Policy to Pollute: Strategic Bargaining and Dissolved Oxygen Depletion in Streams and Rivers in the American West

The Case of American Indian Water Rights

Laura Davidoff Taylor*

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Abstract

Do legal proceedings worsen water quality? I investigate whether lengthy and expensive processes for quantifying American Indian water rights, which have long-been judicially recognized, but not enforced or implemented, engenders pollution. I create the first granular spatial dataset mapping, networking, and connecting millions of water-quality readings in U.S. streams and rivers with official start and end dates for tribal water-rights adjudications. I find causal evidence that water pollution worsens as a result of proceedings upstream of reservations, especially close to the border. This worsening stops once rights are settled, illustrating key predictions of the property-rights literature.

Keywords: Natural resources, property rights, procedural justice, water quality, Indigenous governance

*Division of the Humanities and Social Sciences, California Institute of Technology (email: `ltaylor@caltech.edu` website:`laurataylorecon.com`. This paper has benefitted tremendously from the guidance and feedback of Jean-Laurent Rosenthal and comments from the history/finance working group in applied economics at Caltech. In addition, this work has benefitted greatly from the feedback and guidance of Price Fishback, Joe Kalt, Derek Lemoine, Mo Xiao, Cihan Artunç and Ashley Langer at the University of Arizona. I am also thankful for the support of University of Arizona's Native Nations Institute and the Economic History Association, for financial and advisory support.

1 Introduction

Disputes over property rights can often be seen in a simplified view: courts make decrees that resolve disputes and parties implement rulings and re-distribute or affirm holdings of property. This solution seems straightforward when disputes are between individuals or are over relatively simple resources. Yet in practice, and particularly when resources are costly to measure, source, transport, or put to use, a court ruling does not imply a mechanism to *implement* justice. If setting or establishing such a process is delayed, the resources in dispute may be used or damaged in the interim. If the lag between decree and implementation is long, parties may find ways to obfuscate, delay and entrench property use that may make it difficult for parties to redistribute at all.

Property rights disputes are resolved in two steps: first, a judicial ruling or out-of-court settlement. How this resolution comes into effect, depends in the procedures for implementing them. When the government is party to these disputes, government inaction on procedures has serious consequences for the ability to implement such rights and leads to measurable damages to the resource or parties in dispute in the interim. While inaction can stem from poor quality of government institutions, it can also stem from discriminatory implementation or the results of disenfranchisement. In the case of American Indian tribes, in particular, the U.S. government affirmed tribes' rights to water in the early years of the 20th century. Then, for decades, the U.S. government allowed states to erode these *de jure* rights because it made no effort to quantify or and implement its ruling. Inaction allowed state authorities to allocate scarce water to non-Indian American settlers while funding infrastructure for necessary diversions to support such distributions.

As a result, tribes in the American West have faced a three-pronged problem. Firstly, Western expansion in the 19th-20th centuries was driven by resource extraction and land use. Resources allocated to settlers came at the expense of tribes, both before and after treaties were signed between tribes and the U.S. government. In other words, valuable resources were transferred or granted to, or usurped by, non-Indigenous settlers to the detriment or sometimes in opposition to defined legal rights of tribes. Secondly, even though the Supreme Court recognized the rights of tribes to water, it did not enjoin the federal government to define mechanisms for implementation of tribal rights to water. This failure allowed states to allocate water elsewhere and forces tribes to follow lengthy negotiation procedures in seeking to affirm and access their rights to water. The negotiations create a third problem, where once these modern legal processes are initiated, property rights are uncertain until they are finally resolved years later. This can engender incentives for incumbent water users to degrade the resource during these processes as a result of introduced uncertainty. I seek to quantify the impact of this third problem—that once the legal process to resolve conflicts over rights begins it introduces uncertainty and impacts behavior in anticipation of future changes—on resource quality and degradation. This is only one facet of the costs tribes have had to bear as a result of this history.

This paper is organized as follows: Section 2 presents the background history of water rights in the American west as they relate to Native nations. Section 3 presents the property rights issues that result from the history alongside water-quality problems that arise from property-rights uncertainty. I also outline this paper's contributions to the literature in this section. Section 5 presents details of the *Winters* procedure as they relate to the economic framework I use to generate testable hypotheses for the data. I provide a description of the data in Section 6, and then econometric methods—including identification strategy and instrumental variables approach employed to address endogeneity issues in Section 7. Section 8 provides results and Section 9 concludes and contextualizes the findings within current policy debates surrounding water quality. Additional methodological details are presented in the online appendix.

2 Background

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.[1]

Yet almost instantly after the 1908 decree, nearby off-reservation users, supported by the U.S. Department of Interior and the State of Montana, began undoing *Winters* through the harsh "realities of capital flows (Shurts 2000)"—i.e., by largely siphoning investment in water development projects to off-reservation users and not to the tribe. That same year, the U.S. Bureau of Reclamation took 2,587 acres of irrigable land from the Fort Belknap

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

Indian Reservation to construct the Dodson Dam and its canal.[2] In the the years that followed, local off-reservation irrigators successfully lobbied for the construction of several additional water diversion and conveyance projects from the U.S. government, including the Nelson Reservoir, the Glacier Park and St. Mary Canals, and the Sherburne, Vandalia and Fresno dams (Wolfe 1992). Meanwhile, the Fort Belknap Indian Irrigation Project (the oldest federal Indian irrigation project in the U.S.[3]), began construction in 1889 but was never completed (FBIC 2021), and the Fort Belknap Indian Community still has no congressionally-ratified quantification standard upon which to base their legal rights to this day.

This pattern unfolded in many locations over the ensuing decades, with the federal government allowing states to defer allocation to tribes in order to support non-Indian water users. In the meantime, while the judicial mandate clearly defined the existence of tribal water rights reserved and protected by the federal government, there was not such a clear policy mandate to implement the legality, leaving wide latitude for *de facto* delay. Despite widespread reporting of the Supreme Court decree, the federal government deferred the allocation of surface water to states, allowing them to erode tribes' rights with few options for mitigation. They followed this path despite the legal trust relationship that has existed between tribes and the U.S. government, which is charged with protecting and preserving rights vested to tribes. Under that trust 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, and did not even provide an actionable quantification standard for these rights until 1963 when they defined "practically irrigable acreage". The U.S. government had also by that time waived sovereign immunity and essentially forced 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 and eventually had to rely on engaging in long and costly negotiations with other stakeholders and state authorities to officially adjudicate their rights to water.

As such, many *Winters* conflicts are still pending or yet to begin, and the ones that have been settled followed long and protracted battles between the tribes and competing

[2] Seepage from this canal waterlogged nearby tribal land, making it unusable for agriculture.

[3] Interview with FBIC Water Resources Department Administrator, `https://irrigationleadermagazine.com/water-resources-in-the-fort-belknap-indian-community/`

stakeholders who often represent powerful state interests. These adjudications can take many decades to resolve, if at all, and can comprise several procedural steps and hurdles, including being ratified and funded by Congress as the final step after all parties have agreed to terms. As of 2020, since the initial *Winters* decree in 1908, of the approximately 200 western tribes that could ostensibly have claims to reserved water, 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, less than 60 are fully adjudicated and funded.[4]

The quantity of water these negotiations represent is potentially vast and valuable. Of the 30 federally recognized tribes in the Colorado River Basin, 22 have successfully negotiated for recognized, reserved water rights, representing some 25% of water in the entire basin.[5] Further, in marrying the reserved-rights doctrine with that of prior appropriation, the courts affirmed that seniority in use dates back to reservation establishment. Because most reservations were established in the mid-to-late 1800s, once quantified, many reserved water rights would also be of the most senior in the region, and the least likely to be affected by major droughts or supply shortages (i.e., the most valuable). This is contextually an important factor for why resolving *Winters* rights can be so complicated.[6]

The complexity was exacerbated by the fact that the ambiguity introduced by not having an implementation policy allowed states to keep allocating water to other users. Table 2.1 shows a timeline of key federal events related to establishing and implementing *Winters* rights. It was not until 1963, more than 50 years since the *Winters* decree, that a quantification standard was proposed in *Arizona v California*,[7] allotting water rights for the

[4] 26 of these cases were still ongoing as of 2020, 43 were resolved out of court, and 12 were resolved via court decree.

[5] Water and Tribes Initiative (2021). The Status of Tribal Water Rights in the Colorado River Basin. Policy Brief #4, April 9, 2021. Last accessed June 1, 2023 at `https://www.getches-wilkinsoncenter.cu.law/wp-content/uploads/2021/04/Policy-Brief-1-The-Status-of-Tribal-Water-Rights.pdf`; Within the state of Arizona, tribal water rights account for a third of the state's Colorado River apportionment (Biddle 2023.

[6] In the 1970's the process of adjudicating the rights to water, *all at once* as opposed to one conflict at a time, indefinitely, became more and more popular (Browne and Ji 2023). These adjudications became unwieldy, complicated and long-lasting, with conflicting claims to uses difficult to verify and to reallocate over decades where water supplies were falling sharply. In Arizona, for example, there are two pending 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.

[7] 373 U.S. 546 (1963)

five tribes named in that settlement over Colorado River water based on the "practicably irrigable acreage", or, PIA, of their reservations. It was not until 1978 that there was a first negotiated settlement for quantified *Winters* rights, and not until the Bush Administration in 1990 that settling these negotiations became an official policy directive of the federal government.

