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New Mexico EARTH MATTERS

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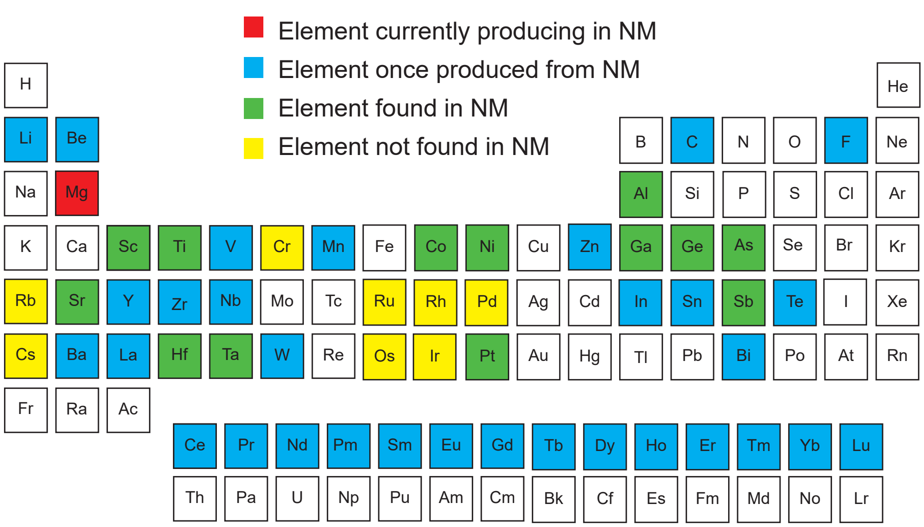
Critical Minerals in New Mexico

Before 2010, most Americans had never heard of critical minerals, except perhaps in high school chemistry class when studying the periodic table of elements. Today, however, critical minerals are so essential in the manufacturing of products required for our lifestyle, economy, and national security that many more Americans are aware of their importance in cell phones, tablets, laptops, computer chips, solar panels, wind turbines, batteries, electric cars, desalination plants, carbon sequestration facilities, military equipment, and so much more. For example, each electric car currently requires about 20 lbs of lithium, 29 lbs of cobalt, 54 lbs of manganese, 88 lbs of nickel, and 146 lbs of graphite. However, the ever-increasing demand for such products has created shortages of some critical minerals, which in turn have resulted in global supply disruptions of some consumer goods.



Note that any element or commodity could be considered critical in the future depending upon its use and availability. Coal contains several of these critical elements.

U, Re, He, and K (found in potash) were removed from the critical minerals list in 2022, and Zn and Ni were added.

Periodic table showing elements composing critical minerals in New Mexico.

In geology, a *mineral* generally refers to a chemical compound with a well-defined chemical composition and a specific crystal structure that exists naturally in its pure form. For example, quartz and diamond are minerals, but coal and gravel are not. However, in the mining industry a *mineral* refers to any rock, mineral, element, or other naturally occurring material of economic value, including metals, industrial minerals, energy minerals, gemstones, aggregates, and synthetic materials sold as commodities. Thus, the term mineral includes all inorganic substances, hydrocarbons such as oil and natural gas, and carboniferous deposits such as coal.

Although the definition of a critical mineral varies from country to country depending on strategic conditions and supply and demand, in the United States critical minerals are commonly defined as a nonfuel mineral commodity essential to U.S. economic and national security and provided by a supply chain vulnerable to global and national disruption. Disruptions in supply chains can be caused by natural disasters, labor strife, trade disputes, resource nationalism, conflict, and other conditions.

Many critical minerals are produced in other countries and imported into the United States. Current global production is sufficient to meet present-day demands for some critical minerals, but the real threat to our economy and security is from future supply disruptions and dwindling inventories. Therefore, knowledge of the life cycles (defined as exploration, mining, processing, refining, manufacturing of products, and recycling) of critical minerals is essential.

The concept of critical minerals is not new in the United States. In 1922, after World War I, the Joint Army and Navy Munitions Board was established by the War Department to plan for obtaining raw materials required by the military. Two separate Strategic and Critical Minerals Stockpiling Acts were passed in 1939 and 1946 to establish reserves of commodities required for national defense. The stockpiles increased through the early 1960s but then were partially or completely sold when the materials were no longer needed.

