COLORADO FOREST RESTORATION INSTITUTE

Colorado State University

Watershed Investment Tool Technical User Guide

Version V
Last Updated 05/07/2018

This document provides technical details on the Peaks to People Water Fund Watershed Investment Tool.

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Introduction

The Watershed Investment Tool has two main components: 1) GIS pre-processing, which includes fire and erosion modeling to quantify the effects of treatments, and 2) the optimization model interface, which takes the results of the GIS pre-processing and user inputs to analyze treatment benefits, costs, and feasibilities, including treatment plan optimization. The GIS pre-processing is a comprehensive and largely automated workflow that takes in a range of publicly available and custom data sources on current landscape fuel conditions, land cover, hydrography, soils, and climate to estimate the effects of different fuel treatment types on avoiding wildfire-related sediment and sediment costs. Many computationally-intensive GIS tools are applied to large datasets in the GIS pre-processing, so it is not practical to combine the GIS pre-processing and optimization model interface to go from raw input data to treatment planning in a single process. The current configuration separates tasks that require a higher level of technical knowledge and more computing power from those that can be run quickly to support decisions.

The first section of the user guide covers the modeling approach and limitations with references to the supporting science. The second section covers the input data requirements and GIS pre-processing workflow in sufficient detail for an experienced GIS user to replicate the analysis. The third section covers proper use of the Watershed Investment Tool for anticipated workflows.

Modeling Approach

Summary

Landscape-scale fuel treatment planning requires a risk-based approach that considers variability in wildfire likelihood and intensity, and in susceptibility of values and resources to fire effects (Scott et al. 2013). Large watersheds in mountainous topography can include significant intra-watershed variability in climate and vegetation that drive differences in fire regimes, especially the characteristic frequency and intensity of fire. In the Colorado Front Range, fourth level hydrologic unit code (HUC-8) watersheds can cover more than 9,000 ft of relief and the full range of regional vegetation from shortgrass steppe to alpine tundra, which includes considerable variability in forest vegetation and associated fire regimes (Peet 1981). Primary effects of wildfire on hydrological and sedimentological processes are from changes in surface cover and soil properties (Shakesby and Doerr 2006), but these effects are patterned on top of spatial variability in other controls of post-fire erosion, including rainfall, topography, and soils (Pietraszek 2006). Fire effects on watershed resources and assets are secondary, occurring over multiple years following a fire event and at offsite (downstream) locations, requiring spatial topology that quantifies the connections between the upland forests we can manage with fuel treatments and the downstream water values we seek to protect from post-fire sediment.

The modeling approach (Figure 1) was designed to plan a landscape-scale fuel treatment program to maximize avoided costs in post-fire sediment delivered to water infrastructure features of concern (hereafter infrastructure). Intermediate products can be used for analysis and planning at other scales, but project-level planning should always involve critique of the input data and results using higher resolution data sources and/or field visits to verify site conditions.

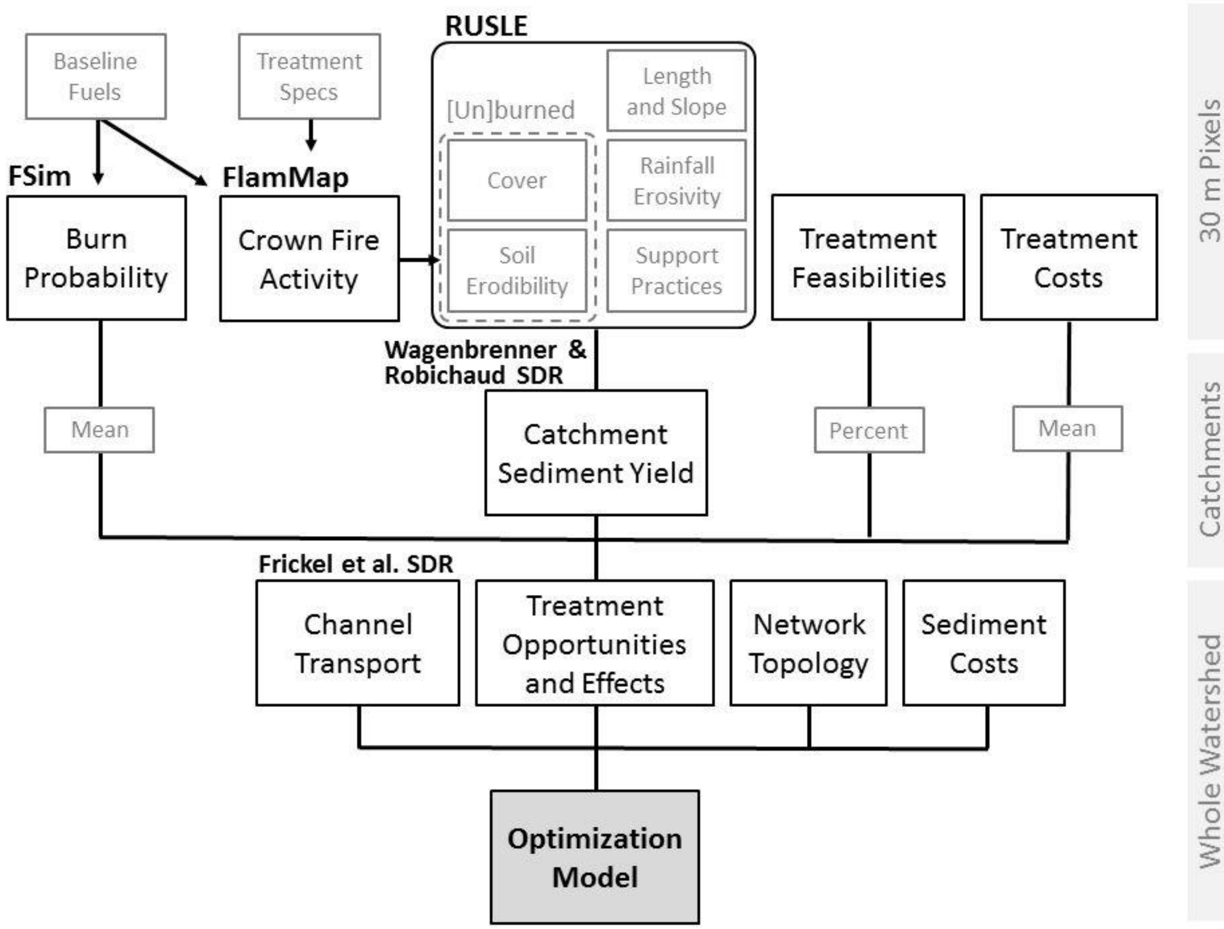


Figure 1: conceptual diagram of the modeling approach showing the workflow and spatial scale that each process model is applied.

Fire Modeling

Fire was characterized in terms of likelihood and severity using different modeling systems that share the same base models for fire spread and intensity (Rothermel 1972, 1991, VanWagner 1977, Finney 2004).

Fire Likelihood

Fire likelihood is most-often modeled using burn probability tools in FlamMap (Finney 2006) or FSim (Finney et al. 2011), or the same fire spread model re-packaged in another fire modeling system. Burn probability is calculated by simulating many thousands of fires under specified fuel and weather conditions to estimate the likelihood of experiencing fire in discrete units of the landscape. As with any model, there are assumptions and limitations. The input data on fuels, weather, and ignition patterns determine how fast fires spread, in what direction, and from where; the degree to which model conditions match future fire conditions determines the applicability of the results. “Many thousands of fires” might represent hundreds of years of fire events, so there is need to calibrate the raw results. Although we might already be seeing increased wildfire activity due to climate change (Westerling et al. 2006), the recent historical record of fire occurrence is used to calibrate the mean burn probability. It is unknown how well the absolute values from burn probability modeling will match future fire regimes, but the spatial patterns and relative values across different vegetation types largely agree with historical fire regimes.

Burn probability tools are quickly evolving to meet the demands for wildfire risk assessment, and the most-advanced tool, the large-fire simulator (FSim; Finney et al. 2011), has not yet been developed into a supported software package for public distribution. FSim has functions that other burn probability tools cannot easily replicate, most notably a fire suppression algorithm (Finney et al. 2009) that assigns higher containment success in non-timber fuel types, leading to much lower burn probability estimates for low elevation grass and shrub fuel types, as well as areas recently burned at high severity (e.g. the Bobcat Fire and the High Park Fire). Feedback from the Peaks to People Water Fund and Working Group favored the use of the National FSim burn probability product (Short et al. 2016) over custom burn probability modeling done in FlamMap, because of its predictions for grass and shrub fuel types. The national burn probability product from Short et al. (2016), which is based on 2012 LANDFIRE data and distributed at 270 m resolution, is incorporated in the model framework (Figure 1) by calculating the catchment-level mean burn probability.

Fire Behavior

FlamMap 5.0 (Figure 1) is used to model crown fire activity (Scott and Reinhardt 2001) as a proxy for soil burn severity. Remote automated weather station (RAWS) data from Red Feather and Estes Park were used to define 97th percentile fuel and weather conditions for the project area. Most area in the Colorado Front Range burns under similar extreme fuel and weather conditions when fires escape initial attack. Basic fire behavior outputs from FlamMap are calculated assuming a head fire, as opposed to flanking or backing which support lower intensity fire. The wind blowing uphill option is used to model the worst-case scenario for each pixel, instead of assuming a single constant wind direction, which would produce different fire behavior across aspects.

Crown fire activity (Scott and Reinhardt 2001) classifies fire type as no fire, surface fire, passive crown fire, or active crown fire consistent with Van Wagner (1977). Crown fire activity has been used as a proxy for soil burn severity in several studies of debris flow risk (Tillery et al. 2014, Tillery and Haas 2016, Haas et al. 2017) by mapping surface, passive crown, and active crown fire to low, moderate, and high severity. This is a reasonable approach, given that many fire effects on watershed processes are only described by coarse levels of fire severity. It may be argued that crown fire activity misses important variation in the effects of surface fire intensity and duration, but fire types tend to map well to soil burn severity levels in most conditions. Future improvements to this process could include use of fire effects models to predict changes in surface cover and soil properties from continuous estimates of intensity or other relevant metrics such as the depth and duration of soil heating.

Fuel Treatments

Common fuel treatments applied in western US forests are mechanical thinning, mechanical thinning followed by prescribed (Rx) fire, and Rx fire. The three common fuel treatment types vary in their effects on fire behavior due to differences in their effects on canopy and surface fuels (Agee and Skinner 2005, Stephens and Moghaddas 2005, Stephens et al. 2009, Fulé et al. 2012). In brief, mechanical treatments can be effective at reducing the crown fire hazard by raising canopy base heights and reducing canopy bulk densities, but they also tend to increase surface fuel loads unless followed by Rx fire. Rx fire is most effective at reducing surface fuel loads, but it has smaller effects on the canopy under the fuel and weather conditions it is typically applied. There are other fuel treatment effects that are important to consider, such as changes in wind speeds and understory vegetation response from reduced canopy cover (Agee and Skinner 2005). Custom fuel treatment prescriptions were developed for mechanical only, mechanical followed by Rx fire, and Rx fire only based on effect sizes reported in the literature (Stephens and Moghaddas 2005, Stephens et al. 2009, Fulé et al. 2012, Ziegler et al. 2017).

Treatment types also differ in their feasibility constraints, which may be physical, administrative, or social in nature. Binary feasibility maps were developed for each of the treatment types based on barriers to their use, such as legal restrictions on mechanical harvesting or fuel conditions that can support extreme fire behavior under typical Rx fire conditions. Cost is sometimes considered as part of feasibility, but the Peaks to People Water Fund specifically asked that costs not be used in determining feasibility, so that economics can determine the value of treating expensive acres. A model of mechanical treatment costs was developed based on distance from roads and slope. In the absence of better local data on Rx fire, we assumed a uniform cost that was added to mechanical treatment costs in the case of combined treatments.

Erosion modeling

There are several erosion models or erosion modeling systems that can predict sediment yields from wildfires at various temporal and spatial scales. Previous studies have used a range of tools for pre-fire fuel treatment planning, post-fire response planning, and sediment budget accounting. Linked modeling approaches have recently been proposed to quantify the effects of fuel treatments on post-fire sediment yields (Elliot et al. 2016, Sidman et al. 2016, Jones et al. 2017), building on advancements in post-fire response planning (Miller et al. 2016). The most common methods employ the Water Erosion Prediction Project Model (WEPP; Flanagan and Nearing 1995), the Kinematic Runoff and Erosion Model (KINEROS; Woolhiser et al. 1990), or the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997). WEPP and KINEROS are both physical process models that can compute runoff and erosion from hillslopes and channels. WEPP simulates these processes over multiple years of randomly generated climate to estimate the range of possible responses over diverse conditions. GeoWEPP (Renschler 2003) and the Automated Geospatial Watershed Assessment tool (AGWA; Guertin et al. 2008) are spatial extensions of WEPP and KINEROS for watershed analysis in GIS. RUSLE is an empirical model of soil loss developed from extensive field experiments (Wischmeier and Smith 1960) computed by multiplying factors for rainfall erosivity (R), soil erodibility (K), cover

(C), length-slope (LS), and support practices (P). RUSLE has been adapted for use in GIS to examine soil loss across large landscapes (Theobald et al. 2010), for post-fire response planning (Yochum and Norman 2014, 2015), and for forecasting erosion under future wildfire-climate scenarios (Litschert et al. 2014).

RUSLE (Figure 1) was chosen to model erosion because of its computational efficiency, flexibility in sources of input data, ease of use, and simple data structure. A custom workflow was developed to automate RUSLE using Python, ArcGIS, and R following the methods of Theobald et al. (2010) with minor modifications. RUSLE cover and soil erodibility factors are reported in the literature for local fires (Larsen and MacDonald 2007, Schmeer 2014) and RUSLE has reasonable accuracy for predicting post-fire erosion when evaluated against local field measurements grouped by fire and severity level (Larsen and MacDonald 2007). RUSLE is ideally restricted to slopes without channelized flow and where erosion is the dominant process (versus aggregation). We masked the channel network from estimates and limited the length-slope factor to the maximum reported in Renard et al. (1997) to adhere to the intended use of the model. Output from our GIS implementation of the RUSLE is annual soil loss at a 30 m resolution.

Network Topology

Given the intended application is planning a landscape-scale fuel treatment program to optimize avoided costs in post-fire sediment delivered to water infrastructure, a spatial topology is needed to represent the connections between the land to manage and the downstream values to protect. Multiple tools exist for discretizing watershed networks, but the National Hydrography Dataset Plus (NHDPlus) was identified as an off-the-shelf data model with the necessary characteristics for the analysis.

NHDPlus includes delineated small watershed areas, or catchments, that correspond to each NHD flowline (Figure 2), and same unique identifier. The catchment represents the area contributing sideflow to each flowline. The project area has 1,827 catchments and the mean size is 651 ac. NHDPlus includes attributes on flow direction, stream order, and other useful variables for watershed network analysis. Infrastructure is connected to the network via contributing flowlines.

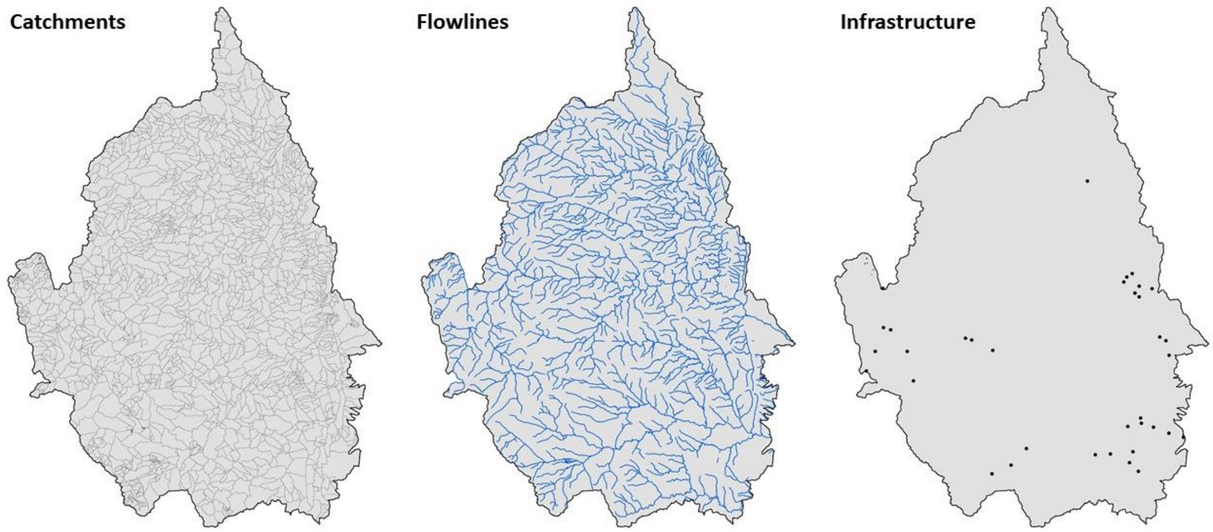


Figure 2: network topology connects NHDPlus catchments to NHDPlus flowlines and routes sediment down the network to infrastructure.

The NHDPlus catchments are a reasonable scale to identify landscape-level fuel treatment priorities, recognizing that project-level planning will utilize higher resolution data and/or site visits. The RUSLE soil loss predictions can be scaled up to catchment sediment yields (Figure 3) using an empirical model of post-fire sediment delivery ratio (SDR) from watersheds burned in the western US, including Colorado (Wagenbrenner and Robichaud 2014).

The per acre avoided sediment from fuel treatment can be calculated at the catchment-level as the difference in catchment sediment yields for untreated and treated scenarios divided by the feasible acres for treatment.

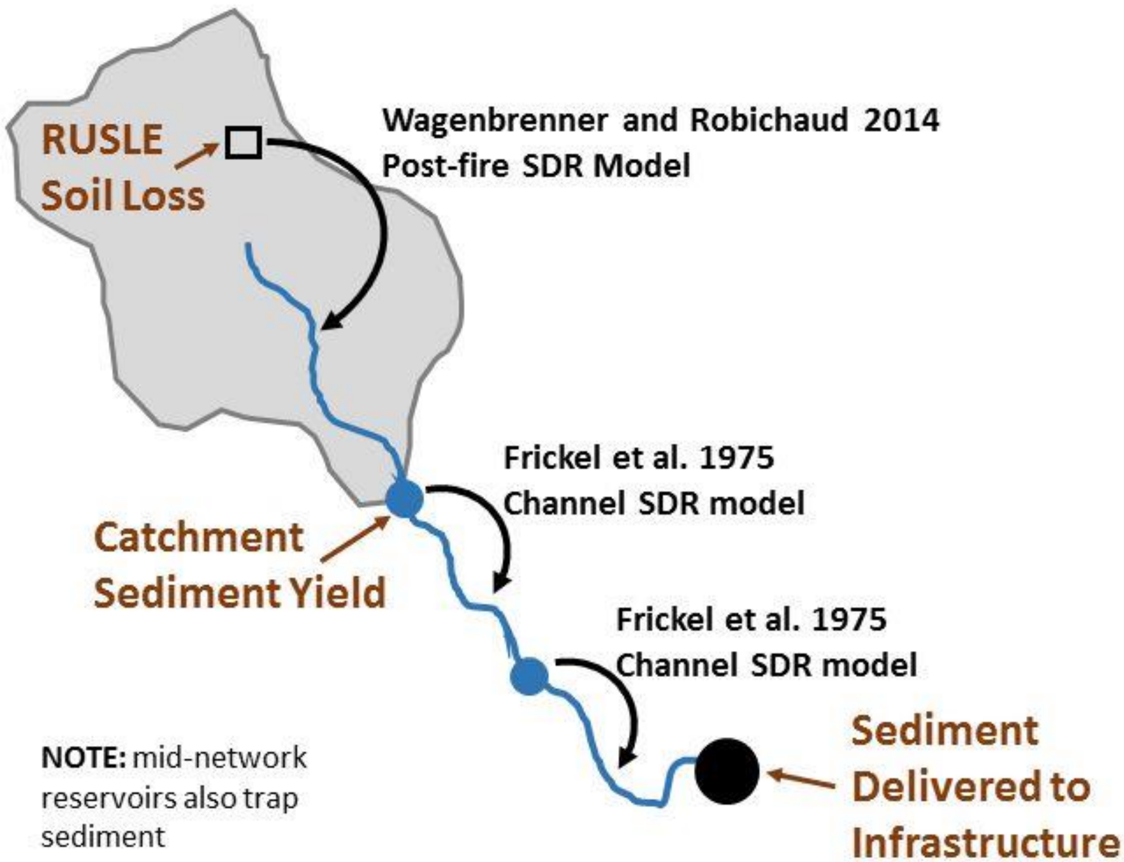


Figure 3: conceptual diagram showing how RUSLE soil loss predictions are scaled up to the catchment using the Wagenbrenner and Robichaud (2014) post-fire SDR model and then channel transport efficiency is modeled as a sediment delivery ratio based on stream order (Frickel et al. 1975) to account for sediment stored in the watershed.