Year	Event
1880	Office of Indian Affairs warns that American Indian access to water is being eroded by encroachers
1902	Passage of the Reclamation Act (Bureau of Reclamation Established)
1905	*U.S. v Winans* (198 U.S. 371, 1905) USSC asserts that treaties are a grant of rights to tribes, not a grant of rights from them. This acts as an important precedent for recognizing federal reserved water rights as part of reservation establishment.
1908	*Winters v United States* (207 U.S. 564, 1908) Established federal reserved water rights for tribes with seniority in right aligining with establishment date of reservation.
1922	Seven Colorado River basin states sign the Colorado River Compact, dividing water between them.
1963	*Arizona v California* (373 U.S. 546, 1963) Quantification standard introduced ("PIA"); provides guidance for the integration of reserved rights into state water law.
1975	Congress enacts The Indian Self-Determination and Education Assistance Act (Public Law 93-638)
1978	U.S. Water Resources Council estimates that nearly all regions west of the Mississippi have "inadequate" surface water supplies for irrigation. In the Lower Colorado River basin, USWRC estimated that due to inadequate surface water supplies, groundwater levels were declining at an average rate of 8 to 10 feet per year.
1978	First negotiated settlement—Ak-Chin Indian Community Settlement Act—is ratified by Congress.
1990	Bush administration implements a policy to permanently institutionalize settling unresolved tribal water rights as a federal priority of the Department of Interior (DoI). The DoI is charged with negotiating settlements and exchanging "equivalent benefits for the rights" asserted by tribal nations.
2009	Establishment of the Reclamation Water Settlements Fund - a U.S. Treasury fund established to provide $120 million through 2034 to implement settlement agreements or resolve litigation (Public Law 111-11). Federal agencies expressly directed to manage water resources to ensure sustainable water resources.
2021	Establishment of the Indian Water Rights Settlement Completion Fund to satisfy obligations for tribal water rights. Congress initially appropriated $2.5 billion for this fund via the Infrastructure Investment and Jobs Act (Public Law 117-58).
2023	U.S. Department of Interior announces allocation of nearly $580 million to implement tribal water settlements nationally. The funding is split across 14 different water rights settlements, with an average allocation of $41 million per project.

Table 2.1: Key *Winters* Implementation Events

Even today, tribes still find themselves in a holding pattern created by over a century of government inacation and obfuscation. In June of 2023, Justice Neil Gorsuch, writing the dissenting opinion for the U.S. Supreme Court case *Arizona v. Navajo*, remarked that the Navajo Nation had a simple ask: "They want the United States to identify the water rights it holds for them ... And if the United States has misappropriated the Navajo's water rights, the tribe asks it to formulate a plan to stop doing so prospectively (Gorsuch 2023)."

Justice Gorsuch's dissent was in response to the 5-4 opinion of the court to reject the United State's obligation to identify and account for Navajo Nation water rights in the Colorado River, despite the clear *de facto* and *de jure* understanding that the United States had legally granted such rights in establishing the tribe's reservation in 1868. In his dissent, Justice Gorsuch compared the experience of the Navajo Nation to that of an annoyed consumer: "To date, their efforts to find out what water rights the United States holds for them have produced an experience familiar to any American who has spent time at the Department of Motor Vehicles ... The Navajo have waited patiently for someone, anyone, to help them, only to be told (repeatedly) that they have been standing in the wrong line and must try another."

"Everyone agree[d]," Gorsuch continued, that the tribe in fact received enforceable treaty rights; that the U.S. currently holds a portion of them in reserve, but they have never been assessed. The majority opined they need not be. From Gorsuch's perspective, the Court's opinion makes clear that the "government's constant refrain is that the Navajo can have all they ask for; they just need to go somewhere else and do something else first (Gorsuch 2023)."

Like the Fort Belknap Indian Community, Navajo Nation is a case in point for a situation many tribes find themselves in. Situated in the northern Arizona desert, nearly half of the tribe's reservation is bordered by streams, rivers or reservoirs that branch off of the Colorado River. Yet its community has very little usable water to show for it, and the tribe's rights to the Colorado River still have not been adjudicated, despite its legal efforts to do so since the 1950's. Approximately 30% - 40% of households on the Navajo Nation do not have piped water (Tanana 2021), and the average person on Navajo's reservation uses just 7 gallons of water per day, less than one tenth of the average amount for the typical American elsewhere (Gorsuch 2023).

These statistics are similar elsewhere in Indian country. Approximately 58 out of 1000 Native American households do not have access to indoor plumbing;[8] and nearly 30% of homes surveyed by the Indian Health Service (IHS) needed improvements in sanitation for sewer and/or solid waste systems.[9] 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. Part of this is due to the fact that the federal government failed to provide infrastructure to divert supplies to tribal nations, exacerbated by the lack of quantification and funding of tribal water rights. In 1910, for example, shortly after the Winters ruling, the U.S. Commissioner of Indian Affairs stated that there were millions of acres of irrigable land on Indian reservations,[10] ostensibly ready to be watered, yet by the 1970's, only about 7 percent of such acreage had been irrigated (Wolfe 1992).

During this time, western populations exploded, as did the demand for sustainable water resources. This coupled with climactic and weather changes over the last several decades has created intensifying scarcity, with supplies of water dropping and value increasing. These patterns have been exacerbated by the laws and institutions that have governed non-tribal property rights to water: the doctrine of prior appropriation, which incentivizes over-use by its design of having to maintain use of water to define and protect a right to it. By the 1970's, the federal government warned that the supply of surface water was "inadequate" to meet irrigation needs in almost every region west of the Mississippi (U.S. Water Resources Council 1978), with use outstripping surface water supplies in the Lower Colorado Basin by more than double (U.S. Water Resources Council 1978). With only a small handful of *Winters* rights successfully defined and quantified by this point coupled with increasing scarcity and competition for water, the problem of defining and settling historic tribal claims has thus become increasingly difficult year by year.

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

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

[10] U.S. Annual Report of the Office of Indian Affairs, 1910 *in* Wolfe 1992.

3 The Property Rights Problem and Pollution

The impact of this *Winters* deferment has been profound. Litigation and/or negotiation processes are often very costly for all parties involved, including the federal and state governments.[11] These costs include both explicit expenditures for the settlement process, and the opportunity costs associated with the financial investment in having to go through these settlement processes; loss of development opportunities from generational lack of access to water, loss of water in general due off-reservation use and over-use, damage to water quality, and ensuing health and environmental effects. Of these many costs, relatively few are straightforward to measure and estimate in broad scale.

Additionally, a lack of defined property rights makes management and regulation of the water system more difficult, as poorly-defined property rights create difficulties in internalizing externalities or holding parties accountable for damages. This has left American Indian reservations susceptible to water quality contamination, particularly for those locations without adequate infrastructure investment, or lack of defined rights, or jurisdictional ambiguities in creating and enacting water quality standards—all results of judicial ambiguity relating to tribes and water. While the Supreme Court has indicated that tribes should have the ability to regulate non-Indigenous persons on non-Indigenous land when conduct threatens the "political integrity, the economic security, or the health or welfare of the tribe,"[12] it has proven difficult to navigate federal, state, and local laws, regulations and procedures, in addition to effectively measuring pollution, having recognized and adjudicated rights, and setting in place a water management plan on those bases.

Further, water quality has often taken a backseat to figuring out the quantitative allocations. Yet decades of mitigation efforts have shown how costly these decisions can be. Declines in water quality can have potentially large-scale impacts both on current use and on current and future mitigation efforts. Dissolved oxygen levels, nutrient loads, and salinity, for example, are all serious and often inter-related indicators of worsening water quality that stem directly and indirectly from human activity. The EPA has warned that

[11] In a 1983 report by the Western States Water Council, the authors reported that at the time the Bureau of Indian Affairs (BIA) estimated that the average tribal water rights case cost the BIA $3 million, and that was not including expenditures by the Justice Department or other divisions of the Department of Interior, not to mention the millions of dollars that states expended at the time in addition to those of tribes and off-reservation stakeholders.

[12] Montana v. United States, 450 U.S. 544, 565-66 (1981), *in* (Erickson 2002).This has been applied—via the Clean Water Act—to tribes regulating water quality vis-à-vis upstream-of-reservation polluters.

nitrogen and phosporus levels could become "one of the costliest and the most challenging environmental problems" in the country (United States Environmental Protection Agency 2011 *in* Tang et al. 2018). Since the original treaty promises that *Winters* is based on also included implied (and sometimes explicit) necessary federal investments for water infrastructure, also largely deferred alongside *Winters* implementation, lacking infrastructure has exacerbated water quality degradation, as many tribes lack the ability to deal with contaminated water. The Hopi tribe, for example, estimates that approximately 75% of residents on the reservation are drinking water contaminated with arsenic (Lakhani 2021 *in* Tanana 2023). They have been attempting to officially settle reserved water rights since the 1980s.

Economic theory would suggest that settling these long-contested disagreements over water and establishing clearer property rights should increase efficiency in water markets, and help prevent further 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). A key criticism of Coase's "The Problem of Social Cost" 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). This can turn what ought to be a straightforward process towards improved efficiency into one that can last so long it becomes entrenched in how users behave within the strategic setting.

The protracted ambiguity and strategic setting between tribes and off-reservation stakeholders sets up a context that can incentivize pollution (see Section5). If, with the onset of *Winters* adjudication processes, users face uncertainty in future ownership of the resource, they may be incentivized to invest less in abatement measures or more heavily use water resources or create pollution in demonstrating a "need" for water through development activities. If borne out, these polluting activities can then have compounding effects throughout a river system.

This leads to an empirical question: does the adjudication process itself lead to increased pollution? I focus on this question directly, marrying decades of water quality readings matched to specific latitude and longitude points merged with the hydrologic network of streams and rivers and then related to key information about tribes and *Winters* adjudication dates. This allows me to investigate whether water pollution increases as a result of *Winters* processes, and where it is most pronounced.

