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Valuing the Hidden Benefits of Reservoir Storage: A Stochastic Assessment of Flood Damage Reduction in an Irrigation-Dominated System

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Abstract

Multipurpose reservoirs provide both irrigation water and flood protection, yet flood risk reduction is rarely valued alongside market-priced water supply benefits. As a result, reservoir evaluations and storage allocation decisions may underestimate the economic contribution of flood mitigation. This study estimates the economic value of flood protection provided by Navajo Dam on the San Juan River, New Mexico, where irrigation and municipal water supply are the reservoir's primary authorized purposes. Historical hydrologic records were used to compare regulated and unregulated flow conditions and quantify the reduction in expected agricultural flood damages attributable to reservoir operations. Results indicate that dam regulation reduces expected annual agricultural flood damages by approximately \$366,000, equivalent to a marginal flood protection value of \$1.34 per acre-foot of flood-control storage. Expressing flood protection in the same units as irrigation water values enables a direct comparison of competing reservoir services and highlights the extent to which conventional appraisal methods may undervalue risk-reduction benefits. The proposed framework provides a practical approach for incorporating flood mitigation into economic assessments of multipurpose reservoirs and supports more comprehensive and balanced water resources planning.

Keywords: reservoir storage; flood protection; Expected Annual Damage (EAD); Navajo Dam; San Juan River

1. Introduction

1.1. Reservoirs as Multi-Functional Assets

Federal water resource management in the United States has long recognized the potential of reservoir infrastructure to deliver multiple, complementary economic functions within a single system. Early federal involvement began with navigation improvements under the Rivers and Harbors Act of 1824, followed by large-scale irrigation expansion under the Reclamation Act of 1902, which simultaneously established the Bureau of Reclamation as the principal federal agency for water development in the arid West. Subsequent flood crises precipitated the Flood Control Act of 1936, which formalized flood risk reduction as an explicit federal responsibility, while the Flood Control Act of 1944 institutionalized a truly multipurpose approach by integrating hydropower, recreation, irrigation, and municipal and industrial water supply into a unified operational framework. Contemporary governance is largely guided by the Water Resources Development Act, under which



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agencies such as the U.S. Army Corps of Engineers and Bureau of Reclamation manage extensive dam portfolios collectively delivering a broad spectrum of water resource services. According to Bonner et al. [1], over 80% of federal reservoirs are authorized for three or more functions, underscoring a systemic shift from single-purpose hydraulic infrastructure toward complex, multi-objective water resource systems.

Within this institutional context, the two functions that most directly shape reservoir operating decisions—and that generate the most economically significant and spatially extensive benefits—are flood damage reduction and agricultural water supply. These functions are not merely co-located within the same physical infrastructure; they are structurally interdependent, sharing storage capacity in ways that create inherent operational trade-offs and potential synergies. Understanding the economic magnitude of each function, and the nature of their interaction, is therefore central to the efficient management of multipurpose reservoir systems.

1.2. Study Objectives

The study provides a stochastic economic valuation of flood protection benefits generated by reservoir storage in an irrigation-dominated system. By comparing regulated and unregulated flow conditions, it estimates expected annual avoided agricultural damages attributable to reservoir operation and derives a unit value of flood protection expressed in dollars per acre-foot of storage capacity. Rather than treating irrigation supply and flood control as competing operational objectives, the analysis conceptualizes them as joint and complementary economic outputs of the same infrastructure asset, thereby enabling a more complete assessment of reservoir value than conventional single-function appraisals permit. In doing so, the study contributes empirical evidence from a semi-arid, agriculture-dependent basin where both water scarcity and flood risk are significant and advances the broader literature by integrating stochastic flood risk valuation with water resource economics.

This study differs from prior stochastic EAD and multi-benefit reservoir valuation work in three respects. First, where existing stochastic EAD applications [2,3] value flood risk in isolation, and existing multi-benefit reservoir studies [1] typically report physical or qualitative benefit shares across functions, this study monetizes flood protection and irrigation supply in a single, directly comparable \$/acre-foot unit of storage. Second, unlike [4], who quantify flood damage reduction from irrigation reservoirs in physical terms, we carry the analysis through to full economic monetization using a county-scale econometric damage model linked to Monte Carlo-simulated hydrology. Third, we apply this framework to a U.S. semi-arid, irrigation-first reservoir system—a setting distinct from the flood-control-dominated or European contexts of most prior multi-benefit valuation studies [5,6]—thereby extending the empirical evidence base to a system where flood protection is explicitly secondary to consumptive use. The study builds methodologically on companion research examining agricultural flood risk in the Lower Missouri River Basin; the study [7] develops an integrated stochastic framework disaggregating agricultural flood damage into prevented planting, unharvested acreage, and yield loss components, an approach that informs the acreage- and yield-based damage disaggregation applied here; ref. [8] extends this work by incorporating crop phenology into the EAD calculation, showing that the timing of a flood relative to crop growth stage is often a stronger determinant of loss than flood magnitude alone. Applying a comparable storage-regulation valuation framework to the semi-arid, irrigation-dominated San Juan Basin extends this line of work to a hydro-climatically and institutionally distinct setting.

2. Conceptual Background and Literature Review

2.1. Theoretical Foundation and Literature Review

From an economic perspective, reservoirs may be understood as capital assets that allocate water across time, states of nature, and competing uses [9,10]. Classical water resource economics emphasizes the marginal value of water in productive use, particularly in irrigated agriculture, where water inputs contribute directly and measurably to crop yields and farm income [9]. Under conditions of hydrological uncertainty, however, stored water also acquires a state-contingent protective value associated with the mitigation of flood risk. In flood-prone systems, reservoir storage attenuates peak flows, alters the frequency distribution of downstream discharges, and thereby reduces the probability and severity of inundation events. This protective function can be quantified through the concept of Expected Annual Damage (EAD), which integrates flood losses probabilistically across the full range of flood magnitudes [11]. Flood control benefits are conventionally estimated as avoided damages—the difference in EAD with and without reservoir regulation—derived using floodplain mapping, hydrologic simulation, and depth–damage functions that translate inundation extent into monetary losses [1]. Empirical evidence confirms the material scale of these benefits—flood wave attenuation of between 45% and 80% has been documented in multipurpose systems where flood control is secondary to water supply, with individual events yielding retention volumes on the order of tens of millions of cubic meters [6].

In this sense, reservoir storage produces joint economic outputs—*productive value* in the form of irrigation supply, and *protective value* in the form of flood damage reduction—that together constitute the primary social return on reservoir infrastructure investment [12]. Agricultural users benefit from storage in a manner broadly analogous to other consumptive users, with reservoirs enabling both intra-annual seasonal storage and inter-annual resilience to drought. This is particularly significant for irrigators operating under abstraction licenses that restrict withdrawals during periods of low river flow—conditions that frequently coincide with peak crop water demand in summer months [13]. Agricultural water requirements are further distinguished by their pronounced seasonality, with demand concentrated in the summer growing season, and by generally lower water quality standards compared to public supply, which can allow greater operational flexibility in source management [13].

The interaction between flood control and irrigation supply objectives, however, is characterized by a fundamental storage trade-off. Flood attenuation benefits are maximized when reservoir levels are kept sufficiently low to accommodate large inflow events, while water supply benefits are maximized by maintaining high storage volumes to buffer against periods of low inflow [13,14]. This tension between drawdown for flood readiness and impoundment for supply security defines one of the central operational challenges in multipurpose reservoir management. Nevertheless, the temporal asymmetry of the two demands—flood risk concentrated in wet winter months, irrigation demand concentrated in dry summer months—suggests that substantial co-benefit delivery may be achievable through carefully designed operating rules that exploit the seasonal complementarity between the two functions [13].

2.2. Research Gaps

Despite the broad recognition of reservoirs as multipurpose assets, the economic evaluation of reservoir infrastructure has traditionally been guided by primary design objectives, with secondary benefits—including flood mitigation, recreation, and ecosystem services—rarely quantified within a consistent analytical framework [15]. This gap persists even where operational evidence suggests that secondary functions yield substan-

tial economic value, and even where reallocation of existing storage among competing uses could generate significant net social benefit without any physical modification of infrastructure [13,15]. The consequence is a systematic bias in how reservoir benefits are measured, reported, and incorporated into investment and operational decision-making.

