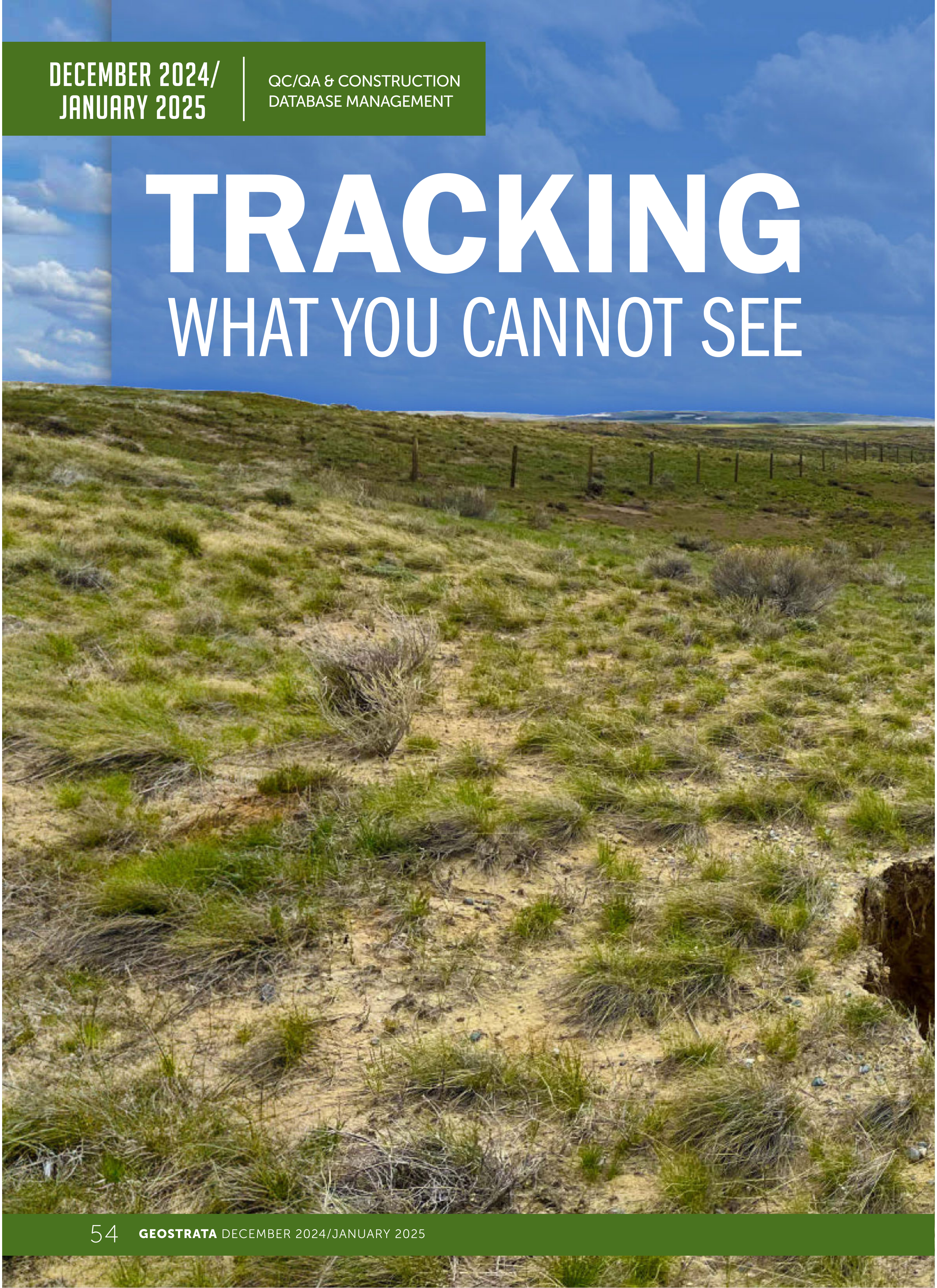
TRACKING
WHAT YOU CANNOT SEE



Using GIS as a Construction Database to Help Mitigate Subsidence Risk from Abandoned Underground Coal Mines

