Geologic Hazards Mapping Project for Montrose County, Colorado

by

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Foreword

The purpose of this geologic hazards mapping project by the Colorado Geological Survey (CGS) is to improve Montrose County's Mitigation Plan by identifying, describing, and analyzing the geologic hazards for private lands in Montrose County. This area encompasses the Uncompahgre Valley and highlands to the east and west. The CGS has assessed the vulnerabilities of geologic hazards where they may be developed in the future. Senior geologist Jon White was the manager and lead researcher of this project and was assisted by other CGS staff geologists. TC Wait and Matt Morgan contributed map coverages to the project and assisted in writing this report. Dave Noe provided the rating matix to constructed the swelling soils map. Nick Watterson, Chris Quinn, and Sean Gaffney provided GIS techical assistance.

This mapping and geologic hazard assessment project was funded by the Federal Emergency Management Administration (award number 6EM75C44) with matching funds by Montrose County, and the Colorado Geological Survey using the Colorado Department of Natural Resources Severance Tax Operational Funds. This project also benefited from concurrent STATEMAP geologic mapping in the Uncompahgre Valley. This mapping program is funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program, which is authorized by the National Geologic Mapping Act of 1997 (award number 07HQAG0083) and the Colorado Geological Survey, using the Colorado Department of Natural Resources Severance Tax Operational Funds. The CGS matching funds come from the severance tax paid on the production of natural gas, oil, coal, and metals.

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Purpose of the Study

Montrose County is located approximately 300 miles west of Denver on the Western Slope of the Continental Divide. At the lowest point of the county, the elevation is 4,700 feet and at the highest point the elevation is 11,453 feet. The surrounding area includes Grand Mesa to the north, and the San Juan Mountains to the south. The Uncompahgre Plateau bisects Montrose County from north to south. The eastern portion is further cut by the Black Canyon of the Gunnison and the Gunnison River. According to the Montrose County web site, the population of Montrose County is 39,527. The two largest population centers in the county are the City of Montrose and the Town of Olathe.

The most significant industry in Montrose County is tourism but historically has been agriculture, which continues to have a large presence in the Uncompahgre Valley. With 70 percent of the county being public lands, there is a large influx of people who come to recreate on the public lands. As of 2006, the Uncompahgre Valley of Montrose County experienced virtually all of the growth pressures for the entire county (2-3% average annual growth since early 1990's). The southern half of the valley is growing faster than the northern half and the City of Montrose is growing faster than the unincorporated areas of the county. While Montrose County is still a largely rural populace, the City of Montrose has most of the amenities of a bigger city. Single family residences that supply the middle and upper-middle income brackets appear to be the major component of the growth that has occurred during this period from the early 1990's to today. In-migration due to the attractiveness of the area appears to be the major stimulus to growth rather than job creation.

Recent subdivision proposals are encroaching towards some of the more geologically difficult out-lying land (i.e., steep unstable slopes, drainage issues, poor soils, etc.) that present a much greater challenge to properly subdivide and provide a safe and attractive living environment. The geologic hazard and geologic constraint maps of this project were created to assist Montrose County, as well as private developers, property owners, and the consulting and construction industry, to develop proper land-use plans for the conditions that exist within the project area that encompasses the greater Uncompahgre Valley. The project area was defined jointly by Colorado Geological Survey (CGS) and Montrose County government officials to include the majority of private land holdings from the northern boundary with Delta County to the southern boundary with Ouray County and, from west to east, the Bureau of Land Management public lands on the Uncompahgre Plateau to the Black Canyon of the Gunnison National Park.

The deliverables of this project specified in the CGS contract with Montrose County are the GIS shapefiles of the various datasets on CD/ROM. This final report document, which discusses the project area and the specific geologic hazards, has also been included on the CD in Adobe PDF format. Included in this report are large-scale 11x17-inch map plates of the various map layers. In addition to the report, also included on the CD is a more useful 1:60,000 map scale of the various map layers, presented on topographic basemaps as 43x36-inch plates in Abode PDF format.

Overview of Physiographic and Geologic Settings

A map showing major, named physiographic, geomorphic, and geologic features in the Montrose County Project Area are shown on a hillshaded basemap in Figure 1.

Most of Montrose County lies within the Canyonlands section of the Colorado Plateau physiographic province, an area characterized by deep canyons and monoclinal folds. The Uncompahgre Uplift, which trends through the southwestern half of the project area, has deformed the overlying Mesozoic rocks into gently dipping, monoclinal folds that are well exposed on the gently-rising Uncompahgre Plateau and the steep Gunnison Uplift areas. The relatively uniform dip slope of the resistant Dakota Sandstone, incised with many side valleys such as Dry Creek and Shavano, rises to the southwest onto the Uncompahgre Plateau at a regional inclination of ~3 degrees. The steep Gunnison Uplift along the eastern margin of project area is also an orogenic (i.e., mountain-building event) structure where vertical movement of basement blocks occurred and faulted Precambrian crystalline rocks against Mesozoic rocks along the Cimarron and Red Rocks faults.

The sedimentary bedrock exposed in the Project Area records the transition from terrestrial flood plains, through marginal marine, to predominantly marine conditions during Triassic through Early to Late Cretaceous time (253 – 65 million years ago). Red siltstones, sandstones, and variegated mudstones and channel sandstones of the Morrison Formation record the depositional history of wide upland flood plains and saline lakes while the Dakota and Burro Canyon Formations record swamp and near-coastal flood plain sedimentary environments as the epicontinental, Western Interior Seaway was opening from the east to the west. These rocks are well exposed in the canyons of the Uncompahgre Uplift and rocks flanking the Gunnison Uplift east of Bostwick Park. The overlying Mancos Shale and its various subunits were deposited within the fully transgressed epicontinental seaway and represent muddy shallow-shelf deposits derived from deltas and shorelines that existed further to the west in Utah. In the project area, the Mancos Shale is best exposed in the “adobe hills” on the east side of the Uncompahgre River. On the west side of the Uncompahgre River, it is covered by extensive Quaternary deposits and generally poorly exposed, except along the mesa edges.

Overview of Quaternary Geologic Setting

The Quaternary geologic history of the project area is complex, controlled by downcutting of the Uncompahgre River through the more-easily eroded Mancos Shale and deposition of glacio-fluvial sediments that were shed out onto the flood plains during periodic glacial ages in the Pleistocene Period (10,000 year ago to 1.8 million years ago). Early Pleistocene gravel deposits, predating the modern Uncompahgre River, also created the high, flat areas such as Bostwick and Shinn Parks (Fig. 1). The gravel, being more resistant to weathering and downcutting than the adjacent Mancos Shale, formed the many gravel-capped parks and mesas in the project area as downcutting continued in the adjacent shale terrain. The three major sources of Quaternary alluvial deposits in the study area include the San Juan Mountains, the Uncompahgre Plateau, and the Gunnison Uplift.

INSERT FIGURE 1

The most widespread units were deposited by the ancestral Uncompahgre River that records middle to late Pleistocene steam levels during the formation of the Uncompahgre Valley. Long-term incision by the river and its tributaries commenced approximately 2.5 million years ago when the Uncompahgre River migrated northeastward down the eastern flank of the Uncompahgre Plateau. The clasts of the Uncompahgre River sediments are mainly of volcanic and metasedimentary composition that was sourced from the San Juan Mountains. The Uncompahgre River has five major geomorphic surfaces associated with it; prominent gravel-capped mesas that are terrace-tread remnants of former glacio-fluvial flood plains. Prominent mesas in the project area include: Franklin Mesa, High Mesa, California Mesa, Sims Mesa, Ash Mesa, Spring Creek Mesa, North Mesa, and East Mesa (Fig. 1). The current flood plain of the Uncompahgre River forms the lowest terrace.

The surface distribution of terraces for the Uncompahgre River Valley indicates the middle Pleistocene course of the Uncompahgre River incised Shavano Valley. Three major terrace surfaces (Franklin Mesa, High Mesa, and California Mesa) were formed when the floodplain passed through Shavano valley. Subsequent stream capture and diversion of the Uncompahgre River to near its present course, east of Shavano Valley, did not occur until the late Pleistocene. This diverted floodplain became Spring Creek, Ash, and portions of North and East Mesas near Olathe. Due to the river abandonment, Shavano Valley became a wind gap and does not currently contain a major drainage.

Concurrent with the deposition of the main Uncompahgre River flood plain gravels, smaller flood plains and wide alluvial fans were deposited as tributary streams that flowed from many of the subparallel side canyons of the Uncompahgre Plateau (i.e., Dry Creek, Roatcap Gulch, Big Sandy Wash) onto the Uncompahgre River paleovalley floor.

From subsequent erosion and topographic inversion, the former river floodplains and alluvial fans with high gravel content now form the broad mesas, which are underlain by Mancos Shale. The continued downcutting of the Uncompahgre River has exposed the Mancos Shale below the gravel cap on the steeper slopes. Modern mass-wasting deposits are common along the edges of the mesas. Gravelly colluvium can variably cover these slopes and landslides commonly occur where near-surface weathered and weakened Mancos Shale has been saturated and is now unstable.

Project Methodology

The basis of generating the geologic hazards was the collection and mapping of geologic data, as well as other spatial thematic data including terrain models, derived slope classification and aspect maps, climatic data, and National Resource Conservation Service Soil Survey data (SSURGO). The following maps and digital data sets were collected during the literature search:

- National Resource Conservation Service (NRCS) Soil Survey data from the Ridgway-Montrose area;
- United States Geological Survey (USGS) 1:24,000-scale geologic maps of the Buckhorn Lakes, Cerro Summit, Colona, Government Springs, Montrose West, and Washboard Rock quadrangles;
- USGS 1:31,680-scale geologic map of the Black Canyon of the Gunnison;
- USGS 1:48,000-scale geologic map of the Delta quadrangle;
- USGS 1:250,000-scale geologic map of the Moab 1° X 2° quadrangle;
- USGS digital 1:24,000-scale topographic maps;
- Sinnock's (1978) 1:84,210-scale geomorphic map of the Uncompahgre Valley;
- Gallant's (1976) 1:24,000-scale H.B. 1041 (1974) geologic hazards map of the immediate vicinity of the town of Montrose;
- The CGS Quaternary fault and earthquake databases (Kirkham and Rogers, 1981 and Widmann and others, 2002);
- The CGS land-use review database (LURD)
- National Agriculture Imagery Program (NAIP) 1-m resolution, orthorectified color aerial photograph;
- 10-m digital elevation model (DEM);
- Hydrologic 6^{th} order basin maps;
- FEMA Flood Insurance Rate Maps (FIRMs);
- Other digital and cultural map data including
    - County road coverage
    - County property ownership coverage
    - River and irrigation canal coverage
    - Precipitation coverage

While some of the data was already in GIS formats, much was not. Most of the earlier USGS geologic maps had to be scanned, georeferenced, vectorized, and attributed early in the project. During the analyses of this data it was apparent that many of the USGS geologic maps were preliminary in nature or the scale was too small for the accuracy standards needed for this project. Much of the earlier geologic mapping of the southwest and west portions of the project area were photorevised by the CGS.

