Do Debris Flows Pose a Hazard to Mountain-Front Property in Metropolitan Phoenix, Arizona?*

Ronald I. Dorn
Arizona State University

Remnants of old debris flows occur on mountains that have been surrounded by growing suburbs of metropolitan Phoenix, Arizona, including on steep slopes above large single-family dwellings. Varnish microlamination and lead-profile dating techniques measured ages of 34 debris-flow levees in nine randomly selected catchments above home sites. Four catchments experienced debris flows in the last century, and four others had events in the last 350 years. Debris flows likely pose a modern hazard in Phoenix and perhaps other growing cities in the desert Southwest. **Key Words: debris flow, desert, geomorphology, hazards, urban sprawl.**

古泥石流的残余发生在被亚利桑那州的大都市凤凰城扩展的郊区所包围的山脉，包括大单户住宅上方的陡峭的山坡上。我们用光油微层压和铅剖面测年技术测量了位于住宅上方随机选择的流域中的 34 个泥石流堤。四个流域在上个世纪经历了泥石流，另外 4 个在过去 350 年发生过泥石流事件。泥石流可能会在凤凰城和其他沙漠西南部扩展的城市造成现代的危害。关键词：泥石流，沙漠，地貌，灾害，城市扩张。

Los restos de antiguos flujos de detritos se presentan en las montañas que están siendo rodeadas por suburbios del área metropolitana de Phoenix, Arizona, incluso en las laderas inclinadas situadas más arriba de residencias unifamiliares. Con técnicas de datación por barniz de microlaminación y perfil de plomo se midió la edad de 34 elevamientos de flujo de detritos para nueve captaciones situadas arriba de las viviendas, seleccionadas aleatoriamente. Cuatro de esas captaciones experimentaron flujos de detritos durante el pasado siglo, y otras cuatro tuvieron eventos de tal naturaleza durante los pasados 350 años. Los flujos de detritos sin duda representan un riesgo moderno en Phoenix y quizás en otras ciudades en expansión en el Sudoeste desértico. **Palabras clave: flujo de detritos, desierto, geomorfología, riesgos, expansión urbana descontrolada.**

Debris flows are fast-moving mass wasting events where torrents of rock and mud launch down steep mountain slopes, sometimes disturbing only wild lands (Innes 1983; Iverson 1997; Bovis and Jakob 1999). Where the built environment abuts steep slopes, however, debris flows can impact homes and urban infrastructure. Debris flows are not floods. They are not giant rockslides. They are slurries that often contain large amounts of rock material that start on steep slopes, continue down channels, and can eventually reach buildings and roads. The Federal Emergency Management Agency (FEMA) treats debris flows as a distinct type of natural hazard (FEMA 2009).

Debris flows are a recognized hazard in a host of urban settings (McCall 1997), including beneath burned hillsides of Southern California (Cooke 1984; Keeley 2002), within urban steeplands of humid tropical settings (Gupta and Ahmad 1999), and where structures are built under steep slopes in cold, wet environments (Decaulne 2002; Glassey et al. 2002). Despite this general awareness, debris flows are not recognized as a hazard for development in metropolitan Phoenix and other arid southwestern cities. More than fifty different mountain masses are contiguous with homes in metropolitan Phoenix (Figure 1), and housing developments now abut twenty-three

Figure 1 *Locations of randomly selected study sites, where numbers identify catchments that generated debris flows now abutting housing. Study sites are superimposed on a Landsat 5 image of metropolitan Phoenix acquired 29 October 2009, courtesy of NASA Earth Observatory Image of the Day 42252. At the time, metropolitan Phoenix, Arizona, hosted a population of more than 4 million in an area of more than 37,000 km². Urban growth has brought housing into contact with fifty different mountain masses, twenty-three of which show evidence of debris flows.*

mountainous areas with slopes containing evidence of debris flows. Metropolitan Phoenix, Arizona, represents a world-class example of urban sprawl (Helm 2003; Gober 2005), where expensive single-family dwellings occur beneath the steepest mountain slopes with spectacular views (Figure 2). Building homes next to mountain slopes facilitates the additional amenity of being able to walk from a backyard into mountain preserves designed to protect wild lands and open space (Ewan, Ewan, and Burke 2004).

Hazard assessment carried out prior to home construction in Arizona in general, and Phoenix zoning ordinance in particular, does not con-

sider debris flows coming from steep mountain slopes (City of Phoenix 2009). The Maricopa County Flood Control District (Maricopa County 2010) exists to identify hazards related to flooding, but debris flows are a type of mass wasting event. Although the U.S. Geological Survey sometimes mentions desert debris flows in reports about flooding in southwest urban contexts (Norman and Wallace 2008), little attention has been paid to the potential for debris flows to do serious damage in expanding urban centers in the desert Southwest.