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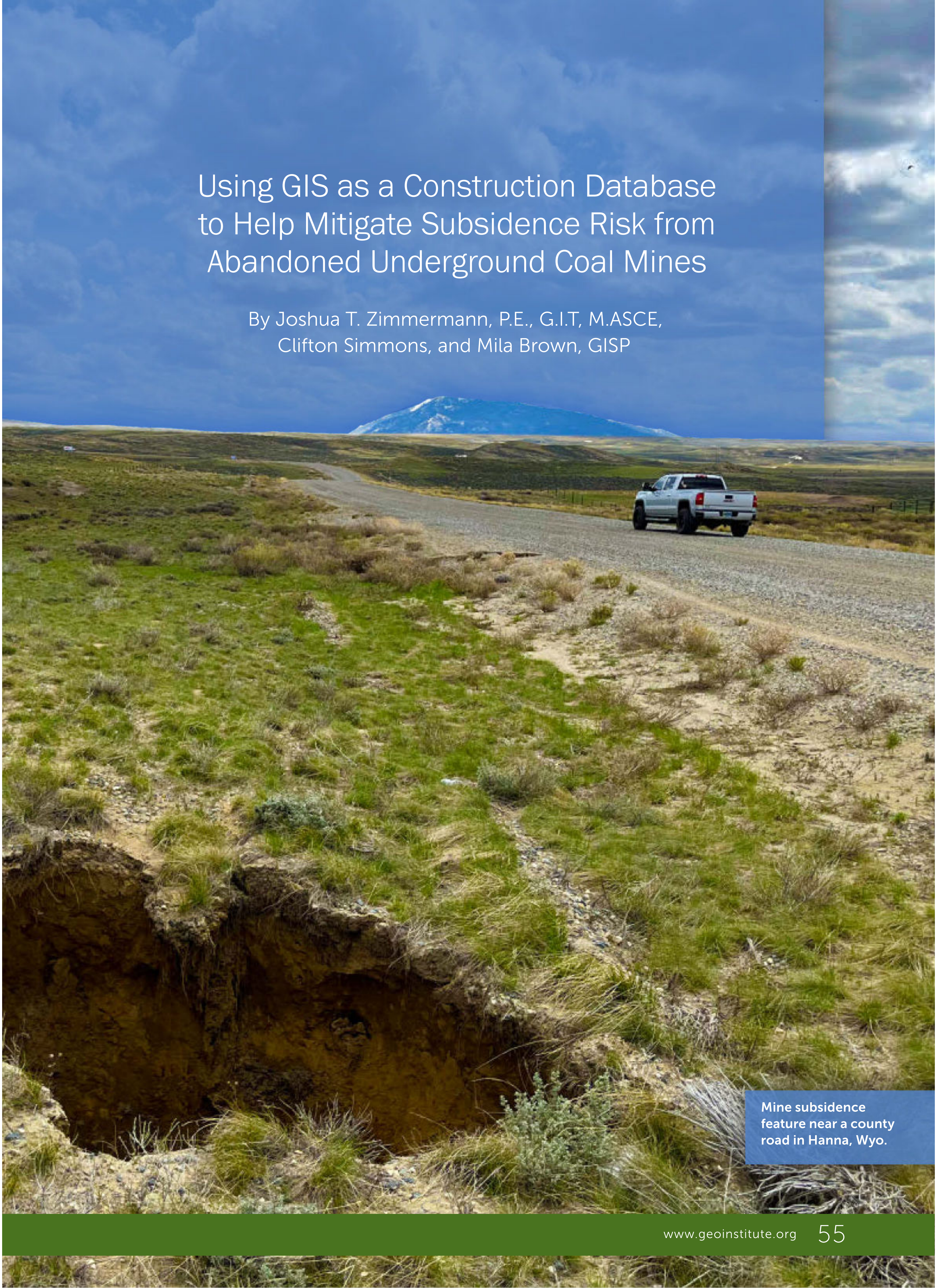

Mine subsidence feature near a county road in Hanna, Wyo.