At the beginning of this project it was discovered that appropriately-scaled (1:24,000) geologic mapping did not exist for the rapidly growing areas of the Uncompahgre Valley. The CGS altered its long term STATEMAP geologic mapping program to immediately map these quadrangles. The Montrose West and Olathe quadrangles were mapped in 2006 and the

Delta, Olathe NW, and Hoovers Corner quadrangles were mapped in 2007. All or portions of these 5 quadrangles lie within the project area. While not funded by the Montrose Geologic Hazard Project, the detailed geologic mapping of these quadrangles cost about $300,000. The STATEMAP program to map these 5 quadrangles is funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program and the Colorado Geological Survey, using the Colorado Department of Natural Resources Severance Tax Operational Funds. The compiled geologic map of the project area is shown in Figure 2

All of the data were entered into a GIS project using ArcGIS with a defined projection as NAD 83, UTM Zone 13N. The following datasets were developed:

1. The compiled 1:24,000-scale geologic map of the project area – Figure 2
2. A compiled inventory of all mapped landslides – Plate 1
3. Landslide susceptibility map – Plate 1
4. Rockfall hazard map – Plate 2
5. Avalanche hazard map – Plate 2
6. Debris/mud flow hazard map – Plate 3
7. Swelling soil hazard rating map – Plate 4
8. Collapsible soil susceptibility map – Plate 5
9. Soil corrosion hazard map – Plate 6
10. Digital scans of georeferenced FEMA FIRMs – Plate 7
11. NRCS flood hazard map – Plate 8
12. Compiled earthquake and Quaternary fault map – Plate 9
13. Poorly drained/salt pan area map – Plate 10
14. Mancos Shale and susceptibility for selenium impairment map – Plate 10
15. Slope classification map

The deliverables for this project are the GIS shapefiles. The following section of the report discusses the specific geologic hazard and the development of the individual GIS shapefiles and the risk assessment for each.

Scaling issues are pertinent. The GIS map shapefiles should not be used at a scale larger than 1:24,000 (1 inch = 2,000 feet). The GIS map shapefiles are not meant to be used to give a site-specific assessment of a specific geologic hazard. Only that the conditions of that general location have been shown to contain that specific hazard in other locations. Site-specific engineering geology and geotechnical engineering investigations by knowledgeable professionals will best assess the potential geologic hazards and the risks they may bear on development at a particular site.

To minimize risk of geologic hazards, the planning and design process should include a multi-disciplinary approach that includes geologic and geotechnical investigations, foundation and infrastructure design by engineers experienced in the geologic hazard terrain, and all other subsequent work by knowledgeable civil and structural engineers, building contractors, and landscape designers. Home owners and property owners should pay attention to the recommendations that are given by these professionals to improve the long-term performance of structures and the risk exposure to geologic hazards.

INSERT FIGURE 2

Landslides and potentially unstable slopes – Plate 1

Overview

The CGS descriptive definition (Rogers and others, 1974) of landslides are, *a mass movement where there is a distinct surface of rupture or zone of weakness which separates the slide material from more stable underlying material. Such slides involve en masse downward and outward movement of a relatively dry body of rock and/or surficial material in response to gravitational stresses.* Landslides are the result of the force of gravity acting on a slope where the soil/rock strength is sufficiently weak enough that the slope-forming materials shear against each other and begin to move, flow, or slide downhill. The rates of these movements can range from a rapid earth flow to slow creeping ground movements that are only perceptible over months or years. Structures, which are not designed for earth movements, generally, do not survive landslides. The tremendous earth forces will shift, shear, crack, move, or bury buildings. Once initiated, landslide movements often continue until the damage is such that the structure is completely destroyed or the distress makes the structure unusable, requiring demolition and/or costly remedial design and repair. Critical facilities such as highways underground pipelines and utility lines are similarly affected.

Background

In general, the term "landslide" is used to describe the mass movement of rock or earth material down a slope. Gravity acts on a slope that is oversteepened with respect to the inherent internal strength of the rock or soil materials that compose that slope. This general description also includes debris flows and rockfall, which are included in separate map coverages. Landslide movements can generally be described as being rotational (following a curved failure surface), translational (following a planar failure surface), or a complex combination of these movements. Landslide movements are highly sensitive to accumulated subsurface water. At times the landslide mass can contain so much water that it may behave like a viscous fluid and is termed an earth flow.

The main factors that affect whether a landslide will occur are topography, geology, and hydrology. These factors influence the inherent strength of the rock or soil materials that comprise the slope, the forces bearing on the slope, and, accordingly, the slope stability. Very strong, massive rock can hold a vertical slope without failure. Weak rock and soil materials can only hold a low or moderate slope without experiencing shear failure and lateral ground movements.

Landslides are "caused" or triggered when some critical slope-stability threshold is exceeded and the driving forces (causing instability) become larger than the resisting forces that increase stability. This may occur when the internal strength is lowered as a result of natural processes (e.g., precipitation, weathering, erosion, or earthquakes) or from human influences (e.g., water introduction or adverse ground modification). Ground modifications that contribute to unstable-slope conditions include ground removal or loss of lateral support (e.g., excavation or erosion into the lower portions of the slope, called the toe), and the addition of weight, or loading (e.g., artificial fills, structures, water loading, or natural sediment deposition on the upper portions of the slope) that adds weight and increases the driving forces that increase slope instability. Adverse water introduction can weaken soils and bedrock by weathering and selective dissolution but, most importantly, the increased pore-water pressures in the soil or weathered rockmass weakens the slope by reducing the shear strength.

Landslide deposits have distinct morphology. Most landslides have a headscarp (showing vertical or near vertical movement) at the top and a mounded toe at the bottom of the deposit. The ground surface that has moved within the landslide often appears crumpled or is described as having a "hummocky" topography. Commonly, intermediate scarps and depressions may form above rotated blocks or retrogressive rotational complexes, creating a "step-and-bench" morphology that can hold small ponds. Often, there is evidence of water influence, seen as seeps and/or vegetation indicative of moist ground, along landslide margins or in susceptible areas at risk. On landslide-prone or potentially unstable slopes that are in the beginning stages of a landslide, ground (tension) cracks can sometimes be seen that show subsurface strain and are the visible precursor of a landslide. In some cases, the slope may actually be moving but the soil materials stretch or compress rather than break or tear, and slope movement can only be determined by detailed surface surveys and/or subsurface monitoring devices. This type of behavior in landslides generally occurs only briefly at onset of movement before displacement is evident and seen at surface. In cases where shallow soils and weak rock move and remold without defined slide planes, the movement is generally considered to be "slope creep."

Geology, including the formational-material composition (or rock type) and geologic structure, is one of the major influences to slope stability. Clay-rich formations are often associated with landslide-prone areas. The orientation of bedding and jointing or fracturing can also adversely affect slope stability. Clay-rich rock types (claystones and shales), bedding planes, bentonite seams, historic failure surfaces, and weathering zones can exhibit physical properties associated with weak rock or soil: low shear strength, and strength lowered further to residual values on slopes or bedding planes that have previously failed where the material has been disturbed and remolded. The presence of water contributes by increasing the pore-water pressure between soil grains or within rock structures, creating a hydraulic "lifting" effect and loss of material strength. A slope that may be stable under dry or moist conditions can suddenly become unstable with increased moisture, such as from wetter seasonal cycles, irrigation, or even septic system effluent in absorption fields or lines.

Topography is a major factor in landslide susceptibility. As slope grades increase, gravity has a greater driving force contribution. Slopes that are already inherently weak, weathered, or within existing landslides can fail at low-angle slope grades. Slope aspect (the direction a slope face is oriented) can also be a factor that affects the amount of seasonal moisture. North-facing slopes that do not receive direct sunlight will generally be moister. If a steeper slope is oriented in approximately the same direction as the dip of bedrock, the bedding planes or fracture planes may "daylight" into the slope so that there is no lateral support of the rock mass. Shearing and landslides can occur along these planes of weakness.

Map Methodology

The CGS creates landslide susceptibility coverages from GIS data of landslide history, geology, geologic structure, topography, geomorphology, slope grade, and slope aspect (White and Wait, 2003). The coverage integrated these data with known engineering characteristics of the local bedrock and derived soils and other image-based digital information including shaded relief maps derived from 10-m digital elevation model (DEM) and high resolution aerial photography. The draft coverage was then field checked by CGS engineering geologists.

Past landslide activity was used as an aid to determine areas that may be susceptible to landslides. Areas with a history of past slope stability problems may be prone to future failure and may also indicate geologic factors that contributed to landslide occurrence. Many of these landslide sites are sensitive to disturbance by human activity and modification. Existing landslide data was compiled from the geologic maps to create the landslide inventory. This inventory was supplemented by additional mapping of previously unrecognized landslides by photo-interpretation of stereo aerial photography of the project area.

As described above, weak rock masses, and the soils derived from them, are generally clay-rich materials. Several sedimentary formations contain these weak bedrock materials. The Mancos Shale underlies the Uncompahgre Valley floor and is one of the weakest formations in the study area. Other lesser formations on the perimeter of the project area include the Summerville Formation, and the Brushy Basin Shale Member of the Morrison Formation. Most of these formations are easily weathered, overconsolidated Jurassic and Cretaceous shales with pronounced zones of weakness (having low or only residual shear strengths) and possible displacement shears along bedding planes. The Mancos Shale is also commonly highly fractured within the near-surface weathered zone. These fractures are commonly filled with easily dissolvable gypsum filling. Derived products include *in-situ* weathered and disturbed claystones, and residual and colluvial clayey soil deposits. These formational materials and derived soils were selected where they are exposed or are near the ground surface.

In the Montrose area, slopes with grades greater than 10 (H):1(V) (10% grade or 5.7 degrees) and having geologic factors favorable for landsliding such as colluvial slopes underlain by Mancos Shale were considered for inclusion in the susceptible coverage. Ten percent was used as a criterion based on past studies, mapped landslides, and reported residual shear strength properties found in the Mancos Shale and other similar shales. Another GIS coverage of slopes exceeding 3(H):1(V) (33% grade or 18 degrees) within the susceptible zone was also delineated. This steeper-slope zone should be considered a higher risk area.

Basic mechanics of landslides were used in generation of the susceptibility coverage. “Margin zones” that fall outside of the above-defined slope gradients at the top and bottom of slopes were also included in the susceptibility coverage to account for common behavior of landslides. The head scarp of a landslide commonly encroaches onto upslope areas that may not have been involved in the initial movement. Similarly, a landslide toe can move out as an earth flow onto relatively flat terrain beyond the base of the steeper slope.

The preliminary susceptibility boundaries were created by digitally tracing a zone that includes areas of landslide-prone geology, mapped landslides, and at defined slope gradients and slope aspects. A more-accurate landslide susceptible boundary was then refined by the inclusions of margin zones and interpretations of stereo aerial photographs and DEMs. The final susceptibility area was then field checked and revised as necessary.

During the field checking, areas were visited that had been identified as potentially having geologic and topographic conditions that might produce landslides. Observations made regarding the extent of the slide area, geologic factors contributing to the slide, and topographic characteristics of the site were used to refine the mapped boundaries.

Mapping Results

The landslide susceptibility layer was developed for private lands at a mapping scale of 1 inch = 2,000 feet (1:24,000) to discern landslide prone areas identified during this study. Within the study area, five general zones of landslide-susceptible lands were identified within the private lands of Montrose County:

Mancos shale capped by old glacial/debris flow deposits on the Uncompahgre Plateau in the southwest part of the study area. Prehistoric outwash and debris flows originating from the mountains southwest of the study area have acted as resistant covers for areas of Mancos Shale. Left as remnants, these isolated clayey deposits form rounded hills containing boulders on the Dakota Sandstone dipslope of the plateau. Some of these deposits have slid, and future movement may be possible, particularly if the slopes are disturbed.

