Informing zoning ordinance decision-making with the aid of probabilistic debris flow modeling

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ABSTRACT
Globally, population and infrastructure continue to grow in the Wildland Urban Interface (WUI) despite the recognition of wildfire and secondary geohazards (i.e.- landslides, debris flows, flooding). In urban and rural settings, expansion into the WUI is the result of a need for space, the subsequent development of cheap marginalized land or, paradoxically, the development of expensive and highly desirable land. As development continues, updated zoning ordinances that reflect the dynamic environment can reduce the risks associated with wildfire and debris flow hazards. Here, we focus on the growing issue of debris flows in the USA. We integrate two case studies from our recent work to illustrate a new approach to developing zoning ordinance boundaries that can reduce debris flow hazards to communities and infrastructure. The case studies use historical data, field observations, and debris flow modeling to provide new information on the hazard in space and time that can be used to define development or prospective development areas prone to debris flows in the WUI. The results provide definitive data for establishing zoning ordinances where debris flow hazards exist, and data that is useful to mitigate these hazards. These diverse case studies show the broader applicability of this approach in locations where the WUI encroaches on steep, fire- and debris flow-prone terrain is highlighted in the case studies. Results and recommendations from this work can ultimately lead to the development of safer and more resilient communities.

À l'échelle mondiale, la population et les infrastructures continuent de croître dans les interfaces habitat-forêt (IHF) malgré la reconnaissance des feux de forêt et des géorisques secondaires (c'est-à-dire les glissements de terrain, en particulier les coulées de débris, ainsi que les inondations). En milieu urbain et rural, l'expansion dans les IHF est le résultat d'un besoin d'espace, le développement ultérieur de terres marginalisées bon marché ou, paradoxalement, le développement de terres dispendieuses et très désirables. Au fur et à mesure que le développement se poursuit, la mise à jour d'ordonnances de zonage reflétant la présence d'environnements dynamiques peut réduire les risques associés aux feux de forêt et aux coulées de débris. Dans cet article nous nous concentrons sur le problème grandissant des coulées de débris aux États-Unis. Nous intégrons les données issues de deux études de cas afin d'illustrer une nouvelle approche d'élaboration des limites de zonage qui peuvent contribuer à réduire les risques de coulée de débris pour les communautés et les infrastructures. Ces études de cas reposent sur des données historiques, des observations sur le terrain ainsi que sur la modélisation de coulées de débris afin de fournir de nouvelles informations pouvant être utilisées afin de définir les zones potentiellement exposées aux coulées de débris dans les IHF. Les résultats fournissent des données définitives pour établir des ordonnances de zonage là où des risques de coulée de débris existent, et des données utiles afin d'atténuer ces risques. Ces diverses études de cas démontrent l'applicabilité plus large de cette approche dans les endroits où les IHF empiètent sur des terrains escarpés sujets aux incendies et aux coulées de débris. Au final, les résultats et recommandations de ces études contribuent au développement de communautés plus sûres et plus résilientes.

1 INTRODUCTION

The wildland-urban interface (WUI) has been defined as the area occupied by housing and infrastructure near and within wildland vegetation (grasslands, shrubs, and forests) and an area where wildfires may ignite homes (Radeloff, et al., 2018). Where urban sprawl extends to the WUI, the potential impact of wildfires on infrastructure and communities increases (Radeloff, et al., 2018). The number of publications devoted to the WUI, and wildfire activity has increased exponentially since the 1990s (Bento-Goncalves & Vieira, 2020).

While wildfires result in direct hazard to infrastructure and communities, secondary hazards including flooding, erosion, and debris flows often take place in recently burned areas as the landscape adjusts to post-wildfire conditions and certain thresholds are reached that initiate debris flows. The risk of secondary hazards such as these increases after wildfires because of destabilization of soil and surface material, deforestation and removal of low-lying vegetation, changes in chemical and physical properties of soil, and other factors (Shakesby & Doerr, 2006).

Zoning and building ordinances can reduce the risk and impact of debris flow and other geohazards activity in areas prone to wildfire and post-wildfire geohazards (Jakob, 2005). Here, we present a general approach for debris flow modeling and discuss two post-wildfire case studies.