The past perspective, in the Arizona Geological Survey home owner's guide, was that "[m]ost of the debris flows that have occurred

Figure 2 *Examples of homes in wealthy mountainside neighborhoods built under debris-flow-generating catchments. The upper left image shows a debris-flow fan near Taliesen West, Scottsdale. The upper right image displays a large home and a future home site under debris-flow channels at Mummy Mountain, Paradise Valley. The lower left image shows homes placed under bedrock channels at Camelback Mountain; the lower middle image from Ludden Mountain illustrates home placement on former debris-flow levees, and the lower right image from Hedgpeth Hills reveal homes placed on a debris-flow fan. These images follow permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html). (Color figure available online.)*

in Arizona in the past several decades have been restricted to mountain valleys and canyons" (Harris and Pearthree 2002, 16). However, many of these mountain canyons have been overcome by housing developments in just the past half-decade since publication of this guide. An extreme July 2006 precipitation event near Tucson, Arizona (Griffiths et al. 2009), resulted in debris flows that impacted roads and some structures. The Arizona Geological Survey then undertook mapping and a hazard assessment (Pearthree and Young 2006; Magirl et al. 2007; Webb et al. 2008; Youberg et al. 2008). This event led to a change of thinking toward the view that desert debris flows could potentially be an underappreciated hazard (Pearthree, Youberg, and Cook 2007).

Flooding can be a form of social injustice in urban Arizona where the poor often live

in the most dangerous settings in floodplains (McPherson and Saarinen 1977; Committee on Public Works and Transportation, Subcommittee on Water Resources 1979; Saarinen et al. 1984; Graf 1988; House and Hirshboeck 1997; Honker 2002). In contrast, the wealthy citizens in metropolitan Phoenix, who build homes next to desert mountains, are the ones who might be at risk from debris flows. The question asked here is whether desert debris flows pose a significant hazard for the urban wealthy living next to steep mountains in metropolitan Phoenix.

For debris flows to pose a hazard in metropolitan Phoenix, as well as other expanding desert cities, they must occur frequently enough to put structures and people at risk. To understand occurrence rates of debris flows in a single mountain range, debris flows originating from 127 catchments on the north flank of the Ma Ha Tuak Range were sampled for dating by the varnish microlaminations (VML) and lead-profile chronometric methods; results yielded an estimate of fifty-six flows in the last century (Dorn 2010), leading to the conclusion that debris flows could pose a modern hazard. The question posed here is whether the results from a single mountain range reflect hazards found on the other ranges that have been surrounded by the sprawl of metropolitan Phoenix.

This article explores the hypothesis that rates of debris-flow occurrence above home sites scattered throughout metropolitan Phoenix are similar to rates observed for the intensively sampled north side of the Ma Ha Tuak Range (Dorn 2010). Homes back up against twenty-three different mountain areas that have produced debris flows, so sampling every single boulder levee in metropolitan Phoenix was not feasible. Thus, this attempt at a systematic urban hazard assessment of debris flows in metropolitan Phoenix involved random sampling of debris flows in mountain ranges abutting urban development.

This article starts by reviewing the nature of debris flows in metropolitan Phoenix, providing background on a topic that has skirted the awareness of urban geographers and planners. The Methods section explains the random sampling strategy and also the approach used to assess occurrence rates. The final section analyzes results with an attempt to answer the basic question of whether or not these debris flows pose enough of a hazard to warrant future restrictions.

Study Area

Urbanization in metropolitan Phoenix has enveloped what were once isolated mountains (Figure 1). Some of these mountains have been made into open space preserves (Ewan, Ewan, and Burke 2004), but many others are privately held. In circumstances where private land abuts mountains, homes have been built at the very base of mountain slopes steeper than 20° and in some cases steeper than 30° (Figure 2). Some homes have been built directly on fans composed of debris-flow deposits, and other homes have been built where slopes have been undercut through material removal (Figure 3).

