

Least-cost provision of ecosystem services from water: When, where, and how much?

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Abstract

Changes in surface or groundwater management influence water use patterns as well as the economic value and sustainability of all water uses. In water-scarce regions, programs that establish environmental flows will usually involve reallocating water from another productive use. Few peer-reviewed papers to date have investigated impacts on system-wide economic performance resulting from environmental flow regimes. This work presents an original approach to address that gap by developing and applying a basin scale hydro-economic optimization model of North America's Middle Rio Grande Basin to explore impacts of environmental pulse flows on the region's economy and water stocks. The model accounts for surface and groundwater storage, irrigation, urban, recreational, and environmental demands, surface water inflows under various climate scenarios, groundwater pumping and recharge, substitute water prices, crop water use, evaporation, as well as institutional constraints governing water use. Results show that climate change, in the form of highly variable inflows, has an impact on the total and marginal cost of implementing environmental pulse flows, amplified by the conjunctive nature of the system.

29 Introduction

30 For over 100 years, the Rio Grande River has been the primary water source for the
31 Middle Rio Grande basin, which includes southern New Mexico, Far West Texas, and northern
32 Chihuahua (Mexico) (see Figure 1) (Wilcox, Bowman, and Shafike 2007). In this region, the Rio
33 Grande has been developed into a highly managed network that delivers water to agriculture
34 and municipal and industrial (M&I) uses. Groundwater also supplies a substantial portion of
35 agricultural and M&I demand (Hardberger 2004). Pumping rates from the major aquifers are
36 typically considerably greater than recharge rates. Recent periods of drought and increasing
37 regional demand for water have resulted in the total demand for water exceeding the supply of
38 surface water in the basin and greater dependence on groundwater (Sheng 2005). Consumptive
39 uses of river water, combined with storage reservoir operations, have altered river flow
40 magnitudes and timing relative to natural flow regimes. Blythe and Schmidt (2018) estimate
41 that annual flood maxima have been reduced from greater than 300 m³/s to less than 50 m³/s
42 and the duration of the floods have been reduced from more than 100 days to less than 70 days
43 at the El Paso gauge (see Figure 1), compared to naturalized flows prior to the 20th century.
44 These flow alterations, along with channelization and other modifications of the river course,
45 have reduced ecosystem services provided by riparian habitats, such as habitat provisioning for
46 threatened and endangered species (Finch et al. 1995). Storage and periodic releases of water
47 (environmental pulse flows) have already been prescribed for protecting aquatic habitats
48 upstream of the Middle Rio Grande basin (Alo and Turner 2005; Cowley 2006; Lane, Sandoval-
49 Solis, and Porse 2015).

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An environmental pulse flow is a high magnitude, short duration event, whose primary ecosystem function is to disperse seeds from native vegetation and provide soil moisture for emerging vegetation, complementing efforts to restore riparian vegetation and associated habitat. The pulse flow regime and associated ecological target is only one of many ways of formulating flow regimes (e.g. Poff, Tharme, & Arthington, 2017) to emulate the ecological functions of naturally occurring floods. An example of a similar project is the 2014 Colorado River Delta pulse flow, which was the first environmental flow release across an international boundary. These flows totaled 158 KAF (thousands of acre-feet, 195 Mm³, millions of cubic meters), and were allocated to the Colorado River Delta over a five-year period from 2013 to 2017, with Mexico providing a one-time pulse flow delivery of 105 KAF (130 Mm³) in 2014. The results of the Colorado River Delta pulse flow showed the resilience of riparian ecosystems, demonstrating that even these small volumes of water can produce ecological restoration, as well as providing additional benefits such as increased water levels in groundwater (e.g. Kendy et al., 2017; Ramirez-Hernández, Rodriguez-Burgueño, Kendy, Salcedo-Peredia, & Lomeli, 2017).

In 2009, the US International Boundary and Water Commission (USIBWC) issued a record of decision (ROD) which outlines volumes of water to be allocated for environmental pulse flows in the Middle Rio Grande below Elephant Butte reservoir (UISBWC 2009). The plan identifies 30 riparian locations, totaling 553 acres, to restore by returning water to the river's floodplain. The locations selected are habitat for, among other native species, the endangered Southwestern Willow flycatcher (*Empidonax traillii extimus*). According to the plan, 227 acre-feet (0.00280 Mm³) of water would be released from Caballo Dam (Figure 1) annually for habitat restoration

and, once every 3 to 10 years, a pulse release of 9,300 acre-feet (11.5 Mm³) would occur over at least four days.

Environmental flow regimes can range from simple requirements of a single minimum flow to complex schedules meant to reproduce the timing, magnitude, and duration of natural flows. Most of these regimes rely on prescriptions of flow frequency, implying that there is flexibility as to when water is set aside for environmental flows. In the case of the USIBWC pulse flow prescriptions, for example, releases could occur as infrequently as one in ten years, or as frequently as every three years, leaving room for decision-makers to consider socioeconomic and environmental factors in choosing when to schedule the pulse flows. In water scarce systems such as the Rio Grande, quantifying the economic tradeoffs of allocating surface water to the competing demands across space (which users sell water, or what uses are offset?) and time (which years should flow pulses occur?) is essential for development of efficient and sustainable water policy (Dyson, Bergkamp, and Scanlon 2003; Richter 2010; Acreman et al. 2014).

