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Authors

Sanchez, Leslie

Edwards, Eric C

Leonard, Bryan

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The economics of indigenous water claim settlements in the American West

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Leslie Sanchez¹ , Eric C Edwards² and Bryan Leonard³

¹ Tufts University, Friedman School of Nutrition Science and Policy, Boston, MA, United States of America

² North Carolina State University, Department of Agriculture and Resource Economics, Raleigh, NC, United States of America

³ Arizona State University, School of Sustainability, Tempe, AZ, United States of America

E-mail: leslie.sanchez@tufts.edu

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Abstract

The American West confronts the challenge of fulfilling indigenous claims to water within the context of increasingly scarce and variable water supplies. 170 of 226 American Indian reservations have unresolved water claims that potentially exceed the region's hydrological capacity, generating uncertainty for tribes and off-reservation water users. To help resolve key uncertainties about dispute origins and outcomes, we construct a complete and novel dataset on Indian water settlements and reservation characteristics which we then analyze using a bargaining framework from economics. We find that rapid off-reservation population growth, water scarcity, and large anticipated water entitlements catalyze disputes. When more users are involved in the negotiations, transaction costs delay settlement, increasing water insecurity. We use our findings to predict allocations for 25 ongoing water right negotiations. These estimates help bound the uncertainty facing water managers throughout the American West.

1. Introduction

Competition over limited water resources is a defining characteristic of the American West, where population growth, climate change, and persistent drought exacerbate the gap between water supply and demand [1]. Sustainable water management in the western United States requires changes in the pattern and overall level of water use to reconcile the historic concentration of water use in irrigated agriculture and growing urban demands and with supplies that are becoming more variable at scales ranging from small streams to the Colorado River itself [2, 3]. The recognition of Native Americans' long-neglected—and often substantial—rights to water looms large in the future of water in the West because satisfying these claims is costly and could entail major changes in distribution of water rights [4].

The U.S. Supreme Court ruled in *Winters vs. United States* that the treaties signed with tribes in western states entitle them to federally reserved water rights that supersede other water uses developed subsequent to the formation of reservations in the late 19th century [5]. Since the original ruling in 1908, only 56 of 226 federally recognized reservations in

the western US have settled Winters claims. The most commonly cited figure for the potential amount of Winters claims of 45.9 million acre-feet per year comes from a rough estimate made in 1983 by the Western States Water Council [6]. This is three times the annual usage for the entire Colorado River, which is diverted to such an extent by seven arid western states that its waters no longer regularly reach the Gulf of California [7].

Despite the potential importance of tribal water claims, the process that determines the ultimate outcome is not well-understood. Womble *et al* quantify the approved and proposed adjudication agreements, but do not quantify the water resources under dispute, examine the outcomes of ongoing adjudications, or examine the determinants of adjudications or the duration of negotiations [4]. Deol and Colby compare a cross-section of 51 reservations using USDA and US Census data from 2010 and 2015 to show that reservations with adjudicated water rights appear to be stronger economically and agriculturally, but do not explore a complete set of western reservations over time [8].

We fill this critical knowledge gap by combining historical documents and settlement agreement texts

for all settled Winters claims with historical geospatial data on land and water use, government reports, and surveys of reservation-level socioeconomic characteristics for the full set of western reservations. We then adopt the economic framework developed by Ayres *et al* for the adjudication of groundwater rights [9] to our setting and study both the determinants and outcomes of Winters claims. Hence, we contribute to the literature on water rights adjudication by extending Ayres *et al* to a new setting and also provide important new insights into ongoing tribal water rights settlements. We then use these insights to predict the total volume of outstanding tribal water allocations.

Uncertainty about when and where tribes will assert Winters claims, the costs of resolving those claims, and potential changes in the distribution of water rights constrains economic development, inhibits investments and long-term water supply and demand planning, and impedes drought adaptation strategies and regional water-sharing agreements—all of which rely on well-defined and secure water rights. Thus, while understanding the outcomes of adjudications themselves is important, so too is understanding adjudication catalysts, the causes of delay and discord, and how delays can be overcome.

In the first stage of our analysis, we test for factors that increase a reservation's likelihood of initiating adjudication [10], and find that tribes are more likely to assert their claim in response to rapid population growth off-reservation, water scarcity, and large anticipated water entitlements. We then examine adjudication, or transaction, costs which may impede settlements [9], and find that adjudications involving more bargaining parties take significantly longer to resolve—the mean adjudication involves 33 parties and lasts 21 years. Finally, we use these insights to estimate the expected volume of water entitlements allocated to each tribe in ongoing settlement agreements. Our predictions of total water entitlements range between 1.2–1.6 million AFY, which is considerably less than the Western States Water Council's 1983 estimates of ~ 16 million AFY for these 25 reservations [6].

2. Historical background

Surface waters in western states are governed by the prior appropriation doctrine, which assigns water rights based on the timing of the initial claim. This 'first in time, first in right' allocation of water mandates that in times of shortage, senior water claims are fully satisfied before junior claims are filled. However, surface water rights were appropriated without regard for the needs of American Indian reservations. Although the federal government had treaty obligations to provide water for tribes, the allocation of individual water rights is the responsibility of states, which favored the interests of white settlers over pre-existing uses by indigenous peoples [11].

By the mid-1900's, most streams were fully allocated and dammed, diverted, and appropriated for irrigated agriculture, as well as energy, mining, and urban development, by non-indigenous water users [12]. As off-reservation water use exceeded the limits of natural system sustainability, tribal water availability became highly constrained and uncertain. Reservation agriculture in the Southwest and tribal fisheries in the Pacific Northwest declined when off-reservation irrigators depleted reservation streamflow and springs [13–16]. The National Water Commission acknowledged in 1973 that '[i]n the history of the United States Government's treatment of Indian tribes, its failure to protect Indian water rights for use on the Reservations it set aside for them is one of the sorrier chapters' [17].

