

A GIS PROCEDURE FOR ASSESSING ABANDONED COAL MINE SUBSIDENCE HAZARD,
BOULDER-WELD COUNTIES, COLORADO

by

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ABSTRACT

The objective of this research is to explore a new GIS-based procedure for predicting coal mine subsidence hazard by geographically relating data from past subsidence investigations. A coal mine subsidence susceptibility map was created using the procedure for the Tri-Towns communities, Weld County, Colorado, much of which is underlain by abandoned coal mines. The literature from past mine subsidence investigations was evaluated for causative indicators and their applicability to the project. The primary indicators utilized were extent of mining, depth of mined interval, percentage of claystone in the overburden, estimated condition of mine workings, groundwater withdrawal, and subsidence event history. The elapsed time since a mine was closed is another traditional subsidence factor; however, it was ruled out as a predictive factor since the last mine closed in 1979 and the primary failure period of 15 years has passed. A drilling program helped to assess the factors in some locations. Past site investigation data used in the project, primarily an extensive borehole data compilation, were available at the Mine Subsidence Investigation Center, a component of the Colorado Geological Survey (study sponsors). A few different GIS techniques were explored for combining the data and the selected procedure was developed to reduce bias resulting from incomplete, unknown, or unreliable data. The technique combines depth to workings and percent claystone borehole extrapolations using the *Fuzzy Overlay* toolset. The overlay is then factored on a mine-by-mine basis incorporating groundwater withdrawal and mine void presence. The resulting mosaic is then reclassified into an interpretive map displaying the severity of abandoned mine subsidence hazard. The model was calibrated based on observed mine condition and validated through an analysis of past subsidence events. A map of subsidence hazard was constructed that may aid in city planning and future subsidence studies

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CHAPTER 1

INTRODUCTION

Mine subsidence occurs when earth settles to fill subsurface voids created by the extraction of resources. Abandoned coal mines present a higher risk than many other mine types in that activity frequently occurs near areas subject to increased urbanization (Singh, 1986). In addition, weak host rock, temporary supports, and mapping inconsistencies lead to the unpredictability in evaluating coal mine subsidence hazard and the ability of mined voids to propagate to the surface.

Numerous subsidence events have been recorded by the Colorado Geological Survey (CGS) in Boulder and Weld Counties, Colorado. Suspected observed subsidence events in the region are shown in Figure 1.1. Utilities, roadways, and both commercial and residential structures have been damaged at considerable expense to landowners. The inherent risk of abandoned coal mine subsidence in Colorado has led to the creation of the Mine Subsidence Information Center (MSIC) to raise public awareness and collect public data on the hazard. Additionally, the hazard prompted the creation of the Mine Subsidence Protection Program, a federally-backed insurance program managed by the Colorado Division of Reclamation, Mining and Safety (DRMS) for homes constructed over abandoned coal mines (DRMS, 2013).

Detailed mine subsidence investigations are prohibitively expensive and would be aided by an interpretive subsidence susceptibility map. Existing susceptibility maps are incomplete and outdated, lacking present resources such as the extensive borehole data and site-specific subsidence investigations compiled by the MSIC. Past hazard evaluation systems were disadvantaged as they lacked the ability to spatially evaluate the individual investigations and composite data at once through the use of Geographic Information Systems (GIS) techniques. The local geology, unknown condition and extents of the historic mines differentiate the present research from subsidence investigations of recent or active mines. The MSIC data compilation, along with modern GIS capabilities, contribute to the uniqueness of the present research project as it allows for the numerical incorporation of multiple subsidence factors into a usable map.

1.1 Statement of Purpose

The purpose of this thesis is to develop a new GIS-based procedure for predicting coal mine subsidence hazard in Boulder and Weld Counties, Colorado by geographically relating data from past

subsidence investigations. As no GIS procedures have been created to combine such a unique dataset, a new procedure will be explored and used to create a reliable map. Additionally, GIS-compatible subsidence indicators will be evaluated for use in the project. The proposed GIS procedure, calibrated to observed subsidence events and present mine condition, will be used to estimate the subsidence potential and prepare hazard maps of the area. The maps will aid in directing city planning and are not to be consulted in lieu of detailed site-specific investigations.