Modeling and estimating the economic value of water allocation to agriculture and M&I sectors usually relies on readily available datasets, including quantities and prices of goods and services produced using surface water as an input. Though the quantity of water allocated for environmental flows can be observed, identifying and valuing the goods and services produced is obscured by the complexity of ecosystem services, as well as the lack of markets and well-defined prices. A large literature in environmental economics attempts to measure society's

value, or “willingness to pay” for non-market goods and services, by either directly or indirectly eliciting individual preferences (Champ et al. 2003; Carson, Flores, and Meade 2001). Other analyses use market prices to examine the opportunity cost of resource allocation for ecosystem service production (Dinar and Howitt 1997). Applications of the latter type would define the diverted water as the opportunity cost of conservation, or the market and non-market goods that must be foregone to allocate water to conservation efforts.

Integrated hydrologic-economic models have been used to simulate the impacts of water use on water supplies and regional economies. More recently, these frameworks have been used to inform the economic impacts and value of surface water use policies on cropping choices, agricultural yields, and economic outcomes (Ward, Booker, and Michelsen 2006; Booker, Michelsen, and Ward 2005; Ward et al. 2019). Other work has specifically estimated the economic values of flows of water by location within various basins around the world (see, for example Pulido-Velazquez et al. (2008) and Jenkins et al. (2004)). Management of surface flows and groundwater availability, environmental flow, and ecological concerns that relate to water management have been a concern in many parts of the world, and for many river systems (see for example, Acreman and Dunbar 2004; Baker et al. 2004; Garcia and Pargament 2015; Pahl-Wostl et al. 2013; Zhang et al. 2007).

These examples demonstrate progress in understanding the implications of water scarcity and competing uses. However, little is known about how to efficiently allocate surface water across all potential uses, the long-term trade-offs of purchasing or diverting water from least-cost

users and implications for water supplies. We contribute to the literature in two ways. First, we identify the optimal response of the economic system of the Middle Rio Grande River basin to policies that vary the timing of water allocation for environmental flows. The scale of the optimization model allows us to select the least-cost reallocation of water after the imposition of environmental pulse flows in the Middle Rio Grande, taking into account the institutions that govern the operation of the basin along with the market and non-market benefits that will be offset. Secondly, we calculate the direct costs and foregone benefits or opportunity costs of facilitating provision of environmental pulse flows in the Middle Rio Grande, and our model allows us to present these values as marginal costs on a per-acre basis, because the model is constrained to provide pulse flow water on a per-acre basis.

The unique contribution of this analysis is to discover the economic costs of allocating water for environmental flows, as prescribed in the IBWC's record of decision to support environmental flows in the Middle Rio Grande basin. Advancing an existing hydro-economic models developed for the region, we discover and present the opportunity cost of diverting water from other uses (agriculture, urban, and recreation), and characterize the locations in the basin for which agents bear these opportunity costs. By maximization of discounted net present values of water uses and values in our river system, we assess 1) the timing of environmental flows that minimizes their economic cost, 2) which economic activities across the basin will be offset to produce the environmental flows, 3) the economic costs and hydrological impacts of the pulse flow policy, and 4) the sensitivity of the economics costs to variability in climate, manifested by variability in surface water flows into the Middle Rio Grande basin. In addition, we derive and present

estimates of marginal cost for allocating water to environmental flows. The results of this analysis can guide development of future water policy with a better-informed understanding of the costs of environmental services. This analysis, when paired with future potential willingness to pay studies, can be used to determine the economically optimized allocation of water to environmental flows that equates marginal willingness to pay for the additional environmental services from wildlife habitat with marginal costs of providing those benefits.

Methods

To assess water demand and the impact of reallocating irrigation water (the opportunity cost of environmental water flows), we use the Rio Grande Hydro-Economic Model (RGHEM, introduced in Booker, Michelsen, and Ward (2005) and used in Ward, Booker, and Michelsen (2006) and Ward et al. (2006). The RGHEM is a basin-wide nonlinear programming model that optimizes resource allocations and water use in the Middle Rio Grande and delivers these optimal water allocations to users given physical and institutional water constraints. Optimal allocations are based on the economic value of water to production across the basin, such as arable acreage, types of crops that can be grown in each region, and municipal demands. The model has been calibrated using responses from focus groups and interviews, as well as 60 years of water demand and utility data from the basin (Hargrove and Heyman, 2020). In addition, the economic model is linked to hydrological models of surface and groundwater interaction in the basin (Booker, Michelsen, & Ward, 2005). This linkage allows for representing the water quantity outcomes of individual decision-making and allocations. Here, we use model simulations over a 30-year time horizon to illustrate how differences in water supply and

timing of imposed environmental pulse flows impact economic sectors and long-term surface and groundwater levels. The model's timestep is annual, and the resulting economic and hydrological conditions are carried forward to the next time period (e.g. volumes of water stored in reservoirs and depths to groundwater in aquifers).

Hydrology

Water is represented as stocks and flows and based on water mass balance. Water flows are tracked throughout the model as headwater flows, water diversions, water allocated to crops and M&I, reservoir releases, groundwater pumping, recharge to aquifers from surface water applications, and surface water returns. A hydrologic mass balance for surface water and groundwater is enforced in the model. For surface water, the mass balance equation for reservoir stocks is the starting reservoir level plus inflows minus releases and evaporation. Groundwater stocks are influenced by aquifer recharge from water application and groundwater pumping. The basin's water availability at the beginning of each year in the optimization model is determined by historical headwater inflows, reservoir storage levels, and aquifer storage levels from the previous period.