I develop the first, to my knowledge, spatial mapping of the granular water quality readings over time relative to all American Indian reservation lands in the western United States. I am then able to map water quality readings based on their relative position to American Indian federal reservations that are bases of ongoing *Winters* negotiations. I find empirical evidence that indeed water pollution increases upstream of reservations during negotiations, and particularly so closer to the upstream border. I also find these effects ameliorate once rights are resolved and quantified.

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 (D. A. Keiser and J. S. Shapiro 2018) or boundary changes (Lipscomb and Mobarak 2016), and the incentive for users to pollute more at the downstream end of a jurisdictional border (Sigman 2002 and Sigman 2005). Keiser and Shapiro link streams and rivers to pollution monitoring stations to assess the impacts of the Clean Water Act. I follow their geospatial 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. Finally, Sigman (2005) considers the free-riding impact on water quality, exploiting time variation in treatments at specific locations in order to use a fixed-effects approach to study the impact of policy change on water quality outcomes. I also exploit time-varying treatment effects and control for unobserved location effects where water quality readings are monitored.

This paper also contributes to research both in law and economics about the *Winters* doctrine. The questions comparing areas that are affected directly by *Winters* with those that are not, and studying the factors that influence selection into *Winters* is not the focus of this paper and has been studied elsewhere (Sanchez, Edwards, and Leonard 2020 and working paper Taylor 2022). In addition, several papers have looked at the impact of resolving or clarifying property rights on some outcome (Browne and Ji 2023 and Deol and Colby 2018 relating to American Indian tribes and agricultural revenue). 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 Costello 2014), and heterogeneity in attitudes towards transitioning from common-pool access to private property for natural resources (Grainger and 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.

4 Procedure in "*Winters*" Cases

The process of quantifying the theoretical reserved water rights that were protected under *Winters* is an essential part of safeguarding water resources from encroachment and degradation, and in facilitating the federal investment in diversion infrastructure that was often promised (explicitly or implicitly) in treaties from the 1800's. In more recent decades, tribes have been able to claw back some of these tribal water rights, and gain the bargaining power to help manage and control surface water flows. This has been aided by the 1975 passage of the Indian Self Determination Act,[13] which allowed Native nations significantly more sovereignty to act with autonomy in many aspects relating to federal policy, including negotiating or litigating for water rights. Due to the complications outlined earlier, post-1975 tribes have increasingly turned to negotiating settlements with current, non-Indian water users to resolve their long-unenforced rights to water. Despite advancements in autonomy over the past decades, many tribes still have poor access to water, directly resulting from erosion of rights as water has largely already been diverted elsewhere.

To help resolve these issues, the U.S. government eventually formalized the negotiation process tribes can enter into with other stakeholders, instead of or in addition to pursuing lititgation. 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]).

[13] 88 Stat. 2203

For this analysis, I generalize to the three periods of "before", "during" and "after", the "after" when 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.

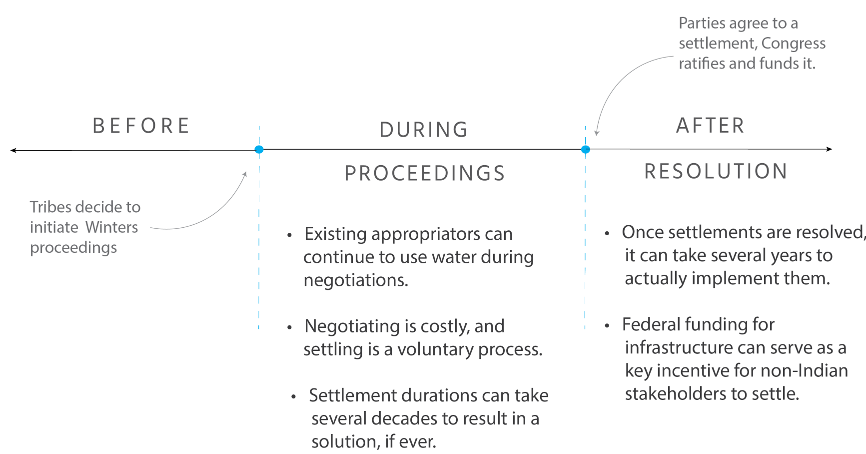


Figure 1: *Winters* Timeline

5 Economic Framework and Hypotheses

The following section provides a theoretical framework for deriving testable predictions about pollution, and where pollution will be most pronounced in the context of settling American Indian reserved rights to water. The framework takes the perspective of an upstream-of-reservation user, and considers how a change in certainty of future ownership in water rights can impact the amount of pollution emitted before water flows to a tribal reservation.

To provide a simplified motivation for the set up, consider the following graphic of an upstream landowner (L1) and a reservation along a river:

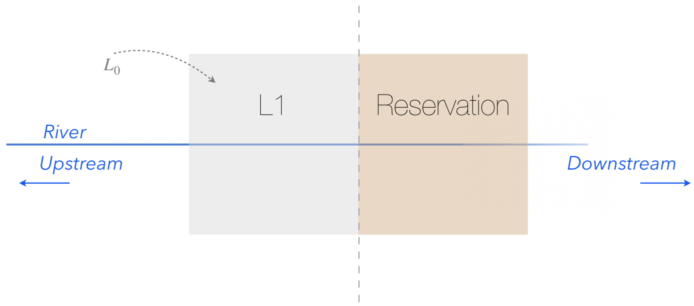


Figure 2: *Water Users on a River*

There are many activities that create a water pollution externality. For the purposes of a straightforward example, I use fertilizer in agriculture as the landowner's decision variable. Fertilizer is a known source of pollution, particularly dissolved oxygen depletion[14], and it accumulates as it is polluted along a river system[15]. A landowner, L1 in the above figure, uses fertilizer as an input to agricultural production. The landowner's profit in period t (Π_t) is a function of its own fertilizer use (F_t), offset by internalized environmental damages ($D(\cdot)$) resulting from the landowner's own use (F_t) plus upstream users' pollution (i.e., the state of the water resource (L_{0t}) as it enters $L1$'s property). Without the consideration of pollution damages, the landowner's profit is increasing in own-fertilizer use at a decreasing rate.

Consider the landowner's profits over two periods. A landowner decides how much fertilizer to use in period 1 considering the agricultural profits they will earn offset by environmental damages in both the present and future periods. As shown in Equation 1, the quality of water, and thus overall profits, in the second period is affected by both fertilizer use in that period and from the previous one (in addition to the state of the water coming onto the property in each period):

$$\Pi = \Pi_1(F_1) - D_1(L_0, F_1) + \delta[\Pi_2(F_2) - D_2(L_{01}, L_{02}, F_1, F_2)] \tag{1}$$

In the above equation, $\delta = \frac{1}{1+r}(1-\alpha)$, and $\alpha \in [0, 1]$ represents the probability that the

[14] `https://www.epa.gov/caddis-vol2/dissolved-oxygen`

[15] In fact, studies have shown that the more polluted, or disturbed, a river is the less able it is to remove pollutants such as nitrates that commonly occur in fertilizer runoff (Biello 2008)

water user will lose water in the future. If $\alpha = 0$, the water user has full certainty that they will retain ownership in period 2. If α increases, there is a non-zero probability that the water user will lose rights to water in the next period. If $\alpha = 1$, the current water user knows with certainty they will lose their water allocation in period 2, and all decisions collapse down to the one-period case.

Tying this to the *Winters* context, if there are no *Winters* proceedings, there is no uncertainty in future ownership of the water right and $\alpha = 0$. Future costs and benefits are just discounted in terms of time preference of consumption, or $\frac{1}{1+r}$. In this case, when the landowner has **certainty** over two periods that they will retain ownership of the resource, the first-order condition for selecting the optimal amount of fertilizer in period 1 (F^c) to maximize profits is:

$$\Pi_1'(F_1) = D_1'(\overline{L_{01}}, F_1) + \delta[D_2'(\overline{L_{01}}, \overline{L_{02}}, F_1, \overline{F_2})] \tag{2}$$

where $\overline{F_2}$, $\overline{L_{01}}$, and $\overline{L_{02}}$ are taken as constant.

Now consider a scenario where certainty in future water ownership is not clear. If a *Winters* proceeding begins, for example, a landholder can adjust their belief in future expected loss of water, α, which can become positive. So the start of proceedings in this model impacts fertilizer decisions through the α parameter. In the extreme, if $\alpha = 1$ (landowners are sure to lose water rights in period 2), their maximization problem collapses to a one-period case:

$$\Pi = \Pi_1(F_1) - D_1(L_0, F_1) \tag{3}$$

The ensuing first-order condition for choosing optimal F_1^P (for the one-period context) in order to maximize profits is:

$$\Pi_1'(F_1) = D_1'(\overline{L_{01}}, F_1) \tag{4}$$

where $\overline{L_{01}}$ is taken as constant. All else equal, optimal fertilizer use increases in the one-period case, as landowners do not have to account for damages in the future accruing from use in the present: $F_1^c < F_1^p$.

If there is uncertainty in future ownership, or $0 < \alpha < 1$, then the optimal fertilizer use (F^u)will fall somewhere in between the cases where $\alpha = 1$ and $\alpha = 0$: $F_1^c < F_1^u < F_1^p$.