Failure of the Morrison Formation within canyons and gullies of the Uncompahgre Plateau. Downcutting of the canyons that are oversteepened by the resistant rim of the Dakota and Burro Canyon Formation sandstones expose and erode the much weaker Morrison Formation claystones, causing landslides. Many large extensive landslide complexes occur in these canyons. Most lie within public lands and are not of real concern with future land development.

Slope edges of alluvial terraces and mesas in the central valley area. The Uncompahgre River has shaped the wide valley where the easily-eroded Mancos Shale lies on the valley floor. Ancient river terraces are more resistant to weathering and erosion than the shale bedrock. Through topographic reversal and further downcutting of the Uncompahgre River and its tributaries, gravel-capped mesas (e.g., Franklin Mesa, Ash Mesa, Spring Creek Mesa, California Mesa, and High Mesa) form where the flanks of the mesa are exposed with weathered and weakened Mancos Shale. Landslides commonly rim these mesas because natural precipitation and irrigation has the supplied water that percolates through the permeable gravel and perch on the relatively impermeable claystone. The water migrates laterally to seep out along the mesa edges. Weak clay materials, water, and steeper slopes ultimately results in slope failures. Landslide susceptible terrain exists along the entire rim of these terraces and mesas, and margin areas may extend laterally into the flatter surrounding areas at the headscarp and the toe of the landslide.

Buttes, mesas, and slopes in the Mancos Shale in the eastern part of the project area. The eastern part of the study area consists of Mancos Shale that forms buttes, mesas, and steeper slopes known as the "adobe hills," which may be prone to landslide activity if they are disturbed and appreciable wetting occurs. Even smaller ridges may have localized slope failures. Drainage plays a significant role in these movements, and areas where irrigation ditches, ponds, and natural streams are located may have increased risk of slope failure. Several large landslides occur in exposed Mancos Shale on the western flank of Bostwick and Shinn Parks.

Historic landslide deposits in the southeastern part of the study area. Approximately 80,000 acres in the southeast corner of the study area includes landslide deposits from large landslide complexes around the Cimarron Ridge/Waterdog Basin and Cedar Creek vicinities. The topography in this area consists of hummocky hills with steep scarps on higher hills. The area includes multiple drainage basins. Although the large historic landslide complexes were likely triggered during wetter climatic conditions than that of the present day, these locations are much higher in elevation and receive much more precipitation than the valley floor below. Reactivation of landslides occurs almost yearly and cause major impacts to county and forest service roads and irrigation canals. Well known historic landslides along Cedar Creek impacted the Denver and Rio Grand Western rail lines in the early 1940s. Recent and ongoing landslides are evident throughout the area and major landslide studies have been completed for the U.S. Forest Service along Cimarron Road to Silver Jack Reservoir.

Risk Assessment and Hazard Vulnerabilities

Landslides are a serious geologic hazard that generally results in total loss of a structure and, in extreme rapid-moving situations, can be life threatening. Landslides can also disrupt pipelines, transportation corridors, and utilities. Extreme care should be made with any development that is being proposed within the landslide susceptibility zone. By the nature of this map creation, risk is implied for those areas inside the susceptibility zone. That risk will be generally higher near or within existing landslides and slopes that exceed a 3:1 grade.

Development Considerations and Recommendation for Future Land Use Planning

Where new developments have parcels that lie within the landslide susceptible zone, the county should require in-depth geologic and geotechnical investigations during the sketch plan application level of the proposed development plan, before lots are even laid out. These geologic hazards reports or preliminary geotechnical engineering reports must specifically address slope instability. The standard of practice for geologic hazard reports that include stability analyses include a slope classification map, a geologic hazards and constraints map with boring locations, and the cross-section lines used for stability analysis, a discussion on soil strength parameters, and copies of the slope stability analyses that models existing and post-development conditions. It should also include a sensitivity analysis with variable ground water conditions to model plausible seasonal ground-water fluctuations.

Safety factors are generally calculated based on the summation of resisting forces divided by the summation of the driving forces. A safety factor of 1.0 means the resisting forces equal the driving forces and the slope is in equilibrium. Any safety factor less than 1.0 indicates the slope is in incipient failure. Modeled safety factors should be in the 1.3 plus range to be considered on the low side of acceptable (1.5 would be preferable where raw slope conditions are being modeled and slope geometry, water, and soil strength parameters are mostly assumptions). These investigations should also include consideration of site conditions not only within the property boundaries, but how adjacent areas impact the proposed development, and vice versa. This is especially true where off-site irrigation in adjacent agricultural lands is saturating and potentially destabilizing parcels within the proposed development; a very common occurrence on the mesas in the irrigated Uncompahgre Valley.

It is recommended that no residential structures be constructed on a geologically recent landslide, which is one that has moved in the last few thousand years. Recent landslides can be discerned by a trained geologist by the relatively fresh landslide morphology. It might be prudent if future county master plans exclude residential development zoning in those susceptible areas where existing landslides have been mapped and slopes exceed a 3:1 grade.

Human activities can often worsen the risk of landslides in susceptible areas as a result of poor grading and improperly controlled drainage. Understanding of the slope stability of a given area prior to development may allow a susceptible area to be developed if rigorous investigations and slope stability analyses are conducted and the development plan and mitigation measures work towards stabilizing a slope, rather than creating a greater risk. Grading and placement of engineered fills, slope drainage, or engineered ground retaining and/or support systems may be necessary as mitigation measures; or avoidance of specific area if the risks are judged as being too high. In some cases, it may not be economically feasible or physically possible to mitigate the risks of potential slope instability and the entire site should be avoided for any real estate development.

Where development does, or has occurred, within landslide susceptible areas, consideration should be given to the formation of special bond districts, called Geologic Hazard Abatement Districts (GHADs), to reduce the financial risks on an area-wide or neighborhood basis. There should be full disclosure if a home lies within a mapped landslide susceptibility zone for all prospective buyers of not only new homes, but in secondary resale markets. Prospective buyers of existing homes and other real estate that lie within the landslide susceptibility areas should exercise due diligence and examine this map and/or retain an experienced professional geologist or geotechnical engineering for a site-specific evaluation of the property, similar to a standard building inspection report that is generally recommended before closing.

Map Usage and Limitations

The study area was mapped on a 1 inch = 2000 feet (1:24,000) scale. The coverage shows areas that are potentially unstable and may be susceptible to landslides. The map is not intended to give site-specific information as to the level of risk; rather, it serves as a tool for determining areas where slope stability issues may occur. Only privately owned lands were evaluated, but land use or ownership was not a factor that was given any weight in the generation of the susceptible area. Because of the uncertainties inherent to geologic science (i.e., subsurface geology and geometry, geologic structure, and water conditions) that are only assumed for most locations, no levels of risk assessment were made within the susceptible zone. For locations that lie within the susceptible area, this designation does not imply that landslides will occur during the life of a residential structure, only that landslides have occurred in similar nearby geologic and topographic conditions in the project area. It should be noted that extreme natural or human activity (e.g., earthquakes, broken water mains and saturated condition, or poorly designed excavations) may trigger slope instability in areas that are not included in the susceptible area.

Small, naturally-occurring landslides could exist outside of the susceptible area within the study area. This possibility is not very likely, provided that significant land use or grading changes do not occur. However, discrete and sporadic clay-rich lenses are known to exist in some of the geologic formations and may fail where steeper slopes are present. There are also shallow but steep drainage channel banks that are also susceptible to stream-side slumping. Care should be used when locating structures near these slopes and arroyos.

As stated above, locations of lands within the landslide susceptible zone should be evaluated by a qualified geotechnical engineer or engineering geologist for ground stability and presence of landslide deposits during further development, renovations, ground alterations, road alignments, and residential resale Appropriate disclosure should be made to prospective buyers.

Rockfall – Plate 2

Overview

The CGS descriptive definition (Rogers and others, 1974) of rockfall is: *relatively large fragments of rock become detached and by means of free-fall, rolling, bounding or rapid sliding, or a combination of these methods, moves rapidly down a very steep slope under the force of gravity.* Rockfall occurs in steep topographic areas where rock outcrops or eroding rocky soil are exposed. Weathering and gravitational pull causes fractured rock fragments to break away from the outcrop and fall, bounce, or roll down the steep slope to come to rest at the base of the slope where grades flatten. Because the steep slopes are more difficult to develop, most of the areas with potential rockfall hazards are avoided; however, as more growth is occurring at the base of steeper slopes, there are some areas that have been (and are being) developed within potential rockfall hazard areas. Rock contains great mass so the velocity and size of falling rock have a direct relationship with the impact force. Even small rockfall can pose a safety risk and significantly damage structures.

Background

For the purposes of this project, the term "rockfall" includes modes of ground failure where weathering and gravity causes rock blocks to fall, topple, roll, or slide down a steep slope. Rockfall can be a continuous process over a considerable period of time, a single event, or series of single intermittent events. A rockfall event can involve a single rock or large volumes of broken material, more commonly called a rockslide. Rockfall has three basic areas: the source area, or failure zone, where the rock initially falls from; the run-out zone, which is the steeper slope area where the rock actively falls, bounces, and rolls down the slope; and the accumulation zone where the slopes flatten and the falling or rolling rock ultimately comes to rest. Where accumulations of falling rock occur, the slope is generally referred to as a talus slope.

Source areas of rockfall are hard rock formations and to a lesser extent rocky surficial deposits (soil). These materials are generally more resistant to erosion and, over geologic time and by differential weathering, erosion, and removal of surrounding and adjacent softer rock and soil, become landforms characterized by topographic highs such as ridges, mesas, and cliffy rock-outcrop areas. Generally, rockfall initiates from these outcrops of more resistant rock and fall or roll onto the slopes below. The run-out zones are steeper slopes below that have a relatively hard substrate where, once the rock has detached and begins to fall or roll, the momentum is retained and the rolling rock accelerates down the slope. The accumulation zone is where the slope flattens to an angle of repose, which is defined as the maximum angle of a stable slope that is determined by the friction, cohesion, and size and shape of the rocks. The rock speed slows and eventually comes to rest in the accumulation zone.

Resistant rocks in the Montrose area include Precambrian igneous and metamorphic rocks in the Gunnison/Black Canyon Uplift areas and Mesozoic resistant sandstone units (Dakota/Burro Canyon, sandstones beds of the Morrison Formation, and the red Chinle Formation in canyons of the Uncompahgre Uplift.

Rockfall can range from a single rock falling or rolling to large-scale catastrophic events. The size of the falling rock depends on the source area geology (bedding thickness, bedding dip and dip direction, hardness, jointing/fracturing orientation), weathering, and position. Factors for triggering rockfall can include precipitation (water lubricates rock joints and fractures, weakens them, and causes them to slip and/or separate), temperatures extremes ("ice jacking" forces rocks apart during winter freeze/thaw cycles), chemical weathering (decomposition of rock), seismic (earthquake shaking, blasting), undercutting (natural or human-caused), or adverse loading (snow loads, animals, home locations, etc.) that can loosen or overturn an unstable rock.

Rockfall events can quickly demolish structures and can be fatal if a person is struck. Most, but not all, areas susceptible to rockfall can be identified and steps can be taken to avoid, reduce, or mitigate rockfall risk. In some areas, tree-covered slopes are currently acting as rockfall barriers, however, should this forest cover burn, rollout zones may extend farther down the slopes than they do under the current conditions.

