Montana Wildfire Risk Assessment: Methods and Results

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1 Overview of MWRA

1.1 Purpose of the Assessment

The purpose of the Montana Quantitative Wildfire Risk Assessment (MWRA) is to provide foundational information about wildfire hazard and risk to highly valued resources and assets across the state. Such information supports wildfire response, fuel management planning decisions, and revisions to land and resource management plans. A wildfire risk assessment is a quantitative analysis of the assets and resources across a specific landscape and how they are potentially impacted by wildfire. The MWRA analysis considers several different components, each resolved spatially across the state, including:

- likelihood of a fire burning,
- the intensity of a fire if one should occur,
- the exposure of assets and resources based on their locations, and
- the susceptibility of those assets and resources to wildfire.

Assets are human-made features, such as commercial structures, critical facilities, housing, etc., that have a specific importance or value. Resources are natural features, such as wildlife habitat, vegetation type, or water, etc. These also have a specific importance or value. Generally, the term “values at risk” has previously been used to describe both assets and resources. For MWRA, the term Highly Valued Resources and Assets (HVRA) is used to describe what has previously been labeled values at risk. There are two reasons for this change in terminology. First, resources and assets are not themselves “values” in any way that term is conventionally defined—they *have* value (importance). Second, while resources and assets may be exposed to wildfire, they are not necessarily “at risk”—that is the purpose of the assessment.

To manage wildfire in Montana, it is essential that accurate wildfire risk data, to the greatest degree possible, is available to inform land and fire management strategies. These risk outputs can be used to aid in the planning, prioritization and implementation of prevention and mitigation activities. In addition, the risk data can be used to support fire operations in response to wildfire incidents by identifying those assets and resources most susceptible to fire.

1.2 Quantitative Risk Modeling Framework

The basis for a quantitative framework for assessing wildfire risk to highly valued resources and assets (HVRAs) has been established for many years (Finney, 2005; Scott, 2006). The framework has been implemented across a range of scales, from an individual county (Ager, 2017), a portion of a national forest (Thompson et al., 2013b), individual states (Buckley et al., 2014), to the entire continental United States (Calkin et al., 2010). In this framework, wildfire risk is a function of two main factors: 1) wildfire hazard and 2) HVRA vulnerability (Figure 1).

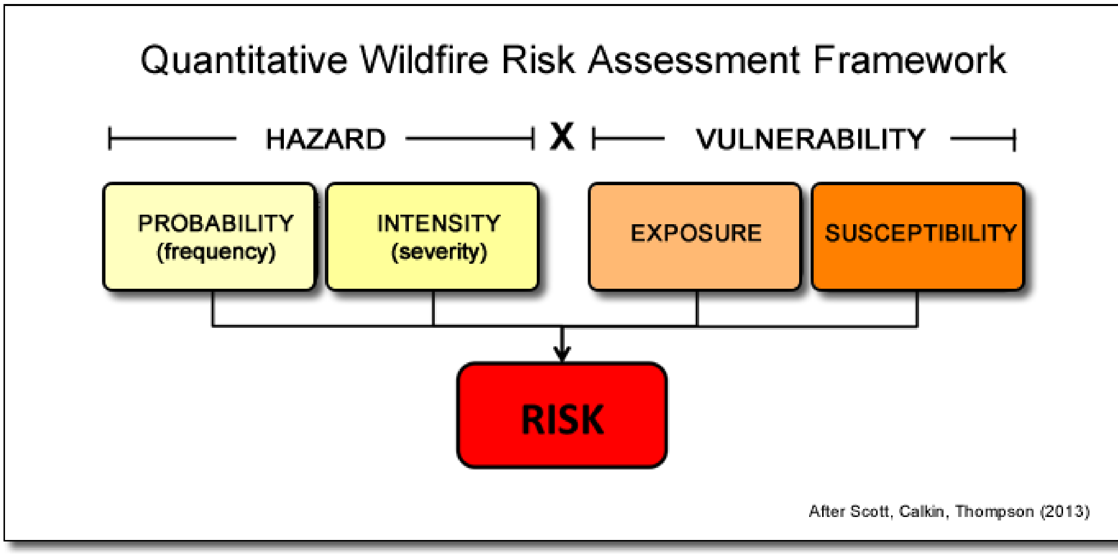

Figure 1. The components of the Quantitative Wildfire Risk Assessment Framework used for MWRA.

Wildfire hazard is a physical situation with potential for causing damage to vulnerable resources or assets. Quantitatively, wildfire hazard is measured by two main factors: 1) burn probability (or likelihood of burning), and 2) fire intensity (measured as flame length, fireline intensity, or other similar measure).

HVRA vulnerability is also composed of two factors: 1) exposure and 2) susceptibility. Exposure is the placement (or coincidental location) of an HVRA in a hazardous environment—for example, building a home within a flammable landscape. Some HVRAs, like wildlife habitat or vegetation types, are not movable; they are not "placed" in hazardous locations. Still, their exposure to wildfire is the wildfire hazard where the habitat exists. Finally, the susceptibility of an HVRA to wildfire is how easily it is damaged by wildfire of different types and intensities. Some assets are fire-hardened and can withstand very intense fires without damage, whereas others are easily damaged by even low-intensity fire.

1.3 Landscape Zones

1.3.1 *Analysis Area*

The Analysis Area is the area for which valid burn probability results are produced. The Analysis Area for the MWRA project was defined as the Montana state boundary with a 10-kilometer buffer of adjacent lands within the United States.

1.3.2 *Fire Occurrence Areas*

To ensure valid BP results in the Analysis Area and prevent edge effects, it is necessary to allow FSim to start fires outside of the Analysis Area and burn into it. This larger area where simulated fires are started is called the Fire Occurrence Area (FOA). We established the FOA extent as a 30-km buffer on the Analysis Area including a 30-km buffer beyond the U.S. border and into Canada. The buffer provides sufficient area to ensure all fires that could reach the Analysis Area are simulated. The Fire Occurrence Area covers roughly 120.5 million acres characterized by diverse topographic and vegetation conditions. We divided the overall fire occurrence area into eleven FOAs to more accurately model this large area where historical fire occurrence and fire weather is highly variable. Individual FOA boundaries were developed to group geographic areas that experience similar wildfire occurrence. These boundaries were generated using a variety of inputs including larger fire occurrence boundaries developed for national-level work (Short, 2020), aggregated level IV EPA Ecoregions, and local fire staff input. For consistency with other FSim projects, we numbered these FOAs 351 through 361.

1.3.3 *Fuelscape Extent*

The available fuelscape extent was determined by adding an additional 30-km buffer to the FOA extent. This buffer allows fires starting within the FOA to grow unhindered by the edge of the fuelscape, which would otherwise truncate fire growth and affect the simulated fire-size distribution and potentially introduce errors in the calibration process. A map of the Analysis Area, FOA boundaries, and fuelscape extent are presented in Figure 2.

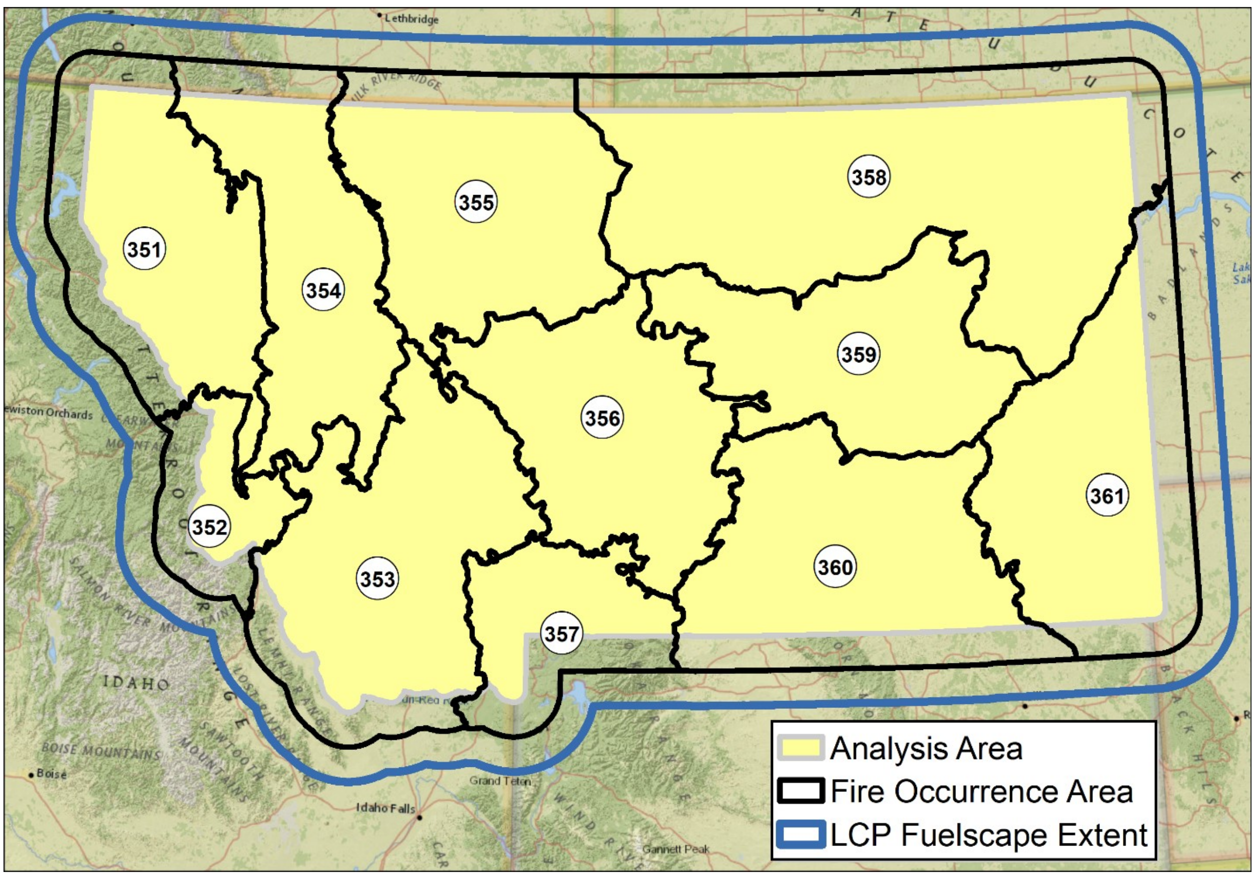

Figure 2. Overview of landscape zones for MWRA FSim project.

2 Analysis Methods and Input Data

The FSim large-fire simulator was used to quantify wildfire likelihood across the Analysis Area at a pixel size of 120 meters. FSim is a comprehensive fire occurrence, growth, behavior, and suppression simulation system that uses locally relevant fuel, weather, topography, and historical fire occurrence information to make a spatially resolved estimate of the contemporary likelihood and intensity of wildfire across the landscape (Finney et al., 2011).

FSim focuses on the relatively small fraction of wildfires that escape initial attack and become "large" (>247.1 acres). Since the occurrence of large fires is relatively rare, FSim generates many thousands of years of simulations, in order to capture a sample size large enough to generate burn probabilities for the entire landscape. An FSim iteration spans one entire year. All FOAs within the MWRA project area were run with 10,000 to 20,000 iterations.

There is no temporal component to FSim beyond a single wildfire season, consisting of up to 365 days. FSim performs independent (and varying) iterations of one year, defined by the fuel, weather, topography and wildfire occurrence inputs provided. FSim does not account for how a simulated wildfire might influence the likelihood or intensity of future wildfires (even within the same simulation year). Each year represents an independent realization of how fires might burn given the current fuelscape and historical weather conditions. FSim integrates all simulated iterations into a probabilistic result of wildfire likelihood.

Estimates of wildfire intensity were developed using a custom Pyrologix utility called FLEP-Gen (Scott, 2018). FLEP-Gen is a deterministic wildfire tool that integrates variable weather input variables and weights them based how they will likely be realized on the landscape. FLEP-Gen is more robust than the stochastic intensity values developed with FSim. This is especially true in low wildfire occurrence areas where predicted intensity values from FSim are reliant on a very small sample size of potential weather variables. The FLEP-Gen methodology is further described in section 2.4.3.

2.1 Fuelscape

A fuelscape is a quantitative raster representation of the fuels and topography of a landscape. The fuelscape consists of geospatial datasets representing surface fuel model (FM40), canopy cover (CC), canopy height (CH), canopy bulk density (CBD), canopy base height (CBH), and topography characteristics (slope, aspect, elevation). These datasets can be combined into a single landscape (LCP) file and used as a fuelscape input in fire modeling programs.

In the following sections we discuss the process of generating a fuelscape. The process outlined in sections 2.1.1- 2.1.3 is utilized within the United States portion of the landscape. Our methods for generating a fuelscape within Canada is subsequently discussed below in section 2.1.4. After development, the fuelscape was resampled to 120 meters for wildfire simulation. Additional information on customizing fuelscapes can be found in the LANDFIRE data modification guide (Helmbrecht and Blankenship, 2016).

2.1.1 *Fuelscape Inputs*

Our vegetation and disturbance inputs for the United States portion of MWRA were derived from the newly released LANDFIRE Remap 2016 (LF2016) 30-m raster data. This new release had significant changes from previous versions of LANDFIRE, including the use of new imagery and continuous vegetation cover and height classifications[1]. Capitalizing on the new features of the LF2016 data release,

[1] Additional information can be found on the LANDFIRE website at www.LANDFIRE.org.

Pyrologix developed a custom fuelscape-generation method. In this approach, the generation of the surface fuels portion of the fuelscape (FM40) was handled differently than the generation of the canopy fuels (CC, CH, CBD, CBH). The two approaches are discussed in the following two sections.

2.1.1.1 Surface Fuels

To accurately estimate a landscape's fire behavior and appropriately assign a surface fuel model, we need an informed estimation of the surface fuel load and potential ladder fuels. To obtain this, we must know the current site characteristics for undisturbed areas and the pre-disturbance site characteristics for disturbed areas. LF2016 determined these site characteristics using newly remotely sensed imagery to model non-disturbed areas and relied on previous vintages of LANDFIRE for disturbed areas.

A custom Pyrologix approach was developed to determine site characteristics but avoid relying on vintage LANDFIRE data. Pyrologix instead derived site characteristics for disturbed areas by applying severity adjustment factors to the most recent imagery, thereby walking 'backwards' in time to a pre-disturbance representation of cover and height. Although a custom approach was used to determine site characteristic inputs for canopy fuel, the LANDFIRE Total Fuel Change Toolbar (LFTFCT, Smail *et al.* (2011)) was used to generate the FM40 dataset.

2.1.1.2 Canopy Fuels

LF2016 canopy fuels datasets (CC, CH, CBH and CBD) are created in conjunction with surface fuels. The inputs used to generate canopy datasets include vegetation type, vegetation cover, and vegetation height. In the default LF2016 process, the vegetation cover and height datasets are binned to appropriate classes and midpoint values are used to calculate canopy fuel characteristics. Although continuous cover and height are now available from LF2016 vegetation data, the default LFTFCT method relies on cover and height midpoint values. In the custom Pyrologix approach, we modified LANDFIRE's process and instead generated canopy datasets using the newly available LF2016 continuous cover and height. Although the canopy fuels were developed outside of LFTFCT, we mimicked the LANDFIRE process and calculations, adjusting canopy fuels based on disturbance scenario and time since disturbance.

2.1.2 *Fuelscape Calibration*

The LANDFIRE fuel mapping process assigns fuel model and canopy characteristics using two primary input layers: Existing Vegetation Type (EVT) and LANDFIRE map zone. Using these inputs (and information about the fuel disturbance(s), vegetation height and cover, and biophysical setting), a rule is queried from the LANDFIRE ruleset database to assign surface fuel model and, if applicable, canopy characteristics for the given EVT and map zone. When working with a large project extent, such as MWRA, many map zones are present. The challenge in fuelscape calibration is to produce a set of output fuel rasters without artificial and often arbitrary seamlines across map zones. In order to do so, the rules from multiple zones must be reconciled and filtered to one ruleset per EVT. As an unbiased way to reconcile rules from multiple map zones, we determined which zone holds the greatest share of each EVT on the landscape and applied those rules across the entire fuelscape. After unifying rulesets to produce a preliminary fuelscape, we conduct fuelscape calibration workshops to further customize and calibrate rulesets to the project area of interest.

Prior to the fuel calibration workshops, we produced an initial set of fire behavior results with gNexus[2] using the preliminary fuelscape. The gNexus results include maps of Rate of Spread (ROS), Heat Per Unit Area (HPUA), Flame Length (FL), Fireline Intensity (FIL), Crown Fraction Burned (CFRB),

[2] gNexus is a custom spatial implementation of the fire behavior calculator software, NEXUS 2.1 (available at http://pyrologix.com/downloads/)

Torching Index (TI), and Crowning Index (CI). These maps were then summarized by each rule in the LFTFCT database for landscape critique and evaluation by workshop participants.

A prioritized list of EVTs was determined to focus calibration efforts. The set of EVTs reviewed in fuel calibration were identified as being among the top ten most abundant EVTs, EVTs that encompass a large portion of the Analysis Area, and EVTs with inconsistencies in fire behavior across the range of vegetation cover and height values (i.e. passive crown fire is possible at all windspeeds for part of the rule while the remainder of the rule could only ever experience surface fire under all observable windspeeds).

The MWRA fuel calibration workshop was held on October 16-17, 2019 in Bozeman, MT. At the workshop we solicited feedback from local fire and fuels staff from DNRC as well as interagency partners across the state. The intent of the workshop was to review the preliminary gNexus fire modeling results and refine the rulesets to produce fire behavior results consistent with the experience of workshop participants.

In addition to calibrating fuel rulesets, both the surface and canopy inputs were updated to reflect fuel disturbances occurring between 2017 and 2019, inclusively. Pyrologix gathered fuel disturbances across the region and assigned appropriate disturbance codes. Fuel disturbances included events such as mechanical treatments, prescribed fire, wind events, insect mortality, and wildfires. Datasets were collected from a variety of sources but included sources such as the USFS Forest Service Activity Tracking System (FACTS), Department of Interior National Fire Plan Operations & Reporting System (NFPORS) and the State of Montana Department of Natural Resources harvest polygons.

Pyrologix incorporated recent wildfire disturbances using three difference sources: Monitoring Trends in Burn Severity (MTBS) data, Rapid Assessment of Vegetation Condition after Wildfire (RAVG) data, and Geospatial Multi-Agency Coordination (GeoMAC) perimeter data. We gathered severity data as available from MTBS, then RAVG, and where severity data was unavailable, we relied on final perimeters from GeoMAC. We cross walked MTBS and RAVG severity to the appropriate disturbance code (112, 122, or 132) corresponding with fire disturbances of low, moderate, or high severity, occurring in the past one to five years. GeoMAC perimeters were assigned a severity disturbance code of 122.

After disturbances were incorporated into the final calibrated fuelscape, we generated the MWRA United States fuel raster shown by fuel model group in Figure 3.

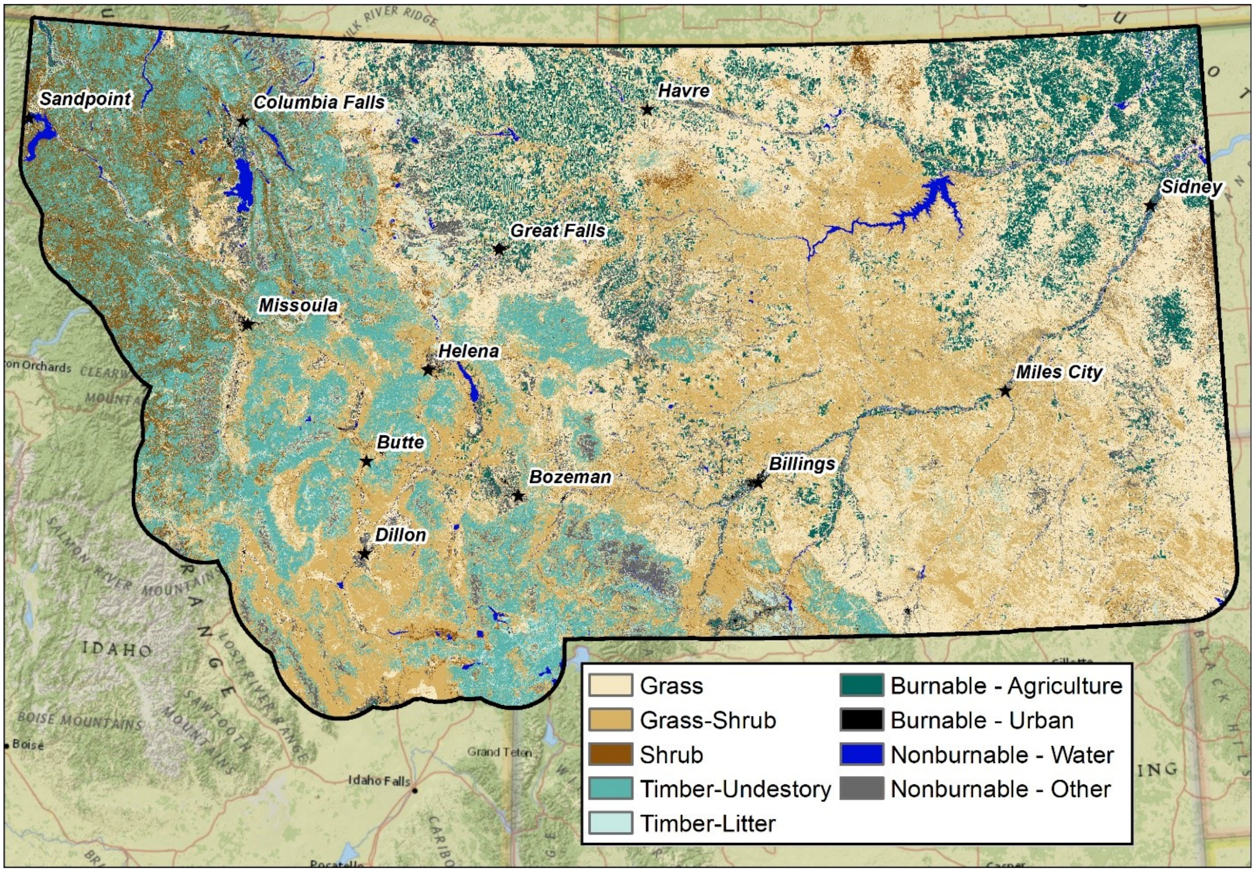

Figure 3. Map of fuel model groups across the MWRA LCP extent.

Two additional fuelscape edits warrant highlighting: the development of an updated process for calculating CBH in areas with insect and disease disturbances and the inclusion of Northern Region Wildfire Risk Assessment (NoRRA) fuelscape edits to provide consistency with other Montana fuelscape calibration efforts.

A preliminary review of the fuelscape highlighted the need for adjustments to the LF2016 canopy cover and base height calculations in areas disturbed by insect and disease. Adjustments were made to both CC and CBH coefficients to better align these areas with the expected increase in fire behavior and surface winds due to a reduction in canopy cover from insect mortality. Adjustments were made to CC and CBH coefficients to maintain fuelscape characteristics similar to the non-disturbed scenario. This change ensured the fuelscape would produce more active fire behavior in moderate conditions and no worse than the non-disturbed fuel in the more extreme conditions.

The second edit involved the review and inclusion of appropriate NoRRA fuelscape edits. This assessment covered large portions of Montana and incorporated various improvements to mitigate underprediction of crown fire potential. Many of the EVTs addressed in the NoRRA assessment were also reviewed in the MWRA fuelscape calibration workshop. However, four remaining EVTs were reviewed after the workshop where default CBH values were too high to produce crown fire behavior under any modeled weather conditions. To address this, we mimicked adjustments made in the NoRRA Wildfire Risk Assessment Report (Gilbertson-Day, 2018) to CBH and fuel model assignments in EVTs 2048, 2049, 2057, 2167 in the MWRA fuelscape.

The complete set of calibrated EVTs are listed in the final 'Fuel Boxes' spreadsheet provided with the project deliverables[3].

2.1.3 *Custom Fuel Models*

The 40 Scott and Burgan Fire Behavior Fuel Models (FBFM40) represent distinct distributions of fuel loading found among surface fuel components, size classes and fuel types. The spatial representation of fuel model assignments serve as input into wildfire simulation modeling systems like FARSITE, FlamMap, and FSim. Although the FBFM40 fuel model set covers a wide array of fuel bed scenarios, it is sometimes necessary to develop custom fuel model assignments for specific instances where one needs to simulate fire behavior not reflected in any standard fuel model.

Many spatial wildfire simulation systems associate certain simulation inputs to the fuel model raster. For example, FSim allows input of live and dead fuel moisture content to vary by fuel model. FSim further allows input of a rate of spread adjustment factor by fuel model. Therefore, it is sometimes necessary to use a "custom" fuel model only so that certain locations can be given different simulation inputs. For example, certain high-elevation locations may be characterized by a standard fuel model, but with different fuel moisture inputs. In that case, a custom fuel model can be made with the same parameters as the standard fuel model but a different fuel model number. Then, because the fuel model number is different, it can be given different fuel moisture inputs.