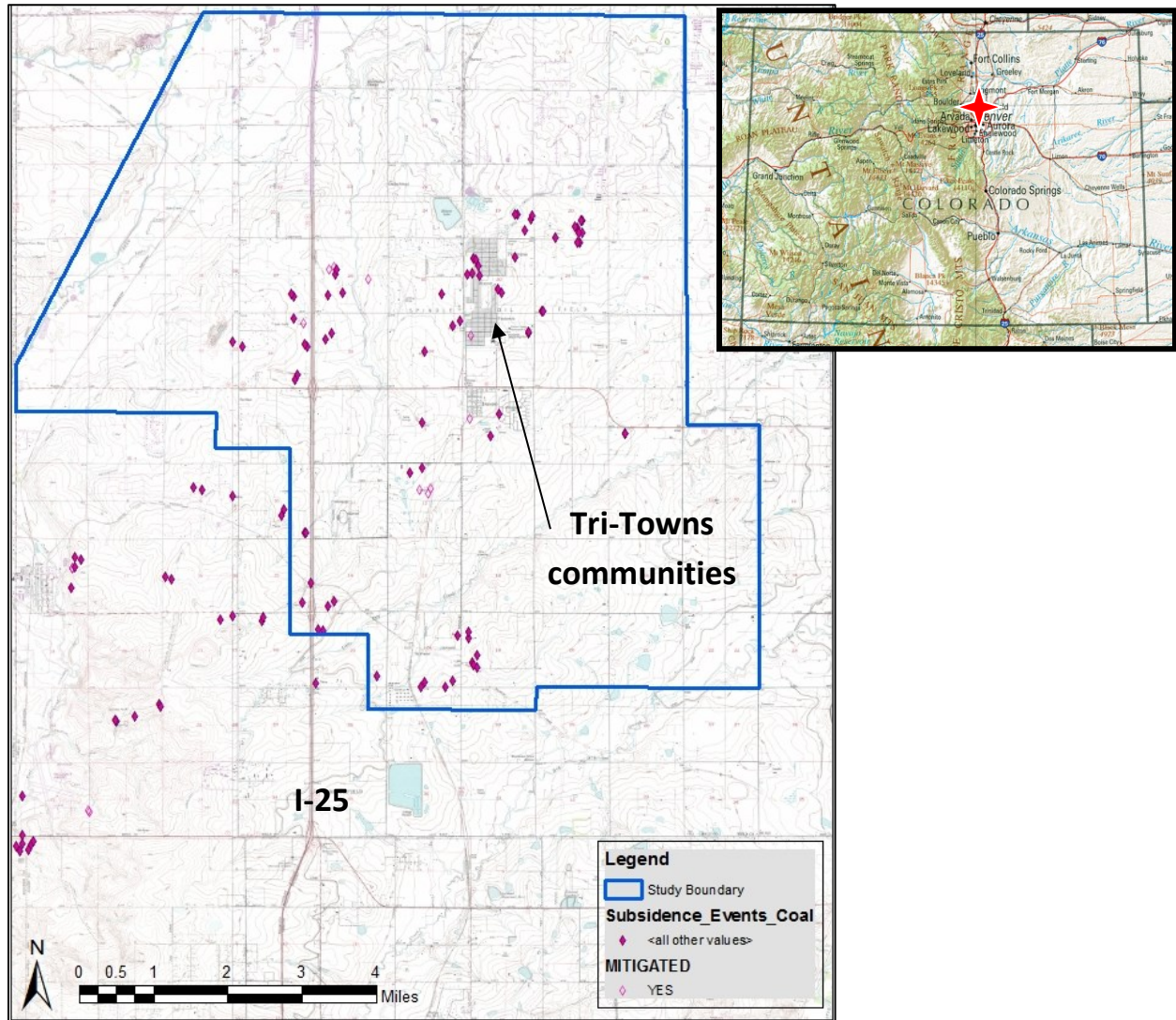


Figure 1.1: Study area (outlined in blue). Interstate 25 crosses the study area in the north-south direction. Frederick, Dacono and Firestone (Tri-Towns) are located east of the Interstate. Suspected coal mine subsidence events are also shown, as well as confirmed events where the hazard has been mitigated (modified from MSIC).

1.2 Scope of Research

The scope of the project is to develop a model to accurately predict subsidence hazard over undermined areas in the Laramie Formation of Colorado. The primary research deliverable is a coal mine subsidence hazard map for Weld County that will serve as an aid in city planning and development. GIS techniques will be utilized to create the hazard map and the map properties will derive from a compilation of mine data and subsidence investigation reports available at the CGS. The model will be calibrated through analysis of observed subsidence events available at the Mine Subsidence Information Center (MSIC).

The primary project tasks were to:

1. Compile and evaluate available data

The data available at the MSIC and in the public domain were evaluated for usability, consistency, and validity. The task is further described in Section 3.1.

2. Research and evaluate prediction criteria

Relevant subsidence prediction criteria were established from existing literature. The criteria were supported by the available data and could be implemented in GIS. The task is further described in Section 3.2.

3. Design drilling program

A drilling program was designed to better estimate mine extents and to investigate locations where subsidence events may have occurred despite no known mining occurring under the location. The task is further described in Section 3.3.

4. Expand and prepare current dataset

The MSIC dataset was expanded to include relevant information concerning the prediction criteria. The dataset was manipulated for ease of use in GIS. The task is further described in Section 3.4.

5. Develop a GIS procedure for predicting subsidence

The dataset and prediction criteria were analyzed with respect to GIS and a relative hazard was estimated. The task is further described in Section 3.5.

6. Develop a classification scheme

The relative subsidence hazard predicted in GIS was subjected to a standardized scale and given a hazard classification to assist in usability. The task is further described in Section 3.6.

7. Calibrate and validate model

The weights of prediction criteria were adjusted and the model results were validated with respect to past known subsidence events. The task is further described in Section 3.7.

1.3 Site Description

The project location includes the area within and surrounding the towns of Firestone, Frederick, and Dacono, collectively known as Tri-Towns, and nearby lands adjacent to Interstate-25 (Figure 1.1). The site is centrally located between Denver, Boulder, Loveland, and Greeley, Colorado. The site was chosen based on available data and due to the presence of large, underground mines underlying a significant percent of the project site. The site is subject to increased urbanization pressures along the interstate corridor. The town of Erie to the southwest declined to be included in the study.

1.4 Involved Parties

The project is the result of collaboration between the Colorado Geological Survey (CGS) and the Colorado School of Mines (CSM), with knowledgeable consultation provided by Western Environmental. T.C. Waite (CGS), Jill Carlson (CGS), Karen Berry (CGS), Dr. Jerry Higgins (CSM), and Greg Sherman (Western Environmental) were involved in directing the project. The Tri-Towns City Council was informed of the project. Funding was provided by the Colorado Geological Survey.

CHAPTER 2

BACKGROUND

The following section discusses site geology, a brief history of mining activity, the subsidence hazard itself, and past literature. This section will provide a background upon which research assumptions rely.

2.1 BACKGROUND OF SITE GEOLOGY

The geology of the site is characterized by interbedded sandstone, claystone, and coal of the Cretaceous Laramie Formation. The Laramie Formation is underlain by the Fox Hills Sandstone, a distinctive unit helpful in locating coal seam lenses in the lower Laramie Formation and is regularly used to specify drilling depths in a subsidence investigation. A stratigraphic column is available in Figure 2.1 and a generalized cross-section is available in Figure 2.2. Coal is deposited as beds of organic matter in a fluvial, terrestrial environment. The marshy, vegetated beds are interbedded with sand deposited by shifting streams and clay deposited during flood events. Most coal seams in the United States are Late Mesozoic to Early Cenozoic in age. Cretaceous-Tertiary (early Mesozoic/Late Cenozoic) aged major coal seams mined in Colorado are found within the Vermejo, Raton, and Laramie Formations in the Front Range corridor and the Mount Garfield, Williams Fork, Mesaverde, Fruitland and Menafee Formations on the western slope of the Rocky Mountains (Kirschbaum and Biewick, 2009).

