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# Socio-Economic Impact of the Rapid Response Erosion Database (RRED)

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## Abstract

Rapid response is critical following natural disasters like wildfire. Fire, runoff, and erosion risks are highly heterogeneous in space, creating an urgent need for rapid, spatially-explicit assessment. In the past, data preparation has been time consuming and expensive, resulting in extensive losses in values-at-risk (VARs). The Rapid Response Erosion Database (RRED, http://rred.mtri.org/rred/) allows researchers and land managers to access properly-formatted spatial model inputs for the Water Erosion Prediction Project (WEPP) anywhere within the continental US and eventually beyond. Comprehensive support for post-fire hydrological modeling is provided by allowing users to upload spatial soil burn severity maps, and within moments download spatial model inputs. The database has been used to help assess and plan remediation on more than a dozen wildfires in the Western U.S. RRED has already saved $694,000 between May 2016-December 2018 in administrative costs. In the future, the potential to save time and money on data preparation can extend beyond wildfire to include tracking contaminated sediments, agricultural pollution, and construction site erosion. RRED may also be a useful tool to protect VARs as illustrated by our analysis of recreation, property values, and clean drinking water.

## Keywords

Wildfire, Fire Effects, Hydrology, Erosion, GIS, Modelling, Non-Market Values

## 1. Introduction

Soil erosion by water is a critically important global hydrological problem impacting both natural resources and agricultural productivity (Pimentel et al., 1995; Verheijen et al., 2009). Water detaches and transports soil from the landscape affecting soil productivity, water quality, reservoir storage, and wildlife habitat (Pimentel et al., 1995; Turner et al., 2007; Huffman et al., 2013). Eroded sediments can represent a significant source of phosphorus and nitrogen delivery in areas with high erosion losses. These two nutrients result in hypoxic environments in freshwater rivers, lakes, and coastal estuaries (Carpenter et al., 1998; Turner et al., 2007). The removal of protective ground cover and vegetation from soils by wildfire or any other process has the potential to dramatically increase runoff and erosion (Robichaud & Brown, 2000; Moody & Martin, 2001; Moody et al., 2013). Vegetation and soil duff protect mineral soil from raindrop splash and increase flow path lengths resulting in less runoff and erosion. High temperatures from the fire can change soil structure making them more erodible (Certini, 2005; Larsen et al., 2009) and gases formed by burning organics can result in soil hydrophobicity further increasing run-off and erosion (DeBano, 2000; Doerr et al., 2006; Shakesby & Doerr, 2006). Wildfire, forest management, agriculture, unpaved roads, military exercises, and construction all have the potential to accelerate soil loss (Pimentel et al., 1995; Moody & Martin, 2001; Elliot, 2004; Grace III, 2017).

Healthy forests are highly valued for the protection they provide to water resources as canopies and litter layers protect soils from erosion (Robichaud, 2000; Moody & Martin, 2001). Wildfire removes this protection and that can lead to post-fire flooding and erosion that can then threaten lives, property, and natural resources such as water reservoirs. In the western US, post-wildfire erosion and flooding have been major concerns for many years (Robichaud et al., 2000). After the flames of an active wildfire have passed, land managers must rapidly assess the threat from runoff and erosion. After the Buffalo Creek Fire in 1996, flooding resulted in the deaths of two people and resulted in extensive damage to the town of Buffalo Creek. Sediment from this fire also reduced Denver's municipal reservoir capacity by roughly a third (Agnew et al., 1997). Similar losses of life and/or damage to property have been reported from floods following the 2010 Four Mile Canyon Fire in Boulder, CO and near Colorado Springs following the 2012 Waldo Canyon Fire. Post-fire hazards are of special concern near the wildland urban interface (WUI) (Radeloff et al., 2005), cultural sites, municipal water sources, and sensitive wildlife habitats (Robichaud & Brown, 2000; Moody & Martin, 2001; Cannon et al., 2010; Moody et al., 2013).

Planning the mitigation of post-fire runoff and erosion is typically undertaken by USDA Forest Service Burned Area Emergency Response (BAER) teams, state agencies such as the California Department of Forestry (Cal Fire), and Department of Interior Emergency Stabilization and Rehabilitation (ESR) teams who work to estimate erosion and flood risk. BAER and ESR teams must first determine if treatments to reduce erosion and runoff are needed, and if they are, to prioritize their spatial application to protect watersheds and downstream values at risk (Parsons et al., 2010). Time is critically important as emergency plans and remediation treatments need to be in place before the first major storm to be effective (Parsons et al., 2010). Multiple remediation options are available and include installing warning signs, closing trails and recreation areas, seeding, mulching, checking dams, replacing culverts, and even the installation of large sediment and debris basins (Girona-García et al., 2021; Robichaud et al., 2021; Napper, 2006). Mulching has been found to be one of the most effective treatments as it immediately provides surface cover (Robichaud et al., 2013a; 2013b). One of the first BAER team tasks is to create a soil burn severity (SBS) map using Earth Observation data and ground surveys to identify the areas of high, moderate, and low burn severity (Parsons et al., 2010). The SBS map helps ascertain risk of increased runoff and erosion, and prioritize treatment areas. Slope, soil properties, climate, and location are important factors in determining post-wildfire risk (Renard et al., 1997; Pietraszek, 2006). Process-based hydrological modeling can be used to synthesize and predict the impact of these spatially varying conditions. Remediation planning and work often starts before a wildfire is fully contained.