The MWRA fuelscape uses custom fuel models for this second purpose. We used them to represent the potential for wildfire spread into burnable agricultural and urban areas. By making these areas custom fuel models with a different fuel model number than the standard model on which it was based, we were able to control the weather scenarios during which simulated fire spread could take place. These areas were originally mapped by LANDFIRE as non-burnable, and therefore, do not allow simulated wildfire-spread as observed in past wildfire events. In this application of custom fuel models, the parameters are identical to standard FBFM40 fuel models but are labeled with custom numbers to allow for additional customization within FSim. The burnable urban custom fuel models were spatially identified using the LANDFIRE EVTs designated as low and moderate intensity developed: burnable developed areas are represented with 251/BU1; identical to TL9 and burnable roads are represented with 252/BU2; identical to TL3. Burnable agriculture custom fuel models were spatially identified using the EVT layer in conjunction with the location of row crops and wheat in the CropScape[4] data: burnable row crops are represented with an AG1/241 fuel model; identical to GR1 and burnable wheat fields are represented with an AG2/242 fuel model; identical to GR2.

The addition of the custom burnable urban and agriculture fuel models allows for the transmission of wildfire in simulation across these areas. In order to not overestimate the likelihood of wildfire in custom fuel models, fuel moisture inputs were edited to allow for wildfire only under 97th percentile ERC conditions. Fuel moisture inputs are further detailed in section 2.3.3.

2.1.4 *Mapping Fuels in Canada*

Two methods were used in the development of the MWRA fuelscape: one for the lands within the United States where landscape data is readily available nationally, and another for fuels mapped within Canada, where fuels data is limited. Methods for the United States portion were more rigorous, given that the analysis area is located entirely within the United States. For the portion of the fuelscape in Canada, we cross walked the 30-m North American Land Change Monitoring System (NALCMS) 2010 land cover

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[3] MWRA_FuelBoxes_with_WorkshopEdits_202004011_v2.xlsx
[4] The CropScape data was download on 10/24/2019 from https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php

data to obtain surface fuel model, canopy base height, canopy bulk density, canopy cover, and canopy height rasters. Additionally, we extracted the 30-m Canadian Digital Elevation Model (CDEM) raster for our project extent within Canada, from which we generated slope and aspect rasters. The fuels and topographic rasters were resampled to 120 m and mosaicked with the final United States fuel rasters to generate a final fuelscape for MWRA.

Estimates of fuel characteristics are much less accurate than those developed from the LANDFIRE methodology within the United States. While it is important to recognize the limitations of the Canada fuel mapping process, care was taken to map fuels as accurately as possible given the data limitations and to minimize introduced fire modeling seamlines at the Canadian border.

2.2 Historical Wildfire Occurrence

The Fire Occurrence Database (FOD) that spans the 26-year period 1992-2017 was used to quantify historical large-fire occurrence (Short, 2017). Historical wildfire occurrence data were used to develop model inputs (the fire-day distribution file [FDist] and ignition density grid [IDG]) as well as model calibration targets. Table 1 summarizes the annual number of large fires per million acres, mean large-fire size, and annual area burned by large fires per million acres for each FOA. For this analysis, we defined a large fire as one greater than 247.1 acres (100 hectares).

Table 1. Historical large-fire occurrence, 1992-2017, in the MWRA FSim project FOAs.

FOA	Mean annual number of large fires	FOA area (M ac)	Mean annual number of large fires per M ac	Mean large-fire size (ac)	Mean annual large-fire area burned (ac)	FOA-mean burn probability
351	8.38	10.27	0.76	3,663	30,713	0.0028
352	14.04	3.65	3.85	5,631	79,057	0.0217
353	4.12	13.15	0.31	5,354	22,032	0.0017
354	7.69	9.40	0.92	8,544	65,723	0.0079
355	2.19	11.46	0.22	1,993	4,369	0.0004
356	3.92	9.90	0.40	1,957	7,679	0.0008
357	2.65	5.31	0.50	8,466	22,468	0.0042
358	6.50	22.46	0.35	2,037	13,243	0.0007
359	4.69	9.47	0.50	6,421	30,130	0.0032
360	15.62	12.66	1.23	5,237	81,773	0.0065
361	5.12	12.09	0.42	3,280	16,779	0.0014

Historical wildfire occurrence varied substantially by FOA (Table 1), with FOA 352 experiencing the highest annual average of 3.85 large wildfires per million acres. FOA 355 had the least frequent rate of occurrence with an annual average of 0.22 large wildfires per million acres.

To account for the spatial variability in historical wildfire occurrence across the landscape, FSim uses a geospatial layer representing the relative, large-fire ignition density. FSim stochastically places wildfires according to this density grid during simulation. The entire landscape is saturated with wildfire over the 10,000/20,000 simulated iterations, but more ignitions are simulated in areas that have previously allowed for large-fire development.

The Ignition Density Grid (IDG) was generated using a mixed methods approach by averaging the two grids resulting from the Kernel Density tool and the Point Density tool within ArcGIS for a 120-m cell size and 75-km search radius. All fires equal to or larger than 247.1 acres (100 ha) reported in the FOD were used as inputs to the IDG. The IDG was divided up for each FOA by setting to zero all area outside of the fire occurrence boundary of that FOA. This allows for a natural blending of results across adjacent FOA boundaries by allowing fires to start only within a single FOA but burn onto adjacent FOAs.

Additionally, all burnable urban, agriculture and small burnable areas less than 50 acres within other non-burnable or urban areas were masked out of the IDG layer. The IDG enables FSim to produce a spatial pattern of large-fire occurrence consistent with what was observed historically. Figure 4 shows the ignition density grid for the MWRA Fire Occurrence Area.

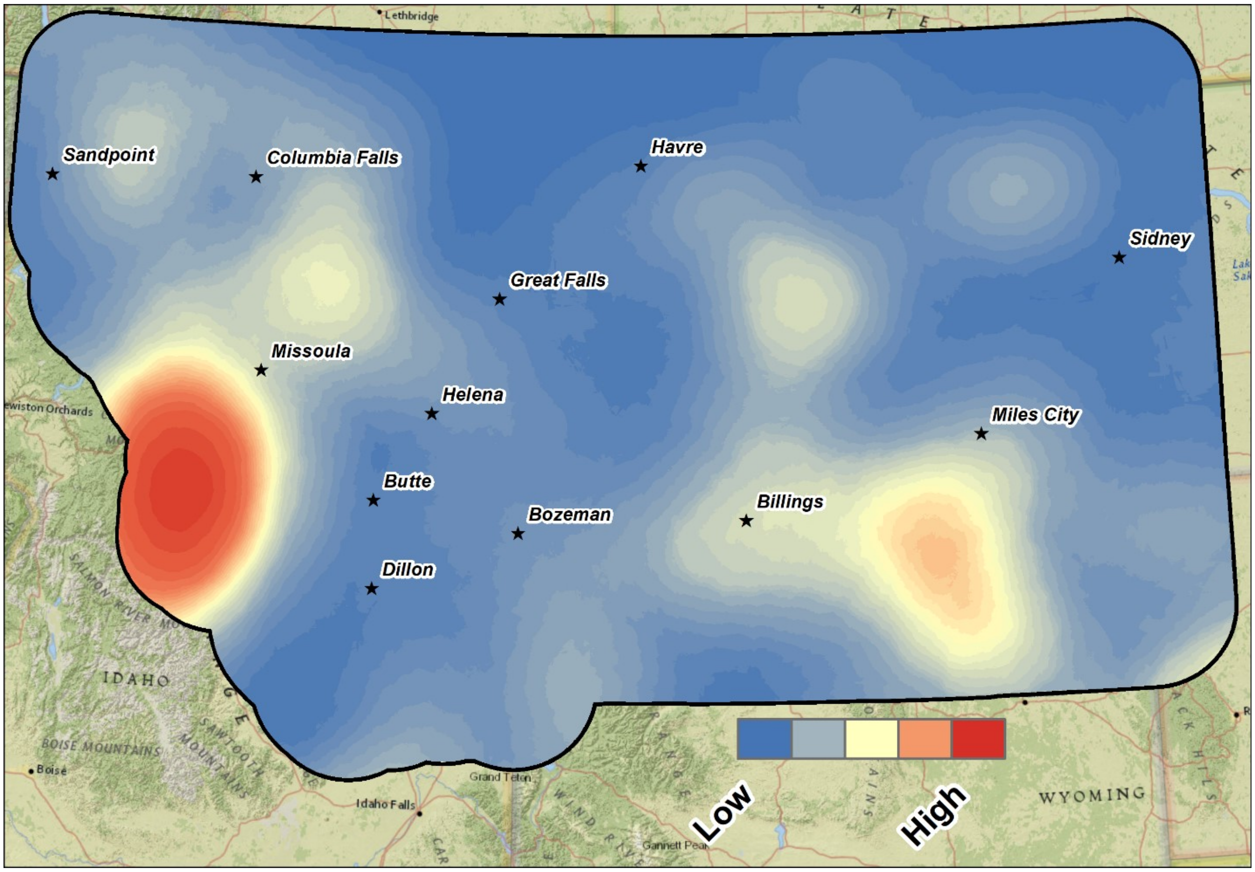

Figure 4. Ignition density grid used in FSim simulations.

2.3 Historical Weather

FSim requires three weather-related inputs: monthly distribution of wind speed and direction, live and dead fuel moisture content by year-round percentile of the Energy Release Component (ERC) variable of the National Fire Danger Rating System (NFDRS, 2002) for fuel model G (ERC-G) class, and seasonal trend (daily) in the mean and standard deviation of ERC-G. We used two data sources for these weather inputs. For the wind speed and direction distributions we used the hourly (1200 to 2000 hours), 10-minute average values (2 mph calm wind), recorded at selected Remote Automatic Weather Stations (RAWS). Stations with relatively long and consistent records and moderate wind activity were preferentially selected to produce the most stable FSim results. Station selection was reviewed by local fire and fuels personnel at the October 16-17, 2019 fuel calibration workshop in Bozeman, MT.

Energy Release Component (ERC) values were extracted from Dr. Matt Jolly's historical, gridded ERC rasters for the period 1992-2017. This nationally available dataset provides values that are not influenced by periods of RAWS inactivity outside of the fire season. The RAWS stations selected for winds and ERC sample sites for each FOA are shown in Figure 5, and discussed further in the following sections.

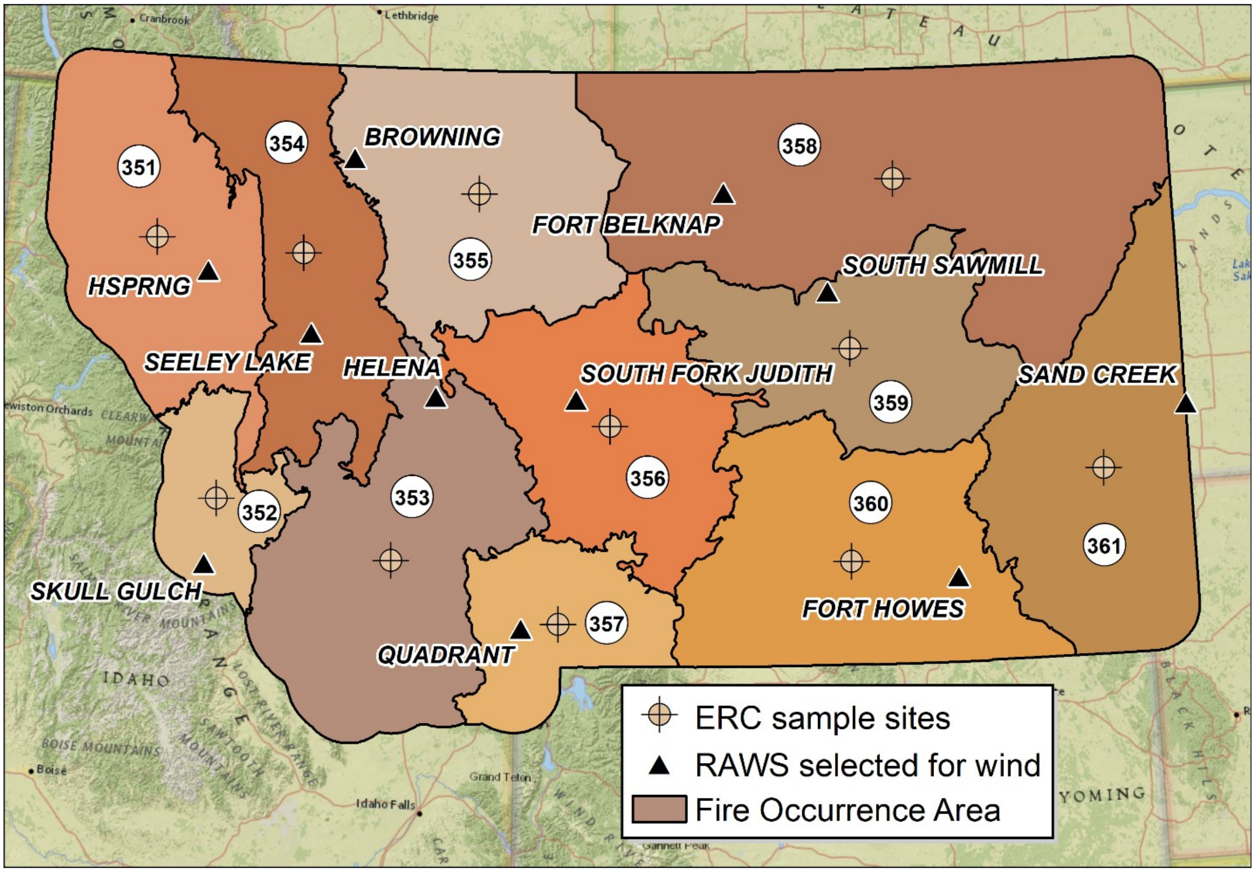

Figure 5. RAWS stations and ERC sample sites used for the MWRA FSim project. Selected RAWS data were used for hourly sustained wind speed and direction.

2.3.1 *Fire-day Distribution File (FDist)*

Fire-day Distribution files are used by FSim to generate stochastic fire ignitions as a function of ERC. The FDist files were generated using an R script that summarizes historical ERC and wildfire occurrence data, performs logistic regression, and then formats the results into the required FDist format.

The FDist file provides FSim with logistic regression coefficients that predict the likelihood of a large fire occurrence based on the historical relationship between large fires and ERC and tabulates the distribution of large fires by large-fire day. A large-fire day is a day when at least one large fire occurred historically. The logistic regression coefficients together describe large-fire day likelihood *P(LFD)* at a given ERC(G) as follows:

$$P(LFD) = \frac{1}{1 + e^{-B_a * - B_b * ERC(G)}}$$

Coefficient *a* describes the likelihood of a large fire at the lowest ERCs, and coefficient *b* determines the relative difference in likelihood of a large fire at lower versus higher ERC values.

2.3.2 *Fire Risk File (Frisk)*

Fire risk files were generated for each RAWS using FireFamilyPlus version 4.1 and updated to incorporate simulated ERC percentiles (as described in section 2.3.4). These files summarize the historical ERC stream for the FOA, along with wind speed and direction data for the selected RAWS. The final selection of RAWS stations represents suggestions by local fire personnel with knowledge of nearby stations and their ability to represent general wind patterns within a FOA. Some of the recommended stations produced wind speeds that could have introduced data seamlines by skewing average modeled wildfire intensities either too high or too low. In order to generate intensities that best matched historically observed fire behavior; winds speeds were manually adjusted up or down. For example, in FOAs 354, 358, and 361 we adjusted wind speeds to meet historical calibration targets, while maintaining the wind directions recommended by local experts.

2.3.3 Fuel Moisture File (FMS)

Modeled fire behavior is robust to minor changes in dead fuel moisture, so a standardized set of stylized FMS input files (representing the 80th, 90th, and 97th percentile conditions) for 1-,10-, 100-hour, live herbaceous and live woody fuels was developed (Table 2).

Table 2. Fuel Moisture values used in wildfire simulation for the 80th/90th/97th percentile ERCs

Fuel Model Group	1-hr	10-hr	100-hr	Live-Herb	Live-Woody
Grass / Shrub	5 / 4 / 3	6 / 5 / 4	7 / 6 / 5	90 / 65 / 45	110 / 100 / 90
Timber / Slash	7 / 6 / 5	8 / 7 / 6	9 / 8 / 7	90 / 65 / 45	110 / 100 / 90
Burnable Agriculture	45 / 45 / 3	45 / 45 / 4	45 / 45 / 5	120 / 45 / 45	110 / 100 / 90
Burnable Urban	45 / 45 / 5	45 / 45 / 6	45 / 45 / 7	120 / 120 / 45	110 / 100 / 90

Fuel moistures in the custom Burnable Agriculture (FM 241, 242 & 243) and Burnable Urban (FM 251 & 252) fuel models were set above the moisture of extinction for the 80th and 90th percentile ERC bins. This was done to only allow simulated wildfire to burn within these fuel groups under the most extreme weather conditions (97th percentile). This method maintains the potential for high modeled fire intensity while not vastly over predicting burn probability. The custom fuel models are further described above in section 2.1.3.

2.3.4 Energy Release Component File (ERC)

We sampled historical ERC-G values from a spatial dataset derived from North American Regional Reanalysis (NARR) 4-km ERC-G dataset (Jolly, 2014). Historical ERC-G grid values are available for the years 1979-2017 and historical fire occurrence data is available for 1992-2017. We used the overlapping years of 1992-2017 to develop a logistic regression of probability of a large-fire day in relation to ERC-G.

Historical ERCs were sampled at an advantageous location within each FOA. Those locations are found on relatively flat ground with little or no canopy cover, in the general area within the FOA where large fires have historically occurred. These historical ERC values were used in conjunction with the FOD to generate FSim’s FDist input file, but not to generate the Frisk file. ERC percentile information in the Frisk file was generated from the simulated ERC stream, described below. This approach ensures consistency between the simulated and historical ERCs.

For simulated ERCs in FSim, we used a feature of FSim that allows the user to supply a stream of ERC values for each FOA. Isaac Grenfell, statistician at the Missoula Fire Sciences Lab, has generated 1,000 years of daily ERC values (365,000 ERC values) sampled from Jolly’s historical ERCs. The simulated ERC values Grenfell produces are “coordinated” in that a given year and day for one FOA corresponds to the same year and day in all other FOAs—their values only differ due to their location on the landscape. This coordination permits analysis of fire-year information across all FOAs.

2.4 Wildfire Simulation

The FSim large-fire simulator was used to quantify wildfire hazard across the landscape at a pixel size of 120 m (4 acres per pixel). FSim is a comprehensive fire occurrence, growth, behavior, and suppression simulation system that uses locally relevant fuel, weather, topography, and historical fire occurrence information to make a spatially resolved estimate of the contemporary likelihood and intensity of wildfire across the landscape (Finney et al., 2011). Figure 6 diagrams the many components needed as inputs to FSim.

Due to the highly varied nature of weather and fire occurrence across the large landscape, we ran FSim for each of the eleven FOAs independently, and then compiled the eleven runs into a single data product. For each FOA, we parameterized and calibrated FSim based on the location of historical fire ignitions within the FOA, which is consistent with how the historical record is compiled. We then used FSim to start fires only within each FOA but allowed those fires to spread outside of the FOA. This, too, is consistent with how the historical record is compiled.

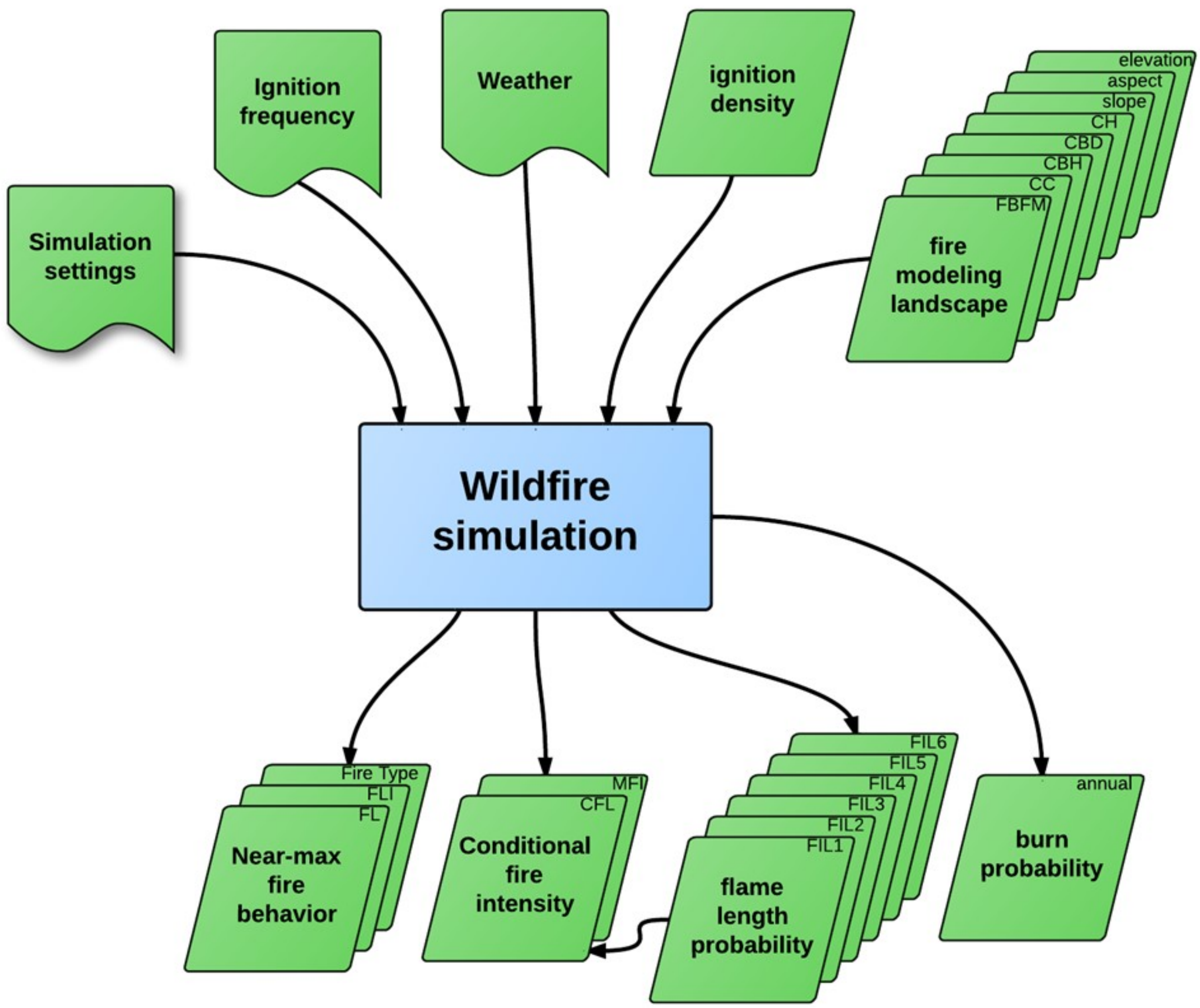

Figure 6. Diagram showing the primary elements used to derive burn probability.

2.4.1 *Model Calibration*

FSim simulations for each FOA were calibrated to historical measures of large fire occurrence including mean historical large-fire size, mean annual burn probability, mean annual number of large fires per million acres, and mean annual area burned per million acres. From these measures, two calculations are particularly useful for comparing against and adjusting FSim results: 1) mean large fire size, and 2) number of large fires per million acres. Additionally, care was taken to match simulated wildfire size distributions to the historical record and allow for the occurrence of simulated fires larger than any observed historically. While only large-fire sizes (>247.1 acres) were considered in calibration, numerous small fires were also simulated. However, the impact of small fires on landscape-level burn probability is negligible.

To calibrate each FOA, we started with baseline inputs and a starting rate-of-spread adjustment (ADJ) factor file informed by experience on previous projects. The final model inputs can be seen below in Table 3. All runs were completed at 120-m resolution. Each FOA was calibrated separately to well within the 70 percent confidence interval and final simulations were run with either 10,000 or 20,000 iterations. The eleven FOAs were then integrated into an overall result for the analysis area.

Table 3. Summary of final-run inputs for each FOA.

Final run	Number of Iterations	ADJ file	Trimming factor	Frisk	FDist file	LCP file
351r15	10,000	foa351v4	2.0	foa351v3	foa351v3	FOA_351_120v6
352r15	10,000	foa352v5	2.0	foa352v3	foa352v3	FOA_352_120v6
353r15	10,000	foa353v4	2.0	foa353v3	foa353v3	FOA_353_120v6
354r15	10,000	foa354v5	2.0	foa354v3	foa354v2	FOA_354_120v6
355r15	20,000	foa355v5	2.0	foa355v3	foa355v4	FOA_355_120v6
356r15	20,000	foa356v5	2.0	foa356v3	foa356v4	FOA_356_120v6
357r15	20,000	foa357v5	2.0	foa357v3	foa357v4	FOA_357_120v6
358r15	10,000	foa358v8	2.0	foa358v4	foa358v4	FOA_358_120v6
359r15	10,000	foa359v4	2.0	foa359v3	foa359v3	FOA_359_120v6
360r15	10,000	foa360v5	2.0	foa360v5	foa360v4	FOA_360_120v6
361r15	10,000	foa361v4	2.0	foa361v5	foa361v3	FOA_361_120v6

2.4.2 *Integrating FOAs*

We used the natural-weighting method of integrating adjacent FOAs that we developed on an earlier project (Thompson et al., 2013a). With this method, well within the boundary of a FOA (roughly 30 km from any boundary) the results are influenced only by that FOA. Near the border with another FOA the results will be influenced by that adjacent FOA. The weighting of each FOA is in proportion to its contribution to the overall burn probability at each pixel.

2.4.3 *FLEP-Gen: Modeling Wildfire Intensity*

Estimates of flame-length probability (FLP), mean flame length (FL), and mean fireline intensity (FLI) were generated using a custom methodology called FLEP-Gen (Scott, 2018). The FLEP-Gen process produces a set of FLPs comparable to those produced by a stochastic simulator such as FSim (Finney et al. 2011) and improves upon other deterministic approaches to generating flame-length potential by incorporating non-heading fire spread and appropriately weighting high-spread conditions into the calculations of flame-length results. FLEP-Gen was run for each FOA using the 120-m fuelscape for MWRA. Integration of FOA results in discussed in the section 2.4.4.