New Mexico has a wealth of mineral resources, including critical minerals. New Mexico is currently producing copper, coal, potash, magnesium, and a variety of industrial minerals, and it has the potential to produce critical minerals such as rare-earth elements (REE), vanadium, barite, and lithium in the future. Some critical minerals, such as REE, lithium, tellurium, niobium, and vanadium, are associated with pegmatite, gold, lead-zinc, coal, and uranium deposits. Although many deposits in the state have been explored for critical minerals in recent years (such as pegmatites and REE deposits in the Cornudas and Gallinas mountains), most of the favorable areas in New Mexico require additional district-scale geologic mapping coupled with modern geophysical and geochemical studies to properly define exploration drilling programs. Additionally, to aid such future exploration efforts, more research is needed to understand how critical mineral deposits are formed.

What Are the Critical Minerals?

The U.S. Department of Defense, Department of the Interior, and Department of Energy established a preliminary list of critical minerals in 2019 and revised that list in 2022. Currently, 53 minerals are listed as critical for the United States. Copper is not considered a critical mineral because the nation currently produces enough copper for domestic use. Copper is also imported from countries with which there are secure trade agreements, so the current supply of copper for domestic use is not in jeopardy. Uranium was listed as a critical mineral in 2019 because of its use in Navy nuclear reactors. However, because uranium is used as a fuel, it was removed from the list in 2022. The critical minerals list is reviewed by the government every 2 to 3 years.

A number of critical minerals do not exist as economically viable, stand-alone mineral deposits but rather as co-minerals or by-products of other mineable deposits. These primary mineral deposits are called gateway minerals—the principal mineral deposits recovered from mining that provide additional critical minerals which add value to the deposit. For example, copper in porphyry Cu deposits is the gateway mineral for cobalt, gallium, tellurium, indium, rhenium, and REE. Gold in epithermal gold deposits is the gateway mineral for antimony, tellurium, and arsenic. Lead and zinc in sediment-hosted Pb-Zn deposits are the gateway minerals for indium, gallium, germanium, antimony, bismuth, and tellurium. Uranium is the gateway mineral for vanadium, rhenium, and potentially REE. Coal deposits could potentially become economic for REE, cobalt, germanium, and gallium. Gateway mineral deposits need more detailed study in order to determine the distribution of critical minerals in them.

Critical minerals found or suspected to exist in New Mexico.

COMMODITY	FOUND IN NEW MEXICO?*	PRODUCED FROM NEW MEXICO?
Aluminum (bauxite) (Al)	?	No
Antimony (Sb)	Yes	Yes
Arsenic (As)	Yes	Yes
Barium (barite) (Ba)	Yes	Yes
Beryllium (Be)	Yes	Yes
Bismuth (Bi)	Yes	Yes
Carbon (graphite) (C)	?	Yes
Cesium (Cs)	?	No
Chromium (Cr)	?	No
Cobalt (Co)	?	No
Fluorine (fluorite) (F)	Yes	Yes
Gallium (Ga)	Yes	No
Germanium (Ge)	?	No
Hafnium (Hf)	?	No
Indium (In)	Yes	No
Lithium (Li)	Yes	Yes
Magnesium (Mg)	Yes	No
Manganese (Mn)	Yes	Yes
Nickel (Ni)	Yes	No
Niobium (Nb)	Yes	Yes
Platinum group elements (PGE: Pd, Pt, Os, Ir, Rh)	?	No
Rare-earth elements (REE), including yttrium (Y)	Yes	Yes
Rubidium (Rb)	?	No
Scandium (Sc)	Yes	No
Strontium (Sr)	?	No
Tantalum (Ta)	?	No
Tellurium (Te)	Yes	Yes
Tin (Sn)	Yes	Yes
Titanium (Ti)	Yes	No
Tungsten (W)	Yes	Yes
Vanadium (V)	Yes	Yes
Zinc (Zn)	Yes	Yes
Zirconium (Zr)	Yes	No

* ? indicates potential critical minerals under investigation in the state.