Northeast trending, normal, listric, growth faults are theorized to be responsible for the regional faulting and presence of near-surface coal (Weimer, 1973). In turn, the fault splays control the scale and extent of the mines in the area (Figure 2.3). The mined region is distinctive in that the Laramie Formation is near-surface, allowing for conventional mining access.

2.2 HISTORY OF MINING ACTIVITY

Coal mine activity in the Boulder-Weld Coal Field occurred from 1859 to 1979 with over 160 mines in operation. At the peak of Colorado coal mining in the early 20th century, coal was mined extensively along the Front Range corridor, with major coal fields in the Boulder, Weld, Las Animas, and El Paso Counties. A majority of the mines in the Front Range corridor have been closed as production has

shifted to industrial scale operations. A summary of Front Range coal mining operations is shown in Figure 2.4.

Era	System	Series	Stratigraphic Unit	Unit Thickness (feet)	Physical Description
Cenozoic	Quaternary	Holocene	Alluvium	0-125	Unconsolidated gravel, sand, silt, and clay
		Pleistocene			
	Tertiary	Oligocene	Castle Rock Conglomerate	0-50	Fine to coarse arkosic sandstone and conglomerate
		Eocene	Dawson Formation	0-1,200	Sandstone and conglomeratic sandstone with interbedded siltstone and shale
Paleocene					
Mesozoic	Cretaceous	Upper Cretaceous	Denver Formation	800-1,000	Shale, silty claystone, and interbedded sandstone; beds of lignite and carbonaceous siltstone and shale common
			Arapahoe Formation	400-700	Sandstone, conglomeratic sandstone, and interbedded shale and siltstone
			Laramie Formation	100-600	Upper part shale, silty shale, siltstone, and interbedded fine sandstone; bituminous coal seams common Lower part sandstone and shale
			Fox Hills Sandstone	100-200	Sandstone and siltstone interbedded with shale
			Pierre Shale	4,500-7,000	Shale, calcareous, silty, and dense.

Figure 2.1: Stratigraphic column of the Laramie Formation. Laramie Formation outlined in red (Robson and Banta, 1987).

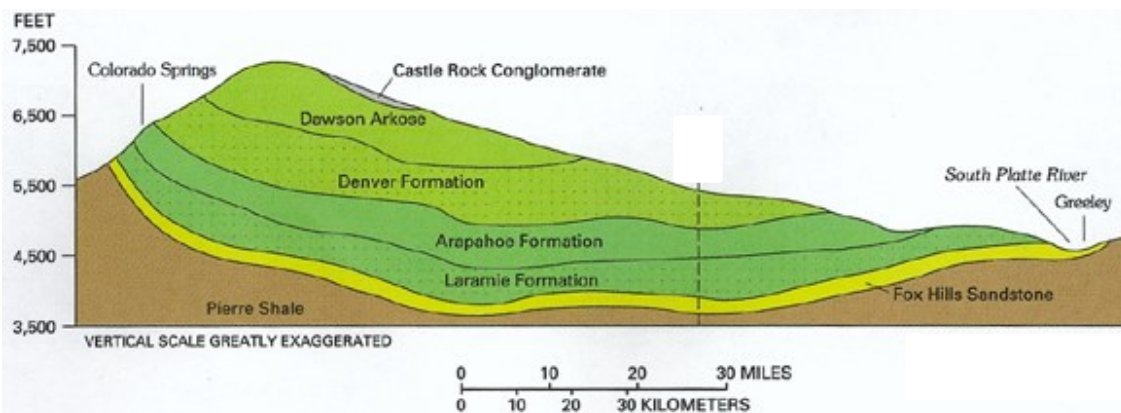


Figure 2.2: Geologic cross-section of the Denver Basin. The Laramie Formation is underlain by the Fox Hills Sandstone and overlain by the Arapaho Formation (Robson and Banta, 1987).



Figure 2.3: Regional faulting in the study area. Heavy NE trending faults (black lines) in the area influence known mine extents (red polygons) (Spencer, 1986).

2.3 BACKGROUND OF HAZARD

Abandoned, underground coal mines present a hazard to structures built above them since the ground may subside into mining cavities and severely weaken or damage the overlying structure(s) (see Figure 2.5). In Colorado, there are 1,736 inactive, abandoned coal mines, both mapped and unmapped and verified to varying levels of confidence (CDMG, 2005).