FLEP-Gen evaluates multiple weather scenarios, involving seven wind speeds and three sets of fuel moisture contents. Upslope wind direction was assumed, so wind direction was not incorporated. FLEP-Gen uses the head fire fireline intensity (FLI) and fire type (surface or crown fire) for a given weather scenario to look up the flame-length probability distribution that would occur when factoring in non-heading intensity. This results in the generation of a flame-length exceedance probability (FLEP) raster for each of five flame-length divisions (>2ft, >4ft, >6ft, >8ft, and >12ft). This set of five exceedance probability rasters is produced for each of the 21 weather scenarios characterized above.

The 21 sets of FLEPs must then be combined into a single raster using an area-weighted mean calculation which factors in the likelihood of the weather scenario (based on the weather analysis) and the rate of spread associated with each weather scenario. All weather information other than moisture conditions was derived from the FSim Frisk input file for the FOA. Moisture conditions for all FOAs were taken from the FSim FMS files. Once the final FLEPs are calculated, the final FLPs can be derived for each of the six flame-length classes (0-2ft, 2-4ft, 4-6ft, 6-8ft, 8-12ft, and >12ft). These six FLP rasters have a cumulative probability equal to one for each burnable pixel on the landscape. The complete FLEP-Gen methodology is outlined in Scott (2018).

We use the same weighting process to produce rasters of mean flame length and mean fireline intensity. Those are useful for mapping the fire intensity that characterizes each pixel on the landscape.

2.4.4 *Integrating FLEP-Gen Results*

The individual-FOA 120-m FLEP-Gen rasters were integrated into an overall result for the project area using a distance-weighting method that Pyrologix developed. With this method, the FLEP-Gen values for pixels well within the boundary (> 30 km) of a FOA are influenced only by that FOA. Near the border with another FOA the results are also influenced by that adjacent FOA. The weighting contribution of neighboring FOAs in a given pixel is in proportion to the inverse distance from the FOA boundary.

After calculating the overall FLEP-Gen value at each pixel at 120 m, the results were downscaled from 120 m to 30 m using the process described in section 3.5.3.

2.5 Wildfire Modeling Results

The FSim model produces estimates of burn probability as well as measures of fire intensity including flame length exceedance probability, conditional flame length, and mean fireline intensity. While FSim does generate measures of wildfire intensity, the FLEP-Gen derived intensity estimates (described above in section 2.4.3) are more reliable than those generated stochastically within FSim. The FLEP-Gen intensity values were used in all developed effects analysis. The 120-m resolution estimate of burn probability generated with the FSim model using the 2020 ready fuelscape and calibrated to the historical record (1992-2017) is presented below in Figure 7. These results were further downscaled to 30-m resolution using a methodology described in section 3.5.2 and presented in Figure 15.

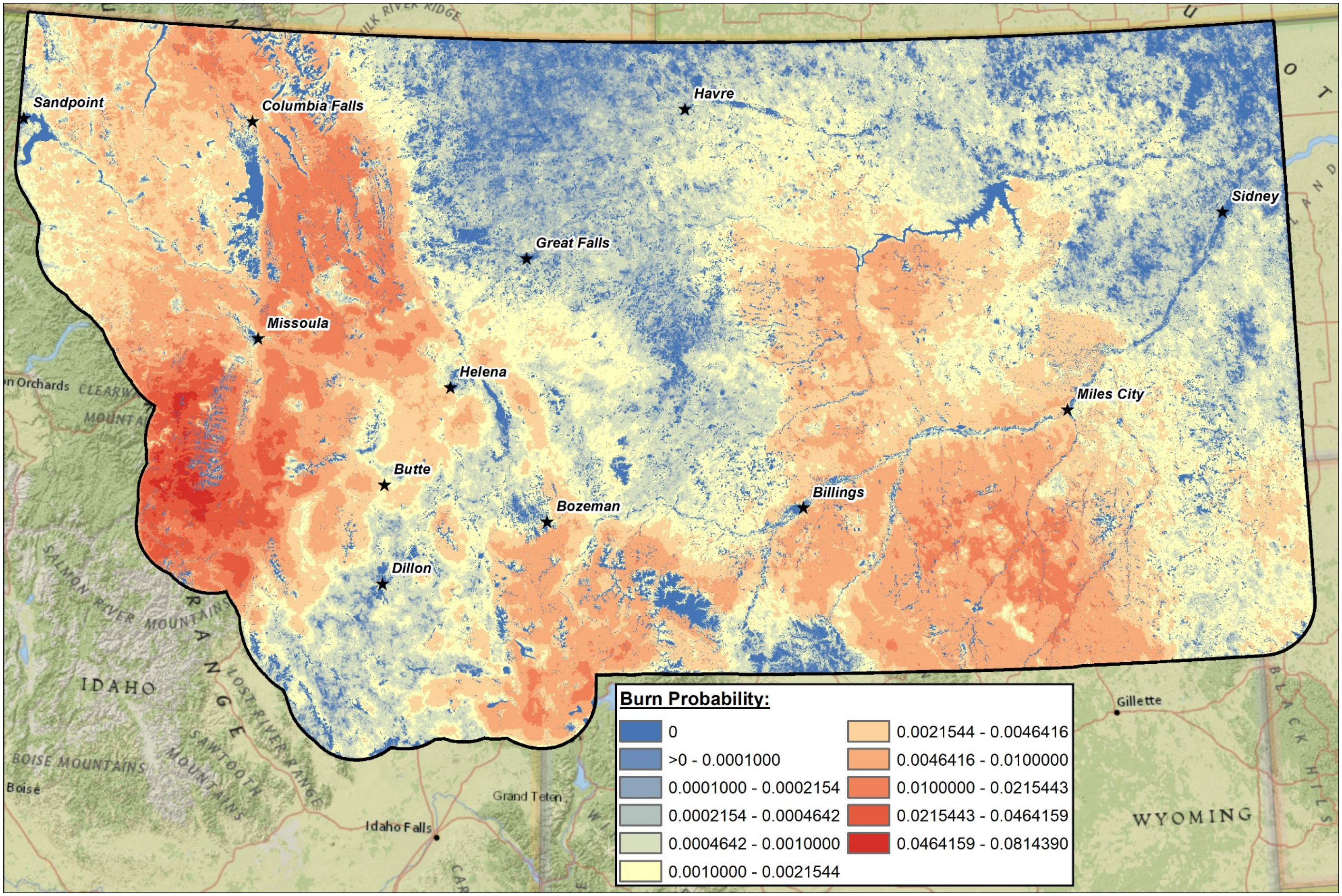

Figure 7. Map of integrated FSim burn probability results for the MWRA study area at 120-m resolution.

3 HVRA Characterization

Highly Valued Resources and Assets (HVRA) are the resources and assets on the landscape most likely to warrant protection if found to be at risk of wildfire. The key criteria for inclusion in the MWRA is an HVRA must be of greatest importance to Montana communities, the spatial data must be readily available, and the spatial extent of the identified HVRA must be complete for the entire state and on all land ownerships.

There are three primary components to HVRA characterization: HVRAs must be identified and their spatial extent mapped, their response to fire (negative, or neutral) must be characterized, and their relative importance with respect to each other must be determined. For this assessment only negative or neutral responses to fire were applied.

3.1 HVRA Identification

A set of HVRA was identified through a workshop held at the Missoula, Montana Forestry Division office of the Department of Natural Resources and Conservation (DNRC) on November 26, 2019. A group consisting of the State Forester, DNRC Line Officers, Resource Specialists, Geospatial Analysts, and Interagency Partners from Montana identified three HVRA in total: two assets and one resource. The complete list of HVRA and their associated data sources are listed in Table 4.

Table 4. HVRA and sub-HVRA identified for the Montana Wildfire Risk Assessment and associated data sources.

HVRA & Sub-HVRA	Data source
People and Property	
People and Property (Structures)	The "Structures & Addresses Framework" dataset was downloaded from the Montana State Library, Geographic Information Clearinghouse. A supplemental dataset was provided by DNRC for Big Sky, MT.
Infrastructure	
Electric transmission lines – high & low voltage (<345)	Electric Power Transmission Lines acquired from the Homeland Infrastructure Foundation-Level Data (HIFLD) program.
Communication Sites	Communication sites from the from the Homeland Infrastructure Foundation-Level Data (HIFLD) program including cellular towers, land mobile towers, FM/AM transmission towers, microwave service towers, paging transmission towers, antenna structure, TV analog/digital transmitters, broadband radio transmitters, internet service providers, and internet exchange points along with DNRC Radio Sites from DNRC.
Watershed	
Drinking Water	Surface drinking water intakes and delineated basins provided by USFS Region 1.

To the degree possible, HVRA are mapped to the extent of the Analysis Area boundary (Figure 2). This is the boundary used to summarize the final risk results. Some HVRA are limited to the State boundary, due to the nature of the data (e.g., extracted from Montana State databases for state land only).

3.2 Response Functions

Each HVRA selected for the assessment must also have an associated response to wildfire, whether neutral or negative. We relied on input from the State Forester, DNRC Line Officers, Area Fire Management Officers, interagency representatives and additional fire and resource staff at a Fire Effects workshop held on December 19, 2019 in Missoula, MT. In these workshops, the group discussed how each resource or asset responded to fires of different intensity levels and characterized the HVRA response using values ranging from -100 to 0. Though some resources can incur a beneficial effect from wildfire, in keeping with the DNRC Suppression objective, the response functions employed represented only neutral and negative wildfire effects. The flame-length values corresponding to the fire intensity levels reported by FSim are shown in Table 5. The response functions (RFs) used in the risk results are shown in Table 6 below.

Table 5. Flame-length values corresponding to Fire Intensity Levels used in assigning response functions.

Fire Intensity Level (FIL)	1	2	3	4	5	6
Flame Length Range (feet)	0-2	2-4	4-6	6-8	8-12	12+

Table 6. Response functions for all selected HVRA.

Sub-HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6
People and Property - Tree/Shrub Lifeforms	-20	-30	-50	-70	-80	-95
People and Property - Grass/Sagebrush Lifeforms	-10	-20	-30	-50	-60	-70
Communication Sites - Tree/Shrub Lifeforms	0	-10	-20	-30	-40	-50
Communication - Grass/Sagebrush Lifeforms	0	0	-10	-10	-20	-30
Low Voltage (wooden poles) Electric Transmission Lines	-70	-80	-90	-100	-100	-100
High Voltage (> 345) Electric Transmission Lines	0	0	0	-10	-30	-30
Surface Drinking Water	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx

3.3 Relative Importance

The relative importance (RI) assignments are needed to integrate results across all HVRA. Without this input from agency line officers to prioritize among HVRA, the default is to assume equal-weighting among HVRA – a result that is never a desired outcome. The RI workshop was held in Missoula, MT on February 25, 2020 and was attended by the State Forester, DNRC Line Officers, Area Fire Management Officers, and interagency representatives. The focus of this workshop was to establish the importance and ranking of the primary HVRAs relative to each other. The People and Property HVRA received the greatest share of RI at 60 percent, followed by Infrastructure HVRA, receiving 25 percent of the total importance. Finally, Surface Drinking Water received 15 percent of the total landscape importance (Figure 8). These importance percentages reflect the importance per unit area of all mapped HVRA.

Sub-HVRA relative importance was also determined at the RI workshop. Sub-RIs consider both the relative importance per unit area and mapped extent of the Sub-HVRA layers within the primary HVRA category. These calculations need to account for the relative extent of each HVRA to avoid overemphasizing HVRA that cover many acres. This was accomplished by normalizing the calculations by the relative extent of each HVRA in the assessment area. Here, relative extent refers to the number of 30-m pixels mapped in each HVRA. In using this method, the relative importance of each HVRA is spread out over the HVRA's extent. An HVRA with few pixels can have a high importance per pixel; and an HVRA with a great many pixels can have a low importance per pixel. A weighting factor (called Relative Importance Per Pixel [RIPP]) representing the relative importance per unit area was calculated for each HVRA

In Table 8 through Table 11, we provide the share of HVRA relative importance within each primary HVRA.

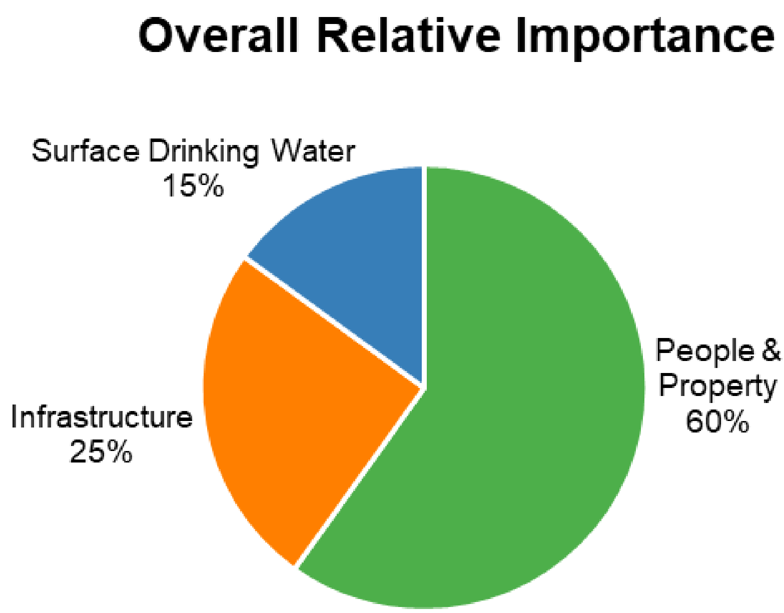

Figure 8. Overall HVRA Relative Importance for the primary HVRAs included in MWRA.

3.4 HVRA Characterization Results

Each HVRA was characterized by one or more data layers of sub-HVRA and, where necessary, further categorized by an appropriate covariate. Covariates separate HVRA by their response to wildfire, such as different response functions for transmission lines by voltage classes and different response functions for structures and communication sites by vegetation lifeform. The main HVRA in the MWRA are mapped below along with a table containing the set of response functions assigned, the within-HVRA share of relative importance, and total acres for each sub-HVRA. These components are used along with fire behavior results from FSim and FLEP-Gen in the wildfire risk calculations described in section 3.5.1.

3.4.1 *People and Property*

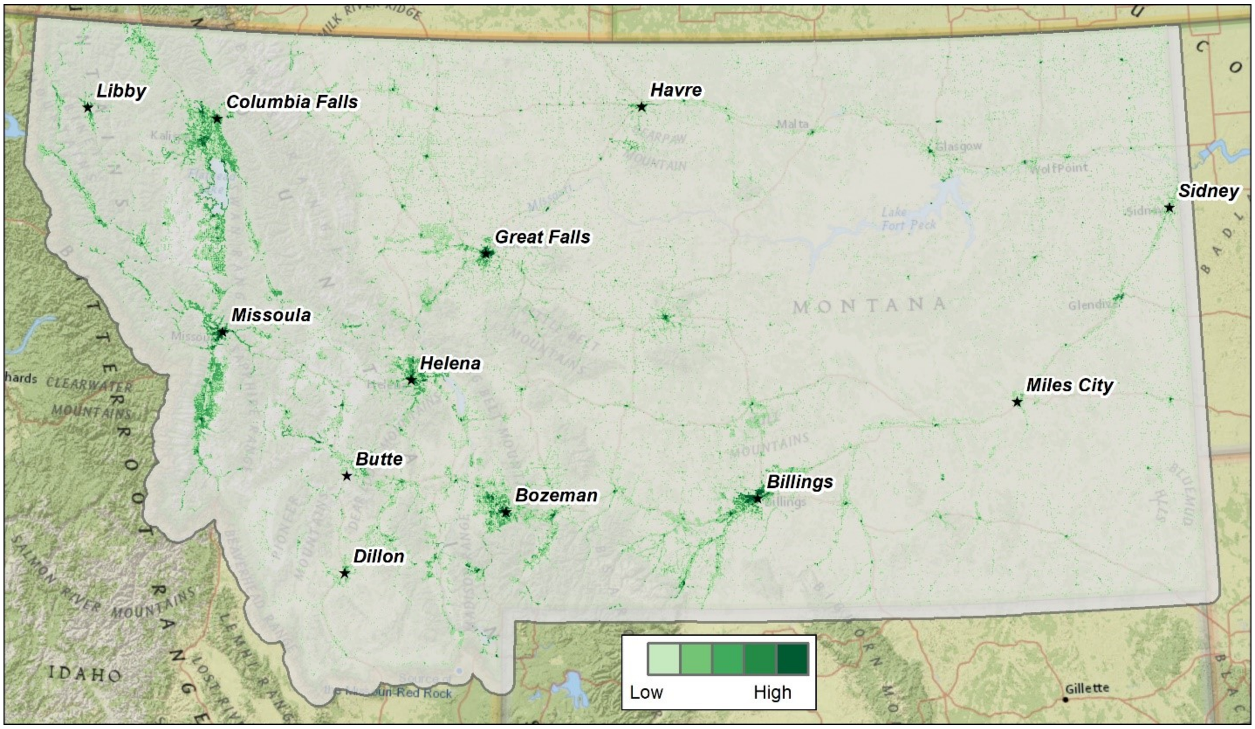

Figure 9. Map of structure importance across Montana

The People and Property HVRA is comprised of two input data layers. The “Structures & Addresses Framework” dataset was downloaded from the Montana State Library, Geographic Information Clearinghouse[5] and supplemental structure data was provided by DNRC for Big Sky, MT after structures in that area were identified as missing from the statewide dataset. The People and Property HVRA represents residential structures, commercial buildings, and other structures across the state.

Importance within the People and Property HVRA was determined by structure type attributes listed in the original data. Each structure was assigned an RI value between 0.5 and 100, based on the rationale shown in Table 7. The RI values were reviewed during the Relative Importance workshop and minor adjustments made for category consistency before implementing in the wildfire risk calculations. The final, complete set of structure RI importance values are shown in Appendix C.

Table 7. Relative importance values for within the People and Property HVRA

RI	Rationale and structure type examples
100	Structures of greatest importance/impact to individuals (hospitals, dorms, care facilities, and multi-family dwellings)
30	Single-family residences, schools and education buildings, clinics and health-related (non-emergency) buildings
10	General commercial and non-residential buildings
3	Wind turbines and structures labeled as “not present” but visible in imagery
1	Storage structures, parking sites, park/recreations areas, golf-course structures, etc.
0.5	Disposal sites, mine sites, structures labeled as “NULL” with unknown importance

[5] The “Structures & Addressed Framework” dataset was downloaded from http://geoinfo.msl.mt.gov/home/msdi/structures_and_addresses.aspx on 3/11/2020.

Final RI values were assigned to each structure type and converted to 30-m pixels using the ArcGIS Point to Raster tool. The resulting raster was smoothed and converted to an 'importance density' by first calculating the focal sum of importance within a moving circular 300-m radius window using ArcGIS Focal Statistics, then dividing that result by a similar moving-window sum of habitable land cover[6] with the same circular window. This two-step approach minimizes the artificial reduction of importance adjacent to uninhabitable land cover. The final raster of structure importance across Montana is shown in Figure 9.

Response Functions were applied in conjunction with burnable vegetation type derived from lifeform in the LANDFIRE Existing Vegetation Type (EVT) grid and the final fuel model raster from the calibrated fuelscape. A value of '1' was assigned to sites associated with tree or shrub lifeforms and a value of '2' for sites designated as grass or sagebrush lifeforms.

The People and Property HVRA received negative response functions for all fire intensity levels (Table 8). People and Property HVRA located in tree/shrub lifeform pixels were assigned a stronger negative response due to the likelihood of ember-cast from these fuel types and the suppression difficulty presented with such fire behavior. Conversely, People and Property HVRA located in grass/sagebrush pixels may present less challenges to fire suppression efforts – resulting in less loss overall.

Structure importance described above is independent of vegetation lifeform. However, because there are more acres of the grass/sage lifeform where the People and Property HVRA is mapped, it received more total importance across the landscape. The share of HVRA importance is based on relative importance per unit area and mapped extent.

Table 8. Response functions for the People and Property HVRA.

Sub-HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6	Share of RI[1]	Acres
P&P - Tree/Shrub	-20	-30	-50	-70	-80	-95	39.9%	2,180,082
P&P - Grass/Sagebrush	-10	-20	-30	-50	-60	-70	60.1%	3,280,365

[1] Within-HVRA relative importance.

[6] Habitable land cover includes all fuel models other than snow and ice.

3.4.2 *Infrastructure*

3.4.2.1 Communication Sites

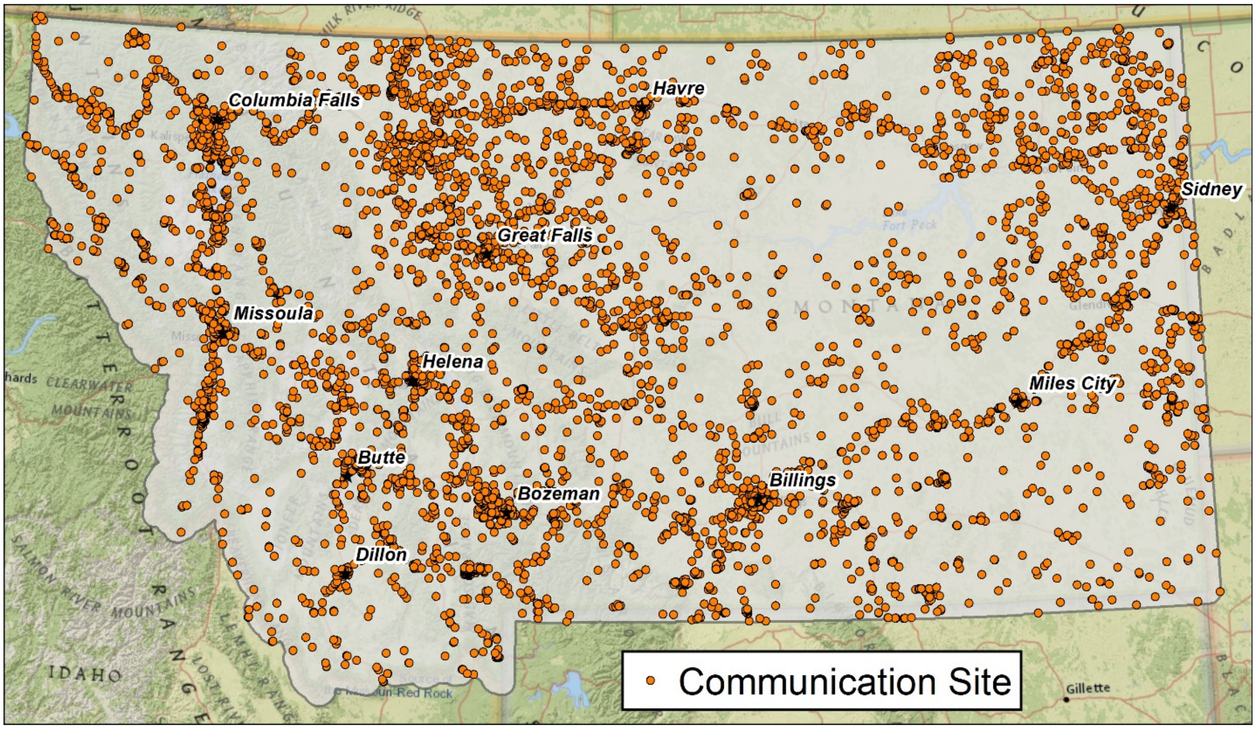

Figure 10. Map of Communication Sites within the MWRA analysis area.

Communication sites for the analysis area (Figure 10) were provided by DNRC and acquired from Homeland Infrastructure Foundation-Level Data (HIFLD)[7]. The types of communication sites compiled for the assessment include: cellular towers, land mobile towers, FM/AM transmission towers, microwave service towers, paging transmission towers, antenna structure, TV analog/digital transmitters, broadband radio transmitters, internet service providers, internet exchange points and DNRC Radio Sites. Each location was assigned a burnable vegetation type derived from lifeform in the LANDFIRE Existing Vegetation Type (EVT) grid. A value of '1' was assigned to sites associated with tree or shrub lifeform and value of '2' for sites designated as grass or sage. All communication sites were merged into a single feature class and converted to 30-m pixels using the ArcGIS Focal Statistics tool. Focal statistics were calculated using the sum of an annulus neighborhood with an inner radius of zero and outer radius of two, resulting in a point feature being represented by thirteen, 30-m pixels.

The RFs for all communication sites demonstrate a similar patter, a neutral response at the lowest flame length (FIL1) but show increasing negativity to fires of increasing intensity (Table 9). As expected, the burnable vegetation type associated with higher fire intensities (tree/shrub) show a greater negative response to increasing intensities when compared to grass/shrub.

Communication sites were allocated 50 percent of the share of the Infrastructure HVRA importance – split evenly between the two lifeform classes. The share of HVRA importance is based on relative importance per unit area and mapped extent.

---

[7] HIFLD data on communication sites was downloaded from https://hifld-geoplatform.opendata.arcgis.com/ on 2/17/2020

Table 9. Response functions for the Infrastructure HVRA to highlight communication sites.

Sub-HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6	Share of RI[1]	Acres
Comm Sites - Tree/Shrub	0	-10	-20	-30	-40	-50	25%	11,707
Comm Sites - Grass/Sagebrush	0	0	-10	-10	-20	-30	25%	11,412

[1] Within-HVRA relative importance.

