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Article

Mitigating Wildfire Impact on Water Quality through Climate-Based Financing: A Case Study of the Provo River Watershed

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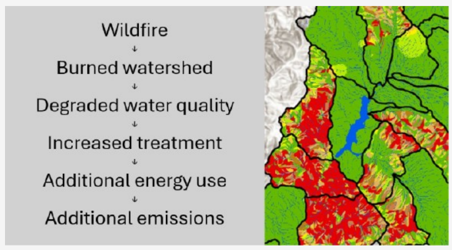

ABSTRACT: Following wildfires, riverine water quality in forested watersheds is prone to degradation, impacting drinking water treatment and potentially causing increased carbon emissions because of additional electricity consumption during treatment. We explore the potential for climate-based financing to support wildfire mitigation and watershed restoration by reducing potential water treatment energy demand following a fire within the Provo River watershed, Utah, USA. We model pre- and post-wildfire erosion and water quality in the Provo River using GeoWEPP. We use energy data from a water treatment plant in the watershed and literature data to estimate the increase in energy use for treating degraded water. We find that most watershed areas are not subject to large treatment demand changes, but a few hotspots are prone to increased sediment loads. In the Provo River watershed, on average, a fire in a single 12-digit hydrologic unit code (HUC) subwatershed corresponds to an additional 350 metric tonnes of carbon-dioxide-equivalent (CO_2e) emissions for one year following a wildfire event due to increased energy required by the water treatment plant. If wildfire risk is reduced, the avoided emissions can generate a potential of \$88,500 annually in carbon credit revenue (at \$10/CO_2e credit) for the contributing HUC8 sub-basin.

KEYWORDS: *energy-water nexus, wildland fires, erosion, GeoWEPP, carbon credits*

INTRODUCTION

Surface waters from forested watersheds supply over half of the drinking water to people across the United States.[1,2] Wildfires can increase upland erosion and introduce new pollutants such as ash, which lowers the water quality of the watershed,[3,4] impacting the receiving water for drinking water treatment facilities. Severe wildfires are increasing in frequency and intensity,[5,6] threatening the water quality of these critical watersheds.

Wildfires have been found to increase turbidity, total nitrate (TN), total carbon (TC), total organic carbon (TOC), dissolved organic carbon (DOC), and other water contaminants in watersheds.[7] Hohner et al.,[3] in their analysis of treating water impacted by a wildfire, recommended that water treatment plants prioritize turbidity and DOC removal in the shorter term, but also phosphorus in the longer term. This phosphorus is bioavailable and associated with sediment and can promote algal blooms that can significantly increase treatment needs and associated energy consumption.

The United States Environmental Protection Agency (EPA) regulates both surface water and drinking water quality. The EPA regulates point-source pollution to surface water through the Clean Water Act; however, there is currently no policy that regulates nonpoint-source pollution due to wildfires and other hard-to-control contaminant sources.[8] Drinking water for the general public is protected through the Safe Drinking Water Act which requires water utilities to meet certain water quality metrics in the finished drinking water.[9,10] Most surface water treatment requires filtration plants or equivalent technologies to meet these metrics, requiring systems with low-quality source water to use relatively energy-intensive technology.

In the event of a wildfire affecting water quality, water suppliers may be required to treat more-impaired water, leading to additional electricity demand to meet regulations[11−13] and, in some instances, capital costs for facility upgrades,[14] both referred to as gray infrastructure.

Drinking water and wastewater treatment plants are the largest energy consumers for many municipal governments, often accounting for 30% to 40% of total energy consumtion.[15] Across the US, water and wastewater treatment plants account for nearly 2% of total energy consumed, resulting in 45 million metric tonnes of carbon dioxide equivalent (CO_2e) emissions per year,[16] potentially increasing by another 30 million metric tonnes of CO_2e per year as regulatory bodies increase treatment obligations on utilities.[17]

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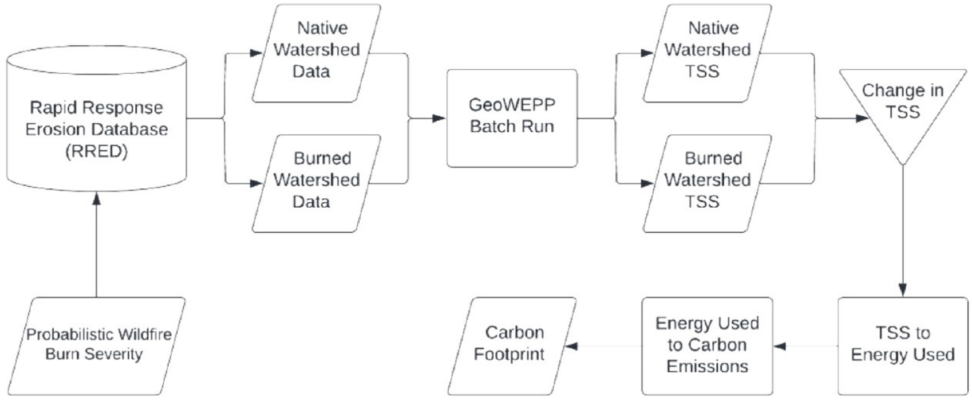

Figure 1. Process flowchart, starts at bottom left and follows arrows.

