Natural Capital and Municipal Debt*

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Abstract

A loss of natural capital is priced into an issuer's bonds in the same way as a loss of produced or financial capital. We derive this prediction by extending a standard bond pricing condition to an issuer backed by both produced and natural capital. Losing natural capital leaves more debt per unit of capital, so investors demand a higher premium, but less so for issuers with diversified natural capital. We test these predictions using wildfires in the forested watersheds that supply drinking water in California. When a public water system draws all of its water from a single surface water watershed, a fire in that watershed in the 18 months before an issue increases the offering spread by 58 basis points, a 68 percent increase over comparable systems without a fire. Systems diversified across watersheds or into groundwater pay a smaller premium, consistent with the model predictions. The pricing condition converts the response of single-watershed systems into a forest value of at least $1,187 per acre.

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1 Introduction

Nature is a capital asset (Dasgupta and Heal, 1974; Weitzman, 1976). Consider, for example, a public water system (PWS) that draws its water from a forested watershed and depends on the forest to filter the water before it reaches the treatment plant.[1] However, the forest *does not* appear on the water system's balance sheet, so the value of its natural capital is not measured in financial statements. In this paper, we develop and test a model, rooted in natural capital theory, to value natural capital using changes in municipal bond pricing.

If nature is a capital asset, conserving it today expands the production choices available tomorrow (Arrow et al., 2004; Hulten, 2006).[2] Conversely, a loss of natural capital can limit future revenue-generating opportunities and increase the risk associated with the entity. A loss of natural capital therefore is expected to be priced into the entity's bonds in the same way as a loss of produced or financial capital. We derive this prediction by extending a standard bond pricing condition to a bond backed by two stocks, produced or financial capital and natural capital (Fenichel and Abbott, 2014; Yun et al., 2017). In the extended condition, a loss of natural capital raises the risk that investors attach to the debt and therefore raises bond spreads. The increase is smaller when the issuer can replace the lost stock with another natural stock or with produced capital, and larger when the entity depends on a single natural stock.

We provide empirical evidence for this prediction by studying the effect of wildfires on municipal bond spreads. This setting is useful for three reasons. First, a public water system's revenue is geographically defined and coincides with its spending obligations, so it cannot diversify away from the state

[1] Using natural capital *in situ* as a factor of production is common. The Panama Canal Authority, for example, uses the water in Gatun Lake to move ships through the canal. The value of the water lies in the draft that a deep lake provides, not in extracting the water. The more ships that transit, and the larger they are, the greater the Authority's revenue, which gives it an incentive to conserve water (Rouhi Rad et al., 2021).

[2] A timber company illustrates the point. When it cultivates trees for a future harvest, the standing trees are a "work in progress" that sits in the production process, generates no revenue today, and can be liquidated later. Expenditures that enhance tree growth increase future production rather than current consumption, which satisfies Hulten's (2006) definition of capital, and a company with larger holdings of trees can, all else equal, borrow at lower cost.

of nature in its own territory as a private firm can (Nakhmurina et al., 2026).[3] Public water systems also regularly borrow by issuing municipal bonds. Second, a wildfire is a discrete loss of natural capital that arrives unexpectedly at a time and place unlikely to be predicted by the affected public water system. Moreover, because the issuer rarely owns the forest, the loss changes the natural capital that supports the municipal bond without changing the issuer's financial statements.[4] Third, public water systems differ in how many watersheds and water sources they draw on, which can provide variation in dependence on any specific forest.

Wildfires are costly for public water systems. Fires alter forests by destroying forest canopy and vegetation and reducing soil permeability (Warziniack and Thompson, 2013). These effects can lead to increased vulnerability to flooding and erosion, and increased runoff during precipitation events, which can carry ash, sediment, and debris downstream (Parise and Cannon, 2012). The result is degraded water quality and faster accumulation of sediment in reservoirs (Warziniack and Thompson, 2013). Although fires burn in the same forests that supply drinking water, the effect of wildfire on water treatment costs remains understudied (Warziniack and Thompson, 2013; Bayham et al., 2022). Water provision is a primary motive for much forest management in the region, including protection from wildfire (Warziniack and Thompson, 2013). In the American West, municipalities typically do not own the forests that supply their water, which, together with data availability, is why we focus primarily on public water systems in California.

We link each California public water system's bond issues to the watersheds that contain its surface water sources or intakes and to the wildfires that burned in them. In our design, a bond is treated if a fire burned one of these watersheds in the 18 months before its issuance. We compare the offering spreads of treated bonds with those of untreated bonds, issued by the same system at other times or by systems whose watersheds never burned, controlling for water system, year, quarter, and credit rating

[3] The Panama Canal Authority is a comparable case: it depends on water from a single watershed and has no spatial substitute for it. Private firms, by contrast, can diversify localized nature-related risks by sourcing from many suppliers or selling to different customers, and they have easier access to insurance that covers revenue shortfalls than do municipalities.

[4] In the eastern United States, public water systems sometimes own forestland. It is not clear that changes in the condition of the forests that they own appear on financial statements either.

fixed effects.[5]

For PWSs that draw all of their water from a single watershed, a fire in that watershed increases the offering spread over the Municipal Market Advisors (MMA) yield curve (Schwert, 2017) by 58 basis points (bps). To put this into context, the average spread on bonds issued by comparable PWSs that did not experience a fire is 85 bps, so a fire increases the spread by about 68 percent.[6]

Consistent with model predictions, diversification is associated with a smaller premium. When we add PWSs that draw surface water from several watersheds to the sample, the average wildfire premium decreases to 39 bps.[7] For a PWS that draws on groundwater as well as on surface water from a single watershed, a fire in that watershed increases the spread by 30 bps. For PWSs that have both groundwater and several surface-water watersheds, the estimate is economically small and statistically indistinguishable from zero.

We acknowledge two important limitations of our analyses. First, our design captures bonds issued within 18 months of a fire and cannot say whether the premium persists as PWSs substitute produced capital over time. Second, we observe which sources a PWS uses but not the share of water drawn from each source. Our diversification comparisons therefore capture whether a PWS has access to an alternative source, not how heavily it relies on any one source.

We make three contributions to the literature. First, we connect the municipal bond and nature risk literature to the theory of natural asset pricing (Fenichel and Abbott, 2014; Yun et al., 2017; Abbott et al., 2026). The connection clarifies when natural capital substitutes for, and when it complements, financial and produced capital. Because the spread response is derived from a natural capital pricing condition (Fenichel and Abbott, 2014; Yun et al., 2017; Hashida and Fenichel, 2022; Abbott et al., 2026), it converts

[5]The main identification challenge is that a fire may change when a water system borrows. A PWS that must replace a burned forest's services with produced capital may issue debt sooner, so treated bonds would differ from untreated bonds in timing as well as in exposure. Consistent with this concern, the time between issues for public water systems that depend entirely on surface water is about 17 percent shorter after a fire than before, although the difference is not statistically significant. To address this, we use a control function approach. We instrument the timing of issuance with the share of the system's outstanding debt that is non-callable, a proxy for the PWS's position in its capital cycle. Our results are unchanged.

[6]We caveat that this estimate comes from 28 surface-water PWSs, of which only six experience a fire within the 18-month window. For scale, partisan misalignment between a city and its governor increases municipal borrowing costs by about 9 bps (Dagostino and Nakhmurina, 2026b).

[7]The multi-watershed subsample alone is too small to estimate separately.

into a lower bound on the value of an asset the borrower does not own. The natural capital literature has so far obtained such values from models of resource and economic program dynamics (e.g., Fenichel and Abbott, 2014) rather than from decomposing market prices. Such market-based values may be easier to estimate, defend, and use in natural capital accounts than model-based estimates.

Second, while a growing empirical literature finds that the spreads and prices of municipal bonds respond to the state of nature and to nature-related risks, this literature has developed without reference to natural capital theory (see, for example, Painter, 2020; Acharya et al., 2022; Auh et al., 2022; Goldsmith-Pinkham et al., 2023; Lu and Nakhmurina, 2024; Jeon et al., 2025; Lopez et al., 2025; Rizzi and Lewis, 2025; Nakhmurina et al., 2026). Our theory generates a testable hypothesis that losing natural capital raises the debt-to-capital ratio of an entity that depends on natural capital, which raises borrowing costs measured as bond spreads. The theory also identifies the variables that an empirical model needs in order to test the assertion that nature is capital. We test the nature-is-capital hypothesis empirically and show that forest fires increase the bond spreads of PWSs that depend on surface water. We also find that risk diversification applies to natural capital as it does to other forms of capital. The effect of forest fires on bond spreads decreases when a PWS diversifies its water sources.

Third, we combine the theoretical and empirical results to provide lower-bound estimates of the value of a forest as a capital input into drinking water provision, based on the cost of forest fires in California. The average forest fire costs a diversified PWS that depends on surface water $1.7 million in lost forest natural capital, and an undiversified PWS that relies on a single watershed $3.7 million. For a PWS that relies exclusively on surface water from a single watershed, an acre of forest in that watershed is worth at least $1,187. When the PWS is diversified across more than one watershed, the value of an acre decreases to $264.[8] Groundwater provides a further form of diversification. Such valuations from the initial offer market may be helpful for natural capital accounting and capital planning, insurance, and conservation finance.

[8]We caveat that the secondary market implies a substantially lower value of forest.

2 Theory

To bridge municipal bond prices and spreads with natural capital, we develop theory in three stages. In Section 2.1, we show that the standard bond pricing equation is a special case of the asset value equation for invested capital, where capital is financial or highly fungible produced capital. In Section 2.2, we add a second, non-fungible stock of natural capital and derive how a change in that stock changes the bond's price. In Section 2.3, we examine when natural and financial capital act as substitutes or complements in the issuer's portfolio.

2.1 Capital and Bond Prices

The value of a bond, V, equals the present value of the payments to its holder. These payments have two parts: a flow of coupon payments (i.e., interest payments) and the principal (i.e., the face value of the bond, which the issuer repays at maturity).

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

where C is the coupon payment (commonly fixed at issuance), M is the principal, T is the time to maturity in payment periods (e.g., $T = 10$ for a five-year bond that pays twice per year), and r is the bond-specific discount rate at the time of valuation. For a bond, the terms "bond value" and "bond price" can be used interchangeably, because a bond is a discretely traded asset valued at the price at which it trades.[9] Eq. (1) gives the bond's value in two forms. The first, with the discount factor $(1+r)^{-T}$, is the standard discrete-time form, because bonds typically pay coupons at discrete intervals (e.g., twice per year). The second, with the discount factor e^{-rT}, approximates the first in continuous time, which simplifies the derivations that follow. Multiplying both sides of Eq. (1) by r gives the instantaneous linearized contribution to the bond's value:

[9] A bond is a special case, distinct from the more common case of capital analyzed as a stock. For a stock of capital, the value of the aggregate stock differs from the price of the marginal unit.

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

which is the standard asset value equation (Shapiro and Stiglitz, 1984).

Eq. (2) is a special case of the value of invested capital in Fenichel and Abbott (2014), who build on Jorgenson (1963). To see this, note that in Fenichel and Abbott (2014), the value of any asset $K(t)$, subject to time-autonomous dynamics, is

$$\mathcal{V}\left(K\left(t\right)\right) = \mathbb{E}\Big[\int_{t}^{\infty} C\left(K\left(\tau\right)\right) e^{-\rho(\tau - t)} d\tau\Big], \tag{3}$$

where ρ is the risk-free discount rate. To facilitate exposition, think of $K(t)$ as financial capital or fungible produced capital that pays a dividend C, just as a bond pays a coupon.[10] While Fenichel and Abbott (2014) value capital as the present value of its net benefits in a deterministic setting, we add the expectations operator to indicate that the stream of benefits is uncertain because of stochastic shocks that can affect the state of the asset K. Following Abbott et al. (2026), we model a shock to K as a Poisson event, a sudden loss that arrives at a random time and reduces the asset's ability to make dividend payments (for a bond, coupon payments). After the shock, the value of the asset is Z, which can be as low as zero. The shock arrives at an instantaneous hazard rate $h(K(t))$, which depends on the state of the capital stock. The probability that the asset survives the shock until time t is given by a survival function, $S(t) = e^{-\int_0^t h(K(\zeta))d\zeta}$.

The holder receives the dividend C until the shock arrives at a random time $\tilde{\tau}$ and holds an asset worth Z after it. Following Reed and Heras (1992), we decompose this payoff into two parts. The first is $Z(K(t))$, the value the asset would have if the shock occurred at time t. The second is the dividend net of the payment that Z provides before the shock, $Y(K(t)) = C(K(t)) - \rho Z(K(t)) + Z_K(K(t))\dot{K}(t)$ (with $Z_K = \partial Z/\partial K$ and $\dot{K} = dK/dt$), which the holder receives until the shock arrives. The value of the asset is then

[10] In what follows, we omit time notation to reduce clutter, as long as doing so causes no confusion.

$$\begin{aligned}\mathcal{V}\left(K\left(t\right)\right) &= \mathbb{E}\Big[\int_t^{\tilde{\tau}} C(K(\tau))\, e^{-\rho(\tau-t)}\, d\tau + e^{-\rho(\tilde{\tau}-t)}\, Z(K(\tilde{\tau}))\Big] \\ &= \int_t^{\infty} Y\left(K\left(\tau\right)\right) e^{-\rho(\tau-t)-\int_0^t h(K(\zeta))d\zeta} d\tau + Z(K(t)) = \int_0^{\infty} \psi(t) Y(K(t)) d\tau + Z(K(t)),\end{aligned} \tag{4}$$

with $\psi(t) = e^{-\rho(\tau-t)-\int_0^t h(K(\zeta))d\zeta}$, so that $\frac{d\psi}{dt} = (\rho + h(K(t)))\psi(t)$. Let the asset be a perpetual bond, so that $V = \mathcal{V}$. We differentiate Eq. (4) with respect to t. By the Leibniz rule, the lower limit of the integral contributes $-Y(K(t))$, and the derivative of ψ scales the integral by $\rho + h(K(t))$. Because V depends on time only through K, $dV/dt = V_K \dot{K}$. Substituting the definition of Y and rearranging gives

$$\big[\rho + h(K(t))\big] V\left(K\left(t\right)\right) = C(K(t)) + V_K \dot{K} + h(K(t)) Z(K(t)). \tag{5}$$

If the shock is sufficient to make the asset worthless, then $Z(K(t)) = 0$, and Eq. (5) simplifies to $\big[\rho + h(K(t))\big] V(K(t)) = C(K(t)) + V_K \dot{K}$.[11]

To compare Eq. (5) to Eq. (2), it is important to recall that a bond's value is not autonomous in time, because the value changes as the maturity date approaches. Arrow et al. (2003) show that when dynamics are not autonomous in time, then time itself is treated as a state variable. In this case V_t is the value of a pure time change, dt/dt = 1, and time changes are deterministic. So, following the same approach as above, but where $K(t)$ is a stochastic state variable and t is a deterministic state variable, Eq. (5) is modified to

$$\big[\rho + h(K(t))\big] V\left(K\left(t\right), t\right) = C(K(t)) + V_K \dot{K} + V_t + h(K(t)) Z(K(t)). \tag{5'}$$

If the shock is sufficient to make the asset worthless, then $Z(K(t)) = 0$, and Eq. (5′) simplifies to $\big[\rho + h(K(t))\big] V(K(t), t) = C(K(t)) + V_K \dot{K} + V_t$.

In Eq. (5′), ρ is the risk-free rate and $h(K(t))$ is an idiosyncratic risk adjustment.[12] Both Eq. (2)

[11] A shock may destroy the asset completely or reduce it to the point where it is economically worthless, even if some of the stock persists.

[12] We are assuming the only source of uncertainty is through asset K.

and Eq. (5′) write the bond's return as the coupon C plus a second term. If the bond's yield equals the risk-free rate plus the idiosyncratic risk adjustment, $r = \rho + h(K(t))$, the two left-hand sides coincide, and $h(K(t))$ is the bond's spread over the risk-free rate. The second terms must then also be equal: $(rM - C)\, e^{-rT} = V_K \dot{K} + V_t$. The second and third terms of the bond pricing equation are therefore the change in the bond's value over time, that is, a capital gain.A bond as a specific structure of dynamics that are not autonomous in time, namely the bond repays its principal M at an established finite maturity so the value changes as maturity approaches. Write $m = T - t$ and $V = V(K, m)$. Note that $V(K, 0) = M$, substitute $-V_m$ for V_t in Eq (5′). The two parts of the bond's capital gains term are $V_K \dot{K}$, the change in value as the capital stock changes, and $-V_m$, the change in the value of time as the bond approaches maturity. Setting $t = 0$, and assuming that the capital stock is approximately constant, $\dot{K} \approx 0$, which is likely the case for a standing forest with respect to its water filtering services, the yield $r = \rho + h(K)$ is constant. Then, the RHS of Eq(5′) with $V(K, 0) = M$ and $V_t = -V_m$ gives $V = C/r + (M - C/r)e^{-rm}$, which is Eq. (1), with $-V_m = (rM - C)e^{-rm}$, the second term of Eq. (2). The bond pricing equation is therefore the asset value equation evaluated at the yield $r = \rho + h(K)$. Changes in capital move the bond's price through its spread $h(K)$. Together, Eqs. (2) and (5′) link the price of a bond to the value of the capital that supports it:

$$[\rho + h(K(t))]\, V(t) = C + (rM - C)\, e^{-r(T-t)} = C + V_K(t)\dot{K}(t) - V_m + h(K(t))Z(K(t)). \quad (6)$$

2.2 Natural Capital and Bond Prices

So far, K has been financial or fungible produced capital. Assume that the issuer also uses natural capital, N, in production. A public water system, for example, uses the forests in its watershed as a first-stage filter. We generalize Eq. (6) to these two capital stocks, following Yun et al. (2017), and assume that all dividends are paid as the coupon C. The water system therefore internalizes all services from the standing forest. We assume away public spillover benefits, such as recreation access, because they do not affect the bond's spread or price. Because these benefits are excluded, we recover a lower bound

on the value of natural capital. Both stocks contribute to the coupon C and determine the idiosyncratic risk adjustment $h(K, N)$:

$$r(K, N, t)V = (\rho + h(K, N))V = C(K, N) + V_K \dot{K} + V_N \dot{N} + V_t + h(K, N)Z(N, K), \tag{7}$$

where we suppress the dependence on t, and $Z = 0$ if the shock eliminates the economic viability of the system.[13] Eq. (7) formalizes the climate risk pathway that the climate municipal bond literature relies on (Painter, 2020; Auh et al., 2022; Goldsmith-Pinkham et al., 2023; Lu and Nakhmurina, 2024; Jeon et al., 2025). Specifically, climate change reduces natural capital N, and because $h_N < 0$, the loss of natural capital increases spreads.

Eq. (7) can be written as

$$r\left(K, N\right) V = C\left(K, N\right) + V_K \dot{K} + V_N \dot{N} + V_t = C\left(K, N\right) + \left(r(K, N)M - C\left(K, N\right)\right) e^{-r(K,N)T}. \tag{8}$$

Differentiating the right-most expression in Eq. (8) with respect to N, and writing r for $r(K, N)$, gives

$$r_N V + r V_N = C_N \left(1 - e^{-rT}\right) + r_N \left(M - T\left(rM - C\right)\right) e^{-rT}. \tag{9}$$

Solving for V_N and substituting V from Eq. (1) gives

$$V_N = C_N \frac{1 - e^{-rT}}{r} + \frac{r_N}{r} \left[\left(\frac{C}{r} - T\left(rM - C\right) \right) e^{-rT} - \frac{C}{r} \right]. \tag{10}$$

For a bond of given size and maturity, a change in natural capital affects the bond's value through its coupon, its yield r, or both. Because the risk-free rate does not depend on natural capital, a change in the yield is a change in the spread $h(K, N)$. In the primary market, the issuer sets the coupon rate, so

[13] It could be that the shock destroys the forest completely or it could be that the forest is sufficiently damaged that it cannot be counted on to provide filtration services. In the latter case some forest persists, but it is no longer economically viable as part of the water provisioning system.

both channels can operate. The first term of Eq. (10) captures the coupon channel. It is the present value of the change in coupon payments from a marginal increase in natural capital, holding the yield constant.