3.4.2.2 Electric Transmission Lines

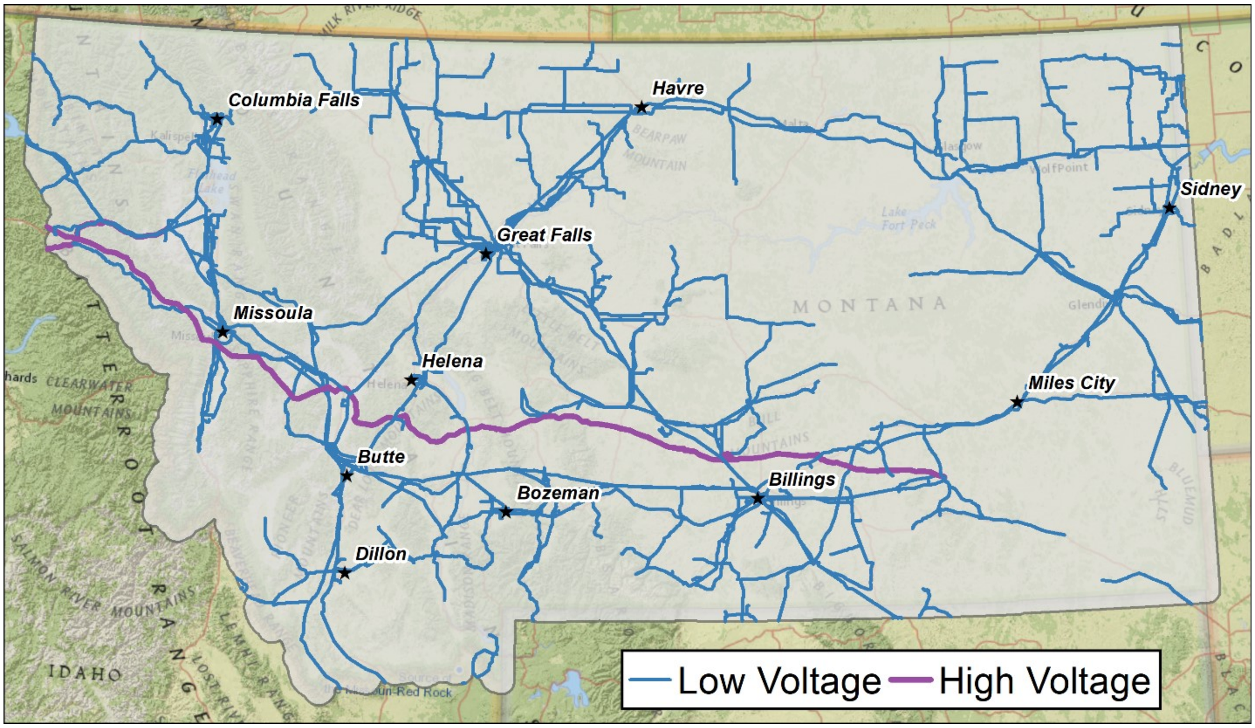

Figure 11. Map of Low and High Voltage Transmission lines within the MWRA analysis area.

Transmission lines within the analysis area (Figure 11) were acquired from the Homeland Infrastructure Foundation-Level Data (HIFLD)[8]. The lines were classified using a voltage break of 345 volts (transmission lines carrying less than 345 volts classified as ‘1’, and those greater than 345, classified as ‘2’). The data were converted to 30-m raster and expanded out one additional pixel (per side) using the ArcGIS *Expand* tool to capture more of the area impacted by wildfire.

Low voltage lines (<345 kV) are thought to be mostly wooden poles, and therefore, respond with a strongly negative response to all fire intensities. Total loss was expected for fires greater than FIL4 (Table 10). High voltage transmission lines (≥345 kV) are expected to be constructed of largely non-burnable materials that will withstand exposure to lower fire intensities and experience less loss at the higher intensity classes as well. Therefore, high voltage transmission lines have a neutral response in FILs 1-3 and a slightly negative response in FILs 4-6 (Table 10).

Due to the number of acres mapped on the landscape and their importance to infrastructure, electric transmission lines received 50 percent of the share of the Infrastructure HVRA importance. The share of HVRA importance is based on relative importance per unit area and mapped extent.

Table 10. Response functions for the Infrastructure HVRA to highlight electric transmission lines.

Sub-HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6	Share of RI[1]	Acres
Low Voltage (wooden poles)	-70	-80	-90	-100	-100	-100	48.8%	495,013
High Voltage (> 345)	0	0	0	-10	-30	-30	1.2%	12,080

[1] Within-HVRA relative importance.

[8] HIFLD data on transmission lines was downloaded from https://hifld-geoplatform.opendata.arcgis.com/ on 2/17/2020

3.4.3 *Watersheds*

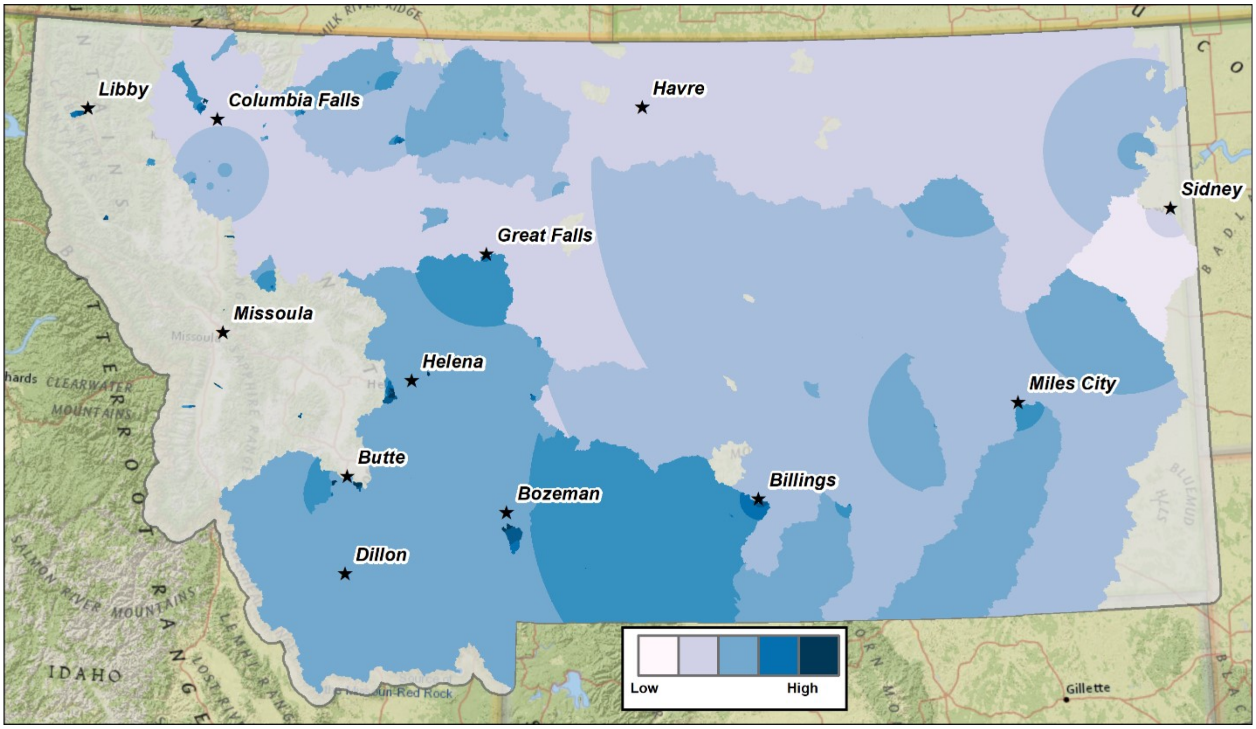

Figure 12. Map of the Watershed relative importance weighted by distance to intake and people served.

Watershed resources were mapped using a custom approach to determine the importance of each pixel within a basin based on population served and distance to intake. We calculated the Euclidean distance to the drinking water intake for each pixel within its associated watershed. We then divided the raster resolution (30 meters) of each pixel by the distance to the intake and multiplied by the population served by that intake. The sum of importance for of each watershed was then normalized to the total population served to prevent overweighting of the largest watersheds. Because a single pixel can belong to one or more overlapping watersheds, the values are cumulative across any overlapping watersheds. The resulting importance map is shown in Figure 12.

The response functions used for erosion cannot be shown in Table 11 because response to fire was determined spatially according to erosion modeling results for the analysis area. The Geospatial Technology and Applications Center (GTAC) produced a set of modeled erosion and deposition potential maps based on a current condition (no-fire) situation, along with low and high fire severity scenarios. We used only erosional pixels that were negative values in the modeled results and converted them to positive integers. Using the differences between the no-fire scenario and the low fire severity scenario, we applied a logarithmic base-ten transformation. We applied the same transformation to the difference values between the no-fire scenario and the high fire severity scenario and determined the 95th percentile value. We set this value as the maximum loss value (response function of -100) for both scenarios and scaled all other values relative to this. This resulted in two grids ranging from 0 to -100 for low severity fire and high severity fire. The GTAC model used a 'c-factor' value to determine the change in cover due to wildfire, and cover types were derived from the National Land Cover Dataset (NLCD). Where the c-factor value was constant across low and high severity fire, we assigned the low severity RF values. These pixels were generally associated with grass and shrub-type vegetation. Where c-factor increased from low to high severity, typically in timbered vegetation, we used the low severity RF values for FILs1-3 and the high severity RF values for FILs 4-6. The municipal watersheds HVRA had just one sub-HVRA, which received the full share of the HVRA importance.

Table 11. Response functions for the Drinking Water HVRA to highlight watersheds.

Sub-HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6	Share of RI[1]	Acres
Drinking Water	XXXX	XXXX	XXXX	XXXX	XXXX	XXXX	100.0%	79,610,784

[1] Within-HVRA relative importance.

3.5 Effects Analysis Methods

An effects analysis quantifies wildfire risk as the expected value of net response (Finney, 2005; Scott *et al.*, 2013) also known as expected net value change (eNVC). Effects analysis relies on input from resource specialists to produce a tabular response function for each HVRA occurring in the analysis area. A response function is a tabulation of the relative change in value of an HVRA if it were to burn in each of six flame-length classes. A positive value in a response function indicates a benefit or increase in value; a negative value indicates a loss or decrease in value. Response function values for the MWRA ranged from -100 (greatest possible loss of value) to 0 (no change in value).

3.5.1 *Effects Analysis Calculations*

Integrating HVRAs with differing units of measure (for example, habitat vs. homes) requires relative importance (RI) values for each HVRA/sub-HVRA. These values were identified in the RI workshop, as discussed in Section 3.3. The final importance weight used in the risk calculations is a function of overall HVRA importance, sub-HVRA importance, and relative extent (pixel count) of each sub-HVRA. This value is therefore called relative importance per pixel (RIPP).

The RF and RIPP values were combined with estimates of the flame-length probability (FLP) in each of the six flame-length classes to estimate conditional NVC (cNVC) as the sum-product of flame-length probability (FLP) and response function value (RF) over all the six flame-length classes, with a weighting factor adjustment for the relative importance per unit area of each HVRA, as follows:

$$cNVC_j = \sum_{i}^{n} FLP_i * RF_{ij} * RIPP_j$$

where i refers to flame length class (n = 6), j refers to each HVRA, and RIPP is the weighting factor based on the relative importance and relative extent (number of pixels) of each HVRA. The cNVC calculation shown above places each pixel of each resource on a common scale (relative importance), allowing them to be summed across all resources to produce the total cNVC at a given pixel:

$$cNVC = \sum_{j}^{m} cNVC_j$$

where cNVC is calculated for each pixel in the analysis area. Finally, eNVC for each pixel is calculated as the product of cNVC and annual BP:

$$eNVC = cNVC * BP$$

3.5.2 *Downscaling FSim Results for Effects Analysis*

FSim's stochastic simulation approach can be computationally intensive and therefore, time constraining on large landscapes. A challenge, therefore, is to determine a resolution sufficiently fine to retain detail in fuel and terrain features yet produce calibrated results in a reasonable timeframe. Moreover, HVRA are often mapped at the same resolution as the final BP produced by FSim. To enable greater resolution on HVRA mapping, we chose to downscale the FSim BP raster to 30 m, consistent with HVRA mapping at 30 m.

We downscaled the FSim BP raster using a multi-step process. First, we used the ESRI ArcGIS Focal Statistics tool to perform two low-pass filters at 120-m resolution, calculating the mean value of burnable pixels only, within a 3-pixel by 3-pixel moving window. This allowed us to “backfill” burnable pixels at 30 m that were coincident with non-burnable fuel at 120 m. We subsequently resampled the 120-m FSim BP raster to 30 m using bilinear smoothing. This final smoothed BP raster resulted in original FSim values for pixels that were burnable at both 120 m and 30 m, non-zero BP values in burnable pixels that were previously non-burnable (at 120 m), and a BP of zero in non-burnable, 30 m pixels.

3.5.3 *Downscaling FLEP-Gen Results for Effects Analysis*

FLEP-Gen’s approach can also be computationally intensive and HVRA are often mapped at the same resolution as the final FLPs produced by FLEP-Gen. To enable greater resolution on HVRA mapping, we chose to also downscale the FLEP-Gen results to 30 m, consistent with HVRA mapping at 30 m and the downscaled BP raster described above in section 3.5.2.

We downscaled FLEP-Gen results using a multi-step process. First, we used the ESRI ArcGIS Focal Statistics tool to perform two low-pass filters at 120-m resolution, calculating the mean value of burnable pixels only, within a 3-pixel by 3-pixel moving window. Next, we stamped the original 120-m FLEP-Gen results on top of this smoothed version to retain intensity values associated with underlying fuel types and “backfill” burnable pixels at 30 m that were coincident with non-burnable fuel at 120 m. We subsequently resampled the mixed-method 120-m FLEP-Gen result grids to 30 m using bilinear smoothing. These final smoothed grids resulted in original FLEP-Gen values for pixels that were burnable at both 120 m and 30 m, non-zero probability values in burnable pixels that were non-burnable at 120 m, and a probability of zero in non-burnable, 30 m pixels. Additionally, because we needed to integrate the FSim burn probability with the FLEP-Gen products for further analyses, any pixels in FLEP-Gen products with a 30-m FSim burn probability of zero were also set to zero. FLEP-Gen results for Mean Flame Length (Figure 17) and Mean Fireline Intensity (Figure 18) were downscaled to 30 m using the same approach.

3.5.4 *Hazard in Context*

3.5.4.1 Risk to Potential Structures

Risk to Potential Structures (Hazard in Context) integrates wildfire likelihood and intensity with generalized consequences to a home everywhere on the landscape. The Risk to Potential Structures data can help answer the hypothetical question, "What would be the relative risk to a house if one existed here?". It asks that question whether a home currently exists at that location or not. This allows for the comparison of risk in places where homes already exist to places where new construction may be proposed as well both within and between communities across the state.

The Risk to Potential Structures dataset was developed using similar methods as the People and Property HVRA described in sections 3.5.1 with the response functions detailed in Table 8. The data product incorporates the response functions by modeled wildfire intensity and weighted by wildfire likelihood (Figure 15). The difference between Risk to Potential Structures (RPS) and the People and property HVRA is that RPS does not include mapping of the current location or importance of structures. It only considers the likelihood and intensity of simulated wildfire. It should be noted that RPS assumes all homes that encounter wildfire will be damaged, and the degree of damage is directly related to wildfire intensity. RPS does not account for homes that may have been mitigated with localized fuel reduction efforts or the overall susceptibility of a home to ignition from construction materials and design. The Risk to Potential Structures data are presented in Figure 19.

3.5.4.2 Conditional Risk to Potential Structures

Conditional Risk to Potential Structures (CRPS) is similar to RPS except it is not weighted by wildfire likelihood (burn probability). CRPS is a measure of hazard to structures across the landscape independent of the likelihood of a given area to experience wildfire.

3.5.5 *Suppression Difficulty Index (SDI)*

Wildfire Suppression Difficulty Index is a quantitative rating of relative difficulty in performing fire control work. SDI factors in topography, fuels, expected fire behavior under severe fire weather conditions, firefighter line production rates in various fuel types, and accessibility (distance from roads/trails) to assess relative suppression effort.

Severe fire behavior was modeled in FlamMap at 30-m resolution with 15 mph, up-slope winds and fully cured fuels (reference Table 2 for 90th percentile fuel moisture inputs). Non-burnable fuel models 91, 92, 93, 98 as well as custom urban fuel models 251 and 252 were set to an SDI value of 0. Custom burnable agriculture fuel models 241 and 242 were set to the production rates of GR1 and GR2 respectively. O'Connor *et al.* (2016) and Rodríguez y Silva *et al.* (2014) provide additional information on the methods and data inputs of the SDI model. A map of the 30-m resolution SDI results for Montana can be found in Figure 20.

3.5.6 *Wildfire Transmission (Risk-Source)*

The potential for wildfires to transmit risk is a function of the spatial variation in fire occurrence and fire growth potential, in conjunction with spatial variation in HVRA location. To evaluate this potential, we summed cNVC values within each simulated FSim fire perimeter, then attributed the start location of each fire with that value. We summarized each individual HVRA (People and Property, Infrastructure, and Watersheds) and calculated the total as the sum of all HVRA. Additionally, we evaluated wildfire transmission risk to MT structures only, independent of the weighting applied to HVRA in the full wildfire risk assessment.

The final raster dataset created from the perimeter overlay exercise (Annual Risk-Source) represents the expected annual consequence per km^2 (or total wildfire transmission risk) for all HVRA from ignitions across the landscape (Figure 21). The Annual Risk-Source raster was generated using a multi-stage process. The MWRA analysis area includes Fire Occurrence Areas (FOAs) for which a varying number of iterations was used – ranging from 10,000 to 20,000 iterations. The number of iterations used in the simulation was added to the attribute table for each fire. A new attribute representing cNVC per iteration was then generated. This step is needed to accommodate fires from adjacent FOAs with unequal numbers of iterations. Using the ArcGIS Point Statistics tool, the sum of cNVC per iteration within a 10-km moving-window radius was calculated for a 30-m output cell size. The second step involved calculating the sum of ignitable[9] land area using the same tool and parameters on a point feature class differentiating ignitable and nonignitable fuel models. Finally, the sum of cNVC per iteration was divided by the sum of ignitable land area per km^2 to get the expected risk-source per km^2 of source area. These results are named 'Expected Risk-Source' in the project deliverables and are used to look at the relative likelihood and consequence of ignitions occurring across the landscape.

The mean consequence of an ignition, given a fire starts, is called Conditional Risk-Source. The Conditional Risk-Source raster is calculated by dividing the sum of cNVC per iteration by the sum of "1/iterations" to account for differences across FOA boundaries and remove the annual estimate of

[9] Ignitable fuel includes burnable fuel and custom burnable-agriculture fuel models.

number of fire-starts from the calculation. This process was repeated for each individual HVRA and totaled for all HVRA.

A total of 10 risk-source rasters were generated for this analysis. Both conditional and expected risk-source raster sets were generated for each HVRA, for the total of all HVRA, and for MT structures separate from the other HVRA. Expected Risk-Source rasters consider both the consequence of transmitted wildfire risk to HVRA and the relative likelihood of ignitions occurring. Conditional Risk-Source rasters compare consequence across the landscape without consideration of ignition likelihood and are useful in active incident decision making when the likelihood of ignition is already known.

3.5.7 *Tabulated Wildfire Risk Summaries*

The map products described in the sections above provide a visual comparison of wildfire risk and hazard variability across Montana. Tabular summaries of these map products allow for comparison of risk and hazard attributes at finer spatial scales within the state.

We summarized a set of Effects Analysis results for a suite of polygon zones including:

1. MT Counties
2. MT Census County Divisions
3. MT Communities (core plus zone combined)
4. MT Communities (core and zone separate)
5. MT 6-th Level Watersheds

Within each polygon zone we summarized burnable acres, burn probability, total eNVC (sum of all pixels) for each HVRA individually and for all HVRA combined, mean eNVC (calculated as the sum of eNVC divided by burnable acres/100 acres) for each HVRA individually and for all HVRA combined, and mean cNVC (calculated as the sum of eNVC divided by the sum of burn probability) for each HVRA individually and for all HVRA combined. An example of the NVC summary results for Montana counties is shown in Table 12.

3.5.8 *Ranking Communities and Water Sources at Risk*

Detailed analyses of the relative wildfire risk to individual communities and surface water drinking intakes were completed as part of the MWRA. Results and rankings of communities at risk can be found in Appendix A and results and rankings for water sources at risk can be found in Appendix B.

4 Results

4.1 Effects Analysis Results

The cumulative results of the wildfire risk calculations described in section 3.5.1 are the spatial grids of cNVC and eNVC, representing both the conditional and expected change in value from wildfire disturbance to all HVRAs included in the analysis. Results are therefore limited to those pixels that have at least one HVRA and a non-zero burn probability. Both cNVC and eNVC reflect an HVRA's response to fire and their relative importance within the context of the assessment, while eNVC additionally captures the relative likelihood of wildfire disturbance. Cumulative effects of wildfire across the landscape vary by HVRA (Figure 13) with a net negative eNVC for all of the HVRA. Results are scaled to cumulative eNVC values for the People and Property HVRA in the MWRA analysis area. People and Property show the greatest cumulative wildfire losses (eNVC) result followed by Infrastructure, and finally Watersheds.

Figure 14 shows cNVC results at a 30-m resolution across the analysis area. The most adverse or negative effects are shown in dark red and are largely concentrated around Montana communities. Adjusting cNVC by fire likelihood (i.e., burn probability) narrows the range of values for negative outcomes and highlights areas more likely to be visited by wildfire as seen in the eNVC map in Figure 16.

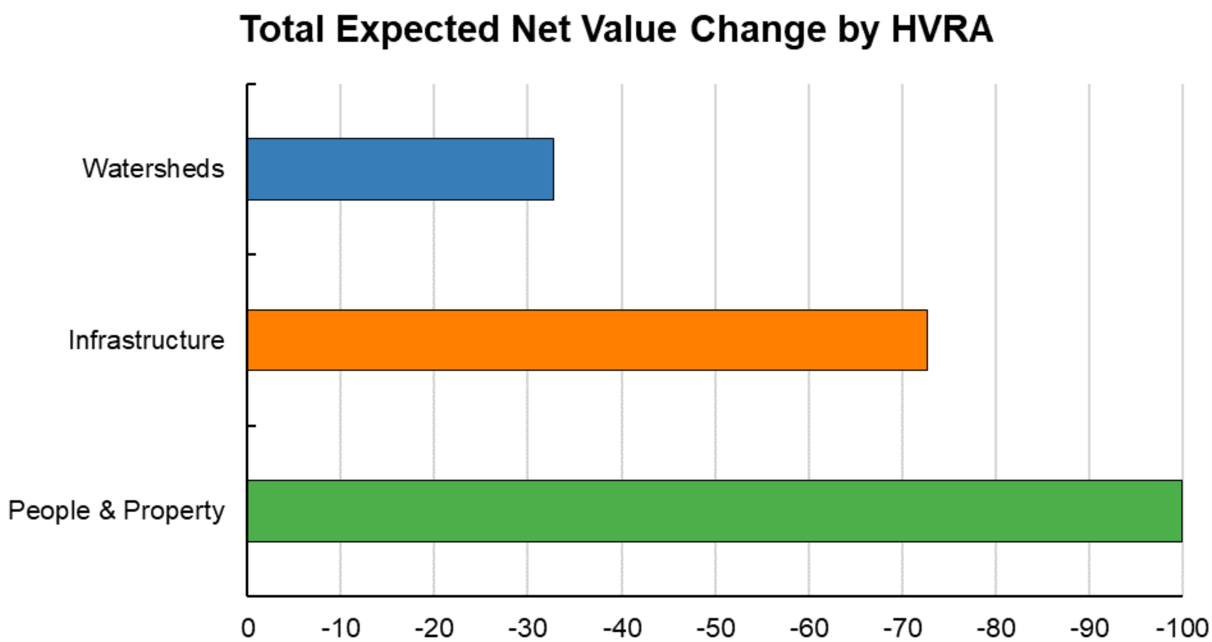

Figure 13: Weighted net response over all highly valued resources and assets (HVRAs) in the assessment. HVRAs are listed in order of net value change and scaled to eNVC values for the People and Property HVRA.