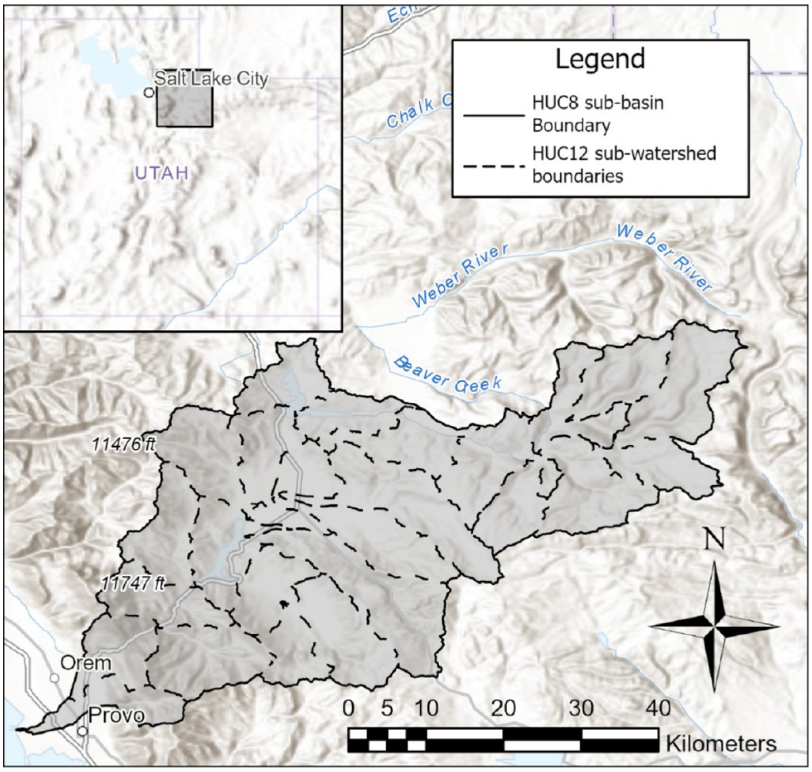

Figure 2. Study area of the Provo River watershed.

Electricity consumption by water treatment plants due to effects from a wildfire could be reduced with low-tech restoration and watershed management methods,[18] referred to as green infrastructure. This includes riparian, floodplain, and wetlands restoration; wildfire mitigation efforts; erosion barriers; improved forestry management; and other efforts to reduce nonpoint source contamination to meet water quality standards.[19−21] Implementing measures to mitigate wildfire severity and upland erosion can prevent and mitigate nonpoint source pollution, thereby averting the associated increase in energy consumption by the water treatment plant.

Market-based water quality trading programs have been established and recently strengthened by the EPA[22,23] and several state-level regulators. These green infrastructure trading programs are often more cost-effective than gray infrastructure alternatives.[17,24−26]

This research evaluates the potential for climate-based financing to mitigate the impact of wildfires in the Provo River Watershed. This is achieved through modeling pre- and post-wildfire upland erosion and total suspended solids (TSS) loads via downstream sediment delivery. Subsequently, we estimate greenhouse gas (GHG) emissions at the water treatment plant (WTP) from additional energy requirements, which can serve as substitutes for green infrastructure methods through watershed management and stream restoration. Finally, we assess and evaluate the Voluntary Carbon Markets (VCM) potential to generate revenue for these avoided emissions

■ METHODS

In this study, we evaluated the potential impact on WTP energy consumption and carbon emissions from increased sediment due to wildfires for the Provo River sub-basin. We modeled expected wildfire burn severity and associated upland erosion for each subwatershed and aggregated the loads to estimate increased water treatment requirements for the Don

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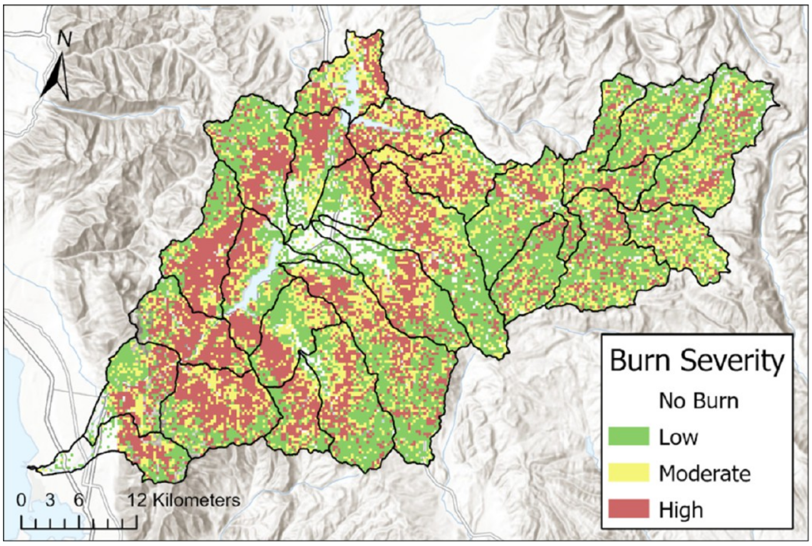

Figure 3. Predicted burn severity for the Provo River watershed.