The headwater flows are represented as annual inflows to Elephant Butte reservoir, the principle storage reservoir for the Middle Rio Grande Basin, based on a combination of historical inflows and projections of inflows in the near future . Historical inflows are based on the most recent 21-year period for which complete streamflow data is available (data exists for the period of 1976-2015, we consider flows from 1994 to 2015) from the two gauges at the

reservoir inflow (USGS gauge # 08358400 Rio Grande Floodway at San Marcial, NM and USGS gauge # 08358300 Rio Grande Conveyance Channel at San Marcial, NM). Annual inflows averaged 815,000 acre-feet (with a median of 735,000 acre-feet) and a range of wet to dry years occurred over this period. Projections of future inflows (from 2016-2024) are based on estimates from the MIROC RCP 2.6 simulation model, as described in (Ward et al. 2019). Inflows for each assumed level of drought (baseline, 75% of baseline, and 50% of baseline) are shown in Figure 2.

The model respects the constraint set by the U.S. Mexico Treaty of 1906, under which the U.S. must deliver 60 KAF of water to Mexico at the Acequia Madre at the El Paso-Ciudad Juarez border in every year and under any drought conditions, so long as at least 60 KAF of water is available. The model also accounts for the agreement between New Mexico and Texas to share water based on historical acreage in agricultural production in each state, prior to 2008. Land in New Mexico received deliveries of up to 57% of any year's allocation while lands in Texas received up to 43%.

Economics

The economic model maximizes the sum of the discounted net present value of the net benefits (DNPV), estimated as benefits B minus costs C , of water allocation for each node n and use u across the t years of the simulation:

$$DNPV = \sum_n \sum_u \sum_t \frac{B_{n,u,t} - C_{n,u,t}}{(1 + r_u)^t}$$

where r_u is the discount rate. Users are represented as agricultural irrigation, municipal and industrial, recreational, or downstream environmental flow requirement nodes. Constraints on the objective function include the institutional constraints described above and operational constraints described below.

There are three agricultural irrigation nodes in the model, each modeling one of three distinct areas of irrigation in the region; these are Elephant Butte Irrigation District in New Mexico, El Paso County Water Irrigation District #1 and Hudspeth County Conservation And Reclamation District #1 in Texas (which are modeled as one single area), and Irrigation District DR-009 Valle de Juarez in Mexico. For each agricultural irrigation node, the optimization model selects the acres to plant for each crop, based on the cropping pattern for which farm annual income is calculated as the crop price multiplied by per-acre yields minus production costs. The choice of planted acres and whether to draw upon surface water or groundwater is a function of production costs, which include the energy costs and operations and maintenance associated with groundwater pumping, and water availability. At each node, groundwater pumping is allowed to compensate for surface water scarcity, up to the point where it is economically viable or until a maximum pumping capacity constraint is reached. Ceasing production is an option for the producers in the model if surface water is scarce and groundwater irrigation is too costly. Crop prices, production costs, and yields per acre, as well as total acreage in production, are model inputs, derived from cost and return budgets for the region. The cropping and irrigation choices in the economic model feed into the hydrological model through water application, recharge and surface water return flows per acre which are specific

to each crop and source of irrigation water. In order to calibrate the initial cropping patterns, the first order conditions for profit maximization are used to specify and estimate two parameters of a crop yield function that shows declining yields in the face of an expanded scale of land and water use, using the method of positive mathematical programming PMP. The PMP method was pioneered by (Howitt, 1995), and the method used in this paper is based on refinements made by (Ward and Dagnino, 2012). The PMP method ensures that adjustments in cropping patterns are smooth in the face of changes in water availability, policy changes, or price changes.

The model has three urban water-use nodes- Las Cruces (New Mexico, USA), El Paso (Texas, USA), and Ciudad Juarez (Chihuahua, Mexico). Each of the urban nodes uses groundwater, and only El Paso has capacity for urban surface water use. For all three urban nodes, the economic value of water is calculated as a flat water rate multiplied by the quantity of water sold to customers at that rate plus consumer surplus, where consumer surplus is the area below the aggregate customer demand function and above the flat water price. Costs for the urban sector include water pumping and treatment costs, which were obtained from delivery cost data from each water utility.

Recreational benefits from water use in the model are derived from demand for use of the Basin's two major reservoirs. Recreation benefits accrue as a function of surface area in reservoirs, where increased surface area allows more recreational boating and fishing to occur. Recreation benefits, expressed as dollars per area of reservoir, were derived from an assumed

benefit function based on preliminary work by the authors. The model also ascribes a small benefit to water that flows past the last gauge in the Middle Rio Grande at Fort Quitman. This section of the river, from Fort Quitman to Presidio, is often called “The Forgotten Reach”, and water that flows in this section of the river is assumed by the model to provide environmental benefits within Texas (Parcher, Woodward, and Durall 2010; Landis 2001; Teasley and McKinney 2005). The environmental benefit per water flow was derived from an assumed benefit function, consistent with Teasley and McKinney (2005). Additional flow at the lower end of the basin assures that water will not accumulate at the node in wet years.