Debris flows can start in a number of different ways: originating from large, impulsive loads derived from adjacent slopes; from movement of water through bedrock fractures; from a fire hose effect of bedrock funneling water toward colluvium; from wildfires; from mobilization of material in channels; from slumping of channel banks; and from other processes (Innes 1983; Bovis and Dagg 1987; Webb, Pringle, and Rink 1989; Coe, Cannon, and Santi 2008). The vast majority of metropolitan Phoenix debris flows appear to have initiated from saturation of colluvium located in the lower center of spoon-shaped catchments (e.g., Figure 4). These catchments are often small, most being less than 20,000 m². Because they can be quite steep, often in excess of 30°, the slopes are unstable, and there is an abundance of exposed bedrock. Extensive exposed rock means that rain turns into overland flow that moves quickly toward the center of a slope catchment. Intense precipitation and this overland flow can saturate colluvium collected in catchments, turning fines into a flow through changes in Coulomb friction and the internal pore-fluid pressure applied by too much water (Iverson 1997).

Once the flow starts, there is enough force to scour out channels down to bedrock. Channels are often only a few hundred meters long. As the flow moves, it entrains debris accumulated in bedrock channels. Then, at the base of bedrock channels, debris flows encounter slope colluvium—a mixture of boulders and cobbles.

Figure 3 *Location of a debris-flow event in Phoenix that occurred about 1,100 years ago and then again less than 350 years ago (Dorn 2009). Debris-flow deposits are found at the slope break. If these events had occurred after suburban development, several homes would have suffered major damage. (Color figure available online.)*
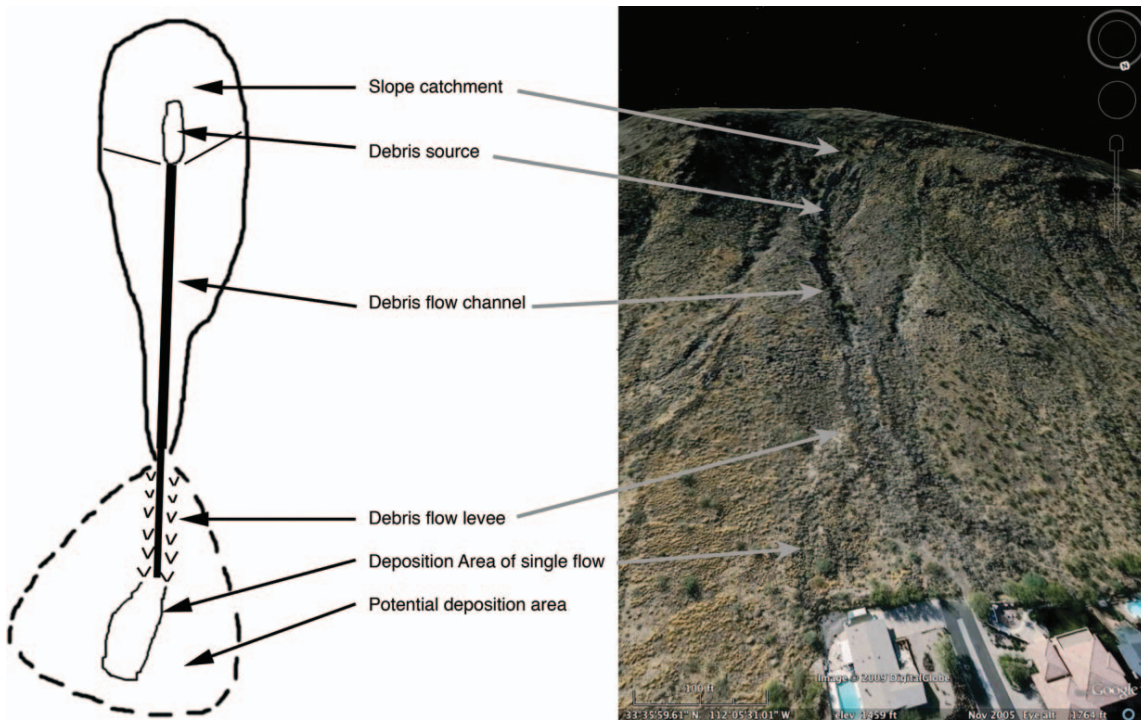
Figure 4 *Idealized diagram of a debris-flow system in small steep drainages of central Arizona, compared with the study site randomly selected at Shaw Butte, Phoenix. The right image is used following permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html). (Color figure available online.)*

Table 1 *Partial inventory of debris-flow pathways interfacing with urbanism in metropolitan Phoenix*

Mountain	City	Debris-flow catchments	Homes
Black Mountain, west side	Cave Creek	19	12
Camelback Mountain	Phoenix	22	12
Daisy Mountain, south side	Anthem	23	8
Gila Range, south side	Phoenix	77	11
Hedgpeth Hills	Glendale	28	15
Ludden Mountain	Glendale	13	8
Ma Ha Tuak Range, north side	Phoenix	127	17
McDowell Mountains, Lost Canyon	Scottsdale	27	10
McDowell Mountains, McDowell Ranch	Scottsdale	21	3
McDowell Mountains, Shea area	Scottsdale	32	14
Mummy Mountain	Phoenix	51	32
Shaw Butte	Phoenix	29	17

Note: Homes refers to number of houses that occur in the pathway of former debris flows.