A. Christiansen Regional WTP at the point of diversion in Provo Canyon. The process used in this research is outlined in Figure 1. Subsequent sections describe the methods of each step.

Study Area. This study analyzed the Provo River watershed, identified as 8-digit Hydrologic Unit Code (HUC8) 16020203 in the United States Geological Survey (USGS) database.[27] The HUC8 sub-basin consists of 25 HUC12 subwatersheds. The boundaries are provided by the USGS and are representative of watershed delineation of second- and third-order streams.[28] Within the Provo River Watershed the HUC12 subwatersheds are on average 71 km^2.

This HUC8 sub-basin is approximately 1800 km^2. Starting in Uinta-Wasatch-Cache National Forest, the Provo River flows from east to west into Utah Lake. From there the Jordan River flows north to the Great Salt Lake. Elevations within the watershed range from 1400 to 3600 m above sea level. The extent of this watershed is shown in Figure 2.

Fire Burn Severity. In selecting modeled wildfire burn severity we chose a spatial data set of probabilistic wildfire components from the United States Forest Service (USFS).[29] This tool uses FlamMap to predict the probability of the occurrence of a wildfire burn and its intensity based on inputs of environmental variables including weather conditions, elevation, slope, and fuel moisture. The burn intensity is ranked by six classes of flame length. We converted flame lengths to wildfire burn severity using the methods outlined by Buckley et al.[30]

The burn severity data does not predict if a wildfire occurs across the entire study area, merely the likely burn severity if a wildfire occurs in the location.[30] The data provides 270 m spatial resolution of burn severity as seen in Figure 3. We modeled upland erosion and sediment transport changes by assuming that the entire subwatershed unit burned.

Soil, Land Cover, and Elevation Data. For soil and land cover inputs, we used the Rapid Response Erosion Database (RRED).[31] This database compiles soil data from the United States General Soil Map (STATSGO) or the Soil Survey Geographic Database (SSURGO), which is the preferred source if available since it has more detail. We compiled the land cover from the Landscape Fire and Resource Management Planning Tools (LANDFIRE). Finally, elevation data was provided by the USGS. Because of size limitations of the online database interface, we partitioned the burn severity map into 100 km by 100 km tiles. We individually uploaded each tile into the RRED interface to access the database, which contains elevation and land cover classes (56 in total), and soil data at a 30 m spatial resolution. We compiled the RRED data for each tile into a single raster for each data type. We used the National Hydrography Dataset (NHD)[32] to remove water bodies from the elevation raster, thus preventing GeoWEPP from calculating upland erosion within these bodies.

GeoWEPP Modeling. There are many different models available to estimate soil erosion. Among the most common are the Universal Soil Loss Equation (USLE), Modified USLE (MUSLE), and Revised USLE (RUSLE); however, these models are limited since they are empirical.[33,34] We used the Water Erosion Prediction Project (WEPP), which was initiated in 1985 by the United States Department of Agriculture (USDA) to develop a new generation of water erosion modeling technology.[35] WEPP is process-based, giving it advantages over empirically based models by being capable of estimating spatial and temporal distributions of net soil loss.[36] WEPP models can also be extrapolated to a broad range of conditions which may not be practical to test in the field.[36] The RRED allows the direct input of the wildfire burn severity to produce the required WEPP inputs, whereas the MUSLE equation requires changes in several variables to reflect wildfire burn disturbance.[37]

WEPP allows a Geographic Information System (GIS) interface through two applications: Quantum GIS WEPP (QWEPP) and Geospatial-Interface WEPP (GeoWEPP).[38] These interfaces are designed for 10 km^2 watersheds and require additional optimization efforts when applied to larger basins; however, details of erosion distribution are less accurate.[39]

To model erosion, we used GeoWEPP 10.4.0.[40] The model runs small watersheds, so we analyzed the Provo River HUC8 sub-basin as 25 separate HUC12 subwatersheds. We performed two model runs for each subwatershed: one for the native conditions and the other for post-fire conditions, resulting in 50 runs of the GeoWEPP model. To manage the workload efficiently, we performed them as a batch job.[39]

