Beggar Thy Neighbor: Strategic Resource Depletion and Environmental Outcomes for Water Quality

The Case of American Indian Water Rights

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Abstract

Do legal processes for allocating rights impact a resource's use and quality? In this paper I study how the process of resolving property rights affects resource use and externalities in the interim, and after resolution. I show that negotiating for American Indian water rights in the western United States is associated with increases in pollution during negotiation (even after controlling for water use). These increases are most pronounced for pollutants related to increased human or agricultural development, and impacts are concentrated upstream and on reservations. I also find that once rights are settled, water use increases (evidenced by streamflow changes) and pollution declines, illustrating key predictions of the property rights literature that defined allocations help to mitigate pollution externalities. In addition, tribes that negotiate for non-consumptive environmental flow rights seem to further mitigate a portion of the previous pollution increases once rights are settled, with effects also concentrated in upstream and on-reservations areas.

Keywords: Natural resources, property rights, procedural justice, water quality, institutions

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1 Introduction

In August of 2021, for the first time in its 99-year record-keeping history, the U.S. Bureau of Reclamation declared an official shortage of water in the Colorado River.[1] For many, this was not surprising, as the western United States has been plagued by historic drought conditions for two decades. But adding to the confluence of weather and climactic factors affecting the Colorado River are long-standing conflicts over water rights and distribution. The river's fundamental framework for sharing its water amongst the seven basin states, and Mexico, has been largely unchanged since it was written 100 years ago, despite drastically changing conditions in the water supply and population pressures. As drought conditions have mounted, water users in the west have increasingly found collaborative methods to manage streamflow and the water supply, such as the development of water markets for reallocation; increasingly stringent regulations on water use; synergistic partnerships between groups of users, and ecosystem management.

Despite these advancements, there are still several ongoing conflicts and competing claims to water, some of the most significant of which involve American Indian tribes' claims to reserved water. These claims are based on the U.S. Supreme Court case *US v Winters, 207 U.S. 577, 1908* ("*Winters*"), which ruled that tribes had legal rights to water reserved by the U.S. federal government when establishing reservations, and that seniority in rights was based on the date of this establishment. These rights, however, largely went unrecognized and unquantified, forcing tribes to negotiate or litigate for them in recent decades. Further, the quantity of water they represent is potentially vast, with tribes that have successfully regained these rights back playing a pivotal role in the collaborative water management agreements mentioned above. Tribes now hold senior use rights to about 20% of water in the entire Colorado River Basin[2], and will eventually control 46% of the Colorado River water delivered throughout Arizona by the Central Arizona Project.

Many *Winters* conflicts are still pending or yet to begin. Since the initial decree in 1908, there have been 81 negotiations and/or litigation processes undertaken by or on behalf of 80 tribes to settle rights to surface water and fund infrastructure to put that water to use. Of these, 25 are still ongoing, 44 were resolved out of court, and 12 were resolved via court decree. These substantial shifts in use rights occurred after long-fought negotiations or litigations, and going through this process represents significant investments by all stakeholders, with negotiations potentially lasting several decades, all the while incumbent users are still able to extract and use water. Of the approximately 200 western tribes in the U.S., many have ongoing or potential future claims to water, making this set of conflicts a key factor in the shifting water use and management landscape in the region.

To illustrate the expansiveness of these processes, in Arizona alone, there are two pending

[1] https://www.usbr.gov/newsroom/#/news-release/3950
[2] Circle of Blue, 2015: https://tinyurl.com/46t832ky

state adjudications for how to divvy up surface water from the Gila and Little Colorado rivers, the boundaries of which include more than half the state and flow through most of the tribal and federal land in Arizona. The Little Colorado adjudication includes almost 40,000 claimants, including the Navajo and Hopi tribes, in a judicial process that began in 1978, and has no end in sight.

Economic theory would suggest settling these long-contested disagreements over water and establishing clearer property rights should increase efficiency in water markets, and help correct for environmental degradation resulting from overuse or pollution of the resource due to externalities associated with development of the region and overuse of water (Hardin 1968, Coase 1960, Libecap 2016, Anderson et al. 2019). From Coase (1960), an externality will be resolved efficiently so long as transaction costs are low and rights are fully specified. A key criticism of Coase has been that in practice, transaction costs can be so high, particularly when there are multiple stakeholders, fragmented ownership, diffusion of responsibility for and claims from environmental damage that the process can be create insurmountable barriers for the parties to reach a negotiated settlement (Medema 2014).

What happens then *on the way* to settling these rights? If property rights themselves help to make a system more efficient, and account for external social costs, does the process of negotiating for, or resolving conflict around, these rights incentivize over-use or increased pollution, due to prolonged uncertainty or the onset of a strategic setting?[3] The conflicts over tribal rights present a unique setting for answering these questions. In this paper I study how the process of resolving property rights affects resource use and externalities in the interim. I am able to do this by creating a highly granular and spatial dataset containing millions of observations of water quality and streamflow in the western United States, connected to time periods of these *Winters* negotiations for water.

I also develop the first ever spatial mapping of the data relative to American Indian reservation lands and watersheds, to show which locations are upstream of reservations, on reservations, or downstream along the water flow lines. I employ a two-way fixed effects model[4] to analyze changes in water use (proxied by streamflow) and water pollution before, during and after negotiations for federal reserved water rights for tribes. To assess whether different groups make different decisions based on their geographic position in the negotiation, I run models for different subsets: upstream, downstream, and on reservations, and also account for different types of negotiated settlements, such as those that include clauses for environmental stewardship and/or management of streams and rivers.

I find that although water use does not change significantly during negotiation, compared

[3]The green paradox (Sinn 2012, Ploeg and Withagen 2015), for example, focuses on how future expected policy change for an exaustable resource impacts current use, potentially exacerbating climate change. My setting involves different mechanisms incentivizing behavior since water is a renewable resource.

[4]I use year, season, and individual station fixed effects.

to before, it it does increase significantly once rights are settled. These results are largely concentrated upstream of, and to a lesser extent, on reservations. When constraining the sample to just observations during a negotiation phase, I find that with each extra year of negotiation, water use increases (evidenced by falling streamflow), and these results are concentrated completely off reservations. This suggests that as conflicts persist, incumbent, non-Indian users are able to still use water, and increasingly so while parties are tied up in long settlements (presenting opportunities for overuse or strategic use during this time).

In terms of water quality, I find that pollution worsens during negotiations and, once rights are settled, ameliorates somewhat. These effects are mostly concentrated upstream of and on reservations. In addition, tribes that negotiate for non-consumptive environmental flow rights seem to further mitigate a portion of the previous pollution increases once rights are settled, with effects also concentrated in upstream and on-reservations areas.

These results imply as a first order that the process of essentially re-defining rights to a resource that has already been allocated, and can continue to be used during the process, can create spillover effects in terms of environmental quality and resource extraction. The results also imply that policy-driven negotiations, where parties agree to environmental management or stewardship clauses explicitly do seem to help mitigate damages to resource quality.

This research fits into several literatures. First, in the environmental literature, there have been a handful of empirical papers looking at changes in water quality as a result of policy (Keiser and Shapiro 2018) or boundary changes (Lipscomb and Mobarak 2016). Keiser and Shapiro link streams and rivers to pollution monitoring stations to assess the impacts of the Clean Water Act. I follow their geo-spatial approach in mapping pollution readings to location for my analysis. Lipscomb and Mobarak find that individuals pollute more towards a downstream jurisdictional boundary, effectively developing in one jurisdiction but offloading the pollutants in another. I use this approach too in considering why upstream-of-reservation users might pollute more, and closer to a reservation boundary.

This paper also contributes to research both in law and economics about the *Winters* doctrine. Sanchez *et al* (2020) study the factors that incentivize starting *Winters* negotiations, and find that population growth and water scarcity increase the likelihood a tribe will start a claim. Deol and Colby (2018) examine patterns in the quantification of water rights across Native American nations and find that tribes with quantified water rights have higher agricultural revenue, are more likely to operate a casino, and are closer to major cities. Colby has written extensively about the Winters doctrine, inherent issues with conflict resolution, developing water markets, streamflow restoration, and (B. G. Colby, Thorson, and Britton n.d., Kendy et al. 2018, and B. G. Colby and D'Estree 2000), to name a few). Finally, my research adds to the body of literature on property rights (as cited above relating to *Coase*), the impact of property rights on natural resource valuation and markets (Grainger and C. J. Costello 2014), and heterogeneity in attitudes towards transitioning from common-pool access to private property for natural resources (Grainger and C. Costello 2016), by looking at the impacts on environmental quality as a result of setting property rights, and how this process is affected by varying strategic incentives in the negotiation process from incumbent or new users of water.

The paper is organized as follows: Section 2 presents historical and environmental context, followed by the economic framework in Section 3. Section 4 outlines the details of the panel data set employed, and Section 5 presents my empirical strategy and econometric methods. Section 6 provides results and Section 7 concludes. Additional methodological details are presented in appendices.

2 Historical Setting

In 1908, the first "Winters" case was decided by the U.S. Supreme Court. The decision affirmed that the U.S. government had reserved rights to water for the tribes of the Fort Belknap Indian Reservation, prioritizing their treaty with the U.S. government over the states' appropriation of water to settlers. The court claimed that the power of the United States to reserve such water "could not be" denied.[5] This has often been hailed as a major and historic victory for tribes. Yet no American Indian was involved directly in the filing, negotiating, procuring or planning for the litigation, and the tribes' role in the process was seen as indirect by the Office of Indian Affairs (Shurts 2000). In earlier attempts to secure water rights, one superintendent of the reservation had filed for tribal water rights in his own name (Luke Hays in 1898), and another opened up much of the irrigable reservation land to grazing leases for non-Indian stock farmers, including himself (William R. Logan), and to develop a sugar beet industry using tribal water. Tribes on the Fort Belknap reservation were routinely dissuaded from using water to support a stock industry (the more lucrative venture) in favor of agriculture, which in turn just supported non-Indian stock farmers. Revenue from leased reservation land was spent on Indian wage-labor in support of the non-Indian industries who leased the land.

Fast forward over 100 years later, and tribes currently hold an important seat at many water negotiating tables, are the primary drivers of their own negotiations for water rights, and often serve as a serious strategic lynchpin for water management plans. To be sure, they have faced and continue to face significant headwinds in reclaiming rights to land and water, but with the passage of the Indian Self Determination Act in 1975,[6] they have been supported by federal policy in acting with sovereignty in these negotiations. The Gila River Indian Tribe in Arizona played a pivotal role in crafting the state's Drought Contingency Plan and influences price setting for water market transactions. As a result of the first ever

[5] *US v Winters, 207 U.S. 577, 1908*

[6] 88 Stat. 2203

"shortage" in the Colorado River, the Arizona population will have to reduce their water intake by over 500,000 acre-feet per year, but none of the reduction will come from tribal allocations.

This is a stunning reversal from the complete erosion of rights to resources, land and sovereignty experienced by tribes throughout American history. Yet still, several tribes still languish with little access to water, directly resulting from those erosions of rights to water. Approximately 58 out of 1000 Native American households do not have access to indoor plumbing[7]; nearly 30% of homes surveyed by the Indian Health Service (IHS) needed improvements in sanitation for sewer and/or solid waste systems[8]; and 30% - 40% of households on the Navajo Nation do not have piped water (Tanana 2021). Another recent study found that compared to white households, Native American households are 19 times more likely to live in a home without indoor plumbing (Tanana, Combs, and Hoss 2021). Households without plumbing or piped water often rely on hauling-in water, which is often several magnitudes higher in cost per acre foot to procure.

Despite the court's clear ruling over 100 years ago recognizing federally-reserved rights to water or American Indian tribes, following that ruling, the federal government largely deferred the allocation of surface water to states, allowing them to erode those rights. Additionally, the federal government—through the Bureau of Reclamation—actively funded and facilitated large-scale irrigation projects that supported western expansion, and were necessary for development, mostly benefitting non-Indian settlers. This also coincided with a concerted federal effort to dispossess tribes of protected reservation areas for the purpose of opening up western land to settlers. By 1934, over 100 million acres of protected reservation land had been lost to western encroachment, much of this land in key resource-rich areas, including near streams, rivers, and planned irrigation projects.

This is despite the profound legal trust relationship that has existed between tribes and the U.S. government, the latter of which is charged with protecting and preserving rights vested to tribes. Due to this legal relationship, tribes required the participation of the federal government in order to enforce or litigate for the protection of their rights to water as they were being appropriated elsewhere. Yet the U.S. government largely ignored this responsibility, not even providing an actionable quantification standard for these rights until 1963 ("practically irrigable acreage"), and then waiving sovereign immunity and essentially forcing tribes to litigate for their rights in state courts. Tribes were hard pressed to find the resources, access, and amenable state courts to enforce their rights to water. In the meantime, by 1975, the western states had allocated an estimated 300% of available surface water resources elsewhere, with only a small handful of tribes able to put their water rights to use (70 years after the original *Winters* case). The federal government, by this

[7] According to the Water Alliance `https://www.latimes.com/world-nation/story/2021-06-26/native-americans-clean-water`

[8] `https://www.latimes.com/world-nation/story/2021-06-26/native-americans-clean-water`

time, had exhaustively built dams and irrigation infrastructure in order to facilitate this rapacious extraction of resources. Also in 1975, the federal government passed the Indian Self Determination Act, which allowed tribes increasing autonomy to govern and administer their own policies within tribal nations. Finally able to act with some autonomy to seek back their rights to water, it had been diverted elsewhere.

Due to the vast aridity of the region, and prevalence of agriculture, mining and other natural resource extraction activities that require water, development necessarily relied upon diverting water from a source to its use. This practice evolved into "prior appropriation", where the ability to use water is based on a "first in time, first in right" organization, where early water users are prioritized before later ones. In addition, retaining one's usufruct right to water required continued use. "Use it or lose it" is the mantra of the west.

In fact, when *Winters* was brought to the U.S. Supreme Court, there were already serious concerns over water in the west, connected to a blind ambition to irrigate and develop the arid region. As far back as the 1890's, the great western explorer and early director of the U.S. Geological Survey John Wesley Powell warned western irrigators that there was not enough water to sustain the insatiable demand. "Not one more acre of land should be granted to individuals for irrigating purposes," he proclaimed at the Second International Irrigation Conference in Los Angeles in 1893. "I tell you," he continued, "gentlemen, you are piling up a heritage of conflicts and litigation over water rights, for there is not sufficient water to supply these lands (Thomas 2007)."

Even in the earliest years of its adoption, prior appropriation was seen to carry a heavy social cost by encouraging rapid development, maximum production and the boom-and-bust mentality (Pisani 1992). It was seen as less adaptable, less reliant on irrigating alluvial soils, and did not incorporate measures that would protect water quality in its use. In wetter areas, riparian rights, where water rights are tied to the land and location, adjacent to streams and rivers, have been the predominant mechanism for allocating water rights.

The initial Winters case was argued on several grounds, including prior appropriation, interpretation of treaty language, and recognition of riparian rights (Shurts 2000) (indicative of how nascent the concepts surrounding water law were at this time). *Winters* was eventually decided on the grounds of treaty rights, where the court interpreted and asserted in general that the federal government, in setting aside certain lands for a certain purpose, may reserve water under federal law for that purpose (Cosens and Royster 2012). Reserved water rights were not subject to the "use it or lose it" characteristic that state-allocated, prior appropriation rights were, which had been in use in most western states by the mid 1800's (Leonard and Libecap 2019). It was widely acknowledged in the decades before the Winters case that tribes' rights to water were insecure—at best—and completely eradicated at worst, with "the prevailing opinion being that Indians have no water rights which white men are bound to respect."[9] And yet, as settlement continued, irrigation by white settlers on Indian lands soon made water more scarce, and the availability of water supply became of "first importance," with cession agreements for Indian land including provisions for tribes to secure irrigation, paid for with all of part of the proceeds from the land sale itself (Office off Indian Affairs Report, 1906, page 82).

Even in cases where the Office of Indian Affairs wanted to secure water for the actual tribes, the method for doing so was unclear. In 1880, an Office of Indian Affairs agent with the San Carlos Agency implored, "[i]If there is any law in regard to this it should be enforced, so that the Indians can be protected in their water rights, a matter of vital importance..." (Office of Indian Affairs Annual Report, page XXII). Before, the Commissioners' reports outlined several tactics to try and legally assert rights, from leasing land to white cattlemen and farmers (in order to put water to use), to allotting land in order to assert individual property rights and use water through individual farms (which often did not happen in practice, particularly since very little money was available for irrigation infrastructure to tribes, especially before 1900). Many plans documented in the historic reports also indicate even if a scheme to retain water or build water infrastructure was devised, it often was not put into action due to either lack of funds, or because the water had already been used surrounding the reservation.