Challenges in Producing Critical Minerals

Meeting the demand

Are there enough critical minerals in the global and domestic pipelines to meet future demand? Knowing exactly what supplies are available and predicting what will be needed in the future is difficult. Geologists are familiar with the locations of known mineral deposits and can help discover new resources. But financing exploration is expensive, and investors are unwilling to fund such work without realistic predictions of the types and amounts of critical minerals that will be needed. Companies will explore and conduct feasibility studies once the price is high enough for investors to be willing to fund such projects. Some critical minerals must be mined in higher amounts than ever before to meet global increases in consumption. Substitution, recycling, and technological developments can affect demand, even after a mine is in production. Meanwhile, exploration, permitting, mining, and production can take decades before the raw material becomes available. Alternative low-grade sources for critical minerals, such as recycled cellphones, are not currently adequate to meet increasing demands; increased reprocessing of recycled products is projected to become more important in the future. In order to meet demand, state geologic surveys and the U.S. Geological Survey must undertake research on critical mineral deposits and improve mineral resource inventories to inform the potential development of domestic mineral resources.

Environmental considerations in the United States

Mining today is different from mining in the past. Today, environmental issues are identified up front, and mine plans are designed to avoid environmental problems. For example, REE deposits commonly exist with small quantities of radioactive uranium and thorium in concentrations high enough to be of concern in the waste rock remaining after mining and processing. The waste rock must be stored properly to avoid contaminating the environment. Some critical minerals such as REE require the use of toxic chemicals to separate the minerals from the rock. Researchers are working to develop safer and more responsible extraction technologies. Other environmental issues such as traffic, dust, acid mine drainage, and water contamination must be mitigated by law. However, many critical minerals and other metals originate abroad, where regulations may be less stringent than in the United States. Therefore, an assessment of where we import our critical minerals from is needed.

