Natural Capital and Municipal Debt

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Abstract

The value of tradable debt securities (bonds), issued by entities that depend on nature as a capital input, would be expected to change with the condition of that nature capital. Municipalities are highly geographically constrained and often face strong dependencies on nature. We contribute to the literature by connecting the emerging empirical literature on the connection between the state of nature and municipal bond spreads with the theoretical and empirical literature on valuing natural capital. First, we provide a theoretical bridge between bond pricing and valuing natural capital. Then, we estimate the sensitivity of bond spreads to changes in the condition of nature and show how these estimates could be used to provide a low bound on the marginal value of natural capital. We apply these theoretical contributions to forests managed for water supply. We estimate that forest fires increase the spread on the first bond issued within 18 months of a fire for the California public water suppliers that depend all or somewhat on surface water. Spreads rise by as much as 29bps basis points for average public water supplier, increasing to 35bps when the majority of a watershed where the PWS takes water burns or to 60bps for PWSs that are fully dependent on surface water. We use these results to estimate a lower bound value of lost forest, as natural capital, when the average acre of forest, generating water services, is burned of $616 per acre for the average public water supplier or $1,125 per acre for public water suppliers that are fully dependent on surface water. These values are sensitive to financial conditions as well as ecological conditions. This approach enables entities looking to accurately attribute value added from their capital stock and potentially provides for a systematic approach to providing lower bound values for a variety of natural assets in the United States that could be used in natural capital accounts.

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1 Introduction

Revenue generating entities have a private incentive to invest in nature conservation when enhanced states of nature increase net revenue flows for the entity. Forests are a traditional example, where private forest companies cultivate tree growth for future extraction. This makes trees a "work in progress," and expenditures on enhanced tree growth increase future production rather than current consumption, satisfying Hulten's (2006) definition of capital. Similarly, Rouhi Rad et al. (2021) show how the Panama Canal Authority has a private incentive to conserve water because high lake levels in the dry season increase revenue generation for the Panama Canal Authority by facilitating ship transits. These conservation actions are "avoid defensive expenditures." When entities have sufficiently strong dependencies on nature and issue tradable securities, the prices of those securities are expected to be influenced by capital reserves, including the state of nature.

Entities with production process that are strongly spatially dependent are likely to have strong dependencies on the state of nature. For example, the Panama Canal Authority strongly depends on water, and there are no readily available substitutes to spatially diversify water related risks with water outside the Panama Canal watershed. Conversely, many private firms can and do diversify localized, nature-related supply chain risks by sourcing across many suppliers. Even large forestry companies can diversify risks by managing many spatially isolated stands. Nakhmurina et al. (2026) argue that municipalities are uniquely exposed to the state of nature because their sources of revenue are geographically defined and align with their spending obligations. Municipalities also have more limited access to insurance compared with private firms.

In the United States municipalities issue tradable debt securities on a public market, i.e., municipal bonds, that categorizes them as a kind of entity with unique and transferable fiscal dependencies on natural capital. There is growing empirical evidence that the spreads and prices of municipal bonds are affected by the state of nature and nature related risks (Lu and Nakhmurina, 2024; Painter, 2020; Auh et al., 2022; Rizzi and Lewis, 2025; Jeon et al., 2025; Goldsmith-Pinkham et al., 2023; Nakhmurina et al., 2026; Lopez et al., 2025). This identified relationship has been primarily empirical, idiosyncratic, and disconnected from natural capital theory. Here, we connect the literature on the capitalization of nature within municipal bonds to natural asset pricing theory (Fenichel and Abbott, 2014; Yun et al., 2017). In so doing, we develop a process for recovering a lower-bound marginal value of natural capital that municipal bond issuers could use to value natural capital on their balance sheets.

To fix ideas we apply natural capital theory connected to municipal bonds to the use of forests by public water suppliers (PWSs) in the provision of water within the state of California. A substantial amount of forest management, and protection from wildfire, is driven by the forest management goal of water provision (Warziniack and Thompson, 2013). In the American west, where municipalities tend not to own forests, wildfire provides a plausible exogenous shock to identify the effect of forest fire, and forest damage, on the spreads of municipal bonds. Fires alter ecosystems by destroying forest canopy and vegetation and reducing soil permeability (Warziniack and Thompson, 2013), which leads to increased vulnerability to flooding and erosion, and increased runoff during precipitation events, carrying ash, sediment, and debris downstream (Parise and Cannon, 2012). In turn, degrading water quality and accelerating accumulation of sediment in reservoirs (Warziniack and Thompson, 2013). Although fires can burn in the same forests that supply drinking water (Warziniack and Thompson, 2013), the impact of wildfires on water treatment costs remains understudied in the economics literature (Bayham et al., 2022).

2 Theory

To bridge municipal bond prices and spreads with natural capital, we develop theory in three stages. First, we connect common bond pricing approaches to the value of invested capital generally, where capital is thought of as financial or highly fungible produced capital. Then, we introduce non-fungible natural capital. Finally, bring the two together and consider the implications for natural capital valuation.

2.1 Capital and Bond Prices

Bond valuations, V, are determined by returns from holding the bond and are composed of a flow of coupon payments (i.e., dividends) and a capital gains term (principal repayment), which for bonds are realized at the time of maturity.

$$V = \frac{C}{r} + \left(M - \frac{C}{r}\right)(1+r)^{-T} \approx \frac{C}{r} + \left(M - \frac{C}{r}\right)e^{-rT} \tag{1}$$

V is the valuation, or price, of the bond as a whole.[1] C is the coupon payment that represents a dividend paid by the borrower. The amount of the coupon is commonly fixed at the time of issuance. M is the size of the bond and the nominal amount that must be repaid at the time of maturity, T.[2] The yield, interest, or discount rate is represented by r. If the dynamics of the underlying system are deterministic, then all terms are fixed. However, if there is uncertainty about the future, then $r(t) = \hat{r}(t) + \epsilon(t)$, and the yield changes overtime, where $\hat{r}$ is a common yield term that would be applied to all debt securities, and ϵ represents the idiosyncratic spread that is applied to a specific debt security. It is common to see expression (1) as the expression on the left of the approximated equality because bonds are often paid at discrete periods, e.g., twice per year. The right-most side of expression (1) is an approximation as if payments and discounting were applied continuously rather than in the common twice-per-year fashion. This continuous time approximation is helpful for developing theory. The two right-hand side (RHS) terms can be interpreted as a stream of dividends payments or coupons plus the capital gains that realize upon repayment. Equation (1) can be expressed as the instantaneous linearized contribution to value of the bond:

$$rV = C + (rM - C)\,e^{-rT} \tag{2}$$

which is the common asset value equation Shapiro and Stiglitz (1984) and a special case of the value of invested (natural) capital developed by Fenichel and Abbott (2014), based on Jorgenson (1963).

Following Fenichel and Abbott (2014), the value of any asset $K(t)$ at time t is

$$\mathcal{V}\left(K\left(t\right)\right) = \int_t^{\infty} C\left(K\left(\tau\right)\right)e^{-r(\tau - t)}d\tau \tag{3}$$

To facilitate exposition, think of $K(t)$ as financial capital or fungible produced capital. Also, let the asset be a bond so that $V = \mathcal{V}$. Differentiating (3) with respect to time, using the Leibnitz rule, and without relying on optimization assumptions, implies

$$rV\left(K\left(t\right)\right) = C + V_K\dot{K} \tag{4}$$

[1] The price and value of a bond are the same because a bond is a single unit.

[2] Precisely, T is the number of payment periods. For example a bond with a 5-year maturity, but paid twice per year, leads to $T = 10$.

Integrating $V_K\dot{K}$ with respect to time over a finite time interval $[t,T]$ and letting $M = V(T) - V(t)$, implies $(rM - C)\,e^{-rT} = \frac{dV}{dt} = V_K\dot{K}$ assuming time autonomous dynamics,

$$\begin{aligned}\int_t^T \frac{dV}{dK}\frac{dK}{d\tau}d\tau &= V(T) - V(t)\\ &= \int_T^\infty Ce^{-r(\tau-T)}d\tau - \int_t^\infty Ce^{-r(\tau-t)}d\tau\\ &= rV(T) - C(T) - rV(t) + C(t)\\ &= r(V(T) - V(t)) - (C(T) - C(t))\end{aligned}$$

Letting $t = 0$, implies $(rM - C)\,e^{-rT}$. Showing that the value of a bond is the sum of the coupon and the value of capital gains, $V_K\dot{K}$, or capital appreciation $(rM - C)\,e^{-rT}$, where the shadow price $V_{K(t)}(t)$ is determined by an appropriate transversality condition at time T.[3]

Having established a link between the value of an asset and bond price in a deterministic system, we introduce the probability of complete loss of the value of the bond, λV, which is the risk of default. Let λ denote the probability of the event. Assume that there exists a decision or investment that can reduce the expected losses γV, with $\gamma \in [0,1]$. So that

$$\hat{r}V = C + (rM - C)\,e^{-rT} - \lambda\,(1-\gamma)\,V = C + V_K\dot{K} - \lambda\,(1-\gamma)\,V \tag{5}$$

Risk is the probability and consequence of an event. It can be managed through protection that reduces its probability of bad outcomes, or through insurance that reduces the consequences of the event (Ehrlich and Becker, 1972). The formulation in equation (5) allows adjustment to γ to work on either risk management pathway. Collecting terms, yields

$$[\hat{r} + (1-\gamma)\,\lambda]\,V \;= C + (rM - C)\,e^{-rT} = C + V_K\dot{K} \tag{6}$$

The spread, $\epsilon = (1-\gamma)\lambda$, is the difference between the risky yield, r, and the risk-free rate, $\hat{r}$. The discount factor at the time of maturity is $e^{-(\hat{r}+(1-\gamma)\lambda)T}$.

2.2 Natural Capital and Bond Prices

To this point we have treated K as financial or produced capital. Assume an entity also uses natural capital, N, in production, such as in the case of a public water supplier that uses forests in the watershed as a first stage filtration system. The dynamics of the two stocks, in the absences of shocks, are

$$\begin{aligned}\dot{K} &= I - \delta K - C\\ \dot{N} &= G(N) - \alpha N\end{aligned} \tag{7}$$

where I is investment and δ is depreciation of produced or financial capital, and $G(N)$ is a growth equation associated with natural capital and α is the share of natural capital that is lost or extracted each moment. The term for investment may include the new borrowed capital collected through the issue of a

[3]Being careful, one would say the expressions shows $(rM - C)e^{-rT} = V_{K(t)}(t)\dot{K}(t) - V_{K(T)}(T)\dot{K}(T)$. However, from the stand point of the value of the bond, the marginal effect of capital at time T is zero, i.e., $V_{K(T)}(T) = 0$. That is, capital holdings do not matter the instant the bond is repaid. One could introduce an alternative appropriate transverality condition and that would alter $V_{K(t)}(t)$.

bond, and payment of coupons on the bond must be taken from increases in capital. The factor α may be a parameter or the result of an economic program or a human impact function (Fenichel et al., 2016).

To introduce natural capital, we generalize Equation (3) for the two-stock system and assume that all dividends are paid as a coupon, C. This means the water supplier internalizes all services from standing forest and assumes away public spillover benefits because such benefits do not matter for the bond spread and price dynamics. Stocks K and N help generate C and $\gamma(K,N)$, with $\gamma_K(K,N) \geq 0$ and $\gamma_N(K,N) \geq 0$. This implies that γ must go smoothly to 1 as N or K get large, such as with a Michaelis-Menten functional form. It is possible that there are constraints so that γ remains less than one or greater than zero for all N or all K. Following Yun et al. (2017) the deterministic extension of Fenichel and Abbott (2014) is

$$V(K,N) = \int_t^{\infty} \left(C\left(K(\tau), N(\tau)\right)\right) e^{-r(\tau - t)} d\tau \tag{8}$$

differentiating with respect to time and applying the Leibnitz Rule as before

$$rV(K,N) = C(K,N) + V_K \dot{K} + V_N \dot{N} \tag{9}$$

introducing risk of default as before (in Eqn. 5), but allowing natural and produced capital to provide the pathway for risk reduction

$$\hat{r}V(K,N) = C(K,N) + V_K \dot{K} + V_N \dot{N} - (1 - \gamma(K,N))\lambda V \tag{10}$$

An increase in K or N, in the factor $(1 - \gamma(K,N))$, could be interpreted as reducing the probability or consequences of a negative event (e.g., default). This is important because often ecosystem management can do both at the same time. Moreover, greater K can be thought of as self-insurance (Ehrlich and Becker, 1972) that reduces the consequences of a bad shock.