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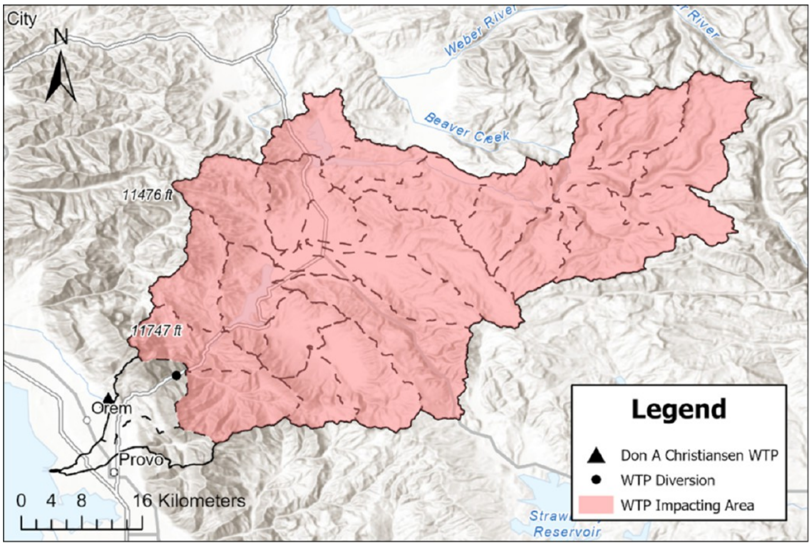

Figure 4. TSS impacting watersheds.

GeoWEPP is not setup to batch run, so we produced a Python code utilizing a graphical user interface (GUI) control to automatically run the GeoWEPP program for each HUC12 subwatershed. Further advancement of the WEPP GIS interfaces would aid in performing large-scale studies such as this one, bypassing the need for laborious manual GUI control, as exemplified by the Python program's reliance on button clicks.

Extracting TSS Output at Each Outlet. To obtain the TSS results at the outlet of each HUC12 we used the text output from the GeoWEPP program. From the model output we extracted the water discharge, hill slope soil loss, sediment delivery ratio at the outlet, and percent clay particles variables.

For the sediment yield, our focus is primarily on clay particles given their large role in contributing to turbidity and effects on WTPs.[41] We are primarily concerned with the change in sediment yield (SY) from the hill slope, as defined in eq 1.

$$\begin{aligned} &\text{SY (metric tonnes)} \\ &\quad = \text{Hill Slope Erosion (metric tonnes)} \times \text{Delivery Ratio} \\ &\quad \times \%\text{Clay} \end{aligned} \tag{1}$$

Using the upland sediment yield and discharge, we estimated the downstream sediment delivery as TSS (mg/L) using eq 2. GeoWEPP does not account for bodies of water such as a reservoir, lake or pond, which can lead to some watersheds having multiple outlets. If more than one outlet occurred in a watershed, because of a lake or reservoir that was not modeled, we took the weighted average TSS, using discharge as the weight.

$$\text{TSS}\left(\frac{\text{mg}}{\text{L}}\right) = \frac{\text{SY (metric tonnes)}}{\text{Q (m}^3)}\left(\frac{1\ \text{m}^3}{1{,}000\ \text{L}}\right)\left(\frac{10^9\ \text{mg}}{1\ \text{metric tonne}}\right) \tag{2}$$

TSS Routing. The sediment and discharge from each HUC12 subwatershed combine with other watersheds as they flow downstream to the point of diversion for the WTP. To simplify, we assume that the water and sediment will reach the point of diversion without any losses. We model the change in TSS at the WTP diversion as the increase of one individual HUC12 subwatershed rather than the cumulative change of all watersheds. We computed this using a mass balance for the sediment and discharge shown in eq 3.

$$\frac{\Delta \text{SY}_{\text{HUC12}} + \text{SY}_{\text{Total}}}{\Delta \text{Q}_{\text{HUC12}} + \text{Q}_{\text{Total}}} - \frac{\text{SY}_{\text{Total}}}{\text{Q}_{\text{Total}}} = \Delta \text{TSS}_{\text{WTP}} \tag{3}$$

The "total" terms represent the native total of sediment yield and discharge that is upstream of the WTP diversion. The "delta" terms represent the additional load modeled from the fire. The overall expression is thus the diluted TSS at the WTP diversion.

Conversion to Energy. Sediment from burned watersheds is primarily mobilized by rainfall and snowmelt. The time from when the fire occurred to the first major storm event impacts how severe the contamination will be.[42] A laboratory simulation[43] found that leachate from post-fire soils requires more coagulation to meet typical water quality standards than that of pre-fire soils. This decrease in effectiveness would require WTPs to use more coagulation, raising the energy used and cost to treat water.[14]

However, unpublished data we analyzed from four Utah WTPs seem to belie such logic. The data instead show a negative correlation between energy use and turbidity, suggesting that turbid water is less energy-intensive to treat than clean water. This counterintuitive finding may be attributed to the small sample size or to confounding effects of other variables that are not affected by water quantity or quality. One example is the energy-intensive process of ozone disinfection at two of the plants, therefore masking energy use from other processes. Another theory is that certain clay particles act as dense floc nuclei, actually aiding settling. Yet another potential reason for these data is the strong seasonality of these plants and their operations, where benefits from economy of scale may outweigh any additional energy associated with poor raw water quality at a given point in time. More-turbid water may require more chemical addition and therefore cost,[12] but not necessarily more energy use. Regardless, the pattern we observed in the data exposes an important gap in the water−energy nexus: empirical relation-

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ships between raw water quality and WTP energy use need to be investigated further.