Debris-flow levees, consisting of boulders, typically deposit where the flow leaves the confines of the bedrock channel. These boulder levees form through "complex interplay between the resistance of the first-deposited debris and the momentum of subsequently arriving debris" (Iverson 1997, 260). Debris-flow levees are important here, because they can be sampled to determine when former flows took place.

The debris-flow channels and levees are often obvious to a knowledgeable observer (e.g., Figures 2 and 4). Bedrock channels form distinctive troughs. Parallel levees form distinct topographic ridges. There are about fifty mountain areas within metropolitan Phoenix, and field observations of debris-flow catchments that abut housing developments revealed evidence of prior debris flows on twenty-three of these mountain areas. An ongoing survey of debris-flow routes reveals that more than 150 home sites occur on former pathways (Table 1). These homes occur directly underneath debris-flow chutes, on former levees, and on fans built by debris flows (Figure 4)—all attesting to lack of awareness or concern about debris flows.

Methods

The first step in this initial assessment of the potential hazard of debris flows required removal of operator bias in the selection of study sites. The author is quite familiar with a number of cases where hazards exist (e.g., Figure 3). Although these cases make interesting anecdotes, the goal of this study rests in understanding whether a metropolitan-wide hazard exists for mountain-front development—focusing on the question of whether occurrence rates of fifty-six debris flows in the last century in 127 Ma Ha Tuak catchments (Dorn 2010) mirror hazards in the larger metropolitan area. Thus, a stratified random sampling approach was employed to remove operator bias.

The entire Phoenix metropolitan region, most broadly interpreted (Figure 1), was subdivided into cells of one square mile each, using township and range sections. Sections were then selected using a random number generator. The closest debris-flow catchment to the center of each of the selected sections was then identified. Debris-flow catchments that did not impinge on developments were eliminated from any further study, as the purpose of this investigation was to understand urban hazards.

All debris-flow levees were sampled for dating in the randomly selected catchments that rest above or near development. A catchment often generates multiple debris-flow events, and it is possible to identify and sample multiple events—if pathways of later debris flows differ from earlier events. Sampling every levee ceased at the catchment where the thirtieth debris flow was dated—leading to a total of thirty-four dated debris flows; in all, nine basins were studied with an average of about four boulder levees sampled at each location.

The purpose of dating debris-flow events rests in estimating rates of occurrence. Events taking place once every 10,000 years would not

be considered hazardous, but multiple events that have taken place in the last hundred years would constitute a hazard. To assess frequency, all identifiable debris-flow levees derived from the randomly selected catchments were sampled for VML dating (Liu 2003, 2010; Marston 2003; Liu and Broecker 2007, 2008a, 2008b). The idea behind VML dating is that layering patterns of rock varnishes are produced by climatic changes. Wetter periods produce black layers, semiarid periods generate orange layers, and arid periods generate yellow layers. These VML patterns have been calibrated at dozens of locations in the southwestern United States using independent radiometric age control (Liu 2003, 2010; Marston 2003; Liu and Broecker 2007, 2008a, 2008b).

Following field procedures as described next, collected varnishes were made into cross sections thin enough to identify the layering pattern. Once the patterns were identified, VML were then compared with calibrations (Liu 2003, 2010; Marston 2003; Liu and Broecker 2007, 2008a, 2008b). The VML dating method does not give a precise age, like radiocarbon dating or tree-ring dating. Instead, matching varnish layers with the established calibrations generates age categories, such as younger than 350 years, between 350 and 650 years ago, between 900 and 1,100 years ago, between 1,100 and 1,400 years ago, and so forth. Although VML dating can provide only rough ages, this method is one of the few techniques that can determine the ages of debris flows in metropolitan Phoenix. Organic matter appropriate for radiocarbon dating has not been found embedded in levees, and cosmogenic nuclide dating suffers from boulders accumulating a prior exposure history in the catchment.