Collecting terms, enables the spread to be expressed as in equation (6)

$$r(K,N)V = (\hat{r} + (1 - \gamma(K,N))\lambda)V = C(K,N) + V_K \dot{K} + V_N \dot{N} \tag{10'}$$

This formalizes the implicit climate risk pathway leveraged in of the climate municipal bond literature (Auh et al., 2022; Jeon et al., 2025; Painter, 2020; Goldsmith-Pinkham et al., 2023), which is that climate change reduces natural capital (N) raising γ and increasing spreads. The bond with value V, however, is now supported by two capital stocks, K and N, that may be substitutable, but are not perfect substitutes. Therefore, it is helpful to understand how the value of the bond changes as each of these two assets change.

First, consider the marginal effect of an exogenous increase in financial or highly fungible produced capital by differentiating both sides of equation (10) with respect to K, and collecting V_K terms, yields

$$\begin{aligned} \left(\hat{r} + \lambda(1 - \gamma(K,N)) - \dot{K}_K\right) V_K(K,N) = \\ C_K + V_{KK}\dot{K} + V_{KN}\dot{N} + V_N \dot{N}_K + \gamma_K \lambda V \end{aligned} \tag{11}$$

The left-hand side is the marginal effect of a change in capital K on marginal value multiplied by a discount rate that is adjusted for risk and marginal own effects on depreciation. Abbott et al. (forthcoming) decompose the risk term when stochastic events are diffusions, e.g., GBM or Poisson jumps. They show that with stochastic shocks there are multiple terms that relate to probability of events and their consequences.

Fenichel et al. (2018) and Yun et al. (2017) have discussed the first four right-hand side (RHS) terms in detail: marginal dividends, own price effects on capital gains, cross price effects on capital gains, and cross stock effects on capital gains. Recognizing that the coupon is fixed, the marginal value of financial capital is associated with a set of capital gains terms

$$\left(\hat{r}+\delta+\lambda\left(1-\gamma\left(K,N\right)\right)\right)V_K = \; V_{KK}\dot{K}+V_{KN}\dot{N}+V_N\dot{N}_K \tag{12}$$

Where the right-most expression follows from the explicit capital dynamics in equation (7). Further, the marginal spread has two terms, the risk premium identified in Eqn. (6) or (10') and the exogenous depreciation rate $-\dot{K}_K = \delta$. If K is financial capital and completely fungible across all possible investments, then $\hat{r}$ likely already includes the effect of δ, or δ can be treated as if it were zero. In other words, depreciation is absorbed in the base rate and is not the project specific rate that leads to the spread. This is the real opportunity cost of capital plus an additional forbearance shared by all investment opportunities.

Now, explicitly consider the role of a marginal change in non-fungible natural capital, and differentiate both sides of equation (10) by N

$$\begin{aligned}\hat{r}V_N = C_N + V_{KN}\dot{K} + V_K\dot{K}_N + V_{NN}\dot{N} + V_N\dot{N}_N \\ + \lambda\gamma_N(K,N)V + \lambda(1-\gamma(K,N))V_N\end{aligned} \tag{13}$$

Collecting V_N terms and recalling that C is constant yields

$$\begin{aligned}\left(\hat{r}-\dot{N}_N+\lambda\left(1-\gamma\left(K,N\right)\right)\right)V_N = \\ V_{KN}\dot{K}+V_K\dot{K}_N+V_{NN}\dot{N}+\lambda\left(\gamma_N\left(K,N\right)\right)V\end{aligned} \tag{14}$$

The LHS is the product of the natural capital-attributable yield and the marginal value of the natural capital on the bond value. V_N is interpreted as the marginal value of natural capital if, and only if, natural capital's contribution is to providing revenue for coupon payments or funds to repay the bond. Otherwise, V_N is a lower bound on the marginal value of natural capital. We think of this as lower bound value if there are dividends generated by natural capital that are not paid to the bond investor. However, if the bond generates negative externalities, then this might be an upper bound.

The yield expressions in (12) and (14), which are the LHS terms in parenthesis, differ if

$$\delta \neq G'\left(N\right)-\alpha \tag{15}$$

Expression (15) is likely to be an inequality, assuming N is changing through time in ways uncorrelated with macroeconomic factors that may alter δ. For expression (15) to become an equality the rate of natural capital reduction, α would need to be chosen, each period, to align the net growth rate of the natural stock with the depreciation rate of K. However, this is not the solution to the optimal management of N. The optimal solution is $\frac{dln(V_N)}{dt} = \delta - G'(N) - \alpha$, only if stock does not provide any service flows. So, Eq(15) could only possibly hold in a steady state. Nor does it align with any heuristic resource management rules. Sustainable yield would require $G\left(N\right)=\alpha$. Therefore, systems where production depends on natural capital have an additional modifier in the yield expression. This expression may be relevant even after default risks have been realized and priced, creating additional arbitrage opportunities if these depreciation effects are

not priced. Expression (15) implies that spreads can increase because of capital loss or depreciation even if the influence on default risk is indirect. In other words, the spread rises when the ratio of debt to capital rises because of asset loss or depreciation.

2.3 Valuing natural capital using bonds

Observe that equation (10') can be written as

$$\begin{aligned} r(N)V = (\hat{r} + (1-\gamma(N))\lambda)V &= C(K,N) + V_K\dot{K} + V_N\dot{N} \\ &= C(K,N) + (r(N)M - C(K,N))e^{-r(N)T} \end{aligned} \tag{16}$$

Again, taking the derivative with respect to N, but focusing on the right most equality, suppressing the dependence of r on N, and imposing the assumption that $C_N = 0$ yields

$$r_N V + rV_N = (r_N M - r_N T(rM - C))e^{-rT} \tag{17}$$

Which implies

$$\begin{aligned} V_N &= \frac{r_N}{r}\left[(M - T(rM - C))e^{-rT} - V\right] \\ &= \frac{r_N}{r}\left[\left(\frac{C}{r} - T(rM - C)\right)e^{-rT} - \frac{C}{r}\right] \end{aligned} \tag{18}$$

The first RHS factor is the yield elasticity with respect to natural capital. This is the estimated marginal effect of natural capital on the bond spread, because the spread and base rate are additively separable, divided by the yield. The second term is the marginal effect of the change in natural capital on the premium (or discount). To provide interpretation of equation (18) consider an increase in natural capital and where r happens to equal the coupon rate. When r equals the coupon rate, $rM - C = 0$, and (18) simplifies to $\frac{r_N}{r}\left[M\left(e^{-rT} - 1\right)\right]$. The term in the square brackets is negative (assuming $r > 0$). However, increases in natural capital are expected to reduce the spread rate, $r_N < 0$, making (18) positive and increasing the value of the bond. Indeed, this follows the standard relationship that when yields fall, prices rise. The rise in price, associated with the change in the fall of the spread from an increase in natural capital, is the lower bound fiscal value of the change in natural capital. The effects are reversed when natural capital falls: spreads rise and prices fall. Moreover, standard bond data and the effect of a change in natural capital on spread is sufficient to measure the change value in the financeable value of natural capital.

Yun et al. (2017) show capital assets are substitutes when the cross stock partial derivative of the value function, e.g. V_{KN}, is negative and complements when positive. The intuition is that a change in quantity of one stock lowers the asset price of the other in the case of substitutes and increases it in case of complements, with V_K being the asset price. From an investment standpoint, however, an important question is whether the stocks are complements in a portfolio – more like Hicksian substitutes. For example, could an entity maintain value V by replacing stock N with K? Using the implicit function theorem implies yields the substitution ratio to maintain an arbitrary level of V

$$\frac{dK}{dN} = -\frac{\left(\hat{r} - \dot{N}_N + \lambda\left(1 - \gamma\left(K, N\right)\right)\right)}{\left(\hat{r} + \delta + \lambda\left(1 - \gamma\left(K, N\right)\right)\right)} \frac{\left(V_{KK}\dot{K} + V_{KN}\dot{N} + V_N\dot{N}_K + \gamma_K\lambda V\right)}{\left(V_{NN}\dot{N} + V_{KN}\dot{K} + V_K\dot{K}_N + \gamma_N\lambda V\right)} \tag{19}$$

This ratio must be negative for an entity to be able to preserve value and substitute one asset for the other. It is possible for expression (19) to be negative, while the V_{KN} is positive. That is two assets can be capital complements generally, but substitutes in the portfolio. Unless $\dot{N}_N$ is very large. The first factor in (19), natural capital stock elasticity on yields, is positive. It may be great or less than 1 depending on the sign of $\dot{N}_N$, but is unlikely to be negative. For it to be negative, the marginal effect of stock on the growth rate would have to exceed the $\hat{r}$ plus any risk premium. The second factor is also likely to be positive because it is ratio of capital gains terms between two stocks that assets, as opposed to liabilities, by assumption. Indeed, for this second factor to be negative, the numerator and denominator would need to have opposite signs. This can occur, e.g., if $\dot{K}$ and $\dot{N}$ have opposite signs.

To fix ideas, the goal of a portfolio is maximize risk-adjust returns. Eq (19) says the the marginal rate of substitution must be equal to ratio of prices within the portfolio. This is a standard optimization condition, where prices are taken as given.

In the sections that follow, we explore our ability operational this theory in the context of forests that are used as capital inputs into public water supply.

3 Data

We use primary market information on California municipal water supply bonds from 2001 through 2021, which includes information on the bond issuer (with a unique CUSIP6 identifier), issue date, location of bond issuer, value of bond (total offering amount and total maturity offering amount), time to maturity, alongside other issue related factors.[4] In the context of municipal bonds, the spread is empirically measured as the difference in yield between a municipal bond and a bench mark – either based on the US Fed treasury curve (available between 1990 and 2019) or the Bloomberg Municipal Market Analytics (MMA) coupon curve (available from 2001) – and represents the extra return required by an investor to take on the risk associated with a bond. For a municipal issuer, a higher bond spread suggests an increase in perceived credit risk by investors who require a higher return (i.e., it is more expensive for the bond issuer to raise funds). We follow standard practice and use the MMA curve to compute the difference between the bond's yield-to-maturity and the maturity-matched par yield (Goldsmith-Pinkham et al., 2023), which allows us to compare bonds issued at different times or with different face values. To mitigate the influence of outliers, the spread, total offering amount, and total maturity offering amount are winsorized at the 1% level in both tails for the sample.

We focus our attention on water and sewage facilities, as these have the most direct relationship to forest-linked water changes resulting from a wildfire. The spatial dependency of a public water system (PWS) in our data is identified using information from Dave Keiser and Dan Phaneuf, who link every US PWS in the EPA's Safe Drinking Water Information System (SDWIS) to the HUC-12 watershed(s) where its intake facilities are located. We connect PWS to municipal bond issuers using a combination of LLM supported matching and manual review. With the help of Mitchell Horn, we develop a multi-stage LLM pipeline that expands PWS abbreviations and names into searchable variants (LLM: *gemma-3-27b-*

[4]We are working to expand the sample to the western United States.

it); scrapes the Electronic Municipal Market Access (EMMA) website (https://emma.msrb.org/) based on name and related search variants, location, and county of the PWS, stores CUSIP6 and links, and downloads official statements; scores potential CUSIP6 candidates based on their match to the PWS (LLM: *Qwen3-30B-Thinking*); classifies water-relatedness of use of funds in the official statements (LLM: *Qwen3-Next-80B*); and in the last stage, a list of candidates for each PWS is reviewed by people to confirm or reject matches with high certainty based on whether the CUSIP6 is the same entity as or the parent of the PWS (see Appendix C for more details).[5] In instances where a set of separate PWSs are connected to the same CUSIP6(s) they are treated as a connected/clustered unit in the empirical analysis and given a new umbrella identifier that is the same across the PWS that share funding structure.[6] It is common for a PWS to issue multiple bonds, often of varying maturity lengths, at the same time. It is also possible that a PWS issues multiple bonds of different maturity amounts at the same time. Bond issuers are identified by CUSIP6, a 6-digit code unique to a common issuer of bonds, while bonds are identified by a nine digit CUSIP9 (the first 6 characters are shared with the CUSIP6 and the latter 3 digits are unique to the bond). However, it is possible that a PWS issues bonds using different CUSIP6s, and these bonds may be issued at the same time. This happens when multiple interacting agencies, perhaps within a single municipality have somewhat independent issuing authority.