There are more than 240,000 documented abandoned mines across the U.S., each one with unique hazards that can pose risks to surrounding communities, infrastructure, and the environment. One risk that's common to these mine sites is subsidence, where abandoned underground workings collapse, ultimately forming sinkholes at the surface. These events damage homes, roads, utilities, and other critical pieces of infrastructure with little to no warning. To fully identify the risks that these underground workings pose to the public can require reviewing and analyzing extensive quantities of historical data, and large-scale geotechnical or geophysical investigation programs.

Additionally, mitigating subsidence hazards can entail drilling hundreds of boreholes over many acres of land, constant logging of field information (e.g., pressures, volumes, and locations), and conducting and reporting the results of dozens of field and laboratory tests performed by multiple parties. Clear and concise organization of these data is critical to track progress, ensure that project specifications are met, and provide consistent means for tracking individual pay items and budgets. Therefore, it's essential that a single, easily accessible database be developed and employed to ensure that construction remains on schedule and within budget. This article describes the use and development of Geographic Information Systems at Brierley Associates to fulfill this role on subsidence mitigation projects, and how GIS can be used as a construction database for use on other aspects of abandoned mine land projects.

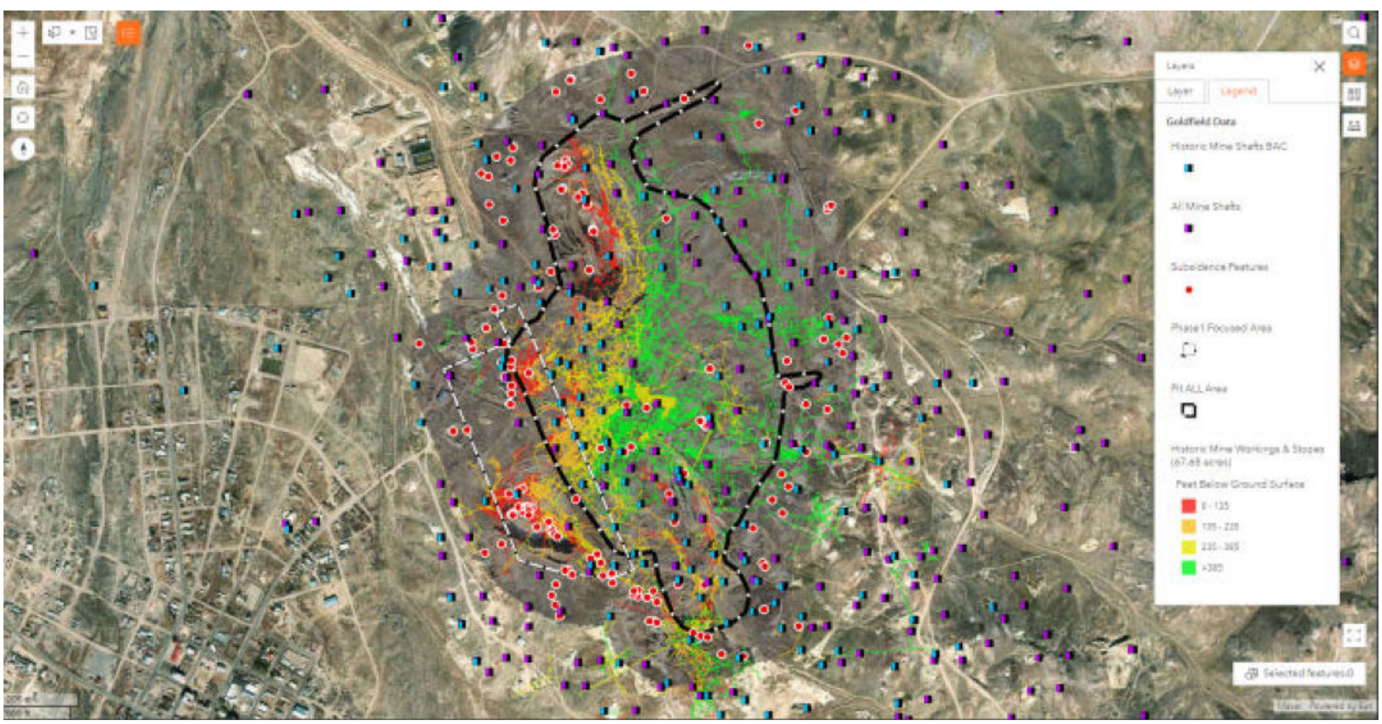

Figure 1. **GIS portal interface displaying numerous layers of data documenting mine-related features, such as shafts, mine workings, and drill hole locations.**

Extent of the Problem

Before passage of the Surface Mining Control and Reclamation Act of 1977, there were no federal laws requiring reclamation of surface or underground coal mining operations, and no guidance for reclamation practices in the U.S. In many locales, coal mine owners could simply abandon their operations, never mitigating current or future problems caused by historic mining activities on their property. After SMCRA was passed, however, coal mine operators were required to pay a fee to the federal government per ton of coal mined to fund the reclamation of previously abandoned coal mine sites. SMCRA also created a reclamation bonding requirement and program to ensure future site reclamation and prevent the continuation of abandoning mining operations. The reclamation of these sites is often up to the various state Abandoned Mine Land programs.