Where the federal government did expend money for water infrastructure, it was often for non-Indian purposes, or to keep American Indians contained on reservations. As early as 1867, the federal government had funded the irrigation of Indian lands, understanding that in order to contain American Indians on newly-created reservations—many of which were in desert areas, they might have to think about water. The initial round of funding constituted $76,000, and then in 1890, after 9,000 American Indians left the Navajo reservation in search of water, the federal government expended more (Pisani 1986), particularly as western settlement began to grow. By the end of the century, larger irrigation projects on tribal land had been undertaken, such as $257,599 spent on the Crow reservation water system by 1896, which was largely paid to tribal laborers. As in the Milk River case, tribal laborers were often paid from proceeds of tribal land sales—turning what was meant to be tribal profits for aggregate land sales into small wages paid to tribes on hourly bases Pisani 1986. In some cases, the Department of Interior made tribal members labor to construct irrigation ditches that would never be filled,[10] turning wealth into wages, and arguing that labor was important for character building, all the while creating wealth for land speculators and western non-Indian settlers.

The Office of Indian Affairs did continue to fund reclamation projects, but many of them were taken back for the Bureau of Reclamation projects, essentially transferring higher-

[9]Office of Indian Affairs Annual Report, 1880, page XXII

[10]In Pisani, 1986, he recounts history of the Pima Indians in Arizona being forced to labor on infrastructure where there was no water to populate it

value irrigated land (that tribes had—sometimes without consent—paid to irrigate out of their "surplus" land sales) directly to settlers. By 1910, over half a million dollars had been expended on tribal reclamation projects, creating over 375,000 acres under ditch. Pisani (1986) points out that this represented, at the time, nearly half the irrigable land within BoR projects. Twenty-four Reclamation Service projects were approved by 1906, without the land to construct these projects. They turned to reservations, relying on federal law that enabled the Reclamation Service access to any land within a reservation, as long as they provided a small individual farm in return (Pisani 1986). This is in addition to the fact that proceeds from public land sales, including American Indian reservations, funded the reclamation service, and such sales "largely increased" after the passage of the reclamation act (Office of Indian Affairs Annual Report, 1906, pg. 42). See Appendix A.

Thus, Winters settled the legal question over priority between existing reservations and new water users and settlers. But the quantification of these rights was not addressed, and fights over water in the Colorado River basin states, for example, were also not settled. Misallocation continued, and states kept appropriating water to settlers, who kept diverting from surface water and drawing from groundwater resources. It was not until 1963 that a quantification standard was proposed in *Arizona v California*,[11] allotting water rights for the five tribes named in that settlement over Colorado River water based on the "practicably irrigable acreage", or, PIA, of their reservations. This inherently expanded the connection of *Winters* rights to reservation land not only in terms of the priority date, but in terms of productive land mass.[12] Ostensibly, tribes that had larger quantities of irrigable acreage had stronger claims to water. Over the decades, there has been significant pushback to this, both by tribes (who want to develop other industries besides agriculture), and the courts. In fact, an unpublished opinion by Sandra Day O'Connor in the Big Horn adjudication in Wyoming,[13] indicated that the PIA standard could be on shaky ground if challenged further in courts. This further incentivized tribes to pursue water rights via settlement and bypass courts entirely.[14] Further, wary of the excessive costs of litigating and amenability of states courts to recognize tribal interests, tribes began to pursue negotiated settlements for the quantification and enforcement of their long-unenforced rights to water. The federal government, as a policy since 1978, has promoted this as a the prioritized procedure for getting water back to tribes, although the process can be long, expensive, and highly political.

[11]373 U.S. 546 (1963)

[12]This of course opens up issues of fairness in terms of tribes with no defined "reservation" lands either ever, or anymore, but who were similarly displaced and in need of water.

[13]*Wyoming v United States, 492, U.S. 406 (1989)*

[14]Another reason tribes were keen on bypassing the court system was that, thanks to the McCarren Amendment, which waived the federal government's sovereign immunity, these trials were often litigated in state courts, which could be much less amenable towards tribes.

2.1 Procedural Details for Resolving *Winters* Rights

Post 1975, as tribes have increasingly turned to negotiating settlements with current, non-Indian water users to resolve their long-unenforced rights to water, the U.S. government has formalized this process. There are five typical stages of the settlement negotiation process: pre-negotiation (or, "before" in our model); negotiation; agreement (parties sign an agreement); settlement resolution (once negotiation is completed and parties agree, the settlement is presented for Congressional approval and funding); and implementation (once approved by Congress, the U.S. Department of Interior's Secretary's Indian Water Rights Office (SIWRO) overseas implementation via implementation teams. Note, negotiation teams are also deployed from SIWRO) (Congressional Research Service n.d.[a]).

For this analysis, I generalize to the three periods of before, during and after (the last of which is after Congress has approved any settlement and the rights are fully quantified and resolved). Because of the trust relationship between the U.S. government and tribes, any agreements signed between stakeholders for tribal water must be ratified by Congress, and then typically Congress will also appropriate funding to provide the infrastructure necessary to implement these settlements. The figure below (Figure 1) presents a stylistic representation of the three periods outlined above.

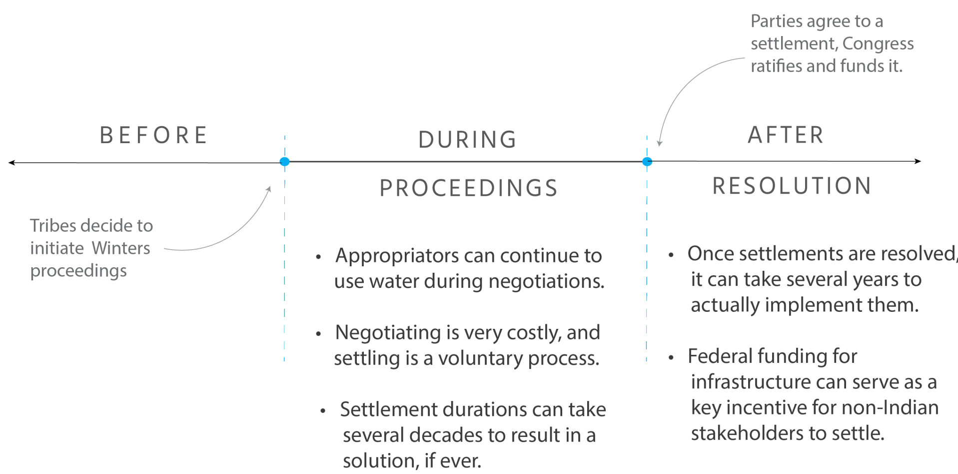


Figure 1: *Winters* Timeline

Also due to the trust relationship, unlike other entities (like irrigation districts), if tribes want to trade their recognized and quantified federally reserved water rights, they also must gain approval by Congress. This can be a lengthy and costly project, so many tribes, in more recent decades, have negotiated for water marketing abilities in their settlements, and/or environmental (non-consumptive) rights to water, which can also be linked to specific water management practices and water quality codes that tribes implement. I code the existence of these types of arrangements within agreements in order to analyze whether they have impacts on streamflow or pollution.

3 Economic Framework

I utilize two distinct value functions to illustrate the maximization problem faced by the water user. During the negotiation phase, V^N represents the value function with respect to maximizing water use, pollution, and bargain-stalling activities. $V^S(Q^S(Q^N), S_{t+1})$ represents the value to the water user once rights are settled, which is a function of the settled quantity, and the state of environmental quality in period $t+1$. $V^S(Q^S(Q^N), S_{t+1})$ captures the present value from all future time with settled water rights $Q^S(Q^N_t)$, and V^N solves a Bellman equation whose continuation value is $V^S(Q^S(Q^N), S_{t+1})$ with probability p and V^N with probability $1-p$. With probability q, the settled value is Q^S, and with probability $1-q$, the settle value is zero. This introduces the possibility that a water user will lose water rights in the future, and fail to internalize longer-term pollution externalities in present decision-making.

In this setting, switching from *negotiation* to *resolved* is permanent, and dynamics after settlement are fundamentally different than before. Once *Winters* rights are agreed upon and funded by Congress, there is no going back to the negotiation setting. Water supplies or demand may change, or parties might continue to contest claims, but the "initial" allocation of rights is fundamentally shifted. Other dynamics could include changing political power, changing uses and flows of water, development and infrastructure investments, and different demographics and economic opportunities.

In each phase, the water user solves an infinite horizon dynamic optimization problem. In the negotiation period, the water user considers effects on both the negotiation and resolved value functions. Equation 1 presents the value function in the negotiation period:

$$\begin{aligned} V^N = \max_{Q^N_t, P_t, \delta_t} \{ & u(Q^N_t, P_t, S_t) - c\delta_t + \beta_t \int [(1-p+\delta_t p)V^N - c\delta_t + \\ & (1-\delta_t)p[qV^S(Q^S(Q^N), S_{t+1}) + (1-q)V^S(0, S_{t+1})]] \\ \textbf{s.t.: } & S_{t+1} = g(S_t, P_t) \end{aligned} \tag{1}$$

In the above models, I assume $g_S \geq 0$ and $g_P < 0$. Additionally, in the V^N model, $u_{Q^N} \geq 0$, but changes to $u^N_Q < 0$ for sufficiently large values of Q, accounting for extraction costs and decreasing marginal utility of water use.

Further, $u_P \geq 0$; $u_S \geq 0$; and V^S cross partial derivative in both Q^S and S_{t+1} is increasing. The utility function $u(Q_t^N, P_t, S_t)$ represents the utility from using water, Q_t^N minus the costs associated with use and extraction; the fixed annual costs of negotiating; pollution costs[15] and the overall quality of the resource. The assumption that the cross partial derivative of V^S arguments is positive illustrates that water use is more valuable when water quality is higher. The settled water quantity, Q^S, is a function of negotiation-period water use, capturing potential incentives to modulate water use as a negotiation tactic in anticipation of post-settlement results.

Some stakeholders may prefer to remain in the status-quo, bargaining setting (since they expect to lose water in the resolved state), and they may have the opportunity and incentive to stall negotiations. The term $\delta \in [0,1]$ represents a "stall tactic" action that a water user can take in the negotiation phase to reduce the probability of settling. When δ=1, the water user will attempt to fully stall negotiations. When δ=0, there is no action taken by the water user to stall. The term $c\delta_t$ represents the cost of implementing this stall tactic.

Optimizing the V^N function with respect to water quantity used; pollution; and stall action uncovers the following first-order conditions:

$$Q_t^N: \qquad u_{Q^N} = \beta(\delta_t - 1)pq \cdot \frac{\partial V^S(Q^S(Q^N), S_{t+1})}{\partial Q^S} \cdot \frac{\partial Q^S}{\partial Q_t^N} \tag{2}$$

$$P_t: \qquad u_P = \beta(\delta_t - 1)p \cdot [q\frac{\partial V^S(Q^S(Q^N), S_{t+1})}{\partial S_{t+1}} \cdot \frac{\partial g}{\partial P_t} + (1-q)\frac{\partial V^S(0, S_{t+1})}{\partial S_{t+1}} \cdot \frac{\partial g}{\partial P_t}] \tag{3}$$

$$\delta_t: \qquad V_N - \frac{c(1-\beta)}{\beta p} = qV^S(Q^S(Q^N), S_{t+1}) + (1-q)V^S(0, S_{t+1}) \tag{4}$$

These equations imply that a strategic user will choose to stall up until the point that the negotiation phase value function minus any stall costs equals the expected settled phase value function. So long as $V^N \geq V^S$ (and negotiation costs are not prohibitively high), an optimizing bargaining will stall if possible. The smaller that q is (the probability of receiving a nonzero amount of water, $Q^S(Q^N)$, the more incentive the incumbent user will have to stall. These conditions further imply:

$$\frac{U_{Q^N}}{U_P} = \frac{\frac{\partial V^S(Q^S(Q^N),S_{t+1})}{\partial Q^S} \cdot \frac{\partial Q^S}{\partial Q_t^N}}{\frac{\partial V^S(Q^S(Q^N),S_{t+1})}{\partial S_{t+1}} \cdot \frac{\partial g}{\partial P_t} + (\frac{1}{q} - 1)\frac{\partial V^S(0,St+1)}{\partial S_{t+1}} \cdot \frac{\partial g}{\partial P_t}} \tag{5}$$

[15] pollution is a function of direct water use, or nearby development, and has both stock and flow characteristics. Pollution can be mitigated by abatement activities.

From the above, water users will use water and pollute up until the point that the marginal rate of substitution between consuming water and polluting equals the expected marginal rate of substitution between these activities in the settlement phase (Equation 5).

If pollution costs are not internalized (if $q = 0$ in the extreme), stakeholders will continue to pollute and use water until U_Q and U_p equal zero.

As a note, while this is a general model, the incumbent, non-Indian users of water would likely have more capacity to modulate water use, or act strategically with respect to water use, than tribes who need to begin *Winters* proceedings in the first place. Additionally, their next-period water allocation would be more plausibly a function of fQ_t since they are already putting water to use.

3.1 Predictions

From the above relationships, I make a few testable hypotheses for this scenario.

Hypothesis 1: From Equation 2, water users will optimally increase Q_N until the current marginal utility from Q equals the future discounted marginal net benefit from increasing Q. Note, at very large Q, $U_Q < 0$. If $Q^{S\prime}(Q_t^N) > 0$ water users will have an incentive to increase quantity used during negotiation if possible, to secure a higher amount post negotiation (so long as $U_Q \geq 0$).

Hypothesis 2: Based on the above FOCs, U_P is decreasing in q. That is, with more internalization of pollution costs, marginal utility of polluting falls. Therefore, once settled (and q is effectively 1), pollution will fall. During the negotiation phase, if q falls (i.e., there is less certainty that the water user will retain a non-zero allocation post settlement), pollution will increase. This may be more pronounced closer to the downstream outflow of an upstream-of-reservation area since water users may feel less long-term responsibility for stewardship of the resource if it flows out of their jurisdiction.

Hypothesis 3: Since strategic users will choose δ up to the point that $V_N - \frac{c(1-\beta)}{\beta p} = qV^S(Q^S(Q^N), S_{t+1}) + (1-q)V^S(0, S_{t+1})$, and will be incentivized to do so as long as $V_N \geq V^S(Q^S(Q^N), g(S_t, P_t))$, costs of stalling, $c\delta$, are not prohibitively high, and in the V^N model, $u_{Q^N} \geq 0$, longer negotiations will be associated with higher Q_t^N at least if stall tactics are used.

In regards to pollution, there is a long history of either the government or non-Indian water users creating environmental damage on and around American Indian reservations. For example, the Army Corps of Engineers installed a dam and lock system on the Mississippi River two years after the Prairie Island Indian Community in Minnesota gained federal recognition status in 1934, flooding the reservation land and sacred burial sites. Years later, a power plant left a nuclear waste stock pile near the reservation, which the federal government promised to remove in the 1990s but did not. Both of these factors left much of the reservation land either under water or unusable.[16]

In 2015, a gold mine spilled 3 million gallons of wastewater into the San Juan river, contaminating water for the Navajo Nation. The Hopi tribe estimates, based on levels of arsenic and uranium in ground water as a result of mining operations in the southwest, that 75% of its community members are drinking contaminated water (Tanana, Combs, and Hoss 2021). Thus, investigating whether the act of having to negotiate for their own water further pollutes tribal resources in and around reservations, and providing a measurable answer to this question, can have important implications for environmental justice and stewardship.

4 Data

I use several types of data to conduct this analysis, which is based on connecting spatial, environmental, economic, and legal data together in order to analyze how property rights changes, and the bargaining environment, impact water quality in and around reservations. This analysis is reliant on using Geographic Information System (GIS) techniques to generate geographic information and to make spatial links in the data.

Tables 4.1 to 4.3 show summary statistics from the streamflow model, and the pollution system datasets. Note that all of these statistics represent the "clean" sample, which is the subset of data where a monitoring station is only ever upstream or downstream of just *one* reservation (in addition to the stations that are on reservations, or are neither upstream or downstream. This ensures data is not representative of multiple data generating processes in one model (downstream of one reservation, upstream of another).

As indicated by Table 4.1, streamflow is lower on reservations that off, and similar between stations that are in the vicinity of a *Winters* case or not. Drought conditions across subsets, but are somewhat drier in the vicinity of *Winters* areas, on average. Precipitation and temperature are lower on reservations compared to off, and for *Winters* vicinities vs. no *Winters*. Population densities are lower on reservations compared to off, but similar between *Winters* versus no *Winters*. Finally real per capita income (reported in 1967 dollars) is fairly similar across the board.

Table **??** repeats this exercize, but using the pollution-system dataset. The control results are similar (for rain, temperature, real per capita income, etc.), but the table also shows average pollution readings. In general, reservations tend to have less polluted water on average compared to off-reservation areas (with the exception of total suspended solids and dissolved oxygen), and somewhat mixed comparing *Winters* versus no *Winters* areas. Table **??** also shows the distribution of pollutants in the sample.