1.1 DISASTER PLANNING CONTEXT

Disaster planning for natural hazards, whether flooding, earthquakes, hurricanes, landslide, or debris flow hazards, depends on land use planning to reduce the potential exposure to, and the losses from, these events. Local governments must adopt plans required by the United States' Disaster Mitigation Act of 2000 to be eligible for federal disaster funds to protect against the hazards (Lyles, Berke, & Smith, 2014). However, standard practices for addressing these hazards are often limited by emergency response capacity, education efforts, or other factors rather than comprehensive planning regulations (Lyles, Berke, & Smith, 2014; Mockrin, Fischler, & Stewart, 2020; Mockrin, Fishler, & Stewart, 2018)

Disaster planning for wildfire has been treated differently. The federal government encourages wildfire mitigation efforts through the Community Wildfire Protection Plans (CWPPs), emphasizing forest conditions and wildland fuel treatments (Ge & Lindell, 2016). Land use planning to reduce wildfire risk is not federally mandated (Muller & Schulte, 2011; Mockrin, Fischler, & Stewart, 2020); thus, much of the responsibilities lay on local governments and communities. However, the research found local government disinterests, ignorance, and public objections to pursue land use planning due to the limited capacity of their planning agencies, political influence, and economic impacts (Ge & Lindell, 2016; Mockrin, Radeloff, Stewart, Steel, & Hammer, 2020).

Some regulatory efforts are not realistic in rural or urban fringe areas (Muller & Schulte, 2011). One longitudinal study showed the informal efforts by individual homeowners instead of formal actions or policies (Labossiere & McGee, 2017). The Fire-Adapted Communities effort (https://fireadapted.org/) is another convincing community project that emphasizes citizens' education and empowerment to create communities which are ecologically functional while minimizing risks to human lives and property (Schumann, et al., 2020).

Although wildfire losses in the U.S. have been detrimental in response to the recent higher frequency and larger magnitude wildfires (Westerling, Hidalgo, Cayan, & Swetnam, 2006), there is scarce planning literature about the potential risks. Post-fire debris flows and floods following intense rainstorms are hardly addressed in planning literature, especially in the U.S. context. Studies examine the risk assessments (Kean, et al., 2019) and the community vulnerability from the 2018 debris flows in Montecito, California (Goto, Gray, Keller, & Clarke, 2020; Goto, Gray, Keller, & Clarke, 2021). The research identifies the lack of public understanding of debris flow risks and local authorities' failure to educate the community before the event. A long search for proactive prevention actions in the planning and response decision-making process has been discussed for increased safety of the public and emergency responders (Cannon, Boldt, Laber, Kean, & Staley, 2011; Chester & Li, 2020; Cydzik, 2019; Kean, et al., 2019; Serra-Llobet, Radke, Kondolf, & Lindbergh, 2021). However, there are no formal regulatory planning actions to address the risks fundamentally. Cydzik (2019) has posited that the best approach to reducing the loss of life and property is to avoid the hazard in the first place. Society can avoid these hazards, but as the literature states there is a general reluctance to act on methods and use evidence-based knowledge in land-use planning.

2 METHODS

DebrisFlow Predictor (DFP) is an agent-based probabilistic model (Guthrie & Befus, 2021; Guthrie R. H., Deadman, Cabrera, & Evans, 2008), to determine the probability of a debris flow occupying portions of the landscape downslope of the initiation. DFP is landslide runout software that, at its root, predicts landslide travel paths, and erosion and deposition along those paths. DebrisFlow Predictor was originally conceived to answer questions about the magnitude-frequency characteristics of open slope debris flows and debris avalanches (Guthrie & Befus, 2021; Crescenzo, Pecoraro, Calvello, & Guthrie, 2021). The program requires limited inputs and provides both visualization and analytic capabilities (Guthrie & Befus, 2020a, 2020b).