Even with this regulatory change, however, many sites to this day remain unmitigated because they're difficult to fully assess. This is particularly true when attempting to address at-risk zones for subsidence because the extent and condition of the underground workings may not be readily identifiable until a potentially damaging and/or deadly event has already occurred. Mine maps or records of these areas may be incomplete, erroneous, improperly georeferenced, or completely missing, making it difficult to determine the full extent of the impacted area. Furthermore, the subsidence risk between sites is highly variable and is based on a variety of factors, such as age, mine depth, overlying geology, mine geometry, and groundwater regimes.

Establishing the areas with the highest risk factors can require extensive historical research, geotechnical/geophysical investigations, and laboratory testing programs to accurately determine subsidence mechanisms, risks, and the viability of potential mitigation approaches. Additionally, subsidence mitigation programs are among the more costly mine mitigation practices as they can involve modifying preexisting structures through foundational improvement, collapsing the mine workings through explosives or dynamic compaction, or some form of grouting, ground improvement, or void filling program. These efforts can require collecting and analyzing thousands of data points from different drilling locations, pressures, volumes of void infill material, and other parameters to conduct an effective mitigation program.

With so much information being generated on a near-constant basis, it's critical to have a single database where everything can be integrated and analyzed before, during, and after subsidence investigation and mitigation programs. Combining these seemingly disparate data points into a single, searchable location can help visualize the data and be used to identify trends and future focus areas as illustrated in Figure 1. Such visualizations are frequently created in a GIS database. They've been used as a historic archive and a reference for geotechnical investigations extending across large geographic areas, a tool for more accurate referencing of mine maps for improved investigative accuracy, and a tool to track construction costs and unit quantities, to document precise drilling locations and results, and to facilitate the final assessment of mitigation results.

Figure 2. A water truck has fallen into a sinkhole formed from the collapse of a shallow, underground abandoned coal mine.