The NASA applied sciences program recognizes the value of modeling and Earth Observations for both preparing for and responding to disasters (Tralli et al., 2005; Joyce et al., 2009). To better utilize Earth Observations and to fulfill a need for rapid assessment of burned watersheds NASA funded the development of the Rapid Response Erosion Database (RRED, Miller et al., 2016). The inspiration for RRED was to create a modeling database to support hydrology models used by the USDA Forest Service. RRED is similar to LANDFIRE which provides spatial information needed for fire behavior models used in wildfire management (LANDFIRE, 2011; Calkin et al., 2011). In this paper, we are reporting on a socio-economic impact analysis conducted to evaluate current and future impacts of RRED.

The objective of the socio-economic impact analysis is to quantify the net benefits of the RRED database. A database usage analysis was performed to estimate potential cost savings. Non-market values for ecological and human-use services were also examined based on a well-directed literature review of journal articles that estimate relevant non-market values; these studies are published in highly regarded venues and are specifically relevant to the human-use service losses associated with post-fire weather events. We used case studies to demonstrate the impacts and utility of using both Earth Observations and spatial process-based models to support BAER assessments and fuels planning projects. Demonstrating the utility of the database can garner ongoing support for maintaining the database and for providing training to BAER team members, engineers, and students in the use of spatial process-based models.

## 2. Background

Many modeling tools and datasets have been developed to predict post-fire runoff and erosion, but more accurate process-based models have historically been under-utilized compared to simpler, lumped-element models because they are both more difficult to set up and require spatial inputs (Miller et al., 2016). This has been changing with the advent of spatial online modeling tools and databases such as RRED created to facilitate the wider use of process-based models for spatially explicit predictions of erosion and runoff. RRED focuses on use of Water Erosion Prediction Project (WEPP) based models, but the basic idea of advanced preparation of model inputs is adaptable to other models. Another spatial model commonly used in post-fire remediation planning is AGWA, the Automated Geospatial Watershed Assessment tool (Guertin et al., 2019). AGWA is a spatial interface for running the KINEROS2, RHEM (Rangeland Hydrology and Erosion Model), and SWAT (Soil Water Assessment Tool) models (Goodrich et al., 2012).

The inspiration and need for RRED is clearly demonstrated with two wildfires: the 2011 Rock House fire that burned 127,500 ha (315,000 acres) in Texas and the 2012 High Park fire that burned 35,300 ha (87,287 acres) in Colorado. The Rock House fire impacted historic Fort Davis, a national park site located in the Hospital Canyon watershed (217 ha; 536 acres). Even though the Hospital Canyon watershed that needed to be modeled was relatively small, the time needed to create spatially explicit soil and vegetation data for modeling in WEPP Watershed prohibited the operational use of the predictions by the National Park BAER team. When the High Park fire burned in 2012, the data layers representing soil, land cover, and DEM layers were already prepared from a previous project along with GIS tools for rapidly modifying soil and vegetation data with new information from satellite-derived burn severity maps. The entire burn scar for the High Park fire (35,300 ha) was modeled using GeoWEPP in less than three days which allowed the predictions to be available for operational use. These example fires demonstrate the efficacy of preparing both the modeling tools and datasets before they are needed.

### 2.1. Water Erosion Prediction Project (WEPP)

WEPP based interfaces have been created to predict runoff and erosion in recently burned watersheds (https://forest.moscowfsl.wsu.edu/fswepp/; accessed 19 May 2020). WEPP is a process-based hydrological model developed by a team of interagency scientists (Laflen et al., 1997). WEPP technology encompasses two versions: a hillslope model to estimate the distribution of erosion on individual hillslopes, and the WEPP Watershed model that links the hillslope version with channels and in-stream structures in order to predict sediment delivery from small watersheds. The focus in this study is on interfaces designed to be utilized for BAER applications. Disturbed WEPP (Elliot, 2004) is an online hillslope interface for WEPP designed by USDA Forest Service scientists to facilitate the use of WEPP in forested areas. Disturbed WEPP input files can be used to simulate a variety of forest conditions and management scenarios within WEPP based models, including the effects of fuel treatments and wildfire (Soto & Diaz-Fierros, 1998; Elliot et al., 1999; Larsen & MacDonald, 2007; Spigel & Robichaud, 2007; Dun et al., 2009).

### 2.2. Rapid Response Erosion Database (RRED)

For modeling, the user can select a spatial resolution of either 10 or 30 m based on DEM data available through RRED from the USGS national elevation map (http://seamless.usgs.gov/). If an area is selected with a bounding box tool, the soil properties are parameterized for agricultural applications; however, if an SBS map is uploaded or the user selects a historical fire, the soil properties are parameterized for forest soils. Historical burn severity data are from the Monitoring Trends in Burn Severity Project (MTBS). It is important to remember the MTBS burn severity data has not been adjusted by a BAER team to reflect ground surveys on soil burn severity, soil surface cover, and water repellency (Parsons et al., 2010; Eidenshink et al., 2007; US Department of Agriculture and Department of the Interior, 2009). The land cover data delivered by RRED is created within the web interface by combining the SBS map with land cover derived from the LANDFIRE Existing Vegetation Type (EVT) data (Rollins, 2009; LANDFIRE, 2011). RRED uses both SSURGO and STATSGO soil data. SSURGO datasets contain detailed soil maps created by the Natural Resource Conservation Service but contain some data gaps (Miller & White, 1998; Soil Survey Staff, 2014). To fill in the gaps, RRED uses the STATSGO database, which has complete coverage and is a seamless layer (U.S. Department of Agriculture, 1991). The STATSGO database has a coarser spatial resolution than SSURGO. RRED delivers the soils, land cover, and DEM data in a UTM projection formatted for use by two spatial WEPP models, GeoWEPP and QWEPP. GeoWEPP, is the Geo-spatial interface for WEPP and works within ESRI ArcMap (Renschler, 2003). QWEPP is an open-source interface for WEPP Watershed developed as a plugin for QGIS (QGIS Development Team, 2017). QWEPP fulfills a need for a stable and flexible spatial interface for WEPP Watershed tailored to work with RRED (Miller et al., 2019).