A substantial body of literature has examined the economic valuation of water in irrigated agriculture and the role of reservoir storage in water allocation. Methods such as residual imputation, production function approaches, and optimization-based shadow pricing have been widely applied to estimate the marginal value of irrigation water across a range of climatic and institutional contexts [9]. Hydro-economic models have further advanced this field by integrating hydrological process representation with economic decision-making, enabling the joint analysis of water allocation efficiency, scarcity rents, and policy constraints across river basin scales [16–18]. In parallel, the flood risk literature has developed robust frameworks for estimating expected damages and evaluating the economic benefits of mitigation measures, with increasing emphasis on probabilistic approaches, depth–damage functions, and the treatment of uncertainty [11]. Taken together, these traditions provide well-established methodological foundations for quantifying both the productive and protective dimensions of reservoir storage.

Despite these advances, relatively few studies explicitly quantify the economic value of secondary reservoir functions, particularly flood protection benefits in systems where irrigation or water supply is the dominant operational purpose. As it was demonstrated by [5], the feasibility of integrating flood risk reduction into a broader cost–benefit framework for water management in the Netherlands, yet their analysis focused on dedicated flood control infrastructure and land-use policies rather than on reservoirs operating primarily under supply objectives. Another study took an important step toward bridging this gap by explicitly evaluating the flood damage reduction potential of irrigation reservoirs across Japan, finding that pre-emptive drawdown of irrigation storage could yield measurable reductions in downstream flood damage costs—yet their study remained focused on physical damage metrics and did not extend to the full economic monetization of forgone flood protection value under supply-first operating rules [4]. At the broader infrastructure level, it was noted that any approach seeking to value all uses of a multipurpose reservoir risks systematic over- or undervaluation of secondary and tertiary benefits, and that flood control benefits in particular lack explicit market prices, making consistent quantification rare in practice [1]. Existing analyses therefore tend to treat flood protection and irrigation supply as analytically separate problems, addressed by distinct disciplinary communities using distinct methods, rather than as jointly produced outputs of a single infrastructure asset. As a result, conventional economic assessments may systematically undervalue reservoir storage by neglecting its role in reducing stochastic flood damages and may fail to capture the full social return on existing infrastructure investment.

3. Study Area

3.1. The Basin

The San Juan River is a major tributary of the Colorado River, originating as snowmelt near Pagosa Springs (Archuleta County, CO, USA) in the San Juan Mountains. Flowing 383 miles through the arid southwestern region of Colorado, New Mexico, and Utah, it terminates at Glen Canyon, Utah, where it joins the Colorado River and contributes to Lake Powell [19]. The basin encompasses areas in Colorado, New Mexico, Utah, and Arizona [20], draining approximately 60,000 km² of the Four Corners Region upstream from Mexican Hat, Utah (Figure 1) [21]. Water resources within the watershed support recreational, agricultural, biological, cultural, and residential uses [22]. The San Juan River provides habitat for at least eight native fish species, including the federally endangered

Colorado pikeminnow, razorback sucker, and bonytail chub [20]. These species are endemic to the Colorado River Basin [20]. Protecting and restoring critical habitat for these species is a central focus of the San Juan River Basin Recovery Implementation Program (SJ RIP).



Figure 1. Map of the San Juan River drainage basin (source: <https://www.uncovercolorado.com/activities/san-juan-river/>, accessed on 17 June 2026).

Near its headwaters, the San Juan River is joined by six principal tributaries: the Navajo River, Chaco River, and Chinle Creek on the left bank, and the Piedra, Los Pinos, Animas, and Mancos Rivers on the right bank (Figure 1) [19]. Among these, the Animas River is the most significant in terms of streamflow, originating in the mountain peaks northeast of Silverton, Colorado, and flowing southward to its confluence with the San Juan at Farmington, New Mexico [22].

Navajo Dam and Reservoir (NDR) is located primarily in northern New Mexico (Rio Arriba County, NM, USA), with the upper portion of the reservoir extending several miles into southern Colorado. In New Mexico, Navajo Reservoir is the second largest body of water after Elephant Butte Reservoir, situated approximately 34 miles east of Farmington [23]. NDR is a unit of the Colorado River Storage Project (CRSP), authorized under the Colorado River Storage Project Act of 11 April 1956, with the dam dedicated in September 1962 and formally completed in April 1963 [23]. It was designed as a multipurpose project providing

irrigation, municipal and industrial water supply, flood control, recreation, and hydroelectric power—the latter generated by a 32 MW plant constructed in the 1980s and operated by the City of Farmington under a Federal Energy Regulatory Commission license [23]. The primary purpose of the dam is to impound water for irrigation and municipal and industrial use, with flood control and recreation serving as secondary functions [24]. The reservoir supports irrigation withdrawals for approximately 110,000 acres of land under the Navajo Indian Irrigation Project (NIIP), representing the largest single allocation of storage within the reservoir [25].

3.2. Flow and Flood Dynamics

The river's flow regime is primarily snowmelt-driven, with approximately 90% of annual discharge originating from the Rocky Mountains of Colorado, and peak flows historically occurring between late spring and early summer coinciding with snowmelt recession [20]. Prior to regulation by Navajo Dam, the San Juan River exhibited a highly variable and flood-prone natural flow regime. The gauging station near Bluff, Utah has recorded flood events from 1914 to 1916 and continuously from 1927 to the present. Historically, the largest floods occurred between late summer and early fall (August–October), driven by intense monsoonal precipitation. The largest flood in the systematic gauging record reached a peak discharge of 70,000 cubic feet per second (cfs) (1980 m³/s) on 10 September 1927, with a stage of approximately 31 ft (10 m) [21]. Pre-gauging accounts document even larger events: a September 1909 flood was described by Farmington residents as the largest since European settlement of the area in 1880 [26], and a subsequent flood on 6 October 1911 destroyed most bridges on the mainstem San Juan, including the first Goodridge bridge at Mexican Hat, which stood 39 ft (12 m) above the river channel. [27] estimated this event at approximately 150,000 cfs (4250 m³/s), though without documentary support [21].

Navajo Dam, completed in 1963, substantially altered the downstream flood regime. Since regulation commenced, peak discharges at Farmington have rarely exceeded 10,000 cfs (283 m³/s) under normal conditions, though higher releases remain possible during flood operations [24]. The largest post-regulation flood recorded at the Bluff gauging station was 38,500 cfs (1090 m³/s), generated by Tropical Storm Norma on 6 September 1970—a flood whose runoff originated predominantly downstream of Navajo Reservoir and thus bypassed dam regulation entirely [21,28]. This event illustrates both the flood attenuation capability of the dam for upstream-generated events and its limitations in controlling tributary inflows from unregulated catchments below the dam.

3.3. Agriculture and Irrigation Projects

The agricultural landscape of the San Juan River Basin downstream of Navajo Dam reflects a complex intersection of federal infrastructure, tribal sovereignty, and arid-land hydrology. The river functions as the primary water source for a diverse set of agricultural stakeholders, from large-scale commercial operations to traditional small-holder irrigators on tribal lands.

The dominant consumptive water user in the basin is the Navajo Indian Irrigation Project (NIIP), authorized under the Colorado River Storage Project Act as amended in June 1962. The project is designed to deliver 508,000 acre-feet of water annually to irrigate 110,630 acres of Navajo Nation benchland in northwestern New Mexico, with day-to-day operations managed by the Navajo Agricultural Products Industry (NAPI), a tribally owned enterprise established in 1970 [23]. As of the most recent assessments, approximately 72,000 acres across eight of eleven planned development blocks have been brought into active production, with construction of the remaining blocks subject to ongoing

federal appropriation [29]. Cropping is concentrated in high-yield commodities including alfalfa, corn, and small grains. Further downstream, the Hogback and Fruitland projects support traditional Navajo Nation farming communities through gravity-fed ditch systems administered by the Bureau of Indian Affairs (BIA). Additional federal infrastructure includes the Hammond Irrigation Project near Bloomfield, which provides supplemental water supply for non-tribal agricultural users in the middle reach of the basin.

A further significant feature of basin-scale water management is the San Juan–Chama Project, which diverts water from three headwater tributaries of the San Juan River in southern Colorado—the Rio Blanco, Little Navajo River, and Navajo River—through tunnels beneath the Continental Divide into the Rio Grande Basin. The project’s annual firm yield is 96,200 acre-feet, contracted primarily to municipal users including the cities of Albuquerque and Santa Fe, with average annual diversions of approximately 89,800 acre-feet over the 1991–2020 period [23]. This transmountain diversion represents a material reduction in basin-available supply and is a structurally important constraint on water allocation within the San Juan River system. Over the longer term, the basin faces chronic drought stress associated with reduced snowpack and declining inflows across the Colorado River system, conditions that compound existing pressure on water allocation frameworks and the reliability of irrigation supply for both tribal and non-tribal agricultural users [30].

