal snowmelt (to varying degrees) and freedom from Article VII restrictions are what make the SJC contract water the second in line for production withdrawals.

City Wells

The City Wells are a collection of seven wells within municipal area conentrated along the Santa Fe River. These wells were drilled in the 1950's in response to an intense drought during that erea.[22] The City Wells tap a shallow alluvial aquifer running under the City, which is recharged by mountainfront infiltration and river seepage. Altogether, the City Wells can legally produce up to 4865 afy in any single year and 3507 afy on a 10yr trailing average.[22] The production is much less than this in reality however, averging 1025 afy since the BDD come into use. The estimated sustainable pumping rate for the City Wells is 2000 afy.[22] Because the source is an unconfined alluvial aquifer in close connection with its recharge zones, it recharges at relatively short time scales compared to the regional aquifer. This makes the City Wells a more immediate supply source than the Buckman Wellfield.[22]

Buckman Wellfield

The Buckman Wellfield (BWF) is the fourth and final source of water production for the City of Santa Fe, linking the City's water management to the broader regional basin and transfer rules of the Middle Rio Grande.[22] The wellfield comprises 13 wells positioned northwest of the City, extending towards the Rio Grande, at an approximate distance of 15 miles from the urban center.[26] The first wells 1-9 were drilled starting in 1971 in response to drougt, and are screened at shallower depths closer to the Rio Grande, with Well 1 located about 600 feet from the river.[27] Wells 10-13, drilled between 2000 and 2002, are deeper and further from the River.[28] All 13 wells tap into a regional aquifer at varying depths ranging from 233 to 2,000 feet, but only some of the wells are in production at any given time.[28,29]

BWF has been in continuous production since 1972, with peak production occurring in the 1990s. The highest historical diversion was 5,890 af in 1995, predating the drilling of wells 10 through 13.[29] Between 1972 and 2011 the BWF supplied approximately 40% of the City's water needs, leading to substantial declines in well water levels.[29] Conservation efforts and the construction of the BDD in the mid-2000s alleviated demand pressure on the wellfield, resulting in a significant decrease in pumping rates.[22] Since then, groundwater levels near the production wells have recovered approximately 85% of the historical drawdown, with some wells even experiencing occasional artesian outflows due to local recovery.[29] Currently, the BWF contributes about 7% of the City's potable water supply.[29]

The Buckman wells penetrate both confined and unconfined regions of the Tesuque Aquifer system in the Española Basin, itself part of the broader Santa Fe Group.[30] Recharge to the aquifers comes from various sources, including rainfall, stream seepage, and movement from other groundwater bodies.[31] However, the majority of recharge for the Tesuque system is mountain front precipitation and alluvial streambed infiltration into fractured bedrock along Sangre de Cristo Mountains.[27] The Rio Grande and sinks in the lower Santa Fe River watershed at the La Cienega wetlands, are the natural discharge zones for the Tesuque aquifer, which tilts downward towards the Rio Grande with groundwater generally flowing westward towards the river.[26,27] Additionally, some water from the Tesuque aquifer system discharges into nearby streams in the Pojoaque River drainage basin including the Rio Nambe, Rio en Medio, Tesuque Creek, and Pojoaque River, all of which flow into the Rio Grande north of Santa Fe above the Otowi Gage.[27]

Pumping from the BWF induces depletion in Rio Grande flows which must be offset. This legal requirement represents a broader principal known as *conjunctive management*, and is enforced by the OSE to ensure that surface water depletions caused by groundwater pumping do not impair existing water rights or other State and environmental obligations.[32] Early Espanola Basin models established a hydraulic connection between the Rio Grande and the BWF which later became the basis for offset determinations.[28] This connection implies that BWF production results in some amount depletion in Rio Grande flows due to reduced pressure gradiants in the wellfield zone of influence, which encompasses the natural discharge zones of the Tesuque aquifer system.

There are three possible sources of water derived from wells – induced recharge from surface water bodies, captured subsurface flow that would have discharged elsewhere, and aquifer storage.[31] Original studies suggested that approximately 40% of BWF depletions accounted for induced recharge and captured flow over a multi-decade time span.[27] This implies the remaining 60% derives from regional aquifer storage. Validity over the degree of hydraulic connectivity between the Rio Grande and the BWF has come into doubt in recent years, including the portion of depletions caused by induced recharge as opposed to captured flow.[30] However, current legal arrangements remain based on original models, which construe induced recharge from the Rio Grande as the primary depletion. depletion is Rio Grande flow. Although these depletions represent around 0.09% of total Rio Grande flows, the quantity is non-negligable from a mangement perspective, and legal offsets are required.[29]

Pumping rates and hydrogeologic conditions determine the magnitude and timing of the relationship between groundwater production and its effects on surrounding surface and groundwater flows. Rules for meeting these requirements are stated under the BWF permit RG-20516 and stipulate that offsets be met through either sewage effluent, SJC water, or from retirement of water rights[33]. The permit further approves a maximum diversion is 10,000 afy, with wells 10-13 are permitted a maximum of 6,000 afy out of the total allowable diversion.[22] The City had originally intended to meet its offset requierments using SJC water, having assumed the BWF aquifer was sufficiently linked to the Rio Grande to provide continual recharge. But studies for the BDD permit 4842 indicated pumping did not induce enough Rio Grande recharge to sustainably use the full SJC. The City also recognized the strategic value in using its SJC water for direct supply, as outlined in the previous sections. Since 2014, the City has chosen to meet offsets exclusively with Pre-1907 retired native Rio Grande water rights. On average, this is around 740 afy of historical and current pumping.[29]

OSE offset calculations are based on models from two notable studies. The first of these was in 1988 by McAda and Wasiolek characterizing the regional hydrology of the Tesuque aquifer system.[26] Second was a 1990 study by McAda, which built on the previous Tesuque report but focused more exclusively on BWF drawdown effects on the Rio Grande.[27] The OSE subsequently developed a superposition model based primarily on the McAda-Wasiolek reports and run in modflow96. This OSE administrative model calculates depletions caused by BWF pumping on multiple surface water bodies in the region both above and below Otowi Gage.[28] These depletions are minor relative to those calculated on the Rio Grande and are treated as distinct depletions administratively. In this study, OSE's BWF depletions refer only to those on the Rio Grande below Otowi gage. Model outputs are run on an annual basis as part of the State's conjunctive management policy to determine Santa Fe's offset requirements.[28]

As mentioned aquifer characterization in the original studies has come into question in the subsequent years, particularly regarding the effects of confining layers in the of the Chamita formation and the implications for aquifer-river connectivity.[30] There is also considerable variability in river depletion depending on screen depth and distance among the wells currently in production, as well as time lags unique to each well. Despite these uncertainties, the OSE model is presently the best publicly available data source for our study. Further studies will likely improve depletion estimates, but we assume OSE values here with the acknowledgement that further investigation is required. Furthermore, since the OSE model outputs are the basis of legal offset requirements for the City, they remain a crucial part of the study.

The San Juan Retunflow Project

To reduce reliance on groundwater and native Rio Grande water supplies, the City is pursuing return flow credits through the San Juan – Chama Return Flow Project. This initiative aims to extend the City's SJC allocation by reusing water indirectly at the BDD, thus lessening the need for BWF pumping.[29] Return flow is projected to add a significant volume to the City's annual supply portfolia, perhaps trippling its current SJC consumptive capacity. Completion of the project has becomes imperative for several reasons, in additon to reducing dependence on native Rio Grande water rights, it will BWF produciton to be more reliably capped at a sustainble production rate of 2,600 afy.[28]

New Era of Santa Fe Water Management Planning

The current planning paradigmn of comprehensive and adaptive water management is relatively new in Santa Fe's history. Two significant events shaped this trajectory. The first, was the 1995 public acquisition of the water utility from the Sangre de Cristo Company. This put water planning under direct community controal and cultivated a management of resource strewardship.[22] The second event was the 2011 Construction of the BDD, which allowed Santa Fe to fully utilize its SJC allocation and thus the ability to infrastructurally integrate and dynamically manage the four sources of supply.[22] Together, these events fostered an ethos of water planning focusing on long-range supply conservation and demand reduction, and technical adaptability in near-term management of supply sources.[22]

Before 1995, Santa Fe relied on the Sangre de Cristo Company for its water supply, with potable water demand increasing rapidly and little emphasis on conservation. In 1995, the City gained control and ownership of its water utility. Public ownership of the utility elevated the sense of collective stewardship for the City's water resouces, initiating a new era focused on conservation and paving the way for subsequent management innovations. Shortly after the acquistion formerly intense groundwater mining began a steep downward trend, along with a significant decline in per capta water use to the present 88 gpcd.[22] The completion of the BDD in 2011 marked a crucial advancement in Santa Fe's water management abilities, made possible through collaborative funding efforts between the City and Santa Fe County.[29] By granting direct access to the City's full SJC allocation, the BDD enabled Santa Fe to shift its reliance predominantly to surface water sources, thereby drastically reducing groundwater extraction.[22] This reduction in groundwater production had a profound effect on the Buckman Wellfield, allowing it to rebound from historical over-pumping and resulting in substantial rises in water levels.[22]

The City of Santa Fe Water Bank

Another management tool that emeregec under the new planning pardighm was the Santa Fe Water Bank. Although the Bank was formed in 2009 before construction of the BDD, it was likely created in anticipation of replacing the BDD's former role. Prior to 2011, the City faced interdependent problems of inaccess to SJC surface water and overreliance on BWF goundwater.[22] The inability to convey SJC water forced greater dependency on the BWF, with SJC water being relegated to the single function of offsetting BWF depletions – one of the three possible options granted under the BWF permit.[33] Once the BDD came online, SJC water could be delivered and used as a direct supply source. This solved the issue of groundwater dependence, but it created a new issue. Prior years of groundwater extraction created residual drawdown effects on the Rio Grande that required continued offsets. With SJC water now serving as direct supply source, an alternate offset source was needed. The Santa Fe Water Bank conveniently filled that role.

Once the BDD became operational, the Water Bank assumed a genuinely legitimate hydrologic function. Its value in this capacity permeated higher-level planning, enabling adaptive management strategies that were previously unavailable. This is clearly illustrated in figure 5. The chart suggests that starting in 2004 a new management paradigm was beginning to emerge, whereby BWF depletions no longer be offset by SJC water, and instead gradually replaced by Pre-1907 water rights in the Bank. Quite likely discussions about the BDD where already occuring at this time. Then, in 2009, the year of the Bank's formal establishment, a remarkable shift occurred whereby native Rio Grande retired water rights became the primary offset supplier. This transition correlated with a decline in groundwater production from the BWF, further aided by the establishment of the BDD in 2011. By 2014, depletion offsets had decreased sufficiently such that retired water rights became the sole supplier of offsets going forward.

The Water Bank's role in that transition is clearly evident. And since that transition, the Bank has continued to serve the purpose of offsetting Rio Grande depletions caused by new City demand. But through time, intepretations of the Bank, its explicit value and purpose have evolved. Not all interperpretations have been fully supportive of the Bank's existence. Supportive or not, agreement among interpretations has been particularly ellusive. This may be due to the lack of clarity about how the Bank actually works, and the ease with which its administrative and hydrologic aspects are conflated.

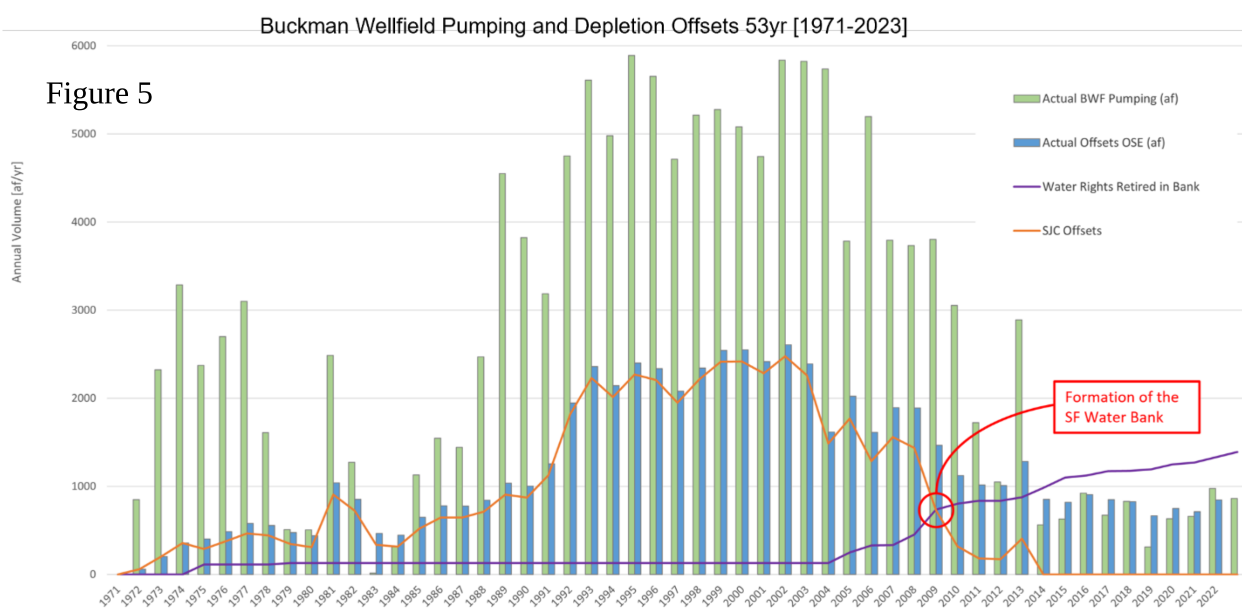


Figure 5

The Dual Nature of the Santa Fe Water Bank

As previously mentioned, water banks can be purely virtual institutional exchange mechanisms, physical volumes of stored water, or a combination of these.[5] The Santa Fe Water Bank is of the latter type, having a dual nature through its operation as an administrative bank account and a physical pool of water. The administrative aspect of virtual exchange is a necessary feature in any water bank typology and is relatively easy to grasp, because it comports nicely with abstract units of accounting. But the physical pool aspect is less clear. Since not all retired water rights are immediately used after transfer, they must be physically stored in some sense. However, both the institutional and hydrologic complexities in Water Bank transfers ambiguate what physical storage actually means for the Santa Fe Water Bank. The disparity between pre- and post-transfer hydrologic settings, their distances apart, the fate of retired water, and the incongruities between groundwater production and Rio Grande depletion, all conspire in making the physical bank poorly understood and easily conflated with its administrative counterpart. For these reasons, the following sections define the Bank in its entirety.

The Bank as an Administrative Bank Account

In its administrative form, Water Bank is a virtual or non-physical accounting system. In this sense, the Bank operates like a digital financial bank account, albeit with 'paper' water rights instead of digital deposits. These paper rights are a conceptual representation of real quantities measured in acre feet, signifying the theoretical consumptive use volume associated with retired farms. When water rights are transferred, the new points of diversion are administratively moved from their original locations to the BWF because of the legal need to separate diversion locations and acknowledge the physical role of BWF pumping.[4,33] However, there is no physical relocation of water between transfer locations. Instead, water rights within the Bank should be understood as withdrawal allowances based on the theoretical consumptive use of the original diversions which, collectively, form an upper limit for what BWF pumping can deplete from the Rio Grande. All such volumes are contingent on the theoretical consumptive use constant of $2.1\ afa$, and so the virtual pool of Bank deposits is primarily a function of retired acreage, creating a simplified environment for water offset accounting in relation to City development.

The administrative form of the Water Bank serves an important function of regulating City demand requiring water deposits from developers seeking new projects.[34] In addition, they function as the metric by which conjunctive management offsets are calculated and communicated to the OSE according to New Mexico legal statutes. In this latter sense, the Bank complies with closed-basin transfer rules, and couples new water demand with the City's conservation goals of sustainable development. Thus, the administrative functionality of the Bank constitutes an upper constraint on what developers have available for building new projects.

The Water Bank as outlined in City Code 25-10, links land use planning to available water supply by requiring developers to offset new demands on the water system.[34] The Water Bank monitors available water rights and conservation credits to support development; aiming to maintain enough water rights and system capacity for growing water demands from new construction. *Large developments* exceeding thresholds of 10, 7.5, and 5 afy for residential, mixed-use, and commercial projects respectively, must offset their water demand by purchasing MRG water rights for transfer into the BWF permit. *Smaller developments* below these thresholds can use similar offsets, toilet retrofit credits, or pay a fee.[34]

Water offset fees collected from developers are used by the City to acquire MRG water rights, toilet retrofit credits, or support conservation.[34] The Water Bank also tracks cumulative demand offsets achieved through its various rebate programs, which includes affordable housing, standard development, development met with retrofits, and development demands met by fees. Water rights transferred into the Bank are acquired through purchases water right owners or transfers from developers. Currently, the City holds 1,390 af of pre-1907 MRG water rights for offsetting effects downstream from Otowi gage.[22,34]

The primary conduit of depositing water rights in the Bank is through the *Development Water Budget Program*, which represents acquisitions by private development.[34] Since 1995, the City has acquired 1,169 af of water rights in the BWF from third-party transfers for development and 221 af from direct City acquisition.[22] Thus, private developers have accounted for the majority Water Bank deposits. The transfer hurdles encountered in this process are substantial. Both the Water Bank and developers address this issue by allowing water brokers to bridge the thicket of transactional barriers – finding and connecting water right sellers with the City and developers.[34] The smart option for developers is to call on brokers to locate available water rights in the MRG, and the smart option for the City is to place that obligation of bringing in water rights on the developer.

Balances and transfers within the Water Bank have been monitored since its inception, and presumably, as rights go in, they do not come back out. We could not legally substantiate this claim, however. Developers are not required to transfer legal title to the City until they officially designate a project.[34] Until then, it may be possible for them to speculate on the right or transfer it back out of the bank. There doesn't seem to be any evidence of this happening however, as demonstrated by the cumulative increase in Bank storage. It may simply be that water rights remain in the Bank out of practical difficulties in transferring, or the premium value they accrue by remaining deposited. Water brokers and markets surely play a role, but the finer details of these of these relationships are not always subject to City review and are often unclear.

The Bank as a Physical Volume of Water

The paper water rights in the Bank must still bear some correspondence with real water somewhere.[7] Even though no physical relocation of water takes place between transfer locations, the fact remains that BWF pumping causes upstream depletion, and the retirement of water rights reduces depletion downstream. And we know some version of *storage* must occur because many water rights sitting in the Bank are not actively engaged fulfilling depletion offsets. This suggests idle volumes of water exist in the system, which must be available for future use. In general, retired water rights represent a greater administrative volume than pumping offsets require.[29] This is evident through simple comparison of OSE annual offset calculations and the Water Bank's annual account. Unused water rights in the Bank provide a buffer for future demand, but their existence theoretically necessitates physical water flowing in the system; a retained surplus which can be thought of as storage. So, how can this storage be described, and where is the water stored? Furthermore, is the volume stored accurately represented by the administrative calculation, or is the actual volume different? Indeed, this latter question is something our study sought to answer.

There are multiple ways of conceptualizing the physical volume of water administratively represented in the Bank. A common way construes the BWF aquifer as the Bank's physical storage. This is an intuitively valid concept because the BWF is the legal point of diversion, and withdrawals from the aquifer are what impact Rio Grande flows. Furthermore, aquifers conform with our notions of physical storage as static reservoirs. But there are significant practical problems with this interpretation. First, it suggests that any water rights retired to offset depletions represent water added to the aquifer, residing there for future use. We know this is not the case in any direct manner.

Indirectly, we could try to interpret River contributions to aquifer storage as captured flow or induced recharge, which is also problematic. While it is true that BWF pumping induces Rio Grande depletions via captured flow (and perhaps some induced recharge), interpreting aquifer storage as water contributed from Rio Grande through these transient processes conflates distinct hydrologic processes.[31] Furthermore, Rio Grande depletions are a small fraction of the Bank's total volume, so captured flow and induced recharge could not physically account for inactive water rights in the Bank. Inactive water rights would have to be thought of as physically residing in the regional aquifer. But this would entail some fraction of Rio Grande offsets being physically supplied by regional groundwater storage not directly linked to the Rio Grande. This not only raises legal conjunctive management issues, but also leads to a double counting of Water Bank storage, because now both the retired water downstream *and* the regional aquifer represent offset volumes belonging to the Bank. It must be one or the other, and the Tesuque regional aquifer is not a viable physical or legal candidate for paying depletion offsets.

While it may yet be possible to construe Water Bank and aquifer storage as one in the same, it is not necessary. The transferred volume represents the consumptive use portion of an agricultural diversion that is no longer used for irrigation, and therefore not lost through ET. These volumes, which are real, are in direct correspondence with the administrative volumes in the Bank, and therefore offer better accounting clarity. Furthermore, the retired water is directly tied to Rio Grande surface flows, and therefore offers natural candidacy as a storage pool for River depletions. In the ideal transfer scenario, we can posit the existence of this pool as water not diverted and therefore kept instream. This *pool* is not statically fixed, like in a typical reservoir, but flows instream across the northern and southern boundaries of the Middle Rio Grande. We can therefore define the physical Water Bank as instream storage of former crop consumptive use. It is the annual volume of water kept in the river by retiring its agricultural use. The depletion is caused by BWF pumping and occurs in the river upstream of the retired farm, but it is theoretically nullified by instream storage of retired water.

The nature of being *kept* in the Rio Grande requires further clarification, however. Although cessation of diversion makes the water physically available, its fate afterward is immediately unclear. Water flowing in the MRGCD includes flows extending off the main stem into nearby diversion networks and canals. These are all possible locations where retired water could reside, as well possibly infiltrating from these locations. Instream storage must be thought of as being either dispersed across these various locations or consolidated in the river as withholdings prior to main stem diversion points. If instream storage is not consolidated in the river, it is likely to be consumed by other users or lost through other processes.[1] So, although instream storage is initially physically available, unless certain conditions are in place, it is immediately withdrawn by another use. Thus, for instream storage to persist as a functional reserve for the Water Bank, conditions must be in place to prevent withdrawals by other users or processes.

