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Dated: December 28, 2017

Subject: Wildland Fire Evacuation Plan for Safari Highlands Ranch

Please accept these comments regarding the Safari Highlands Ranch draft evacuation plan as prepared by DUDEK in July 2017. I was retained by Endangered Habitats League to evaluate this evacuation plan.

I am a professor at the University of Utah where I conduct research on wildfire evacuation analysis and modeling (See Attachment 1). My original inspiration for pursing this topic in the 1990s was the 1991 Oakland Fire, and I have published a number of articles on the topics of community egress, traffic simulation, and public safety as it pertains to wildfire evacuation analysis and planning. In 2005, I proposed a suite of community egress codes in the *Natural Hazards Review* for improving public safety in fire-prone communities that the National Fire Protection Agency adopted in their document *NFPA 1141: Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural and Suburban Areas.*

Background

The Safari Highlands Ranch (SHR) development will be situated in a fire-prone area with an abundance of steep, rugged terrain just east of I-15 in northern San Diego County. More specifically, it will be east of Rancho San Pasqual and north of the San Diego Zoo Safari Park. SHR will consist of 550 single-family residences on 1098 acres with a Village Core and associated amenities that include open space and trails (Figure 1). The property has a fire history that includes 41 fires greater than 10 acres in its direct vicinity (within 5 miles) in the last 107 years (i.e. one every 2.6 years on average), and the area itself burned completely in the 2007 Witch Fire. CALFIRE designated the area a Very High Fire Hazard Severity Zone (VHFHSZ) in 2015.

DUDEK prepared a SHR wildland fire protection plan for the City of Escondido Fire Department in San Diego County, California dated July 2017 (DUDEK 2017). The plan includes sections on risk analysis, fire behavior, emergency response, fire safety requirement, evacuation planning, and homeowner wildfire evacuation. The focus of the comments herein will be Section 9 entitled "Emergency Pre-Planning – Evacuation" in the Fire Protection Plan (FPP).

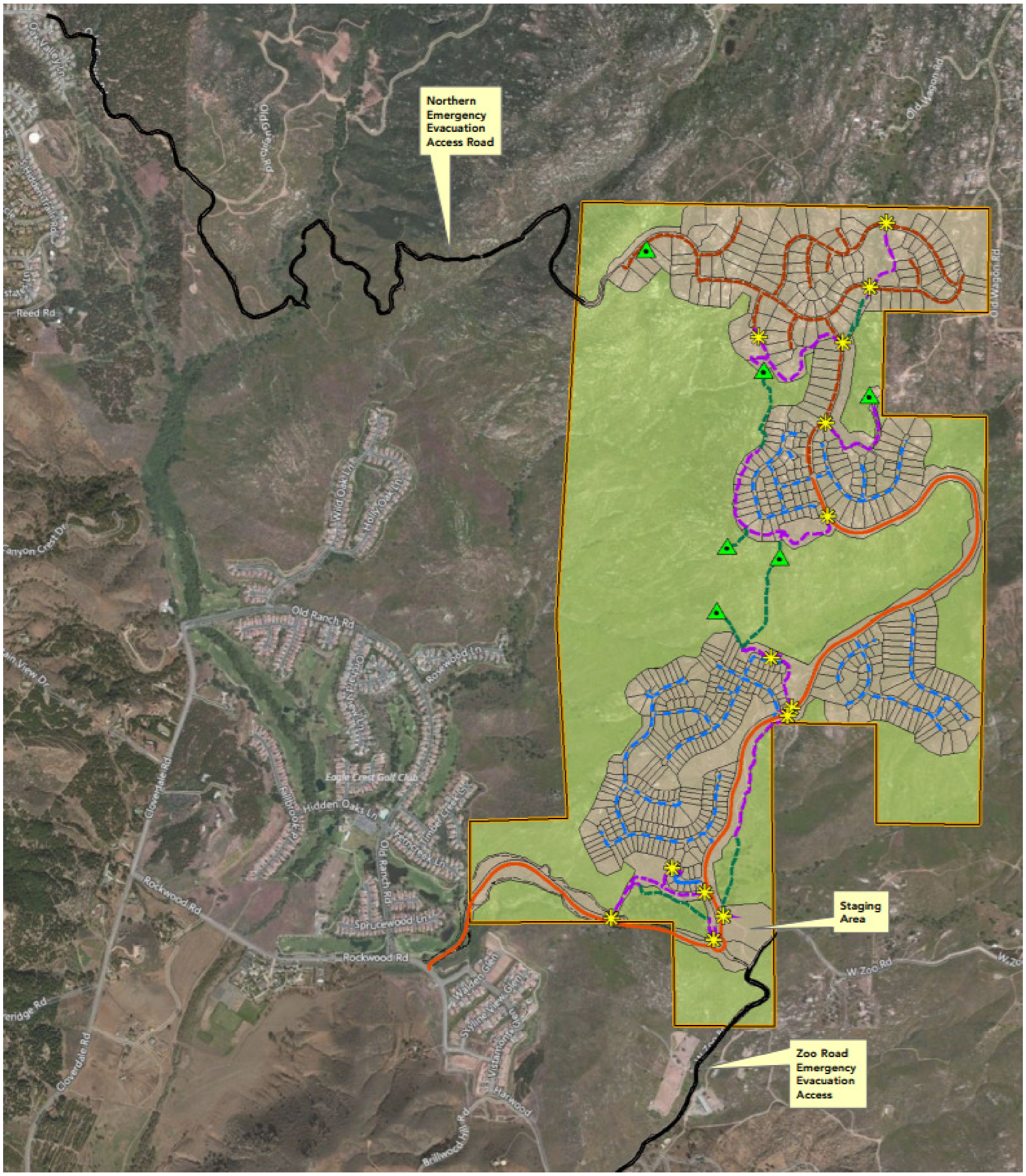

Figure 1. Safari Highlands Ranch (Source: City of Escondido Safari Highland Ranch DEIR).

Evacuation

The three planned evacuation routes for SHR will begin with internal neighborhood roadways and progress to primary evacuation routes that lead to off-site regional evacuation routes. The primary SHR evacuation route and public access road will be Safari Highlands Ranch Road (a new road with one lane in each direction) that will lead to Rockwood Road. Rockwood Road connects to Cloverdale Road (CR), which offers egress to the south (Cloverdale Road to the north is a dead end). Cloverdale Road leads to State Road 78 (SR-78), which offers travel options to the east or west.

Two additional emergency access roads are slated to be developed. The northern emergency access road (NEAR) will be 2.4 miles long and connect SHR to Stonebridge Road in the Hidden Trails Development with a minimum 12-foot wide travel lane in each direction, although this access road will only be improved following the 275th Certificate of Occupancy for the project (City of Escondido 2017). A second southern road that will be approximately 1 mile long will be upgraded to connect to the gated emergency access Zoo Road (ZR) which leads to State Road 78 (Figure 2). Thus, the SHR local exits will offer directional egress to the west, southwest, and south with downstream options to travel north, west, south, or east (Cova et al. 2013).

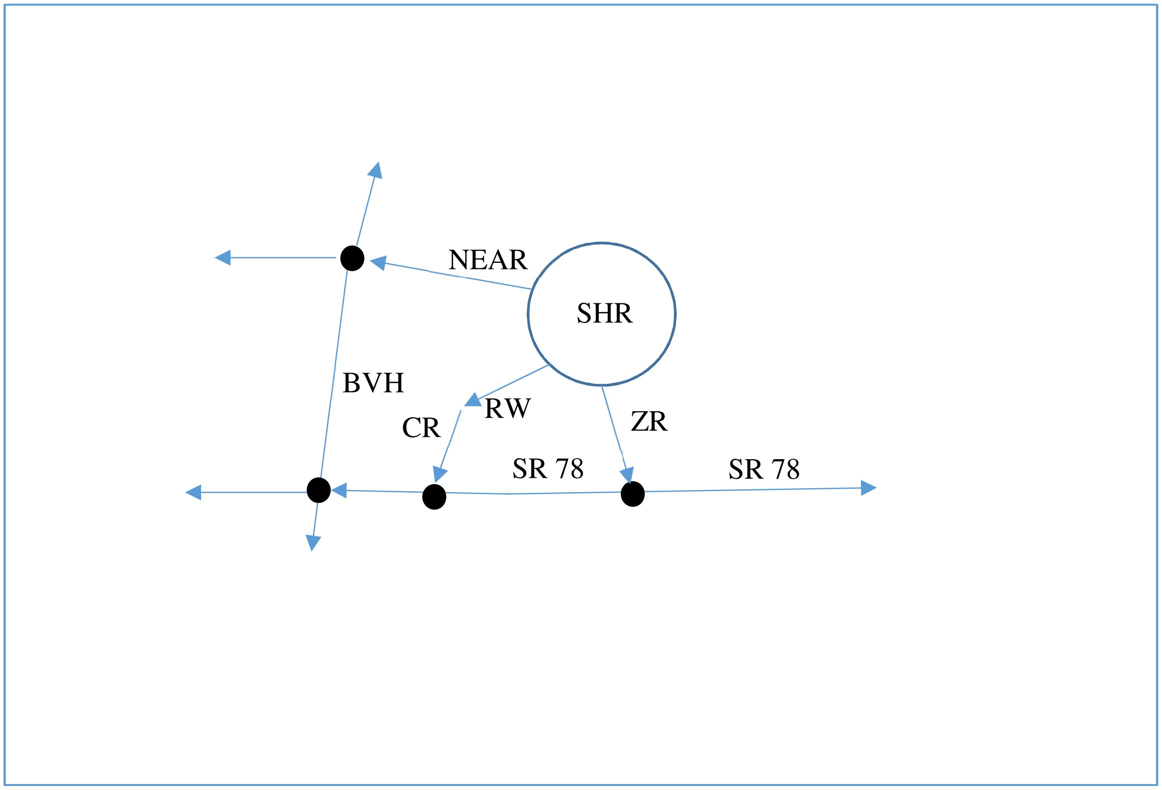

Figure 2. A schematic diagram of the egress road context for Safari Highland Ranch.

Available Time for Evacuation

DUDEK's fire protection plan (FPP) includes seven likely wildfire scenarios that were modeled using Behave Plus with fire spread rates ranging from 2.2 mph (scenario 6) to 9.5 mph (scenario 7) with the five other scenarios assume a spread rate of 9.1 mph. This means that a fire front about 9 miles from SHR and traveling towards SHR would offer emergency managers about an hour to warn residents and clear the community, and ignition points closer to the community could offer much less time to act. For example, an ignition 4 miles away would offer less than 30 minutes under these assumed spread rates. Note that all lead-time estimates come with significant uncertainty, as fires can travel much further and faster with fire branding and wind funneling.

DUDEK's scenarios include estimates of lead times, or the time from an ignition to the project boundary, that range from 4 hours to 40 minutes. The scenarios assume ignition points 13 miles away from SHR. Based on the FlamMap analysis of during Peak fire conditions, and consistent with the FARSITE analysis, the rate of spread was approximately 3.4 miles per hour (covering a distance of 13.5 miles in 4 hours).