Experimental Design

The analysis in this paper uses a 2x3x5,938 factorial design, with six experimental conditions per pulse flow schedule. The three factors are 1) discount rates, with a 5% discount rate and a 0% discount rate considered, 2) alternative volumes of inflows into the basin, with baseline inflows, 75% of baseline inflows, and 50% of baseline inflows considered, and 3) the 5,938 pulse flow schedules that include every combination of timings for pulse flows following the USIBWC’s environmental ROD criteria, elaborated below. We include results for a 0% discount rate to compare the impacts of various pulse flow timings without the influence of discounting.

The USIBWC Record of Decision (ROD) describes desired pulse flow schedules as occurring once every 3 to 10 years. The plan produces considerable flexibility in terms of the range of schedules that meet this criterion. To investigate economic consequences of pulse flow schedules, our model enforces the USIBWC ROD by supplying water released from Caballo Dam

with periodic pulse releases of 9,300 acre-feet generated over our 30-year time horizon. Pulse flow schedules are generated for the 30-year simulation period as a sequence of 30 binary choices, with a value of 1 representing a pulse flow of 9,300 acre-feet for the given year or 0 representing no pulse flow for the given year. All possible pulse flow schedules ($N = 5,938$) were generated that met the condition of $1/10 \leq f_{10} \leq 1/3$, where f_n is the frequency of a pulse flow occurrence in any n -year period, and $f_{30} = 5$. To test the sensitivity of our model and identify the impact of water scarcity, the pulse flow schedules are performed assuming inflows to Elephant Butte reservoir of 75% and 50% of the values used for the baseline inflows.

Our investigation has a particular interest in three outcomes: 1) the timing of the environmental pulse flows that maximizes the discounted net present value (DNPV) of the system 2) the economic activities in the basin that will offset to provide the environmental flows, and 3) the per-acre opportunity cost of taking water from existing economically valued uses in order to produce environmental pulse flows. This per-acre opportunity cost or shadow value calculates the foregone benefits (reduction in yield, for example) from reallocating water from a sector in the model to the environmental flows. For each model run, when environmental pulse flows are prescribed and land is “irrigated” with environmental pulse flows, production of other marketed uses of irrigation are restricted, and the change in the mix of uses in the basin is reflected in changes in the shadow prices. The shadow price paid by users in the basin is the minimized discounted net present value displaced from additional pulse flows from the reduction in urban and agricultural benefits, as well as the impact on water availability for all uses, which both reduce basin-wide returns. The shadow prices are the

marginal cost of environmental pulse flows, providing information to guide the most cost-effective ways of achieving the goals of ecosystem services targets. The shadow prices reflect the scarcity underlying the changes in optimal production that occur when pulse flows are imposed on the system.

Results

When should pulse flows should be released?

The model produces estimates of the total discounted net benefits (DNB) across the basin by summing across each sector's DNB in each time period. Table 1 illustrates the change in DNB attributable to imposition of pulse flows, , drought , and discount rates. For brevity, we present the impacts of the timing of pulse flows that produces the greatest DNB (best performing) and timing of pulse flows that produces the lowest DNB (worst performing) pulse flow, compared to the base case where no pulse occurs. When considering a 0% discount rate, the pulse flow schedule that has the smallest impact on DNB places pulses during years with high inflows into the basin, reducing DNB by 0.059%, when compared to the no pulse flow baseline (Pulse flows occur in 1997, 2005, 2008, 2017, and 2022 in this pulse schedule). The worst performing pulse flow schedule has the opposite pattern, where pulse flows occur during low inflow years, reducing DNPV by 0.072% (Pulse flows occur in 1996, 2000, 2003, 2011, and 2015). Considering the impact of severe drought, the difference between the best and worst performing pulse flow timings becomes negligible when inflows are assumed to 50% of baseline inflows, with DNPV falling by 2.50% in both pulse flow schedules when compared to baseline inflows and no pulse flows.

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313 The difference in impact between the highest and lowest performing pulse flow schedules is
314 larger when considering a positive discount rate. The best performing pulse flow schedule
315 places pulse flows later in time (Pulse flows occur in 1999, 2008, 2017, 2021, and 2024), with a
316 0.051% reduction in DNPV. The worst performing flow schedule has pulse flows that both occur
317 earlier in time and coincide with low inflow years (Pulse flows occur in 1996, 2000, 2003, 2006,
318 and 2015), with a 0.092% reduction in DNPV. Considering the impact of severe drought, DNPV
319 is again reduced by 2.5% for both the best and worst performing pulse schedules.

320

321 *From where should water for pulse flows be allocated?*

322 Water sources available to produce environmental pulse flows can come from five sources: 1)
323 increased releases from the reservoir, 2) reduction of cropland in production, 3) reduced
324 surface water use and increased groundwater pumping, 4) reduction in water allocated for
325 aquifer recharge and management, or 5) from capturing surface water that would have flowed
326 to the effluent of the basin , reducing environmental flow-related benefits at that location. The
327 model searches for the least cost source of those pulse flows, for which discounted marginal
328 benefits are equal from all five sources. In our analysis, we find that increased groundwater
329 pumping, reduced aquifer recharge, and flows at Fort Quitman are the least expensive sources
330 of water for producing environmental pulse flows. Additional releases from the reservoir
331 reduce both recreation benefits and compromise water storage, creating larger economic
332 losses. Offsetting of irrigated crops reduces direct downstream returns to agriculture. Figure 3
333 presents the change in flows to each of these allocations under different annual inflow