4. Materials and Methods

4.1. Data Acquisition

The analysis integrates multiple datasets to construct a consistent long-run panel of agricultural production, land use, prices, and costs for San Juan County, New Mexico. Primary agricultural data were obtained from USDA-NASS QuickStats and CroplandCROS, complemented by Farm Service Agency (FSA) records where necessary to address missing observations and improve temporal continuity. When overlapping sources existed for a given variable and year, preference was given to the larger reported observation to reduce underestimation bias, particularly in pastureland accounting where discrepancies between FSA and NASS CroplandCROS were non-trivial.

Crop price series were derived primarily from USDA-ERS normalized price formulations, combining state-level and national farmgate prices where available. In cases where state-level series were unavailable or incomplete, national-level prices were used as proxies. For New Mexico-specific price series, state-to-national price ratios were applied where historically consistent relationships were observed. For perennial forage systems and pasture, valuation relied on NASS QuickStats and extension-based estimates rather than market prices due to limited observability of direct price signals.

Cost of production (COP) data were constructed using USDA-ERS operating cost and labor series for major row crops (corn, sorghum, wheat), supplemented by enterprise budget data from state extension services. New Mexico State University extension budgets were used for alfalfa, other hay, and pasture systems, while University of Idaho budgets were used as proxies for dry beans and potatoes, consistent with Risk Management Agency (RMA) prevent-plant cost factor classifications.

Hydro-meteorological inputs include river flow and precipitation data used to construct stochastic dependence structures. Daily flow observations were aggregated into quarterly maxima, while precipitation was aggregated into quarterly averages from monthly data. These variables formed the basis for correlation matrices and Cholesky decompositions distinguishing pre- and post-dam hydrological regimes. Pre-dam hydrology was represented using October 1934–June 1962 flow records, while post-dam conditions used July 1962–September 2025. Precipitation was held constant across counterfactual scenarios to isolate the marginal effect of river regulation.

Table 1 presents summary statistics of the aforementioned data, organized by the eight main crops for which flood-related losses and damages have been estimated in this study.

Table 1. Summary statistics and description of the variables.

Crop	Variable	Mean	Min	Max	St. Dev.	Data Range
Corn	Planted acres	19,111	6000	27,733	5439	2000–2024 excl. 2003–08
	Harvested share (%)	79.95	20.00	100.00	21.36	1978–2002
	Yield	156.03	73.00	213.90	32.55	1978–2002 excl. 2003–16
	Price (\$)	3.41	1.31	7.30	1.42	1969–2024
	Total variable costs (\$)	379.57	321.15	458.24	59.43	2019–2024
Dry beans	Planted acres	10,540	4695	16,674	3975	2008–2024
	Yield	2052	1649	2426	304.1	2017–2024
	Price (\$)	23.96	7.60	42.10	8.51	1969–2024
	Total variable costs (\$)	509.83	498.52	521.14	15.99	2017, 2019
Wheat	Planted acres	7768	200	17,600	4059	1979–2024 excl. 2007–08
	Harvested share (%)	81.86	38.09	100.00	17.49	1979–2009 excl. 2007–08
	Yield	85.97	32	120	22.72	1979–2024 excl. 2007–16
	Price (\$)	3.94	1.29	8.30	1.65	1969–2024
	Total variable costs (\$)	194.45	321.15	458.24	59.43	2019–2024
Sorghum	Planted acres	1501	35.80	3777	1239	2018–2024
	Yield	37.89	30.00	45.00	4.57	1969–1977
	Price (\$)	4.91	1.93	13.30	2.06	1969–2018
	Total variable costs (\$)	169.99	321.15	458.24	59.43	2019–2024
Potato	Planted acres	4850	1300	7319	1545	1983–2024
	Harvested share (%)	99.15	95.16	100.00	1.71	1983–2000
	Yield	4648	1300	6900	1956	1983–2000
	Price (\$)	5.28	2.38	8.30	1.62	1969–2009
	Total variable costs (\$)	1671	1626	1716	63.33	2017, 2019
Alfalfa	Harvested acres	26,069	18,000	37,000	4134	1979–2024 excl. 1981, 2008
	Yield	4.95	3.60	6.10	0.57	1979–2018 excl. 1981, 2008
	Price (\$)	173.81	100.00	298.00	60.81	1989–2024
	Total variable costs (\$)	1671	1626	1716	63.33	2016–19, 2023–24
Other hay	Harvested acres	1973	600	8200	1688	1978–2022 excl. 2008–15, 2018
	Yield	2.57	0.79	7.61	1.47	1978–2022 excl. 2011–2020
	Price (\$)	136.9	76.50	241.0	45.34	1989–2024
	Total variable costs (\$)	455.9	337.1	647.3	144.6	2016–19, 2023–24
Pasture	Total acres	633,268	240,810	1,481,214	303,666	2008–2024
Hydrology	Streamflow pre-dam *	7032	617	33,300	7078	1934–1962
	Streamflow post-dam *	2883	333	13,700	2568	1962–2024
	Precipitation **	17.17	0.00	104.1	16.05	1978–2024

Notes: * Streamflow statistics based on the maximum monthly discharge in cfs using USACE and USGS data; ** Precipitation statistics based on average monthly precipitation totals from NOAA station data for Farmington, New Mexico.

4.2. Hydrology

Historical observations of flood hazards and associated damages are critical for developing robust analytical frameworks and for validating model outputs, as emphasized in prior studies [31]. Accordingly, daily river discharge data were obtained from the U.S. Geological Survey (USGS) National Water Information System for a long-term streamgage representing the upstream hydrologic boundary of the study area. The dataset spans more than nine decades (1934–2025), providing a sufficiently long record for reliable flood frequency analysis and probabilistic characterization of extreme flow events.

Figure 2 presents the empirical distribution of daily discharge at the Shiprock stream-gage, disaggregated into pre-dam (unregulated) and post-dam (regulated) periods. The comparison reveals a clear structural shift in the flow regime associated with river regulation. Under pre-dam conditions, the distribution is strongly right-skewed, with a high frequency of low-to-moderate flows and a pronounced upper tail extending to very large discharge values. This long tail reflects the natural variability of the system, where episodic snowmelt and storm-driven runoff generate infrequent but extreme flood events. The variability is high, and the dispersion of flows indicates limited natural attenuation of peak discharges. In contrast, the post-dam distribution is noticeably more compressed and exhibits reduced skewness. The frequency of extreme high-flow events is substantially diminished, as evidenced by the truncation of the upper tail. Peak discharges above key flood thresholds occur far less frequently, indicating effective attenuation of flood waves by upstream storage. At the same time, the distribution shows a relative increase in mid-range flows and a reduction in very low flows, suggesting flow stabilization.

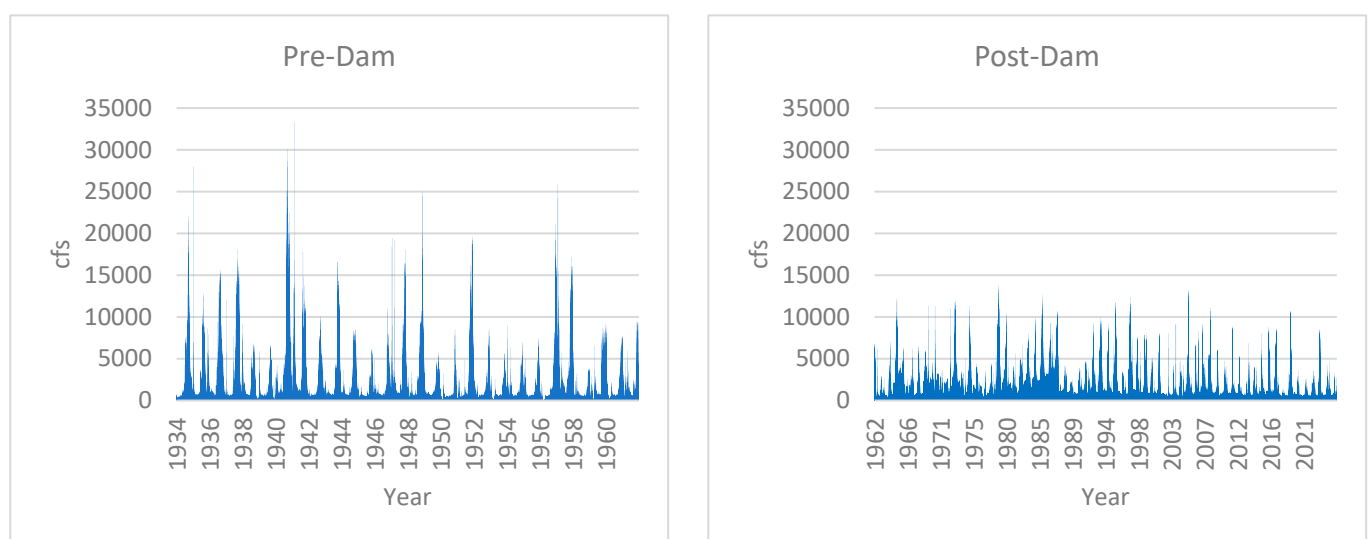


Figure 2. San Juan River daily discharge at Shiprock, NM (USGS streamgage 093680000).