Methodology

The rockfall susceptibility map was created by selecting a coverage from the slope classification map (generated from the DEM) that contains all slopes steeper than 60% (31 degrees), which is an average angle of repose where falling and rolling rocks generally come to rest. The slope coverage was digitally compared to geologic data and aerial photography to compile the hazard map in a GIS framework. These initial data were used during the field checking process, and the hazard areas were digitally adjusted and refined as field observations were made to more accurately reflect the observed rockfall potential, and extent of the run-out areas and accumulation zones.

The mapped boundaries include potential source areas, the run-out area where bouncing or rolling material may extend, and the accumulation zone where the rocks come to rest. The mapped boundaries represent the maximum extent of possible rockfall hazard based on a "worst case scenario" for a probable volume of falling rock. This includes the effects following wildfires, modest earthquakes, and extreme weathering. Effects from very-low-probability, large-volume "catastrophic" events such as rock avalanches triggered by large earthquakes were not included in this map.

Mapping Results

The rockfall susceptibility data on private lands was developed at a scale of 1 inch = 2,000 feet (1:24,000) to discern rockfall areas identified during this study. Four general types of rockfall areas were identified within the private lands of Montrose County during this study.

Steep slopes and fractured outcrop areas in Precambrian rocks. These areas are primarily limited to the northeastern portion of the study area around the Black Canyon of the Gunnison. Typically the landforms here are massive, cliffy outcrops of rocks, steep chutes, and talus slopes near the base of the slopes.

Areas where resistant, highly fractured Precambrian outcrops are located above steep slopes can produce rockfall. Most rockfall in such areas is produced by the exposed rock mass failing along prominent joints or fractures. A minority of rockfall can be caused from weathering and undercutting by steams, or sloughing of rocks in chutes, or partially embedded in rocky colluvial soil. The falling rocks tend to break up unto talus slopes below the source outcrops, but can also bounce erratically and launch onto flatter adjacent terrain

Resistant, gently to moderately dipping, sedimentary bedrock of the Uncompahgre Plateau. Sandstones and conglomerates in the Dakota/Burro Canyon Formation and, to a lesser extent, the Morrison, Chinle, and Entrada Formations may be susceptible to rockfall when undercut. The Dakota Sandstone generally rims all the canyons, and other resistant rock form cliffy areas along the canyon walls that are prone to rockfall in the western portion of the study area on the Uncompahgre Plateau. Failure occurs when differential weathering or stream erosion accelerates erosion of underlying weaker shale beds and undercuts the more resistant sandstone layers. Undercut rock blocks on the leading edge of the bluff, ridge, or canyon outcrop may begin to slump and topple. Rockfall results when these blocks ultimately separate from the rock mass behind along pre-existing joints and fractures.

Rockfall within landslide areas. The large landslide complexes in the Morrison Formation located in canyons and basins of the Uncompahgre Plateau in the southeastern portion of the study area includes areas where rockfall may occur from scarps that expose resistant bedrock. Additionally, rockfall may occur as blocks of resistant material in the rocky landslide deposit being undercut by erosion. Generally, these areas may produce a local risk of rockfall. If the landslide is active, ongoing movement in these areas may contribute to isolated and site-specific potential for rockfall that is not shown on this map.

Rocky alluvial terraces and mesas edges. Observed during the field checking were potential rockfall areas related to the ongoing downcutting of streams and topographic reversal that forms gravel capped mesas. Rockfall can occur where the mesa edges are steep and the gravel that rim the mesa are exposed. Some of these steeper slopes are human-made excavations. Generally, these areas may produce a local risk of rockfall, but may be difficult to map without knowing the location of dispersed boulder and cobble-sized rocks within the deposit. Ongoing erosion in these areas may contribute to isolated and site-specific potential for rockfall that is not shown on this map.

Risk Assessment and Hazard Vulnerabilities

Rockfall is a serious geologic hazard that could result in catastrophic damage to a structure poses a significant risk to human safety, and can be fatal if a person is hit. Fortunately, there are only a few isolated locations in the study area where private land is significantly exposed to rockfall hazards. The canyon floors and walls of the Uncompahgre Plateau that are rimmed with sandstone cliffs are at elevated risk for rockfall, including private land holdings along Roubideau Creek, the Dry Creek basin, Spring Creek, and near the walls of Shavano Valley. The same is true for some of the rocky steep slopes areas of Vernal and Poverty Mesas, and where private landholdings occur in the Black Canyon of the Gunnison. Some of the steeper scarps of landslides in the Cimarron Ridge area, such as Castle Rock and Washboard Rock, are also at elevated risk. By the nature of the development of this map, risk is implied for those areas inside the susceptibility zone.

Human activities can increase the risk of rockfall hazards or cause rocks to fall sooner than they would naturally. Excavations, such as road cuts, often remove support for overlying or overhanging rock and create rockfall risks, as can development-related changes in surface and ground water conditions. Talus (loose rock fragments) on steep slopes is often the result of numerous small rockfall events. Construction on talus slopes can increase rockfall risks to areas above and below construction by increasing or renewing movement of talus. Over-steepened cuts and other excavations are common causes and create dangerous areas for rockfall events to occur.

Hazard avoidance is by far the simplest, most effective, and least costly mitigation strategy. However, other forms of mitigation can reduce, but not eliminate, rockfall risk. Some typical types of mitigation include:

- Stabilization of rock outcrops by removal of unstable rocks (scaling) or rock reinforcement such as rock bolting, grouting, buttressing, and cable lashing;
- Protection systems to stop, slow, or diverting moving rocks, such as rock fences, draped cable nets or wire mesh screens, impact walls or barriers, berms and ditches, or rockfall sheds;
- Structural reinforcement solutions such as integrated concrete barriers and walls for vulnerable structures and facilities.

All these measures are expensive, require regular maintenance, and do not completely eliminate the risk of rockfall.

Development Considerations and Recommendation for Future Land Use Planning

Where new development includes parcels that lie within the rockfall susceptible zone, the county should require geologic and geotechnical investigations during the <u>sketch plan application level</u> of the proposed development plan, before lots are even laid out. These geologic hazards report or preliminary geotechnical engineering report must specifically address the potential rockfall hazard and determine what mitigation, if any, should occur. Where residential sites are being proposed within a rockfall susceptibility zone, the reports should include a rockfall hazard map that delineates the source area and run-out zone, and the methodology used to create either the buffer or no-build zone to avoid the hazard, or the proposed mitigation.

There should be full disclosure if a home lies within a mapped rockfall susceptibility zone for all prospective buyers of not only new homes, but also in secondary resale markets. Prospective buyers of existing homes and other real estate that lie within a susceptibility area should exercise due diligence and examine this map and/or retain an experienced professional geologist or geotechnical engineering for a site-specific evaluation of the property, similar to a standard building inspection report that is generally recommended before closing.

An important factor to keep in mind is that although the place of potential rockfall is to some degree predictable, the time of failure is not. Hence, complete avoidance of areas of potential rockfall is the most sensible mitigation measure where lives or high property values are at stake.

Map Usage and Limitations

The study area was mapped on a 1 inch = 2000 feet (1:24,000) scale. Inclusion of properties within the mapped boundaries does not imply that rockfall events will impact that particular property at any given time - only that that property has a higher risk of being impacted compared to areas not included in the mapped area, based on the geologic and topographic conditions. Conversely, areas that are not identified in the rockfall boundaries could be exposed to potential rockfall occurrences if adverse blasting, grading, excavation, or wildfire occurs. Isolated areas of localized rockfall hazard potential outside of the mapped boundaries may include the areas surrounding erosional remnants, as well as on-going excavation and grading activities.

This study does not consider or include the potential of very large, catastrophic failures of mountainside rock outcrops that could result in a large-volume rock avalanche. Such failures may be related to severe earthquake shaking. Detailed investigations of rock mass structure was beyond the scope of this study.

The potential rockfall hazard areas shown on this map were constructed qualitatively using the available geologic, topographic, and field evidence. No levels of risk assessment were made within the mapped boundaries, which include not only source areas, but also probable down-slope run-out areas.

Avalanche – Plate 2

Overview

The CGS descriptive definition (Rogers and others, 1974) of snow avalanches are, *the rapid downslope movement of snow, ice, and associated debris such as rocks and vegetation.* Avalanches are typically seen in higher mountainous terrain.

Background

There are two basic types of avalanches: dry, powder avalanches that create turbulent air-blasts; and wet, snowslide-type avalanches that flow down a chute or drainage channel much like an earth flow or debris flow. Both types leave identifiable scars and trim-lines in vegetated areas. The air-blast avalanche type is visible as scars in mountainsides and swales, not necessarily corresponding to a drainage channel. Wet snowslide avalanches tend to follow existing chutes and drainage channels. The scarring is much more limited in this situation; confined to near the channel itself.

Methodology

In a GIS framework, slope classification maps were draped on high-resolution aerial photography. Using stereo aerial photography, steep terrain in high elevation areas were examined on private lands to determine where scars occur on hillsides that are suggestive of avalanche paths.

Mapping Results

Only small sections of private lands in the southeast corner of the project area near the boundary with Ouray County have elevations and winter snowpack that are conducive for the generation of significant avalanches. Only localized areas of the Cimarron Ridge near Castle Rock and Washboard Rock at elevations of between 10,000 and 11,400 feet show the scarring that is typical of an avalanche path.

Risk Assessment and Hazard Vulnerabilities

The risk and hazard vulnerability of dry air-blast avalanches is pretty limited for the project area. The small areas with avalanche risk near Cimarron Ridge should be avoided by any residential development, including seasonal cabins.

It should be understood that wet snowslides down pre-existing steep drainage channels are another matter. When snowfall is heavy and the snow is especially wet, or during rapid runoff from spring melting, it can slump and flow along these channels to spread on alluvial fans much like debris flows. These types of avalanches are typically constrained in chutes and along drainage channels so the visual evidence of open-slope scarring and tree trim-lines from avalanche activity is more difficult to map. Such conditions may occur along the steeper chutes and drainage channels along the Gunnison Uplift east of Bostwick Park and the highlands west of Cimarron Creek.

Development Considerations and Recommendation for Future Land Use Planning

Structures should not be allowed in the areas mapped as avalanche hazards. Concerning wet snowslide avalanches, for the reasons stated above, home construction near drainage channels, chutes, and run-out fans in higher terrain with significant winter snowfall should also be avoided. CGS Special Publication 7 (Mears, 1979) contains additional information on avalanches and hazard planning in avalanche hazardous terrain.

Map usage and limitations

The avalanche map reveals those areas where slope, morphology, and vegetative scarring indicate that avalanches have occurred there. This map does not include locations where wet snowslide-type avalanches may occur when heavy and wet snow slumps and flows down existing chutes and steep drainage channels. Steep chutes and swales that may generate wet snowslides are also prone to debris/mud flows.