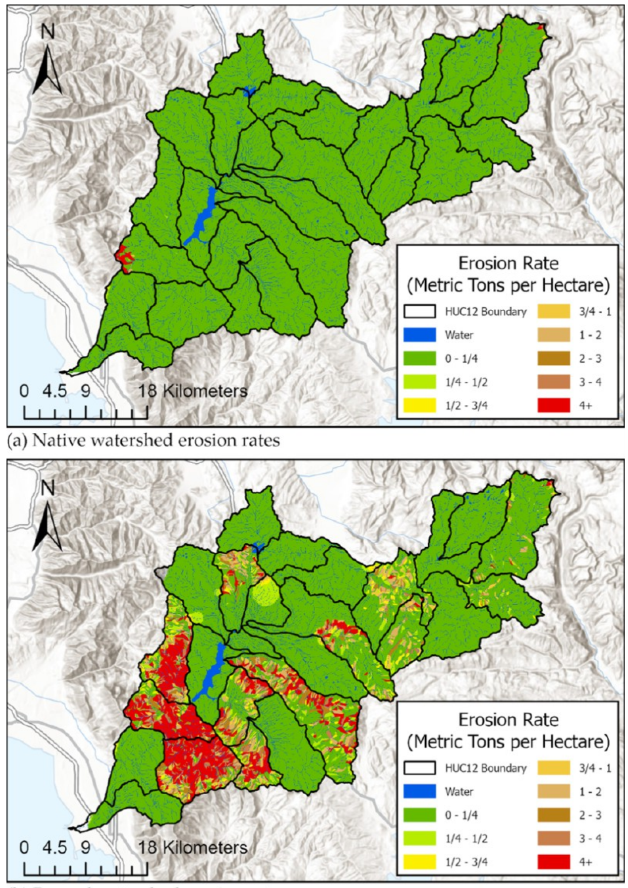
For this study, we obtained three years (2016−2018) of monthly energy use records from the Don A. Christiansen Regional WTP, which can divert and treat up to 380,000 m^3/d of water from the Provo River.[44] Its energy use averaged 2,955 MWh/yr during the period of record. In their study of 146 Chilean WTPs, Molinos-Senante and Maziotis[11] found that, on average, a 1% increase in TSS corresponded to a 0.175% increase in energy use. In the absence of adequate local data, we applied the same ratio to the Don A. Christiansen Regional WTP; a 1% increase in TSS to the plant would correspond to a 5,171 kWh/yr increase in energy use.

Since the Don A. Christiansen Regional WTP receives water from a diversion at the Olmstead Dam before the outlet of the HUC8 sub-basin, we only included increases in TSS from watersheds upstream of the diversion (shown in Figure 4).

Energy to Carbon Emissions. Since watershed management is a long-term maintenance obligation and wildfire effects can range from weeks to years, we considered single-year emissions. We used the Cambium National Renewable Energy Lab (NREL) energy forecast data from 2022[45] to convert energy consumption to carbon-dioxide-equivalent (CO_2e) emissions. We opted to use data from the midcase scenario, which has central or median values for core inputs such as technology costs and fuel prices, moderately paced demand growth, and electricity sector policies.[45] For our analysis, we analyzed predictions from a few select years to better understand how carbon emissions may vary in the future. The electricity to emissions conversion can be found in Table 1.

Table 1. Cambium Electricity Generation Emission Predictions

Year	CO_2e kg/MWh
2024	704.6
2026	616.5
2028	550.6
2030	502.8



(a) Native watershed erosion rates

(b) Burned watershed erosion rates

Figure 5. Modeled erosion rates.

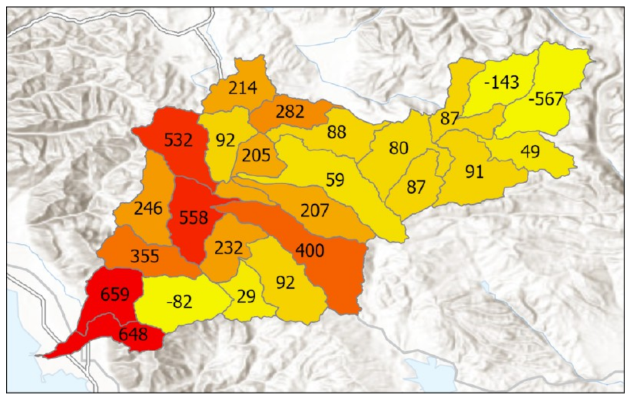


Figure 6. Change in TSS at outlet of subwatershed shown in mg/L.