### 2.3. Values-At-Risk (VAR): Benefits from RRED

Weather-related sedimentation occurs post-fire in the absence of mitigation due to loss of ground cover and changes in soil structure (Larsen et al., 2009). The strong inverse relationship between ground cover and sediment yields suggests that declines in erosion rates to pre-burn conditions can be obtained primarily by post-fire rehabilitation techniques that increase ground cover (Benavides-Solorio & MacDonald, 2001; Robichaud et al., 2013a; 2013b). Quick responses may avert the loss of VARs, particularly if the mitigation is in place prior to a major rainfall event.

As wildfires are expected to increase in spatial extent and severity given fuel accumulations, shifting land management practices, and climate-change influences, it is important to understand the impacts of sedimentation following these fires and their effects on VARs (Westerling et al., 2006; Miller et al., 2012; Jolly et al., 2015; Sankey et al., 2017). The primary effects of the fire itself include "the removal of soil-mantling vegetation and litter, the deposition of ash, the creation of water-repellent soils, and the effects of temperature extremes on soil and rock" (Robichaud, 2000; DeBano, 2000; Parise & Cannon, 2012). These primary effects are what lead to post-fire susceptibility of soils to flooding, sedimentation, and debris flows that negatively affect recreation, water quality and quantity, and property values, among other services. In watersheds, resulting loss of vegetation and decreased soil infiltration can cause an increase in peak flows and sediment mobilization that increase turbidity and negatively impact water quality (Moody et al., 2013; Sham et al., 2013; Raucher et al., 1995). In addition, depending on fire properties and site conditions, delivery of phosphorus and nitrogen can significantly rise, increasing the risk of eutrophication of rivers, lakes, and reservoirs; and adversely impact aquatic resources and water supplies (Elliot et al., 2015; Rhoades et al., 2018).

In assessing post-fire damage and guiding direct mitigation efforts, a few issues need to be addressed. First, BAER teams typically only have one week to report their findings. Delayed responses can create problems given that the longer it takes to put mitigation practices in place, the greater the likelihood of an erosion event occurring (Ice, 2004). Second, to date, typical benefit-cost analyses of post-fire damages tend to base lost benefits on market-driven estimates of costs of replacement (Calkin et al., 2007). While it may be important to recognize costs of replacement determined by market values, the majority of losses are likely to be "non-market" VARs, discussed below, which are the true lost benefits while costs of replacement are not. These non-market values should be considered more fully in benefit analysis than they have in the past. RRED can help address both of these problems because it is quick and easy to use, and because it can be used in conjunction with another NASA-developed tool, RECOVER, which provides information on VARs (Schnase et al., 2014).

## 2.4. Values-At-Risk (VAR): Benefits Estimation

The development costs of RRED have already been incurred through NASA funding, and it is in use in several states. The costs of using RRED, and the cost savings over slower traditional methods, are documented in this paper. Prior to the existence of RRED, spatially explicit model inputs and parameters would have to be created for each fire individually from the ground up. This would require sizable administrative and research budgets on a case-by-case basis, and could lead to delays in response actions, and thus lost VARs that could have been averted using this new database. Ideally, a response program that utilizes both earth observations and process-based models would be in place within one week of a fire, but that often did not occur.

### 2.5. Values-At-Risk (VAR): Non-Market Valuation of Human-Use Services Provided by Ecological Resources

The natural environment provides services to human beings that often cannot be measured using market data. As such, we turn to "non-market valuation" methods to fill this gap, and these values are widely used and accepted for this purpose. Nonetheless, VARs in past studies have been generally relegated to replacement costs for losses that can be monetized using market data (e.g., culverts, land leases) based on the belief that the valuation of non-market services is "unrealistic" because the necessary data are "not consistently available" (Calkin et al., 2007). Costs are not an approximation of benefits, although this seems to be a misunderstanding in BAER research, and may omit the values of many ecological and human-use services. Consequently, a deeper investigation into lost benefits may provide a more adequate basis to evaluate the economic contributions of RRED.

Non-market values associated with sedimentation can be linked to human-use services such as recreation, quality/quantity of drinking water sources and their reliability, property values, in-stream flows and water quality for fisheries, wetland habitats, and passive uses, to name just a few. An example where non-market values have influenced post-fire analysis and activities is in the Lake Tahoe Basin, where the values of homes and recreation are due in part to the pristine condition of the lake. Major management activities to reduce fire risk are occurring in the basin, and in 2016, a fire as small as 80 ha warranted the use of the RRED database to evaluate erosion risk (Elliot et al., 2018). Although there is a myriad of VARs impacted by sedimentation, this study will only focus on three direct, active services that are reliably quantified: services related to recreation, clean water, and property values.