Mudflows and Debris Flows – Plate 3

Overview

The CGS descriptive definition (Rogers and others, 1974) of a mudflow is, "*a geologic phenomenon whereby a wet, viscous, fluid mass of fine- to course-grained material flows rapidly and turbulently downslope, usually in a drainageway. This results typically from torrential rainfall or very rapid snowmelt runoff that initiates rapid erosion and transport of poorly consolidated surficial materials that have accumulated in the upper reaches of the drainage area.*" These fast-flowing hyper-concentrated flows have the ability to fan out over ground terrain and can cover large areas. They behave more like a rapidly moving earth flow than a flood in the sense that debris flows don't necessary flow down a narrowly defined flood plain or an established drainage channel. For that reason, debris floods are categorized as a geologic hazard and not a flooding hazard. Mud is composed predominantly of silt- and clay-sized particles, whereas the term "debris" is commonly applied to material that consists mostly of boulder- and cobble-sized rocks mixed with displaced soil and vegetation. It is a potentially damaging geologic hazard in mountainous terrain, but also in semi-arid Colorado where steep slopes and poorly vegetated slopes exists, and intense, cloud-burst-type rainfall events can occur.

Background

Mudflows and debris flows typically are formed where heavy precipitation in a basin becomes concentrated such that unconsolidated soil and earth materials become entrained in the flow so that a bulked mud or slurry forms, and the entrained particles have no shear strength. The viscous fluid then rapidly moves downslope. The hydraulic nature of this hyper-concentrated flow enables it to "lift" and carry debris, such as boulders, downed trees, and any other material that may lie in its course. At a point where the slope flattens, the flow slows, friction occurs between soil particle and shear strength re-engages, and the flow stops. They are typically recurrent events from the drainage basin so mud and debris flows hazard can be identified by a specific geomorphic landform called an alluvial fan or debris fan, which is a thickened wedge of sediments that formed by the deposition of successive flows. The apex of the fan rises to the mouth of the drainage basin.

Alluvial fan flooding is much more random than typical flood plain flooding along river streams. Mud/debris flooding is characterized by lateral moving of flow over a wide area from the mouth of drainage basin onto a valley or mesa floor. Old channels are abandoned and new ones form as additional flows deposit more material on the valley floor. For that reason, structures located anywhere on a fan are susceptible to mudflow flooding, even if the structure is not located near the current channel.

Another consideration with alluvial fan and mud/debris flooding is that wildfires in the drainage basin can raise the risk of debris flooding. The loss of the vegetal cover in burn areas increases run-off rates and the denuded slopes are more prone to erosion, thus increasing both the peak discharge and bulking rate of the resultant flows.

Methodology

The mudflow map was created by selecting all alluvial fan deposits from the geologic maps that were completed by CGS in 2007 and 2008. On other geologic maps where alluvial fans were not separately mapped, aerial photography and analyses of topographic maps were conducted to discern alluvial fan morphology and drainage basins that could produce bulked flows. These fans were compiled and digitized into a GIS shapefile. Specific or questionable areas later field checked. This shapefile does not include typical flood zones in river and stream flood plains that are typically mapped in FEMA Flood Insurance Rate Maps (FIRM).

Mapping Results

The mud/debris flow hazard susceptibility coverage was developed for private lands at a mapping scale of 1 inch = 2,000 feet (1:24,000). Alluvial fans where mud/debris flows have occurred are found in the following project areas.

<u>Tributary streams of the Uncompahgre Plateau that debouche onto the west side of the Uncompahgre River valley.</u> Many broad alluvial fans outlet onto California Mesa and Shavano Valley from the many subparallel canyons that have cut into the eastern flank of the plateau. Historic mud flows have been reported from many of these canyon and flood control dams and detention basins have been constructed in Roatcap Gulch and Shavano Valley.

<u>Mud fans from the Mancos Shale Adobe Hills.</u> Several small but steep basins extend into the "adobe hills." The mudflows from these areas are generally less viscous and, instead of creating alluvial fan morphology, create a broader mud-flat environment typical of tributary drainages to Montrose and Loutzenhizer Arroyos, and the lower reaches of Cedar Creek.

<u>Large mud fans in the southern project area along the Uncompahgre River valley.</u> Large mud fans originate from the high terrain to the east of the river that is underlain by Mancos Shale, including the higher reaches of Beaton Creek.

<u>Typical alluvial fans in the steep terrain of the eastern project area</u>. Classic alluvial fan morphology and typical debris flow hazards occur in many valley areas in steeper terrain such as the east side of Bostwick Park, the upper reaches of Cedar Creek, Pool Gulch near Poverty Mesa, and the Cimarron River valley.

Risk Assessment and Hazard Vulnerabilities

Risk assessment for mud/debris flows was difficult for this project area, specifically in the "adobe hills" area near Montrose. Most of the surficial soils in the area are derived from mud flows from the "adobe hills" nearby but rarely is a well-recognized alluvial fan discernable. The mud that formed from the claystone is thin and water-rich and results only in mud flats. The CGS could only map a few areas that are considered a potential hazard.

This situation was rendered even more uncertain by the extensive irrigation canal and lateral ditch network in the Uncompahgre River valley. Many of these canals and ditches cross natural drainageways and so they provide a, albeit undefined, mitigative effect to bulked storm flows down the drainageway.

The risks of mudflows (and traditional flooding) from the many side canyons of the Uncompahgre Plateau is probably higher. Many of these drainage channels also benefit by the canyon mouths being crossed and intercepted by irrigation canals. We would expect the same to be true in the higher elevations areas on the east side of the project area in the Gunnison Uplift and Cimarron Creek areas.

Where the threat of debris flooding occurs, there are mitigative solutions. Avoidance is the preferred strategy, but other solutions include raising the structure on fill pads, grading, diversion berms and walls, flumes, detention basins, and debris racks that span the basin mouth.

Development Considerations and Recommendation for Future Land Use Planning

Where new development includes parcels that lie within the debris/mud flow hazard areas, the county should require, at sketch plan, an in-depth hydrologic/drainage study be completed that specifically addresses off-site drainage mud/debris flows onto the property, and model peak flows that are appropriately bulked with sediment.

Map Usage and Limitations

This map coverage shows locations where the geomorphology suggests that overland flow of debris and mud periodically occurs outside of established drainage channels on alluvial fans. This map does not consider or reflect flooding in established flood plains that is under the jurisdiction of the Watershed Protection and Flood Mitigation Program of the Colorado Water Conservation Board. Federal Insurance Rate Maps by FEMA of the Montrose vicinity only includes major tributary streams.

Swelling Soils (Expansive soil and rock) – Plate 4

Overview

The CGS descriptive definition (Rogers and others, 1974; Noe and others, 2007) of swelling soil and expansive bedrock is: *soil and rock that contain clay minerals that attract and absorb water.* The rock or soil swells in volume when wet and shrinks when dry. Clay minerals are hydrous aluminum phyllosilicates that have a structure similar to mica, and form micron-sized sheets or plates. The swelling is caused by the chemical attraction of water to certain clay minerals, predominantly smectite and, to a lesser extent, illite. Layers of water molecules can be incorporated between the clay plates. As more water is made available to the clay, more layers of water molecules are added between the plates and the adjacent clay plates are pushed farther apart. The swell pressure from the addition of water on the molecular level can be quite high and can easily heave typical foundations and slabs, resulting in severely damaged structures.

The terms swelling soil, expansive soil and bedrock, heaving soil, and shrink-swell soils are used interchangeably to describe that same type of mineralogical volume expansion mentioned above.

Background

The major bedrock units that contain expansive clay minerals in the project area are the Mancos Shale and shales of the Morrison Formation. Within the project area, claystone bedrock is very common. The Uncompahgre River valley is in its present location because the Mancos Shale is more easily eroded compared to the more resistant rocks on the Gunnison Uplift and Uncompahgre Plateau. The east side of valley is almost entirely exposed shale (i.e., "adobe hills").

These rock formations were deposited during the Mesozoic Period when volcanic eruptions were more prevalent to the west in present day Arizona, Nevada, and California. Weathering and alteration of volcanic ash formed the smectite clay particles that were incorporated into the mud that lithified to become the claystones and shales. Bentonite is a special type of smectite that may have especially high swelling characteristics. Relatively pure bentonite seams or layers are commonly seen in the Mancos Shale. These layers record ash falls from heavy volcanic eruptions in the geologic past, that sank into the Cretaceous mid-continental seas to deposit on the sea bottom with little mixing of other sediments.

Volume change is influenced by the amount and type of clay minerals in the soil and the moisture content. Soils that are derived from the erosion of the claystone bedrock contain the same swelling clay minerals. The semi-arid climate of western Colorado has resulted in dry, native, clay soils with lower moisture contents. Residential development, with the related concentration of drainage from roof downspouts, impermeable slabs, and landscape irrigation, usually results in the addition of moisture to these soils. Those soils with swell potential will see volume expansion as the moisture content increases.

Methodology

The swelling soil map was created by integrating GIS geologic mapping data, GIS soil data from the NRCS, and consultation with the local geotechnical engineering community. Selected NRCS data that was used for this coverage were: 1) linear extensibility, which is the main NRCS indicator for shrink-swell potential of soils; it is a measurement of volume changes in a soil clod as the moisture content is decreased; 2) the percent of the soil that is composed of clay-sized particles; and 3) the Plasticity Index (PI) of the soil. PI is a measure of the ability of a clay soil to hold moisture, which is the percent range from when a soil crumbles (plastic limit) to when it behaves as a fluid (liquid limit). Swelling soils tend to be "fat" clays with high PI, typically getting extremely greasy and slippery, and caking onto shoes and tires, when it becomes wet.

A matrix was created assigning a rating of low, low to medium, medium, medium to high, and high risk of swelling soils for the geologic map units in the project area, based on the bedrock lithology and/or sediment types of the map units and incidents of swelling soil that have been reported. Those hazard zones were then further adjusted based on the selected NRCS GIS data mentioned above.

Mapping Results

The mapping results indicate that higher hazard potential of swelling soils occur where: 1) the Mancos Shale is exposed at the surface; 2) clayey colluvial sediments (including landslide deposits) are derived from the Mancos Shale, and 3) Morrison Formation claystone is exposed at the surface and within any clayey soils that are derived from the Morrison Formation. Those areas with low risk of swelling soils include the gravel terrace and mesa areas, the modern Uncompahgre River floodplain, the highlands of the Gunnison Uplift, and the Dakota Sandstone exposed on the Uncompahgre Plateau.

Claystone bedrock units of the Mancos Shale tend to be rated higher than the soils derived from them. That is especially true when those soils are alluviums derived from mud flows. These types of soils may have swelling clay mineralogy but were deposited in a low-density condition as the turbulent mud flow stopped. Collapsible and compressible soil hazards may be a more critical geologic hazard with mud flow-type soils, even with swelling clay minerals. More discussion on these types of clay-rich soils in is the "Collapsible Soil" section of this report.

Risk Assessment and Hazard Vulnerabilities

Swelling soil is the most costly geologic hazard in Colorado, but most of the damage and expense is along the Front Range in the major metropolitan areas. Swelling soils should be viewed as a geologic constraint that can be mitigated with a proper geotechnical engineering investigation and appropriate foundation design, even in areas rated in the high hazard categories. Proper landscaping and irrigation practices are very important in swelling-soil hazard areas. The key is an appropriate structural foundation and preventing undue wetting of the swelling-clay soil.

Commonly conducted soil tests that indicate swell potential of a soil are the Atterberg limit test, which measures the plastic and liquid limits of the soil to calculate the PI, and, most importantly, the swell/consolidation test (modified from ASTM D-2435 and D-4546 soil-testing methods). In this test, an apparatus loads an undisturbed soil sample with a surcharge pressure in pounds per square foot (psf), which is then wetted. The percent expansion of the soil sample after absorbing the water is then recorded, as well has the swell pressures. The swell potential rating varies depending on the surcharge pressure (load) at the time the samples are wetted. The following swell potential rating criteria is from the Colorado Association of Geotechnical Engineering (CAGE).