When the coupon is fixed, for example for bonds issued before the shock to natural capital and traded in the secondary market, $C_N = 0$, the first term of Eq. (10) drops out, and all adjustment occurs through the yield. The second term is the product of two factors. The first factor, r_N/r, is the proportional change in the yield from a marginal increase in natural capital. The expression r_N/r is also the yield elasticity with respect to natural capital. The second factor, in square brackets, is the effect of that change in the yield on the bond's premium (or discount). To interpret it, consider a bond whose coupon rate equals its yield, so that $rM - C = 0$ and Eq. (10) simplifies to $V_N = \frac{r_N}{r} M \left(e^{-rT} - 1\right)$. The term $M(e^{-rT} - 1)$ is negative for $r > 0$. Because increases in natural capital are expected to decrease the spread ($r_N < 0$), V_N is positive, and more natural capital increases the value of the bond. This is the standard relationship between yields and prices: when yields decrease, prices increase. If, in addition, $T \to \infty$, the expression simplifies further to $V_N = -\frac{r_N}{r} M$. Under these conditions a similar expression exists for K, i.e., $V_K = -\frac{r_K}{r} M$. Furthermore, under these restrictions and using the identity that $V(K, N, t = 0) = M$, $-\frac{dln(M)}{dt} = -\frac{1}{M}\frac{dV}{dt} = V_k + V_N = \frac{r_K}{r} + \frac{r_N}{r}$. This suggests that under these restrictive assumptions the value of natural capital can be thought of as natural capital's share of the growth in bond value. Most bonds do not satisfy these restrictions, so the value of natural capital must be its share of growth in bond value adjusted for time effects and the gap between the coupon rate and the yield.

The bond's price response to a change in natural capital is a lower bound on the fiscal value of that change, because bondholders do not benefit from all the services that natural capital provides, such as recreation access. When the coupon is fixed, as for bonds trading in the secondary market, the entire price response runs through the spread. Eq. (10) then recovers this response from standard bond data and an estimate of how the spread responds to natural capital.

2.3 Substitution and Complementarity of Financial and Natural Capital

With financial and natural capital supporting the bond, a natural question is whether the two stocks are substitutes or complements. Let the two stocks evolve according to

$$\dot{K} = I - \delta K - C, \qquad \dot{N} = G(N) - \alpha N, \tag{11}$$

where I is investment, δ is the depreciation rate of financial capital, $G(N)$ is a concave growth function of the natural stock, and α is the rate at which the natural stock is lost, for example through harvest.

Differentiating Eq. (7) with respect to each stock gives its marginal rate of return. For financial capital, this rate is $\rho + h - \dot{K}_K = \rho + h + \delta$. It has three parts: the risk-free rate ρ, the idiosyncratic risk adjustment h, and the depreciation rate $\delta = -\dot{K}_K$. Because financial capital can be moved freely from one investment to another, its depreciation affects every investment equally. The risk-free rate already compensates investors for this common depreciation, so δ adds nothing to the bond's spread and can be treated as zero. For natural capital, the marginal rate of return is $\rho + h - \dot{N}_N$, where $\dot{N}_N = G'(N) - \alpha$ is the net growth rate of the natural stock.

The marginal rates of return on the two stocks are equal only if the natural stock changes at the same marginal rate as financial capital, $\dot{N}_N = \dot{K}_K = -\delta$.[14] This condition is unlikely to hold, because natural capital grows and declines for ecological reasons and through use that is likely unrelated to the macroeconomic factors that drive δ. Because the two stocks earn different returns at the margin, a loss of natural capital cannot be offset one-for-one with financial capital.

This raises the question of whether natural and financial capital are substitutes or complements. In the sense of Yun et al. (2017), two capital stocks are substitutes when the cross-partial derivative of the value function, V_{KN}, is negative, so that an increase in one stock decreases the asset price of the other. They are complements when V_{KN} is positive, so that an increase in one stock increases the asset price of the other. For an issuer, the more relevant question is whether, and at what rate, financial capital can

[14] Horan et al. (2018) show that when there are multiple capital stocks, the optimal program requires that they all provide the same expected rate of return.

replace natural capital while keeping the bond's value V unchanged.

Holding the coupon fixed and setting $Z = 0$, the implicit function theorem implies that keeping V unchanged requires financial capital to replace natural capital at the rate $dK/dN = -V_N/V_K$. Differentiating Eq. (7) with respect to each stock gives V_N and V_K, so that

$$\frac{dK}{dN} = -\frac{V_N}{V_K} = -\left(\frac{\rho + h + \delta}{\rho + h - \dot{N}_N}\right)\left(\frac{V_{KN}\dot{K} + V_K\dot{K}_N + V_{NN}\dot{N} - h_N V}{V_{KK}\dot{K} + V_{KN}\dot{N} + V_N\dot{N}_K - h_K V}\right). \tag{12}$$

Financial capital can replace lost natural capital only if Eq. (12) is negative. The first factor in Eq. (12) is the ratio of the marginal rates of return on the two stocks. It is positive unless the net growth rate of the natural stock exceeds $\rho + h$, and it is greater than one when $\delta > -\dot{N}_N$. Eq. (12) is therefore negative whenever the second factor is positive, that is, whenever its numerator and denominator have the same sign. The numerator and denominator equal $(\rho + h - \dot{N}_N)V_N$ and $(\rho + h + \delta)V_K$, each stock's marginal value multiplied by its marginal rate of return. The second factor is therefore positive when both stocks add to the bond's value at the margin. Because V_{KN} does not determine this sign on its own, Eq. (12) can be negative even when V_{KN} is positive. Two stocks can thus be complements in the sense of Yun et al. (2017) but substitutes within the issuer's portfolio.

Eq. (12) says that the marginal rate of substitution must be equal to the ratio of prices within the portfolio. In the sections that follow, we take this theory to data, using forests that serve as capital inputs to supply public drinking water.

3 Data and Summary Statistics

In much of the United States, forests are managed to supply water and recreation. These services require maintaining forest *in situ*. In many places, the main threat to maintaining these forests is wildfire, which is expected to become larger and more frequent in the future as the climate becomes warmer and drier.

We study how wildfires affect the bonds issued by public water systems (PWSs), the regulated facilities that provide drinking water and depend on these forests. We obtain the universe of PWSs

derived from the EPA's Safe Drinking Water Information System (SDWIS) and the EPA's crosswalk that links the water source location to the finest level of the U.S. Geological Survey's (USGS) Watershed Boundary Dataset (WBD) 12-digit hydrologic unit codes (HUC-12, or HUC for short).[15] These HUC-12 codes are linked to mapped polygons across the United States. We then link every PWS in 11 western states (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming) to the watersheds that contain its intake facilities.Unlike political boundaries, which often run along rivers, watershed boundaries follow the flow of water and capture the land that drains into each intake. Because bonds are issued by financial entities rather than by individual water systems, we group the systems that belong to the same financial entity and assign each group every HUC-12 that contains an intake of any of its member systems (described below).[16]

We obtain bond data from the Mergent Municipal Bond Securities Database (Mergent). We select bonds issued in western U.S. states between 2001 and 2024 with "water" as the use of proceeds, which limits the sample to bonds that fund water or sewer projects.[17] Each bond is identified by a nine-digit CUSIP (CUSIP9), and the first six digits (CUSIP6) identify the issuer. For each bond, Mergent provides the issue date, offering yield, coupon rate, total offering amount, total maturity offering amount, time to maturity, credit rating, and whether the bond is bank qualified, callable, tax-exempt, or insured.

We define the municipal bond spread as the difference between the bond's offering yield and the yield on the AAA-rated Municipal Market Advisors curve (MMA, downloaded from Bloomberg), matched or linearly interpolated to the bond's maturity (Schwert, 2017; Goldsmith-Pinkham et al., 2023). To account for differences in state tax regimes, we gross up each bond's offering yield by the top state income tax rate (Ang et al., 2010; Babina et al., 2021). The resulting spread is the return that investors require for bearing the risk of a specific bond, net of the risk-free rate and state tax differences, which makes spreads comparable across bonds issued at different times and in different states. A higher

[15] We thank Dave Keiser and Dan Phaneuf for generously sharing these data. The WBD is available at https://www.epa.gov/enviroatlas/data-download.

[16] Appendix Table A1 lists the PWSs in our California sample, the SDWIS identifiers (PWSIDs) of the systems each one groups, and the short names we use in figures and tables.

[17] Because the "water" category also includes sewer projects, we keep only those issuers that we match to a drinking-water system in SDWIS (described below).

spread indicates that investors perceive greater credit risk and that borrowing is more expensive for the issuer (Gao et al., 2019, 2020; Cao et al., 2025; Dagostino and Nakhmurina, 2026b). The empirical counterpart of r_N in Eq. (10) is therefore the change in the spread from a change in natural capital.

We match PWSs to municipal bond issuers in five steps that use three different locally run, open-source large language models (LLMs) and manual review. First, Gemma-3 27B expands each PWS's names and abbreviations into searchable variants. Second, we search the Electronic Municipal Market Access (EMMA) website for these variants and collect candidate issuers.[18] Third, Qwen3 30B-A3B-Thinking, a reasoning model, scores each PWS–issuer pair on geographic alignment, entity type, and name similarity, and keeps every candidate with a positive score for review. Fourth, we download each candidate's official statements and use Qwen3-Next-80B-A3B to classify whether the bond proceeds fund water projects. Fifth, trained researchers review the remaining candidates and keep only issuers that are the PWS or its parent entity. Because the matching starts from systems in SDWIS, every matched issuer provides drinking water, and sewer-only entities drop out. Appendix B describes each step of the pipeline in detail.[19]

CUSIP6s and water systems do not map one to one. A single system may borrow under several CUSIP6s, and several systems may share the same CUSIP6s.[20] We treat all systems connected to the same CUSIP6s as a single PWS.

To determine which PWSs experience a wildfire and when, we use two sources of fire data. Monitoring Trends in Burn Severity (MTBS), run by the USDA Forest Service and the U.S. Geological Survey, maps the boundary of each fire from 1984 through 2024.[21] We supplement MTBS with the spatial database of U.S. wildfires from 1992 to 2020 compiled by Short (2022). We overlay each fire's final boundary on the HUC-12 watersheds to identify the watersheds that burned, dating each burn by the

[18] EMMA is the Municipal Securities Rulemaking Board's public disclosure website (https://emma.msrb.org/).

[19] We plan to make the GitHub repository for this pipeline publicly available.

[20] For example, the systems "CCWD - Sheep Ranch," "CCWD - West Point," and "CCWD - Ebbetts Pass" are all operated by the Calaveras County Water District (CCWD) and matched to five 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." We treat them as a single PWS.

[21] Available at https://data-usfs.hub.arcgis.com/datasets/usfs::monitoring-trends-in-burn-severity-mtbs-conterminous-united-states/about.

month the fire was contained. A PWS experiences a fire when one of its intake watersheds burns.

To limit the influence of outliers, we winsorize the spread, bond size, and maturity at the 1% level in both tails, separately for surface-water-only and mixed-source PWSs.

We classify PWSs along two dimensions of water-source diversification: whether they draw only surface water or also groundwater, and whether their surface-water intakes lie in one HUC-12 or several. We observe which sources a PWS uses but not the share of water drawn from each.

Table 1 shows that only California has enough undiversified PWSs that experience a fire within 18 months of issuing a bond (Colorado, for example, has only two), so our primary-market analysis focuses on California. We exclude Contra Costa Water District and the Metropolitan Water District of Southern California, which differ markedly from the other PWSs in the sample (Figures 1 and C2).

Our main sample includes 89 California PWSs (Table 2). The 38 PWSs that rely solely on surface water issue 1,878 bonds between 2001 and 2024. Of these, 28 draw surface water from a single HUC-12 and 10 from several. Fires are more common among PWSs with several watersheds: 6 of the 10 experience a fire within 18 months of an issue, compared with 6 of the 28 that draw from a single watershed. The 51 PWSs that draw on both groundwater and surface water issue 4,462 bonds.[22] Of these, 24 draw surface water from a single HUC-12 and 27 from several. The small size of this sample limits the empirical strategies available to us (Section 4.2). Table 2 reports summary statistics for these PWSs and bonds.

Figure 2 maps the intake watersheds and service areas of the PWSs in our sample. The intake watersheds cluster in the Sierra Nevada foothills and in Southern California, and many of them burned between 2001 and 2024 (panel a). A typical intake watershed lies about five miles from the area it serves, and some lie more than 20 miles away (panel b). Because watersheds and service areas rarely coincide, a fire in a source watershed destroys the forest that supplies a PWS's water but seldom reaches the community it serves. We can therefore interpret a change in spreads after a fire as a response to the loss of natural capital rather than to damage to local property or the tax base.

[22] The pooled regression sample for mixed-source PWSs (Table 5) has 50 PWSs and 4,461 bonds. Tuolumne Utilities District issues a single bond, so the PWS fixed effect absorbs it as a singleton.

Table 1: Primary-Market Bonds and Issuers by State

					Issuers by SW intake HUCs			
	Bonds		Issuers		Single		Multi	
State	Total	Treated	Total	Treated	Total	Treated	Total	Treated
Panel A: PWSs that only access surface water								
CA	1,878	226	38	12	28	6	10	6
CO	1,838	133	32	7	9	1	23	6
WA	712	0	9	0	8	0	1	0
OR	719	21	21	2	17	2	4	0
UT	241	70	2	1	0	0	2	1
AZ	0	0	0	0	0	0	0	0
NM	0	0	0	0	0	0	0	0
NV	68	0	2	0	2	0	0	0
MT	129	0	3	0	2	0	1	0
WY	0	0	0	0	0	0	0	0
ID	20	0	1	0	1	0	0	0
Total	5,605	450	108	22	67	9	41	13
Panel B: PWSs that access both surface and groundwater								
CA	4,462	837	51	21	24	7	27	14
CO	835	37	18	1	12	1	6	0
WA	1,221	16	15	1	13	1	2	0
OR	351	0	10	0	10	0	0	0
UT	695	53	8	3	6	2	2	1
AZ	315	0	6	0	4	0	2	0
NM	309	17	4	1	0	0	4	1
NV	231	56	2	1	1	0	1	1
MT	16	0	1	0	0	0	1	0
WY	26	0	1	0	1	0	0	0
ID	0	0	0	0	0	0	0	0
Total	8,461	1,016	116	28	71	11	45	17

Notes: Counts of primary-market bonds and issuers by state, 2001–2024. Panel A covers public water systems (PWSs) that use only surface water; Panel B covers PWSs that use a mix of surface water and groundwater. Contra Costa WD (Panel A) and Metropolitan WD (Panel B) are excluded, as are mixed-source PWSs with no surface-water intake HUC, whose only sources are groundwater wells and wells under the influence of surface water. Treated bonds are issues that experience a fire in one of the issuer's surface-water intake HUCs within the 18 months prior to issue. Issuers are split by the number of HUC-12s from which they draw surface water: Single (one) and Multi (more than one); groundwater intakes are not counted. In every row, Issuers = Single + Multi.

3.1 Secondary Market Sample

Our secondary-market sample consists of MSRB trades between 2005 and 2024 in the bonds of surface-water-only PWSs, aggregated to bond-months. A bond is treated if a fire burns one of its PWS's intake watersheds after the bond is issued and before it matures. Only three states, California, Colorado, and Oregon, have enough treated issuers to support the analysis (Table 3). Table 4 reports summary statistics for the pooled sample and for California alone.

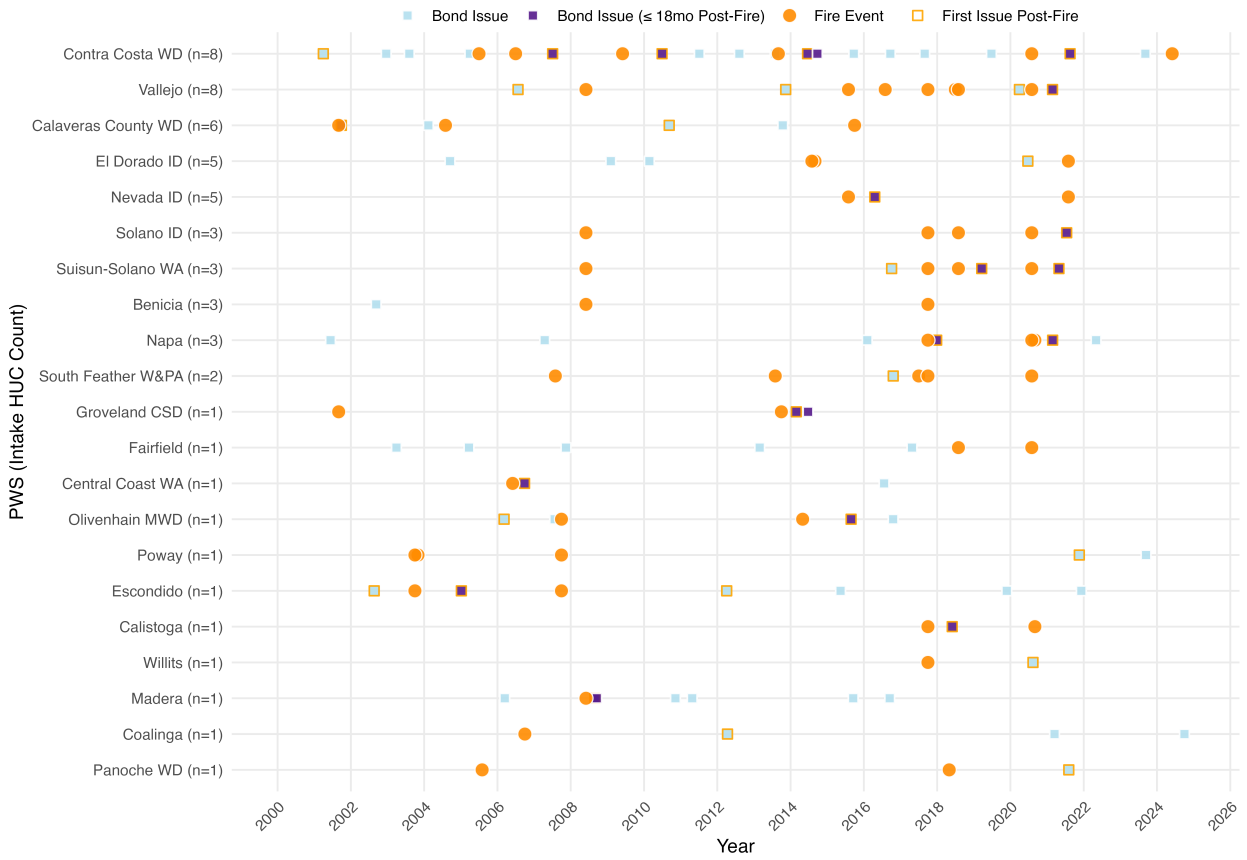
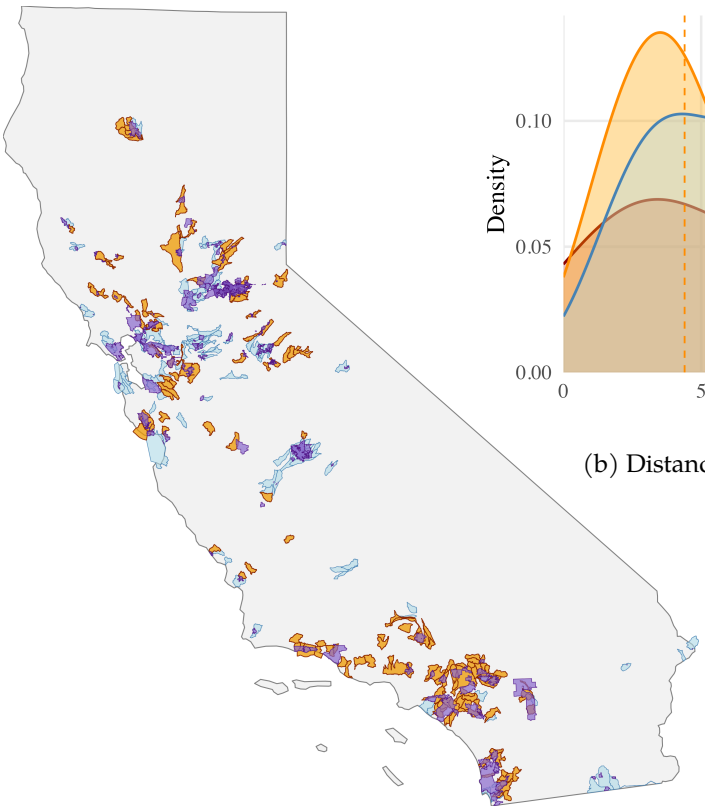


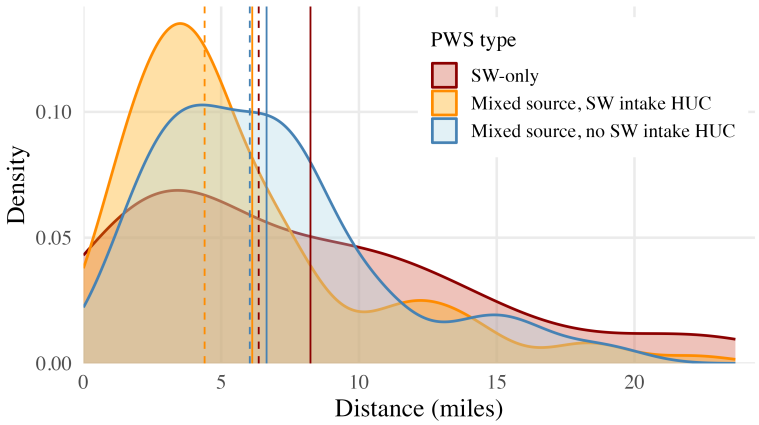
Figure 1: Fire Events and Bond Issuance: SW-Only PWSs with a Fire. Timeline of fire events and bond issuances for California SW-only PWSs with at least one fire in a direct intake HUC between 2000 and 2024, by PWS. Purple squares mark bond issues within 18 months after a fire (the 18-month lookback window); orange-outlined squares mark a PWS's first issue after a fire. n is the number of the PWS's intake HUC-12s. Never-treated SW-only PWSs and mixed-intake PWSs are shown in Figures C1, C2, and C3.