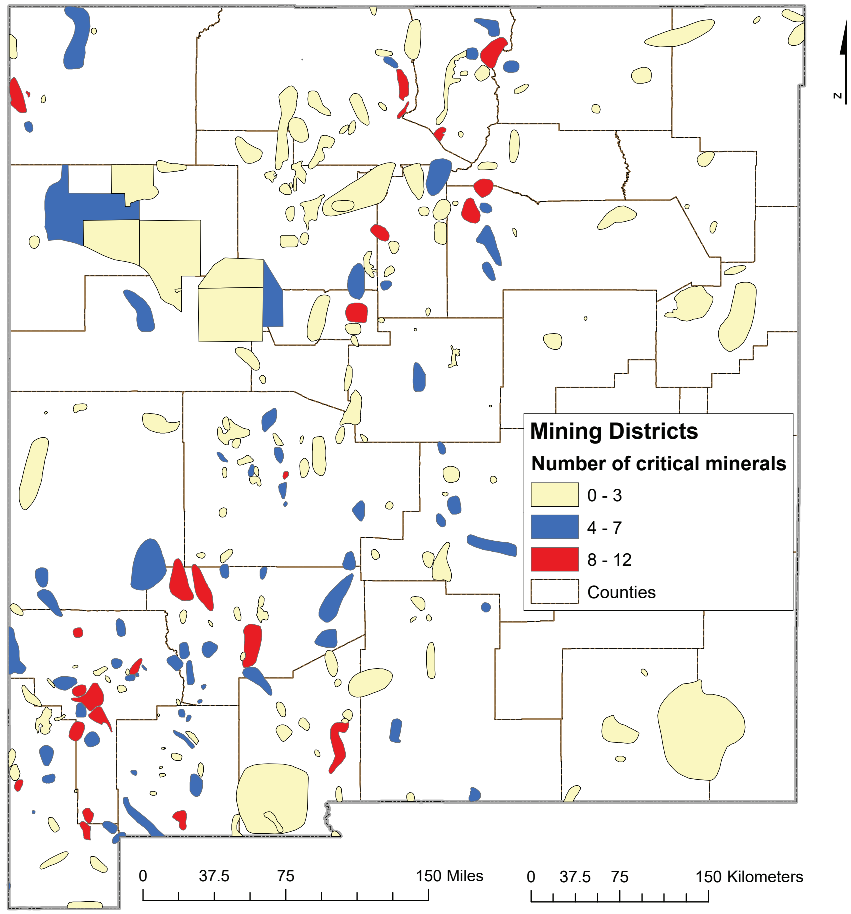
Other challenges

A major challenge for mining companies is access to areas to explore and develop minerals. Mines have to be located where minerals are located. Mineral deposits form by natural geologic processes. These same processes also form the aesthetic landscapes, wildernesses, and other natural resources that we treasure and want to protect. Finding a balance between mining and environmental protection requires honest debate and engagement between mining companies and local communities.

Mineral-resource supply is a global industry. Financing for exploration, mining, and development of new products is competitive on a global scale. In the past, many mining companies could rapidly respond to an increase in demand and a shortage in supply by increasing production, but today companies may find it difficult to make quick adjustments because of financing and permitting challenges. Mining companies, regulating agencies, and universities now recognize a shortage of trained personnel as the experienced workforce reaches retirement age. Finally, planning for natural disasters (volcanic activity, earthquakes, droughts, floods, and wildfires) and dealing with climate change can also create serious challenges for companies attempting to cost-effectively mine critical minerals.

Critical Mineral Deposits in New Mexico

Innovative models of how mineral deposits have formed are needed to guide new exploration for critical minerals in New Mexico. Although the only critical mineral now produced in the state is magnesium (as a by-product of potash production), New Mexico is an exceptional natural laboratory to study critical mineral deposits. Many different types of geologic deposits that could be of interest for future mining are found in the state, including types of igneous rocks called alkaline complexes, carbonatites, and pegmatites. Many of these mineral deposits are formed in underground geologic systems through igneous magmatic-hydrothermal processes, which are characterized by the growth of minerals from hot magma and the interaction of hot fluids with surrounding rocks. Surface processes such as erosion and weathering can later overprint the igneous deposits or form sedimentary deposits that contain critical minerals, such as coal, uranium, and sandstone copper deposits. All of these geologic processes affect the final distribution of elements and ore formation and hence are important for exploration and resource assessment of critical minerals. Our Economic Geology Group studies the mineral resources in the state and has compiled a geochemical database to assist in evaluating areas for potential critical minerals research and exploration (https://geoinfo.nmt.edu/staff/mclemore/projects/mining/REE/McLemoreMasterChem_altered_v6.xlsx).

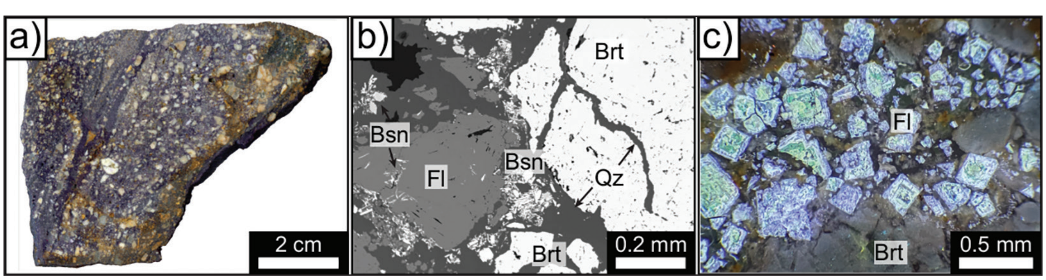


Map of mining districts in New Mexico that have critical minerals. Other areas in the state host high-magnesium dolomites, lithium-bearing playas, and coal fields, which are not found in specific mining districts but also have potential for critical minerals.

Ore Deposits and Critical Minerals Experimental Laboratory

In response to the need for pioneering research on New Mexico's critical minerals potential, Dr. Alexander Gysi established the Ore Deposits and Critical Minerals (ODCM) laboratory at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR). The laboratory contains cutting-edge experimental equipment funded through National Science Foundation (NSF) and Department of Energy (DOE) grants that is used to study ore-forming processes in critical mineral deposits. The laboratory allows scientists to reproduce the high-temperature and high-pressure conditions relevant to these deposits and to measure the thermodynamic properties of critical minerals in hydrothermal fluids. All results are open access and available in the MINES thermodynamic database developed by the ODCM research group (https://geoinfo.nmt.edu/mines-tdb/).