RESULTS AND DISCUSSION

The resulting sediment yield at the mouth of each HUC12 subwatershed before and after a wildfire is shown in Figure 5. Again, we are not predicting that a wildfire occurs across the whole HUC8 sub-basin; these are representative of the hillslope sediment yield if a wildfire occurs at any location.[30]

The change in TSS shown in Figure 6 represents the increase from the discharge for each HUC12 subwatershed between pre- and post-fire conditions. While the values illustrate individual change in each watershed, they do not reflect the direct impact to the Don A. Christiansen Regional WTP, which receives water at the diversion point shown in Figure 4. Values reflecting the TSS impact to the WTP diversion for fires in each HUC12 subwatershed are presented in Figure 7.

By utilizing the TSS changes at the WTP diversion, we determined the carbon footprint for burns in each HUC12 subwatershed, as illustrated in Figure 8. Additionally, we identified the HUC12 average and HUC8 total CO_2e savings for one year following a wildfire event in the given year, detailed in Table 2. Also we present data on the potential for carbon credits, with a carbon credit price of \$10/metric tonne of CO_2e. These values are representative of the potential savings in electricity usage at the WTP after a wildfire.

Observations. As observed in Figure 5, forested areas exhibit varying upland erosion potential patterns. There is no universal pattern for upland erosion and downstream sediment delivery increases after a wildfire; instead, there are a few natural hotspots of increased erosion, while the majority of the watersheds experience little increase in erosion. The few hotspots are in regions with steeper slopes, deciduous forests, and higher burn severity.

Some HUC12 subwatersheds showed enhanced water quality after wildfires. These areas typically had shallower

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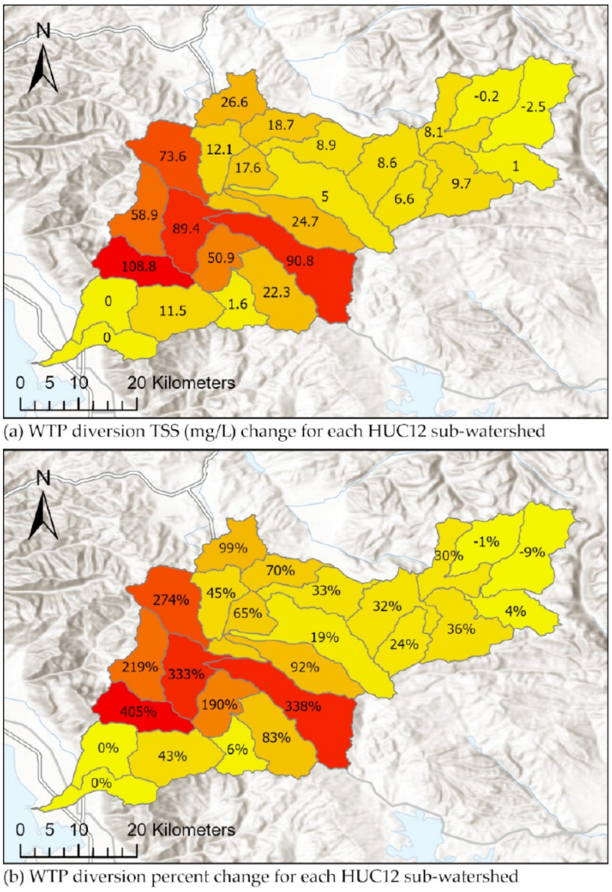

Figure 7. Predicted TSS increase at the WTP diversion.

slopes, evergreen forests or barren land, and lower burn severity. Low burn severity allows some plants to quickly regenerate from surviving roots or seeds, benefiting from nutrient release and reduced competition. This contributes to increased soil stability and decreased erosion.[46] The runoff likely increases due to hydrophobic soils, reduced evapotranspiration, and interception by plants.[47] Therefore, the improved water quality may be attributed to the absence of additional upland erosion coupled with increased runoff downstream, leading to the dilution of sediment load.

Table 2. Estimated CO_2e Savings and Carbon Credit Value

		2024	2026	2028	2030
HUC12 Average	CO_2e (metric tonnes)	354	310	277	253
	Carbon Credit	$3,540	$3,100	$2,770	$2,530
HUC8 Total	CO_2e (metric tonnes)	8,859	7,751	6,922	6,321
	Carbon Credit	$88,590	$77,510	$69,220	$63,210

There are several critical parameters that must be considered in determining erosion, such as slope, vegetation, and soils.[48] Raoelison and Valenca[49] investigated many postwildfire studies and similarly found that each watershed responded differently. This reinforces the need for erosion models, as the correct model will reflect how erosion changes across different geological, atmospheric, and ecological regions. The results from our study will vary if applied to different watersheds; we demonstrate a method for evaluating water treatment energy impacts through a case study.