4 Research Design

To test the hypothesis that damage to forest natural capital increases borrowing costs, we estimate the average effect of wildfire exposure on the spreads of bonds issued by PWSs with a fire in a watershed that contains at least one of their surface-water intakes. We first analyze the primary market for California PWSs and then the secondary market for PWSs in California, Colorado, and Oregon. We expect the effect to be largest for PWSs with undiversified water sources, which draw only surface water and all of it from a single HUC-12. We therefore divide each analysis into four groups: surface-water-only PWSs with intakes in a single HUC-12, surface-water-only PWSs with intakes in any number of HUC-12s,



(a) Study area



(b) Distance from intake watershed to service area

Figure 2: Study Geography. Study geography and the distance between source watersheds and population centers. Panel (a) maps the intake HUC-12 watersheds of in-sample PWSs, in orange if they burned between 2001 and 2024 and in blue otherwise, and the service areas of in-sample PWSs in purple. Panel (b) shows the distribution of distances between intake HUC-12 centroids and service-area centroids, one observation per PWS–intake HUC-12 pair, for SW-only PWSs and, for mixed-source PWSs, separately for HUC-12s with and without a surface-water intake. Solid lines mark group means and dashed lines group medians; the horizontal axis ends at the 99th percentile.

PWSs that also draw on groundwater but take surface water from a single HUC-12, and PWSs that also draw on groundwater and take surface water from any number of HUC-12s.

We focus on the primary market for two reasons. First, the secondary market is thin and dominated by retail investors (Harris and Piwowar, 2006; Cuny et al., 2025; Dagostino and Nakhmurina, 2026a), whereas underwriters and institutional investors price bonds at issuance after reviewing the issuer's disclosures (Green et al., 2007; Schultz, 2012). Offering spreads are therefore more likely to reflect information about the issuer's risk. Second, the offering yield determines the interest a PWS pays on its debt, whereas secondary-market prices affect only the investors who trade the bond.

Table 2: Primary Market Bond Summary Statistics (California)

Statistic	Mean	SD	Median	Obs
Panel A: PWSs that only access surface water				
Spread (bps)	77.8	65.7	59.6	1,878
Offering amount ($ millions)	25.4	24.0	19.6	1,878
Bond size ($ millions)	1.4	2.0	0.7	1,878
Coupon rate (%)	4.0	1.1	4.0	1,878
Offering yield (%)	2.9	1.4	3.0	1,878
Annual coupon ($ thousands)	58.3	97.4	25.8	1,878
Years to maturity	10.6	6.5	10.0	1,878
Burn acreage per fire	6,564.3	9,599.5	3,247.6	14
Bond issues per PWS	2.9	2.0	2.0	38
Panel B: PWSs that access both surface and groundwater				
Spread (bps)	66.4	56.9	54.9	4,462
Offering amount ($ millions)	63.6	87.0	31.0	4,462
Bond size ($ millions)	3.1	6.2	1.3	4,462
Coupon rate (%)	4.2	1.0	4.4	4,462
Offering yield (%)	3.0	1.3	3.0	4,462
Annual coupon ($ thousands)	139.1	294.3	50.7	4,462
Years to maturity	11.2	6.5	11.0	4,462
Burn acreage per fire	2,031.4	4,408.1	684.9	39
Bond issues per PWS	4.7	4.5	3.0	51

Notes: Primary-market bonds issued by California PWSs, 2001–2024, in the samples of the pooled TWFE regressions: surface-water-only PWSs in Panel A and PWSs drawing on both surface water and groundwater (mixed-source) in Panel B. As in the regressions, Panel A excludes Contra Costa Water District, and Panel B excludes the Metropolitan Water District of Southern California and the mixed-source PWSs with no surface-water intake HUC-12. The first seven rows have one observation per bond (CUSIP9). *Spread* is the offering spread: the offering yield, grossed up by the top state income tax rate, minus the MMA benchmark yield interpolated to the bond's maturity. *Offering amount* is the par amount of the whole issue the bond belongs to; *bond size* is the par amount of the bond itself, which varies across the maturities of an issue. *Annual coupon* is bond size times the coupon rate, i.e., the coupons paid over a year whatever the payment schedule (most issuers pay semiannually). *Burn acreage per fire* is the area burned in the PWS's intake HUC-12s (for mixed-source PWSs, those with a surface-water intake) in the month of an MTBS fire that occurs in the 18 months before one of the PWS's issue dates, summed across HUC-12s and fires in that month, with one observation per PWS and fire. *Bond issues per PWS* counts distinct issue dates, one observation per PWS. Spread, offering amount, and bond size are winsorized at 1%/99%, separately for SW-only and mixed-source PWSs.

4.1 Baseline Specification

We estimate a two-way fixed effects (TWFE) model that exploits the timing and location of fires relative to bond issuance (Figure 1). The model yields a consistent estimate of the effect of a fire on a PWS's spreads under two conditions. First, selection into issuing bonds must be absent or unrelated to the effect of the fire on spreads. Second, the treatment effect must be sufficiently homogeneous across PWSs, conditional on covariates. Our baseline specification is

$$Spread_{ipt} = \beta PostBurn_{pt,w} + \mathbf{X}'_{ipt}\alpha + \phi z_{pt} + \xi q_{pt} + \mu_p + \eta_r + \delta_{1t} + \delta_{2t} + \varepsilon_{ipt}, \tag{13}$$

Table 3: Secondary Market Sample Coverage across States (SW-only)

	Bond-months		Bonds			Issuers	
State	Total	Post-fire	Total	Treated	Both sides	Total	Treated
Panel A: Single-HUC issuers							
CA	13,640	1,343	870	125	103	26	5
CO	2,366	199	170	38	30	8	4
WA	5,958	0	354	0	0	6	0
OR	4,994	262	359	78	37	17	4
UT	0	0	0	0	0	0	0
AZ	0	0	0	0	0	0	0
NM	0	0	0	0	0	0	0
NV	94	0	13	0	0	1	0
MT	687	53	51	12	7	2	1
ID	5	3	1	1	1	1	1
WY	0	0	0	0	0	0	0
Total	27,744	1,860	1,818	254	178	61	15
Panel B: Multi-HUC issuers							
CA	10,097	5,184	543	381	292	11	8
CO	12,509	2,121	863	281	200	23	10
WA	0	0	0	0	0	0	0
OR	501	4	49	4	1	4	2
UT	3,524	1,014	146	90	67	2	2
AZ	0	0	0	0	0	0	0
NM	0	0	0	0	0	0	0
NV	0	0	0	0	0	0	0
MT	56	0	12	0	0	1	0
ID	0	0	0	0	0	0	0
WY	0	0	0	0	0	0	0
Total	26,687	8,323	1,613	756	560	41	22
Total, all issuers	54,431	10,183	3,431	1,010	738	102	37

Notes: Bonds of surface-water-only PWSs in the primary sample with at least one MSRB trade in 2005–2024, by the PWS's state. A bond-month is one bond traded in one calendar month. A bond is *treated* if a fire in its PWS's intake HUCs is contained after the bond's dated date and before its maturity; its *post-fire* bond-months are its trade months from the month of that fire on. *Both sides* counts the treated bonds that trade both before and after the fire, the bonds that identify the within-bond comparison. An issuer is treated if any of its bonds is. Single-HUC issuers have one intake HUC-12, multi-HUC issuers several. Counts are before the exclusions that define the analysis sample (Table 4).

where $Spread_{ipt}$ is the offering spread, in basis points, of bond i issued by PWS p at time t.

PWSs typically borrow by selling a series of bonds with staggered maturities on a single date, which we call an issuing event. A bond is treated ($PostBurn_{pt,w} = 1$) if a fire burned one of the issuing PWS's surface-water intake HUC-12s within the w months before the bond's issue date. We call w the look-back window and set $w = 18$ months in our baseline specification. Eighteen months is long enough to capture most issuing events that follow a fire, but short enough to avoid overlapping fires and to

Table 4: Secondary Market Summary Statistics (SW-only)

Statistic	Mean	SD	Median	Obs
Panel A: California, Colorado, and Oregon				
Spread (bps)	62.7	69.1	49.9	35,740
Offering amount ($ millions)	37.5	42.2	26.1	2,588
Bond size ($ millions)	1.9	2.3	1.2	2,588
Coupon rate (%)	4.1	0.9	4.0	2,588
Offering yield (%)	2.9	1.2	3.0	2,588
Annual coupon ($ thousands)	84.3	108.4	48.5	2,588
Years to maturity	11.9	5.9	11.0	2,588
Burn acreage per fire	5,342.7	8,348.2	2,163.3	38
Bond issues per PWS	2.9	2.6	2.0	86
Share of months with a trade (%)	19.8	18.6	13.1	2,588
Months with a trade per year	2.4	2.3	1.6	2,588
Trades per month with a trade	4.7	2.4	4.0	2,588
Trades per year	12.3	16.7	6.4	2,588
Panel B: California				
Spread (bps)	85.3	82.5	71.0	16,834
Offering amount ($ millions)	28.7	24.6	22.9	1,161
Bond size ($ millions)	1.7	2.0	0.9	1,161
Coupon rate (%)	4.1	0.9	4.0	1,161
Offering yield (%)	3.0	1.2	3.1	1,161
Annual coupon ($ thousands)	73.1	97.7	37.3	1,161
Years to maturity	12.2	6.2	11.0	1,161
Burn acreage per fire	7,174.3	10,570.8	2,664.7	18
Bond issues per PWS	2.8	2.0	2.0	35
Share of months with a trade (%)	18.0	14.0	13.9	1,161
Months with a trade per year	2.2	1.7	1.7	1,161
Trades per month with a trade	4.7	2.2	4.1	1,161
Trades per year	10.4	11.2	6.7	1,161

Notes: Panel A pools the California, Colorado, and Oregon analysis samples; Panel B is California alone. Relative to Table 3, they drop months after a refunding or redemption, when-issued trades, zero-coupon bonds, and three issuers (Contra Costa and Western Hills Water Districts in California, Warm Springs Reservation in Oregon). *Spread* is the state-tax-adjusted secondary yield over the MMA curve, one observation per bond-month (the bond's MSRB trades in the month, par-weighted). The issue characteristics have one observation per bond and are measured at issuance; annual coupon is bond size times the coupon rate. *Burn acreage per fire* is the area burned in the PWS's intake HUCs in the month of the fire that treats its bonds, one observation per PWS and fire. *Bond issues per PWS* counts distinct issue dates. The last four rows have one observation per bond over its sample window, from its dated date to its maturity, refunding, or redemption date within 2005–2024: *share of months with a trade* is the number of months with at least one trade over the months in the window; *months with a trade per year* and *trades per year* divide that number and the bond's trades by the years in the window; *trades per month with a trade* divides the trades by the months with a trade, so that for each bond, trades per year = months with a trade per year × trades per month with a trade. Spread, offering amount, bond size, and the four trading rows are winsorized at 1%/99%.

keep the focus on the first post-fire bonds. A longer window would add treated bonds but would dilute the effect of the initial fire. Appendix Tables C1 and C2 show results for 12- and 36-month look-back windows.

In Eq. (13), we compare treated bonds with bonds issued by PWSs that never experience a fire or

have not had a fire within the look-back window. A PWS can move in and out of treatment several times over the sample period, depending on the timing of its bond issues relative to fires (Figure 1; Appendix Figures C1, C2, and C3). The estimate is therefore identified by PWSs that issue both treated and untreated bonds.

The vector $\mathbf{X}_{ipt}$ contains bond characteristics that capture risk and the structure of the issue. Our theory informs the main set of controls: the coupon rate (in percent), the natural log of the maturity offering amount, and time to maturity (in years). Eq. (10) shows that the spread response to natural capital depends on the bond's size, maturity, and coupon. We control for the coupon rate rather than the coupon amount, which equals the coupon rate times the offering amount, to avoid collinearity with the offering amount. The remaining controls are informed by the municipal bond literature (e.g., Painter, 2020; Acharya et al., 2022; Goldsmith-Pinkham et al., 2023). They are indicators for whether the bond is bank qualified, callable, tax-exempt, or insured. The variable z_{pt} counts the months since PWS p's previous new-money water bond, top-coded at 240 months. The indicator q_{pt} equals one for longer gaps or when the PWS has no prior issue.

We include a comprehensive set of fixed effects. PWS fixed effects μ_p absorb time-invariant issuer characteristics, such as location, baseline fire risk, the number of CUSIP6 entities, intake facilities, and HUC-12s, and the size of the attached watersheds. Credit rating fixed effects η_r absorb differences in default risk across rating categories, where r is the bond's rating category (AAA, AA, etc.).[23] Year and quarter fixed effects δ_{1t} and δ_{2t} absorb aggregate shocks to the bond market, seasonal patterns in issuance, and statewide changes in fire risk and weather, such as El Niño years. We include year and quarter fixed effects additively, not interacted. With so few fire events and an unbalanced panel, interacted fixed effects risk weak factor bias (see Armstrong et al., 2026). Appendix Tables C3 and C4 report estimates with year-by-quarter fixed effects. We cluster standard errors by PWS to account for serial correlation in spreads within an issuer.

The coefficient β identifies the causal effect of a wildfire on offering spreads if, conditional on

[23] Credit rating alignment across rating agencies follows the methods in Nakhmurina et al. (2026).

the fixed effects and bond characteristics, the timing and location of wildfires are unrelated to other determinants of spreads.

4.2 Addressing Identification Concerns

There are three potential threats to identification in the primary market strategy. The first is the common risk that results are driven by analyst assumptions related to necessary, but ultimately arbitrary, research design decisions. The second is the possibility of heterogeneous treatment effects. The third is selection into the sample caused by the fire, which can lead to selection bias if that selection is correlated with the fire's effect on the spread.

In any analysis there are research design decisions that an analyst must make that are based on judgment. In our case, there are three modeling decisions that merit robustness checks given their somewhat arbitrary nature. The first is the treatment of time fixed effects. We investigate various specifications of time fixed effects to ensure that our estimates of β are not sensitive to the precise way time is included in the model. Second, in order to include the time since last issue in the model we need to account for the first issue we observe. Ultimately, we are uncertain as to whether PWSs issued bonds before our data begin or if we observe the first issue. Either way, we must decide how to treat this case. We top code time since last issue and verify that our results are not sensitive to the top-coding decisions. Third, a PWS can issue bonds on multiple occasions and can experience forest fires more than once. Over a long time period, there exist a large number of issue-fire-issue sequences. The exact sequence may also influence the effect of the most recent fire event on bond spreads. Therefore, we choose a look-back window and only consider bonds as treated by fire if they were issued within the look-back window that follows a fire. For our primary specification, we balance the desire to have one fire and one issue event within the look-back window period with maintaining the size of the treated group. In the robustness analysis we explore the sensitivity of results to the definition of the look-back window.

Modern causal identification has focused on event study designs and heterogeneous treatment effects models (e.g., Callaway and Sant'Anna, 2021; Borusyak et al., 2024). These data-hungry approaches

work well for panels or traditional staggered difference-in-differences designs. However, the data on PWS bond issues and wildfires do not support these methods. Bond issues and wildfires are sporadic events that happen at repeated, but irregular, intervals. Furthermore, the concern over selection into the sample makes an event study design challenging and the standard set of heterogeneous treatment effects models infeasible. In our case, this is further complicated by the relatively small number of issuing PWSs.

In a small sample, concern for heterogeneous treatment effects is rooted in a single unit driving the results. Some such units, e.g., Contra Costa or Metropolitan WD, are easy to identify *ex ante* through passive observation of the data (as in Figures 1 and C2 discussed in the Data section). An alternative to modern heterogeneous treatment effect designs, feasible because of the small sample, is to conduct a complete set of leave-one-out analyses to determine if any one unit is driving the results. This is the strategy we pursue.

The other important threat to identification is that fire events may be sufficiently important events that they require PWSs to raise new capital for recovery. In this case, fires could cause PWSs to issue bonds.[24] A fire could potentially lead to selection into the sample by moving an issue that would have been out of the look-back window into the look-back window. For example, if the capital cycle of a PWS led it to issue bonds every four years, and a fire in year one of the cycle led the PWS to issue bonds in year two, then the counterfactual bond would have been issued 24 months in the future, pushing the counterfactual outside the look-back window. This exemplifies selection into the sample, and while it does not necessarily bias the bond price, it could. Thus, conditional on selection into the sample, we evaluate whether the selection is correlated with bond spreads, and even if the two are correlated, whether this shift into the sample affects a sufficient number of bonds by a sufficient amount to bias the treatment effect conditional on other covariates.

To test for selection into the sample, consider that if bond issue events are unaffected by a fire event,

[24] Alternatively, federal or state recovery aid could potentially over-capitalize PWSs, the so-called FEMA put (Lu and Nakhmurina, 2024). If this happens systemically, then bond issuing could be delayed. However, such aid cannot always be taken for granted, as factors such as political alignment can affect state aid, even in financial distress (Dagostino and Nakhmurina, 2026b).

then starting at the time of a fire, the arrival rate of a bond issue event should be the same forward and backward in time – i.e., the bond arrival is random relative to the fire, or the fire arrives at random between two bond issue events. We test this assumption using a Poisson duration-between-issuing model. In the results section, we show that the point estimates indicate a shorter time to the next issue after a fire, although imprecise, and the difference is only statistically significant in the pooled sample without the top-coding control (Section 5.2.3). This can be interpreted as suggestive evidence that experiencing a fire may lead entities to issue bonds sooner than would be expected at random.

If experiencing a fire leads to non-random bond issuing events, then it is possible that selection into the treated sample biases the TWFE model. We use a control function approach to address the potential bias from selection into bond issuing due to a fire. The Heckman selection model can be viewed as a special case of the control function approach because the inverse Mills ratio from a probit model acts like a generalized residual owing to the normality property of the probit model (Wooldridge, 2015). Rather than using the probit model, which would require interpolating unobserved covariates, we use a Poisson duration-between-issuing model as the first stage of the control function, also known as an endogenous switching model (Terza, 1998), and then use the generalized residual from that model in the second stage with the generalized residual added as a covariate.

The first stage of the control function approach requires a plausibly exogenous instrument that is excluded from the second stage. The instrument should explain the probability of issuing a bond but should be uncorrelated with the fire event. To instrument for the probability of issuing a bond we rely on the fact that most municipalities have a capital plan that leads to a capital cycle. Where a PWS is in its capital cycle depends, at least partially, on when it issued bonds last, i.e., prior to the fire event, and the structure of those bonds. Therefore, we use the share of outstanding non-callable debt just prior to the new issue as a proxy for where a PWS is in the capital cycle. This leads to a specification where the first-stage Poisson model is specified with $IssueDuration_{pt} \sim Poisson(\mu_{pt})$, where $IssueDuration$ is the observed time between issuing events and

$$\mu_{pt} = \mathbb{E}(IssueDuration_{pt}|\mathbf{X}_{pt}, Debt_{pt}) = \\ exp(\beta PostBurn_{pt,w} + \gamma Debt_{pt} + \mathbf{X}'_{ipt}\alpha + \mu_p + \eta_r + \delta_{1t} + \delta_{2t}) \tag{14}$$

The variable $Debt$ is the share of outstanding non-callable debt (or other debt measures in the robustness checks). The generalized residual is $\hat{z_{pt}} = IssueDuration_{pt} - \hat{\mu_{pt}}$, and the second stage is

$$Spread_{ipt} = \beta PostBurn_{pt,w} + \phi\hat{z_{pt}} + \mathbf{X}'_{ipt}\alpha + \mu_p + \eta_r + \delta_{1t} + \delta_{2t} + \varepsilon_{ipt} \tag{15}$$

4.3 Secondary-Market Specification

We estimate a similar TWFE model on secondary-market trades. Repeated trades let us observe the same bond's spread before and after a fire. Our specification is

$$Spread_{it} = \beta PostBurn_{it} + \theta \log(Gap_{it}) + \psi_i + \lambda_t + \varepsilon_{it}, \tag{16}$$

where $Spread_{it}$ is the secondary-market spread, in basis points, of bond i in month t. $PostBurn_{it}$ equals one from the month of the first fire in the PWS's intake HUC-12s after the bond is issued and before it matures. Gap_{it} is the number of months since the bond's previous trade. ψ_i are bond (CUSIP9) fixed effects, and λ_t are year-by-month fixed effects. Because of the bond fixed effects, β compares a bond's spread after a fire with its own spread before the fire. We cluster standard errors by PWS.