It is important to note that many variables affect what happens to the volume once retired. Retiring an irrigative right presumes the cessation of diversion and the continuation of that water as in-stream storage. That is the operating principle at any rate. But the MRGCD system can lose water to seepage or evaporation from canals, and also direct diversions into wasteways.[1] Some of this seepage is intercepted by drains, with some of the intercepted water is redirected for beneficial use. The remaining water eventually flows into the Rio Grande floodway. Water from wasteways may flow directly into the Rio Grande floodway or into drains. If water from a wasteway enters a drain, it may be diverted yet again.[1] During periods of ample water supply, the MRGCD typically maintains full canals, minimizing direct water management costs. This approach leads to more water being diverted from the Rio Grande floodway than necessary for farm deliveries, resulting in increased seepage losses and larger wasteway flows.[1] While most of these losses return to the Rio Grande floodway, they do so downstream of the diversion point.[1]

These issues impact how successfully retired water can re-enter the Rio Grande. Consequently, the fate of retired water is uncertain, and the Water Bank as a pool represents potential water, contingent on assumed practices and local hydrology. Both our study and the existing legal scenario assume – contrary to existing practice – that diversion methods are in place such that retired water is kept fully in-stream. This is highly unlikely of course, but it is within the realm possibility under different management strategies. We therefore assume retirement volumes represent the ideal management scenario in which terminated diversions are withheld at the point of diversion from the main stem and not rediverted. Under this assumption, the Water Bank pool of retired ET kept in-stream is valid representation. Deviation from the ideal scenario is discussed in greater detail later in the study.

Part II: Developing A Formal Model

Our central proposition is that epistemic uncertainty leads to wide ranging transfer effects on hydrology and impairs the functionality of the Water Bank as an adaptive management strategy. As a first step in understanding these effects, we sought to improve system definition and quantifiability of the Water Bank using structured language less prone to misinterpretation and uncertainty. This required identification of the important quantities involved and developing a set of logical relationships to coherently bind them. To do this, we organized transfer processes into more clearly defined constituent parts, classified their corresponding types of uncertainty, and described their logical interactions within a mass balance conceptual model. Mathematical relationships were used to formally describe relationships and generate model outputs. The transfer model was also useful for uncovering processes and scale dependencies not readily apparent in complex water transfer systems. A modeled understanding such as this can form a basis for mutually informed decision-making, potentially reducing transfer conflicts, creating new opportunities for water savings, and mitigating hydrological impairments.

Formalization

A broader theme of our study is the importance of knowledge systems that are accessible to everyone involved. People have different views and assumptions about the Water Bank and how it functions, forming an ambiguous *collective model* filled with personalized uncertainties.[3] We wanted to reduce this ambiguity by articulating the Water Bank in a formal language i.e., a system of rule-bound writing and corresponding symbology.[35] This situates the Bank in mutually accessible knowledge system, whose relationships are expressed in a common and well-defined language. Formalizing the Water Bank in such a way allows us to offer arguments and justify claims in a rule-based knowledge system.

Formalization also assists in handling crucial empirical phenomena involved in water transfers. Understanding physical processes like crop evapotranspiration requires a scientific approach combining measurement and hypothesis testing to reject unsupported theories. This methodology is itself predicated on logical inference expressed through the formal language of mathematics.[35] Formalizing conceptual models into mathematical relationships is what allows them to be empirically tested and made suitable for aid in decision making. In this way, the collective model transforms into a workable conceptual model, with rulesets that can be realized to simulate real-world processes and test assumptions.[3] Santa Fe Water Bank transfers currently lack the empirical data required for testing assumptions, but they also lack a formalized model for systematically testing assumptions in general.

Although formal models typically involve quantification, formalization can also be *non-quantitative*, relying on symbolic expressions to represent relationships between objects without numerical values.[35] Some formal models directly correspond to specific real-world situations, while others are generic and deal with the governing rules of system.[35] Specific models require precise, typically quantitative, observations as input data, while generic models can operate with unmeasurable inputs.[35] For our purposes, a formal model is used to describe water transfer processes involving both specific numerical measures of quantities and generalized variable representations of quantities. But greater emphasis is placed on generic rules, as these have yet to be developed.

The Idealized Transfer Scenario

By combining its administrative and physical aspects, the Water Bank functions as both a regulatory accounting mechanism and a tangible reservoir of retired crop consumptive use, kept in stream to offset upstream depletions. These aspects of the Bank allow it to operate as a regulatory intermediary for transfers between agricultural sellers and municipal buyers. In doing so, the Bank ideally creates a framework in which sustainable municipal development, sellers of water rights, existing water users, and State efforts to protect existing water users and public welfare, all agree. This is of course, an ideal outcome that faces uncertainties and challenges we have discussed. Nevertheless, the Water Bank in practice – as with all adaptive planning mechanisms – is structured according to an idealized process with hopeful outcomes. Understanding the idealized process is important for ascertaining how hopeful and actual outcome's part ways. We therefore present the idealized planning scenario by which a Santa Fe Water Bank transfer unfolds. The following scenario describes a standard water right transfer from the perspective of the Bank and in conformity with State and City legal processes.[1]

Steps in the Idealized Santa Fe Water Bank Transfer Scenario:

1. *Determination of New Demand:*

   The City determines a need for acquiring water rights, or as is more typical, a private developer proposes a project requiring deposition of water rights in the Bank. A water broker or designated party is contacted to seek and secure a valid water right in the open market.

2. *Identification of Candidate Land and Water Rights:*

   A search ensues for potential lands within the MRGCD district possessing appurtenant water rights. Properties with pre-1907 water rights are prioritized due to their seniority. Careful consideration is given to factors such as historical yield, cost-effectiveness of acquisition, and the validity of water rights. Clear legal title through a warrantee deed is also important.

3. *Evaluation of Water Rights:*

   The evaluation process is meticulous with multiple phases. Initially, existing records and OSE files are scrutinized to ascertain the status of the water right, including any adjudications or previous transfers. For rights lacking documentation, field visits are conducted to assess the physical infrastructure and irrigation practices. A more thorough analysis is then conducted into aerial photography, irrigation surveys, and historical usage patterns to determine the validity and reliability of the water rights. Anticipating OSE evaluation, the process is especially focused on the legal principal of *Beneficial Use*, attempting to verify if the farm has been applying their irrigative water right continuously after the declaration date.

4. *Water Purchase Agreement and Application:*

   The purchase process is conducted between designated parties and the water right seller. Unless the City is internally acquiring the rights, it will not be a party to the purchase.[34] The process involves three distinct stages. First, negotiations are initiated, culminating in the execution of a letter of intent. This preliminary agreement allows for the evaluation of water rights and negotiation of terms. Second, a detailed purchase contract is drafted, contingent upon successful water rights transfer. The terms of the contract address such issues as water rights validity, transfer conditions, and risk mitigation. Third, the closing stage formalizes the transfer, ensuring all legal requirements are met, and a notification of transfer must be published in local newspapers. Notification of transfer is usually when protests will start to occur.[1]

5. *Protest Period:*

   The protest period may or may not result in a protest. If protests occur, the OSE will generally interpret water right injury according to traditional Prior Appropriation statutes. Under interpretation of these laws, only those with legal water rights can claim injury from transfers that affect those rights. Therefore, irrigators cannot claim injury or harm if the water depleted upstream was water, they did not have a legal entitlement to use in the first place. Essentially, if they had no legal right to the water that was diverted or depleted upstream, they cannot argue that they have been injured by its diversion, as they were not legally entitled to that water.

6. *Transfer of Water Right through the OSE:*

   If no protest occurred, or were resolved through settlement or hearings, the OSE will formally commence legal changes in the key features of the water right, it occurs. Except for ownership, applications for changing the place and purpose of use, and point of diversion are prepared and submitted, adhering to OSE regulations and guidelines. The City of Santa Fe and the developer are listed as co-applicants on these forms, with the legal agreement that Santa Fe will become the full owner of the water right once the developer has designated for a project. The new place of use and point of diversion are defined as the City of Santa and the BWF permit RG20516, respectively. The purpose of use is changed from an irrigative surface diversion to municipal use. Special attention is given to the quantitative aspects of the transfer found in step 3, with the OSE scrutinizing evidence in detail to verify historical beneficial use and compliance with impairment and conjunctive use standards.

7. *Validation:*

   If the validity of the transfer is approved, then the theoretical consumptive use constant of $2.1\ ft$ is multiplied to the assessed irrigative acreage, stipulating consumptive use transfer volume. In cases where State and transfer parties disagree, it is usually over the historically irrigated tract acreage, or the continuity of beneficial use. We found no evidence of any disputation of the assigned consumptive use accuracy. The consumptive use constant is applied uniformly to any tract area deemed to have been in continuous irrigation i.e., based on area of continuous beneficial use. Again, historical aerial photos, records, and field visits are generally used to establish this. Sometimes, only part of a water right claim will be validated and transferred if beneficial use is partially in doubt or if an owner wishes to keep some of their original irrigative right. The approved volume for transfer is then finalized according to step 5. It's important to note, however, that *Change of Ownership* has not yet happened at this phase. Legal change of ownership to Santa Fe is not required until the developer chooses to designate the transferred right to a City project. This does not affect the transfer, but it can create problems for Santa Fe.

8. *Dry-Up or Termination of Old Use:*
   Any irrigation of the former land must cease unless it is conducted through a new water right. This is to prevent increased basin depletions, by ceasing water use on transferred. Theoretically the entire on-farm delivery, including consumptive use, is retained within the hydrologic system in virtue of not being diverted. There may be several ways of ensuring this happens, but we were unable to find any evidence of actual practices doing so. For the tracts we examined, some appeared to have indeed been dried post-transfer, while others appear to have continued historical irrigation rates.

These steps outline the idealized administrative water transfer process and the legal requirements that all Water Bank transfers must meet.[1] However, even with legal compliance, this idealized scenario may not achieve the intended goals of preserving water balance and protecting public welfare. Unexpected outcomes can arise from flaws in the idealized assumptions, such as inaccuracies in the estimated on-farm consumptive use or the assumed retention of retired water. Furthermore, the idealized process does not account for legally permissible ways to continue irrigation on lands whose water rights were transferred. These could include farm-to-farm water right transfers or, more likely, alternative mechanisms like leasing from the MRGCD Water Bank.[1] Of course, there is potential for criminal violations of the dry-up condition through illegal diversions, but we leave that unexplored in this study.

Finally, while the idealized administrative transfer provides a protest period for the localized movement of depletions upstream – this is the movement of a depletion's location without a net increase – it does not account for *unprotested* local effects, or the systemic implications of cumulative and prolonged legal conflicts. Although statutes allow for the relocation of depletions under the non-injury principle, non-water right holders could suffer adverse effects from shifting local depletions, posing a legitimate public welfare and environmental concern.[3] And should protests become frequent and prolonged, the idealized transfer process would start to become dysfunctional, impairing water markets in general and thus indirectly reshaping processes for distributing and reallocating water.

As mentioned, transfers can affect water balance through failure to accurately represent true consumptive use: the idealized theoretical constant $CU_0\ or\ 2.1\ afa$ could simply be in error. In that sense, the *actual* total pool of retired water could be larger or smaller depending on the cumulative error. But even if we assume the accuracy of CU_0, changes in balance are still possible. In practice, on an annual basis there is a greater volume of water rights held in the Bank than the volume of Rio Grande depletion caused by BWF pumping. Using CU_0 as metric, this implies a potential surplus of retired consumptive use somewhere in the basin: the existence of water that was transferred under the idealized process, is no longer depleted by crop ET, and is not required for meeting depletion offsets. Technically, the City of Santa Fe is the owner of these theoretical surpluses of unused retired water, but they are not formally accounted for by the OSE. The uncertainties and corresponding errors contained in the idealized Water Bank transfer raise concerns and warrant better conceptualization of Water Bank processes and quantitative estimations. The following section delves into each of these issues in greater detail.

Epistemic Uncertainty

The scientific knowledge system is not perfect. Many phenomena are highly complex and require acceptance of varying levels of epistemic uncertainty.[35] Emphasizing the word *epistemic* in addition to uncertainty may seem redundant, but we do it here to highlight the presence of an applied epistemological system. Unqualified uncertainty (simply not knowing) can occur without any conscious effort to know in a systematic way. But by emphasizing *epistemic* we specify the occurrence of uncertainty in a systematized effort to acquire knowledge.[2] There are multiple kinds of epistemic uncertainty. It may arise from empirical limitations, poor definition, or from categories of complexity for which the knowledge system is ill-equipped methodologically. Our use of *epistemic* refers to all such knowledge limitations which pose a special challenge for the knowledge system in use.

Epistemic Uncertainty:

Within an epistemological approach, a state of limited knowledge or understanding about a system, process, or phenomenon, characterized by unpredictability or ambiguity regarding possible outcomes or future events. It reflects the lack of precise information or confidence in the accuracy of available data, models, or assumptions, leading to difficulty in making reliable predictions or decisions.[35]

Epistemic uncertainty impacts mutual problem solving by challenging the accuracy and reliability of data, models, and assumptions. These uncertainties can exacerbate conflicts by fostering divergent narratives among groups, as the wider range of scenarios provides more opportunities for differing interpretations and points of confidence.[2] Epistemic uncertainty itself does not directly cause changes in hydrologic systems. Instead, it is the choices and actions made by managers when faced with this uncertainty that impact hydrology. Epistemic uncertainty refers to the limitations in our knowledge and understanding of a system, which can lead to varied interpretations and decisions. These decisions, based on incomplete or uncertain information, are what activate changes in hydrologic systems depending on how water is managed, policies are implemented, and actions are taken.

Reducing uncertainties, and thereby minimizing impacts caused by decision errors, is a significant challenge in the context of Water Bank transfers due to the lack of comprehensive knowledge. Matters are further complicated by differences between policy and practice, legal actions, rule compliance, supply disruptions, economic fluctuations, cultural and political changes. These institutional uncertainties are categorically distinct from empirical uncertainties focused solely on hydrological parameters. Quantitative models generally struggle with the extreme complexity of emergent processes introduced by human behavior and societal systems. And yet, these systems play a profound (if not major) role in driving uncertainty.[35] In recent years, models integrating human and geophysical systems have become more common to try and capture hydro-bio-human linkages. But these types of uncertainties remain one of the most intractable aspects of any model and often dwarf empirical parameter uncertainties or measurement error. In the sections below we provide a brief summary of the categories of uncertainty identified in the study, and the main sources of uncertainty within the model.

Categories of Uncertainty

Institutional uncertainty

- Arises from the structure, procedures, or policies within organizations or institutions that govern decision-making processes
- Factors include changes in regulations, unclear decision-making protocols, or discrepancies between legal frameworks and practical implementation.
- Manifests as ambiguity regarding roles and responsibilities, as well as unpredictability in the enforcement of rules or policies.
- Example: Changes in water rights regulations or shifts in policy priorities can create uncertainties for the long-term planning and operation of the BWF and Water Bank. Features include the willingness of institutions to enforce regulations or member willingness to comply, especially problematic in large institutions where oversight is difficult and competition over resources is fierce. May also involve inter-institutional competition.

Model Uncertainty

- Pertains to the uncertainties inherent in predictive or explanatory models used to represent real-world phenomena.
- Arises due to simplifications, assumptions, or limitations in the models themselves.
- Includes uncertainties related to the accuracy of input data, the appropriateness of model structure, and the validity of underlying assumptions.

- Example: Models used to predict the impact of BWF pumping on Rio Grande flows may have limitations in accurately capturing the complex interactions between groundwater and surface water systems.
- Implicit measures, such as the administrative theoretical consumptive use constant, fall into this category, representing assumptions that go unexamined.

Empirical Uncertainty

- Stems from variability or limitations in observed data or empirical evidence.
- Arises from factors such as measurement error, sampling bias, or natural variability in observed phenomena.
- Includes uncertainties associated with the quality, reliability, and representativeness of empirical data used for analysis or decision-making.
- Example: Empirical uncertainty can affect the accuracy and robustness of conclusions drawn from data on groundwater levels, river flows, and pumping rates.
- Can be measured or bounded within a range, usually relying on statistical methods in combination with existing empirical data to gauge variation and create range of possibilities.

Key Uncertainties in the Water Bank Transfer Model

We outline below some of the major uncertainties in the Water Bank transfer process, and consequently in our model. This is far from an exhaustive list, but it captures some of the main issues. Handling these uncertainties is partially addressed in the model, but not well. Rather, the model more clearly demonstrates where and how these uncertainties can have an effect.

Theoretical Consumptive Use (CU_0):

Theoretical consumptive use is classified as a model uncertainty, though in practice it functions more as an administrative figure rather than an actual measure. This figure is set at a constant value of 2.1 afa and is uniformly applied to nearly all water right transfers in the MRG.[1] This value likely stems from historical crop coefficient models like Blainey-Criddle but is not derived from specific parameters. The uncertainty in this constant arises from unexamined assumptions, leading to a generalization that fails to reflect the variability in hydrological and agricultural conditions. Confidence in CU_0 should be low as it does not account for site-specific factors such as soil conditions, crop types, and seasonal irrigation practices. Although it might be a fair estimate on average, its precision at the scale of individual tracts is likely very high. Despite its issues, the administrative constant's role in decision-making significantly impacts basin hydrology. Its use in transferring depletion allowances means the entire pool of retired water in the Bank is equally suspect. This uncertainty motivated our study to gain a better quantitative understanding of CU_0 by comparing it with empirical estimates.

Actual Evapotranspiration (ET_a) and Actual Consumptive Use (CU_a):

Actual evapotranspiration (ET_a) and actual consumptive use (CU_a) are derived from empirical observations and models, representing a hybrid of model and empirical uncertainty. Measurement error can arise from environmental variability or inaccuracies in remote sensing algorithms. The OpenET interpolation process introduces assumptions from reference crop models and relies on statistical approximations, with discrepancies observed between different evapotranspiration measurements, particularly during winter months and under certain weather conditions. Edge effects around field boundaries and variations in crop and vegetation heterogeneity add to the uncertainty, particularly for smaller farms. CU_a, being more complex, requires subtracting effective precipitation (P_e) derived from empirical models. In our study, we used the SCS method to compute P_e, facing uncertainties from empirical precipitation data and assumptions about soil moisture. Despite its common use, these data and assumptions could be improved, as seen in more sophisticated models like the ET Demands Model used in the UCRB report.

BWF Rio Grande Depletions:

BWF pumping from the Tesuque aquifer and its effects on the Rio Grande, epitomize model uncertainty. These estimates rely heavily on mathematical models, limited data, and broad assumptions due to the inaccessible nature of subsurface processes. The McAda-Wasiolek Model used by the OSE for computing annual offsets has not been updated for years. Recent studies indicate a higher level of heterogeneity and confining layers than previously assumed. This casts doubt on the current model's direct drawdown impacts on the Rio Grande, suggesting that BWF production might be drawing more from regional aquifer storage rather than the Rio Grande.[29] Consequently, BWF pumping might cause less depletion below Otowi than the State requires in offsets, indicating potential inaccuracies in offset payments. However, these remain speculative without more rigorous modeling. As no alternative models or empirical data exist for BWF pumping impacts, we had to rely on current estimates, acknowledging their uncertainties.

Management Decisions and Practices:

Water policies and practices encompass institutional uncertainties, merging model and empirical uncertainties with the unmeasurable phenomena of individual and institutional behaviors. These include uncertainties from political developments, compacts, and adjudications. A critical uncertainty in our study relates to the fate of formerly consumed irrigation water after retirement. This was referred to in previous sections relating to MRGCD water that is lost or potentially consumed in the diversion network once it has been withheld from diversion. It is entirely unclear what happens to retired water, but most likely it is not maintained as instream storage.

Model Description

The transfer model focuses on the hydrologic impacts of Water Bank transfers, specifically assessing changes to Rio Grande flows based on administrative transfers. Transfers result in changes regardless of whether the model uses theoretical consumptive use CU_0 or actual consumptive use CU_a as a parameter due to relative balance. The model outputs a numeric value for these effects under different scenarios and at different scales. The model primarily expresses the following two concepts:

1. *Relative Balance* (δ)*:* The existing steady-state balance reflected by BWF depletions (D_{RG}) relative to the total volume of retired water (W). Relative balance is a measure of system balance in the pre-transfer state, and then separately in the post-transfer state. It can assume a value for W based on either CU_0 or CU_a. Relative Balance is expressed as a ratio.

$$\delta = \frac{D_{rg}}{W}$$

2. *Consumptive Use Error* (ε_{cu})*:* Compares the difference between the ideal administrative water use constant CU_0 and the actual consumptive use estimate CU_a based on OpenET. Consumptive use error treats CU_a and the true consumptive use and assumes CU_0 differs

by some amount. Consumptive use error is measured in feet, but it's also a factor in each individual retired water right w

$$\varepsilon_{cu} = CU_a - CU_0$$

Relative balance tells us about the global state of the system, and consumptive use error quantifies the difference between what was theoretically planned to be retired (w_0) and what was actually retired (w_a). If w_a is greater than w_0 it indicates that the actual amount of water retired and transferred to instream storage was higher than what was originally estimated or planned. Because W is the sum of all w's in the Bank, then relative balance is sensitive to consumptive use error. This situation can exist in the pre-transfer state or the post-transfer state. The post-transfer state occurs after a transfer, and results from both the quantity of the retied water right relative to pumping depletions (affecting relative balance) and the propagation of consumptive use error (also affecting relative balance). Local changes within the control region that are not reflected at the system scale result from post transfer flow changes in combination with the size and spatial configurations of retired water rights.

The transfer model is designed according to the operational rules of the administratively idealized Water Bank transfer. However, it can accommodate different datasets as inputs within the ideal rule set. This feature allows the model to be iterated using either the theoretical consumptive use constant CU_0 or empirical estimates of actual consumptive use CU_a. This is important for obtaining ranges of uncertainty and comparing the two metrics. The model rules are expressed through mathematical equations with symbols corresponding to the various quantities involved. Equations are essentially arithmetic, often employing subindexes and conditional statements. For simplicity, we start by describing basic model terms and relationships under purely administrative assumptions and without notions of consumptive use error.

Mass Balance System

The transfer model is a mass balance system, accounting for inflows and outflows associated with Water Bank transfers in the region between the Buckman BWF and the San Marcial gage. The upper boundary of the control region is at the Otowi gage above BWF. The lower boundary is at the San Marcial gage. Horizontally the control region spans the Rio Grande approximately the width of the MRGCD. The vertical direction is an axis having ordinal significance, due to the north to south flow of the river and the vertical spatial dependencies of local transfer impacts. Changes in depletion are activated by a transfer between pre- and post-transfer conditions referred to as *Phase I* and *Phase II*.

Phase I (Pre-Transfer Condition):

Represents total inflows and outflows of the relative balance. Inflows are everything coming in across Otowi gage, including volumes that are depleted downstream in the control. Outflows are everything depleted from the control, these are either consumptive use depletions or BWF depletions. River flow is the key metric, as it represents instream-outflows past San Marcial and indicates the loss or gain to the system due to transfers. River flow is the system difference between all inflows and outflows. In Phase I, BWF depletions are assumed to be zero. Instream storage refers to the total retired consumptive use in the Bank W. It does not represent an accumulative buildup of volume like a reservoir, but rather the internal gain caused by retirement flowing instream. Instream storage is zero in Phase I. In our visualizations, depletion outflows are shown leaving the system laterally.