To support scenario analysis and account for hydrologic uncertainty, a stochastic simulation model was developed to generate synthetic sequences of river flows and precipitation. The simulation was designed to reproduce the key statistical properties of the historical record, including mean conditions, variability, seasonality, and the correlation between streamflow and precipitation, while preserving the probability of extreme flood events. The simulation was conducted separately for pre-dam and post-dam hydrologic regimes. Estimating separate distributions for these two periods is necessary because reservoir regulation substantially reduced both the magnitude and frequency of peak flows in the San Juan River Basin.

Precipitation inputs in stochastic flood-risk frameworks such as this one are conventionally derived from historical station records, which constrains the representation of short-term rainfall variability and limits the ability to incorporate forward-looking forecast information. Recent advances in Global Navigation Satellite System (GNSS)-derived precipitable water vapor (PWV) offer a promising complementary data source for improving rainfall forecasting accuracy, since PWV is closely related to atmospheric moisture content and can be observed at high temporal resolution. The study demonstrates a machine-learning fusion strategy that improves rainfall-amount forecasting accuracy by combining GNSS-PWV observations with rainfall-event constraints [32], while ref. [33] develops an improved GNSS-observation-based rainfall forecasting model that incorporates monthly and

seasonal PWV variation as predictors. Because rainfall uncertainty is a key driver of flood-simulation accuracy in stochastic EAD frameworks, integrating GNSS-PWV-based forecasting products represents a valuable direction for refining the precipitation inputs used in future extensions of the present modeling framework, particularly for improving the representation of short-duration, high-intensity storm events that are imperfectly captured by monthly aggregated station data.

Annual maximum flows for each period were fitted using a two-parameter lognormal (LN2) distribution. Among candidate distributions compared using RMSE, correlation, bias, and Nash–Sutcliffe efficiency, the (LN2) distribution achieved a good overall fit in both the pre-dam ($NSE = 0.955$, $r = 0.980$) and post-dam ($NSE = 0.873$, $r = 0.952$) periods and closely reproduced the flood-frequency relationships reported by the U.S. Army Corps of Engineers. Several higher-parameter distributions, notably the four-parameter Kappa distribution, achieved marginally higher fit statistics; LN2 was still retained for the primary analysis on grounds of parsimony, comparability with established USACE benchmarks, and numerical tractability within the Monte Carlo correlation-preservation procedure as discussed in Appendix A. The lognormal distribution is commonly used in hydrologic applications because streamflow data are non-negative and typically right-skewed, and its parsimonious two-parameter form reduces estimation uncertainty relative to more flexible alternatives [34,35]. The fitted distributions indicate a substantial reduction in flood magnitudes following dam construction. For example, the estimated 100-year flood (1% Annual Exceedance Probability, AEP) declined from 51,846 cfs under pre-dam conditions to 21,099 cfs under post-dam conditions (Table 2).

Table 2. Transform method fitted historical distribution using LN2 distribution.

AEP (%)	Return Period	Pre-Dam Discharge (cfs)	Post-Dam Discharge (cfs)
0.2	1 in 500 years	75,083	27,722
1	1 in 100 years	51,846	21,099
2	1 in 50 years	43,178	18,437
4	1 in 25 years	35,232	15,870
10	1 in 10 years	25,716	12,582
20	1 in 5 years	19,142	10,121
50	1 in 2 years	10,882	6674

To preserve the historical relationship between streamflow and precipitation, correlated monthly values were generated using a Cholesky decomposition of the observed covariance matrix. These monthly values were then aggregated into quarterly indicators used in the econometric damage models. A total of 1000 Monte Carlo simulations of 51 years each were generated for both the pre-dam and post-dam periods, yielding approximately 51,000 synthetic years for each regime. This sample size provides sufficient precision to estimate expected damages and evaluate flood risk under alternative scenarios.

4.3. Valuation of Flood Protection

Flood-related economic losses are estimated through a stochastic Expected Annual Damage (EAD) framework that links hydrological variability to agricultural production responses and associated economic outcomes [2,3]. The valuation approach compares EAD under counterfactual hydrological regimes with and without dam regulation, isolating the flood protection benefits attributable to flow regulation.

4.3.1. Crop Acreage and Production Response Under Flood Risk

For annual row crops, historical planted acreage series were estimated using ordinary least squares (OLS) regressions linking acreage decisions to hydrological and climatic

variables. Observed relationships between acreage and hydrological stressors were used to infer flood-responsive adjustments in planting behavior. These econometric estimates were used to project crop-specific planted acreage for a 51-year simulation horizon. A baseline “normal” acreage level was constructed using a truncated historical mean of the most recent available observations, excluding extreme low values to mitigate flood-driven downward bias. The difference between projected planted acreage and this baseline is interpreted as flood-induced unplanted area. This formulation provides a reduced-form representation of flood impacts on cropping intensity at the county scale.

For perennial forage systems (alfalfa and other hay), planted acreage is not an appropriate production metric due to multi-year establishment cycles and weak statistical relationships between planting decisions and hydrological variables. Instead, harvested acreage is used as the operative variable, and deviations from baseline harvested area are interpreted as flood-induced production losses.

Pastureland, which is not consistently reported in planted or harvested terms, is constructed using a combined FSA and NASS CroplandCROS dataset. Annual pasture area is defined as the maximum observed value across sources, ensuring conservative land-use representation. Flood impacts on pasture are monetized using net returns derived from New Mexico State University enterprise budgets, following a normalized revenue-cost framework consistent with ERS-style accounting. This disaggregated treatment of acreage and yield response follows the three-component agricultural flood-damage structure developed earlier [7].

4.3.2. Baseline Construction and Flood Deviation Measurement

Baseline production systems—including planted area (row crops), harvested share (row crops), harvested acreage (perennials), yields, and pasture area—are constructed using a five-year truncated mean based on the most recent available reporting window for each variable and crop. This smoothing approach reduces short-run volatility while preserving structural land-use patterns. Flood impacts are identified as deviations from this baseline under simulated hydrological conditions. These deviations are applied consistently across land-use categories to generate counterfactual production losses attributable to flood events.

4.3.3. Price and Cost Valuation

Economic valuation is conducted using normalized price series derived from USDA-ERS methodologies, supplemented by USDA-NASS observed prices where available. Crop-specific prices are constructed at the national level and adjusted to New Mexico using historical price ratios where state-level data permit. For sorghum, national prices are directly applied due to strong alignment between state and national series in recent years. Potatoes prices incorporate historical New Mexico-to-U.S. price differentials where data coverage allows.

Cost of production is estimated using a combination of ERS operating cost and labor series and extension enterprise budgets. Unplanted cost adjustments follow RMA loss factor structures for prevent plant acres, applied to operating and labor cost components when planted acreage falls below baseline. Harvest cost savings associated with reduced harvested acreage are computed using cost share parameters derived from university extension budgets for row crops. For alfalfa, other hay, dry beans, and potatoes, historical averages of harvest cost shares are applied due to data heterogeneity. Pasture costs reflect maintenance expenditures rather than conventional production costs and are valued using extension-based grazing return estimates from New Mexico State University. These are treated as net economic returns per acre rather than yield-based production values.