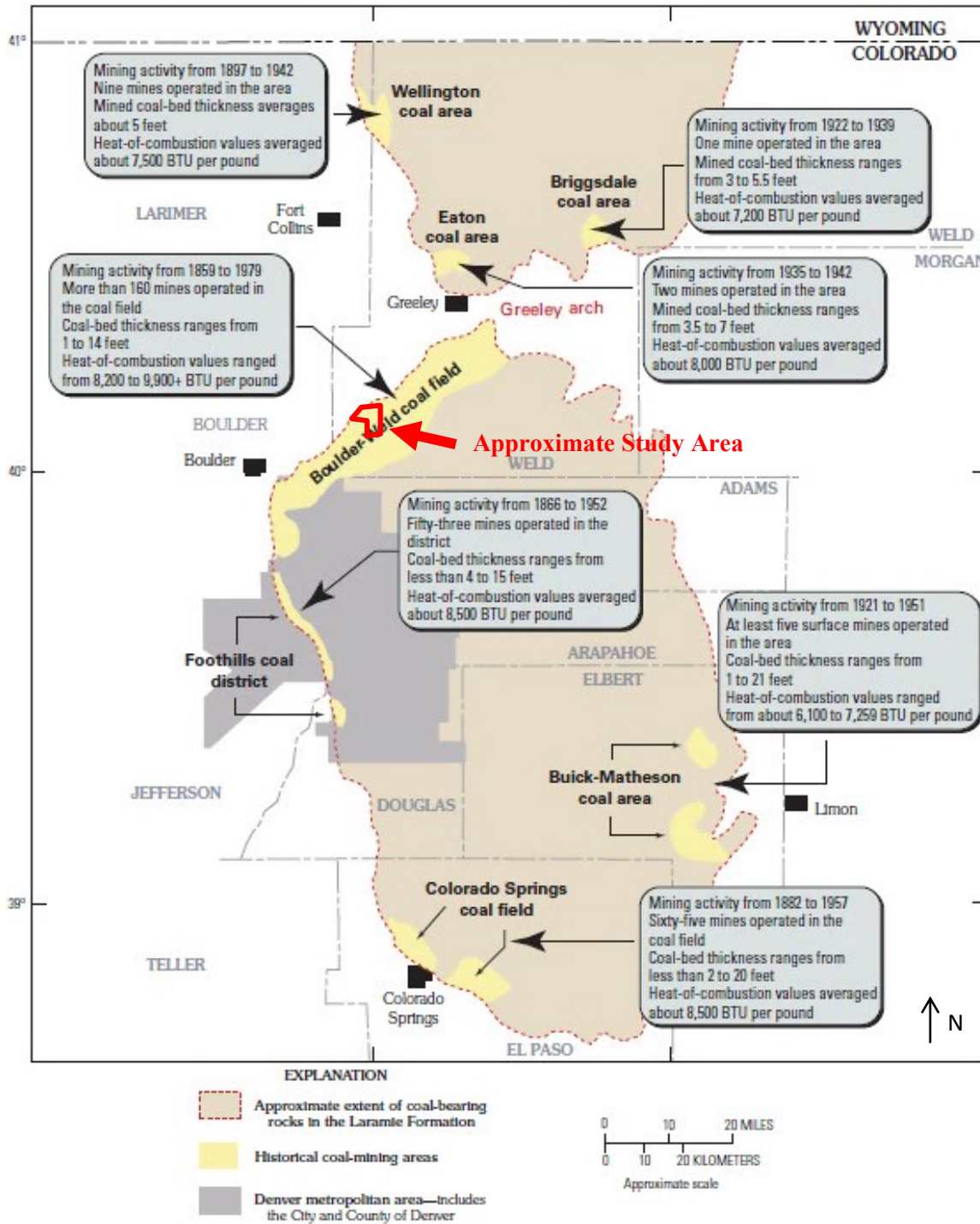


Figure 2.4: Summary of Front Range coal mining. The project site is located within the Boulder-Weld coal field (Roberts, 2007).

Coal mine subsidence above abandoned mine cavities has caused damage to homes, streets and sidewalks, industrial plants and factories, utilities, surface drainage, groundwater flow, and farmland,

among other overlying structures (Bhattacharya and Singh, 1985), Mine subsidence hazards are usually limited to structural damage as the collapses are rarely of a magnitude to cause fatalities, except in indirect circumstances. In addition, temporary or smaller structures, such as a shed or trailer home, may be at lower risk and settle as a single unit, whereas larger structures, like a warehouse or large home, are more likely to sustain damage as the surface area and weight are distributed over ground subsiding at different rates. Utilities and roadways may see large distortions and ruptures, which could prove hazardous in some cases.

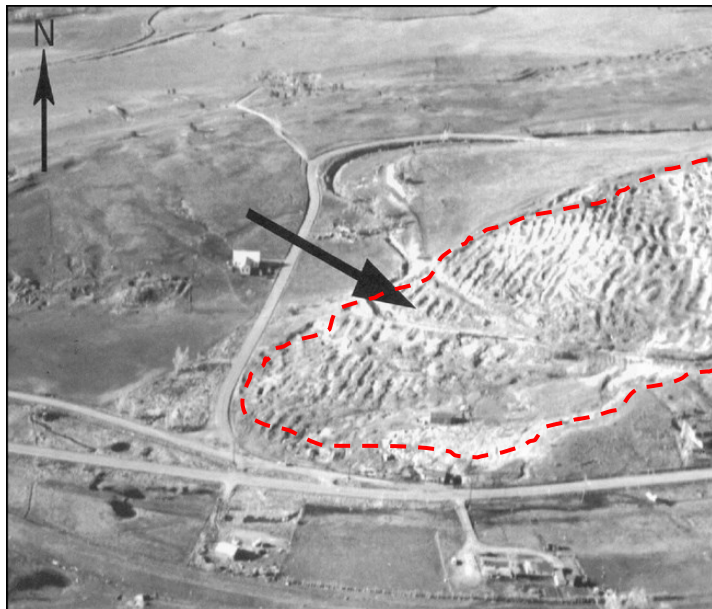


Figure 2.5: Example of coal mine subsidence (outlined in red) in the Boulder-Weld coal field (Knepper, 2002).

The state of Colorado is combatting the risk by providing homeowner insurance for homes in undermined areas and by maintaining a database of past subsidence events and investigations.

2.4 PAST RESEARCH

A number of coal mine subsidence studies in the urban Front Range corridor have been conducted, though none have developed a GIS intensive procedure combining numerous factors and studies.

Matheson (1987) used statistical analysis to show correlations between causative mine subsidence factors and actual subsidence development in the urban Front Range corridor. The focus of his study was not to provide a susceptibility map, but to evaluate the dependency on certain factors in estimating future subsidence. Those factors include elapsed time since mining occurred, inherently weak materials, the depth of mining, and the type of mining.