4.1.1 *Consequence – Conditional Net Value Change (cNVC)*

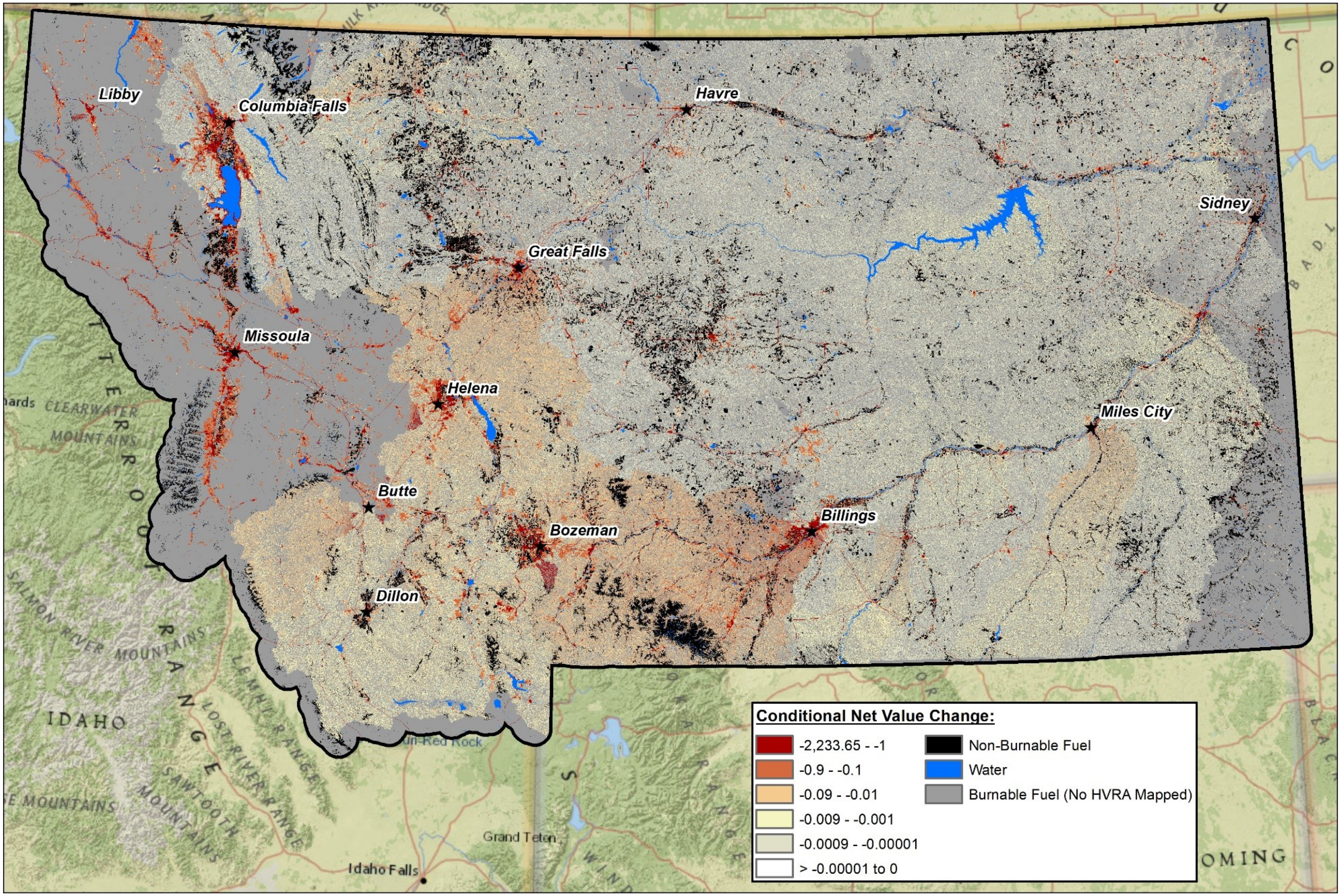

Figure 14. Map of Conditional Net Value Change (cNVC) for the MWRA analysis area.

4.1.2 *Likelihood – Annual Burn Probability (BP)*

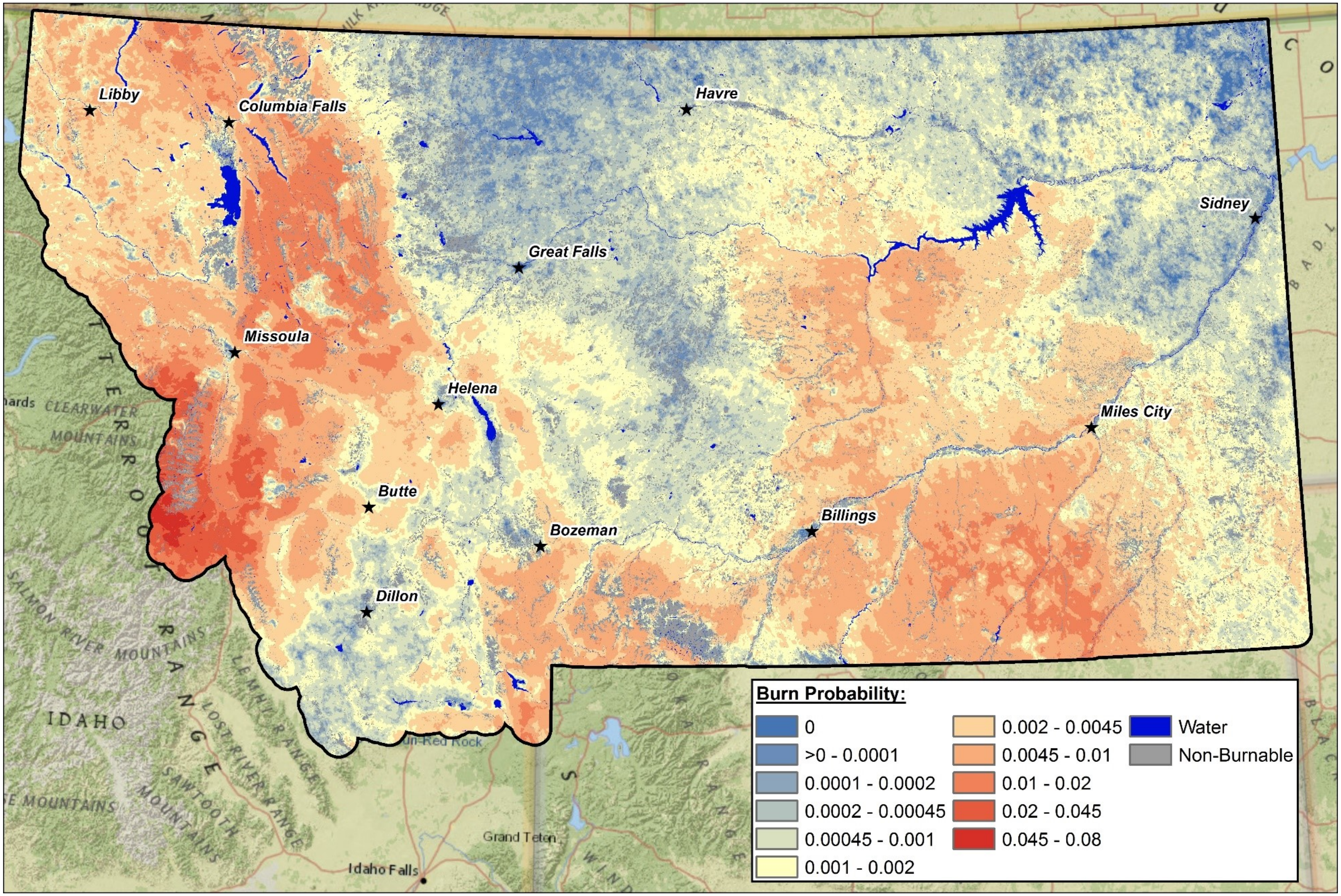

Figure 15. Map of integrated FSim burn probability results downscaled to 30-m resolution for the MWRA analysis area.

4.1.3 *Risk – Expected Net Value Change (eNVC) - Total*

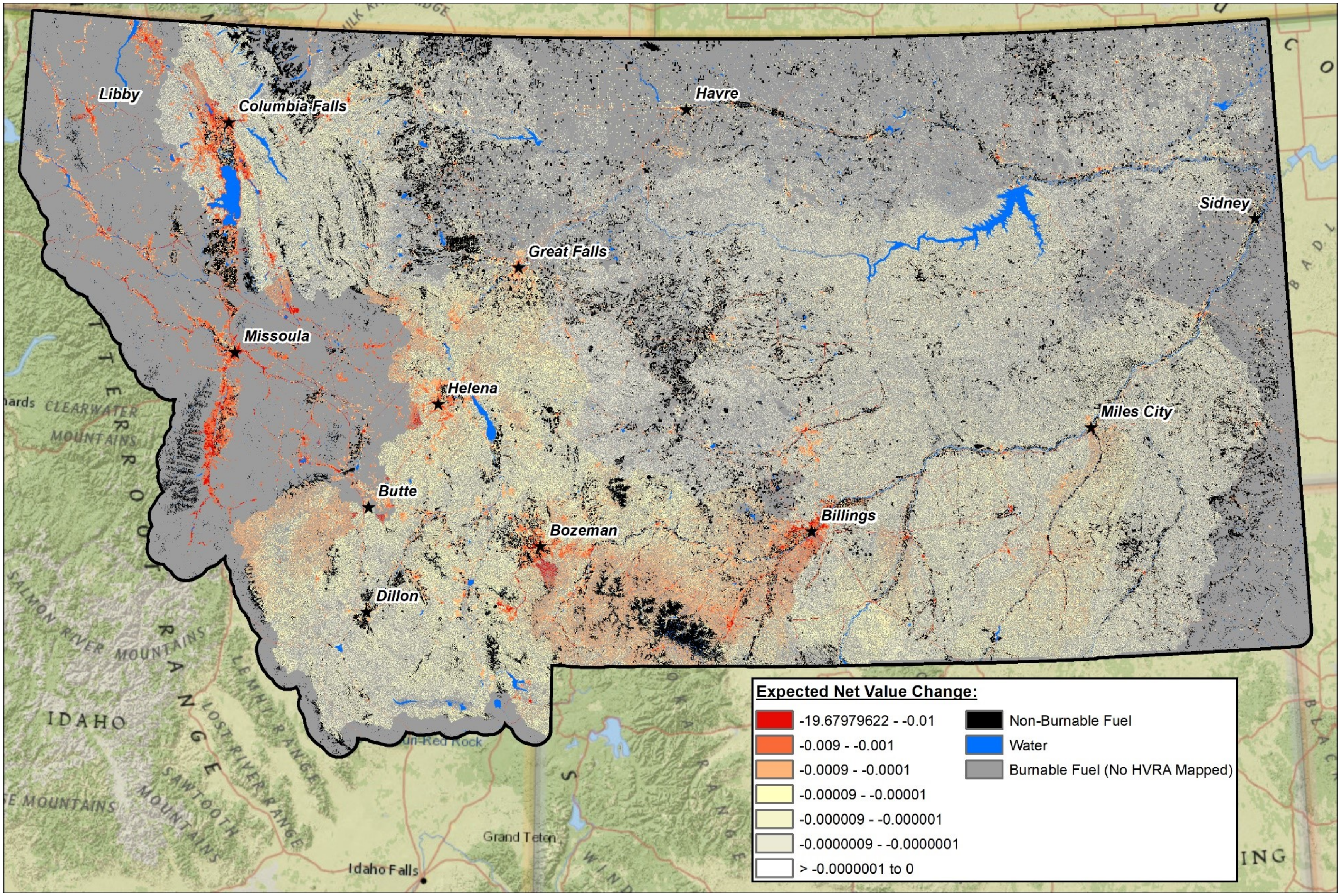

Figure 16. Map of Expected Net Value Change (eNVC) for the MWRA analysis area.

4.1.4 *Mean Flame Length (ft)*

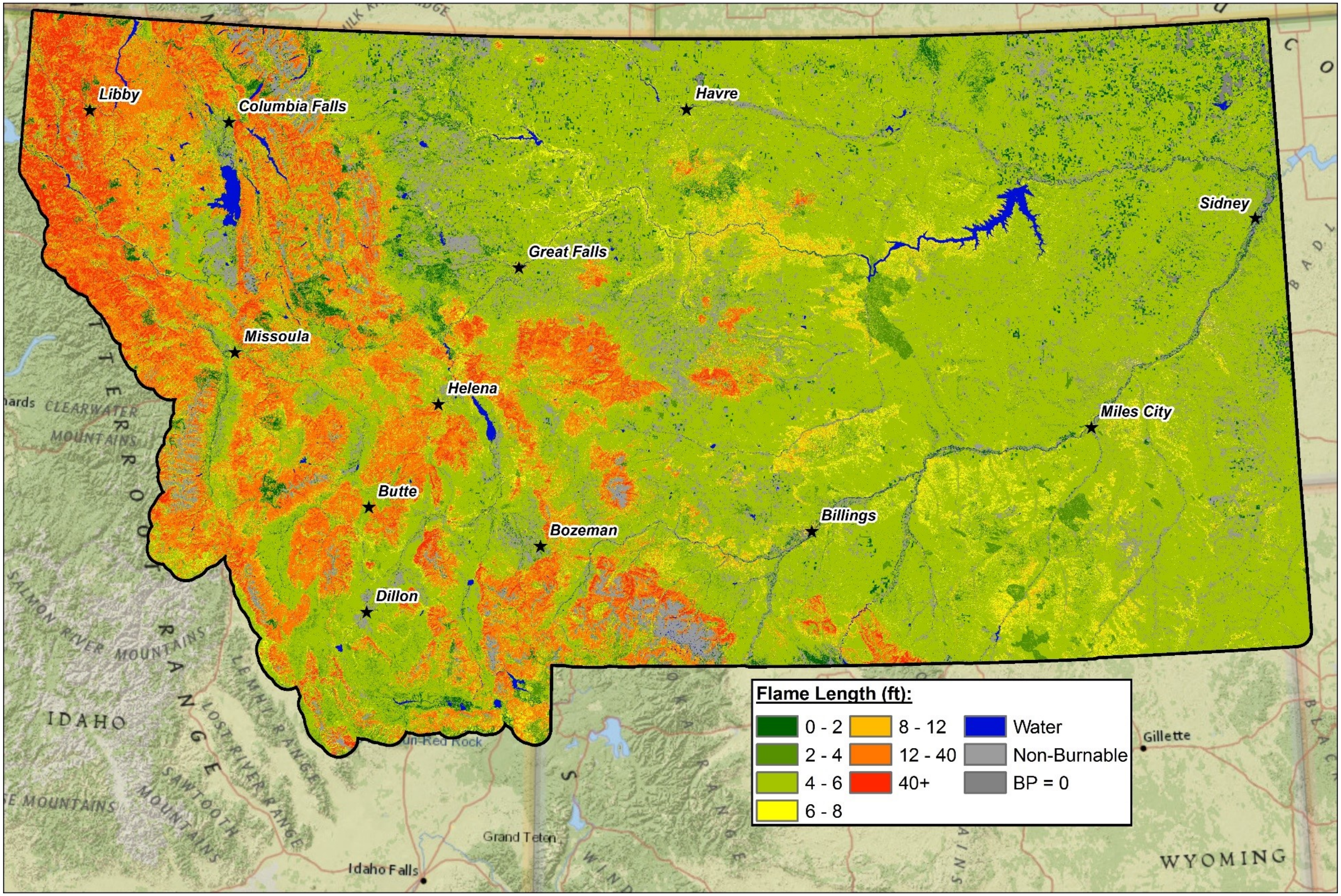

Figure 17. Map of FLEP-Gen 30-m Mean Flame Length (ft) for the MWRA analysis area.

4.1.5 *Mean Fireline Intensity (kW/m)*

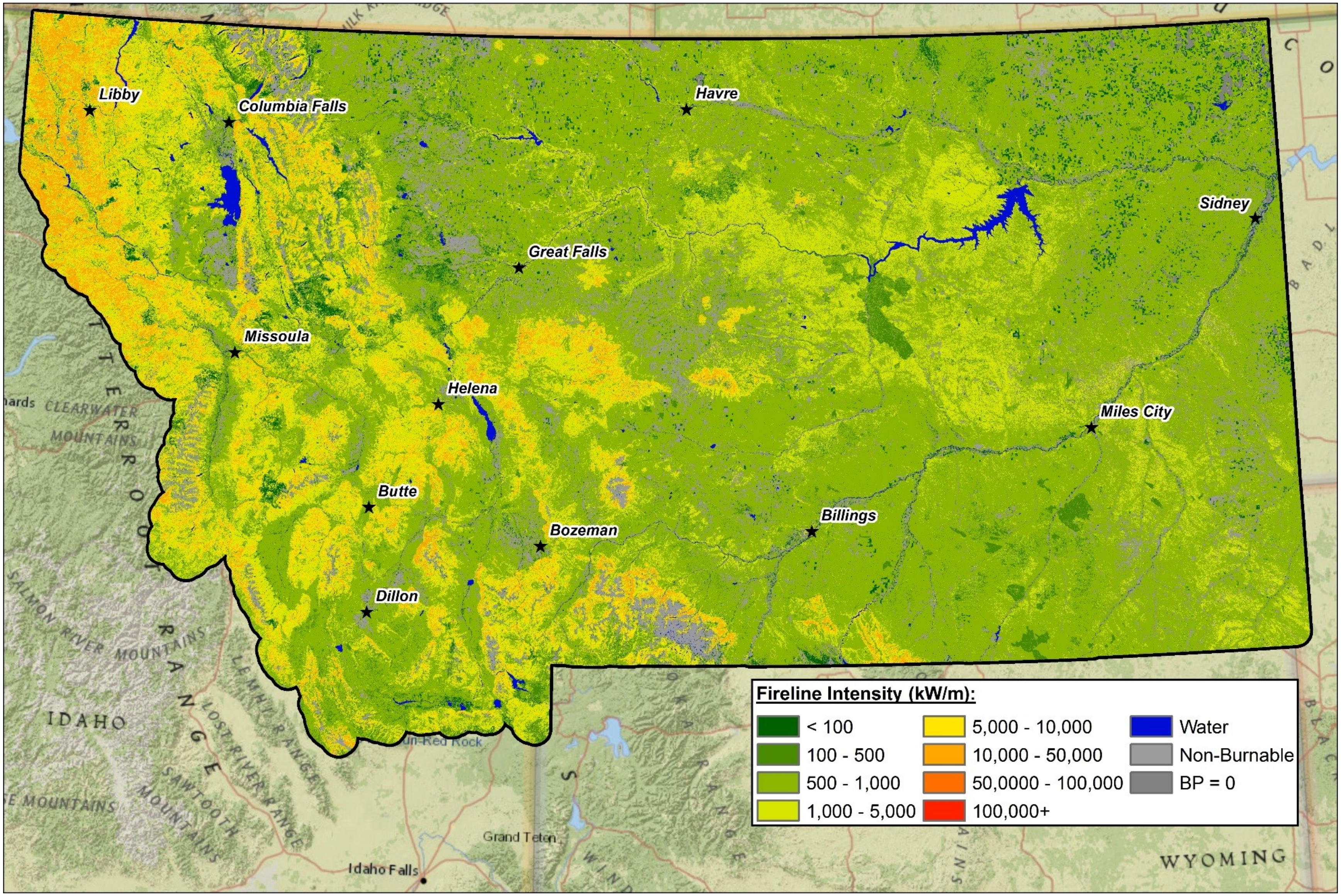

Figure 18. Map of FLEP-Gen 30-m Mean Fireline Intensity (kW/m) for the MWRA analysis area.

4.1.6 *Risk to Potential Structures*

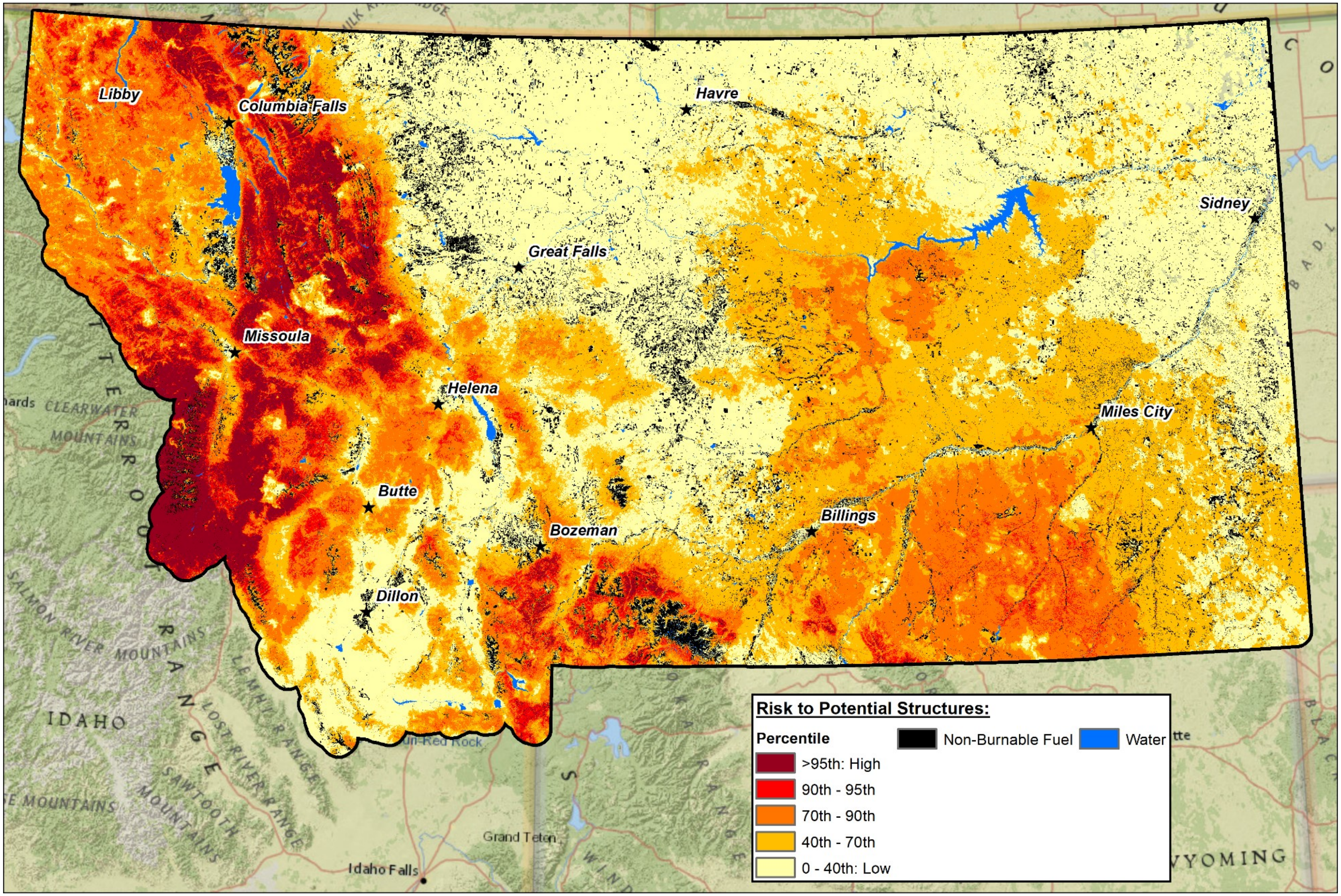

Figure 19. Map of 30-m Hazard in Context – Risk to Potential Structures for MWRA analysis area.

4.1.7 *Suppression Difficulty Index (SDI)*

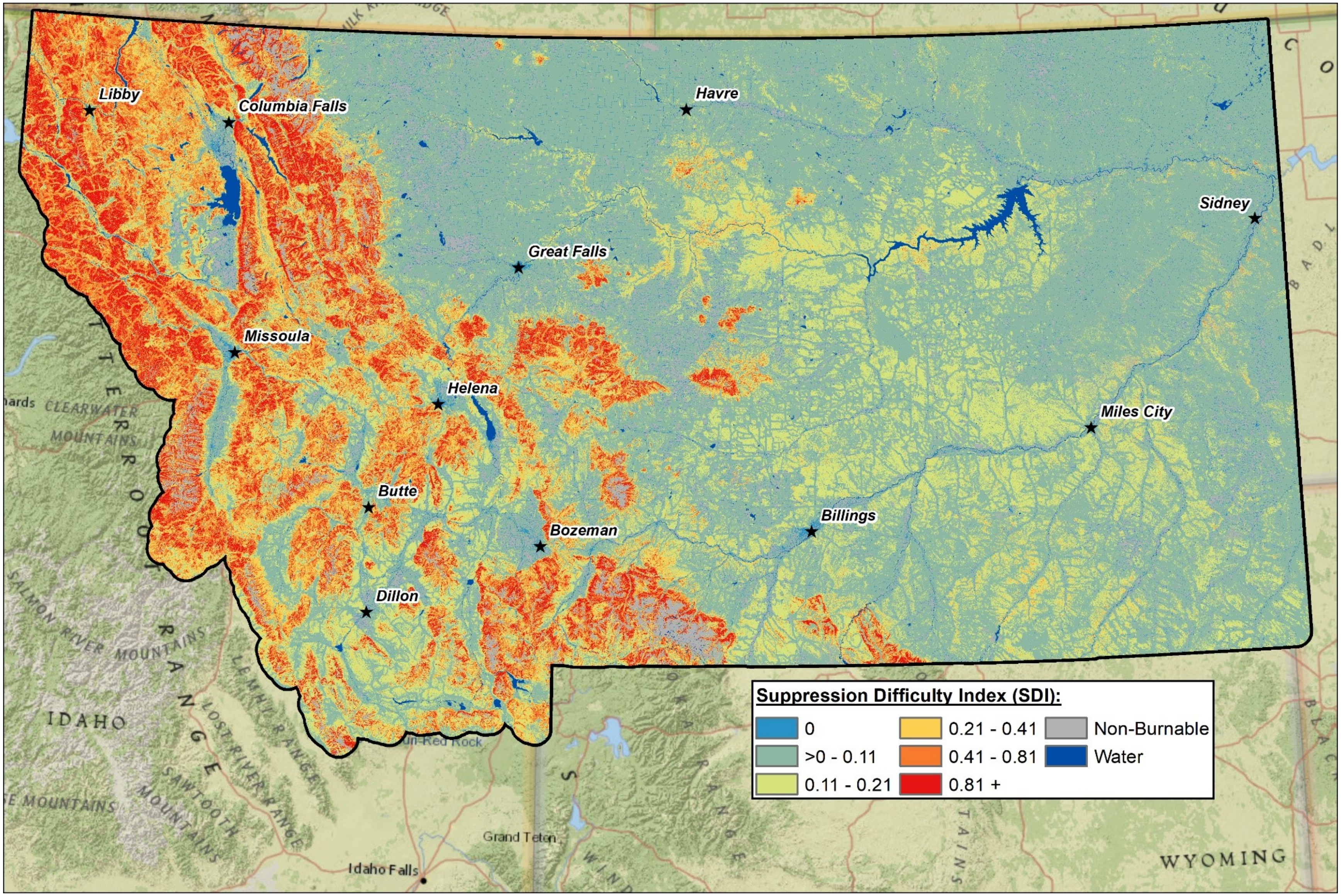

Figure 20. Map of 30-m Suppression Difficulty Index (SDI) for the MWRA analysis area.