Using GIS as a Database

Using a GIS system like ESRI ArcGIS Pro as a construction database on AML subsidence projects, was piloted during the mid-2010s on subsidence mitigation projects performed in south-central Wyoming under the state's AML Program. During this period, there was a large expansion in the time and effort spent to address subsidence issues due to the formation of several notable sinkholes across various towns in the region after heavy spring rains. These sinkholes would frequently damage roads and infrastructure and would trap or damage heavier vehicles as shown in Figure 2. Initially, GIS software was used by these programs and consultants mainly to overlay mine maps over modern imagery and to document the locations of these hazards to determine their eligibility for potential reclamation. While useful as a general referential tool, the potential for GIS to be used as a construction management and reporting tool was recognized early on by Brierley staff, and was quickly expanded to address other aspects of these projects using recent technological advancements built into them.

After performing nearly two dozen mitigation projects over the next decade, and with the input of engineers, geologists, and project managers, a comprehensive GIS system using ESRI ArcGIS Pro software was designed and progressively improved by Brierley staff to become a more interactive and useful tool during planning, investigation, and mitigation phases of projects. Initially, this program started with the logging and digitization of borehole information. After boreholes were drilled, information regarding the material encountered (e.g., mine voids, rubble, and solid coal), and borehole criteria (e.g., total depth drilled and casing installed) would be uploaded to a GIS database to create static maps with superimposed mine workings. These maps were used daily by field staff to plan the next drilling locations and improve the consistency of construction operations that encounter mine workings. These maps helped mitigation efforts, even with largely inaccurate mine maps, by allowing field personnel to better visualize construction activities in comparison to suspected historic mining methods.

When this recent drilling data was combined with information from historic boreholes, mitigation data from prior projects in the area, drill angles, injected material quantities and more, a powerful database with thousands of reference points was created. This production data, when combined with digitized historic data, enabled subsidence-mitigation project teams to better understand the spatial component of their subsidence mitigation, and improved their ability to plan future mitigation projects with knowledge of site-specific information like the average depth to mine workings in an area and the average amount of material injected per borehole. This data was also combined with information regarding construction boundaries and private property consents for mitigation to create design documents for bidding and construction of remedial programs.