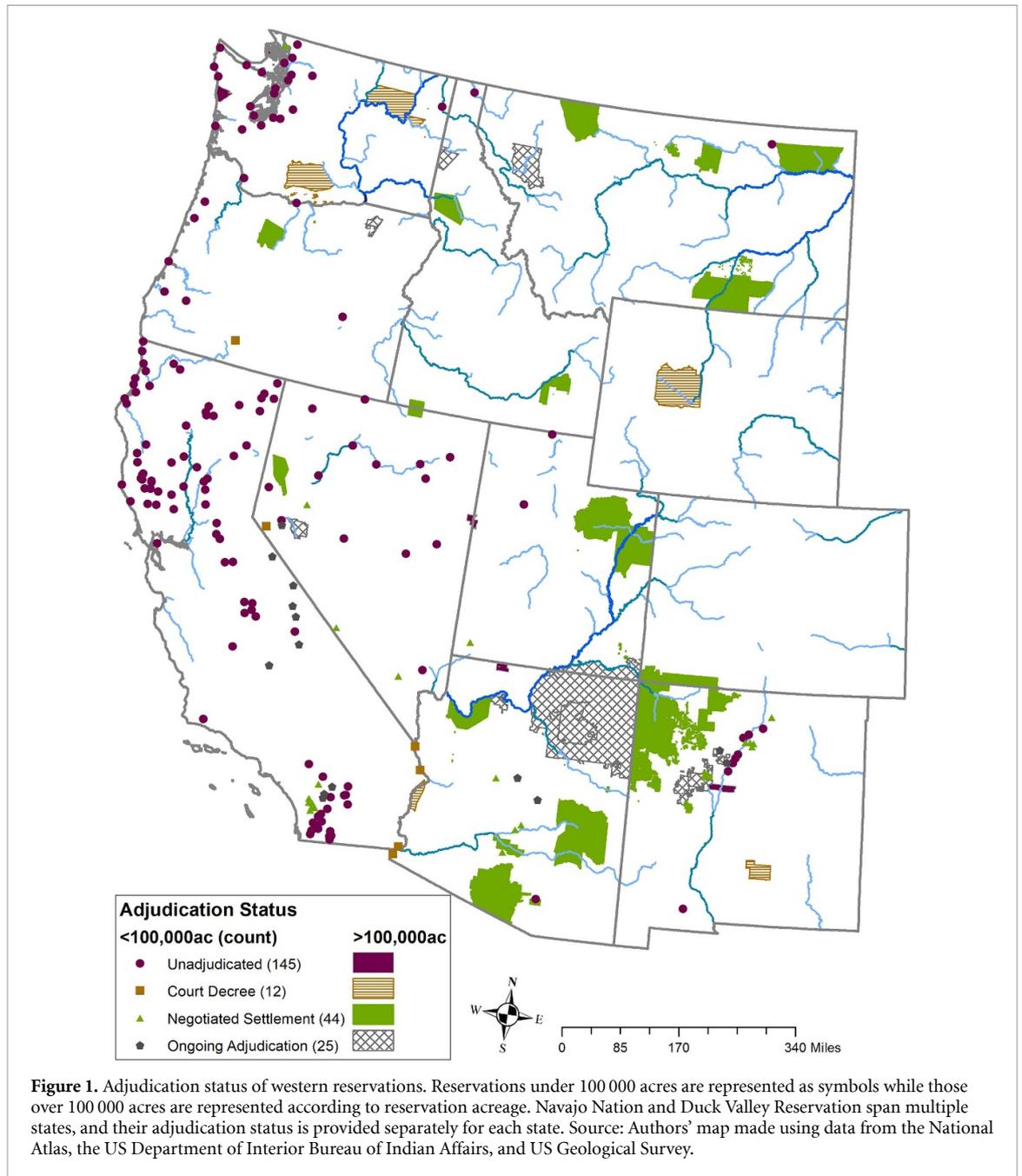
In 1908, the US Supreme Court (*Winters v. United States*) ruled that tribes have water rights 'sufficient to fulfill the need of the reservation as a homeland' [5]. Crucially, these 'Winters Rights' are federally reserved water rights with priority based on the date a reservation was established. In many basins, this meant that tribes had implicit but unquantified rights with greater seniority than most existing water users that established water rights *after* reservations were formed. However, because the ruling did not explicitly grant tribes appropriative rights or establish metrics to determine what quantity of Winters Rights tribes should receive, conflict persists between existing water users and contemporary Winters Right claims [17].

Winters Rights are adjudicated either via court decree achieved through litigation or negotiated settlement agreement. Negotiated settlements, the most prevalent adjudication strategy, typically result in a combination of water entitlements and federal funding for tribes. Tribes can pursue Winters Rights by filing 'breach of trust' claims against the U.S. government for damages they incurred when the government—which holds tribal resources in trust—neglected to claim water on tribes' behalf after the initial 1908 Winters ruling. If these claims are found to have merit, the federal government is legally bound to assert claims to water for tribes, assist tribes in resolving these claims through litigation and negotiation, and support settlement implementation. Figure 1 shows the location of reservations in western states and their adjudication status.

3. Methods

3.1. Economic framework

Ayres *et al* develop an economic framework to study the adjudication of previously unquantified groundwater rights. Their approach first examines the likelihood of adjudication, finding it is increasing in the benefits to users. Then, they examine the role of contracting costs, defined as costs 'that arise during



private bargaining to redefine ownership arrangements as well as efforts to define the resource's extent and characteristics' [17, p. 47]. Their results show that where contracting costs are high, agreements are delayed or never reached [9]. We adapt this approach to the institutionally similar process undertaken by tribes and off-reservation water users in a basin during a Winters claim.

Generally, parties participate in an adjudication when their expected benefits from doing so exceed their costs. Physical water scarcity and the corresponding growth in the value of water, as in other resources, may increase the benefits of resolving property right claims, if sufficient water is available [18]. The marginal value of surface water increases where precipitation and streamflow are scarce [19]. Tribes benefit from legally defining their priority rights to

water because they acquire the ability to generate income from water through sales, leases, or productive use [20]. For example, after settlement the Navajo Nation in New Mexico developed the Navajo Agricultural Production Industry and the Gila River Indian Community earned \$97.5 million per year leasing 18 000 acre-feet of water [21]. Off-reservation right holders participate in negotiations to resolve uncertainty about how Winters Rights will be accommodated (i.e. from which appropriators), or to avoid being litigants to proceedings in state courts.

Agreement may prove elusive even when the net gains from settlement are positive for the basin as a whole [22]. Some users who do well under the status quo may oppose agreement, and the costs to bring them on board may be high. Perramond finds evidence that adjudications in New Mexico required

such high levels of spending to facilitate agreement that the costs may have exceeded the aggregate value of the water in the agreement [23]. Increases in the number and heterogeneity of bargaining parties tend to increase the transaction costs of negotiation and make agreement less likely, although this is not always the case [10, 24]. Heterogeneity in physical water availability, such as across water users in a basin, influences information costs and bargaining positions of adjudication parties [25].