DebrisFlow Predictor is calibrated using data from historical debris flows within the study area. In most instances, these include debris flow volume, runout, deposition area, scour depth, initiation point, and mapping data. Documented debris flows within the study area provide initial input data for DFP model calibration and modeling scenario setup. Modeling parameters are adjusted in DFP until the model output reflects documented debris flow conditions from the study area.

Once calibrated, multiple DFP modeling scenarios incorporating varying debris flow initiation points (number, location, and size) are executed. Model looping allows individual scenarios to be run multiple times, producing a range of probabilistic outputs for potential debris flow runout distance, depth of cover, depth of scour, and area of influence for each scenario.

3 CASE STUDIES

The case studies presented include North Ogden, Utah, and Larimer County, Colorado, USA. Each of these locations have experienced historical debris flow activity, are undergoing population expansion along the WUI, and could benefit from zoning and building ordinances that are data-driven and designed to reduce and mitigate the impacts of potential debris flow and other geohazards on communities.

3.1 NORTH OGDEN, UTAH, USA

North Ogden, a small city with approximately 20,000 residents, is located along the western boundary of the Wasatch Range in northern Utah. The steep valleys and mountains of the range, coupled with seasonal variation in precipitation and the presence of the Wasatch fault, result in a local landscape prone to earthquake, flood, rockfall, and debris flow hazards. Recent and planned (future) urban growth in along the range front has resulted in infrastructure and community development at the wildland urban interface.

Urban growth has resulted in investment in debris flow mitigation infrastructure, including the construction of debris flow channels, berms, and basins along the WUI as communities push closer to the mountains east of the city.

3.1.1 Historic Debris Flows

Historic debris flows originating from canyons east of North Ogden have impacted homes and infrastructure in the city. In 1991, a debris flow originating from an unnamed canyon resulted in damage to homes and infrastructure in the Cameron Cove neighborhood of North Ogden (Mulvey & Lowe, 1991).

Recent work by Stantec has revealed that communities and infrastructure in the city remain in the pathway of potential debris flows from this and other canyons of the Wasatch Range.

3.1.2 Project Approach and Results

We modeled probabilistic debris flow runout pathways using publicly available LiDAR data (Utah Automated Geographic Reference Center, 2011), Stantec's DebrisFlow Predictor, and data on the 1991 Cameron Cove debris flow from Mulvey and Lowe (1991). A LiDAR-based hillshade model was created in ArcMap 10.8.1 software and provides the backdrop for debris flow modeling and visualization for this project. A map and data from the Cameron Cove Subdivision debris flow were used to calibrate the DFP model to closely match the debris flow runout pathway, erosion, and deposition conditions produced by the event (Mulvey & Lowe, 1991). The DFP model parameters were further refined after review of historical aerial imagery (Google, Inc., 2021). Figure 1 shows the calibrated single run DFP output, in blue, over the debris flow path mapped by Mulvey and Lowe (1992), in red. DebrisFlow Predictor input parameters are adjusted during the calibration until the model results match documented conditions for historic debris flows as closely as possible, reflecting the conditions of the local field area.

Debris flow initiation points were chosen based on geomorphological characteristics interpreted from LiDAR and aerial imagery data, and review of relevant scientific literature. Model outputs from DFP were then draped over the hillshade model and areas where urban growth may intersect with potential debris flow pathways were identified.

After calibrating the DFP input parameters, 50-run and 500-run models were generated using the same initiation points and calibration parameters as the single-run model. The outputs generated were draped over the hillshade model and aerial imagery to assess where debris flow pathways might intersect with urban growth at the WUI (Figure 2).

