



Building a Statewide Inventory of Landslides in Arizona

Cook, J.P., joecook@email.arizona.edu, Youberg, A.M., ayouberg@email.arizona.edu, Pearthree, P.A., pearthre@email.arizona.edu, Hudman, G.M., garyhudman@email.arizona.edu, Bookman, L.M., lbookman@email.arizona.edu, Gootee, B.F., bgootee@email.arizona.edu, Conway, F.M., fmconway@email.arizona.edu
Arizona Geological Survey, University of Arizona, Tucson, AZ 85721

ABSTRACT: Landslides in Arizona are an under-appreciated geologic hazard. Prior to this project, the nature and extent of landslides was limited to an incomplete array of geologic maps and reports. To address this knowledge and data gap, the Arizona Geological Survey (AZGS) initiated a Landslides Hazards Program. Working with our partner agency, the Arizona Division of Emergency and Military Affairs (DEMA), we compiled the first comprehensive landslide inventory for the State of Arizona.

We designed and built a GIS database and toolbar to aggregate landslide data from many sources. The Arizona Statewide Landslide Inventory Database (AzSLID) utilizes a comprehensive metadata structure, is versatile, and can incorporate new mapping and data as available. We compiled documented mass movements (all forms) from available maps, reports, and journal articles; we also added unmapped landslides features based on interpretation of aerial imagery and topography. Features were imported into the database and attributed according to failure type, mechanism, and source. AzSLID contains >6,300 landslide features covering approximately 2000 km². Large rotational landslides were most common, and mostly unmapped, in the northern half of the state. Debris flows are found throughout the state, and spot observations indicate that many unmapped debris flows are not included in AzSLID. AzSLID is updated as new geologic mapping and research identifies new landslides. AzSLID data will be used by DEMA to update the Landslide Profile in the upcoming 2018 Arizona Hazard Mitigation Plan. AzSLID data is also available to local, county and tribal governments to use for their mitigation planning efforts. The public can access the data through the Natural Hazards in Arizona viewer (<http://data.azgs.az.gov/hazard-viewer/>).

INTRODUCTION

The economic and social impact of landslides throughout the U.S. is poorly understood, but each year there are an estimated 25 to 50 fatalities with billions of dollars in costs, rivaling annual flood losses (NationalAtlas.gov, 2014). While economic costs from impacts by landslides have not been estimated in Arizona, three recent landslide events illustrate the high costs of landslides within the state. In 2006, extreme precipitation caused ~1,000

debris flows in four mountain ranges in southern Arizona (Magirl et al., 2007; Pearthree et al, 2007). The cost to repair infrastructure destroyed in Sabino Canyon was ~\$1.5 million while costs from damages in other areas were not documented. In 2008, a section of a large rotational landslide re-activated, destroying a part of State Route 87 in central Arizona. Repair costs were ~\$18 million (Bechman, 2008). Two years later, during an intense winter storm, this section of landslide failed

again resulting in another closure of SR87, a presidential disaster declaration (FEMA-1888-DR; Federal Emergency Management Agency, 2010) and additional costs, though not documented. In February, 2013, a large landslide in northern Arizona, about 23 miles south of Page, destroyed a significant section of US 89A. Costs to establish a detour and to repair the highway for this landslide were ~\$60 million (Arizona Department of Transportation, 2015). These three events alone have cost ~\$80 million in direct repair costs; the indirect economic impacts to affected communities have not been calculated. Without documentation of landslide occurrences and an accounting of associated costs, it is difficult to determine the extent of landslide hazards and their economic impacts to the State's economy.