As the DUDEK report notes that the fire history in the SHR region includes 41 fires within 5 miles of the community boundary in the last 107 years. Table 1 extends the analysis to include available (lead) time for closer ignition distances ranging from 1 mile to 10 miles. With these extended scenarios, the time available could range from 168 minutes (i.e. an ignition location 7 miles from SHR with a 2.5 mph rate-of-spread) to as little as 15 minutes (i.e. an ignition location 1 mile from SHR with a 4.0 mph rate-of spread). While 15-24 minutes is very short time, this is the approximate time that some residents northeast of Santa Rosa had in the 2017 Tubbs Fire in October.

Available time (minutes)		Fire spread rate (mph)			
		2.5	3.0	3.5	4.0
Ignition distance from SHR boundary (miles)	1	24	20	17	15
	2	48	40	34	30
	3	72	60	51	45
	4	96	80	68	60
	5	120	100	85	75
	6	144	120	102	90
	7	168	140	120	105
	8	192	160	137	120
	9	216	180	154	135
	10	240	200	171	150

Table 1. Available time to evacuate SHR as a function of ignition distance and fire spread rate.

Evacuation Travel Demand Scenarios

Evacuation times for communities are commonly estimated using the ratio of vehicles (demand) to road access (supply) with both expressed in vehicles per hour. DUDEK's vehicle demand scenarios for SHR are for 550 homes and assume 2.2 cars per household, which leads to 1210 vehicles in a full evacuation of the community. Neighboring evacuation demand that could interact or impede an SHR evacuation include 580 units in Rancho San Pasqual (1276 vehicles), 80 units in Rancho Vistamonte (176 vehicles) and San Pasqual Union School (200 vehicles) for a total of 2862 vehicles (i.e. 1652 plus 1210).

On the evacuation route (supply) side, the analysis assumes that Rockwood Road to Cloverdale Road could serve 2600 vehicles per hour (vph), or 45 vehicles per minute (vpm), the Northern emergency access road could serve 1000 vph (if the planned improvements are made), and Zoo Road could serve 1900 vph. While these numbers can be debated or modified, along with the assumptions regarding the rate that vehicles depart over time (also in vph), as well as upstream evacuation time components like decision time, notification time, and household preparation time, the report conclusion that it would take between 1 and 3 hours to evacuate SHR is entirely reasonable (assuming the planned access road improvements are completed).

The fire spread analysis assumes ignitions that are 13 or more miles away from SHR, but as noted above, given the fire history of this region, ignitions much closer are not only likely but common (i.e. a 10-acre fire within 5 miles of SHR occurred every 2.6 years in the last century, on average). Given the lead-time analysis shown in Table 1 for ignitions less than 10 miles from SHR, it is worth examining the number of vehicles that could clear SHR in the full range of available evacuation times.

Table 2 shows the number of vehicles that might not be clear of SHR when a wildfire strikes as a function of the lead (available) time to evacuate and the estimated evacuation time. For example in the case where 30 minutes is available to evacuate SHR and the estimated evacuation time is 60 minutes, 605 vehicles could still be in SHR when the fire impacts the community (i.e. assuming that vehicle departure is uniform at 1210 vehicles per hour).

A second example is the case where 120 minutes (2 hours) is available to evacuate the community and the estimated evacuation time is 180 minutes (3 hours). In this case, 403 vehicles could be trapped in SHR when the fire impacts the community (i.e. assuming that the 1210 vehicle depart uniformly across the 180 minute evacuation). As highlighted above, these lead-time estimates are realistic give the 41 fires within 5 miles of the SHR site in the last 107 years. Given the potential threat to public health and safety, additional analysis regarding different ignition locations and evacuation time estimates should be evaluated.

Additional Complicating Factors

Real-world evacuations are almost always more complicated than simple analyses predict. Emergency managers may delay the decision to warn the public (or not warn them at all) leading to much greater evacuation times. Households may delay the decision to leave, either in hopes they can defend property or that they will not be impacted, which can also increase evacuation times. Furthermore, route choice can also be problematic, as evacuees rarely choose exits in the balanced way that analysts apportion their trips.

Estimated vehicles in SHR at wildfire impact		Evacuation Time (minutes)		
		60	120	180
Lead time (minutes)	30	605	908	1008
	60	0	605	807
	90		303	605
	120		0	403
	150			202
	180			0

Table 2. Varying the lead time available to evacuate SHR (30-180 minutes) and the evacuation time (60-180 minutes) to estimate the number of vehicles that might not be clear of the SHR community when a wildfire front arrives.

One assumption In the DUDEK evacuation analysis for SHR is that all evacuation routes are open and operating at full capacity in vehicles-per-hours. While this case is possible, wildfire can block exits, both in terms of radiant heat and smoke, which can reduce the capacity of roads (i.e. a reduction in vehicles per hour). It should also be noted that the Northern Emergency Access Road will only be built following the issuance of the 275^{th} Certificate of Occupation for the project (i.e. it may not be improved). There may also be significant ambient through-traffic on the surrounding roads during a regional evacuation that can impede the evacuation of fringe communities such as the proposed SHR community. Assessing these impacts requires a more in-depth traffic simulation study beyond ideal lead times and manual capacity analysis of the best case.

Summary

The proposed Safari Highland Ranch Community will be in a very fire-prone area, and for this reason, evacuation egress is a critical public safety factor. While the intent is for SHR to eventually have three improved exits if the various phases are completed, the fire history in this area is such that many fires ignite in very close proximity to the development site and offer little lead time to evacuate (i.e. warning, preparation, and evacuation time). The analysis herein considered ignitions less than 10 miles from SHR, which was not considered in the DUDEK wildfire evacuation plan. There are many factors and assumptions that go into any analysis from the time to warn residents through to the time it will take for residents to travel to safety.

A critical point in this letter is that wildfire ignitions that are less than 10 miles from the SHR site and traveling at average speeds of 2.5 to 4.0 miles per hour would offer less time that the estimate evacuation times reported in the DUDEK analysis. This could result in scenarios where evacuating residents (vehicles) might be caught in-transit during a wildfire, and as SHR is not a designated shelter-in-place community, this issue needs further study.

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Education

1999	Ph.D., Geography, University of California Santa Barbara. Dissertation: *A general framework for optimal site search*.
1995	M.A., Geography, University of California Santa Barbara. Thesis: *A spatial search for neighborhoods that may be difficult to evacuate.*
1986	B.S., Computer and Information Science, University of Oregon. Minor in math; emphasis in software engineering.

Research and Teaching Interests

Environmental Hazards, Emergency Management, Geographic Information Science, Transportation, Sustainability, Coupled Natural-Human Systems.

Professional Experience

2012 –	Professor, Department of Geography, University of Utah.
2005 – 2012	Associate Professor, Department of Geography, U. of Utah.
1999 – 2005	Assistant Professor, Department of Geography, U. of Utah.
1993 – 1996	Research Assistant, National Center for Geographic Information and Analysis (NCGIA), UC Santa Barbara.
1992 – 1997	Teaching Assistant, Department of Geography, UCSB.
1987 – 1992	Systems Analyst, Matthew Bender & Co., Oakland, California.

Other Professional Activities

2014 –	Director, *Certificate in Environmental Hazards & Emergency Management*, Department of Geography, University of Utah.
2003 –	Director, *Center for Natural & Technological Hazards*, Department of Geography, University of Utah.

2001 – 2016 Director, Certificate in Geographic Information Science, Department of Geography, University of Utah.

2011 – 2013 Chair, Hazards, Disasters & Risk Specialty Group, Association of American Geographers, Washington, D.C.

2007 – 2008 Program Chair, 5th International Conference in Geographic Information Science (GIScience 2008), Park City, Utah.

2005 – 2008 Chair (Vice Chair, Past Chair), GIS Specialty Group, Association of American Geographers, Washington, D.C.

2005 – 2008 Chair, Research Projects Committee, University Consortium for Geographic Information Science (UCGIS).

2004 – 2006 Secretary/Treasurer, GIS Specialty Group, Association of American Geographers, Washington, D.C.

2001 – 2003 Academic Councilor, GIS Specialty Group, Association of American Geographers, Washington, D.C.

1999 – 2003 Associate Director for Research, Center for Natural & Technological Hazards, Department of Geography, U of Utah.

Editorial Board Memberships

2011 – *Journal of Geography & Natural Disasters*.

2011 – 2014 *Journal of Spatial Science*

2009 – 2011 *Professional Geographer*, Sharmistha Bagchi-Sen (ed).

2001 – 2004 *Computers, Environment & Urban Systems*, P. Longley (ed).

Professional Honors and Awards

2016 Excellence in Mentoring Award, College of Social & Behavioral Science (CSBS), University of Utah.

2014 – 2016 Advisor, *Enabling the Next Generation of Hazards Researchers*, D. Thomas, S. Brody, & B. Gerber (PIs), National Science Foundation, CMMI-IMEE.

2008 – 2010 Mentor, *Enabling the Next Generation of Hazards Researchers*, Tom Birkland (PI), National Science Foundation, CMMI-IMEE.

2005 John I. Davidson Award for Practical Papers, American Society for Photogrammetry & Remote Sensing – with P. Sutton and D. Theobald.

2005 Leica Geosystems Award for Best Scientific Paper in Remote Sensing, American Society for Photogrammetry & Remote Sensing (ASPRS) – with P. Sutton and D. Theobald.

2003 – 2005 Fellow, *Enabling the Next Generation of Hazards Researchers*, Raymond Burby (PI), National Science Foundation, CMMI-IMEE.

2003 University Consortium for Geographic Information Science (UCGIS) Young Scholar's Award.

1996 – 1999 Dwight D. Eisenhower Doctoral Fellowship, National Highway Institute, Federal Highway Admin., Dept. of Transportation.

1995 International Geographic Information Foundation (IGIF) Award for Best Student Paper, GIS/LIS '95, Nashville, TN.

1995 Outstanding Student in Transportation, UC Santa Barbara, Western Coal Transportation Association.

RESEARCH AND SCHOLARSHIP

Edited volumes and special issues

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Invited Lectures, Presentations and Participation

2017 "Improving situational awareness in wildfire evacuations with volunteered geographic information." NSF IBSS/IMEE Summer Workshop, San Diego, August.

2014 "Modeling adaptive warnings with geographic trigger points." Department of Geography, SDSU, San Diego, CA, April 18.

2013 "Wildfires and geo-targeted warnings." Geo-targeted Alerts and Warnings Workshop. *National Academy of Sciences*, Washington DC, February 21-22.

2012 "Evacuation planning in the wildland-urban interface." California Joint Fire Science Program, Webinar Speakers Series, September.

2010 "Evacuating threatened populations in disasters: space, time & information." University of Minnesota, Spatial Speakers Series (Geography/CS/CE), April.

2009 "The art and science of evacuation modeling." Utah Governor's Conf. in Emergency Management, Provo, May.

2008 "GIScience and public safety." Brigham Young University, November.

2007 "Fire, climate and insurance." Panel Discussion. Leonardo Museum, Salt Lake City, November.

2007 "GIScience and public safety." University of Northern Iowa, April.