We connect the PWS-HUC12 linkages to the EPA's Watershed Boundary Dataset (WBD),which delineates US watersheds into Hydrologic Unit Codes (HUCs) that identify drainage areas, to identify the direct and upstream watersheds for a given bond issuer. Each grouped PWS entity (referred to as PWS hereafter) is linked to every HUC-12 containing an intake facility for its constituent PWS units. We use the HUC-12 watershed unit because it is the smallest and most detailed watershed unit within the WBD and commonly used for studies related to water management. It is also the finest resolution where drinking water intakes are disclosed. A benefit of using drainage areas is that the delineations follow the flow of water, rather than political boundaries that often use rivers as dividers.

We rely on two sources for information on wildfires. Monitoring Trends in Burn Severity (MTBS) is a project from the USDA Forest Service and the U.S. Geological Survey, providing data on "Fire Occurrence" and "Burned Area Boundaries" from 1984 through 2024. We combine these data with a spatial database of wildfires between 1992 and 2020 in the United States from Short (2022). We intersect the HUC-12 watershed boundaries with the universe of wildfire boundaries from MTBS to identify wildfire "treated" sub-watersheds. We calculate the area of intersection as the burned area and compute acres and percentage of watershed burned. Our approach uses the final fire perimeter and containment date, aggregated at the month-year level, to define treatment.

Our final dataset consists of 78 unique PWS in California, connected to bond entities that issued 7,553 water related bonds between 2001 and 2021. We exclude PWSs that relied solely on groundwater. On average, each PWS in our sample issued more than 68 bonds over the sample period, ranging from a low of 1 to a high of 365 issues.[7] The frequency with which PWS issue bonds averages around once every 36 months,

[5] We plan to make the Github repository for this pipeline publicly available.

[6] For example: PWSs "CCWD - Sheep Ranch", "CCWD - West Point", and "CCWD - Ebbetts Pass" are all operated by the Calaveras County Water District (CCWD) and matched to the following bond issuers "Calaveras CNTY CALIF WTR DIST", "Calaveras CNTY CALIF WTR DIST IMPT BD ACT 1915", "Calaveras CNTY CALIF WTR DIST REV CTFS PARTN", "Calaveras CNTY CALIF WTR DIST CTFS PARTN", and "Calaveras CNTY CALIF WTR DIST REV". In the empirical specification these PWSs are given a shared identifier.

[7] For PWS in our working sample, the minimum number of connected CUSIP6 entities is 1 and the highest number is 5. PWSs connected to more CUSIP6s are more likely to issue more bonds, but there is substantial variation and the correlation between a PWS's number of CUSIP6s and bond issues is 0.49. In the empirical estimation the number of connected CUSIP6s is captured by the PWS fixed effects.

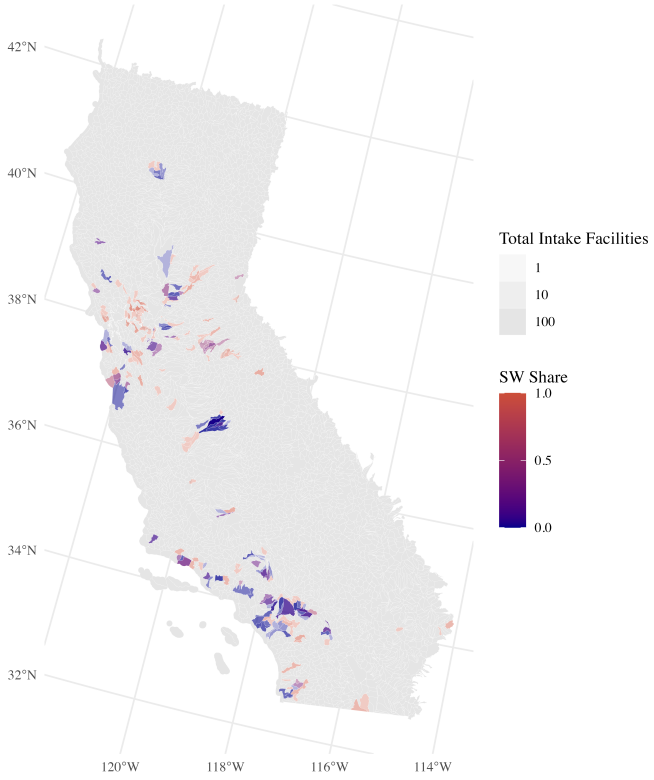


Figure 1: A map of HUC12 watersheds in California, colored by share of intake facilities in our sample that draw only on surface water (Red =1, Blue =0; Opacity by total intake facility count).

with standard deviations of a similar magnitude (see Appendix Table 8 for comparisons between PWS that never experience fires or ever experience fire by treatment status). Anecdotal evidence suggests it takes approximately 6 months to prepare a bond issue. The average spread across the bonds in our sample was 59.2 basis points (1 bps = 0.01%) suggesting investors perceived the sample as a generally riskier investment (demanding higher return) than the benchmark coupon curve.

Table 1: Summary of bond variables

Statistic	Min	Median	Mean	Max	Obs
Spread (bps)	-63.56	45.64	59.23	269.33	7,553
Total Offering Amount	1,216,800.00	28,805,000.00	52,139,556.07	286,945,000.00	307
Maturity Offering Amount	40,000.00	1,270,000.00	3,720,467.19	48,595,000.00	7,553
Coupon rate (%)	0.00	4.25	4.15	7.20	7,552
Offering Yield (%)	0.05	2.80	2.83	7.24	7,553
Annual Coupon Payments	0.00	49,500.00	164,667.72	3,498,840.00	7,552
Time to Maturity	1.00	10.05	10.85	29.98	7,553
Recent Burn Acreage	0.54	1,329.13	3,788.45	52,053.23	255
Bond issues per PWS	1.00	46.50	68.40	365.00	78

[1] Total offering amount refers to the total issue amount for bonds issued at the same date, while total maturity offering amount varies at the individual bond issue (CUSIP9) level (by maturity horizon). Both values are winsorized at the 1% tails.
[2] Total offering amount and Recent burn acreage are summarized across unique PWS-issue dates.
[3] The annual coupon payment ($) is calculated by multiplying the total maturity offering amount with the coupon rate (divided by 100). Most bonds issuers pay a coupon twice per year. However, we provide the sum total of coupon payments per year to normalize for cases that deviate from the twice per year payment schedule.
[4] Recent burn acreage is the area burned in the most recent fire prior to the PWS's issue date. If a PWS is attached to multiple HUC12s that burn in the same month (using containment date), the total acres burned is used.

4 Econometric Model

To establish if there is a relationship between a forest fire in a watershed, where the public water system (PWS) has at least one water intake facility, and the bond spread of that PWS, we estimate an average treatment effect of wildfire exposure on bond spreads. We employ a two-way fixed effects model exploiting the timing and location of fires relative to bond issuance. We estimate the following specification for bond issue i, issued by a PWS p at time t:

$$Spread_{ipt} = \beta PostBurn_{pt,w} + \mathbf{X}'_{ipt}\alpha + \mu_p + \eta_r + \delta_t + \varepsilon_{ipt}$$

where the outcome of interest is $Spread_{ipt}$ of the bond, measured in basis points.

A bond is classified as treated by a forest fire ($PostBurn_{pt,w} = 1$) if the PWS issuing the bond had a fire in any of it's intake watersheds within w months preceding the bond issue date, referred to as the lookback window. Treated bond issues are compared to bonds issued by PWS that either never experience a fire or have not experienced a fire within the lookback window. This treatment specification preserves important within-PWS variation, as a PWS can leave and enter treatment status multiple times over the study period, depending on the time between bond issues and the lookback window. This lookback window may be measure of event salience for investors.

We explore alternate treatment specifications. First, we interact the treatment variable with a binary indicator for whether the bond is the first issued following a fire event ($FirstPost_{ipt,w}$). This allows us to test whether the effect of a fire is absorbed by the first set of bonds issued after a burn, or if the treatment effect persists for subsequent issues. Second, we weight the treatment effect by a PWS's share of intake facilities in watersheds that burn to test the effect of fire exposure. This also allows us to explore whether diversification of intake facilities across watersheds can be an effective mitigation strategy for fire-exposed PWS. Additional specifications and robustness checks are provided in Appendix B.

The vector $\mathbf{X}_{ipt}$ includes bond-specific characteristics to account for risk and structural features. These include the natural log of the maturity offering amount, the natural log of time-to-maturity (in years), and indicator variables for whether the bond is callable, tax-exempt, a general obligation (GO) bond, or bank qualified. We also control for bond insurance status, interacting the insurance indicator with a *post-2009* dummy to account for structural changes in the insurance market following the financial crisis.[8]

We include a comprehensive set of fixed effects to isolate the causal mechanism: μ_p are PWS fixed effects, controlling for time-invariant issuer characteristics such as location, whether the PWS ever experiences a fire, and the number of associated CUSIP6 entities, intake facilities, and HUC-12s (as well as the size of attached watersheds). η_r denotes credit rating fixed effects (at the issue level) to capture observed default risk across bonds with the same rating, where r is the rating category (AAA, AA, etc.).[9] δ_t represents year-quarter fixed effects to absorb aggregate macroeconomic shocks and seasonal fluctuations in the bond market as well as aggregate changes fire risk within and across years, and larger weather events including El Niño. Controls and fixed effects are informed by the bond literature (e.g., Painter, 2020; Acharya et al., 2022; Goldsmith-Pinkham et al., 2023).

Standard errors are clustered at the PWS-level to account for serial correlation in spreads within issuers. Causal identification relies on the assumption that, conditional on fixed effects and bond characteristics, the specific timing and location of a wildfire are exogenous to factors determining bond spreads.[10] Furthermore, due to the time it takes to prepare and process a bond issue with non-trivial fixed costs the issue decision is unlikely to be affected by a fire in the short term. In contrast, the issue price is set at the time of offer and should therefore reflect economic conditions and investor expectations.

5 Econometric Results

5.1 The impact of a fire in a PWS's water intake HUC on bond spread

On average, when a wildfire occurs within any of a PWS's intake HUCs within 9-36 months prior to its bond issue date (Columns 1-5), the fire does not affect the bond spread (Table 2). The comparison group is made up of a PWS that either did not experience a fire in the lookback window or never experienced a fire. For the longest lookback window, spreads appear to fall as result of the burn (Column 6, 48 months). However, we suspect this result is more likely to suggest a specification error than well identified marginal effect.

Across the columns the number of treated PWSs and bond issues increase as the lookback window expands, because we are including PWS that experienced a fire further back in time into the treated group and moving them out of the comparison group. This can be observed in the final rows of Table 2, where the count of treated observations shows that bond issues and fires are relatively infrequent. As the treated group

[8] Bonds primarily went from insured to uninsured following the financial crisis.
[9] Credit rating alignment across rating agencies follows the methods in Nakhmurina et al. (2026)
[10] Robustness checks for staggered treatments and heterogeneous treatment effects are in progress.

expands the estimates gain in statistical precision, which can be observed as a tightening of the standard errors. This is a mechanical effect of the sample size.

There is suggestive, but imprecise, evidence that a fire occurring close to the bond issue date may increase bond spreads, a penalty that decreases and flips as we include older fires that mechanically dilute the signal from recent salient events. In Appendix table 8 we summarize the number of months between consecutive bond issues by treated (pre vs. post) and control groups ("never fire" and "no fire in lookback"). While on average a PWS issues a bond every 36 months, for the 18 PWS that never experience a fire this average is slightly higher at 56 months and for the PWS not experiencing a fire in the lookback this average is around 40 months. In contrast, for the treated group the average moves from 26-34 months pre-fire (depending on lookback window) to 31-59 months in the post-fire period (the average declines as the lookback window increases). This suggests that as the lookback window increases firms are more likely to have issued subsequent bonds after the fire event, and it may be that the effect of a fire in a PWS's watershed is absorbed in their first bond issuance, where they attempt to substitute produced capital for the lost natural capital. After this transition, they may have lower dependence on forests.