Creating a statewide landslide inventory database is the first, most basic step for assessing landslide hazards (Spiker and Gori, 2000; National Research Council, 2004). Many states across the U.S. have well-developed landslide hazard programs (e.g. California, Kentucky, Oregon, Washington) to document and monitor landslides, assess landslide hazards and produce landslide susceptibility maps. Because no comprehensive statewide landslide hazards assessment existed for Arizona, landslide occurrence and hazard information was quite sparse, especially in rural areas and tribal lands. Thus, landslide risk studies were based on a very limited dataset, indicative of our fragmentary and incomplete understanding of the nature and extent of landslide hazards in Arizona. To address this knowledge and data gap, the Arizona Geological Survey (AZGS) initiated a Landslides Hazards Program in 2014. Working with our partner agency, the Arizona Division of Emergency and Military Affairs (DEMA), we obtained funding from FEMA's Pre-Disaster Mitigation grant program to conduct the first comprehensive landslide inventory for the State of Arizona. The program goal is to provide information about potential landslide hazards in Arizona by documenting historic (≤ 150 years) and prehistoric (> 150 years) landslides, and to provide local, tribal and state authorities with the tools for informed decision-making. This information can help facilitate better planning, mitigation and recovery from disasters, allowing for long-term disaster resiliency (National Research Council, 2012).

The statewide inventory project consists of four key components: 1) designing and developing a geodatabase to store the data and a toolbar to import the data, 2) compiling data of documented landslides across the state in a GIS framework, 3) identifying and mapping undocumented landslides in areas where landslide information is not available, and 4) conducting outreach and education to ensure the data is accessible, understandable and useful for all levels of government in support of planning efforts and mitigation projects, and for education and outreach purposes. The Arizona Statewide Landslide Inventory Database (AzSLID) is the repository of landslides across the state of Arizona compiled during the statewide inventory. We located and identified rotational, translational, and block (Toreva) landslides, large (> 10 m) rock falls/topples, and debris flows, all of which have been documented in Arizona. Herein, we use the term "landslides" as shorthand for all of these phenomena. Data in AzSLID is available to all interested jurisdictions, and is publicly available on and downloadable from the Natural Hazards in Arizona Viewer (<http://data.usgin.org/hazard-viewer/>). With this inventory, we have begun to address the knowledge gap of landslide hazards across the State of Arizona.

METHODS

Database development

Version 1 of the AzSLID database was developed using the National Geologic Map Database (NCGMP09) format, which is a standard design for publication of digital geologic maps. The reason for using a NCGMP09 format was that the database could be used with our in-house NCGMP09 toolbar, which was developed by the AZGS for use in geologic map production. It requires specific feature classes and tables in the database so the toolbar can validate individual elements against the NCGMP09 schema to ensure data harmonization and consistency. As data was collected and implemented it became apparent that available documented landslide data did not conform well to this template and there were too many fields within each feature that were not being populated. Thus, Version 2 of the AzSLID schema was created (Table 1).

Table 1. Key fields in AzSLID schema, v2.

Field Name	Contents
MapUnitPolys_ID	<i>Unique feature identifier</i>
MapUnit	<i>Short text identifier for the feature</i>
IdentityConfidence	<i>Certain, questionable, or unspecified feature confidence</i>
Label	<i>Map unit label</i>
Symbol	<i>Polygon fill symbol or color, may be defined with an accompanying style file</i>
Notes	<i>Open text field for additional information specific to the individual feature</i>
DataSourceID	<i>Customizable tracking records for context about modified features, user edits, method of import, and other tracking details</i>
LandslideID	<i>Identifier for named landslide complexes with smaller, associated, individual features</i>
Citation	<i>Map or report from which the feature was imported</i>
GeologicEvents_ID	<i>Identifier associating the landslide feature with a particular event</i>
LocMethod	<i>Method used to locate feature e.g. air photo, field mapping, LiDAR/DEM, existing geologic maps, etc.</i>
GeologicMapLabel	<i>Source map cartographic label</i>
FeatureType	<i>Drop-down menu picklist; Deposit, Removal-Headscarp Zone, Removal-Transport Zone, Slide Outline General, etc.</i>
MoveType	<i>Fall, Topple, Slide-rotational, Slide-translational, Flow, Complex</i>
MoveClass	<i>Rock, Debris, Earth</i>
FailureDepth	<i>Shallow, Deep, Unknown (limits must be defined)</i>
Age	<i>Active, Historic (< 150 years), Holocene, Pleistocene, etc.</i>
Volume	<i>Reported volume estimates if available</i>
CostTotal	<i>Reported cost totals (repair, monitoring, maintenance, and other associated costs) if available</i>

Version 2 AzSLID was designed to integrate the standard NGCMP structure into a fully normalized schema, adding tables and relationships for landslides, movements, events, citations, costs, and photographic records using NGCMP feature sets over time. Going forward this allows flexible entry of data that accurately characterizes landslides

spatially and financially over time without extraneous unpopulated fields.