2006 "Evacuation and/or Shelter in Place." Panel Discussion, Firewise Conference: Backyards & Beyond, Denver, CO, Nov.

2006 "Evacuation modeling and planning." Colorado Springs Fire Department, Colorado Springs, CO, October.

2006 "Evacuation modeling and planning." Sante Fe Complexity Institute, Sante Fe, NM, August.

2006	"Evacuation modeling and planning." Colorado Wildfire Conference. Vail, CO, April, $1000.
2006	"Dynamic GIS: in search of the killer app." Center for Geocomputation, National U. of Ireland, Maynooth, April.
2006	"Setting wildfire evacuation trigger points with GIS." University Consortium for Geographic Information Science, Winter meeting, Washington, DC.
2005	"Setting wildfire evacuation trigger points with GIS." Pennsylvania State University, State College, PA, November.
2004	"The role of scale in ecological modeling," NSF PI meeting for Ecology of Infectious Diseases, Washington D.C., September.
2004	"The 2003 Southern California wildfires: Evacuate and/or or shelter-in-place," Natural Hazards Workshop, Boulder, CO.
2004	"When all hell breaks loose: new methods for wildfire evacuation planning," colloquium, Department of Geography, University of Denver, February.
2004	"When all hell breaks loose: new methods for wildfire evacuation planning," Colorado Governor's Conference and Colorado Emergency Management Association (CEMA) Conference, Boulder, CO, February.
2004	"When all hell breaks loose: new methods for wildfire evacuation planning," colloquium, Department of Geography, University of California Los Angeles, February.
2003	"When all hell breaks loose: new methods for wildfire evacuation planning," colloquium, Natural Resources Ecology Lab (NREL), Colorado State University, April.
2003	"When all hell breaks loose: new methods for wildfire evacuation planning," Departmental colloquium, Department of Geography, University of Arizona, January.
2002	"When all hell breaks loose: new methods for wildfire evacuation planning," Departmental colloquium, Department of Geography, Western Michigan University, November.
2001	"Regional evacuation analysis in fire-prone areas with limited egress," Departmental colloquium, Department of Geography, University of Denver, May.

2000 "Integrating Site Search Models and GIS," Colloquium, Department of Geography, Arizona State University, Feb.

1999 "Site Search Problems and GIS," Colloquium, Department of Geography, University of Utah.

1996 "A spatial search for neighborhoods that may be difficult to evacuate," Colloquium, Department of Geography, UC Santa Barbara.

1995 "A spatial search for neighborhoods that may be difficult to evacuate," Regional Research Lab, Bhopal, India.

1995 "A spatial search for neighborhoods that may be difficult to evacuate," Indian Institute of Technology, Bombay. India.

Papers Presented at Professional Conferences

2017 Cova, T.J., Simulating warning triggers. Association of American Geographers Annual Meeting, Boston, MA, CA, April.

2016 Cova, T.J., Spatio-temporal representation in modeling evacuation warning triggers. Association of American Geographers Annual Meeting, San Francisco, CA, March.

2015 Cova, T.J. and Jankowski, P., Spatial uncertainty in object-fields: the case of site suitability. Association of American Geographers Annual Meeting, Chicago, IL, April.

2014 Cova, T.J. and Jankowski, P., Spatial uncertainty in object-fields: the case of site suitability. International Conference on Geographic Information Science (GIScience '14), Vienna, Austria, September.

2013 Cova, T.J., Dennison, P.E. and Drews, F.A., Protective-action triggers: modeling and analysis. *Association of American Geographers Annual Meeting*, Los Angeles, CA, April.

2012 Cova, T.J., Dennison, P.E. and Drews, F.A., Protective-action triggers. Poster presented at the Natural Hazards Workshop, University of Colorado, Boulder, July.

2012 Cova, T.J., Dennison, P.E. and Drews, F.A., Protective-action triggers. Poster presented at the NSF CMMI Innovation Conference, Boston, July.

2012 Cova, T.J., Dennison, P.E. and Drews, F.A., Protective-action triggers, *Association of American Geographers Annual Meeting,* New York, NY, February.

2011 Cova, T.J., Modeling stay-or-go decisions in wildfires, *Association of American Geographers Annual Meeting,* Seattle, WA, April.

2010 Cova, T.J., Theobald, D.M. and Norman, III, J., Mapping wildfire evacuation vulnerability in the West, *Association of American Geographers Annual Meeting,* Wash. D.C., April.

2010 Cova, T.J., and Van Drimmelen, M.N., Family gathering in evacuations: the 2007 Angora Wildfire as a case study. *National Evacuation Conference*, New Orleans, February.

2010 Siebeneck, L.K., Cova, T.J., Drews, F.A., and Musters, A. Evacuation and shelter-in-place in wildfires: The incident commander perspective. *Great Basin Incident Command Team Meetings*, Reno, April.

2009 Cova, T.J. et al., Protective action decision making in wildfires: the incident commander perspective. *Association of American Geographers Annual Meeting,* Las Vegas, March.

2009 Siebeneck, L.K. and Cova, T.J. Using GIS to explore evacuee behavior before, during and after the 2008 Cedar Rapids Flood. *Association of American Geographers Annual Meeting*, Las Vegas, March.

2009 Lindell, M.K., Prater, C.S., Siebeneck, L.K. and Cova, T.J. Hurricane Ike Reentry. *National Hurricane Conference*, Austin, March.

2008 Cova, T.J., Simulating evacuation shadows, *Association of American Geographers Annual Meeting,* Boston, April.

2007 Cova, T.J., An agent-based approach to modeling warning diffusion in emergencies, *Association of American Geographers Annual Meeting,* San Francisco, March.

2006 Cova, T.J., New GIS-based measures of wildfire evacuation vulnerability and associated algorithms. *Association of American Geographers Annual Meeting,* Denver, March.

2005 Cova, T.J., Dennison, P.E., Kim, T.H., and Moritz, M.A., Setting wildfire evacuation trigger-points using fire spread modeling and GIS. *Association of American Geographers Annual Meeting,* Denver, March.

2004 Cova, T.J., Sutton, P.C., and Theobald, D.M. Light my fire proneness: residential change detection in the urban-wildland interface with nighttime satellite imagery, *Association of American Geographers Annual Meeting*, Philadelphia, March.

2004 Cova, T.J. and Johnson, J.P., A network flow model for lane-based evacuation routing. *Transportation Research Board (TRB) Annual Conference*, Washington, D.C., January.

2003 Cova, T.J. Lane-based evacuation routing, *Association of American Geographers Annual Meeting*, New Orleans, March.

2002 Cova, T.J., Extending geographic representation to include fields of spatial objects, *GIScience 2002*, Boulder, September.

2002 Husdal, J. and Cova, T.J., A spatial framework for modeling hazards to transportation systems, *Association of American GeographersAnnual Meeting,* Los Angeles, March.

2001 Cova, T.J. and Johnson, J.P., Evacuation analysis and planning tools inspired by the East Bay Hills Fire, *California's 2001 Wildfire Conference: 10 years after the 1991 East Bay Hills Fire*, Oakland, October.

2001 Cova, T.J., Husdal, J., Miller, H.J., A spatial framework for modeling hazards to transportation networks, *Geographic Information Systems for Transportation Conference (GIS-T 2001*), Washington DC, April.

2001 Cova, T.J., Miller, H.J., Husdal, J., A spatial framework for modeling hazards to transportation systems, *Association of American Geographers Annual Meeting*, New York, New York, February.

2000 Cova, T.J., Church, R.L., Goodchild, M.F., Extending geographic representation to include fields of spatial objects, *GIScience 2000,* Savannah, Georgia, November.

2000 Cova, T.J. Microscopic simulation in regional evacuation: an experimental perspective, *Association of American Geographers Annual Meeting*, Pittsburgh, Pennsylvania, March.

1999	Cova, T.J., and Church, R.L., "Exploratory spatial optimization and site search: a neighborhood operator approach," *Geocomputation '99*, Mary Washington College, Fredricksburg, Virginia.
1999	Cova, T.J., and Church, R.L., "Integrating models for optimal site selection with GIS: problems and prospects," *Association of American Geographer Annual Meeting*, Honolulu, Hawaii, March 29.
1998	Cova, T.J., and Church, R.L., "A spatial analytic approach to modeling neighborhood evacuation egress," *Association of American Geographers Annual Meeting,* Boston, Massachusetts.
1997	Church, R.L., and Cova, T.J., "Location search strategies and GIS: a case example applied to identifying difficult to evacuate neighborhoods," *Regional Science Association Annual Meeting*, November, Buffalo.
1997	Cova, T.J. and Church, R.L., "An algorithm for identifying nodal clusters in a transportation network," *University Consortium for Geographic Information Science (UCGIS) Summer Retreat*, Bar Harbor, June.
1996	Cova, T.J., Church, R.L., "A spatial search for difficult neighborhoods to evacuate using GIS," *GIS and Hazards Session*, *Association of American Geographers Annual Meeting*, Charlotte, April.
1995	Cova, T.J., Church, R.L., "A spatial search for neighborhoods that may be difficult to evacuate," *GIS/LIS '95*, Nashville, November.
1995	Goodchild, M.F., Cova, T.J. and Ehlschlaeger, C., "Mean geographic objects: extending the concept of central tendency to complex spatial objects in GIS," *GIS/LIS '95*, Nashville, November.
1994	Cova, T.J. and Goodchild, M.F., "Spatially distributed navigable databases for intelligent vehicle highway systems," *GIS/LIS '94*, Phoenix, November.

Grants

Externally funded

2017 –	Shoaf, K. (PI) and Cova, T.J. *RAPID: Evacuation Decision-making process of Hospital Administrators in Hurricane Harvey*. National Science Foundation, Civil Mechanical and Manufacturing Innovation – Infrastructure Management and Extreme Events, $49,301.
2011 – 2015	Cova, T.J. (PI), Dennison, P.E. and Drews, F.A., *Protective action triggers*. National Science Foundation, Civil Mechanical and Manufacturing Innovation – Infrastructure Management and Extreme Events, $419,784.
2012 – 2014	Cova, T.J. (PI), *State Hazard Mitigation Mapping II.* Utah Division of Emergency Management, $51,608.
2011 – 2012	Cova, T.J. (PI), *State Hazard Mitigation Mapping.* Utah Division of Emergency Management, $51,608.
2007 – 2010	Cova, T.J. (PI) and Drews, F.A. *Protective-action decision making in wildfires.* National Science Foundation, Civil Mechanical and Manufacturing Innovation – Infrastructure Management and Extreme Events, $288,438.
2004– 2006	Yuan, M. (PI), Goodchild, M.F., and Cova, T.J. *Integration of geographic complexity and dynamics into geographic information systems,* National Science Foundation, Social and Behavioral Science—Geography and Spatial Sci., $250,000.
2003– 2004	Cova, T.J. (PI) *Mapping the 2003 Southern California Wildfire Evacuations*, National Science Foundation, Small Grants for Exploratory Research (SGER), CMMI-IMEE, $14,950.
2003 –2008	Dearing, M.D. (PI), Adler, F.R., Cova, T.J., and St. Joer, S. *The effect of anthropogenic disturbance on the dynamics of Sin Nombre*, National Science Foundation and NIH, Ecology of Infectious Diseases, $1,933,943.
2000–2004	Hepner, G.F. (PI), Miller, H.J., Forster, R.R., and Cova, T.J. *National Consortium for Remote Sensing in Transportation: Hazards (NCRST-H),* U.S. Department of Transportation, $437,659.
2000–2001	Cova, T.J. (PI) *Modeling human vulnerability to environmental hazards*, Salt Lake City and Federal Emergency Management Agency (FEMA), $20,000.