Optimization

The optimization model is designed to assemble an optimal treatment plan under specified costs for sediment delivered to infrastructure and constraints for budget and project area. It also produces several intermediate products that may be useful for data visualization, communication, or further analysis. The optimization model uses data from the GIS pre-processing and the network topology to calculate the mean avoided sediment costs ($/acre) for the feasible acres of each treatment type (mechanical thinning only, mechanical thinning followed by Rx fire, and Rx fire only) in each catchment. Treatment costs are also estimated for each treatment type in each catchment as the mean cost for feasible acres. Catchments are selected for treatment to maximize the benefit-cost ratio of treated acres until the budget is exhausted using a sort and spend algorithm with enforcement of constraints. This approach yields solutions that are close to, or identical to, the solutions from a linear program, with the added benefits that: 1) the treatment plan is ordered based on catchment-treatment type rank, and 2) the benefit-cost ratios calculated as an intermediate product of the model are more-interpretable than linear program results.

The numerator in the benefit-cost ratio is the expected avoided fire-related sediment cost, consistent with the definition of wildfire risk (Finney 2005, Miller and Ager 2013, Scott et al. 2013), incorporating elements of wildfire likelihood, intensity, and effects. To review, burn probability comes from the Short et al. (2016) National FSim product, capturing the variability in wildfire likelihood across a project area with different vegetation, climate, and sources of ignition. Wildfire behavior is modeled using FlamMap and the results are linked to the erosion model (RUSLE) using the crown fire activity output. Treatment effects (benefits) are quantified in terms of the avoided post-fire erosion (RUSLE) and the exposure of downstream infrastructure to sediment (network topology, Wagenbrenner and Robichaud 2014 post-fire SDR model, Frickel et al. 1975 channel SDR model). Benefits are measured in $ over the planning period by specifying costs for sediment delivered to infrastructure. Multiplying the estimated benefits by planning period burn probability results in a measure of expected benefits in terms of risk reduction *sensu* Finney (2005).

The optimization model decides which catchments and treatment types will maximize benefits under the specified costs for sediment delivered to infrastructure and constraints for budget and project area. Each catchment-treatment type combination is a separate decision conditional on earlier decisions, i.e. a catchment can be selected for multiple treatment types, but the combined treatment decisions cannot exceed the total area feasible for treatment in the catchment. The minimum project area constraint can focus treatment decision towards projects large enough to justify the overhead expenses for planning and implementation. The maximum percent area constraint can limit the proportion of area treated within the catchment to balance various social, administrative, or ecological objectives.

The optimization model makes several assumptions, the most important of which is that burn probability and the effects and costs of treatment are constant at the catchment-scale. Since the decision is how to spend the budget on each catchment-treatment type combination, this means the model will exhaust all opportunities for the highest value catchment-treatment type combination before allocating treatment to the next highest value catchment-treatment type combination. Although intra-catchment variability exists, the assumption that burn probability, effects, and costs are constant at the catchment scale is consistent with the scale at which most local, state, and federal agencies plan landscape-scale fuel treatment projects.

All estimates of benefits are scaled to a planning period length (~ 25 years is recommended based on expected fuel treatment longevity) by converting annual burn probability to the planning period burn probability. Treatments are assumed to occur simultaneously at the start of the planning period with constant effectiveness for the duration of the planning period. All estimated benefits are non-discounted, i.e. they are not corrected to net present value to account for the time value of money.

GIS Pre-processing

Summary

The GIS pre-processing is separated into two workflows by the fire behavior modeling. The first workflow (pre-fire setup) prepares spatial fuels data for fire modeling by modifying it for local conditions and by updating it with existing fuel treatments. Feasibility and cost rasters are also created for each of the fuel treatment types (hereafter treatment types). Fire behavior modeling is then completed manually in FlamMap 5.0. The second workflow (post-fire) automates a GIS version of the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997) to calculate annual soil loss at a 30 m resolution for unburned, burned untreated, and burned treated (for each treatment type) scenarios. A hillslope-scale sediment delivery ratio model (Wagenbrenner and Robichaud 2014) is used to aggregate pixel-scale soil loss to catchment-scale sediment delivered to the channel network. A channel transport model, based loosely on Frickel et al. (1975) is parameterized for the channel network based on stream order.

The GIS pre-processing is mostly automated using a combination of Python and R, except for the fire behavior modeling in FlamMap. The GIS pre-processing requires an ArcGIS license with the Spatial Analyst extension and an installation of R (free and open source). The GIS pre-processing scripts in Python and R were developed and tested on Windows 7 and Windows 10 operating systems.

The input data and formatting requirements will be described for each sub-process.

Pre-fire Setup

The pre-fire setup workflow prepares baseline fuels data for fire modeling by adjusting it for local conditions and by simulating application of each of the treatment types. Feasibilities and costs are also modeled for each of the treatment types.

The LANDFIRE program "produces consistent, comprehensive, geospatial data and databases that describe vegetation, wildland fuel, and fire regimes across the United States" (https://www.landfire.gov/index.php). LANDFIRE data products are ideal for large watershed analysis of wildfire risk because they are consistent and comprehensive across the planning area, unlike agency-specific data sources that differ in content, quality, and coverage. LANDFIRE data products are modeled from satellite remote sensing and topographic data and are intended for landscape- to regional-scale analysis. LANDFIRE data are updated (generally on a two-year cycle) using a variety of data from national-level programs tracking wildfire occurrence and fuel treatment accomplishments from federal agencies. It is recommended that end users critique and modify LANDFIRE data as needed to accurately reflect current fuel conditions (Stratton 2009). The Adjust LANDFIRE script in the pre-fire setup accomplishes this.

FlamMap and other spatial fire modeling systems in the United States use a stack of co-registered rasters to describe surface and canopy fuels and topography. Surface fuels are described in terms of categorical fire behavior fuel models (FBFMs), which describe surface fuel beds (loading by size class, depth, surface area to volume ratio, etc.) that produce generalized fire behavior (Anderson 1982, Scott and Burgan 2005). Canopy fuels are described by factors that influence crown fire initiation, crown fire spread, and surface fuel bed sheltering from wind, including canopy bulk density (CBD), canopy base height (CBH), canopy cover (CC), and canopy height (CH). Fuel treatments are simulated by modifying the surface and canopy fuel variables to reflect the mean effect sizes of different treatment types. Elevation, slope, and aspect are used to account for the influence of topography on fire behavior. The Treat script in the pre-fire setup simulates fuel treatments on the modified data from the Adjust LANDFIRE script.

There are practical, administrative, and legal constraints to applying certain treatment types on different parts of the landscape, e.g. mechanical treatments are prohibited in federally-designated wilderness and Rx fire is generally not used as a first entry tool in wet forest types. Treatment costs also vary based on accessibility and operability. Feasibility and costs are estimated in the Management Costs and Restrictions script.

Adjust LANDFIRE

The Adjust LANDFIRE script makes global adjustments to lodgepole pine systems to better reflect behavior observed during recent fires and makes local adjustments to reflect existing fuel treatments. This is done before and outside the pre-fire setup shell script because the output is used to model crown fraction burned (Scott and Reinhardt 2001) using FlamMap for 70th percentile conditions to constrain the feasibility of Rx fire.

Input:
cbh – canopy base height raster from LANDFIRE
cbd – canopy bulk density raster from LANDFIRE
cc – canopy cover raster from LANDFIRE
ch – canopy height raster from LANDFIRE
fbfm40 – fire behavior fuel model raster from LANDFIRE (Scott and Burgan 2005)
evt – existing vegetation type raster from LANDFIRE
All_agency_trts – polygon feature class of recent fuel treatment accomplishments with effect sizes in the attribute table for cbh, cbd, cc, and ch
fdist – fuel disturbance raster from LANDFIRE

Output:
mod_cbh – modified canopy base height raster
mod_cbd – modified canopy bulk density raster
mod_cc – modified canopy cover raster
mod_ch – modified canopy height raster
mod_fbfm40 – modified fire behavior fuel model raster

Process summary:

The fuel variables for lodgepole pine do not allow crown fire behavior that has clearly been demonstrated in recent fires. Global adjustments are made for lodgepole pine to reduce the canopy base height 20% and to change the fuel model from moderate load conifer litter (TL3) to high load conifer litter (TL5) in the Scott and Burgan (2005) classification.

There are existing fuel treatments and disturbances that are not represented in the LANDFIRE fuels data. The Front Range Fuel Treatment Database (FRFTDb; Caggiano 2017) was updated with USDA Forest Service Hazardous Fuel Treatment accomplishments (current 04/2017) and attributed with treatment type (mechanical only, mechanical and Rx fire, and Rx fire only) using available data from the reporting agencies. When information was insufficient to classify the treatment type, it was assumed to be the most commonly implemented mechanical only treatment. Some fuel treatment accomplishments in the FRFTDb were already reported to LANDFIRE and reflected in the fuels data, so only treatments not in the LANDFIRE FDIST2014 layer (composite fuel disturbance for period ending in 2014) were applied to the fuels data. Treatment effects were informed by figures reported in the literature for fuel treatment and forest restoration work in the western United States (Stephens and Moghaddas 2005, Stephens et al. 2009, Fulé et al. 2012, Ziegler et al. 2017). These effects will be described in more detail in the Treat section (below).

Treat

Simulates treatment on adjusted LANDFIRE data layers by modifying CBH, CBD, CH, CC, and FBFM40.

Input:

mod_cbd – modified canopy bulk density raster from Adjust LANDFIRE script
mod_cbh – modified canopy base height raster from Adjust LANDFIRE script
mod_cc – modified canopy cover raster from Adjust LANDFIRE script
mod_ch – modified canopy height raster from Adjust LANDFIRE script
mod_fbfm40 – modified fire behavior fuel model raster from Adjust LANDFIRE script
FBFM40_mech_only.txt – fire behavior fuel model transition lookup table for mechanical only
FBFM40_mech_and_Rx.txt – fire behavior fuel model transition lookup table for mechanical and Rx fire
FBFM40_Rx_only.txt – fire behavior fuel model transition lookup table for Rx fire only

Output:
[TrtType]_cbd – treated canopy bulk density raster
[TrtType]_cbh – treated canopy base height raster
[TrtType]_cc – treated canopy cover raster
[TrtType]_ch – treated canopy height raster
[TrtType]_fbfm40 – treated fire behavior fuel model raster density raster

Process Summary:

Treatments are simulated on the modified LANDFIRE data so that fuel treatment effects can be modeled using FlamMap. The directions and magnitudes of change in fuel parameters for mechanical only, mechanical followed by Rx fire, and Rx fire only treatments are based on effect sizes reported in the literature (Stephens and Moghaddas 2005, Stephens et al. 2009, Fulé et al. 2012, Ziegler et al. 2017).

Canopy effects (Table 1) are similar for mechanical only and mechanical and Rx fire treatment types, but the Rx fire only treatment has smaller canopy effects (Stephens and Moghaddas 2005, Stephens et al. 2009, Fulé et al. 2012).

Table 1: treatment effects are applied to the modified LANDFIRE data as adjustment factors, e.g. an adjustment factor of 0.6 for mechanical only treatment on canopy bulk density (CBD) equates to a 40% reduction.

Canopy Parameter	Mechanical Only	Mech + Rx Fire	Rx Fire Only
CBD	0.6	0.5	0.92
CBH	1.2	1.2	1.09
CC	0.7	0.75	0.95
CH	1.2	1.2	1.13

There is some uncertainty in the magnitude and uniformity of fuel treatment effects on FBFM trajectories (Table 2), but in general, mechanical only treatments increase surface fuels, mechanical followed by prescribed fire treatments tend to keep fuel loads about the same, and Rx fire only treatments decrease surface fuels (Fulé et al. 2012, Stephens et al. 2009). There is a lack of consensus on how these effects should be modeled, i.e. do we see enough of an effect to change the FBFM category, or should a smaller effect be imposed through creation of a custom fuel model? We assume that only timber understory (TU), timber litter (TL), and slash/blowdown (SB) fuel model types have sufficient canopy fuels that may be transferred to the surface fuel stratum during treatment. We make the conservative assumption that mechanical only treatments will bump the FBFM up a category to higher rates of spread and flame lengths, unless the current FBFM is already the highest in the fuel model type (e.g. TL9 has the highest rates of spread and flame lengths in the TL fuel type). We assume that FBFM does not change with mechanical followed by Rx fire because the surface fuel additions from the mechanical treatment are balanced with surface fuel reductions from the Rx fire. We assume that Rx fire will drop the FBFM down a category to lower rates of spread and flame lengths, unless the current FBFM is already the lowest in the fuel model type (e.g. TL1 has the lowest rates of spread and flame lengths in the TL fuel type).

Table 2: fuel model transitions modeled for the three treatment types. We assume that only timber understory, timber litter, and slash/blowdown fuel types have sufficient canopy fuels that may be transferred to the surface fuel stratum from treatment.

Pre-treatment fuel model	Pre-treatment fuel model #	Mechanical Only fuel model #	Mech + Rx Fire fuel model #	Rx Fire Only fuel model #
TU1	161	162	161	161
TU2	162	164	162	161
TU3	163	163	163	162
TU4	164	163	164	162
TU5	165	163	165	161
TL1	181	182	181	181
TL2	182	183	182	181
TL3	183	184	183	182
TL4	184	187	184	183
TL5	185	186	185	187
TL6	186	189	186	185
TL7	187	185	187	184
TL8	188	189	188	185
TL9	189	189	189	188
SB1	201	202	201	201
SB2	202	203	202	201
SB3	203	204	203	202
SB4	204	204	204	203

Most of the studies used to inform fuel model changes are based on short-term effects of treatment. There is limited information about longer term effects, especially the understory response.

Management Costs and Restrictions

The Management Costs and Restrictions script defines mechanical only, mechanical and Rx fire, and Rx fire only treatment costs and feasibilities.

Input:
us_slp2010 – slope raster from LANDFIRE
mod_cc – modified canopy cover raster from Adjust LANDFIRE script
evt – existing vegetation type raster from LANDFIRE
CFB_70th_10mph.asc – crown fraction burned raster from FlamMap for moderate 70th percentile conditions
TRAN_roads – road polyline feature class from the USGS
extent – polygon feature class of the project extent
lf_extent – polygon feature class of the LANDFIRE data coverage for the fire modeling
wilderness – polygon feature class of USDA Forest Service wilderness areas
roadless – polygon feature class of USDA Forest Service roadless areas
romo – polygon feature class of Rocky Mountain National Park management units
WUI_structures – point feature class of wildland urban interface structures from Caggiano et al. 2016 extended to cover project extent in southeast Wyoming
Rx_feasibility_from_EVT.txt – reclassification table of LANDFIRE existing vegetation type based on ecological appropriate application of Rx fire (0=inappropriate, 1=appropriate)

Output:
mocost – mechanical only treatment cost raster
mofeas – mechanical only treatment feasibility raster
mRxcost – mechanical and Rx fire treatment cost raster
mRxfeas – mechanical and Rx fire feasibility raster
Rxocost – Rx fire only treatment cost raster
Rxofeas – Rx fire only feasibility raster
cfeas – combined (total) feasibility raster for any treatment type

Process Summary:

Mechanical only treatment costs are approximated as a function of distance from roads and slope with linear functions fit between a base price ($2,500/ac) and a maximum price ($10,000/ac) for the range of distance from roads > 800 m and the range of slopes > 40%.

```
# Calculate Euclidean distance from roads
Euc_Dist = EucDistance(rbin)

# Calculate road-distance additional costs
m1 = (MaxCost-BaseCost)/(Euc_Dist.maximum-800)
rcost = Con(Euc_Dist <= 800,0,(Euc_Dist-800)*m1)

# Calculate slope additional costs
m2 = (MaxCost-BaseCost)/(Raster(slope).maximum-slopeTH)
scost = Con(Raster(slope) <= slopeTH,0,(Raster(slope)-slopeTH)*m2)

# Combine base, road, and slope costs
```

```
mocost = rcost + scost + BaseCost

# Limit to max cost
mocost = Con(mocost > MaxCost,MaxCost,mocost)
```

Mechanical only treatment is restricted from wilderness and upper tier roadless areas.

Rx fire only treatment costs are assumed to be a uniform $1,000/ac based on communication with local fuels and fire planners, Bryan Karchut (ARP) and James White (CLRD). Current costs are estimated at $1,000/ac, but costs of $500/ac could be achieved by increasing the scale of application. Rx fire only treatment is restricted in the model from within 250 m of structures, areas predicted to experience > 30% crown fraction burned (some passive crown fire is acceptable) under 70th percentile weather conditions, and high elevation, wet forest types (lodgepole pine, spruce-fir). An existing spatial dataset of wildland-urban interface structures that were collected using object-based image classification (Caggiano 2016) was extended into southeast Wyoming via on-screen digitizing of structures from NAIP imagery (2013-2015).

Mechanical and Rx fire costs are estimated as the sum of mechanical only and Rx fire only costs. Mechanical and Rx fire feasibility is assumed to be the same as mechanical only feasibility, i.e. we assume it's feasible to apply Rx fire anywhere that mechanical treatment has already been completed.

The combined (total) treatment feasibility is the sum of the mechanical only and Rx fire only treatment feasibilities.

Assemble LCPs

The fuel rasters modified in the pre-fire setup steps are manually converted into the landscape file format (.lcp) used in US spatial fire modeling systems to generate untreated and treated landscape files for each of the treatment types. The ArcFuels (https://www.fs.fed.us/wwetac/tools/arcfuels/index.php) toolbar was used to assemble treated and untreated landscape files, but there are a variety of other tools that can be used to accomplish this task.

Fire Modeling

Analyze Weather Data

Remote automated weather station (RAWS) data for Red Feather Lakes (station # 050505) and Estes Park (station # 050507) were analyzed with FireFamilyPlus 4.1 (Bradshaw and McCormick 2000) to characterize the 70th and 97th percentile weather conditions (Table 3) during the fire season (defined as April 1st through October 31st). 70th percentile conditions are used to approximate the conditions under which Rx fire is locally applied (B. Karchut and J. White, personal communication). 97th percentile conditions are used to approximate extreme conditions that characterize most fires that escape initial attack and overwhelm suppression resources (similar to Haas et al. 2014, Sherriff et al. 2014), like large growth periods of the Hayman (2002), High Park (2012), Waldo Canyon (2012), and Black Forest (2013) fires. Wind speeds from RAWS were converted to 1 min average wind speeds (Crosby and Chandler 1966), which better predict fire behavior.

Table 3: weather conditions summarized for local RAWS stations used for the fire behavior modeling. 70th percentile conditions are used to approximate Rx fire conditions and 97th percentile conditions are used to approximate extreme fires that will overwhelm suppression resources.

Percentile	**Dead 1-hr moisture content**	**Dead 10-hr moisture content**	**Dead 100-hr moisture content**	**Live Herbaceous moisture content**	**Live Woody moisture content**	**Wind speed (mph @ 20 ft)**
70th (Rx fire)	5	6	10	36	79	10
97th (Escaped fire)	2	3	6	4	63	24

Wind direction was analyzed in R to characterize the distribution of wind directions for all wind speeds and high wind speeds (Figure 4). The wind direction distribution is bimodal for all wind speeds capturing both strong westerly winds and upslope winds, but the wind direction distribution is strongly unimodal when considering only those winds >= 10 mph, which are associated with large fire growth periods. A wind direction of 255 deg is a reasonable approximation for the modal direction of high speed winds.