## 3. Approach

### 3.1. Time Savings Analysis through Data Mining

A simple cost analysis was carried out to estimate the monetary value of time saved by RRED. The salaries of four federal positions were assessed; hydrologist, soil scientist, geologist, and environmental engineer. Additionally, since it was determined from IP addresses that university researchers are using RRED, a student category was included. Non-identifying user data was collected for each instance RRED was used to successfully download data. This included the internet protocol (IP) address, date, and download type (indicating historical fire, user supplied SBS map, or a user-defined region of interest). Using the IP address, the organization and approximate location (city and state) of each user was determined using an IP lookup website (what is my ipaddress.com/ip-lookup).

Between May 2016 and December 2018, more than 1,000 data downloads were recorded, with further filtering indicating that 368 downloads were non-duplicates. The following federal agencies were identified as users based on IP search results: Bureau of Land Management (BLM), Environmental Protection Agency (EPA), USDA Forest Service, National Oceanic and Atmospheric Administration (NOAA), and National Park Service (NPS). The average salary for the five major federal agencies that have accessed RRED were determined (https://www.federalpay.org/; accessed 20 Feb 2019). Mean annual salaries were tabulated with hourly rate, fringe rate, overhead rate. The fully loaded rate ($/hr) was calculated as the sum of the hourly, fringe, and overhead rates. Graduate student rates were used to represent university database users. Out of 15 schools with RRED users, only nine had rates readily available. These hourly rates were averaged together to estimate the value of student labor to be $20.30. Salaries are summarized in **Table 1**.

Time savings was based upon three WEPP-based modeling projects. The first was predicting erosion and runoff for the 2011 Rock House fire. The next two modeling projects required assembling data for sites in Canada. In 2016, our team helped model post-fire erosion risk for the Horse River fire that burned through Fort McMurray in Alberta, and in 2018 we assembled model inputs for a forested site in Ontario, Canada. Assembling land cover and elevation data is usually straight forward; however, creating spatial soil files with necessary WEPP soil parameters can be time consuming. Based on three projects completed without RRED, assembling spatial WEPP inputs required approximately 80 hours of labor to download, process, and properly format required spatial data and input parameters. Using RRED, assembling the required modeling data would take five minutes or less for sites in the continental US. The estimation of savings for each user group is calculated using equation 1.We utilized a compilation of database users and hourly rates to estimate the cost savings generated by the use of RRED. Cost savings were estimated as the difference in cost of 80 hours of labor vs. 5 minutes, as shown in Equation (1). Fully loaded hourly rates for federal hydrologists ranged between $54 (BLM) and $78 (EPA).

$$\text{Savings} = \text{number of users} * \text{fully loaded rate} * (80 - 5/60) \tag{1}$$

## 3.2. Benefits Transfer

Non-market values were obtained using accepted practices for conducting a directed Type A natural resource damage assessment based on existing literature, primarily in reputable, peer-reviewed journal articles, to approximate the value of the RRED. This is common practice when time and budget are limited, but order-of-magnitude monetary approximations for avoided losses (which are estimates of RRED benefits) are needed, primarily for benefits categories that are not readily obtainable for specific sites or case studies. Benefits are more difficult to quantify beyond the cost reductions resulting from savings in time. This is due to a number of unknowns. For example, in the absence of the spatial analysis that RRED enables on specific fires, it is not known what the alternative treatment decisions would have been or the outcomes of these decisions.

Table 1. The average yearly salaries and hourly rates for hydrologists by federal agency.

| Agency/Academia | Yearly Salary | Hourly Rate | Fringe | Overhead | Fully Loaded Rate |
|---|---|---|---|---|---|
| U.S. EPA | $114,799 | $55.19 | $11.59 | $11.83 | $85.79 |
| Forest Service | $75,019 | $36.07 | $12.26 | $7.73 | $56.06 |
| NPS | $91,895 | $44.18 | $15.02 | $9.47 | $68.67 |
| BLM | $72,557 | $34.88 | $11.86 | $7.48 | $54.22 |
| Avg Student (20 hr) | $19,556 | $20.30 | $2.07 | $12.72 | $35.09 |

Perhaps more money would have been spent to treat areas that did not need treating. Alternatively, the team may have chosen to treat less area. Uncertainty in future weather conditions in the critical first few years after a wildfire compounds this difficulty as precipitation amounts and intensities impact whether or not treatments are needed.

Nevertheless, a technique called "benefits transfer" is used when there are gaps in the monetary valuation of certain critical and high-value end-use services. "Benefits" are obtained from highly-regarded sources that are relevant to the current need to assess values and then are "transferred" to the current application.

## 4. Results

### 4.1. RRED Case Examples Demonstrating Value

The database was used for assessing and planning post-fire remediation on several recent major US fires (Telegraph, 2021; Cameron Peak, 2020 CO; Chetco Bar, 2017 OR; Soberanes Fire, 2016 CA; Butte Fire, 2015 CA and Washburn, 2022 CA). RRED has been used on at least four fuel management projects from a watershed perspective (Mokelumne, CA; Flagstaff, AZ; East Deer Creek, WA; and Clear Creek, ID) (Elliot et al., 2016; Elliot & Miller, 2017; Srivastava et al., 2018). Recent non-fire applications for RRED include the use of the database to predict erosion from silver mining activities in Idaho (Martin Jacobson, personal communication, 9 Sep 2016) and utilizing the database to predict the long-term effects of clear cutting in the Pacific Northwest (Banach, 2017).