4.1.8 *Wildfire Transmission (Risk-Source Analysis)*

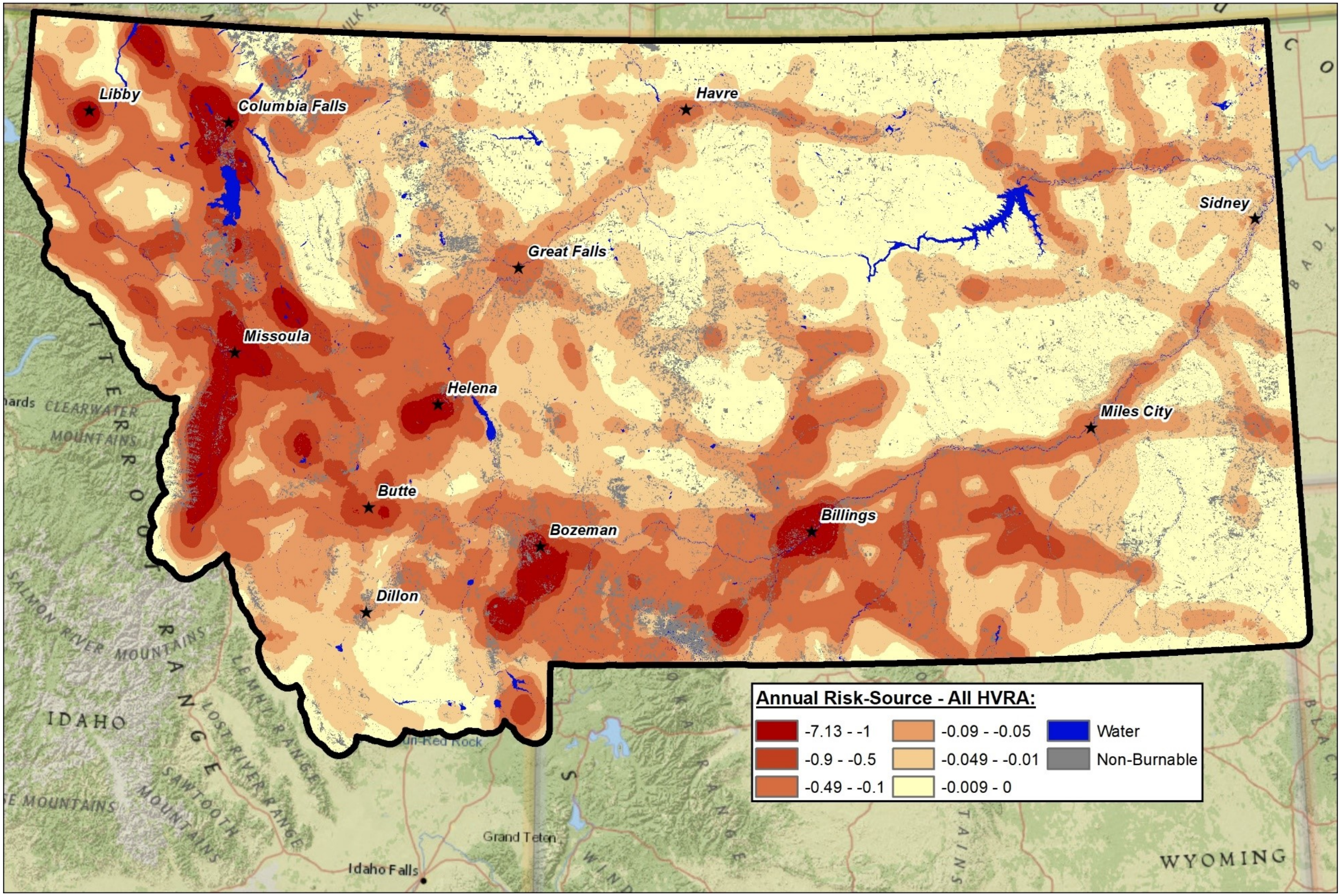

Figure 21. Map of the annual wildfire transmission risk to all HVRA from ignitions across the landscape.

4.1.9 *Tabulated Summaries for Montana Counties*

The summary of mean wildfire risk (mean eNVC) for all HVRA by Montana counties is provided in Table 12. The table highlights a sample of the risk attributes summarized for each polygon zone outlined in Section 3.5.7. The tabular summaries provided with the complete set of project deliverables include the full list of risk attributes, but Table 12 displays a limited set of attributes to compare between mean eNVC and total eNVC for all counties.

The total eNVC metric highlights which counties have the greatest cumulative risk, but because county sizes are variable, it is useful also examine risk concentration, or mean eNVC. Ranking by mean eNVC is most useful to examine which counties, on average, have the greatest wildfire risk. The mean eNVC by HVRA shows which HVRA are most at risk in each county and which contribute to the overall mean eNVC. Mean eNVC can help identify which counties might be prioritized for potential wildfire risk mitigation efforts, but the level of funding and mitigation efforts must be informed by the total eNVC.

Mean eNVC is a useful metric for larger summary zones, however, for smaller community polygons with very few burnable acres, the mean can be arbitrarily inflated by the small number of burnable acres in the denominator. Caution must be used when interpreting these results and establishing a minimum threshold for burnable acres may be needed to accurately rank mean eNVC values.

Table 12. Tabular summary of Mean and Total Wildfire Risk (eNVC) for Montana counties.

County	Burnable Acres/ 100 Acres	Total (All HVRA) Sum eNVC	Total (All HVRA) Mean eNVC	People and Property Mean eNVC	Water Mean eNVC	Infra Mean eNVC	Rank by Mean eNVC
Ravalli	14,140	-8,010.199	-0.567	-0.464	-0.019	-0.084	1
Gallatin	15,345	-5,872.625	-0.383	-0.165	-0.176	-0.041	2
Missoula	16,143	-5,859.007	-0.363	-0.228	-0.015	-0.120	3
Silver Bow	4,504	-1,161.953	-0.258	-0.037	-0.162	-0.059	4
Lake	8,260	-2,112.225	-0.256	-0.162	-0.023	-0.070	5
Yellowstone	15,666	-3,931.679	-0.251	-0.132	-0.033	-0.085	6
Carbon	11,400	-2,027.861	-0.178	-0.075	-0.042	-0.061	7
Flathead	30,659	-5,090.513	-0.166	-0.114	-0.023	-0.029	8
Lewis and Clark	21,091	-3,336.829	-0.158	-0.073	-0.055	-0.030	9
Granite	10,805	-1,687.730	-0.156	-0.082	-0.004	-0.070	10
Deer Lodge	4,383	-605.955	-0.138	-0.078	-0.016	-0.044	11
Lincoln	22,909	-2,800.260	-0.122	-0.073	-0.011	-0.038	12
Park	15,893	-1,742.012	-0.110	-0.033	-0.044	-0.033	13
Mineral	7,736	-846.046	-0.109	-0.067	0.000	-0.043	14
Powell	14,406	-1,415.791	-0.098	-0.033	0.000	-0.065	15
Sanders	17,255	-1,524.045	-0.088	-0.040	-0.004	-0.044	16
Big Horn	30,961	-2,704.984	-0.087	-0.013	-0.005	-0.070	17
Stillwater	9,871	-746.973	-0.076	-0.013	-0.032	-0.031	18
Musselshell	11,470	-856.399	-0.075	-0.024	0.000	-0.050	19
Jefferson	10,408	-771.485	-0.074	-0.034	-0.008	-0.033	20
Treasure	5,987	-338.873	-0.057	-0.003	-0.001	-0.052	21
Rosebud	31,031	-1,735.954	-0.056	-0.010	-0.003	-0.043	22
Sweet Grass	10,869	-576.796	-0.053	-0.009	-0.026	-0.018	23
Madison	21,453	-1,049.981	-0.049	-0.028	-0.004	-0.017	24
Cascade	15,734	-677.915	-0.043	-0.016	-0.007	-0.020	25
Glacier	16,394	-611.621	-0.037	-0.015	-0.008	-0.014	26
Petroleum	10,114	-284.568	-0.028	-0.007	0.000	-0.021	27
Broadwater	7,223	-180.633	-0.025	-0.007	-0.007	-0.010	28
Powder River	19,575	-476.949	-0.024	-0.006	-0.005	-0.014	29
Custer	22,704	-499.905	-0.022	-0.005	-0.005	-0.012	30
Beaverhead	34,360	-741.801	-0.022	-0.003	-0.011	-0.008	31
Roosevelt	14,116	-302.826	-0.021	-0.006	0.000	-0.016	32
Fallon	8,805	-158.368	-0.018	-0.003	0.000	-0.015	33
Teton	12,094	-209.518	-0.017	-0.009	0.000	-0.008	34
Golden Valley	7,012	-119.923	-0.017	-0.002	0.000	-0.015	35
Meagher	14,760	-250.755	-0.017	-0.005	-0.007	-0.005	36
McCone	16,034	-220.695	-0.014	-0.002	0.000	-0.012	37
Dawson	14,166	-189.298	-0.013	-0.002	0.000	-0.011	38
Judith Basin	10,206	-134.134	-0.013	-0.003	0.000	-0.010	39
Wheatland	8,258	-99.050	-0.012	-0.002	0.000	-0.010	40
Pondera	8,559	-101.769	-0.012	-0.004	-0.001	-0.007	41
Hill	17,781	-206.958	-0.012	-0.005	0.000	-0.006	42
Fergus	24,471	-273.955	-0.011	-0.005	0.000	-0.006	43
Prairie	10,331	-106.335	-0.010	-0.001	-0.001	-0.008	44
Valley	29,549	-287.760	-0.010	-0.004	0.000	-0.006	45
Wibaux	5,158	-42.902	-0.008	-0.001	0.000	-0.007	46
Blaine	25,802	-210.667	-0.008	-0.002	0.000	-0.006	47
Richland	12,384	-97.059	-0.008	-0.002	0.000	-0.006	48
Chouteau	24,008	-185.777	-0.008	-0.002	0.000	-0.006	49
Sheridan	10,320	-73.214	-0.007	-0.003	0.000	-0.005	50
Garfield	28,900	-195.147	-0.007	-0.003	-0.001	-0.003	51
Carter	19,622	-110.554	-0.006	-0.001	0.000	-0.004	52
Toole	11,101	-50.346	-0.005	-0.002	0.000	-0.003	53
Daniels	8,539	-37.837	-0.004	-0.002	0.000	-0.003	54
Phillips	31,519	-139.225	-0.004	-0.001	0.000	-0.003	55
Liberty	8,670	-18.507	-0.002	-0.001	0.000	-0.002	56

5 Analysis Summary

The Montana Wildfire Risk Assessment provides foundational information about wildfire hazard and risk across all landownerships in the state. The results represent the best available science across a range of disciplines. While this report was generated by Pyrologix LLC, the overall analysis was developed as a collaborative effort with numerous local resource planning staff and Fire/Fuels Planners. This analysis can provide great utility in a range of applications including resource planning, prioritization and implementation of prevention and mitigation activities, and wildfire incident response planning. Lastly, this analysis should be viewed as a living document. While the effort to parameterize and to calibrate model inputs should remain static, the landscape file should be periodically revisited and updated to account for future forest disturbances.

6 Data Products

The Montana Wildfire Risk Assessment required the development of a wide range of data products. The section below outlines those datasets, with a brief description, based on provided data deliverables. More detailed descriptions pertaining to data product background and development procedures can be found in the metadata of each data product.

1) Fuel Calibration
   a) Updated and edited fuel, vegetation and topography rasters suitable for making current-condition (2020) LCP files across the state of Montana
2) FSim Results/FLEP-Gen Results
   a) Wildfire hazard modelling
      i) FOAs
      ii) Large-fire ignition density grid
      iii) Historical mean and 90 percent confidence interval for annual large number of fires
   b) Historical weather analysis
      i) List of RAWs per FOA
         FSim Frisk and FDist file per FOA
   c) Wildfire Simulation
      i) Seamless rasters for BP, MFI and FLPi
      ii) Vector data of start locations, final perimeters and associated fire characteristics
      iii) FSim inputs, outputs and intermediate runs per FOA
3) HVRA Characterization
   a) HVRA Risk Calculation Rasters (**HVRA_RiskCalcs_Rasters_20200310.gdb**)
      i) INFRA_CommSites – Infrastructure, communication sites within the analysis area used for risk calculations
      ii) INFRA_TransLines – Infrastructure, transmission lines within the analysis area used for risk calculations
      iii) PP (People and Property) – Buildings or structures from the Montana State Library "Structures and Address Framework" dataset and Big Sky structures data.
      iv) PP_Importance (People and Property Importance) – Importance for People and Property determined using structure RI assignments from Table C.1.
      v) *WATER_Importance* – Surface drinking within the analysis area; data provided by USFS Region 1. Importance of each pixel within a basin is based on population served and distance to intake.
4) Effects Analysis
   a) Effects Raster Results
      i) Consequence – cNVC (**MWRA_RiskResults_cNVC_20200403.gdb**)
         (1) _Total_cNVC – sum of cNVC for all HVRA included in MWRA assessment.
         (2) INFRA_CommSites_cNVC – individual infrastructure cNVC for communication sites.
         (3) INFRA_HVRAcNVC – sum of infrastructure cNVC (transmission lines and communication sites).
         (4) INFRA_TransLines_cNVC – individual infrastructure cNVC for transmission lines.
         (5) PP_HVRAcNVC- cNVC for people and property.
         (6) WATER_cNVC – cNVC for surface drinking water.
      ii) Likelihood – Burn Probability (**MWRA_BP_30m.gdb**)

(1) *mwra_bp_30m* – FSim generated stochastic simulation data based on many thousands of iterations (downscaled from 120 m).

iii) Risk – eNVC (**MWRA_RiskResults_eNVC_20200403.gdb**)

(1) *_Total_eNVC* – sum of eNVC for all HVRA included in MWRA assessment

(2) *INFRA_CommSites_eNVC* – individual infrastructure eNVC for communication sites.

(3) *INFRA_HVRAeNVC* – sum of infrastructure eNVC (transmission lines and communication sites).

(4) *INFRA_TransLines_eNVC* – individual infrastructure eNVC for transmission

(5) *PP_HVRAeNVC*- eNVC for people and property.

(6) *WATER_eNVC* – eNVC for surface drinking water.

iv) Mean Flame Length (**MWRA_FL_30m.gdb**)

(1) *mwra_fl_30m* – the weighted flame length (in feet) for a given pixel in the fuelscape. Weighting incorporates both temporal relative frequency and area-weighted relative frequency.

v) Mean Fire Intensity (**MWRA_FLI_30m.gdb**)

(1) *mwra_fli_30m* – represents the weighted fireline intensity (in kilowatts per meter) for a given pixel in the fuelscape. Weighting incorporates both temporal relative frequency and area-weighted relative frequency.

vi) Hazard in Context (**MWRA_Risk_to_PotentialStructures_20200310.gdb**)

(1) *CRPS* (Conditional Risk to Potential Structures) – The conditional effect of a wildfire on a potential structure. CRPS uses flame-length probabilities only, without burn probability. Response functions characterizing this effect were applied to all burnable fuel types on the landscape.

(2) *RPS (Risk to Potential Structures)* – The relative effect of a wildfire on a potential structure. RPS considers both burn probability and flame-length probabilities. Response functions characterizing this effect were applied to all burnable fuel types on the landscape.

vii) Suppression Difficulty Index (SDI) (**MWRA_SDI_30m.gdb**) – SDI is a quantitative rating of relative difficulty in performing fire control work.

viii) Wildfire Transmission Analysis

(1) Risk Source (**RiskSource_Rasters.gdb**)

(a) *IMPACT_conRiskSource (Structures Only Conditional Risk Source)* – Representation of the spatial transmission risk of fire ignition location to MT structures.

(b) *IMPACT_expRiskSource (Structures Only Expected Risk Source)* – Representation of the annual spatial transmission risk of fire ignition location to MT structures.

(c) *INFRA_conRiskSource (Critical Infrastructure Conditional Risk Source)* – Representation of the spatial transmission risk of fire ignition location to infrastructure.

(d) *INFRA_expRiskSource (Critical Infrastructure Expected Risk Source)* – Representation of the annual spatial transmission risk of fire ignition location to infrastructure.

(e) *PP_conRiskSource (People and Property Conditional Risk Source)* – Representation of the spatial transmission risk of fire ignition location to people and property.

(f) *PP_expRiskSource (People and Property Expected Risk Source)* – Representation of the annual spatial transmission risk of fire ignition location to people and property.
(g) *TOTAL_conRiskSource (All HVRA Conditional Risk Source)* – Representation of the spatial transmission risk of fire ignition location to identified valuable resources and assets.
(h) *TOTAL_expRiskSource (All HVRA Expected Risk Source)* – Representation of the spatial transmission risk of fire ignition location to identified valuable resources and assets.
(i) *WATER_conRiskSource (Surface Drinking Water Conditional Risk Source)* - Representation of the spatial transmission risk of fire ignition location to drinking water through potential erosion, distance to drinking water intake, and population served.

ix) Tabular Summaries - NVC tabular summaries for various geographic subdivisions
(1) *MT County NVC results.xlsx* - Tabular NVC summaries at Montana county level.
(2) *MT Census County Division NVC results.xlsx* - Tabular NVC summaries at Montana county division level.
(3) *MT Community (core plus zone) NVC results.xlsx* - Tabular NVC summaries at Montana community level. The community core and zone are dissolved together into one polygon.
(4) *MT Community (core and zone) NVC results.xlsx* - Tabular NVC summaries at Montana community level. Contains two separate entries: one for community core and one for community zone.
(5) *MT 6th-Level Watershed NVC results.xlsx* - Tabular NVC summaries at Montana 6th-Level watershed.

b) Ranking Communities at Risk
i) Ager communities: *3 - MT Communities (core plus zone).xlsx* - Tabular summaries of wildfire risk to Montana communities. The community core and zone are dissolved together into one polygon.
ii) Counties: *1 - MT Counties.xlsx* - Tabular summaries of wildfire risk at Montana county level.
iii) County Subdivision: *2 - MT Census County Divisions.xlsx* - Tabular summaries of wildfire risk at Montana county division level.
iv) Census Populated Places: *4 - MT Communities (core and zone).xlsx* - Tabular summaries of wildfire risk at Montana community level. Contains two separate entries: one for community core and one for community zone

c) Ranking Drinking Water Sources at Risk
i) *1- MT drinking water risk.xlsx* – Tabular summary of wildfire risk to surface drinking water sources across Montana.

5) Final Report – this report titled *Montana Wildfire Risk Assessment: Methods and Results.*

7 References

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Appendix A Wildfire Risk to Structures

As part of Montana DNRC's Montana Wildfire Risk Assessment (MWRA), wildfire risk to homes, commercial buildings, and other structures was assessed across the state. The purpose of this assessment is to identify the counties and communities whose structures are most threatened by wildfire—both on average and in total.

The risk-to-structures methods used for this assessment are identical to the methods used for structures within the overall MWRA project. See earlier section 3.4.1 of the report (page 20) for details. This portion of the report addresses only the tabular summaries. The summary methods used in this section were customized to the MWRA results from similar methods previously developed for the Pacific Northwest Risk Assessment (PNRA) and for the national Wildfire Risk to Communities (WRC) project[10].

The risk-to-structures results were summarized for four sets of summary polygons:

1. MT Counties
2. MT Census County Divisions
3. MT Communities (core plus zone combined)
4. MT Communities (core and zone separate)

Each set of summary polygons captures nearly all structures in Montana, without overlap. In the MT Counties set, a summary polygon is an individual county (e.g. Ravalli County). In the MT Census County Divisions[11] (CCD) set, a summary polygon is an individual CCD (e.g., the Sula CCD within Ravalli County). In the MT Communities (core plus zone combined) set, a summary polygon is the community core plus the zone surrounding the core (as defined below). In the MT Communities (core and zone separate) set, a summary polygon is either the community core or the zone surrounding the community core.

There are 56 counties in Montana. Each Montana county is divided into at least two Census County Divisions (CCDs), with mean of 3.5 CCDs per county (194 CCDs in total) and a maximum of 11 (Flathead county).

For this assessment, a community core was defined as a Populated Place Area (PPA) as identified by the U.S. Census Bureau. PPAs include incorporated cities and towns as well as Census Designated Places (CDPs). A CDP is an unincorporated concentration of population—a statistical counterpart to incorporated cities and towns. There are 364 PPAs across Montana. Of those, 127 (35 percent) are incorporated cities or towns, and 235 (65 percent) are CDPs. Two PPAs—Butte-Silver Bow and Anaconda-Deer Lodge—are unique in that they represent the balance of a county that is not otherwise incorporated; they are much larger in size than most PPAs. In the PPA dataset, the CDPs represent the location of highest concentration of population for a community; they do not include the less-densely populated areas surrounding the PPA.

We refer to the U.S. Census PPA delineation as the community "core." Approximately 66 percent of Montana's total structure importance can be found within these PPA core areas (Figure A.1). To include the populated area and structures surrounding the PPAs, Ager and others (2019) used a travel-time

[10] Visit www.wildfirerisk.org for more information.
[11] For certain statistical purposes, the U.S. Census Bureau has divided all counties nationwide into Census County Divisions (CCDs).

analysis to delineate the land areas closest by drive-time to each PPA core, up to a maximum of 45 minutes travel time. Approximately 33 percent of Montana's total structure importance can be found within 45 minutes travel time of the cores. Only 1 percent of the total structure importance is not within 45-minutes travel time of any community core.

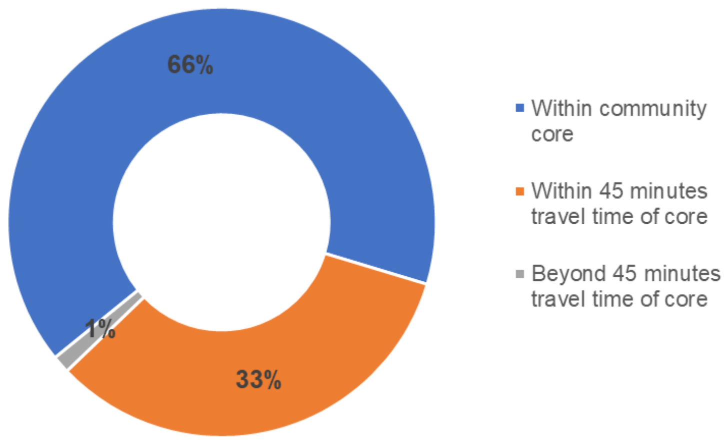


Figure A.1. Structure importance across Montana community zones. Two-thirds of the statewide structure importance is found within the community cores (U.S. Census Populated Place Areas). Another one-third is found in the 45-minute travel-time zones around the cores. Only 1 percent of the overall structure importance is not located within one of the community zones. Thus, the community travel-time zones can be considered to cover practically all Montana structures.

We generated two tabulations for communities. For the first we combined each community core (the PPA) and its associated surrounding area (the zone) into a single summary polygon. For the second tabulation we summarized the community core and the community zone separately. Because both records exist in the tabulation there are 728 records in the "core and zone separate" tabulation.

A.1 Risk-to-structures attributes

The following Risk-to-Structures attributes have been calculated for each summary polygon in the four tabulations (county, CCD, community core plus zone, and community core and zone separate). Each tabulation exists as a separate and complete table.

A1.1 *Total Structure Importance*

We summed the structure importance values for all pixels within a summary polygon. The sum of structure importance in a polygon is proportional to the number of structures in the polygon and the mean importance of those structures. Structure importance is related to the type of structure, not its size or value.

A1.2 *Mean Burn Probability*

We calculated the mean burn probability where the structures are located within each summary polygon. This measure represents the average likelihood that structures in the polygon will experience a wildfire in one year. The higher this value, the more likely it is that an individual structure will experience a wildfire. Mean burn probability is not a cumulative measure for a summary polygon, so it does not necessarily increase as the number or importance of structures increases. Instead, this measure is sensitive to the general location of structures in a polygon within the burn probability map (Figure 15).

A1.3 *Mean Burn Probability percentile*

This is the percentile rank of the polygon's Mean Burn Probability within its set (county, CCD, or community).

A1.4 *Mean Conditional Risk to Structures*

We calculated the mean Conditional Risk to Structures—given that a wildfire occurs—in each summary polygon. Mean Conditional Risk to Structures is a function of the conditional intensity of wildfire and vegetation type where the structures in a summary zone exist. Higher intensity means greater conditional risk, as does the presence of forest and tall-shrub vegetation (compared to grass and low-shrub vegetation). Mean Conditional Risk to Structures is not a cumulative measure for a summary polygon, so it does not necessarily increase as the number or importance of structures increases.

A1.5 *Mean Conditional Risk to Structures percentile*

This is the percentile rank of the polygon's Mean Conditional Risk to Structures within its set (county, CCD, or community).

A1.6 *Mean Risk to Structures*

We calculated the Mean Risk to Structures as the product of Mean Conditional Risk to Structures and Mean Burn Probability (multiplied by 1000 to remove decimal places).

This is the primary variable by which the summary polygons are ranked. Like the components used to calculate it, Mean Risk to Structures is not a cumulative measure for a summary polygon, so it does not necessarily increase as the number or importance of structures increases. It represents the average of the structures in the polygon regardless of the total number or importance of structures.