5.2 Treatment effect captured by the first bond issue

To test whether the effect of a fire in a PWS's intake HUC is absorbed by its first set of bond issues we use the interaction with "First Post" to allow the treatment effect to differ between a PWS's first and subsequent issues (Table 3). The point estimates show that the average effect of a fire in a PWS's HUC is to decrease the bond spread, but for the first issue after the fire there is a positive penalty on the spread. In the first three columns of Table 3, a large share of the treated bonds are first issues (44-39%) and we find that the effect of the first issues are statistically different from the underlying average effect of a fire on bond spreads. The total effect of a fire occurring within 18 months of the bond issue date is a penalty of 18-24 bps for the PWS's first issue(s). The magnitude and precision of this penalty falls as we expand the lookback windows and the treated group is diluted by the inclusion of subsequent issuances (e.g., in Column 6 only 29% of the treated issues are "First") and PWS issuing bonds further-in-time from the fire event.

5.3 Treatment effect is not predominantly driven by bonds with short maturity horizons

We split the sample by the bond's years to maturity (≤ 10)[11] to test whether the treatment effect is driven by bonds with shorter maturity horizons. We present estimates for the 9-month (Column 1), 18-month (Column 2), and 3-year (Column 3) lookback windows in Table 4, but prefer the 18-month lookback window as this treatment specification gives us the best power and the ratio of first issues to treated issues allows us to estimate the treatment effect of the first issues more precisely.[12] On average the spread for bonds with a maturity longer than 10 years is much higher than for bonds with fewer years to maturity: 45.8 bps for SR compared to 74 bps for LR bonds.

The treatment effect is similar in magnitude to what we saw previously in Table 3, and the penalty of a fire in the lookback window is higher and statistically different for the first sets of bonds issued compared to subsequent issues by the PWS. Specifically, the total effect of a fire in the 18-month lookback window is to increase bond spread by 25.5 bps for the first set of bonds issued with a short maturity horizon (≤ 10

[11] Splitting the sample at 5 or 7 years yield similar results but lack power in the SR group and the observations are less balanced between the two groups.

[12] Appendix table 11 shows the specification without accounting for heterogeneous treatment effects.

years), and by 22.8bps for the first set of bonds issued with a long maturity horizon (> 10 years). While the total effect of a fire on the first bond issued is not significantly different between bonds with a short or long time to maturity, the relative penalty is much higher on SR bonds where a fire in the 18 months leading up to the issue date can increase the spread by 56% compared to bonds with long maturity horizons where the penalty is closer to 31%.

5.4 Diversification of treatment effect across intake watersheds or facilities

Next, we investigate whether the magnitude of the borrowing penalty varies with intensity of physical or natural capital exposure to forest fire. We interact the treatment indicator ($PostBurn$) with an indicator for the share of a PWS's intake facilities in HUCs that burned in the lookback window (in Columns 2, 4, and 6 we include the additional interaction with $FirstPost$). This can help shine light on whether PWS with higher share of intake sources affected by the loss of natural capital, or with a higher probability of damage to physical capital, are more likely to be penalized in borrowing post-fire, or whether it is a market-wide effect for PWS with any intakes in a fire-exposed watershed. In effect, it is a proxy for whether the PWS can substitute within its natural capital stock.

This measure relies on two simplifying assumptions due to data limitations. First, we lack precise geospatial coordinates for individual intake structures, necessitating the use of HUC-level fire occurrence as a proxy for exposure rather than calculating exact intersections with fire perimeters. Second, as facility-specific capacity data (e.g., millions of gallons per day) is unavailable, we assume equal importance across all intake facilities for a given PWS. We define two levels of exposure: Partial Burn ($0 < Share < \theta$) and High Burn ($Share \geq \theta$), with θ= 75% (we test for sensitivity to alternate thresholds at 80 and 85%).

For fires that occur close to the bond issue date (within 18 months, Columns 3 and 4), there is a large penalty of 31.7 bps associated with having a high share of intake facilities in a HUC that burned (Column 3). Similar to the previous results, we find that the effect is higher in the first bonds issued by the PWS (Column 4). If less than 3/4ths of a PWS's intake facilities are located in HUCs with a fire in the lookback window the fire penalty is absorbed in the first issue where there's a 24bps penalty. For PWS where more than 75% of intake facilities are affected the average treatment effect persists beyond the first issue (for a short lookback window) and the spread increases by an average of 29.3bps or 35.5bps for the first issue. However, when the lookback window expands to 3 years the effect is diluted by later issues, and the effect of a fire on the first issue is not statistically different from zero (Column 6).[13]

5.5 Diversification on source of water intake

An alternative way a PWS can diversify is through its type of water intake facility. We hypothesize that PWSs relying solely on intake facilities that draw on surface water (SW) sources are more exposed to a fire in a supplying watershed, compared to PWS that receive water from a mix of SW, ground water (GW), or ground water under the influence of surface water (GU). We explore this by splitting our sample between PWS that only rely solely on surface water intakes and those that have a mix of intake sources, when there is a fire in a supplying watershed in the lookback window. In table 6 we present the estimates for the 9-month (Columns 1 and 2), 18-month (Columns 3 and 4), and 3-year (Columns 5 and 6) lookback windows, but as noted previously we prefer the 18-month lookback window as this sample gives us better power for estimating

[13]The negative effect on partial burn in Column 6, may be the result of heterogeneous treatment effects. The aggregate effects are indistinguishable from zero.

the treatment effects.[14]

The PWS that rely solely on surface water intakes (n=27) make up a smaller share of our sample than the mixed water intake PWSs, and on average have a higher spread (81.1 bps compared to 52 bps). Across all the lookback windows presented in table 6,[15] we find a large penalty on spreads for the first issue post-fire for PWS that rely on only surface water intake facilities, which persists as we increase the lookback window. For these PWS, a fire in one of its supplying watersheds increases spreads on the first set of bonds issued after the fire by 58.9-79.1 bps. In comparison, for PWS with mixed intake facilities we observe a fire-penalty on the first issue of 23-29 bps, but the treatment effect tapers off as the look-back window expands beyond 18-months (similar to the effect we see in Table 4 above).

5.6 Application to Natural Capital Valuation

In the Theory section we derived the marginal value of forest in terms of supporting the bond payments as V_N, (Eq 18). Here, we use the estimate effect of a forest fire on the bond spreads to compute the lower bound value of forests in water provision. There are two important assumptions for interpretation (setting aside questions about validity of the estimate itself). First, all monetizable service flows from the forest are lost as a result of the fire. Violation of this assumption would bias our estimates upward. Second, and perhaps more important, all monetizable service flows would have been used to make the coupon payments so that there are no additional benefits from the forest that do not contribute to servicing the bond.

Most of the quantities need to apply Eq (18) for a PWS represented by the average characteristics are available in Table 1. The quantity not in Table (1) is r_N, which was estimated by regression. Consider the estimate of $r_N = 23.9$bps from Table 3. Substituting quantities into (Eq 18) implies that for a PWS experiencing the average characteristics in the data set, the per acre value lost from a forest fire is \$616. When extrapolated to the average fire, the cost of the average fire in terms of lost forest capital is \$2,333,420. This is small share of the debt that PWS's issue. The average total offering amount of debt is greater than \$52 million. Still, in 2022 the U.S. Congressional Budget Office (CBO, 2022) reported the cost of treating an acre of forest to prevent fire ranged from \$125 to \$489 for prescribed burns or between \$700 to \$2,000 for mechanical treatments. This value suggests that value preserving investment opportunities related to forest fire prevention exist for at least some PWSs.

A critical piece of the theory is that the forest is being leveraged into paying the bond. That is the natural capital is part of the capital stack that is generating returns. The market is price the risk of those returns and enabling the issuer to issue a given amount of debt based on the underlying capital. Therefore, when PWS is able to issue more debt, all else equal – include the extent of forest dependency, this implies the capital market places a greater value of the underlying assets including forests. The distribution of offering amounts and coupon amounts is highly skewed (Appendix A, Figures 2-5). Therefore, it is informative to consider how the results would change if we used the median values from Table 1, which may provide a better measure of central tendency. Doing so implies a per acre value of lost forest capital of \$88 (assuming a median sized fire) or loss from a median sized fire of \$166,311. This illustrates the sensitivity of the imputed value of forest is to financial conditions, irrespective of ecological conditions. It also suggests that investment opportunities are likely skewed towards more heavily leveraged PWSs, all else equal.

Diversification and dependence on forest matter for the implied value of the forest. In Section 5.4 we

[14] Appendix table 15 shows the specification without accounting for heterogeneous treatment effects.

[15] Lookback window 1-year closely resembles the 9-month lookback window, the 2-year window is similar to the 18-month window, and the 4-year window resembles the 3-year window.

show how spatial diversification can limit the effect of a forest fire on bond spreads. Section 5.5 shows that diversifying away from full dependence on surface water also limits borrowing cost risk. There are, however, 27 PWSs in the sample that are fully dependent on surface water. Table 14 recreates Table 1 only using data from surface water dependent PWSs. Applying Eq (18) using the means summary statistics from Table 14, and the estimated effect of a forest fire on the spread (58.9bps) for surface water dependent PWSs (based on the 18-month lookback window), implies a per acre value of forest lost to fire of $1,125 or a loss of $3,338,558 for the average fire these PWSs experience.

The price per acre is based on the *marginal* value concept. However, if one were to apply Eq (1) with the estimated spread adjustment and without and take the difference, then one finds that the change in the *average* value of an acre of forest is $398 for the average forest and $729 for forest is surface water dependent surface water. These average values are what bond investors and trades would likely use. The suggests that average value of an acre of forest is less than the marginal value.

Table 2: Subsequent bond issues post-fire, within the lookback window, stay treated

Dependent Variable:	BPS (wins 1%)					
	≤ 9 Mo	≤ 12 Mo	≤ 18 Mo	≤ 24 Mo	≤ 36 Mo	≤ 48 Mo
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	2.290	2.385	4.766	1.193	-8.067	-13.38***
	(7.541)	(6.681)	(6.176)	(4.440)	(5.759)	(4.984)
ln(Mat Off Amt, wins)	-1.417	-1.429	-1.380	-1.440	-1.336	-1.233
	(1.858)	(1.860)	(1.861)	(1.879)	(1.815)	(1.756)
Yrs to Maturity (ln)	22.51***	22.50***	22.46***	22.49***	22.28***	22.21***
	(2.100)	(2.082)	(2.052)	(2.067)	(2.060)	(2.033)
Callable	12.48***	12.49***	12.48***	12.54***	12.54***	12.49***
	(3.221)	(3.233)	(3.242)	(3.296)	(3.326)	(3.337)
Insured	-45.88***	-45.88***	-44.77***	-45.97***	-47.71***	-48.53***
	(12.30)	(12.33)	(12.29)	(12.27)	(12.14)	(12.36)
Tax Exempt	-117.9***	-117.7***	-117.6***	-117.7***	-117.3***	-116.8***
	(5.608)	(5.454)	(5.431)	(5.469)	(5.465)	(5.450)
General Obligation	1.498	1.502	1.550	1.511	1.797	1.946
	(4.903)	(4.889)	(4.836)	(4.880)	(4.921)	(4.920)
Bank Qualified	-8.521	-8.917	-9.790	-8.543	-9.282	-8.859
	(16.98)	(17.18)	(17.28)	(16.91)	(16.61)	(16.23)
Insured × post-2009	53.61***	53.82***	53.14***	54.01***	57.64***	59.32***
	(14.12)	(14.02)	(13.91)	(13.73)	(13.10)	(13.62)
Fixed-effects						
PWS (n=78)	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating (n=10)	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr (n=77)	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81024	0.81026	0.81054	0.81021	0.81122	0.81292
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Treated PWS	19	22	28	32	37	39
Untreated PWS	59	56	50	46	41	39
Treated Bonds (CUSIP9)	634	806	1,130	1,405	1,916	2,212

Clustered (PWS (n=78)) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 3: Separate out the effect of the first bond (or serial bonds) issued post-fire within the lookback window