The new AZGS Landslide toolbar was developed using the NGCMP09 as baseline and provides a workflow based user interface, allowing flexible data entry and validation as additional details and events occur. As part of the entry process, standard NGCMP feature classes are entered within ESRI ArcGIS and the AZGS in-house tool builds the association between different tables that describes the landslide data. The NCGMP09-compliant enterprise database allows multiple users to manage data simultaneously. Individual station datasets are then used to create digitized map elements.

Data Sources

Landslide features in AzSLID include 1) polygons outlining landslide deposits by type (rock, debris, earth; slide, fall, topple; rotational, translational, general) and debris-flow deposits (levees, snouts, fans), 2) lines representing deposit outlines, head scarps, internal scarps, and debris-flow chutes, and 3) points representing the locations of debris-flow initiation or basin outlet, depending on how mapped, and rock fall locations. The landslide features in AzSLID were derived from many sources including digital geologic map and geographic information system (GIS) data, published and unpublished geologic maps and reports, unpublished field studies, and aerial photo and Google Earth imagery and topographic interpretations. Unpublished data consists of AZGS studies, maps, and other institutional information that has not yet been released.

We first performed a comprehensive review of all AZGS maps and reports. Any mention of landslide hazards was noted and later incorporated into AzSLID. During this discovery stage, a bibliography of Arizona landslide maps and reports (Welty et al., 1988) was encountered that proved useful for discovering many other maps and reports containing relevant landslide hazard data and information. All known resources including geologic maps, reports, articles, and unpublished AZGS data were examined for landslide hazard data. Interpretation of Google Earth aerial imagery and topography proved very useful when locating unmapped landslide features described in articles or reports. Many additional landslide features not included in published maps and reports were

identified in this manner and incorporated into AzSLID.

Recent geologic maps containing landslide data were usually available in a GIS format. Incorporation of GIS data into AzSLID was relatively straightforward; a selection query of the landslide map units was performed and those polygons were imported into AzSLID and attributed accordingly. All information available for the source map unit polygons were preserved and accompanies additional AzSLID classification fields. GIS data were not available for many older geologic maps. In these instances a digital scan of the map was imported and georeferenced within ArcMap. Because no selection query can be performed on scanned maps, individual landslide map units were manually located and digitized into AzSLID. Due to a combination of georeferencing errors, source map accuracy, and map scale, the boundaries of many landslide features imported in this manner were modified based on interpretation of modern high resolution aerial imagery and topographic data. Any changes to the source data were noted in AzSLID.

Many landslides included in AzSLID were identified or modified based on interpretation of Google Earth imagery and topographic data. The combination of high resolution imagery draped on topography and the ability to pan and tilt within Google Earth constitutes an excellent tool for identifying large landslide features. Hundreds of additional landslides were located outside the footprint of geologic maps within a similar geologic setting (Fig. 1). Very large landslide complexes were also identified in this manner in parts of Arizona that have not been mapped extensively. Many of these areas lie within Tribal Lands.

RESULTS

AzSLID contains landslide data from more than 100 published geologic maps and reports mostly from AzSLID contains landslide data from more than 100 published geologic maps and reports mostly from contains more than 6,300 landslide polygons AZGS and USGS archives. Currently AzSLID covering over 2,000 km² throughout Arizona. Many of these polygons are large and represent impressive landslide complexes. Approximately 10% of these polygons are unique to AzSLID and do not appear on published maps or reports. Most undocumented landslides occur on Tribal Lands. These landslides