The King fire burned 39,500 ha in the El Dorado National Forest in California during the fall of 2014. The BAER team on the King fire utilized multiple models and modeling scenarios that included predicting the impacts of mulching on post-fire erosion rates. The King fire SBS map was uploaded into RRED which generated the formatted spatial DEM, land cover and soils data needed for modeling in just a few minutes (**Figure 1**). The new land cover map was automatically reclassified within RRED to create the burned soils data layer. The burned and unburned areas within and near the King fire were modeled with input files developed by the USDA Forest Service for modeling grasslands and forests. The soil input layer was automatically created by combining the burned land cover

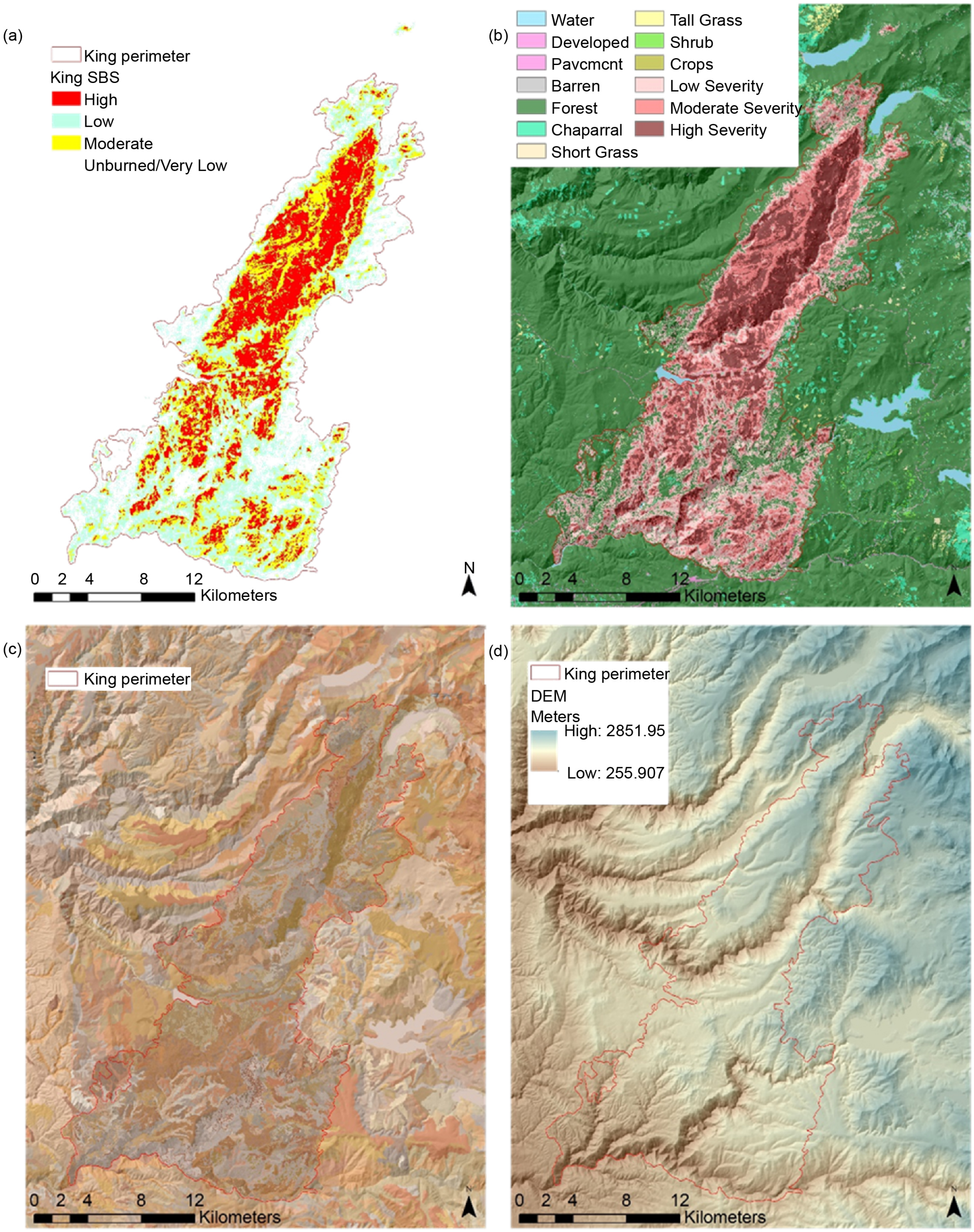

**Figure 1.** Modeling datasets for the King Fire that burned in California. (a) Soil burn severity map created from Landsat 8 imagery the pre-fire image was collected on September 3, 2014 and the post-fire image was collected on October 2, 2014; (b) Post-fire land cover map generated by RRED for the King Fire. The new land cover map was created by combining the soil burn severity map with reclassified LANDFIRE Existing Vegetation Type data; (c) Soils map generated by the database depicting more than 500 soils modified by the burned King Fire land cover layer. d) 30-m DEM downloaded for modeling the King Fire.

data with a base soil layer derived from both the SSURGO and STATSGO datasets. When soils are impacted by fire, the soil parameters are adjusted using Disturbed WEPP parameters based on land cover prior to burning (for example forest or grass), soil texture, and low or high severity soil impacts (Elliot, 2004).