[16] https://www.nytimes.com/2021/11/13/us/politics/tribal-lands-flooding-nuclear-waste.html

	Full Sample mean/sd	On Res mean/sd	Off Res mean/sd	Winters mean/sd	No Winters mean/sd
Mean Daily Flow (CFS)	1,143.66	197.44	1,159.51	1,090.17	1,172.50
	(9,506.59)	(1,000.43)	(9,584.21)	(14,234.73)	(5,461.94)
pdsi	0.01	0.05	0.01	-0.07	0.05
	(2.61)	(2.56)	(2.61)	(2.81)	(2.49)
Monthly Precip.	56.97	33.86	57.29	40.16	66.03
	(77.36)	(32.97)	(77.74)	(52.57)	(86.52)
Monthly Temp.	12.39	9.60	12.43	11.51	12.87
	(8.20)	(8.53)	(8.18)	(8.82)	(7.80)
Pop. Denisty	0.22	0.02	0.22	0.17	0.24
	(0.80)	(0.02)	(0.80)	(0.69)	(0.85)
Real Per Cap Inc. (Cty)	4,240.74	3,628.08	4,251.38	4,273.44	4,221.45
	(1,215.91)	(791.47)	(1,219.26)	(1,402.73)	(1,090.35)
Observations	1261653	20787	1240866	442037	819616

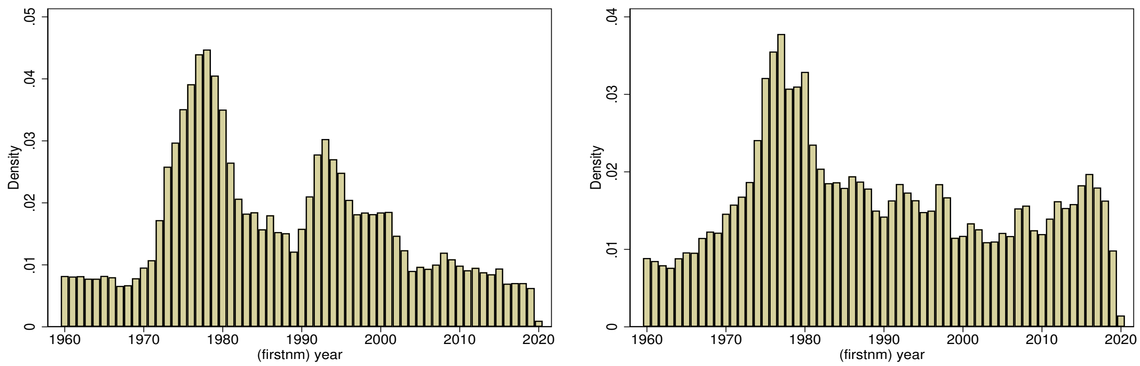
Table 4.1: Streamflow Model Database, Summary Statistics

	Full Sample mean/sd	On Res mean/sd	Off Res mean/sd	Winters mean/sd	No Winters mean/sd
Streamflow (CFS)	983.35	167.47	996.80	1,095.14	927.31
	(10,825.36)	(783.90)	(10,913.25)	(18,177.70)	(3,208.29)
BOD	0.22	0.07	0.23	0.18	0.24
	(3.61)	(1.03)	(3.64)	(3.85)	(3.52)
FC	1,446.56	46.36	1,466.63	1,152.73	1,559.39
	(55,979.10)	(1,377.79)	(56,378.41)	(49,536.39)	(58,263.89)
TSS	15.41	26.32	15.26	20.56	13.44
	(267.46)	(307.24)	(266.85)	(293.84)	(256.59)
Dissolved Oxygen	1.28	1.34	1.28	1.17	1.33
	(11.37)	(11.18)	(11.38)	(11.44)	(11.35)
pH	-0.32	-0.44	-0.32	-0.38	-0.30
	(0.56)	(0.67)	(0.56)	(0.60)	(0.54)
Monthly Temp.	12.54	11.11	12.56	11.67	12.88
	(7.69)	(8.01)	(7.68)	(8.48)	(7.32)
Monthly Precip.	67.93	39.12	68.30	41.83	78.26
	(96.39)	(44.82)	(96.82)	(54.52)	(106.84)
Real Per Cap Inc. (Cty)	4,379.59	4,123.55	4,383.50	4,343.11	4,394.81
	(1,252.41)	(978.01)	(1,255.73)	(1,381.08)	(1,194.30)
Pop. Denisty	0.26	0.03	0.27	0.22	0.28
	(1.09)	(0.04)	(1.09)	(0.76)	(1.19)
Observations	4667908	65968	4601940	1295218	3372690

Table 4.2: Pollution System of Equations Database, Summary Statistics

	Frequency b	pct
bod	199,212	4.27
fecal coliform	511,329	10.95
oxy	1,156,435	24.77
ph	2,075,091	44.45
tss	725,841	15.55
Total	4,667,908	100.00
Observations	4667908	

Table 4.3: Frequency of Pollutants in Clean Dataset



(a) Streamflow Dataset (Clean Sample)

(b) Pollution Dataset (Clean Sample)

Figure 2: Years in Datasets (Streamflow and Pollution Sets)

4.1 Water Quality Data

I use the Environmental Protection Agency's (EPA) Legacy and Modern STORET databases to assess changes in water quality in and around reservations. I focus on six types of indicators: flow (mean daily, cubic feet per second (cfs); biochemical oxygen demand (BOD 5-day); fecal coliform (FC); total suspended solids (TSS); pH; and dissolved oxygen (reported as mg/L and percent saturation). The combined modern and legacy STORET databases provide water quality metrics dating back to the turn of the twentieth century, and they are mostly self-reported indicators of water quality at specific monitoring-station locations. The monitoring stations have distinct latitude and longitude location data.

The initial analysis presented in this paper focuses predominantly on streamflow as an imperfect proxy indicator of water use, and also of water scarcity. Human development of water management systems and resources greatly alters the natural flow of rivers (Richter et al. 1997), but measuring direct effects of water allocation on water quality is difficult given the complexity of the ecosystem. Streamflow can serve as something of a "master variable" in riverine ecosystems since it affects so many different facets of the ecosystem (Kendy et al. 2018). Additionally, a direct measure of water use is almost impossible to find for a broad-scale geographic region or a significant time frame. Since water use is so contentious, and conflicts are rampant, water users—even states themselves—keep this information private. In the state of Arizona, for example, just getting a basic account of actual water use across the state is almost impossible outside of certain administrative jurisdictions. There is not a straightforward, accessible document of even the global universe of all allocations (particularly because so many are under adjudication status in the state), and there is no publicly available, broad-scale accounting of surface water use for the entirety of the state, outside of community water systems, over time. Further, there is no accounting of the vast amounts of groundwater put to use, which, in many parts of the state, can be extracted with little to no oversight.

While rainfall is one of the key determinants of streamflow, human use of water, including groundwater, will certainly impact the amount of water flowing through streams and rivers.[17] I focus on the impacts first on streamflow, as this can be an indicator for behavior changes in wholesale water use and extraction. Additionally, since most pollutants are reported in concentration amounts, flow is an important control variable for assessing changes to pollution.

The process for using water quality data most closely follows the work of Keiser and Shapiro (Keiser and Shapiro 2018), who look at changes in water quality as a result of the Clean Water Act. As in that paper, I focus on ambient surface water, including streams, rivers, lakes and reservoirs. I do not include oceans, or groundwater. I also do not include non-ambient water pollution readings, such as those from inside of facilities. There are 589,684 STORET monitoring stations over the contiguous U.S. that fit the above surface-water distinction. My study area is the region west of the 100th meridian, which includes 186,720 monitoring stations. For full details, see Appendix B.1

4.2 Spatial Data on Waterbodies and Watershed Boundary Areas

In order to map locations upstream and downstream of American Indian reservations, it is first imperative to map where American streams and rivers are. I use the National Hydrography Dataset Plus High Resolution (NHDPlus HR) resource by the U.S. Geological Survey (USGS).[18] This dataset acts as an atlas of all waterbodies in the United States and includes streamflow direction. I map all streams and rivers, link them to STORET monitoring stations, and trace upstream and downstream flowlines from reservations. This process allows me to designate which monitoring stations are upstream, downstream, on reservation, or neither, from American Indian reservations.

Appendix B.2 details the steps involved in using the data and also the rationale behind organizing the stream networks by HUC4 watershed boundary areas. A watershed boundary defines the spatial extent of surface water drainage to a certain point.[19] Watersheds in the United States are delineated by hydrologic units. The largest hydrologic unit is the "region" (2-digit HUC code), which is divided into "sub-regions" (4-digit HUC code), and then eventually to sub-watershed areas (12-digit HUC code). The United States and Caribbean are divided into 21 regions, and 221 sub-regions (Figure 3).

[17] https://www.usgs.gov/special-topic/water-science-school/science/streamflow-and-water-cycle?qt-science_center_objects0#qt-science_center_objects

[18] `https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution`

[19] `https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042207.pdf`

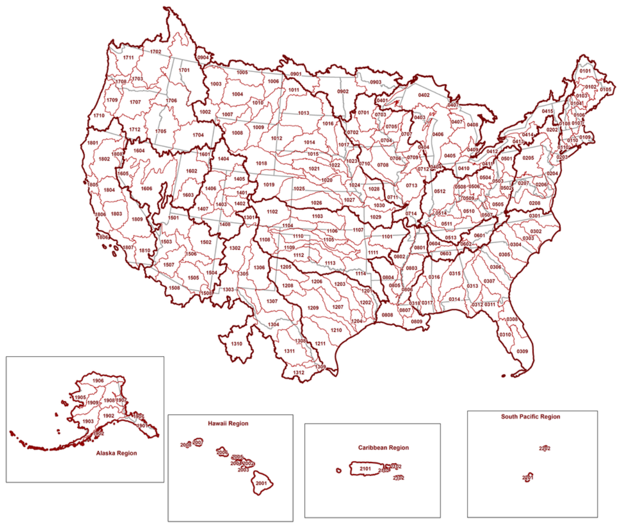


Figure 3: HUC4 Boundary Areas

USGS Watershed Boundary Dataset: `https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset?qt-science_support_page_related_con=4#qt-science_support_page_related_con`.

For my analysis, the largest area in which I can trace upstream and downstream networks is the 4-digit HUC code area ("HUC4"). Thus, the HUC4 area is the watershed subregion extent to which I trace to, and which I control for.

4.3 Other Spatial Indicators

I incorporate other characteristics of the streams and rivers and of monitoring stations into my panel data. Specifically, by using other datasets in the NHDPlus HR, I can also incorporate details such as stream order (see Appendix B.2.4 for details). This is useful in aggregating water quality metrics to higher-aggregation levels. Using GIS, I calculate for each monitoring station the distance to the nearest American Indian reservation, and individual distances from each station to any reservation within 100 miles of the station. This allows me to know, for each station, whether they are "close" to a specific reservation or not.[20] In future research I will also be able to incorporate taxonomic soil characteristics into the monitoring station location detail. Finally, I am able to spatially match each monitoring station to their respective HUC4 boundaries, in addition to locations within

[20]Going beyond 100 miles was infeasible to calculate for each monitoring station and each reservation in the western U.S. due to computing limitations

the county, state, census areas, and the locations of the nearest towns.

4.4 American Indian Reservations

In order to map water pollution measurement locations on and near American Indian reservations, I use 1990 census-designated federally-recognized American Indian reservation boundary files.[21] These boundaries change slightly over time in more modern years, but for the most part are indicative of reservation areas over the course of the study period. Future work can incorporate changing reservation boundaries.[22]

These boundaries then serve as an anchor point for identifying locations on reservations and upstream and downstream of reservations, and to establish links to other spatial statistics. Figure 4 depicts STORET monitoring stations, juxtaposed against 1990 orange-shaded reservation areas in the study area west of the 100th meridian. Approximately 7% (12,773) of U.S. monitoring stations intersect with western reservations. Figure 5 provides a zoomed-in look at the Navajo Nation in Arizona, with connected reservation boundaries (pink-shaded areas), monitoring stations (black dots) and streams and rivers.

4.5 Winters Dates, Negotiation Periods, and Types of Clauses

I use several sources to determine start and end dates for *Winters* negotiations. Most importantly, I use the excellent work by (Sanchez, Edwards, and Leonard 2020) in aggregating adjudication start and end dates for Winters. The information includes when agreements were signed versus when a Winters settlement was ratified by Congress and thus completely resolved and funded. This dataset also includes whether the rights were settled in a negotiation or or secured by a a court decree. I supplement this dataset with information from the Congressional Research Service (CRS) (Congressional Research Service n.d.[b]), and (Deol and B. Colby 2018). I use the University of New Mexico's Native American Water Rights Settlement Project's Digital Repository[23] to examine settlement documents to code whether the final settlement incorporated rights to market water (the ability for tribes to lease or sell water), and/or whether the tribes negotiated for environmental stream flow rights (not just consumptive uses of water). Further, I note, where possible, from the CRS

[21]IPUMS NHGIS: https://www.nhgis.org/gis-files, 1990 Census Boundary files for American Indian/Alaskan Native Reservation or Statistical Entity areas).

[22]Reservation boundaries changed substantially in earlier periods—1880s through 1934, but settled after the Indian Reorganization Act, which put an end to the allotment of reservation land, which had drastically reduced reservation land in the western United States. My other work (Taylor, 2018) looks at these changes and digitized annual reservation boundary changes between 1880 and 1915). One reason incorporating more modern boundary changes is not included here is that the process would be extremely arduous in terms of tracing upstream and downstream flows from each set of reservation boundaries, for very few large scale changes in reservation area over the study time period

[23]https://digitalrepository.unm.edu/nawrs/

the amount funded by the federal government in implementing the settlement terms when finalized.

Figure 6 depicts a map of where these cases occur, and current *Winters* status.

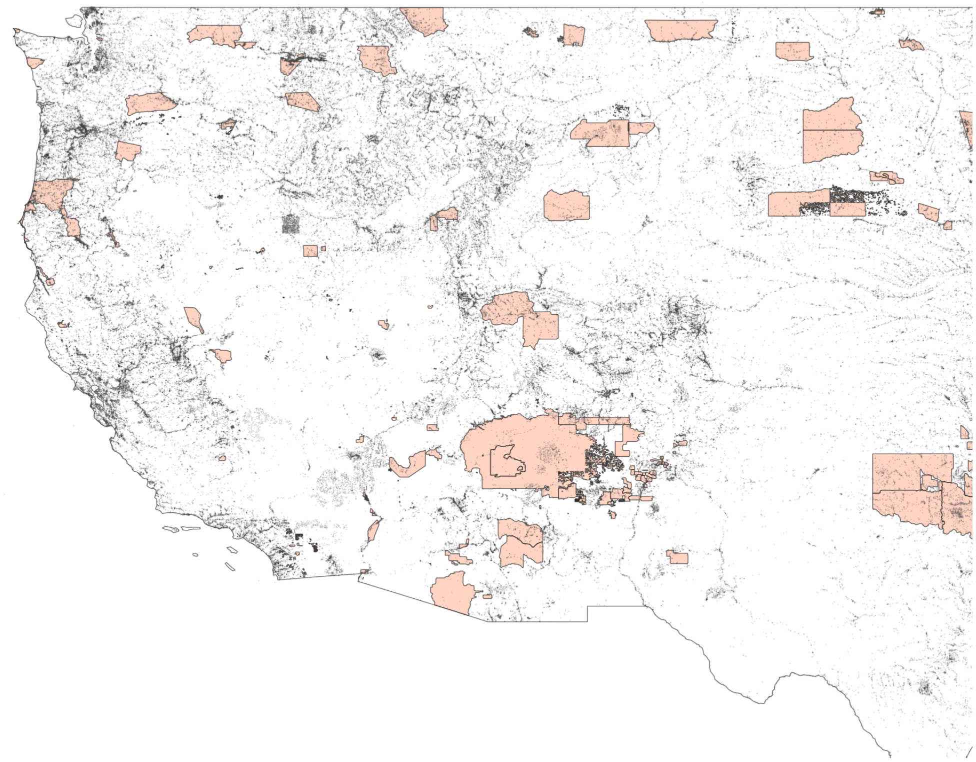


Figure 4: STORET Monitoring Stations and American Indian Reservations, Western U.S.