volumes, averaged over all of the 5,938 pulse flow schedules that meet the USIBWC's criteria in the ROD. Figure 3a shows the average difference in water allocated for aquifer recharge in Texas compared to a baseline simulation with no environmental pulse flows. Figure 3b shows the average difference in flows at the last gauging station in the Upper Rio Grande basin, the Fort Quitman gauge, compared to a baseline of no environmental pulse flows in the middle Rio Grande. Figure 3c presents the average difference in groundwater pumping for the pulse flow regimes compared to a baseline of no environmental pulse flows. Overall, Figure 3 illustrates that in years with higher-than-average inflows into the basin, water allocated to the pulse flow displaces water for aquifer recharge and water passed further down the Rio Grande (water flowing through Fort Quitman gauge). In drier than average years, groundwater pumping increases. The result of decreases in groundwater recharge and increases in pumping is that water for pulse flows is offset in the system by reductions in groundwater storage. There is little difference in results across discount rates, since periodic water scarcity is the largest driver of the decision of from where water for pulse flows should be sourced.

Table 2 shows the impacts of pulse flows in the middle Rio Grande, by sector. Because of the relatively small volume of water required to produce pulse flows, the impacts on total DNB are quite small, less than 1% for all experimental conditions. The agricultural sector has the largest losses in DNB, losing around 1% in value over the study period. This is followed by environmental benefits forgone at the outlet of the basin, since water below Fort Quitman is used to produce pulse flows farther upstream. Finally, urban benefits are largely unchanged by pulse flows, since the urban sector experiences only very small increases, due to small increases

in cost as depths to groundwater increases from increased groundwater pumping and reduced aquifer recharge.

How much economic impact is associated with pulse flow releases?

Figure 4 shows the shadow prices of an additional acre of land irrigated with environmental pulse flow water. These shadow prices represent the foregone economic value among water users that results from water being required to be shifted into pulse flows. Results in Figure 4 are averaged over all of the 5,938 pulse flow schedules that meet the USIBWC's criteria in the ROD. When there is a positive discount rate, opportunity costs of environmental flows are largest in earlier years, as expected. Shadow prices under baseline inflows begin at \$950 per acre in the first year of the analysis, peak at \$1,093 in 1996 (a year with relatively low inflows to the basin) and fall over time due to discounting. These results demonstrate that environmental pulse flows reduce total system benefits by roughly \$1,000 per acre irrigated when compared to a baseline case of no pulse flows. As inflows into the basin are assumed to fall, shadow prices increase due to increased water scarcity. As expected, the highest shadow prices are found when inflows to the basin are reduced from baseline inflows by 50%. The shadow prices peak at \$1,147 in 1995 under a 50% reduction in flows, and fall in subsequent years due to discounting.

The perspective taken with a 0% discount rate is that all time periods are given equal weight in the analysis, which is often considered a preferred valuation guideline when natural ecosystems and species risk facing extinction (Diaz-Balteiro and Romero 2008). These results demonstrate more clearly the impact of water scarcity on shadow prices, as the volume of basin inflows have a nearly direct impact on shadow prices; consistent with our prior expectations, shadow prices

are highest in the years that have the lowest basin inflows, falling when these inflows increase.

With a 0% discount rate, shadow prices range from \$993 in 1995 and 1997 in the baseline inflow case, to \$1,213 in 1995 and 1996 under 50% reduction in basin inflows. The small reduction in shadow prices in later years can be attributed to returns flows to aquifers that occur because of the application of environmental flows; these small amounts of recharge reduce pumping costs for other water users slightly, so the basin-wide costs are lower.

Discussion

The goal of this paper is to determine the answers to three questions regarding the least-cost provisioning of ecosystem services from environmental pulse flows: when, where and how much. In general, even though the number and variability of pulse flow schedules that meet the criteria set forth by USIBWC is large (with nearly 6,000 possible pulse flow schedules over a 30-year period), the variation in costs across the schedules is relatively small. This indicates that amount of water that USIBWC proposes be used for pulse flows is small enough that the exact timing of these flows is not critical. As expected, implementing environmental pulse flows in dry years has a larger economic impact, yet the impact is still small even in the direst of years. One implication of this result is that ecological factors and requirements for restoration of ecosystems can be a larger factor in determining timing than temporal variations in economic values.

The least-cost sources of water for environmental pulse flows are increased groundwater pumping, reduced groundwater recharge, and reduced production of environmental benefits in

other regions within the basin. The proposed pulse flows are not large enough to necessitate a reduction in area of cropland planted, nor do municipal and industrial users face particularly large increases in pumping costs or future water availability. However, this modeling effort does not have explicit constraints on the total amount of water that can be depleted from aquifers, or a sustainability constraint that requires aquifers to be returned to particular levels. Therefore, a longer-run view may find the costs of aquifer depletion to be prohibitive or otherwise undesirable.

The total cost of the proposed environmental pulse flows is relatively small, with total DNPV across the basin being reduced by less than 1%, even under the most severe drought conditions. However, these costs (although small) are borne disproportionately by the agricultural sector. Further, the proposed pulse flows can have the effect of reducing environmental benefits elsewhere in the basin, an outcome that could be considered incompatible with holistic environmental goals. One caveat to note is that while the agricultural sector bears the largest share of the costs, this is merely an outcome of their disproportionate use of water, and is an outcome of the design of the water system, as agricultural water use has expanded since the creation of the modern irrigation systems in the region.