Automating the generation of modeling data freed up time for the BAER team to spend assessing remediation effectiveness. Modeling scenarios for the King fire included predictions of average first year post-fire erosion with 25 years of typical climate and post-fire erosion from a single five-year storm event. Burned watersheds were modeled in both a pre- and post-fire state for both climates to estimate additional erosion due to the fire. Results from initial modeling runs were used to plan several mulch treatment options designed to protect critical infrastructure. Mulching is highly effective for reducing post-fire erosion and runoff as it restores protective ground cover (Wagenbrenner et al., 2006; Robichaud et al., 2013a; 2013b). Mulch treatments were expected to increase ground cover in moderate and high severity areas from 20% - 55% up to 72%. The effects of increased ground cover due to mulching were modeled and the costs and benefits of mulching were compared to the expected costs of dredging sediments from Brush Creek and Slab Creek reservoirs. The rapid modeling results were used to help spatially target more than $1 million in mulching designed to protect critical infrastructure including Eleven Pines Road and reservoirs Ralston Afterbay, Oxbow, and Ralston Powerhouse. The modeling helped justify treatment costs, half of which were paid for by the Sacramento Municipal Utility District to protect their hydroelectric and water supply reservoir downstream of the fire (Jeff Tenpas, USFS Region 5, personal communication, 10 April 2015).

The initial design for RRED included support for pre-fire planning from a watershed perspective. The LANDFIRE EVT data used within RRED to provide land cover was selected to be compatible with USDA Forest Service fire behavior models that were used to forecast fire effects (Buckley et al., 2014; Elliot et al., 2016). Ensuring RRED could support fuel planning from a watershed perspective meets a growing need from land and water management agencies including the USDA Forest Service, EPA, and USGS to better understand and assess threats of wildfire to drinking water source areas. The potential for dramatic increases in post-fire runoff, erosion and sedimentation is well documented (Robichaud et al., 2013a; 2013b; Moody & Martin, 2001; Cannon et al., 2008; Moody & Martin, 2009). Water utilities relying on water from landscapes recently impacted by wildfire can spend millions of dollars treating water supplies to remove sediment and nutrients, and dredging post-fire sediments that reduce water storage capacity in critical water reservoirs. Denver Water spent $26 million treating drinking water and dredging Strontia Springs Reservoir, and the Los Angeles County Public Works needed $190 million for dredging four reservoirs impacted by sediment from the 2009 Station Fire (US Department of the Interior 2013).

RRED provides modeling support to land and water managers seeking ways to mitigate post-fire erosion and flooding before a wildfire even occurs. By reducing fuel loads in critical watersheds, communities are trying to reduce the severity and frequency of fire so that when the inevitable wildfire does occur, the impacts will be lessened. In the Mokelumne Basin in California a diverse set of stakeholders joined forces to create the Mokelumne Avoided Cost Analysis (MACA) committee (Buckley et al., 2014). The goal of MACA was to plan and evaluate fuel reduction treatments to protect both their community and water supplies from high severity wildfire. A four-step modeling technique was followed to assist in planning fuel's treatments to protect water supplies (Elliot et al., 2016). Erosion predictions from the four steps were used to spatially prioritize fuel's treatments and quantify potential benefits. Reducing fuel loads in the watershed was predicted to significantly reduce long term overall erosion rates (Elliot et al., 2016).

### 4.2. Time Savings Analysis through Data Mining of Internet IP Addresses

Based on these hourly rates and the number of users per federal agency, the total cost savings were calculated and ranged between $5,500 for the National Park Service and up to $300,000 for the USDA Forest Service. We included students in our analysis even though they earn significantly less than the federal agency employees, because the number of academic users makes this group responsible for the largest cost savings. By compiling database usage between May of 2016 and December of 2018 we were able to estimate the total cost savings at $694,000 (**Table 2**). This is roughly $22,000 per month which over a ten-year period of operation for RRED would total over $2.6 million in savings assuming current usage continues.

### 4.3. Illustrative Examples: Order-of-Magnitude Benefits

The first search strictly focused on sedimentation following forest fires, yet few studies provided the types of data that were sought. These studies are presented in **Table 3** and include information from the King fire.

Due to limited results from the first search, a second search was undertaken that examined the impacts of sedimentation from stressors other than fire (Heathcote, 2013). These studies are just as relevant because the consequence

**Table 2.** Cost benefit of time savings from RRED.

| Agency | # | 80 hrs | RRED (5 min) | Savings (rounded) |
|---|---|---|---|---|
| U.S. EPA | 4 | $27,453 | $29 | $27,424 |
| Forest Service | 67 | $300,494 | $313 | $300,181 |
| NPS | 1 | $5,494 | $6 | $5,488 |
| BLM | 7 | $30,365 | $32 | $30,333 |
| Student | 118 | $331,249 | $345 | $330,905 |
| Sum | 197 | $695,055 | $724 | $694,331 |