Finally, as an anchoring point of reference, we could imagine the case where there is one period, and there are no pollution damages at all that the landowner internalizes. In this scenario, the landowner just selects F^* to maximize profits (which is a function of fertilizer). The first-order condition is:

$$\Pi'(F^*) = 0 \tag{5}$$

In the one-period, no environmental consequences scenario, optimal fertilizer use (F^*) is the highest amount. Figure 3 shows all optimal fertilizer choices in each of the scenarios laid out above. As $\alpha \to 1$ (i.e., as uncertainty in future ownership gets larger), fertilizer use, and water damage, increases from $F^c \to F^p$:

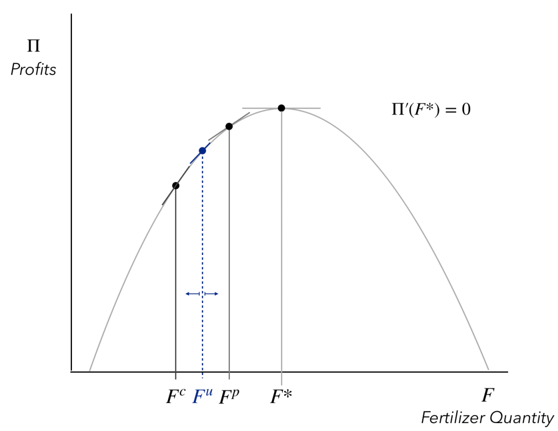


Figure 3: *A Farmer's Profit Function and Certainty in Future Rights*

One final characteristic to note about this framework is that pollution will tend to build up as they move downstream within a regional area. This is in part a natural function of the mechanics of water pollution and where users are placed. As the upstream users build up, pollution accumulates as water flows downstream. No landowner in this setup has incentive to "better" the water quality (i.e., clean L_0). Since profits are increasing in fertilizer use, if a landowner naturally has fairly clean water as an input (i.e., L_0 is relatively low), they will use fertilizer to maximize profits, which will be higher without excess damages from a dampened state of the resource. The $D(\cdot)$ function is increases in L_0 and F_t.

Finally, while this framework is built off of intuition from agricultural production and fertilizer use, it can be applied in several contexts to pollutants arising from other activities such as mining, urban development and industrial activities.

5.1 Predictions

The above framework helps to develop the main testable hypotheses that I take to the data.

Hypothesis 1: Pollution readings will be higher closer to the border between upstream-of-reservation areas and reservations. This is due to the fact that pollutants accumulate over a river system as it flows downstream. Due to the historical context, there are more agricultural and industrial water users off reservations than on, and the runoff from their activities builds up in the system.[16]

Hypothesis 2: Pollution increases in and downstream of a particular location when uncertainty of furture ownership of the water right increases. In the context of this study, that would be when *Winters* proceedings begin and expectation of water loss increases. The introduction of future uncertainty can affect the decision to increase use of a polluting input (like fertilizer), or reduce investments in abatement or investments in cleaner technologies and divert resources elsewhere. Combined with Hypothesis 1, this will be especially pronounced closer to reservation borders.

A second reason not explicitly contained in the models, but drawn from on-the-ground knowledge, is that as a negotiation tactic, a user can demonstrate "need" for water through current water use and/or development projects that will require water.These could include the renewal of coal power plants or wasteful agricultural practices. These activities would increase production, q_x^t, which is positively correlated with pollution in the model.

[16]There is also a body of research that finds that pollution will accumulate at the downstream end of a jurisdictional boundary before crossing over into a new jurisdiction due to a lack of internalizing pollution externalities that accrue to users in different jurisdictions or communities (Lipscomb and Mobarak (2016.

6 Data

I use Geographic Information System (GIS) software to connect spatial, environmental, economic, and legal information together to analyze how property rights changes, and the bargaining environment, impact water quality in and around reservations. The main types of data are based on the latitude-longitude location of water quality readings; to tribe- or reservation-level geography; surrounding-county geography (area surrounding the latitude-longitude location of water quality readings); or subwatershed basin ("HUC4" area) geography.

6.1 Water Quality Data and American Indian Reservation Areas

The unit of observation in the main regression analysis is the station-year level.[17] These pollution readings are from the Environmental Protection Agency's (EPA) Legacy and Modern STORET databases, which contain user-reported water quality readings taken at specific monitoring station locations that date back to the turn of the twentieth century. They are typically collected and reported in by both individuals or environmental groups, agencies, government entities or private collectives. I focus on six water quality indicators from these repositories: streamflow (mean daily, cubic feet per second (cfs); dissolved oxygen (reported as mg/L and percent saturation); biochemical oxygen demand (BOD 5-day); fecal coliform (FC); total suspended solids (TSS); and pH. A water-quality reading is taken at a specific monitoring station listed in the STORET repository. There are 589,684 STORET monitoring stations over the contiguous U.S. that fit the surface-water distinction. My study area is the region west of the 100th meridian, which includes 186,720 monitoring stations. Approximately 7% (12,773) of U.S. monitoring stations intersect with western reservations.

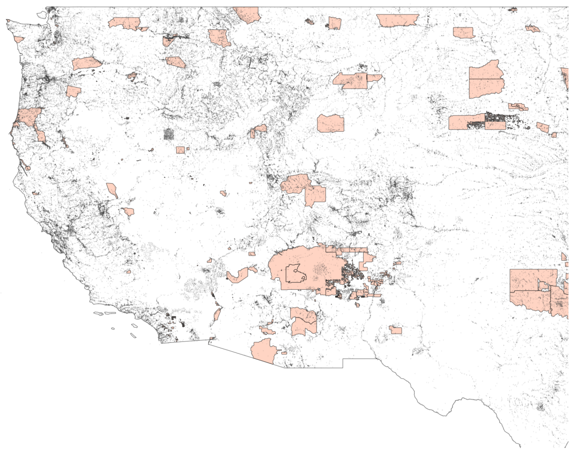
For reservation boundaries, I use official geographies from the 1990 Census.[18] These boundaries change slightly over time in modern years, but for the most part are indicative of reservation areas over the course of the study period.[19] Figure 4 illustrates in the left

[17]The "stations", or "monitoring stations", are the latitude-longitude points where pollution readings are taken.

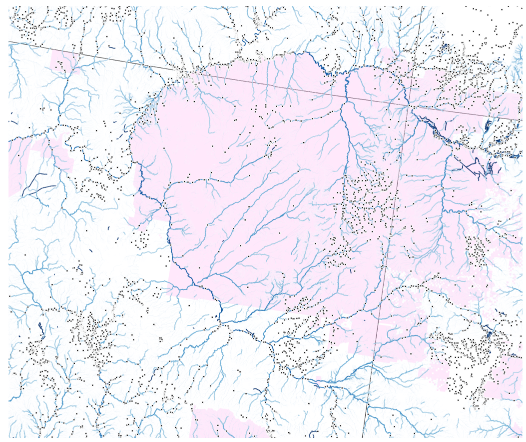
[18]IPUMS NHGIS: https://www.nhgis.org/gis-files, 1990 Census Boundary files for American Indian/Alaskan Native Reservation or Statistical Entity areas).

[19]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

plot the span of the STORET monitoring stations across the western region (black dots), juxtaposed against the 1990 Census reservations (orange-shaded areas); and a zoomed-in depiction (right plot) of stations relative to American Indian reservations in northern Arizona (pink-shaded areas), and surface water flow lines (streams and rivers).



(a) STORET Monitoring Stations



(b) Navajo and Hopi Reservations Detail

Figure 4: STORET Monitoring Stations General and Arizona Inset

The process for retrieving water quality data from the STORET systems most closely follows the work of Keiser and Shapiro (D. A. Keiser and J. S. 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. For full details, see Online Appendix B.1.

6.2 Winters Dates and Negotiation Periods

The primary source material for the start and ends of *Winters* processes is from (Sanchez, Edwards, and Leonard 2020). This information includes when parties came to agreement;

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 networking upstream and downstream river flows from each set of reservation boundaries, for very few large scale changes in reservation area over the study time period. Also, while census boundary files include both federally-recognized reservations and tribal statistical areas (such as in Oklahoma), I use the term reservations in this paper in the context of the empirical study, as *Winters* is specifically linked to the establishment of federal reservations.

when settlements were ratified by Congress or when court cases were decided; and which tribes and reservations were involved. This dataset also includes whether the rights were settled in a negotiation or secured by a a court decree. I supplement this data with information from the Congressional Research Service (CRS) (Congressional Research Service n.d.[b]), (Deol and Colby 2018), and the University of New Mexico (UNM) Native American Water Rights Settlement Project's Digital Repository.[20] I used the UNM repository especially to determine whether the final resolution incorporated rights to lease or sell water, and/or whether the tribes negotiated for environmental stream flow rights or to implement environmental management practices (not just consumptive uses of water).[21] Figure 5 depicts a map of settled and ongoing *Winters* cases as of 2020:

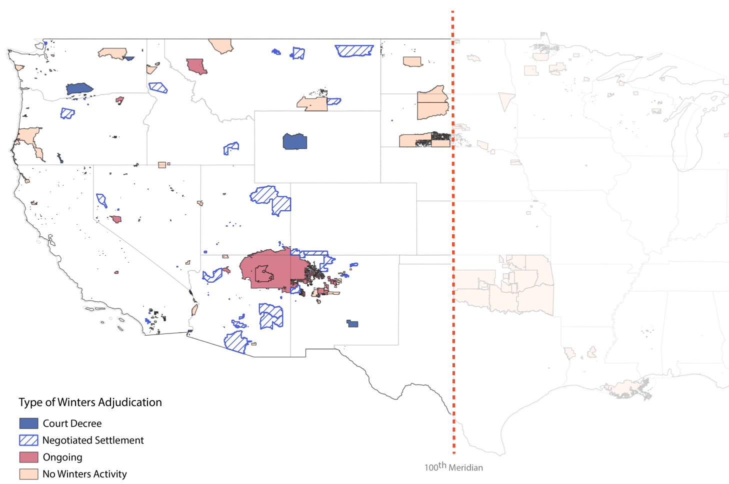


Figure 5: Winters Status and American Indian Reservations, Western U.S.