Some questions remain about environmental pulse flows in general, and with pulse flows in the Middle Rio Grande – we would like to highlight two. Firstly, the work in this paper lends itself particularly well to a consideration of the benefits of restoration that occur due to pulse flows,

and using both the benefits and costs to find the societally optimal amount of restoration to perform. In the case of the Willow Flycatcher, this could take the form of a contingent valuation study to determine people's willingness to pay for the non-use benefits that come from the species' further existence. Secondly, our finding that pulse flows can lead to groundwater depletion and other reduced environmental benefits elsewhere in the basin leads to the question of how the simultaneous management of multiple environmental goals can affect costs and the associated design of pulse flow schedules.

Conclusions

In conjunctive surface and groundwater systems facing scarcity, plans to establish pulse flows to protect ecosystem services will significantly influence water use patterns, especially where those proposed pulse flows are significant. Despite ongoing interests to assess impacts of proposed environmental flows, this is the first work to date to investigate impacts on system-wide economic performance resulting from environmental pulse flow proposals. This investigation has presented an original approach to address existing gaps in the policy analytic literature.

This paper describes development of a basin-scale hydroeconomic optimization model of North America's Middle Rio Grande Basin to investigate impacts of proposed pulse flows on irrigation, urban, and other environmental water users in the basin. The objective was carried out by developing an approach to discover the optimized discounted net present value of economic benefits summed over uses, sectors, and regions from use of surface water and connected

aquifers. We assessed total and marginal cost of implementing an environmental pulse flow policy, by identifying optimized surface use and groundwater pumping with and without the pulse flows for each of two discount rates and three surface inflow levels to the system. Results showed that climate water stress, in the form of highly variable inflows, considerably drives up the total and marginal cost of implementing environmental pulse flows, magnified by the conjunctive nature of the system. Future work points to a need to assess the benefits of environmental pulse flows to compare to their optimized costs as well as developing the capacity to forecast future system inflows that would be affected by climate water stress.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Tables and Figures