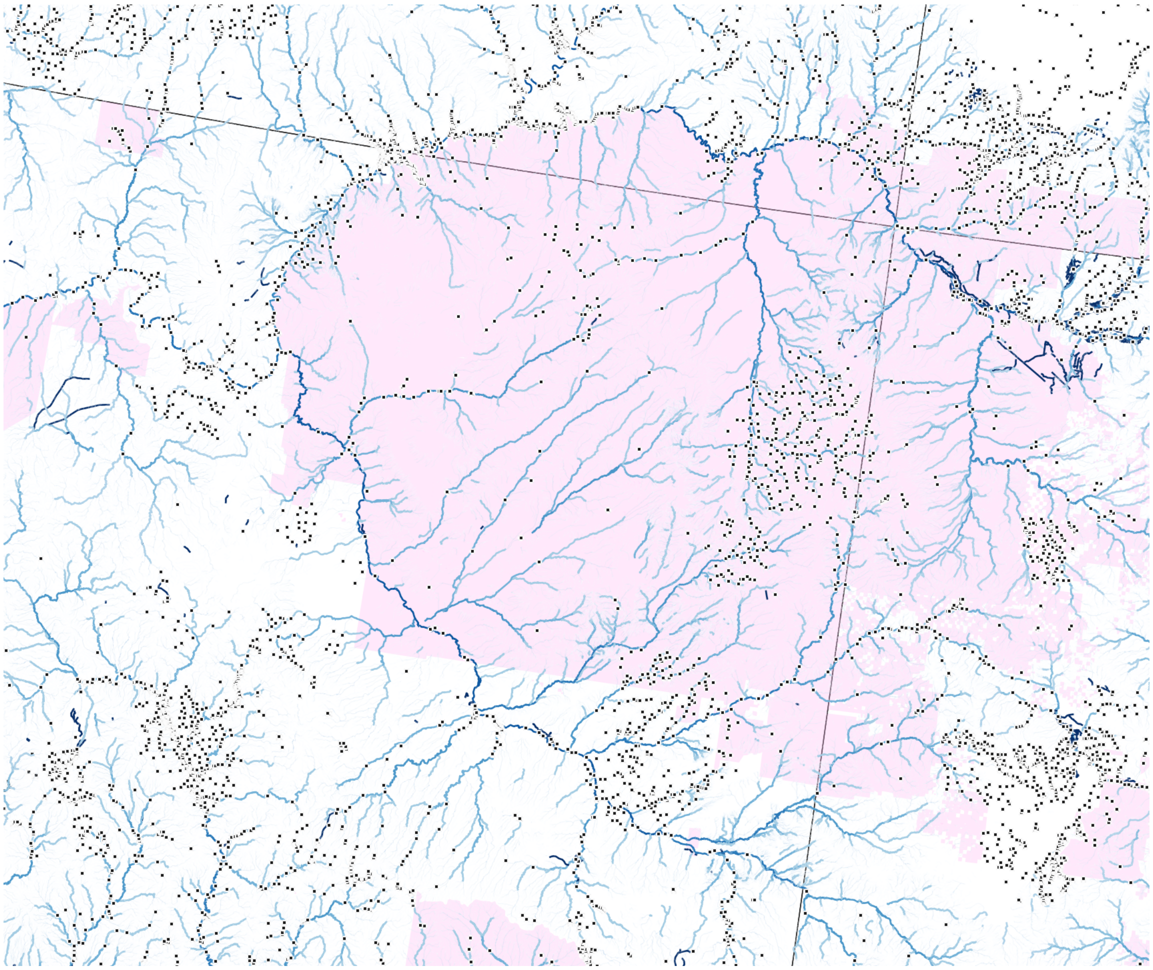


Figure 5: U.S. Streams and Rivers, STORET Monitoring Stations and American Indian Reservations Around the Navajo Nation and Hopi Reservation Region (Arizona)

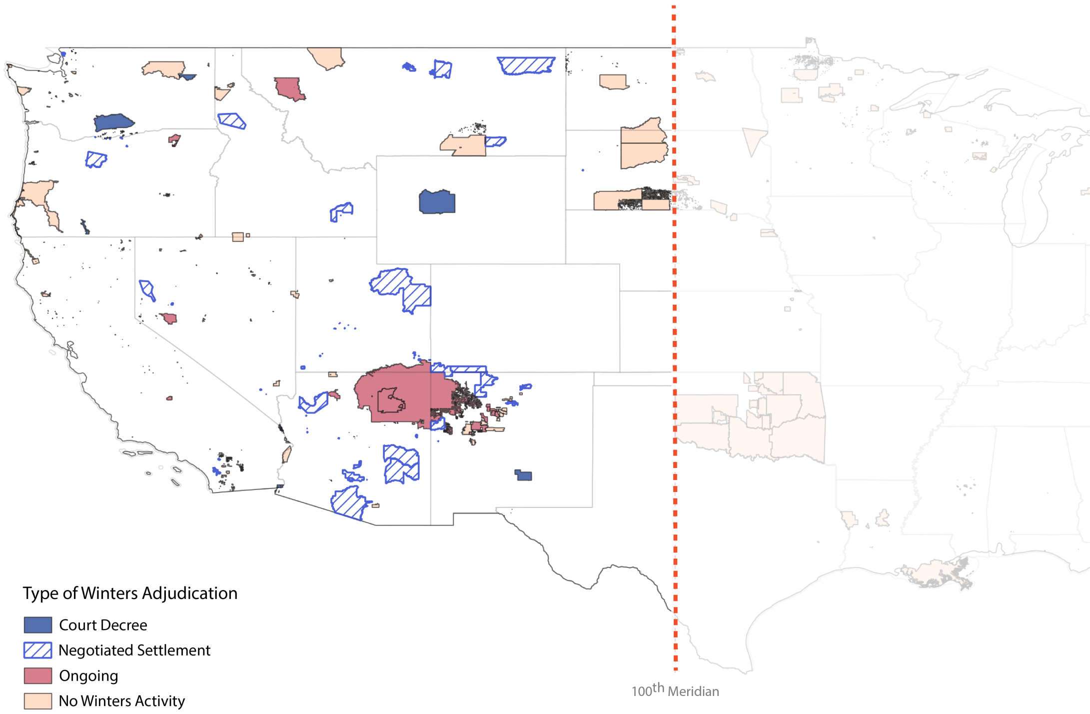


Figure 6: Winters Status and American Indian Reservations, Western U.S.

4.6 Weather and Climate Data

In addition to the above-mentioned statistics, I also incorporate monthly mean precipitation and monthly mean temperature from January 1960 - August 2020 using the Oregon State University PRISM Climate Group observational climate data. Specifically, I use the 4km AN81m grid data. Data from 1980 onwards is from the "recent" data repository, and information from 1960-1980 is from PRISM's historical repository.[24] The data are presented as raster data files (in 4km grid format), and I extract precipitation and temperature information at all of the monitoring station points using GIS software.

In order to account for shifts in overall climate conditions, I also include the Palmer Drought Severity Index to the climate divisions surrounding each monitoring station. I have this data in monthly form, from 1895 onwards. This index represents "wetter" conditions the higher it is, and drier conditions the lower it is.

[24] https://prism.oregonstate.edu/recent/; and https://prism.oregonstate.edu/historical/

4.7 County Census Data

I use annual county census data broken into three types: occupational/employment data; vital statistics; and historic census data compiled by MIchael Haines (ICPSR 2896). The employment data are the number of employed persons per year per county between 1964 and 2010. This includes information broken down by sector, including mining, manufacturing, construction, and other. The statistics are used to calculate the proportion of employed persons in each industry.

I also incorporate vital statistics on births, deaths and population from ICPSR 36603 (1915-2007). I am able to extend population and real per capita income data through 2016 thanks to Schaller, Fishback and Marquardt (2020)(Schaller, Fishback, and Marquardt 2020). I then use Michael Haines' historic census data on land, land in farming, cropland, irrigated acreage, and Indian- owned farms (much of these data are reported every five years, from 1949-2002, although some indicators are truncated). (Haines, 2010) (Haines, Political, and Research 2010).

4.8 Reservation-Level Census Data

I include time-varying reservation-level data by using census data from 1979, and interpolating it between census years. The 1979 data was collected by Cornell and Kalt 2000, and the other census years from the decennial census tables and American Community Survey. The variable used is median household income, and I deflate it to be in real terms.

5 Empirical Methods and Identification Strategy

The following models employ a difference-in-difference approach with two treatments: being in the negotiation period, and being in the resolved ("after") period. I compare within-station changes over time using station fixed effects, and I control for demographics, climate, weather, season and year. I explain variations in flow and water pollution based on these treatments.

My identifying assumption is that the timing of these periods is exogenous. I believe there is endogeneity in the timing of when *Winters* negotiations begin and end, and so the results presented here are not causal in nature. I am working on an instrumental variables approach, which will be incorporated into future work using the momentum of democratic presidential administrations in the lead-up to treatment connected to historic, time-invariant land loss data as instruments.

5.1 Changes in Water Use Expressed Through Streamflow

In order to test the above hypotheses I run the following two-way fixed effects model to assess whether various stages of *Winters* proceedings has measurable effects on water use (as expressed by streamflow). Streamflow falling corresponds to human use increasing, all else held constant. The unit of observation in the dependent variable is mean daily streamflow per station i and day t. This is an unbalanced panel.

$$\begin{aligned} Flow_{it} = \beta_0 &+ \gamma_1 \mathbf{I}\{NegotiationStart_{ry}\} + \gamma_2 \mathbf{I}\{Resolution_{ry}\} \\ &+ \gamma_3 DroughtIndex_{im} + \mathbf{X}_{iy}\beta^x + \mathbf{W}_{im}\beta^w + \xi_{year} + \eta_{season} + \nu_i + \epsilon_{it} \end{aligned} \tag{6}$$

In this equation, there are **three dimensions of time**: day, month and year. The coefficients of interest, γ_1 and γ_2 represent the change to streamflow from being in the "during" phase as compared to "before", and the "after" resolution phase compared to the "during" period, respectively. Both treatment dummies for being after the negotiation start, and then after the resolution, are zero before their respective state switches, and then 1 afterwards indefinitely. This allows the coefficients γ_1 and γ_2 to be additive compared to the "before" period.[25] The sample is constrained to only those areas that are near reservations that have at least initiated *Winters* proceedings, meaning the control group is "before", and I run this equation multiple times for different subsets: all; those stations that are upstream of reservations, downstream of reservations and on reservations.

Matrix $\mathbf{X}_{iy}$ includes county census data such as population density and real per capita income (annually by county that the station i is in), and matrix $\mathbf{W}_{im}$ includes mean monthly precipitation and temperature data at the station level. I include year, season, and station fixed effects and cluster at the reservation-HUC4 region level. My sample in all regressions is a clean subset of monitoring stations that are on or near only one reference reservation (as opposed to those that can be upstream/downstream of more than one reservation).

5.2 Changes in Pollution

The following equation estimating the impacts of different *Winters* periods on pollution is similar to the streamflow model (two-way fixed effects), but controls for streamflow and is run as a system of equations for the five pollutants tested. This setup allows for all equations' errors to be correlated.

$$\begin{aligned} Pollution_{j,i,t} = &\alpha_{j1} + \alpha_{j2} 1\{Negotiation_{ry}\} + \alpha_{j3} 1\{Resolution_{ry}\} \\ &+ \alpha_{j4} Flow_{it} + \alpha_5 DroughtIndex_{im} + \mathbf{X}_{iy}\beta^{xj} + \mathbf{W}_{im}\beta^{wj} \\ &+ \xi_{yj} + \eta_{seasonj} + \gamma_{ij} + \varepsilon_{ijt} \end{aligned} \tag{7}$$

[25] Having this linearly additive set of treatment dummies (where once they switch to 1 they never return to 0) also helps address the issues with negative weights in two-way fixed effects models raised by Chaisemartin and D'Haultfœuille 2020. Additionally, according to Wooldridge 2021, using a flexible model controlling for time also helps mitigate this issue.

where j represents one of five pollutants:

- Biochemical Oxygen Demand (BOD) 5-day
- Fecal Coliforms
- Total Suspended Solids
- Dissolved Oxygen (reported as difference from 100% Saturation)
- pH (reported as difference from 7)

These pollutants are presented in ways where increasing numbers means more pollution. For example, for dissolved oxygen as percent saturation, lower saturation concentrations are more harmful for the environment. Following Keiser and Shapiro (2018), I report the percent saturation as difference from 100, so larger "differences" equate to lower percent saturation levels.[26] Errors are also clustered at the reservation-HUC4 level, and run on successive "clean" samples for all stations, upstream of reservations, downstream of reservations and on reservation.

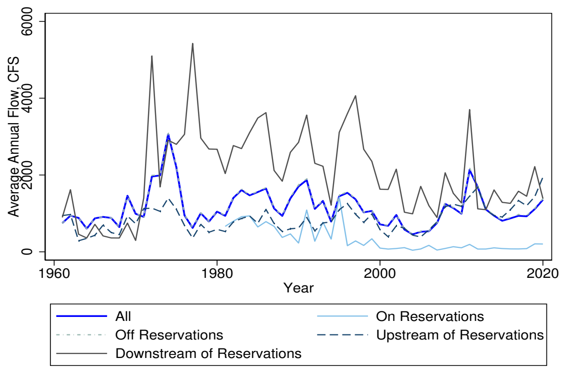
6 Empirical Results

6.1 Streamflow and Pollution Summary Data

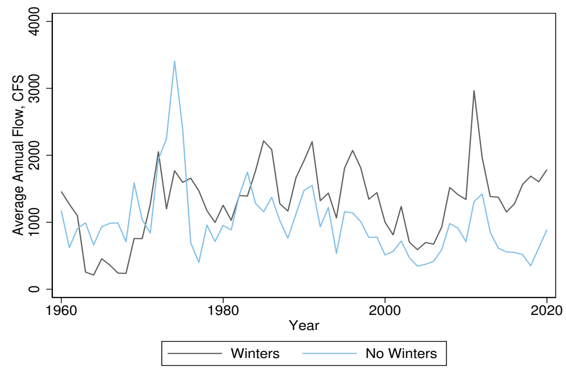
Average annual streamflow has remained relatively steady over the past several decades, with differences in variation across relative positions from reservations (Fig. 7a). In particular, since the 1990s, streamflow on reservations has been substantively lower than at upstream, downstream, or other monitoring stations in the vicinity ("All" includes neither upstream nor downstream from reservations). Note that while on-reservation streamflow was fairly similar to upstream and total average measures, by the 1990's, these trajectories began to separate, and on-reservation streamflow remained markedly lower than other areas. This is in line with colloquial narrative that water resources on reservations have been increasingly scarce over the decades, serving as a key impetus for initiating *Winters* proceedings.

Figure 7b also shows average annual streamflow for monitoring stations within a subwatershed region with a "*Winters*" proceeding at some point, versus those without. While very similar, in recent years, areas "with *Winters* have clocked higher average annual streamflow measures than those without.

[26] Low levels of oxygen saturation in water are unsustainable for aquatic life. Less than 60% is considered very poor; 60% to 80% is considered acceptable, and 80% to 125% is considered good.



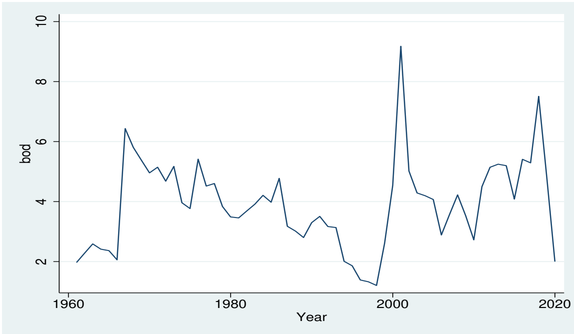
(a) By Relative Position to Reservation



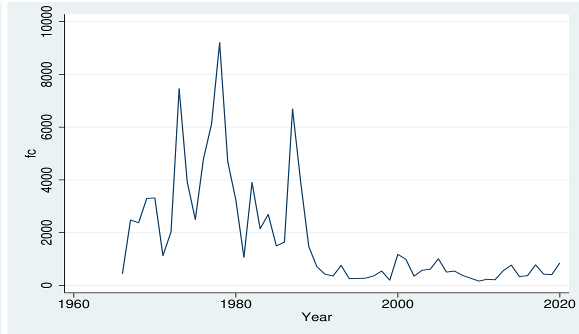
(b) Winters vs. No Winters

Figure 7: Average Annual Streamflow Over Time

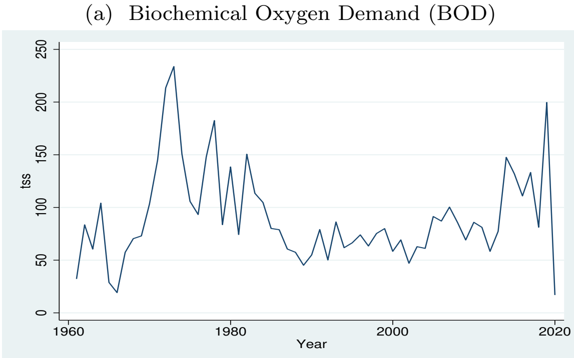
Figures Figure 8 shows how pollution has changed over time. For all pollutants, quality has generally gotten better (evidenced by downward movement in the data) since the 1960s and 1970s until about the early 2000's, where it either flattened or began trending upwards again. Biochemical Oxygen Demand (BOD), top-left-most figure below, has shown higher average levels in later years compared to the 1970s. BOD in particular mainly comes from anthropogenic sources (Vigiak et al. 2019). Average annual pollution readings over time have been similar across relative positions (on-reservation, vs. upstream, for example), although there is some variation in volatility and overall upward or downward trend within that (see Appendix **??**).