6.3 Geographic Covariates

Several environmental factors can influence concentration of pollutants, and I control for as many impacting factors as possible in order to isolate the causal impact of the *Winters* proceedings. These include streamflow, monthly rainfall, temperature, and drought con-

[20] `https://digitalrepository.unm.edu/nawrs/`

[21] While this information is not used in the empirical study in this paper, it will be for future work. I also keep track, where possible, from the CRS the amount funded by the federal government in implementing the settlement terms when finalized.

ditions. For all indicators I am able to either have a direct reading at the point location (such as for streamflow), or I use gridded raster data to estimate an average reading at the latitude-longitude station points.

I collect streamflow readings from the STORET database, using a daily average of instant, inter-temporal daily readings, which are measured in cubic feet per second (cfs) at monitoring stations. I incorporate monthly mean precipitation and also temperature from January 1960 - August 2020 using the Oregon State University PRISM Climate Group observational climate data. The 4km AN81m grid data from 1980 onwards is from the "recent" data repository, and information from 1960-1980 is from PRISM's historical repository.[22] I extract precipitation and temperature information at all of the monitoring station points using the 4km gridded raster files.

To account for shifts in overall climate conditions, I also include in the model the Palmer Drought Severity Index (PDSI), which is a standardized index conveying relative dryness. Its values typically span -10 to +10, with higher values indicating "wetter" conditions, and negative values conveying "drier" conditions. The PDSI can convey long-term drought conditions and can capture "the basic effect of global warming on drought through changes in potential evapotranspiration." [23] I use the 4km gridded PDSI to join monthly PDSI measures spatially to monitoring station locations.

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).[24] 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.

The Online 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

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

[23] National Center for Atmospheric Research: `https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi`

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

boundary defines the spatial extent of surface water drainage to a certain point.[25] 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). For my analysis, the largest area in which I can trace upstream and downstream networks is the 4-digit HUC code area ("HUC4").[26] This is thus the hydrologic region that I control for, and these boundaries also define geographic features like the continental divide. The United States and Caribbean are divided into 221 sub-regions. Figure 6 depicts these regions juxtaposed against American Indian reservations (gray-shaded areas); the western designation at the 100th meridian; and the continental divide, which is denoted by the blue-shading representing west of the continental divide.

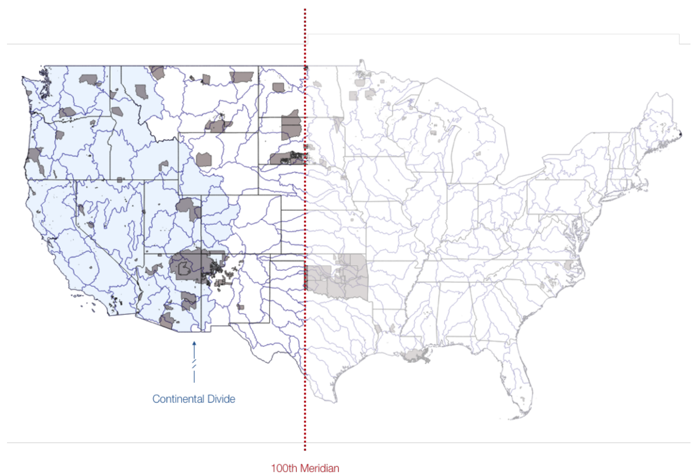


Figure 6: HUC4 Boundary Areas and Continental Divide

I also incorporate other characteristics of the streams and rivers from the NHDPlus HR, and of monitoring stations, into my panel data, including stream order (a measure of stream size and position relative to other tributaries)[27] and distances from each monitoring station to any American Indian reservation within 100 miles. Finally, I am able to spatially match each monitoring station to their respective HUC4 boundaries, in addition to locations within the county, state, census areas, and the locations of the nearest towns.

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

[26] This is based on the extreme processing times it takes to network streams and rivers. In phone conversations with the USGS in 2020, networks that are stitched together beyond the HUC4 area can take months to piece together, and may not stitch completely correctly.

[27] (see Online Appendix B.2.4.

6.4 County Census Data

To control for surrounding socio-economic factors that may influence pollution, I include the surrounding county's real per capita income and population density in the surrounding county (surrounding the latitude-longitude monitoring station location).[28] To calculate county-level population density, I use land size data which is reported every five years from 1949-2002 from Haines (Haines, Political, and Research 2010), and run a straight-line interpolation forward to have an annual estimation. I then merge this data with more recent information from Schaller, Fishback and Marquardt to calculate an annual population density measure through 2016.

7 Estimation

7.1 Baseline Regression - Dissolved Oxygen and System of Pollutants

The econometric method employed is aimed at identifying the causal effect of engaging in *Winters* adjudication procedures on water quality outcomes. To do this, I use a station-level, difference-in-difference approach with two treatments: being in the negotiation period, and being in the resolution ("after") period, with the dependent variable being pollution at station i, in period t. The control group is the "pre-negotiation" period ("before" in the timeline). I compare within-station changes over time using station fixed effects, and I control for demographics, climate, weather, streamflow, season and year. In order to test whether the onset of negotiations causes an increase in pollution upstream of reservations, I run these regressions for different samples: upstream-of-; downstream-of-; and on-reservations; and within various distances off-reservation.

A major challenge in assessing time-varying patterns in water pollution is the difficulty in measuring pollution, in a continuous location, over time. There is a disparate array of monitoring stations and time horizons per station across the U.S., and it is a challenge to weave together different, localized readings of water quality data. Further, there are uncertainties in how pollutants travel hydrologically in both surface and groundwater across varying geologies. To mitigate these issues, I first focus on only one pollutant that has a

[28] Annual population data have been compiled from historic censuses by Michael Haines (2010) from 1915-2007, and extended to 2016 thanks to Schaller, Fishback and Marquardt (Schaller, Fishback, and Marquardt 2020). Schaller, Fishback and Marquardt also provide annual data on real per capita income in census areas through 2016.

low signal-to-noise ratio: dissolved oxygen (DO). DO is an important indicator of water quality because all aquatic animals need it to survive. When DO saturation levels fall and become low, it typically occurs alongside excessive organic materials and nutrient loads in the water. A benefit of using DO saturation as a proxy for general pollution is that it is not resultant from only small, specific actions and is not overly difficult to detect and quantify in samples (such as specific microorganisms that might die or exist in small concentrations). Low oxygen levels are often the result of pollution from urban and rural activity which creates phosphorus and nitrogen, and other microorganisms that decay and die in the water. When algae die and decompose, oxygen that has dissolved in the water is used up for this process (known as eutrophication). Lower dissolved oxygen levels impair the ability for aquatic life, such as fish, to live in the affected water. Increased algae blooms also block light that is necessary for plants and seagrasses to grow. [29]

While DO levels fluctuate seasonally, significant shifts or drops in the indicator outside of typical seasonal (or daily) fluctuations is indicative of worsening water quality as a result of pollution.[30] Scientists have studied how noisy and informative less-frequent quality signals are. pH, for example, has been found to be less variable for different water quality conditions (Silva, A. L. d. Silveira, and G. L. d. Silveira 2019), so may be less informative overall as a stand-alone measure of water quality than other indicators. Dissolved oxygen, on the other hand, has been shown to require less frequency in sampling to reach a steady state for information collected (along with other indicators like conductivity and temperature that track recurrent paths over a day or season (Coraggio et al. 2022)). DO is affected by attributes such as temperature, seasonality, aeration (captured in part by streamflow), so I control for as many observable environmental factors as possible in order to isolate variation in DO that are reflective of other sources, such as additives of pollutants in water stemming from stormwater, agricultural or sewerage runoff, and other post-industrial processes.

After investigating the single-pollutant case, I then rerun my analysis using a suite of pollutions in a system of equations as a robustness check. Many pollutants move together or are affected by other chemicals, activity or pollutants in surface water. There are many inter-related phenomena that occur as a result of similar or related natural or human

[29] `https://oceanservice.noaa.gov/facts/nutpollution.html`

[30] Environmental Protection Agency: `https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen`. Last accessed August 2023.

activity, and thus may show up together in quality readings. Repeating the analysis as a system of equations allows for the errors to be correlated across different pollution models. I incorporate four other pollutant variables as outcomes, representing indicators that are—with dissolved oxygen—of the most sampled in the database (D. A. Keiser and J. S. Shapiro 2018). While they are distinct, and represent different kinds of pollution sources, they are positively correlated over time and can move together in surface water environments. I also include mean daily streamflow at the station level, since most readings of pollution are in terms of concentrations. Both the single-outcome equation and the system follow the following form (the single-pollutant case just allows j to only equal dissolved oxygen):

$$\begin{aligned} Pollution_{j,i,t} = {} & \alpha_{j1} + \alpha_{j2}\mathbb{1}\{Negotiation_{ry}\} + \alpha_{j3}\mathbb{1}\{Resolution_{ry}\} \\ & + \alpha_{j4}Flow_{it} + \alpha_{j5}DroughtIndex_{im} + \mathbf{X}_{iy}\beta^{xj} + \mathbf{W}_{im}\beta^{wj} \\ & + \xi_{yj} + \eta_{seasonj} + \gamma_{ij} + \varepsilon_{ijt} \end{aligned} \tag{6}$$

where j represents one of the five pollutants: Biochemical Oxygen Demand (BOD) 5-day; Fecal Coliforms; Total Suspended Solids; Dissolved Oxygen (reported as difference from 100% Saturation); and pH (reported as difference from 7).

There are **three dimensions of time** in the regression equation: day, month and year. The coefficients of interest, α_{j2} and α_{j3} represent the change to pollutant j 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 α_{j2} and α_{j3} to be additive compared to the "before" period.[31] The sample is constrained to only those areas that are near reservations that have at least initiated *Winters* proceedings. The control group is therefore "before". I run this equation multiple times for different subsets of the data: 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

[31] 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.

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 uses 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, in order to isolate one potential data-generating-process at a time.