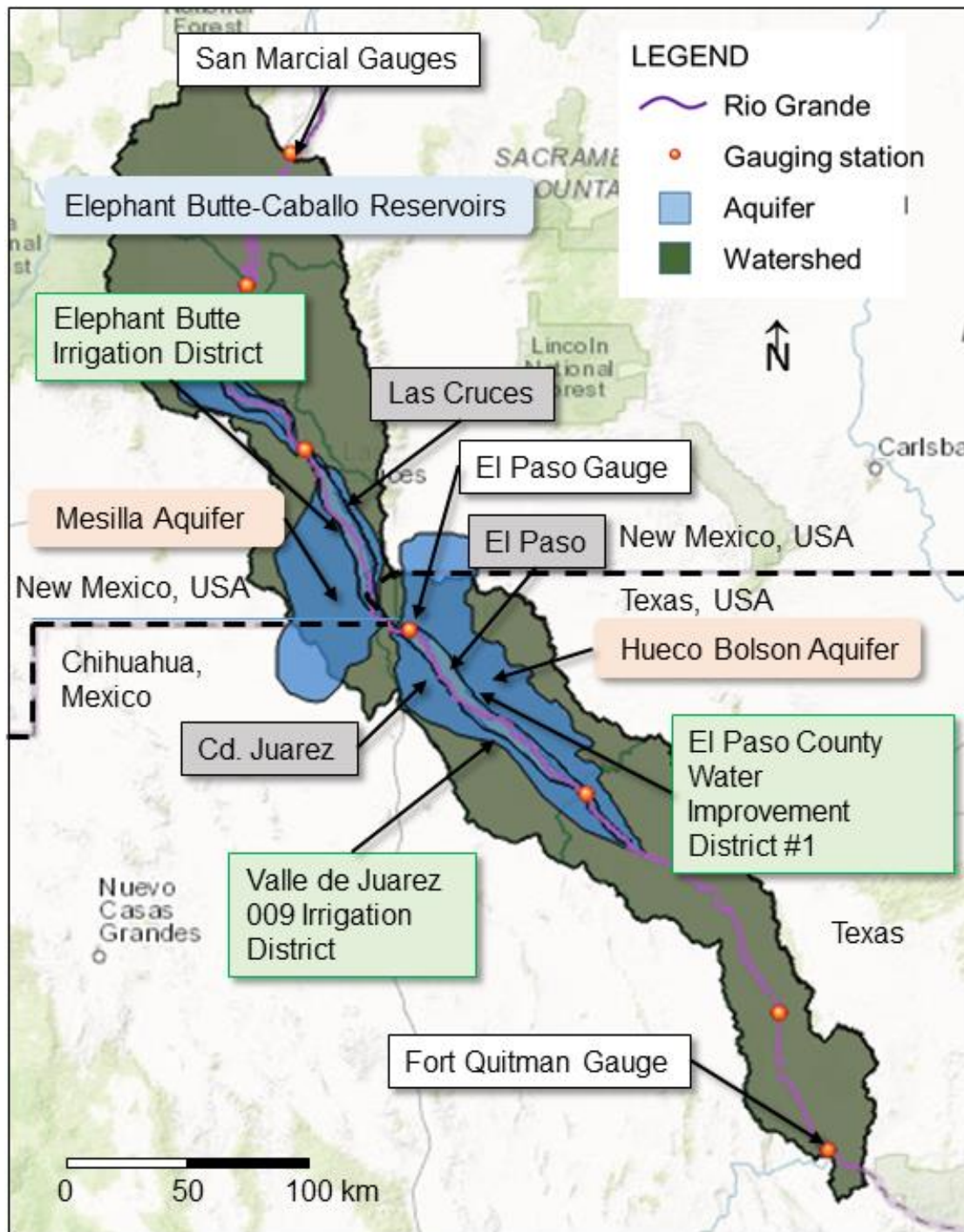


Fig. 1. Map of the Middle Rio Grande Basin from San Marcial to Fort Quitman. (Map by author using ArcGIS © Esri; data from Esri, USGS.)

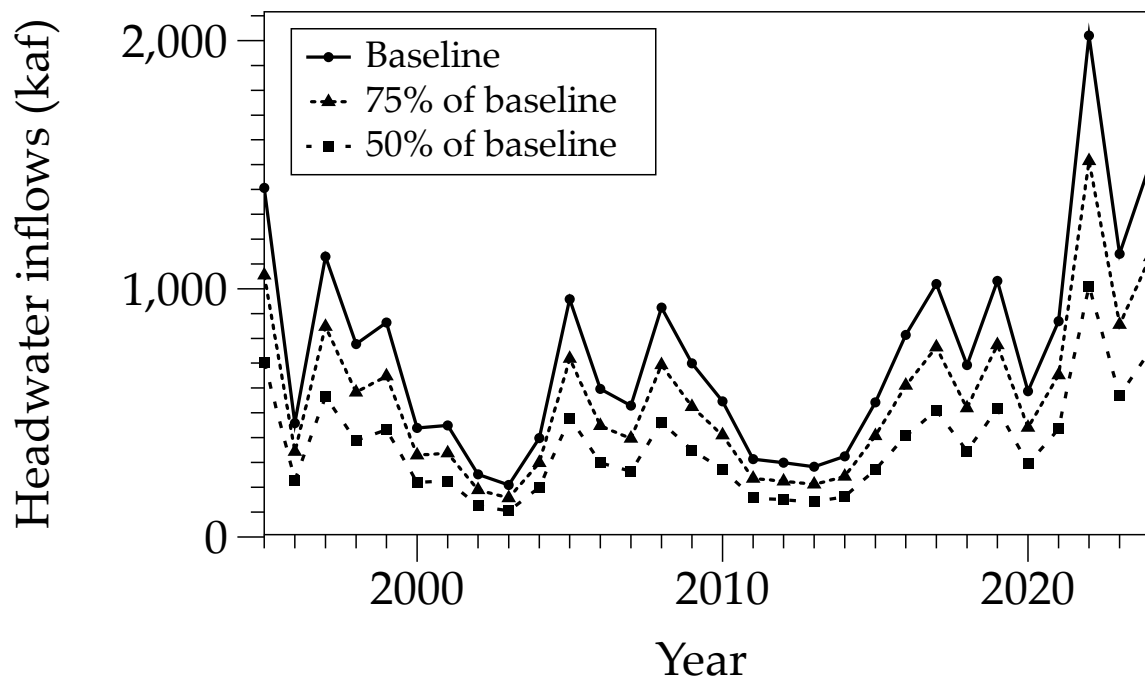


Fig. 2. Inflow Middle Rio Grande Basin at San Marcial Gauge. Baseline inflows are indicated by the dark solid line, 75% of baseline flows indicated by light solid line, and 50% of baseline flows indicated by dashed line.

Table 1. DNB across inflow cases and pulse flow schedules (values presented are in millions of USD)

	0% Discount Rate		5% Discount Rate	
	Baseline Inflows	50% of Baseline Inflows	Baseline Inflows	50% of Baseline Inflows
Base case NB (no pulse)	\$42.344		\$20.932	
NB: Best Performing Pulse Flow	\$42.319	\$41.287	\$20.922	\$20.413
NB: Worst Performing Pulse Flow	\$42.314	\$41.286	\$20.913	\$20.405