Analyzed samples were collected from the edges of the largest boulders on the debris-flow levees. Sampling on edges is important, because they receive the most abrasion during transport—resetting the VML clock after a debris flow. The climate of the Sonoran Desert fosters the growth of lichen and microcolonial fungi (MCF) in rock-surface depressions that are centimeter sized and larger. These organisms dissolve varnish and destroy VML patterns (Dragovich 1987, 1993; Dorn 1998, 2007). Thus, chips were removed from rock-surface depressions that are just a few mil-

limeters wide. Even in these tiny depressions, hand lens examination resulted in the rejection in the field of more than 90 percent of these chips because of growth of lichen and MCF. Of the samples that were brought to the lab, only one out of five showed VML patterns that were not disturbed by ancient growth of MCF. Thus, twenty rock chips were collected from each debris-flow levee to produce four viable samples to replicate VML ages for each of the thirty-four dated debris-flow levees.

Where the VML dating method revealed that a debris flow was younger than about 350 years, a second method was employed to refine the age estimate: lead-profile dating. Twentieth-century lead and other heavy metal pollution is recorded in rock varnish, because iron minerals in varnish scavenge lead and other metals. This scavenging leads to a detectable pollution "spike" in the top micrometer of a rock coating. The lead-profile method (Dorn 1998; Merrell and Dorn 2009) has been replicated (Fleisher et al. 1999; Thiagarajan and Lee 2004; Hodge et al. 2005; Wayne et al. 2006) and yielded a finding that (1) the varnish coating hosts the twentieth-century lead spike, or (2) the varnish started to form before the period of lead contamination. Thus, whereas VML dating can only establish that a varnish is less than 350 years old, lead-profile dating establishes whether the coating and the underlying levee formed in the twentieth century.

Calculation of occurrence rates of debris flows in each catchment requires knowledge of the number of events in a given time period. Unfortunately, it is not possible to know the true number of debris-flow events in a catchment; an unknown number of past debris-flow events could have been obliterated by newer flows. In an extreme example, if the most recent event was extensive enough, then only one datable debris-flow deposit would exist in a catchment, even if that catchment generated dozens of debris flows previously. Sedimentological analyses might reveal more complexity than surficial expressions of debris-flow levees, but excavation work at each site is beyond the scope of this research. Thus, the approach used here is to calculate a *minimum* occurrence rate by dividing the approximate age of the oldest event by the number of known debris flows from that catchment.

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Table 2 Randomly selected debris-flow catchments in metropolitan Phoenix and the ages of thirty-four debris flows from nine catchments

Mountain	Neighborhood and city	Catchment coordinates (degrees)	Catchment area (m²)	Vertical relief (m)	Fan gradient (degrees)	Varnish microlaminations ages (thousands of years)	Lead-profile dating for debris flows <350 years	Minimum occurrence in years
Usery (1)	Las Sendas, Mesa	N 33.49449 W 111.64324	54,000	149	8	<0.35, 16.5	Twentieth century	~8,000
McDowell (2)	Quail's Nest, Phoenix	N 33.69718 W 111.85439	16,000	140	9	<0.35, 2.8, 8.1, 17.8–24	Older than twentieth century	~6,000
Gavilan Peak (3)	New River	N 33.90623 W 112.12503	17,400	216	4	<0.35, 2.8, 8.1, 16.5	Twentieth century	~4,100
McDowell (4)	Saddleview, Scottsdale	N 33.57412 W 111.77495	2,150	140	5	0.35–0.65, 8.1, 16.5, 24	Older than twentieth century	~6,000
Ludden (5)	Glendale	N 33.71981 W 112.18985	19,000	226	4	<0.35, 0.35–0.65, 2.8, 8.1, 24	Twentieth century	~4,800
Shaw Butte (6)	Moon Valley, Phoenix	N 33.59789 W 112.09188	22,000	177	5	0.35–0.65, 8.1. 16.5, 24	N/A	~6,000
Mummy (7)	Paradise Valley	N 33.54914 W 111.95201	14,500	165	6	<0.35, 0.35–0.65, 8.1	Older than twentieth century	~2,700
McDowell (8)	Taliesen West, Scottsdale	N 33.61133 W 111.83254	11,500	183	7	<0.35, 8.1, 24	Older than twentieth century	~8,000
Gila (9)	Ahwatukee, Phoenix	N 33.30242 W 112.12086	16,500	146	7	<0.35, <0.35, 0.9–1.1, 2.8, 8.1	Twentieth century	~1,600

Note: The order presented in the table reflects the order of the random selection process and numbers match sites in Figure 1.

Frequency of Debris Flows: Is There a Hazard?

Minimum occurrence rates of thousands of years for the nine randomly selected catchments (Table 2) could be interpreted to suggest that debris flows pose no serious hazard to homeowners underneath these source areas. Using these minimum occurrence rates and a probability scale that ranks debris flows as very high, high, moderate, or low (Hungr 1997), the studied catchments would have a low probability of occurring in a homeowner's lifetime. This analysis, however, is flawed. Dozens of debris flows could have occurred over the past 500 years, and these minimum occurrence rates would not change so long as the youngest event erased evidence of prior flows. A much more meaningful finding is that four of the nine study sites experienced debris flows in the period of lead pollution during the twentieth century, and another four catchments generated debris flows in the last 350 years (Table 2).