4.3.4. Hydrological Stochastic Structure and Scenario Design

Hydrological dependence structures are estimated using correlation matrices and Cholesky decompositions constructed separately for pre- and post-dam regimes. Quarterly flow extremes (maximum daily flows) and aggregated precipitation measures are used to represent joint hydroclimatic variability. This structure is used to generate stochastic realizations of flood events under alternative hydrological regimes. To isolate riverine flood effects, precipitation is held constant across dam and no-dam scenarios, ensuring that differences in outcomes are driven exclusively by changes in river flow dynamics rather than local rainfall variability. This design choice is well suited to identifying the marginal effect of reservoir regulation, which is the primary object of this study, but it necessarily abstracts from compound flood dynamics—the joint or sequential occurrence of intense local precipitation and elevated river discharge—that can amplify flood damages beyond what either driver would produce independently. This simplification is particularly relevant for the San Juan River Basin’s historically largest recorded floods, which were monsoon-driven (August–October) rather than snowmelt-driven, and for the 1970 Tropical Storm Norma event, whose runoff originated predominantly below Navajo Dam and therefore bypassed dam regulation entirely [21,28]. Because the present framework holds precipitation constant, it does not capture scenarios in which intense monsoonal rainfall coincides with, or compounds, elevated regulated releases, and the resulting EAD estimates should be interpreted as reflecting riverine flood risk under average precipitation conditions rather than compound flood risk under joint extremes.

4.3.5. Expected Annual Damage and Flood Protection Valuation

Expected annual damage is computed as the probabilistic expectation of monetized agricultural losses across stochastic hydrological realizations. Flood protection benefits are defined as the reduction in EAD under the regulated (dam) scenario relative to the unregulated (no-dam counterfactual) scenario. This difference captures the marginal economic value of flood risk mitigation attributable to hydrological regulation. Formally, flood protection value is expressed as the stochastic reduction in expected damages arising from changes in flow distributions, land-use responses, and production losses across crops and pasture systems.

To provide a physical-normalized interpretation of flood protection efficiency, we also compute the marginal flood protection value per unit of effective flood storage, defined as:

$$\text{Flood protection value} = \frac{EAD_{pre-dam} - EAD_{post-dam}}{\text{Reservoir effective flood storage (acre} - \text{feet)}}$$

4.4. Irrigation Water Value

While this study develops a detailed stochastic framework to quantify flood protection benefits, irrigation water values are not independently re-estimated within the present analysis. Instead, marginal irrigation water values are drawn from an existing peer-reviewed agricultural economics study conducted in a directly comparable institutional and climatic setting. Specifically, we draw upon [36], which applies a calibrated Positive Mathematical Programming (PMP) model to estimate the shadow price of irrigation water under alternative water availability scenarios and shortage-sharing institutions across six counties of the Rio Grande Basin, New Mexico.

The PMP approach used by [36] calibrates a nonlinear optimization model to replicate observed land use and water allocation by crop and county, deriving endogenous shadow prices—that is, the marginal contribution of an additional acre-foot of water to farm income—without imposing arbitrary parameter assumptions. This is widely regarded as a theoretically consistent and empirically grounded method for estimating irrigation

water value under realistic behavioral and institutional constraints [16,37]. Under a drought scenario representing 75% of full water supply—a plausible stress condition in semi-arid systems—[36] reports an equalized shadow price of \$68.67 per acre-foot under unrestricted water trading, with values ranging from \$1.73 to \$482.91 per acre-foot across crops and locations under proportional shortage sharing without trading, reflecting substantial heterogeneity in the marginal productivity of water across crop types.

Several features of the study [36] support its use as a reference for irrigation water values in the present analysis. First, the study is set entirely within New Mexico, operating under the same prior appropriations water law framework and arid climatic conditions that characterize the San Juan River Basin. Second, the crop mix examined—alfalfa, corn, wheat, peppers, cotton, and pecans—overlaps substantially with the irrigated agriculture downstream of Navajo Dam, including the dominant alfalfa and corn production on the Navajo Indian Irrigation Project (NIIP). Third, the PMP shadow prices are derived under water scarcity conditions analogous to those faced in the San Juan Basin, where abstraction constraints and drought exposure create binding limitations on irrigation supply. It should be noted that the study [36] focuses on the Middle Rio Grande Basin rather than the San Juan River Basin specifically, and direct estimation of irrigation water values for the NIIP service area would constitute a valuable refinement. Nevertheless, given the absence of a publicly available calibrated optimization model for the San Juan Basin, the Rio Grande Basin shadow prices represent the most methodologically rigorous and geographically proximate reference currently available in the peer-reviewed literature and are adopted here as representative estimates of irrigation benefits for comparison with the flood protection benefits derived from stochastic EAD reduction.

5. Results

The stochastic simulation framework yields an estimated reduction in expected annual agricultural damages of \$366,377 representing the mean annual benefit of flood regulation attributable to reservoir operations. Additional technical details on the simulation structure and distributional fitting appear in Appendix A. This value reflects avoided losses from reductions in harvested area and yield impacts across cropping systems under regulated flow conditions. To facilitate comparison with alternative water uses, the estimated reduction in expected annual damage is normalized by reservoir storage capacity relevant to flood control. For Navajo Dam, flood control storage is 273,000 acre-feet [38]. Unlike total or active storage, this measure reflects the portion of reservoir capacity specifically allocated to flood attenuation and is therefore most appropriate for valuing flood protection benefits. Based on this assumption, the marginal value of flood protection is estimated as \$1.34/acre-foot. This estimate represents the economic value of flood damage reduction per unit of stored water and provides a consistent basis for comparison with irrigation water values expressed in similar units.

Table 3 summarizes the estimated annual agricultural flood losses avoided by Navajo Dam, disaggregated by crop. Perennial forage and row crops account for the large majority of avoided damages: alfalfa and corn together represent 78.1% of the total avoided loss (\$149,779 and \$136,264 per year, respectively), consistent with their dominant share of irrigated acreage in San Juan County and their comparatively high value per acre relative to lower-acreage crops such as sorghum and dry beans. Losses avoided for potatoes, dry beans, other hay, wheat, sorghum, and pasture are comparatively minor, together accounting for the remaining 21.9% of total avoided damages. This distribution reflects both the relative economic value of each crop and its exposure to flood-driven acreage and yield losses under the unregulated counterfactual.

Table 3. Estimated agricultural flood losses avoided by Navajo Dam by crop.

Crop	Annual Average Avoided Losses (\$/Year)	Share of Total Avoided Losses (%)
Alfalfa	149,779	40.9
Corn	136,264	37.2
Potatoes	31,403	8.6
Dry beans	24,634	6.7
Other hay	12,070	3.3
Wheat	9017	2.5
Sorghum	2984	0.8
Pasture	227	0.1
Total	366,377	100

The underlying econometric relationships linking hydrological conditions to acreage and yield outcomes (Appendix A, Tables A1–A3) indicate that prior-period river flow and precipitation variables are statistically significant determinants of planted acreage for several crops—notably corn and wheat, where lagged flow terms enter with negative and statistically significant coefficients, consistent with the expectation that elevated flood-season flows reduce subsequent planted acreage.

Results from [36] indicate that the marginal economic value of irrigation water varies substantially depending on water availability and the institutional arrangements governing its allocation. Under a representative drought scenario—defined as 75% of full water supply—and assuming unrestricted reallocation across crops and locations, the shadow price of irrigation water converges to approximately \$68.67 per acre-foot across all crops and counties. This equilibrium value reflects the marginal productivity of water when it is allocated to its highest-valued uses across the system under conditions of scarcity and represents the theoretically efficient benchmark against which alternative water uses can be assessed. Under more institutionally constrained allocation regimes—specifically, proportional shortage sharing without any water trading—shadow prices exhibit substantial heterogeneity, ranging from \$1.73 per acre-foot for low-value crops such as wheat to \$482.91 per acre-foot for high-value specialty crops such as onions. This wide range reflects the economic inefficiency introduced by rigid allocation rules, under which water cannot freely move toward its most productive uses. These extremes are therefore not adopted as comparison benchmarks, as they reflect crop-specific and institutionally constrained outcomes rather than a system-wide measure of irrigation water value.

For the purposes of this study, the equilibrium shadow price of \$68.67 per acre-foot is adopted as a representative estimate of irrigation water value against which the flood protection benefits derived from stochastic EAD reduction are compared. Two important qualifications attend this comparison. First, as noted in the methodology, the study models the Middle Rio Grande Basin rather than the San Juan River Basin specifically [36], and direct estimation of irrigation shadow prices for the NIIP service area would constitute a refinement beyond the scope of the present study. Second, the shadow price of \$68.67 per acre-foot represents the marginal value of water consumed in irrigation, whereas the flood protection value estimated in this study is expressed per acre-foot of reservoir storage capacity. These are conceptually distinct units—one reflects the productivity of a flow of water applied to crops, the other the economic benefit attributable to a unit of physical storage that modifies downstream flood risk. The comparison is therefore indicative of relative magnitudes rather than a precise unit-for-unit equivalence and should be interpreted accordingly.