Dependent Variable:	BPS (wins 1%)					
	≤ 9 Mo	≤ 12 Mo	≤ 18 Mo	≤ 24 Mo	≤ 36 Mo	≤ 48 Mo
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	-13.23	-6.152	-5.429	-2.085	-12.66*	-16.46***
	(9.592)	(6.559)	(4.949)	(4.374)	(6.739)	(5.428)
First Post × Post Burn	32.65**	24.48**	29.31***	9.462	14.20	9.822
	(15.14)	(11.95)	(9.341)	(7.957)	(9.845)	(9.173)
ln(Mat Off Amt, wins)	-1.555	-1.437	-1.375	-1.533	-1.319	-1.192
	(1.866)	(1.886)	(1.868)	(1.896)	(1.776)	(1.708)
Yrs to Maturity (ln)	22.80***	22.75***	22.65***	22.58***	22.34***	22.25***
	(2.144)	(2.124)	(2.109)	(2.081)	(2.051)	(2.023)
Callable	12.18***	12.21***	12.16***	12.52***	12.46***	12.38***
	(3.228)	(3.269)	(3.259)	(3.293)	(3.300)	(3.297)
Insured	-42.44***	-42.86***	-39.62***	-45.81***	-47.27***	-48.63***
	(12.16)	(12.08)	(12.08)	(12.42)	(12.54)	(12.59)
Tax Exempt	-118.1***	-118.6***	-118.9***	-118.0***	-117.5***	-116.7***
	(5.558)	(5.374)	(5.368)	(5.515)	(5.630)	(5.566)
General Obligation	1.138	1.109	1.172	1.500	1.773	1.986
	(4.950)	(4.929)	(4.942)	(4.902)	(4.887)	(4.893)
Bank Qualified	-12.86	-11.20	-11.52	-8.161	-6.702	-6.803
	(14.81)	(15.39)	(15.79)	(16.54)	(16.22)	(16.02)
Insured × post-2009	46.09***	46.41***	40.71***	51.97***	57.06***	59.17***
	(14.37)	(14.21)	(13.68)	(14.20)	(13.65)	(14.00)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81342	0.81262	0.81497	0.81070	0.81238	0.81353
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Total Effect (First Issue)	19.419*	18.324	23.885**	7.377	1.536	-6.643
	(11.688)	(11.559)	(9.619)	(7.627)	(7.881)	(7.938)
Treated PWS	19	22	28	32	37	39
Untreated PWS	59	56	50	46	41	39
Treated Bonds (CUSIP9)	634	806	1,130	1,405	1,916	2,212
Treated First Bonds (CUSIP9)	276	314	442	518	574	647

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 4: Splitting sample by short term ($\leq$ 10 years) and long term (>10 years) maturity horizons, heterogeneous treatment effect by issue

Dependent Variable:	BPS (wins 1%)					
Lookback	9-Mo		18-Mo		3-Yr	
Maturity	SR	LR	SR	LR	SR	LR
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	-15.67	-14.06	-13.23***	-0.3982	-24.91***	-1.741
	(12.48)	(10.22)	(4.878)	(4.998)	(8.230)	(7.557)
Post Burn × First Post	44.03**	25.28*	38.76***	23.18**	24.89**	13.43
	(19.23)	(13.95)	(11.95)	(8.833)	(12.30)	(10.35)
ln(Mat Off Amt, wins)	-0.5648	-4.730***	-0.2991	-4.419***	0.3401	-4.561***
	(2.256)	(1.589)	(2.300)	(1.628)	(1.995)	(1.499)
Yrs to Maturity (ln)	18.24***	38.55***	18.35***	37.98***	17.98***	38.32***
	(1.750)	(5.124)	(1.701)	(5.206)	(1.646)	(4.857)
Callable	16.75	0.9631	16.62	-0.7239	17.42*	1.107
	(11.16)	(7.313)	(11.04)	(7.936)	(10.31)	(7.425)
Insured	-30.49**	-48.95***	-33.18**	-44.47***	-41.08**	-51.18***
	(13.73)	(16.27)	(14.22)	(15.15)	(15.81)	(15.84)
Tax Exempt	-104.5***	-130.9***	-105.4***	-130.9***	-103.1***	-132.2***
	(8.911)	(8.508)	(8.707)	(8.301)	(8.414)	(8.701)
General Obligation	7.846***	1.592	7.563***	0.4733	8.199***	2.816
	(2.221)	(7.207)	(2.223)	(7.396)	(2.226)	(7.980)
Bank Qualified	2.585	-25.89	6.296	-27.60	8.939	-17.83
	(14.20)	(20.53)	(15.46)	(21.48)	(15.30)	(23.02)
Insured × post-2009	25.94*	60.52***	24.20*	51.40***	41.05**	65.27***
	(13.74)	(20.80)	(14.53)	(18.89)	(16.41)	(18.53)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	3,956	3,596	3,956	3,596	3,956	3,596
R^2	0.83065	0.86020	0.83189	0.86167	0.83159	0.85955
Dependent variable mean	45.840	73.974	45.840	73.974	45.840	73.974
Total Effect (First Issue)	28.365**	11.218	25.532**	22.779***	-0.020	11.690
	(13.870)	(10.555)	(11.516)	(8.577)	(9.065)	(7.145)
Treated PWS	19	18	27	28	36	37
Untreated PWS	58	55	50	45	41	36
Treated Bonds (Total)	339	295	600	530	1,015	901
Treated Bonds (First Issue)	148	128	210	232	293	281

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 5: Treatment effect weighted by the share of a PWS's intake facilities in burned watersheds, within the lookback window

Dependent Variable:	BPS (wins 1%)					
Lookback	9-Month		18-Month		3-Year	
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Partial Burn (<75%)	-0.4588	-15.03	0.4525	-8.410	-9.443*	-14.34**
	(8.239)	(11.49)	(6.533)	(5.282)	(5.187)	(5.642)
High Burn (≥75%)	41.24**	20.42	31.74***	24.27**	-2.972	-5.080
	(18.68)	(13.13)	(11.18)	(10.47)	(12.56)	(18.70)
First Post × Partial Burn (<75%)		31.24*		29.38**		21.63*
		(17.98)		(12.17)		(12.63)
First Post × High Burn (≥75%)		44.48		11.22		1.113
		(29.41)		(15.01)		(16.23)
ln(Mat Off Amt, wins)	-1.509	-1.672	-1.436	-1.329	-1.337	-1.408
	(1.842)	(1.851)	(1.861)	(1.852)	(1.818)	(1.758)
Yrs to Maturity (ln)	22.55***	22.81***	22.30***	22.59***	22.19***	22.42***
	(2.071)	(2.109)	(2.047)	(2.115)	(2.105)	(2.107)
Callable	12.55***	12.30***	12.64***	12.15***	12.59***	12.44***
	(3.214)	(3.199)	(3.229)	(3.235)	(3.284)	(3.245)
Insured	-45.75***	-42.30***	-45.21***	-39.39***	-48.18***	-45.61***
	(12.24)	(12.02)	(12.26)	(12.38)	(12.37)	(12.70)
Tax Exempt	-118.1***	-118.4***	-117.1***	-118.1***	-117.1***	-117.4***
	(5.634)	(5.584)	(5.662)	(5.580)	(5.514)	(5.647)
General Obligation	1.930	1.637	2.142	1.498	1.908	1.591
	(4.899)	(4.932)	(4.831)	(4.912)	(4.953)	(4.908)
Bank Qualified	-12.41	-17.55	-13.82	-13.01	-9.661	-5.688
	(14.86)	(14.12)	(15.82)	(15.76)	(16.23)	(15.94)
Insured × post-2009	54.31***	46.20***	56.56***	45.38***	57.95***	55.57***
	(14.33)	(14.67)	(14.65)	(14.54)	(13.20)	(13.56)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81190	0.81513	0.81261	0.81612	0.81137	0.81290
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Total Effect: Partial Burn (<75%)		16.210		20.967*		7.285
		(12.606)		(12.168)		(10.666)
Total Effect: High Burn (≥75%)		64.899**		35.490**		-3.968
		(32.239)		(15.700)		(12.135)
Treated PWS	19	19	28	28	37	37
Untreated PWS	59	59	50	50	41	41
Treated Bonds (Total)	634	634	1,130	1,130	1,916	1,916
Treated Bonds (Partial)	497	497	831	831	1,329	1,329
Treated Bonds (High)	137	137	299	299	587	587
Treated Bonds (First Issue)	276	276	442	442	574	574

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 6: All Issues Post Fire Are Treated, First issue is separated: Separating by SW-only and Mixed water intake facilities

Dependent Variable:	BPS (wins 1%)					
Lookback	9-Mo		18-Mo		3-Yr	
Water Source	SW Only	Mixed	SW Only	Mixed	SW Only	Mixed
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	-26.04	-2.664	7.771	0.6815	-3.968	-14.11
	(2,181,216.1)	(5.430)	(8.706)	(6.008)	(3.693)	(10.27)
First Post	90.69	25.78**	51.12***	27.89***	83.03***	3.528
	(2,181,183.8)	(9.776)	(18.03)	(7.562)	(18.55)	(16.50)
ln(Mat Off Amt, wins)	-0.6044	-2.042	-0.1818	-1.916	-0.5581	-1.705
	(2.019)	(2.006)	(2.272)	(1.949)	(2.049)	(1.735)
Yrs to Maturity (ln)	24.58***	22.96***	24.06***	22.59***	23.93***	22.51***
	(2.816)	(2.588)	(2.950)	(2.512)	(2.809)	(2.463)
Callable	13.35***	9.856**	14.22***	10.03**	14.15***	10.06**
	(2.102)	(3.816)	(2.053)	(3.751)	(2.049)	(3.904)
Insured	-3.196	-25.03**	28.52	-21.33*	28.80	-26.63**
	(19.89)	(11.22)	(30.65)	(11.29)	(22.80)	(11.36)
Tax Exempt	-111.8***	-125.1***	-110.9***	-125.1***	-110.6***	-123.9***
	(10.72)	(6.353)	(10.62)	(6.373)	(10.65)	(6.439)
General Obligation	-9.171**	3.848	-7.926*	4.063	-7.760*	4.544
	(4.376)	(5.462)	(3.990)	(5.468)	(3.962)	(5.505)
Bank Qualified	-36.79***	10.60	-52.16***	12.69	-50.97***	11.60
	(12.47)	(11.78)	(6.297)	(10.88)	(5.743)	(15.85)
Insured × post-2009	-27.92	46.40***	-64.64*	42.24***	-70.02***	54.22***
	(18.74)	(12.55)	(33.15)	(10.89)	(24.56)	(12.91)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	1,883	5,670	1,883	5,670	1,883	5,670
R^2	0.93448	0.80591	0.93835	0.80797	0.94055	0.80649
Dependent variable mean	81.127	51.964	81.127	51.964	81.127	51.964
Total Effect (First Issue)	64.654*	23.118**	58.891***	28.568***	79.066***	-10.587
	(36.026)	(9.991)	(21.568)	(8.457)	(20.048)	(9.698)
N GU-Only PWS	0	1	0	1	0	1
Treated PWS	5	14	8	20	10	27
Untreated PWS	22	37	19	31	17	24
Treated Bonds (Total)	106	528	209	921	329	1,587
Treated Bonds (First Issue)	93	183	152	290	173	401

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 7: Summary of bond variables for PWSs that are fully dependent on surface water.

Statistic	Min	Median	Mean	Max	Obs
Spread (bps)	-45.42	56.71	81.13	269.33	1,883
Total Offering Amount	1,216,800.00	22,870,000.00	33,466,270.60	127,630,000.00	91
Maturity Offering Amount	40,000.00	810,000.00	1,797,801.69	48,595,000.00	1,883
Coupon rate (%)	0.00	4.00	4.07	6.75	1,882
Offering Yield (%)	0.05	3.25	3.10	6.92	1,883
Annual Coupon Payments	0.00	30,225.00	76,628.77	1,457,850.00	1,882
Time to Maturity	1.00	9.78	10.56	29.98	1,883
Recent Burn Acreage	27.57	1,376.17	3,011.57	36,170.73	54
Bond issues per PWS	13.00	46.00	57.44	226.00	27

[1] Total offering amount refers to the total issue amount for bonds issued at the same date, while total maturity offering amount varies at the individual bond issue (CUSIP9) level (by maturity horizon). Both values are winsorized at the 1% tails.

[2] Total offering amount and Recent burn acreage are summarized across unique PWS-issue dates.

[3] The annual coupon payment ($) is calculated by multiplying the total maturity offering amount with the coupon rate (divided by 100). Most bonds issuers pay a coupon twice per year. However, we provide the sum total of coupon payments per year to normalize for cases that deviate from the twice per year payment schedule.

[4] Recent burn acreage is the area burned in the most recent fire prior to the PWS's issue date. If a PWS is attached to multiple HUC12s that burn in the same month (using containment date), the total acres burned is used.