5 Results

5.1 Primary market: Average treatment effect of fire on bond spreads

California PWSs differ in how diversified their water sources are. Some draw surface water from a single HUC-12. Others combine surface water from several HUC-12s with groundwater. This variation lets

us study how diversification affects the fire premium. We first analyze PWSs that rely only on surface water, and then PWSs that use both surface water and groundwater.

Surface-water-only PWSs lack the diversification that groundwater provides, so they depend more on forest natural capital. We therefore expect a fire in one of their intake watersheds to increase their spreads more.

Table 5 presents the effect of a fire in any intake HUC-12 within the 18 months before an issuing event. Column 1 includes PWSs that draw surface water from a single HUC-12. For these PWSs, a fire increases spreads by 58.0 bps, about 68 percent of their mean spread of 85.4 bps. Column 2 pools single- and multi-HUC PWSs. In the pooled sample, a fire increases spreads by 38.6 bps. Single-HUC PWSs have higher mean spreads (85.4 against 77.8 bps), but the gap remains relative to the mean: 68 against 50 percent. The smaller effect suggests that drawing water from several watersheds reduces the fire premium.[25] Both estimates remain positive across alternative time fixed effects, top-coding choices, and look-back windows (Appendix Tables C1, C3, and C5).[26]

Columns 3 and 4 report results for mixed-source PWSs, which also draw on groundwater. Column 3 includes mixed-source PWSs that draw surface water from a single HUC-12. For these PWSs, a fire increases spreads by 30.2 bps, about half the effect for surface-water-only PWSs with a single HUC-12. Column 4 pools all mixed-source PWSs. In the pooled sample, the effect falls to 6.6 bps and is not statistically different from zero. Groundwater therefore provides a second form of diversification that reduces the fire premium.

We assess sensitivity to omitted variables with the method of Oster (2019).[27] The Oster delta measures how strong selection on unobservables would need to be, relative to selection on observables, to drive the treatment effect to zero. A delta of 1 means that unobservables are as important as observables. In all four samples, the Oster bounding set excludes zero and the delta is below -1 (Table 5). Selection

[25] Attempts to estimate a model on a subsample of only PWSs that rely exclusively on surface water but diversify across HUC-12s yield unstable results owing to the small number of PWSs ($N = 10$) and a relatively large number of conditioning variables.

[26] A 12-month window leaves four treated PWSs in the single-HUC sample and 10 in the pooled sample. A 36-month window adds treated PWSs (seven and 13), but some of them experience several fires or issue bonds several times within the window.

[27] We use the R package 'robomit', based on Oster's 'PSACALC' for Stata.

on unobservables would therefore need to be stronger than selection on all of our controls and fixed effects combined, and to go in the opposite direction, to explain away the effect. The delta is smaller in the pooled samples (-1.73 and -1.52) than in the single-HUC samples (-11.72 and -4.23). The pooled samples also have a lower R^2 (0.80 against 0.84, and 0.71 against 0.77). Adding multi-HUC PWSs therefore introduces heterogeneity that our controls capture less well.

5.2 Robustness of Primary Market Estimates

As outlined in the empirical strategy section, there are three main threats to identification: research design decisions, heterogeneous treatment effects, and selection into the sample (sample selection bias).

5.2.1 Research Design Decisions

There are three research design decisions that are not strongly informed by theory and could affect results. These include the length of the look-back window, the nature of time fixed effects, and decisions about top coding. To address these concerns, we vary all three decisions in Appendix C: the look-back window in Tables C1 and C2, the time fixed effects in Tables C3 and C4, and top coding in Tables C5 and C6. Here, robustness means that we can vary the assumptions over the reasonable scope of possible choices and the results do not change in a meaningful way.

5.2.2 Heterogeneous treatment effects

There is a tradeoff between pooling observations to increase sample size and power. Designs that split or combine observations may lead to results that vary in economically meaningful ways. When treatment effects are heterogeneous, pooling can obscure important differences across units and yield estimates that are difficult to interpret. Large samples often provide sufficient support to estimate heterogeneous effects directly, but in smaller samples doing so can substantially reduce precision. This tradeoff is particularly relevant in our setting because public water systems differ considerably in their access to water supplies and other features. Systems that rely on a single surface-water source are

Table 5: TWFE: Average Effect of Fire in HUC (18mo lookback window)

	SW-Only PWSs		Mixed-Source PWSs	
	Single HUC	Pooled	Single SW HUC	Pooled
	(1)	(2)	(3)	(4)
Post Burn	58.023**	38.645***	30.208***	6.573
	(23.490)	(14.038)	(7.384)	(9.520)
Months Since Last Issue	-0.247*	0.079	-0.032	-0.089
	(0.130)	(0.180)	(0.132)	(0.096)
Top-Coded (No Issue in 20 Years)	76.259***	-1.594	11.234	18.910
	(22.183)	(46.640)	(32.357)	(21.755)
Coupon Rate	-1.597	-0.225	8.035***	6.698**
	(1.850)	(1.565)	(2.176)	(2.660)
Log(Bond Size)	2.516	1.144	-7.771***	-8.337***
	(2.828)	(3.550)	(2.500)	(2.325)
Years to Maturity	2.115***	2.236***	2.207***	2.418***
	(0.437)	(0.398)	(0.405)	(0.300)
Bank Qualified	28.102*	28.387**	-27.747	-9.491
	(14.416)	(13.097)	(20.826)	(19.955)
Callable	16.349***	17.469***	14.620***	14.775***
	(2.703)	(2.549)	(4.125)	(2.589)
Insured	-21.032	-24.548	-13.303	-4.232
	(18.763)	(14.992)	(21.312)	(9.889)
Tax Exempt	-111.902***	-108.129***	-134.196***	-140.767***
	(13.568)	(7.822)	(11.921)	(10.364)
Mean Dependent Variable	85.403	77.766	68.760	66.423
N Total PWS	28	38	24	50
N Treated PWS	6	12	7	21
N Treated Bonds	108	226	329	837
PWS Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes
Oster Bounding Set	[58.023, 148.382]	[38.645, 193.015]	[30.208, 103.071]	[6.573, 16.193]
Oster Delta*	-11.722	-1.727	-4.233	-1.518
R^2	0.842	0.801	0.774	0.706
Observations	1,362	1,878	1,804	4,461

Notes: Two-way fixed effects regressions of offering spreads on fire exposure for California PWSs, 2001–2024: surface-water-only PWSs in columns 1–2 and PWSs drawing on both surface water and groundwater (mixed-source) in columns 3–4. The dependent variable is the offering spread in basis points: the offering yield, grossed up by the top state income tax rate, minus the MMA benchmark yield interpolated to the bond's maturity. *Post Burn* equals one if a fire recorded by MTBS burned one of the PWS's direct intake HUC-12s (for mixed-source PWSs, one with a surface-water intake) in the 18 months before issue. *Single HUC* covers SW-only PWSs whose intakes all lie in one HUC-12, and *Single SW HUC* mixed-source PWSs whose surface-water intakes all lie in one HUC-12. *Pooled* adds the PWSs with intakes in several HUC-12s, excluding Contra Costa Water District (SW-only) and the Metropolitan Water District of Southern California (mixed-source); mixed-source PWSs with no surface-water intake HUC are dropped. *Months Since Last Issue* counts months since the issuer's previous new-money water bond, top-coded at 240; *Top-Coded* flags longer gaps or no prior issue. *Coupon Rate* is the bond's coupon rate in percent. Spread, bond size, and maturity are winsorized at 1%/99%, separately for SW-only and mixed-source PWSs. Fixed effects: PWS, year, quarter, and underlying credit rating. Standard errors clustered by PWS in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

likely systematically different from systems that draw from multiple surface-water sources, have access to groundwater, or both. These differences may alter the consequences of wildfire exposure and the response of borrowing costs to wildfire risk.

Our goal here is to improve the interpretation of the results that we estimate from the relatively small universe of PWSs in California that use surface water and experience forest fire. First, we demonstrate that pooling across water diversification strategies imposes meaningful restrictions on the estimated model using a Wald (or Chow) test. Second, we make use of the small sample size and conduct a systematic leave-one-out analysis. The leave-one-out analysis does not directly identify heterogeneous treatment effects. Rather, it provides a transparent assessment of whether the estimated treatment effect is supported across units or is disproportionately influenced by a specific PWS. Such influence may arise from extreme treatment-effect heterogeneity, but may also reflect other forms of heterogeneity in the data.

We implement the pooling Wald test using a Chow-inspired F-test to compare model estimations on subsamples of the PWSs that are solely dependent on surface water. We compare those PWSs that rely on intake facilities in a single watershed to those that rely on intake facilities across multiple watersheds. The F-test rejects the null hypothesis that pooling imposes no meaningful restriction in both samples (SW-only F statistic 32.93, mixed 19.76), but the wild-bootstrap version, which respects the small number of clusters, rejects it only for the SW-only sample ($p = 0.033$; mixed $p = 0.405$; Appendix Table C7). For surface-water-only PWSs, this implies that the effect of a fire differs between PWSs accessing water from a single watershed and those accessing multiple watersheds. Therefore, we expect the pooled sample to represent the average of the treatment effect on PWSs that use water from a single watershed and those that access water from multiple watersheds. We do not present direct estimates from multiple watersheds because the small sample size leads to unstable estimates for that subset. Therefore, we use the pooled estimates to infer that diversifying across watersheds reduces the effect of a forest fire on spreads.

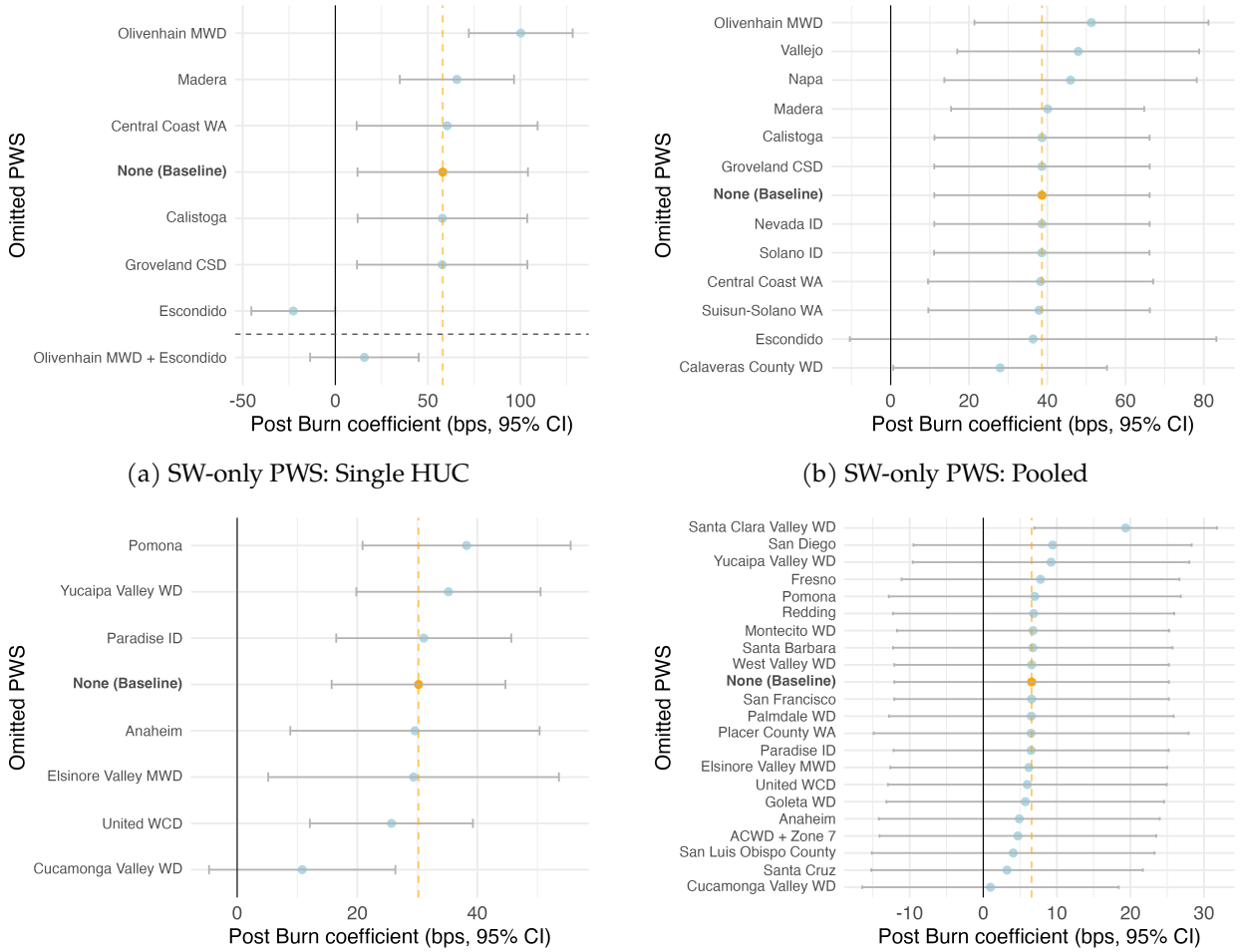
The Wald test investigates how aggregation might influence the interpretation of results. Next, we

implement a leave-one-out analysis to determine if any PWS has undue influence over the estimates (Figure 3). *Ex ante*, we identified Contra Costa and Metropolitan WD as likely having undue influence because of their sizes, diversification, and frequency of fires and bond issues. Generally, omitting any specific PWS from a given estimate does not qualitatively change the estimate, with exceptions among the single-watershed samples. In the case of PWSs that only have a single surface water source, omitting Olivenhain MWD increases the estimated effect size and omitting Escondido decreases the estimated effect (potentially flipping the sign). Omitting Escondido suggests the greatest threat to our general interpretation. However, a few features about Escondido somewhat ameliorate some of these concerns. First, Escondido was treated by a high-profile fire that resulted in human death. Second, Escondido has the greatest number of bonds included in this estimation (Appendix Table A1). This suggests that Escondido is providing substantial information for the conditioning variables and potential fixed effect estimation. This is implied by the increase in standard errors in the pooled estimate when Escondido is omitted. However, in the pooled estimates there is not a meaningful effect on the point estimate. Omitting Olivenhain MWD and Escondido jointly lowers the estimate to about 16 bps, with a narrower confidence interval that includes zero (Figure 3). This suggests that some residual, unaccounted-for, and potentially meaningful heterogeneity remains. The single-HUC estimate should therefore be read with these two PWSs in mind. In the mixed-source samples, omitting Cucamonga Valley WD lowers the single-watershed estimate to 10.8 bps, while omitting Santa Clara Valley WD raises the pooled estimate to 19.3 bps (Figure 3).[28]

5.2.3 Sample selection

The theory section suggests that a loss of natural capital, such as when a forest is damaged by wildfire, may lead a PWS to substitute produced capital for natural capital in order to maintain a given level of service. Therefore, wildfire exposure may influence when a bond is issued along with the price a

[28] Attributes of the fires can also introduce heterogeneity. Controlled burns are a type of fire intended to prevent other fires. The only controlled burn in the sample takes place in Santa Barbara, which uses surface water from multiple HUC-12s and groundwater. Omitting Santa Barbara does not affect the results. There are no other controlled burns in HUC-12s where PWSs get water. So, it is not possible to test specifically the potential for controlled burns to be seen as a natural capital investment.



(a) SW-only PWS: Single HUC

(b) SW-only PWS: Pooled

(c) Mixed-source PWS: Single SW HUC

(d) Mixed-source PWS: Pooled

Figure 3: Leave-One-Out Sensitivity. Leave-one-out sensitivity of the *Post Burn* coefficient. Each panel re-estimates one column of Table 5, dropping one treated PWS at a time: panels a and b use the SW-only columns, panels c and d the mixed-source columns. Points show the *Post Burn* coefficient with its 95% confidence interval (standard errors clustered by PWS); the orange point (bold label) and dashed line mark the full-sample estimate. Below the dashed rule, panel a drops Olivenhain MWD and Escondido together.

PWS pays when issuing debt. The TWFE specification assumes that, conditional on observed controls, including the time since the previous bond issuance, issuance timing is orthogonal to unobserved determinants of bond spreads. However, if the need to replace damaged natural capital creates financial pressure, a PWS may issue debt sooner than it otherwise would have. In that case, wildfire exposure could affect the likelihood that a bond issuance is observed within the treatment look-back window and the spread at which the bond is issued. This potentially generates a selection bias in the TWFE estimates. Specifically, the TWFE model would imply the wrong counterfactual because it compares the

bonds issued by treated PWSs to bonds issued by PWSs that are issuing bonds more frequently than the treated PWS would have had it not experienced a fire. If time since last issuance is omitted, this selection process generates omitted-variable bias. If time since last issuance is included as a control, issuance timing may nevertheless remain endogenous because wildfire exposure affects issuance timing and issuance timing may remain correlated with unobserved determinants of bond spreads. If issuing bonds frequently implies financial distress, then this would bias the TWFE estimates downward.

We first focus on the PWSs that only use surface water and then repeat all analyses on the PWSs that use a mix of surface and groundwater. If bond issuance follows an approximate cycle with random deviation, then we expect the arrival rate of issuance related to fire to follow a Poisson process. We can test for an issuing behavior shift following a forest fire by testing if the Poisson arrival rate is altered by a forest fire (Table 6).The coefficient estimates suggest that the count of months between a bond issue and a fire is greater prior to the fire than after. This difference is not statistically significant after top-coding and controlling for top-coding with a dummy variable. However, the top-coding dummy is precisely different from zero. One possible interpretation of this result is that, in this small sample, fires are having little effect on the intensity or frequency of issuing, but may lead some PWSs to enter the bond market and begin issuing, which represents a change on the extensive margin.

We use a two-stage control function (CF) approach to purge potential selection bias. We instrument time since last bond issue with the share of outstanding debt that is non-callable. This is a strong instrument (see the Excluded Instrument Wald statistic in Table 7). Furthermore, the share of outstanding debt that is non-callable has a relatively large and precise role in explaining the duration between issuance events.

Controlling for selection into the treatment group has virtually no impact on the sensitivity of spreads to a fire event (Table 8). The standard errors in the second stage are estimated using wild-cluster bootstrapped standard errors to propagate the uncertainty from the first stage, while addressing the small number of clusters and uneven cluster sizes in the sample (Roodman et al., 2019). The coefficients that the control function moves are those on the issue-timing controls, in particular the top-coding

Table 6: Poisson duration-between-issuing test: Months to/from Fire Exposure

	Single HUC			Pooled		
	Top-Coded	Top-Coded	Not Top-Coded	Top-Coded	Top-Coded	Not Top-Coded
Panel A: PWSs that only access surface water						
Post Burn	-0.029	0.209	-0.069	-0.189	-0.039	-0.741**
	(0.183)	(0.402)	(0.441)	(0.120)	(0.306)	(0.344)
Top-Coded	1.589***			1.547***		
	(0.157)			(0.115)		
(Intercept)	3.901***	4.344***	3.909***	3.993***	4.498***	4.301***
	(0.150)	(0.189)	(0.159)	(0.116)	(0.133)	(0.186)
RMSE	35.720	79.230	39.090	36.820	83.120	75.510
Observations	36	36	30	61	61	51
Panel B: PWSs that access both surface and groundwater						
Post Burn	-0.259	-0.339	-0.372	-0.002	0.046	-0.038
	(0.217)	(0.365)	(0.302)	(0.121)	(0.204)	(0.187)
Top-Coded	1.692***			1.822***		
	(0.134)			(0.079)		
(Intercept)	3.827***	4.151***	3.847***	3.659***	3.970***	3.695***
	(0.138)	(0.148)	(0.141)	(0.084)	(0.099)	(0.093)
RMSE	43.080	68.320	44.460	40.250	66.160	44.320
Observations	74	74	68	204	204	190

Notes: Poisson regressions of the months since the issuer's previous new-money water bond on *Post Burn*, with one observation per PWS issue date. *Top-Coded* columns cap the gap at 240 months and set first-ever issues to 240; the first *Top-Coded* column of each sample adds the top-code dummy, which equals one when the PWS has not issued in the previous 20 years, and the second omits it. *Not Top-Coded* columns use the raw gap and drop first-ever issues, which have no previous issue. Panel A: California surface-water-only PWSs with at least one recorded fire in an intake HUC-12; *Single HUC* and *Pooled* are defined as in Table 5. Panel B: California PWSs drawing on both surface water and groundwater with at least one recorded fire in a HUC-12 that contains one of their surface-water intakes; there *Single HUC* means a single surface-water intake HUC-12, and Metropolitan Water District of Southern California is excluded. *Post Burn* equals one if a fire recorded by MTBS burned one of the PWS's direct intake HUC-12s in the 18 months before issue. Heteroskedasticity-robust standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

indicator, while the Post Burn estimates are essentially unchanged (58.0 bps for single-HUC PWSs and 38.6 to 34.2 bps for the pooled sample), suggesting that while the timing of bond issuance may be influenced by the forest fire event, it does not appear to bias the estimated treatment effect of the forest fire on the spread.