Matheson (1987) estimated that 95 % of subsidence occurs within 15 years of mine closure in the Tri-Towns area, which statistically supports the conclusions of other researchers that elapsed time since the closure of a mine is a dominant factor in mine subsidence (Price, 1995; Dames and Moore, 1985). After 15 years have passed since undermining occurred, subsidence failures become statistically independent of time.

Matheson (1987) found that depth to mining is perhaps the most important mine subsidence predictor with the strongest correlation between shallow depth and observed subsidence features, both during the primary failure period and after. Matheson recognized that during a collapse event, bulking of material can have a significant effect with a 19 % to 21 % volume increase common among failed materials. This translates to an upwards failure progression of five to six times the mining height before the bulked materials fully support the overburden and failure slows. A dense, rubble-sized zone is less hazardous than a mine with numerous open voids, which may still yet propagate to the surface. Hynes (1984) also observed a correlation between subsidence events and depth to mining in the Tri-Towns area specifically and used it as the basis of his analysis. Hynes developed a community wide approach for assessing mine subsidence from past mining activity, similar to the goals of this project. However, the approach relied exclusively on depth to mining as it was the only factor known with some accuracy at his location. Dames and Moore (1985) suggested an empirical relationship between the overburden thickness to mined height ratio and approximate settlement; however, the relationship requires knowing the mined height.

The third major subsidence factor researched by Matheson (1987) addressed the material itself. The Laramie Formation geologic units are inherently weak and offer little collapse support. The region was also subject to faulting and tectonic activity, which had further degraded the quality of the material. The sedimentary units are not tilted; however the seams are commonly shifted by hundreds of feet vertically with altered groundwater flow due to the faulting. The coal itself is classified as “very weak with moderate slaking potential” (Matheson, 1987). However, coal is the strongest unit in the formation while claystone is the weakest and the strength of sandstone falls between the two. The sandstone is clay-rich and weakly-cemented, with reduced strength characteristics differing from those commonly found in

sandstone in other coal mining regions. The materials fluctuate widely in unconfined compressive strength from approximately 100 to 500 PSI. Matheson proposed that the percent claystone within 50 feet above the mined interval was capable of predicting the subsidence potential of an area with low rock strength, which was confirmed via a high correlation shown by statistical analysis.

The type of mining – room and pillar options, retreat, or longwall methods – has a significant effect on the type and extent of subsidence seen. The differing extraction ratios available with each method affect the amount of subsidence that will take place. In addition, the orientation, geometry and thickness of the mining passages affect the orientation of the failures (Price, 1995).

The subsidence failure mode (sinkhole versus trough) can also be used as an indicator of subsidence and help locate the extents of potential subsidence (Price, 1995). Roof failures, pillar failures, underburden pressures, and combinations of those and other failure types have an effect on the surface expression of the related subsidence event. Large scale trough subsidence typically occurs during or within several years after a mine closes and is usually associated with retreat and longwall mining (Singh, 1986). Trough subsidence can also occur during a domino effect of pillar failures. Chimney sinkhole subsidence has a lower correlation with time and is usually associated with progressive failures of room and pillar mines or auxiliary features of other mine types (Matheson, 1987).

The National Coal Board (NCB) uses a percent strain design method for active mines with known dimensions, but their focus is not on regionally extensive predictive modeling of inactive mines. In addition to site-specific investigation data, the NCB studies consider the weight and dimensions of proposed overlying structures to estimate strain. The NCB studies are inapplicable to this project due to unknown future structures and the differing geologic conditions and unit properties (Matheson, 1987).

Amuedo and Ivey (1981) evaluated a number of inactive coal mines in the Front Range and developed a process for site specific mine subsidence investigation that was later expanded by the CGS. The investigations include mine map analysis and borehole programs with geologic interpretations, caliper readings, and gamma/resistivity log. The investigation approach is utilized or reflected in numerous consultant studies by firms such as Western Environmental, Dames and Moore/URS, CTL Thompson, and others. Those reports make up the majority of the MSIC database. Again, the investigation techniques are used for privately-funded, site-specific investigations and are not intended as a comprehensive community-wide approach.

Other GIS techniques developed to assess subsidence are intended to: 1) locate the hazard, but not determine the degree of hazard (Kuan and Juanle, 2004; McDonald, 2010); 2) predict subsidence in active

mining with well-known mine layouts and calibrative strain measurements (Djamaluddin, et. al., 2005); 3) or use resources unavailable to this project, such as expensive modeling or detailed Rock Mechanics Ratings for underground mines (Suh, et al., 2010). The suspected mining extents are currently used by the CGS to locate the hazard. Evaluating the degree of hazard will help to economize subsidence investigations and aid in city planning.

CHAPTER 3

METHODS

The following section discusses the GIS-based procedure created to predict abandoned coal mine subsidence. The process is supported by previous research and is specific to the data provided by the MSIC.

3.1 COMPILE AND EVALUATE AVAILABLE DATA

It was necessary to assess the available data, look for data gaps, and gauge applicability to the project goals prior to developing a GIS-based procedure. Available data included borehole information from numerous mine subsidence investigations submitted to the MSIC. The borehole data mostly included lithologic logs, drilling notes, occasional gamma and caliper logs, and geographic information. In addition, the general collapse state of mined intervals was sometimes given if a mine was encountered. The data gaps were addressed and are described in Section 3.4.

Mine maps and areas suspected to be undermined for the region were available at the CGS, as were reported subsidence events. There are over a dozen mines of various sizes and ages located in the study area. The extents and locations of the mapped mine portions and the nature of the subsidence events were inconsistently recorded by the original surveyors.

Both surficial and bedrock geologic maps are available from the United States Geological Survey database. The Colorado Division of Reclamation Mining and Safety (DRMS) provided information on previously mitigated areas, abandoned shaft locations, and other information.

3.2 RESEARCH AND EVALUATE PREDICTION CRITERIA

Once the project goals and available data were established, a set of mine subsidence criteria were established and evaluated for applicability to this project. The indicators were derived from prior research discussed in Chapter 2. The mine subsidence factors considered are described subsequently.