6 Discussion

There are strong claims that forests are essential to the American drinking water system. Forests are positioned as natural capital or natural infrastructure that keeps treatment costs down. Therefore, one would expect bonds issued by public water suppliers (PWSs) to be sensitive to forest fires near water intakes. Our empirical results are suggestive of short-term, but not persistent, effects. This may be because PWSs may be able to preserve bond value by substituting produced capital for natural capital to maintain bond value, even if forests are gross complements to produced capital. However, the effects become more clear and persistent for PWSs that are fully dependent on surface water (Section 5.5). In California, full dependency on surface water is relatively rare. This may limit the general value of forest in water production.

We provide preliminary evidence for a link between loss of a forest from fire and increases in public water system bond spreads. We connect these changes to a measure public water supply companies can use as a lower bound value for the forests that provide these inputs. Taking our primary estimate at face value implies the loss of an average acre of forest, which is part of a water treatment process, results minimally in an average loss of $616 per acre. This value increases to $1,125 per acre for surface water dependent public water supply systems. However, the assumption of the method implies that the value of forest depends on the amount of debt the PWS can issue, the amount of forest, and the amount of other capital. For the median PWS that uses a mix of surface and groundwater the value is much lower, $88 per acre.

A PWS may engage in defensive expenditures, which means it invests in produced capital that can deliver the services that the forest provided before the fire. Defensive expenditures make it difficult to identify the effects on bond spreads. PWSs may strategically deploy financial capital to limit borrowing costs. It is also possible that PWSs can respond to fires by raising utility rates or receiving state or federal transfers to boost produced capital, which also helps prevent increases in bond prices. Ultimately, these are not expenditures on new productive capacity, but defensive expenditures required to replace lost natural capital. This has implications for California's balance sheet because the forests were not purchased and the standing forest is valued at zero on the balance sheet. Yet, it is unlikely the forest was fully depreciated before the fire. Thus, expenditures that are masking effects on bonds should be netted out as defensive expenditure, but seldom are.

The results are surprising in that, while we hypothesized that wildfires would drive borrowing costs through structural damage or long-term sediment issues requiring capital upgrades, the transient nature of the spread increase suggests that (1) either investors view these risks as transient, (2) PWSs can address most of the risk with a one-time capital infusion, or (3) the risk that is being priced is the risk of not receiving transfers or rate hikes following a fire that might take longer to realize. If the market anticipated a need for a large, long-term filtration investments, the spread differential would persist beyond 18 months. Instead, generally the rapid recovery of bond spreads supports the view that investors price the immediate operational disruption but do not foresee lasting capital impairment. However, the effect is persistent for surface water dependent PWSs.[16] There are a few reasons this might be the case. Our hypothesis relies on forest fires increasing water production costs while not affecting revenues. However, if revenues are affected for some, but not all, PWSs this could lead to heterogeneous treatment effects. Specifically, in the months immediately following a fire, there may be uncertainty about revenue modification or external transfers. Specifically, it may take time for PWSs to adjust rates or receive transfers from state or federal sources. After two years, this uncertainty may be resolved. If PWSs are able to fully compensate for forest loss with

[16] It could also be the case that fires in non-surface water dependent PWSs are more common than in surface water dependent PWSs simply because non-surface water dependent PWSs are more common in California and the effect is diluted over time.

revenue shifts after about two years, this could explain why we do not find persistent results. It would, of course, mean the costs are shifted to either rate payers or tax payers.

The results do suggest that natural capital can be part of a diversification strategy, which provides a finance perspective on "biodiversification". By having multiple intake HUCs, when a fire hits, only some burn, and this results in less of an increase on bond spreads. This may reveal how investors are likely to approach biodiversity. It also means moderate biodiversification may be sufficient for most investors rather than protecting all of the diversity of life.

The pattern of effects and reported estimated prevention costs do suggest that PWSs could benefit from instruments that let them finance forest fire prevention. One possibility is an insurance product that insures bond rates for PWSs in exchange for payments that could be put towards reducing fire risk. However, it is empirical question as to whether that would be the best risk management strategy.

Fiscal recovery, however, is conditional on the severity of exposure. We identify larger and more persistent spread increases for issuers with high concentrations of intake facilities in burn zones. This indicates that while investors may forgive some wildfires, they impose higher costs on issuers whose productive natural capital is fundamentally threatened. Investors do not appear to price wildfire risk linearly; rather, they demand a substantial premium only when the threat to critical infrastructure crosses a threshold of severity.

Aside from timber firms, water suppliers may be the most likely entities to capitalize on forests and suffer from loss of forests from fire (not considering damage to structures or smoke effects).[17] Our results are suggestive of forest fires causing a loss of natural capital that do indeed raise borrowing cost for public water suppliers. However, these effects appear short lived, perhaps owing to the ability substitute produced capital. This raises the question of why water suppliers are concerned with forest conservation as a way of controlling operating costs. Here, we have begun to provide some evidence that there may be some space for financing forest conservation via municipal water supply bonds, but currently that opportunity is small and noisy. This is somewhat consistent with Vincent et al. (2016), who find the the value of forests in Malaysia for treating water is non-zero, but most of the value of forest conservation is for recreation, not water supply.

While our empirical results are not yet conclusive, it is clear that bridging natural capital theory with bond pricing theory has the potential to provide new insights into the value of natural capital. It also provides new insights into the nature of substitution between natural and financial capital.

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A Additional summary statistics

Table 8: Summary of month gap between a PWS's consecutive bond issues, by treatment status

Lookback Window	Avg. Months	SD Gap	Total Bonds	Avg. Bonds	n PWS
Control: Never Fire Group					
Full Sample	55.90	41.19	967	53.72	18
Control: No Fire in Lookback					
$\leq$ 9 Mo	40.09	34.93	2,191	53.44	41
$\leq$ 1 Yr	44.31	36.40	1,900	50.00	38
$\leq$ 18 Mo	42.50	37.26	1,464	45.75	32
$\leq$ 2 Yrs	40.44	36.13	1,277	45.61	28
$\leq$ 3 Yrs	41.60	36.30	1,104	48.00	23
$\leq$ 4 Yrs	41.60	36.30	1,073	51.10	21
Treated Group: Fire in Lookback (Pre-Fire)					
$\leq$ 9 Mo	26.10	27.58	1,543	96.44	16
$\leq$ 1 Yr	27.33	28.99	1,662	92.33	18
$\leq$ 18 Mo	33.54	32.97	1,774	77.13	23
$\leq$ 2 Yrs	34.14	34.88	1,686	67.44	25
$\leq$ 3 Yrs	32.55	39.09	1,348	51.85	26
$\leq$ 4 Yrs	29.58	34.66	1,083	47.09	23
Treated Group: Fire in Lookback (Post-Fire)					
$\leq$ 9 Mo	59.73	69.10	634	33.37	19
$\leq$ 1 Yr	43.56	56.44	806	36.64	22
$\leq$ 18 Mo	35.83	47.27	1,130	40.36	28
$\leq$ 2 Yrs	32.50	43.71	1,405	43.91	32
$\leq$ 3 Yrs	35.82	42.42	1,916	51.78	37
$\leq$ 4 Yrs	31.44	35.39	2,212	56.72	39
Full Sample					
All Observations	36.02	35.75	5,335	68.40	78

[1] The total number of PWS in the Treated Group (PWS that experience a fire in any intake HUC in the lookback window) may differ between Pre-Fire and Post-Fire if a PWS only issued bonds in one of the periods.

[2] The total number of bond issues in this calculation may differ from the summary statistics table (1) if a PWS only issues one bond or a set of bonds at the same date.

Table 9: Total Offering Amounts After Fire in Lookback

	Avg Amt	SD	Min	Max	Mos. to Next	N CUSIP9
Panel A: 18-Month Lookback						
All Treated PWS	77,089,580	75,939,876	2,200,000	396,270,000	23.61	1,130
First Issue (w/ Second)	31,950,092	18,112,700	2,240,000	105,580,000	24.25	143
First Issue (w/o Second)	51,654,949	83,590,332	7,135,000	396,270,000	65.50	299
All Second Issues	52,540,594	42,163,322	4,410,000	172,635,000	25.55	180
Panel B: 3-Year Lookback						
All Treated PWS	73,409,587	73,170,019	2,200,000	436,955,000	27.94	1,916
First Issue (w/ Second)	33,106,579	30,452,641	2,240,000	113,045,000	40.99	321
First Issue (w/o Second)	65,057,095	102,168,742	8,920,000	396,270,000	99.04	253
All Second Issues	40,998,042	44,623,553	4,410,000	436,955,000	38.07	375

Note: The "Mos. to Next" column is calculated using the full sample to determine the average number of months until the subsequent bond issuance for each PWS. This forward-looking measure captures "transition gaps" (i.e., the time elapsed between the final pre-treatment and first post-treatment issue) that are included in the subsample averages. In contrast, Table 8 above reports the average number of months elapsed since the previous bond issuance, calculated locally within each group, which measures within-treatment issuance frequency and excludes intervals spanning across treatment/group boundaries.

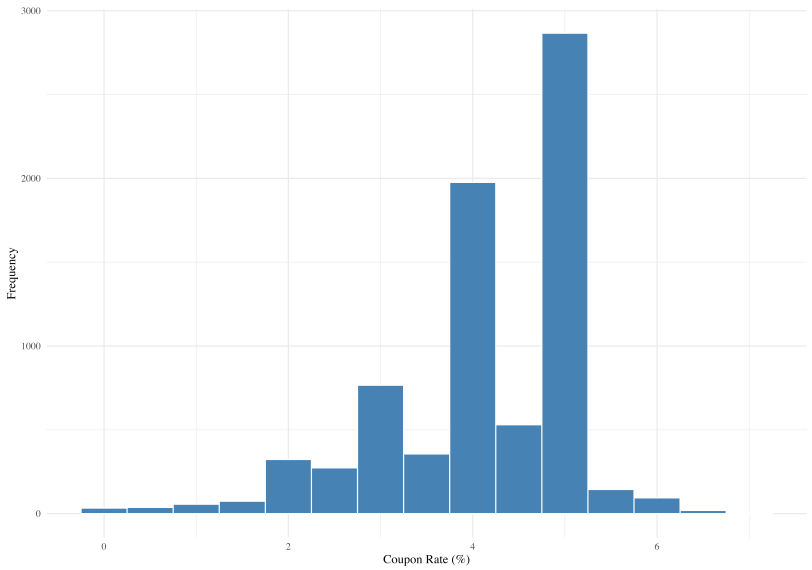


Figure 2: Distribution of Coupon Rates

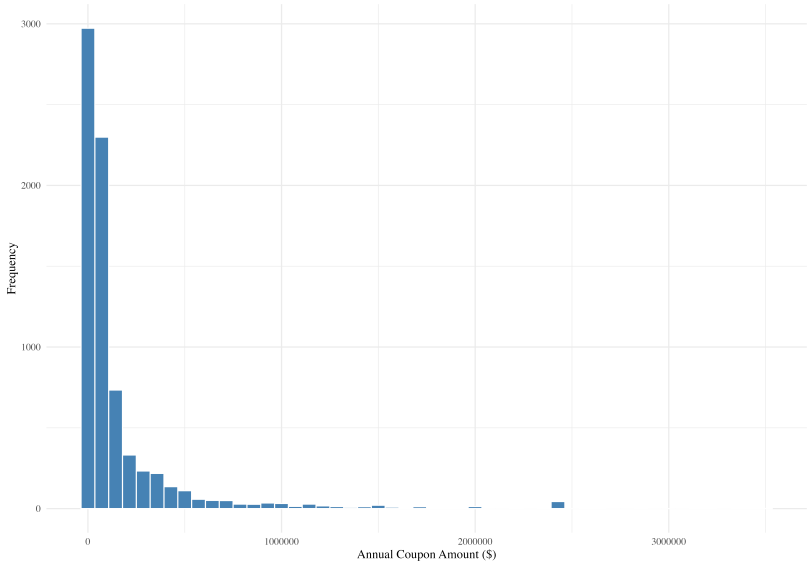


Figure 3: Distribution of Annual Coupon Amount (Winsorized)