Conflicting bargaining positions arise from different perceptions of fairness and from information asymmetries [22]. If the legal outcome of cases is not clear because of limited precedent, opportunities for negotiation may be reduced. For example, the Walker River Irrigation District in Northern Nevada has effectively delayed quantification of the Walker River Paiute Tribe's water rights for almost 95 years through litigation [26]. Off-reservation appropriators argue that the legal seniority of their water rights should be maintained, whereas tribes argue that appropriators have no inherent right to water, but rather have benefited from free use of the tribes' water [27]. Federal funding in negotiated settlements can defray high contracting costs and facilitate agreement. For instance, many settlements include compensation for irrigation districts that forfeit water to satisfy newly defined Winters Rights [28].

Our empirical study focuses on 226 federally recognized reservations in the 11 western states that use the appropriative rights doctrine, as shown in figure 1. Eighty-one reservations have initiated the process of adjudicating their water rights, leaving 145 that have not yet started the process. Figure 2 depicts adjudication timelines for these 81 reservations. Of these, 56 reservations have resolved their Winters claims—44 through negotiated settlements and 12 through court decree. We treat Navajo Nation and Duck Valley Indian Reservation as distinct reservations in each state they overlap because they must pursue separate adjudications in each state.

3.2. Likelihood of adjudication

Using the full sample of 226 reservations, we test for the probability of a reservation having initiated the Winters adjudication process as a function of underlying determinants of adjudication benefits using a logistic regression model. We model the unobserved benefits of an adjudication for reservation i , adj_i^* , as a function of \mathbf{B}_i , a vector of adjudication benefit factors for each reservation:

$$adj_i^* = \mathbf{B}_i\beta + e_i \quad (1)$$

where e_i is the standard econometric error term. We observe the outcome of whether a tribe has initiated the adjudication process adj_i , where $adj_i = \{0, 1\}$ represents non-adjudicating, adjudicating. We assume that $adj_i = 1$ when the unobserved benefits of adjudication exceed the cost, $adj_i^* > \kappa$, and estimate our

model using a logistic regression. The magnitude of slope estimates, $\hat{\beta}$, indicate the extent to which an independent variable increases or decreases the likelihood of entering the adjudication process.

Independent variables, described in table 1, are either time-invariant or constructed to measure conditions prior to the start of adjudication. The approach is potentially susceptible to omitted variable bias. We include several robustness checks controlling for common metrics that affect reservation outcomes like access to credit, casino operation, and reservation per capita income, to reduce these concerns. Prime acreage, adapted from Leonard *et al*, is an exogenous measure of the area of land that irrigation water could be put to agricultural use on-reservation [29]. It is indicative of larger water claims, and therefore a larger opportunity cost of forgoing adjudication. Stream order measures water availability. To the extent that adjudication costs are fixed, larger volumes of water found in larger streams will result in lower adjudication costs per unit of [30]. Off-reservation population growth reflects water value over time; point-of-diversion density and precipitation are measures of water scarcity. Summary statistics are presented in table A1-1.

3.3. Adjudication duration

Next, we test for factors that increase the duration of the legal resolution of Winters claims by focusing on reservations that have completed an adjudication. Duration is measured as the number of years between initiating and finalizing the adjudication. We construct a second dataset for 44 adjudication agreements that have resolved Winters claims for 56 reservations. We use a Cox Proportional Hazard Model (CPH) to test the effect of covariates on the time to resolve Winters claims. The hazard function represents the probability that an adjudication ends after having lasted t years:

$$\lambda(t|\mathbf{C}) = \lambda_0(t) e^{t\hat{\gamma}} \quad (2)$$

where $\lambda(t|\mathbf{C})$ represents the proportional hazard as a function of the number of years to complete adjudication conditional on covariates, \mathbf{C}_i , representing determinants of contracting costs, and λ_0 is the hazard function. The estimated coefficients, $\hat{\gamma}$, describe the effect of covariates on the hazard rate once a reservation has initiated adjudication (a negative sign indicates a lower probability of adjudication in a given time period and thus a longer adjudication process). Table 2 describes the independent variables used in this analysis, while summary statistics are presented in table A1-2.

Primary data on negotiated settlement agreements, settlement terms, bargaining parties, water entitlements, and federal funding were collected from individual settlement texts housed at the University of New Mexico's (UNM) Native American Water Rights