Finally, 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.[32] Similarly, pH is reported as difference from 7, so that positive values are more basic and negative values are more acidic.[33]

7.2 Identification Strategy and Instrumental Variables Approach

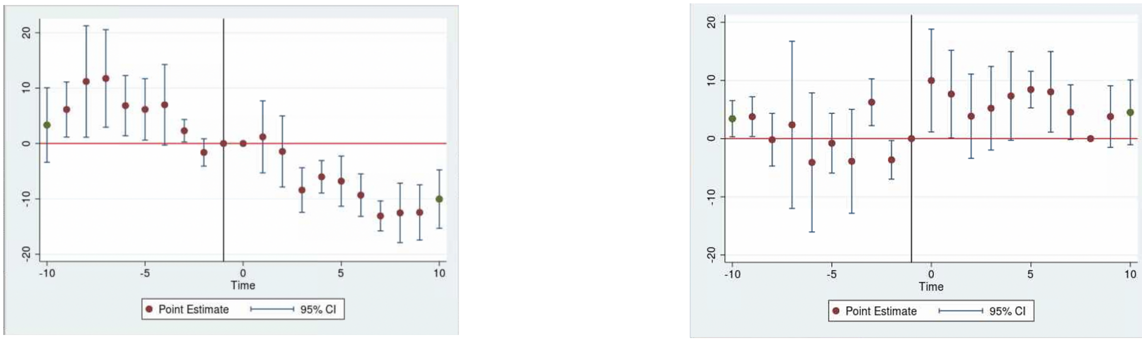
Firstly, as a motivation for employing a diff-in-diff model, I check overall patterns in the data for pre-trends in all data and my main subsamples of interest, upstream-of-reservation areas, by running event-study analyses. Figure 7 displays the results of two of these event-study models, showcasing dissolved oxygen saturation outcome for all monitoring stations (Figure 7a) and for upstream-of-reservation areas within 50 miles of a reservation border (Figure 7b), before and after the onset of winters proceedings.[34] I find no evidence of pre-trends that would threaten independence. In the event-study that focuses on all data (Figure 7a) in a subwatershed region (whether the stations are upstream, on, downstream (or neither) from the relevant reservation), I find some evidence of a slight downward trend before *Winters* begins, although, importantly, this is in the opposite direction of the hypothesized and empirical findings evidenced by the subsample investigations (downward movement represents "better" water quality; upward represents worsening conditions such as more pollution). This activity also may be indicative of some of the selection issues

[32] 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.

[33] This is a generalization. Extreme basic values can also be unhealthy for an ecosystem, but in general, acidic conditions based on pollutants can lead to wide-scale fish kills and be an indicator of poor quality and health of the resource.

[34] The event study model follows the diff-in-diff models by including the same relevant covariates and controlling for location fixed effects. The event-study graph portrays the pattern of dissolved oxygen outcomes within station over time.

motivating a two-stage-least-squares approach. In the other subsamples (upstream-of-reservation areas), I find no significant pre-trends.



(a) All Monitoring Stations

(b) Upstream of Reservations, $\leq$50 mi.

Figure 7: Dissolved Oxygen Before and After *Winters* Starts

In order to claim a causal interpretation of the baseline regression results for the impact of the two treatments on pollution outcomes, I must believe that the timing of negotiations (and resolutions) are completely exogenous to the process. Given the intense political connectivity between many stakeholders and government officials, and between each other, I do not believe this to be an exogenous process.

As such, I employ a two-stage-least-squares approach to estimate how pollution changes as a result of being in the *Winters* process. The goal of using an instrumental variable in this context is to remove endogeneity biases stemming from omitted variables (political ability, federal appetite for funding settlements, etc.) and from selection bias. Before correcting for endogeneity, those biases were embedded in the estimation for the effect of entry (α_{j2} and α_{j3}), as entry and exit decisions were also correlated with the error term.

Because of the interconnected nature between outcome (water pollution), entry and exit variables, and underlying observables and potential instruments, it is difficult to find instruments that do not violate the exclusion restriction and are not subject to reverse causality. As such, I construct instruments that are disconnected from the estimation period over time and space, exploiting resulting exogeneity of the instruments with respect to the per-station analysis.

For entry, I use an average measure of the number of *Winters* starts in other HUC4 areas in the years before 1975. For exits, I use an average measure of *Winters* resolutions in other HUC4 areas for the 10 years from 1975 to 1984[35]. These instruments are distinct hydrologically and temporally. With separation over time and space, the resulting instruments help to estimate start and end dates with information that is exogenous to the reduced-form setting, yet provides structural information of unobserved variables from the pre-period. If, for example, there were more *Winters* entries in other HUC4 areas, it is a signal that tribes felt the setting was amenable to engaging in the *Winters* process, whether due to political ability, or bargaining power, or lack of competition at that time for resolution services, or both. More exits in other HUC4 areas is a signal of the federal government's amenability towards spending money to fund projects, and support resolving cases. It's a positive signal in general for wrapping up negotiations. I am assuming that unobserved structural factors that led to the differential start and end dates per tribe that existed in the pre-1975, and 1975-1984 entry and exit periods used for the first stage are persistent into the current time period as well.

7.2.1 First stage specifications

I use these instruments in two different first-stage equations to produce a predicted year of entry and year of exit that is not subject to reverse causality and does not violate the exclusion restriction. These two first-stage equations also incorporate the exogenous variables from the second-stage, but averaged in the same way for the pre-period time frame. The following equations represent this, and convey two, cross-sectional first-stage equations to separately estimate years-to-enter and years-to-exit, calculated from an anchor start year of 1908.

$$YearstoStart_r = \beta_0 + \beta_1 Z_1 + \beta_2 Flow_r + \beta_3 Drought_r + \mathbf{X}_r\beta^x + \mathbf{W}_r\beta^w + \eta_r, \tag{7}$$

where Z_1 represents the average number of starts in previous five-year periods pre-1975 in other HUC4 regions than the one the reservation-in-question is in. The other covariates are the same as in the second-stage, except they are constructed to represent the average, pre-1975 measurement within the HUC4-area the reservation is in. As an example of this

[35] These years were chosen because pre 1975 there are very few "exits", but most resolutions occur from 1985 and after. Using 1975 as a start period also includes post-Self-Determination-Act, which allows tribes to act with more autonomy within the federal system. I calculate "other" HUC4-area exits as those in other subwatershed regions (HUC4 areas), but in the same side of the continental divide.

calculation, monthly precipitation in the above equation is averaged annually across the reservation's HUC4 area (using GIS techniques), and then collapsed on its mean for all pre-1975 years. The same technique is used for the other covariates.

The first-stage estimation for the "start resolution phase" treatment is similar:

$$YearstoExit_r = \gamma_0 + \gamma_1 Z_2 + \gamma_2 Flow_r + \gamma_3 Drought_r + \mathbf{X}_r\gamma^x + \mathbf{W}_r\gamma^w + \nu_r, \tag{8}$$

where Z_2 represents the average number of exits in previous five-year periods from 1975-1984 in other HUC4 regions than the one the reservation-in-question is in.[36] Similar to above, the other covariates are the same as in the second-stage, except they are constructed to represent the average, 1975-1984 measurement within the HUC4-area the reservation is in. As an example of this calculation, monthly precipitation in the above equation is averaged annually across the reservation's HUC4 area (using GIS techniques), and then collapsed on its mean for all 1975-1984 years. The same technique is used for the other covariates.

I then use the predicted years-to-event variables to construct estimated binary indicators for the start-of-negotiation and start-of resolution treatment variables in the second stage: $\mathbb{1}\{\widehat{Resolution}_{ry}\}$ and $\mathbb{1}\{\widehat{Negotiation}_{ry}\}$.

7.2.2 Second stage specifications

From the above first-stage estimation, I then re-run Equation 6 with the estimated coefficients:

$$\begin{aligned} Pollution_{j,i,t} =& \alpha_{j1} + \alpha_{j2}\mathbb{1}\{\widehat{Negotiation}_{ry}\} + \alpha_{j3}\mathbb{1}\{\widehat{Resolution}_{ry}\} \\ &+ \alpha_{j4}Flow_{it} + \alpha_5 DroughtIndex_{im} + \mathbf{X}_{iy}\beta^{xj} + \mathbf{W}_{im}\beta^{wj} \\ &+ \xi_{yj} + \eta_{seasonj} + \gamma_{ij} + \varepsilon_{ijt} \end{aligned} \tag{9}$$

As with the OLS results, the coefficients of interest are α_{j2} and α_{j3}, which now represent effect of being in the negotiation phase versus before, and being in the resolution phase versus negotiation phase, respectively. These coefficients can now be interpreted as being causal in nature, as they are identified by the exogenous variation stemming from the first-stage estimations.

[36]within the same side of the continental divide.

8 Results

The following sections show results from OLS and instrumental variables analysis for both the single-pollutant case (dissolved oxygen) and the full system of pollutants. Pollution increases most significantly once *Winters* negotiations begin in upstream-of-reservation areas, and particularly so the closer the readings get to the reservation border, as predicted by Hypothesis 1. Dissolved oxygen readings become significantly higher closer to the upstream border, and this result is confirmed in both the OLS and IV results. These results are consistent with the full system of pollutants, and especially so for dissolved oxygen readings, biochemical oxygen demand, and fecal coliform—all pollutants that are indicative of agriculture, urban development or other human-related activities. The following sections provide more detail of the above summary.

8.1 Baseline OLS Results - Dissolved Oxygen

On average, dissolved oxygen saturation worsens significantly during negotiations as compared to before they begin (Table 8.1, first column). When breaking out by relative location, these results are driven largely by the behavior of upstream users, where pollution increases significantly and increasingly so as monitoring stations move closer to the upstream-of-reservation boundary (Table 8.1, fourth through sixth columns).