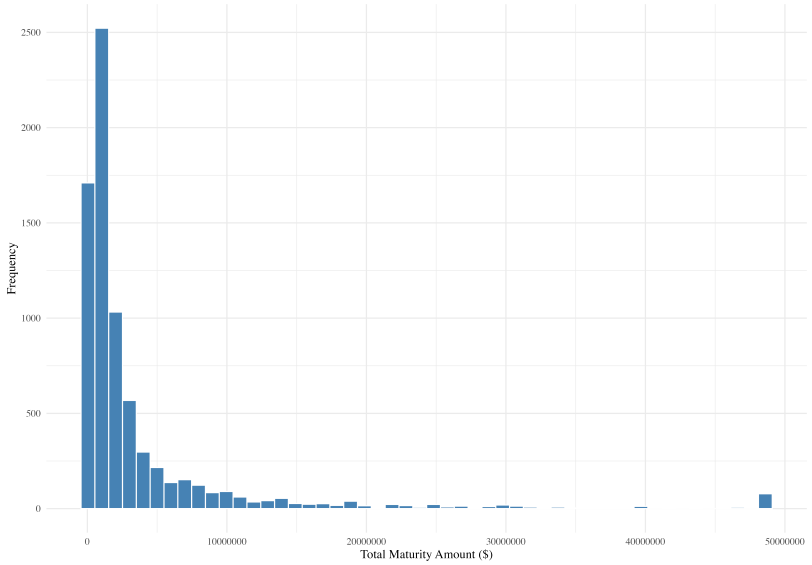


Figure 4: Distribution of Total Maturity Amount (Winsorized)

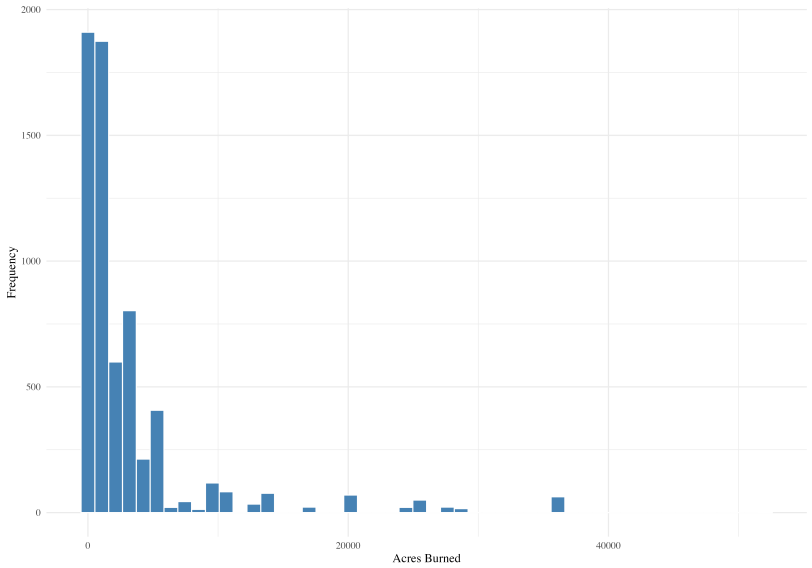


Figure 5: Distribution of Acres Burned in Recent Fire (by PWS and bond issue date)

B Bond spread (bps) Regressions

B.1 Additional explorations

B.1.1 Separate out second set of bond issues

Table 10: All Issues Post Fire Are Treated: Separating the effect of First and Second sets of bond issues

Dependent Variable:	BPS (wins 1%)					
	≤ 9 Mo	≤ 12 Mo	≤ 18 Mo	≤ 24 Mo	≤ 36 Mo	≤ 48 Mo
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	-8.427	-4.062	-4.785	-4.753	-14.08*	-17.05***
	(9.409)	(6.293)	(4.930)	(3.884)	(7.679)	(5.691)
First Post × Post Burn	26.16*	21.52*	28.48***	13.12	16.72	10.78
	(15.47)	(11.68)	(9.040)	(8.450)	(11.99)	(10.63)
Second Post × Post Burn	-15.51**	-9.064	-2.928	12.56	5.202	2.269
	(7.772)	(6.964)	(8.216)	(10.13)	(7.694)	(6.437)
ln(Mat Off Amt, wins)	-1.685	-1.526	-1.404	-1.314	-1.220	-1.130
	(1.862)	(1.885)	(1.854)	(1.825)	(1.687)	(1.635)
Yrs to Maturity (ln)	22.80***	22.73***	22.64***	22.59***	22.33***	22.24***
	(2.155)	(2.136)	(2.131)	(2.066)	(2.037)	(2.007)
Callable	12.41***	12.36***	12.21***	12.30***	12.37***	12.34***
	(3.101)	(3.175)	(3.180)	(3.339)	(3.268)	(3.263)
Insured	-41.74***	-42.40***	-39.35***	-45.32***	-47.21***	-48.72***
	(12.33)	(12.17)	(12.12)	(12.22)	(12.42)	(12.48)
Tax Exempt	-118.8***	-118.9***	-119.0***	-117.8***	-117.4***	-116.6***
	(5.608)	(5.401)	(5.365)	(5.456)	(5.589)	(5.457)
General Obligation	1.229	1.149	1.176	1.430	1.700	1.961
	(5.035)	(4.984)	(4.961)	(4.857)	(4.921)	(4.916)
Bank Qualified	-12.96	-12.03	-11.86	-7.949	-6.930	-6.863
	(14.86)	(15.47)	(15.52)	(16.50)	(16.25)	(16.00)
Insured × post-2009	45.49***	46.63***	40.86***	49.58***	55.94***	58.76***
	(14.34)	(14.26)	(13.70)	(13.88)	(13.94)	(14.15)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81396	0.81289	0.81500	0.81141	0.81255	0.81356
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Total Effect (First Issue)	17.729	17.456	23.697**	8.367	2.646	-6.268
	(12.005)	(11.650)	(9.576)	(7.816)	(8.476)	(8.465)
Total Effect (Second Issue)	-23.934*	-13.126	-7.713	7.805	-8.874	-14.778**
	(12.358)	(10.218)	(8.987)	(11.056)	(7.204)	(7.077)
Treated PWS	19	22	28	32	37	39
Untreated PWS	59	56	50	46	41	39
Treated Bonds (CUSIP9)	634	806	1,130	1,405	1,916	2,212
Treated First Bonds (CUSIP9)	276	314	442	518	574	647
Treated Second Bonds (CUSIP9)	151	167	180	217	375	369

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

B.1.2 Split sample by years to maturity ≤ 10

In this section we split the sample by the cusip9's years to maturity (≤ 10) and repeat the regression specifications with average treatment effect for a fire in the lookback window (Table 11), and allowing the first (set of) bond(s) issued to have a different effect from the average treatment effect (Table 4).

Similar to our main specification, for a 18-month lookback window, the average effect of a fire in the year leading up the bond issue may increase the bond spread but the effect is not statistically different from zero. However, by splitting the sample into short- and long-run maturity horizons we can see that the average spread for bonds with a maturity longer than 10 years is much higher than for bonds with fewer years to maturity.

If we allow the effect of the first sets of bonds to differ from the average treatment effect, we find that for bonds with shorter maturity horizons (≤ 10) there is a bond spread penalty from having had a fire in any of a PWS's intake HUCs in the 18 months leading up to the bond issue date. Specifically, the total effect of a fire in the lookback window increases bond spreads by 25.5 bps for the first set of bonds issued with a short run maturity horizon of less than 10 years, and by 22.8bps for the first set of bonds issued with a long run maturity horizon greater than 10 years.

For both groups, the effect of a fire in the lookback window is higher and statistically different for the first sets of bonds issued compared to subsequent bonds issued by the PWS.

Table 11: All Issues Post Fire Are Treated: Separating by SR and LR maturity horizons

Dependent Variable:	BPS (wins 1%)					
Lookback	9-Mo		18-Mo		3-Yr	
Maturity	SR	LR	SR	LR	SR	LR
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn Treatment	5.133	-1.957	2.064	6.987	-15.47**	2.175
	(10.67)	(6.957)	(6.716)	(5.228)	(6.511)	(5.891)
ln(Mat Off Amt, wins)	-0.0636	-4.603***	-0.1152	-4.437***	0.2833	-4.605***
	(2.265)	(1.571)	(2.281)	(1.578)	(2.078)	(1.514)
Yrs to Maturity (ln)	18.22***	38.28***	18.20***	38.07***	18.01***	38.40***
	(1.656)	(5.086)	(1.640)	(5.111)	(1.641)	(4.904)
Callable	18.78*	2.315	18.80*	1.601	18.24*	1.678
	(11.00)	(7.198)	(11.01)	(7.441)	(10.86)	(7.477)
Insured	-36.97**	-51.86***	-37.51**	-49.51***	-41.85***	-51.26***
	(16.21)	(15.50)	(16.11)	(15.14)	(15.80)	(15.12)
Tax Exempt	-103.8***	-131.3***	-103.4***	-130.8***	-102.8***	-131.3***
	(8.897)	(8.526)	(8.445)	(8.580)	(8.445)	(8.557)
General Obligation	7.908***	3.348	7.969***	2.134	8.148***	2.757
	(2.192)	(7.859)	(2.154)	(7.983)	(2.215)	(8.139)
Bank Qualified	6.819	-21.17	6.641	-23.33	4.825	-21.01
	(16.47)	(22.41)	(16.49)	(22.48)	(15.49)	(23.34)
Insured × post-2009	36.57**	66.85***	37.80**	63.89***	43.53***	65.00***
	(17.36)	(18.64)	(16.84)	(18.23)	(16.16)	(17.92)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	3,956	3,596	3,956	3,596	3,956	3,596
R^2	0.82471	0.85862	0.82453	0.85927	0.82815	0.85866
Dependent variable mean	45.840	73.974	45.840	73.974	45.840	73.974
Treated PWS	19	18	27	28	36	37
Untreated PWS	58	55	50	45	41	36
Treated Bonds (CUSIP9)	339	295	600	530	1,015	901

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

B.1.3 Separate out large areas burned

Post Burn = Average effect of a fire (0-1,000 acres burned)
Total effect = Post Burn + Post Burn * > 1k acres burned – this is the effect of large fires on bond spread

Table 12: All Issues Post Fire Are Treated, fires greater than 1,000 acres are separated

Dependent Variable:	BPS (wins 1%)					
	≤ 9 Mo	≤ 12 Mo	≤ 18 Mo	≤ 24 Mo	≤ 36 Mo	≤ 48 Mo
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	0.4918	-1.164	1.524	-5.660	-16.09**	-23.19***
	(18.68)	(9.552)	(7.473)	(5.665)	(6.764)	(6.565)
Post Burn × > 1,000 Acres	2.163	5.182	5.065	11.59	11.83*	13.46**
	(22.23)	(12.06)	(11.42)	(9.764)	(6.940)	(6.482)
ln(Mat Off Amt, wins)	-1.409	-1.405	-1.366	-1.420	-1.232	-1.101
	(1.819)	(1.842)	(1.847)	(1.868)	(1.779)	(1.705)
Yrs to Maturity (ln)	22.53***	22.58***	22.56***	22.72***	22.46***	22.42***
	(2.122)	(2.095)	(2.101)	(2.079)	(2.030)	(1.983)
Callable	12.45***	12.38***	12.35***	12.21***	12.17***	12.02***
	(3.118)	(3.156)	(3.132)	(3.182)	(3.241)	(3.262)
Insured	-45.84***	-45.77***	-45.26***	-47.09***	-49.80***	-50.87***
	(12.37)	(12.41)	(12.44)	(12.60)	(12.66)	(12.86)
Tax Exempt	-117.8***	-118.0***	-118.0***	-118.7***	-117.8***	-117.4***
	(5.577)	(5.549)	(5.553)	(5.562)	(5.432)	(5.409)
General Obligation	1.455	1.381	1.418	1.218	1.592	1.715
	(4.918)	(4.896)	(4.877)	(4.907)	(4.888)	(4.873)
Bank Qualified	-8.187	-7.477	-8.226	-5.197	-5.217	-4.875
	(17.44)	(17.78)	(17.72)	(17.35)	(16.77)	(16.54)
Insured × post-2009	53.70***	53.50***	52.66***	53.10***	59.18***	60.50***
	(14.09)	(14.09)	(14.16)	(14.12)	(13.69)	(14.17)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81025	0.81038	0.81069	0.81114	0.81229	0.81440
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Total Effect (> 1,000 Acres)	2.655	4.018	6.589	5.931	-4.268	-9.733*
	(8.989)	(8.281)	(8.627)	(6.901)	(6.313)	(5.136)
Treated PWS	19	22	28	32	37	39
Untreated PWS	59	56	50	46	41	39
Treated Bonds (CUSIP9)	634	806	1,130	1,405	1,916	2,212
Treated Large Fire Bonds (CUSIP9)	414	499	698	836	1,111	1,346