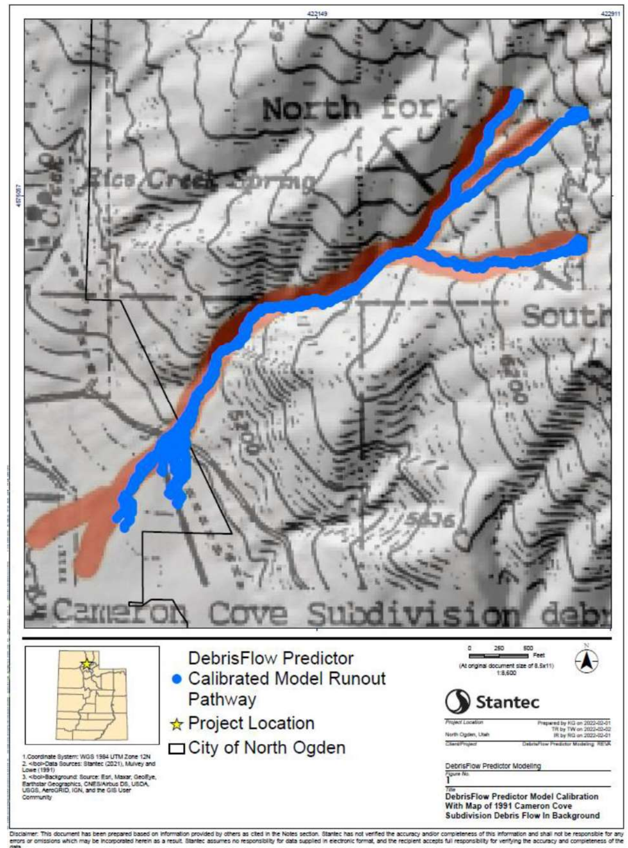

Figure 64. DebrisFlow Predictor calibration (blue) and map of the 1991 Cameron Cove Subdivision debris flow path (red) (modified from Mulvey & Lowe, 1992). Note: historical aerial imagery indicates that the 1991 event did not run out to the west as far as indicated by Mulvey and Lowe (1992).