Our study found that the resulting TSS concentrations increased for some burned watersheds, with the highest values increasing by up to 600 mg/L. This is consistent with studies that have measured data following a wildfire.[50] However, by the time it reaches the diversion for the WTP, the increased sediment is diluted. We computed that the largest increase in TSS at the diversion was 109 mg/L − not nearly as impactful as the TSS increase of the individual watershed. Regardless, this difference still represents a fourfold increase in TSS, which impacts the WTP performance.

Potential for Wildfire Burn. The carbon emissions suggested in Table 2 and Figure 8 assume a fire occurs in each area but do not consider their actual potential to occur. Predicting the occurrence of a wildfire is difficult given the

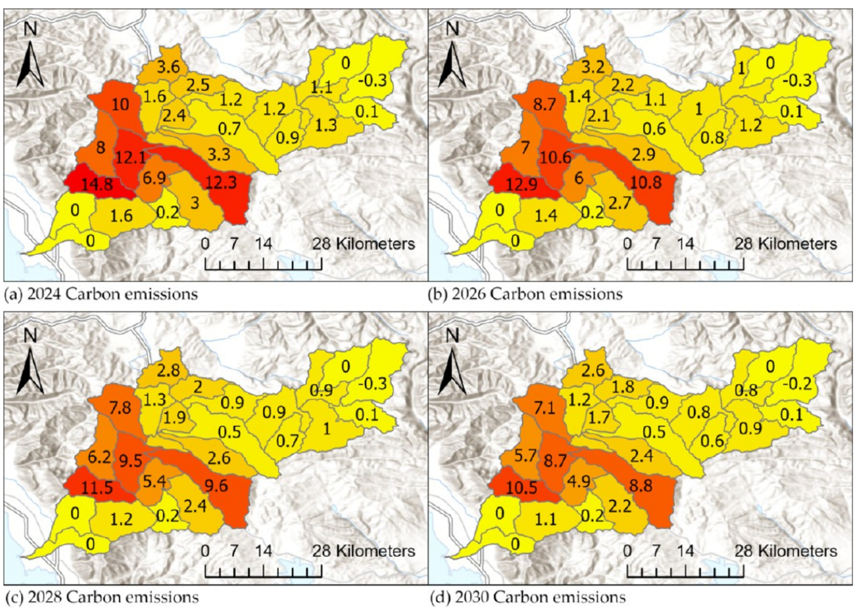

Figure 8. Predicted WTP carbon emission increase after wildfire burn by years, values shown in thousand metric tonnes.

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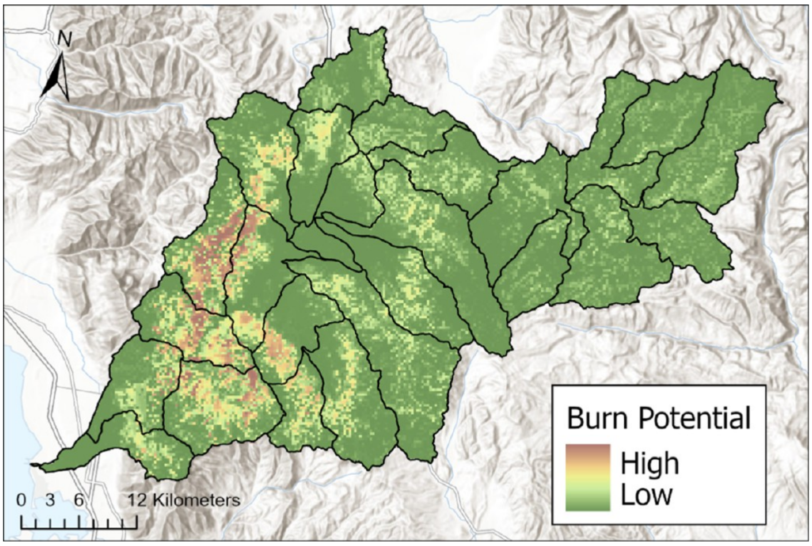

Figure 9. WHP burn potential.

many variables that could ignite and fuel a wildfire.[51] In determining the potential for preventing a wildfire, it is critical to consider the likelihood of a wildfire occurring in the first place. One helpful tool is the Wildfire Hazard Potential (WHP) map,[52] which presents the potential for a wildfire to occur. Figure 9 shows the WHP map for the Provo River watershed. It is evident that some HUC12 subwatersheds contain little potential to burn. However, those that do contain a high burn potential are among the ones that contribute the highest TSS increase for the WTP diversion, making them a higher risk for both fire and increased sediment load. The potential for a burn should be analyzed before a decision is made about watershed management activities, carbon credits, or related investments.