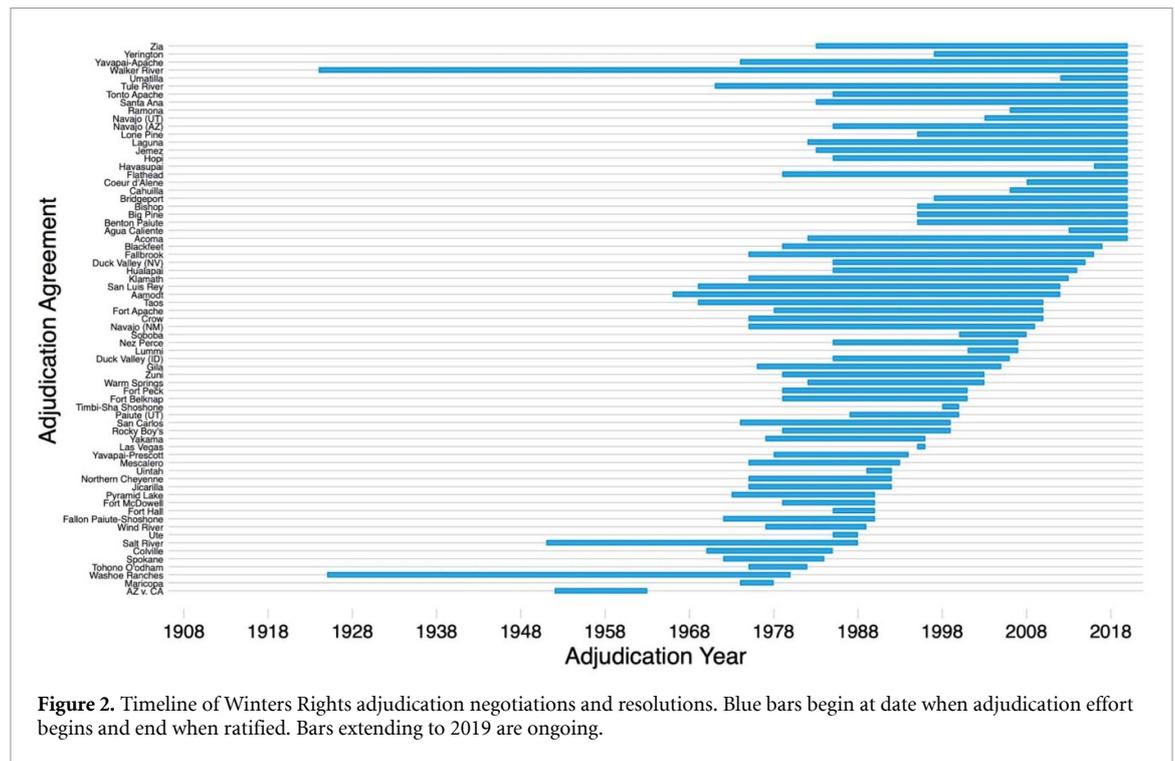


Figure 2. Timeline of Winters Rights adjudication negotiations and resolutions. Blue bars begin at date when adjudication effort begins and end when ratified. Bars extending to 2019 are ongoing.

Table 1. Independent variables for logistic probability model.

Variable	Definition	Source
Prime Acreage	Reservation logged acreage with a productivity index ≥ 9	Schaetzl, 2012
Stream Order	Highest stream order within reservation boundaries	USGS
Off-Reservation Pop. Growth Rate	Population growth rate (%) of counties overlying reservation in the decade prior to adjudication start. The measure excludes reservation populations	US Census
POD Density	Number of off-reservation surface water points of diversion per square mile of HUC6 basins intersecting the reservation.	State Water Resource Depts
Precipitation	1980–2010 mean 30-year normal precipitation (mm) that fell within reservation boundaries during the months of Apr.-Sept.	PRISM
BIA Region	Categorical variable representing BIA region in which reservation is located	BIA
Credit (2018)	Number of tribal lending institutions to which a reservation had access in 2018	Minneapolis Federal Reserve
Casino Prior to Adjudication Start	A reservation is assigned a value of 1 if it operated a casino prior to adjudication start and is assigned a value of 0 if it did not. Reservations with unadjudicated water rights are assigned a value according to their current casino operation	500nations.com Worldcasinodirectory.com
Reservation PCI	Per capita reservation income in year 2000	US Census

Settlement Project. Primary data on litigated adjudications comes from State and District court filings and from the Indian Claims Commission Decisions housed at the Oklahoma State University Library. A large number of bargaining parties may complicate, and thus delay the resolution of Winters claims. Unique party types and spatial covariance of precipitation are measures of bargaining party and resource heterogeneity, which may increase time to resolve Winters claims. Democratic Congressional majority, from Congressional Research Service (CRS) data,

measures the partisan priorities involved in resolving Winters claims.

3.4. Predicting future adjudications

Finally, we assess the distribution of water entitlements of 36 negotiated settlements to the 44 reservations included in those agreements to create a prediction of pending adjudications. The ultimate distribution of a tribal water entitlement as defined in each adjudication agreement is measured as the

Table 2. Independent variables for CPH duration analysis.

Variable	Definition	Source
Bargaining Parties	The total number of either a) signatories to the settlement agreement, or b) the total number of parties recorded in individual court case dockets.	UNM; US Courts
Unique Party Types	Bargaining parties are categorized as (a) reservations, (b) state or federal government, (c) irrigation entities, (d) municipal water providers, (e) individuals, and (f) other. The variable is calculated as the total number of party categories present in each adjudication.	UNM; US Courts
Basin Precipitation Spatial Covariance	Square root of spatial precipitation variance on basins overlying reservations within an adjudication, divided by mean precipitation in those basins.	PRISM
Democratic Congress	Number of years of Democratic majority in the House and Senate, as a percentage of total years to resolve claims.	CRS

annual acre-foot per year (AFY) volume of non-consumptive water rights assigned under the agreement.

We identify settlement-level covariates that potentially affect the ultimate distribution of water entitlements. Prime acreage, reservation acreage, and farmed acreage (1974) reflect the volume of legal claims to water, as well as water demand. Although farmed acreage was not used in our test of likelihood of adjudication because 1974 data do not predate earlier court decreed adjudications, we use it here as a predictor. Farmed acreage is available from the U.S. conterminous wall-to-wall anthropogenic land use trends (NWALT) 1974–2012 dataset [31]. The year when a settlement is finalized, stream order, off-reservation population growth rate prior to settlement, mean basin precipitation, and adjudicated reservation area within a state as a percentage of state area are measures of water scarcity. Controls include casino operation; reservation population prior to settlement, and BIA region.

We use the Akaike Information Criterion corrected for small sample size (AICc) to select a parsimonious model for predicting water entitlements of pending adjudications [32]. First, we calculate the AIC score for potential model specifications:

$$AIC_i = 2K - 2\ln(\mathcal{L}) \quad (3)$$

where AIC_i is a relative score assigned to each potential model, i , K is the number of parameters in the model, and \mathcal{L} is the maximum value of the likelihood function of the model. We correct for small sample size using the AICc formula:

$$AICc_i = AIC_i + \frac{2K^2 + 2K}{n - K - 1} \quad (4)$$

where $AICc_i$ is the second order AIC_i score assigned to each potential statistical model and n is the number of observations.

We select the model with the lowest AICc score, and use a multilinear regression model to test the relationship between our predictors and AFY outcomes:

$$\ln(AFY_i) = \alpha + \mathbf{X}_i\eta + u_i \quad (5)$$

Our dependent variable, $\ln(AFY_i)$, is the logged AFY entitlement awarded in settlement, i , and \mathbf{X}_i , is a vector of explanatory variables selected via AICc. The magnitude of the estimated coefficients, $\hat{\eta}$, indicate the extent to which independent variables are correlated with water entitlement outcomes. Using these model parameters, we predict water entitlements for 25 ongoing adjudications.

4. Results

4.1. Water scarcity drives adjudications

We first test the relationship between adjudication benefits and the probability the adjudication process is initiated. Because the coefficient estimates are difficult to interpret, we estimate equation (1) and report the odds ratios in table 3. A larger odds ratio indicates that a variable makes adjudication more likely. The results indicate that the probability of pursuing adjudication increases when the value of water rises through increasing demand, constrained supply, and rising opportunity costs of forgoing adjudication. Off-reservation population growth rate in the decade prior to adjudication start is positively correlated with the probability of tribal adjudication. As populations grow, water demand increases, as do the expected benefits of legally secure water rights. Mean precipitation is negatively and significantly correlated with the probability of a reservation having initiated adjudication. Less precipitation is indicative of water scarcity, which increases the relative value of water.