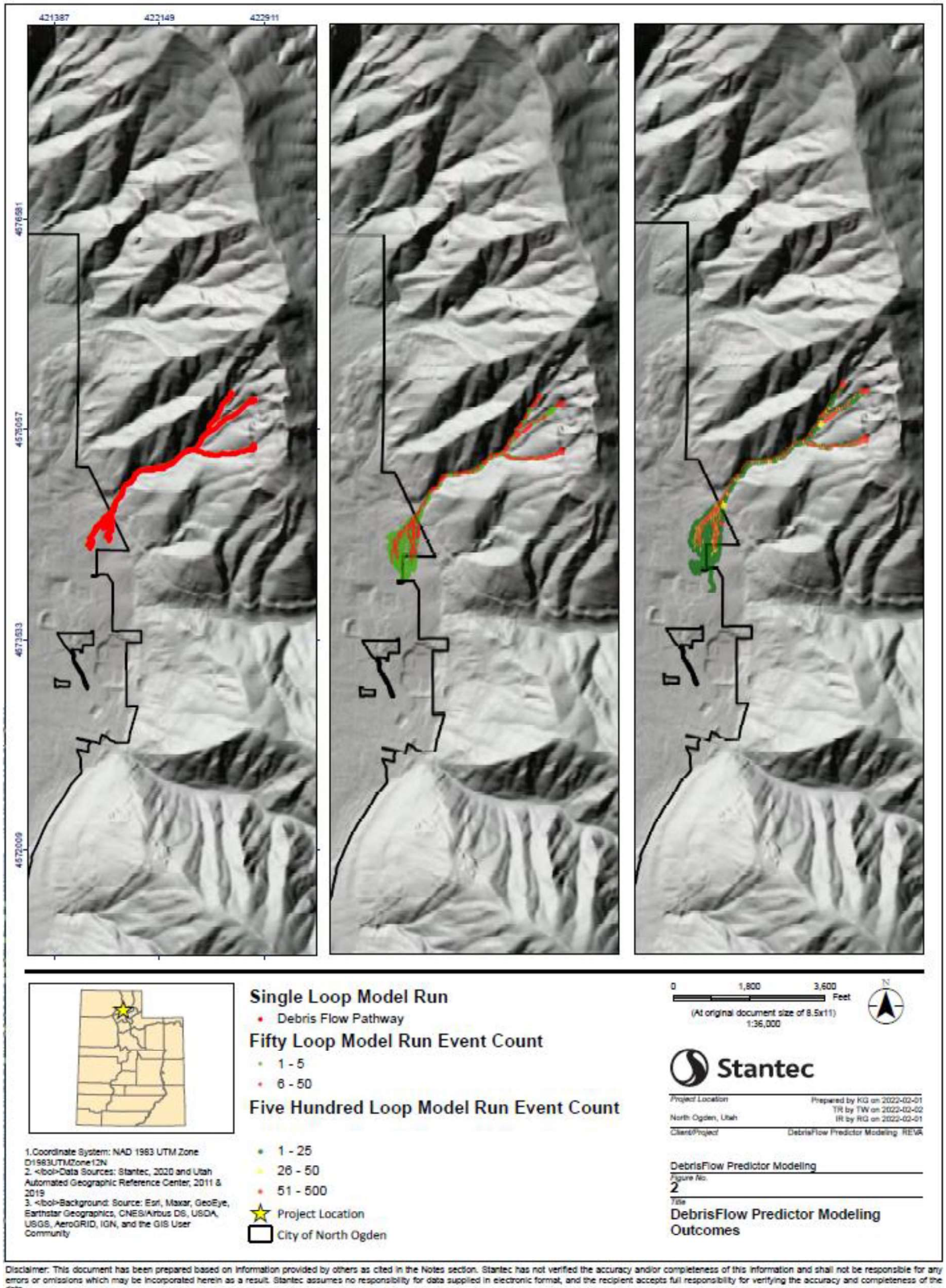

Figure 65. Single (A), 50-loop (B), and 500-loop (C) DFP results. In multi-run models, red and yellow points indicate a high number of debris flow events are likely to intersect a location and green indicates a low number.

3.1.3 Discussion

This project indicates that urban growth along the WUI near the site of the Cameron Cove Subdivision debris flow is taking place within the probabilistic pathway of potential debris flows, and that a debris flow is more likely to impact the southern half of the existing debris flow fan at this location if an event like the 1991 Cameron Cove Subdivision debris flow take place. Other, similarly steep canyons with geomorphic evidence of past debris flow activity (e.g., fan complexes, debris flow channels and levees) extend from the Wasatch Range to the WUI in North Ogden and other cities in the area.

Coupling probabilistic debris flow runout modeling with information from aerial imagery, digital elevation models, and historical debris flows improves our understanding of debris flow hazards along the WUI. In the North Ogden area, applying debris flow hazard modeling to land use planning, city zoning, and community development could help reduce the potential exposure to, and losses from, debris flow events.

3.2 LARIMER, COLORADO

The Cameron Peak Fire was reported on Thursday, August 13, 2020, and ceased on December 2, 2020. A total of 84,544 hectares in steep, rugged terrain burned in the fire. Extreme warm temperatures, low humidity, rough terrain, and winds that exceeded 113 kph and a large number of beetle-kill trees and the drought-stricken Ponderosa Pine, Engelmann Spruce and mixed conifer stands all led to the large fire.

Forest canopy and ground cover were reduced or eliminated during the fire and the fire altered the soil structure (BAER, 2020). Vegetation loss reduced rainfall interception and soil infiltration capacity while increasing runoff volumes compared to discharges prior to the wildfire. Burn severity and soil hydrophobicity dictates runoff in the steeper drainages and varies dependent on the rainfall intensity (among other factors).

Hydrophobicity was highly inconsistent across the Cameron Peak Fire (BAER, 2020). Estimated hydrophobicity across the site was 55% of the total fire area (46,499 hectares). Intense rainfall within watersheds could produce debris floods (higher water to ash, sediment, and woody debris concentrations) and debris flows (lower water to sediment/woody debris ratio).

3.2.1 Project Results

The modeled results indicate 44 homes could be impacted by the debris flows should debris flow thresholds be exceeded. Houses near the apex and middle portions of the alluvial fans had the highest probability of being impacted by a debris flow as identified from 500 debris flow simulations. Houses within the flow pathway near the middle and lower portions of the alluvial fans also had a high probability of being impacted by debris flows. Flow depths recorded in the modeling exercises showed houses in fan apex as well as the mid-fan section could be impacted by depths of 60-80 cm on average, but maximum flow deposition could be more than 1.5m. This magnitude of deposit indicates debris flow depths would be higher than 1.5 m, which would cause damage to houses found in these fan locations (Ciurean R. L., et al., 2017). The Black Hollow Road debris flow also exhibited large wood debris transport that further increased the load and impact of debris flow. A total of five homes were destroyed in the Black Hollow Road debris flow.