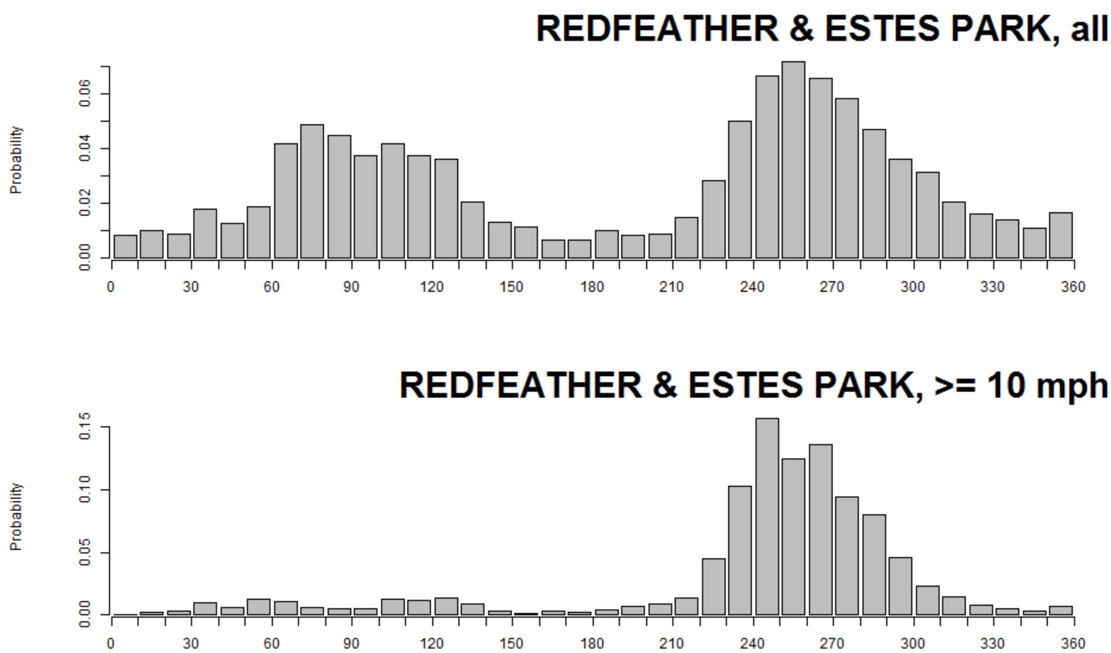


Figure 4: wind direction diagram for Red Feather Lakes and Estes Park RAWS stations for all wind speeds and for wind speeds >= 10 mph. The wind speeds >= 10 mph are generally associated with large fire growth periods and have a unimodal distribution with a modal wind direction ~ 255 deg.

Run FlamMap

FlamMap 5.0 (Finney 2006) was used for all fire behavior modeling.

To inform Rx fire feasibility, 70th percentile weather conditions and the untreated landscape file were used to model crown fraction burned (CFB; Scott and Reinhardt 2001). The following conditions were specified:
70th percentile fuel moisture (fms) file
Wind direction = 255
Wind speed = 10 mph (Bryan Karchut, ARP)
Wind blowing uphill
Scott/Reinhardt (2001) Crown Fire Calculation Method

To inform hazard assessment, 97th percentile weather conditions were used with untreated and treated landscape files to model crown fire activity. The following conditions were specified:
Hazard Run:
97th percentile fuel moisture (fms) file
Wind direction = 255
Wind speed = 24 mph (converted to 1 min average wind speeds)
Wind blowing uphill
Scott/Reinhardt (2001) Crown Fire Calculation Method

The fuel moisture file, wind direction, wind speed, and wind blowing uphill option can all be accessed from the New Run Inputs tab (Figure 5).

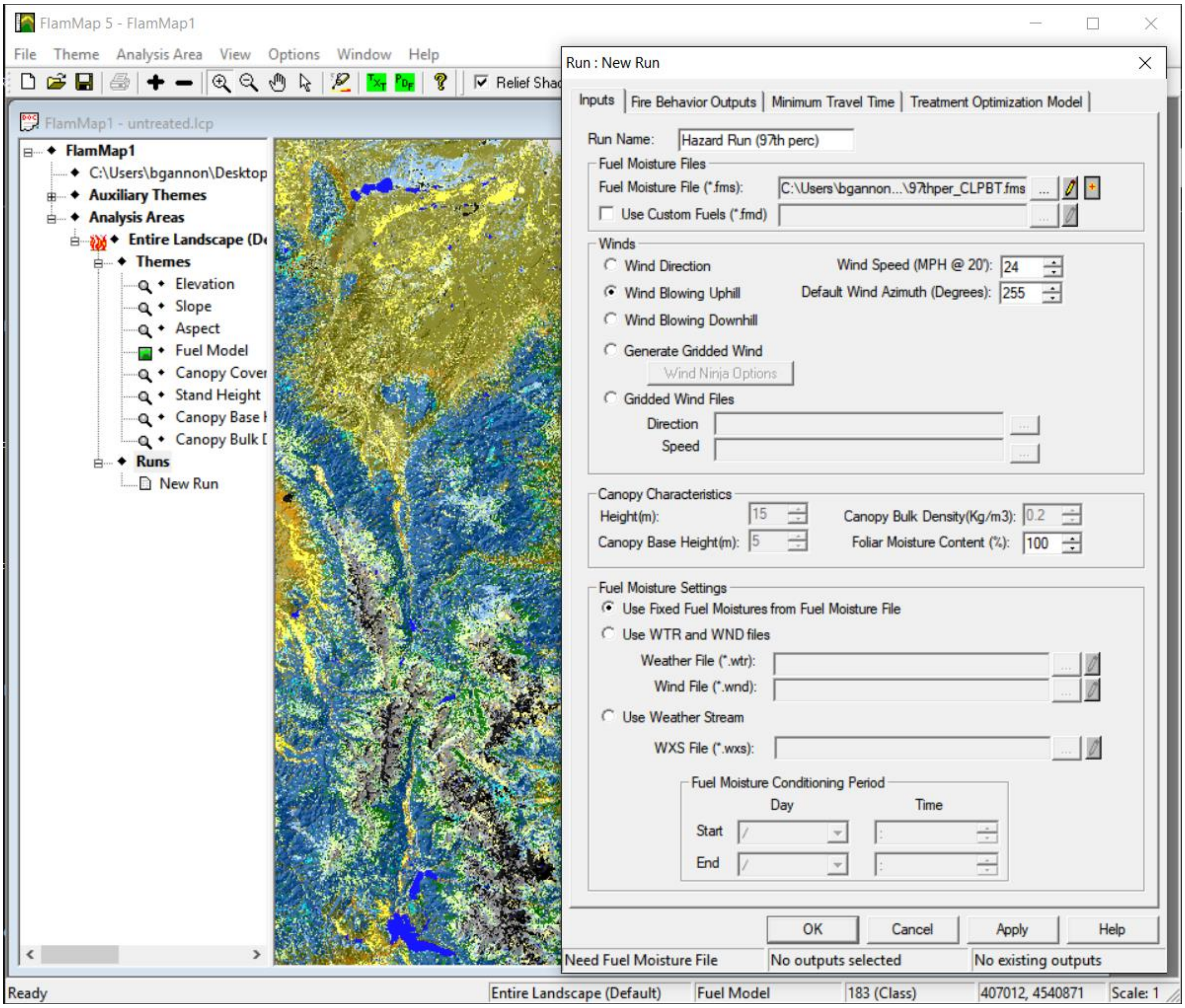


Figure 5: screen capture of the New Run Inputs tab. The relevant inputs are the appropriate fuel moisture file (fms), wind speed, wind direction, and change to wind blowing uphill.

The Crown Fire Activity output and the Scott/Reinhardt (2001) Crown Fire Calculation Method can be specified on the Fire Behavior Outputs tab (Figure 6).

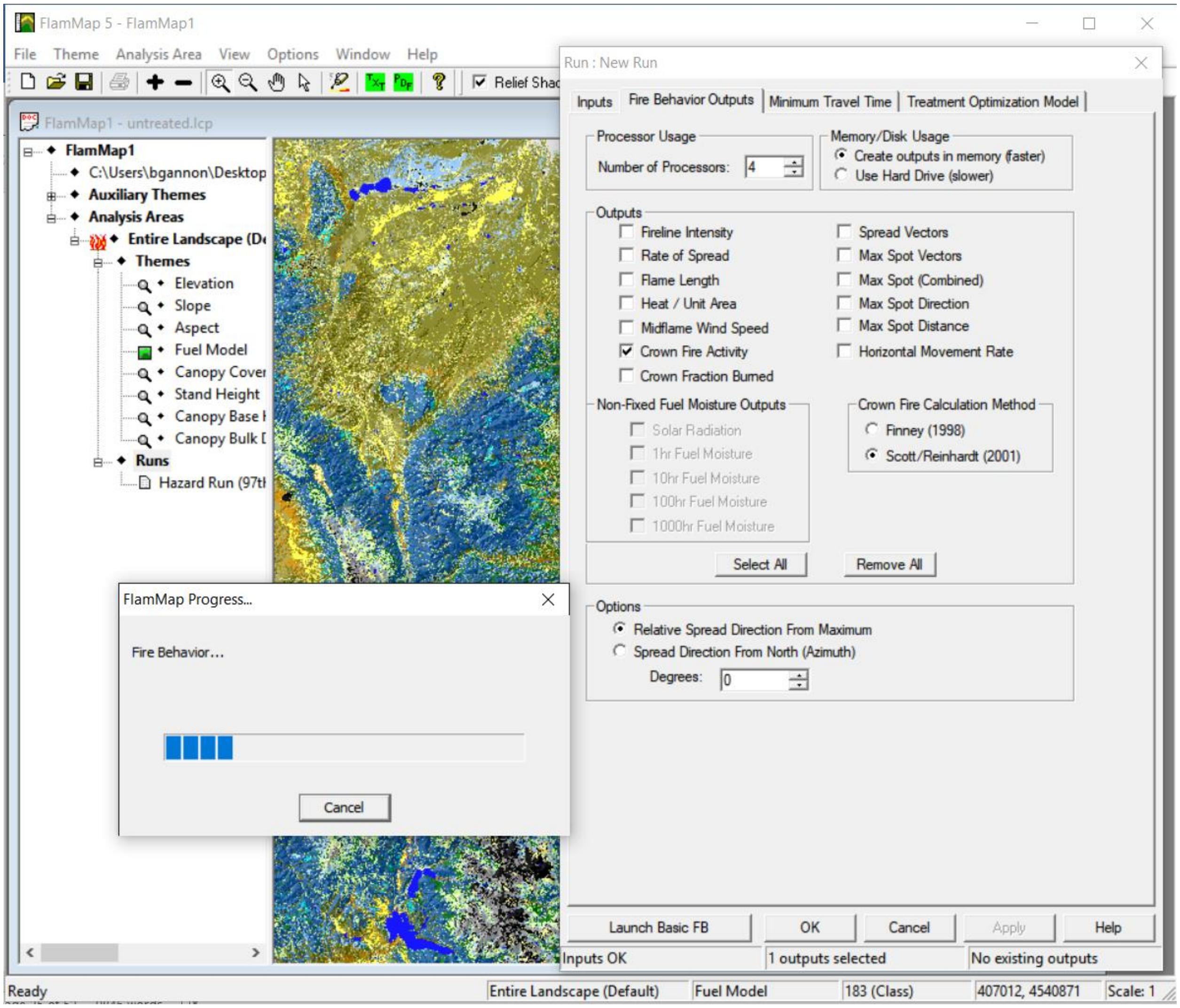


Figure 6: screen capture of the New Run Fire Behavior Outputs tab. Check Crown Fire Activity and change the Crown Fire Calculation Method to Scott/Reinhardt (2001).

Crown fire activity (CFA) and crown fraction burned (CFB) output should be saved (Figure 7) in asci format to the Input and Intermediate Data folders with the following naming convention:

Input:
CFB_70th_10mph – for untreated Rx fire run

Intermediate:
CFA – for untreated
CFA_trt_mech – for mechanical only treatment
CFA_trt_mechRx – for mechanical and Rx fire treatment
CFA_trt_Rx – for Rx fire treatment

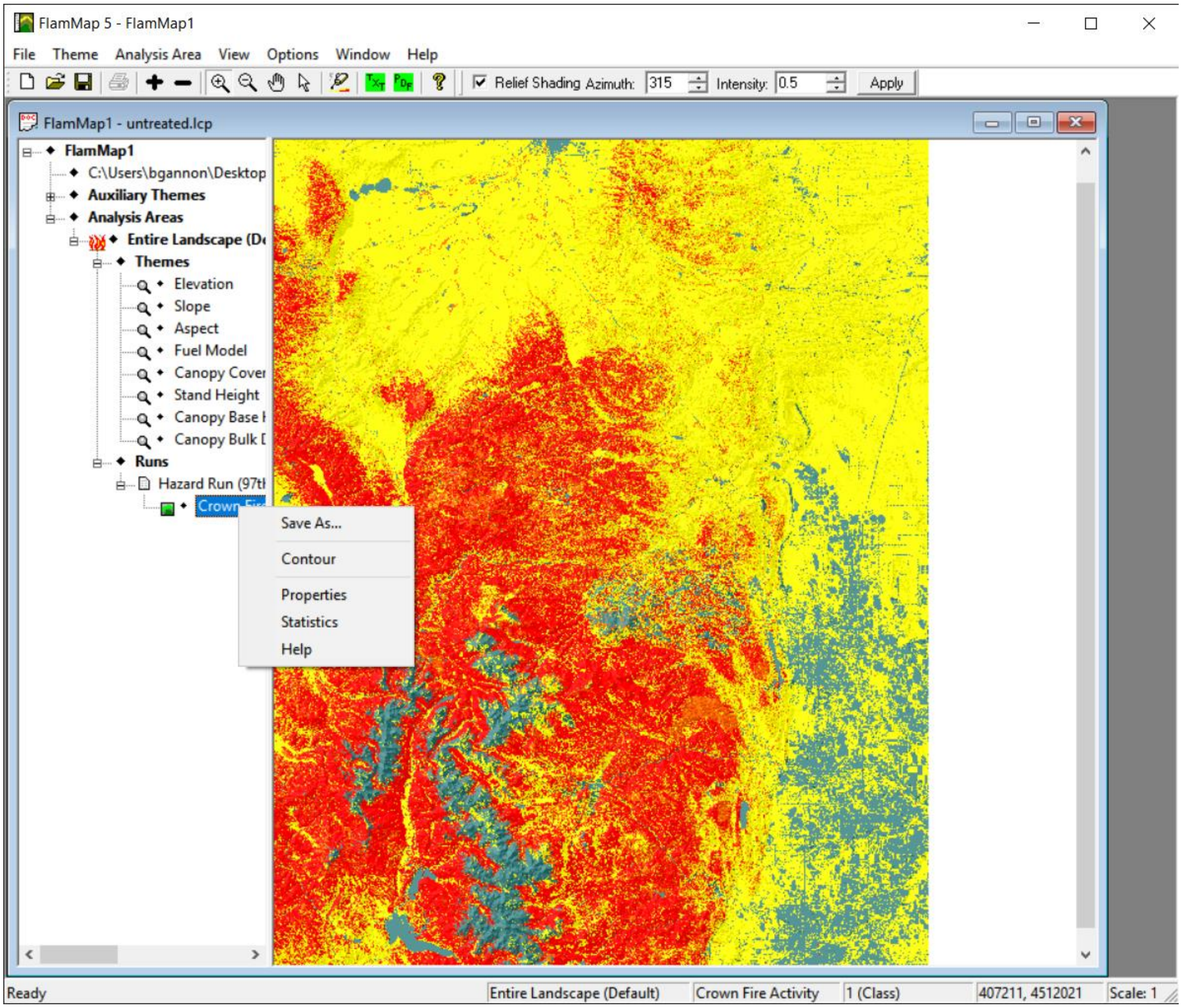


Figure 7: screen capture of FlamMap GUI demonstrating how to right click and save the output to an asci file.

Post-fire Processes

The RUSLE is used to model local soil loss for baseline, untreated, and treated scenarios for each of the three treatment types. The difference between the treated and untreated soil loss represents the benefit of applying each treatment type in terms of avoided erosion. The difference between untreated and baseline soil loss can be used to describe the effect of fire for the untreated scenario, but this is not necessary for the model. Treatments are applied to all pixels in the landscape for estimating benefits, but are constrained to areas feasible for treatment when summarizing treatment opportunities (acres to treat in each catchment by treatment type) and mean benefits (avoided sediment per acre of treatment by treatment type).

Two different sediment transport models are used to route sediment to infrastructure features. The first is an empirical hillslope- to small watershed-scale model of post-fire sediment delivery ratio developed from fires in the western United States, including Colorado (Wagenbrenner and Robichaud 2014). This is used to scale up from the RUSLE 30 m pixel erosion estimates to the mass of sediment delivered to streams from each NHDPlus catchment. The second is a channel sediment delivery ratio model (adapted from Frickel et al. 1975) based on stream order.

Treatment opportunities and benefits, as well as burn probabilities are summarized at the catchment-scale. Treatment opportunities are calculated as the percent of the catchment feasible for each treatment type individually, and all treatment types combined. Treatment benefits are calculated in the optimization model as the mean benefit per acre for each treatment type in each catchment. Burn probability for the catchment is calculated as the zonal mean.

RUSLE

The RUSLE (Renard et al. 1997) consists of five subfactors that are multiplied together to calculate the predicted annual soil loss (A). The subfactors are rainfall-runoff erosivity (R), soil erodibility (K), length-slope (LS), cover-management (C), and support practices (P). Annual soil loss is calculated by multiplying the five subfactors, as follows:

$$A = R * K * LS * C * P$$

Where
A = estimated average soil loss in tons per acre per year
R = rainfall-runoff erosivity factor
K = soil erodibility factor
LS = slope-length factor
C = cover-management factor
P = support practice factor (ignored for now)

Support practices generally refer to agricultural interventions such as tilling patterns and buffer strips. In forestlands, there are limited to no management interventions of this type, so no support practice factor was modeled.

R Factor

The rainfall-runoff erosivity factor (R) is an annual metric of rainfall that integrates total rainfall energy and maximum 30 min intensity (EI30; $MJ*mm*ha^{-1}*hr^{-1}$). The R factor can be estimated from several coarse resolution datasets (Theobald et al. 2010; Litschert et al. 2014), or from local rainfall data. We acquired rainfall data from the 11 Front Range NOAA Stations with 15-minute rainfall records (Figure 8) that were assembled for a separate study (Wilson et al. 2017) and processed with the Rainfall Intensity Summarization Tool (RIST; Dabney 2016) to calculate event-level rainfall erosivity. This data set spans the years 1971 to 2010 and includes 403 station-years of annual erosivity observations.

A common practice is to model rainfall erosivity from mean annual precipitation (Renard and Freimund 1994), so we analyzed annual erosivity metrics for trends with elevation (Figure 9). We found no significant trends between annual erosivity and elevation using individual years, station means, or station medians. Summer convective thunderstorms, which are responsible for the majority of erosion in the Front Range (Larsen and MacDonald 2007), can produce intense local precipitation, leading to high spatial and temporal variability in erosion outcomes (Kampf et al. 2016). The NOAA station data confirm that high spatial and temporal variability overwhelm any minor trends with physical gradients at this scale (Figure 10), so we decided to treat rainfall as a random process across space and time, described by the annual erosivity distribution of the pooled dataset (Figure 11). In the GIS pre-processing, we model the R factor as the median of this distribution (615 $MJ*mm*ha^{-1}*hr^{-1}$) and adjust predictions for different erosivity percentiles in the WIT.