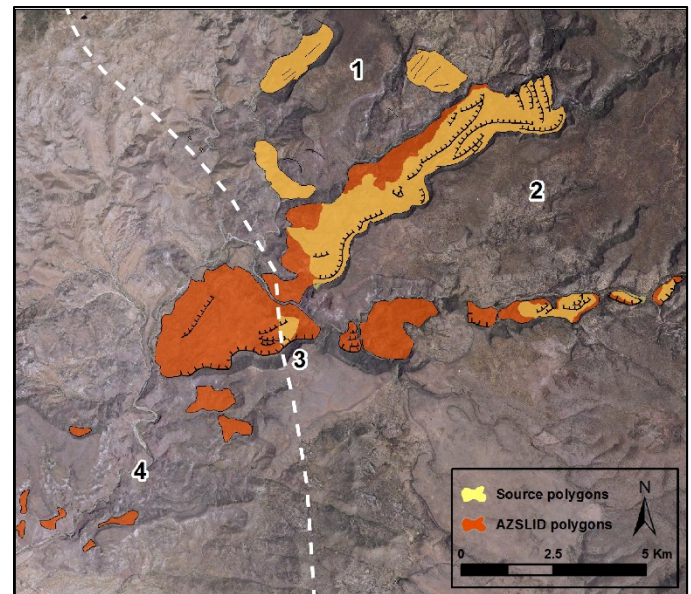


Figure 1. Examples of differences between AzSLID and source map data. Polygons near area 1 were imported directly from an existing GIS source and are unmodified in AzSLID. Area 2 orange polygons were modified from the source data based on modern imagery interpretation. Orange polygons in areas 3 and 4 are outside (west) the source map boundary (white dashed line) but occupy the same geologic setting.

commonly are large; they account for approximately 48% of the total landslide feature area in AzSLID. In addition to polygon data, there are over 1,400 landslide points in the database that represent debris-flow initiation scarps or basin outlets where debris flows were documented.

During this project, a previously mapped landslide at Mormon Flat Dam in the Salt River Canyon of central Arizona (Scarborough, 1981; Ferguson and Gilbert, 1997) was called into question. AZGS conducted a limited field assessment to determine if this feature should remain part of the landslide database. In order to evaluate potentially conflicting interpretations of the feature and deposits near Mormon Flat Dam, AZGS reviewed existing geologic maps, evaluated several generations of aerial imagery and the general topography of the area, and conducted 2 days of field reconnaissance on site. We concluded that the landform morphology and the chaotic deposits do suggest a landslide complex that likely also includes massive rockfalls (Figs. 2 and 3).

AZGS found no evidence indicating that the main landslide has been active since the early 1920s based on historical photos from when the dam was constructed. Re-evaluation of this previously mapped landslide provided an opportunity to locate

other nearby slides that may warrant review due to their proximity to important reservoirs.

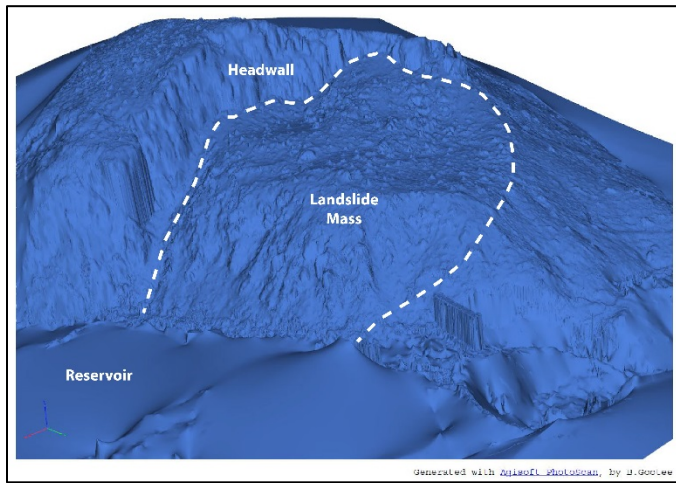


Figure 2. Shaded relief image of the landslide at Mormon Flat Dam with features outlined. View south towards the headwall and mass. Image generated with Agisoft PhotoScan by B. Gootee.