Phase II (Post-Transfer Condition):

Represents the new relative balance steady-state system after transfer. Inflows and outflows are defined the same as in Phase I, only now BWF depletion-outflow is non-zero and consumptive use depletion-outflows are zero. Phase II captures the effect of transfer, with BWF depletions occurring and retired consumptive use volumes w kept in-stream. Sincer retired volumes sum to the total volume in the Bank, instreams storage is non-zero in Phase II.

Transfer (Action Between Phases):

A transfer is defined as an administrative relation between Phase I and Phase II, marking the transient switch between them. A scenario combines both phases and the transfer relation into a unified process resulting in change. The pre-transfer Phase I establishes the baseline in a scenario where the transfer results in a deviation represented in Phase II. The difference between Phase I and Phase II constitutes a flow change, interpreted as an increase or decrease in depletion or its complement augmentation.

Scenario Analysis:
A scenario combines both phases and their transfer relation into a single event resulting in change. The pre-transfer Phase I establishes the baseline in a scenario where the transfer causes a potential deviation represented in Phase II. The difference between Phase I and Phase II constitutes a flow change, interpreted as an increase or decrease in depletion or its complement augmentation. This flow change registers as river flow crossing the San Marcial boundary. Phase I and Phase II represent steady-state conditions, with transience occurring between phases. Since the model focuses on the changes brought about by the transfer, and these changes are fully represented in Phase II (the post-transfer state), it is possible to conduct the analysis solely based on Phase II.

Spatial Scale:
Depletion status varies depending on the scope of the control region and the internal latitudinal arrangement of individual tracts and their respective retirement volumes. The model computes total system-scale depletions as well as local-scale depletions within the control region that do not constitute basin net losses.

In-Stream Storage Interpretation:
Retired water is withheld from diversion at approximately the same latitude as the original on-farm use. Since this water is retained in the system until it flows out at San Marcial, it is referred to as in-stream storage rather than system inflows. This storage should be regarded as a potential volume due to the uncertainty about the fate of retired water.

Key Terms

1. Total Rio Grande Inflow Q_{in}:
Represents all inflows coming into the system which include instream flow and flows available for diversion.

2. Total Rio Grande Outflow: Q_{out}:
Represents all depletion-outflows which consist only of consumptive use depletion and BWF depletion.

3. *River Flow Q_{river}:*
The difference between Q_{in} and Q_{out} as a flow past San Marcial. Indicates relative balance.

4. *Consumptive Use Inflow* w_{in}*:*
   Water flowing into the control in Phase I which is slated for consumption by on-farm crop ET in Phase I. This value can represent either CU_0 or CU_a in the model.

5. *Consumptive Use Depletion* w_{out}*:*
   Water withdrawn from the river in Phase I and consumed by on-farm crop ET, representing a depletion outflow component. This value can represent either CU_0 or CU_a in the model. Consumptive use depletion is zero in Phase II.

6. *Retired Consumptive Use* w_{in}*:* The portion of water rights withheld from diversion and retained within the river system as Water Bank in-stream storage and becoming a part of river flow past San Marcial in steady-state Phase II. Retired consumptive use is zero in Phase I.

7. *Total Retired Consumptive Use (Bank)* W*:*
   Represents the total volume of retired water in the Bank (in either phase) and the water retained instream until it eventually flows out at San Marcial. In reality this, should be treated as a potential volume due to the uncertainty about the fate of retired water. This is the same value as total retired water rights in either phase.

8. *BWF depletion below Otowi* D_{RG}*:*
   Represents the depletion-outflow of the river system at its highest point at the BWF. This value is modeled by the OSE calculated annually for Rio Grande depletion offsets. In the idealized transfer scenario using CU_0, BWF depletions are practically always less than or equal to the total volume of water rights in the bank. This is an implicit outcome of the Banks purpose and the City's operational policy of prioritizing SJC water for domestic delivery and using native Rio Grande flows for offsets.

9. *Bypass Flow* Q_{BP}*:*
   Stream inflow that circumvents diversion points and passes through the river system before transfers. This is automatically cancelled in the difference between phases but shown here to indicate the existence of Rio Grande flow unrelated to the transfer.

10. *System Change in River Flow* ΔQ_{river}*:*
    Represents the net change in river flow past San Marcial resulting from water rights transfers between phases I and II. Within each phase it is the difference between total inflow and outflow indicative of relative balance. Because the model changes are reflected in Phase II, all terms cancel except $W$and D_{RG}. Consequently, a scenario change in river flow is represented as $W - D_{RG}$.

11. *Local Change in River Flow* Δq*:*
    Denotes local internal river flow changes at specific locations within the river system. These variations provide insight into spatial dependencies and localized flow dynamics. These can be deletions or augmentations. Local depletions occur at the top of the system in Phase II and are gradually reduced by local additions of instream storage w.

12. Local Depletions dep_i:
Depletions caused at the top of the system by BWF pumping in Phase II, but which diminish iteratively at nodes where local instream storage w from retired Bank water is retained.

13. Relative Balance: Represents the difference between total retired water in the Bank and BWF depletions as a ratio. A larger ratio means more system depletion, a smaller ratio means less depletion. In our simplified Phase I in which no water has been retired and the Bank is empty, this relative balance is necessarily zero. In Phase II the ratio captures the system effects of transfer.

Equations and Relationships:

1. *Water Balance Equation:*

   The relationship between inflows, outflows, and changes in in-stream storage:

   $Q_{in} - Q_{out} = \Delta Q_{river}$

   Where:

   Q_{in}: Total inflows into the system.

   Q_{out}: Total depletion-outflows from the system (consumptive use and BWF depletion), bypass flow.

   ΔW: Change in the Water Bank's instream storage after transfer.

2. *Local Instream Storage Change:*

   Local (internal) instream storage changes after transfer Δw contributing to the overall change in instream storage ΔW in Phase II: $\Delta W = \sum_{i=1}^{n} \Delta w_i$

3. *Local River Flow Change:*

   Sum of local (internal) river flow changes Δq summing to ΔQ_{river} in Phase II:

   $$\Delta Q_{river} = \sum_{i=1}^{n} \Delta q_i = \sum_{i=1}^{n} (dep_{i-1} + w_i)$$

4. *Pre and Post Transfer Phases (Between Phase I and II):*

   Before water right transfer:

   $Q_{in,pre} - Q_{out,pre} = \Delta Q_{instream,pre}$

   After water rights transfers:

   $Q_{in,post} - Q_{out,post} = \Delta Q_{instream,post} = W - D_{RG}$

5. *Relative Balance (Only in Phase II):*

$$\delta = \frac{D_{RG}}{W}$$

Incorporating Consumptive Use Error

In this section we bring in errors stemming from differences between CU_a and CU_0.

We focus on analyzing the error in consumptive use transfers in the post-transfer Phase II and ignore the Phase I baseline. We focus on the differences between theoretical and actual consumptive use volumes, then propagate these upward and apply them to the post-transfer bank volume and relative balance ratios.

Consumptive Use Terms:

$$CU_0 = Theoretical\ CU = 2.1\ in\ ft$$

$$CU_a = Actual\ CU = (ET_a - P_e)\ in\ ft$$

$$w_0 = Theorectial\ CU\ volume = 2.1 \cdot acres\ in\ af$$

$$w_a = Actual\ CU\ volume = (ET_a - P_e) \cdot acres\ in\ af$$

$$W_0 = Total\ Theorectial\ CU\ volume\ in\ Bank = \sum w_0$$

$$W_a = Total\ Actual\ CU\ volume\ in\ Bank = \sum w_a$$

Error Propagation:

$$CU_a - CU_0 = \varepsilon_{cu}$$

$$w_a - w_0 = (CU_a - CU_0) \cdot acres = \varepsilon_{cu} \cdot acres = \varepsilon_w$$

$$W_a - W_0 = \sum \varepsilon_{cu} = \varepsilon$$

Error Relationships:

$$CU_a = CU_0 + \varepsilon_{cu}$$

$$w_a = w_0 + \varepsilon_w$$

$$W_a = W_o + \varepsilon$$

Relative Balance Phase II (Actual Expressed Using Theoretical CU):

$$\delta_a = \frac{D_{rg}}{W_0 + \varepsilon}$$

Positive Error ($\varepsilon > 0$):

Actual CU volume is higher than theoretical. The ratio δ_a decreases, indicating a better balance with more water retained in the system relative to the depletion. This is beneficial for the river system.

Negative Error ($\varepsilon < 0$):

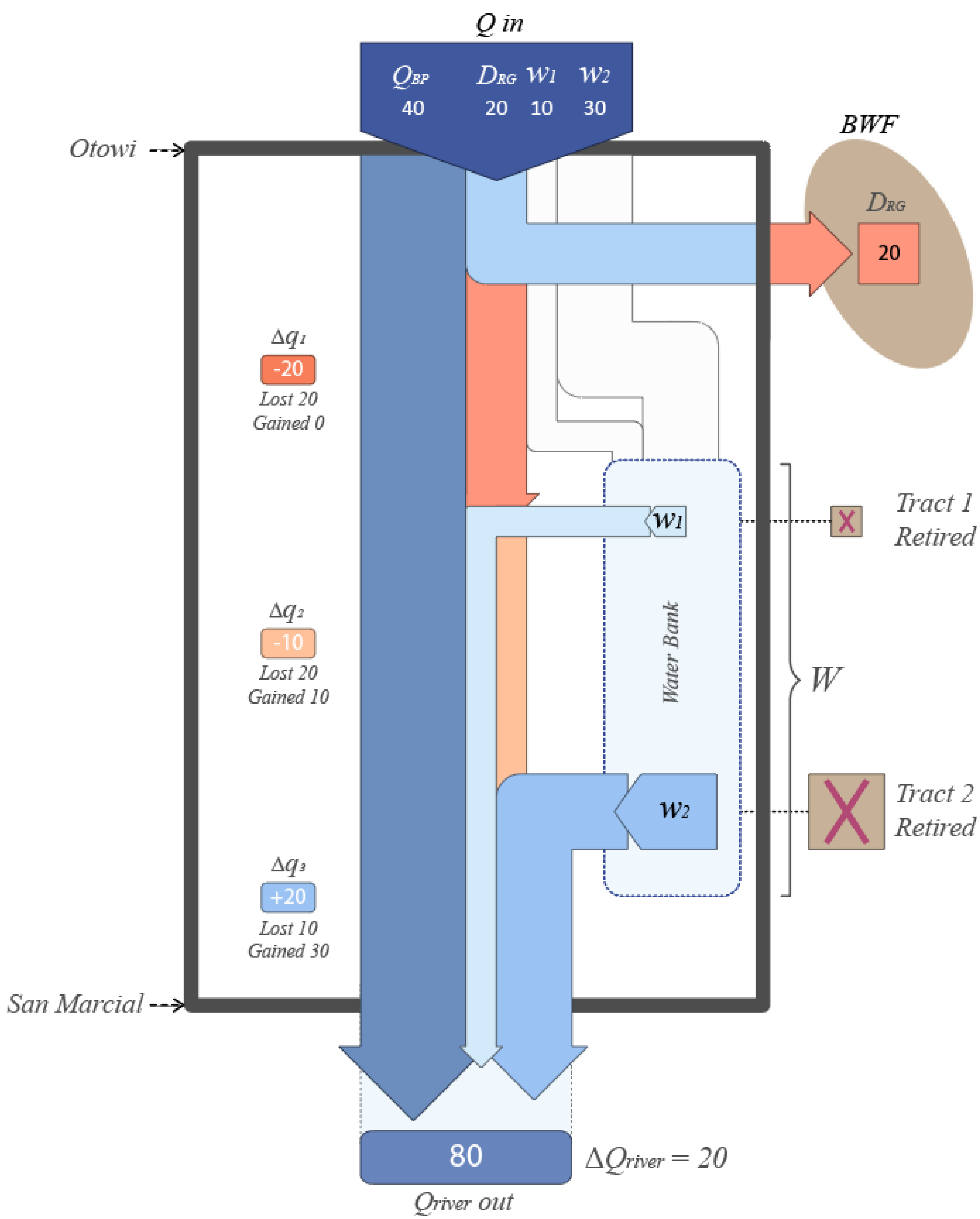
Actual CU volume is lower than theoretical. The δ_a increases, indicating a poorer balance with less water retained in the system relative to the depletion. This can be detrimental to the river system.

Model Summary:

The model describes the hydrologic impacts of Water Bank transfers through a mass balance system accounting for inflows and outflows in the region between the BWF and San Marcial gage. It distinguishes between theoretical and actual consumptive use and assesses balance. The model operates under the administrative idealized Water Bank transfer rules but can accommodate different datasets. It simplifies the conceptual complexity by focusing on in-stream storage changes and system scale dependency.

Figure 6: Transfer Model Diagram: Phase II Post-Transfer

$$Q_{in} = 100\ af, \Delta Q_{river} = 20, W = 40, D_{rg} = 20, \delta = \frac{D_{RG}}{W} = 0.50$$



Part III: Methods and Results

The previous section described model parameters and relationships forming the rules and logical structure of Water Bank transfers. The following section describes steps and methods used for populating the model with real data and deriving results. Retrieving OSE water right records and organizing their individual information into data compatible with analysis was challenging. Because of the time involved we were unable to conduct a full analysis of every water right in the Water Bank. This meant we were unable to compute an empirical estimate of the Banks total retired volume. Instead, we selected a subset of active and retired water rights from each of the four MRGCD districts for analysis. While not ideal, the subset of specific tracts still provided insightful information, and demonstrated how our methods can be applied to larger collections of tracts in the future.

Data

To gain insights into the potential local and system-level impacts of transfers – under both administrative and empirical assumptions – we needed data to answer a few basic questions. Answering the basic questions would then allow us to make broader inferences about potential impacts. The basic question we needed to answer were:

1. What is the relative balance under current administrative assumptions?
2. What is the error (difference) between the consumptive use rates CU_0 and CU_a among our selected samples at specific points in time?
3. What is the range of cumulative errors for these same tracts over the period of record?

Answering these three questions allowed us to speculate on a range of other questions and possibilities. The first question was relevant in providing a total system summary of the model under the current administrative conditions, necessarily relying on CU_0. This administrative model summary was used to infer potential transfer impacts at different scales. Questions 1 and 2 more specifically addressed the use of empirical estimates and how consumptive use errors play a role in transfer impacts on top of relative balance assumed in the ideal transfer scenario. This emphasis on *range of errors* was important for providing empirical uncertainty ranges and demonstrating how much error potentially exists in current practices.

The core bits of data we needed to answer the above questions were simple in theory, but obtaining some of these data was a challenge. To conduct our analysis, we needed the following data:

1. The total volume of transferred water rights in the Bank over time.
2. The unique transfer volumes of sample tracts in the Bank.
3. The location of and shape of sample tracts.
4. The OpenET actual evaporation estimate of each sample tract.
5. The effective precipitation for each sample tract.
6. Measures of accuracy and reliability in OpenET estimates from current research.
7. BWF depletion offsets for the period of record.

Data represented in 1 through 3 came from OSE records, City of Santa Fe Water Bank records, and MRGCD records and shapefiles. These data were the most challenging to obtain for several reasons. The OSE maintains a water rights lookup website for public use.[36] This online database is not complete, and records consist of scanned historical pdf documents. It can take several hours to obtain relevant information about each water right's history and transferred details. Although Santa Fe maintains a historical log of water rights in the Bank, the original water rights transferred in are broken up over time by developers splitting them for different designation projects. This made backtracking the original water right (as it existed in the MRGCD) confusing and time consuming. We later had better records from the City which expedited this process.

Tract location and area were necessary for computing ET_a in in the OpenET API. We obtained a 2021 GIS shapefile from the MRGCD for assisting with this process, but unfortunately, the shapefiles did not reliably match retired water tracts, as farm tracts are sometimes subdivided, sold, or get re-platted after their water rights have been retired. Still, the MRGCD shapefile was helpful for locational purposes and ancillary data. The OpenET platform displays current field boundaries and so historical shapefiles of retired tracts must be independently obtained. Because of discrepancies in the MRGCD shapefile, some tracts required manual construction in ArcGIS. This was done using field boundaries and coordinates from the original OSE water right file. Shapefiles were then uploaded into Google Earth engine for making API queries. Python code was used for querying the OpenET API.

Steps

Spatial and Temporal Scope

The boundary region was the same as that chosen for the transfer model (figures 6,7). We specified time boundaries for a 24-year period from 2000 to 2023 inclusive. This time interval was chosen to provide a meaningful historical record both prior to and after the formation of the Water Bank in 2009.

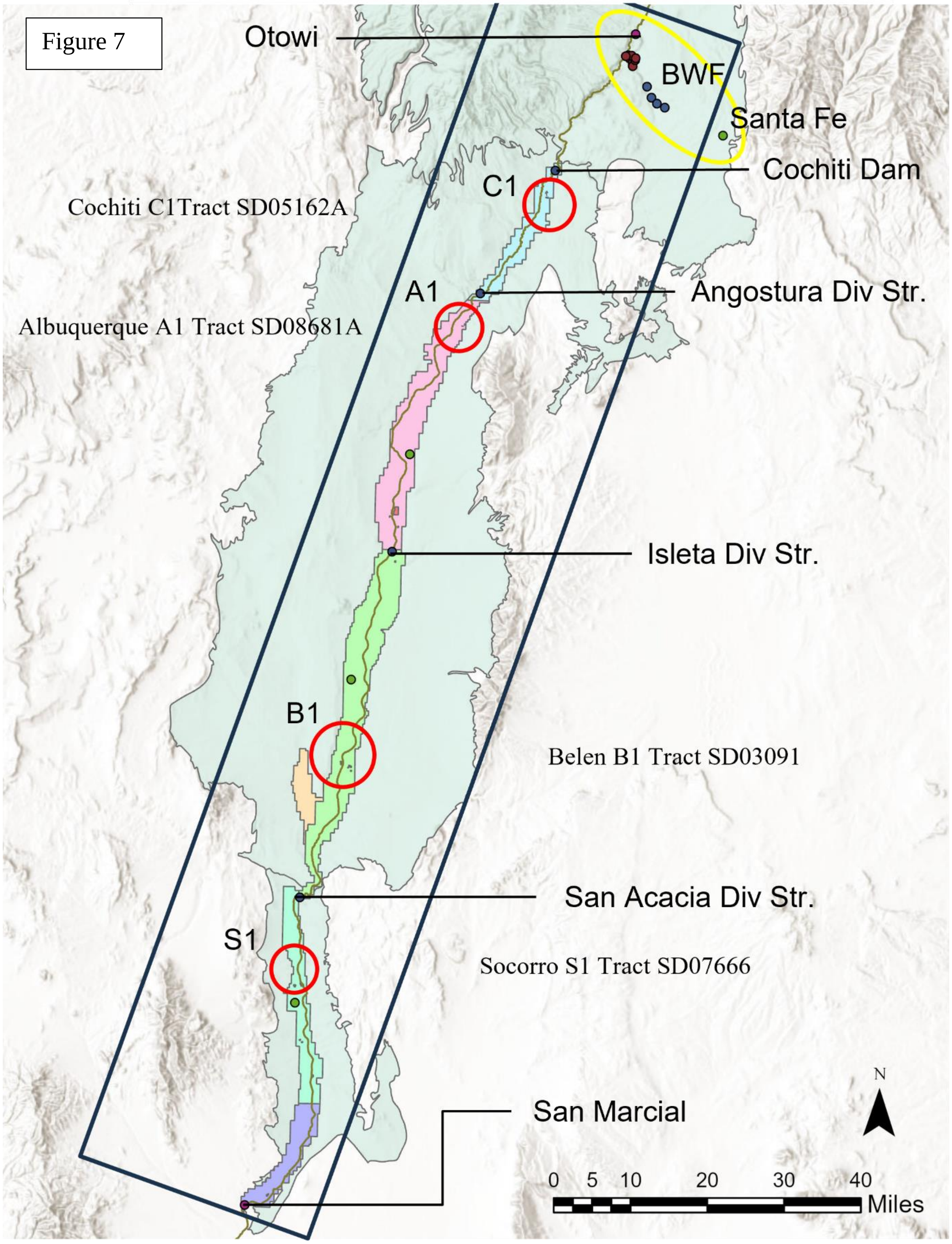
Identify and Spatially Locate Retired Water Rights

This required use of City records for identifying specific water rights, transfer volumes, and OSE water right ID's. An excel table was used to keep track of retired water rights in the Bank. We used ArcMap in combination with 2021 MRGCD ISOLog shapefiles to create polygons for most retired water rights in the bank. Centroids were then placed within these polygons, and several spatial statistical tests were applied for cursory understanding of distributions. Kernal Density analysis and a Local Moran's I for autocorrelation were used for spatial analysis. There were no productive results from tests, as spatial distributions of retired tracts displayed no apparent pattern other than the expected: more retired tracts occur where there is more irrigative land, primarily in the southern Divisions of the MRGCD.

Select Water Right Samples

Four retired water rights were chosen from the Bank, one from each MRGCD division. Water right selection was based on the clarity of its historical record, length of time since transfer, and proximity to comparable tracts. Clarity of the historical record was the most challenging condition. We were simply looking for tracts with transfer histories easy to decipher, not strung out over a long time, and not partially transferred off in pieces to different buyers. For the period of record, we wanted tracts retired at different points in time, but not so recently as to have no meaningful post-transfer empirical information, and not so far back as to have no prior history. We also wanted water rights to be typical representatives of the surrounding agricultural area. Some tracts had interesting stories to tell, and we considered selection based on that, but decided it was out of scope.