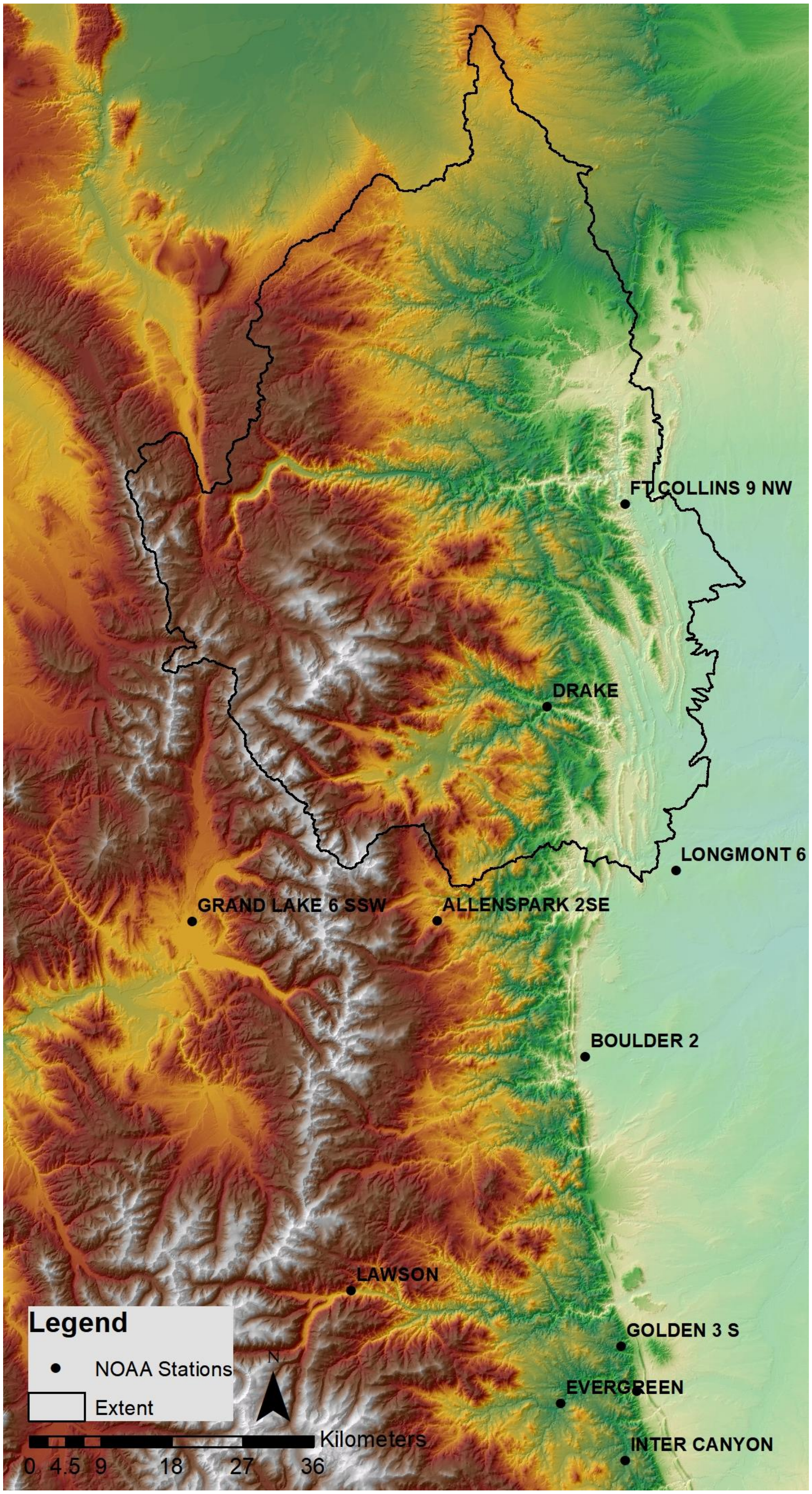


Figure 8: map of 11 NOAA stations with 15-minute rainfall data used for the analysis.

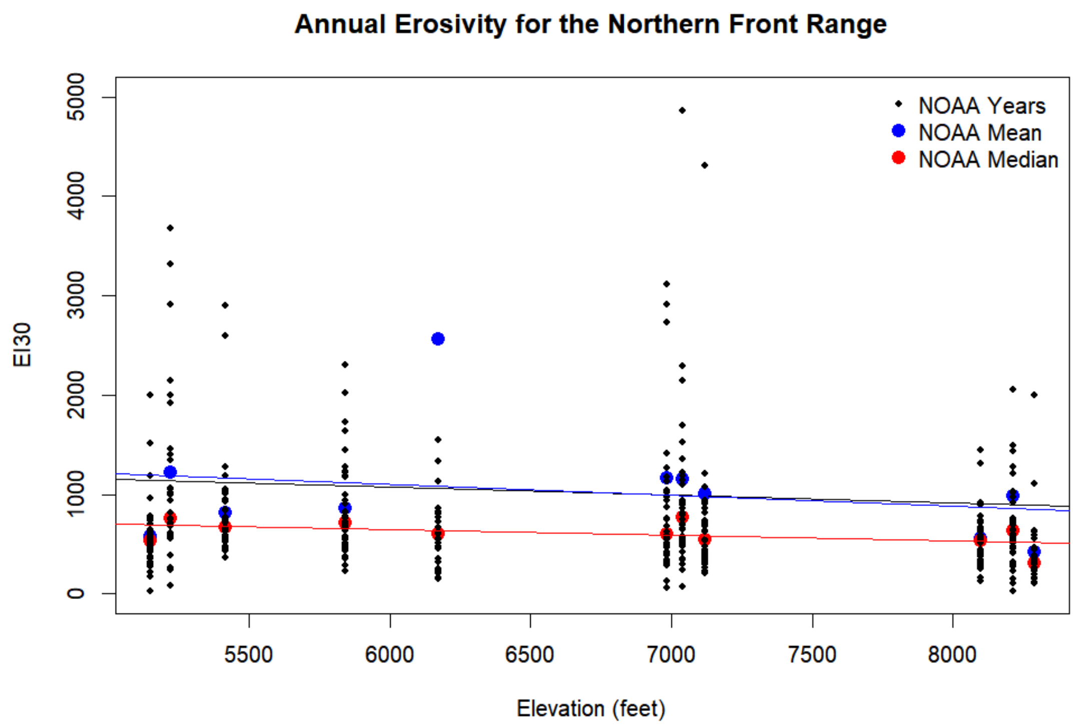


Figure 9: annual erosivity for the 11 Front Range NOAA stations with 15-minute rainfall data. Data are presented for individual years (black dots), station means (blue), and station medians (red). Linear trend lines are shown for each data set, but slopes were not significantly different from zero. Also, note that several outliers are not shown, including the storm that caused the 1976 Big Thompson Flood.

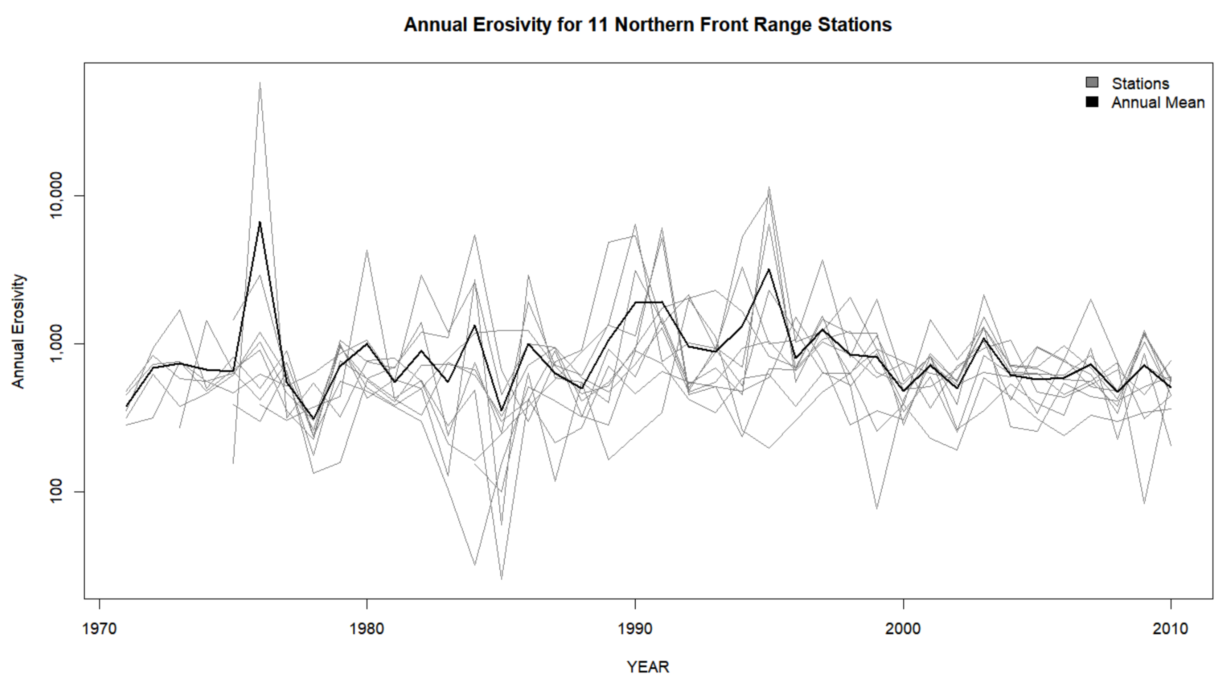


Figure 10: annual erosivity by station and year for the 11 Front Range NOAA stations with 15-minute rainfall data. Note that the y-axis is log-scale.

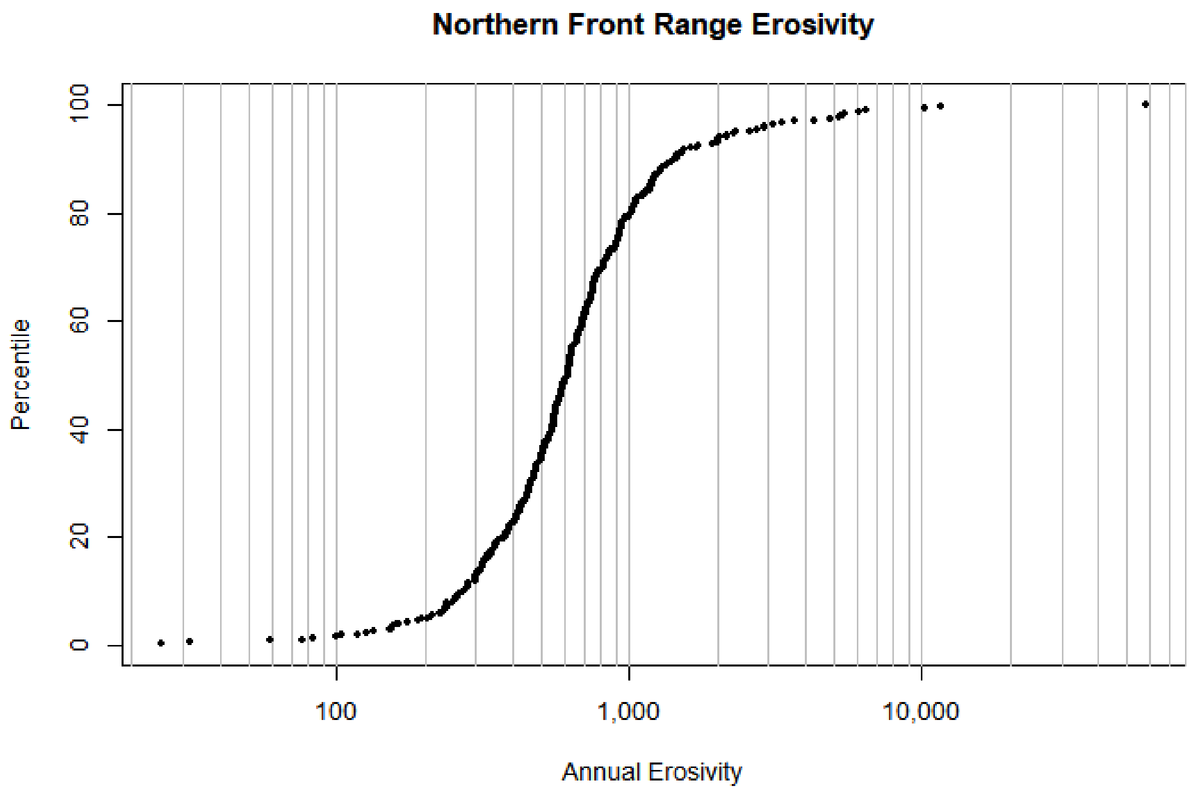


Figure 11: pooled distribution of annual erosivity across space and time for the Colorado Front Range. Note that the x-axis is log-scale.

K Factor

The soil erodibility factor (K) is the rate of soil loss per rainfall erosion index unit (Renard et al. 1997) and is generally determined empirically, or sometimes using equations based on soil texture. The K factor is an attribute recorded in the national cooperative soil survey data maintained and distributed by USDA Natural Resources Conservation Service (NRCS). Soils data for the project area includes coverage from the higher-resolution Soil Survey Geographic Database (SSURGO) and the coarser-resolution State Soils Geographic Database (STATSGO). We used the whole soil K factor (kwfact) which is adjusted for the effect of rock fragments and attributed at the horizon level. In both SSURGO and STATSGO, map units are made up of multiple components with specified percent cover and components are made up of multiple horizons with specified depth. We followed the methods of Yochum and Norman (2015) to calculate the K factor for each component as the depth-weighted mean for each horizon in the top 15 cm of the soil profile and for each map unit as the area-weighted mean of any non-water or -rock component types.

SSURGO data was used preferentially due to its higher resolution, but it was gap-filled as needed with STATSGO for map units missing K factor data. The complete project coverage of SSURGO and STATSGO map unit polygons were converted to a 30 m raster to match the spatial resolution of the LANDFIRE data products.

LS Factor

The length-slope factor (LS) is the product of the slope length factor (L) and the slope steepness factor (S), which together represent the influence of topography on erosion and are discussed jointly here because they are calculated in a single process. The original intent for the RUSLE was for these factors to be measured in the field, but numerous GIS adaptations of USLE/RUSLE can be used to approximate LS across large landscapes. We follow the methods of Theobald et al. (2010), Litschert et al. (2014), and Yochum and Norman (2014, 2015), with minor modifications.

We used the same 30 m resolution DEM used to generate the NHDPlus network (NHDPlus elev_cm raster) to maintain consistency between hydrography data products. The key processing steps can be summarized as follows:

```
# Fill DEM
fDEM = Fill(DEM)

# Calculate slope and aspect in radians
S_rad = Slope(fDEM,'DEGREE')*(math.pi/180)
A_rad = Aspect(fDEM)*(math.pi/180)

# Calculate S subfactor
Sf = -1.5 + 17/(1 + Exp(2.3 - 6.1*Sin(Con(S_rad <
55*(math.pi/180),S_rad,55*(math.pi/180)))))

# Calculate beta
beta = ((Sin(S_rad)/0.0896)/(3*Power(Sin(S_rad),0.8) + 0.56))

# Calculate m
m = beta/(1 + beta)

# Calculate x
x = Abs(Sin(A_rad)) + Abs(Cos(A_rad))

# Calculate flow accumulation
fdir = FlowDirection(fDEM)
facc = FlowAccumulation(fdir)
facc_Thresh = 10   # Flow accumulation threshold (in # of cells)
cfacc = Con(facc <= facc_Thresh,facc,facc_Thresh)

 # Calculate LS
LS = Sf*((Power((cfacc*D*D) + D*D,m + 1.0) - Power((cfacc*D*D),m + 1.0))/(Power(D, m +
2.0)*Power(x*22.13,m)))

# Constrain to maximum value from Renard et al. 1997
LScap = Con(LS > 72.15,72.15,LS)
```

The modifications we made include a flow accumulation threshold meant to approximate the hillslope length limit (~ 1,000 ft) and a step to constrain the final LS factor values to the maximum from Renard et al. (1997). The LS factor output was reprojected and resampled to match the LANDFIRE data products.

C Factor

Cover factor (C) was mapped to the existing vegetation type (EVT) from LANDFIRE (Table 4) using values assembled in Yochum and Norman (2014) and Litschert et al. (2014). The barren EVT, which has a very high C factor value, is assigned to some alpine areas that have low rates of erosion (S. Kampf, personal communication), so barren areas >=2900 m was reassigned a C factor of zero.

Table 4: cover factor values mapped to exiting vegetation types from LANDFIRE in descending order of coverage within the project area with the original references.

EVT CLASSNAME	C Factor	Reference	Description in reference	Area (%)
Rocky Mountain Lodgepole Pine Forest	0.0020	Breiby (2006)	Coniferous forest	13.8
Inter-Mountain Basins Big Sagebrush Shrubland	0.0290	McQuen 1998	Shrubland Other	9.9
Western Great Plains Shortgrass Prairie	0.2000	Dawen et al. 2003	Sparse Grassland	7.7
Southern Rocky Mountain Ponderosa Pine Woodland	0.0027	Miller et al. (2003)	Ponderosa pine	7.0
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland	0.0020	Breiby (2006)	Coniferous forest	6.9
Rocky Mountain Lower Montane-Foothill Shrubland	0.0250	Breiby 2006	Deciduous Shrubland	5.3
Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland	0.0020	Breiby 2006	Coniferous Forest	4.8
Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland	0.0010	Breiby 2006	Mixed Forest	2.8
Western Cool Temperate Developed Ruderal Grassland	0.2000	Dawen et al. 2003	Sparse Grassland	2.8
Artemisia tridentata ssp. vaseyana Shrubland Alliance	0.0290	McQuen 1998	Shrubland Other	2.4
Western Cool Temperate Pasture and Hayland	0.1400	McCuen, 1998	Pasture Hay	2.1
Snow-Ice	0.0010	Dawen et al. 2003	Snow field	2.0
Inter-Mountain Basins Montane Sagebrush Steppe	0.0290	McQuen 1998	Shrubland Other	2.0
Inter-Mountain Basins Big Sagebrush Steppe	0.0290	McQuen 1998	Shrubland Other	1.9

Western Cool Temperate Row Crop	0.5000	Dawen et al., 2003	General Cropland	1.9
Barren	1.0000	Toy and Foster 1998	Barren	1.7
Rocky Mountain Aspen Forest and Woodland	0.0010	Breiby 2006	Deciduous Forest	1.7
Inter-Mountain Basins Semi-Desert Shrub-Steppe	0.2000	Dawen et al. 2003	Sparse Grassland	1.6
Open Water	0.0000	Breiby 2006; McCuen 1998	Open Water/Exposed Rock	1.5
Developed-Roads	0.0001	Toy and Foster, 1998	Asphalt	1.5
Wyoming Basins Dwarf Sagebrush Shrubland and Steppe	0.0290	McQuen 1998	Shrubland Other	1.1
Western Cool Temperate Close Grown Crop	0.5000	Dawen et al., 2003	General Cropland	1.1
Western Cool Temperate Fallow/Idle Cropland	1.0000	McCuen, 1998	Fallow	0.9
Developed-Low Intensity	0.0020	Guobin et al. 2006	Developed Suburban	0.9
Introduced Upland Vegetation-Annual Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.8
Western Great Plains Floodplain Forest and Woodland	0.0100	Breiby 2006	Floodplain Forest	0.8
Southern Rocky Mountain Montane-Subalpine Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.8
Western Cool Temperate Wheat	0.2300	McCuen, 1998	Small Grains	0.7
Rocky Mountain Montane Riparian Forest and Woodland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.6
Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland	0.0020	Breiby 2006	Coniferous Forest	0.6
Introduced Upland Vegetation-Perennial Grassland and Forbland	0.2000	Dawen et al. 2003	Sparse Grassland	0.6
Rocky Mountain Subalpine/Upper Montane Riparian Shrubland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.6
Inter-Mountain Basins Semi-Desert Grassland	0.2000	Dawen et al. 2003	Sparse Grassland	0.6
Rocky Mountain Alpine Turf	0.0120	Breiby 2006	Medium-tall grassland	0.6
Northwestern Great Plains Mixedgrass Prairie	0.0120	Breiby 2006	Medium-tall grassland	0.5
Developed-Medium Intensity	0.0030	Guobin et al. 2006	Developed General	0.5
Western Cool Temperate Developed Ruderal Shrubland	0.0290	McQuen 1998	Shrubland Other	0.5

Inter-Mountain Basins Mat Saltbush Shrubland	0.0290	McQuen 1998	Shrubland Other	0.5
Northern Rocky Mountain Lower Montane-Foothill-Valley Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.4
Western Great Plains Floodplain Herbaceous	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.4
Western Cool Temperate Urban Shrubland	0.0290	McQuen 1998	Shrubland Other	0.4
Rocky Mountain Foothill Limber Pine-Juniper Woodland	0.0020	Breiby 2006	Mixed Forest woodland	0.3
Rocky Mountain Subalpine Mesic-Wet Spruce-Fir Forest and Woodland	0.0020	Breiby 2006	Coniferous Forest	0.3
Rocky Mountain Subalpine-Montane Mesic Meadow	0.0120	Breiby 2006	Medium-tall grassland	0.3
Western Cool Temperate Urban Deciduous Forest	0.0015	Breiby 2006	Lowland Deciduous Forest	0.2
Western Cool Temperate Urban Herbaceous	0.0080	McCuen, 1998	Recreational Grasses	0.2
Central Mixedgrass Prairie Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.2
Southern Colorado Plateau Sand Shrubland	0.0290	McQuen 1998	Shrubland Other	0.2
Inter-Mountain Basins Mixed Salt Desert Scrub	0.0290	McQuen 1998	Shrubland Other	0.2
Colorado Plateau Pinyon-Juniper Woodland	0.0928	Miller et al. (2003)	Pinyon–juniper	0.2
Northern Rocky Mountain Subalpine-Upper Montane Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.2
Quercus gambelii Shrubland Alliance	0.0250	Breiby 2006	Deciduous Shrubland	0.2
Southern Rocky Mountain Ponderosa Pine Savanna	0.0027	Miller et al. (2003)	Ponderosa pine	0.2
Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland	0.0290	McQuen 1998	Shrubland Other	0.1
Western Great Plains Sandhill Grassland	0.0290	McQuen 1998	Shrubland Other	0.1
Rocky Mountain Subalpine/Upper Montane Riparian Forest and Woodland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.1
Southern Rocky Mountain Pinyon-Juniper Woodland	0.0928	Miller et al. (2003)	Pinyon–juniper	0.1
Developed-High Intensity	0.0010	Guobin et al. 2006	Developed Urban	0.1
Inter-Mountain Basins Greasewood Flat	0.0290	McQuen 1998	Shrubland Other	0.1
Western Cool Temperate Undeveloped Ruderal Grassland	0.2000	Dawen et al. 2003	Sparse Grassland	0.1