We repeat this analysis for PWSs that use surface and groundwater, and the results parallel the results of the surface-water-only PWSs. Any effect of forest fires on the time of issuance does not appear to bias the estimate of the effect of forest fires on the bond spread (Tables 7 and 8).

The fact that the point estimates hardly change across surface-water and mixed-intake PWSs builds confidence that, despite some evidence that forest fires influence the timing of bond issuing, this does

Table 7: Control Function Stage 1: Months Since Last Issue

	SW-Only PWSs		Mixed-Source PWSs	
	Single HUC	Pooled	Single SW HUC	Pooled
Post Burn	-0.606	-0.606***	-0.296	-0.115
	(0.401)	(0.182)	(0.244)	(0.107)
Share Non-Callable Outstanding Debt	-1.447***	-1.531***	-1.554***	-1.061***
	(0.384)	(0.230)	(0.293)	(0.253)
Top-Coded (No Issue in 20 Years)	1.391***	1.335***	1.380***	1.343***
	(0.471)	(0.286)	(0.443)	(0.247)
Coupon Rate	-0.010	-0.001	0.014	0.019
	(0.011)	(0.011)	(0.019)	(0.019)
Log(Bond Size)	0.006	-0.014	0.078***	0.043*
	(0.039)	(0.020)	(0.029)	(0.025)
Years to Maturity	-0.000	0.001	-0.005*	-0.003
	(0.006)	(0.003)	(0.003)	(0.004)
Bank Qualified	-0.444	-0.591**	0.081	0.250
	(0.440)	(0.266)	(0.420)	(0.233)
Callable	-0.005	0.011	-0.040	-0.031
	(0.022)	(0.016)	(0.032)	(0.024)
Insured	0.229	0.268*	0.398	0.324***
	(0.256)	(0.142)	(0.248)	(0.111)
Tax Exempt	0.128**	0.025	-0.224	-0.029
	(0.065)	(0.069)	(0.170)	(0.109)
Mean Dependent Variable	89.288	89.520	58.639	51.418
PWS Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes
Excluded Instruments Wald Statistic	14.172	44.466	28.103	17.589
Excluded Instruments Wald p-Value	0.000	0.000	0.000	0.000
RMSE	15.990	16.780	18.880	19.700
Observations	1,362	1,878	1,804	4,461

Notes: First stage of the control function. Poisson regressions of the months since the issuer's previous new-money water bond (top-coded at 240; first-ever issues set to 240) on the excluded instrument, *Post Burn*, the top-code dummy, and the controls of Table 5, with PWS, year, quarter, and credit-rating fixed effects; columns as in Table 5 (SW-only PWSs in columns 1–2, mixed-source PWSs in columns 3–4). The instrument is the share of the issuer's outstanding debt that is non-callable at the issue date; the Wald statistic tests its exclusion. Standard errors clustered by PWS in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

not appear to influence PWS bond spreads. This is in line with the Oster bounding sets for the true treatment effects, which exclude zero and suggest the estimate is robust to omitted-variable bias (see Table 5).

Table 8: Control Function Stage 2: Bond Spread (wild-cluster bootstrapped SEs)

	SW-Only PWSs		Mixed-Source PWSs	
	Single HUC	Pooled	Single SW HUC	Pooled
Post Burn	58.039***	34.208**	29.077***	5.734
	(20.689)	(14.763)	(8.888)	(8.899)
Months Since Last Issue	-0.246	-0.050	-0.083	-0.208*
	(0.166)	(0.160)	(0.132)	(0.123)
Top-Coded (No Issue in 20 Years)	75.951**	24.235	20.115	40.930*
	(36.318)	(39.614)	(30.959)	(24.153)
Coupon Rate	-1.596	-0.370	7.945***	6.656***
	(1.695)	(1.509)	(1.992)	(2.403)
Log(Bond Size)	2.517	1.196	-7.634***	-8.038***
	(2.705)	(3.157)	(2.336)	(2.249)
Years to Maturity	2.114***	2.250***	2.198***	2.395***
	(0.434)	(0.380)	(0.372)	(0.274)
Bank Qualified	28.097*	27.808**	-27.268	-7.856
	(14.264)	(12.289)	(18.790)	(17.968)
Callable	16.350***	17.400***	14.513***	14.604***
	(2.602)	(2.387)	(3.813)	(2.601)
Insured	-20.993	-23.895	-12.458	-2.789
	(19.618)	(14.522)	(17.393)	(9.422)
Tax Exempt	-111.920***	-107.273***	-134.736***	-140.919***
	(13.739)	(7.843)	(10.274)	(8.989)
1st Stage Residuals	-0.002	0.189	0.078	0.154
	(0.269)	(0.190)	(0.154)	(0.138)
Mean Dependent Variable	85.403	77.766	68.760	66.423
N Treated PWS	6	12	7	21
N Treated Bonds	108	226	329	837
PWS Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes
Wild Bootstrap Draws	999	999	999	999
Wild Bootstrap p-Value	0.002	0.019	0.000	0.600
R^2	0.842	0.802	0.774	0.707
Observations	1,362	1,878	1,804	4,461

Notes: Second stage of the control function: the specification of Table 5 with the first-stage residual from Table 7 (observed minus predicted months since last issue) added as a control; SW-only PWSs in columns 1–2, mixed-source PWSs in columns 3–4. Standard errors in parentheses come from a wild-cluster bootstrap (999 draws, Rademacher weights by PWS) that re-estimates both stages in every draw; stars use these standard errors, and the *Wild Bootstrap p-Value* refers to *Post Burn*. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.3 Secondary Market: Average treatment effect of fire on bond spreads

The initial offer market restricts the sources of variation to within a PWS. There is more variation within the secondary market and this enables us to consider variation within a specific bond. This is especially important given the small sample size in the primary market. There are also fewer design choices in the secondary market. There is no need to top code time since last issue and there is no look-back window

Table 9: Within-Bond Spread Regressions, Secondary Market (CA, CO, and OR Pooled, SW-only)

	Full Sample 2005–2024			Recent Sample 2012–2024		
	Single HUC	Multi HUC	Pooled	Single HUC	Multi HUC	Pooled
Post Fire	12.032	-1.445	8.328	17.089**	-6.133	3.468
	(9.027)	(12.352)	(8.498)	(6.517)	(4.092)	(4.120)
Log Months Since Last Trade	4.575***	3.452***	4.036***	4.248***	3.317***	3.794***
	(0.530)	(0.265)	(0.335)	(0.500)	(0.315)	(0.316)
Mean Dependent Variable	72.874	52.740	63.197	62.301	48.844	55.954
N Total PWS	47	37	84	45	35	80
N Treated PWS	11	18	29	10	18	28
N Treated Bonds	140	345	485	112	276	388
Bond Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year × Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.654	0.623	0.639	0.645	0.666	0.646
Observations	17,680	16,362	34,042	13,551	12,097	25,648

Notes: One observation per bond-month in the California, Colorado, and Oregon analysis samples pooled (Table 4, Panel A). The outcome is the secondary yield spread over the MMA curve in basis points, adjusted with each state's top income tax rate, which makes it comparable across states, and winsorized at 1%/99% on the pooled sample. *Post Fire* equals one from the month of the first fire in the PWS's intake HUCs after the bond's dated date and before its maturity, and stays one; bonds with no such fire are never treated. All regressions include bond, year × month, and state fixed effects and the log of the months since the bond's previous trade month; a bond never changes state, so the state fixed effects leave the estimates unchanged. Columns 4–6 keep only trade months from January 2012 on, which excludes crisis-era spread levels. Pooled combines single- and multi-HUC PWSs. Standard errors clustered by PWS in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

to establish. However, the secondary municipal bond market is known to suffer from liquidity and other market imperfections (Cestau et al., 2019). Moreover, it is possible that the retail investor-heavy secondary market does less due diligence than investors who access the initial offer market (Cuny et al., 2025, 2026). Indeed, we find little evidence that forests are priced in the secondary market (Table 9 and Table 10). In California the sample of treated PWSs is similar in size to the initial offer market (5 single-HUC and 12 pooled treated PWSs, against 6 and 12). It is only after 2012, in the least diversified surface-water-dependent PWSs across the West, that we see some evidence of the secondary market pricing the loss of forests from fire.

Table 10: Within-Bond Spread Regressions, Secondary Market (California, SW-only)

	Full Sample 2005–2024			Recent Sample 2012–2024		
	Single HUC	Multi HUC	Pooled	Single HUC	Multi HUC	Pooled
Post Fire	-8.654	16.715	10.194	-7.505	-3.427	2.974
	(16.909)	(14.450)	(9.578)	(9.060)	(3.492)	(4.602)
Log Months Since Last Trade	5.129***	3.851***	4.604***	4.585***	3.839***	4.222***
	(0.608)	(0.628)	(0.523)	(0.649)	(0.712)	(0.502)
Mean Dependent Variable	87.888	80.990	85.820	73.339	68.748	71.963
N Total PWS	24	10	34	23	10	33
N Treated PWS	5	7	12	5	7	12
N Treated Bonds	81	144	225	64	125	189
Bond Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year × Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.693	0.728	0.695	0.678	0.748	0.687
Observations	11,226	4,808	16,034	8,184	3,501	11,685

Notes: As Table 9, on the California analysis sample alone (Table 4, Panel B), without state fixed effects; the spread is winsorized at 1%/99% on the California sample. Standard errors clustered by PWS in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.4 Robustness of Secondary Market Estimates

When data from the secondary market is used to measure the effect of forest fires on bond spreads, the source of variation used to identify the effect does not depend on top coding or look-back window decisions. In Appendix Tables C8 and C9, we show that our main estimates for the secondary market are not strongly influenced by the time fixed effects structure.

5.5 Valuation

To recover the value of the forest capital lost in a fire, we apply Eq. (10), assuming that the fire affects bond prices only through the spread. All variables in Eq. (10) are observable in the data (Table 2) except r_N, which is recovered in Table 5 as the marginal effect of the change in natural capital on spread. We use the mean yield of untreated bonds and the mean coupon and maturity of treated bonds. The estimated value of r_N, normalized to the average burn size and the number of bonds issued during an issuing event, is substituted into Eq. (10) to provide a lower bound on the per-acre value of forests as a

capital input into water provision.[29]

For surface-water-only PWSs that draw water from a single HUC-12, an acre of forest in the intake watershed is valued at $1,187 (Table 11). In the pooled sample, it is valued at $264. This suggests that the value per acre of access to multiple watersheds to diversify natural capital inputs is $923. This aligns with the economic intuition of declining marginal value. Scaling these values to the average burn size implies that a fire destroys $3.65 million of forest capital for single-HUC PWSs and $1.73 million in the pooled sample. The per-acre value is lower in the pooled sample for two reasons. The spread response is smaller, and the average fire burns more acreage (6,564 against 3,080 acres), which may simply reflect that having more HUC-12s means there is more area to burn.

The value of the forest does not appear to be strikingly different for PWSs that use groundwater. Despite smaller increases in spreads following a fire, the implied value of the forest is about the same (Table 11). This is because the average watershed size for this group of PWSs is substantially smaller, and the change in spread acts like a share parameter in the valuation equation. Thus, the small effect on spreads is scaled to a reduced loss of forest from fire. The area burned during fires that affect mixed-source PWSs is about a third of the area that burns in the average fire for PWSs that rely only on surface water.

[29]The scaling is required because the formula depends on the coupon size per bond, so what is required is the total coupon payments on the tranche of treated bonds.

Table 11: Valuation summary table (fire in 18mo lookback window)

	Primary: SW-only		Primary: mixed-source		Secondary: CA, CO, OR	
Statistic	Single HUC	Pooled	Single HUC	Pooled	Single HUC 2012–2024	Pooled 2012–2024
Spread shock, TWFE (bps)	58.0	38.6	30.2	6.6	17.1	3.5
Spread shock, CF (bps)	58.0	34.2	29.1	5.7	–	–
Base spread, untreated (bps)	84.8	79.0	68.4	67.1	65.5	55.8
Shock, % of base, TWFE	68.4	48.9	44.2	9.8	26.1	6.2
Shock, % of base, CF	68.4	43.3	42.5	8.5	–	–
Base yield, untreated (%)	2.9	2.9	3.1	3.0	2.4	2.4
Annual coupon ($ thousands)	104.4	67.0	67.7	116.1	74.0	90.8
Bond size ($ millions)	2.2	1.5	1.6	2.9	1.6	2.2
Offering amount ($ millions)	35.3	26.0	31.7	49.4	28.8	38.1
Years to maturity	10.3	10.0	10.7	10.8	11.8	10.5
Burn acreage per fire	3,079.5	6,564.3	1,161.7	2,031.4	2,089.4	5,758.1
N Treated Bonds	108	226	329	837	112	388
Value lost per acre, TWFE ($)	1,187	264	1,421	278	525	44
Value lost per acre, CF ($)	1,187	233	1,368	242	–	–
Value lost per fire, TWFE ($)	3,654,532	1,731,302	1,650,579	564,289	1,096,824	256,083
Value lost per fire, CF ($)	3,655,556	1,532,529	1,588,778	492,275	–	–

Notes: Value of watershed natural capital lost when a fire burns a PWS's intake watershed. The spread shocks are the *Post Burn* coefficients of Table 5 for TWFE and of Table 8 for CF (SW-only and mixed-source columns); the secondary-market shocks are the *Post Fire* coefficients of Table 9 (California, Colorado, and Oregon) for 2012–2024, which have no control-function counterpart. Each shock is also shown relative to the untreated mean spread of its sample. The average treated bond (treated mean coupon payment, bond size, and years to maturity T) is priced at the untreated mean yield over a horizon of $2T$; the loss is the first-order fall in its price when the yield rises by the spread shock, scaled to the average treated issue (total offering amount over bond size) and divided by the average acreage burned per fire. *Value lost per fire* is that issue-level loss. In the primary columns, bond parameters are means over treated bonds at issuance and the yield is the untreated mean offering yield; for mixed-source PWSs, *Single HUC* means a single surface-water intake HUC-12. In the secondary columns, treated bonds are those traded after their fire, T is their remaining maturity at the fire, the yield and base spread are means over the trade months of never-treated bonds, and the acreage is that of the fire that treats the bonds, all over 2012–2024 trade months. Offering amounts are winsorized at 1%/99%.

6 Discussion

There is a clear link between the theory of pricing natural capital and the theory of pricing bonds. This link has implications for understanding nature as capital. It implies that as nature changes, it is reasonable to expect the cost of financial capital to change. This relationship creates a pathway for valuing non-tradable natural capital as a capital input for entities that pay to borrow financial capital, i.e., issue bonds, and have at least a partial dependence on natural capital. It also reveals that for a given level of output, it is likely that some level of fiscal and produced capital can substitute for natural capital even in cases when produced and natural capital are gross complements.

Public drinking water systems that process and deliver surface water depend on forest natural

capital. In most western public water systems, PWSs do not directly manage the forested watershed where they extract water. So, fires arrive as exogenous shocks to the PWS. This provides an opportunity to assess whether and how an active capital market, the municipal bond market, prices and responds to changes in real natural capital and the fiscal risk that those changes create.

We find that the initial offer municipal bond market has a sophisticated approach to pricing forest natural capital. Following a forest fire, spreads rise the most for the PWSs with the greatest dependencies on the affected forests. If a PWS draws all of its water from a single watershed, then a fire in that watershed, within 18 months prior to issuance, raises the offering spread by 58 bps or roughly 68 percent of the spread compared to the spread experienced by undiversified PWSs that do not experience a forest fire (Table 5). This response aligns with theory. A loss of natural capital reduces the capital that supports the bond, leading to a higher debt-to-capital ratio, so that investors demand greater compensation. However, the market recognizes that not all PWSs face equal financial risk following a forest fire, which implies that not all forests have the same asset value. Combining PWSs that use surface water from multiple watersheds with the undiversified PWSs reduces the average effect of a fire to 39 bps, and this reduction appears to be attributable to diversification (Appendix Table C7). Access to groundwater also reduces the premium. When a PWS uses groundwater and surface water from a single watershed, a fire in that watershed increases spreads by 30 bps. However, if a PWS accesses surface water from multiple watersheds and uses groundwater, a fire in a single HUC-12 appears to have no effect on spreads (Table 5).

These empirical results align with theory. PWSs with more diversified water sources, i.e., natural capital, face a reduced risk premium following a forest fire. So, dependence on natural capital is priced. If multiple forms of natural capital were included in Eq. (10), then effectively one could think of an r_N estimate for each watershed or water source. This would average down the overall risk, which is exactly what diversification does. This is because the premium is not associated with the risk of fire, but rather the financial strain and increased default risk created by the loss of natural capital. To fix this idea, consider that, all else equal, if a firm with a sole factory suffered a loss of that factory, then we

would expect it to face higher borrowing costs compared to a firm that lost one of many factories. Thus, our results provide a precise definition of natural capital that bridges theory and empirical results. It may also point towards a practical financial definition of biodiversity or biodiversification.

The effects we find in the initial offer market are not well replicated in the secondary market, which may be the result of well-known imperfections in the municipal bond market (Cestau et al., 2019; Cuny et al., 2025). We do find that in recent years the secondary market may recognize a risk premium following a forest fire, but the size of the premium is substantially smaller than the premium in the initial offer market and is concentrated in the least diversified PWS segment. The direction of this effect is consistent with results comparing Painter (2020) and Goldsmith-Pinkham et al. (2023) or presented within Nakhmurina et al. (2026).

The municipal bond market responds to changes in natural capital, which implies a value for that natural capital. Our theoretical results show how to calculate this value in a way consistent with natural capital theory (Fenichel and Abbott, 2014; Abbott et al., 2026). We find that an acre of forest is worth at least $1,187 for single-watershed PWSs and $264 per acre for the pooled sample (Table 11). This implies that the average fire in California has a $1.73 million capital cost rising to $3.65 million when the affected PWS depends on water from a single watershed.

The estimates of forest value are a lower bound for a variety of reasons. First, forest fires may not completely destroy the forest, and the forest may continue to provide some water supply services. Second, these estimates exclude any capital costs that a PWS can directly pass to ratepayers or recover through state and federal transfers such as emergency forest fire recovery funds. Therefore, these estimates are lower-bound estimates even in the context of water provision. Third, the estimates are lower-bound estimates because they exclude any other "dividends" that the forest might provide, such as access to recreation, air quality, or cooling services. Vincent et al. (2016) find that the water-supply value of forests in Malaysia is positive but small relative to a forest's recreation value. Ramelli et al. (2026) find that forests may provide substantial cooling benefits, and associated energy savings, to downwind cities. Therefore, our estimates could be a starting point for valuing forest in a natural

capital account, but should not be confused with "the total value of a standing forest". Rather, what the results reveal is the value currently recognized in a capital market that is not specifically focused on environment, ESG, or sustainability.

These results have three important implications. First, PWSs that wish to account for the value of natural capital have a reasonable estimate to do so. This can provide a fiscal justification for allocating funding to forest management. Second, most of the forests in California, and perhaps throughout the western United States, have zero marginal value in water provisioning because they are simply not in watersheds that support surface drinking water systems. Valuing forests needs to account for more than timber and drinking water services to provide an accurate picture of the asset value of forests. Hashida and Fenichel (2022) find that even private forest managers appear to manage forests for some set of services beyond timber, and there is still work to do to determine what that source of value is. Third, the results provide clear evidence that natural capital is more than a metaphor, and that nature can be priced in a capital market that is primarily focused on fiscal risk.