Laboratory equipment includes hydrothermal reactors and flow-through cells, calorimetric instruments, and in-situ spectroscopy tools. Hydrothermal reactors are similar to a kitchen pressure cooker, but we "cook up" rocks in a pressure-temperature and corrosion-resistant vessel made of titanium or hastelloy.



Hydrothermal veins from the Gallinas Mountains fluorite-REE deposit in Lincoln County, New Mexico. a) Sample showing fluorite-barite veins; b) backscattered X-ray image showing the complex mineralogy of the veins; c) cathodoluminescence in fluorite that can be activated from trace elements such as REE. Bsn = bastnäsite-(Ce); Fl = fluorite; Brt = barite; Qz = quartz. *Photos by Evan Owen, a graduate student in Dr. Gysi's research group recently hired as Economic Geologist*

Ore Deposits and Critical Minerals (ODCM) experimental laboratory and Raman spectroscopy laboratory. (Left) Dr. Gysi teaching the NSF CAREER-sponsored undergraduate summer school in July 2022 in the ODCM lab; (center) the hydrothermal reactors that synthesize critical minerals; (right) Dr. Hurtig teaching students in the new Raman laboratory. *Photos by Alex Gysi*

Calorimetry is used to measure the heat of a reaction, such as the dissolution of a mineral in a fluid at high temperature. Spectroscopy detects the interaction of light (photons) with materials and is used to measure spectra produced by the interaction of photons with minerals and fluids. Instruments we use include a UV-Vis spectrophotometer and a new confocal Raman laser.

You might ask: why are we taking all these measurements? Thermodynamics is a fundamental branch of physical and chemical sciences and gives us clues about heat, energy, and order/disorder in minerals and fluids. The ODCM laboratory can be used to predict the stability of minerals, gases, and liquids in geologic systems by geochemical modeling. Thermodynamic work was conducted in the United States from the early 1960s through the late 1990s for the major rock-forming minerals, especially by the U.S. Geological Survey and the U.S. Bureau of Mines. However, expertise in this field has largely been lost in North America. With recent renewed interest in critical minerals, need exists for research into their fundamental properties; hence, the ODCM laboratory was established. We strive to conduct interdisciplinary research by linking fundamental and applied sciences relevant to society and also to provide education for the next generation of scientists. We train undergraduate and graduate students as well as postdoctoral researchers, and we conduct training and workshop events such as the Minerals and Fluids Camp summer school for undergraduates.

New Confocal Raman Spectroscopy Laboratory

In 2022, a Horiba LabRAM HR Evolution confocal Raman spectroscopic system was installed at the NMBGMR. This state-of-the-art laboratory is supported by an NSF Major Research Instrumentation (NSF-MRI) grant and is available to the New Mexico Tech (NMT) community for research and outreach activities. The system consists of a focused laser and an optical microscope that are used to characterize chemical compounds and bonding properties in fluids, hydrocarbons, and solid materials. Dr. Nicole Hurtig of NMT is the lead investigator on the NSF-MRI grant and states that “it is a fantastic tool for teaching NMT undergraduate students about physics, chemistry, material properties, and geology.” The lab recently hosted a group of highly motivated undergraduate students from all over New Mexico and neighboring states for the NSF CAREER-funded Minerals and Fluids Camp summer research experience. The students learned about mineral analysis and studied the properties of REE phosphates they synthesized in the ODCM laboratory. The Raman laboratory is also a major addition to the mineral characterization instrumentation already available at the NMBGMR, such as the X-ray diffractometer (XRD), scanning electron microscope (SEM), and electron probe microanalyzer (EPMA). Raman spectroscopy is a non-destructive method that does not need any major sample preparation and is therefore an ideal characterization tool for gemstones, which will be of great interest to local mineral collectors.