	(1) All	(2) On	(3) Upstream	(4) Up, $\leq$ 100 miles	(5) Up, $\leq$ 50 miles	(6) Up, $\leq$ 25 miles
Negotiation:						
After Winters Start	5.328	-0.553	1.304	1.184	6.786	8.466
	(2.494)	(10.63)	(2.013)	(2.403)	(1.330)	(1.660)
Resolution:						
After Winters Resolution	-2.758	4.669	-1.133	-1.107	-6.976	-8.644
	(1.844)	(5.088)	(0.936)	(1.011)	(2.321)	(2.192)
Constant	-7.944	-31.48	-16.91	-16.87	-12.76	-1.564
	(3.003)	(15.72)	(2.137)	(2.203)	(2.630)	(8.460)
Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes	Yes	Yes
Climate Control	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	42020	3688	9208	8753	5474	2907
Adjusted R^2	0.030	0.058	0.041	0.043	0.063	0.056

Standard errors in parentheses

Errors Clustered at Res-HUC level

Table 8.1: Dissolved Oxygen During and After Negotiations, OLS Results

What happens once property rights are resolved? According to the OLS baseline results, dissolved oxygen saturation rebounds (indicated by the negative value since the outcome reading is expressed as difference in percent saturation from 100) once rights are resolved, and particularly so upstream of reservations (Table 8.1). Again, the changes are larger the closer the readings are to the upstream border. These results are as predicted by the framework - that the strategic incentives are particularly pronounced in areas where uncertainty of future ownership may most affected, and where pollution is built up from upstream users.

8.2 Baseline OLS Results - System of Pollutants

Table 8.2 shows results from the system of equations. Dissolved oxygen displays similar results to the single-pollutant case. The other metrics also convey that pollution changes during negotiation periods. On reservations (column 2), pollution increases significantly for biochemical oxygen demand (BOD) compared to those monitoring stations' readings before *Winters* processes began. While not statistically significant, fecal coliform, total suspended solids and pH readings also increase during negotiations compared to before. Dissolved oxygen for on-reservation monitoring stations show somewhat negative correlation with the start of negotiation timing, but the coefficient is relatively small and statistically insignificant, as in the single-pollutant case.

These results in part move in correlation with what has been sampled upstream of reservations. Fecal coliform, for example, a pollutant that increases in concentration on reservations during negotiation periods compared to before, also increases upstream of reservations. As the readings move closer to the upstream border of a reservation (from any-distance away, to within 100 miles, then within 50 miles, to within 25 miles of a reservation), the coefficient on fecal coliform pollution steadily increases (Table 8.2, columns four through six), and is the largest and significant upstream of reservations, within the closest cohort.

Other upstream results (Table 8.2) also confirm this type of result - that during negotiations, the coefficients increase as stations get closer to the upstream reservation border. This is in line with hypotheses presented in Section 5 that pollution will increase once negotiations started, and especially so closer to the reservation border of upstream (thus we can more precisely identify this behavior).

Once rights are "resolved", quality improves across several types of pollutants after resolution compared to during negotiations (Table 8.2. On reservations, fecal coliform, total suspended solids, and pH readings all decline on average after resolution.[37] In the upstream regions within 25 miles of a reservation, the increase in dissolved oxygen recorded during negotiations is reversed once rights are resolved (as in the single-pollutant case); in addition to declines after resolution in fecal coliform concentrations and pH.

[37] there are not enough observations on reservations post-settlement for BOD results.

	(1)	(2)	(3)	(4)	(5)	(6)
	All	On	All Upstream	Up, ≤ 100 mi.	Up, ≤ 50 mi.	Up, ≤ 25 mi.
After Negotiation Start:						
Fecal Coliform	12.08	2058.8	2620.2	2597.0	3220.3	4871.9
	(463.7)	(1234.4)	(1765.1)	(1727.8)	(1870.1)	(2403.5)
BOD	-5.514	1.809	-4.758	-4.732	-5.078	-4.414
	(2.769)	(0.0364)	(2.147)	(2.162)	(2.684)	(5.568)
TSS	49.86	159.5	-90.17	-83.58	-46.73	-66.99
	(36.57)	(150.9)	(58.67)	(58.66)	(71.90)	(141.8)
Dis. Ox.	5.356	-0.944	1.319	1.194	6.804	8.471
	(2.457)	(10.73)	(1.954)	(2.328)	(1.272)	(1.608)
pH	-0.000982	0.0132	0.0525	0.0522	0.0641	0.0307
	(0.0178)	(0.0397)	(0.0251)	(0.0254)	(0.0177)	(0.0181)
After Resolution:						
Fecal Coliform	48.53	-2560.5	-604.7	-609.6	-1519.9	-1910.1
	(190.9)	(1476.9)	(487.4)	(483.9)	(964.0)	(1818.4)
BOD	-2.581	0	8.632	8.523	25.15	0
	(1.538)	(.)	(3.965)	(4.041)	(8.776)	(.)
TSS	94.46	-514.2	99.93	96.66	92.68	361.0
	(43.79)	(270.0)	(58.34)	(53.87)	(61.69)	(113.4)
Dis. Ox.	-2.769	4.730	-1.127	-1.083	-6.900	-8.613
	(1.812)	(4.922)	(0.869)	(0.949)	(2.215)	(2.098)
pH	0.0131	-0.0373	-0.0676	-0.0606	-0.121	-0.178
	(0.0245)	(0.0351)	(0.0469)	(0.0512)	(0.0634)	(0.0201)
Constant	-81.79	-3227.0	229.3	194.5	439.1	242.9
	(292.5)	(702.8)	(215.6)	(212.4)	(322.1)	(989.5)
Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes	Yes	Yes
Climate Control	Yes	Yes	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	218437	21932	47331	44742	27764	14927
Adjusted R^2	0.003	0.087	0.028	0.028	0.033	0.050

Standard errors in parenthesentheses

Errors Clustered at Res-HUC level

Table 8.2: Pollutants During and After Negotiations, OLS Results

8.3 Instrumental Variables Results - Dissolved Oxygen

As mentioned above, the baseline OLS results include endogeneity biases based on the connections between selecting into negotiating for water rights; finally resolving terms and passing resolutions through Congress; and unobservable characteristics about the Native nation itself, political climate, and shifts in bargaining power. The biases stemming from these issues can be both positive or negative, so the IV estimation corrects for this.

The IV results for the dissolved oxygen single outcome model shows that indeed pollution increases significantly, particularly upstream of reservations once negotiations start (Table 8.3). On-reservation saturation of dissolved oxygen worsens significantly, largely driven by changes upstream-of-reservations and close to the reservation border. Once rights are resolved, all coefficients for on- and upstream-of-reservation samples are negative.[38]

[38] While these results are not significant, I believe part of the lack of precision for after resolution may be due to wide variation in implementation of planned diversion and infrastructure projects. There can be a large lag between Congress finalizing a water settlement and completely changing diversion practices. This treatment boundary likely has some fuzziness to it, although it still serves as an important shifter.

	(1)	(2)	(3)	(4)	(5)
	All	On	Up	Up, $\leq$ 50 mi	Up, $\leq$ 25 mi
After Negotiation Start:					
Dissolved Oxygen	0.556	8.170**	-0.0729	1.552	3.594**
	(2.370)	(2.482)	(1.496)	(0.974)	(1.405)
After Resolution:					
Dissolved Oxygen	0.482	-6.125	-1.685	-2.009	-4.980
	(1.627)	(6.278)	(1.601)	(2.886)	(4.172)
Constant	-9.170***	-33.57*	-18.30***	-20.34***	4.626
	(2.740)	(16.21)	(0.793)	(4.765)	(12.40)
Year Effects	Yes	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes	Yes
Climate Controls	Yes	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes	Yes
Observations	40099	3686	7342	5053	2645
Adjusted R^2	0.029	0.060	0.057	0.069	0.069

Standard errors in parentheses

Errors Clustered at Res-HUC level

neg start pred1, neg end pred12

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

Table 8.3: Dissolved Oxygen During and After Negotiations, Instrumental Variables Results

8.4 Instrumental Variables Results - System of Pollutants

The system of equation results confirms findings for the dissolved oxygen analysis. In the system version, dissolved oxygen saturation also worsens on reservations during negotiations, and upstream of the reservation boundary (especially so close to the border). Other pollutants follow this pattern (Table 8.4): In the closest cohort to the upstream-of-reservation border (where one would expect hypothesized behavior to be most pronounced), fecal coliform, biochemical oxygen demand, and dissolved oxygen concentrations all increase significantly as a result of being in the negotiation phase as compared to before negotiations began (total suspended solids also increase, although not with statistical significance). On reservations, total suspended solids and dissolved oxygen increases in concentrations while tribes are engaged in the negotiating/litigating process.

Once rights are resolved, upstream pollution declines, and reservation water quality also improves. For fecal coliform in particular, declines in pollution on reservations after resolution is able to make up for increases on average during the negotiation phase.