A1.7 *Mean Risk to Structures percentile*

This is the percentile rank of the polygon's Mean Risk to Structures within its set (county, CCD, or community).

A1.8 *Total Structure Risk*

We calculated Total Structure Risk as the product of Mean Risk to Structures and Total Structure Importance.

This is the secondary variable by which the summary polygons are ranked. Unlike the previous measures, the total importance of structures (their number and mean importance) strongly influences Total Structure Risk.

A1.9 *Total Structure Risk percentile*

This is the percentile rank of the polygon's Total Risk to Structures within its set (county, CCD, or community).

A1.10 *Rank by Mean Risk to Structures*

This is the rank of *Mean* Risk to Structures (1 to N) within its set (county, CCD, or community).

A1.11 *Rank by Total Risk to Structures*

This is the rank of *Total* Risk to Structures (1 to N) within its set (county, CCD, or community).

A.2 Results

Full results are provided in the Excel workbooks provided as Deliverable 4.2. Limited results for counties and for community core-plus-zones combined are tabulated and plotted in the following sections.

A2.1 *Mean Risk to Structures*

The Mean Risk to Structures for counties and communities is displayed as a scatterplot of Mean Burn Probability versus Mean Conditional Risk to Structures (Figure A.2). On each panel, the top 20 most at-risk counties and communities—as measured by mean Risk to Structures—are highlighted and numbered by their rank. A tabulation of the counties is provided in Table A.1 below. The top 50 most at-risk communities are tabulated in Table A.2 below.

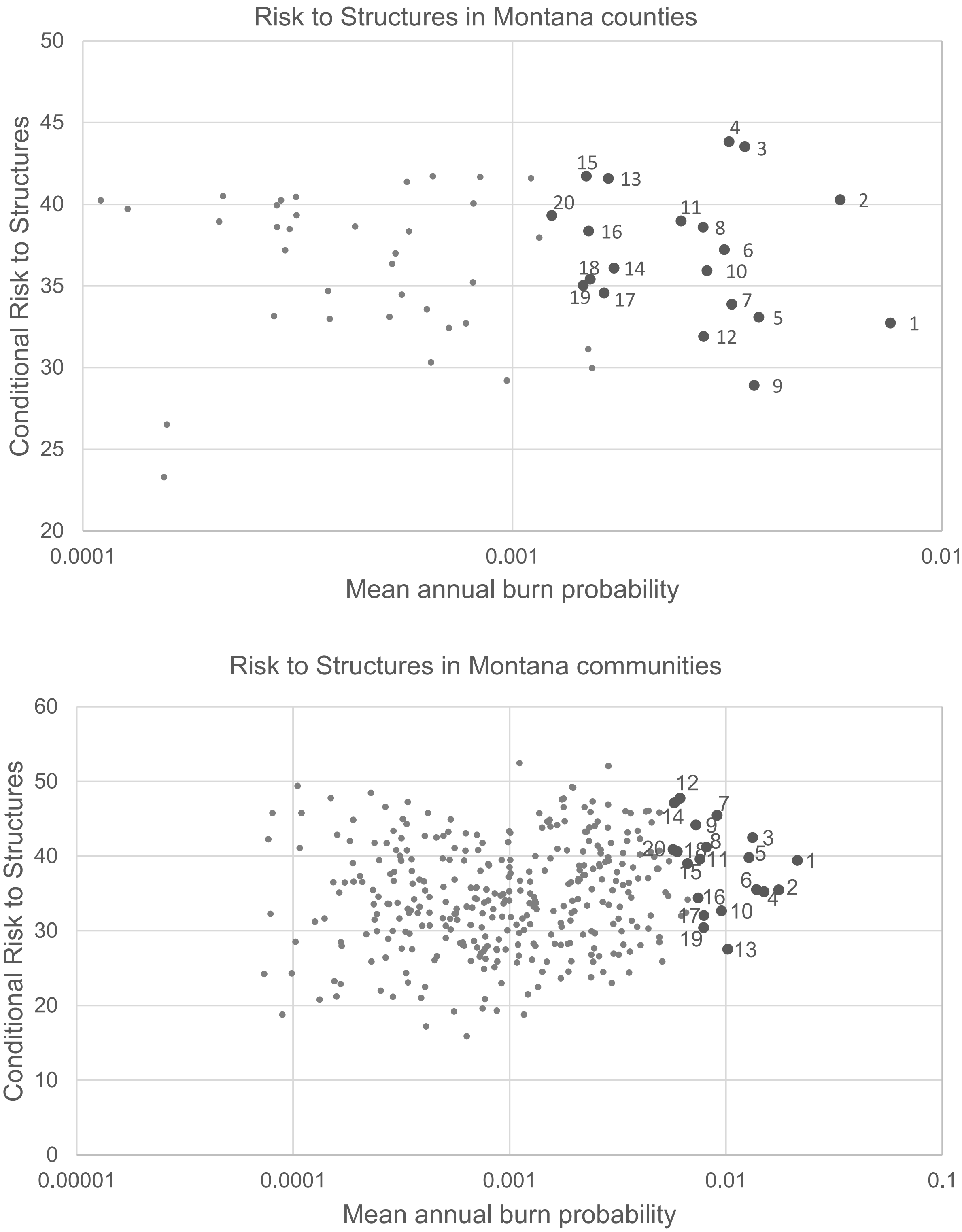


Figure A.2. Mean Risk to Structures across Montana counties (top) and communities (bottom). Note the X- and Y-axes are not identical on the two panels. The top 20 most at-risk counties and communities are numbered by rank (See Table A.1 and Table A.2)

Table A.1. Mean Risk to Structures in Montana counties.

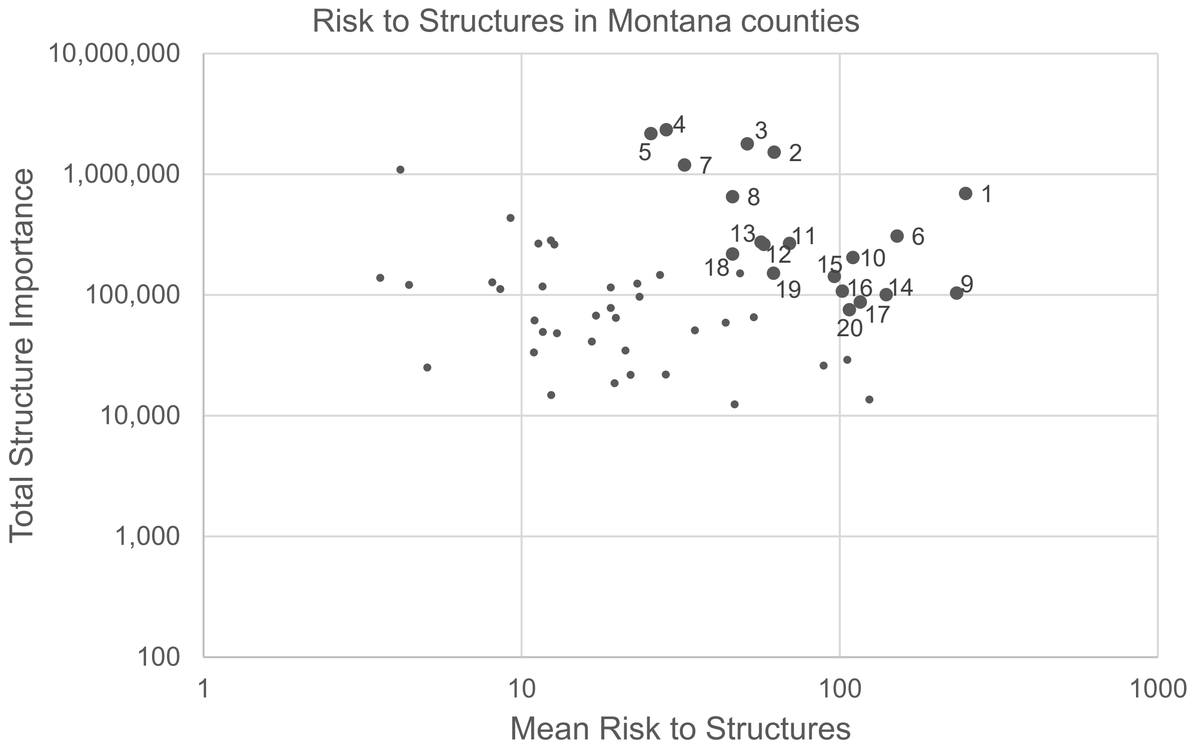
Rank by Mean Risk to Structures	County	Total Structure Importance	Mean Burn Probability	Mean Conditional Risk to Structures	Mean Risk to Structures
1	Ravalli	694,214	0.007590	32.7	248
2	Granite	103,734	0.005792	40.3	233
3	Lincoln	307,620	0.003477	43.5	151
4	Mineral	100,676	0.003193	43.8	140
5	Petroleum	13,572	0.003750	33.1	124
6	Rosebud	87,590	0.003117	37.2	116
7	Carbon	204,919	0.003246	33.9	110
8	Musselshell	75,569	0.002780	38.6	107
9	Powder River	29,032	0.003654	28.9	106
10	Big Horn	107,369	0.002839	35.9	102
11	Powell	142,437	0.002470	39.0	96
12	Garfield	25,887	0.002789	31.9	89
13	Sanders	267,491	0.001672	41.6	70
14	Missoula	1,521,762	0.001724	36.1	62
15	Jefferson	151,876	0.001486	41.7	62
16	Park	262,594	0.001506	38.4	58
17	Madison	273,415	0.001637	34.6	57
18	Stillwater	65,389	0.001517	35.4	54
19	Flathead	1,783,952	0.001463	35.0	51
20	Glacier	150,783	0.001237	39.3	49
21	Treasure	12,420	0.001503	31.1	47
22	Deer Lodge	218,772	0.001106	41.6	46
23	Lake	652,130	0.001534	30.0	46
24	Sweet Grass	58,723	0.001157	37.9	44
25	Meagher	50,905	0.000843	41.7	35
26	Lewis & Clark	1,192,735	0.000812	40.0	33
27	Gallatin	2,333,944	0.000810	35.2	29
28	Carter	21,921	0.000972	29.2	28
29	Custer	146,220	0.000653	41.7	27
30	Yellowstone	2,169,823	0.000780	32.7	26
31	Roosevelt	96,425	0.000569	41.3	24
32	Beaverhead	123,709	0.000713	32.4	23
33	Prairie	21,678	0.000575	38.3	22
34	McCone	34,649	0.000633	33.6	21
35	Phillips	64,497	0.000535	37.0	20
36	Golden Valley	18,526	0.000647	30.3	20
37	Broadwater	77,744	0.000525	36.3	19
38	Teton	114,840	0.000553	34.5	19
39	Blaine	67,058	0.000518	33.1	17
40	Fallon	41,096	0.000431	38.6	17
41	Judith Basin	47,928	0.000373	34.7	13
42	Valley	260,140	0.000314	40.4	13
43	Wibaux	14,782	0.000376	33.0	12
44	Fergus	283,033	0.000315	39.3	12
45	Wheatland	49,318	0.000303	38.5	12
46	Chouteau	117,028	0.000290	40.2	12
47	Hill	265,243	0.000283	39.9	11
48	Sheridan	61,541	0.000296	37.2	11
49	Daniels	33,408	0.000283	38.6	11
50	Silver Bow	432,874	0.000279	33.1	9
51	Dawson	111,643	0.000212	40.5	9
52	Pondera	126,580	0.000208	38.9	8
53	Liberty	25,038	0.000127	39.7	5
54	Toole	120,627	0.000110	40.2	4
55	Cascade	1,090,408	0.000157	26.5	4
56	Richland	137,923	0.000155	23.3	4

Table A.2. Mean Risk to Structures in the 50 most at-risk Montana communities (by average risk).

Rank by Mean Risk to Structures	Community Name	Total Structure Importance	Mean Burn Probability	Mean Conditional Risk to Structures	Mean Risk to Structures
1	Conner	22,592	0.021428	39.4	845.0
2	Darby	35,052	0.017561	35.5	623.5
3	Sula	13,230	0.013271	42.5	564.2
4	Charlos Heights	21,148	0.015006	35.2	528.9
5	Condon	28,293	0.012786	39.8	509.3
6	Pinesdale	29,920	0.013852	35.5	492.2
7	Fortine	15,445	0.009106	45.5	414.0
8	Seeley Lake	56,972	0.008127	41.2	335.0
9	Eureka	32,863	0.007255	44.2	320.5
10	Victor	56,656	0.009551	32.7	312.3
11	Clinton	31,947	0.007584	39.6	300.5
12	Trego	12,489	0.006146	47.8	293.5
13	Birney	1,878	0.010194	27.5	280.8
14	Stryker	976	0.005783	47.1	272.6
15	Avon	7,058	0.006659	39.0	259.9
16	Busby	5,184	0.007455	34.4	256.5
17	Ovando	20,665	0.007903	32.1	253.3
18	Lincoln	46,673	0.005961	40.6	242.1
19	Ashland	10,992	0.007883	30.4	239.9
20	Philipsburg	35,990	0.005702	40.9	233.2
21	Lame Deer	9,157	0.006665	34.2	227.7
22	Olney	14,180	0.004934	45.8	226.1
23	Swan Lake	12,230	0.005466	39.3	214.8
24	Midvale	12,018	0.006553	32.5	212.7
25	Marysville	7,552	0.004552	44.5	202.6
26	Riverbend	20,873	0.004395	46.1	202.5
27	Maxville	11,256	0.004935	40.7	201.0
28	Muddy	2,924	0.006226	32.0	199.2
29	Alberton	24,602	0.004281	46.0	196.7
30	Turah	9,560	0.005419	34.7	187.8
31	Indian Springs	14,373	0.004883	38.3	187.0
32	Red Lodge	85,277	0.004671	39.9	186.4
33	Hamilton	216,916	0.005268	35.1	185.1
34	Evaro	10,082	0.004814	38.3	184.4
35	East Glacier Park	15,814	0.004502	40.6	182.7
36	Cooke City	5,404	0.004014	42.3	169.9
37	Piltzville	5,029	0.003916	43.3	169.8
38	Pioneer Junction	23,781	0.003633	45.7	166.1
39	Crow Agency	14,452	0.004380	37.0	162.3
40	Bonner	42,461	0.004017	40.2	161.5
41	Bridger	11,462	0.003445	46.0	158.5
42	Elliston	8,997	0.003521	43.2	151.9
43	Basin	4,105	0.002873	52.1	149.6
44	Rexford	11,555	0.003502	42.1	147.3
45	Drummond	20,303	0.003942	37.0	145.9
46	Florence	72,217	0.004499	32.0	144.2
47	Stevensville	137,415	0.004945	29.1	144.1
48	Huson	22,162	0.003731	38.5	143.5
49	Wyola	3,410	0.004940	28.5	140.8
50	Jardine	1,229	0.003357	40.4	135.7

A2.2 *Total Risk to Structures*

The charts in the previous section displayed the mean Risk to Structures for counties and communities across Montana. Those summaries are useful for identifying the most at-risk counties and communities, regardless of the number of structures. This section includes the number and type of structures in a community to tabulate the Total Structure Risk in counties and communities. A chart comparing Total Structure Risk in counties and communities is shown in Figure A.3.



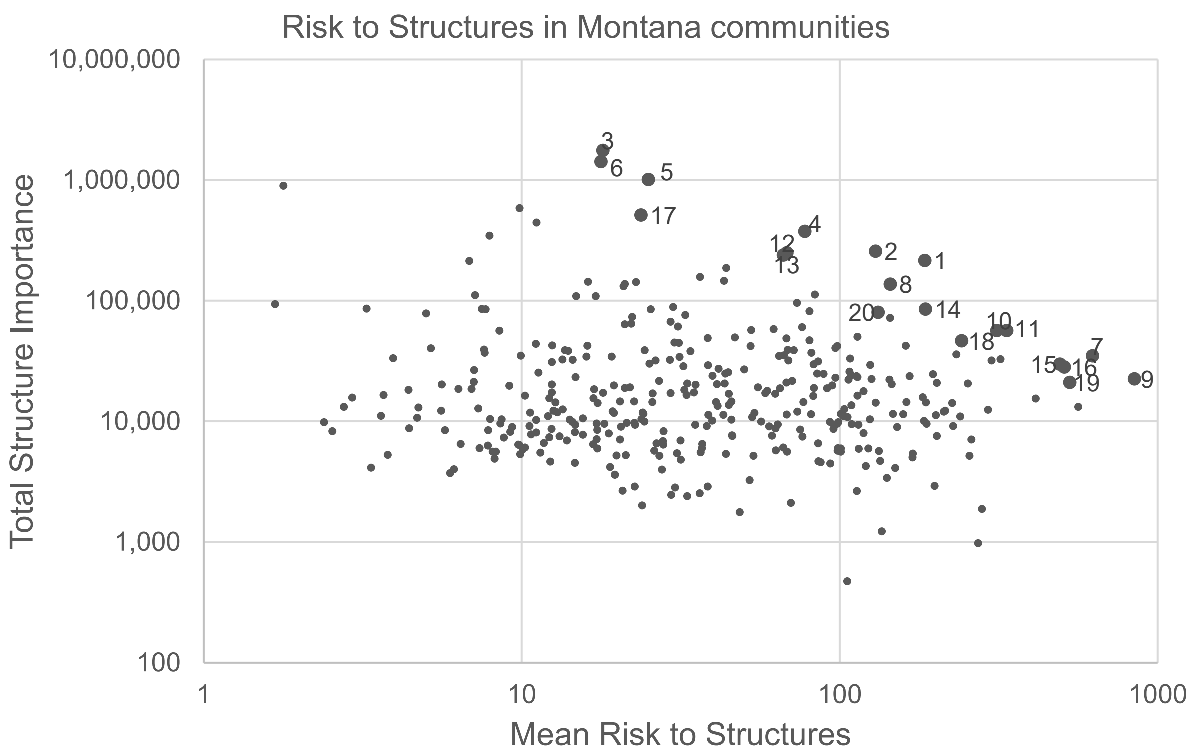


Figure A.3. Total Structure Risk in Montana counties (top) and communities (bottom). The top 20 most at-risk counties and communities are numbered by rank (See Table A.3 and Table A.4)

Table A.3. Summary of Total Structure Risk in Montana counties.

Rank by Total Structure Risk	County	Total Structure Importance	Mean Risk to Structures	Total Structure Risk
1	Ravalli	694,214	248	172,509
2	Missoula	1,521,762	62	94,685
3	Flathead	1,783,952	51	91,398
4	Gallatin	2,333,944	29	66,563
5	Yellowstone	2,169,823	26	55,354
6	Lincoln	307,620	151	46,562
7	Lewis and Clark	1,192,735	33	38,788
8	Lake	652,130	46	29,983
9	Granite	103,734	233	24,199
10	Carbon	204,919	110	22,530
11	Sanders	267,491	70	18,593
12	Madison	273,415	57	15,470
13	Park	262,594	58	15,168
14	Mineral	100,676	140	14,091
15	Powell	142,437	96	13,712
16	Big Horn	107,369	102	10,953
17	Rosebud	87,590	116	10,163
18	Deer Lodge	218,772	46	10,061
19	Jefferson	151,876	62	9,415
20	Musselshell	75,569	107	8,107
21	Glacier	150,783	49	7,330
22	Cascade	1,090,408	4	4,537
23	Silver Bow	432,874	9	4,003
24	Custer	146,220	27	3,985
25	Stillwater	65,389	54	3,512
26	Fergus	283,033	12	3,500
27	Valley	260,140	13	3,300
28	Powder River	29,032	106	3,068
29	Hill	265,243	11	2,998
30	Beaverhead	123,709	23	2,858
31	Sweet Grass	58,723	44	2,577
32	Garfield	25,887	89	2,304
33	Roosevelt	96,425	24	2,268
34	Teton	114,840	19	2,189
35	Meagher	50,905	35	1,788
36	Petroleum	13,572	124	1,683
37	Broadwater	77,744	19	1,484
38	Chouteau	117,028	12	1,364
39	Phillips	64,497	20	1,276
40	Blaine	67,058	17	1,150
41	Pondera	126,580	8	1,024
42	Dawson	111,643	9	959
43	McCone	34,649	21	736
44	Fallon	41,096	17	684
45	Sheridan	61,541	11	677
46	Carter	21,921	28	623
47	Judith Basin	47,928	13	620
48	Treasure	12,420	47	581
49	Wheatland	49,318	12	575
50	Toole	120,627	4	535
51	Richland	137,923	4	497
52	Prairie	21,678	22	478
53	Daniels	33,408	11	366
54	Golden Valley	18,526	20	363
55	Wibaux	14,782	12	183
56	Liberty	25,038	5	127

Table A.4. Total Structure Risk in Montana communities (top 50 by Total Structure Risk).

Rank by Total Structure Risk	Community Name	Total Structure Importance	Mean Risk to Structures	Total Structure Risk
1	Hamilton	216,916	185.1	40,151
2	Big Sky	257,612	129.6	33,394
3	Billings	1,769,297	18.0	31,857
4	Whitefish	377,886	77.8	29,393
5	Missoula	1,016,458	25.0	25,442
6	Bozeman	1,424,992	17.8	25,333
7	Darby	35,052	623.5	21,853
8	Stevensville	137,415	144.1	19,804
9	Conner	22,592	845.0	19,090
10	Seeley Lake	56,972	335.0	19,086
11	Victor	56,656	312.3	17,692
12	Anaconda-Deer Lodge County	251,087	68.2	17,134
13	Bigfork	239,751	66.5	15,939
14	Red Lodge	85,277	186.4	15,893
15	Pinesdale	29,920	492.2	14,726
16	Condon	28,293	509.3	14,409
17	Kalispell	514,056	23.7	12,205
18	Lincoln	46,673	242.1	11,301
19	Charlos Heights	21,148	528.9	11,185
20	Corvallis	80,694	132.0	10,652
21	Eureka	32,863	320.5	10,534
22	Florence	72,217	144.2	10,410
23	Clinton	31,947	300.5	9,601
24	Lockwood	112,772	83.7	9,438
25	Philipsburg	35,990	233.2	8,391
26	Columbia Falls	187,494	44.1	8,260
27	Sula	13,230	564.2	7,465
28	Libby	96,250	73.4	7,070
29	Bonner-West Riverside	42,461	161.5	6,856
30	Lolo	82,048	80.5	6,604
31	Fortine	15,445	414.0	6,395
32	Livingston	146,039	43.3	6,324
33	Helena	585,731	9.9	5,778
34	Laurel	157,337	36.4	5,727
35	West Yellowstone	50,198	114.0	5,723
36	Ovando	20,665	253.3	5,234
37	Butte-Silver Bow (balance)	443,821	11.1	4,947
38	Alberton	24,602	196.7	4,840
39	Lakeside	60,409	76.2	4,604
40	Riverbend	20,873	202.5	4,227
41	Shepherd	42,081	98.3	4,138
42	Craig	40,716	97.1	3,955
43	Pioneer Junction	23,781	166.1	3,949
44	Helena West Side	46,884	80.4	3,771
45	Superior	29,362	125.0	3,671
46	Trego	12,489	293.5	3,666
47	Thompson Falls	58,101	62.0	3,604
48	East Missoula	33,239	107.9	3,587
49	Troy	48,644	68.1	3,313
50	Helena Valley Southeast	143,296	22.9	3,285

A.3 Discussion

The mean risk to structures for a county or community is influenced by the burn probability and conditional risk to structures where the structures exist in a community. Conditional risk to structures is a function of flame length and the presence of timber or shrub vegetation. Of those factors, variability in burn probability accounts for much of the relative ranking among counties and communities. The highest-ranked community by mean risk to structures are located in the southern Bitterroot Valley, where burn probability, fire intensity and timber fuel represents a great threat to the structures that exist there.

The total risk to structures within a county or community is influenced by the mean risk to structures and the total amount of structure importance. The community of Hamilton has the greatest total structure risk but is ranked only 33rd in average risk. Likewise, the community of Big Sky has a relatively modest average risk (not even among the top 50 communities in the state) but is ranked second in total structure risk due to the relatively high amount of structure importance there. The community of Connor, in the southern Bitterroot Valley, has the highest average risk to structures of any Montana community. Its high average risk combined with its modest total structure importance puts it 9th in total structure risk.

In general, risk mitigation resources can be *prioritized* by mean risk and *allocated* by total (cumulative) risk. For example, the structures in the highest-ranked counties and communities as measured by mean Risk to Structures (Table A.1 for counties and Table A.2 for communities) are the highest priorities for risk mitigation because the structures there are, on average, more at risk than structures in other counties or communities. However, because counties and communities vary in size (number of structures), mean Risk to Structures does not provide full guidance on how much effort may be needed for mitigation. The level of mitigation effort—that is, allocation of mitigation resources—can be allocated by total Risk to Structures.

Appendix B Wildfire Risk to Surface Drinking Water

Surface drinking water is often a critical component of community health and wildfire impact to drinking water systems is frequently identified as a subject of concern in fire-prone environments. We assessed wildfire risk to surface drinking water intakes and watersheds across Montana. The purpose of this assessment is to identify the water supply systems whose surface drinking water is most threatened by wildfire—both on average and in total.

The data used in this section are identical to those for watersheds introduced in 3.4.3. Please reference this section for information about how watershed importance was determined spatially, and for methods on spatial response functions to map wildfire impacts on erosion. The importance values used in this Appendix are used as-is and are not adjusted for their importance relative to other HVRA as in Section 3 of this report.