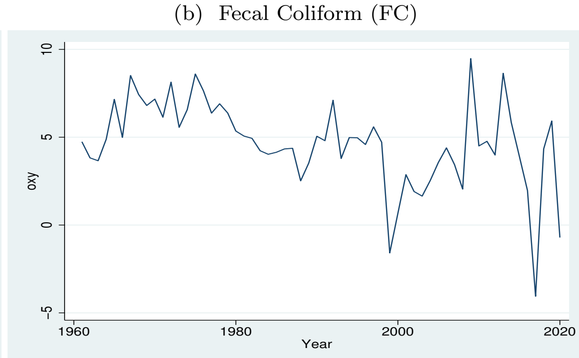
(a) Biochemical Oxygen Demand (BOD)



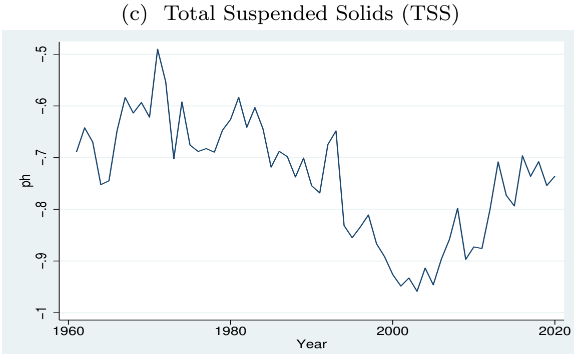
(b) Fecal Coliform (FC)



(c) Total Suspended Solids (TSS)



(d) Dissolved Oxygen (% Saturation, Diff from 100)



(e) pH (Difference from 7)

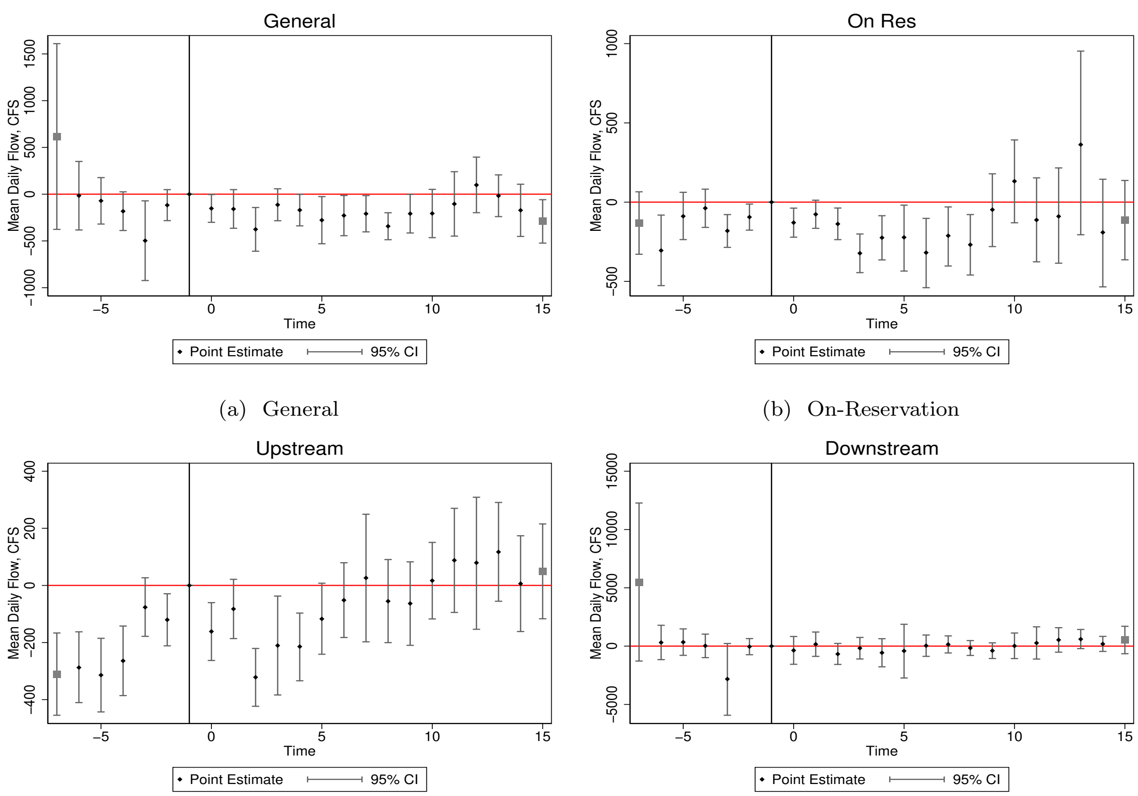
Figure 8: Average Annual Pollution Over Time

Note: All pollutants are reported as "worse" defined as increasing, and "better" defined as decreasing. Percent oxygen saturation, for example, is reported as difference from 100%. Therefore, larger numbers mean the actual percent saturation is lower. To represent increasing acidity, pH is reported as difference from 7 (neutral), so larger numbers are lower pH values, and lower, or negative numbers are higher pH values.

6.2 Event Study Graphs

Before turning to the empirical results of the models outlined above, I present event-study graphs to examine pre-trends, and understand how streamflow and pollution are changing year by year around the event. Figures **??** to **??** show streamflow around the start of *Winters* proceedings, for all monitoring stations, upstream stations, downstream stations, and on-reservation stations. These models are very similarly specified as the difference-in-difference models above, where I use streamflow, or pollution, as an outcome variable, and control for weather, demographics, economic conditions, climate, year, season and station. Here, I use wild bootstrap standard errors because some models have few numbers of clusters (below 40), although results are similar between the two.

6.2.1 Streamflow Before/After *Winters* Starts



(a) General

(b) On-Reservation

(c) Upstream of Reservation

(d) Downstream of Reservation

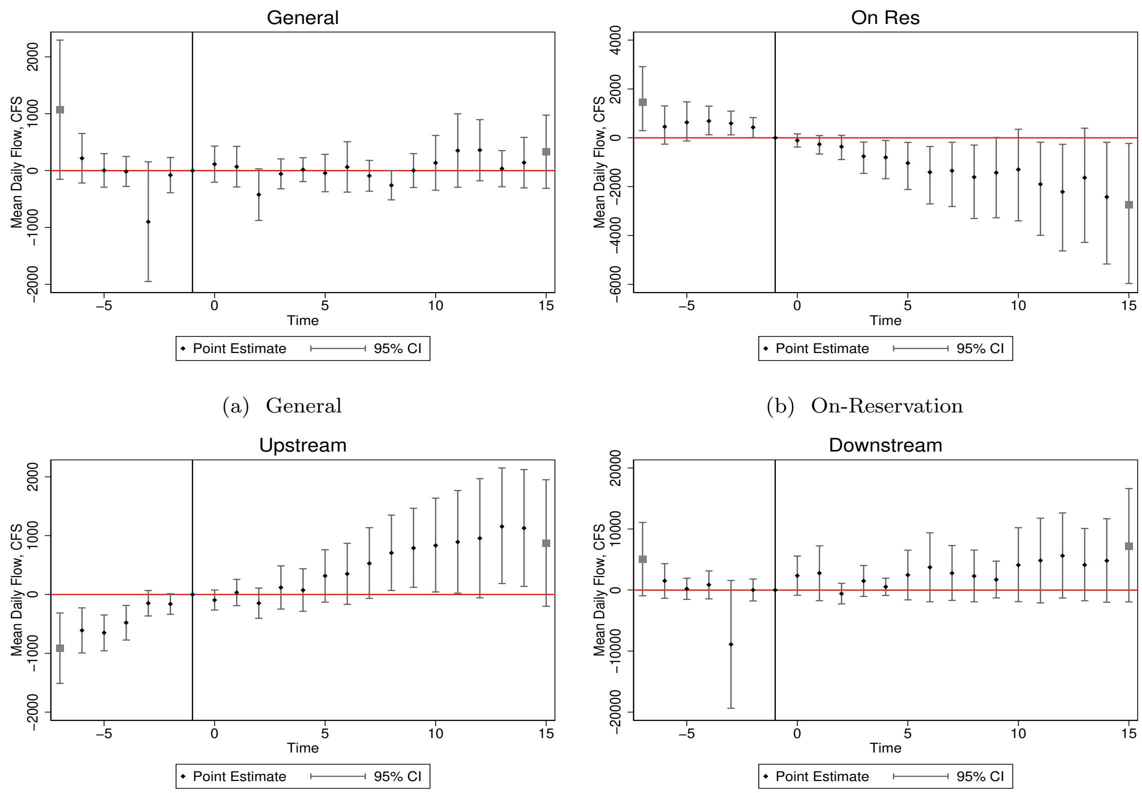
Figure 9: Streamflow Around *Winters* Starts

Streamflow tends to fall early in the process, and then recovers later on[27] This is largely driven from upstream and on-reservation areas, as downstream streamflow is fairly constant during this time.

6.2.2 Changes in Water Use as Evidenced by Streamflow - Settlement Cases Only

When we just focus on settlement cases only (not ones that resolved via litigation), a somewhat different picture emerges. On-reservation streamflow clearly falls and keeps falling after the start of negotiations, but upstream flow rises. This is something of a contradiction, and may hint at increased use from other sources of water, like groundwater, close to reservation boundaries. Further data and research would be needed to assess this.

[27]Note, ll of these event studies restrict the sample to exclude observations where resolutions have been settled. So the reading for 15 year lag only includes observations for stations that are still in the negotiation process – i.e., there is no bleeding in from resolved processes.



(a) General

(b) On-Reservation

(c) Upstream of Reservation

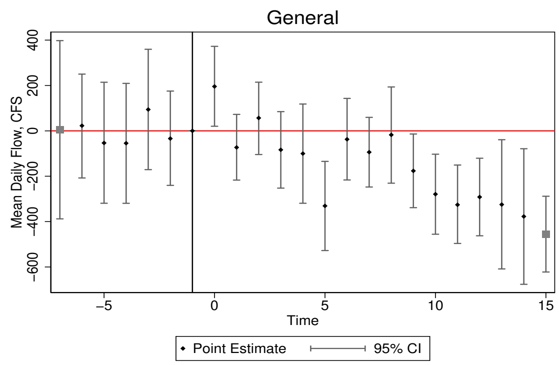
(d) Downstream of Reservation

Figure 10: Streamflow Around *Winters* Starts - Negotiated Settlements Only

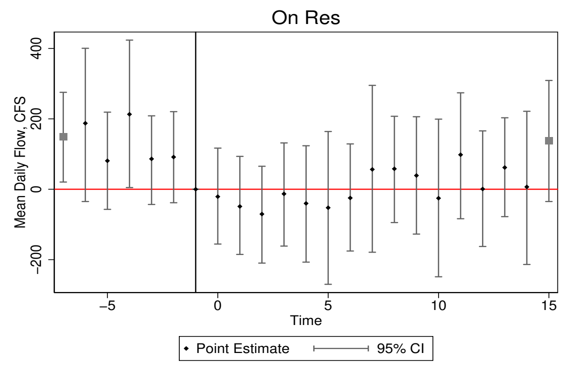
6.2.3 Streamflow After Resolution

Once resolved, streamflow tends to fall overall in the general vicinity of a *Winters* resolution, evidenced by the event-study analysis, especially later in the lag periods (Figures 11a to 11d). This is mostly driven by downstream results (or other areas which are neither upstream nor downstream, nor on reservations). On-reservation readings show somewhat lower readings just after resolution, and somewhat higher after that. Upstream readings tend to go through an initial period of being somewhat lower, then higher, then settle at original levels again.[28]

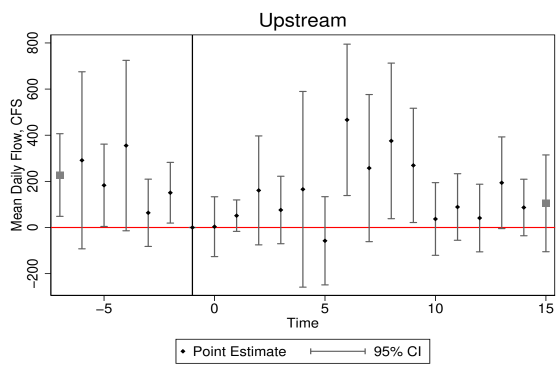
[28] A key piece of future research is including groundwater levels in this model. It is entirely plausible, and possible, that users are making up for lack of surface water rights by pumping groundwater. This should in general affect surface water flow rates too, but it also depends on where groundwater is being pumped (if it is).



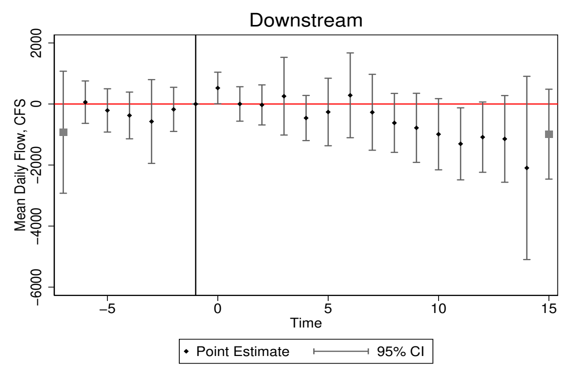
(a) General



(b) On-Reservation



(c) Upstream of Reservation

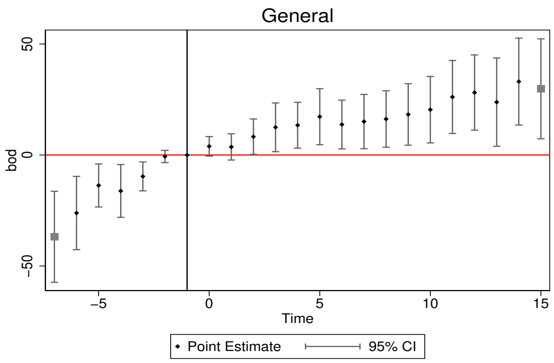


(d) Downstream of Reservation

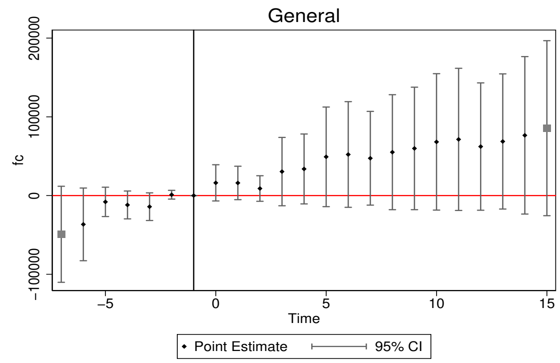
Figure 11: Streamflow After Resolution

6.2.4 Pollution After *Winters* Starts

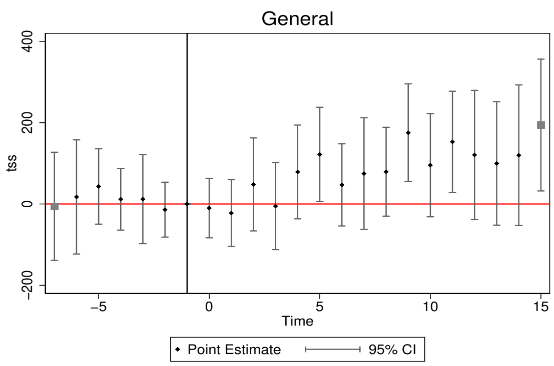
Pollution tends to increase once negotiations start, across most pollutants (pH is the exception in general).



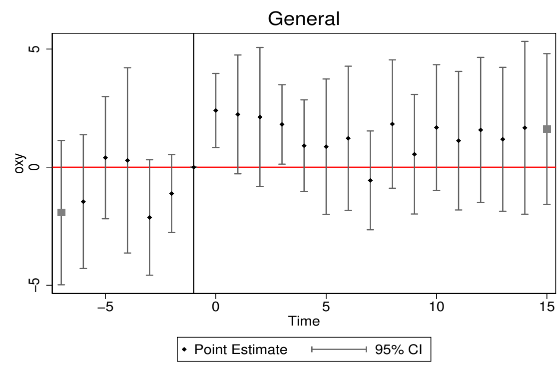
(a) BOD



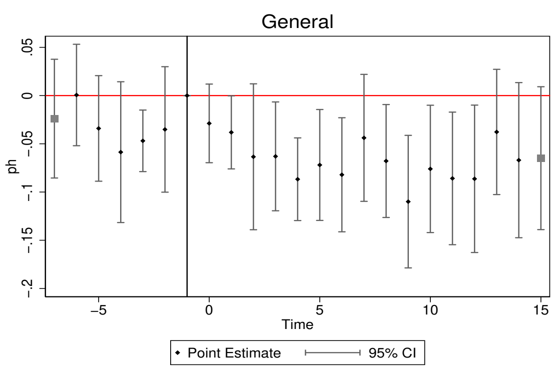
(b) FC



(c) TSS



(d) Dissolved Oxygen (% Saturation)



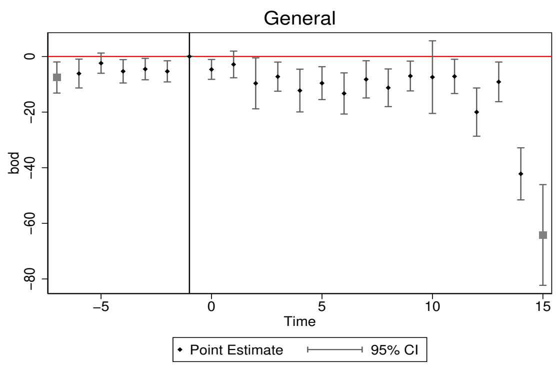
(e) pH (Difference from 7)

Figure 12: Pollution Around *Winters* Starts

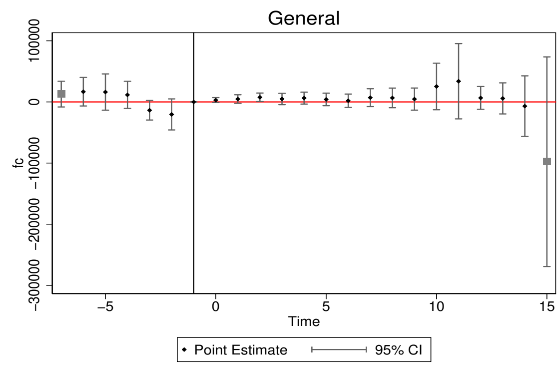
Appendix C.4 shows the related graphs for upstream, downstream and on-reservation areas.