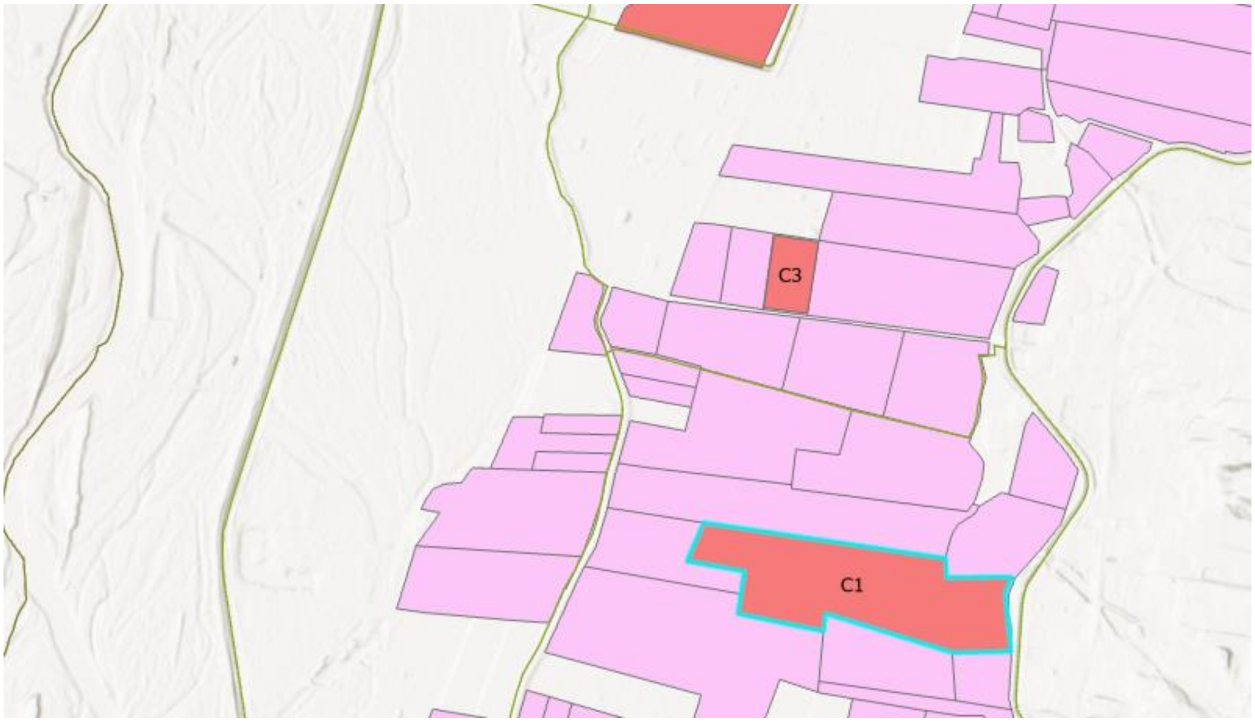
Study Sample Region: Four Retired Tracts in the Water Bank



Sample Tracts Selected from Water Bank

Cochiti C1Tract SD05162A 17 ac

Figure 8

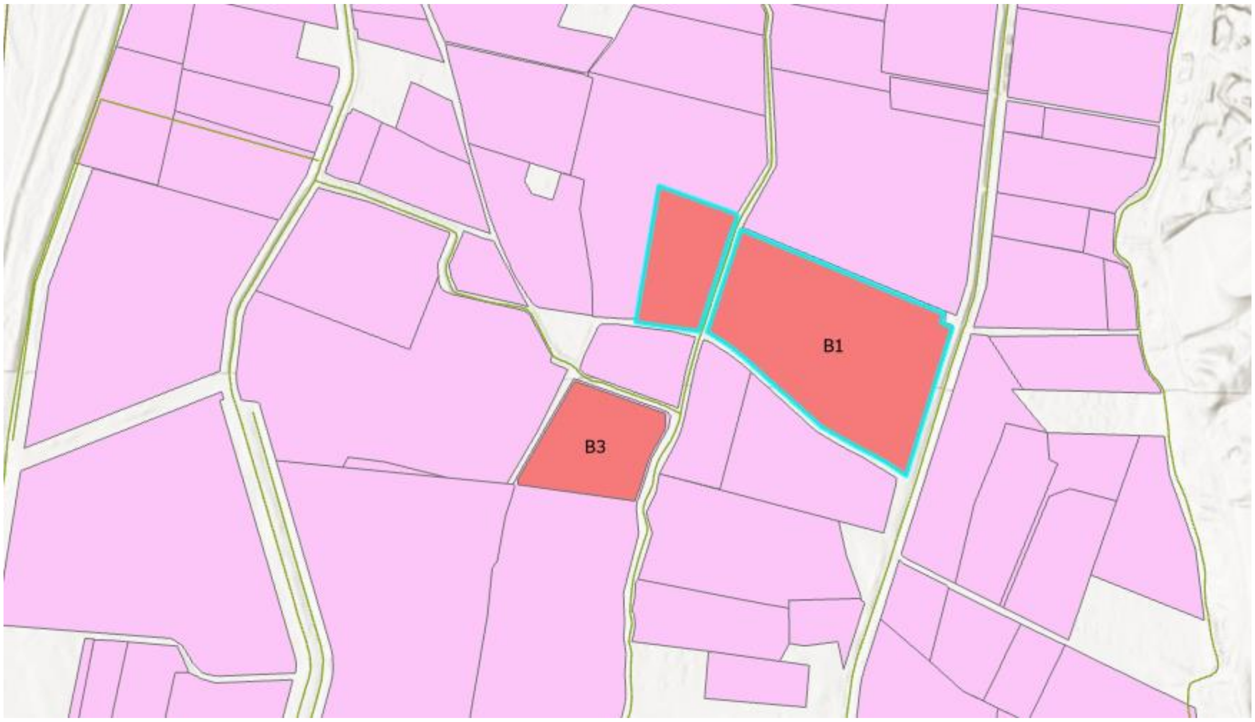


Albuquerque A1 Tract SD08681A 4.39 ac

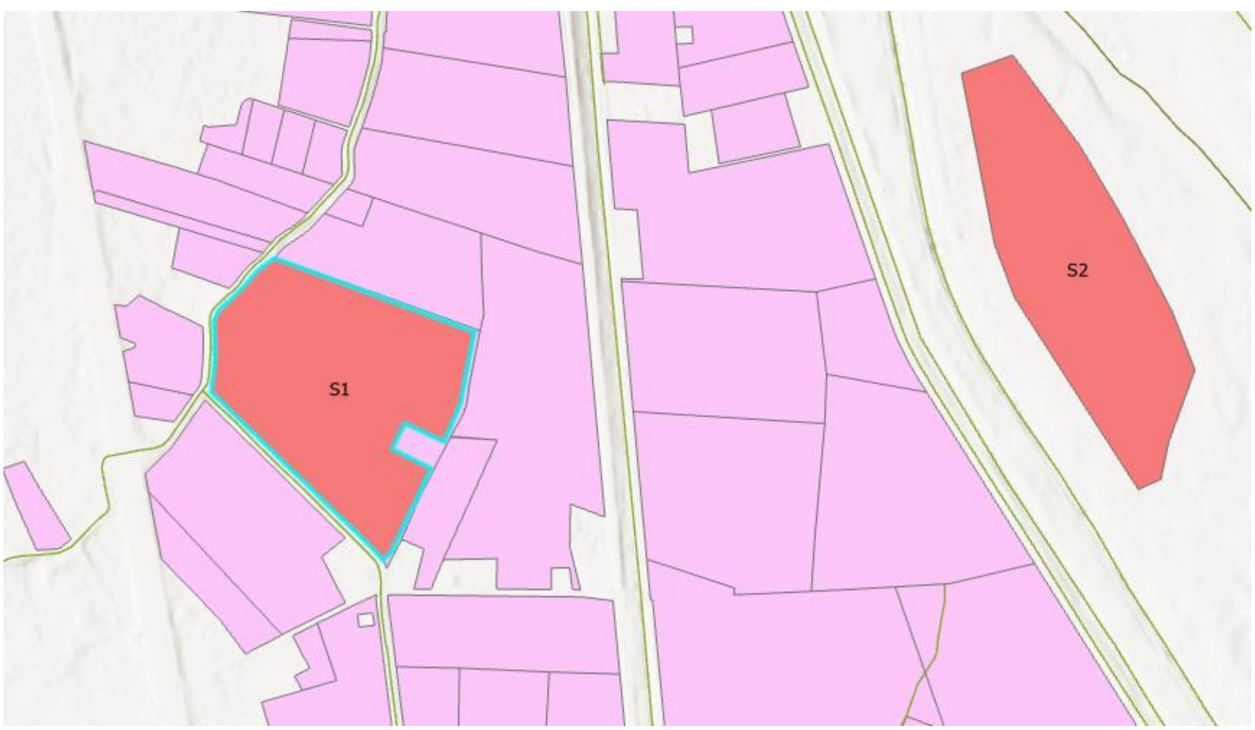
Four Sample Tracts Selected from Water Bank

Figure 9

Belen B1 Tract SD03091 35.48 ac



Socorro S1 Tract SD07666 38.13 ac



Other samples were chosen to provide ancillary information and facilitate comparisons. The selection criteria included spatial proximity to brushy, fallowed, or undeveloped fields. The goal was to conduct OpenET analysis on lands that had not received irrigation for a long time, if ever. This was done to see if fallowed and irrigated fields were distinguishable in our study, and to determine if the long-term replacement of crops by brushy encroachment produced had comparable ET. A non-retired water right (Belen B5) was selected as representing the quintessential irrigated farm, in full production each year without supply-limitation. This was to provide insights about ideal consumptive use rates when following is not present.

OpenET API and Data Tables

To acquire OpenET data, Python scripts were employed to interface with the platform's API, facilitating data retrieval. Initially, spatial polygons delineated in ArcMap were transferred to Google Earth Engine to establish connectivity with OpenET's API. The dataset comprised three key parameters: Actual Evapotranspiration (ET) calculated with the grass reference crop, Precipitation, and the Normalized Difference Vegetation Index (NDVI). The selection of grass reference crop ET was predicated on its alignment with the findings of the 2024 ET accuracy study, ensuring data consistency. Precipitation GridMET data was pivotal for the development of Effective Precipitation metrics, while NDVI served to distinguish between cultivated crop vegetation and fallow brushy fields, enriching the analysis with vegetation insights.

Generate Data Tables:

Python was used to create data dictionaries, which housed the data tables necessary for statistical analysis and time series generation. These Python scripts specifically restricted the time series records to reflect the MRGCD irrigation season, which spans from March to October. Initially, the time steps were monthly, and later these were aggregated into annual periods to align with administrative nomenclature and facilitate the calculation of annual transfer units. This methodical approach ensured that the data was accurately processed and formatted for subsequent modeling and analysis.

Error and Accuracy Bounds:

Mean Absolute Error (MAE) and Mean Bias Error (MBE) for *Köppen-Geiger Zone 2* (kgz2) were selected from the two climate regions in the 2024 OpenET accuracy study.[13] These terms were applied as error factors to the raw ET_a data and used as inputs in the effective precipitation function prior to subtracting P_e from ET_a (see Appendix III). The MAE and MBE were based on Eddy Flux tower comparison and therefore represent ET_a deviation from the truest measure of ET available.[13] This resulted in six possible values for our measure of ET_a, an uncorrected median representing the raw ET_a measure from OpenET with corresponding upper and lower bounds based on the MAE, and bias corrected median with corresponding upper and lower bounds based on the same MAE percentage. The 2024 study showed a negative bias for kgz2 indicating underestimation of approximately 6% (Table 2). Because of the negative bias, ET_a was shifted upward for the corrected median. The purpose was to produce empirical uncertainty ranges for CU_a and corresponding uncertainty ranges for the cumulative difference between w_a and w_0.

Table 2 2024 OpenET Accuracy Study: Zone 2 MAE and MBE (Bwh+Bwk)

Köppen–Geiger (KG) climate zones (from 'Assessing OpenET, Volk, et.al. 2024')							
Description	KGZ	Statistic	mm	in	ft	af	%
cold and hot semi-arid steppe: Bsk + Bsh	Bsk + Bsh	MBE	-6.94	-0.273	-0.0228	-0.023	-0.052
cold and hot semi-arid steppe: Bsk + Bsh	Bsk + Bsh	MAE	20.74	0.817	0.0680	0.068	0.156
cold and hot semi-arid steppe: Bsk + Bsh	Bsk + Bsh	RMSE	26.38	1.039	0.0865	0.087	0.198
cold and hot semi-arid steppe: Bsk + Bsh	Bsk + Bsh	r^2	0.89	nan	nan	nan	nan
cold and hot semi-arid steppe: Bsk + Bsh	Bsk + Bsh	Ensemble mean	133.00	nan	nan	nan	nan
hot and cold desert: Bwh + Bwk	Bwh + Bwk	MBE	-6.78	-0.267	-0.0222	-0.022	-0.061
hot and cold desert: Bwh + Bwk	Bwh + Bwk	MAE	13.24	0.521	0.0434	0.043	0.120
hot and cold desert: Bwh + Bwk	Bwh + Bwk	RMSE	17.02	0.670	0.0558	0.056	0.154
hot and cold desert: Bwh + Bwk	Bwh + Bwk	r^2	0.91	nan	nan	nan	nan
hot and cold desert: Bwh + Bwk	Bwh + Bwk	Ensemble mean	110.00	nan	nan	nan	nan

(Volk, J. M. et al., 2024)

Effective Precipitation SCS Method:

Because the theoretical constant represents irrigative on-farm consumptive use, we needed to adjust the raw ET_a values by subtracting effective precipitation and thereby obtain CU_a. Python was initially used to deduct effective precipitation from actual ET on monthly timesteps. We later began to create the model in Goldsim dynamic modeling software, but that effort remains in progress. Excel was used for simple computations and data tables. Effective precipitation was estimated using GridMET precipitation data from OpenET and the SCS soil moisture balance model with a soil moisture depth of 3 inches. The SCS method involved a quartic function combining both precipitation data and our ET_a data.[15] The parameters for the SCS function were fed into python for generating tables.

Ranges and Volumes:

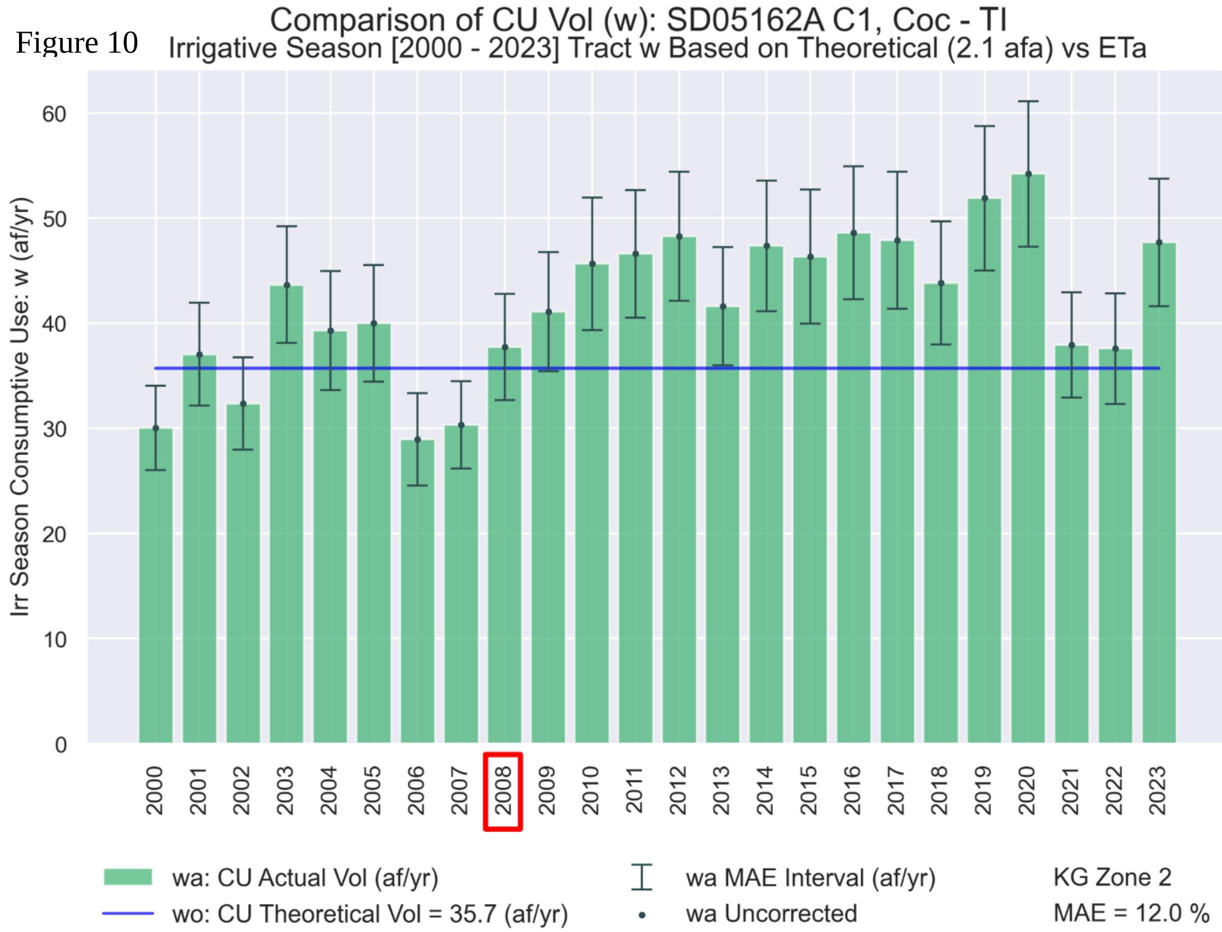
After computing consumptive use as a linear value, we then computed volumetric consumptive use using both Python and Excel. Linear CU_a was multiplied by corresponding tract acreage to get tract volume: $w = (ET_a - P_e) \cdot acres = CU_a \cdot acres$. These volumes represented *actual* consumptive use quantities associated with each retired tract, measured in acre-feet. Thus, were now able to compare these values against the theoretical transfer volumes found in OSE and City records. We compared these values with the historical ranges for each of the four tracts (plus ancillary tract) and took their differences as errors. Errors were then cumulatively integrated at annual time-steps to see how much cumulative error represented potential surplus or deficit over the period of record. These cumulative changes were shown as ranges as well, including adjustments for MBE and MAE.

Relative balance:

Relative balance was calculated based on BWF depletions below Otowi and Water Bank records. Consequently, relative depletion represented the current administrative theoretical consumptive use constant. This approach afforded an overarching view of system balance within the existing administrative framework. However, to achieve a comprehensive comparison of relative balance, an estimation of actual consumptive use across all tracts within the Bank was necessary. Nonetheless, within the model, we depicted relative balance in relation to its administrative ratio, facilitating speculation on potential changes in relative balance driven solely by cumulative error. This representation allowed for insightful analysis into how relative balance might fluctuate under varying scenarios, aiding in decision-making processes.

Results

Figure 10



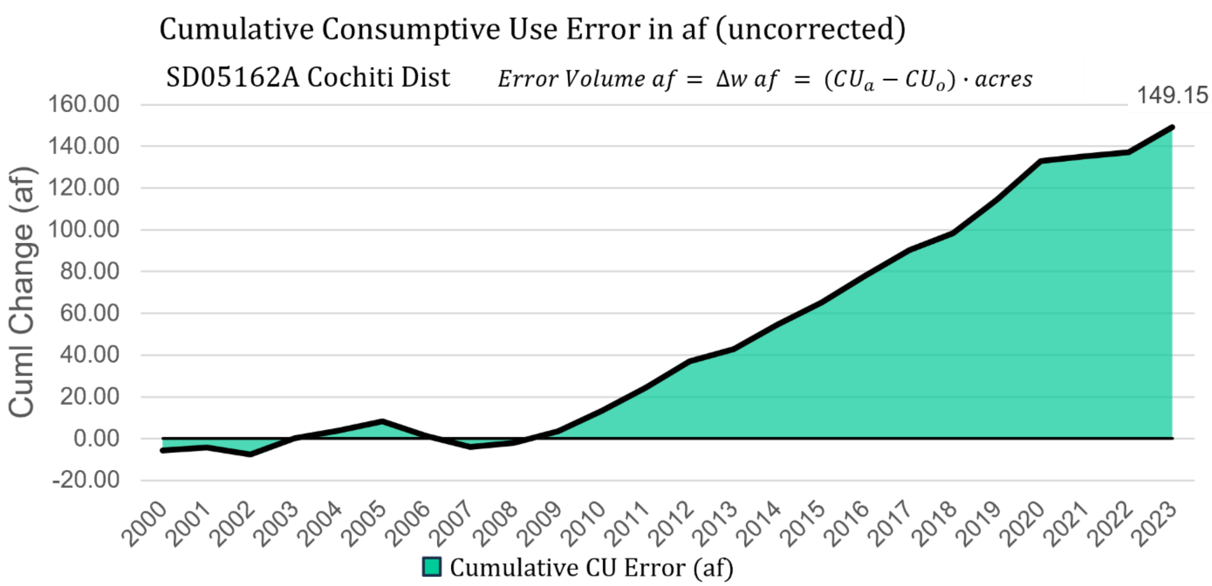
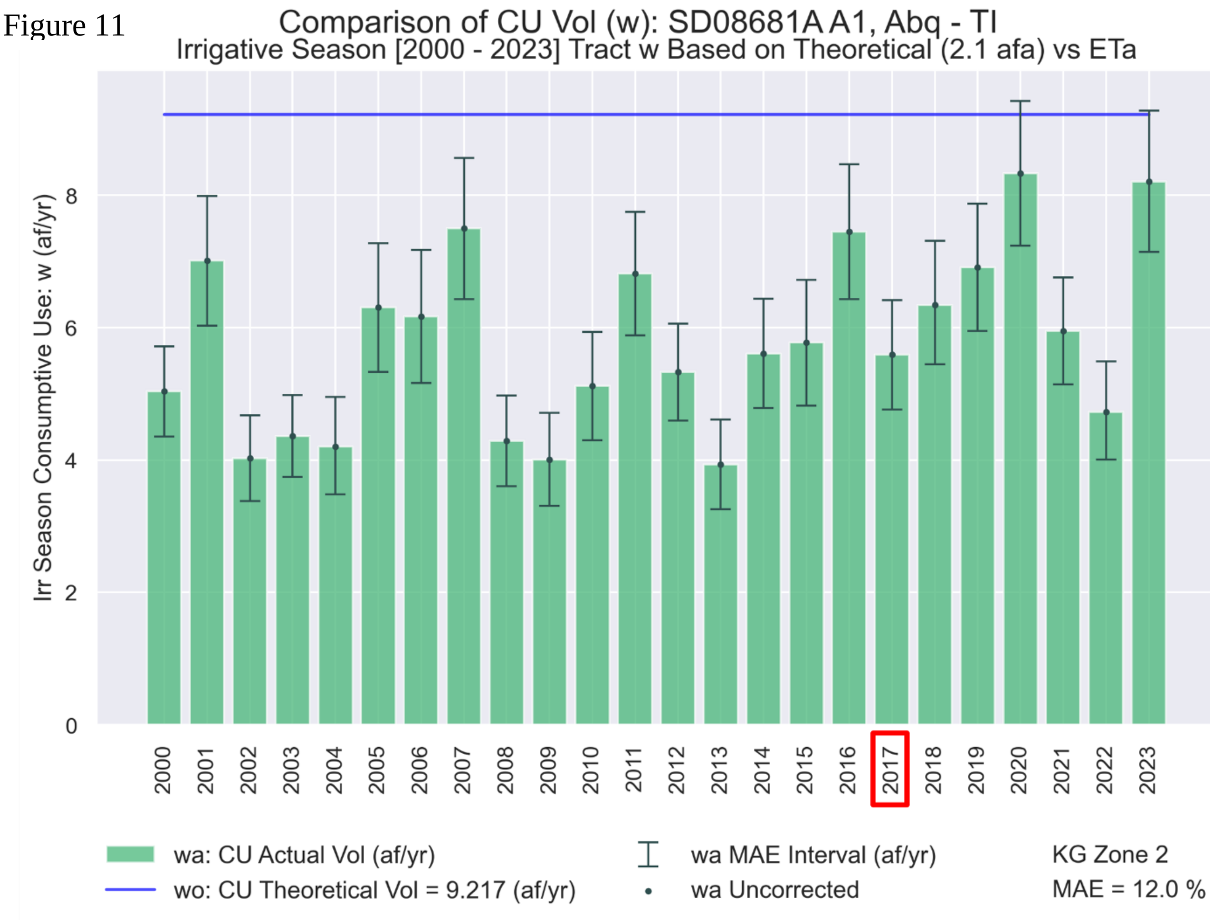
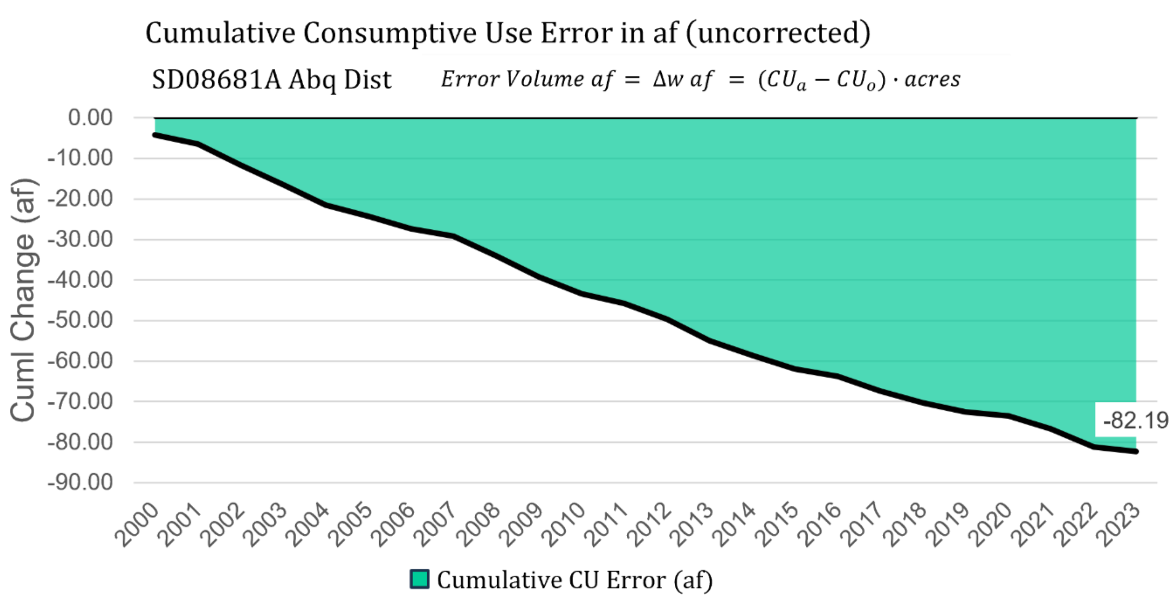