Middle Rocky Mountain Montane Douglas-fir Forest and Woodland	0.0020	Breiby 2006	Coniferous Forest	0.1
Rocky Mountain Wetland-Herbaceous	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.1
Rocky Mountain Alpine/Montane Sparsely Vegetated Systems II	0.2000	Dawen et al. 2003	Sparse Grassland	0.1
Rocky Mountain Alpine Dwarf-Shrubland	0.0290	McQuen 1998	Shrubland Other	0.1
Rocky Mountain Gambel Oak-Mixed Montane Shrubland	0.0250	Breiby 2006	Deciduous Shrubland	0.1
Quarries-Strip Mines-Gravel Pits	1.0000	Guobin et al. 2006	Aggregate mining	0.1
Western Cool Temperate Urban Evergreen Forest	0.0040	Guobin et al. 2006	Mixed Urban	0.1
Introduced Upland Vegetation-Annual and Biennial Forbland	0.2000	Dawen et al. 2003	Sparse Grassland	0.1
Rocky Mountain Subalpine-Montane Limber-Bristlecone Pine Woodland	0.0020	Breiby 2006	Mixed Forest woodland	0.1
Western Cool Temperate Urban Mixed Forest	0.0040	Guobin et al. 2006	Mixed Urban	0.0
Inter-Mountain Basins Curl-leaf Mountain Mahogany Shrubland	0.0290	McQuen 1998	Shrubland Other	0.0
Inter-Mountain Basins Sparsely Vegetated Systems II	0.2000	Dawen et al. 2003	Sparse Grassland	0.0
Rocky Mountain Montane Riparian Shrubland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.0
Northern Rocky Mountain Montane-Foothill Deciduous Shrubland	0.0250	Breiby 2006	Deciduous Shrubland	0.0
Western Great Plains Sparsely Vegetated Systems	0.2000	Dawen et al. 2003	Sparse Grassland	0.0
Western Great Plains Floodplain Shrubland	0.0100	Breiby 2006	Floodplain Forest	0.0
Western Cool Temperate Undeveloped Ruderal Shrubland	0.0290	McQuen 1998	Shrubland Other	0.0
Inter-Mountain Basins Sparsely Vegetated Systems	0.2000	Dawen et al. 2003	Sparse Grassland	0.0
Western Cool Temperate Developed Ruderal Deciduous Forest	0.0040	Guobin et al. 2006	Mixed Urban	0.0
Northern Rocky Mountain Subalpine Deciduous Shrubland	0.0250	Breiby 2006	Deciduous Shrubland	0.0
Rocky Mountain Alpine/Montane Sparsely Vegetated Systems	0.2000	Dawen et al. 2003	Sparse Grassland	0.0
Western Cool Temperate Developed Ruderal Evergreen Forest	0.0040	Guobin et al. 2006	Mixed Urban	0.0
Western Great Plains Depressional Wetland Systems	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.0

Western Great Plains Foothill and Piedmont Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.0
Inter-Mountain Basins Juniper Savanna	0.0928	Miller et al. (2003)	Pinyon–juniper	0.0
Inter-Mountain Basins Montane Riparian Forest and Woodland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.0
Northwestern Great Plains-Black Hills Ponderosa Pine Woodland and Savanna	0.0027	Miller et al. (2003)	Ponderosa pine	0.0
Northern Rocky Mountain Subalpine Woodland and Parkland	0.0020	Breiby 2006	Mixed Forest woodland	0.0
Colorado Plateau Mixed Low Sagebrush Shrubland	0.0290	McQuen 1998	Shrubland Other	0.0
Western Cool Temperate Undeveloped Ruderal Deciduous Forest	0.0010	Breiby 2006	Deciduous Forest	0.0
Southern Rocky Mountain Juniper Woodland and Savanna	0.0928	Miller et al. (2003)	Pinyon–juniper	0.0
Western Cool Temperate Row Crop - Close Grown Crop	0.5000	Dawen et al., 2003	General Cropland	0.0
Western Cool Temperate Undeveloped Ruderal Evergreen Forest	0.0020	Breiby 2006	Coniferous Forest	0.0
Western Great Plains Sand Prairie Grassland	0.0120	Breiby 2006	Medium-tall grassland	0.0
Northwestern Great Plains Shrubland	0.0290	McQuen 1998	Shrubland Other	0.0
Introduced Riparian Forest and Woodland	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.0
Western Great Plains Wooded Draw and Ravine	0.0010	Breiby 2006	Marsh/Riparian /Wetland	0.0
Abies concolor Forest Alliance	0.0020	Breiby 2006	Coniferous Forest	0.0
Western Cool Temperate Developed Ruderal Mixed Forest	0.0040	Guobin et al. 2006	Mixed Urban	0.0

Fire Effects in RUSLE

Most post-fire erosion research has described burn severity as an ordinal variable, usually in classes of low, moderate, and high severity. The crown fire activity output (Scott and Reinhardt 2001) classifies fire type as no fire, surface fire, passive crown fire, or active crown fire consistent with Van Wagner (1977). Crown fire activity has been used as a proxy for soil burn severity in several studies of debris flow risk (Tillery et al. 2014, Tillery and Haas 2016, Haas et al. 2017) by mapping surface, passive, and active fire to low, moderate, and high severity.

For forested areas (> 10% canopy cover in LANDFIRE) we assign the mean C factor values for the first year after burning from Larsen and MacDonald (2007) using a remap table (Table 5).

Table 5: mean cover factor values from Larsen and MacDonald (2007) calculated from nine wildfires in the Colorado Front Range. C factor values are applied as a remap to forests (> 10% canopy cover in LANDFIRE).

CFA Value	Fire Severity	C Factor Remap
1 (surface)	Low	0.01
2 (passive)	Moderate	0.05
3 (active)	High	0.20

For areas with < 10% canopy cover we applied a set of effect sizes (multiplication factors) to estimate post-fire C factor (Table 6). These effect sizes are conservative compared to the ~ 100x increase in cover factor for forested areas burned at high severity. Effect sizes are used due to the diversity of non-forest vegetation types and the limited post-fire erosion work in these systems (see Pierson and Williams 2016 for discussion).

Table 6: cover factor effect sizes applied as multiplication factors for non-forest vegetation types (<= 10% canopy cover).

CFA Value	Fire Severity	C Factor Effect
1 (surface)	Low	1.2
2 (passive)	Moderate	1.5
3 (active)	High	2.0

There are some slight mismatches between EVT forest classes and the 10% canopy cover threshold, so any "improved" pixels were replaced with their original values. We expect that these very low-density forest vegetation types would be minimally impacted by fire and they also represent a very small fraction of the landscape.

Fire effects on soils are diverse, but generally lead to decreased infiltration and cohesion, from a range of processes including deposition of hydrophobic compounds, soil sealing, and consumption of organic material (Neary et al. 2005, Shakesby and Doerr 2006). Quantitative measure of post-fire K factors is lacking, but Larsen and MacDonald (2007) back-calculate an effect size of 2.5 for high severity. Given the assumptions of this methodology, we adopted the more conservative values (Table 7) used in Schmeer (2014).

Table 7: soil erodibility factor effect sizes applied as multiplication factors, from Schmeer 2014.

CFA Value	Fire Severity	K Factor Effect
1 (surface)	Low	1.5
2 (passive)	Moderate	1.75
3 (active)	High	2.0

Other RULSE factors (rainfall erosivity and length-slope) are unchanged by fire.

Sediment Transport

It is important to consider sediment transport processes when measuring the exposure of infrastructure to post-fire sediment because there are many opportunities for sediment retention in large watersheds. At hillslope-scales, Hortonian overland flow and concentrated rill flow detach and transport sediment to streams. Given the steep slopes over much of the project area, it is expected that rill erosion is the dominant process at the hillslope-scale (McCool et al. 1989, Renard et al. 1997). Sediment transport in channels is controlled by a range of factors, but is generally related to discharge (Ryan and Emmett 2002).

Physical process models of sediment transport have high data, user experience, and computing requirements. Predicting sediment delivery at different scales is complicated by many factors, including vegetation, topography, soils, channel geometry, and the timing and sequence of storm events (Walling 1983). Given this complexity, prediction of sediment delivery to downstream locations in large watersheds comes with a moderate-to-high level of uncertainty.

A simple and computationally efficient approach to the scaling problem is to describe typical sediment delivery ratios (SDRs), which represent the proportion of gross erosion that is delivered the catchment outlet. It is often calculated by dividing the per unit area sediment yield at a larger catchment size to the per unit area erosion measured at a hillslope plot or smaller catchment size. Although sediment transport may be represented by a continuum of processes across scales, there are somewhat distinct processes that occur in areas with and without channelized flow. For this reason, we utilize two different SDR models to predict sediment delivery from the hillslope (RUSLE) to the streams (NHDPlus flowline associated with each NHDPlus catchment), and to predict sediment delivery from the point of input to the channel network to the downstream infrastructure features.

<u>Hillslope SDR</u>

The RUSLE soil loss predictions can be scaled up to catchment sediment yields using an empirical model of post-fire SDR from watersheds burned in the western US, including Colorado (Wagenbrenner and Robichaud 2014). SDR is modeled for each pixel using the annual length ratio equation (Wagenbrenner and Robichaud 2014), where the flow path length across the pixel is treated as the small catchment length and the flow path length to the nearest channel is treated as the larger catchment length. In most cases, the NHDPlus flowline network underestimates the extent of channelized flow so the mean flow accumulation from Henkle et al. (2011) was used to extend the channel network. Sediment delivery ratio in this model can vary between 0 and 1 and can be used as a multiplier to scale the gross erosion at the 30 m pixel-scale to the sediment delivered to the stream. The key processing steps can be summarized as follows for the NHDPlus DEM:

```
# Calculate flow direction and flow accumulation
fdir = FlowDirection(DEM)
facc = FlowAccumulation(fdir)

# Combine flowline paths and synthetic stream network
flowlines = Con(Raster(DEM) < 0,1,0)
```

```
facc_th = 108258
gt_th = Con(facc > (facc_th /[cellarea]),1,0)
synstream = Con((flowlines + gt_th) > 0,1,0)

# Null out the stream network from the flow direction raster
nullfdir = SetNull(synstream,fdir,'VALUE = 1')

# Calculate downstream flow length
flength = FlowLength(nullfdir,'DOWNSTREAM')

# Calculate cell flow length
Ddiag = math.sqrt(Power([cell dimension],2) + Power([cell dimension],2))
clength = Con(nullfdir,Ddiag,D,'"VALUE" in (2,8,32,128)')

# Calculate length ratio
lrat = flength/clength

# Calculate annual sediment delivery ratio
SDR = Exp(-0.56-0.0094*lrat)

# Fill in streams
SDR = Con(synstream > 0,1,SDR)
```

Channel SDR

Channel SDR generally focuses on suspended sediment rather than bedload transport and models have been proposed that are based on channel gradient, order, or morphology. We adapted Frickel et al. (1975) model for the Piceance Basin in Western Colorado for the channel types represented by the NHDPlus flowlines in the project area (Table 8).

Table 8: sediment delivery ratio (SDR) by NHD+ stream order adapted from Frickel et al. 1975.

Stream Order	SDR
1	0.75
2	0.8
3	0.85
4	0.95
5	0.95
6	0.95

The NHD+ flowlines dataset contains segments of various lengths that are generally shorter in steep and complex mountain terrain and longer in the plains. The difference in length requires some type of normalization. We assume the SDR ratios (Table 8) are representative of a 10 km channel length and therefore calculate the SDR for each segment as SDR^(flowline length in km/10 km). The channel SDR script does not do the routing, it just calculates the SDR for each flowline segment in the network.

Some large reservoirs contain multiple flowline segments. Only the terminal flowline in each reservoir is assigned to the infrastructure feature and the other flowlines within the reservoir are assigned SDR values equal to one so that all sediment entering the reservoir is accounted for at the terminal flowline. The terminal flowline segment of each reservoir is assigned an SDR value of 0.05 to account for the trapping effect of reservoirs, i.e. only 5% of sediment is passed through the reservoir to downstream flowlines.

Summary

The NHDPlus catchment is the spatial unit for treatment decisions in the watershed optimization tool, so treatment opportunities, benefits, and costs are summarized for each treatment type in each catchment.

Treatment opportunities are measured as the percent area of the catchment feasible for each treatment type and for all treatment types combined. Binary feasibility rasters developed in the Pre-fire Setup Management Costs and Restrictions script are summarized to the catchment-level using the tabulate area tool for each treatment type. The total feasibility is calculated as the percent of the catchment feasible for treatment with any type and is used in the optimization model to constrain the total amount of treatment assigned to the catchment.

The Summary script uses the output from the hillslope SDR model to scale each 30 m pixel's contribution to the NHDPlus catchment sediment yield. The RUSLE soil loss rate (Mg ha^{-1} yr^{-1}) is multiplied by the pixel area (ha) and the SDR (unitless; 0-1) to get the annual sediment delivered to the channel (Mg yr^{-1}) for each pixel, and summed for all pixels in the catchment to get the annual catchment sediment yield (Mg yr^{-1}). Feasibility was ignored in the Pre-fire Treat script, so it must be considered here when calculating the effect of each treatment type. For each treatment type, the annual soil loss estimates from RUSLE are merged with the untreated estimates with a conditional statement to constrain treatment benefits to feasible areas. The difference between the treated and untreated annual catchment sediment yields divided by the area feasible for treatment is the per area benefit of treatment in that catchment.

Costs are summarized to the catchment-level as zonal means for areas feasible for treatment. Burn probabilities are also summarized to the catchment-level as zonal means.

The output is a table with catchment-level burn probabilities and treatment opportunities, benefits, and costs.

Watershed Investment Tool

Summary

The Watershed Investment Tool consists of several modules that are written entirely in the R statistical computing language, which is free, open source, and works on a variety of operating systems. A basic HTML application (HTA) was developed to make the model more user friendly. The HTA is just a wrapper that dresses the R scripts up into a graphical user interface, so buttons can be used to: 1) navigate to, modify, and save changes to input files; 2) run the modules; and 3) view results.

Computer Setup

Install and Setup R

To install R on your computer, navigate to the website and select your preferred download option:

https://www.r-project.org/

The optimization model module scripts all have the .R extension which allows them to be opened in the R graphical user interface (GUI), which is typically used when writing and testing the code. If you want to be able to execute a script without opening it in the R GUI, you must tell the computer to open files with the .R extension using Rscript.exe. Right click on any of the R script files, select *Open with…*, and navigate to the location of the Rscript.exe file. The location of Rscript.exe may vary depending on the download options you selected, the version of Windows you are running, and the processor in your computer (32- or 64-bit) but is should be somewhere like this:

C:\Program Files\R\R-3.3.1\bin\Rscript.exe

Now you can double click on an R script file to run it as an executable, which will launch a command window as it runs. The program will execute, and the command window will close when the program terminates. Error messages that may have printed to the screen will also be recorded in error.log files stored in the output folders (discussed below).

To make the R accessible to command line calls, Windows need to know where the Rscript.exe program resides. This is done by modifying the Path Environment Variables to include the directory that contains Rscript.exe. Read instructions from Microsoft carefully before modifying any Environment Variables. On Windows 10, you should be able to access and modify the Path Environment Variables via Control Panel -> System and Security -> System -> Advanced system settings -> Environment Variables -> System variables -> Path -> Edit -> Add New. The path should be something like this:

C:\Program Files\R\R-3.3.1\bin

The Watershed Investment Tool working directory names are set to the OPTIMIZATION parent directory via the command arguments that windows sends to Rscript.exe when you double click on the R script file. The model will not work if the script locations are changed relative to the directory structure. This method of setting the working directory has not been tested for operating systems other than Windows 7 and Windows 10.

The map treatments and program objectives modules call R packages, which are libraries of functions developed by the R user community to perform specialized tasks beyond the base R library of functions. Packages are installed and stored in a directory on your computer before they can be used. The first time the map treatments or program objectives scripts are run, they will install the necessary packages and print extra messages to the command window and log file reporting on the installation progress.

Do not rearrange the directory structure within the OPTIMIZATION parent directory. The outputs from one process become the inputs to another. Rearranging the scripts, files, or folders will break the model. The model is designed to erase and replace files from the last run, so results should be copied and saved to another folder if desired.

Although R works on a variety of operating systems, the optimization model modules were developed and only tested extensively using Windows 7 and Windows 10.

HTA Graphical User Interface

A basic graphical user interface (GUI) was developed to improve user experience and to provide some guidance to standardize work flows. It is possible to run the model using only the R scripts, but non-technical users will want to use the GUI. The GUI is an HTML application (HTA), which is like an HTML document used to display content on the web, but with greater permissions to launch programs and to interact with data on your computer. HTA only works on Windows and the optimization GUI has only been extensively tested so far on Windows 10. Like any file or application in Windows, a shortcut can be made for the optimization GUI to launch from the desktop. The GUI resides in the top level of the optimization model directory (Figure 12).

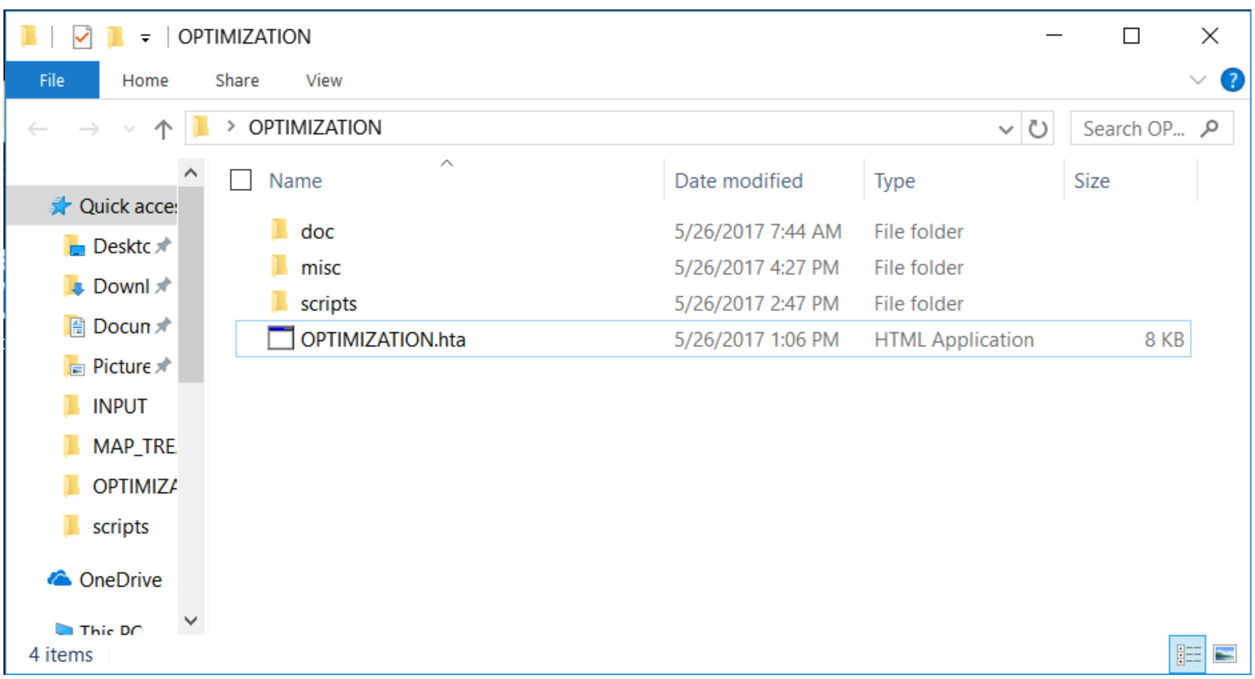


Figure 12: Optimization model file directory showing the optimization model GUI HTML application file (OPTIMIZATION.hta). A shortcut can be made for the desktop to access the application.