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Post Burn = Average effect of a fire (0-1,000 acres burned)

Total effect (1) = Post Burn + Post Burn interacted with a dummy for between 1,000 and 10,000 acres burned – this is the effect of large fires on bond spread

Total effect (2) = Post Burn + Post Burn interacted with a dummy for greater than 10,000 acres burned – this is the effect of very large fires on bond spread

Table 13: All Issues Post Fire Are Treated, fires greater than 1,000 acres are separated

Dependent Variable:	BPS (wins 1%)					
	≤ 9 Mo	≤ 12 Mo	≤ 18 Mo	≤ 24 Mo	≤ 36 Mo	≤ 48 Mo
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn	1.396	0.1782	2.402	-5.263	-14.80**	-22.36***
	(18.19)	(9.317)	(7.355)	(5.595)	(6.526)	(6.303)
Post Burn × Fire 1k-10k ac	3.996	6.945	6.446	15.07	15.58**	15.27**
	(22.49)	(12.40)	(11.74)	(10.89)	(7.721)	(7.266)
Post Burn × Fire > 10k ac	-14.05	-13.64	-14.63	-8.021	-6.142	2.512
	(22.27)	(15.89)	(15.78)	(10.51)	(7.763)	(5.801)
ln(Mat Off Amt, wins)	-1.518	-1.547	-1.518	-1.522	-1.370	-1.115
	(1.829)	(1.848)	(1.852)	(1.916)	(1.843)	(1.706)
Yrs to Maturity (ln)	22.56***	22.62***	22.57***	22.82***	22.48***	22.42***
	(2.141)	(2.110)	(2.110)	(2.136)	(2.049)	(1.988)
Callable	12.50***	12.44***	12.46***	12.17***	12.16***	11.99***
	(3.112)	(3.144)	(3.128)	(3.175)	(3.232)	(3.256)
Insured	-46.37***	-46.43***	-45.95***	-47.00***	-49.86***	-50.73***
	(12.33)	(12.37)	(12.36)	(12.03)	(12.17)	(12.54)
Tax Exempt	-117.8***	-117.9***	-117.8***	-118.5***	-117.7***	-117.3***
	(5.600)	(5.574)	(5.601)	(5.611)	(5.537)	(5.481)
General Obligation	1.312	1.228	1.309	0.9846	1.761	1.818
	(4.933)	(4.905)	(4.876)	(4.977)	(4.838)	(4.850)
Bank Qualified	-7.346	-6.745	-7.431	-4.699	-4.109	-4.587
	(17.55)	(17.78)	(17.64)	(17.16)	(16.43)	(16.43)
Insured × post-2009	54.91***	54.99***	54.29***	54.49***	60.02***	60.94***
	(14.39)	(14.41)	(14.42)	(13.85)	(13.23)	(13.92)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	7,553	7,553	7,553	7,553	7,553	7,553
R^2	0.81059	0.81082	0.81119	0.81219	0.81373	0.81495
Dependent variable mean	59.234	59.234	59.234	59.234	59.234	59.234
Total Effect (1k-10k ac)	5.392	7.123	8.848	9.803	0.775	-7.086
	(10.263)	(9.622)	(9.872)	(8.452)	(6.819)	(5.934)
Total Effect (> 10k ac)	-12.651	-13.459	-12.232	-13.284	-20.943**	-19.848***
	(13.680)	(13.848)	(13.398)	(10.240)	(9.786)	(6.690)
Treated PWS	19	22	28	32	37	39
Untreated PWS	59	56	50	46	41	39
Treated Bonds (Total)	634	806	1,130	1,405	1,916	2,212
Treated Bonds (0-1k ac)	220	307	432	569	805	866
Treated Bonds (1k-10k ac)	358	443	624	703	895	1,100
Treated Bonds (> 10k ac)	56	56	74	133	216	246

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

B.1.4 Split sample by PWS w/ only surface water (SW) intakes vs. mixed sources for intake facilities (SW, Ground water, or ground water under the influence of surface water)

Table 14: Summary of bond variables for SW-only PWS

Statistic	Min	Median	Mean	Max	Obs
Spread (bps)	-45.42	56.71	81.13	269.33	1,883
Total Offering Amount	1,216,800.00	22,870,000.00	33,466,270.60	127,630,000.00	91
Maturity Offering Amount	40,000.00	810,000.00	1,797,801.69	48,595,000.00	1,883
Coupon rate (%)	0.00	4.00	4.07	6.75	1,882
Offering Yield (%)	0.05	3.25	3.10	6.92	1,883
Annual Coupon Payments	0.00	30,225.00	76,628.77	1,457,850.00	1,882
Time to Maturity	1.00	9.78	10.56	29.98	1,883
Recent Burn Acreage	27.57	1,376.17	3,011.57	36,170.73	54
Bond issues per PWS	13.00	46.00	57.44	226.00	27

Table 15: All Issues Post Fire Are Treated: Separating by SW-only and Mixed water intake facilities

Dependent Variable:	BPS (wins 1%)					
Lookback	9-Mo		18-Mo		3-Yr	
Water Source	SW Only	Mixed	SW Only	Mixed	SW Only	Mixed
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
Post Burn Treatment	64.65*	6.120	45.81**	5.976	34.77*	-13.21*
	(36.01)	(5.478)	(21.93)	(6.754)	(20.37)	(7.097)
ln(Mat Off Amt, wins)	-0.6044	-1.972	-0.7374	-1.957	-0.5720	-1.747
	(2.019)	(1.999)	(2.156)	(1.975)	(2.125)	(1.812)
Yrs to Maturity (ln)	24.58***	22.85***	24.47***	22.73***	24.69***	22.53***
	(2.815)	(2.507)	(2.924)	(2.430)	(2.919)	(2.451)
Callable	13.35***	10.01**	14.24***	10.06**	13.85***	10.10**
	(2.101)	(3.832)	(2.091)	(3.780)	(2.137)	(3.911)
Insured	-3.196	-25.05**	24.16	-24.55**	3.439	-26.48**
	(19.89)	(11.52)	(33.24)	(11.75)	(31.50)	(11.44)
Tax Exempt	-111.8***	-125.1***	-111.3***	-124.4***	-111.4***	-123.8***
	(10.72)	(6.448)	(10.42)	(6.502)	(10.44)	(6.467)
General Obligation	-9.171**	3.876	-7.114*	4.040	-7.850*	4.517
	(4.375)	(5.375)	(4.005)	(5.292)	(4.055)	(5.481)
Bank Qualified	-36.79***	13.77	-52.98***	12.20	-51.12***	11.05
	(12.47)	(15.79)	(7.771)	(14.87)	(8.680)	(16.57)
Insured × post-2009	-27.92	50.52***	-59.73	51.94***	-37.09	53.79***
	(18.73)	(12.44)	(35.60)	(12.30)	(31.96)	(12.63)
Fixed-effects						
PWS	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating	Yes	Yes	Yes	Yes	Yes	Yes
Year × Qtr	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	1,883	5,670	1,883	5,670	1,883	5,670
R^2	0.93448	0.80382	0.93724	0.80403	0.93616	0.80643
Dependent variable mean	81.127	51.964	81.127	51.964	81.127	51.964
N GU-Only PWS	0×10^{-16}	1	0×10^{-16}	1	0×10^{-16}	1
Treated PWS	5	14	8	20	10	27
Untreated PWS	22	37	19	31	17	24
Treated Bonds (CUSIP9)	106	528	209	921	329	1,587

Clustered (PWS) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

B.2 Total offering amount on bond spread

Table 16: Total offering amount on bond spread (no treatment)

Dependent Variable:	BPS (wins 1%)
Model:	(1)
Variables	
Total Offering Amount (Wins.)	7.64×10^{-8}
	(1×10^{-6})
Mat Off Amt (wins)	2.15×10^{-7}
	(1×10^{-6})
Yrs to Maturity (ln)	21.33***
	(1.951)
Callable	12.52***
	(3.216)
Insured	-51.57***
	(12.11)
Tax Exempt	-115.6***
	(5.228)
General Obligation	1.683
	(4.497)
Bank Qualified	-7.257
	(16.40)
Insured × post-2009	57.84***
	(13.40)
Fixed-effects	
PWS (n=78)	Yes
Credit Rating (n=10)	Yes
Year × Qtr (n=77)	Yes
Fit statistics	
Observations	7,553
R^2	0.81179
Dependent variable mean	59.234

Clustered (PWS (n=78)) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

C LLM Pipeline

AutoEmma is a computational pipeline that constructs linkages between Public Water Systems (PWS) entities and Municipal Securities Rulemaking Board (MSRB) bond issuer data through the Electronic Municipal Market Access (EMMA) platform. The system is an attempt to resolve a fundamental entity-matching problem across these two databases through orchestration of browser-based data collection, large language models (LLMs), and human oversight.

The pipeline is organized into seven sequential phases. Each phase is implemented as a standalone module that reads its predecessor's output, stores its intermediate outputs, and prepares a structured output for the next phase.

Phase One: Name Resolution. The sourced PWS names in EPA records are frequently abbreviated, truncated, or use non-standard conventions that differ from MSRB issuer names (e.g., "TUD" for Tuolumne

Utilities District). To bridge this gap, each PWS name is submitted to a locally-hosted large language model (Gemma-3 27B, FP8) along with its city and state context. The model generates one to five search variant expansions per PWS, including full entity name reconstructions, component geographic terms, and county-level alternatives. These search variants are then cached for each PWS name and passed to the next phase.

Phase Two: Candidate Collection. Search variants for each PWS are queried against the EMMA issuer search interface via browser sessions using the Playwright package in Python. For each search variant, the resultant list of issuers is collected as candidates for potential linkage Rate limiting with exponential backoff is employed to maintain responsibly query behavior. The output is a de-duplicated set of candidate issuer records per PWS, each with the issuer name, issuer type, and EMMA URL.

Phase Three: Semantic Interpretation. Candidate matches are evaluated using a locally-hosted reasoning-capable LLM (Qwen3 30B-A3B-Thinking, FP8). Each PWS-issuer pair is submitted to the model, which evaluates geographic alignment, entity-type consistency, and name similarity to produce a confidence score (0.0-1.0) with natural-language reasoning. All candidates scoring above 0.0 are forwarded to subsequent phases to minimize false-negative filtering.

Phase Four: Issuer Enrichment. Candidate issuers are aggregated across all PWS records, de-duplicated, and individually accessed from the EMMA platform to extract detailed metadata. This includes contact information, issue descriptions (CUSIP identifiers, dated dates, par amounts), and Official Statement (OS) documents URLs. Available OS documents are downloaded as native PDF formats and tagged as either searchable (text-layer present) or scanned (image-only) based on extractable character density. An enrichment cache ensures that issuers appearing as candidates for multiple PWS records are collected only once.

Phase Five: Text Extraction. OS documents for each candidate issuer undergo text extraction through two pathways depending on the document type. Searchable PDFs are processed with pdfplumber, a deterministic text extraction library. Scanned PDFs are processed with an open-source vision-language model (olmOCR-2 7B, FP8) that performs page-level optical character recognition (OCR). All pages of each document are extracted and stored as structured JSONL files with extraction metadata.

Phase Six: Water-Relatedness Classification. Extracted OS text is classified for water-relatedness using an open-source LLM (Qwen3-80B-A3B, FP8). Classification proceeds in two steps. First, a keyword scan for identifying water-infrastructure terminology (drinking water, sewer, wastewater, stormwater, irrigation, flood control) across all pages of the document and computes signal strength metrics based on term frequency and distribution. Second, a page-selection algorithm identifies the most informative pages for LLM analysis to keep within LLM context limits and prevent dilution of the LLM-classifier's attention. The document-wide keyword frequency results are bundled with the selected pages for classification. The model returns a structure classification including water-relatedness (boolean), entity-match confidence, water coverage level (primary, partial, none), water infrastructure type, bond purpose description, issuer type taxonomy, supporting evidence examples, and classification reasoning.

Phase Seven: Human Review. Each PWS record is displayed with match reasoning, OS classification results, and issuer metadata in a web-based interface built with the Streamlit package. Trained researchers review the classified matches for final adjudication. Reviewer's confirmed matches are conferred for inter-rater variability and saved for downstream analysis.