All else equal, reservations with higher prime acreage are more likely than their counterparts to

Table 3. Logistic regression results: net effects of adjudication determinants (odds ratios).

	All reservations			2010 reservation population ≥ 100		
	[1]	[2]	[3]	[4]	[5]	[6]
ln(Prime Acres)	1.217** (0.0998)	1.188* (0.105)	1.152 (0.0996)	1.210** (0.104)	1.178* (0.107)	1.155* (0.0997)
Stream Order	1.334*** (0.145)	1.389*** (0.166)	1.185 (0.172)	1.285** (0.151)	1.262* (0.173)	1.152 (0.172)
Off-Res. Pop. Growth Rate	1.026*** (0.00796)	1.029*** (0.00938)	1.024** (0.0111)	1.022*** (0.00853)	1.023** (0.0103)	1.023** (0.0111)
POD Density	1.402 (0.289)	1.575* (0.407)	1.551 (0.500)	1.353 (0.294)	1.494 (0.408)	1.494 (0.470)
Precipitation	0.970** (0.0132)	0.969** (0.0137)	0.952** (0.0190)	0.970** (0.0137)	0.967** (0.0131)	0.953** (0.0179)
BIA Region	1.409*** (0.179)	1.098 (0.157)	1.073 (0.171)	1.461*** (0.198)	1.048 (0.174)	1.035 (0.169)
Casino		0.102*** (0.0483)	0.0742*** (0.0486)		0.0829*** (0.0439)	0.0699*** (0.0456)
Credit (2018)			1.734* (0.524)			1.707* (0.524)
Reservation PCI 2000			1.000 (5.78e-05)			1.000 (5.89e-05)
Observations	216	216	138	154	154	135

Notes: Columns 4–6 serve as robustness checks based on reservation population. Restricting our sample to reservations with populations ≥ 100 excludes most California rancherias, and smaller reservations that generally do not practice agriculture. Linear probability model results, presented in table A2-1, serve as a robustness check and are consistent with logistic regression results. All model specifications include a constant. Robust standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

pursue adjudication. Stream order positively predicts adjudication in model specifications that exclude controls for income and access to credit. Both results are statistically significant at the 10% or higher level in most, but not all, the specifications. Greater prime acreage and larger streams are key variables determining the volume of water per dollar of fixed adjudication costs and are indicative of larger anticipated adjudication benefits relative to costs. Findings are generally consistent across the full sample of reservations and a restricted sample of reservations with a 2010 population of at least 100.

4.2. Contracting costs lengthen negotiations

We test the relationship between the duration of negotiations and predictors of high contracting costs. CPH results are shown in table 4. Despite the small number of observations, we observe statistically significant results across model specifications: an increasing number of bargaining parties is highly correlated with a more protracted adjudication process. We test for the effect of heterogeneity in the types of bargaining parties but find ambiguous results. Spatial precipitation heterogeneity is, unexpectedly, weakly correlated with more expeditious resolution of claims.

Results also suggest that a higher percentage of years of Democratic congressional majority is significantly correlated with a more expedited adjudication process when controlling for economic characteristics of tribes. This finding is supported by anecdotal accounts of tribes waiting to have settlements

ratified by a Democratic congress and suggests the key role government financing plays in facilitating agreement.

4.3. Determinants and predictions of water entitlements

AICc results (tables A3-1 and A3-2) relating entitlement outcomes and control variables indicate that a model with the lowest AICc score ($AICc = 108.999$) includes logged farmed acreage (1974), mean basin precipitation, and logged reservation acreage. Using this model, we use a multilinear regression to analyze the outcomes of completed negotiated settlement agreements (table 5).

All else equal, water entitlement volumes are positively and significantly correlated with reservations' farmed acreage in 1974, and with total reservation acreage. Mean basin precipitation, indicative of water available to satisfy water claims, is negatively correlated with water entitlement levels within a settlement.

We extend these parameters to predict water entitlement outcomes to 25 reservations currently undergoing adjudication. Figure 3 shows the predicted outcomes of the 25, in red, along with actual negotiation outcomes relative to the amount the model predicts of the 36 reservations from table 5, in blue. Prediction results for 25 individual adjudicating reservations are shown in table A3-3, where we provide the 95% confidence interval around the mean settlement prediction. Our prediction of total water entitlements range between 1.2–1.6 million

Table 4. Cox proportional hazard regression results.

	[1] Duration	[2] Duration	[3] Duration	[4] Duration	[5] Duration	[6] Duration
Bargaining Parties	-0.00525** (0.00255)	-0.00839** (0.00343)	-0.00940*** (0.00361)	-0.00578** (0.00248)	-0.00897*** (0.00340)	-0.0103*** (0.00361)
Democratic Congress	0.0142 (0.0120)	0.0252** (0.0110)	0.0262** (0.0107)	0.0139 (0.0106)	0.0248** (0.00967)	0.0252*** (0.00912)
Unique Party Types	0.0367 (0.107)	-0.00944 (0.123)	-0.0639 (0.136)			
Basin Precipitation				1.902* (1.105)	2.215 (1.383)	2.566* (1.433)
Spatial COV						
Casino		-0.270 (0.802)	-0.621 (0.854)		0.255 (0.831)	-0.115 (0.843)
Reservation PCI 2000		3.35e-05 (8.00e-05)	3.57e-05 (7.80e-05)		1.34e-05 (7.99e-05)	2.13e-05 (7.69e-05)
Credit (2018)			-0.186 (0.130)			-0.238** (0.119)
Observations	44	41	41	44	41	41

Notes: Results are displayed as coefficients. A negative sign on the coefficient implies a negative marginal effect on the hazard rate, which, all else equal, increases the expected duration of the adjudication process. Robust standard errors in parentheses ***p < 0.01, **p < 0.05, *p < 0.1