Internally funded

2004	Cova, T.J. (PI) and Sobek, A. *DIGIT Lab GPS Support*, U. of Utah Technology Instrumentation Grant, $15,000.
2003	Cova, T.J. (PI) *New methods for wildfire evacuation analysis*, Proposal Initiative Grant, College of Social and Behavioral Science, University of Utah, $4000.
1999	Cova, T.J. (PI) *Microscopic traffic simulation of regional evacuations: computational experiments in a controlled environment*, Faculty Research Grant (FRG), University Research Committee, University of Utah, $5980.
1999	Cova, T.J. (PI) *Regional evacuation analysis in fire prone areas with limited egress*, Proposal Initiative Grant, College of Social and Behavioral Science, University of Utah, $4000.

Media Outreach

2013	Ryman, A. and Hotstege, S. "Yarnell evacuation flawed and chaotic, experts say." *Arizona Republic and USA Today*, Nov.
2013	Bryson, D., and Campoy, A. "Quick fire response pays off: Colorado credits early alerts with limiting deaths from state's worst-ever blaze." *The Wall Street Journal*, June 17.
2013	Beri, A. "Due to the sequester: people are going to be unsafe, homes are going to burn." *Tampa Bay Times*, Feb.
2012	Zaffos, J. "What the High Park Fire can teach us about protecting homes." *High Country News*, July.
2012	Meyer, J.P. and Olinger, D., "Tapes show Waldo Canyon fire evacuations delayed two hours." *The Denver Post*. July.
2011	Siegel L, and Rogers, N. "Monitoring killer mice from space." *USA Today*, *SLTribune, Fox 13 News, KCPW*, Feb. 15.
2010	Cowan, J., "Esplin defends stay or go policy." *Australian Broadcast Corporation (ABC)*, April 30.
2010	Bachelard, M., "Should the fire-threatened stay or go? That is still the question." *The Age*, Australia, May 2.
2008	Boxall, B., "A Santa Barbara area canyon's residents are among many Californian's living in harm's way in fire-prone areas." *Los Angeles Times*, July 31.
2007	Welch, W.M. et al., "Staggering numbers flee among fear and uncertainty." *USA Today*, Oct. 24.
2007	Krasny, M., "Angora Wildfire Panel Discussion." *KQED Radio*, San Francisco, June 27.
2004	Wimmer, N., "Growing number of communities pose fire hazard." *KSL Channel 5,* Salt Lake City, July 22.

2004	Disaster News Network, "The face of evacuation procedures might be changing as a result of lessons learned from last year's fierce wildfires in California."
2004	Perkins, S., "Night space images show development." *Science News*, Week of April 3rd, 165 (14): 222.
2003	Keahey, J., "Canyon fire trap feared." *SL Tribune*, June.

TEACHING AND MENTORING

Undergraduate Courses

Introduction to Geographic Information Systems (~60 students).
Human Geography (~40 students).
Geography of Disasters and Emergency Management (~20 students).
Methods in GIS (~40 students).

Graduate Courses

GIS & Python (~15 students)
Spatial Databases (~30 students)
Seminars: Hazards Geography, Transportation, Vulnerability, GIScience.

Graduate Student Advising

<u>Chaired Ph.D. Committees</u>

2019	Coleman, A.	Geographic data fusion for disaster management
2016	Li, D.	Modeling wildfire evacuation triggers as a coupled natural-human system (Asst. Professor South Dakota State University)
2010	Siebeneck, L.	Examining the geographic dimensions of risk perception, communication and response during the evacuation and return-entry process. (Assoc. Professor, U. of North Texas)
2010	Cao, L.	Anthropogenic habitat disturbance and the dynamics of hantavirus using remote sensing, GIS, and a spatially explicit agent-based model. (Postdoc, Kelly Lab, UC Berkeley)

<u>Chaired M.S. committees</u>

2017	Yi, Y.	A web-GIS application for house loss notification in wildfires
2017	Latham, P.	Evaluating the effects of snowstorm frequency and depth on skier behavior in Big Cottonwood Canyon, Utah

2016	Bishop, S.	Spatial access and local demand for emergency medical services in Utah
2015	Hile, R.	Exploratory testing of an artificial network classification for enhancement of a social vulnerability index
2015	Unger, C.	Creating spatial data infrastructure to facilitate the collection and dissemination of geospatial data to aid in disaster management
2014	Klein, K.	Tracking a wildfire in areas of high relief using volunteered geographic information: a viewshed application
2012	Amussen, F.	Greek island social networks and the maritime shipping dominance they created (technical report)
2012	Martineau, E.	Earthquake risk perception in Salt Lake City, Utah
2010	Smith, K.	Developing emergency preparedness indices for local government
2010	VanDrimmelen, M.	Family gathering in emergencies: the 2007 Angora Wildfire as a case study
2007	Pultar, E.	GISED: a dynamic GIS based on space-time points
2007	Siebeneck, L.	An assessment of the return-entry process for Hurricane Rita, 2005
2007	Johnson, J.	Microsimulation of neighborhood-scale evacuations
2004	Chang, W.	An activity-based approach to modeling wildfire evacuations

Membership on Ph.D Committees

2017	Campbell, M.	Wildland firefighter travel times
2016	Zhang, L.	Economic geography of China
2015	Huang, H.	Spatial analysis and economic geography
2014	Lao, H.	Spatial analysis, GIS, and economic geography
2013	Burgess, A.	Hydrologic implications of dust in snow in the Upper Colorado River Basin
2012	Davis, J.	
2012	Li, Y.	
2011	Hadley, H.	Transit sources of salinity loading in the San Rafael River, Upper Colorado River Basin, Utah
2009	Medina, R.	Use of complexity theory to understand the geographical dynamics of terrorist networks
2008	McNeally, P.	Holistic geographical visualization of spatial data with applications in avalanche forecasting
2008	Sobek, A.	Generating synthetic space-time paths using a cloning algorithm on activity behavior data
2007	Clay, C.	Biology

2006	Backus, V.	Assessing connectivity among grizzly bear populations near the U.S.-Canada border
2006	Atwood, G.	Shoreline superelevation: evidence of coastal processes of Great Salt Lake, Utah
2006	White, D.	Chronic technological hazard: the case of agricultural pesticides in the Imperial Valley, California
2005	Ahmed, N.	Time-space transformations of geographic space to explore, analyze and communicate transportation systems
2004	Shoukrey, N.	Using remote sensing and GIS for monitoring settlement growth expansion in the eastern part of the Nile Delta Governorates in Egypt (1975-1998)
2004	Hernandez, M.	A Procedural Model for Developing a GIS-Based Multiple Natural Hazard Assessment: Case Study-Southern Davis County, Utah
2003	Wu, Y-H.	Dynamic models of space-time accessibility
2003	Hung, M.	Using the V-I-S model to analyze urban environments from TM imagery
2002	Baumgrass, L.	Initiation of snowmelt on the North Slope of Alaska as observed with spaceborne passive microwave data

Membership on M.S. Committees

2015	Farnham, D.	Food security and drought in Ghana
2015	Fu, L.	Analyzing route choice of bicyclists in Salt Lake City
2014	Li, X.	Spatial representation in the social interaction potential metric: an analysis of scale and parameter sensitivity
2013	Johnson, D.	Parks, Recreation & Tourism
2012	Fryer, G.	Wildland firefighter entrapment avoidance: developing evacuation trigger points utilizing the WUIVAC fire spread model.
2011	Groeneveld, J.	An agent-based model of bicyclists accessing light-rail in Salt Lake City
2011	Matheson, D.S.	Evaluating the effects of spatial resolution on hyperspectral fire detection and temperature retrieval
2010	Larsen, J.	Analysis of wildfire evacuation trigger-buffer modeling from the 2003 Cedar Fire, California.
2010	Smith, G.	Development of a flash flood potential index using physiographic data sets within a geographic information system
2010	Song, Y.	Visual exploration of a large traffic database using traffic cubes

2010	Evans, J.	Parks, Recreation & Tourism
2008	Naisbitt, W.	Avalanche frequency and magnitude: using power-law exponents to investigate snow-avalanche size proportions through time and space.
2008	Kim, H.C.	Civil Engineering
2007	Gilman, T.	Evaluating transportation alternatives using a time geographic accessibility measure
2004	Baurah, A.	An integration of active microwave remote sensing and a snowmelt runoff model for stream flow prediction in the Kuparak Watershed, Arctic Alaska
2004	Bosler, J.	A Development Response to Santaquin City's Natural Disasters.
2004	Bridwell, S.	Space-time masking techniques for privacy protection in location-based services
2004	Deeb, E.	Monitoring Snowpack Evolution Using Interferometric Synthetic Aperture Radar (InSAR) on the North Slope of Alaska, USA
2004	Sobek, A.	Access-U: a web-based navigation tool for disabled students at the University of Utah
2003	Barney, C.	Locating hierarchical urban service centers along the Wasatch Front using GIS location-allocation algorithms
2002	Koenig, L.	Evaluation of passive microwave snow water equivalent algorithms in the depth hoar dominated snowpack of the Kuparuk River Watershed, Alaska, USA
2002	Larsen, C.	Family & Consumer Studies
2002	Krokoski, J.	Geology & Geophysics
2000	Granberg, B.	Automated routing and permitting system for Utah Department of Transportation
2000	Bohn, A.	An integrated analysis of the Tijuana River Watershed: application of the BASINS model to an under-monitored binational watershed

Graduate student awards

2015	R. Hile., M.A. Geography: Jeanne X. Kasperson Award, Hazards, Risk & Disasters Specialty Group, Association of American Geographers.
2015	D. Li, Ph.D. Geography: Jeanne X. Kasperson Award, Hazards, Risk & Disasters Specialty Group, Association of American Geographers.
2012	K. Klein, M.A. Geography: *Jeanne X. Kasperson Award*, Hazards, Risk & Disasters Specialty Group, Association of American Geographers.

2010	L. Cao, Ph.D. Geography: *Student Paper Award*, Spatial Analysis and Modeling (SAM) Specialty Group, Association of American Geographers.
2008	L. Siebeneck, M.A. Geography: *Jeanne X. Kasperson Award*, Hazards Specialty Group, Association of American Geographers.
2007	E. Pultar, M.A. Geography: *Best Paper*, GIS Specialty Group, Association of American Geographers.
2006	J. VanLooy (not primary advisor): *Best Paper*, Rocky Mountain Regional Meeting, Association of American Geographers.