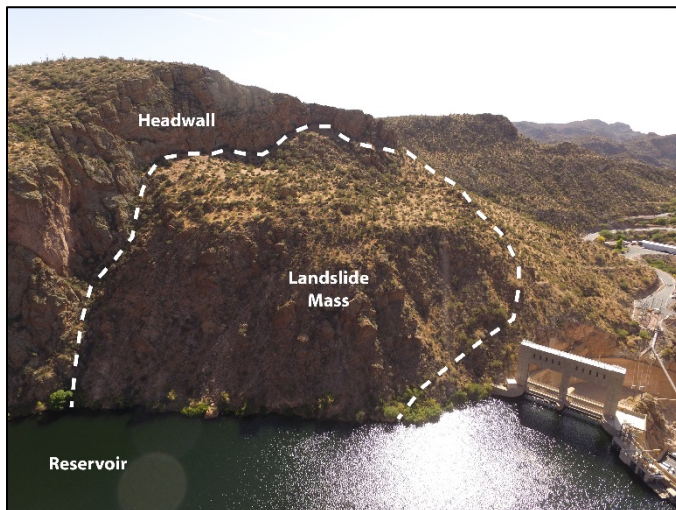


Figure 3. View of the landslide at Mormon Flat Dam. Looking south towards the headwall and mass. Photo: B. Gootee.

DISCUSSION

Version 2 of AzSLID provides a simplified geodatabase for storing landslide information such as features, movement characteristics, event and cost data, citations, and photographs and station points when available. The Landslide toolbar provides a method for efficiently importing data with citations and attributing features. In the future

it will be straightforward to add new data from other sources or from our own new mapping.

AzSLID provides an excellent dataset of the distribution of known landslide hazards throughout the state, but it does not currently include many recently active landslide features. This portion of the database could be improved if data were available from other state agencies such as Arizona Department of Transportation, which maintains and repairs the state's roadways.

AZGS works closely with the Arizona Department of Water Resources (ADWR) on a number of projects. ADWR runs a statewide land subsidence monitoring program that employs Interferometric Synthetic Aperture Radar (InSAR). The objective of the InSAR data collection is to monitor land subsidence on a regional scale but several examples of apparent movement within known landslide complexes in the Vermillion and Echo Cliffs in northern Arizona have been captured by InSAR interferograms (Fig. 4). Possible land subsidence through slumping processes outside of any known landslide features was also detected near Hwy 87 in Navajo County, Arizona. Although not collected with landslide detection in mind, InSAR has shown promise in detecting actively slumping areas that have not yet been recognized in the field.

Coverage and completeness of AzSLID varies substantially across Arizona based on the quality of existing geologic mapping and scale of landslide features. In particular, two areas of the state with the largest data gaps are in the northeast and southwest/south-central parts of Arizona (Fig. 5).

During this project we used high-resolution imagery and topography to identify and map numerous large rotational landslides that were not previously documented. Most of these are located in northeastern Arizona on Tribal lands (Fig. 5, blue box) and account for almost half of the area represented by landslide polygons ($\sim 1000 \text{ km}^2$) in the geodatabase. This is an area where we hope to focus future efforts.