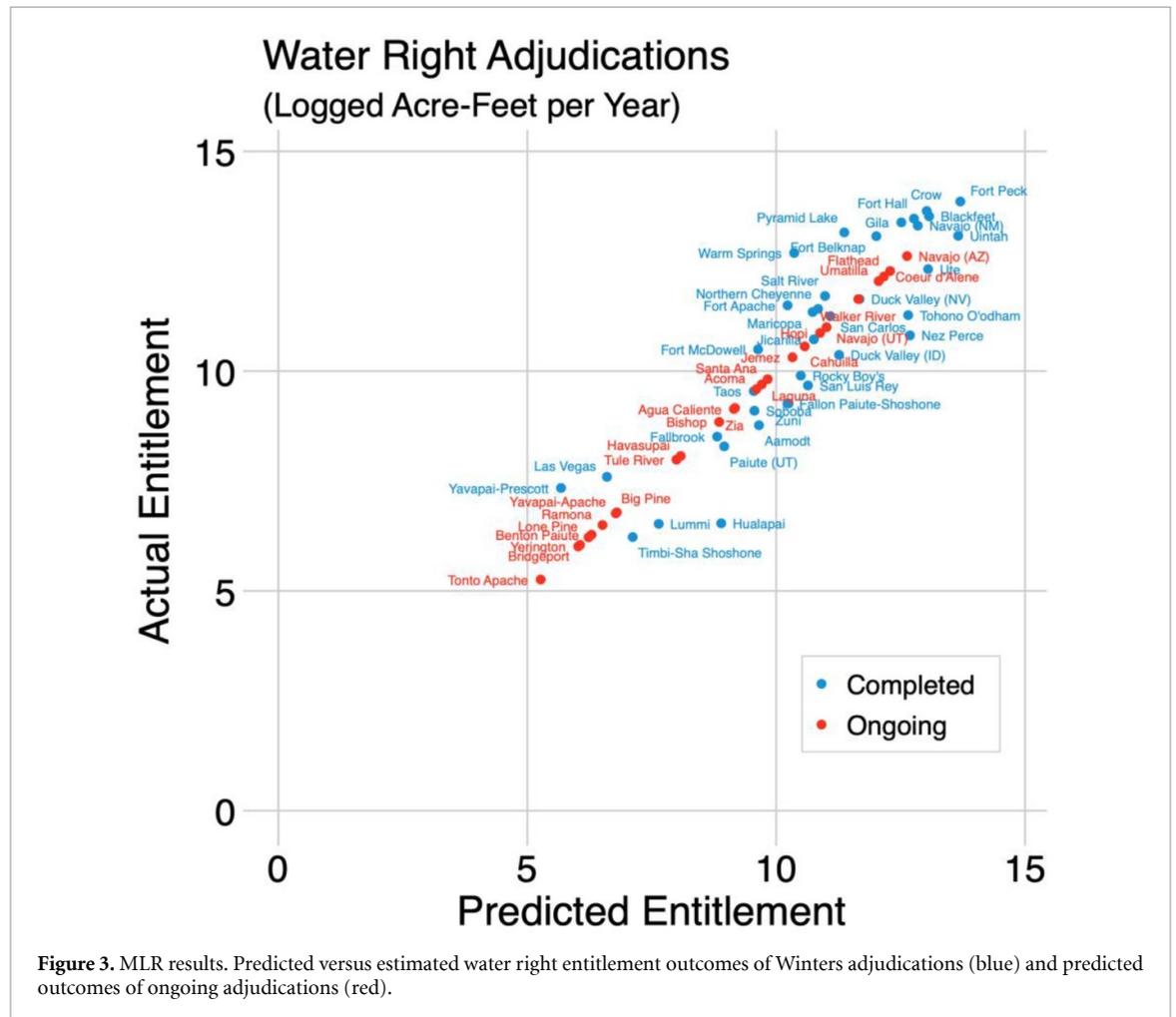


Figure 3. MLR results. Predicted versus estimated water right entitlement outcomes of Winters adjudications (blue) and predicted outcomes of ongoing adjudications (red).

AFY, which is considerably less than the Western States Water Council's 1983 estimates of ~ 16 million AFY for these 25 reservations [6]. Prediction estimates should be interpreted with some caution

because there is no established metric for quantifying tribal water allocations; the confidence intervals represent modeling uncertainty, not uncertainty of expected outcomes.

Table 5. MLR estimates of AFY entitlements.

	ln(AFY)
Logged reservation acreage	0.4047*** (0.1263)
Mean basin precipitation	−0.0419*** (0.0146)
Logged reservation farmed acreage (1974)	0.4030*** (0.0891)
Observations	36
R-squared	0.7811

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

5. Discussion

This article provides new insight into the physical and economic context in which legal disputes over tribal water rights are resolved. These outcomes are informative beyond the western United States. In Chile and Australia, for instance, indigenous groups received land titles without appurtenant water rights. In Australia, indigenous land exceeds 30% of the country's land base, while indigenous water rights are less than .01% of total water allocations [33]. In arid northern Chile, the desiccation of indigenous water sources via legal groundwater right extractions has led to considerable legal uncertainty over the use and transfer of all water rights [34].

Our analysis of a new, comprehensive dataset of Winters outcomes shows that tribes are more likely to assert claims when physical water availability is limited, competing demand for water grows, and the relative value of water increases. Tribes are also more likely to pursue adjudication when the amount of settlement is expected to be sufficiently large to overcome the costs of negotiating. However, high contracting costs deter tribes from resolving legal claims. Ayres *et al* also found bargaining costs hampered agreement, but the outcomes of tribal adjudications suggest a greater importance of the number of bargaining parties, rather than the heterogeneity of bargaining parties, in raising these costs.

Because many tribes face lengthy adjudication, reservation populations and ecosystems may continue to endure water shortages for years after an adjudication is initiated. Hence, transaction costs that slow the adjudication process amplify the impacts of water scarcity on public health, tribal economies, and the environment. Anecdotes describing tribes' experiences of water scarcity include depleted wells for irrigation and household drinking water as well as streamflow depletion that collapses fisheries [13, 35]. Meanwhile, off-reservation water users forego economic benefits of water right security, as disputes over water deter investments in agriculture and urban development and inhibit accurate water planning.

Winters adjudications typically begin in state courts prior to negotiation, and litigation involves more parties because of legal requirements to involve all water users in the basin. Once a tribe begins to pursue a negotiated settlement, the number of parties typically falls. Our work provides insight into reducing the length of the adjudication process: high numbers of users delay settlement, so opting to negotiate earlier in the adjudication process may reduce the overall duration—and costs—of resolving Winters claims.

Even as off-reservation agricultural water use is declining [36], the incentives embedded in Winters adjudication process may steer reservation economies *towards* agriculture because Winters claims, entitlements, federal funding, and settlement infrastructure are premised on and provided to support the pursuit of agriculture, and settlement agreement funding is often targeted at agricultural water delivery infrastructure [37]. Given that agriculture is an inherently water-intensive activity, tribes can improve their bargaining positions by asserting Winters claims based on the amount of farmed acreage on a reservation, or on plans to develop reservation agriculture. This dynamic potentially pushes tribes toward less sustainable water use in a landscape where managers are focused on moving water use out of agriculture to urban and environmental uses [38].