The data for this assessment were shared by the US Forest Service Northern Region and were originally acquired by the Regional Hydrologist for a regionwide wildfire risk assessment completed by Pyrologix in 2017. The data consist of one or more surface drinking water intake points, attributed with the population served, along with the delineation(s) of basin(s) capturing the area that drains to the intake for each Public Water Supply System (hereafter referred to as 'watershed'). The importance for each water system is proportional to the population served by the intake. If multiple intakes serve a single community/system, the population is split equally among the intakes in the system.

The data identify 54 surface drinking water systems. The watersheds that drain to those systems cover approximately 83 percent of Montana's total area and serve approximately 32 percent of the state's population based on population-served information provided in the data and 2019 Montana population estimates[12].

B.1 Risk-to-drinking-water attributes

The following attributes have been calculated for each watershed and summarized to a Public Water Supply ID and generalized name for the system.

B1.1 *Total Drinking Water Importance*

We summed the drinking water importance values for all pixels within a system. For systems with multiple watersheds and intakes, the total importance is cumulative over all watersheds.

B1.2 *Mean Burn Probability*

We calculated the mean burn probability for each watershed as the raster product of burn probability and watershed importance, divided by the sum of watershed importance. This gives more weight to the burn probability values associated with greater watershed importance and represents, on average, the likelihood of being visited by wildfire within the watershed in one year. The higher this value, the more likely it is that the watershed will experience a wildfire. Mean burn probability is not a cumulative measure for a watershed, so it does not necessarily increase with the population served or size of the watershed. Instead, this measure is sensitive to the general location the greatest importance values in a watershed within the burn probability map (Figure 15).

[12] Census population estimates for July 2019 (https://www2.census.gov/programs-surveys/popest/tables/2010-2019/state/totals/nst-est2019-01.xlsx)

B1.3 *Mean Burn Probability percentile*

This is the percentile rank of the system's Mean Burn Probability across all watersheds and intakes.

B1.4 *Mean Conditional Watershed Risk*

We calculated the Mean Conditional Risk to drinking water—given that a wildfire occurs—in each system. Mean Conditional Risk is the raster product of unweighted Conditional Net Value change (cNVC) and watershed importance, divided by the sum of watershed importance and is a function of the conditional intensity of wildfire and erosion potential where the watershed importance is located within a watershed. Higher intensity means greater conditional risk, as does the presence of steeper slopes with less stable soils. Mean Conditional Risk is not a cumulative measure for a watershed, so it does not necessarily increase with the population served or size of the watershed.

B1.5 *Mean Conditional Watershed Risk percentile*

This is the percentile rank of the system's Mean Conditional Risk across all watersheds and intakes.

B1.6 *Mean Watershed Risk*

We calculated the Mean Risk to Watersheds as the raster product of unweighted Expected Net Value change (eNVC) and watershed importance, divided by the sum of watershed importance. This method gives more weight to eNVC values where watershed importance is greatest.

This is the primary variable by which the drinking water systems are ranked. Mean Watershed Risk is not a cumulative measure for a system, so it does not necessarily increase with the population served or size of the watershed. Instead it represents the average of all pixels within a drinking water system.

B1.7 *Mean Watershed Risk percentile*

This is the percentile rank of the system's Mean Watershed Risk across all watersheds and intakes.

B1.8 *Total Watershed Risk*

We calculated Total Watershed Risk as the raster product of eNVC and Watershed Importance – summed for the entire watershed.

This is the secondary variable by which drinking water systems are ranked. Unlike the previous measures, the total population served by the system and – to a lesser degree – watershed size, influence Total Watershed Risk.

B1.9 *Total Watershed Risk percentile*

This is the percentile rank of the system's Total Watershed Risk across all watersheds and intakes.

B1.10 *Rank by Mean Watershed Risk*

This is the rank of *Mean* Watershed Risk (1 to N) compared with other surface drinking water systems in Montana.

B1.11 *Rank by Total Watershed Risk*

This is the rank of *Total* Watershed Risk (1 to N) compared with other surface drinking water systems in Montana.

B.2 Results

Full results are provided in the included Excel workbook. Limited results for each system are tabulated and plotted in the following sections.

B2.1 *Mean Watershed Risk*

The Mean Risk to drinking water systems is displayed as a scatterplot of Mean Burn Probability versus Mean Watershed Conditional Risk (Figure B.1). In the figure, the top 20 most at-risk systems—as measured by Mean Watershed Risk—are highlighted and numbered by their rank. A tabulation of Mean Watershed Risk for all systems is provided in Table B.1 below.

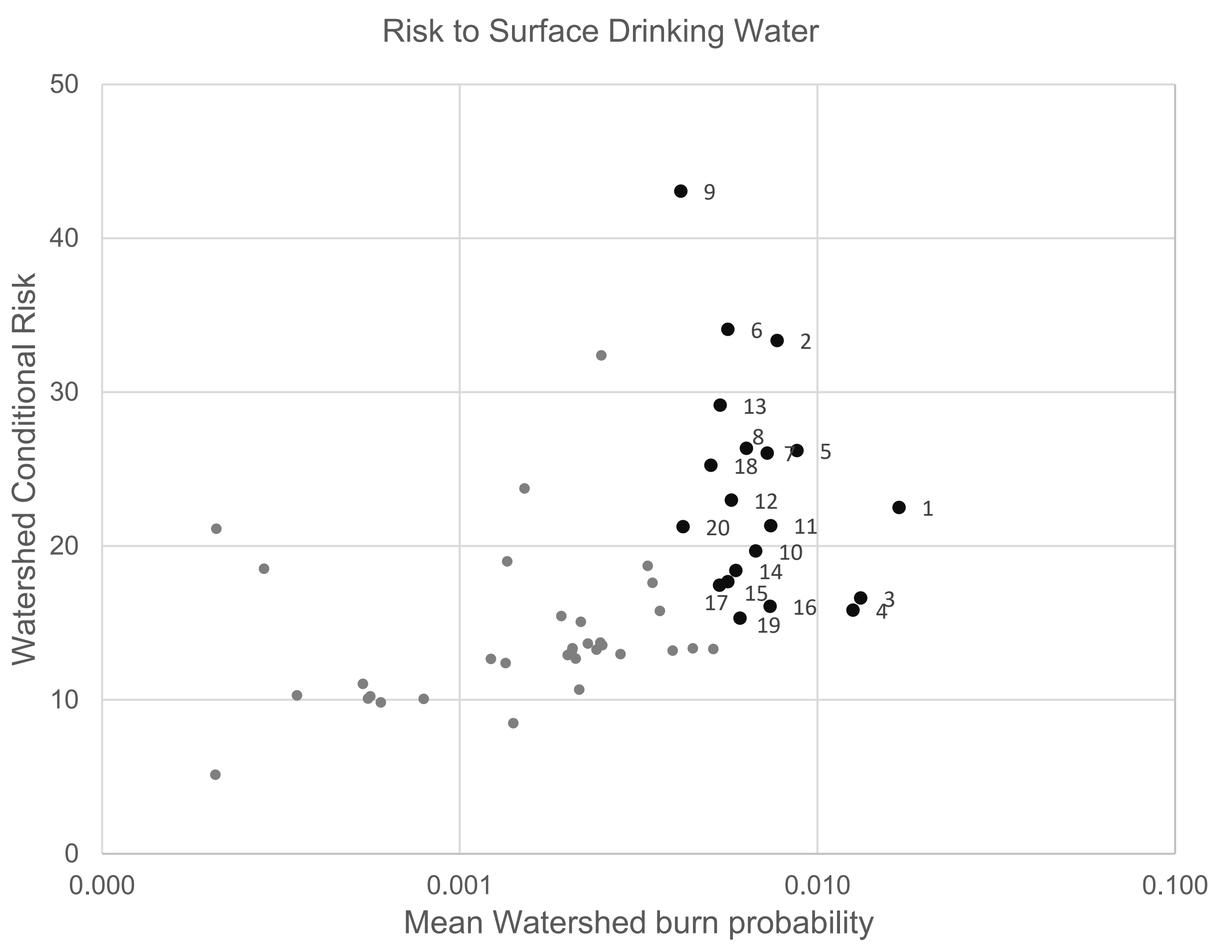


Figure B.1. Mean wildfire risk to surface drinking water in Montana. The top 20 most at-risk systems are numbered by rank (See Table B.1).

Table B.1. Mean Watershed Risk in Montana.

Rank by Mean Watershed Risk	System Name	Total Watershed Importance	Mean Burn Probability	Mean Conditional Watershed Risk	Mean Watershed Risk
1	Pinesdale	800	0.017	22.498	0.419
2	Glacier Haven	31	0.008	33.354	0.261
3	Seeley Lake	1,575	0.013	16.609	0.251
4	Lodges at Seeley Lake	107	0.013	15.821	0.244
5	Snowbowl Lodge	521	0.009	26.198	0.232
6	Essex	59	0.006	34.078	0.205
7	Bozeman	32,000	0.007	26.040	0.191
8	Ronan	2,350	0.006	26.337	0.182
9	Logan Pass	1,000	0.004	43.053	0.179
10	Many Springs	27	0.007	19.665	0.175
11	Polebridge Ranger Station	62	0.007	21.322	0.171
12	Whitefish	9,671	0.006	22.972	0.161
13	Christikon	100	0.005	29.142	0.153
14	Ridgewood Estates	250	0.006	18.399	0.152
15	Big Sky	97	0.006	17.672	0.142
16	Stevensville	1,970	0.007	16.083	0.138
17	Juniper Bay	26	0.005	17.458	0.133
18	Libby	4,477	0.005	25.242	0.132
19	Philipsburg	925	0.006	15.310	0.118
20	Glacier Park	765	0.004	21.245	0.112
21	Thompson Falls	1,950	0.002	32.374	0.080
22	Miles City	8,800	0.005	13.289	0.071
23	Helena	31,005	0.003	17.585	0.071
24	Hardin	3,500	0.004	13.337	0.068
25	Butte-Silver Bow	33,000	0.003	18.692	0.067
26	Yellowtail Dam	48	0.004	15.768	0.065
27	Forsyth	1,944	0.004	13.193	0.058
28	Lockwood	5,900	0.002	13.701	0.042
29	Billings	114,000	0.003	13.536	0.042
30	Laurel	6,339	0.002	15.065	0.042
31	Glendive	5,500	0.003	12.952	0.041
32	Great Falls	60,000	0.002	15.423	0.036
33	Neihart	229	0.002	23.719	0.036
34	Hell Creek State Park	50	0.002	13.643	0.035
35	Montana Dakota Utilities Co.	25	0.002	13.242	0.035
36	Glasgow	3,253	0.002	13.337	0.033
37	MT Aviation Research Co.	62	0.002	13.337	0.033
38	Rock Creek Marina/Campground	50	0.002	13.156	0.032
39	Fort Peck	240	0.002	12.888	0.031
40	Camp Tuffit	151	0.002	10.647	0.031
41	Melstone	170	0.002	12.677	0.029
42	White Sulphur	1,000	0.001	18.984	0.025
43	Seville Colony	110	0.001	12.378	0.021
44	Culbertson	1,700	0.001	12.647	0.019
45	Mcgregor Lake	163	0.001	8.460	0.018
46	Cut Bank	3,105	0.001	10.041	0.011
47	Chester	870	0.001	9.810	0.010
48	Devon	75	0.001	10.207	0.009
49	Tiber County	750	0.001	10.072	0.009
50	Golden Sunlight	160	0.000	18.514	0.009
51	Loma County	200	0.001	11.026	0.009
52	Sperry Chalet	50	0.000	21.108	0.007
53	Power Teton	167	0.000	10.270	0.004
54	Conrad Water	2,500	0.000	5.122	0.002

B2.2 *Total Risk to Watersheds*

The chart in the previous section displayed the mean Watershed Risk across Montana. Those summaries are useful for identifying the most at-risk drinking water systems, regardless of the population size it serves. This section includes the Watershed Importance (in terms of population served) to tabulate the Total Watershed Risk across Montana (Table B.2). The Total Risk to drinking water systems is displayed as a scatterplot of Mean Watershed Risk (eNVC) versus Total Watershed Importance (Figure B.2Figure B.1.). In the figure, the top 20 most at-risk systems—as measured by Total Watershed Risk—are highlighted and numbered by their rank.

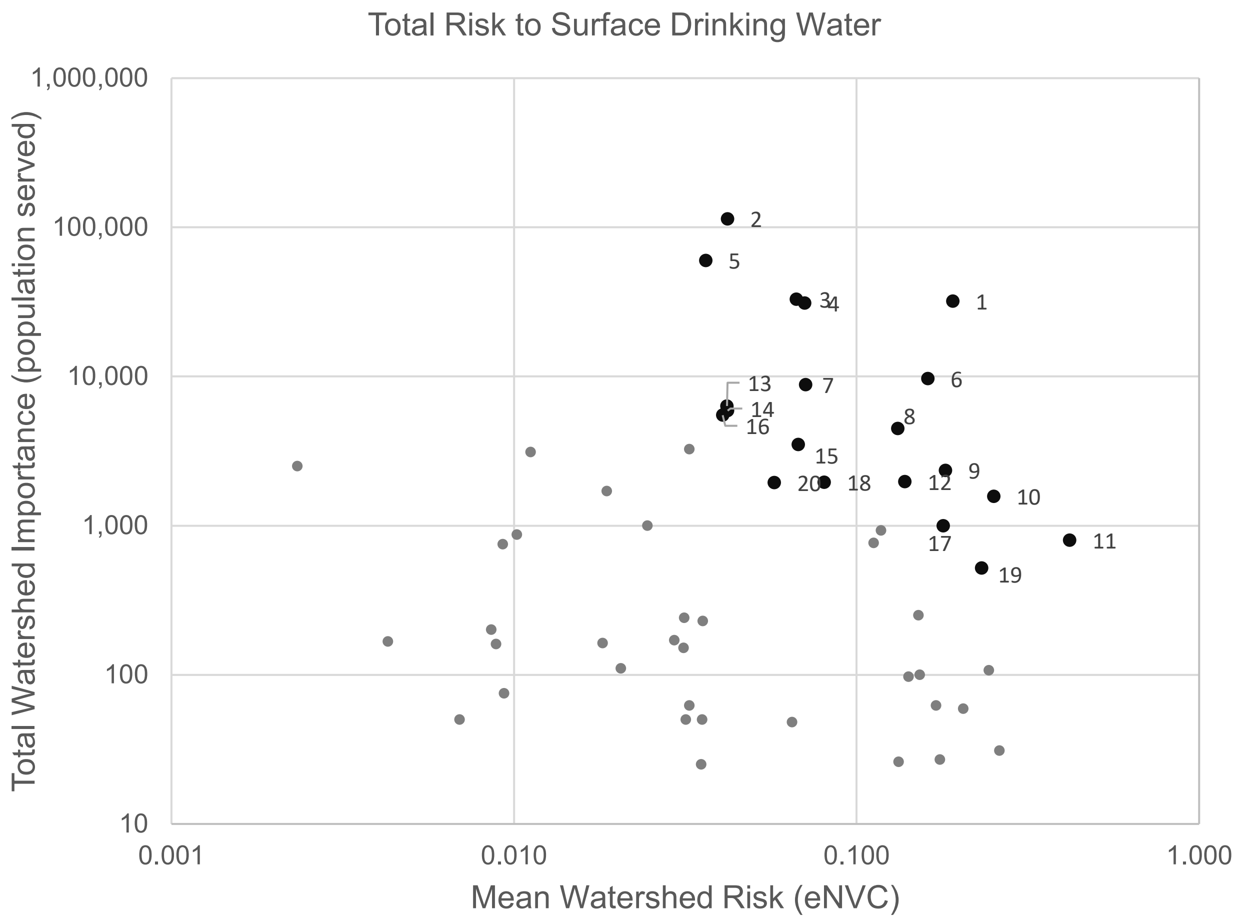


Figure B.2. Total risk to surface drinking water in Montana. The top 20 most at-risk systems are numbered by rank (See Table B.2).

Table B.2. Total Watershed Risk in Montana.

Rank by Total Watershed Risk	System Name	Total Watershed Importance	Mean Watershed Risk	Total Watershed Risk
1	Bozeman	32,000	0.191	6,110.248
2	Billings	114,000	0.042	4,784.526
3	Butte-Silver Bow	33,000	0.067	2,202.060
4	Helena	31,005	0.071	2,186.903
5	Great Falls	60,000	0.036	2,177.231
6	Whitefish	9,671	0.161	1,560.764
7	Miles City	8,800	0.071	624.558
8	Libby	4,477	0.132	590.293
9	Ronan	2,350	0.182	427.333
10	Seeley Lake	1,575	0.251	395.753
11	Pinesdale	800	0.419	335.189
12	Stevensville	1,970	0.138	272.629
13	Laurel	6,339	0.042	265.309
14	Lockwood	5,900	0.042	247.968
15	Hardin	3,500	0.068	236.376
16	Glendive	5,500	0.041	223.625
17	Logan Pass	1,000	0.179	178.846
18	Thompson Falls	1,950	0.080	156.812
19	Snowbowl Lodge	521	0.232	120.772
20	Forsyth	1,944	0.058	111.850
21	Philipsburg	925	0.118	109.125
22	Glasgow	3,253	0.033	105.887
23	Glacier Park	765	0.112	85.894
24	Ridgewood Estates	250	0.152	37.946
25	Cut Bank	3,105	0.011	34.733
26	Culbertson	1,700	0.019	31.766
27	Lodges at Seeley Lake	107	0.244	26.066
28	White Sulphur	1,000	0.025	24.549
29	Christikon	100	0.153	15.294
30	Big Sky	97	0.142	13.777
31	Essex	59	0.205	12.093
32	Polebridge Ranger Station	62	0.171	10.580
33	Chester	870	0.010	8.880
34	Neihart	229	0.036	8.146
35	Glacier Haven	31	0.261	8.102
36	Fort Peck	240	0.031	7.542
37	Tiber County	750	0.009	6.956
38	Conrad Water	2,500	0.002	5.832
39	Melstone	170	0.029	4.995
40	Many Springs	27	0.175	4.730
41	Camp Tuffit	151	0.031	4.723
42	Juniper Bay	26	0.133	3.453
43	Yellowtail Dam	48	0.065	3.112
44	Mcgregor Lake	163	0.018	2.960
45	Seville Colony	110	0.021	2.260
46	MT Aviation Research Co.	62	0.033	2.018
47	Hell Creek State Park	50	0.035	1.772
48	Loma County	200	0.009	1.716
49	Rock Creek Marina/Campground	50	0.032	1.587
50	Golden Sunlight	160	0.009	1.418
51	Montana Dakota Utilities Co.	25	0.035	0.880
52	Power Teton	167	0.004	0.716
53	Devon	75	0.009	0.702
54	Sperry Chalet	50	0.007	0.347

B.3 Discussion

The mean risk to drinking water results are strongly influenced by both burn probability and conditional watershed risk in the areas within a watershed where the drinking water importance is the greatest. Conditional risk to structures is a function of flame length and the potential for soil-loss due to erosion. The top-ranking systems in terms of mean wildfire risk also have the greatest mean burn probabilities, though the rank-order of systems between these two variables shifts due to variability in conditional watershed risk. The five highest-ranked systems by mean watershed risk are located in the western part of the state where burn probability, fire intensity, mountainous terrain, and the prevalence of timber fuel all converge to influence watershed risk.

The total watershed risk is greatly influenced by total watershed importance and secondarily by mean watershed risk. The top five highest-ranked systems by total watershed risk serve approximately 79 percent of the cumulative population served by surface drinking water across the entire state[13]. The system serving Bozeman is ranked highest in total watershed risk, but seventh in average risk. Billings, the system ranked second in total watershed risk, is ranked 29th in average risk. This is because it has high watershed importance (accounting for 33 percent of the population represented in this analysis), but relatively low mean watershed risk. Considering both measures in tandem, only three systems rank among the top ten by both total watershed risk and mean watershed risk: Bozeman, Ronan, and Seeley Lake.

These results can be used to inform risk mitigation efforts. In general, mitigation resources can be *prioritized* by mean risk and *allocated* by total (cumulative) risk. The highest-ranked systems as measured by mean watershed risk (Table B.1) may be among the highest priorities for mitigation efforts because the landscapes are, on average, more at-risk than other landscapes. Because these watersheds vary both in size and in the number of people they serve, mean risk does not provide the entirety of the information needed to allocate mitigation resources. The level of mitigation effort is instead informed by total watershed risk (Table B.2) which considers the total population served by each system.

Wildfire risk to drinking water summarized in this Appendix considers only landscape-level factors along with population served to calculate watershed risk and no additional vulnerabilities existing in these systems. The measures summarized here can be used to identify the need for additional information about a community's vulnerabilities with respect to drinking water. For example, communities with a sole-source, surface-drinking-water intake are likely more vulnerable to wildfire than a community with multiple intakes comprised of both groundwater and surface intakes. Further, some facilities may have undergone wildfire mitigation efforts to minimize the impacts should a wildfire occur. This information is not included in the summarized results, but these rankings can help identify systems where exploration of such efforts may be warranted.

[13] According to the population attributes in the surface drinking water intakes data.

Appendix C Structure Relative Importance

Structure relative importance determined by structure type attributes listed in the original data. The complete list of structure attributes and their associated RI value between 0.5 and 100 are shown in Table C.1.

Table C.1. Full list of included Structures and assigned Relative Importance

Structure-Type Description	RI Category	Scaled RI Value
Dwelling, multi-family	5	100
Institutional residence / dorm / barrack	5	100
Health or medical facility (generic)	5	100
Hospital / medical center	5	100
Nursing home / long term care	5	100
Rehabilitation center	5	100
Day care facility	5	100
Fire station	5	100
Ambulance service	4	100
Emergency shelter	4	100
Emergency Operations Center (EOC)	4	100
Correctional facility	5	100
Residential and general (generic)	4	30
Dwelling, single-family	4	30
Cabin / guest house	4	30
Mobile home	4	30
Outpatient clinic	4	30
School (K-12)	4	30
College / university facility	4	30
Generic or unknown structure	3	10
Garage	3	10
Public health office	3	10
Pharmacy	3	10
Emergency services or law enforcement facility (generic)	3	10
Law enforcement	3	10
Transportation facility (generic)	3	10
Airport	3	10
Border crossing / port of entry	3	10
Railroad facility	3	10
Bus station / dispatch facility	3	10
Government or military facility (generic)	3	10
Court house	3	10
Military facility	3	10
State capitol	3	10
Local government facility	3	10
State government facility	3	10
Federal government facility	3	10
Tribal government facility	3	10
City / town hall	3	10
Education facility (generic)	3	10
Water supply or treatment facility (generic)	3	10
Information or communications facility (generic)	3	10
Radio / TV broadcast facility	3	10
Telephone facility	3	10
Mail or shipping facility (generic)	3	10
Post office	3	10
Commercial or retail site (generic)	3	10
Hotel / motel	3	10
Gas station	3	10
Grocery store	3	10
Shopping mall / center	3	10
Banking or finance facility	3	10
Funeral home	3	10
Office building	3	10
Restaurant / bar	3	10
Automotive retail / service	3	10

Table C.1. Continued - Full list of included Structures and assigned Relative Importance

Structure-Type Description	RI Category	Scaled RI Value
Agriculture, food or livestock facility (generic)	3	10
Veterinary hospital / clinic	3	10
Farm / ranch	3	10
Museum	3	10
Library	3	10
Church / place of worship	3	10
Sports facility	3	10
Civic / community center	3	10
Fairgrounds	3	10
Industrial or manufacturing facility (generic)	3	10
Lumber products facility	3	10
No structure present	2	3
Wind facility	2	3
Storage structure	1	1
Heliport	1	1
Parking site	1	1
Rest stop / roadside park	1	1
Energy or utility facility (generic)	1	1
Grain elevator	1	1
Park / recreation area	1	1
Cemetery	1	1
Golf course	1	1
NULL	0.5	0.5
Disposal site	0.5	0.5
Public attraction or landmark (generic)	0.5	0.5
Mine site	0.5	0.5
Water tower / tank	Other HVRA	0
Dam site	Other HVRA	0
Electric facility	Other HVRA	0
Power substation	Other HVRA	0
Oil / gas facility	Other HVRA	0
Hydroelectric facility	Other HVRA	0
Communication tower	Other HVRA	0
Apartment	Big Sky	100
Clinic/hospital	Big Sky	100
Condo	Big Sky	100
Fire station	Big Sky	100
Multi-family	Big Sky	100
Residential	Big Sky	30
Seasonal cabin	Big Sky	30
Trailer	Big Sky	30
Barn/shop	Big Sky	10
Commercial	Big Sky	10
Garage	Big Sky	10
Garage/apt	Big Sky	10
Government	Big Sky	10
Other	Big Sky	10
Shop	Big Sky	10
Recreation	Big Sky	1
Haz material site	Big Sky	0.5
Restrictive gate	Big Sky	0.5
Cell tower	Big Sky/ Other HVRA	0
Communications	Big Sky/ Other HVRA	0
Electrical	Big Sky/ Other HVRA	0
Water/wastewater	Big Sky/ Other HVRA	0

Appendix D Report Change Log

Table D.1. Report change log

Date of record	Author Initials	Changes made
4/15/2020	ALL	Report *MWRA_QuantitativeWildfireRiskReport_04_15_20_Draft v1.docx* delivered
4/21/2020	KV	Added reference to IDG mask, added text and table on risk-source rasters
4/22/2020	JGD	Incorporated DNRC feedback and edits, remove ‘Quantitative from title’, page numbering, add risk-source rasters
5/5/2020	JGD	Final copy-editing, minor text revision for clarification, expansion of Section 3.5.6
5/8/2020	JGD	Final version delivered – ‘draft’ stamp removed