Percent Swell @ 500 psf	**Percent Swell @ 1000 psf**	**Swell Potential Rating**
0-2%	0-3%	Low
2-4%	3-5%	Moderate
4-6%	5-8%	High
>6%	>8%	Very High

There are several mitigative techniques to address swelling soils, including:

1. Ground modification techniques, such as overexcavating the swelling soils and replace them as a structural fill, conditioned to above optimum moisture content so the swell potential is removed.
2. A water or chemical treatment that either prevents swell or pre-swells the soils.
3. Foundation designed with minimum deadloads to counter heave pressures.
4. Deep foundations.
5. Post-tensioned slab-on-grade foundations.
6. Structural floors instead of interior slab-on-grades.

Where there are homes that may not have been built with a foundation that mitigates swelling soils, proper drainage, grading, and landscaping are critical to keep the subgrade soils from being unduly wetted. Xeriscape™ landscaping techniques are recommended.

Development Considerations and Recommendation for Future Land Use Planning

Where swelling soils exists, or are assumed, the submittal of a preliminary geotechnical report should be included during sketch plan or preliminary plan development application. This preliminary report should include a suitable number of boring and/or test pits to characterize the site and soil testing including swell/consolidation tests. This report will give a more detailed assessment of whether swelling soils exist on the site, and what the swell potential is. Further lot-specific design-level foundation investigations should be required for a building permit.

The CGS has been studying the occurrences of swelling soils for many years. A recommended CGS publication is: *A Guide to Swelling Soils for Colorado Homebuyers and Homeowners* by Noe and others (2007).

Map Usage and Limitations

This map coverage is based on a regional understanding of the geology and soils of the project area. The rating zones are generalized at a 1:24,000 map scale and, based on that understanding, should only be used as a tool for determining areas where swelling soils most likely may occur. It is not meant to be, or should be considered, a substitute for site-specific investigations and soil testing. Pockets of higher swell-potential soils may occur in low rated areas, as well as low swell-potential soils occurring in areas mapped as higher risk.

Collapsible Soils – Plate 5

Overview

Collapsible soils are broadly defined as soils that rapidly settle when exposed to water. These soils are a significant geologic hazard in Colorado and other Western States of the United States in semiarid to arid climates. The collapse can occur under the weight of the soil alone (overburden pressure) or under the additional load of a building or other structure. Most collapse occurs through mechanical means where dry, low-density, high-porosity soil becomes denser when the soil-particle binding agents weaken or break after wetting. The destruction and recompaction of the soil structure at moister conditions cause settlement of the ground surface. Because the introduction of water brings about such collapse, the terms "hydrocompactive" and "hydrocompressible" are commonly used to describe collapsible soils. Other processes of ground subsidence and collapse occur in dispersive or erodible soils through (1) suspension and removal of particles by flowing water (soil piping and pseudokarst formation) and (2) actual chemical dissolution of the soil matrix in gypsiferous soils and soils derived from evaporite bedrock.

Background

Collapsible soil forms in specific, geologically recent (Holocene) sediments that have been deposited in arid to semiarid environments. The deposits include (1) hillside gravity and slope-wash deposits, called colluvium; (2) accumulations of rapidly deposited, unsorted, water-borne mud in alluvial and debris-flow fans; (3) aggraded overbank deposits, called alluvium (silt and clay recently laid along tributary streams, flood plains, and gently sloped mud flats); and (4) windblown deposits of dust, silt, and fine-grained sand, called loess. Where soil collapse exists, an open and inherently unstable skeletal fabric characterizes the soil structure of these sediments. The common factor in the water-laid sediments is rapid deposition. In the generally arid climate, wet sediments quickly desiccate (dry out) in their original condition, without the benefit of further reworking to pack the sediment grains. Locally, ground-water levels generally never rise into these mantles of soil, which can remain unsaturated until land development. During and after development, moisture can be introduced to the subsurface soil through field irrigation, lawn and landscaping irrigation, capillary action under impervious slabs, leaking or broken water and sewer lines, and altered surface and subsurface drainage.

Methodology

The collapsible soil susceptibility map was created using GIS software, utilizing georeferenced 1:24,000 topographic maps and a 10-meter DEM as base maps. Digital versions of the compiled project geologic map and NRCS data were used to select and group surficial geologic deposits and soils that may be susceptible to collapse. The map polygons were created based on climate, geology, engineering properties of the soil, geomorphology, and sediment depositional processes where collapse-prone soils may form. Soil groups with shallow bedrock (<5 feet) were generally excluded, as were wet soils prone to flooding, stony or heavily graveled soils that are more characteristic of river terrace deposits that cap the valley mesas, and steep rocky colluvial (talus) slopes.

The final collapsible soil susceptibility coverage was created from merging edited NRCS soil map areas with geologic map polygons of unconsolidated surficial deposits that have been shown to be collapse-prone. The coverages were then compared to topographic maps, hillshaded 10-m DEM, and high-resolution aerial photography. The final shapefile was digitally adjusted where necessary. Limited field checking was done in certain questionable regions.

Mapping Results

Collapsible soils are found predominantly in the fine-grained soils that are derived from mud flows in the project area. These types of soils typically mantle the lower-lying areas near “adobe hills,” and where streams outlet from the Uncompahgre Plateau, as well as some of the higher mesas and parks. The sediments of alluvial fans and colluvial slopes adjacent to terraces and mesas are generally susceptible to collapse when they become wetted and loaded.

Risk Assessment and Hazard Vulnerabilities

Collapsible soils have been a significant hazard in the Montrose area, and many heavily loaded structures have had significant problems with settlement that required costly remedial repair, or were abandoned and demolished because of the extent of the damage. The hazards of collapsible soils are related to the Collapse Potential and extent of the soil deposit.

Collapse Potential, as with swell potential, is determined by one-dimensional swell-consolidation tests (modified from ASTM D-2435 and D-4546 soil-testing methods). In this test an "undisturbed" soil sample is loaded with weights to a specific pressure. Collapse Potential is the percent of soil consolidation that occurs after the soil sample is wetted. At a load of 1000 pounds per square inch (psf), the hazard rating for collapse potential is as shown.

Percent Collapse	Hazard
0-1%	No Problem
1-3%	Low
3-5%	Moderate
>5%	High

In western Colorado, many geotechnical consultants flood their sample at much lower load pressures in their swell/consolidation testing. In such circumstances, one needs to extrapolate where the steep consolidation curve crosses the 1000 psf load line to use the chart above. One of the purposes of flooding the samples at low loads is that many of the collapsible soils in the Montrose area are derived from the Mancos Shale and contain clay with swell mineralogy. In these circumstances, these types of soils may exhibit both swell and collapse behavior when they become wet. The soil may be slightly expansive at very light loads (i.e., concrete slab-on-grades) as the clay particle take in water and swell, but at higher loads (i.e., structure foundation) the soil fabric begins to shear and collapse and consolidation occurs. This phenomenon is very common in the clay soils of the Montrose area and needs to be properly considered in foundation designs.

The depth and thickness of the collapsible soil is also very important. Even with low collapse potential, the saturation of a thick column of soil could cause settlement at the ground surface. For example, complete saturation of a 10-foot column with 3% collapse potential, still considered low, could result in over 3 inches of settlement.

The CGS has been studying the occurrences of collapsible soils in Colorado for many years and recently completed a publication on the topic. For further information of collapsible soils that contains specific detailed discussion of the Montrose area, see the CGS publication, *Collapsible Soils in Colorado* by White and Greenman (2008).

Development Considerations and Recommendation for Future Land Use Planning

Collapsible soils hazards must be properly identified for any development consideration. The preliminary geotechnical investigation must determine the depth of the collapsible soil and the collapse potential. As with swelling soils, the introduction of water to the subgrade soils is the catalyst for damage and distress to structures. For development in a collapsible soil area, water management is extremely important. Grading, drainage, and landscaping details must be stressed so that undue wetting of the subsoil is minimized.

Map Usage and Limitations

This map identifies locations that may be susceptible to collapsible soils and should be used as a tool to formulate appropriate and proper types of investigations. It should not be used as a stand-along determinator that collapsible soils exist at a particular site, that the collapse and settlement potential is high, or be a substitute for a professionally prepared, site-specific geologic hazards study or geotechnical investigation. This map is meant as a general guide for landowners, planners, municipal and county land-use regulators, and the geotechnical and civil engineering community to show that the geologic, geomorphic, and climatic conditions of a particular location are amenable to the formation of collapsible soils. The intent of the map is to warn users about the potential risk of soil collapse for a given area, and to prompt a proper level of geotechnical investigation that will determine the site-specific collapse potential of the soils there. Such investigations are needed in order to provide the appropriate engineering considerations for mitigation and water-management recommendations.

Corrosive Soils – Plate 6

Overview

Soil corrosion is a geologic hazard that affects buried metals and concrete that is in direct contact with soil or bedrock. Metals tend to be attacked by chloride solutions while high sulfate levels are harmful to concrete. The saline nature of the Mancos Shale with abundant secondary sulfate mineralization (gypsum) is considered corrosive to both metals and concrete.

Background

Corrosion of metal is an electrochemical process that involves oxidation (anodic) and reduction (cathodic) reactions on metal surfaces. Corrosion is typically a result of contact with soluble chloride salts found in the soil or water, which requires moisture to form solutions of these salts. Several key factors that influence the severity and rate of corrosion include: the amount of moisture in the soil, the conductivity of the solution, the pH of the solution, and the oxygen concentration within the soil (aeration). The organic content of the soil, soil porosity, and soil texture indirectly affect corrosion of metals in soil by influencing the key factors listed above.

The rate of corrosion of uncoated steel is related to such factors as soil moisture, particle-size distribution, acidity, and electrical conductivity of the soil. Furthermore, chloride ions from salt-enriched waters, soil, or from anti-icing salts can lead to corrosion of steel reinforcement in concrete and steel structures by dissolving the protective layer of oxides present on the steel surface.

Sulfate ions may also lead to accelerated corrosion of steel reinforcement and concrete. Sulfates react with lime in the concrete to form expansive products that cause the concrete to soften and crack, thus weakening the concrete. Water with other destructive ions can percolate through cracked concrete, attack the reinforcement steel, and speed up the corrosion process.

The presence of high acidity ($pH \leq 5.5$) in water or soil is considered a corrosive condition for concrete and certain metals (carbon steel, zinc, aluminum, and copper). Like the corrosion of metals described above, acidic soils or waters can react with the lime in concrete to form soluble reaction products that can leach out of the concrete, resulting in concrete with greater porosity and weaker condition. Concrete that has been affected by acidic conditions will often have yellowish or rust colored areas on the concrete surface.

Discussion

Characterizing the corrosivity of a soil is complicated by the interaction of the variables described above. For example, metal buried within an aerated or disturbed soil with a particular resistivity and soluble chloride concentration generally will not experience the same amount of corrosion as a similar metal placed in the same soil in a compacted, less aerated state.

Special site examination and design may be needed if the combination of factors results in a severe hazard of corrosion. Uncoated steel or concrete in installations that intersect soil boundaries or soil layers is more susceptible to corrosion than the steel or concrete in installations that are entirely within one kind of soil or within one soil layer.