This paper relies on several key assumptions. First, the statistical analysis is primarily based on statistical correlations and causal interpretations based solely on this work should be undertaken with caution. Second, our analyses have a limited number of observations, especially when focused on the subset of reservations that have settled. However, we emphasize that our dataset comprises the entire population of Winters-eligible reservations, so the results we report are population averages rather than sample statistics. Third, an important assumption in our predictions is that future water right settlements will tend to be determined by the same factors as past settlements. However, because there is no definitive rule for Winters adjudications, this will not necessarily be the case. Finally, the study focuses only on outcomes for federally recognized tribes legally able to claim Winters Rights, but this distinction does not fully capture all potential claims to water by indigenous groups [23].

With these limitations in mind, our results suggest that the future impact of unadjudicated Winters Rights for off-reservation users may not be as severe as anticipated. We find that a key predictor of water allocations is farming capacity, how much agriculture the tribe undertook in 1974, which is fixed for each tribe. The largest reservations, poised to receive the most water, have already adjudicated. As such, previous estimates of unresolved claims to Winters Rights, based on early negotiated settlements, overstated the entitlements that tribes have subsequently received by a factor of 10. Thus, although many tribes still have

'implicit' rights to water, the amount of water that will ultimately result from these claims is likely much smaller than is often assumed. While this may reduce the challenges faced by policymakers and water managers in reallocating water rights, it underscores the enduring negative impacts of reservation-era policies for tribes who now have limited prospects for securing substantial water rights.

Winters settlements, however, do provide benefits for tribes by creating secure property rights and resolving uncertainty. Moreover, they have generated opportunities to implement water marketing activities to address shared water shortages, potentially bringing stressed natural systems into more sustainable use [4]. They have also moved water off-reservation via leases to users who have more capacity to place the water in high-value uses [39]. In a recent example, the Gila River Indian Community

will lease 200 000 acre feet to the Arizona Water Banking Authority in 2019 and 2020 as part of the Lower Colorado River Drought Contingency Plan [40]. The leasing of adjudicated Winters Rights offers revenue for tribes and the potential for water managers to address ecological and urban water shortfalls, but has also been characterized as another pathway for tribally-owned resources to be consumed off-reservation [41]. A key question for future research revolves around characterizing what happens to Winters Rights after agreement, and what the impact of settlements has been on tribal economic, social, and environmental outcomes.

Appendix

A1. Summary statistics

Table A1-1. Reservation-level summary statistics, mean and (standard deviation).

	Adjudicating	Non-Adjudicating	Total
Number of reservations	81	145	226
ln(Prime Acres)	9.420 (4.331)	5.728 (3.048)	7.051 (3.970)
Stream Order	5.319 (2.251)	2.75 (2.139)	3.668 (2.498)
Off-Reservation County Population Growth Rate (%)	30.332 (30.552)	12.809 (12.228)	19.329 (22.590)
POD Density (POD/mi ²)	0.001 (.0013)	0.001 (0.002)	.001 (.001)
1980–2010 mean April-Sept PRECIPITATION NORMAL (mm)	24.805 (14.794)	30.094 (21.808)	28.198 (19.715)
Credit (number of lending institutions to which reservations have access in 2018)	1.086 (1.200)	0.455 (0.764)	0.681 (.987)
Casino operation prior to adjudication start = 1 (dummy variable)	0.086 (.283)	0.503 (0.502)	0.354 (0.479)
Reservation Per Capita Income (2000)	11 160.99 (4175.923)	12 208.88 (5701.663)	11 651.01 (4957.478)

Notes: Standard deviation in parentheses. The sample contains 226 federally recognized reservations in AZ, CA, CO, ID, MY, NM, NV, OR, UT, WA, and WY. Navajo Nation counted as three separate reservations, as Winters claims are adjudicated separately in AZ, NM, and UT. Duck Valley is counted as two separate reservations, as it adjudicated Winters claims separately in ID and NV. Adjudicating reservations include those that have either resolved claims or have initiated the process of resolving claims. Non-adjudicating reservations include those that have not initiated the adjudication process.

Table A1-2. Adjudication-level summary statistics.

	Mean	Standard deviation	n
Number of Bargaining Parties	33.5	79.018	44
Unique Party Types	3.364	1.366	44
Democratic Congressional majority years as a percentage of adjudication years	51.264	27.559	44
Democratic Congressional majority in House and Senate in settlement resolution year = 1 (dummy variable)	0.417	0.5	36
Basin Precipitation Spatial Coefficient of Variance	0.343	0.177	44
Casino operation prior to adjudication start = 1 (dummy variable)	0.0455	0.211	44
Reservation Per Capita Income (2000)	10 857.86	3695.07	41
Credit (number of lending institutions to which reservations have access in 2018)	1.386	1.224	44

A2. Adjudication determinants

Table A2-1. Linear probability model regression results: net effects of adjudication determinants.

	All reservations			2010 reservation population ≥ 100		
	[1]	[2]	[3]	[4]	[5]	[6]
ln(Prime Acres)	0.0339*** (0.0117)	0.0288** (0.0112)	0.0236* (0.0141)	0.0364*** (0.0138)	0.0284** (0.0130)	0.0244* (0.0144)
Stream order	0.0412** (0.0163)	0.0431*** (0.0155)	0.0233 (0.0203)	0.0377* (0.0197)	0.0301 (0.0192)	0.0193 (0.0208)
Off-Res. Pop. growth rate	0.00446*** (0.00122)	0.00432*** (0.00115)	0.00341*** (0.00125)	0.00384*** (0.00130)	0.00327*** (0.00122)	0.00322** (0.00125)
POD Density (POD/mi ²)	0.0376 (0.0313)	0.0411 (0.0278)	0.0482 (0.0340)	0.0369 (0.0364)	0.0419 (0.0307)	0.0437 (0.0344)
Precipitation (mm)	-0.00367*** (0.00140)	-0.00361*** (0.00130)	-0.00631*** (0.00159)	-0.00448*** (0.00166)	-0.00479*** (0.00149)	-0.00636*** (0.00161)
BIA Region	0.0582*** (0.0221)	0.0193 (0.0220)	0.00629 (0.0242)	0.0644*** (0.0242)	0.00577 (0.0239)	0.000641 (0.0241)
Casino Prior to Adj. Start		-0.294*** (0.0550)	-0.429*** (0.0876)		-0.416*** (0.0797)	-0.451*** (0.0882)
Credit (2018)			0.0739* (0.0403)			0.0716* (0.0404)
Reservation PCI 2000			-7.17e-07 (8.44e-06)			-1.31e-06 (8.70e-06)
Constant	-0.242** (0.0984)	0.0314 (0.116)	0.341* (0.198)	-0.201 (0.126)	0.292* (0.161)	0.408** (0.199)
Observations	216	216	138	154	154	135
R-squared	0.392	0.652	0.467	0.348	0.629	0.467