Figure 11

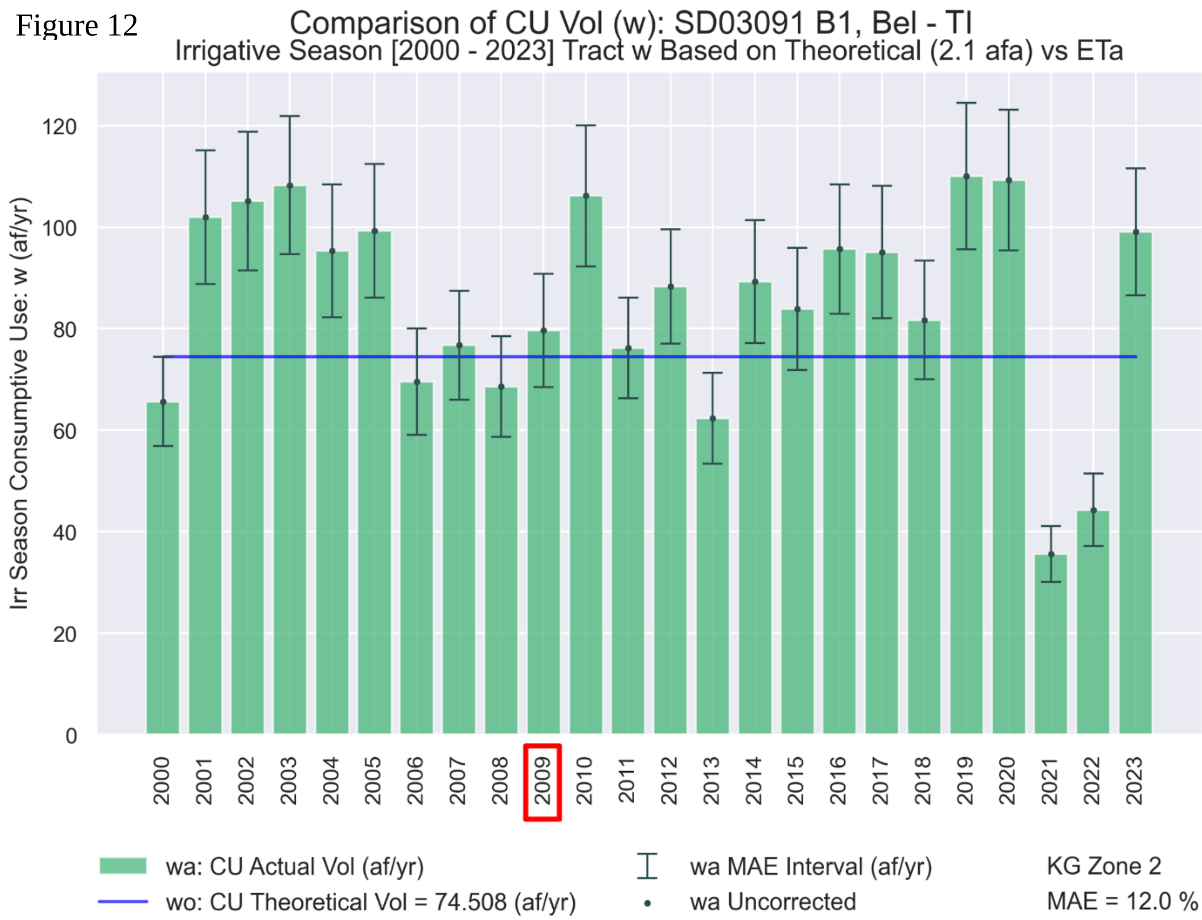


Comparison of CU Vol (w): SD08681A A1, Abq - TI
Irrigative Season [2000 - 2023] Tract w Based on Theoretical (2.1 afa) vs ETa
Irr Season Consumptive Use: w (af/yr)
0
2
4
6
8
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
wa: CU Actual Vol (af/yr)
wo: CU Theoretical Vol = 9.217 (af/yr)
wa MAE Interval (af/yr)
wa Uncorrected
KG Zone 2
MAE = 12.0 %

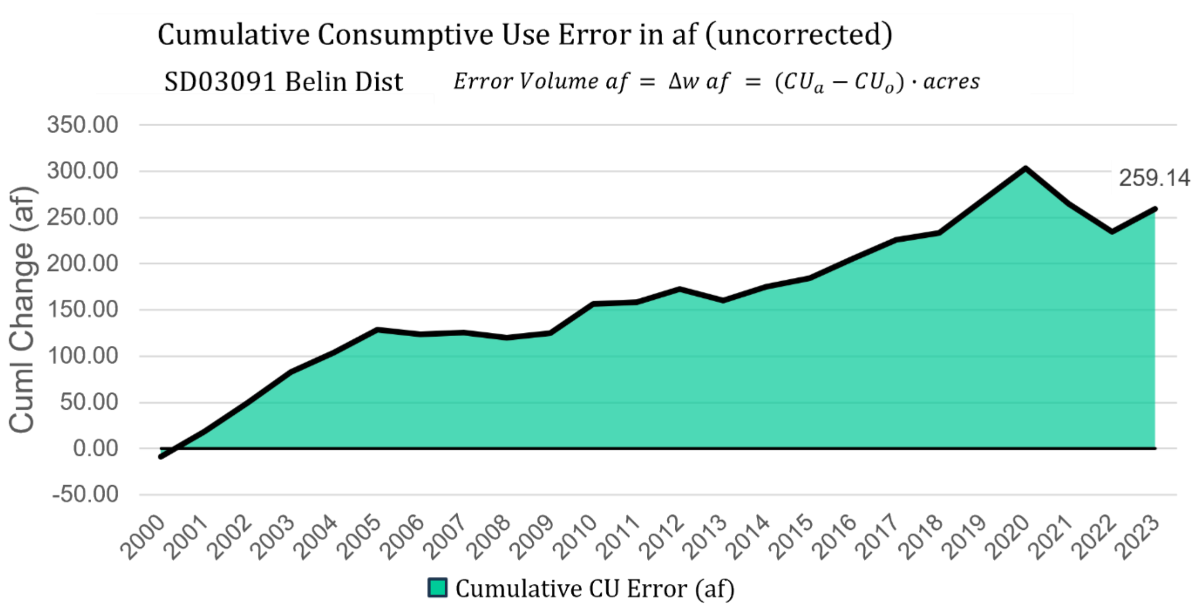


Cumulative Consumptive Use Error in af (uncorrected)
SD08681A Abq Dist
$Error\ Volume\ af = \Delta w\ af = (CU_a - CU_o) \cdot acres$
Cuml Change (af)
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-82.19
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Cumulative CU Error (af)

Figure 12

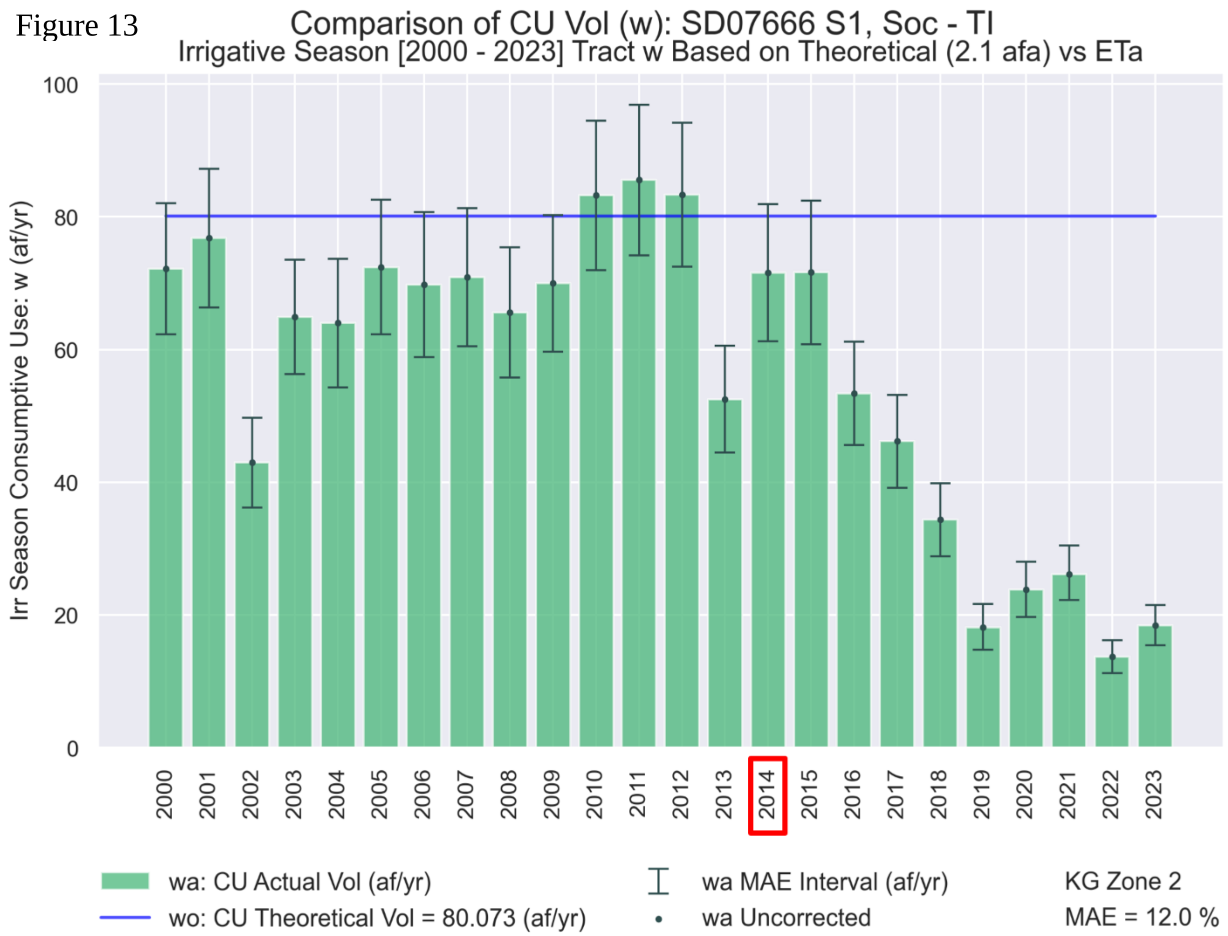


Comparison of CU Vol (w): SD03091 B1, Bel - TI
Irrigative Season [2000 - 2023] Tract w Based on Theoretical (2.1 afa) vs ETa
Irr Season Consumptive Use: w (af/yr)
0
20
40
60
80
100
120
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
wa: CU Actual Vol (af/yr)
wo: CU Theoretical Vol = 74.508 (af/yr)
wa MAE Interval (af/yr)
wa Uncorrected
KG Zone 2
MAE = 12.0 %

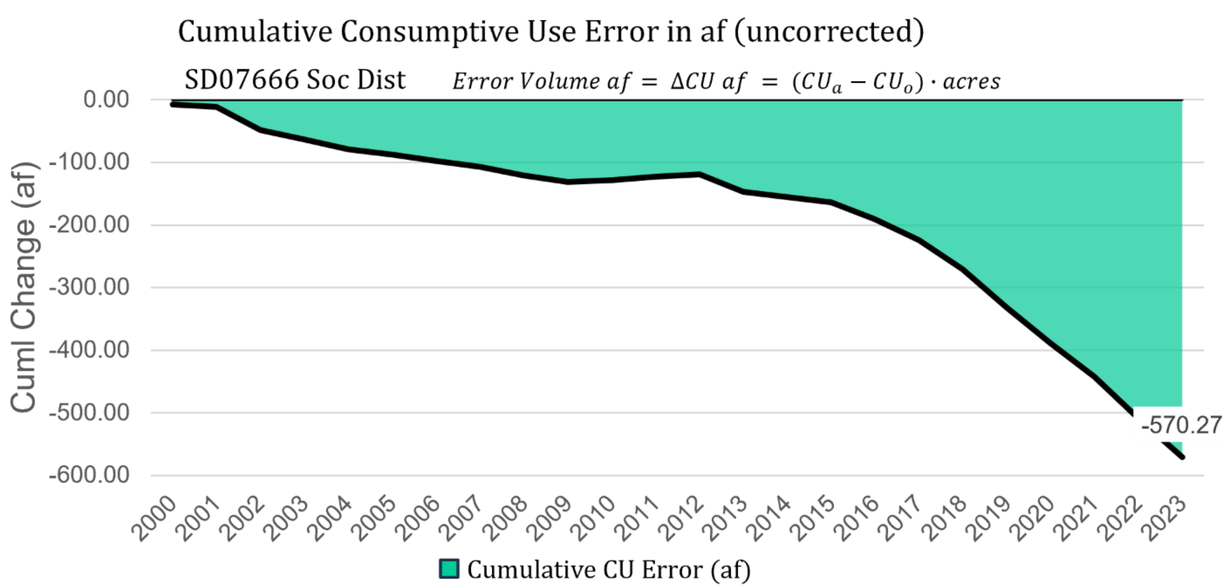


Cumulative Consumptive Use Error in af (uncorrected)
SD03091 Belin Dist
$Error\ Volume\ af\ =\ \Delta w\ af\ =\ (CU_a - CU_o) \cdot acres$
Cuml Change (af)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
259.14
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Cumulative CU Error (af)

Figure 13

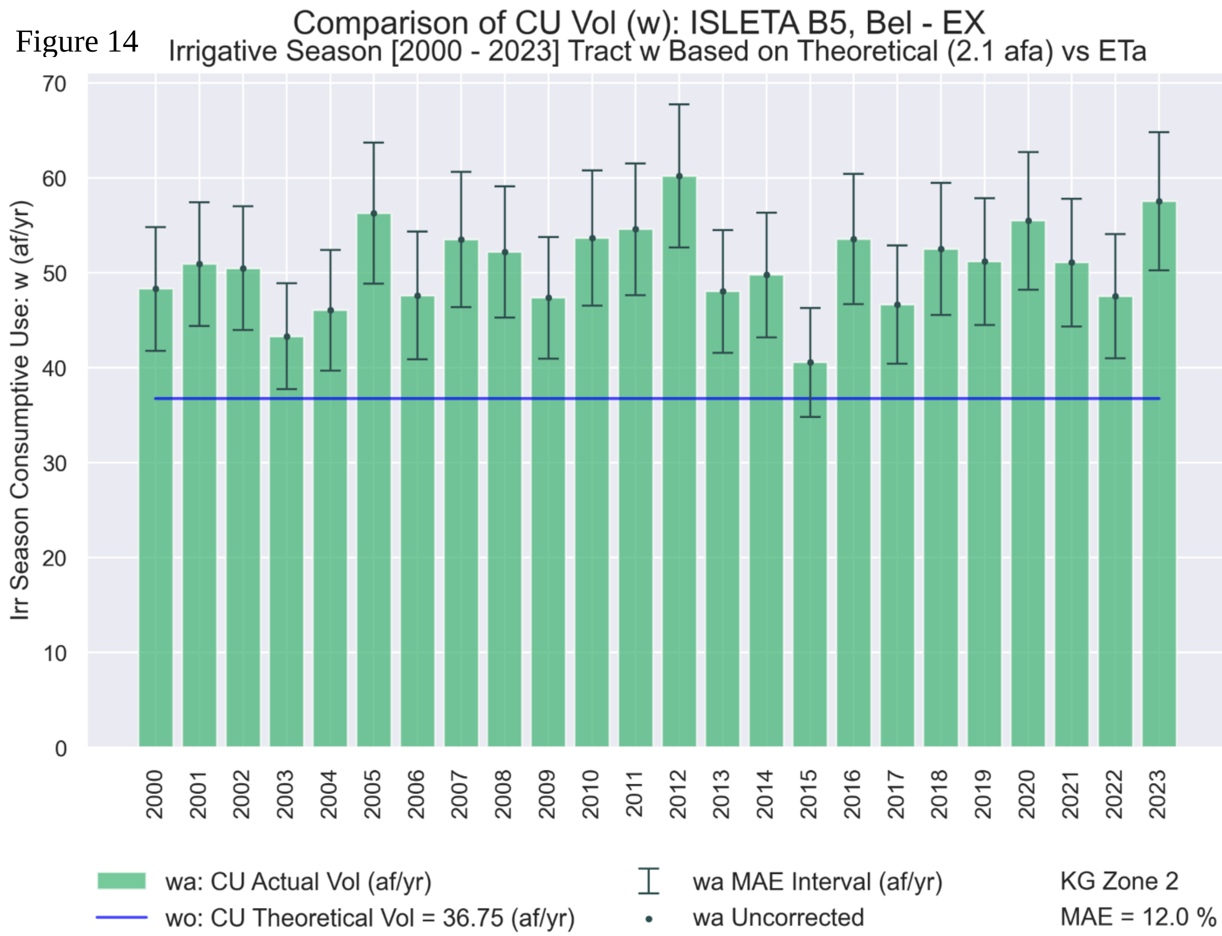


Comparison of CU Vol (w): SD07666 S1, Soc - TI
Irrigative Season [2000 - 2023] Tract w Based on Theoretical (2.1 afa) vs ETa
Irr Season Consumptive Use: w (af/yr)
0
20
40
60
80
100
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
wa: CU Actual Vol (af/yr)
wo: CU Theoretical Vol = 80.073 (af/yr)
wa MAE Interval (af/yr)
wa Uncorrected
KG Zone 2
MAE = 12.0 %



Cumulative Consumptive Use Error in af (uncorrected)
SD07666 Soc Dist
$Error\ Volume\ af = \Delta CU\ af = (CU_a - CU_o) \cdot acres$
Cuml Change (af)
0.00
-100.00
-200.00
-300.00
-400.00
-500.00
-600.00
-570.27
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Cumulative CU Error (af)

Figure 14


Comparison of CU Vol (w): ISLETA B5, Bel - EX
Irrigative Season [2000 - 2023] Tract w Based on Theoretical (2.1 afa) vs ETa
Irr Season Consumptive Use: w (af/yr)
wa: CU Actual Vol (af/yr)
wo: CU Theoretical Vol = 36.75 (af/yr)
wa MAE Interval (af/yr)
wa Uncorrected
KG Zone 2
MAE = 12.0 %