**Table 3.** Values estimates from sedimentation/siltation/runoff due to fires (burned area BAER case study fires).

| Fire (Year) | Location | Types of VARs (what was or is currently at risk) | Lost VARs (what has been assessed) | Mitigation Efforts and Costs Incurred ($2021) |
|---|---|---|---|---|
| Pilot Fire (2008) | San Bernardino National Forest, OR | *Property values:* Increased flooding and sediment along roads<br>*Water quality*: Threat to water quality in Silver Lake<br>*Recreation:* Debris flows, flooding, rockfall, and sediment deposition threaten OHV drivers on roads and hikers on Pacific Crest Trail and Pinnacles Trail | *Recreation:* Killing of trees has affected hiking, biking, and ski/snowshoe use on trails | *Suppression cost*: $15,650,000<br>*Cost of no-action (including loss):* $,000 (based on VAR Tool)<br>*Emergency stabilization treatments:* Invasive species assessment (detection), aerial straw mulching, reinforced driveable drain dips, storm patrol, maintain proper functioning of the road drainage system, signing and traffic control, road-side hydromulching, reconstruct/construct trail drainage structures, trail hazard tree abatement, hazard warning signs/public information, Cooper's Tent Camp and newly discovered Camp Heritage site erosion control/protection, Wagon Road (heritage site) erosion control<br>*Emergency stabilization treatment costs (approved):* $397,900 |
| King (2004) | Eldorado and Tahoe Forests, CA | *Recreation (fishing):* very high risk to roads and trails from flooding and debris flows<br>*Water quality:* very high risk to water quality from hazardous materials<br>*Recreation:* very high risk to trout populations | None assessed yet. | *Suppression cost:* $135,755,000<br>*Cost of no-Action (including loss):* N/A<br>*Emergency stabilization treatments:* strip mulching, bale bombing, straw bale check dams, rock or log grade control structures, channel armoring, culvert treatments, re-establish berms and dips, noxious weeds, hydrologic monitoring, treatment monitoring<br>*Emergency stabilization treatment costs (approved):* $3,767,000 |
| Butte (2005) | Prescott National Forest, AZ | *Water quantity/quality:* while there is likely to be a short term increase in sediment delivery to the channel network, vegetation isexpected to regenerate quickly providing ground cover and reducing erosion | None assessed yet | *Suppression cost:* $1,319,000<br>*Emergency stabilization treatments:* Natural recovery; no treatments reported |
| Cedar (2003) | Cleveland Forest, CA | *Property values:* numerous locations on the road system are at high risk of loss of function and/or are likely to degrade adjacent resources | *Water quantity/quality:* El Capitan reservoir, a major water supply facility for the City of San Diego, will experience increased sedimentation and some loss of storage | *Suppression cost:* >$44,000,000<br>*Cost of no-action (including loss):* $5,443,000<br>*Emergency stabilization treatments:* Aerial hydromulching, fiber rolls, access barriers, restoring drainage function to roads and trails, storm patrols, BAER warning signs, installation of water bars and dips<br>*Emergency stabilization costs (pending approval):* $781,369 |

**Continued**

| | | | | |
|---|---|---|---|---|
| Copper King (2016) | Lolo Forest, MT | *Property Values:* There is a high risk to roads and trails from post fire effects<br>*Water quantity/quality:* Increased sediment and nutrient yield will occur from portions of watersheds that burned at moderate or greater severity | *Recreation:* The Copper King and Clark Memorial campgrounds are recommended to remain closed during the spring until risk of high intensity rains and snow has subsided | *Suppression cost:* $31,000,000<br>*Cost of no-action (including loss):*>$2,776,000<br>*Emergency Stabilization Treatments:* Culvert protection/upgrades/removal, road storm-proofing, drainage maintenance, hazard signs, herbicide, survey and monitoring, hazard tree removal<br>*Emergency Stabilization Costs (pending approval):* $313,000 |

(sedimentation) is the same (Table 4). They provide an even-more compelling story that non-market services and their values can be identified quickly and protected by rapid responses using RRED. While the scope of this project does not provide the opportunity to estimate non-market VARs for sedimentation from a specific fire, the values nonetheless indicate sizable damages associated with even small-to-medium-level impacts. Consider the hypothetical examples presented in Table 5 to support this assertion.

## 5. Discussion and Conclusion

Quantifying the value of RRED is challenging for numerous reasons. Hydrologists and BAER teams currently utilize many different models and methods for predicting erosion and calculating risk. Model predictions have a high degree of uncertainty and the valuation of the resources. RRED could be used to protect such as soil and water quantity and quality can vary and have non-market values (Morrison, 2009). Additionally, an obvious and tangible impact of RRED has been time saved and, therefore, money saved. The estimation of $694,000 in time savings was based on average salaries of federal hydrologists and student stipends. Over the last 5 years, the BAER Imagery support team has provided remote sensing support on roughly one hundred fires per year. If all of these fires were to use RRED, the cost savings over ten years could easily approach $6 million. Although we do not have exact lost non-market VARs, it is easily conceivable that modest post-fire runoff could lead to damages and these damages can be summed, over service categories and future years. In fact, the studies in Table 4 support the possibility that total VARs could be on the order of hundreds of thousands to millions of dollars for each case study, if the correct damage categories are assessed.