6. Discussion

6.1. Significance and Implications of Secondary Reservoir Function Valuation

The contrast between the estimated flood protection value of \$1.34 per acre-foot of storage and the irrigation shadow value of \$68.67 per acre-foot is economically informative and consistent with the operational priorities of Navajo Dam, where irrigation supply is the primary authorized purpose and flood control a secondary function. In arid and water-scarce basins, irrigation water generates continuous and directly observable market returns, reflecting the high marginal productivity of water in agricultural production. By contrast, flood protection is a risk-reducing service whose value is realized through avoided damages and only materializes when flows exceed damage thresholds. As a result, its annualized marginal value is expected to be lower under average hydrologic conditions.

The finding that flood protection value is an order of magnitude smaller than irrigation shadow value here is consistent with, and helps explain, prior observations that flood control benefits in multipurpose reservoirs are frequently undercounted relative to consumptive-use benefits [1]. It also parallels [4], who found that irrigation reservoirs in Japan can generate measurable flood damage reduction even where flood control is not a primary design objective, though their study quantified physical damage reduction rather than a fully monetized, storage-normalized value; the present study extends this line of work by expressing the benefit in the same \$/acre-foot unit used for irrigation valuation, enabling direct comparison. The result contrasts with [6], who documented substantial flood wave attenuation (45–80%) in multipurpose European reservoirs where flood control operating rules were more explicitly engineered; the comparatively modest marginal value estimated here likely reflects the fact that Navajo Dam's flood-control allocation (273,000 acre-feet) is a relatively small share of total storage and that its operating rules are not primarily optimized for flood attenuation. Similarly, [5] found flood risk reduction to be an economically substantial component of integrated water management in the Netherlands, but in a system where flood control—rather than irrigation—was the dominant reservoir function. More broadly, recent U.S. evidence on the marginal value of natural flood-regulating storage—for example, [39,40], who estimate that wetland loss since 1985 has increased U.S. flood insurance claims by \$10.1 billion—reinforces that risk-reduction services of this kind are systematically undervalued in conventional appraisal, even though their marginal value varies widely with system-specific storage allocation and operating priorities.

This difference should not be interpreted as evidence that flood protection is of limited importance. Rather, the estimated flood protection value represents a conservative lower-bound measure for two reasons. First, it includes only direct agricultural damages within the study area and excludes other potentially significant losses, including damages to infrastructure, residential and commercial property, transportation networks, and broader regional economic activity. Second, flood protection benefits are episodic, probabilistic, and highly state-dependent, increasing disproportionately during low-probability, high-consequence flood events.

Because flood protection and irrigation represent fundamentally different benefit streams—one based on avoided losses and the other on ongoing production returns—their marginal values are not fully comparable. The comparison is therefore best interpreted as an indication of the relative order of magnitude of these two reservoir services rather than as a sufficient basis for storage reallocation decisions. A comprehensive assessment of multipurpose reservoir operations would require incorporating the full range of avoided damages, risk reduction benefits, and non-market values associated with flood control, many of which remain difficult to quantify [1,16].

The results have important implications for reservoir valuation and infrastructure planning. Although expressing both irrigation and flood protection benefits in dollars per acre-foot provides a useful common metric, decisions regarding multipurpose reservoirs should not rely solely on average marginal values. In regulated systems such as Navajo Dam, storage allocations must balance consumptive water use with risk-reduction functions whose economic value becomes most apparent during rare but high-consequence flood events. This suggests that the economic justification for flood control depends not only on average annual avoided damages but also on its contribution to reducing exposure to extreme events and enhancing regional resilience.

6.2. Limitations and Assumptions

Several limitations should be considered when interpreting the results. First, the estimation of flood protection benefits is restricted to agricultural damages and does not include impacts on infrastructure, residential property, transportation systems, or indirect economic effects. As a result, the reported values likely underestimate the total economic benefits of flood control.

Second, irrigation water values are adopted from existing study rather than estimated within the same modeling framework. Although these values are theoretically consistent and widely used, differences in model structure, spatial scale, and institutional assumptions may affect direct comparability.

Third, the stochastic framework assumes stationary hydrological relationships within each regime (pre-dam and post-dam) and holds precipitation constant across scenarios to isolate the marginal effect of river regulation. This assumption is a simplification given well-documented, ongoing climate variability and aridification trends across the Colorado River Basin, including declining snowpack, earlier snowmelt timing, and multi-decadal drought conditions that have altered both the mean and variance of streamflow over the post-dam period [30]. A stationary-regime assumption of this kind is standard in flood-frequency practice and is appropriate for isolating the marginal contribution of dam regulation itself—the object of interest in this study—but it does not capture potential shifts in flood risk driven by climate change within the post-dam period, nor compound effects arising from the interaction of a changing climate with reservoir operations. Recent complementary work demonstrates that, in agricultural systems, the timing of a flood relative to crop phenological stage can be a stronger determinant of economic loss than flood magnitude alone [8]. While the present EAD framework aggregates damages across crop-years without an explicit sub-annual phenological dimension, incorporating an FHI/FSI-type structure represents a promising extension for refining the seasonal timing of avoided damages attributable to Navajo Dam's flood-control operations—particularly relevant given the monsoon-driven timing of the basin's largest historical floods discussed above.

7. Conclusions, Policy Implications and Future Research

This study addresses an important gap in the economic evaluation of reservoir systems by providing a stochastic valuation of flood protection benefits in an irrigation-dominated setting. By comparing regulated and unregulated flow conditions in the San Juan River Basin, the analysis estimates expected annual avoided agricultural damages attributable to reservoir operations. These avoided damages are subsequently normalized by storage capacity to derive a unit value of flood protection expressed in dollars per acre-foot. In contrast to approaches that treat irrigation and flood control as competing objectives, this study conceptualizes them as joint and complementary services generated by the same storage infrastructure. Empirically, the results demonstrate that while irrigation benefits dominate in marginal value terms in semi-arid systems, flood protection provides

measurable—albeit smaller—economic benefits through risk reduction. More broadly, the study contributes to the literature by integrating stochastic flood risk valuation with water resource economics, highlighting the importance of incorporating secondary and risk-based benefits into infrastructure appraisal.

The contribution of this study is threefold. First, it quantifies flood protection as a co-benefit of reservoir storage in a system primarily designed for irrigation and water supply. Second, it applies a stochastic valuation framework based on expected annual damage, thereby capturing the full distribution of flood risk rather than relying on discrete return periods. Third, it expresses flood risk reduction in a unit economic metric enabling direct comparison with other water uses and facilitating integrated evaluation of reservoir functions.

The findings have several implications for water resource policy and infrastructure planning. First, in water-scarce basins, decision-making frameworks that prioritize consumptive uses based solely on marginal productivity may undervalue risk-reduction services such as flood protection. While these services may exhibit lower average annual values, they play a critical role in reducing exposure to extreme events and ensuring system resilience. Second, expressing multiple reservoir benefits in comparable units provides a transparent basis for evaluating trade-offs in reservoir operation, particularly under competing demands for water allocation. Third, the results underscore the importance of adopting multi-objective planning approaches that explicitly recognize both production-oriented and risk-mitigating functions of storage infrastructure, especially in regulated systems such as those influenced by the Navajo Dam.

Several avenues for future research emerge from this analysis. Expanding the valuation framework to include additional damage categories—such as infrastructure, residential property, and indirect economic impacts—would provide a more comprehensive estimate of flood protection benefits. Incorporating dynamic reservoir operation rules and seasonal storage constraints could further refine the linkage between storage and flood mitigation capacity. In addition, integrating irrigation and flood protection valuation within a unified hydro-economic optimization model would improve internal consistency and allow for endogenous representation of trade-offs across reservoir functions. Finally, extending the stochastic framework to account for non-stationary climate conditions and compound flood drivers would enhance its relevance for long-term infrastructure planning under climate uncertainty.