Along with our primary contribution, we also identify an empirical challenge in connecting environmental shocks to bond spreads in the initial offer market. Because nature is a capital input to production, loss of natural capital can jeopardize the ability to maintain a service level. The need to replace that capital can alter the timing of municipal bond issues. This has the potential to create sample selection bias. In our case study, within the pooled sample of surface-water-only PWSs, PWSs issue bonds about 17 percent sooner than we would have expected had a fire not occurred (although the difference is not statistically significant, see Table 6). This is consistent with PWSs borrowing to replace the services of a burned forest with produced capital. To address this identification risk, we develop a control function approach that depends on an instrument, which is likely applicable to other similar situations – outstanding non-callable debt. In our example, there does not appear to be a meaningful amount of bias from the shift in issuing behavior. However, we suggest other researchers should verify that this is the case in their examples as well or specifically control for selection driven by shifts in issuing behavior.

The phrase "natural capital" is common. Yet, it has been unclear whether capital markets treat nature as capital, something else, or not at all. The growing empirical literature suggests that municipal bond markets consider nature in some form. By connecting theoretical and empirical results, we have sharpened the connection and shown that at least one market is implicitly pricing natural capital.

References

Abbott, Joshua K, Eli P Fenichel, and Seong D Yun, "Risky (Natural) Assets: Stochasticity, Nonconvexity, and the Value of Natural Capital," *Journal of the Association of Environmental and Resource Economists*, 2026, *13* (5), 1269–1309.

Acharya, Viral V., Timothy Johnson, Suresh Sundaresan, and Tuomas Tomunen, "Is physical climate risk priced? Evidence from regional variation in exposure to heat stress," Technical Report, National Bureau of Economic Research, Cambridge, MA, USA 2022.

Ang, Andrew, Vineer Bhansali, and Yuhang Xing, "Taxes on Tax-Exempt Bonds," *Journal of Finance*, 2010, *65* (2), 565–601.

Armstrong, Timothy B, Martin Weidner, and Andrei Zeleneev, "Robust estimation and inference in panels with interactive fixed effects," *Journal of Political Economy*, 2026, *134* (8), 000–000.

Arrow, Kenneth J., Partha Dasgupta, and Karl-Goran Maler, "Evaluating projects and assessing sustainable development in imperfect economies," *Environmental and Resource Economics*, 2003, *26*, 647–685.

Arrow, Kenneth, Partha Dasgupta, Lawrence Goulder, Gretchen Daily, Paul Ehrlich, Geoffrey Heal, Simon Levin, Karl-Goran Maler, Stephen Schneider, David Starrett, and Brian Walker, "Are we consuming too much?," *Journal of Economic Perspectives*, 2004, *18* (3), 147–172.

Auh, Jun Kyung, Jaewon Choi, Tatyana Deryugina, and Tim Park, "Natural disasters and municipal bonds," Technical Report, National Bureau of Economic Research 2022.

Babina, Tania, Chotibhak Jotikasthira, Christian T. Lundblad, and Tarun Ramadorai, "Heterogeneous Taxes and Limited Risk Sharing: Evidence from Municipal Bonds," *Review of Financial Studies*, 2021, *34* (1), 509–568.

Bayham, Jude, Jonathan K. Yoder, Patricia A. Champ, and David E. Calkin, "The Economics of Wildfire in the United States," *Annual Review of Resource Economics*, 2022, *14*, 379–401.

Borusyak, Kirill, Xavier Jaravel, and Jann Spiess, "Revisiting event-study designs: robust and efficient estimation," *Review of Economic Studies*, 2024, *91* (6), 3253–3285.

Callaway, Brantly and Pedro HC Sant'Anna, "Difference-in-differences with multiple time periods," *Journal of Econometrics*, 2021, *225* (2), 200–230.

Cao, Sean, Anya Nakhmurina, and Tianchen Zhao, "Government Data and Financing: Insights from Internal Controls," Working Paper, University of Maryland and Yale University 2025.

Cestau, Dario, Burton Hollifield, Dan Li, and Norman Schürhoff, "Municipal bond markets," *Annual Review of Financial Economics*, 2019, *11* (1), 65–84.

Cuny, Christine, Ken Li, Anya Nakhmurina, and Edward M. Watts, "Muni Disclosure: All Talk and No Trade?," *Journal of Accounting and Economics*, 2025, *80* (1), 101797.

_ , Raphael Duguay, Ken Li, Anya Nakhmurina, and Edward M. Watts, "Tipped Off: Information Leakage in the Municipal Securities Market," Working Paper, New York University, Yale University, and McMaster University 2026.

Dagostino, Ramona and Anya Nakhmurina, "Monitoring Public Promises: Municipal Debt and Retirement Security," Pension Research Council Working Paper WP2026-08, The Wharton School, University of Pennsylvania 2026.

_ **and** _ , "Partisan Cities: How State–Local Political Alignment Shapes Credit Risk and Information Processing in the Municipal Bond Market," *Journal of Accounting Research*, 2026, *64* (4), 1733–1770.

Dasgupta, Partha and Geoffrey Heal, "The optimal depletion of exhaustible resources," *Review of Economic Studies*, 1974, *41*, 3–28.

Fenichel, Eli P. and Joshua K. Abbott, "Natural capital from metaphor to measurement," *Journal of the Association of Environmental and Resource Economics*, 2014, *1* (1), 1–27.

Gao, Pengjie, Chang Lee, and Dermot Murphy, "Municipal Borrowing Costs and State Policies for Distressed Municipalities," *Journal of Financial Economics*, 2019, *132* (2), 404–426.

_ **,** _ **, and** _ , "Financing Dies in Darkness? The Impact of Newspaper Closures on Public Finance," *Journal of Financial Economics*, 2020, *135* (2), 445–467.

Goldsmith-Pinkham, Paul, Matthew T. Gustafson, Ryan C. Lewis, and Michael Schwert, "Sea-level rise exposure and municipal bond yields," *The Review of Financial Studies*, 2023, *36* (11), 4588–4635.

Green, Richard C., Burton Hollifield, and Norman Schürhoff, "Dealer Intermediation and Price Behavior in the Aftermarket for New Bond Issues," *Journal of Financial Economics*, 2007, *86* (3), 643–682.

Harris, Lawrence E. and Michael S. Piwowar, "Secondary Trading Costs in the Municipal Bond Market," *Journal of Finance*, 2006, *61* (3), 1361–1397.

Hashida, Yukiko and Eli P Fenichel, "Valuing natural capital when management is dominated by periods of inaction," *American Journal of Agricultural Economics*, 2022, *104* (2), 791–811.

Horan, Richard D., Eli P. Fenichel, David Finnoff, and Carson Reeling, "A Portfolio-Balancing Approach to Natural Capital and Liabilities: Managing Livestock and Wildlife Diseases with Cross-Species Transmission and Trade," *Environmental and Resource Economics*, 2018, *70* (3), 673–689.

Hulten, Charles R., "The "architecture" of capital accounting: basic design principles," in Dale W. Jorgenson, J. Steven Landefeld, and William D. Nordhaus, eds., *A New Architecture for the U.S. National Accounts*, Chicago: University of Chicago Press, 2006.

Jeon, Woongchan, Lint Barrage, and Kieran James Walsh, "Pricing climate risks: Evidence from wildfires and municipal bonds," Technical Report 25/398, Economic Working Paper Series 2025.

Jorgenson, Dale W., "Capital theory and investment behavior," *American Economic Review*, 1963, *53* (2), 247–259.

Lopez, Luis A, Dermot Murphy, Nitzan Tzur-Ilan, and Sean Wilkoff, "Up in smoke: The impact of wildfire pollution on healthcare municipal finance," *Dallas Federal Reserve Working Paper https://doi.org/10.24149/wp2503*, 2025.

Lu, Shirley and Anya Nakhmurina, "Financial constraints and short-term planning are linked to flood risk adaptation gaps in US cities," *Communications Earth & Environment*, 2024, *5* (1), 43.

Nakhmurina, Anya, Dale T. Manning, and Eli P. Fenichel, "The fiscal impact of biodiversity loss and a pathway for conservation finance," *Science*, 2026, *391*, 1110–1113.

Oster, Emily, "Unobservable Selection and Coefficient Stability: Theory and Evidence," *Journal of Business & Economic Statistics*, 2019, *37* (2), 187–204.

Painter, Marcus, "An inconvenient cost: The effects of climate change on municipal bonds," *Journal of Financial Economics*, 2020, *135* (2), 468–482.

Parise, Mario and Susan H. Cannon, "Wildfire impacts on the processes that generate debris flows in burned watersheds," *Natural Hazards*, 2012, *61* (1), 217–227.

Ramelli, Stefano, Claudio Rizzi, and Simon Xu, "The Value of Forests: Impacts on Extreme Heat and Electricity Demand," *Available at SSRN 6961558*, 2026.

Reed, William J. and Hector Echavarria Heras, "The conservation and exploitation of vulnerable resources," *Bulletin of Mathematical Biology*, 1992, *54* (2/3), 185–207.

Rizzi, Claudio and Ryan Lewis, "Nature as a Defense from Disasters: Natural Capital and Municipal Bond Yields," *SSRN Electronic Journal*, 2025.

Roodman, David, Morten Ørregaard Nielsen, James G MacKinnon, and Matthew D Webb, "Fast and wild: Bootstrap inference in Stata using boottest," *The Stata Journal*, 2019, *19* (1), 4–60.

Rouhi Rad, Mani, Wiktor Adamowicz, Alicia Entem, Eli P. Fenichel, and Patrick Lloyd-Smith, "Complementarity (not substitution) between natural and produced capital: Evidence from the Panama canal expansion," *Journal of the Association of Environmental and Resource Economists*, 2021, *8* (6), 1115–1146.

Schultz, Paul, "The Market for New Issues of Municipal Bonds: The Roles of Transparency and Limited Access to Retail Investors," *Journal of Financial Economics*, 2012, *106* (3), 492–512.

Schwert, Michael, "Municipal Bond Liquidity and Default Risk," *Journal of Finance*, 2017, *72* (4), 1683–1722.

Shapiro, Carl and Joseph E. Stiglitz, "Equilibrium unemployment as a worker discipline device," *American Economic Review*, 1984, *74* (3), 433–444.

Short, K. C., "Spatial wildfire occurrence data for the United States, 1992–2020 [FPA_FOD_20221014], 6th ed. Fort Collins, CO, https://doi.org/10.2737/RDS-2013-0009.6," Technical Report, Forest Service Research Data Archive 2022.

Terza, Joseph V, "Estimating count data models with endogenous switching: Sample selection and endogenous treatment effects," *Journal of Econometrics*, 1998, *84* (1), 129–154.

Vincent, Jeffrey R., Ismariah Ahmad, Norliyana Adnan, III Burwell Walter B., Subhrendu K. Pattanayak, Jie-Sheng Tan-Soo, and Kyle Thomas, "Valuing water purification by forests: An analysis of malaysian panel data," *Environmental and Resource Economics*, 2016, *64*, 59–80.

Warziniack, Travis and Matthew Thompson, "Wildfire risk and optimal investments in watershed protection," *Western Economics Forum*, 2013, *12* (2), 19–28.

Weitzman, M.L., "On the welfare significance of national product in a dynamic economy," *The Quarterly Journal of Economics*, 1976, *90* (1), 156–162.

Wooldridge, Jeffrey M, "Control function methods in applied econometrics," *Journal of Human Resources*, 2015, *50* (2), 420–445.

Yun, Seong Do, Barbara Hutniczak, Joshua K. Abbott, and Eli P. Fenichel, "Ecosystem based management and the wealth of ecosystems," *Proceedings of the National Academy of Sciences*, 2017, *114* (25), 6539–6544.

A PWS Labels

Table A1: PWS Names Used in the Figures and Tables

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Panel A: PWSs that only access surface water					
Antioch	City of Antioch	CA0710001	180400030907	10	10
Benicia	City of Benicia	CA4810001	180201630603, 180500010104, 180500010105	10	15
Brooktrails CSD	Brooktrails Township Community Services District	CA2310009	180101030403	1	13
Calaveras County WD	Calaveras County Water District	CA0510004, CA0510005, CA0510006, CA0510016, CA0510017	180400100306, 180400100604, 180400110103, 180400110306, 180400120303, 180400510203	8	50
Calexico	City of Calexico	CA1310002	181002040902	21	52
Calistoga	City of Calistoga	CA2810002	180500020201	5	21
Central Coast WA	Central Coast Water Authority	CA4210030	180300121404	2	21
Coalinga	City of Coalinga	CA1010004	180300090602	11	49
Contra Costa WD*	Contra Costa Water District	CA0710003, CA0710010	180400030605, 180400030801, 180400030803, 180400030904, 180400030907, 180500010302, 180500010303, 180500010401	7	247
El Centro	City of El Centro	CA1310700	181002040902	3	89
El Dorado ID	El Dorado Irrigation District	CA0910001, CA0910017, CA0910018	180201290301, 180201290502, 180201290703, 180400130204, 180400130404	5	81
Escondido	City of Escondido	CA3710006	180703030401	22	160
Fairfield	City of Fairfield	CA4810003	180500010108	28	83
Folsom	City of Folsom	CA3410014	180201280604	15	61
Grass Valley	City of Grass Valley	CA2910001	180201260202	8	14
Groveland CSD	Groveland Community Services District	CA5510009	180400091002	3	3
Holtville	City of Holtville	CA1310005	181002040702	7	6
Imperial	City of Imperial	CA1310006	181002040701	10	159
June Lake PUD	June Lake Public Utility District	CA2610002, CA2610004	180901010301	2	20
Madera	City of Madera / Madera Irrigation District	CA2000729	180400010302	21	92
Marin MWD	Marin Municipal Water District	CA2110002	180500020901, 180500050101, 180500050102, 180500050103, 180500050201	10	138
Martinez	City of Martinez	CA0710006	180500010303	13	36
Modesto ID	Modesto Irrigation District	CA5010038	180400091308	5	9

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Mountain House	Mountain House (Community Services District)	CA3910027	180400030604	2	26
Napa	City of Napa	CA2810003	180201630603, 180500020102, 180500020204	24	81
Nevada ID	Nevada Irrigation District	CA2910002, CA2910004, CA2910006, CA2910023, CA3110026, CA5810005	180201250802, 180201250804, 180201251002, 180201260102, 180201260301	10	4
Olivenhain MWD	Olivenhain Municipal Water District	CA3710029	180703030402	4	69
Orange Cove	City of Orange Cove	CA1010023	180300071203	5	9
Panoche WD	Panoche Water District	CA1000345	180400011304	3	13
Poway	City of Poway	CA3710015	180703040205	14	37
San Juan WD	San Juan Water District	CA3410021	180201280604	6	96
Solano ID	Solano Irrigation District	CA4810010, CA4810025	180201630503, 180500010104, 180500010108	3	17
South Feather W&PA	South Feather Water and Power Agency	CA0410006, CA0410012	180201590102, 180201590107	2	21
Suisun-Solano WA	Suisun-Solano Water Authority	CA4810005	180201630503, 180500010104, 180500010108	2	53
Vallejo	City of Vallejo	CA4810007, CA4810015, CA4810021	180201620403, 180201630503, 180201630603, 180500010102, 180500010104, 180500010107, 180500010108, 180500020401	33	56
West Sacramento	City of West Sacramento	CA5710003	180201610402	13	104
Western Hills WD	Western Hills Water District	CA5010039	180400020204	1	46
Willits	City of Willits	CA2310004	180101030402	7	17
Woodland-Davis CWA	Woodland-Davis Clean Water Agency	CA5710012	180201610402	2	47
Panel B: PWSs that access both surface and groundwater					
ACWD + Zone 7	Alameda County Water District / Zone 7 Water Agency (Livermore-Amador Valley)	CA0110001, CA0110010	180500040201†, 180500040302, 180500040405†, 180500040406†, 180500040503, 180500040603, 180500040702†, 180500040804	48	183
AVEK WA	Antelope Valley-East Kern Water Agency	CA1510053, CA1910045	180902061103, 180902061308, 180902061404†, 180902061408, 180902061501†, 180902061601†, 180902061602, 180902062403, 180902062404†	7	57

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Anaheim	City of Anaheim	CA3010001	180701060605, 180702010001, 180702031002†	25	204
Azusa	City of Azusa (Azusa Light and Water)	CA1910007	180701060402†, 180701060601†	4	48
Calleguas MWD	Calleguas Municipal Water District	CA5610050	180701030102†, 180701030103	3	60
Cambria CSD*	Cambria Community Services District	CA4010014	180600060404, 180600060406	5	17
Carmichael WD*	Carmichael Water District	CA3410004	180201110202	2	34
Casitas MWD	Casitas Municipal Water District	CA5610024	180701010104, 180701010105†	1	43
Clovis	City of Clovis	CA1010003	180300090403, 180300090502, 180300090503†, 180300090701	18	123
Cucamonga Valley WD	Cucamonga Valley Water District	CA3610018	180702030704, 180702030705, 180702030804†	5	235
Desert WA	Desert Water Agency	CA3310005	181002010202†, 181002010204, 181002010304†, 181002010606	2	38
East Valley WD	East Valley Water District	CA3610064	180702030501†, 180702030503, 180702030504†, 180702030505, 180702030507†, 180702030508	1	18
Elsinore Valley MWD	Elsinore Valley Municipal Water District	CA3310012	180702020307†, 180702020308, 180702030602, 180702030604	5	155
Fresno	City of Fresno / Fresno County service areas / Fresno Irrigation District	CA1000019, CA1000359, CA1000546, CA1009023, CA1009028, CA1010007, CA1010051	180300090303, 180300090403, 180300090503†, 180300090504, 180300090506, 180300090606†, 180300090607†, 180300090608†, 180300090701†, 180300090703, 180300090802†, 180300090905†, 180400010302†, 180400010303	51	98
Glendale*	City of Glendale (Water and Power)	CA1910043	180701050207, 180701050208, 180701050210	5	57
Goleta WD	Goleta Water District	CA4210004	180600100402†, 180600130201, 180600130202†	9	71
Healdsburg*	City of Healdsburg	CA4910005	180101100507, 180101100605	16	19
Helix WD	Helix Water District	CA3710010	180703040505†, 180703040703†	3	14

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Irvine Ranch WD	Irvine Ranch Water District	CA3010092	180702030901, 180702030902†, 180702031003, 180702040101, 180702040103, 180703010301	7	70
Kern County WA	Kern County Water Agency	CA1510040	180300030111†, 180300120801†, 180300120802	4	74
Lake Arrowhead CSD	Lake Arrowhead Community Services District	CA3610005	180902080103†, 180902080202	6	55
Lake County	Lake County (City of Lakeport, County Service Areas)	CA1710004, CA1710018, CA1710021, CA1710022	180201160103, 180201160310†, 180201160407†	15	20
Lodi	City of Lodi	CA3910004	180400030902, 180400121102†, 180400121104, 180400121105	15	130
Lompoc	City of Lompoc	CA4210006	180600100703†	6	81
Metropolitan WD*	Metropolitan Water District of Southern California	CA1910087, CA3600382, CA3600383	150301010713†, 150301040301†, 180701020305†, 180701020306†, 180701050204†, 180702020305†, 180702030304†, 180702030305†, 180702030603†, 180702030605†, 180703020401†, 180703020405†, 180902080201†, 181001004005†	2	456
Montara WSD	Montara Water and Sanitary District	CA4110010	180500060205†	4	20
Montecito WD	Montecito Water District	CA4210007	180600100202†, 180600130203†, 180600130205†	5	16
North Tahoe PUD	North Tahoe Public Utility District	CA3110001	160501010101†	3	10
Palmdale WD	Palmdale Water District	CA1910102	180902061103†, 180902061403, 180902061501†	10	108
Paradise ID	Paradise Irrigation District	CA0410007	180201580201†, 180201580401	4	15
Placer County WA	Placer County Water Agency	CA3100040, CA3110005, CA3110006, CA3110024, CA3110025, CA3110035, CA3110050, CA3110124	160501010303†, 180201110101†, 180201260103†, 180201260301†, 180201280107†, 180201280603†, 180201280604†, 180201610201†, 180201610302	13	186