Undergraduate Mentoring and Advising

2015	Mentor, Marli Stevens, Undergraduate Research Opportunity Program: "Margin of Licensed Dog and Cat Populations and Adoptions from Animal Shelters in Utah in 2013-2014."
2015—	Advisor, Undergraduate Hazards & Emergency Management Certificate students (~10 students so far).
2006—2010	Advisor, Stewart Moffat, Honor's B.S. in Undergraduate Studies: Disaster Management (published journal article).
2005—2007	Advisor, Brian Williams, B.S. in Undergraduate Studies: Comprehensive Emergency Management.
2001—	Advisor, Undergraduate GIS Certificate Students (> 100 students).

Junior Faculty Mentoring

2014—	Ran Wei, Department of Geography, University of Utah
2011—2014	Steven Farber, Department of Geography, University of Utah
2009—2011	Scott Miles, Dept. of Geography, Western Washington U.
2009—2011	Timothy W. Collins, Department of Sociology, UT El Paso

SERVICE

Referee Duties

Journals
Applied Geography
Annals of the Association of American Geographers
Cartographica
Computers Environment & Urban Systems
Disasters
Environmental Hazards: Policy and Practice

Geographical Analysis
Geoinformatica
International Journal of Geographical Information Science
Journal of Geographical Systems
Journal of Transport Geography
Natural Hazards
Natural Hazards Review
Networks and Spatial Economics
Photogrammetric Engineering and Remote Sensing
Professional Geographer
Society & Natural Resources
Transportation Research A: Policy & Practice
Transportation Research B: Methodological
Transportation Research C: Emerging Technologies
Transactions in GIS

<u>National Science Foundation Panels</u>
Decision Risk and Uncertainty (1)
Geography and Spatial Science, Doctoral Dissertation Improvement Grant (4)
Civil & Mech. Systems – Infrastructure Management and Extreme Events (2)
Civil & Mech. Systems - Rural Resiliency (1)
NSF and NIH: Big Data (1)
Hazards SEES: Type 2 (1)

<u>Proposals</u>
Center for Disaster Management & Humanitarian Assistance
Faculty Research Grants, University of Utah (3)

<u>External Promotional Reviews</u>
Full Professor (5), Associate Professor (12)

Activities at Professional Conferences

2000 – 2017	**Paper session co-organizer, chair,** “Hazards, GIS and Remote Sensing” session, Annual Meeting of the Association of American Geographers.
2002 – 2003	**Paper session organizer, chair, and judge, “**GIS Specialty Group Student Paper Competition,” Association of American Geographers Annual Meeting.
1999	**Paper session organizer**, “Location Modeling and GIS,” Annual Meeting of the Association of American Geographers, Honolulu, Hawaii, March.

University Service

2014 – 2017	Member, Academic Senate
2014 – 2017	Member, University Promotion & Tenure Advisory Committee (UPTAC)

2011 –	Member, Social Science General Education Committee
1999 – 2009	Delegate, University Consortium for GIScience
2013	Member, Graduate Research Fellowship (GRF) Committee
2010 – 2012	Member Student Evaluations Committee, Undergrad. Studies
2009 – 2012	Member, Graduate Council, College of Soc. and Beh. Science
2003 – 2004	Member, Instit. Review Board (IRB) Protocol Committee
2001 – 2004	Member, Social Science General Education Committee

College Service: Social & Behavioral Science

2014 –	Chair, Review, Promotion & Tenure Committee
2012 – 2014	Member, College Review, Promotion, & Tenure Committee
2015	Member, Superior Teaching Committee
2011 – 2012	Chair, Superior Teaching Committee
2007	Member, Search Committee, Inst. of Public and Intern Affairs
2005, 2006	Member, Superior Research Committee
2002, 2004	Member, Superior Teaching Committee

Departmental Service: Geography

2015 –	Member, Undergraduate Committee
2014 –	Representative, University Academic Senate
2014 –	Director, Certificate in Hazards & Emergency Management
2014	Author, Proposal for Cert. in Hazards & Emergency Manage.
2012 –	Chair, Review, Promotion & Tenure Committee
2013	Chair, Search Committee for GIScience Position
2012	Co-author, Proposal for MS in GIScience
2011 – 2012	Director of Graduate Studies
2010	Search Committee Chair, Human Geography Position
2004 – 2015	Member, Graduate Admissions Committee
2004 – 2008	Member, Colloquium Committee
2000 –	Chair, Geographic Information Science Area Committee

Mapping wildfire evacuation vulnerability in the western US: The limits of infrastructure

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GeoJournal
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Mapping wildfire evacuation vulnerability in the western US: the limits of infrastructure

Thomas J. Cova · David M. Theobald · John B. Norman III · Laura K. Siebeneck

Abstract Residential development in fire-prone areas of the western United States is a growing concern. The steady addition of homes to this region places more people and property at risk each year. In many areas housing is increasing without commensurate improvements in the road network, particularly in regards to the number, capacity and arrangement of community exit roads. This results in steadily increasing minimum evacuation times, as each additional household contributes to potential evacuation travel-demand in a wildfire. The goal of this research is to perform a comprehensive geographic search of the western U.S. for communities in wildfire-prone areas that may represent difficult evacuations due to constrained egress. The problem is formulated as a spatial search for fire-prone communities with a high ratio of households-to-exits and solved using methods in spatial optimization and geographic information systems (GIS). The results reveal an initial inventory and ranking of the most difficult wildfire evacuations in the West. These communities share a unique vulnerability in that all residents may not be able to evacuate in scenarios with short warning time. For this reason they represent prime candidates for emergency planning, and monitoring their development is a growing need.

Keywords Evacuation · Wildfire · Transportation

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L. K. Siebeneck
Department of Public Administration, University of North Texas, Denton, TX, USA

Introduction

Residential development in fire-prone areas of the western U.S. (hereafter referred to as the West) is a growing concern. The ongoing addition of homes to areas in or near wildlands (commonly referred to as the wildland-urban interface or WUI) places more people and property at risk each year (Cohen 2000; Haight et al. 2004; Radeloff et al. 2005; Spyratos et al. 2007). Theobald and Romme (2007) estimate that residential development in fire-prone areas in the West expanded by 52% from 1970 to 2000, and the WUI now constitutes more than 12.5 million homes on 465,000 km^2. At the same time, climate change is altering the drought cycle through precipitation and temperature regimes leading to an increase in fire frequency and associated forest consumption (Westerling et al. 2006). Stephens et al. (2009) credit exurban development in fire prone areas combined with extreme, drought-induced wildfire events for a geometric increase in structure loss in recent decades.

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In most cases housing units are added to fire-prone canyons and hillsides without improving the road infrastructure. This means that although new roads may be added to a community to support the development of additional homes, an improvement in the number, direction, and capacity of the primary exits is much less common. This has implications for future evacuations, as exiting roads can place a significant constraint on clearing a community of its residents in an urgent scenario, or one with little warning time (Lindell and Perry 2004; Gill and Stephens 2009). In short, the minimum evacuation time of a community increases incrementally with each new household, as its occupants may contribute to potential evacuation travel demand in a wildfire (Cohn et al. 2006; Dash and Gladwin 2007; Mozumder et al. 2008). At the same time, there is growing concern that the fuel to support an intense wildfire in many communities is accumulating from the addition of wood structures, as well as the suppression of wildfires near populated areas. For this reason, Schoennagel et al. (2009) concluded that strengthening evacuation planning is needed in the WUI, as well as assisting public agencies in coordinating fuel-reduction treatments.

The primary result of the tandem increase in fuel and minimum evacuation times is a steady spiral upward in fire hazard and human vulnerability (Cutter et al. 2000) in many communities. This has been laid bare by enormous losses in recent wildfire events throughout the West, many of which also demonstrate that urgent evacuations can be impeded by limited road infrastructure. Two recent examples include the 2008 Tea Fire and 2009 Jesusita Fire in Santa Barbara County. The Tea Fire, which started just north of the town of Montecito, allowed proximal households less than an hour to evacuate, leading to the extreme case where Westmont College chose to recommend shelter-in-place in a gymnasium for an estimated 800 students, as there was not enough time to ensure that all students could safely leave on the campus roads before the fire arrived. In the 2009 Jesusita Fire, which started just north of the city of Santa Barbara, traffic congestion occurred during an evacuation of Mission Canyon when residents that had been monitoring the fire for days were caught off guard by a sudden increase in the fire's spread-rate and intensity toward their community. This resulted in highly concentrated evacuation travel demand on narrow roads in low visibility due to smoke.

Given this tandem increase in threat (fuel) and exposure (housing and residents) in fire-prone communities throughout the West, emergency planning and mitigation is a growing need (Perry 1985; Tierney et al. 2001; Platt 2006). The level of preparedness among the residents of these areas varies substantially, as evacuation planning is not required in fire-prone communities in the U.S. However, there are many efforts underway, local to national, to address the broader problem of ongoing development in fire-prone areas from many perspectives (Moritz and Stephens 2008). One step toward improving the allocation of planning and response resources in the WUI is a comprehensive geographic assessment of the potential for road infrastructure to impede an evacuation. For example, what fire-prone communities in the West have relatively few exits and a high density of housing units? How are these communities distributed across the eleven states that make up the West? What canyons and hillside communities represent the worst (most constrained) potential evacuations in the West? Answers to these questions would help initially focus emergency planning efforts and resources on communities with the greatest need (Cova and Johnson 2002; Church and Sexton 2002; Wolshon and Marchive 2007; Chen and Zhan 2008).

The goal of this research is to systematically search the western U.S. for fire-prone communities that have the greatest potential to experience evacuation problems due to road infrastructure constraints. Although this geographic variation has been studied at the scale of an individual city (Cova and Church 1997; Church and Cova, 2000), a broad-scale search and comparison of communities across the 11 Western U.S. states represents uncharted territory. The next section provides background on the problem including a discussion of concepts and prior work. The "Methods" Section reviews the data sources, pre-processing and spatial optimization modeling. The "Results" Section presents the findings, and the paper concludes with a discussion of the strengths, weaknesses, implications and potential for further research.

Background

The problem of performing a search for neighborhoods that may be difficult to evacuate due to constraints imposed by road infrastructure was presented by Cova and Church (1997). The concept of *egress*, or a means of exiting an area, is central to this work. The process of developing measures of egress is similar to developing spatial accessibility measures in general, but with a particular focus on the ease (or lack of ease) with which a threatened population can leave an area in an emergency. The initial measure applied in this work was the ratio of population in an area (demand) to the number of lanes in the set of exit roads (supply). This was extended to the concept of "bulk lane demand" where the numerator was changed to an estimate of the number of vehicles that might be used in a worst-case evacuation (i.e. the case where most of the community is at home) (Church and Cova 2000). While egress is rarely the binding constraint in evacuations as most events allow sufficient lead time to clear an area safely, it can represent a bottleneck in urgent scenarios when travel demand exceeds the capacity of the roads (Cova and Johnson 2002).