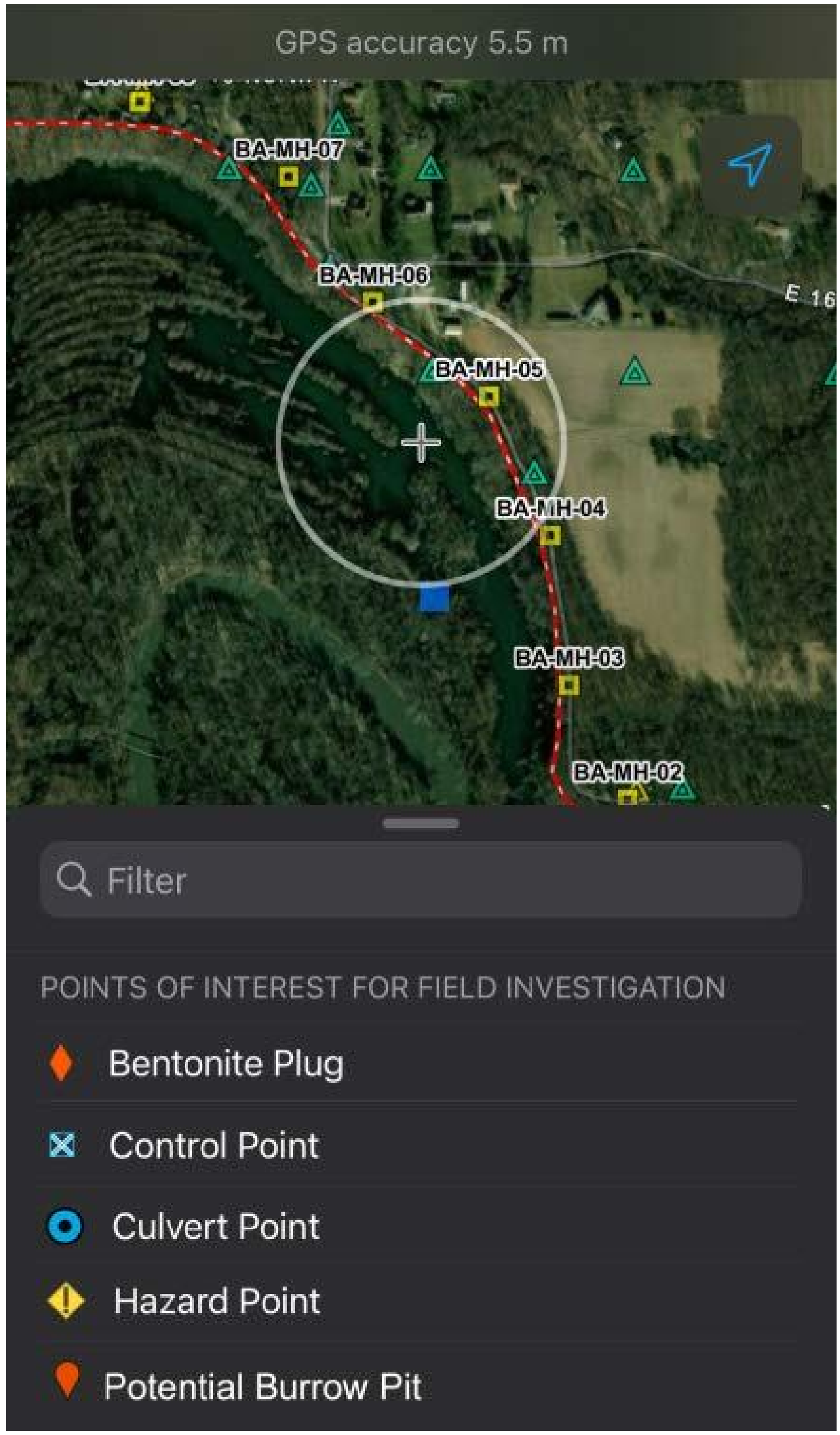

Figure 3. **Field GIS application by field engineers to add data that automatically syncs through cellular service to an online portal.**

Further development of the GIS database has allowed for mobile data collection via the ESRI Field Maps application. Mobile data collection applications allow engineers and geologists to collect data in the field using a phone application to access and annotate maps, and collect data, allowing users to download offline maps to collect location points using GPS units in remote areas (Figure 3). The collected data can be displayed using ESRI's ArcGIS Web Viewer to marry location-based analytics and interactive data visualizations on a single screen. These visualizations allow users to see not only data solely associated with mitigation activities, but also the lab test results by location, construction and project work