Fluorescent apatite crystal from Bolivia of about 4 cm. The fluorescence in ultraviolet light is activated by rare-earth elements (REE) that substitute for calcium in the apatite structure. The prevalence of REE impurities at high concentrations make many apatites ore minerals for REE. *Photo by John Rakovan*

Critical Mineral Projects at the NMBGMR

In recent years, the NMBGMR is grateful to have received funding from a variety of agencies to investigate the geology, mineralogy, geochemistry, and economic potential of some critical minerals found in New Mexico. The funding agencies include the NSF (NSF CAREER Grant 2039674, NSF-EAR Grant 2032761, NSF-MRI EAR-2117061), the DOE (CORE-CM project, Basic Energy Sciences Grant DE-SC0022269, Basic Energy Sciences Grant DE-SC0021106), the U.S. Geological Survey (Mineral Resources External Research Program G12AP20051 and Earth MRI grants G19AC00258, G20AC00170, G19AS0009, G20AP00105, G21AS0007, G22AS00033, and a joint project with the Arizona Geological Survey), and the Jicarilla Apache Nation (A14AP00084). All of these projects involved student research and training.

Mineral resources, including critical minerals, are abundant in New Mexico. Some of the state’s critical minerals are related to known mineral and coal deposits. Researchers at NMT and the NMBGMR are steadily increasing our knowledge of the geologic formation, distribution, economic potential, and environmental issues of critical mineral deposits in the state. The future development of such resources could help the nation avoid economic and national security issues that currently result from uncertain global supply chains.

By Virginia T. McLemore and Alexander Gysi

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Bureau News

Dan Koning Earns Top Mapping Award

Senior Field Geologist Dan Koning received the nation's premiere geologic mapping award at the GSA 2022 annual meeting in Denver. The Florence Bascom Geologic Mapping Award acknowledges published, high-quality geologic maps that led to significant scientific or economic-resource discoveries and a greater understanding of fundamental geologic concepts. The award was made based on Dan's 25-year career of integrating field-based studies with multidisciplinary datasets to interpret tectonic and paleoclimatic controls on basin sedimentation, erosion, depositional facies, and unconformities. He is first author of 25 geologic quad maps, junior author of 20 maps, and first author of 2 compilation maps. His maps, cross sections, and interpretations have vastly increased our understanding of the architecture and evolution of the Rio Grande rift and the development of the Rio Grande.

Mineral Museum Acquires John Rakovan

In September 2022, John Rakovan started work as Research Mineralogist and Senior Mineral Museum Curator. John came from Miami University in Oxford, Ohio, where he was a professor of mineralogy in the Department of Geology and Environmental Earth Science for nearly 25 years. John became interested in the science of mineralogy as a child through collecting. His research examines crystal growth, structural and morphologic crystallography, mineral-water interface geochemistry, and mineral deposit formation, with special focus on the crystal chemistry of apatite supergroup minerals. He hopes to obtain a single crystal X-ray diffractometer to assist with identifying and determining the structure of minerals and other crystalline materials. John has been an executive editor of and regular contributor to *Rocks and Minerals* magazine, an international, bimonthly publication for mineral enthusiasts and professionals.

Groundwater in the Mimbres Basin

A paper in *Hydrogeology Journal* by Senior Field Geologist Geoffrey Rawling interprets groundwater changes in the Mimbres Basin. Repeat measurements of water levels are essential for understanding and managing our aquifers, but they are labor-intensive; during the last 20 years, fewer measurements have been made in the Mimbres Basin. Over 100 measurements made in the winter of 2019–2020 were combined with 40 years of historical data using the method of spatiotemporal kriging to generate water-table maps for 1985, 2000, 2012, and 2020. Declines in these water levels through time and space are tied to declines in precipitation, changes in land use, and agricultural groundwater pumping. This work was funded by the Healy Foundation and our Aquifer Mapping Program. **https://doi.org/10.1007/s10040-022-02549-7**

Honorary Award to Ron Broadhead

Emeritus Principal Petroleum Geologist Ron Broadhead was awarded an Honorary Life Membership from the West Texas Geological Society "in recognition of continued meritorious contributions of time and talent to the science of geology and to the West Texas Geological Society." Located in Midland, Texas, the society consists of geoscientists involved in the exploration and production of energy resources. Ron has been affiliated with the society for 40 years.