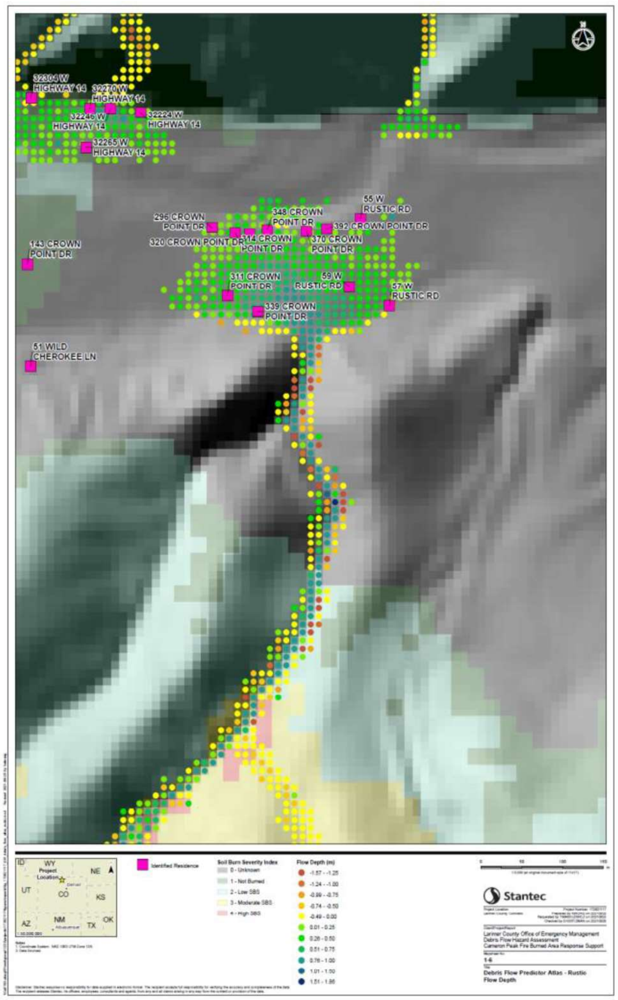

Figure 66. Flow depths from modeling of Cameron Peak Fire near Rustic, Colorado, USA.