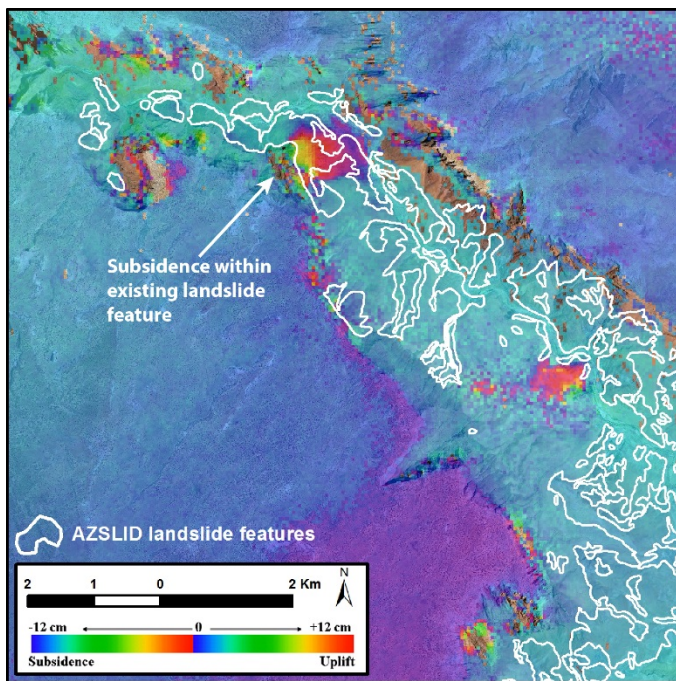


Figure 4. An InSAR interferogram shows movement in portions of the landslide-prone Vermillion Cliffs area of northern Arizona.

Another significant data gap is in southwestern and south-central Arizona. We know from limited detailed geologic mapping and field observations that there are numerous debris-flow deposits along at the base of short, steep drainages in the isolated mountain ranges in this area, most of which are undocumented (Fig. 5, orange circle). For instance, there were numerous debris flows in the Picacho Mountains in 1983 following rains from dissipating tropical storm Octavio, but they were never mapped. We plan to add these data, and other data, as we continue to work in and around these mountain ranges.

CONCLUSIONS

AzSLID is the first comprehensive landslide inventory for the state of Arizona. The primary focus in developing and populating AzSLID was to complete a geospatial database with documented landslides throughout Arizona. The primary purpose is to have better understanding of the distribution and types of landslides across the state to inform the Landslide Profile for the 2018 State of Arizona Hazard Mitigation Plan update. Significant data gaps were identified during this work.

Future potential phases of work in the AZGS Landslide Hazard Program include new mapping of

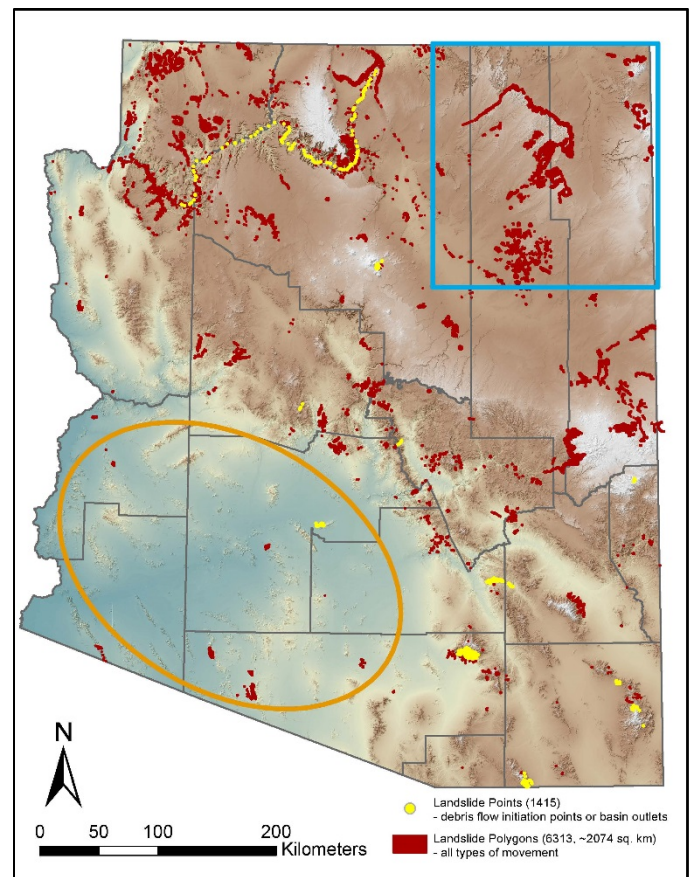


Figure 5. AzSLID features with landslide polygons in red and debris-flow basins marked with yellow points. Data gaps exist throughout the state but are particularly prevalent in northeastern (blue box) and southwestern/south-central (orange circle) Arizona.

previously unidentified landslides 1) along the I-17 corridor between Phoenix and Flagstaff as part of the planning effort to expand the capacity of the interstate system, 2) on tribal lands in northeastern Arizona, and 3) in southwestern mountain ranges where debris-flow deposits have been observed by AZGS personnel but not yet mapped. While there is still work to do, AzSLID significantly advances the state of knowledge of potential landslide hazards within Arizona, providing data that is accessible, understandable and useful for all levels of government in supporting well-informed decision making, planning efforts and mitigation projects, and for education and outreach purposes, thus facilitating long-term disaster recovery and resiliency.