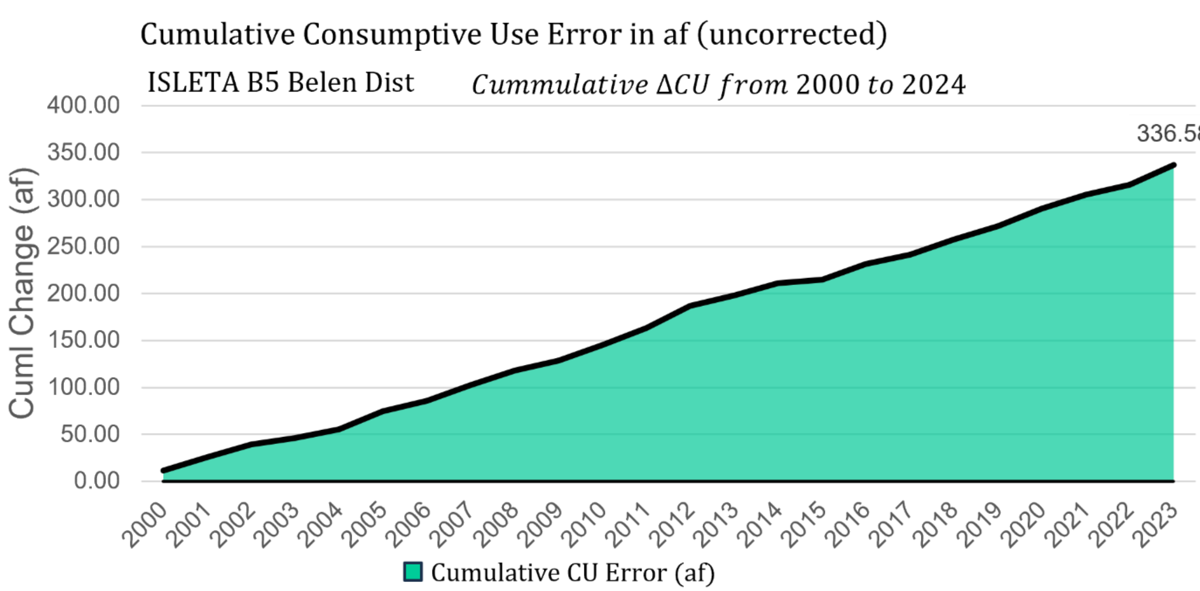
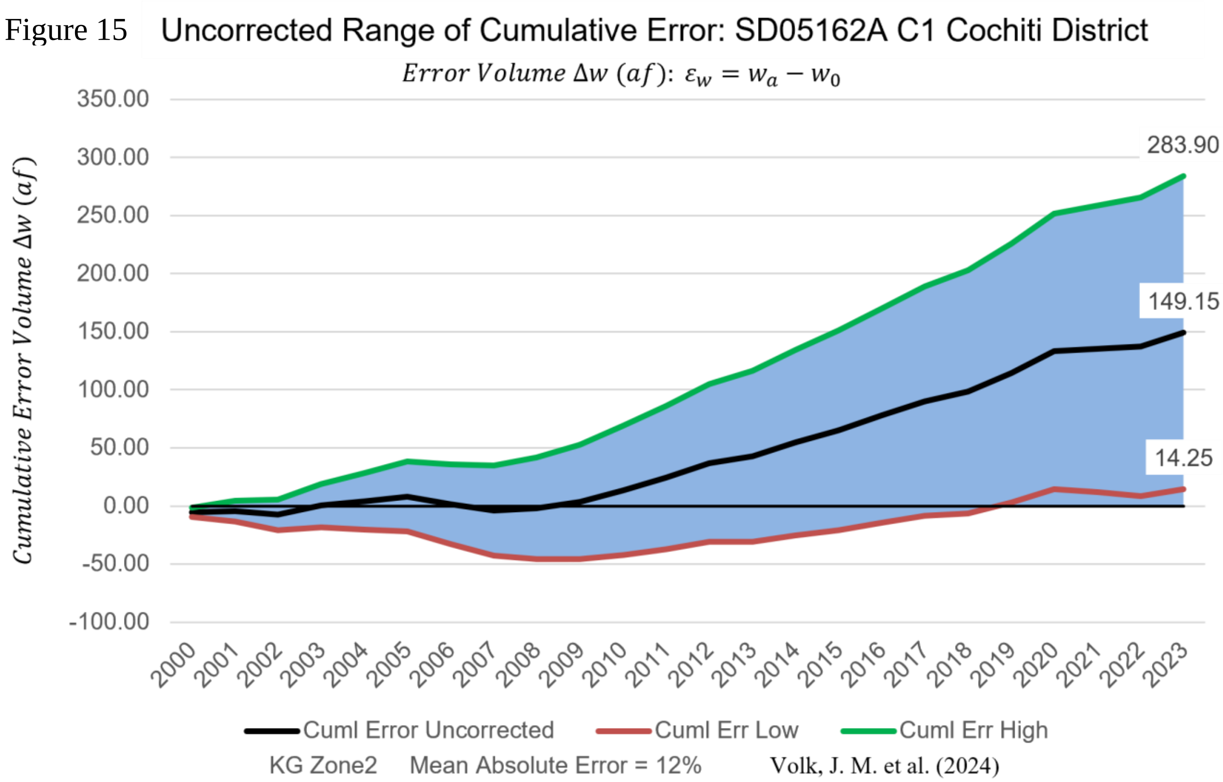

Cumulative Consumptive Use Error in af (uncorrected)
ISLETA B5 Belen Dist
Cummulative ΔCU from 2000 to 2024
Cuml Change (af)
336.58
Cumulative CU Error (af)

Figure 15


Uncorrected Range of Cumulative Error: SD05162A C1 Cochiti District
$Error\ Volume\ \Delta w\ (af)$: $\varepsilon_w = w_a - w_0$
$Cumulative\ Error\ Volume\ \Delta w\ (af)$
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
283.90
149.15
14.25
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Cuml Error Uncorrected
Cuml Err Low
Cuml Err High
KG Zone2
Mean Absolute Error = 12%
Volk, J. M. et al. (2024)

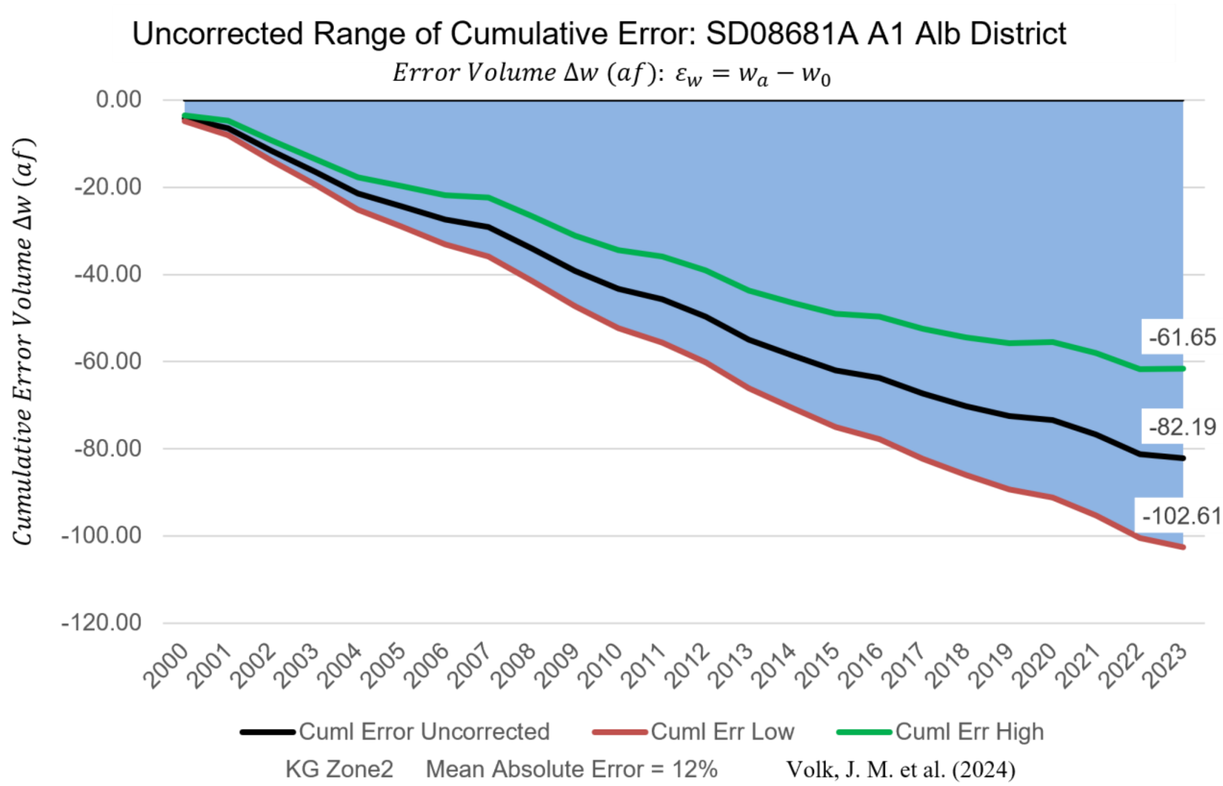
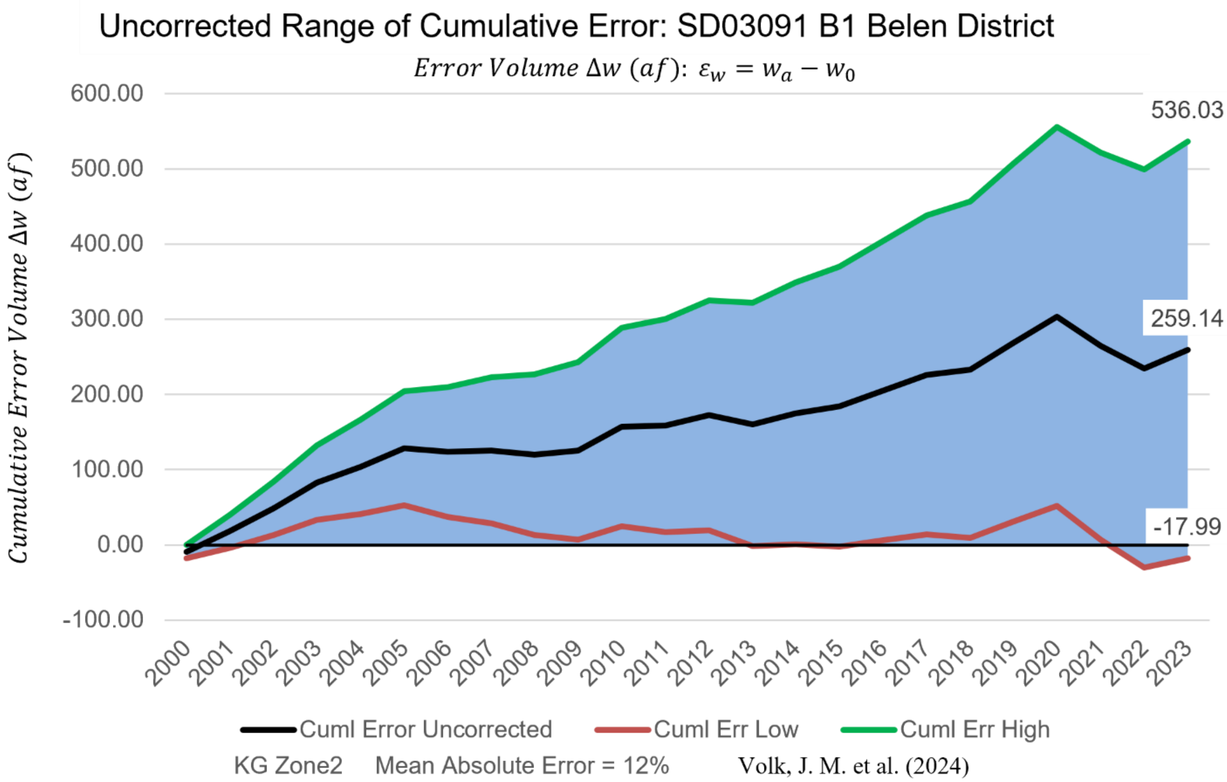
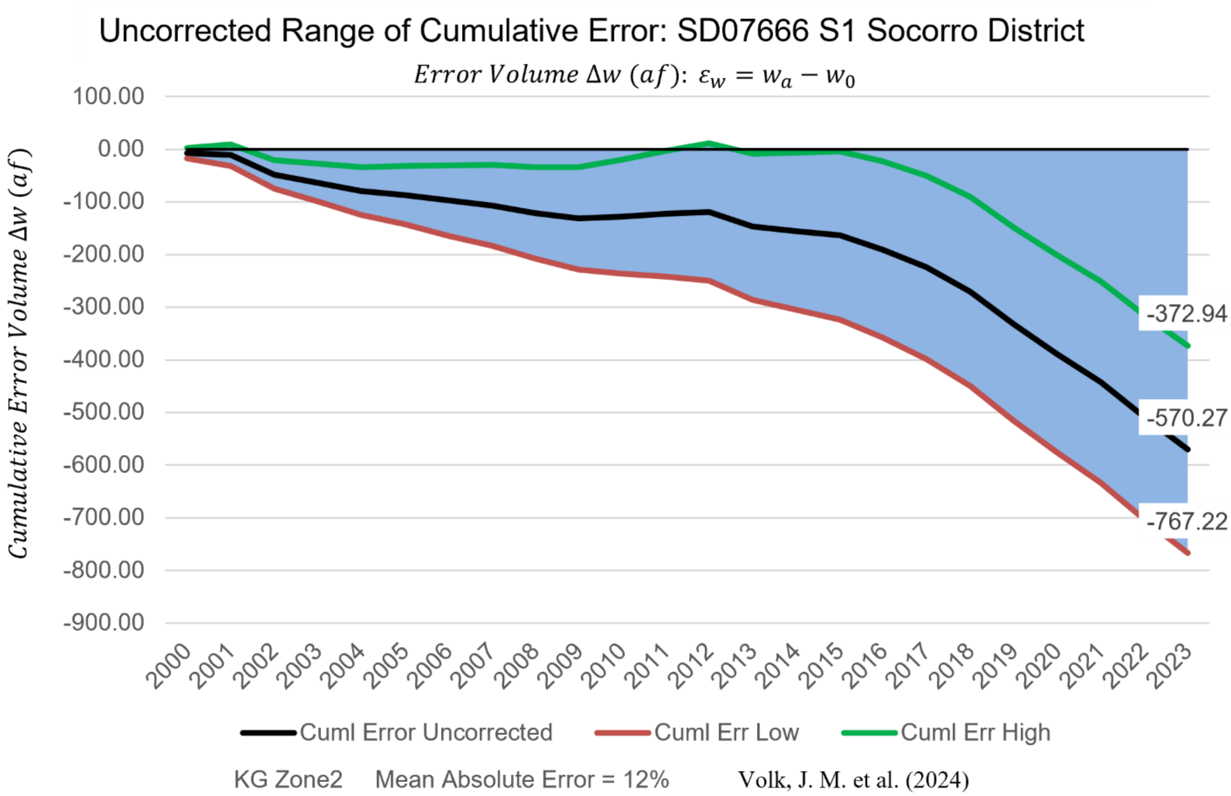

Uncorrected Range of Cumulative Error: SD08681A A1 Alb District
$Error\ Volume\ \Delta w\ (af)$: $\varepsilon_w = w_a - w_0$
$Cumulative\ Error\ Volume\ \Delta w\ (af)$
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-61.65
-82.19
-102.61
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Cuml Error Uncorrected
Cuml Err Low
Cuml Err High
KG Zone2
Mean Absolute Error = 12%
Volk, J. M. et al. (2024)

Figure 16



Uncorrected Range of Cumulative Error: SD03091 B1 Belen District
$Error\ Volume\ \Delta w\ (af)$: $\varepsilon_w = w_a - w_0$
$Cumulative\ Error\ Volume\ \Delta w\ (af)$
600.00
500.00
400.00
300.00
200.00
100.00
0.00
-100.00
536.03
259.14
-17.99
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Cuml Error Uncorrected
Cuml Err Low
Cuml Err High
KG Zone2
Mean Absolute Error = 12%
Volk, J. M. et al. (2024)



Uncorrected Range of Cumulative Error: SD07666 S1 Socorro District
$Error\ Volume\ \Delta w\ (af)$: $\varepsilon_w = w_a - w_0$
$Cumulative\ Error\ Volume\ \Delta w\ (af)$
100.00
0.00
-100.00
-200.00
-300.00
-400.00
-500.00
-600.00
-700.00
-800.00
-900.00
-372.94
-570.27
-767.22
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Cuml Error Uncorrected
Cuml Err Low
Cuml Err High
KG Zone2
Mean Absolute Error = 12%
Volk, J. M. et al. (2024)

Table 3

Administrative Relative Balance and Local Change (Surplus)
Example Assumes CU_0

Non-Shared Change in River Flow

Non-Distributed Local Depletions (Top Down)

		Index (i)	Latitude (i)	Local dw (i)	w (i)	dep (i)	aug (i)
Pumping Depletion	800	0	Lat 0	-800			
Total Water Bank Vol	1390	1	Lat 1	-765	35	35	0
		2	Lat 2	-415	350	350	0
System Depletion	800	3	Lat 3	-340	75	75	0
Rel Balance Ratio	0.58	4	Lat 4	-190	150	150	0
Rel Bal Ratio * W	800	5	Lat 5	-155	35	35	0
		6	Lat 6	45	200	155	45
System Augmentation	590	7	Lat 7	270	225	0	225
Alpha Ratio	0.42	8	Lat 8	340	70	0	70
Alph * W	590	9	Lat 9	430	90	0	90
		10	Lat 10	590	160	0	160
dQriver	590						
System Depletion	Decrease						
System Augmentation	Increase						

Non Shared

Local Relative Contributions

Shared Change in River Flow

Evenly Distributing Surplus Across All Water Rights (Based on Relative Balance)

		Index (i)	Latitude (i)	Local dw (i)	w (i)	dep (i)	aug (i)
Pumping Depletion	800	0	Lat 0	-800			
Total Water Bank Vol	1390	1	Lat 1	-765	35	20.14	14.86
		2	Lat 2	-415	350	201.44	148.56
System Depletion	0	3	Lat 3	-340	75	43.17	31.83
Rel Balance Ratio	0.58	4	Lat 4	-190	150	86.33	63.67
Rel Bal Ratio * W	800	5	Lat 5	-155	35	20.14	14.86
		6	Lat 6	45	200	115.11	84.89
System Augmentation	590	7	Lat 7	270	225	129.50	95.50
Alpha Ratio	0.42	8	Lat 8	340	70	40.29	29.71
Alpha Rato * W	590	9	Lat 9	430	90	51.80	38.20
		10	Lat 10	590	160	92.09	67.91
dQriver	590						
System Depletion	Decrease						
System Augmentation	Increase						

Collectively Shared

Local Relative Contributions

Table 4

Administrative Relative Balance and Local Change (Deficit)
Example Assumes CU_0

Non-Shared Change in River Flow									
Non-Distributed Local Depletions (Top Down)							Non Shared		
Pumping Depletion	1500		Index (i)	Latitude (i)	Local dw (i)		Local Relative Contributions		
Total Water Bank Vol	1390		0	Lat 0	-1500		w (i)	dep (i)	aug (i)
			1	Lat 1	-1465		35	35	0
System Depletion	1610		2	Lat 2	-1115		350	350	0
Rel Balance Ratio	1.00		3	Lat 3	-1040		75	75	0
Rel Bal Ratio * W	1390		4	Lat 4	-890		150	150	0
			5	Lat 5	-855		35	35	0
System Augmentation	0		6	Lat 6	-655		200	200	0
Alpha Ratio	0.00		7	Lat 7	-430		225	225	0
Alph * W	0		8	Lat 8	-360		70	70	0
			9	Lat 9	-270		90	90	0
dQriver	-110		10	Lat 10	-110		160	160	0
System Augmentation	Decrease								
System Depletion	Increase								

Shared Change in River Flow									
Evenly Distributing Surplus Across All Water Rights (Based on Relative Balance)							Collectively Shared		
Pumping Depletion	1500		Index (i)	Latitude (i)	Local dw (i)		Local Relative Contributions		
Total Water Bank Vol	1390		0	Lat 0	-1500		w (i)	dep (i)	aug (i)
			1	Lat 1	-1465		35	35.00	0.00
System Depletion	0		2	Lat 2	-1115		350	350.00	0.00
Rel Balance Ratio	1.00		3	Lat 3	-1040		75	75.00	0.00
Rel Bal Ratio * W	1390		4	Lat 4	-890		150	150.00	0.00
			5	Lat 5	-855		35	35.00	0.00
System Augmentation	0		6	Lat 6	-655		200	200.00	0.00
Alpha Ratio	0.00		7	Lat 7	-430		225	225.00	0.00
Alpha Rato * W	0		8	Lat 8	-360		70	70.00	0.00
			9	Lat 9	-270		90	90.00	0.00
dQriver	-110		10	Lat 10	-110		160	160.00	0.00
System Augmentation	Decrease								
System Depletion	Increase								

Part IV: Discussion and Conclusion

As previously mentioned, formal models can operate without specific values and still uncover general relationships within a system if we hypothesize certain placeholder values or variables. We went a little further than this in our study by relying on real-world data where possible, thereby going beyond purely hypothetical assumptions. The outcome was a mathematized conceptual model having at least some connection with empirical data and measurements. This made it less dependent on the gross theoretical assumptions regarding consumptive use prevalent in current practice, but still reliant on many uncertain assumptions. Perhaps our approach was most valuable for indicating the scale of unknowns related to Water Bank impacts, with empirically testable OpenET data serving that purpose. We argue that this is important since it requires a symbolized and well-defined holistic understanding of Water Bank transfers. Such understanding is essential for developing formal knowledge of the system.

Key Observations

Model Relationships

Establishing mathematical relationships between key elements of transfers allowed us to see how system processes like relative balance may potentially unfold. It demonstrated how changes in hydrologic balance can occur globally or locally under current administrative assumptions, independent of errors in consumptive use estimation. Although time did not permit a comprehensive analysis of all water rights in the Bank, we can glean several insights about overall transfer behavior. Without inclusion of OpenET data, the model shows assumption of ideal administrative transfer conditions results in a surplus of water due to decrease in relative balance. This can be accounted for by the simple fact that to date retired water rights are greater than BWF pumping depletions. It also demonstrated how local depletions occur and then become nullified, leading to augmentations of instream storage and stream outflow compared to pre-transfer conditions.

By integrating OpenET data, the model demonstrated how consumptive use errors at the tract scale, combined with relative balance under transfer, propagate errors at the system level. This indicates that system mass balance is influenced by both relative balance and the magnitude of consumptive use errors for each individual tract within the bank. Initially, we hypothesized that relative balance would be the dominant factor in determining the system level. However, it now appears that cumulative errors could potentially outweigh relative balance.

If cumulative errors result in a greater actual water retirement than assumed, this would simply increase the surplus water already present in the theoretical scenario. Conversely, if cumulative errors result in significantly less actual retired water – less than the total pumping depletions – then basin depletions would exceed the administratively assumed amount. Understanding this dynamic is important for developing a comprehensive and formal knowledge of the system. With this foundational understanding, the empirical accuracy can be further enhanced through model refinements and new estimation methodologies.

Consumptive Use Error

The administrative assumptions imply a surplus in stream outflow by assuming the accuracy the theoretical constant CU_0 and continuous historical irrigation of the tract. We assumed OpenET data represent consumptive use more accurately, and therefore some error exists between the CU_a and CU_0. Deviations from the theoretical constant CU_0 revealed a high potential for cumulative increases and decreases for individual tracts (Appendix III). Error propagation in the model showed how these deviations can build up and eventually affect system balance. Applying uncertainty bounds from other research based on Eddy Covariance comparisons allowed us to speculate potential ranges of uncertainty in these cumulative errors.