The hypothesis explored here is that rates of debris-flow occurrence above randomly sampled home sites scattered throughout metropolitan Phoenix are similar to rates observed for the intensively sampled north side of the Ma Ha Tuak Range (Dorn 2010). The 127 catchments in the Ma Ha Tuak Range, Phoenix, generated approximately 140 debris flows in the last 350 years, with an estimated fifty-six of these in the last century (Dorn 2010). From the perspective of the entire north side of this range, on average, each catchment generated a debris flow in the last 350 years. Similarly, from the perspective of randomly selected catchments examined here, on average, each catchment generated about one debris flow in the last 350 years. Taken as a whole, fifty-six twentieth-century flows derived from 127 catchments in the Ma Ha Tuak Range, and four twentieth-century flows derived from nine randomly selected catchments across metropolitan Phoenix generate a similar finding: about 40 percent of sampled catchments produced a debris flow this past century.

This analysis suggests that a modern hazard could exist for any home placed underneath debris-flow-producing catchments in the desert mountains in metropolitan Phoenix and perhaps in southwestern desert cities elsewhere. This analysis also suggests that a random sampling of catchments appears to mirror occurrence rates for a mountain range where every catchment was studied—a finding that could be important in future studies on debris-flow hazards in desert regions.

A natural question asked by many at this point is whether any observations exist for historic debris flows in metropolitan Phoenix. The only published observation derives from Fuller (2010, 6), who reported that Troy Péwé's field notes left with the Arizona Geological Survey documented "damaging debris flows" in the Phoenix area during the 1970s in steep watersheds. An 18–22 January 2010 precipitation event generated ~70 mm of precipitation in the Ma Ha Tuak Range of Phoenix, leading to at least three debris flows traveling less than 140 m each. The author also found evidence of six debris flows generated in the McDowell Mountains from ~100 mm of precipitation during this storm; these debris flows all traveled less than 200 m. Approximately 158 mm of precipitation led to a 500 m debris flow (Figure 5) in northern metropolitan Phoenix from the 18–22 January storm—with the most intense rate of 104 mm in twenty-four hours. None of these debris flows were covered in the media, despite scars being visible from home sites (Figure 5) indicating that a general paucity of historic records does not provide insight into debris flows as a hazard in metropolitan Phoenix and perhaps other southwestern cities.

There are three major complicating factors in deciding whether to trust in the minimum recurrence intervals (Table 2) or be concerned about occurrence rates of debris flows in the last hundred years: poor preservation of debris-flow events, climate change, and uncertainties in rates of producing new debris. The first complicating factors would elevate the real hazard; the second would reduce the real hazard; and the third factor throws additional uncertainty into the decision-making process.