6.2.5 Pollution After *Winters* Resolutions

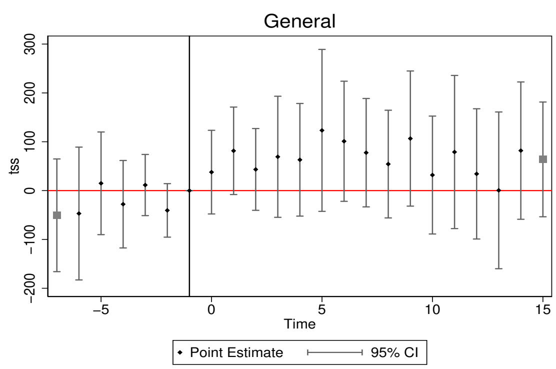
The following graphs depict how pollution changes after *Winters* rights are resolved (due to data limitation issues, I am only able to show event study charts for BOD, fecal coliforms and total suspended solids). Pollution falls post resolution for BOD and, later in the lag period, fecal coliforms, while rising somewhat for total suspended solids. Again, BOD and fecal coliforms are largely resultant of farming, effluent runoff or other anthropogenic sources. Total suspended solids may stem from human develop directly, but also be indicative of soil erosion and other topographic changes.



(a) BOD



(b) FC



(c) TSS

Figure 13: Pollution Around *Winters* Starts

6.3 Difference-and-Difference Empirical Results

Earlier, I presented hypotheses predicting that water use will increase once rights are resolved (uncertainty is mitigated), and that water use may increase or decrease depending on whether entrenchment motives or uncertainty dominates. In concurrent research as part of my dissertation, I calculate the risk premium priced into wholesale water markets, and find that this measure of uncertainty falls during negotiations. Therefore, I would expect water use at least not to fall for strategic stakeholders also acting as part of this negotiation process, i.e., uncertainty effects would not dominate. I would expect most pronounced strategic uses to be upstream of reservations. Even though water is diverted in many areas of the west, incumbent appropriators are still able to increase water use by using groundwater, or increasing use of surface water where possible. I would suspect if water users are attempting to show the "need" water, or find ways to entrench usage, they would at least do so upstream of reservations.

Table 6.1 displays the results of Model 6, showing changes in streamflow for all stations (1), on-reservation stations (2), upstream-of-reservation stations (3), and downstream-of-reservation stations (4). Water use, evidenced by changes in declines in streamflow, does increase upstream of reservations during the negotiation period compared to before, though not significantly. After a resolution is passed and rights are settled, streamflow falls significantly on and upstream of reservations. This impact is even more pronounced upstream when we restrict the analysis to those close to reservations, or, within 100 miles (Table 6.2).

	(1) Gen.	(2) On	(3) Up	(4) Down
After Neg. Start	-78.11	85.71	-83.55	264.3
	(87.48)	(165.8)	(92.85)	(445.8)
After Winters Resolution	-54.78	-72.76**	-189.4**	901.4
	(164.8)	(35.11)	(77.79)	(1027.8)
Palmer Drought Severity Index	33.45	24.88**	33.56***	-16.06
	(20.71)	(10.65)	(11.41)	(88.96)
Monthly Precip.	4.872***	0.229	3.656*	11.63
	(1.080)	(0.620)	(1.848)	(8.292)
Monthly Temp.	10.38	8.096**	21.71***	-40.64
	(13.00)	(3.260)	(7.016)	(87.55)
Pop. Denisty	396.7**	1610.1	-2624.6	639.7
	(199.7)	(1607.6)	(3188.6)	(711.4)
Real Per Cap Inc. (Cty)	-0.0145	-0.0735	-0.0343	0.129
	(0.0183)	(0.0582)	(0.0263)	(0.138)
Constant	555.5***	126.1	587.7**	1021.8***
	(139.1)	(171.0)	(225.9)	(379.0)
Year Effects	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes
Observations	371964	16473	74780	49129
Adjusted R^2	0.001	0.037	0.037	0.000

Standard errors in parentheses
Errors Clustered at Res-HUC level
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6.1: Streamflow During and After Negotiations

	(1) Gen.	(2) On	(3) Up	(4) Down
After Neg. Start	-17.04	85.71	-83.23	251.1
	(85.74)	(165.8)	(99.25)	(469.2)
After Winters Resolution	2.080	-72.76**	-223.5**	933.2
	(200.6)	(35.11)	(87.65)	(1055.0)
Palmer Drought Severity Index	32.58	24.88**	31.15**	-22.46
	(24.80)	(10.65)	(12.30)	(91.80)
Monthly Precip.	4.044***	0.229	3.728*	12.10
	(0.683)	(0.620)	(1.860)	(8.561)
Monthly Temp.	9.953	8.096**	22.14***	-42.06
	(16.14)	(3.260)	(7.427)	(92.80)
Pop. Denisty	478.8**	1610.1	-2754.4	700.2
	(240.3)	(1607.6)	(3277.8)	(806.9)
Real Per Cap Inc. (Cty)	-0.0217	-0.0735	-0.0353	0.113
	(0.0232)	(0.0582)	(0.0268)	(0.134)
Constant	657.6***	126.1	600.2***	1035.7***
	(157.4)	(171.0)	(219.3)	(370.6)
Year Effects	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes
Observations	289422	16473	68469	46262
Adjusted R^2	0.000	0.037	0.036	0.000

Standard errors in parentheses
Errors Clustered at Res-HUC level
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6.2: Streamflow During and After Negotiations - Close to Reservations

One sign of incumbent-user entrenchment that has become insidious in *Winters* negotiations is the prolonged negotiations spanning several years. As hypothesized earlier, when a water user expects $Q_{t+1}(Q_t) < Q_t$, they have motives to stay at the status-quo level, and not agree to a settlement. As opposed to long negotiations signifying burgeoning uncertainty, in these scenarios we would expect non-Indian water users to become more comfortable using more water the longer they are entrenched in the status quo. I test to see if water use (as evidenced by changes to streamflow) increases or decreases with prolonged settlement negotiations. As Table 6.3 shows, I do find that streamflow decreases significantly with each extra year of settlement duration, and that this effect is completely concentrated off reservations (presented for the subset of cases that are resolved via negotiation).

	All Stations in Res-HUC	Off Res	On Res
	Flow (CFS)	Flow (CFS)	Flow (CFS)
Neg. Year	-2.423	-2.617	4.186
	(1.531)	(1.578)	(5.816)
Palmer Drought Severity Index	29.15***	29.46***	27.95
	(6.655)	(6.756)	(13.73)
Monthly Precip.	4.224**	4.257**	1.361
	(1.338)	(1.360)	(2.103)
Monthly Temp.	20.56***	20.99***	10.61*
	(5.484)	(5.764)	(4.660)
Pop. Denisty	278.5***	280.0***	34088.7***
	(56.74)	(56.99)	(4141.3)
Real Per Cap Inc. (Cty)	-0.0180	-0.0156	-0.267*
	(0.0195)	(0.0196)	(0.112)
Constant	87.89	79.93	789.9*
	(155.0)	(157.1)	(350.2)
Year Effects	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes
Observations	124349	119874	4475
Adjusted R^2	0.034	0.034	0.118

Standard errors in parentheses
Errors Clustered at Res-HUC level
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6.3: Streamflow And Year of Negotiation – Settlements Only

6.4 Changes in Pollution During and After Negotiations

Table 6.4 presents the results of the system of pollution equations. While there is some variation, in general there are significant increases in pollution during the negotiation period, as compared to before, particularly amongst fecal coliform and biochemical oxygen demand (BOD). Both of these pollutants can stem from human and agricultural uses, including effluent/waste and industrial processes and urban storm water runoff. Total Suspended Solids (TSS), on the other hand, can be caused by other factors such as erosion. Increasing acidity in water (evidenced by larger differences in pH from 7) are evident in these results, although not significant. Fecal coliform changes are concentrated mostly upstream of reservation and also on reservations.

The second part of Table 6.4 shows how pollution changes after rights are resolved. Fecal coliform actually falls back down, although not significantly. BOD does continue to increase upstream and downstream, but TSS falls on reservations.

I can also run this same regression, but for those settlements that included environmental streamflow fights in their agreement. Here, shown in Table 6.5, pollution does still increase during negotiations (sometimes more so than in the general case from above), but the environmental clauses seem to mitigate pollution after rights are resolved better than in the general case. Fecal coliform falls significantly after resolution upstream and downstream of reservations, despite increasing on reservations. Total suspended solids, dissolved oxygen and pH fall on reservations once rights are settled.

	(1) All	(2) On	(3) Up	(4) Down
Negotiation:				
Fecal Coliform	17162.5	3724.1**	4366.6*	27682.2
	(11170.1)	(1728.5)	(2375.9)	(27488.4)
BOD	9.408***	1.906***	0.871	16.71*
	(3.571)	(0.287)	(2.113)	(8.415)
TSS	4.438	219.7**	-117.6**	13.32
	(32.26)	(91.19)	(47.56)	(83.57)
Dis. Ox.	2.219**	13.36	1.240	1.457
	(1.006)	(8.627)	(1.113)	(3.113)
pH	-0.0341**	0.0539	0.0300	-0.0260
	(0.0136)	(0.0463)	(0.0249)	(0.0192)
Resolution:				
Fecal Coliform	135.1	1018.8	-3460.1	-5773.0
	(3022.2)	(1894.9)	(2309.7)	(6734.6)
BOD	-1.652	0	5.605***	1.699**
	(1.245)	(.)	(1.302)	(0.854)
TSS	89.40**	-584.9**	68.56	117.1
	(35.90)	(254.8)	(51.69)	(86.44)
Dis. Ox.	-1.062	-4.533	-0.217	-2.504
	(0.932)	(4.251)	(1.008)	(1.849)
pH	0.0214	-0.0429	-0.0461	0.0149
	(0.0144)	(0.0367)	(0.0337)	(0.0223)
Constant	-4932.6	51.24	330.1	-15914.6
	(5336.5)	(481.6)	(618.2)	(21589.1)
Year Effects	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes
Observations	475325	20321	94870	70457
Adjusted R^2	0.010	0.056	0.050	0.015

Standard errors in parentheses

Errors Clustered at Res-HUC level

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6.4: Pollutants During and After Negotiations

	(1) All	(2) On	(3) Up	(4) Down
Negotiation:				
Fecal Coliform	1476.3*	4938.9***	5021.6*	161.2
	(804.7)	(1021.7)	(2784.7)	(190.2)
BOD	-2.851	1.906***	-0.291	-0.639
	(1.742)	(0.288)	(1.023)	(0.518)
TSS	6.170	264.7***	-74.50	19.82
	(37.96)	(72.79)	(70.45)	(106.6)
Dis. Ox.	2.990**	13.63	3.049***	5.169***
	(1.253)	(8.792)	(1.130)	(1.321)
pH	-0.00341	0.0826	0.0556*	-0.0359*
	(0.0160)	(0.0551)	(0.0297)	(0.0195)
Resolution:				
Fecal Coliform	933.6	983.0*	-4424.8*	-1040.8*
	(1208.9)	(516.5)	(2533.3)	(603.4)
BOD	-0.839	0	4.287***	0.785***
	(1.272)	(.)	(0.607)	(0.184)
TSS	41.31**	-707.2***	-38.30	55.14
	(18.85)	(129.3)	(42.44)	(61.26)
Dis. Ox.	-1.654	-11.79***	-0.796	-2.881*
	(1.000)	(2.616)	(0.977)	(1.698)
pH	0.0148	-0.0456	-0.0332	0.0187
	(0.0186)	(0.0384)	(0.0373)	(0.0189)
Constant	854.9**	-863.5**	-61.43	309.1
	(377.6)	(393.8)	(476.4)	(221.1)
Year Effects	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes
Observations	318276	19241	72732	56506
Adjusted R^2	0.001	0.060	0.059	0.011

Standard errors in parentheses
Errors Clustered at Res-HUC level
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6.5: Pollutants During and After Negotiations - Environmental Clauses

7 Conclusions and Discussion

The analysis presented above puts together the first set of empirical work attempting to assess the impacts of *Winters* proceedings on environmental quality and water use. Specifically, I find that streamflow upstream of reservations declines during negotiations (though not significantly), and then significantly falls once rights are settled. Additionally, when I compare ongoing settlement negotiations, I find that water use increases with each extra year of negotiation, and these results are concentrated completely off reservations. This implies that entrenchment behavior may persists where certain stakeholders have the negotiating power not necessarily to change the expected outcome of a settlement, but to stop up the process but continue to use water in the interim, avoiding preemption of rights.

In terms of water quality, I find water pollution increases significantly in some key measurements such as fecal coliform, BOD and dissolved oxygen during the negotiation process. In some cases, pollution falls back down once rights are settled. When tribes negotiate for environmental (non-consumptive) uses of water, increases in pollution during negotiation are more significantly mitigated once rights are settled, implying the environmental clauses may be a good policy measure to impact the environmental degredation happening during negotiations.

Taking a step back, this analysis implies that the *Winters* process itself is not neutral when it comes to environmental impacts, and procedural injustice towards tribes. Specifically, non-Indian users are able to continue to use and capitalize on the resource while bargaining is underway. This situation clearly incentivizes some users—who are able to—to maintain this status-quo level, yet again eroding the very property rights tribes are fighting for. At a headline level, the story of *Winters* rights has been that the existence of un-quantified tribal rights to water represents a drag on investment due to the looming uncertainty for current water users they pose. This suggests a positive outcome would be to engage the rest of the tribes in *Winters* negotiations, or prevent them from being able to take up these proceedings in the first place. But the very activity of negotiating for these rights can incentivize their further erosion, an outcome that again leaves tribes at the mercy of powerful forces of the political economy, yet again.

Appendices

A Additional Tables and Figures

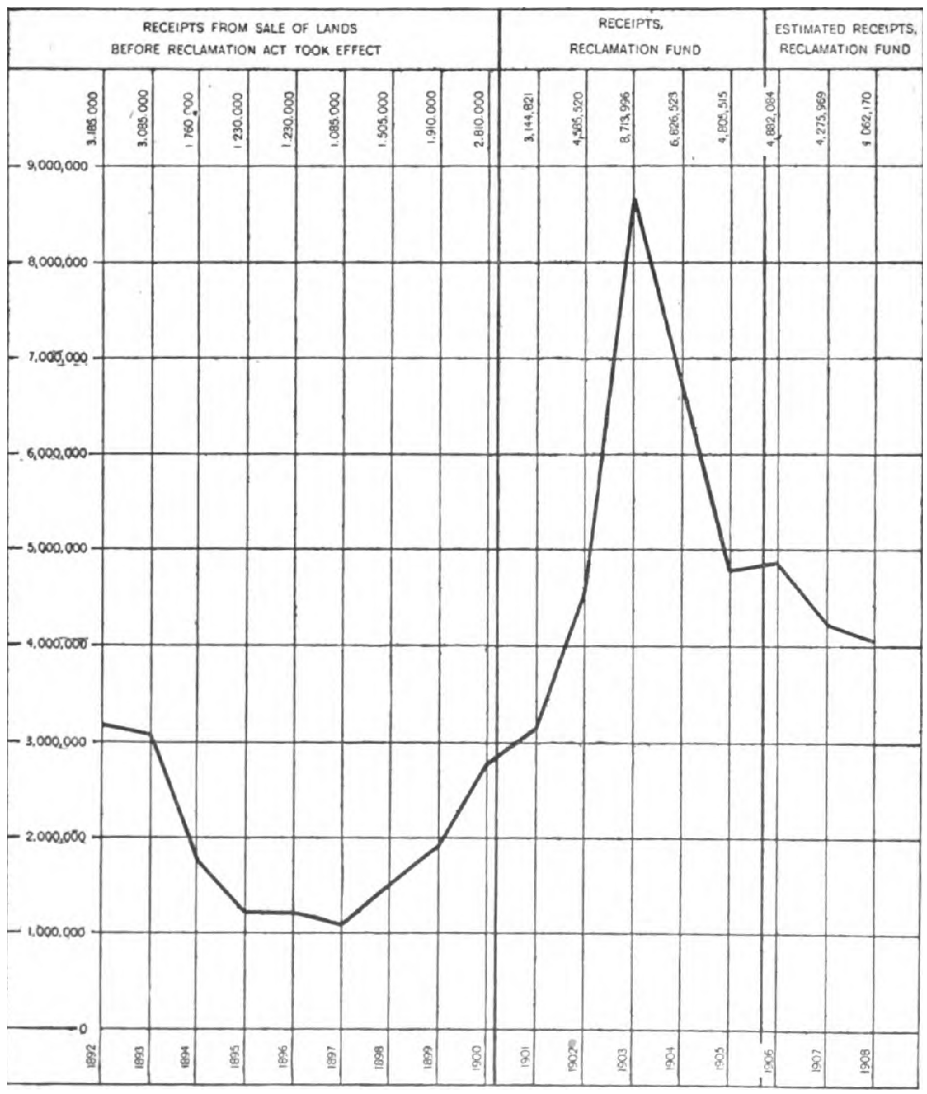


Figure 14: Proceeds from Public Land Sales in Reclamation States, 1891-1908
Source: Annual Report of the Office of Indian Affairs, 1906, page 42..