ArcMap

The Watershed Investment Tool does not need ArcGIS to function, but it includes a subdirectory with base spatial data for interacting with the model outputs. The Watershed Investment Tool GUI includes an optional button for launching an ArcMap document (View_Results.mxd in the scripts/SPATIAL directory), but you need to add the directory containing the ArcMap.exe file to the Path Environment Variable on your machine for it to work. Read instructions from Microsoft carefully before modifying any Environment Variables. On Windows 10, you should be able to access and modify the Path Environment Variables via Control Panel -> System and Security -> System -> Advanced system settings -> Environment Variables -> System variables -> Path -> Edit -> Add New. The path should be something like this:

C:\Program Files (x86)\ArcGIS\Desktop10.3\bin

Using the Watershed Investment Tool

The Watershed Investment Tool GUI (Figure 13) launches in Microsoft Internet Explorer window just like a website, but without an address bar. Instead of navigating the folder directory and manually running the scripts, the GUI provides a simple interface for opening and saving the input files, running the scripts, and viewing the results. The user interacts with the program using buttons, just like many websites and Windows applications. The GUI provides a text narrative guiding the user through typical workflows, but it is still recommended that the user reads and understands the material in this technical user guide.

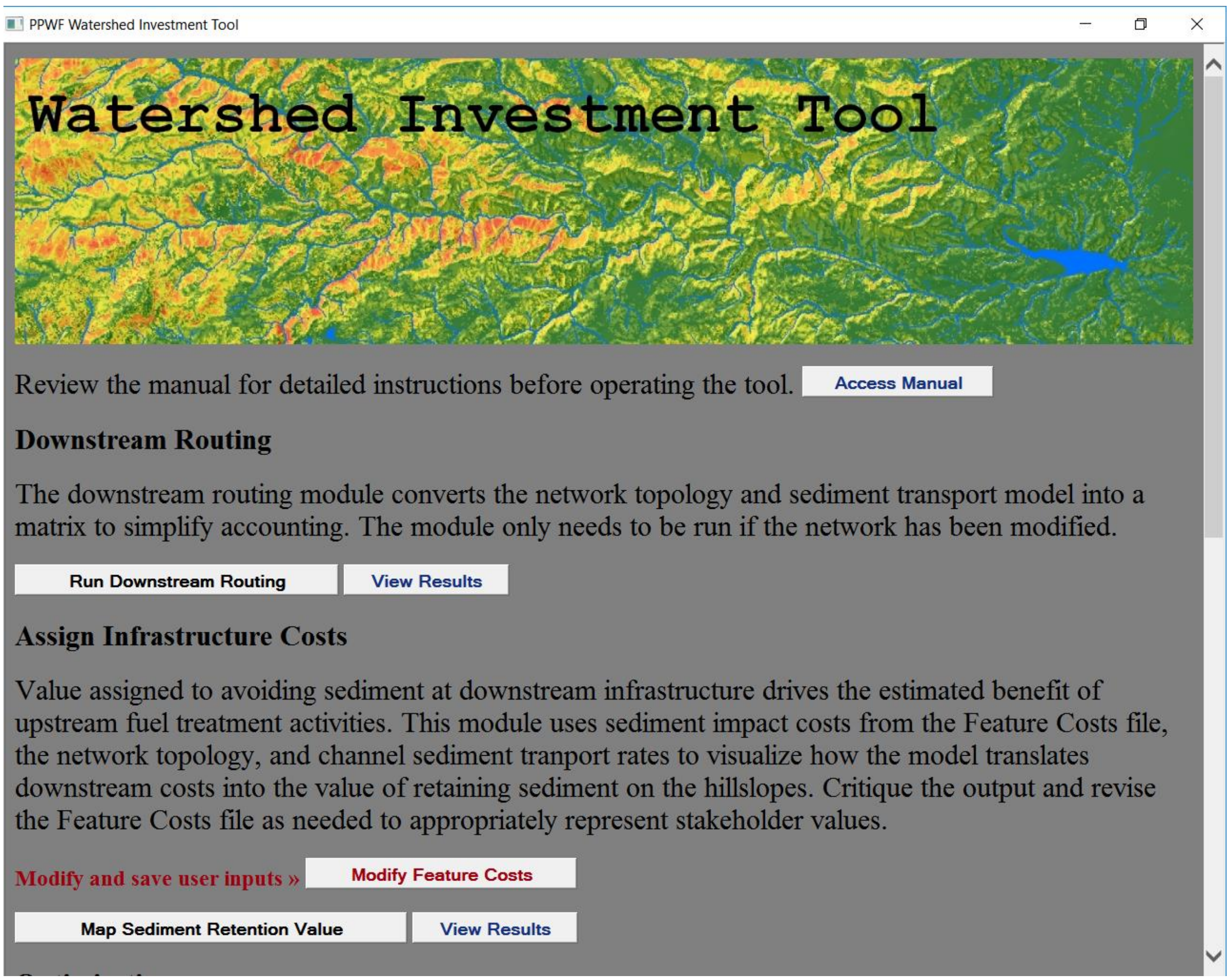


Figure 13: screenshot of the optimization model graphical user interface (GUI). Blue buttons are for optional tasks. Red buttons are for modifying user inputs. Black buttons are for running the optimization model modules.

Input Files

User inputs are highlighted with red text buttons in the GUI (Figure 13) and will follow the “Modify and save user inputs” text. All the inputs (Figure 14) are comma-separated value (.csv) files that will launch in Microsoft Excel from the GUI. Simply make any edits to the input file values in Excel and hit save before closing to save the changes.

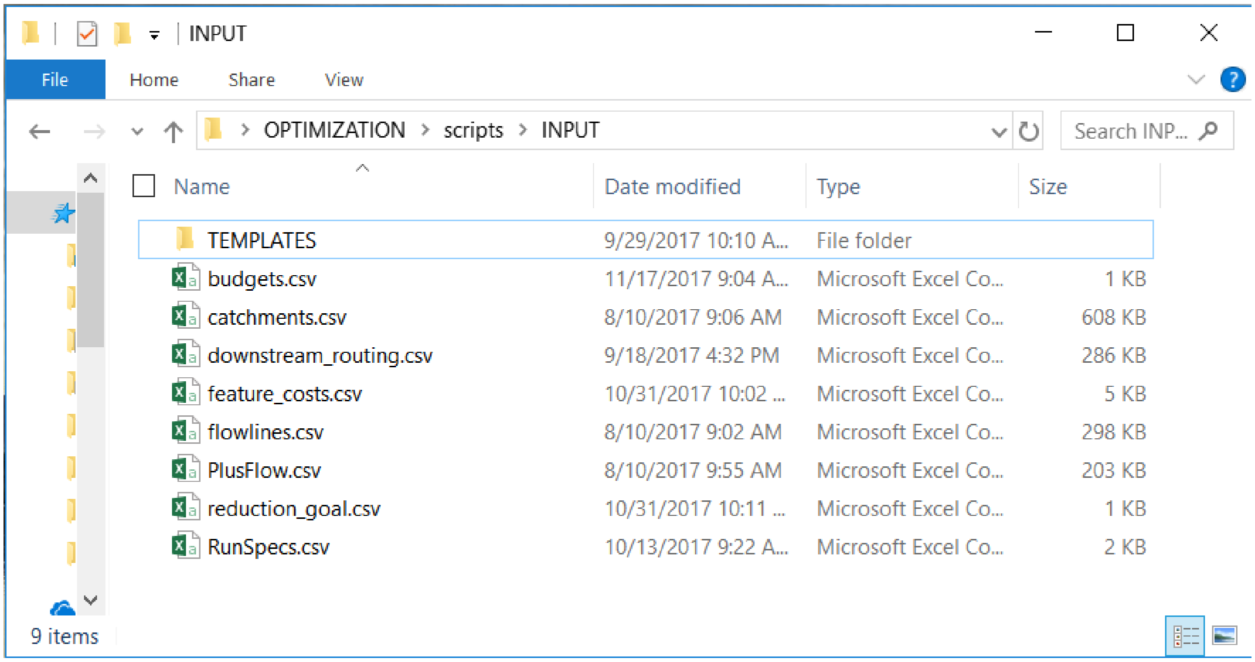


Figure 14: input directory with user and static input files. Note that the TEMPLATES folder contains copies of the input files with the default values.

Running Scripts

R scripts are run from the GUI (Figure 13) using the black text buttons that say "Run...". Each button will launch a command window to run the R script (Figure 15). Minimal information is printed to the command window to report on progress and if any errors are encountered. The command window will remain open when the process is terminated so the user can read the screen before moving on to the next stage in the process. To proceed, either close the window using the X in the upper right corner, or by typing "exit". The text that prints to the command window is also recorded and saved in an error.log file that is stored in the output folder.

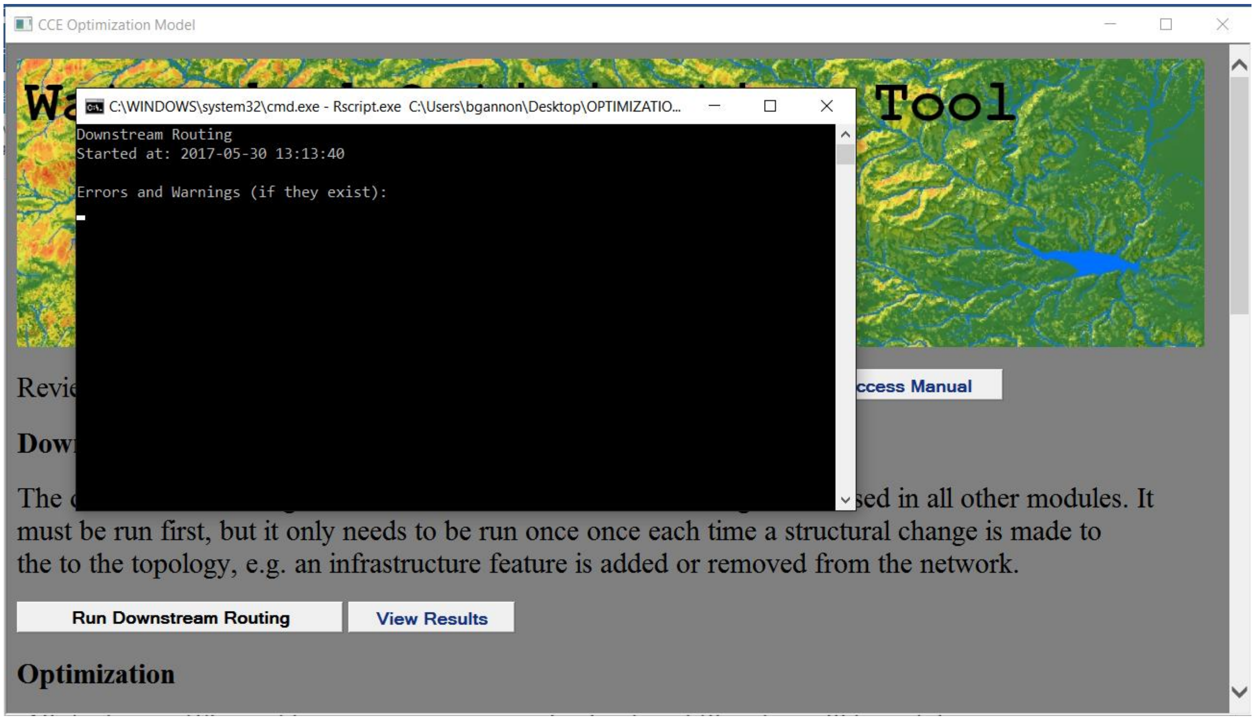


Figure 15: command window launched for the downstream routing module. Minimal information will be printed to the screen to inform the user if there are errors encountered and what the total run time is.

Viewing Results

Results for each process can be accessed from the GUI (Figure 13) using the blue text buttons that say "View Results". File Explorer will launch a window (Figure 16) to browse the output tables and figures. The error.log file is stored in the output folder and records information printed to the screen when the module is run. This can be accessed at any time to confirm when the script was run and if it encountered errors.

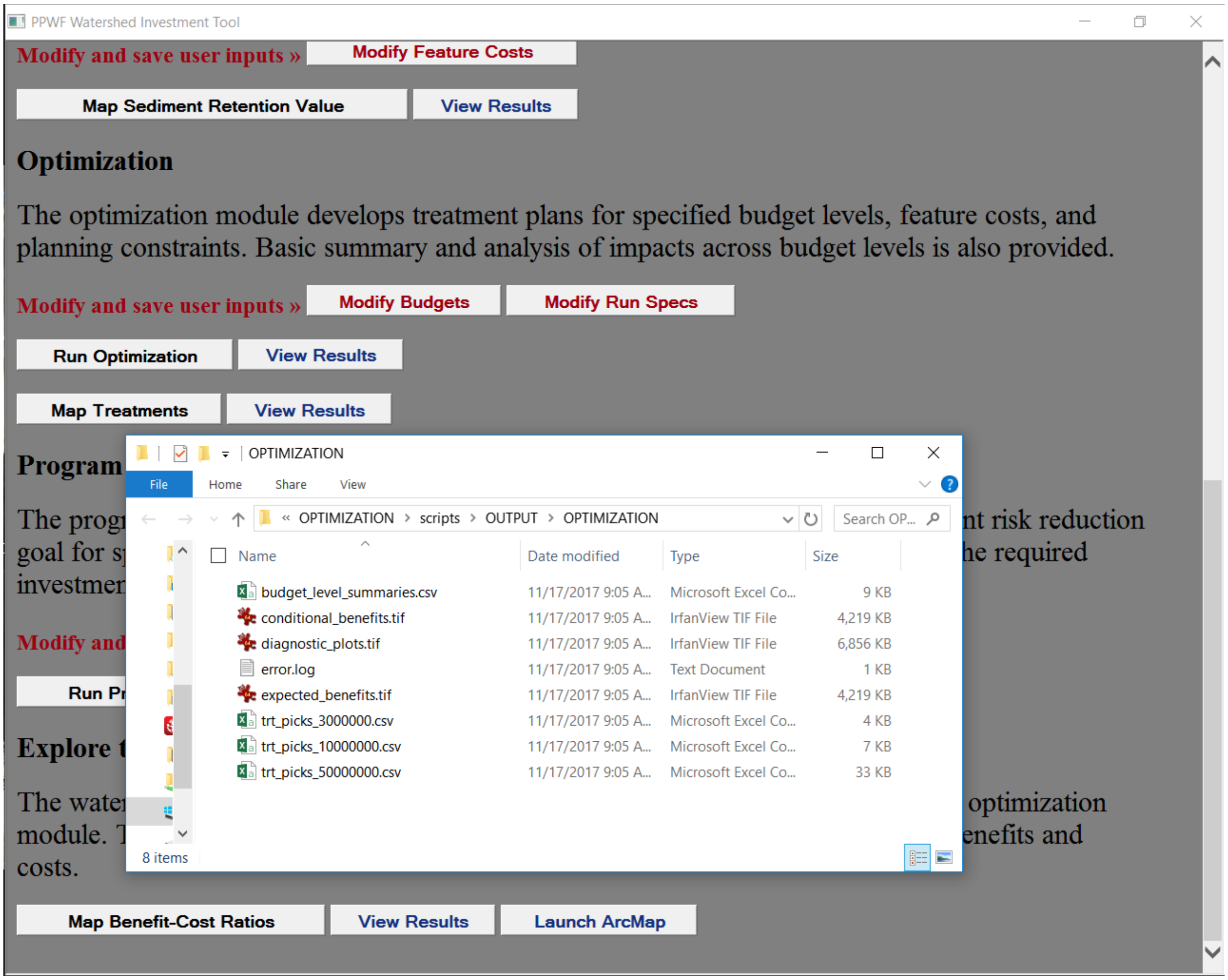


Figure 16: optimization model results can be viewed via File Explorer by clicking on the View Results button.

Module Details

Downstream routing

The downstream routing module quantifies the connections between the catchments and the infrastructure features in a 2 x 2 matrix.

Input:

flowlines.csv – NHDPlus flowlines and their sediment delivery ratio (TransRatio) from GIS pre-processing

PlusFlow.csv – NHDPlus network topology with modifications for divergences

feature_connections.csv – table mapping each infrastructure feature to a flowline

Output:

downstream_routing.csv – 2 x 2 matrix quantifying the connections between each catchment (by FEATUREID) and each infrastructure feature in terms of cumulative sediment delivery ratio (range 0-1 if connections exist, otherwise NA)

Process summary:

The script loops through all the catchment and feature combinations to identify the connecting flow paths (if they exist) and to calculate the cumulative sediment delivery ratio. The cumulative sediment delivery ratio is calculated as the product of the flowline sediment delivery ratios that make up the flow path, excluding the final contributing flowline. The downstream routing module only needs to be re-run if the network has been modified by adding a new infrastructure feature connection or by structurally modifying the catchments, flowlines, or topology table. The *downstream_routing.csv* output is a required input for all other modules to run, so the downstream routing module needs to be run first.

Assign Infrastructure Costs

The values assigned to avoiding sediment at infrastructure are the most important model inputs the user can control for determining spatial treatment priorities. This module converts the input table values into a spatial representation of how the model values sediment retention in each catchment (the "sediment retention value") based on connectivity to downstream values.

Input:

extent.shp – shapefile of project extent for mapping

NHDCatchment.shp – shapefile of NHD+ catchments for mapping
NHDFlowline.shp – shapefile of NHD+ flowlines for mapping
FoCs.shp – shapefile of all infrastructure features for mapping
FoC_polygons.shp – shapefile of infrastructure waterbodies for mapping
Hillcl.tif – hillshade raster for mapping

catchments.csv – NHD+ catchments with data from GIS pre-processing on burn probability, treatment feasibilities, treatment benefits, and treatment costs
feature_costs.csv – lookup table for the costs of sediment delivered to each infrastructure feature ($/Mg)
downstream_routing.csv – the downstream routing matrix described above

Output:

Sediment_Retention_Value.tif – maps the value of retaining sediment in each catchment ($/Mg) based on connectivity to downstream values

Process Summary:

The assign infrastructure costs module reads in the same data used in the optimization module (described below), but does only the calculations needed to describe the connectivity of each catchment to downstream values. The module loops through each catchment in the *downstream_routing.csv* file and multiplies the cumulative downstream sediment delivery ratio (SDR) between the catchment and a connected downstream infrastructure feature by the value it is assigned in the *feature_costs.csv* file. A catchment may be in the contributing area for multiple downstream resources, so the module attributes the sum of all SDR-cost products as the sediment retention value ($/Mg) for the catchment. The sediment retention value map (Figure 17) is useful for explaining the topology and function of avoided sediment costs in the model. The assign infrastructure costs module is not required, but the sediment retention value map is a useful check on the feature costs input to make sure the spatial distribution of values matches stakeholder perceptions.