The first major complication is that there are an unknown number of debris-flow events that were not preserved. For example, the Mummy Mountain study site (Figure 4) preserved
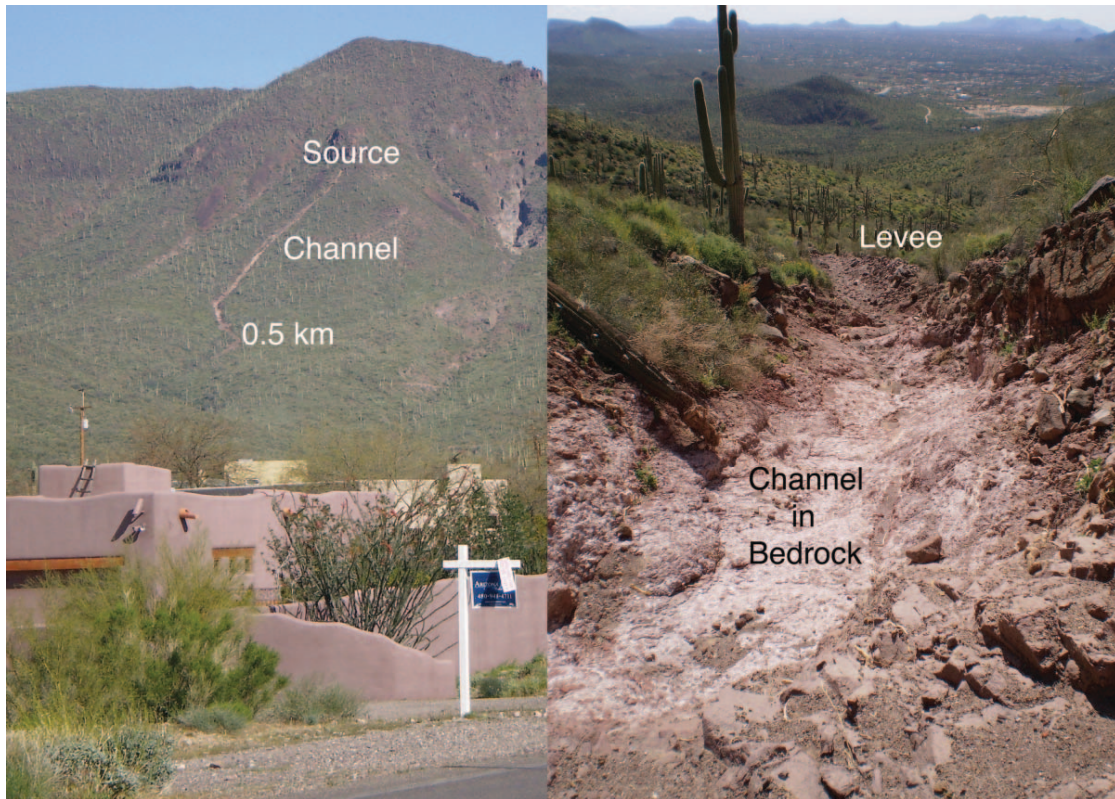
Figure 5 *Five hundred–meter long debris flow that occurred between 18 and 22 January 2010 on the northern fringe of metropolitan Phoenix. Fortunately, the debris flow took place in a county park sufficiently far from Cave Creek to avoid any damage. (Color figure available online.)*

three distinct debris-flow ages (Table 2). If a hundred additional debris-flow events had taken place in the last 8,100 years, but the evidence was obliterated by the two youngest events (and development), then the recurrence interval in this hypothetical scenario would be within a person's lifetime. Although such a scenario is unlikely, given the likelihood of a slow rate of debris production from weathering in the catchment, there is no way to know the accurate occurrence rate. The reason is that debris flows tend to deposit in the same narrow area underneath these slope catchments. Future studies of the sedimentary architecture of buried deposits might record events for which there is no surface evidence.

The second major complicating factor would be climate change. Wetter periods have occurred in the past. These wetter periods leave the signature of layers within rock varnish, and it is these layers that allow the varnish to be dated with the VML method (Liu 2003, 2010;

Marston 2003; Liu and Broecker 2007, 2008a, 2008b). Three quarters of the VML ages measured here place debris-flow events during periods wetter than the current climatic regime. Thus, the climatic information embedded in the dating would suggest that periods wetter than the present-day climate foster more debris flows. However, the same level of wetness needed to produce a distinct VML layer might not necessarily relate to the frequency of precipitation sufficiently intense to trigger debris flows.

The third major complicating factor would be uncertainty in how fast the supply of debris in slope catchments rebuilds to generate future debris flows. Unlike wetter environments where debris supply rates are rapid (Bovis and Jakob 1999), deserts have slower rates of rock weathering. Unfortunately, no data exist in the literature on how long it takes to "reload" the debris source areas in the small catchments that exist on metropolitan Phoenix mountain slopes.
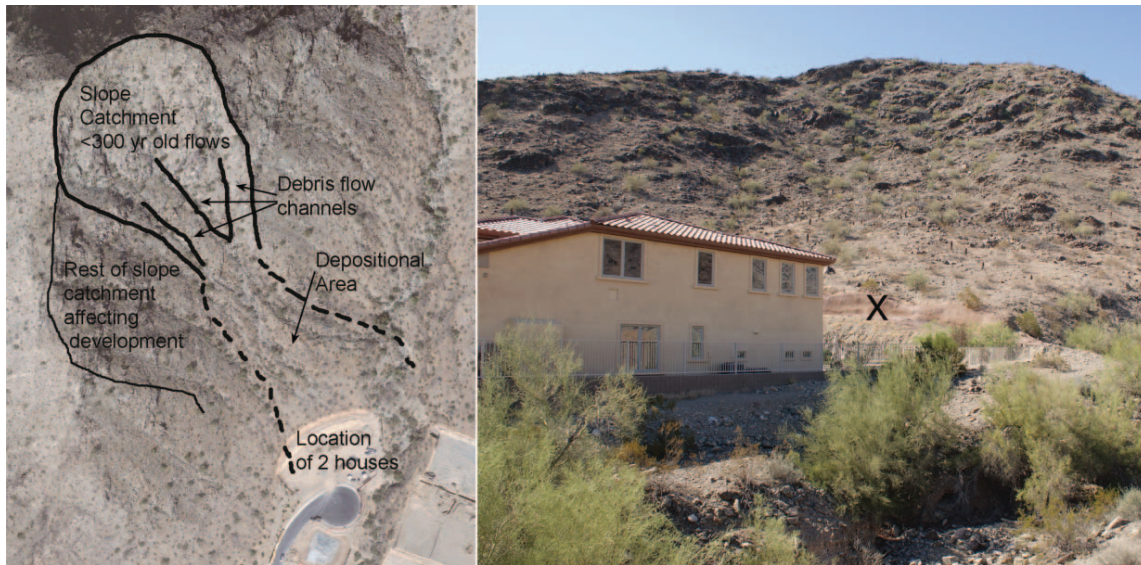
Figure 6 *In 2007 and 2008 in an Ahwatukee neighborhood in Phoenix, two new homes have been placed directly on a debris-flow depositional area. Debris flows less than 350 years old traveled to the property boundaries, and probably further, but construction eliminated the evidence. The right view is ground level, where the X indicates that the back of the house pad is a vertical cut without any barrier to inhibit sediment movement into the backyard or house. The left view an aerial photograph from 2006, used with permission by Maricopa County. The "rest of the catchment" area did not generate any distinctive debris flows. (Color figure available online.)*