B Data Cleaning and Sourcing: Further Details

B.1 Water Pollution Data

For this analysis, I focus on ambient surface water, including streams, rivers, lakes and reservoirs. I do not include oceans, or groundwater. I also do not include non-ambient water pollution readings, such as those from inside of facilities. In the STORET system, results are maintained in a separate set of data files from monitoring stations (the sampling location). One can focus on surface water sampling by filtering the types of monitoring stations included in the analysis. The types of monitoring stations are classified in different ways in modern versus legacy STORET, but the EPA has created an algorithm and linking table to merge legacy classifications with modern ones.[29]

Using the link table mentioned above, I retain monitoring stations in this analysis that represent streams/rivers, lakes, or reservoirs. This is filtered by joining legacy STORET stations with their modern "types", and keeping only those with modern type of "Canal", "Lake", "Reservoir", "River/Stream", or "Spring". Additionally, all observations must be classified as "S" for surface water (I am excluding groundwater). I also removed any non-ambient, municipal or industrial, sewage, outflow, or similar station types (the Legacy STORET variable for type of monitoring station).

For Modern STORET, I followed a similar process, although the station types are more specific than what is in the legacy-to-modern join table. Following Keiser and Shapiro (2019), in filtering for lake, streams, rivers, reservoirs and impoundments, I keep monitoring stations with the following monitoring station type: Stream, River/Stream, River/Stream Ephemeral, River/Stream Intermittent, River/Stream Perennial, Riverine

[29]The main way that monitoring stations were classified in Legacy STORET was through the variable "stationtype". However, the Legacy system was based on mainframe computing, which is heavily dependent on using acronyms and abbreviations for words, meanings and classifications that can change or evolve over time. There is a set of reference tables that correlate with the various "levels" contained in the station type variable, however they do not elucidate how the "levels" relate to each other, or what they are. Based on personal communication with the EPA, there is no further supportive material on what the station type variable means, or its logical flow, aside from the reference tables. Before the system was retired in 1999, one of the key query builders for Legacy STORET created an algorithm to link these station type codes to the modern classification. This was an important step, because until its retirement, most major queries involving substantial data were conducted by a person, who knew and understood the nuances of the classification system, including how it evolved from the 1960s onwards. This entailed understanding that "TYPA/AMBT/STREAM" was effectively the same classification as "TYPA/STREAM/AMBT", and that "TYPA/AMBT/STREAM/FISH/SOLID" might still refer to a stream/river surface water sample (that the code might just denote the monitoring station could support both)

After several rounds of email and telephone communication with the EPA, it became clear that the results of the linking algorithm, the modern classification applied to the legacy stations, was the most reliable classification for monitoring stations. Thus, this is what we use. The linking table can be found here (it mistakenly had not been available publicly before this communication): `ftp://newftp.epa.gov/storet/exports/reference_tables/STATION_Legacy+modernStationTypes.xlsx`.

Impoundment, River/stream Effluent-Dominated, Canal Drainage, Canal Irrigation, Canal Transport, Channelized Stream, Floodwater, Floodwater Urban, Floodwater non-Urban, Lake, Reservoir, Great Lake, "Lake, Reservoir, Impoundment", Pond-Anchialine, Pond-Stormwater.

For both Modern and Legacy STORET, I define a unique monitoring station by the latitude and longitude measure. Another option would be to create a tupple of Agency/Organization ID, Station ID, and station type code. Some stations are technically different on this metric, but are actually in the same location (and are of the same type) based on latitude and longitude measures. In personal discussions with the Water Quality Portal (WQX) Help Desk, the EPA confirmed that a robust way to aggregate any duplicate monitoring stations would be to collapse on latitude and longitude, rounded to the third decimal degree.[30]

Thus, using the concatenation of latitude and longitude (each to the third decimal degree), I collapse Legacy and Modern STORET monitoring station data, separately, on latlon, and then append together the two datasets, and collapse again. The final file is saved as a STATA data file, and then also exported as a text file for use in GIS-based software.

B.2 Identifying Upstream and Downstream Flows Relative to Reservations

The process of identifying upstream and downstream flowlines (aka stream reaches, or stream segments between two stream nodes) was tedious given the nature of how the American stream system network is stored and is available for use by the U.S. Geological Survey.

The data on stream location and flow direction is from the National Hydrography Dataset Plus HD (NHDPlusHR), and was downloaded via The National Map. I . I used The NHD-Plus HR as opposed to the less-complex NHD dataset for one specific reason: the NHDPlus HR environment already had the "flow table" pre-built and loaded into the downloadable data. The NHD area, while easier to work with because I could download this data on a national scale, did not have the flow table built, which was essential for stream navigation, and contained information on flow direction. In order to discover upstream/downstream locations, this flow table had to be populated using the NHD utility tools in conjunction with ArcMap. In terms of processing time, this would be prohibitive. As one NHD expert put it, building the flow table for the state of Texas took four or five days. Processing several states would not only take time, but it would be difficult to open and run the full NHD national file on one computer. ESRI products are not developed for use on linux platforms, so they cannot be used on the High-Performance Computing platform available

[30]Email communication with Kevin from the EPA (WQX@epa.gov) on Wednesday, September 9th, 2:21pm.

at the University of Arizona, which would render the use of the NHD product (where the flow table has to be manually built for several states) infeasible for this analysis.

The other option is using the NHDPlus HR data, which contains the information in the NHD data, in addition to many other value-added attributes. The downside of using the NHDPlus HR data is that there is more information contained in the dataset than is needed – which can be a drain on downloading, drawing and processing time. Additionally, the NHDPlus HR data is only available for download in HUC4 or HUC8 boundaries (HUC 4 being the largest).[31] The major benefit to using the NHDPlus HR data is that the flow tables are already populated. This means that the flow direction is in the map and data when it is downloaded and opened.

B.2.1 Downloading and using NHDPlus HR data to identify upstream and downstream flows

In order to download and use the NHDPlus HR data, I navigated to the National Map viewer, and downloaded NHDPlus HR data by HUC4 region. These were downloadable as zipped geodatabase files. Each zipped folder contains an xml file, a raster jpg, and a geodatabase for each HUC 4 boundary. It turns out that some HUC4 boundaries actually just contain data for smaller boundaries within it (HUC8). There are just a handful like that. It is technically possible to link all of the disaggregated HUC4 layers into one, national layer, but it takes several steps and requires rebuilding the network connections. Due to processing time and limitations, I decided it was most feasible to use the HUC4 layers individually, and to find the upstream/downstream flowlines per HUC4-reservation combination. A clear limitation to this is that it is not possible to continue to trace the upstream/downstream flowlines in HUC4 areas that do not directly intersect with the reservation of interest (i.e., I can't keep tracing out into neighboring HUC's). So, the upstream/downstream analysis is limited to selecting upstream/downstream flowlines in watershed boundaries that intersect with the reservations. This serves as an acceptable buffer to limit data processing and analysis. Future analysis could include linking the entire network, or utilizing national data to rebuild the flow table and go from there.

B.2.2 Identifying and Utilizing Reservation "Starting Flags" for Upstream / Downstream Network Analysis

The National Hydrography Dataset was designed, in part, to be used with the ESRI suite of GIS programs. In order to build the flow table, for example, one must use the NHD Utility Tool specifically with ArcMap.[32] Additionally, the Network Utility tool is recommended for tracing upstream and downstream flowlines. The typical way that the network utility

[31] There are 200 HUC4 boundaries that are available for download with NHDPlus HR data. For an illustrative map, see: `https://www.usgs.gov/media/images/watershed-boundary-dataset-subregions-map`

[32] The NHD Utility tools must be used specifically with ArcMap version 10.5.1 (not earlier, not later).

algorithms work in ArcMap is that they use a defined reference network to trace upstream and downstream flows from particular starting points/flags/events. These starting points can typically be placed by hand onto the map. However, identifying starting flags in this way is not feasible for broad-scale analysis, particular of a national or semi-national scale. While USGS recommends using the Network Utility Tool with ArcMap in order to find upstream and downstream flows, a related tool, the Trace Geometric Network tool allows users to use an already-defined point layer as starting flags. These starting flags, however, must be linked to the network.

Thus, it is not a straightforward task to take a layer of reservation boundaries, and identify upstream flows from each polygon in that boundary layer. The polygon layer needs to be converted to usable starting points, and must be networked. I accomplish this goal in multiple steps. First, to create the starting-flags, for each HUC4 boundary, I intersect the reservation polygon layer with the HUC4 flowlines, and select the output to be constructed as points. Therefore, for each HUC4 boundary, every place a reservation boundary intersects with a stream, a point is created and saved as a new layer. These point layers, for each HUC4 boundary, must then be added to the network in order to use them as starting flags in the trace upstream/downstream algorithm. To do this, I employ the U.S. Environmental Protection Agency's Hydrography Event Manager (HEM) Tool,[33] which allows users to import events into the stream network. Typically, this is used for events such as pollution spills, or species-related events, but from a spatial perspective, it can take points, and join them to the network. Once the points layers are networked, I then separate out each reservation-HUC intersection as their own stand-alone networked points layers, by selecting by reservation code the intersection points in each HUC4 boundary, and creating a new layer for each set of selected HUC-reservation networked intersection points. Therefore, in the end, I have a networked points layer for each HUC4-reservation combination.[34]

B.2.3 Identifying Upstream and Downstream Flowlines per Reservation

I use the Trace Geometric Network tool to trace upstream and trace downstream from reservations, using the above-described reservation-HUC starting points. This process is relatively straightforward using the trace tool. Output is a new flowline layer with the traced upstream or downstream flows selected (Figure 15).

[33]This tool also must be used specifically with ArcMap 10.5.1. `https://www.usgs.gov/core-science-systems/ngp/national-hydrography/tools#HEM`

[34]One complication for the trace geometric network analysis later on, is that the output of tracing upstream or downstream flowlines is a new flowline layer, with upstream (or downstream) flowlines selected. This process does not retain information from the starting flag, making it useless to run one upstream (or downstream) analysis for multiple reservations at the same time, even when multiple reservations intersect within one HUC4 boundary. In order to be able to identify which reservation the upstream (or downstream) flowlines stem from, they must be run separately.

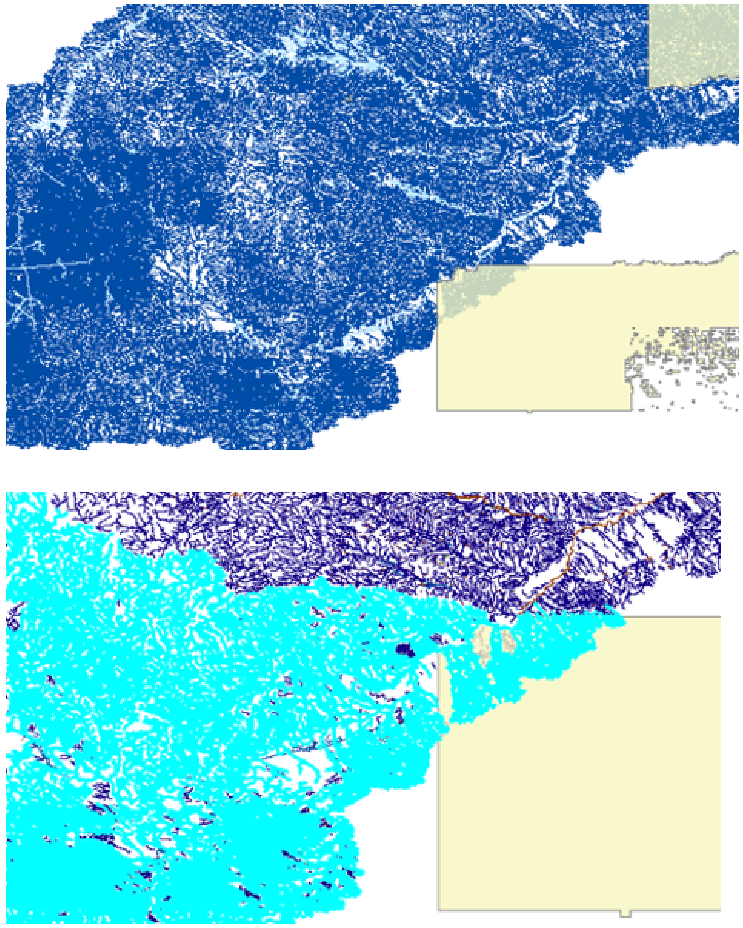


Figure 15: Example of Flowlines and Reservations within a HUC4 Area (top panel), and Traced Upstream Flowlines Zoomed in to a Reservation (bottom panel)

These selections can then be exported as a text file. The reference reservation is not a field in this text file, but using a file naming structure that includes both the HUC4 code and the reservation code, I incorporate the reservation code into the upstream/downstream flowline files post-GIS processing using STATA.

B.2.4 Obtaining Flowline Weights for Aggregating Data

Later, when cleaning data in STATA, I eventually aggregate spatially stream data together (will average, for example, pollution metrics for all upstream locations of a certain reservation). In order to do this, I employ a weighted average methodology, using stream order as the weight. Stream order is a way of ranking flowlines by their relative size or position in the network. The smallest number, 1, represents the smallest tributary or headwater, and the "trunk stream," the segment of which all discharge passes through, is the highest order in the network (Strahler 1957). Given that stream order is dimensionless, and relative within its network, it is a measure that can be used for comparative purposes, and should be proportional with characteristics such as channel size, stream discharge, and relative watershed dimensions.

The NHD employs a modified version of the Strahler stream order, which I use as a weight for aggregating.[35] All headwater reaches are assigned a stream order of 1. The stream order information is contained in the Value Added Attribute table for flowlines in the NHDPlus HR dataset (specifically, the NHDPlusFlowlineVAA Table, streamorder variable). In order to use this information, for each HUC4 network, I join the NHDPlusFlowlineVAA table to the regular Flowline table, using the NHDPLUSID variable as the link. I then export the resulting joined features as a text file.

The range of stream orders went from -9 to 11, with about half listing the stream order as 1. Later, I changed the stream order to 1 for those that listed -9. I then export a data join from the Flowline line layer to the For example, the Amazon River, the largest river in the world, has a stream order of 12 according to the Strahler stream order method (Strahler, 1957). The NHD contains a modified Strahler stream order calculation, Stream order, in the NHD, is classified using a "modified" Strahler Stream Order.[36]

C Merging and Linking Data

The analysis conducted in this paper is based on creating a panel of information from several sources. This section will outline the key methods in linking these disparate data groups.

C.1 Linking Monitoring Stations to NHD Flowlines

After creating the aggregated monitoring station dataset (and exporting to a text file for GIS use), I map the monitoring stations in ArcMap using their latitude and longitude coordinates, rounded to the third decimal degree. Then, one HUC-4 boundary at a time, I intersect the complete set of monitoring stations in the United States with NHD flowlines. For this process I use the NHDPlus HD dataset, because the flow attribute tables are

[35] Specifically, according to the NHD Plus High Resolution User Guide: "Stream Order... in NHDPlus and NHDPlus HR is a modified version of stream order as defined by Strahler (1957). The Strahler stream-order algorithm does not account for flow splits in the network, whereas the algorithm used in NHDPlus and NHDPlus HR for stream order takes flow splits into consideration." (https://agupubs-onlinelibrary-wiley-com.ezproxy4.library.arizona.edu/doi/epdf/10.1029/TR038i006p00913, page 44).