But an additional insight from our results suggests that the assumption of continuous irrigation (unlimited supply) may not hold true. Specifically, both the Albuquerque and Socorro water right tracts exhibited lower historical consumptive use than what CU_0 predicts, with the Albuquerque tract showing a particularly notable difference. For the Socorro tract, this was explainable because its decline in consumptive use occurred rapidly after its transfer and retirement date. But the Albuquerque tract showed no discernable change before or after its retirement date. Drawing from our control sample, Belen tract B5, and other tracts which showed much higher rates over the same period, we suspect that when historical irrigation matches the full diversion of the water right this would be reflected in the rate of consumptive use. This is supported by the Albuquerque tract's urban context, suggesting that similar discrepancies likely exist elsewhere.

In fact, there was marked variability between tracts, significant enough for us to infer that historical irrigation plays a prominent role and is highly variable despite administrative assumptions. So, while CU_0 may underestimate CU_a under conditions of full beneficial use, it's necessary to consider the variability in historical irrigation practices. Factors such as supply limitations or intentional fallowing can act as counterbalances, mitigating the positive errors observed among the tracts as a group. Consequently, error in consumptive use is not the sole contributor to uncertainty in on-farm depletions; institutional assumptions regarding farming practices also play a substantial role. The key takeaway is that, in an administrative sense, we simply cannot assume the amount of water being retired without empirical estimates derived from the historical record for each individual tract. There's just too much variability.

System Interpretation

Without such knowledge, the range of uncertainty in retired consumptive use volume is wide, and the magnitude of possible errors in legally transferred consumptive use is great. These errors propagate upward, cumulatively resulting in a total Water Bank volume that is potentially much *greater* or much *less* than its theoretical value, implying real and important basin-level hydrologic changes. Actual depletions in the basin, whether local or system-level, are obscured by not examining the historical actual consumptive use for each retired tract. For individual tracts, empirical estimation appears to be useful for this purpose, and for deriving statistics of historical usage based on real data capable of making more meaningful projections and inferences. This could be done at the system level but requires applying the same process to all retired tracts.

Each new transfer results in a positive or negative change in the water balance due simply to relative balance. This was shown using current theoretical administrative assumptions. Given that integrating actual consumptive use errors, overall changes in system balance are potentially much greater. At this point, we cannot say whether errors on average represent an increase, decrease, or net zero change in total depletion. Assuming knowledge of this a priori would be irresponsible. Yet, administering transfers without knowledge of the difference will merely perpetuate unforeseen changes in the regional water balance.

Nevertheless, quantities involved in Water Bank transfers are more knowable than what current practice allows. We showed that tract-scale empirical estimation of historical irrigation is possible using OpenET remote sensing. Although we did not estimate the historical consumptive use for each retired water right in the Bank, it would not be a difficult task to accomplish. This would provide an empirical measure of how much water resides in the Bank, giving us improved system-level understanding. Greater flexibility in projecting future transfer impacts from individual tracts within various management strategies could come from this.

We believe the logical structure of the model's key components is valid, but a thorough validation has not been conducted. Doing so will undoubtedly reveal flawed assumptions or mischaracterized relationships. After validation, calibration of the many parameters and their coherence would need to be carried out. Obvious empirical and model uncertainties like BWF hydrogeology and soil moisture balance should be acknowledged and addressed, but these are categories of uncertainty well-suited for improvement with advances in technology and modeling. The category of institutional uncertainty, however, poses a greater challenge beyond the scope of mere scientific improvements.

Retirement Compliance

Despite being limited to select tract-level analysis, the theoretical and empirical comparison revealed much about historical consumptive use post-retirement. We did not intend to use OpenET as a tool for exploring regulatory compliance with water right statutes. And yet, historical estimates of actual consumptive use revealed glaring issues with assumptions for both pre-transfer beneficial use and post-transfer irrigative retirement. Both are relevant uncertainties. Supply limitation likely explains low consumptive use prior to retirement, but some tracts show what appeared to be irrigative use post-retirement. More samples are needed to see if this is prevalent. Unless there is some unaccounted-for alternative (e.g., temporary lease through the MRGCD's agricultural water bank), then the entire idealized administrative transfer is rendered invalid. Furthermore, the epistemic uncertainty of post-transfer retirement is high due to its institutional unpredictability. Something is causing farms to have an irrigative level of consumptive use present when they should have been long retired. The likely explanation is that water is still being applied in large quantities. This leads us to believe that human behavior and institutional practices are driving a high level of uncertainty in post-transfer retirement and consequently, changes in the hydrologic balance.

We anticipated uncertainty in how retired water at the headgate of a farm actually makes it back into the system. But regulatory compliance opens another set of issues. It leads us to question what regulatory compliance really means. If we dismiss the possibility of illegal diversions, such as irrigating from a domestic well or stealing from a conveyance (issues that are matters of law enforcement), then we must conclude the regulations themselves do not necessitate termination of post-transfer consumptive use. What transfer statutes ensure is the cessation of post-transfer diversion under the original water right.[1] It is entirely permissible for the land to continue irrigating under a different water right.[1] This, of course, violates the principle of retirement and the one-to-one concept of depletion reallocation, and it is a classic example of managing paper rather than wet water. It could be argued that the new right supplying the diversion to the old farm requires retirement of diversions elsewhere, but this is not necessarily true. For example, what if an entity possesses water they do not use, and is able to lease this water to another user who then puts it to use, something like a water bank?

This is in fact the case in the MRGCD.[21] Not all holders of water rights are upheld to the standard rules of timely beneficial use. For practical reasons, some institutions are granted exceptions. Some institutions are allowed to hold idle water for a longer period of time than the ordinary statutes.[4] Water banks require these same types of exceptions due to their very nature as secure water reserves.[7] Another water bank we briefly discussed is the MRGCD water bank, which leases surplus water within the District for irrigative diversions to non-water right holders who own lands in the MRGCD.[21]

"…If the Conservancy District finds a specific tract or tracts on which Conservancy Water Rights were placed to beneficial use under historic conditions, but that are no longer being placed to beneficial use, the water is available for leasing."[21]

This seems to run counter to the broader objective of preserving balance by retiring water use after transfer. And because the MRGCD holds surplus water rights throughout the district, there's really no way knowing if that comes from the retired use of a Santa Fe Water Bank transfer, or a retired use at all. The disparate operational purposes of both a Santa Fe Water Bank and an MRGCD Water Bank could result in two allocations of water representing the same allocative withdrawal. This has the physical effect of either doubling the theoretical consumptive use in the basin, or increasing the sum of actual consumptive use from both locations. Although it is an aim of MRGCD district policy to not increase net depletions in the District's boundaries, the possibility exists that this could do just that.[21]

Institutional Challenges

It turns out then, that the issues of returning retired water from the farm headgate to instream storage and keeping it as instream storage, without being re-consumed, are closely related due to non-compliance with post-transfer retirement. Without this condition being met, the entire transfer model folds. The City of Santa Fe and the MRGCD may continue to operate their Banks, siloed in different sectors, but they are essentially trading paper rights only, and hydrologic impacts go unaccounted for. Flexibility and efficiency in transfers may seem plausible under this scenario initially, but ultimately, the hydrologic realities will manifest, and conflicts will escalate. Once more, understanding the resource – both empirically and institutionally – is crucial. Equally vital are rules that articulate and are enforced based on that understanding.

Surplus and Deficit

One particularly surprising discovery was the role of relative balance, i.e., the difference between pumping depletion and retired water rights. This relationship entangles in many of the critical and often contentious issues regarding Water Bank transfers, such as system-level depletion, local depletions and augmentations, and even issues related to the broader Espanola basin. The ratio easily captured the scale of relative balance and made it possible to transpose system-level proportions to individual tract scales. We found this to be not only interesting but highly valuable as a possible tool for new water planning strategies.

This would be especially true in cases of increased system surplus occurring through water right retirement, where surplus water could be used for mutually beneficial allocations of water serving State and environmental needs. On the other hand, if the City owns less actual water than offsets, it would pose a serious management problem in the sense that deficits would be owed. This would likely entail either acquiring more water rights, supplying offsets with SJC water, or reducing BWF pumping and relying on alternative supplies while paying deficits with SJC water, the Bank, or both.

Interesting questions emerge in the surplus scenario. If Santa Fe truly has more water than offsets, that constitutes a net surplus of potential water in the system. Let's assume the City knows empirically its water rights have generated a surplus, but that it's likely being consumed elsewhere in the MRG. They want a surer way of accessing the surplus they have generated. Two questions naturally arise:

1. *Why not transfer water based on actual consumptive use as opposed to theoretical?*
2. *Should Santa Fe increase its BWF depletions to match actual total volume in Bank?*

These are valid questions, but they come with problems. Transitioning from the use of CU_0 to CU_a could have far-reaching legal and administrative implications. For instance, farmers and developers who entered into agreements based on the original constant may seek compensation for any surplus water they were unable to transfer. Moreover, increasing transfer volumes could potentially conflict with the overarching goal of water conservation in the state. While empirical estimates may offer greater accuracy, there's a looming risk of surpassing a safe depletion threshold, particularly when considering the uncertainty surrounding the true depletion levels of the many past transfers unaccounted for. Without a comprehensive understanding of the Middle Rio Grande's overall water budget, administrators face the perpetual risk of inadvertently exacerbating depletion by raising the allowable consumptive use in transfers. Although, there could be an argument for using the theoretical constant as an upper limit for historical tract irrigation based on empirical estimates.

In addressing the second question, obtaining OSE consent to raise the limit on BWF depletions using a new empirical estimate would necessitate significant resources from both parties to establish a robust arrangement. Balancing BWF depletion with a more variable physical Bank pool might prove challenging and could risk surpassing offset limits. Opting for a safety margin between depletions and the total Bank volume would likely be a more feasible approach. Furthermore, boosting production would contradict Santa Fe's long-term planning for the BWF. The City aims to sustain a production rate of about 2,600 afy for the foreseeable future.[29] Depleting Rio Grande flows up to the Bank's full capacity would surpass this sustainable rate because not all water derived from the wells comes from the Rio Grande. In fact, most of BWF production derives from the Tesuque regional aquifer, as suggested by the administrative relative balance. So upping production to match empirical volumes in the Bank could have a noticeable impact in the Espanola Basin.

Comprehensive Water Planning

Comprehensive water planning is an extensive and holistic institutional process that guides collective water use and societal goals within a single framework, ideally through broad engagement and participation in design and implementation.[37] It considers various factors such as environmental sustainability, economic viability, social equity, land use, and resilience to climate change.[37] Comprehensive water plans aim to establish a shared valuation of water and determine its distribution accordingly. This involves assessing current and future water needs, evaluating available water supplies, identifying potential risks and challenges, and developing strategies to address them effectively.[37] Furthermore, comprehensive water planning endeavors to resolve complications among fragmented management policies and procedures.[37] Essentially, it serves as a tool for organizing disparate water resource management practices into a coherent vision.

Integrating communities and sectors siloed in myopic forms of management into a broader, comprehensive plan is ultimately necessary for the responsible and effective maintenance of a common pool. This type of planning could also facilitate the creation of much deeper and more participatory knowledge commons.[2] Broadening collective knowledge would in turn promote more effective and accurate water management science, but also engender much needed stakeholder communication under an umbrella of mutual understanding.[2] Governmental agencies, irrigation districts, municipalities, tribes, environmental organizations, all must be included within comprehensive planning efforts. We argue that such an approach is necessary for addressing the issues discussed in our study. It is not without precedence either. New Mexico currently has both regional and state-level planning efforts in place.[32] And Upper Colorado River Basin (UCRB) member state collaboration is yet a larger example. Their effectiveness may be up for debate, but like all plans they can be improved and made more successful through contribution of new ideas and strategies. Such ideas may seem radical or threatening to individual groups and communities, but that is why planning efforts must be comprehensive, to expose disparate stakeholders to new perspectives and have frank negotiations over reasonable compromise, all based on collective knowledge of what is at stake. In that way, seemingly radical ideas might no longer seem so outrageous, perhaps even mutually necessary.

Consolidating Instream Surplus Storage

One question that remains is: *What should be done about surplus flows occurring at the basin scale?* If surplus flows potentially exist, how can they be actualized to the benefit of the City or other stakeholders? The relative balance ratio discussed at length earlier could have a pivotal role answering that question. At the local level, upstream depletions exist in some cases, even when there is surplus instream storage at the system level. The use of δ could reflect what percentage of overall surplus an individual retired right constitutes, and those volumes could be aggregated at different diversion points along the Rio Grande – including just below Cochiti at the top of the system. All the instream storage could thus be kept instream for the desired lengths of the river. And each transfer could be defined in terms of its relative balance. For Santa Fe, surplus water could be leased to downstream users or allocated to Compact requirements. For transfer protestants, the issue of local depletions upstream could be settled. But all of this would require rule compliance for retired farms, and diversion agreements with the MRGCD. The MRGCD might however see value in this idea. It would at the very least provide better accounting to reduce the possibility of doubling District depletions.

Rule compliance would require greater scrutiny of farms post-transfer. But another area that would need to be investigated is the non-diverted fate of water post-transfer, and the consumptive effects of brush and shrubs encroaching on the dried-up land. We observed significantly lower consumptive use rates in fields that have been fallowed over the course of years. But this would need to be factored into a formal model. If the retired water is consolidated and withheld instream, then the complexities of MRGCD diversion networks no longer play a role in the storage of retired water, and greatly reduce the potential consumptive uses of riparian or other vegetation. All these assumptions require a remarkable amount of cooperation among Rio Grande stakeholders, perhaps too much. But at the very least, there is a path forward to having such discussions in a more informed way.

Regional Water Bank

The ideal Water Bank transfer has historically been the interpretive basis for Santa Fe's internal planning and decision making. Consequently, the process of land use and development operated independently from broader concerns over MRG hydrology. The City's process – tied to the administrative transfer template – did capture nor attempt to characterize water transfer impacts in a formalized, well-defined, or empirically robust manner. After all, this has historically been the purview of the OSE. The OSE *has* managed transfers from a comprehensive perspective to some extent – through its modeling of BWF offsets and the highly generic conjunctive management model based on theoretical consumptive use – but it has never fully captured the underlying issues known to exist. In recent years, however, the City has had to become well-versed in the institutional complexities and hydrological concerns of broader Middle Rio Grande management. This necessity stems from an increasing level of protest from prominent water users in the Middle Rio Grande, including environmental groups, tribes, and the MRGCD.

While some groups are willing to accept the administrative narrative of preserving water balance at a basin scale, they maintain legitimate concerns about depletion between transfer locations at the local scale. Although transfers are within the legal bounds of appropriation, concern arises over those not protected under Prior Appropriation, such as the Bosque ecosystem.[1] Depletions between transfer locations may be recovered at the basin level, but for ecosystems benefiting from existing upstream flows, diminishment of these flows may have a harmful impact. Others are skeptical of the balance narrative entirely, owing to the actual diversion practices in place, which deviate from the idealized scenario, or are simply suspicious of what they perceive to be inter-basin transfers. For the MRGCD, there is likely a sense of encroachment felt in observing the legal transfer of paper rights out of its jurisdiction, as well as an obligation to protect its agricultural constituents by maintaining access to an undiminished pool within the MRGCD Water Bank.

Concerns regarding water transfers have escalated, prompting Santa Fe to find solace in the forthcoming completion of the SJC Return Flow Project.[29] Once operational, developers will be able to access recirculated SJC contract water to fulfill offsets, potentially alleviating the need for contentious Middle Rio Grande rights. However, despite the project's promise, the Water Bank remains a fixture. Over 1,390 acre-feet of paper rights have already been transferred and are set to persist within the Bank. As the SJC Return Flow Project progresses, there's ongoing dialogue about imposing a cap on the total water rights retained in the Bank. This cap would aim to ensure adequate reserves for mitigating sudden supply disruptions while also facilitating the leasing of unused consumed volumes for environmental flows or Rio Grande Compact obligations. So, the Bank plays a role into the future. And potentially more rights would need to be obtained to secure a reliable buffer.

In theory, one way to reconcile all these divergent water communities and allocation systems would be to create a regional water bank. Facilitating water rights under a collective regional scale bank would provide more oversight and better reflect the nature of water as a shared public resource. As our analysis has shown, the issue of non-compliance with post-transfer retirement complicates efforts to return retired water to instream storage. This suggests the need for a well-regulated and flexible legal framework that can address such challenges. A regional water bank, supported by comprehensive governance and accurate water transfer processes, might provide the structure needed to manage these issues effectively. A regional water bank could enhance the fairness and flexibility water right transfers by providing consistency and openness in market exchanges, encouraging participation from various stakeholders, and allowing water to be redirected to higher-valued uses, including environmental needs.[7] Furthermore, a regional bank would have greater administrative leverage in shifting State water policy away from the rigid and often exclusive allocative regimes of the past.

But, all of this begs the question of who is ultimately responsible for spearheading and enforcing such an institution? There are many sociopolitical, legal, economic, and environmental issues currently at work in New Mexico water policy. Transforming the status quo into a new water planning paradigm would surely be met with extreme skepticism by many. The idea of moving water towards higher valued uses does pose a risk of concentrating water into the hands of the wealthy, but not necessarily. What few people have in wealth, many people have in numbers. A regional water bank could be created as a public democratic institution, composed of regional community representation.

While the inertia for creating such institutions ideally comes from the bottom up, the historical constraints of water policy and practice are significant and require high-level coordination. We argue that it is ultimately the state's governing responsibility, along with institutions holding substantial political sway over water management, such as the MRGCD, to resolve these current and looming water crises. Ideally, this would be achieved through comprehensive planning with broad community participation and enforcement capability. In this latter sense, it becomes the collective responsibility for everyone.

Conclusion

Coming back to our study, we showed that epistemic uncertainty hampers the functionality of Water Bank transfers, in addition to generating potentially significant hydrologic impacts. We offered formalization as an approach to solving this problem and suggested empirical estimation techniques be used to better quantify transfers and their effects. We suggested and used OpenET because of its availability, established credibility, and evolving use among water planners and managers across the west. There are other methodologies of course, and likely more on the way, as water scarcity and climate change become more amplified.

But regardless of the technical sophistication, accuracy, and precision of any such tools, they all require an overarching level of critical judgement when making inferences that impact real world circumstances. Depending on the cost and time involved, and the specific management goals, highly technical methods with better estimates may be less suitable for practical implementation. Conversely, there may be a time and place for extreme technical rigor. Experience-based professional judgement must ultimately determine the suitability and benefit for a particular method.

That being said, the choice is not always binary. There may be instances where methods offering greater technical precision and accuracy comport with practical decision making. Factors such as climate change and societal demands will ultimately require finding such an overlap. Intensifying competition for diminishing water necessitates its subdivision and distribution into increasingly minute portions. Within this context, the imperative for precise and accurate quantification becomes more pronounced, underscoring the significance of methodologies that are both epistemically robust and operationally feasible.

The broader political ramifications of moving in that direction may cause trepidation among managers, who are often pressured by traditional water sectors and statutory policies. Revaluation of the existing rules brings new ways of measuring and understanding the resource, beckoning the possibility of new winners and losers. But avoiding improvements in the shared understanding of a common resource to placate traditional allocation regimes may not be a wise choice. The hard politics of dwindling resource allocation cannot be avoided. Harmonious compromises within existing hierarchies, or a total restructuring of them, are both better served by reliable accounting.

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Appendix I: OpenET Interpolation

As a reminder, reference ET denoted ET_0 is the is the amount of crop ET derived from a reference surface, typically a well-watered grass or alfalfa crop[2]. In this case, ET_0 is derived from weather station measurements using the American Society of Civil Engineers (ASCE) Standardized Penman-Monteith equation discussed previously, and is based on solar radiation, air temperature, humidity, and windspeed in conjunction with the ancillary data.[2]

The Reference ET then serves as a calibration factor for scaling the satellite derived ET_a estimates. On days when satellite overpasses are not available, direct measurements of ET_a cannot be obtained. To fill the temporal gaps between satellite overpasses, OpenET uses an interpolation technique based on the fraction of reference ET (ETF) for each satellite overpass date. This fraction represents the proportion of ET_a relative to ET_0 on that day. These fractions are then interpolated in daily time steps.

The interpolation process involves three basic steps:

1. Calculating the reference ET fraction ETF for each satellite overpass date

2. Fraction values are linearly interpolated daily for all days between satellite overpass dates, pixel by pixel.

3. Interpolated fraction values are multiplied by the unique daily ET_{0_i} values between passes to obtain a daily time series of the calibrated ET_a for each pixel.

These daily values are then aggregated into monthly and annual time periods. The interpolation of the fractional reference ETF_i over time is necessary as it varies in proportion to changes in vegetation cover, as does the crop coefficient. Daily ET_0values are further utilized to account for day-to-day variations in weather conditions, thus adjusting ET_a rates accordingly.

Terms

Overpass Actual ET: Recorded on Satellite Overpass Day (ET_a)

$ET_a = Satellite\ Ensemble\ Value$

Overpass Reference ET: Recorded on Satellite Overpass Day (ET_0)

$$ET_0 = Standardized\ Penman\ Monteith\ Estimate$$
$$= f(solar\ radiation, temperature, humidity, windspeed, crop\ coefficient)$$

Non-Overpass Daily Reference ET: Recorded Daily on Non-Overpass Days (ET_{0_i})

$$ET_{0_i} = Standardized\ Penman\ Monteith\ Estimate, \qquad 0 \leq i \leq 7\ is\ daily\ index$$
$$= f_i(solar\ radiation, temperature, humidity, windspeed, crop\ coefficient)$$

Overpass Reference ET Fraction: Calculated on Satellite Overpass Day (ETF)

$$ETF = \frac{ET_a}{ET_0}$$

Overpass Reference ET Fraction: Calculated on Satellite Overpass Day (ETF_i)

$$ETF_i = \left(\frac{ET_a}{ET_0}\right)_i, \qquad 0 \leq i \leq 7\ is\ the\ daily\ linearly\ interpolation\ index$$

Interpolated Actual ET (ET_a^*)

$$\{ET_a^*\}_{i=1}^{i=7} = \left(\frac{ET_a}{ET_0}\right)_i \cdot ET_{0_i} = ETF_i \cdot ET_{0_i} \qquad 0 \leq i \leq 7\ is\ the\ daily\ index$$

Ensemble models eeMETRIC and SSEBop utilize alfalfa reference evapotranspiration (ET_r) internally in OpenET – as opposed to the grass reference crop ET_0. Ratios of ET_r to ET_0 are computed and applied to allow for time integration using ET_0 data. Discrepancies between ET_0 and ET_r are observed and particularly pronounced during winter months under conditions of high wind and low humidity, attributed to greater sensitivity of the wind function within the ET_r equation.[7]

Table of Actual Evapotranspiration Interpolation Using *ETF* *

Satellite Estimate I	Estimations for Non-Overpass Days: *Overpass every 8 days with 7 days between each overpass*							Satellite Estimate II
Overpass I: Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Overpass: II Day 8
ET_a I	No ET_a	No ET_a	No ET_a	No ET_a	No ET_a	No ET_a	No ET_a	ET_a II
ET_0 I	ET_{0_1}	ET_{0_2}	ET_{0_3}	ET_{0_4}	ET_{0_5}	ET_{0_6}	ET_{0_7}	ET_0 II
ETF I	ETF_1	ETF_2	ETF_3	ETF_4	ETF_5	ETF_6	ETF_7	ETF II
ET_a I	$ET^*_{a_1}$	$ET^*_{a_2}$	$ET^*_{a_3}$	$ET^*_{a_4}$	$ET^*_{a_5}$	$ET^*_{a_6}$	$ET^*_{a_7}$	ET_a II

*Table represents a simplification of satellite overpass scheduling:
Landsat satellite overpasses occur every eight days with Landsat 7 and 8 satellites, and every five days with Landsat 7, 8, and 9 satellites in orbit.