For uncoated steel, the risk of corrosion, expressed as *low* or *high*, is based on soil drainage class, total acidity, electrical resistivity near field capacity, and electrical conductivity of the saturation extract.

For concrete, the risk of corrosion also is expressed as *low* or *moderate to high.* It is based on soil texture, acidity, and amount of sulfates in the saturation extract in chemical tests by the NRCS.

Methodology

In order to map the potentially corrosive soil boundaries, existing digital data were compiled in ArcMap GIS version 9.2. The datasets included:

- National Resource Conservation Service (NRCS) Soil Survey data from the Ridgway-Montrose area;
- The merge project area geologic map compiled from CGS and USGS sources;
- National Agriculture Imagery Program (NAIP) 1-m resolution, orthorectified color aerial photograph;
- a 10-m DEM

A map of areas of low, moderate, and high corrosiveness for steel and concrete was generated from the Soil Survey data using the NRCS Soil Data Explorer. We grouped the low and moderate classified polygons together, which left polygons of either low or high corrosive potential. This coverage was overlain on the geologic coverage to determine which corresponding geologic units coincided with the high potential for corrosion. Field observations of known corrosive units were used in conjunction with the overlay layer. The corresponding geologic units were selected out of the coverage and combined with the polygons in the corrosive soil layer.

The mapped boundaries represent an approximation of potentially corrosive soils based on the NRCS Soil Survey data, mapped geologic units, and field data where collected.

Risk Assessment and Hazard Vulnerabilities

Most of the surface water and perched or shallow ground water in the Uncompahgre Valley are exposed to, or flow through the Mancos Shale. Almost uniformly, corrosion protection for steel and sulfate-resistant concrete mixes is recommended for construction. If neither is proposed, soil corrosion testing must be completed. Generally, water-soluble concentrations are measured in soil samples. The American Concrete Institute has standards to determine severity levels of corrosion by sulfate attack in their Manual of Concrete

Practice. Type V concrete, which is sulfate resistant, is generally specified in the Uncompahgre Valley.

Map Usage and Limitations

The study area was mapped on a 1 inch = 2000 feet (1:24,000) scale. Inclusion of properties within the mapped boundaries does not imply that corrosive soils will impact that particular property at any given time - only that that property has a higher risk of being impacted compared to areas not included in the mapped area, based on the geologic conditions.

The potential corrosive soil hazard areas shown on this map were constructed qualitatively using the available soil, geologic, and field evidence. No levels of risk assessment were made within the mapped boundaries. Appropriate soil corrosion testing should be conducted to determine what mitigation, if any, should occur, and appropriate disclosure should be made to prospective buyers. Mitigative measures may be required to reduce the risk from corrosive soils.

Flooding Hazards – Plate 7 and 8

Overview

Flooding is a natural hazard but is not considered a geologic hazard. Flood hazards and designated flood hazard zone assessments are under the jurisdictions of Colorado Water Conservation Board and FEMA. The CGS task for this project was to digitize the available FEMA Flood Insurance Rate Maps (FIRMs) for Montrose County. Those maps within the municipal limits of Montrose and Olathe were excluded from this coverage.

Methodology

Digital scans of all available FIRMS were imported into ArcGIS 9.2 as raster images that were subsequently georeferenced. The flood plain line work was then manually digitized and saved as an ArcGIS shapefile. Flood hazard is a selectable attribute in the NRCS SSURGO soil survey so, in addition to the available FIRMs, a second layer of flood hazard was acquired for a large portion of the project are using the Soil Data Viewer, a GIS extension available from the NRCS.

Risk Assessment and Hazard Vulnerabilities

Risk assessment and hazard potential should be determined by the Colorado Water Conservation Board.

Development Considerations and Recommendation for Future Land Use Planning

The CGS cannot give professional direction in development considerations and recommendations for future land-use planning in flood prone areas but, generally, new development should not be allowed within the 100-year flood plain.

Map Usage and Limitations

During the georefencing process it became apparent that there were spatial issues with the original scanned maps. FIRMs do not use the standard USGS topographic map as a basemaps so control points used in the georefencing process, common to both the FIRMs and the topographic basemaps in the project geodatabase, showed error in certain FIRMs. Spatial readjustment were made as best as could be done with the data available. The digitized FIRMS also do not reflect river course changes that have occurred since the maps were developed. We noted several areas where the mapped flood plain did not match the actual stream course as shown in more recent high-resolution aerial photography.

Most importantly, the FEMA flood plain coverage in the Uncompahgre Valley FIRMs is incomplete. It is not a comprehensive map of all areas that may flood in the project area. Many smaller tributary streams with flooding potential are not shown on maps, or maps do not exist for those areas. FIRMs also do not reflect overland flooding typical with debris/mud flows on alluvial fans.

Earthquakes and Faults – Plate 9

Overview

The scope of the Earthquake and Fault portion of the Montrose County geologic hazard project was to show the mapped Quaternary (less than 2 million years) faults and earthquake epicenters within ~70 miles of the Montrose study area and provide these in digital GIS format to the county. Furthermore, we generated an earthquake hazard assessment report for Montrose County based on a single historic earthquake event. In this discussion of earthquakes and faults, a standard term of time, ka, refers to one thousand years. Also, the scientific literature refers to distances in the metric system so mixed units are used in this discussion.

Background

Earthquakes

Minor seismic activity has been recorded in the Delta-Montrose area. In May of 1992, the U.S. Geological Survey measured an earthquake of magnitude 2.8 approximately 5 miles southeast of Olathe, and on January 13, 1962, a magnitude 4.4 event occurred approximately 6.5 miles southwest of Montrose (Kirkham and others, 2004). Both events were felt at intensity IV (Scale I-XII) in Olathe and Montrose (Kirkham and others, 2004). The Olathe event lies along the trend of the Cimarron and Red Rocks faults, which are suspected to have middle to late Quaternary movement (Lettis and others, 1996). On October 11, 1960, the largest instrumentally recorded earthquake in Colorado measured magnitude 5.5 and occurred approximately 15 miles southeast of Montrose (Kirkham and others, 2004). This event was felt at intensity V in Olathe and damaged buildings in Montrose and nearby communities.

Faults

Many Quaternary faults are within or in close proximity to the Montrose study area. The mapped traces of these faults and geologic information are taken from the study complied by Widmann and others (1998; 2004). We chose to discuss those faults that are suspected to have moved within the late Quaternary (past 130,000 years), as well as the Ridgway fault because of the potential activity of its branch faults at the Ridgway Reservoir dam abutment. Additional information on the faults not discussed here can be found at the CGS web site.

Cimarron fault:

The Cimarron fault is a west-northwest-striking fault between Montrose and Blue Mesa Reservoir. The western end of the fault is parallel to State Highway 50 and the Gunnison River. The fault begins in the Black Canyon of the Gunnison National Park, continues southeast past Powderhorn and Iron Hill, and terminates south of the southeastern end of Huntsman Mesa. The fault is divided into four sections which include from west to east: the Bostwick Park section, the Poverty Mesa section, the Blue Mesa section, and the Powderhorn section. Names for these sections are based on segment names used by Lettis and others (1996). The Powerhorn section lies outside of the Montrose study area and is not discussed here.

The Cimarron fault and the nearby Red Rocks fault are on the southwest margin of the Laramide-age Gunnison Uplift. The Cimarron fault is a high-angle, northeast-dipping reverse fault that was reactivated during the late Cenozoic as a down-to-the-northeast normal or oblique-slip structure (Hansen, 1971; Lettis and others, 1996). Based on geologic relationships exposed at the surface, Lettis and others (1996) suggested the Cimarron fault may merge with the Red Rocks fault at a depth of 5 to 9 km and then flatten to merge with a blind thrust or detachment at a depth of 8 to 10 km. Hansen (1971) reported 5.5 km of left-lateral Laramide displacement across the fault. Bostwick Park is underlain by as much as 50 m of Quaternary deposits that include the Lava Creek B ash dated at 620 ka (Hansen, 1971; Lettis and others, 1996).

The Bostwick Park section of the Cimarron fault is marked by a series of discontinuous, southwest-facing fault scarps, fault-line scarps, or fluvial scarps (Lettis and others, 1996).

A prominent south-facing, 300-m-high escarpment, numerous north- or uphill-facing, 5- to 20-m-high scarps in Quaternary deposits, vegetation lineaments, and ponded sediments occur along the Poverty Mesa section of the fault (Lettis and others, 1996). The high south-facing escarpment is either a fault-line scarp or the headscarp of a landslide. The small uphill-facing scarps are of tectonic or slope failure origin (Lettis and others (1996).

The Blue Mesa section of the Cimarron Fault includes a 1-km-wide graben with low relief. The drainage system within the graben is poorly integrated into the local, well-integrated drainage system (Lettis and others, 1996). The most prominent geomorphic evidence of young activity was noted in an area west of the trench sites, but Lettis and others (1996) were unable to get permission to work on the property.

Age of faulted deposits:

Scarps of unknown origin are present in Quaternary alluvial fans along the Bostwick section of the Cimarron fault (Lettis and others, 1996). These suggest, but do not prove Quaternary activity. A 3- to 5-m-thick soil with a stage II+ calcic horizon developed on the alluvial fans is estimated to be middle to late Pleistocene (100 to 150 ka) in age (Lettis and others, 1996). Latest Pleistocene and Holocene (less than 10 ka) deposits are not offset across the fault (Lettis and others, 1996). Late Tertiary rocks do not occur along this section of this fault.

Along the Poverty Mesa section, Quaternary landslide deposits and middle to late Pleistocene colluvium (50 to 100 ka) are broken by or warped across the fault, although this deformation may not be of tectonic in origin. Holocene deposits are not offset (Lettis and others, 1996).

Middle Tertiary volcanic rocks are offset by the graben along the Blue Mesa section. Late Pleistocene sediments are back-tilted against the fault, and a basal slip plane was encountered in trenches. A landslide origin was postulated for these features (Lettis and others, 1996).

The Cimarron fault may be capable of generating a magnitude 6.75 earthquake (Unruh and others, 1993).

Cannibal fault:

The Cannibal fault lies in the San Juan Mountains in an area of extensive middle and late Tertiary volcanism. Steven and others (1974) outlined as many as 15 collapsed calderas in the San Juan Mountains. Many of the faults in this area are related to collapse of these volcanic calderas. However, the Cannibal fault lies between two large volcanic centers; the nested Lake City and Uncompahgre calderas to the west and the nested La Garita and San Luis calderas to the east. It is a normal down-to-west fault and forms the northeast margin of the Clear Creek graben south of Spring Creek Pass.

Age of faulted deposits:

The Miocene Hinsdale Formation is offset by the northern end of this fault (Steven and Hail, 1989). Kirkham and Rogers (1981) reported 100 m of offset in Miocene volcanic rocks based on oral communication with T.A. Steven. Quaternary deposits were not mapped as offset by the fault by Steven and Hail (1989) or Steven and others (1974), but Lettis and others (1996) noted several lineaments in Pinedale (approx. 10 to 30 ka) to Bull Lake moraine deposits (approx.130 to 300 ka).

This fault has been active since the Miocene, based on offset of Miocene volcanic rocks (Kirkham and Rogers, 1981; Steven and Hail, 1989). Lettis and others (1996) reported "topographic, lithologic, and vegetation lineaments suggestive of recent fault activity" in older Pinedale to Bull Lake moraine deposits. They concluded that the Cannibal fault is a potentially active fault based on these lineaments and "its strong geomorphic expression within the Clear Creek graben..." The most recent paleoevent is herein tentatively considered to have occurred during the late Quaternary.