[36] https://pubs.usgs.gov/of/2019/1096/ofr20191096.pdf(page39,lastaccessedNovember10,2020)

already populated, and run them as a batch process one HUC-4 at a time in order to save processing time and output in case the algorithm runs into errors along the way. Importantly, I decided to intersect using a .001-degree tolerance, allowing for monitoring station points to lie just *off* a stream to count as "intersecting". I do this for two reasons. Firstly, I have rounded the monitoring stations to the third decimal degree, so I do not want to miss a flowline-station match because of this reason. Secondly, in nature, flowlines change. The NHD is a modern atlas, but I have monitoring stations that go back to the beginning of the 20th century. Being *very near* an upstream flowline is implicitly just as important as being right on the atlas of streams as drawn in the latest NHD. The purpose of matching monitoring stations to flowlines is to identify whether those monitoring stations are upstream or downstream of a reservation. For this purpose, I believe .001 tolerance is acceptable and important.

Due to this wrinkle, some monitoring stations "intersect" with multiple flowlines. Again, the important information – whether the monitoring station is on/near an upstream/downstream flowline relative to a reservation is preserved in the matching and aggregating process. Once the intersection algorithm is run in ArcMap, each attribute table is exported to a text file and then imported back into STATA for use in matching upstream/downstream flowlines with monitoring stations. The entire intersection and exporting process is done for 198 HUC-monitoring station pairs as a batch process in ArcMap.

C.2 Linking Monitoring Stations to Upstream/ Downstream Flowlines

After associating NHD flowlines with monitoring stations, I am then able to link upstream/downstream-identified flowlines to monitoring stations. This will allow me to specify pollution measurements based on relative position of monitoring stations to reservations. I will use the flowline $permanent_identifier$, and "latlon" concatenation to link across datasets. I merge flowlines in the upstream/downstream-identified dataset with monitoring stations at the individual reservation-HUC4-upstream (downstream) level. Flowlines are unique in the reservation-HUC4 context, so I can use a 1:m merge with the station-flowline data outlined above (if I merged with the aggregated upstream/downstream data, I would run into a m:m merge, something that is good to avoid). After this merge, and then aggregation of upstream/downstream information, I then have a panel that identifies upstream/downstream flowlines per reservation, and their ensuing STORET monitoring station, if one exists.

C.3 Appending STORET Results: Combining Legacy and Modern Observations

In order to combine the Legacy and Modern STORET datasets, it was essential to create comparable variables to append. A multitude of data decisions went into the process, not just in terms of cleaning the datasets for the pollutants of interest (and making sure they were comparable across platforms), but in making decisions about how to deal with "messy" observations, like those coded as being higher or lower than a particular number, or those coded as being detectable, but below quantification limits, etc. Legacy STORET actually makes these decisions more straightforward, by encoding notes about results in the "r" variable (which links to the remarks table. The following table (16 lists the remarks code, description, and how such a result was coded in my datasets.

Code	Description	Dataset Actions
A	Value reported is the mean of two or more determinations.	Estimated value (estimated=1)
B	Results based upon colony counts outside the acceptable range.	Drop observation
C	Calculated. Value stored was not measured directly, but was calculated from other data available.	Estimated value (estimated=1)
D	Field measurement. Some parameter codes (e.g., 401 "Field pH) imply this condition without this remark.	N/A
E	Extra sample taken in composting process.	N/A
F	In the case of species, F indicates Female sex.	N/A
G	Value reported is the maximum of two or more determinations.	N/A
H	Value based on field kit determination; results may not be accurate.	Drop observation
I	The value reported is less than the practical quantification limit and greater than or equal to the method of detection limit.	Present, but less than quantification limit (pres_lessql=1)
J	Estimated. Value shown is not a result of analytical measurement.	Estimated value (estimated=1)
K	Off-scale low. Actual value not known, but known to be less than value shown.	Present, but less than quantification limit (pres_lessql=1)
L	Off-scale high. Actual value not known, but known to be greater than value shown.	Present, but greater than quantification limit (pres_aboveql=1)
M	Presence of material verified, but not quantified. Indicates a positive detection, at a level too low to permit accurate quantification. In the case of temperature or oxygen reduction potential, M = a negative value. In the case of species, M = male sex.	Present, but less than quantification limit (pres_lessql=1)
N	Presumptive evidence of presence of material.	Present, but less than quantification limit (pres_lessql=1)
O	Sampled for, but analysis lost. Accompanying value is not meaningful for analysis.	Drop observation
P	Too numerous to count.	Present, but greater than quantification limit (pres_aboveql=1)
Q	Sample held beyond normal holding time.	Drop observation
R	Significant rain in the past 48 hours.	N/A
S	Laboratory test.	N/A
T	Value reported is less than the criteria of detection.	Not detected (non_detect=1)
U	Material was analyzed for, but not detected. Value stored is the limit of detection for the process in use. In the case of species, Undetermined sex.	Not detected (non_detect=1)
V	Indicates the analyte was detected in both the sample and associated method blank.	N/A
W	Value observed is less than the lowest value reportable under remark "T".	Not detected (non_detect=1)
X	Value is quasi vertically-integrated sample.	N/A
Y	Laboratory analysis from unpreserved sample. Data may not be accurate.	Drop observation
Z	Too many colonies were present to count (TNTC), the numeric value represents the filtration volume.	Present, but greater than quantification limit (pres_aboveql=1)
$	Calculated by retrieval software. Numerical value was neither measured nor reported to the database, but was calculated from other data available during generation of the retrieval report.	Estimated value (estimated=1)

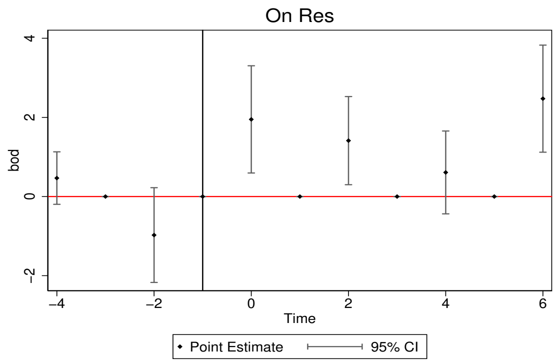
Figure 16: Data Quality/Limit Decisions

Modern STORET is more complicated, in that notes are not coded, and can show up as strings in the result variable itself, or as notes in separate variables. The same basic premise was followed – to code when a result was noted as being in a range (above/below a limit, detected but not quantified, etc.), or estimated. I then created several result variables that dealt with these situations in different ways. For my main analysis, I use a result variable that is the numeric version of the original result variable, with units standardized and corrected, only keeping positive results, keeping all values, including estimated figures, but replacing "non detect" with zero and dropping outliers that seemed resultant of data-entry error.

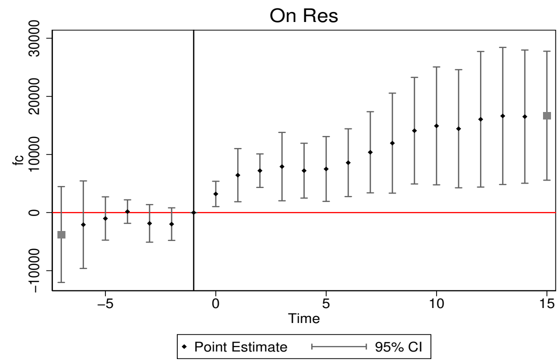
Next, in order to append Legacy and Modern STORET results, their variable names had to be standardized. Please contact the author if you would like access to the linking table.

C.4 Pollution Event Study Graphs - On-Reservation, Upstream and Downstream Readings

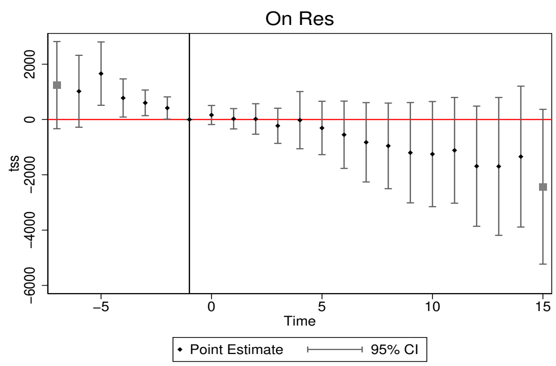
C.4.1 After *Winters* Begins



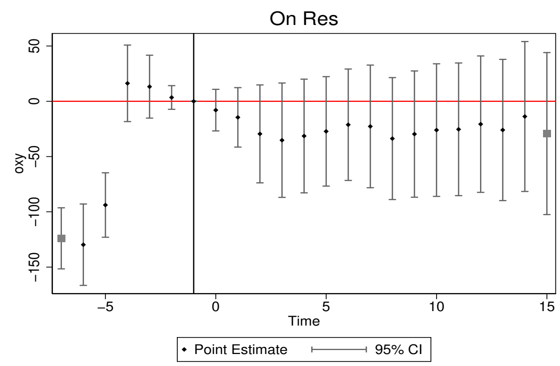
(a) BOD



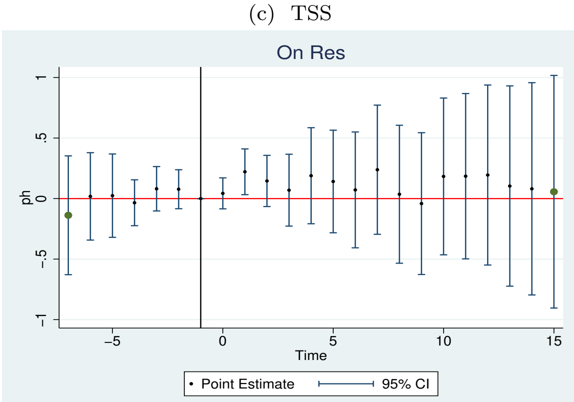
(b) FC



(c) TSS

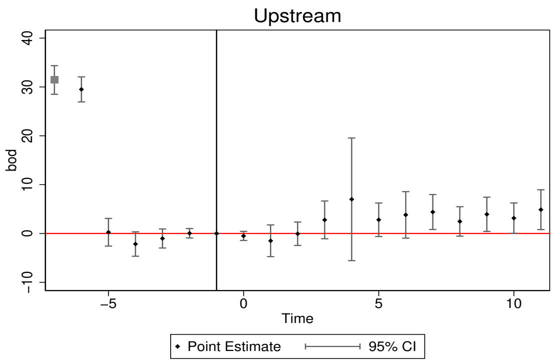


(d) Dissolved Oxygen (% Saturation)

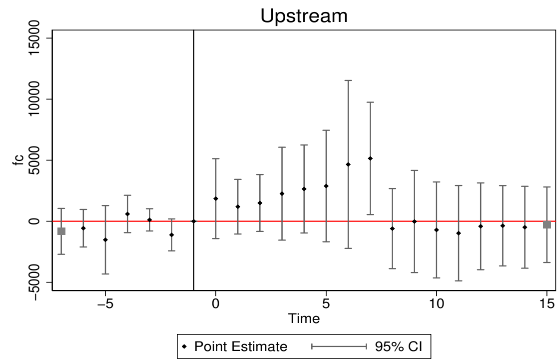


(e) pH (Difference from 7)

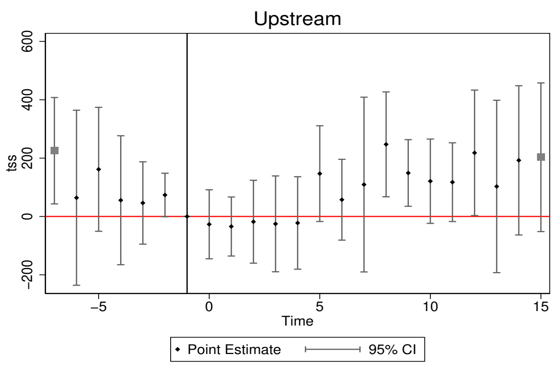
Figure 17: Pollution Around *Winters* Starts, On-Reservations



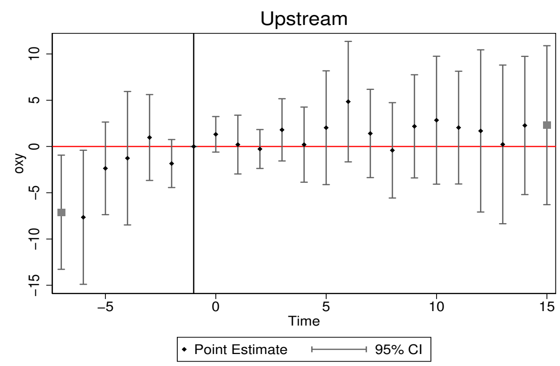
(a) BOD



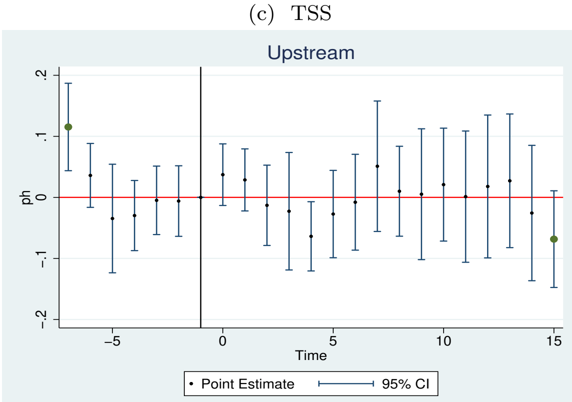
(b) FC



(c) TSS

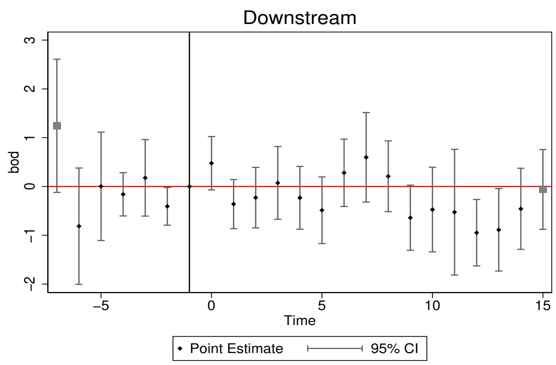


(d) Dissolved Oxygen (% Saturation)

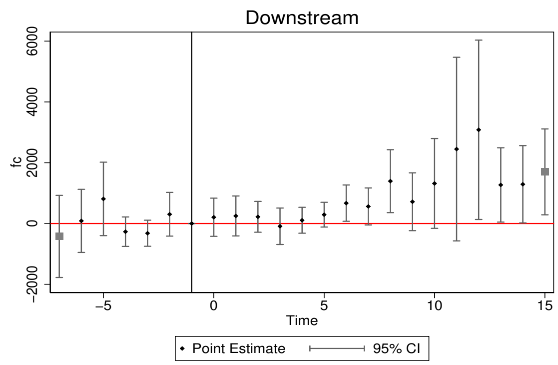


(e) pH (Difference from 7)

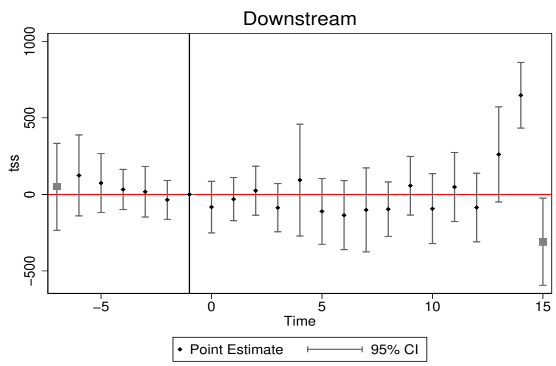
Figure 18: Pollution Around *Winters* Starts, Upstream of Reservations



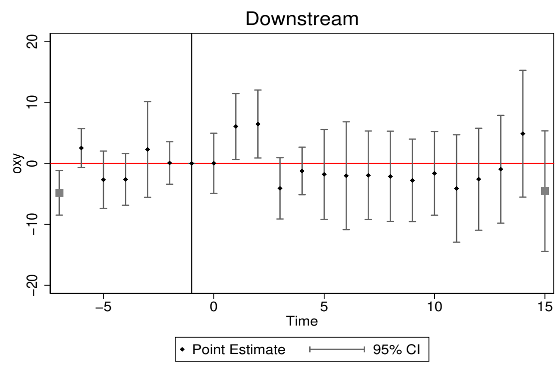
(a) BOD



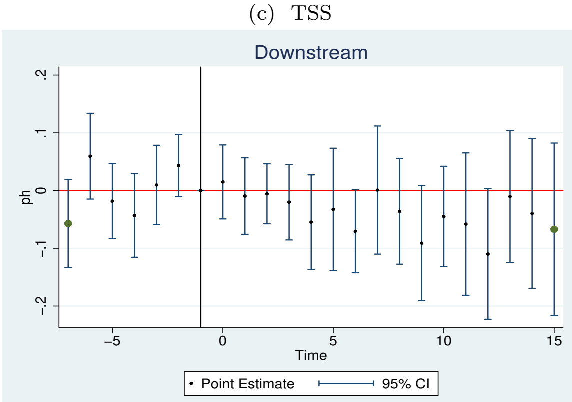
(b) FC



(c) TSS



(d) Dissolved Oxygen (% Saturation)



(e) pH (Difference from 7)

Figure 19: Pollution Around *Winters* Starts, Downstream of Reservations

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