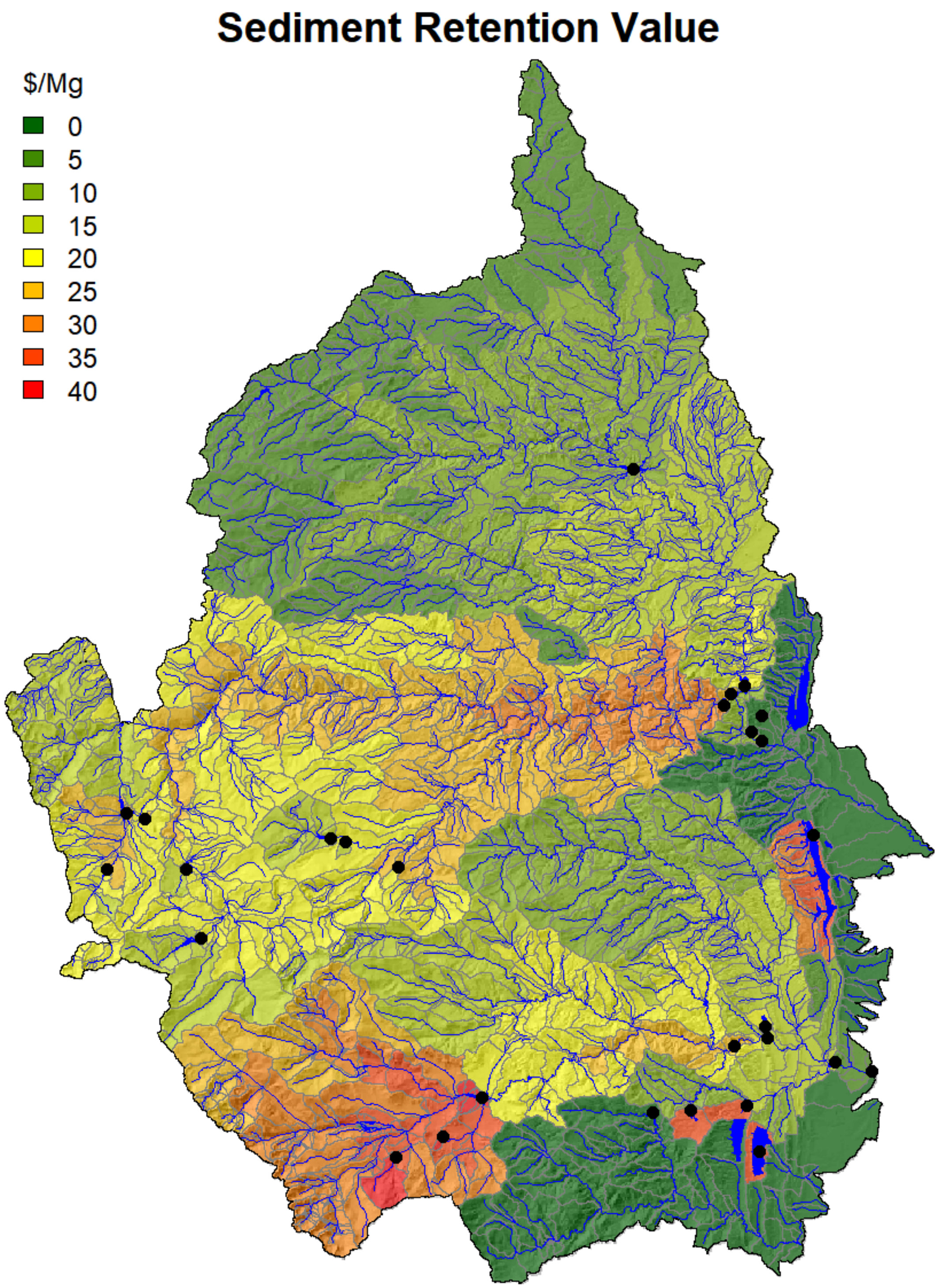


Figure 17: sediment retention value ($/Mg) for each catchment based on connectivity to downstream values assigned in the feature_costs.csv file. The sediment retention value does not include any representation of treatment feasibilities or effects – it only describes the economic value of actions taken to retain sediment in different catchments throughout the watershed.

Optimization

The optimization module identifies the optimal locations to treat for specified budget levels and infrastructure feature costs (weights) using a benefit-cost ratio sort and spend algorithm.

Input:

catchments.csv – NHD+ catchments with data from GIS pre-processing on burn probability, treatment feasibilities, treatment benefits, and treatment costs

downstream_routing.csv – the downstream routing matrix described above

feature_costs.csv – lookup table for the costs of sediment delivered to each infrastructure feature ($/Mg)

budgets.csv – single column of budgets you want optimized treatment plans for ($)

RunSpecs.csv – table for Optimization and Program Objectives module parameters including: minimum project area in each catchments (ac), maximum percent that can be treated in a catchment (%), planning period length (yr), matching funds adjustment factor (%), and burn probability adjustment factor (%)

Output:

budget_level_summaries.csv – table showing the conditional and expected benefits of the optimal treatments in terms of sediment (Mg) and cost ($) reductions by budget level

conditional_benefits.tif – graphic showing the benefits by budget level given fire occurs during the planning period

expected_benefits.tif – graphic showing the benefits by budget level accounting for burn probability

diagnostic_plots.tif – graphic showing continuous response of benefits, spatial dispersion of treatments, and treatment types across budget levels

trt_picks_[BUDGET LEVEL].csv – ordered list of catchments selected for treatment and the acres to be treated (Trt_ac) at the specified budget level

NOTE: the following intermediate products created by the optimization module are saved to the WATERSHED_BENEFITS output folder for further data exploration or analysis

dstr.csv – table of the downstream multipliers for sediment and costs to map catchment connectivity to the downstream values *mechanical_only.csv* – table of absolute and per acre benefits of mechanical only treatment by catchment

mechanical_Rxfire.csv – table of absolute and per acre benefits of mechanical and Rx fire treatment by catchment

Rxfire_only.csv – table of absolute and per acre benefits of Rx fire only treatment by catchment

Process Summary:

The optimization module has three inputs that are modified by the user: 1) budget levels, 2) feature costs, and 3) run specifications.

Budget levels are specified in the *budgets.csv* file (Figure 18). Budgets can be any number of positive values.

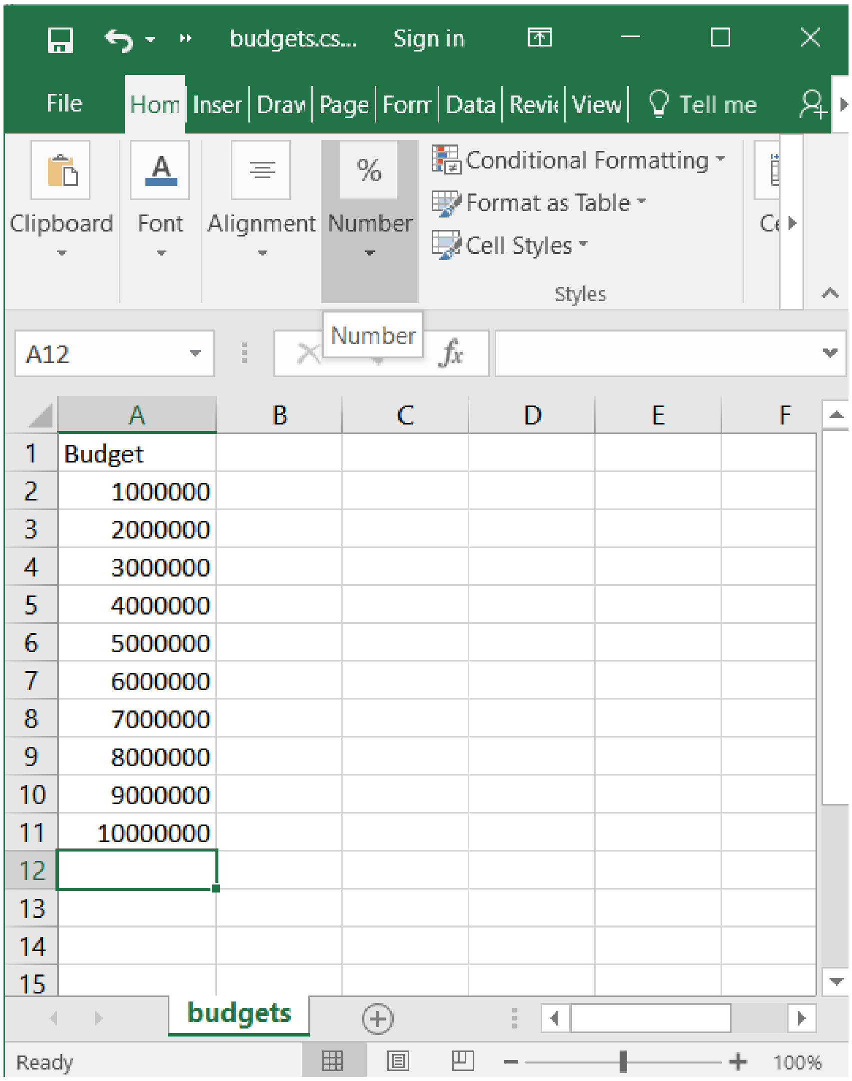
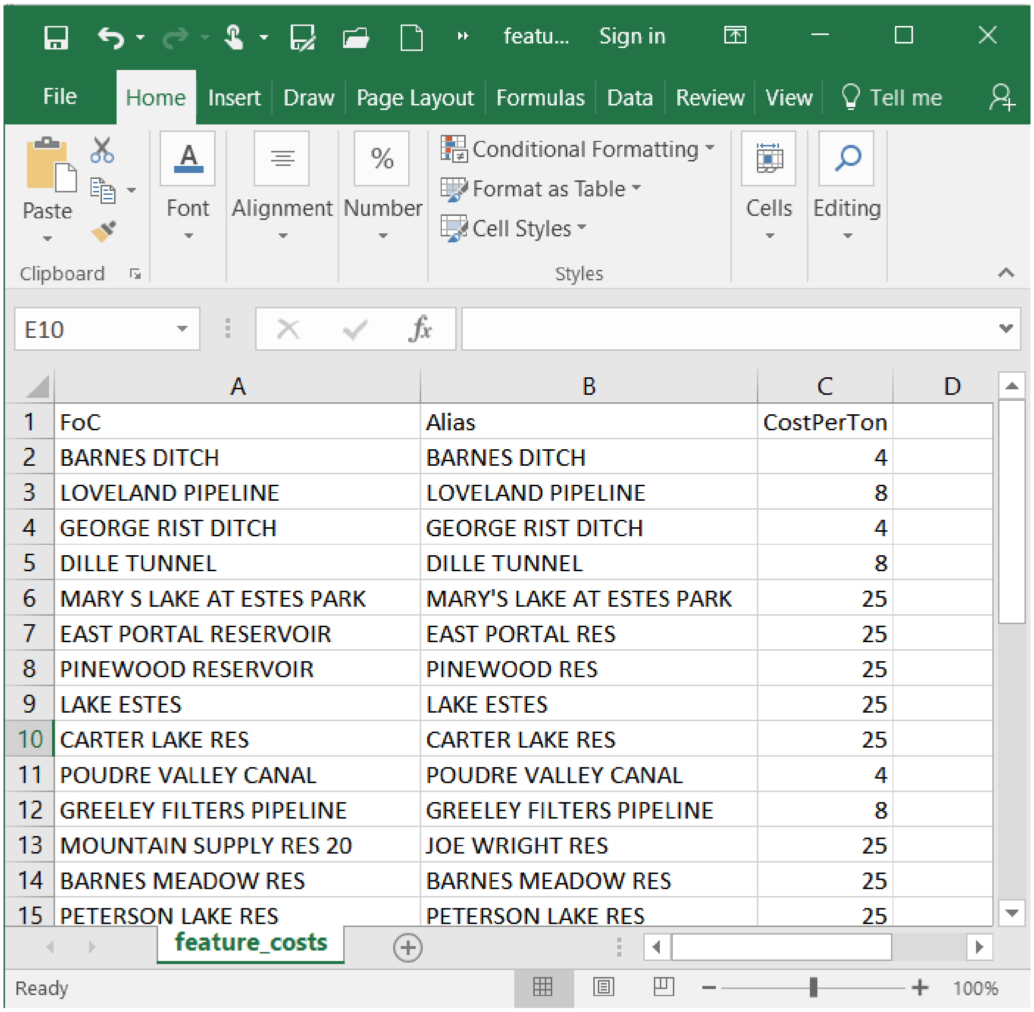


Figure 18: budgets.csv input file showing a run set up to compare $1-10M budget levels. Any number of positive values can be specified in rows 2-n.

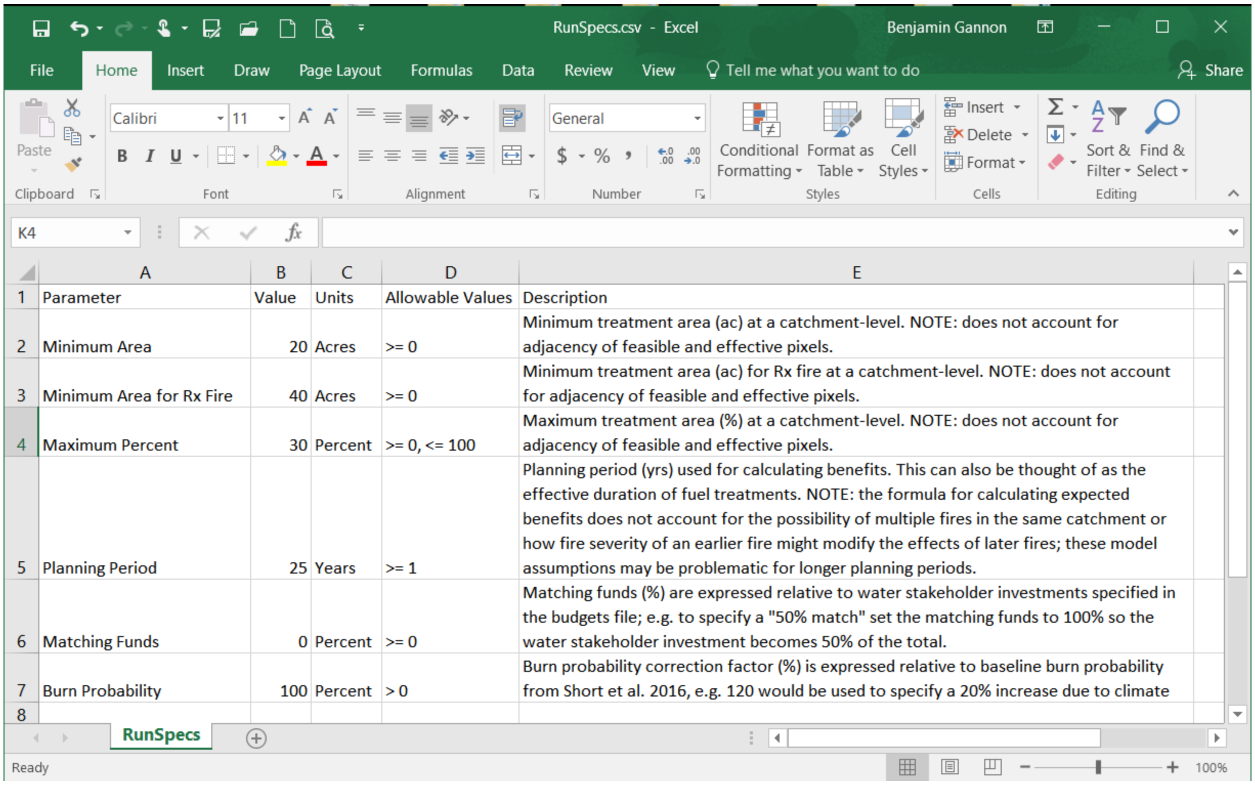
The feature costs are specified in the *feature_costs.csv* file as $/Mg of sediment (Figure 19). The feature costs act as weights in optimization; increasing a feature's cost will bias more treatment to its contributing area. The CostPerTon values determine which features are optimized for and displayed in the reporting. To focus on a subset of features, set the CostPerTon to zero for any features you want to ignore. For example, to produce a custom optimization for the City of Loveland, set CostPerTon equal to zero for features that don't affect Loveland. The FoC field is the official name of the infrastructure feature used in the Colorado Decision Support System, which is used throughout the tool to map costs to features. The alias field stores the more commonly-used or abbreviated name for display purposes.



	A	B	C
1	FoC	Alias	CostPerTon
2	BARNES DITCH	BARNES DITCH	4
3	LOVELAND PIPELINE	LOVELAND PIPELINE	8
4	GEORGE RIST DITCH	GEORGE RIST DITCH	4
5	DILLE TUNNEL	DILLE TUNNEL	8
6	MARY S LAKE AT ESTES PARK	MARY'S LAKE AT ESTES PARK	25
7	EAST PORTAL RESERVOIR	EAST PORTAL RES	25
8	PINEWOOD RESERVOIR	PINEWOOD RES	25
9	LAKE ESTES	LAKE ESTES	25
10	CARTER LAKE RES	CARTER LAKE RES	25
11	POUDRE VALLEY CANAL	POUDRE VALLEY CANAL	4
12	GREELEY FILTERS PIPELINE	GREELEY FILTERS PIPELINE	8
13	MOUNTAIN SUPPLY RES 20	JOE WRIGHT RES	25
14	BARNES MEADOW RES	BARNES MEADOW RES	25
15	PETERSON LAKE RES	PETERSON LAKE RES	25

Figure 19: feature_costs.csv input file with variable weights applied to different infrastructure types.

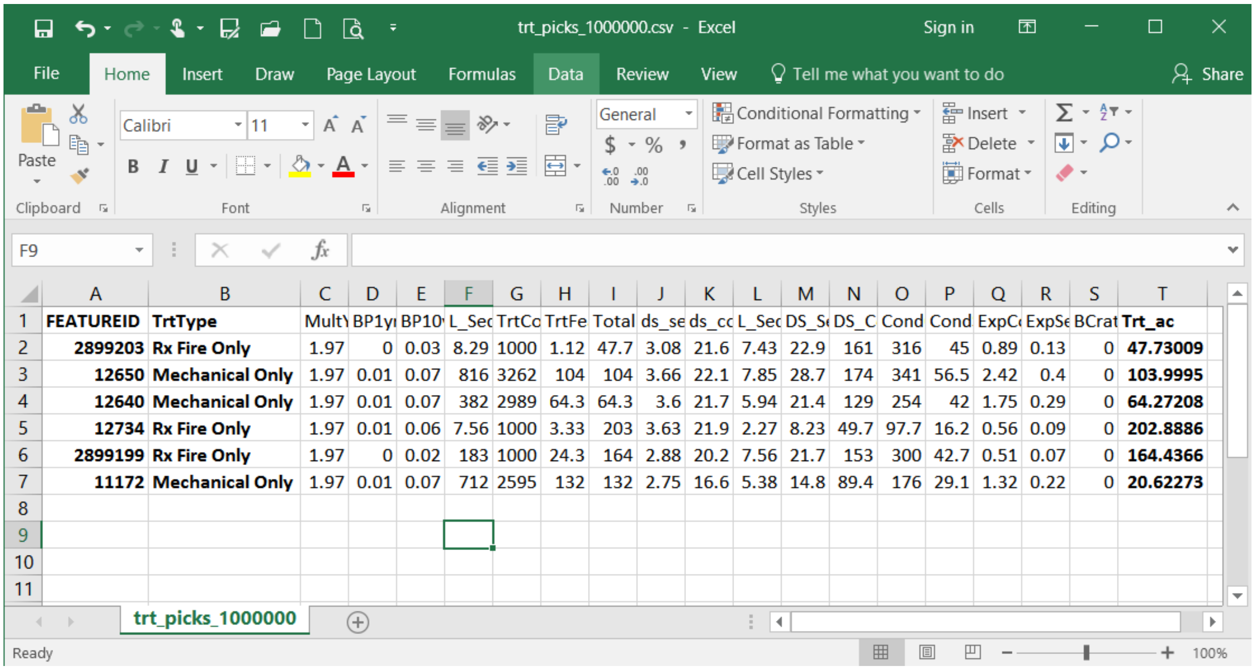
Controls for a few key model parameters related to implementation constraints and economics are provided in the *RunSpecs.csv* file (Figure 20). The *minimum area* parameters (ac) can be any values greater than or equal to zero to constrain the model from selecting small projects. Separate control is provided for the minimum prescribed fire project area. The *maximum percent* parameter is used to constrain the upper end of area treated at the catchment-level, to account for either the rate of voluntary participation on private lands or balancing multiple land management objectives on public lands. The *planning period* parameter (years) is used to correct the annual burn probability (Short et al. 2016) to the probability of treatment experiencing fire over the planning period. The default planning period is set to 25 years to approximate the effective lifespan of fuel treatments in Colorado. The *matching funds* parameter (%) is used to account for the benefits of work completed because of matching funds, i.e. with a budget that is expanded because of some external investment that is not charged to the beneficiaries. The *burn probability* parameter (%) allows for sensitivity analysis or forecasting of benefits for climate change scenarios.



Parameter	Value	Units	Allowable Values	Description
Minimum Area	20	Acres	>= 0	Minimum treatment area (ac) at a catchment-level. NOTE: does not account for adjacency of feasible and effective pixels.
Minimum Area for Rx Fire	40	Acres	>= 0	Minimum treatment area (ac) for Rx fire at a catchment-level. NOTE: does not account for adjacency of feasible and effective pixels.
Maximum Percent	30	Percent	>= 0, <= 100	Maximum treatment area (%) at a catchment-level. NOTE: does not account for adjacency of feasible and effective pixels.
Planning Period	25	Years	>= 1	Planning period (yrs) used for calculating benefits. This can also be thought of as the effective duration of fuel treatments. NOTE: the formula for calculating expected benefits does not account for the possibility of multiple fires in the same catchment or how fire severity of an earlier fire might modify the effects of later fires; these model assumptions may be problematic for longer planning periods.
Matching Funds	0	Percent	>= 0	Matching funds (%) are expressed relative to water stakeholder investments specified in the budgets file; e.g. to specify a "50% match" set the matching funds to 100% so the water stakeholder investment becomes 50% of the total.
Burn Probability	100	Percent	> 0	Burn probability correction factor (%) is expressed relative to baseline burn probability from Short et al. 2016, e.g. 120 would be used to specify a 20% increase due to climate

Figure 20: all optimization controls other than budgets are controlled with the RunSpecs.csv file.