Online Photograph and Document Archive

Our Geologic Information Center has placed photographs and documents on a dedicated portal that uses ResourceSpace, an open-source digital asset management system. Additional materials are regularly added. **https://photoarchive.nmt.edu/**

New Mexico Petroleum Metrics

We've assembled a convenient dashboard showing petroleum metrics for New Mexico, including rig count, spot prices for oil and gas, and production curves. **https://geoinfo.nmt.edu/resources/petroleum/metrics/home.cfml**

Learn About New Mexico Aquifers

Our Aquifer Mapping Program has developed interactive story maps about New Mexico aquifers, including those of the Estancia Basin and the Pecos Slope. Story maps combine a narrative flow with GIS data and other media to provide an interactive learning experience. **https://geoinfo.nmt.edu/resources/water/projects/storymaps/**

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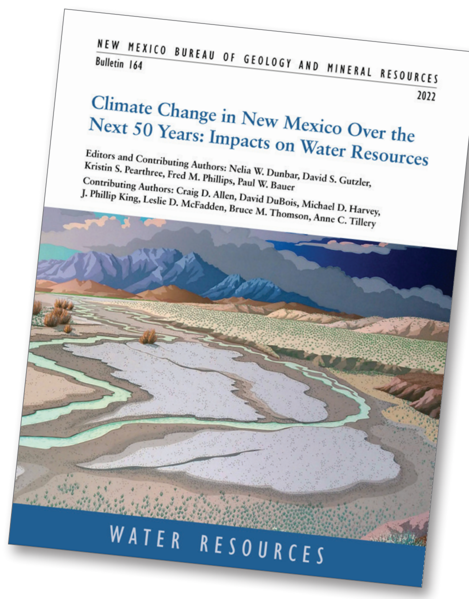
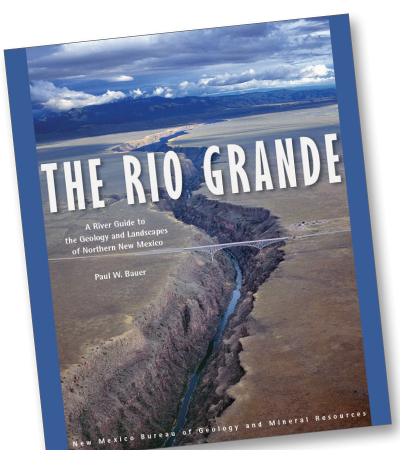
New Publications

Climate Change in New Mexico Over the Next 50 Years: Impacts on Water Resources



The impacts of climate change on New Mexico's water resources are overwhelmingly negative. Earth is warming in response to increasing atmospheric CO_2. Climate models project a temperature increase across the state of 5°F to 7°F over the next 50 years, as well as reduced water supply, lower soil moisture, and increased wildfires. Declines in snowpack and runoff will lower the flow in our major rivers by 16% to 28%, and the frequency of extreme precipitation events, coupled with fire-driven loss of vegetation, will at least double river sediment. This bulletin, which is the scientific foundation for New Mexico's 50-Year Water Plan, is a compilation, assessment, and integration of research relevant to changes to the state's climate and water over the next 50 years. Free download: https://geoinfo.nmt.edu/publications/monographs/bulletins/164/



The Rio Grande Guide is Back in Print

In northern New Mexico, the Rio Grande has carved a pair of spectacular canyons, displaying some of the nation's finest recreation opportunities and scenery. This water-resistant guide contains color maps of 153 miles of the river, from Lasauses, CO, to Cochiti Dam, NM. Divided into 11 river stretches for paddlers of every skill level, the book includes the popular whitewater runs in the Taos Box and Racecourse. Although the guide focuses on the river and surrounding geology, it is packed with information on geography, hydrology, climate, safety, river management, rock art, trails, history, railroads, and mining, making it a resource for hikers, anglers, cyclists, climbers, and casual visitors. Winner of the National Outdoor Book Award for Best Outdoor Adventure Guidebook. Buy now: https://geoinfo.nmt.edu/publications/guides/riogrande/home.cfml