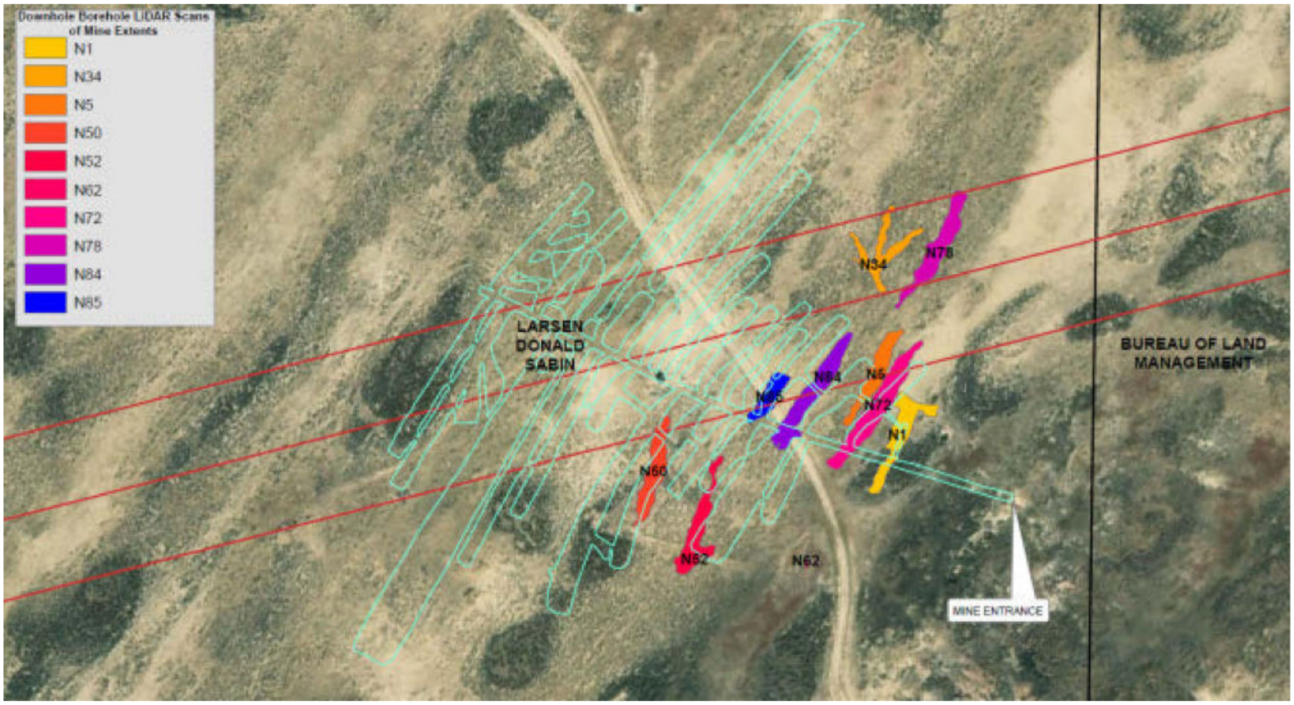

Figure 4. **Difference between the reported mine extents from a mine map (shown in teal), and the actual extent of mine workings as recorded from geotechnical boreholes using downhole LiDAR imagery. The red lines signify the intended placement of a new utility corridor in the area.**

area limits, and other helpful data needed for construction.

Data from grout slump, efflux, cylinder samples sets, and compressive strength testing, water level readings from monitoring wells, and summaries of lab testing, such as slake durability, sieves, hydrometers, moisture contents, tensile strengths, and compressive strength, could be entered into the database via the application and then reviewed in near real time by the project manager to ensure project QA/QC standards were being met or exceeded.

Using ArcGIS Pro and Field Maps applications eventually evolved into dynamic databases that enabled construction and project managers to view and perform detailed statistical analysis, extract data for 2D and 3D modeling of site geology conditions, and overlay remote sensing data for each of the project areas. Technological advancements for visualizing digitized mine workings over thermal, orthomosaic, and LiDAR data allowed project teams to more accurately locate haulage ways, mined out areas, portals, and shafts, which further improved drilling efficiency and reduced drilling target errors in the field.

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The improved understanding of actual conditions compared to those based on historical information is illustrated in Figure 4. The graphic shows the difference between the extent of the mine workings reported to the state from a georeferenced mine map, and the actual extent of mine workings as recorded from geotechnical boreholes using downhole LiDAR imagery to map the true extent of the workings.

Figure 5. **A geologist logs a borehole during an AML subsidence mitigation program using a mobile application for near real-time analysis by the construction manager.**

GIS for Construction and for Project Management

Beyond the planning aspects of AML work, the visualization tools of GIS programs can be used for mitigation projects to analyze the effectiveness and local impacts of remedial strategies during construction. Using software for flight planning and imagery processing, LiDAR data can be collected before, during, and after subsidence mitigation projects. These spatiotemporal datasets have been used to conduct change detection analyses, which enables users to measure differences over time in vegetation, topography, and hydrology. These parameters can be used separately or together to measure the effectiveness of subsidence mitigation. For example, if premitigation imagery indicates a topographic depression (i.e., a sinkhole) and mitigation imagery shows the same sinkhole and ground movement away from the sinkhole location, the project team can update its mitigation strategy to improve results.