One of the initial problems in searching for neighborhoods with a high demand-to-capacity ratio is the definition of an "exit" when the evacuation zone boundary is not pre-defined (Cova 2005). One way to approach this problem is to search for the most constraining bottleneck-set (exit links) for a set of contiguous intersections (nodes). This set of network arcs that connects the nodes to the rest of the network is referred to as the minimum "cut set" in graph theory, as it represents the fewest arcs that, when removed, separate a node set (community) from the rest of the road network. For example, if a community has only one exit, the cut-set is easily identified as this link, but if there are two or more exits, the search for the minimum cut-set in a complex road network is a combinatorial optimization problem. If the minimum cut-set is large (e.g. 5 or more arcs), then the community that depends on these arcs would not generally be considered constrained by road infrastructure in an evacuation, but this depends to a large degree on the housing density, the configuration of the road network, and the urgency of an evacuation scenario (i.e. travel demand in space and time).

To address the combinatorial search for neighborhoods that might be difficult to evacuate from the set of all possible evacuations, Cova and Church (1997) presented an integer programming (IP) model called the Critical Cluster Model (CCM). The focus of this model is maximizing the ratio of population-to-exits for a fixed "root node" and associated scale limit (in nodes) in a larger network. While the CCM defined the problem, it can only be solved optimally on very small networks, and the search in real (larger) road networks is performed with a heuristic region-growing algorithm. This algorithm treats each node in a road network as a separate local problem by posing the question, "What is the worst-case evacuation (greatest ratio of population-to-exits) that this node might experience within a limited scale?" Scale in this context is defined as a node limit that represents a form of network-based search window. Thus, an example search might entail finding the set of contiguous intersections (nodes) that represents the worst-case evacuation (greatest demand to exiting lanes) within which a household assigned to that intersection (or node) might experience.

The CCM and associated region-growing heuristic were originally applied to a city network on the order of 5,000 nodes. Given that each node represents a separate sub-problem in a road network, the procedure can be applied to a network of any size. In other words, the computational effort to solve the CCM for each node is not an exponential function of the total number of nodes in the network. Rather, it is a linear function of the number of nodes, as a network of n nodes requires the heuristic to be solved n times, once at each node. However, the heuristic process is an exponential function of the search window (in nodes). For example, as the search window around a given node is expanded, the solution time to find the node-set that maximizes the ratio of demand (e.g. population, vehicles, housing) to supply (e.g. exiting roads) increases exponentially. Thus, the search can be performed on a network of any size, but the time to solve a given instance of the problem increases rapidly with the scale limit (or search window). Nonetheless, with a reasonably sized search window and modern desktop computing power, a much larger network can be analyzed than addressed in prior studies.

Methods

Study area and data

The primary challenge in this project is the extent of the study area. In moving from the city-scale to the eleven western U.S. states, the initial hurdle was acquiring and pre-processing the required data sets.

Two layers were needed—one representing the fire hazard at a level of detail sufficient enough to assign a hazard level to each node in a road network, and one representing the road network itself with each housing unit (single or multi-family structure) assigned to its closest intersection (or node). The general approach was to use the fire-hazard layer to screen the road network data, so as to only include roads in fire-prone areas—or a WUI roads layer. This greatly reduced the size of the road network by screening urban areas that have little to no wildfire risk. For example, the downtown centers of major cities (e.g. Denver, Phoenix, and San Francisco) were not included in the WUI road data set because they are not prone to wildfires. Other more remote areas with little to no fire hazard (e.g. agricultural land, deserts) were also removed, but these areas typically have sparse roads, so this reduction had less impact on the size of the resulting WUI roads layer (nodes and arcs) than the removal of urban areas. We used a national roads database (ESRI StreetMap 2006), which was pre-processed and separated into 12 files (10 states and Southern and Northern California).

The fire-hazard map used in this study is the LANDFIRE dataset (Rollins 2009), which is a 30-m resolution map with fire-hazard categories assigned to each cell. We based the fire hazard on the fire regime categories III and IV—or vegetation types that are characterized by low to stand-replacing severity with a 35–200-year fire frequency. The fire-hazard level of each intersection (node) in the road network was calculated as the proportion of fire-prone raster cells within a 2-mile radius of each node. This yields a 0–1 scale from no fire-hazard (0) to extreme fuel loads in a node's surroundings (1).

We estimated the number of housing units that would evacuate from each intersection (node) in the road network using the method presented in Cova and Church (1997). Thiessen polygons were computed for the network node layer and the number of housing units in each polygon was interpolated using equal-area weighting. To represent housing units, we used estimates based on U.S. Census 2000 block-level data and refined by land ownership, land cover, groundwater well density, and travel time to urban areas (Theobald 2005; Theobald and Romme 2007; Bierwagen et al. 2010). The resulting 1-hectare resolution raster of housing units was re-sampled to 30-m to ensure that a Thiessen polygon formed around each node would not fall below the resolution of the fire hazard map.

Critical cluster model and region growing heuristic algorithm

The heuristic algorithm used in this research begins at a root node and incrementally adds nodes on the (contiguous) fringe of the existing cluster (node set). The fringe is comprised of all nodes that are adjacent to the current cluster at any iteration by one arc (or link). The objective function that the heuristic attempts to maximize is the ratio of housing units in a node cluster (potential demand) to the road capacity that connects it to the rest of the network (supply):

$$\max \frac{P_k}{C_k} \tag{1}$$

where P_k is the total number of housing units in cluster k and C_k is the total link capacity connecting the cluster to the rest of the network. Additional constraints in the CCM include: (1) the root node must be included in the cluster, (2) the cluster must be contiguous, and (3) the cluster must be limited in size (nodes). These constraints can be handled with a region-growing algorithm that begins at a given (root) node and terminates at a pre-defined cluster size (in nodes). In general, a network-based region-growing algorithm begins at a node (constraint 1), grows by adding nodes on the fringe of the current cluster (constraint 2), and terminates when a given cluster size is reached (constraint 3).

At each step the algorithm evaluates all nodes on the fringe of the current cluster using the following growth function (or rule):

$$g_i = \frac{C_k(P_k - a_i)}{P_k(C_k + (o_i - c_i))} \tag{2}$$

where:

i = index of nodes
k = index of iteration
g_i = gain in the objective if node i is selected
P_k = total population of cluster at iteration k
C_k = total exit capacity of cluster at iteration k
a_i = population at node i
o_i = new exit capacity node i would open, if selected

c_i = existing exit capacity node i would close, if selected

This function assigns a value g_i to each node on the fringe of the current cluster (at each iteration) to specify the gain in the objective value if that node is selected. The algorithm can be run in a straight greedy fashion, in which case the node that most increases the objective function (Eq. 1) is selected, but Cova and Church (1997) demonstrated that a semi-greedy approach (Hart and Shogan 1987) consistently yielded the best results. In this approach, a parameter α is added to the algorithm to allow the selection of the best node to be within α percent of the node with the greatest gain value, which is also known as a GRASP approach (Feo and Resende 1989). The algorithm is then re-started n times from each root node, and the best overall run is saved (i.e. the one with the greatest objective value). One other improvement can be made in that any optimal cluster found from a given root-node can be automatically assigned to all the constituent nodes of that cluster. For this reason, an optimal cluster (i.e. constrained evacuation) will be found in a network if any of its constituent (root) nodes discovers it.

Results

The search for potentially difficult wildfire evacuations across the West due to limited road infrastructure yielded a wide variety of densely populated communities with high fire-hazard and relatively low egress. The search was accomplished by separating the 11 states that comprise the West (AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY) into 12 files, one for each state but two for CA because of its size in terms of nodes and arcs (NoCal and SoCal). The scale limit was set to 100 nodes (or intersections) for the search which means the process was capable of finding relatively complex communities up to 100 contiguous intersections. However, this means that if a low-egress community has over 100 intersections, it would be missed in the search. The implications of this threshold are that changing the scale-limit would yield a different ranking of low-egress communities because larger ones could be included that were not seen at a smaller scale limit. However, this limitation would exist at any selected threshold, and for the purposes of this project, 100 nodes was deemed a sufficient scale limit to locate the low-egress communities that had been discovered visually in prior manual searches.

Table 1 summarizes the input data, which represented a significant geo-computational challenge (Cutter 2003). The data for each state consists of an ESRI Shapefile^{TM} of the road network with node attributes that include the fire-hazard for each node and the respective number of housing units assigned to that node (i.e. closest assignment from Thiessen polygons). This GIS-based data was used to generate a network text-file for input into the heuristic algorithm described in Section "Methods". The heuristic algorithm was set to run in a semi-greedy fashion with 25 re-starts at each node and an alpha parameter of 0.90, and the run times ranged from 15 to 60 min depending on the number of nodes in a given file (i.e. file sizes ranged from Wyoming at 97,980 nodes to SoCal at 481,899). The results of the algorithm runs were then rejoined to the appropriate Shapefile^{TM} for each state to visualize and map the results.

Another challenge in performing this search was defining the minimum fire hazard that must be present in a community for it to qualify as "wildfire prone" and the minimum level of egress for it to be considered a "constrained" evacuation. Initial searches without regard to the fire-hazard level in a community yielded thousands of low-egress communities, many that would not be considered fire-prone. The higher the threshold

Table 1 A summary of the network input data for the 11 western states

State	Nodes	Arcs	Housing units	Mean fire hazard
AZ	206,381	261,776	418,346	0.64
SoCal	481,899	638,032	6,438,861	0.63
NoCal	171,406	209,408	968,636	0.50
CO	196,720	234,151	413,066	0.73
ID	192,480	238,915	398,382	0.74
MT	162,594	189,335	218,789	0.72
NM	202,263	249,134	334,235	0.64
NV	97,980	123,664	186,303	0.69
OR	310,886	360,412	927,770	0.70
UT	162,206	196,011	493,514	0.70
WA	299,781	368,642	1,522,378	0.67
WY	123,186	161,842	97,401	0.81
Total	2,607,782	3,231,322	12,417,680	

that defines the minimum required fire-hazard for a given node cluster (or community) to be considered wildfire-prone, the fewer communities that will found. Similarly, the higher the threshold that defines the minimum ratio of households-to-exits for a community to be considered a "constrained" evacuation, the fewer communities that will be returned. To develop an initial list of communities, we set the median fire hazard in a community (node set) to a minimum of 0.7 on a scale of 0–1 and the minimum ratio of households-to-exits to 200 (e.g. a community with 200 homes and 1 exit). The median fire-hazard threshold was more effective than the mean fire hazard because many nodes had a fire hazard level of 0, and the mean is very sensitive to outliers. This yielded a host of communities with relatively high fire-hazard and low egress in regards to an urgent evacuation scenario (Fig. 1).

While the dots in Fig. 1 depict the spatial clustering and arrangement of some of the communities that were found, Figs. 2, 3, 4 show a representative selection of communities. Figure 2 depicts the Glen Oaks Canyon subdivision in Glendale, California. This community has an estimated 776 homes and 1 exit (776/1 = 776 households-per-exit). Figure 3 depicts the Dillon Lake Area of Silverthorne, Colorado which has an estimated 743 homes and 2 exits (743/2 = 371.5 homes per exit). Figure 4 shows Bryant Ranch in Yorba Linda, California which has an estimated 1,222 homes and 3 exits (1,222/3 = 407.3 homes per exit). All three of these communities met the minimum wildfire-hazard level to qualify as fire-prone, but the actual fuel loads in and around each community returned by the search varied significantly. However, these three cases provide sufficient evidence that, despite the large extent of the search (11 states) relative to the level of detail (individual intersections and street segments), the approach presented locates communities that would represent challenging wildfire evacuations.