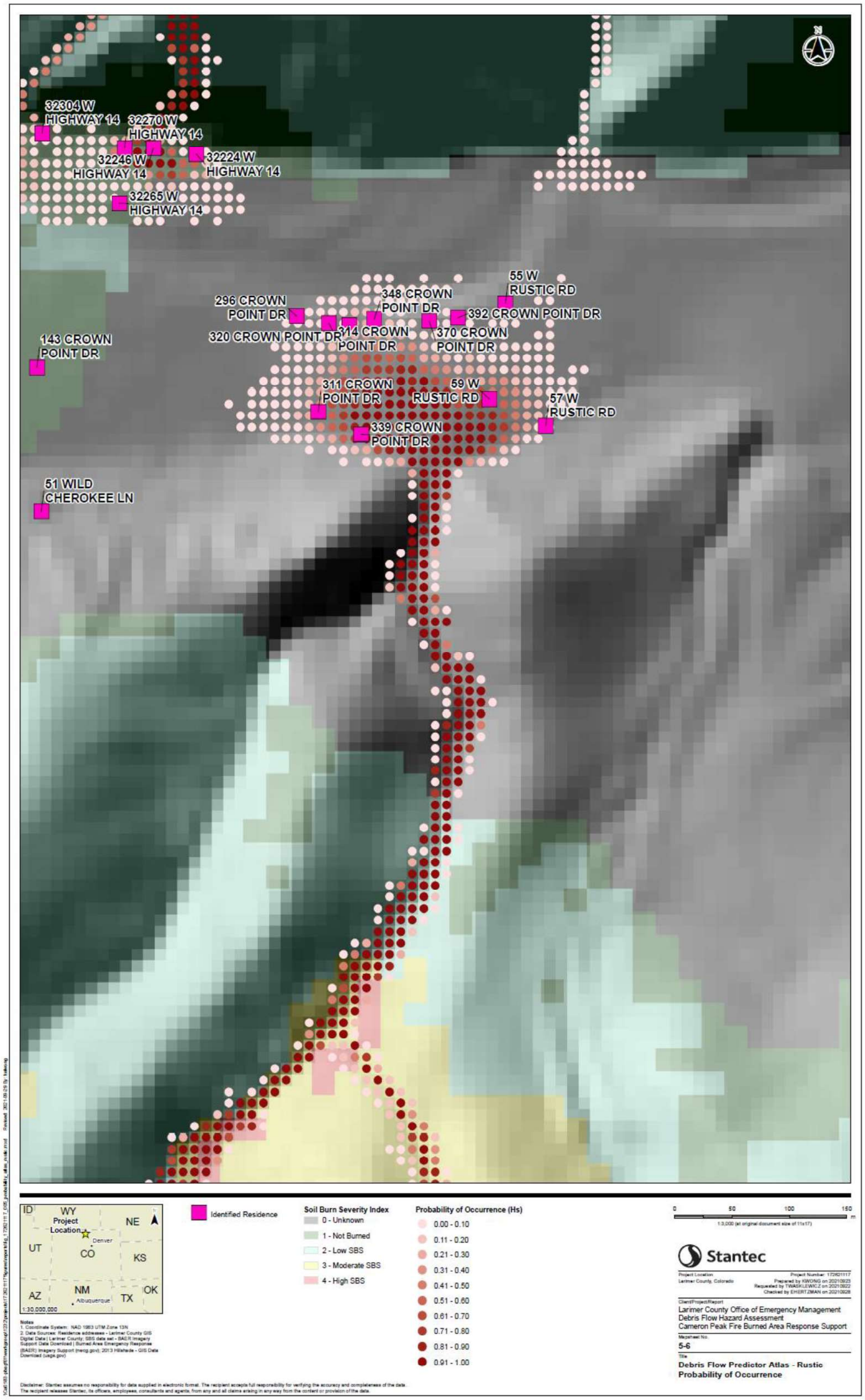

Figure 67. Probability of occurrence from modeling at Cameron Peak Fire near Rustic, Colorado.

4 DISCUSSION AND CONCLUSIONS

Probabilistic debris flow modeling coupled with aerial imagery and data from historic and prehistoric debris flow activity, where available, provides an efficient and effective means for assessing debris flow hazards within existing developments and consideration of future zoning for development. This approach helps identify areas prone to debris flow hazard, sites where additional field data collection is warranted, and can help delineate where land use planning and zoning ordinances may help reduce debris flow hazard risk to infrastructure and communities.

The ability to provide this evidence-based information can inform development in the WUI. We are not inferring that building should not take place within these areas. Instead, our case studies identify locations where development should not occur, areas that could be developed with the proper debris flow mitigation in place, and others where development would have a very low chance of being impacted. Rural areas, like the Colorado example, may not have expertise within local offices to recognize the risks associated with their development decisions. Results like those identified in the case studies presented herein could provide solid underpinnings for zoning and ordinance decision making both before and after areas along the WUI are developed. Prior to development, debris flow modeling can help identify areas prone to geohazards and inform zoning decisions which can help limit the impacts of potential hazards if they take place. After development, this information could be used to inform rebuilding ordinances. Results from the model simulations can also provide valuable information to educate citizens about the hazard and any mitigation built to address the hazard. The data informing these types of decisions could also be conveyed to property developers and owners, and assist with informing local communities about preparing for and responding to debris flow events.

While DebrisFlow Predictor does not predict the probability of debris flow event initiation, it does provide a probabilistic assessment of debris flow pathways, depth of erosion, and depth of cover if an event were to take place in a given location. These data are useful in developing more proactive approachs to managing communities in the WUI.

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