The highest potential socio-economic benefit of RRED is savings generated through additional use of WEPP. RRED facilitates the use of WEPP models by eliminating the time consuming step of creating spatial inputs. RRED and WEPP were used operationally to justify and target over a $1 million in mulch treatments on the 2014 King Fire. The RRED database has rapidly provided spatial inputs for WEPP-based models for more than a dozen fires allowing hydrological modeling work to be carried out quickly and the modeling results have

**Table 4.** Values estimates from sedimentation/siltation/runoff (increases or decreases) due to non-fire causes.

| Author (year) | Location | Source of increase/decrease in VAR | Type of VAR | Values (all in $2021) |
|---|---|---|---|---|
| Braden and Johnston (2004) | North Carolina | Impaired storm water runoff | Property values | 1990 TWTP – loss of $29/household/yr<br>2001 TWTP – loss of $41/household/yr<br>1990 % of Property Value – loss of 0.2%<br>2001 % of Property Value – loss of 0.4% |
| Breffle et al. (2015) | Cravath and Trippe Lakes, WI | Sediment control program | Recreation | MWTP - $14 to $37/household/yr |
| Brox et al. (2003) | Grand River Watershed, Ontario, Canada | Decreased urban runoff | Water quality | MWTP – $6(USD)/household/month for residential water quality improvements |
| Deely and Hynes (2020) | Carlingford Lough, Ireland | Provision of water quality that allows direct-contact activities | Recreation, water quality | MWTP - $25/household/year |
| Greenley et al. (1981) | South Platte River Basin, CO | Agricultural runoff avoidance | Recreation | Total option value - $285 m<br>Total recreational use value - $693 m |
| Irwin et al. (2017) | Baltimore County, MD | Stormwater runoff avoidance | Property values | Loss of property value of 14% |
| Leftwich (2007) | Lake Greenwood, SC | 1% increase in sediment within vicinity of homes | Property values | Mean loss of property value of $2.4m |
| Loomis et al. (2000) | South Platte River, CO | Reduction of erosion of streambanks and a gricultural runoff | Water quality | MWTP – $399/household/yr<br>% of Property Value – 3% |
| Lucas at al. (2021) | Rural AK | In-home water reuse facility | Water quality | MWTP - $67 to $97/mo |
| Martínez-Espiñeira (2006) | Jackson Hole, WY | Maintained levels of runoff | Recreation | TWTP – $13/trip |
| Michael et al. (1996) | Echo Lake, ME<br>Sabbattus Lake, ME | Avoidance of increased eutrophication from fertilizers (phosphorus) | Property values | Property value change – $19/foot frontage<br>Property value change - $345/foot frontage |
| Morey et al. (2002) | Silver Bow Creek and Clark Fork River, MT | Removing runoff of heavy metals from mining | Recreation | MWTP – additional $8-$11/year for the absence of injuries ($1.4 m total damages, all anglers) |
| Stevens et al. (1995) | New England | Wetland runoff reduction | Water quality | Mean WTP $132-$142 dollars per year (over a five-year period) for wetlands providing flood protection, water supply, and water pollution control. Aggregate value estimates ranged between $431 m - $558 m per year. |
| Yoo et al. (2014) | Prescott, AZ | Erosion control services associated with a 10% improvement in current canopy cover | Property values | Total property values for all lakes near Prescott: $8m |

TWTP = Total Willingness to Pay for current (or "baseline") conditions, prior to any changes. MWTP = Marginal Willingness to Pay for the expressed change in current (or "baseline") conditions; may be a gain or a loss.

**Table 5.** Hypothetical examples based on the literature unit values from **Table 3** to illustrate non-market service values.

| | |
|---|---|
| Recreation | Suppose a lake that is a regional destination (e.g., the Finnon Recreation Area near Placerville, California, the town closest to the King fire) is filled in with sediment, leading to a decrease in willingness to pay for fishing of $5/per fishing trip. Further suppose that this lake gets only 20 fishing visits per day on average. That amounts to $37,000 in lost fishing VARs, per year. |
| Water quality | Suppose a small-sized city of 10,000 (about the size of Placerville) experiences a significant degradation in its water quality due to runoff leading to a decrease in consumer surplus of just $5 per year per household (assume 2.5 people/household). That amounts to a loss for water VARs of $5,000 per year. |
| Property values | Suppose a community of 500 homes with a mean value of $400,000 (roughly the average value of homes in Placerville) loses stormwater control intermittently due to sediment runoff, leading to a 0.3% decrease in property values. That amounts to a one-time loss of property VARs of $600,000. |

been used on multiple occasions to aid decision makers in post-fire risk assessment and planning for rehabilitation treatments. During the 2015 Butte fire in California, the BLM spent more than $3 million on mitigation treatments that were justified and targeted using modeling products made possible by the RRED database (William Haigh, BLM, Personal communication, 6 January 2016).

Post-fire effects pose a widespread and increasing threat to US water supplies, as 67 of the 100 largest US cities obtain drinking water solely from surface water. RRED has supported multiple fuels planning projects from a watershed perspective (e.g. Mokelumne Basin, CA, Colville National Forest, WA, Flagstaff Watershed Protection Project, AZ, and the Upper Sacramento Basin, CA). These projects were conducted at the request of local forest managers and national- and community-based conservation groups. These end users are often unable to assess the impacts of fuel treatments themselves due to challenges posed by assembling data inputs and parameterizing and running complex models. RRED is currently being used for a large-scale watershed risk assessment being conducted in partnership with the USDA Forest Service and the EPA, helping to identify critical western watersheds at most risk from wildfire.

RRED recently gained national attention for post-fire mitigation as it was mandated in the “John D. Dingell, Jr. Conservation, Management, and Recreation Act”' which was passed into law on March 12, 2019. A part of the soil components of RRED were incorporated into the online USDA Forest Service WEPP interfaces. The online tools allow for even easier modeling access (Robichaud et al., 2019; Lew et al., 2022; Dobre et al., 2022; https://wepp1.nkn.uidaho.edu/weppcloud/). Efforts are ongoing to improve both accessibility and accuracy of post-fire models and datasets used to assess risks from post-fire flooding and erosion.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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