ACKNOWLEDGMENTS

This project was funded by a Federal Emergency Management Agency Pre-Disaster Mitigation Grant, (PDMC-09-AZ-2014) and by the AZGS. This project would not have been possible without the support of the Arizona Department of Emergency and Military Affairs, particularly Thomas “Duke” Jones and Susan Wood Austin. We thank Bill Burns and Sabastian Dirringer for their thoughtful reviews of this manuscript.

REFERENCES

- Arizona Department of Transportation, 2015: US Route 89 Landslide (Repairs Completed). Electronic document, available at <https://azdot.gov/projects/north-central-district-projects/us-89-landslide/overview>
- Bechman, A., 2008, More potential slides menace Hwy 87. Payson Roundup, Payson, AZ, Dec. 2, 2008. Electronic document available at <http://www.paysonroundup.com/news/2008/dec/02/more-potential-slides-menace-hwy-87/>
- Federal Emergency Management Agency, 2010, Arizona Severe Winter Storms and Flooding – FEMA-1888-DR, Declared March 18, 2010. Electronic document available at <https://www.fema.gov/pdf/news/pda/1888.pdf>.
- Ferguson, C.A., and Gilbert, W.G., 1997, Geology of the Mormon Flat Dam Quadrangle, Maricopa County, Arizona: AZGS Open-File Report 97-14, 3 sheets, map scale 1:24,000, 28 p.
- Magirl, C.S., Webb, R.H., Griffiths, P.G., Schaffner, M., Shoemaker, C., Pytlak, E., Yatheendradas, S., Lyon, S.W., Troch, P.A., Desilets, S.L.E., Goodrich, D.C., Unkrich, C.L., Youberg, A., and Pearthree, P.A., 2007, Impact of recent extreme Arizona storms: Eos, Transactions American Geophysical Union, v. 88, no. 17, p. 191-193.
- NationalAtlas.gov, 2014, Geologic Hazards - Landslides. Electronic document available at http://www.nationalatlas.gov/articles/geology/a_geohazards.html
- National Research Council, 2004, Partnerships for Reducing Landslide Risk: Assessment of the National Landslide Hazards Mitigation Strategy: Washington, D.C., The National Academies Press.
- National Research Council, 2012, Disaster Resilience: A National Imperative: Washington, D.C., The National Academies Press.
- NCGMP (USGS National Cooperative Geologic Mapping Program), 2010, NCGMP09—Draft Standard Format for Digital Publication of Geologic Maps, Version 1.1, in Soller, D. R., Ed., Digital Mapping Techniques 2009, Workshop Proceedings: U.S. Geological Survey Open-File Report 2010–1335.
- Pearthree, P.A., Youberg, A., and Cook, J.P., 2007, Debris flows; an underappreciated flood (?) hazard in southern Arizona. In Geological Society of America, Rocky Mountain Section, 59th annual meeting, Abstracts with Programs - Geological Society of America, Geological Society of America, p. 11.
- Scarborough, R.B., 1981, Reconnaissance geology, Salt River – from Roosevelt Dam to Granite Reef Dam, Central Arizona: AZGS Open-File Report 81-30, 8 sheets, scale 1:24,000, 69 p.
- Spiker, E.C., and Gori, P.L., 2000, National landslide hazards mitigation strategy, a framework for loss reduction: U.S. Geological Survey Open-File Report 00-450, Reston, VA, 49 p.
- Welty, J.W., Roddy, M.S., Alger, C.S., and Brabb, E.E., 1988, Bibliography of Arizona Landslide Maps and Reports: Arizona Geological Survey, Tucson, AZ, 13 p.