The flexibility with either the mobile or desktop-based data collection process makes GIS databases a critical component in planning day-to-day tasks, including construction staging and drilling plans through field applications. Work performed in the field can be quickly surveyed with GPS inputs, such as borehole locations and drill angles, and that data can be synced with field applications on tablets and phones to provide near-real-time updates to project managers and GIS analysts about on-site construction activities. This information is vital to field managers and the contractors who need to view project progress on a daily, or even hourly, basis to see where work is being performed and plan for the next stages. By their very nature, many of these mitigation projects are dynamic and require numerous small tweaks to account for field conditions. As shown in Figure 5, by having these data uploaded to a central database in near real time, decisions regarding next steps can be quickly assessed and analyzed by all parties, reducing compounding delays that can plague these nuanced projects.

These data were synced to a central online dashboard where, using ESRI's ArcGIS Dashboard, construction activities could be correlated with individual pay items having an assigned unit cost (e.g., such as drilling lengths, volume of material injected, and gallons of water used). Anything with a defined system of measurement could be tracked and monitored via the GIS database and dashboard. This allowed for day-to-day tracking of project budgets for all line items, as well as for easy analysis of project progress in relationship to the intended schedule. Budget data for individual projects, including cost-tracking to the nearest cent, was tied from the GIS dashboard to an Excel spreadsheet that was easily accessible to the internal and external project team members. Updates to the dashboard and linked Excel spreadsheets were made daily, allowing for near-real-time monitoring of budget use and quantities and project monitoring.

These tools can also be helpful for community outreach and involvement during an AML remedial program. Many mitigated areas can take place in close-knit, rural communities, with residents who want to understand and follow the mitigation efforts. The user-friendly nature of the GIS interfaces allows community members to view the progress and location of mitigation efforts through time and can serve as a powerful communication tool to show where work will be performed next.

With the combination of all these data sources, planning processes for subsidence mitigation projects were greatly improved during the eight years of work performed in Wyoming by the design team. Through the ESRI ArcGIS Pro, Field Maps, and Dashboard applications, the Brierley team tracked the drilling of more than 5,000 new boreholes, 1,000 historic boreholes, and over 200,000 cy of grout injected. The field staff and contractors used the GIS database to expedite numerous processes to meet both investigative and mitigative project goals. By using GIS databases to help guide field decisions through better amalgamation and visualization of data, the accuracy of cost estimates for projects increased was noted to increase by up to 20 percent because engineers gained a better understanding of site conditions, and investigative boreholes were able to be placed in locations that were 30 percent more likely to intersect mine workings in locations with more GIS information than those locations with no or minimal GIS-associated data. Estimated volumes of grout for mine filling programs also improved due to better understandings of the true mine geometry, size, depth, and extents to within 1 percent of the actualized values used during mitigation.

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Future Applications and Development

As GIS technology continues to advance, there are several ways to continue enhancing the use of GIS as a database tool for AML projects. 3D data viewing and analysis has significantly improved over the last 3-5 years. With the opportunity to view data regularly and easily in 3D, there are more data types and fields that can be added to GIS databases in the near future to improve visualization of AML problems like highwalls, clogged streams, mine fires, and more, and to aid in visualizing associated items better represented in three dimensions, such as geologic profiles and mine geometry.

Outside of AML work, there's a big push from the geospatial data sphere to improve the usability of architecture, engineering, and construction data formats like CAD and BIM in GIS products. Integrating these datasets would improve the quality of desktop studies and allow for more user-friendly viewing of design products for planning and construction in both AML and non-AML projects. Moving forward, GIS technology will continue to evolve, further improving data management, spatio-temporal analysis and visualization, and QA/QC processes in AML and non-AML workflows alike. GS

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