Added to these complicating factors is a lack of consistency in how to conduct a debris flow hazard analysis. Although some countries such as Austria have specific guidelines on how to map and quantify debris-flow hazards (Fiebiger 1997), in "North America, debris-flow recognition, hazard assessment, and mitigation design are, in comparison, still in their infancy" (Jakob and Hungr 2005, 215). There is agreement, however, on the six general steps in analyzing debris-flow hazards (Jakob 2005), where this study has started the first two steps of (1) recognizing that debris-flow hazards exist in an area; and (2) starting the process of estimating the recurrence and hence probability of a future debris flow. The other four steps remain to be completed: (3) estimating debris-flow magnitude and intensity; (4) calculating frequency–magnitude relationships; (5) understanding design issues related to magnitude and intensity issues; and (6) presenting a mapping of these quantified relationships. Thus, it would be inappropriate for this pilot research to declare with certainty that a serious hazard does or does not exist.

Conclusion

A conservative conclusion is that the hazard posed by debris flows in metropolitan Phoenix is serious enough to justify a formal debris-flow hazard analysis (Jakob 2005), a task that is beyond the scope of this project. This conclusion is justified by four out of nine randomly selected study sites having experienced a debris-flow event during the twentieth century—a figure that is similar to occurrence rates in a study of 127 catchments in the Ma Ha Tuak Range, Phoenix (Dorn 2010). This argues for caution in future development up against desert mountains in the southwestern United States.

A case study exemplified in Figure 6 is another way of visualizing this conclusion for urban geographers, planners, developers, and residents. The aerial photograph in Figure 6 shows the house pads of two homes in Phoenix that were constructed in 2007 and 2008. The slope feature behind the homes identified in the ground photograph in Figure 6 offers no protection from flowing debris. The two most recent debris-flow events from the catchment above these homes occurred sometime in the

twentieth century and reached property boundaries. There are also debris-flow deposits preserved that are approximately 1,100, 2,800, and 8,100 calendar years old. Do debris flows pose a danger to these homes? My personal opinion is yes, hinging on the assumption that the two twentieth-century flows reflect the current hazard.

Given data presented in this pilot study, should policymakers consider halting development that abuts steep mountain catchments? Again, my personal opinion is that the prudent decision would be yes, using the assumption that conditions generating twentieth-century flows reflect the current hazard. The minimum occurrence rate is around 1,600 years for the catchment in Figure 6. Had the two most recent debris flows taken place after the homes were built, however, there would have been property damage and perhaps injury.

There are no zoning regulations in Phoenix regarding debris flows. There are no guidelines on how to calculate risk from either the Arizona Geological Survey or the U.S. Geological Survey. I believe that this issue is significant enough to warrant further study, ideally the bringing together of debris-flow experts and climatologists to aid planners and others in studying the level of risk in greater detail to establish appropriate policies—in metropolitan Phoenix and in other southwestern U.S. desert cities. ■

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RONALD I. DORN is a professor in the School of Geographical Sciences and Urban Planning at Arizona State University, Tempe, AZ 85287–5302. E-mail: ronald.dorn@asu.edu. His research interests include geography of weathering, rock coatings, desert geomorphology, and rock art.