3.2.1 Elapsed Time Since Mine Closure

Since the last mine in the area closed in 1979 (Roberts, 2007) and over 34 years have passed since the last mining activity occurred, it is assumed any future subsidence will be statistically

independent of time. Thus, time since mining is an irrelevant factor with respect to predictive capabilities of the GIS procedure in the Tri-Towns area. However, the factor was used to assess the usability of observed subsidence events occurring in the past as events occurring within 15 years of mine closure may be removed from the events used to calibrate the model, as discussed in Section 3.2.7.

3.2.2 Depth to Shallowest Mined Interval

Mines in the Tri-Towns area vary in depth from near surface mines in the north to 300-400 feet deep in the south end of the study area. Accurate mining depths are difficult to determine from the mine maps on record, but the depth of workings can be obtained from the borehole compilation. The mine maps do occasionally depict where multiple coal seams have been mined and workings might be shallower than a borehole interpolation indicates. Considering hand excavation methods available at the time of mining, most mines are around several feet thick (Roberts, 2007). The factor showed good correlation to subsidence, as supported by Matheson (1987) and others.

3.2.3 Low Area-Wide Rock Strength

Evaluating the mechanical rock properties and lateral continuity of units throughout the project area would be problematic and inconsistent with the given borehole data. Other methods were sought to incorporate rock strength into the predictive model.

The percent claystone within 50 feet above the mined interval could be estimated from the data compilation and could also be extrapolated across the study area. Matheson (1987) stated that areas with higher percentages of claystone in the overburden were most at risk of failure; however, it is assumed the high claystone areas have already failed in the primary failure period and the majority of present failures are delayed by the effects of cantilevering strata supporting overburden (Sherman, 2011). Thus, overburden regions with 10 % of other, stronger materials such as sandstone were estimated to be most at risk of delayed failures. A linear scale of decreasing risk was applied to percentage values increasing in magnitude from 10 %. Based on past observations, overburden with percentages of competent material greater than 60 % are at negligible risk of failure (Sherman, 2011). The 10 % figure was analyzed during the final stage of the project.

3.2.4 Present Condition of Mines

The mine condition can only be described in areas with sufficient borehole data. The drilling logs with boreholes through confirmed mining intervals frequently state the depth at which drilling fluid circulation is lost, if at all. In addition, the caliper logs can be used to estimate the depths at which minor

“theoretical” voids are located, as shown by widely-extended caliper arms, and where “actual” voids with fully extended caliper arms are located. Completely collapsed areas show no caliper extension. Since the areal extent of the boreholes with sufficient drilling records and caliper data varies, the present condition of the entire mine was estimated with significant uncertainty on a mine section by mine section basis.

3.2.5 Type of Mining

The mining type, excavation ratio, and related mine features are difficult to verify with the given data and incorporate into a GIS based analysis. The various mining techniques throughout the mining period are indeterminate with the given data as mining technology progressed throughout the lifespan of a mine and adequate records of the mining methods used in each mine segment are not available. Estimates of the mining method can be made by viewing mine maps, but the estimates may not have a high degree of certainty. However, large scale trough subsidence associated with high-extraction longwall mining shortly after mining is likely to have already occurred, based on the conclusions of Singh (1986). Present and future failures are consistent with sinkhole-type subsidence, which is generally associated with room and pillar mining, shafts and auxiliary mine features, or intermittent un-collapsed areas in longwall mining.

3.2.6 Surface Location

Subsidence may occur in areas not directly underlain by mine workings due to the ability of a void to propagate both in the horizontal and vertical directions. The extent of potential failure beyond the surface projection of the mine is described by the “angle of draw” and is referred to as a conservative “buffer” zone henceforth in this report. The angle of draw is commonly taken as 35 degrees out from the vertical plane above the mine boundary with an additional 200 feet to account for surveying inaccuracies (Amuedo and Ivey, 1981). The NCB uses expected percent strain as a buffer measure, which is dependent on the type of structure built. Alternatively, past CGS investigations have used a 45 degree angle of draw (Hynes, 1984), which is better suited to GIS. The failure extents for this project included areas directly underlain by mine workings and the greater value of either a 45 degree buffer or 250 feet. The minimum buffer value of 250 feet was used as a conservative measure (Carlson, 2011).

3.2.7 History of Subsidence

Past subsidence events, recorded in the MSIC, may be used as an indicator of subsidence prone areas, as well as give a general overview of expected mine conditions. However, subsidence events are irregularly reported or recognized and are influenced by factors such as land use and observer training. For example, developed areas with structural loads are more likely to have experienced subsidence

failures than undeveloped areas with agricultural fields. Additionally, trough subsidence depressions may remain unrecognized or unidentified by most civilians. Some subsidence events might have also been recorded during the primary time-dependent failure period of recent mines. Thus, the events have little use as an indicator of future, non-time-dependent failures. Finally, terraforming and urbanization could obscure some events. Due to the inconsistency of reported subsidence events, it was decided to use evaluated events as a calibration technique rather than a predictive one. Observed subsidence events occurring after the primary 15 year failure period of the mine were used to discuss the validity of the model and its predictive capabilities.

3.2.8 Groundwater Withdrawal

High capacity groundwater wells pumping water from flooded mined intervals can exacerbate subsidence. Fluctuating groundwater levels can degrade the structural integrity of a mine. As such, it was necessary to locate such features and incorporate them into the predictive model. The non-calibrated model assumes groundwater withdrawal increases the subsidence hazard by approximately 20 %, based on the opinion professionals with related experience in the study area (Sherman, 2011; Carlson, 2011).

3.2.9 Failure Mode

Due to the time elapsed since mining ceased, it is assumed most trough subsidence events have occurred and future failures are likely to be sinkhole subsidence events. The assumption is supported by the time-dependency conclusions reached by Matheson (1987), Dames and Moore (1985), Price (1995), and professionals with related experience in the study area. Additionally, the failure mode is difficult to determine with the available data and is of little value as a predictive tool for future subsidence events.