Appendix II: Ancillary Tracts

FID	PPID	MRGCD_Div	OSEID	Acreage	DivID	RankID	SampleID	Transfer Date	Status
0	1	**Coc**	**SD05162A**	17.000	C1	1.1	TI	2008	Tans
1	2	Coc	SD05162A	17.000	C2	1.2	TB	NA	Brush
2	3	Coc	SD05302	2.300	C3	1.3	SI	NA	In Agg
3	4	Coc	SD05302	2.300	C4	1.4	SB	NA	Brush
4	5	**Abq**	**SD08681A**	4.389	A1	2.1	TI	2018	Tans
5	6	Abq	SD08681A	4.389	A2	2.2	TB	NA	Brush
6	7	Abq	SD06965	12.900	A3	2.3	SI	NA	In Agg
7	8	Abq	SD06965	12.900	A4	2.4	SB	NA	Brush
8	9	**Bel**	**SD03091**	35.480	B1	3.1	TI	2009	Tans
9	10	Bel	SD03091	35.480	B2	3.2	TB	NA	Brush
10	11	Bel	SD02965A	9.500	B3	3.3	SI	NA	In Agg
11	12	Bel	SD02965A	9.500	B4	3.4	SB	NA	Brush
12	13	**Soc**	**SD07666**	38.130	S1	4.1	TI	2014	Tans
13	14	Soc	SD07666	38.130	S2	4.2	TB	NA	Brush
14	15	Soc	SD07871	11.600	S3	4.3	SI	NA	In Agg
15	16	Soc	SD07871	11.600	S4	4.4	SB	NA	Brush
16	17	Abq	USFWS	345.000	A5	5.1	EX	Bosq Ap	Bosq Ap
17	18	Bel	ISLETA	17.500	B5	5.2	EX	In Agg	In Agg
18	19	Soc	BOSQUE	30.000	S5	5.3	EX	Rio Bosq	Rio Bosq
19	20	Sml	MIX	30.000	M1	5.4	EX	San Mar	San Mar

Appendix III: Effective Precipitation and Ranges

Effective Precipitation and Ranges for uncorrected and corrected bias for KGZ 2

Effective Precipitation: SCS Method

$$P_e = SF\left(0.70917 P_t^{0.82416} - 0.11556\right)\left(10^{0.02426\,ET_c}\right)$$

where:

P_e = average monthly effective monthly precipitation (in)

P_t = monthly mean precipitation (in)

ET_c = average monthly crop evapotranspiration (in)

SF = soil water storage factor

The soil water storage factor was defined by: [2–85]

$$SF = \left(0.531747 + 0.295164\,D - 0.057697\,D^2 + 0.003804\,D^3\right)$$

where:

D = the usable soil water storage (in)

USDA Soil Conservation Service. Irrigation Water Requirements. in *National Engineering Handbook* (US Department of Agriculture, 1993)

Incorporating P_e and KGZ error terms in our study:

$ET_C = ET_a\ (OpenET\ Ensemble)$

$P_t = OpenET\ GridMET\ Precipitation$

$D = 3\ in$

$P_e\ is\ also\ a\ function\ of\ ET_a\ such\ that\ P_e = P_e(ET_a)$

$CU_a = ET_a - P_e(ET_a)$

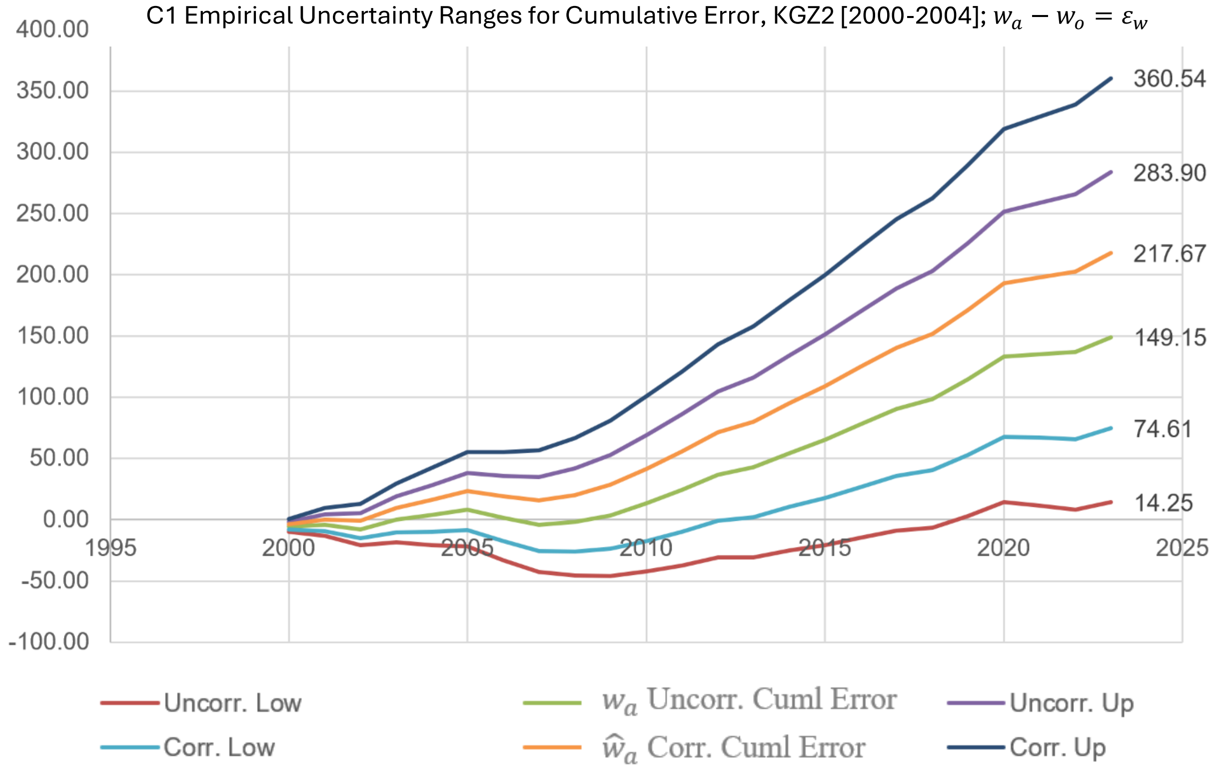
CU_a empirical uncertainty based on KGZ2:

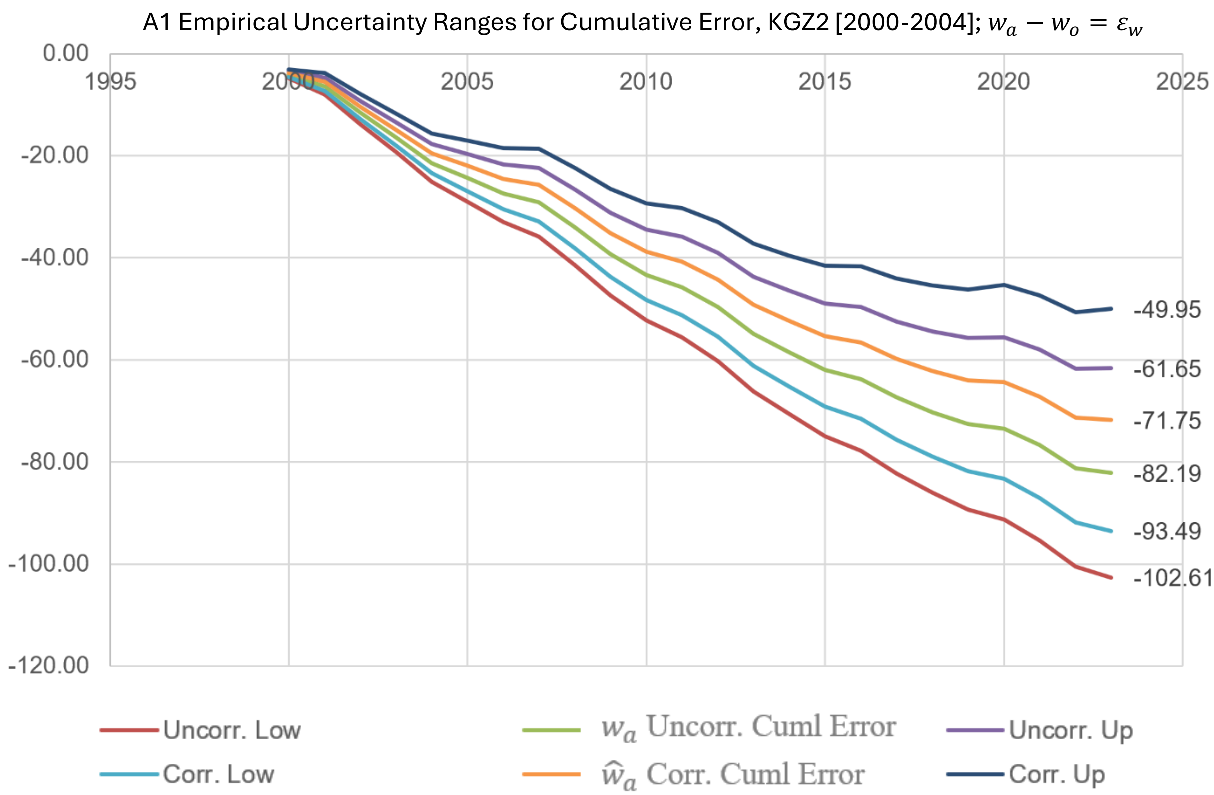
1. Median and Bounds ET_a Uncorrected:
   $ET_a\ median = ET_a\ (Ensemble)$
   $ET_{a_{Up}} = ET_a + |MAE \cdot ET_a|$
   $ET_{a_{Low}} = ET_a - |MAE \cdot ET_a|$

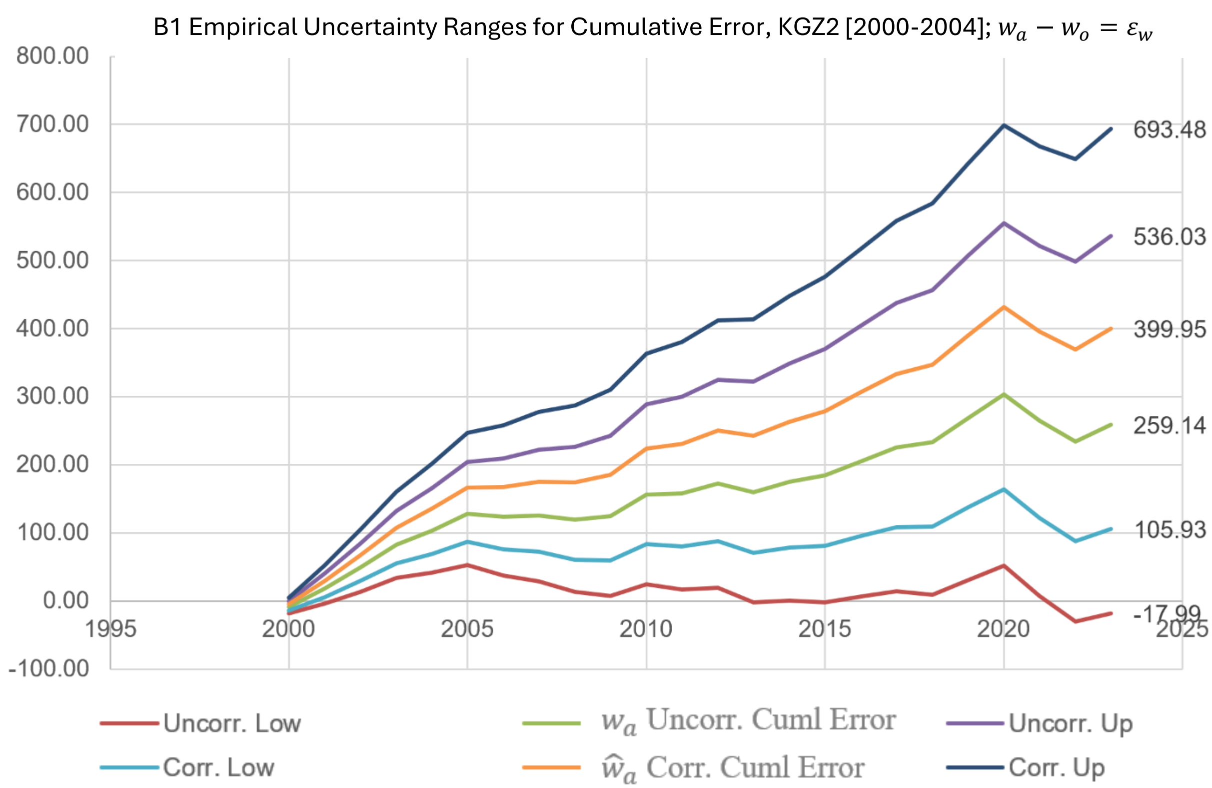
2. Median and Bounds ET_a Corrected:
   $\widehat{ET}_a = ET_a + MBE \cdot ET_a$
   $\widehat{ET}_{a_{Up}} = (ET_a + MBE \cdot ET_a) + |MAE \cdot ET_a|$
   $\widehat{ET}_{a_{Low}} = (ET_a + MBE \cdot ET_a) - |MAE \cdot ET_a|$

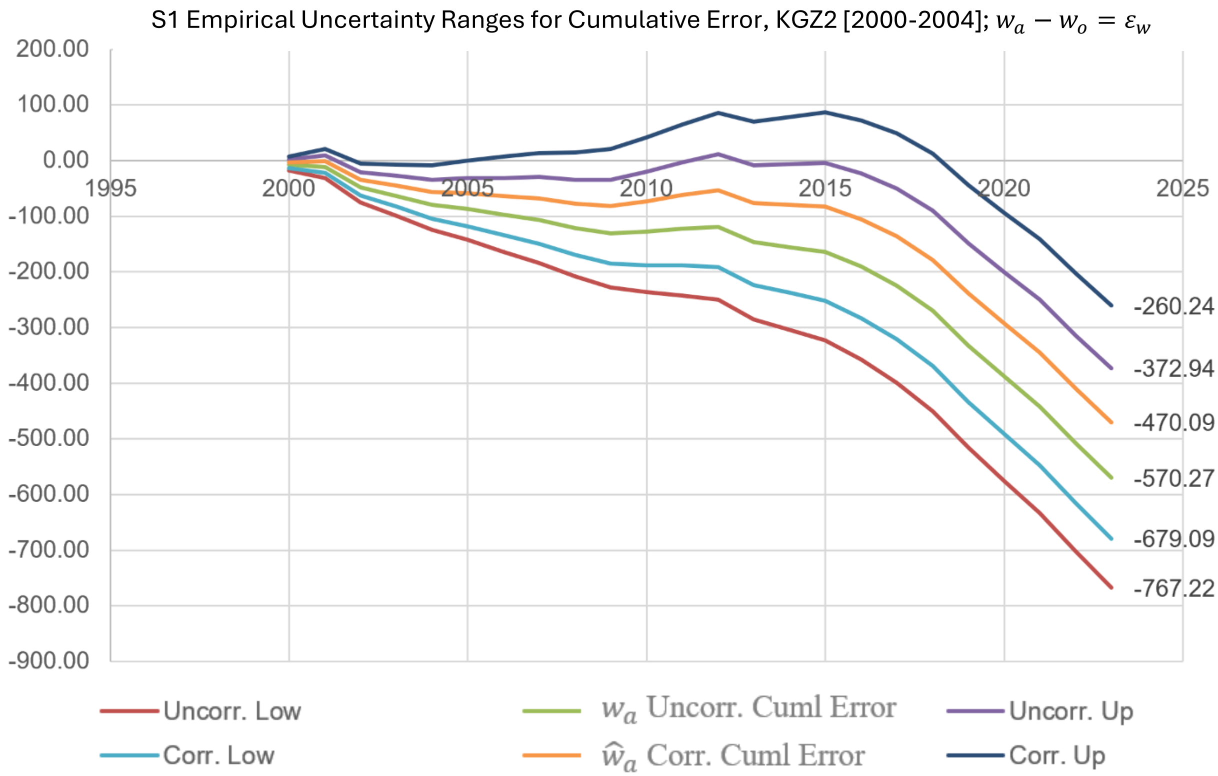
3. Median and Bounds CU_a Uncorrected
   $CU_a = ET_a - P_e(ET_a)$
   $CU_{a_{Up}} = ET_{a_{Up}} + P_e\left(ET_{a_{Up}}\right)$
   $CU_{a_{Low}} = ET_{a_{Low}} - P_e\left(ET_{a_{Low}}\right)$

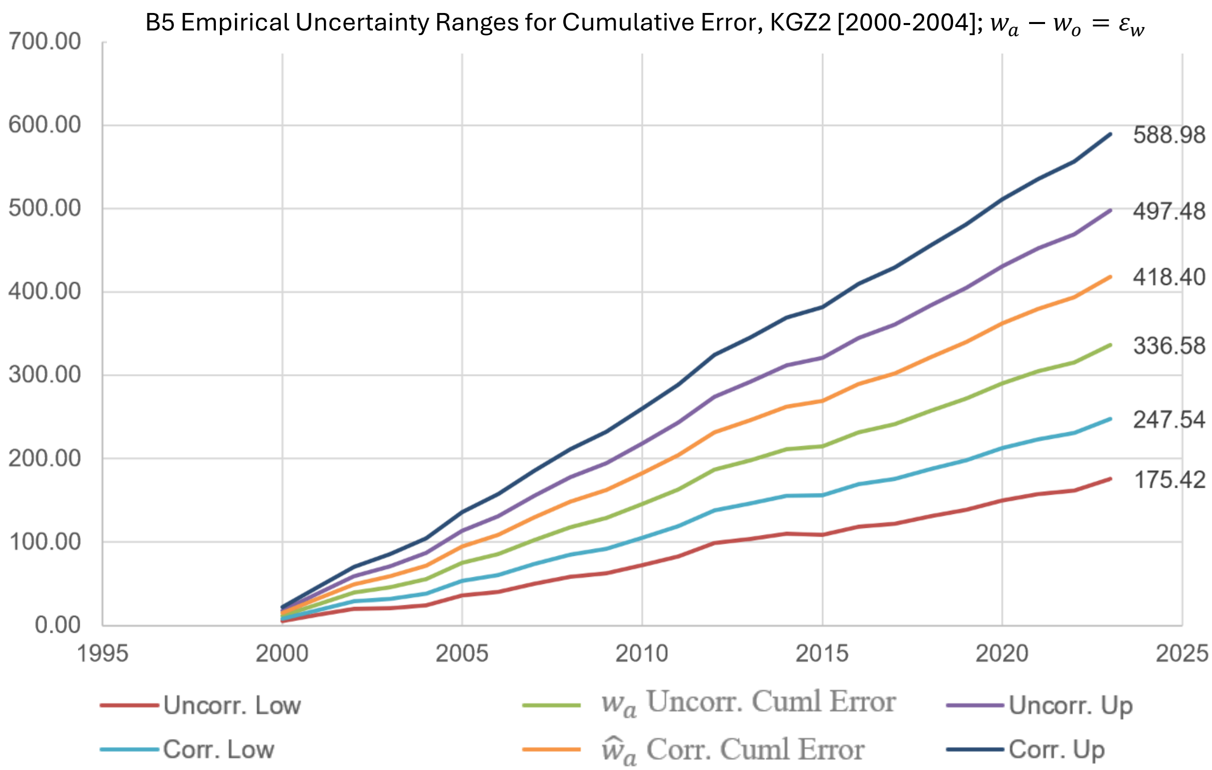
4. Median and Bounds CU_a Corrected
   $\widehat{CU}_a = \widehat{ET}_a - P_e\left(\widehat{ET}_a\right)$
   $\widehat{CU}_{a_{Up}} = \widehat{ET}_{a_{Up}} + P_e\left(\widehat{ET}_{a_{Up}}\right)$
   $\widehat{CU}_{a_{Low}} = \widehat{ET}_{a_{Low}} - P_e\left(\widehat{ET}_{a_{Low}}\right)$




A1 Empirical Uncertainty Ranges for Cumulative Error, KGZ2 [2000-2004]; $w_a - w_o = \varepsilon_w$
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
1995
2000
2005
2010
2015
2020
2025
-49.95
-61.65
-71.75
-82.19
-93.49
-102.61
Uncorr. Low
Corr. Low
w_a Uncorr. Cuml Error
$\hat{w}_a$ Corr. Cuml Error
Uncorr. Up
Corr. Up


B1 Empirical Uncertainty Ranges for Cumulative Error, KGZ2 [2000-2004]; $w_a - w_o = \varepsilon_w$
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
-100.00
1995
2000
2005
2010
2015
2020
2025
693.48
536.03
399.95
259.14
105.93
-17.99
Uncorr. Low
Corr. Low
w_a Uncorr. Cuml Error
$\hat{w}_a$ Corr. Cuml Error
Uncorr. Up
Corr. Up


S1 Empirical Uncertainty Ranges for Cumulative Error, KGZ2 [2000-2004]; $w_a - w_o = \varepsilon_w$
200.00
100.00
0.00
-100.00
-200.00
-300.00
-400.00
-500.00
-600.00
-700.00
-800.00
-900.00
1995
2000
2005
2010
2015
2020
2025
-260.24
-372.94
-470.09
-570.27
-679.09
-767.22
Uncorr. Low
Corr. Low
w_a Uncorr. Cuml Error
$\widehat{w}_a$ Corr. Cuml Error
Uncorr. Up
Corr. Up


B5 Empirical Uncertainty Ranges for Cumulative Error, KGZ2 [2000-2004]; $w_a - w_o = \varepsilon_w$
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
1995
2000
2005
2010
2015
2020
2025
588.98
497.48
418.40
336.58
247.54
175.42
Uncorr. Low
Corr. Low
w_a Uncorr. Cuml Error
$\widehat{w}_a$ Corr. Cuml Error
Uncorr. Up
Corr. Up