A moment magnitude (Mw) 7 maximum credible earthquake was assigned to this fault by Lettis and others (1996).

Busted Boiler fault:

The Busted Boiler fault lies on the southeast margin of the Uncompahgre Uplift, which is a northwest-striking, east-tilted fault block. The Busted Boiler fault is a high-angle normal fault downthrown to the west. It forms the eastern margin of a discontinuous graben.

Age of faulted deposits

Sullivan and others (1980) and Lettis and others (1996) reported late Pleistocene and possibly even Holocene (less than 10 ka) movement on the fault. Evidence for Holocene movement is non-definitive, therefore, the most recent paleoevent on the fault is considered to have occurred during the late Quaternary. The fault lies almost entirely within the Cretaceous Dakota Sandstone with less than 5% of the fault extending through or beneath Quaternary deposits.

A moment magnitude (Mw) 6.5 maximum credible earthquake was assigned to this fault by Lettis and others (1996), while Sullivan and others (1980) suggested a moment magnitude (Mw) 6 maximum credible earthquake.

Roubideau Creek fault:

The Roubideau Creek fault is a northeast-dipping normal fault (Lettis and others, 1996). Quaternary offset, however, seems to suggests down-to-the-southwest movement on the fault (Kirkham and Rogers, 1981), implying reverse faulting at least during the Quaternary. The fault lies on the northeast flank of the Uncompahgre Uplift which is a northwest-striking, east-tilted fault block that has been uplifted as much as 640 m during the mid-Pliocene to Pleistocene (Cater, 1966).

Age of faulted deposits:

Quaternary landslide deposits of late Pleistocene to Holocene (less than 10 ka) age are offset along the fault trace (Sullivan and others, 1980; Kirkham and Rogers, 1981; Lettis and others, 1996). Williams (1964) shows no offset of Quaternary deposits. The majority of the fault extends through Jurassic and Cretaceous bedrock. West (1997) and McCalpin (2003, unpublished) determined the landslide deposits in Roubideau Canyon were not displaced. However, McCalpin (2003, unpublished) suggested that the Uncompahgre Plateau surface in the same area is displaced 6 m by a "broad topographic escarpment underlain by a faulted monocline." The southern part of the monocline is "marked by steep, young-looking fault scarps 4-13 m high that displace Quaternary colluvium and alluvium." According to McCalpin, "the morphology of these compound scarps suggests several surface-faulting events in the mid to late Quaternary. However, at present Quaternary age control is lacking so slip rates and recurrence estimates are poorly constrained."

Ridgway and Cow Creek faults:

The Ridgway fault is a 24-km-long, east-west-striking, down-to-the-south normal fault with 450 m of post-Cretaceous displacement. Related to Ridgway faults are branch faults that curve into the Ridgway State Park. Another associated nearby fault, the Cow Creek fault, was discovered during construction of the Ridgway Dam where it is present in the right abutment and outlet works (Ake and others, 1997).

Age of faulted deposits:

Kirkham and Rogers (1981) indicated Quaternary age of the Ridgway fault but Ake and others (1997) state there is no Quaternary displacement along the trace of the fault but microseismic events appear to be associated with the fault. The nearby associated Cow Creek fault also shows no displacement of middle Quaternary (>130 ka) glacial outwash deposits. More so than the Ridgway fault, Ake and other (1997) state that the Cow Creek fault also has a demonstrable association of microseismicity.

Lettis and others (1996) reported no observable surface rupture since at least 140 ka. They suggested that either the seismicity is being produced by the Ridgway Fault itself but without surface rupture since 140 ka, or that the seismicity is induced by the filling of the Ridgway dam and is occurring on the Ridgway fault and/or associated branch faults in the region. The most recent paleoevent on the Ridgway fault is herein conservatively considered to have occurred during the Quaternary based on possible offset of Quaternary glacial deposits and microseismicity data.

Based on the occurrences of microearthquakes, the Ridgway and Cow Creek faults are considered active. That does not necessarily mean that the faults are capable of generating large earthquakes with accompanying earth ruptures (Ake and others, 1997).

Methodology and Map results

The accompanying GIS coverages of faults and earthquakes were compiled from the following sources:

- The Colorado Late Cenozoic Fault and Fold Database and Internet Map Server (Widmann and others, 2004);
- The Colorado Earthquake Map Server (Kirkham and others, 2004-2007).

From the above databases, we selected faults and earthquakes that were within approximately 70 miles from the city of Montrose. Artificially created “coal bumps”, minor earthquakes caused by stresses created by underground mining operations, were eliminated from the coverage. Furthermore, faults and earthquakes within the Paradox Valley are likely due to movement of subsurface salts which creates stresses within the rocks. As these stresses are released, earthquakes can occur. Many of these events are human-induced, caused by the extraction and subsequent injection of fluids into the subsurface by the U.S. Bureau of Reclamation. Since 1991, over 4000 earthquakes have been recorded in this area (Ake and others, 2005). Because of their significance, the larger events were included in the dataset.

Risk Assessment and Hazard Vulnerabilities

Seismic Hazard Evaluation

A scenario based on the October 11, 1960 Magnitude 5.5 event

Using FEMA’s HAZUS-MH software program, a seismic hazard evaluation scenario was run using similar parameters to the October 11, 1960 Montrose earthquake event. HAZUS-MH is a risk assessment software program for analyzing potential losses from floods, hurricane winds, and earthquakes that runs as an ArcGIS plug-in. The recorded event was Mw 5.5 which, according to Wells and Coppersmith (1994) could occur along a 2.5 km fault length. The depth of the event was approximated at 12 km and the strike (azimuthal rotation) of the fault at depth is roughly 140°. The total economic loss estimated for the earthquake event is $27.2 million in today's dollars, which includes building and lifeline-related losses based on the region's available inventory. More specific results are shown in the accompanying Earthquake Event Report and Peak Ground Acceleration (PGA) Map shown in Appendix B. PGA is a ground acceleration force map of the seismic energy of the earthquake that is measured in terms of percent gravitation force. For more information on peak ground acceleration see the USGS website at: http://eqint.cr.usgs.gov/parm.php. For more information on the FEMA HAZUS model, see the FEMA website at: http://www.fema.gov/plan/prevent/hazus/hz_eq.shtm

Development Considerations and Recommendation for Future Land Use Planning

The International Building Code has most of western Colorado in Seismic Zone 1. The IBC no longer uses zones but seismic design formulas to calculate required seismic design levels based on the USGS National Earthquake Hazard Maps. The CGS believes that seismic hazards and risk should be higher for Colorado (Kirkham and Rogers, 1981 and Matthews, 2003).

A qualified geotechnical engineer or engineering geologist should further evaluate the areas that are identified on this map if they are to be developed. Geotechnical reports for critical facilities should determine a Maximum Credible Earthquake for faults that might generate earthquakes affecting the site under study. Mitigative measures may be required to reduce the risk from seismicity.

Map Usage and Limitations

The datasets provided here were mapped at 1:250,000-scale. Inclusion of faults or earthquakes within the mapped study area does not imply that future seismic events will impact the area at any given time. The earthquakes and faults shown on this map were constructed using previously complied datasets. No levels of risk assessment were made within the mapped boundaries.

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Mancos Shale, Salt precipitate, and Selenium Impairment – Plate 10

Overview

Salt precipitate and related elevated selenium concentrations are an environmental concern in the Uncompahgre River valley. Elevated selenium levels have been shown to be harmful to fish and aquatic birds. The current water quality standards for surface waters indicate that the lower Uncompahgre River from the Town of Montrose to the northern border with Delta County is considered "impaired" with regard to selenium levels. Selenium, as well as all cumulative salt loading, is being investigated by the NRCS, the Bureau of Reclamation, the Bureau of Land Management, and the U.S. Geological Survey. A non-profit umbrella organization that is devoted to the selenium problem in the area is the Gunnison Basin Selenium Task Force. Their web site is: http://www.seleniumtaskforce.org/. The data in this discussion is compiled from many reports that have been completed in the valley. High salinity is a concern with agriculture, and impacts the vegetation and landscaping of land for residential development, as well as the corrosiveness of the soil.

Background

On July 14, 1997, the Colorado Water Quality Control Commission amended the Classifications and Numeric Standards for the Gunnison and Lower Dolores River Basins (Regulation No. 35). These amendments included the adoption of new standards for selenium and the adoption of temporary modifications for selenium standards in four segments of the basin. These segments are now included in the Colorado 303D list of "impaired waters." The Uncompahgre River is one of them.

Irrigation drainage has been found to be the leading cause of selenium and salt loading into the Uncompahgre River. Of the basic soil types in the Uncompahgre Valley, those derived from the Mancos Shale have the highest percent of soluble salts. Subsurface return flow waters from these soils in irrigated areas are high in total dissolved solids, sometimes reaching over 12,000 mg/L. New development in Mancos Shale terrane in previously un-irrigated lands will increase salt and selenium loading into the basin. Previously un-irrigated lands in the Mancos Shale have been shown to contain 34 times the soluble selenium as irrigated lands.

Selenium levels of the Uncompahgre River are about 1 part per billion (ppb) when it enters the irrigated Uncompahgre Valley. That level often rises to over 5 ppb within the valley below irrigated areas. The State Water Quality Control Commission adopted a 5 ppb aquatic-life standard for selenium in the Gunnison River Basin so the lower Uncompahgre River is considered impaired for its higher selenium levels from the town of Montrose to the confluence with the Gunnison River at Delta. More information on the selenium problem can be found at the Gunnison Basin Selenium Task Force website.

Methodology

The CGS could not find any GIS related data on selenium loading for the Uncompahgre Valley waters. High selenium levels are found in the Mancos Shale, which also is high in other dissolved salts and sulfates. While a hazard map cannot be made, the spatial extent of where surface, and perched and shallow ground water flow on, or in the Mancos Shale was shown by creating a bedrock map of the Mancos Shale. This map was created by stripping all surficial soil units off of the map, and superimposing a GIS coverage of surface water features, including major irrigation canals. This approximates the spatial extent of where the Mancos Shale may be affecting water quality. Poorly drained areas with high concentrations of salt precipitation were mapped based on NRCS data and visually from high-resolution aerial photography.

Development Considerations and Recommendation for Future Land Use Planning

Deep percolation, dissolution, and irrigation drainage from the Mancos Shale contributes the most to salt and selenium loading. Ponds can contribute high concentrations because of the long-term wetting can cause deep percolation. Additional information on the impact of ponds in the Uncompahgre Valley is found on the web at: www.usbr.gov/research/science-and-tech/news/LngPndsSelnmLdgReport.pdf. Montrose County should consider requiring new ponds to be lined, as well as all new irrigation canals and ditches to be piped for those areas where Mancos Shale is exposed or bedrock is shallow.

Map Usage and Limitations

The Mancos Shale map approximates those areas of the Uncompahgre Valley where the Mancos Shale is near or at surface, and is in contact with surface water and shallow tributary and non-tributary ground waters that is perched within (generally less than 30 feet) surficial unconsolidated sediment units (soils) that overlie it. The intent of this map coverage is to show the most precise extent of the Mancos Shale in the Uncompahgre Valley, based on the most current 1:24,000-scale mapping. It is for information purposes only and does not imply a "hazardous" area, only that accelerated concentrations of dissolved solids in surface and ground water will occur.

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