3.2.10 Final Criteria

The prediction criteria, utilization, and data source for the model are shown in Table 3.1.

3.3 DRILLING PROGRAM

It was necessary to obtain additional data for areas with questionable observed subsidence events in order to better predict actual mine extents. A drilling program was planned for locations where suspected subsidence features were observed, but a confirmed underground mine was absent in present mine maps. The program was also intended to help resolve discrepancies between various mine maps and prior investigations. In both cases, illegal mine extensions, investment scams, inadequate surveying, and

Table 3.1: Selected Prediction Criteria

Criteria	Project Utilization	Data Source
Surface Location	The extent of possible subsidence in the study site will be limited by the surface projection of an underground mine with the higher value of either a 45 degree angle of draw or a 250 feet. buffer zone	Mine maps; past reports with boreholes encountering workings
Depth to Mining	The depth to the shallowest mined interval was used as a primary indicator for predicting subsidence	MSIC borehole logs; mine maps where boreholes unavailable
Low Rock Strength	The claystone percent within 50 feet above the mined interval was used as a primary indicator for predicting subsidence	MSIC borehole logs
Mine Condition	Void presence and rubble-ization was used as a secondary indicator to upgrade subsidence hazard	MSIC borehole logs
Groundwater Withdrawal	Ground water pumping was used as a secondary indicator to upgrade subsidence hazard	DRMS well completion records
Subsidence History	Past failures were used to calibrate subsidence potential and validate the model	MSIC subsidence records
Elapsed Time Since Mine Closure	Not utilized in model - it is assumed all future failures are statistically independent of time. Criteria will be used to evaluate reported subsidence events.	Amuedo and Ivey (1981) records to confirm elapsed time >15 years

poor record-keeping could have contributed to inaccurate mine maps with subsidence occurring in unexpected locations. Additionally, the drilling program helped to assess the probable cause of observed subsidence events and if the subsidence event could be attributed to undermining.

The DRMS, Jill Carlson of the CGS, Greg Sherman of Western Environmental, and the author were involved in locating areas with data needs. The DRMS provided funds for a borehole program with gamma ray and caliper readings. Carlson and Sherman obtained the necessary landowner permissions for drilling and re-allocated drilling considerations when landowner permission was denied. Twenty-one boreholes were eventually approved, though not all questionable locations could be investigated. Precision Drilling of Colorado Springs conducted the drilling.

The drilling program results were made available during the fall of 2012. Numerous logs were missing location data, lithologic logs, caliper readings, and drilling notes needed for further data evaluation. Drilling progress was delayed due to inadequate equipment and unexpected site difficulties. While most of the data concerns were never rectified, enough data were made available to Western Environmental to conclude that the present interpretation of mining extent is unchanged (Sherman, 2012).

However, the final map was slightly modified in two sections, based on the drilling data and the experience of Sherman in the area.

3.4 EXPAND AND PREPARE CURRENT DATASET

The current MSIC database has been expanded as it contained only depth to workings/rubble, theoretical and actual void spacing encountered, total depth, depth to bedrock, and identifiers for each borehole. The Excel dataset was expanded to include the top of the Foxhills Formation (for interpreting faults and potential mine offset), the mine the borehole intersects, the percent claystone within 50 feet above the mined interval, depth of possible circulation loss, and refined void thicknesses and depth to mining. Boreholes outside of mines were not included in the interpretation since lithology and faulting may cause inconsistencies in the data manipulation. Voids were separated into theoretical voids, where the caliper extends greater than 8 inches, and actual voids, where the caliper fully extends or wraps around. The expanded dataset required re-evaluating every subsidence report in the Tri-Towns area and confirming past interpretations with the data included in the investigations. Most investigations contained lithology descriptions and gamma ray logs, with caliper logs and resistivity readings also encountered.

3.5 DEVELOP A GIS PROCEDURE FOR PREDICTING SUBSIDENCE

A GIS procedure was developed to predict future coal mine subsidence in the Tri Towns region using the available data and with respect to the selected factors. A number of different GIS overlay techniques were evaluated, but most lacked the ability to incorporate chosen criteria without introducing bias. Initially, a weighted percent overlay procedure was considered. However, that procedure relied on spatially reliable data, which were unavailable.

Instead, a fuzzy membership type procedure with multiplicative factors was used, as follows:

1. Prepare the map working space. This was accomplished by importing the existing mine polygons (derived by the CGS from Hynes, 1984), borehole database, and a topographic map base into ArcMap. If the existing mines and boreholes are not in a GIS-usable format, they can be created in ArcCatalog and modified in ArcGIS.

2. Adjust the existing undermined area polygons, developed by the CGS in previous studies, to include an angle of draw of 45 degrees. The undermined areas and buffer also serve as the processing

extent of the model. This was accomplished by separating mine polygons into depth intervals of 50 feet and entering the maximum depth of that mine section in the attribute table of the polygon. Since a conservative, minimum buffer of 250 feet was wanted, any maximum depth less than 250 feet was adjusted to exactly the minimum buffer value. Next, the *Buffer by Attribute* and *Maximum Depth of Workings* tools were used to laterally expand the undermined polygons by approximately 45 degrees or the 250 foot minimum. The mine section depth boundaries were redrawn in the full polygon for use in later tasks. The buffered mine polygons are shown in Figure 3.1.

3. Prepare the borehole attribute table for use in spatial analysis. The expanded dataset was joined with the existing borehole attributes table. The borehole data were separated into two sets – those with available percent claystone records and those with available depth to workings records. Unavailable records were removed from the datasets as numerical values were required.