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Pomona	City of Pomona	CA1910126	180701060501, 180702030701†, 180702030702	5	109
Redding	City of Redding / Shasta County service areas	CA4500006, CA4500015, CA4500028, CA4500317, CA4510004, CA4510005, CA4510013	180200031303†, 180200050203†, 180200050204†, 180200050402, 180200050406†, 180201540104†, 180201540105†, 180201540106, 180201540203, 180201540302†, 180201540303, 180201540304, 180201540305	33	42
Redlands	City of Redlands	CA3610037	180702030501†, 180702030506, 180702030507†	4	2
Riverside*	City of Riverside	CA3310031	180702030505, 180702030506, 180702030507, 180702030508, 180702030804	87	167
Roseville	City of Roseville	CA3110008	180201110104†, 180201610302	27	34
Sacramento	City of Sacramento	CA3410020	180201110202†, 180201110302, 180201110303, 180201610402, 180201630404, 180201630701†	70	240
San Diego	City of San Diego	CA3710020	180703040401†, 180703040505†, 180703040603†, 180703040702, 180703040703, 180703040704†, 180703041003†	67	368
San Diego County WA	San Diego County Water Authority	CA3710042, CA3710047	180703030402†, 180703050402	3	36
San Francisco	City and County of San Francisco (SFPUC)	CA3810001	180400090304†, 180400090405†, 180400090504†, 180400091001†, 180400091202†, 180500040103†, 180500040601†, 180500040602†, 180500040901†, 180500040903, 180500060201†, 180500060204	26	20
San Lorenzo Valley WD	San Lorenzo Valley Water District	CA4410014	180600150201†, 180600150202†, 180600150203	3	20

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
San Luis Obispo County	San Luis Obispo County (Flood Control and Water Conservation District)	CA4010009, CA4010022, CA4010080	180600050203†, 180600050609†, 180600060409†, 180600060602†, 180600060605†, 180600060701†, 180600060702	9	88
Santa Barbara	City of Santa Barbara	CA4210010	180600100402†, 180600130201, 180600130203†	4	31
Santa Clara Valley WD	Santa Clara Valley Water District	CA4310027	180400011202†, 180500030105†, 180500030204†, 180500030301†, 180500030401, 180500040405†	16	493
Santa Cruz	City of Santa Cruz	CA4410010	180500060304†, 180600150202†, 180600150203†, 180600150305	11	178
Sonoma County WA	Sonoma County Water Agency	CA4900532, CA4900549	180101090201†, 180101100904†	14	172
Stockton	City of Stockton / Stockton East Water District	CA3910006, CA3910012	180400030302†, 180400030303†, 180400030403, 180400030404, 180400030405, 180400030504, 180400030903†, 180400121105†, 180400510403	19	52
Sweetwater Authority	Sweetwater Authority	CA3710025	180703040902†, 180703040903, 180703041202	1	39
Three Valleys MWD	Three Valleys Municipal Water District	CA1910041	180702030702†	2	10
Trabuco Canyon WD*	Trabuco Canyon Water District	CA3010094	180703010103	4	7
Tracy	City of Tracy	CA3910011	180400030601†, 180400030605	24	73
Tuolumne UD*	Tuolumne Utilities District	CA5510001, CA5510002, CA5510003, CA5510012, CA5510013, CA5510015, CA5510033	180400090901†, 180400091003†, 180400091101†, 180400091102†, 180400091103†, 180400100503†, 180400100605†	4	1
Ukiah	City of Ukiah	CA2310003	180101100403†	10	19
United WCD	United Water Conservation District	CA5610046	180701020904†, 180701030201	5	37
Watsonville	City of Watsonville	CA4410011	180600020802†, 180600020804	13	16
West Valley WD	West Valley Water District	CA3610004	180702030305†, 180702030508, 180702030804†	1	20
Yuba City	City of Yuba City	CA5110002	180201590400, 180201590502†	16	147

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Table A1, continued

Short name	Full name	PWSIDs	Intake HUC-12s	CUSIP6s	Bonds
Yucaipa Valley WD	Yucaipa Valley Water District	CA3610055	180702030402†, 180702030403, 180702030507	5	83

Notes: One row per California PWS issuer group in the sample: the short name used in the figures and tables, its full name, its public water systems (EPA SDWIS PWSIDs), the HUC-12s containing its intake facilities, the number of CUSIP6 issuer codes linked to it and its bonds in the primary-market sample. A group combines the water systems and bond issuers that the PWS–CUSIP6 crosswalk links to one another. In Panel B, † marks the intake HUC-12s with a surface-water intake, the only ones that count towards treatment. * Not in the regression samples: Contra Costa WD and Metropolitan WD are excluded from the pooled samples by design; Cambria CSD, Carmichael WD, Glendale, Healdsburg, Riverside, and Trabuco Canyon WD have no intake HUC-12 with a surface-water intake, so no fire can treat them; Tuolumne UD has a single bond, which the PWS fixed effect absorbs. Abbreviations: WD water district, MWD municipal water district, ID irrigation district, WA water authority or agency, CSD community services district, PUD public utility district, UD utilities district, WCD water conservation district, WSD water and sanitary district, CWA clean water agency, W&PA water and power agency, ACWD Alameda County Water District, AVEK Antelope Valley-East Kern; a bare place name is the city's water utility.

B LLM Pipeline

We develop a computational pipeline linking Public Water System (PWS) entities and Municipal Securities Rulemaking Board (MSRB) bond issuer data that are available on the Electronic Municipal Market Access (EMMA) platform. The system enables us 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 they 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. We search the variants for each PWS within the EMMA issuer search interface via browser sessions. This is assisted by 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 responsible 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, deduplicated, and individually accessed from the EMMA platform. Metadata are extracted. This includes contact information, issue descriptions (CUSIP identifiers, dated dates, par amounts), and Official Statement (OS) document URLs. Available OS documents are downloaded in native PDF format. Then we tag each document 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. The publicly available 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-Next-80B-A3B, FP8). Classification proceeds in two steps. First, a keyword scan identifies 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 structured 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. Reviewers' confirmed matches are compared to assess inter-rater variability and saved for downstream analysis.

C Internet Appendix

C.1 Additional timelines of fire events and bond issuances

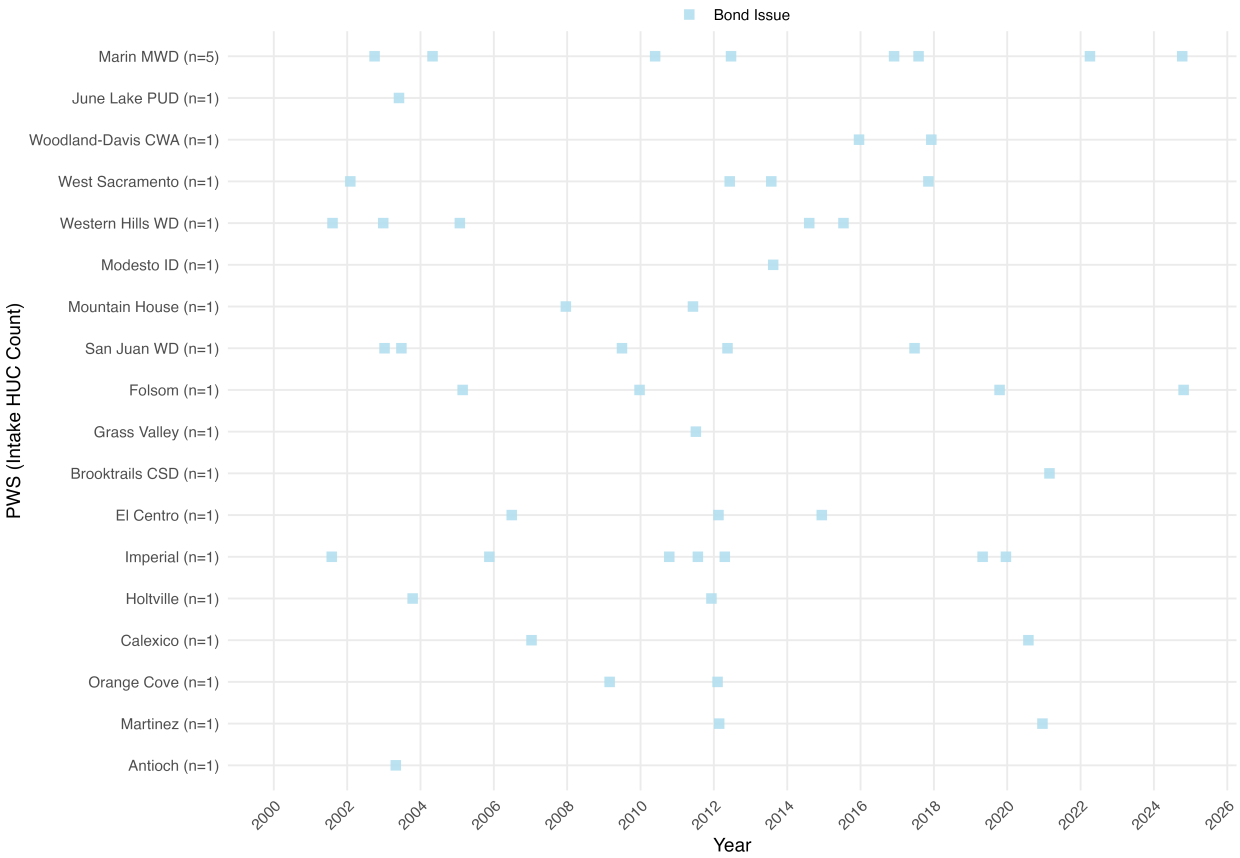


Figure C1: Bond Issuance: SW-Only PWSs without a Fire. Timelines of bond issuances by California SW-only PWSs with no fire in a direct intake HUC between 2000 and 2024, complementing Figure 1, using an 18-month lookback window. Markers as in Figure 1. n is the number of HUC-12s containing the PWS's intakes.

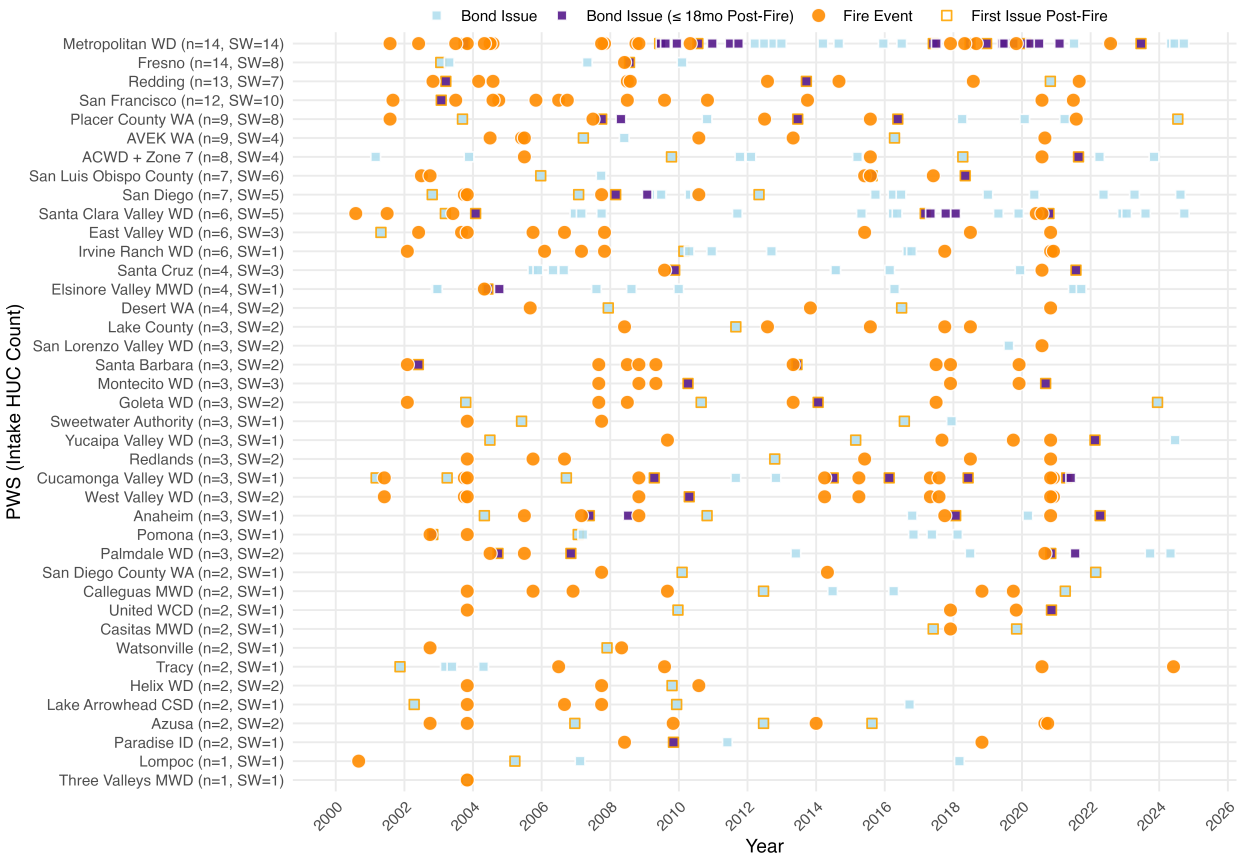


Figure C2: Fire Events and Bond Issuance: Mixed-Intake PWSs with a Fire. Timelines of bond issuances by California mixed-intake PWSs with at least one fire in a direct intake HUC with a surface-water intake between 2000 and 2024, with their fire events, complementing Figure 1, using an 18-month lookback window. Only HUCs with a surface-water intake count towards treatment. Markers as in Figure 1. n is the number of HUC-12s containing the PWS's intakes; SW is the number of those with a surface-water intake.

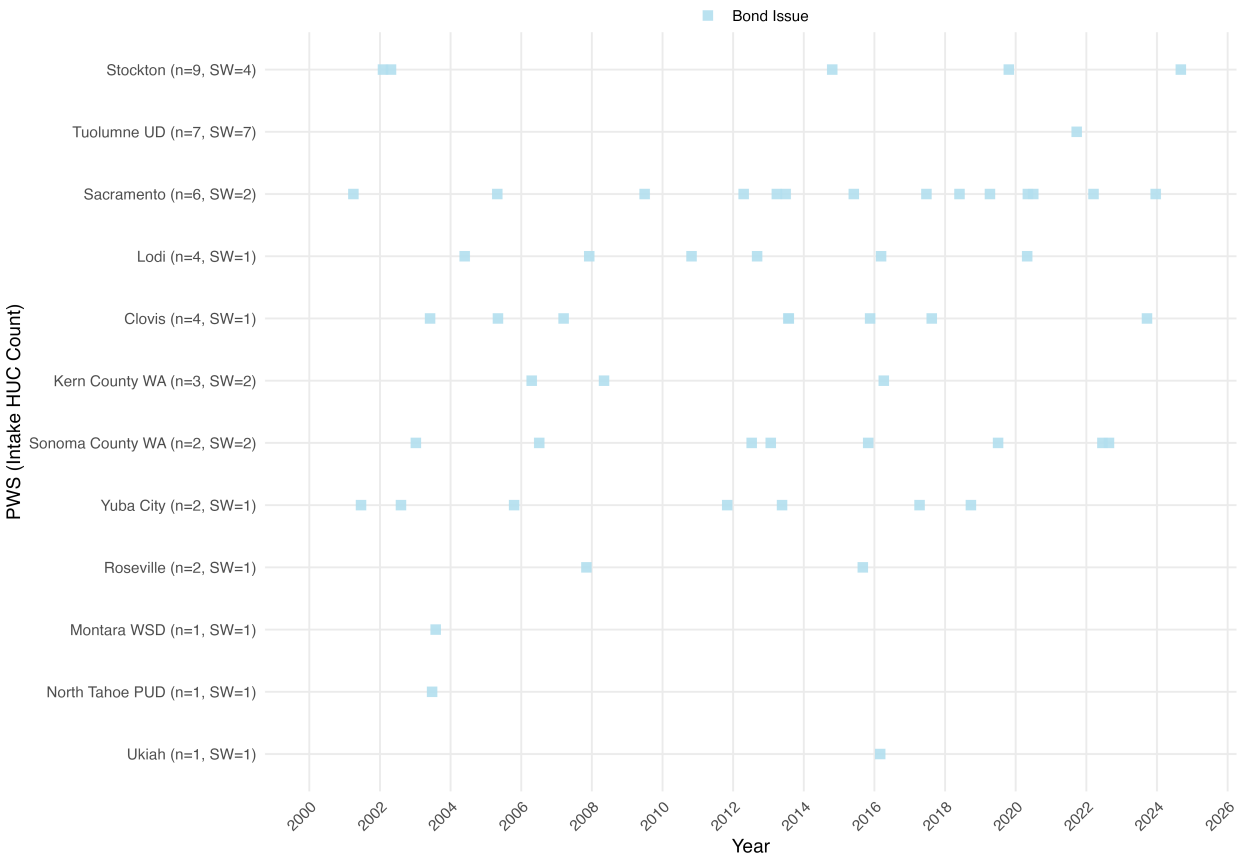


Figure C3: Bond Issuance: Mixed-Intake PWSs without a Fire. Timelines of bond issuances by California mixed-intake PWSs with at least one surface-water intake HUC and no fire in a surface-water intake HUC between 2000 and 2024, complementing Figure 1, using an 18-month lookback window. Only HUCs with a surface-water intake count towards treatment. Markers as in Figure 1. n is the number of HUC-12s containing the PWS's intakes; SW is the number of those with a surface-water intake.

C.2 Robustness to the look-back window

C.2.1 PWSs with surface-water-only intakes

The estimates for the single-HUC subsample are smaller than at the main look-back window (21.4 bps at 12 months and 42.5 bps at 36 months, against 58.0 bps), and as shown in Figure 1 the sample of treated bonds changes as the window is altered. Reducing the window to 12 months, we see that there is a loss of precision as our treated sample drops to four PWSs (from six). Expanding the window to 36 months, we see an increase in the number of treated bonds from 108 to 170. However, the estimated effect is also diluted. Although the estimates are not statistically different from each other, the longer time window includes bonds further removed in time from the fire event and issues subsequent to the first after the event.

C.2.2 PWSs with mixed surface and groundwater intakes

If the look-back window is reduced to 12 months, the coefficient estimate is economically similar despite the reduction in the number of treated PWSs from seven to four, and in CUSIP9s from 329 to 187. Expanding the look-back window to 36 months attenuates the treatment effect and reduces the precision. One explanation is that the first bond a PWS issues after a fire in its surface-water HUC absorbs the main penalty associated with the loss of capital; then, as bonds issued further away in time from the fire are included in the treatment group, the estimate is diluted (and precision reduced).