Tables 2, 3 and 4 show the top communities that were found across the West sorted by the objective value of the ratio of households-to-exits. The tables are separated into communities with 1-exit, 2-exits and 3-exits because the infrastructure vulnerability of these three sets of communities is qualitatively different. While a community with 2 or 3 exits might have a higher ratio of households-to-exits than one with 1 exit, the additional exits provide the community with a backup plan if one (or more) exits is lost to a wildfire or traffic accident. Communities with one exit would be in a shelter-in-place only (e.g. active home-defense) scenario if the sole exit was removed (Handmer and Tibbits 2005; Paveglio et al. 2008; McCaffrey and Rhodes 2009; Cova et al. 2009; Stephens et al. 2009).

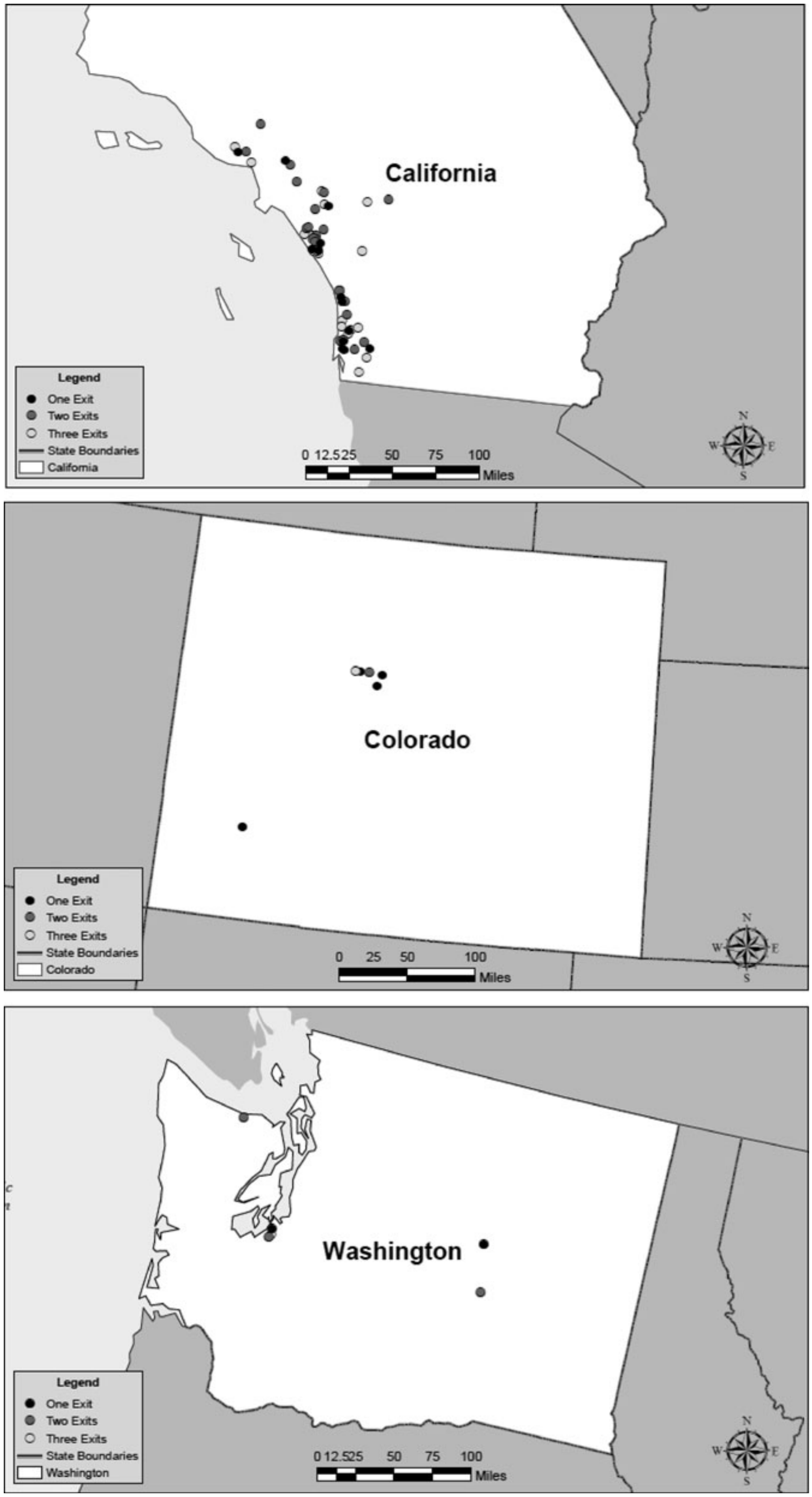
A dominant theme in these tables is the prevalence of Southern Californian (SoCal) communities in the ranking. SoCal has a very unique combination of high fire-hazard, dense population, and topographic constraints that has resulted in scores (if not hundreds) of fire-prone, low-egress developments. Although other western states (including Northern California) may have a similar combination of wildfire hazard and low egress in isolated locales, no region in the West comes close to the widespread coincidence of fire and egress factors present in Southern California.

Discussion

This work provides the first analysis of fire-prone, low-egress communities for a broad geographic extent. The results provide a rigorous comparison of communities in the arid West that may be useful for prioritizing efforts to mitigate or monitor the risk of wildfire events to canyon and hillside communities. Although the findings using this approach were promising, the results of the search can only be considered an initial step toward enumerating and ranking fire-prone, low-egress communities in the U.S. We caution that there are many hurdles in terms of data quality, methods, and validation that stand in the way of strong statements regarding the completeness or quality of the resulting list. This limitation arises primarily from the extent of the study area (11 western states) relative to the level of detail of the analysis (intersections).

From a data quality perspective, there are many issues to be addressed. GIS-based street network data can have missing links and nodes which can lead to results that differ significantly from reality. For example, a missing exit in the network data might lead a 2-exit community to appear as a 1-exit community in the computed ranking, effectively doubling its ratio of households-to-exits. The housing data is also dated and should be updated to the 2010 U.S. Census. From a methodological point of view, there are a number of sources of error and uncertainty that can lead to limitations in the results. This spans many step of the

Fig. 1 Fire-prone, low-egress communities (1–3 exits) in California, Colorado and Washington



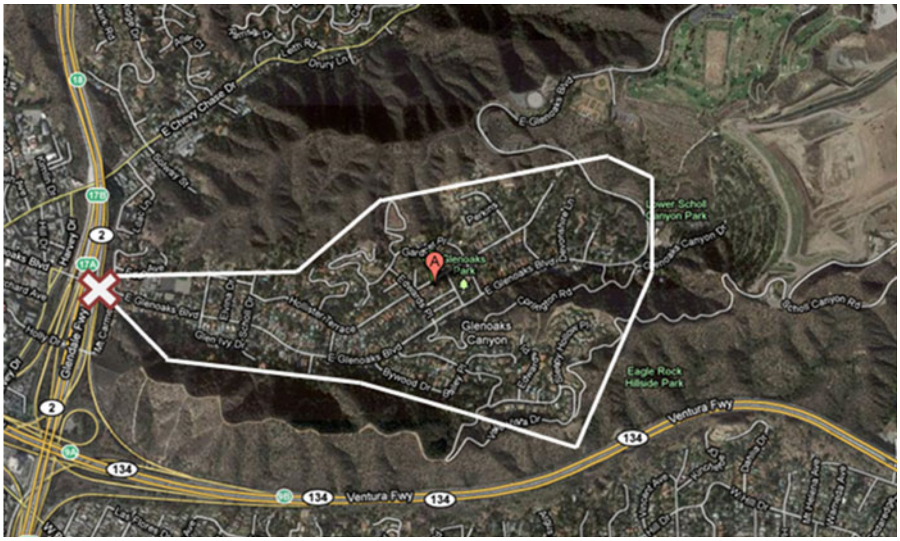


Fig. 2 The Glen Oaks Canyon subdivision in Glendale, CA has an estimated 776 homes and 1 exit (*Image source*: Google Maps)

Fig. 3 The Dillon Lake Area in Silverthorne, CO has a community with an estimated 743 homes and 2 exits (*Image source*: Google Maps)

process from: (1) the creation and assignment of fire-hazard levels to the network nodes (Finney 2005), (2) the assignment of housing units to nodes, and (3) the heuristic nature of the search algorithm.

Another source of uncertainty arises from using housing units as a proxy for travel demand in an emergency without including the time-dependency of the presence of residents. Many of the communities that were found in this search are ski resorts and country clubs, as these facilities can have a very high density of housing units and few exits. This is generally due to either their topographic context or a desire for social exclusivity. For the ski-resort case, occupancy levels during the peak fire season in the northern hemisphere (May–Oct) may be much lower (e.g. less than 50%) than the winter months, but summer use in these areas is increasing (Riebsame et al. 1996). This makes housing units an imperfect measure of potential wildfire-evacuation travel-demand. In terms of the country-club example, the fire hazard may not be as high as the method in this paper implies because the landscaped vegetation in many of these areas is not very fire prone. These issues among others represent fertile areas for improving the overall search process and comparison of fire-prone, low-egress communities.

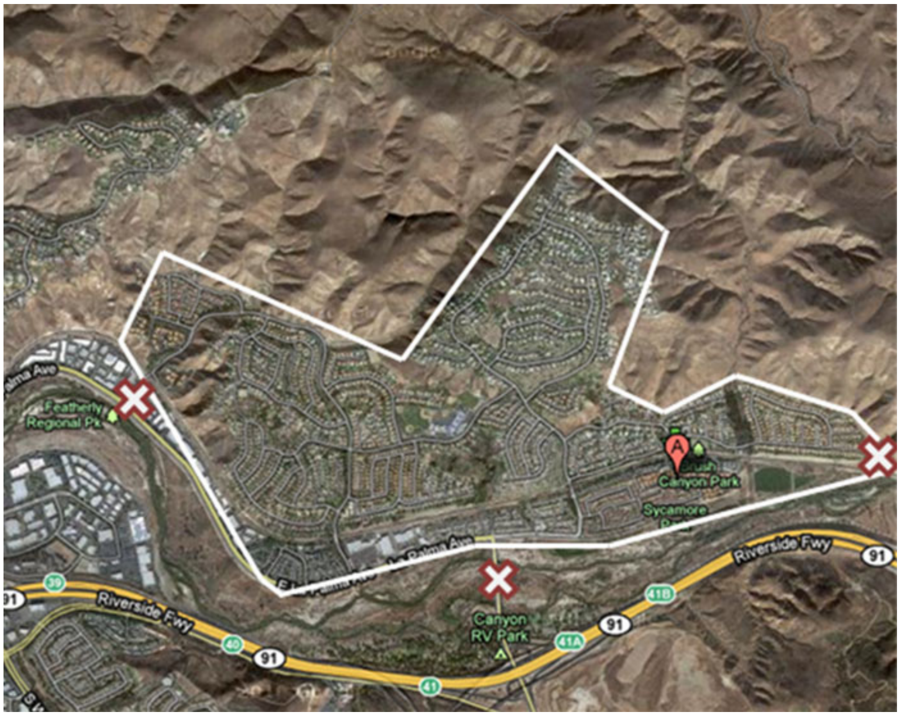


Fig. 4 Bryant Ranch in Yorba Linda, CA has an estimated 1,222 homes and 3 exits (*Image source*: Google Maps)