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Appendix A. OLS Regression Results

The econometric models reported in Tables A1–A3 are intended as reduced-form approximations of the relationship between hydrological conditions and agricultural pro-

duction outcomes at the county scale, rather than as structural behavioral models of farm-level decision-making. Several specifications yield modest R^2 values—which reflects the considerable influence of factors beyond hydrological variability on cropping patterns in a semi-arid irrigated system. Management decisions, input availability, market conditions, crop rotation practices, and tribal agricultural policy all shape observed land use in ways that are not fully captured by streamflow and precipitation regressors alone. This is a recognized challenge in county-level agricultural damage modeling, where data sparsity, aggregation across heterogeneous farms, and the confounding of climatic and institutional drivers routinely constrain the explanatory power of econometric damage functions [2,41]. The low sample sizes for sorghum and dry beans yield, driven by limited historical reporting, further limit the precision of those individual estimates. Importantly, low R^2 does not indicate model misspecification or bias in the estimated direction of the hydrological effect; it indicates that flood-related hydrological variables explain only a portion of total production variance, which is precisely what one would expect in a system where irrigation infrastructure moderates the relationship between river conditions and farm outcomes. The estimated coefficients are therefore used conservatively: they generate projections of flood-induced deviations from baseline production that are, if anything, likely to understate the true hydrological sensitivity of agricultural output, since attenuation of the statistical signal by non-hydrological noise biases the damage estimates toward zero. Taken together, the models represent a transparent, data-constrained effort to ground the stochastic damage framework in empirically observed production relationships, and the resulting EAD estimates should be interpreted as lower-bound approximations consistent with this scope.

In all equations, B_0 represents the intercept term, B_1 through B_n denote the estimated parameters, and e is the error term. The river flow variables R_1 through R_4 capture maximum river flows for each calendar quarter (R_1 = January–March, R_2 = April–June, R_3 = July–September, R_4 = October–December), while P_1 through P_4 represent average precipitation for the same periods (P_1 = January–March, P_2 = April–June, P_3 = July–September, P_4 = October–December). Drought indicators control varying degrees of drought severity, and a linear time trend accounts for technological progress and other temporal effects (D_1 = mild, D_2 = bad, D_3 = worse). These drought indicator variables were created using an ad hoc approach by considering the combination of the annual Palmer Drought Severity Index and residual differences when using a simple linear time trend historically. Trend = Time trend.

Table A1. Estimates of planted area determinants (standards errors are in parenthesis).

	Corn price _{t-1}	Wheat price _{t-1}	R ₂	P ₂
Corn planted area	4686.8 ** (1772.5)	−2118.9 (1382.1)	−0.853 * (0.434)	135.9 (135.91)
Observations			19	
R-Squared			0.5269	
	Dry beans price _{t-1}	R ₂	P ₂	
Dry beans planted area	90.66 (188.65)	−0.135 (0.374)	191.21 (123.87)	
Observations			17	
R-Squared			0.1562	
	R _{3,t-1}	R _{4,t-1}	P _{3,t-1}	P _{4,t-1}
Wheat planted area	−0.155 ** (0.337)	−0.865 (0.524)	93.708 (66.01)	1.604 ** (82.72)
Observations			44	
R-Squared			0.1025	

Table A1. *Cont.*

	Corn price _{t-1}	Wheat price _{t-1}	R ₂	P ₂	
	R ₂	P ₂			
Sorghum planted area	−0.065 (0.2265)	40.387 (107.34)			
Observations			5		
R-Squared			0.1014		
	Potato price _{t-1}	R ₁	R ₂	P ₁	P ₂
Potato planted area	177.51 (137.97)	−0.108 (0.300)	−0.020 (0.158)	−3.831 (41.608)	19.124 (39.074)
Observations			34		
R-Squared			0.1145		

Note: * $p < 0.1$; ** $p < 0.05$.**Table A2.** Estimates of crop yield determinants (standards errors are in parenthesis).

	R ₁	R ₂	R ₃	P ₁	P ₂	P ₃	Trend
Corn yield		−0.0007 (0.00113)	−0.0031 * (0.0019)		0.8802 * (0.4796)	0.2818 (0.3237)	1.709 **** (0.2197)
Observations			33				
R-Squared			0.7904				
Dry beans yield		−0.00016 (0.00015)	−0.15899 (0.07828)			0.02415 (0.05205)	
Observations			12				
R-Squared			0.5135				
Wheat yield	−0.00327 (0.00385)	0.001313 (0.001701)	−0.0003 (0.001957)	0.183282 (0.579476)	0.487964 (0.585078)	0.197816 (0.372082)	0.8314 * (0.29887)
Observations			36				
R-Squared			0.3589				
Sorghum yield		−0.06352 (0.226544)			40.3872 (107.3423)		
Observations			5				
R-Squared			0.1014				
Potato yield		−0.10017 (0.283603)	−0.2452 (0.434902)		70.6509 (80.0136)	3.58805 (78.31009)	
Observations			18				
R-Squared			0.1134				
Alfalfa yield		−0.0000021 (0.0000312)	−0.000115 * (0.0000506)		0.001467 (0.012235)	0.017473 (0.009701)	
Observations			37				
R-Squared			0.1701				
Other hay yield		−0.00016 (0.000151)			−0.15899 * (0.078285)	0.02415 (0.052025)	
Observations			12				
R-Squared			0.5153				

Note: * $p < 0.1$; **** $p < 0.001$.**Table A3.** Estimates of harvested share determinants (standards errors are in parenthesis).

	R ₂	R ₃	R ₄	P ₂	P ₃	P ₄
Corn harvested share		−0.000028 (0.000025)	−0.000004 (0.000033)		0.007499 (0.004831)	0.001112 (0.005423)
Observations			25			
R-Squared			0.1151			

Table A3. Cont.

	R ₂	R ₃	R ₄	P ₂	P ₃	P ₄
Wheat harvested share	−0.00000025 (0.000001)	−0.00000005 (0.000017)		0.006078 (0.005105)	−0.006634 * (0.003588)	
Observations			29			
R-Squared			0.1783			
Potato harvested share			−0.0000003 (0.0000003)			−0.000615 (0.000603)
Observations			18			
R-Squared			0.1343			
Alfalfa harvested area	−0.10885 (0.23009)	−0.13054 (0.347440)		52.07291 (90.23987)	−19.0078 (67.70446)	
Observations			45			
R-Squared			0.0202			
Other hay harvested area	−0.06483 (0.102805)	−0.16361 (0.156418)		25.28401 (45.85988)	−12.4108 (30.92792)	
Observations			36			
R-Squared			0.0836			
Pasture area	−2.530 (26.8816)			14006.32 (8568.801)	−8407.354 (6372.290)	
Observations			16			
R-Squared			0.2840			

Note: * $p < 0.1$.

References

- Bonner, M.; Witt, A.; Stewart, K.; Hadjerioua, B.; Mobley, M. *The Economic Benefits of Multipurpose Reservoirs in the United States-Federal Hydropower Fleet*; ORNL/TM-2015/568; US Department of Energy, Environmental Sciences Division, Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2015.
- Foudi, S.; Osés-Eraso, N.; Tamayo, I. Integrated spatial flood risk assessment: The case of Zaragoza. *Land Use Policy* **2015**, *42*, 278–292. [[CrossRef](#)]
- Wang, L.; Cui, S.; Tang, J.; Fang, L.; Fang, X.; Shrestha, S.; Manandhar, B.; Huang, J.; Nitivattananon, V. Riverine flood risk assessment with a combined model chain in southeastern China. *Ecol. Indic.* **2023**, *154*, 110686. [[CrossRef](#)]
- Ikemoto, A.; Kazama, S.; Yanagihara, H. Evaluation of an adaptation strategy for flood damage mitigation under climate change through the use of irrigation reservoirs in Japan. *Water Resour. Manag.* **2023**, *37*, 4159–4175. [[CrossRef](#)]
- Brouwer, R.; van Ek, R. Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecol. Econ.* **2004**, *50*, 1–21. [[CrossRef](#)]
- Woś, K.; Radon, R.; Tekielak, T.; Wrzosek, K.; Pieron, Ł.; Piórecki, M. Role of Multifunctional Water Reservoirs in the Upper Vistula Basin in Reducing Flood Risk. *Water* **2022**, *14*, 4025. [[CrossRef](#)]
- Maltsbarger, R.; Tsay, J.; Gedikoglu, H.; Jalilov, S.-M. Rapid Assessment of Flood-Induced Agricultural Losses to Support Infrastructure and Policy Decisions. *J. Flood Risk Manag.* **2026**, *19*, e70236. [[CrossRef](#)]
- Jalilov, S.-M.; Maltsbarger, R.; Gedikoglu, H. The Cost of Bad Timing: How Phenology and Frequency Determine Agricultural Flood Risk. *Water Resour. Manag.* **2026**, *40*, 417. [[CrossRef](#)] [[PubMed](#)]
- Young, R.A.; Loomis, J.B. *Determining the Economic Value of Water: Concepts and Methods*; Resources for the Future Press: Washington, DC, USA, 2005.
- Loucks, D.P.; Van Beek, E. *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*; Springer: Berlin/Heidelberg, Germany, 2017.
- Merz, B.; Hall, J.; Disse, M.; Schumann, A. Fluvial flood risk management in a changing world. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 509–527. [[CrossRef](#)]
- Ward, F.A.; Pulido-Velázquez, M. Incentive pricing and cost recovery at the basin scale. *J. Environ. Manag.* **2009**, *90*, 293–313. [[CrossRef](#)]
- CEPA; Agilia. *Multi-Purpose Reservoirs: Economic Analysis*; Environment Agency: Bristol, UK, 2022.
- Jain, S.K.; Singh, V.P. *Water Resources Systems Planning and Management*; Elsevier: Amsterdam, The Netherlands, 2023.