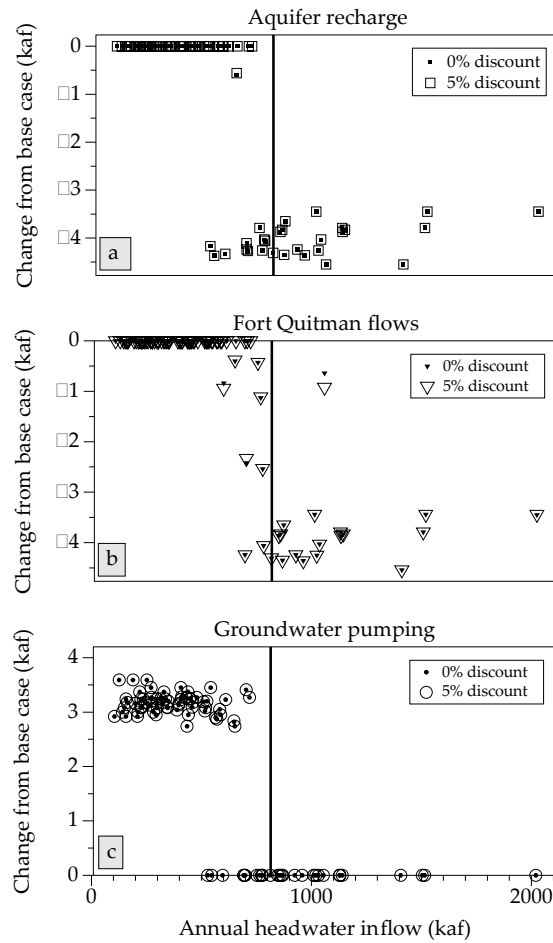


Fig. 3. (a) Change in water flows allocated to aquifer recharge; (b) flows at the Fort Quitman gauge; and (c) groundwater pumping from the base scenario where no environmental pulse flows occur for annual headwater inflows, averaged over all possible pulse flow schedules. Results are presented for simulations using a 5% and 0% discount rate. Vertical line indicates average annual streamflow.

Table 2. Average percentage reduction in DNB by sector

	5% Discount Rate			0% Discount Rate		
	Baseline Inflows	75% of Baseline	50% of Baseline	Baseline Inflows	75% of Baseline	50% of Baseline
Total	-0.07%	-0.07%	-0.08%	-0.07%	-0.07%	-0.07%
Agricultural	-1.01%	-1.08%	-1.19%	-0.96%	-1.03%	-1.13%
Urban	-0.0004%	-0.0010%	-0.0007%	-0.0004%	-0.0010%	-0.0010%
Environmental	-0.27%	-0.30%	-0.02%	-0.25%	-0.26%	-0.05%

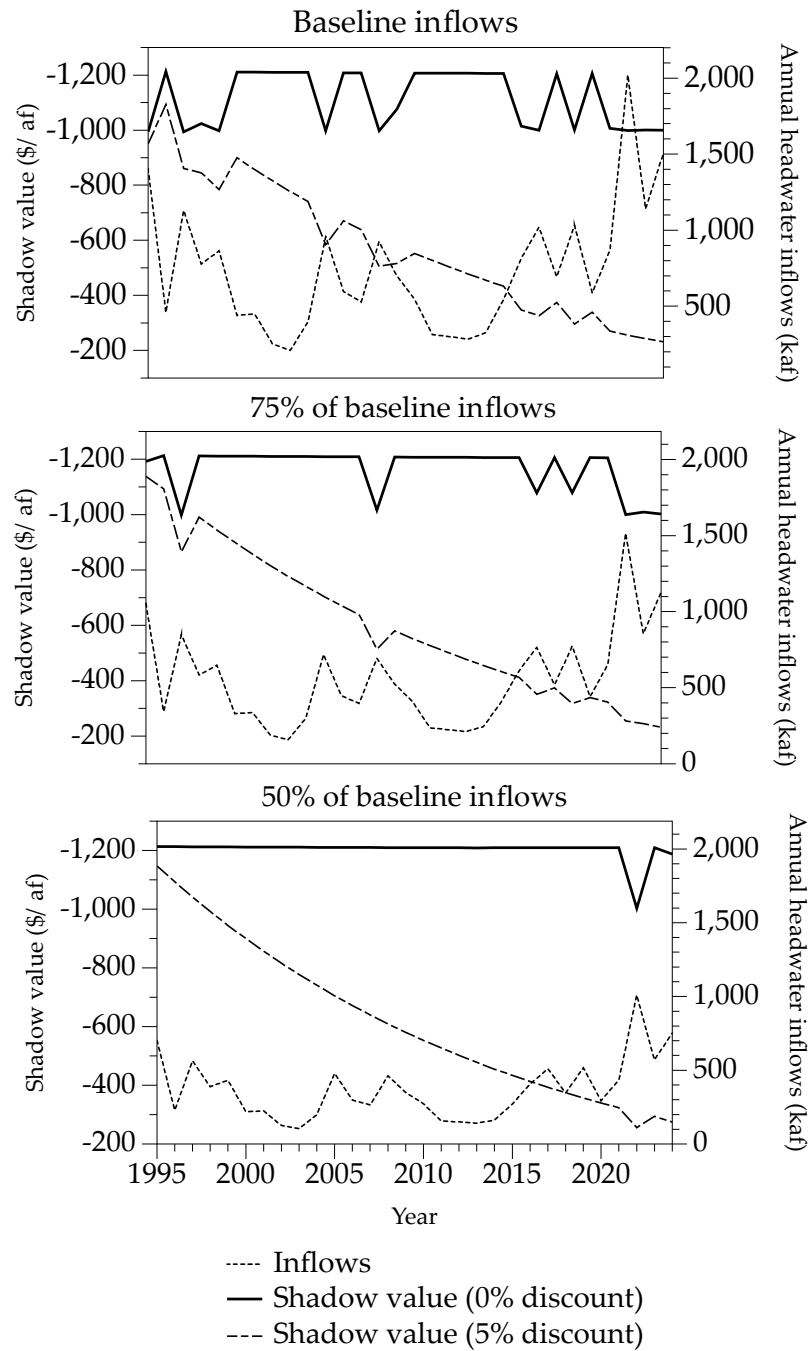


Fig. 4. Shadow prices and inflows into the Middle Rio Grande Basin for three model scenarios run: historic and projected inflows, inflows 75% of historic and projected values, and inflows 50% of historic and projected values.