Conclusion

The WUI now comprises a large and growing number of homes, and many of these communities have relatively few exits and a growing housing density. The goal of this research was to perform a comprehensive geographic search for fire-prone, low-egress communities in the West. The results yielded a wide variety of communities across 11 states with an egress ratio of greater than 200 households-to-exits (and in select cases much higher). These communities represent challenging evacuations in cases when warning time is short. Although we presented an initial ranking of communities that represent the most

Table 2 The top communities in the West with median fire hazard above 0.7 (0–1) and 1 exit

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
1	57	0.75	806.4	1	806.4	33.167	−117.134	SoCal
2	59	0.70	803.6	1	803.6	33.192	−117.319	SoCal
3	64	0.90	776.7	1	776.7	34.152	−118.211	SoCal
4	79	0.95	755.9	1	755.9	39.627	−106.417	CO
5	51	0.84	748.3	1	748.3	39.619	−106.100	CO
6	75	0.88	630.7	1	630.7	39.593	−106.010	CO
7	47	0.81	597.1	1	597.1	39.474	−106.058	CO
8	66	0.86	571.7	1	571.7	32.941	−117.158	SoCal
9	13	0.74	560.2	1	560.2	34.169	−118.530	SoCal
10	44	0.83	552.7	1	552.7	33.150	−117.291	SoCal
11	9	0.77	535.4	1	535.4	39.501	−106.158	CO
12	23	0.88	527.6	1	527.6	47.201	−122.514	WA

Table 2 continued

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
13	31	0.82	514.9	1	514.9	33.881	−117.661	SoCal
14	85	0.84	501.2	1	501.2	33.000	−117.184	SoCal
15	93	0.84	500.4	1	500.4	37.932	−107.855	CO
16	41	0.89	467.8	1	467.8	34.130	−118.723	SoCal
17	41	0.75	467.0	1	467.0	47.49	−122.693	WA
18	35	0.77	458.4	1	458.4	32.833	−116.898	SoCal
19	8	0.79	457.0	1	457.0	32.778	−117.181	SoCal
20	43	0.85	441.3	1	441.3	33.229	−117.141	SoCal
21	19	0.75	436.5	1	436.5	35.144	−106.546	NM
22	19	0.75	435.3	1	435.3	33.572	−117.653	SoCal
23	20	0.76	434.2	1	434.2	34.115	−117.765	SoCal
24	3	0.71	428.5	1	428.5	34.726	−120.511	SoCal
25	5	0.77	425.2	1	425.2	47.11	−122.582	WA
26	22	0.86	423.7	1	423.7	33.746	−117.924	SoCal
27	9	0.77	423.2	1	423.2	33.508	−117.721	SoCal
28	24	0.80	416.7	1	416.7	32.945	−117.206	SoCal
29	49	0.84	399.2	1	399.2	33.559	−117.695	SoCal
30	5	0.90	394.9	1	394.9	33.819	−118.013	SoCal
31	11	0.76	394.7	1	394.7	32.772	−117.170	SoCal
32	19	0.70	394.0	1	394.0	33.660	−117.644	SoCal
33	11	0.88	389.4	1	389.4	32.922	−117.114	SoCal
34	22	0.82	383.0	1	383.0	32.789	−117.181	SoCal
35	100	0.77	378.9	1	378.9	40.624	−111.488	UT
36	38	0.88	375.4	1	375.4	47.551	−119.452	WA
37	25	0.75	373.3	1	373.3	32.784	−117.159	SoCal
38	38	0.74	372.8	1	372.8	33.517	−117.657	SoCal
39	20	0.89	370.6	1	370.6	32.850	−117.187	SoCal
40	9	0.77	368.2	1	368.2	32.837	−116.903	SoCal

Table 3 The top communities in the West with median fire hazard above 0.7 (0–1) and 2 exits

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
1	64	0.77	1,865.1	2	932.6	34.410	−118.452	SoCal
2	60	0.74	1,862.1	2	931.1	33.617	−117.716	SoCal
3	90	0.73	1,729.5	2	864.8	33.686	−117.652	SoCal
4	5	0.84	1,717.8	2	858.9	47.121	−122.526	WA
5	88	0.83	1,558.7	2	779.4	33.161	−117.265	SoCal
6	64	0.81	1,353.7	2	676.8	32.807	−117.056	SoCal
7	37	0.74	1,322.8	2	661.4	33.598	−117.705	SoCal
8	100	0.97	1,287.2	2	643.6	39.640	−106.405	CO
9	72	0.74	1,145.7	2	572.9	32.872	−116.973	SoCal
10	58	0.70	1,125.1	2	562.5	33.492	−117.671	SoCal
11	32	0.71	1,098.5	2	549.3	33.739	−117.847	SoCal

Table 3 continued

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
12	60	0.81	1,002.4	2	501.2	33.595	−117.735	SoCal
13	78	0.84	939.8	2	469.9	33.230	−117.350	SoCal
14	89	0.82	907.7	2	453.9	32.847	−117.224	SoCal
15	43	0.78	889.5	2	444.7	33.661	−117.831	SoCal
16	100	0.75	866.2	2	433.1	33.824	−117.786	SoCal
17	16	0.83	865.2	2	432.6	32.918	−117.139	SoCal
18	45	0.88	852.4	2	426.2	32.858	−117.192	SoCal
19	68	0.81	835.5	2	417.8	33.535	−117.670	SoCal
20	43	0.87	830.5	2	415.2	34.147	−118.827	SoCal
21	100	0.94	790.9	2	395.5	48.075	−123.375	WA
22	82	0.90	773.1	2	386.5	34.147	−118.638	SoCal
23	69	0.70	772.1	2	386.1	34.198	−118.917	SoCal
24	77	0.93	766.7	2	383.4	32.908	−117.066	SoCal
25	33	0.78	764.9	2	382.5	33.673	−117.815	SoCal
26	54	0.81	756.4	2	378.2	33.571	−117.710	SoCal
27	50	0.72	751.0	2	375.5	34.390	−118.560	SoCal
28	57	0.74	745.8	2	372.9	33.970	−117.739	SoCal
29	68	0.86	734.6	2	367.3	39.630	−106.288	CO
30	60	0.80	733.3	2	366.7	32.961	−117.231	SoCal
31	64	0.76	733.0	2	366.5	33.662	−117.976	SoCal
32	100	0.74	716.7	2	358.4	33.505	−117.636	SoCal
33	44	0.76	710.9	2	355.4	33.496	−117.697	SoCal
34	99	0.71	687.9	2	344.0	47.135	−119.323	WA
35	95	0.91	686.3	2	343.1	33.063	−117.215	SoCal
36	8	0.98	678.6	2	339.3	34.124	−118.148	SoCal
37	61	0.85	676.5	2	338.2	33.550	−117.729	SoCal
38	16	0.87	676.0	2	338.0	32.937	−117.116	SoCal
39	6	0.80	674.4	2	337.2	34.030	−117.056	SoCal
40	40	0.73	661.8	2	330.9	34.007	−118.042	SoCal

Table 4 The top communities in the West with median fire hazard above 0.7 (0–1) and 3 exits

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
1	91	0.79	4,700.3	3	1,566.8	33.767	−118.086	SoCal
2	76	0.75	2,070.9	3	690.3	33.607	−117.715	SoCal
3	39	0.86	1,557.4	3	519.1	47.142	−122.504	WA
4	51	0.80	1,517.2	3	505.7	33.603	−117.737	SoCal
5	80	0.76	1,264.7	3	421.6	33.582	−117.207	SoCal
6	90	0.83	1,241.9	3	414.0	32.947	−117.141	SoCal
7	94	0.87	1,228.5	3	409.5	33.981	−117.765	SoCal
8	77	0.76	1,221.9	3	407.3	33.877	−117.702	SoCal
9	90	0.83	1,152.2	3	384.1	33.612	−117.750	SoCal
10	47	0.79	1,147.9	3	382.6	33.777	−118.387	SoCal

Table 4 continued

Rank	Nodes	Fire haz	Homes	Exits	Homes-to-exits	Lat	Long	State
11	91	0.81	1,131.1	3	377.0	33.233	−117.337	SoCal
12	71	0.74	1,119.7	3	373.2	33.220	−117.310	SoCal
13	100	0.92	1,108.4	3	369.5	34.137	−118.660	SoCal
14	98	0.79	1,103.8	3	367.9	33.633	−117.569	SoCal
15	86	0.86	1,102.8	3	367.6	39.62	−106.488	CO
16	64	0.83	1,098.0	3	366.0	33.614	−117.836	SoCal
17	74	0.70	1,083.6	3	361.2	32.634	−116.958	SoCal
18	48	0.82	1,080.4	3	360.1	33.515	−117.689	SoCal
19	88	0.83	1,077.1	3	359.0	32.755	−116.915	SoCal
20	89	0.79	1,075.5	3	358.5	33.497	−117.703	SoCal
21	34	0.85	1,073.3	3	357.8	33.756	−117.910	SoCal
22	99	0.74	1,070.3	3	356.8	34.435	−118.484	SoCal
23	99	0.88	1,059.4	3	353.1	34.009	−117.791	SoCal
24	100	0.78	1,059.3	3	353.1	33.975	−117.265	SoCal
25	87	0.88	1,053.5	3	351.2	33.004	−117.248	SoCal
26	81	0.77	1,052.6	3	350.9	32.916	−117.159	SoCal
27	47	0.74	1,045.1	3	348.4	33.783	−118.128	SoCal
28	100	0.77	1,040.9	3	347.0	39.716	−105.171	CO
29	97	0.70	1,040.0	3	346.7	33.490	−117.647	SoCal
30	59	0.83	1,007.0	3	335.7	33.585	−117.742	SoCal
31	31	0.74	1,003.1	3	334.4	33.508	−117.668	SoCal
32	45	0.74	1,000.1	3	333.4	32.980	−117.070	SoCal
33	59	0.73	994.4	3	331.5	32.957	−117.239	SoCal
34	76	0.74	972.7	3	324.2	34.043	−117.859	SoCal
35	34	0.80	962.7	3	320.9	47.262	−122.521	WA
36	59	0.84	958.8	3	319.6	33.875	−117.630	SoCal
37	85	0.87	951.3	3	317.1	34.074	−118.560	SoCal
38	89	0.79	944.5	3	314.8	34.163	−118.768	SoCal
39	66	0.80	918.3	3	306.1	32.643	−117.045	SoCal
40	90	0.79	909.7	3	303.2	33.681	−117.636	SoCal

constrained cases in terms of road infrastructure, a significant amount of work remains in improving the overall search process and associated results. In the longer term, there is a need to identify and rank these communities to target them for emergency planning, as well as to encourage local governments to consider the public safety implications of unchecked development in fire-prone areas.

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