Potential for Carbon Emission Savings. International carbon credit markets are designed to financially incentivize early, voluntary actions toward climate change mitigation, adaptation, and reduced emissions. New methods have been developed to facilitate the generation of carbon credits by substituting green infrastructure for gray infrastructure, thereby enhancing watershed health and water quality.[53] These initiatives of mitigating emissions offer significant social benefits[54] and have the potential to generate an annual carbon credit of $88,500 (at $10/credit) for the HUC8 sub-basin contributing to the Don A. Christiansen Regional WTP, provided wildfire impacts are mitigated in each of the HUC12 subwatersheds. This would provide an opportunity to further incentivize green solutions that meet water quality standards comparable to gray infrastructure.

With approximately 2,400 HUC8 sub-basins across the conterminous United States, this suggests an estimated potential of $200 million in annual carbon credit revenue if a wildfire impacting the WTP did not occur. The estimated credits that could be realized hold a level of risk as a wildfire cannot be prevented altogether, but can be mitigated to prevent starting or spreading. We acknowledge that each HUC8 sub-basin is different and may yield higher or lower carbon savings, further modeling and investigation should be done for other watersheds.

The proposed carbon credits could be used for either creating a wildfire-resistant community or stream restoration following a wildfire, both of which would prevent CO_2e emissions from WTP operation. Any initiatives aimed at responding to a wildfire should have policies in place before the event. In using green infrastructure, consideration should be given to different methods, as effectiveness may vary.[55]

One may argue that certain wildfire mitigation actions, such as tree thinning, may offset or exceed the carbon emissions saved through reduced energy consumption at the WTP. However, the emissions saved extend beyond energy consumption at the WTP. One of the major carbon sources saved is that of the wildfire itself, which can be a major contributor to greenhouse gases.[56] Additionally, increased upland erosion from unmitigated postfire runoff may result in greater sediment deposition in lakes and reservoirs,[57] subsequently diminishing green energy output from hydropower facilities[58] and necessitating dredging, potentially contributing to additional emissions.[59,60]

Limitations. Inadequate pre- and postwildfire water quality data[61] result in critical assumptions within our model.

The FlamMap tool used in this analysis assumes that the intensity of the fire can be used as a surrogate for soil burn severity, which was suggested by Buckley et al.[30] A few years following that study a fire did indeed occur on part of that study area, burning a small fraction of the lower end of that basin. One of the observations following that fire was that the FlamMap tool that used flame length to predict soil burn severity was a poor estimator of burn severity. More recent studies have tried different approaches with a random forests analysis of nearby fires. There is a need to improve burn severity prediction to support studies such as this one.

The impact of a wildfire on water quality fluctuates over time, typically with water quality improving as vegetation regenerates and mitigates upland erosion.[42] Nevertheless, the restoration of vegetation and other watershed factors hinge on various variables and necessitate the creation of an additional model,[62,63] which falls outside the scope of our current study. Our analysis concentrates on the water quality of a burned watershed for a single year. Future investigations might delve deeper into this aspect to enhance modeling accuracy regarding the long-term watershed reaction to wildfires.

Many WTPs can store water or use another source if the water quality is poor; however, it is not known if all plants have

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this ability. For our analysis we assume that WTPs treat the water regardless of the water quality.

There may be many impacts that improve or impair the water quality before it reaches the WTP diversion. The water may evaporate, the water may infiltrate into groundwater, and clay particles may settle in reservoirs or wetlands. However, in this analysis we assume that the water at the outlet of each HUC12 subwatershed reaches the WTP diversion without interruption.

We also assume that energy consumption at the WTP increases with water degradation linearly. Water treatment energy use is complex; however, a lack of data, especially on relationships between raw water quality and WTP energy use, limits our ability to predict energy consumption as a function of raw water quality.

There is simply not enough research and data regarding the above issues. We join members of the USGS in their call to prioritize efforts to gather better data to improve modeling processes.[62]

CONCLUSIONS

Wildfires can be linked to electric grid emissions through a chain of water quality degradation, treatment demands, and energy use. Some links in the chain are well understood and can be accurately modeled while others are weak and need further attention. Through our case study we have demonstrated one possible approach to modeling the situation and suggest it could be a useful application for climate-based financing to motivate watershed management.

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CRediT: **Braxton W. Porter** conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing - original draft, writing - review & editing; **Robert B. Sowby** formal analysis, funding acquisition, investigation, methodology, resources, supervision, writing - review & editing; **Gustavious Paul Williams** investigation, methodology, writing - review & editing; **Braden J. Limb** investigation, writing - review & editing; **Jason C Quinn** funding acquisition, investigation, writing - review & editing; **Alex Johnson** funding acquisition, investigation, writing - review & editing; **Evan A. Thomas** conceptualization, funding acquisition, investigation, project administration, validation, writing - review & editing.

Notes

The authors declare no competing financial interest.

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