The optimization module uses data from the GIS pre-processing and the downstream routing matrix to calculate the expected per acre avoided cost of sediment delivered to downstream infrastructure features by treatment type in each catchment for the planning period. Treatment selections are then made based on maximizing the benefit-cost ratio until the budget is spent through a sort and spend algorithm with constraints for feasible area for treatment and overall budget. The script has built-in analysis of expected and conditional benefits by budget level. The expected benefits are the downstream avoided costs multiplied by a correction factor to account for multiple years of elevated post-fire sediment over the planning period multiplied by the planning period burn probability. The expected benefits should be interpreted as the mean avoided sediment costs from fire ($) due to treatment over the planning period. The conditional benefits are the downstream avoided costs multiplied by a correction factor to account for multiple years of elevated post-fire sediment. The conditional benefits should be interpreted as the avoided costs given fire burns in the treated catchments ($). Budget level analysis is reported in the summary table and benefits figures. Treatment plans are output to a separate file for each budget level showing an ordered list of the catchments picked for treatment (Figure 21), the treatment type selected (TrtType), and the acres selected for treatment (Trt_ac). The treatment picks are ordered from highest to lowest priority moving down the list.



FEATUREID	TrtType	Mult	BP1y	BP10	L_Sec	TrtCo	TrtFe	Total	ds_se	ds_cc	L_Sec	DS_S	DS_C	Cond	Cond	ExpC	ExpSe	BCrat	Trt_ac
2899203	Rx Fire Only	1.97	0	0.03	8.29	1000	1.12	47.7	3.08	21.6	7.43	22.9	161	316	45	0.89	0.13	0	47.73009
12650	Mechanical Only	1.97	0.01	0.07	816	3262	104	104	3.66	22.1	7.85	28.7	174	341	56.5	2.42	0.4	0	103.9995
12640	Mechanical Only	1.97	0.01	0.07	382	2989	64.3	64.3	3.6	21.7	5.94	21.4	129	254	42	1.75	0.29	0	64.27208
12734	Rx Fire Only	1.97	0.01	0.06	7.56	1000	3.33	203	3.63	21.9	2.27	8.23	49.7	97.7	16.2	0.56	0.09	0	202.8886
2899199	Rx Fire Only	1.97	0	0.02	183	1000	24.3	164	2.88	20.2	7.56	21.7	153	300	42.7	0.51	0.07	0	164.4366
11172	Mechanical Only	1.97	0.01	0.07	712	2595	132	132	2.75	16.6	5.38	14.8	89.4	176	29.1	1.32	0.22	0	20.62273

Figure 21: example optimization output for a $1M budget. The important fields, in bold, are the catchment ID (FEATUREID), the type of treatment (TrtType), and the acres to be treated (Trt_ac). In this example, six catchments are picked for treatment and the highest priority for treatment is catchment 2899203.

Map treatments

The map treatments module (optional) produces a simple map of treatment picks and a bar plot showing the distribution of benefits to downstream infrastructure features by budget level. It also converts each treatment plan into a polygon shapefile for viewing in GIS software.

Input:

extent.shp – shapefile of project extent for mapping
NHDCatchment.shp – shapefile of NHD+ catchments for mapping
NHDFlowline.shp – shapefile of NHD+ flowlines for mapping
FoCs.shp – shapefile of all infrastructure features for mapping
FoC_polygons.shp – shapefile of infrastructure feature waterbodies for mapping
Hillcl.tif – hillshade raster for mapping

downstream_routing.csv – the downstream routing matrix described above

feature_costs.csv – lookup table for the costs of sediment delivered to each infrastructure feature ($/Mg)

trt_picks_[BUDGET LEVEL].csv – the script will identify all treatment pick output files in the optimization module output folder

Output:

trt_picks_[BUDGET LEVEL].tif – map of treatment picks and a bar plot showing the distribution of benefits on downstream infrastructure features by budget level

trt_picks_[BUDGET LEVEL].shp – polygon shapefile of treatment picks for viewing in GIS software

Process Summary:

The map treatments module combines the output from the optimization model with spatial data to map the treatment picks and the distribution of benefits across infrastructure features in terms of risk reduction (expected avoided sediment costs over the planning period). The map and bar plot will only display infrastructure features with non-zero values in the *feature_costs.csv* file. An example for a $100M budget is show in Figure 22. Each treatment plan is also converted to shapefile format for viewing in GIS software (stored in OUTPUT/TREATMENT_PLAN_SHAPEFILES).

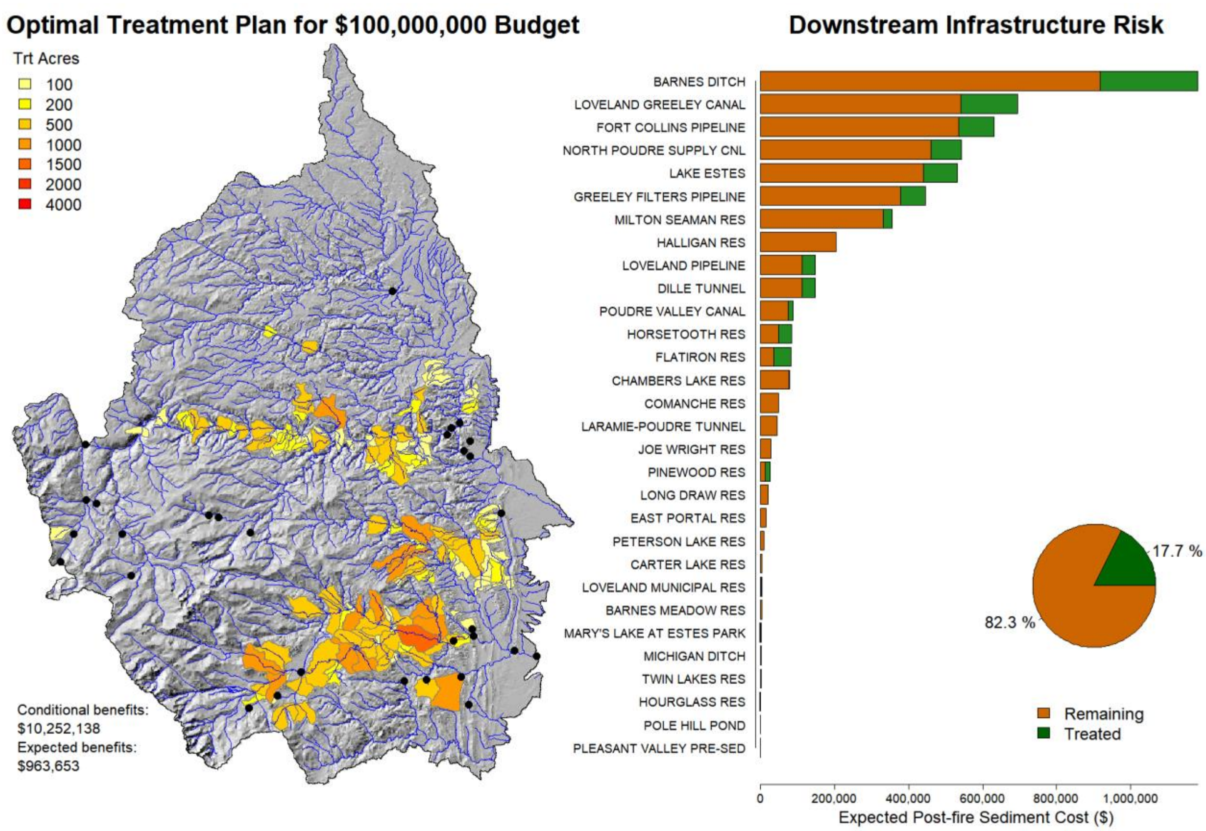


Figure 22: example treatment map for a $100M budget optimized on all infrastructure features. The map shows the spatial distribution of treatments and the bar graph on the right accounts for the baseline risk and risk reduction achieved through the optimal fuel treatment plan for each infrastructure feature assigned non-zero value in the feature_costs.csv file. The pie chart provides a simplified representation of the proportional risk reduction across all infrastructure.

Program objectives

The program objectives module uses the same methodology as the optimization module, but treatment opportunities are instead identified to achieve a stated percentage risk reduction goal, measured in terms of expected wildfire-related sediment costs to infrastructure over the planning period. This module both identifies treatment types and locations required to achieve the stated objective and reports relevant metrics such as the total treatment costs and acres to achieve the program objectives. Since the output is a single treatment plan, the mapping has been integrated into the script.

Input:

extent.shp – shapefile of project extent for mapping
NHDCatchment.shp – shapefile of NHD+ catchments for mapping
NHDFlowline.shp – shapefile of NHD+ flowlines for mapping
FoCs.shp – shapefile of all infrastructure features for mapping
FoC_polygons.shp – shapefile of infrastructure feature waterbodies for mapping
Hillcl.tif – hillshade raster for mapping

catchments.csv – NHD+ catchments with data from GIS pre-processing on burn probability, treatment feasibilities, treatment benefits, and treatment costs

downstream_routing.csv – the downstream routing matrix described above

feature_costs.csv – lookup table for the costs of sediment delivered to each infrastructure feature ($/Mg)

reduction_goal.csv – single cell with header containing the percent reduction goal in post-fire sediment

RunSpecs.csv – table for Optimization and Program Objectives module parameters including: minimum project area in each catchments (ac), maximum percent that can be treated in a catchment (%), planning period length (yr), matching funds adjustment factor (%), and burn probability adjustment factor (%)

Output:

TrtPicks_[REDUCTION PERCENTAGE]perRed_wexpected.tif – map of treatment picks and a bar plot showing the distribution of benefits relative to baseline risk

Process Summary:

The program objectives module has three inputs that are modified by the user: 1) percent reduction goal, 2) feature costs, and 3) run specifications shared with the optimization module (same *RunSpecs.csv* file).

The feature costs are specified in the *feature_costs.csv* file as $/Mg of sediment (Figure 19 above) and function in the same way as described for the optimization module. The implementation constraints and economic parameters are specified in the *RunSpecs.csv* file (Figure 20 above) and functions in the same way as described for the optimization module.

The program objectives module applies the same methods as the optimization module, using data from the GIS pre-processing and the downstream routing matrix to calculate the per acre avoided cost of sediment delivered to downstream infrastructure features by treatment type in each catchment. Treatment selections are then made based on maximizing the benefit-cost ratio until the percent reduction objective is met or there are no more feasible treatment opportunities. If the stated objective is not feasible, a warning message will be printed to the screen and text on the output graphics will note the maximum reduction possible.

The module identifies a treatment plan to achieve the stated reduction goal in the expected wildfire-related sediment costs to infrastructure over the planning period. This metric is equivalent to the expected benefits, which are the expected (mean) avoided costs from fire ($) due to treatment over the planning period. The treatment plan is presented in the same format as the optimization module (Figure 21 above).

Mapping is included in the module script because there is only one treatment plan to map for each model run (Figure 23).

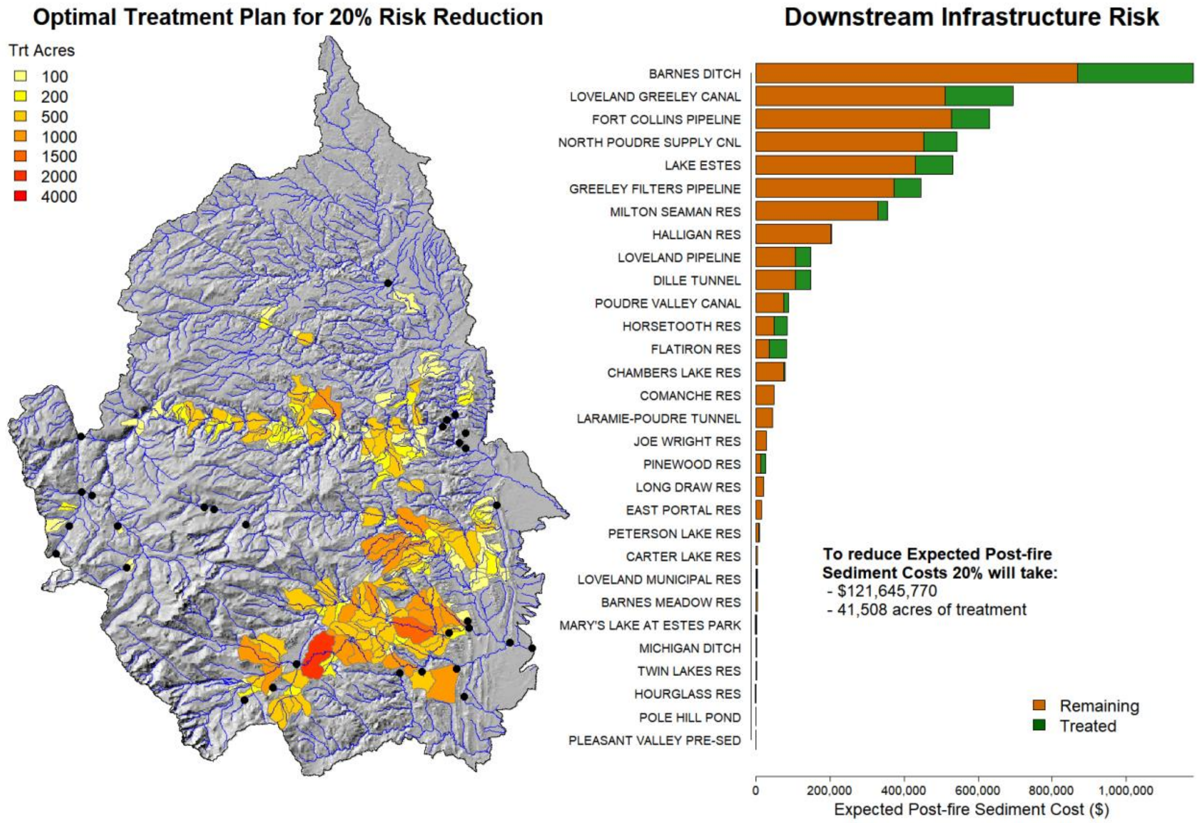


Figure 23: example program objectives run with a stated objective to reduce the risk of wildfire-related sediment costs to infrastructure by 20% over the planning period for all infrastructure features in both watersheds. It includes a total $ amount and acreage required to implement the treatment plan. The bar plot shows the risk reduction (green) relative to the baseline risk (orange + green).

Explore the data

The explore the data module (optional) maps the benefit-cost ratios, which are an intermediate product of the optimization module. The benefit-cost ratio maps can help to explain how the optimization process works and can aid in visual evaluation of trade-offs between different treatment scenarios.

Input:

extent.shp – shapefile of project extent for mapping
NHDCatchment.shp – shapefile of NHD+ catchments for mapping
NHDFlowline.shp – shapefile of NHD+ flowlines for mapping
FoCs.shp – shapefile of all infrastructure features for mapping
FoC_polygons.shp – shapefile of infrastructure feature waterbodies for mapping
Hillcl.tif – hillshade raster for mapping

mechanical_only.csv – table of absolute and per acre benefits of mechanical only treatment by catchment *mechanical_Rxfire.csv* – table of absolute and per acre benefits of mechanical and Rx fire treatment by catchment

Rxfire_only.csv – table of absolute and per acre benefits of Rx fire only treatment by catchment

Output:

BCR_summary.tif – maps of the benefit-cost ratios for each treatment type in each catchment

Process Summary:

The explore the data module reads in the base spatial data for mapping and the *mechanical_only.csv, mechanical_Rxfire.csv, and Rxfire_only.csv* files produced as intermediate products in the optimization module. A simple three panel map is produced (Figure 24) to show the spatial and treatment type variation in cost-benefit ratios. The benefit-cost ratio input files are in an appropriate format for joining to the NHDPlus catchments spatial data in ArcGIS using the FEATUREID field. There is also a button to launch an ArcMap document pre-loaded with relevant spatial data for exploring the intermediate products or optimal treatment plans in ArcGIS. Note that this will not work unless you have an ArcGIS license on your machine.

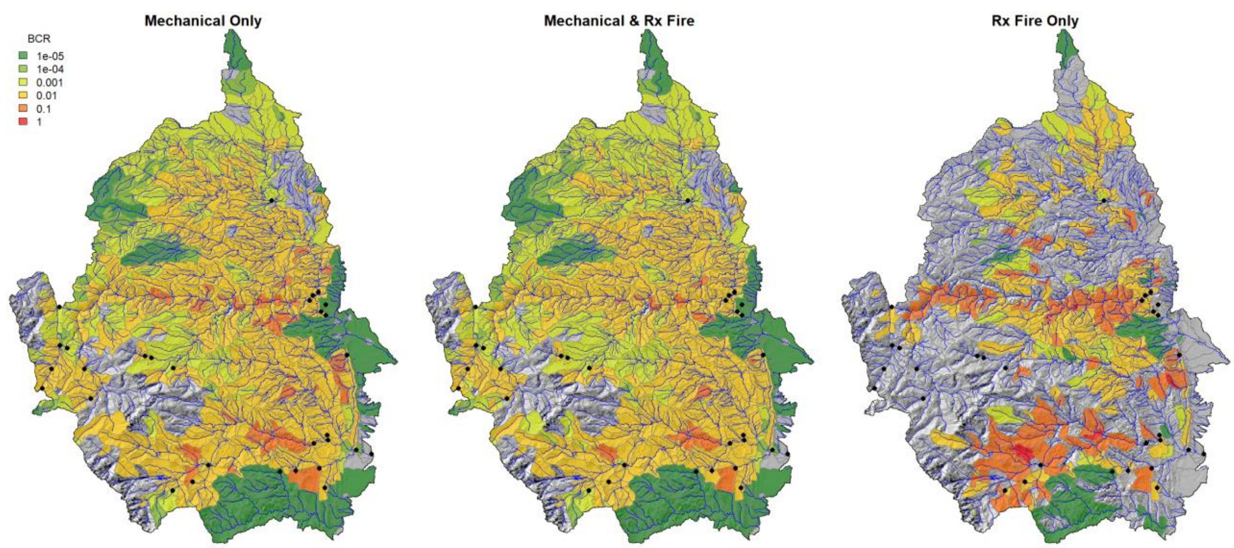


Figure 24: map of benefit-cost ratios calculated in the optimization module. Any un-shaded catchments have no feasible acres in the catchment for that treatment type.

Workflow

The optimization model was broken into separate modules for efficient computing. The slowest tasks are building the downstream routing matrix and mapping, so the core optimization module focuses only on developing optimal treatment plans, so it can be used to quickly develop benefit response curves across a range of budgets.

The downstream routing module script should always be run first. Once the *downstream_routing.csv* file is created, the script will not need to be re-run unless the network has been modified by adding a new infrastructure feature connection, or by structurally modifying the catchments, flowlines, or topology table.

The assign infrastructure costs module should then be used to populate and refine the *feature_costs.csv*. To ignore a feature, set the sediment cost to 0. Uncertainty in infrastructure sediment impact costs can be further explored by running the optimization model multiple times with different feature cost files.

Optimized treatment plans for a set of potential budgets can be developed using the optimization module. The optimization module will automatically run at increments from $1M to the maximum budget level provided as input to generate a benefit response curve, but it will only save treatment plans for the budget levels specified as inputs. The map treatments module can then be used to map the treatment plans and summarize the expected risk reduction across valued infrastructure.

If a quantitative risk reduction goal has been identified, the program objectives module can be used to develop an optimal treatment plan to achieve the goal, with automatic mapping.

The intermediate benefit-cost analysis products can be mapped using the data exploration module. There is also an ArcMap document pre-loaded with relevant spatial data products for viewing and critiquing the results.

Keep in mind that the map treatments script does not automatically run after optimization, so it is possible to have optimization and map treatment outputs that do not match. Make sure to run the map treatments module script after the optimization module script if you want to view maps of the most-recent run. Log files (error.log) are created each time a module is run and saved to the relevant output folder; reference the log file if there is any question about the run specifications used to generate the output.

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