Table C1: TWFE: Average Effect of Fire in 12-, 18-, and 36-month lookback windows (SW-only PWS)

	12-Month Lookback		18-Month Lookback (Main)		36-Month Lookback	
	Single HUC	Pooled	Single HUC	Pooled	Single HUC	Pooled
Post Burn	21.401	19.974	58.023**	38.645***	42.528**	15.067
	(32.785)	(24.595)	(23.490)	(14.038)	(19.268)	(16.559)
Months Since Last Issue	-0.274*	0.039	-0.247*	0.079	-0.227*	0.047
	(0.154)	(0.218)	(0.130)	(0.180)	(0.124)	(0.203)
Top-Coded	84.187***	6.144	76.259***	-1.594	67.132***	2.655
	(28.851)	(53.450)	(22.183)	(46.640)	(21.748)	(52.052)
Coupon Rate	-2.456	-0.484	-1.597	-0.225	-1.302	-0.192
	(1.694)	(1.573)	(1.850)	(1.565)	(2.019)	(1.680)
Log(Bond Size)	4.479	1.896	2.516	1.144	2.924	1.302
	(3.603)	(3.805)	(2.828)	(3.550)	(3.140)	(3.751)
Years to Maturity	2.103***	2.246***	2.115***	2.236***	2.091***	2.262***
	(0.514)	(0.428)	(0.437)	(0.398)	(0.471)	(0.430)
Bank Qualified	28.282*	28.841**	28.102*	28.387**	28.792*	30.416**
	(15.600)	(13.208)	(14.416)	(13.097)	(14.559)	(13.152)
Callable	14.939***	17.003***	16.349***	17.469***	15.683***	17.348***
	(2.949)	(2.863)	(2.703)	(2.549)	(2.817)	(2.757)
Insured	-17.764	-25.764	-21.032	-24.548	-19.154	-27.836
	(20.943)	(16.506)	(18.763)	(14.992)	(17.986)	(17.173)
Tax Exempt	-109.067***	-107.044***	-111.902***	-108.129***	-112.314***	-107.332***
	(12.828)	(7.658)	(13.568)	(7.822)	(13.413)	(8.280)
Mean Dependent Variable	85.403	77.766	85.403	77.766	85.403	77.766
N Total PWS	28	38	28	38	28	38
N Treated PWS	4	10	6	12	7	13
N Treated Bonds	68	186	108	226	170	322
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[21.401, 87,879.128]	[19.974, 998.040]	[58.023, 148.382]	[38.645, 193.015]	[42.528, 107.418]	[15.067, 188.228]
Oster Delta*	0.210	-0.706	-11.722	-1.727	11.113	-0.989
R^2	0.830	0.794	0.842	0.801	0.840	0.795
Observations	1,362	1,878	1,362	1,878	1,362	1,878

Notes: Re-estimates the SW-only specification of Table 5 with *Post Burn* defined over a 12-month (columns 1–2) or 36-month (columns 5–6) fire lookback window; columns 3–4 repeat the main 18-month estimates of Table 5. *Top-Coded* marks bonds whose issuer had no new-money issue in the previous 20 years, including first-ever issues. Controls, fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table C2: TWFE: Average Effect of Fire in 12-, 18-, and 36-month lookback windows (Mixed-intake PWS)

	12-Month Lookback		18-Month Lookback (Main)		36-Month Lookback	
	Single SW HUC	Pooled	Single SW HUC	Pooled	Single SW HUC	Pooled
Post Burn	26.555***	8.417	30.208***	6.573	7.256	4.149
	(7.531)	(8.953)	(7.384)	(9.520)	(9.509)	(4.689)
Months Since Last Issue	-0.068	-0.089	-0.032	-0.089	-0.089	-0.090
	(0.132)	(0.095)	(0.132)	(0.096)	(0.146)	(0.098)
Top-Coded	18.272	19.728	11.234	18.910	23.761	19.168
	(32.499)	(21.721)	(32.357)	(21.755)	(35.569)	(22.014)
Coupon Rate	8.187***	6.658**	8.035***	6.698**	8.451***	6.680**
	(2.144)	(2.649)	(2.176)	(2.660)	(2.210)	(2.688)
Log(Bond Size)	-8.092***	-8.484***	-7.771***	-8.337***	-8.378***	-8.423***
	(2.435)	(2.332)	(2.500)	(2.325)	(2.470)	(2.360)
Years to Maturity	2.218***	2.435***	2.207***	2.418***	2.187***	2.421***
	(0.411)	(0.294)	(0.405)	(0.300)	(0.388)	(0.291)
Bank Qualified	-28.838	-10.497	-27.747	-9.491	-12.739	-7.320
	(21.751)	(19.758)	(20.826)	(19.955)	(27.776)	(21.084)
Callable	14.519***	14.712***	14.620***	14.775***	15.219***	14.780***
	(4.194)	(2.507)	(4.125)	(2.589)	(4.190)	(2.587)
Insured	-14.236	-4.807	-13.303	-4.232	-19.370	-4.251
	(21.156)	(9.897)	(21.312)	(9.889)	(21.938)	(9.956)
Tax Exempt	-134.714***	-141.100***	-134.196***	-140.767***	-134.819***	-140.988***
	(11.670)	(10.337)	(11.921)	(10.364)	(12.176)	(10.258)
Mean Dependent Variable	68.760	66.423	68.760	66.423	68.760	66.423
N Total PWS	24	50	24	50	24	50
N Treated PWS	4	15	7	21	13	31
N Treated Bonds	187	570	329	837	641	1,727
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[26.555, 48.389]	[8.417, 15.916]	[30.208, 103.071]	[6.573, 16.193]	[7.256, 133.492]	[4.149, 9.908]
Oster Delta*	6.323	-2.609	-4.233	-1.518	-0.694	-4.418
R^2	0.770	0.706	0.774	0.706	0.764	0.706
Observations	1,804	4,461	1,804	4,461	1,804	4,461

Notes: Re-estimates the mixed-intake specification of Table 5 with *Post Burn* defined over a 12-month (columns 1–2) or 36-month (columns 5–6) fire lookback window; columns 3–4 repeat the main 18-month estimates of Table 5. *Top-Coded* marks bonds whose issuer had no new-money issue in the previous 20 years, including first-ever issues. Controls, fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.3 Robustness to specification of time fixed effects

C.3.1 PWSs with surface-water-only intakes

Table C3: TWFE: Alternative Time Fixed Effects (SW-only PWS)

	Year + Quarter FE (Main)		Year FE Only		Year × Quarter FE	
	Single HUC	Pooled	Single HUC	Pooled	Single HUC	Pooled
Post Burn	58.023**	38.645***	52.094**	27.451**	48.908**	64.094***
	(23.490)	(14.038)	(22.993)	(13.423)	(18.121)	(20.557)
Months Since Last Issue	-0.247*	0.079	-0.266**	0.072	-0.094	-0.093
	(0.130)	(0.180)	(0.104)	(0.167)	(0.460)	(0.250)
Top-Coded	76.259***	-1.594	76.981***	-5.400	116.588*	74.136
	(22.183)	(46.640)	(18.917)	(43.670)	(63.388)	(48.999)
Coupon Rate	-1.597	-0.225	-1.221	0.494	-1.705	-2.403*
	(1.850)	(1.565)	(1.921)	(1.756)	(1.652)	(1.394)
Log(Bond Size)	2.516	1.144	2.016	-1.126	-4.422	-5.868**
	(2.828)	(3.550)	(2.584)	(3.201)	(2.947)	(2.238)
Years to Maturity	2.115***	2.236***	2.134***	2.446***	2.974***	3.156***
	(0.437)	(0.398)	(0.393)	(0.364)	(0.456)	(0.338)
Bank Qualified	28.102*	28.387**	25.056	22.998	30.558	2.562
	(14.416)	(13.097)	(16.963)	(14.540)	(22.632)	(11.161)
Callable	16.349***	17.469***	16.101***	17.221***	14.506***	14.253***
	(2.703)	(2.549)	(2.702)	(2.906)	(2.548)	(2.220)
Insured	-21.032	-24.548	-23.974	-29.592*	-76.957***	-63.842***
	(18.763)	(14.992)	(18.126)	(17.107)	(22.386)	(14.361)
Tax Exempt	-111.902***	-108.129***	-109.778***	-111.814***	-109.832***	-113.086***
	(13.568)	(7.822)	(13.714)	(8.545)	(10.892)	(9.331)
Mean Dependent Variable	85.403	77.766	85.403	77.766	85.237	77.638
N Total PWS	28	38	28	38	28	38
N Treated PWS	6	12	6	12	6	12
N Treated Bonds	108	226	108	226	107	225
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	No	No
Quarter Fixed Effects	Yes	Yes	No	No	No	No
Year × Quarter Fixed Effects	No	No	No	No	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[58.023, 148.382]	[38.645, 193.015]	[52.094, 142.884]	[27.451, 210.464]	[48.908, 649.755]	[64.094, 365.353]
Oster Delta*	-11.722	-1.727	-12.982	-1.310	10.099	-2.424
R^2	0.842	0.801	0.835	0.780	0.875	0.876
Observations	1,362	1,878	1,362	1,878	1,360	1,876

Notes: Columns 1–2 repeat the main SW-only estimates of Table 5, with additive year and quarter fixed effects. Columns 3–4 use year fixed effects only, and columns 5–6 use year × quarter fixed effects. *Top-Coded* marks bonds whose issuer had no new-money issue in the previous 20 years, including first-ever issues. Controls, PWS and credit-rating fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.3.2 PWSs with mixed surface and groundwater intakes

Table C4: TWFE: Alternative Time Fixed Effects (Mixed-intake PWS)

	Year + Quarter FE (Main)		Year FE Only		Year × Quarter FE	
	Single SW HUC	Pooled	Single SW HUC	Pooled	Single SW HUC	Pooled
Post Burn	30.208***	6.573	30.225***	6.114	36.944***	4.153
	(7.384)	(9.520)	(7.402)	(9.427)	(10.133)	(6.916)
Months Since Last Issue	-0.032	-0.089	-0.043	-0.106	-0.073	-0.102
	(0.132)	(0.096)	(0.127)	(0.086)	(0.290)	(0.133)
Top-Coded	11.234	18.910	13.419	23.120	12.943	15.729
	(32.357)	(21.755)	(31.188)	(20.052)	(59.187)	(27.377)
Coupon Rate	8.035***	6.698**	8.088***	6.620**	3.969*	6.366***
	(2.176)	(2.660)	(2.272)	(2.749)	(1.957)	(2.017)
Log(Bond Size)	-7.771***	-8.337***	-7.462**	-8.157***	-7.430***	-6.728***
	(2.500)	(2.325)	(2.686)	(2.389)	(2.491)	(1.598)
Years to Maturity	2.207***	2.418***	2.159***	2.393***	2.816***	2.590***
	(0.405)	(0.300)	(0.417)	(0.295)	(0.497)	(0.218)
Bank Qualified	-27.747	-9.491	-28.332	-9.233	-68.028*	-12.449
	(20.826)	(19.955)	(18.254)	(20.143)	(33.192)	(18.863)
Callable	14.620***	14.775***	14.714***	14.824***	7.303**	11.269***
	(4.125)	(2.589)	(4.038)	(2.497)	(2.602)	(1.572)
Insured	-13.303	-4.232	-11.085	-3.700	18.292**	-3.441
	(21.312)	(9.889)	(20.252)	(10.024)	(7.079)	(7.797)
Tax Exempt	-134.196***	-140.767***	-134.660***	-140.669***	-141.803***	-143.305***
	(11.921)	(10.364)	(11.767)	(10.490)	(15.426)	(13.138)
Mean Dependent Variable	68.760	66.423	68.760	66.423	68.771	66.440
N Total PWS	24	50	24	50	24	50
N Treated PWS	7	21	7	21	7	21
N Treated Bonds	329	837	329	837	329	836
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	No	No
Quarter Fixed Effects	Yes	Yes	No	No	No	No
Year × Quarter Fixed Effects	No	No	No	No	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[30.208, 103.071]	[6.573, 16.193]	[30.225, 101.818]	[6.114, 15.214]	[36.944, 433.738]	[4.153, 26.736]
Oster Delta*	-4.233	-1.518	-4.208	-1.464	-13.951	-0.932
R^2	0.774	0.706	0.773	0.705	0.857	0.803
Observations	1,804	4,461	1,804	4,461	1,803	4,459

Notes: Columns 1–2 repeat the main mixed-intake estimates of Table 5, with additive year and quarter fixed effects. Columns 3–4 use year fixed effects only, and columns 5–6 use year × quarter fixed effects. *Top-Coded* marks bonds whose issuer had no new-money issue in the previous 20 years, including first-ever issues. Controls, PWS and credit-rating fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.4 Robustness to top coding specification

C.4.1 PWSs with surface-water-only intakes

Table C5: TWFE: Months Since Last Issue Top-Coded at 20, 10, and 5 Years (SW-only PWS)

	20-Year Cap (Main)		10-Year Cap		5-Year Cap	
	Single HUC	Pooled	Single HUC	Pooled	Single HUC	Pooled
Post Burn	58.023**	38.645***	51.852**	38.314**	71.886***	37.561**
	(23.490)	(14.038)	(19.662)	(14.412)	(25.312)	(14.467)
Months Since Last Issue	-0.247*	0.079	-0.350**	0.068	0.569**	0.141
	(0.130)	(0.180)	(0.139)	(0.160)	(0.267)	(0.288)
Top-Coded	76.259***	-1.594	55.313***	7.207	-41.039**	-1.464
	(22.183)	(46.640)	(10.841)	(15.322)	(17.306)	(10.453)
Coupon Rate	-1.597	-0.225	-1.862	-0.140	-0.829	-0.103
	(1.850)	(1.565)	(1.712)	(1.690)	(1.820)	(1.704)
Log(Bond Size)	2.516	1.144	1.920	1.053	1.350	0.950
	(2.828)	(3.550)	(2.537)	(3.219)	(2.735)	(2.977)
Years to Maturity	2.115***	2.236***	2.199***	2.239***	2.142***	2.239***
	(0.437)	(0.398)	(0.430)	(0.398)	(0.390)	(0.390)
Bank Qualified	28.102*	28.387**	28.323*	27.896**	13.214	24.896**
	(14.416)	(13.097)	(14.310)	(11.901)	(15.055)	(12.213)
Callable	16.349***	17.469***	16.614***	17.601***	17.263***	17.418***
	(2.703)	(2.549)	(2.698)	(2.416)	(2.593)	(2.371)
Insured	-21.032	-24.548	-11.681	-24.018	-26.304	-25.855
	(18.763)	(14.992)	(16.603)	(15.496)	(19.151)	(15.679)
Tax Exempt	-111.902***	-108.129***	-110.850***	-108.264***	-107.623***	-107.124***
	(13.568)	(7.822)	(12.686)	(7.947)	(13.382)	(8.463)
Mean Dependent Variable	85.403	77.766	85.403	77.766	85.403	77.766
N Total PWS	28	38	28	38	28	38
N Treated PWS	6	12	6	12	6	12
N Treated Bonds	108	226	108	226	108	226
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[58.023, 148.382]	[38.645, 193.015]	[51.852, 129.092]	[38.314, 185.160]	[71.886, 190.179]	[37.561, 191.337]
Oster Delta*	-11.722	-1.727	-15.785	-1.736	-9.949	-1.700
R^2	0.842	0.801	0.851	0.801	0.845	0.800
Observations	1,362	1,878	1,362	1,878	1,362	1,878

Notes: Columns 1–2 repeat the main SW-only estimates of Table 5, with *Months Since Last Issue* capped at 20 years (240 months). Columns 3–4 cap it at 10 years (120 months) and columns 5–6 at 5 years (60 months). *Top-Coded* marks bonds whose issuer had no new-money issue within the cap, including first-ever issues. Controls, fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.4.2 PWSs with mixed surface and groundwater intakes

Table C6: TWFE: Months Since Last Issue Top-Coded at 20, 10, and 5 Years (Mixed-intake PWS)

	20-Year Cap (Main)		10-Year Cap		5-Year Cap	
	Single SW HUC	Pooled	Single SW HUC	Pooled	Single SW HUC	Pooled
Post Burn	30.208***	6.573	33.784***	6.686	30.109***	5.939
	(7.384)	(9.520)	(6.320)	(9.795)	(6.918)	(9.374)
Months Since Last Issue	-0.032	-0.089	-0.285	-0.059	-0.506*	0.020
	(0.132)	(0.096)	(0.218)	(0.125)	(0.258)	(0.212)
Top-Coded	11.234	18.910	45.878**	0.683	15.423	-12.657
	(32.357)	(21.755)	(17.250)	(13.137)	(9.533)	(9.306)
Coupon Rate	8.035***	6.698**	7.083***	6.738**	7.453***	6.585**
	(2.176)	(2.660)	(2.010)	(2.697)	(2.199)	(2.631)
Log(Bond Size)	-7.771***	-8.337***	-7.978***	-8.312***	-6.564**	-8.118***
	(2.500)	(2.325)	(2.297)	(2.333)	(2.404)	(2.276)
Years to Maturity	2.207***	2.418***	2.313***	2.413***	2.151***	2.404***
	(0.405)	(0.300)	(0.379)	(0.302)	(0.437)	(0.295)
Bank Qualified	-27.747	-9.491	-19.058	-10.381	-31.502	-9.856
	(20.826)	(19.955)	(15.745)	(19.824)	(18.386)	(19.091)
Callable	14.620***	14.775***	14.086***	14.912***	14.464***	14.860***
	(4.125)	(2.589)	(4.399)	(2.663)	(5.091)	(2.646)
Insured	-13.303	-4.232	-14.891	-4.306	-12.576	-3.561
	(21.312)	(9.889)	(20.063)	(9.979)	(21.628)	(9.844)
Tax Exempt	-134.196***	-140.767***	-136.708***	-140.892***	-136.979***	-140.675***
	(11.921)	(10.364)	(11.198)	(10.444)	(10.234)	(10.458)
Mean Dependent Variable	68.760	66.423	68.760	66.423	68.760	66.423
N Total PWS	24	50	24	50	24	50
N Treated PWS	7	21	7	21	7	21
N Treated Bonds	329	837	329	837	329	837
PWS Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Credit Rating Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Oster Bounding Set	[30.208, 103.071]	[6.573, 16.193]	[33.784, 95.372]	[6.686, 16.441]	[30.109, 89.912]	[5.939, 14.920]
Oster Delta*	-4.233	-1.518	-4.227	-1.530	-4.281	-1.439
R^2	0.774	0.706	0.785	0.706	0.779	0.708
Observations	1,804	4,461	1,804	4,461	1,804	4,461

Notes: Columns 1–2 repeat the main mixed-intake estimates of Table 5, with *Months Since Last Issue* capped at 20 years (240 months). Columns 3–4 cap it at 10 years (120 months) and columns 5–6 at 5 years (60 months). *Top-Coded* marks bonds whose issuer had no new-money issue within the cap, including first-ever issues. Controls, fixed effects, and sample are as in Table 5; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.5 Pooling test across single- and multi-watershed PWSs

Table C7: Chow-test: Heterogeneous treatment effects (fire in 18mo lookback window)

Comparison	Full-break wild-boot p	Classical-iid SSR F
Panel A: PWSs that only access surface water		
Single HUC vs Multi HUC	0.033	32.046
Panel B: PWSs that access both surface and groundwater		
Single SW HUC vs Multi HUC	0.405	19.283

Notes: Chow tests of whether the spread regressions in Table 5 differ between single- and multi-HUC PWSs. Each panel uses the corresponding *Pooled* column of that table. Panel A covers California surface-water-only PWSs, excluding Contra Costa Water District, split by whether a PWS's intakes lie in one HUC-12 or in several. Panel B covers California PWSs drawing on both surface water and groundwater with at least one surface-water intake HUC, excluding the Metropolitan Water District of Southern California, split by whether a PWS's surface-water intakes lie in one HUC-12 or in several.

C.6 Robustness of secondary market results

C.6.1 Secondary Market (CA, CO, and OR Pooled, SW-only)

Table C8: Secondary Market TWFE: Alternative Time Fixed Effects (CA, CO, and OR Pooled, SW-only)

	Full Sample 2005–2024			Recent Sample 2012–2024		
Time Fixed Effects	Single HUC	Multi HUC	Pooled	Single HUC	Multi HUC	Pooled
Year × Month (Main)	12.032	-1.445	8.328	17.089**	-6.133	3.468
	(9.027)	(12.352)	(8.498)	(6.517)	(4.092)	(4.120)
Year Only	11.463	0.662	9.412	13.961**	-2.991	4.882
	(8.820)	(12.613)	(8.956)	(5.325)	(5.785)	(5.538)
Year + Quarter	11.481	-0.194	9.165	14.272**	-5.056	4.233
	(8.995)	(12.667)	(8.985)	(5.503)	(5.621)	(5.476)
Year × Quarter	12.526	-1.827	8.351	17.656**	-6.218	3.768
	(9.010)	(12.526)	(8.662)	(6.638)	(4.151)	(4.407)
Year + Month of Year	11.301	-0.114	9.225	14.227**	-4.797	4.459
	(9.048)	(12.702)	(8.974)	(5.503)	(5.643)	(5.434)
Bond Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Log Months Since Last Trade	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Each cell is the *Post Fire* coefficient. The first row repeats the main estimates of Table 9, with year × month fixed effects. The other rows replace them with year fixed effects only, additive year and quarter fixed effects, year × quarter fixed effects, and additive year and month-of-year fixed effects. Bond and state fixed effects, the log of the months since the bond's previous trade month, and the samples are as in Table 9; standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C.6.2 Secondary Market (California, SW-only)

Table C9: Secondary Market TWFE: Alternative Time Fixed Effects (California, SW-only)

	Full Sample 2005–2024			Recent Sample 2012–2024		
Time Fixed Effects	Single HUC	Multi HUC	Pooled	Single HUC	Multi HUC	Pooled
Year × Month (Main)	-8.654	16.715	10.194	-7.505	-3.427	2.974
	(16.909)	(14.450)	(9.578)	(9.060)	(3.492)	(4.602)
Year Only	-5.924	15.489	11.309	-3.937	-6.599	0.880
	(16.665)	(17.272)	(11.065)	(6.163)	(4.813)	(6.828)
Year + Quarter	-6.245	15.421	11.263	-4.911	-7.662	0.885
	(16.872)	(17.578)	(11.121)	(7.111)	(4.642)	(6.607)
Year × Quarter	-7.705	15.639	10.088	-7.470	-4.997	2.136
	(16.572)	(15.652)	(9.702)	(9.978)	(2.809)	(4.621)
Year + Month of Year	-6.686	16.303	11.864	-4.941	-6.924	1.765
	(16.998)	(17.599)	(11.187)	(7.192)	(4.710)	(6.624)
Bond Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Log Months Since Last Trade	Yes	Yes	Yes	Yes	Yes	Yes

Notes: As Table C8, for the California estimates of Table 10: bond fixed effects, without state fixed effects. Standard errors clustered by PWS in parentheses. * p<0.1, ** p<0.05, *** p<0.01.