15. Doyle, M.W.; Patterson, L.A. Federal decentralization and adaptive management of water resources: Reservoir reallocation by the U.S. Army Corps of Engineers. *J. Am. Water Resour. Assoc.* **2019**, *55*, 1248–1267. [\[CrossRef\]](#)
16. Harou, J.J.; Pulido-Velazquez, M.; Rosenberg, D.E.; Medellín-Azuara, J.; Lund, J.R.; Howitt, R.E. Hydro-economic models: Concepts, design, applications, and future prospects. *J. Hydrol.* **2009**, *375*, 627–643. [\[CrossRef\]](#)
17. Ward, F.A. Water in the West: Review of Ten Policy Challenges and Research Needed to Address Them. *J. Water Resour. Plan. Manag.* **2026**, *152*, 03126004. [\[CrossRef\]](#)
18. Lester, R.E.; Robertson, D.; Bailey, J.; Dwyer, G.K.; Holt, G.; Jalilov, S.-M.; Shokri, A.; Watto, M.A. Synergies in environmental and agricultural water availability under climate change. *Nat. Sustain.* **2026**, *9*, 234–246. [\[CrossRef\]](#)
19. Uncover Colorado. San Juan River–Near Pagosa Springs. 2025. Available online: <https://www.uncovercolorado.com/activities/san-juan-river/> (accessed on 16 September 2025).
20. NNWRC (Navajo Nation Water Rights Commission). San Juan River Utah. 2025. Available online: <https://nnwrc.navajonnsn.gov/Basin-Updates/San-Juan-River-Utah> (accessed on 16 September 2025).
21. USGS (United States Geological Survey). Changes in Riparian Vegetation in the Southwestern United States: Floods and Riparian Vegetation on the San Juan River, Southeastern Utah. 2016. Available online: <https://pubs.usgs.gov/of/2001/ofr01-314/> (accessed on 16 September 2025).
22. Utah DEQ (Department of Water Quality). San Juan Watershed Program. 2025. Available online: <https://deq.utah.gov/dwq/san-juan> (accessed on 16 September 2025).
23. USBR (United States Bureau of Reclamation). Navajo Unit. 2011. Available online: https://www.usbr.gov/uc/rm/crsp/navajo/index.html?utm_source (accessed on 16 September 2025).
24. USACE. *Final Environmental Assessment and FONSI*; US Army Corps of Engineers: Washington, DC, USA, 2011; 56p.
25. USACE. *Navajo Dam and Reservoir San Juan River, Colorado, Water Control Manual Revised 2010*; US Army Corps of Engineers: Washington, DC, USA, 1970; 190p.
26. Freeman, W.B. Flood on the San Juan River September, 1909. *Mon. Weather Rev.* **1909**, *37*, 648–649. [\[CrossRef\]](#)
27. LaRue, E.C. *Water Power and Flood Control on the Colorado River Below Green River, UT*; U.S. Geological Survey water supply paper 556; Government Printing Office: Washington, DC, USA, 1925; 176p.
28. Roeske, R.H.; Cooley, M.E.; Aldridge, B.N. *Floods of September 1970 in Arizona, Utah, Colorado, and New Mexico*; Geological Survey Water-Supply Paper 2052; U.S. Government Printing Office: Washington, DC, USA, 1978; 130p.
29. Navajo Agricultural Products Industry (NAPI). NAPI Issues \$1 Million Dividend Payment to the Navajo Nation for FY24. Available online: <https://navajopride.com> (accessed on 8 January 2026).
30. USBR (United States Bureau of Reclamation). Interior Region 7. Upper Colorado Basin. Encompassing All or Parts of Arizona, Colorado, Idaho, Nevada, New Mexico, Texas, Utah and Wyoming, Navajo Unit. 2026. Available online: <https://www.usbr.gov/uc/rm/crsp/navajo/> (accessed on 5 May 2026).
31. Shrestha, B.B.; Perera, E.D.P.; Kudo, S.; Miyamoto, M.; Yamazaki, Y.; Kuribayashi, D.; Sawano, H.; Sayama, T.; Magome, J.; Hasegawa, A.; et al. Assessing flood disaster impacts in agriculture under climate change in the river basins of Southeast Asia. *Nat. Hazards* **2019**, *97*, 157–192. [\[CrossRef\]](#)
32. Su, M.; Chen, C.; Li, Z.; Jiang, W.; Gao, Y.; Shang, J.; Zhou, X. Rainfall Amount Forecast Using GNSS-PWV Based on Machine Learning Fusion Strategy and the Constraint of Rainfall Event. *IEEE Trans. Geosci. Remote Sens.* **2026**, *64*, 4201810. [\[CrossRef\]](#)
33. Zhao, Q.; Liu, Y.; Ma, X.; Yao, W.; Yao, Y.; Li, X. An improved rainfall forecasting model based on GNSS observations. *IEEE Trans. Geosci. Remote Sens.* **2020**, *58*, 4891–4900. [\[CrossRef\]](#)
34. Limpert, E.; Stahel, W.A.; Abbt, M. Log-normal Distributions across the Sciences: Keys and Clues: On the charms of statistics, and how mechanical models resembling gambling machines offer a link to a handy way to characterize log-normal distributions, which can provide deeper insight into variability and probability—Normal or log-normal: That is the question. *BioScience* **2001**, *51*, 341–352. [\[CrossRef\]](#)
35. Helsel, D.R.; Hirsch, R.M.; Ryberg, K.R.; Archfield, S.A.; Gilroy, E.J. *Statistical Methods in Water Resources*. In *Techniques and Methods*; US Geological Survey: Reston, VA, USA, 2020.
36. Ward, F.A.; Potter, N.A.; Hrozencik, R.A. Managing agricultural water use in the Western United States: A search for efficient climate adaptation institutions. *Agric. Water Manag.* **2025**, *308*, 109279. [\[CrossRef\]](#)
37. Howitt, R.E. Positive Mathematical Programming. *Am. J. Agric. Econ.* **1995**, *77*, 329–342. [\[CrossRef\]](#) [\[PubMed\]](#)
38. USDIBR (United States Department of the Interior Bureau of Reclamation). *Hydraulic Model Studies of Navajo Dam Diversion and Outlet Works Structure*; Hydraulic Laboratory report No. Hyd-457; Bureau of Reclamation: Denver, CO, USA, 1960.
39. Gourevitch, J.D.; Gold, A.C.; Garcia, H.M. The economic value of wetlands in reducing riverine flood losses in the USA. *Nat. Water* **2026**, 1–14. [\[CrossRef\]](#)

40. Kubinský, D.; Weis, K.; Fуска, J.; Lehotský, M.; Petrovič, F. Monetary Valuation of Flood Protection Ecosystem Service Based on Hydrological Modelling and Avoided Damage Costs. An Example from the Čierny Hron River Basin, Slovakia. *Water* **2021**, *13*, 198. [[CrossRef](#)]
41. Monteleone, B.; Giusti, R.; Magnini, A.; Arosio, M.; Domeneghetti, A.; Borzì, I.; Petrucci, N.; Castellarin, A.; Bonaccorso, B.; Martina, M.L.V. Estimations of Crop Losses Due to Flood Using Multiple Sources of Information and Models: The Case Study of the Panaro River. *Water* **2023**, *15*, 1980. [[CrossRef](#)]

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