Notes: Columns 4–6 are robustness checks, based on reservation population, which is highly correlated (.8161) with reservation land area. Restricting our sample to reservations with populations ≥ 100 excludes most California rancherias, and smaller reservations that generally do not practice agriculture. Columns 2, 3, 5, and 6 contain additional controls for economic capacity: fractionated land area as a percentage of reservation area, number of lending institutions available to a reservation in 2018, and the presence of a casino prior to adjudication start. Robust standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

A3. Water entitlement predicted outcomes

Table A3-1. Summary of AICc results for models relating AFY water entitlement outcomes with control variables.

Model	K	n	AICc	AIC
M ₁	1	36	123.1589	122.3589
M ₂	2	36	115.5659	114.1866
M ₃	3	36	108.9994	106.8565
M ₄	4	36	110.3824	107.2713
M ₅	5	36	111.5581	107.2504
M ₆	6	36	114.4651	108.7051
M ₇	7	36	117.5304	110.0304
M ₈	8	36	121.3958	111.8306
M ₉	9	35	125.7855	113.7855
M ₁₀	10	35	130.6376	115.7805

Notes: K indicates the number of parameters included in each model specification, while n indicates the number of observations. AICc is the Akaike Information Criterion corrected for small sample size, and AIC is the Akaike Information Criterion. AIC and AICc are relative scores. We select the model (M₃) with the lowest AICc score.

Table A3-2. Predictors for each AICc model.

Model	Predictors
M ₁	Logged farmed acres (1974)
M ₂	Logged farmed acres (1974); logged reservation acres
M ₃	Logged farmed acres (1974); logged reservation acres; mean basin precipitation
M ₄	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area
M ₅	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres
M ₆	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres; casino operation
M ₇	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres; casino operation; off-reservation decadal population growth rate prior to resolution
M ₈	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres; casino operation; off-reservation decadal population growth rate prior to resolution; stream order
M ₉	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres; casino operation; off-reservation decadal population growth rate prior to resolution; stream order; logged reservation population prior to resolution
M ₁₀	Logged farmed acres (1974); logged reservation acres; mean basin precipitation; percentage of adjudicated reservation area to state area; logged prime acres; casino operation; off-reservation decadal population growth rate prior to resolution; stream order; logged reservation population prior to resolution; BIA region

Notes: Table specifies dependent variables included in each AICc model specification. Variables specified in model 3 (M₃), which has the lowest AICc score, are included in our multilinear regression analysis that tests for determinants of AFY water entitlements.

Table A3-3. Upper and lower bounds on predicted water right allocations for completed and ongoing adjudications and actual settlement amounts, where settled.

Adjudication Agreements	Western States Water Council	Entitlement (AF yr ⁻¹)	Prediction (95% CI)		Ongoing Adjudications	Western States Water Council	Prediction (95% CI)	
			Lower bound	Upper bound			Lower bound	Upper bound
Timbi-Sha Shoshone		507	1160	1693	Yavapai-Apache	3000	842	1207
Lummi	21072	685	2122	4279	Tonto Apache		186	297
Hualapai	386	694	7447	14998	Bridgeport		402	579
Yavapai-Prescott	986	1550	278	429	Ramona		630	895
Las Vegas		2000	691	998	Benton Paiute		506	721
Paiute (UT)		4000	7253	9016	Yerington	4725	388	560
Fallbrook	11408	4994	6281	8058	Lone Pine	948	477	682
Aamodt	62517	6467	14600	18044	Havasupai	1120	3173	5649
Soboba	3080	9000	13283	17019	Big Pine		820	1136
Fallon Paiute-Shoshone	13612	10588	25767	34300	Santa Ana	17610	17531	20298
Zuni	9100	10600	26434	35698	Bishop		6575	9377
Taos	21000	14058	13141	16389	Zia	11795	8988	11658
San Luis Rey	25373	16000	38951	48997	Cahuilla		36496	47923
Rocky Boy's	131400	20000	34000	39960	Jemez	10209	28952	32966
Duck Valley (ID)	100800	32062	73670	85086	Hopi		50082	73994
Fort McDowell	45000	36350	14366	17266	Acoma	11239	13832	19326
Jicarilla	36288	45646	43816	57784	Navajo (AZ) ^a	15000000	290863	457859
Nez Perce	14556	50000	302475	380971	Navajo (UT)		56948	83413
San Carlos	350000	77435	61060	83541	Tule River	510	2850	4626
Tohono O'odham	12284300	79200	291664	397159	Laguna	15670	15440	22020
Maricopa	85000	85000	42732	56647	Walker River	25000	107488	131191
Northern Cheyenne	486500	91330	48077	57252	Flathead	614030	202839	262339
Fort Apache	518169	99000	26644	44150	Coeur d'Alene	84075	180157	216984
Duck Valley (NV)	95425	114082	111093	127774	Umatilla	126800	161621	198621
Salt River	191000	122400	54927	67977	Agua Caliente		8819	12246
Ute		225488	437175	531738	Total	15937241	1196905	1616567
Warm Springs	7493	325786	29600	41502				
Fort Belknap	211400	477408	154820	184161				
Uintah	481078	481035	796976	1001579				
Pyramid Lake	4258	520000	80724	104368				
Navajo (NM)		633532	353764	451458				
Gila	1865470	653500	255100	307768				
Fort Hall	563290	711862	328934	398497				
Blackfeet	2025000	750000	445775	544635				
Crow	2114100	847000	424780	515527				
Fort Peck	1050472	1050472	831944	1060762				
Total	22829553	7609731	5401524	6767480				

^aWestern Water Council estimate includes all of Navajo Nation, Hopi Reservation and land under Hopi-Navajo joint ownership.

ORCID iD

Leslie Sanchez  <https://orcid.org/0000-0002-8022-341X>

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