	(1) All	(2) On	(3) Up	(4) Up, ≤ 50 mi	(5) Up, ≤ 25 mi
After Negotiation Start:					
Fecal Coliform	-66.70	-376.9	322.5	682.5*	1563.0**
	(174.7)	(2528.0)	(218.7)	(334.6)	(680.9)
BOD	-17.91***	0	7.819**	5.406	10.87***
	(0.256)	(.)	(2.889)	(6.081)	(1.995)
TSS	159.0**	617.3	348.8*	348.0*	151.5
	(74.99)	(423.8)	(169.9)	(173.0)	(112.9)
Dis. Oxygen	0.554	8.449***	-0.0923	1.545*	3.660**
	(2.303)	(2.368)	(1.325)	(0.845)	(1.354)
pH (Diff from 7)	-0.0295	-0.132**	-0.0917**	-0.104**	-0.132***
	(0.0269)	(0.0609)	(0.0412)	(0.0484)	(0.0295)
After Resolution:					
Fecal Coliform	-20.76	-27562.5**	-253.2	-214.2	-2298.9
	(120.9)	(9631.5)	(276.0)	(188.8)	(2231.2)
BOD	8.664***	0	-3.411	0	0
	(2.029)	(.)	(2.080)	(.)	(.)
TSS	19.24*	-305.0***	-11.11	35.01	160.6
	(10.43)	(101.6)	(45.17)	(44.45)	(138.7)
Dis. Oxygen	0.425	-6.274	-1.548	-1.927	-5.092
	(1.578)	(5.875)	(1.625)	(2.825)	(4.022)
pH (Diff from 7)	-0.0473*	0.0869	-0.106*	-0.102	-0.0169
	(0.0240)	(0.0623)	(0.0539)	(0.0927)	(0.101)
Constant	-98.60	-1749.7***	-183.8	-252.1	779.2
	(254.3)	(440.4)	(177.0)	(317.3)	(2022.3)
Year Effects	Yes	Yes	Yes	Yes	Yes
Season Effects	Yes	Yes	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes	Yes	Yes
Climate Controls	Yes	Yes	Yes	Yes	Yes
Demog. Controls	Yes	Yes	Yes	Yes	Yes
Streamflow Controls	Yes	Yes	Yes	Yes	Yes
Observations	206109	21921	35259	24972	13471
Adjusted R^2	0.003	0.083	0.018	0.020	0.036

Standard errors in parentheses
Errors Clustered at Res-HUC level
neg start pred1, neg end pred12
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8.4: Pollutants During and After Negotiations, Instrumental Variables Results

9 Discussion

Studying how water quality is impacted once *Winters* proceedings begin, this paper presents the first set of empirical evidence that the *Winters* process engenders increasing negative externalities in the form of worsening water pollution upstream of reservations during negotiations over water. This outcome is likely produced by perverse incentives that allow incumbent water users to continue to use the resource while bargaining for it. If off-reservation users perceive they are more likely to lose quantities of water in the future, they will be less likely to abate or mitigate water pollution in the current period (either through incentivizing increasing use of polluting inputs or reducing on abatement investments). Further, the nature of bargaining for water incentivizes showing a need for water through use or development projects which can further damage the water system. Plus, with ambiguity in property rights, there are not clear avenues to hold polluters accountable in terms of damages, regulations or policy mandates. There are not clear ways to internalize pollution externalities. So the incentives that are created to increasingly pollute are not easily alleviated until rights are fully settled.

This is echoed in empirical findings, where I reject the null hypothesis that *Winters* has no effect on water-quality outcomes. In fact, I find that water quality degrades significantly upstream of reservations once *Winters* processes begin, and the worsening largely stops once rights are settled. Coase would have predicted as such, particularly because trading can occur once rights are settled and Congress ratifies agreements. Approximately three-fifths of adjudications that have been fully resolved with tribes include congressionally-ratified clauses to allow for leasing back or sales of water rights to non-tribal users.

These arrangements are becoming an increasingly important mechanism in the management of surface water as supplies become more scarce, and the federal government is proving they are willing to take a heavier hand in managing water use even for state-allocated quantities. For example, the Gila River Indian Tribe (GRIT), which has been very successful in resolving *Winters* rights, the State of Arizona, and the federal government agreed in April 2023 that in exchange for conserving upwards of 100,000 acre-feet of Colorado River water over the next three years, the federal and state governments would pay the tribe \$233 million.[39] This funding would go towards upgrading wells and constructing new water infrastructure on the tribe's reservation (\$150 million); and building a pipeline to bring

[39] https://tinyurl.com/2ne3psv8

recycled wastewater to the reservation for agricultural purposes ($83 million).[40] GRIT in particular has been an important player in conserving water within the state before, but the latest agreement represents the tribe's largest water deal of its kind. The conservation effort is estimated to increase elevation levels in Lake Meade by two feet.

Water pollution is an often-overlooked part of the debate over water allocations and tribal water rights in the west. Yet quality is a pivotal attribute that is highly impacted by how users consume and take care of water and environmental resources. From a cost perspective, the U.S. has spent an estimated $1.9 trillion in mitigating surface-water pollution since 1960, a staggering figure that has exceeded the cost of most other U.S. environmental initiatives (D. Keiser, Kling, and J. Shapiro 2018.) Large-scale negotiations over water are only becoming more difficult and costly as scarcity takes hold of the cities, towns and communities in the arid west. This study brings to light evidence that the process of assigning rights and reallocating water has real impacts on resource health. This is not just an issue of localized boundaries and pollution. On a national, or even, basin-wide, level, individual states may not have incentives to regulate or enforce water quality at the downstream end of their state boundary. This could exacerbate pollution that accumulates between or within states and between conflicting users.

Across many dimensions, the history of setting and enforcing tribal rights has been fraught with issues of implementation, obfuscation, corruption and inequity. This paper is the first study presenting empirical evidence of the environmental costs of delays in implementation of *Winters* rights. That these environmental costs directly impact Indigenous Peoples, who have been disenfranchised from the full enforcement of judicially recognized rights for over 100 years is an inequity that can and should be addressed on both moral, economic and environmental grounds. A silver lining is that many of these outcomes are the result of institutions and processes that incentivize, or do not provide deterrents, for polluting or overusing water. Resolving these claims is one step towards ameliorating worsening water quality, and measures that state or federal governments initiate to mitigate the difficulties in enforcing and clarifying property rights for water resources will have tangible economic and ecosystem effects. Conflicts over water will continue on in force, so understanding the real costs of these conflicts, and lack of action in facilitating faster or more effective enforcement of rights or reallocation of water, provides real opportunities to staving off pollution, and incentivizing resolution, in the years ahead.

[40] `https://tinyurl.com/4p6j39hx`

Appendices

***** Online Appendix - For Online Publication *****

A Correlation Between Pollutants

	Biochemical Oxygen Demand (BOD)	Fecal Coliform	Dissolved Oxygen, % Sat., Diff. from 100%	pH (Difference from 7)	Total Suspended Solids	Streamflow
Biochemical Oxygen Demand (BOD)	1					
Fecal Coliform	0.2048*	1				
Dissolved Oxygen, % Sat., Diff. from 100%	0.2054*	0.0750*	1			
pH (Difference from 7)	0.0434*	0.0091*	0.2562*	1		
Total Suspended Solids	0.0446*	0.0217*	0.0170*	-0.0316*	1	
Streamflow	-0.0163	-0.0052	-0.0133*	0.0117*	0.0032	1

Figure 8: Pollution Correlations, 1% Significance

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.[41]

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 spe-

[41] 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`.

cific 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 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.[42]

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 NHDPlus 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

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

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 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).[43] 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

[43]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`

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.[44] Additionally, the Network Utility tool is recommended for tracing upstream and downstream flowlines. The typical way that the network utility 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.

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

Environmental Protection Agency's Hydrography Event Manager (HEM) Tool,[45] 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.[46]

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 9).

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

[46] 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.

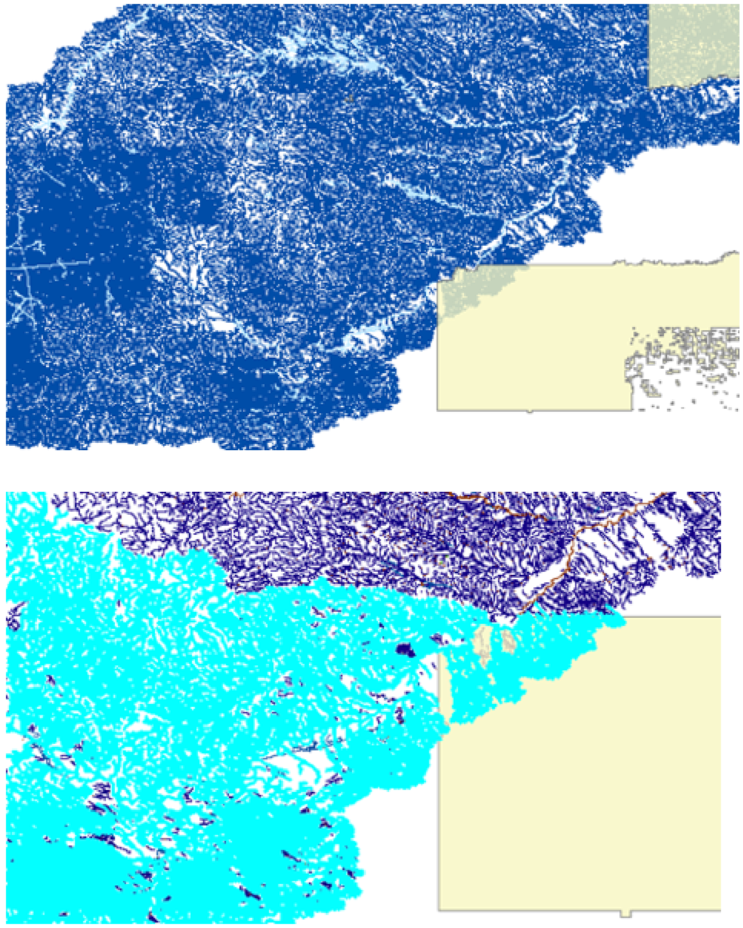


Figure 9: Example of Flowlines and Reservations within a HUC4 Area (top panel), and Traced Upstream Flowlines Zoomed in to a Reservation (bottom panel)

I remove the portion that is also concurrently on reservations to be left with just the off-reservation upstream or downstream flowlines. 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.[47] 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.[48]

[47] 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).

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

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 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 (10 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 10: 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.

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