4. Extrapolate the percent claystone within 50 feet above the mined interval and depth to workings surfaces using the *Kriging* tool with the environment set to the mine polygons. Where depths were known from mine maps but no boreholes were available, “virtual” holes with specified mining depths were created to assist in extrapolating a proper surface. “Virtual” holes were added in the percent claystone extrapolation in a similar manner.

The percent claystone prediction map was originally created using ordinary kriging through the *Geostatistical Analysis* GIS toolset (Figure 3.2). A logarithmic data transformation was used due to a positive skew (high percent claystone common) in the data. The prediction map uses a maximum of 10 nearby borings and a minimum of five borings to calculate the expected percent at a given location. The prediction map was converted to a raster with the *GA Layer to Grid* tool. In addition, the percent claystone layer was adjusted so areas with a small percentage of sandstone represented the highest hazard. Using the *Reclassification* tool, the initial percent claystone associated with the highest susceptibility was estimated at 90 %. This accounts for the cantilevering effects of sandstone in the overburden which leads to delayed failure.

The *Fuzzy Membership* tool was used to re-number the values from 0-1, as required by *Fuzzy Logic* tools. A few different fuzzy membership methods were explored and a linear method was chosen to ensure data value ranges were scaled appropriately. Other fuzzy membership methods incorrectly submitted the data to a normal distribution. After the fuzzy membership transformation was complete, the depths to workings values were inverted to model shallow workings representing a greater hazard. The surfaces are shown in Figure 3.3.

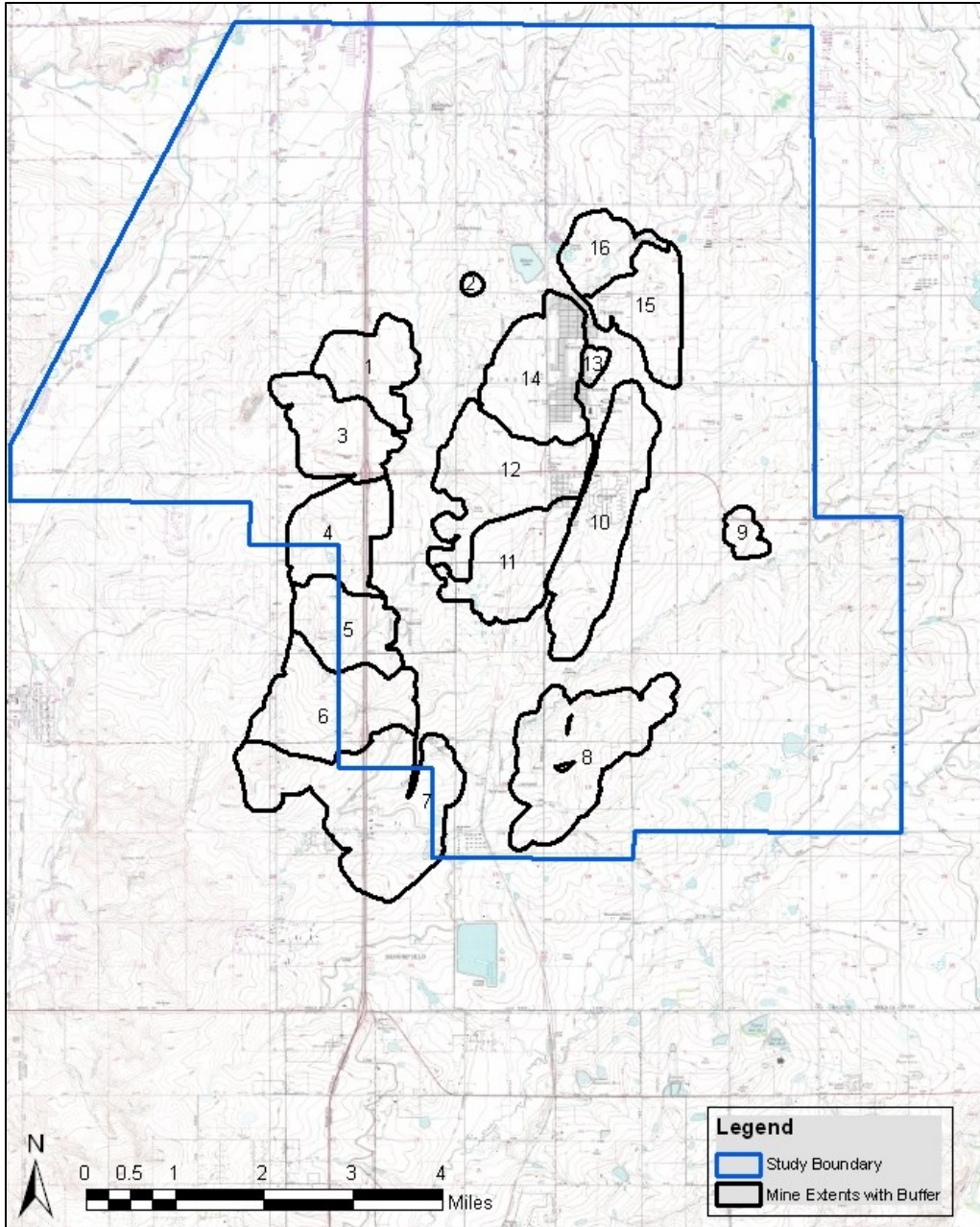


Figure 3.1: Study boundary and extent of undermined areas with a 45 degree buffer (250 ft. minimum). The mine section IDs, differentiated based on mine name, are displayed.

The fuzzy logic procedure was chosen in favor of weighted overlays because it allows the model values to belong to multiple groups and a range of classification values, rather than a binary classification. This better represents the complexity, uncertainty, and limited availability of the data. For instance, a binary system might label a zone as either non-hazardous or hazardous, 0 or 1, using given, logical, and accurate data. In contrast, the fuzzy logic system better accommodates a range in hazard, such as no

hazard, low hazard, medium hazard, and so forth, assigning a decimal value between 0 and 1 for each zone. This allows for more flexibility and compensation in the model when using a large quantity of questionable data.

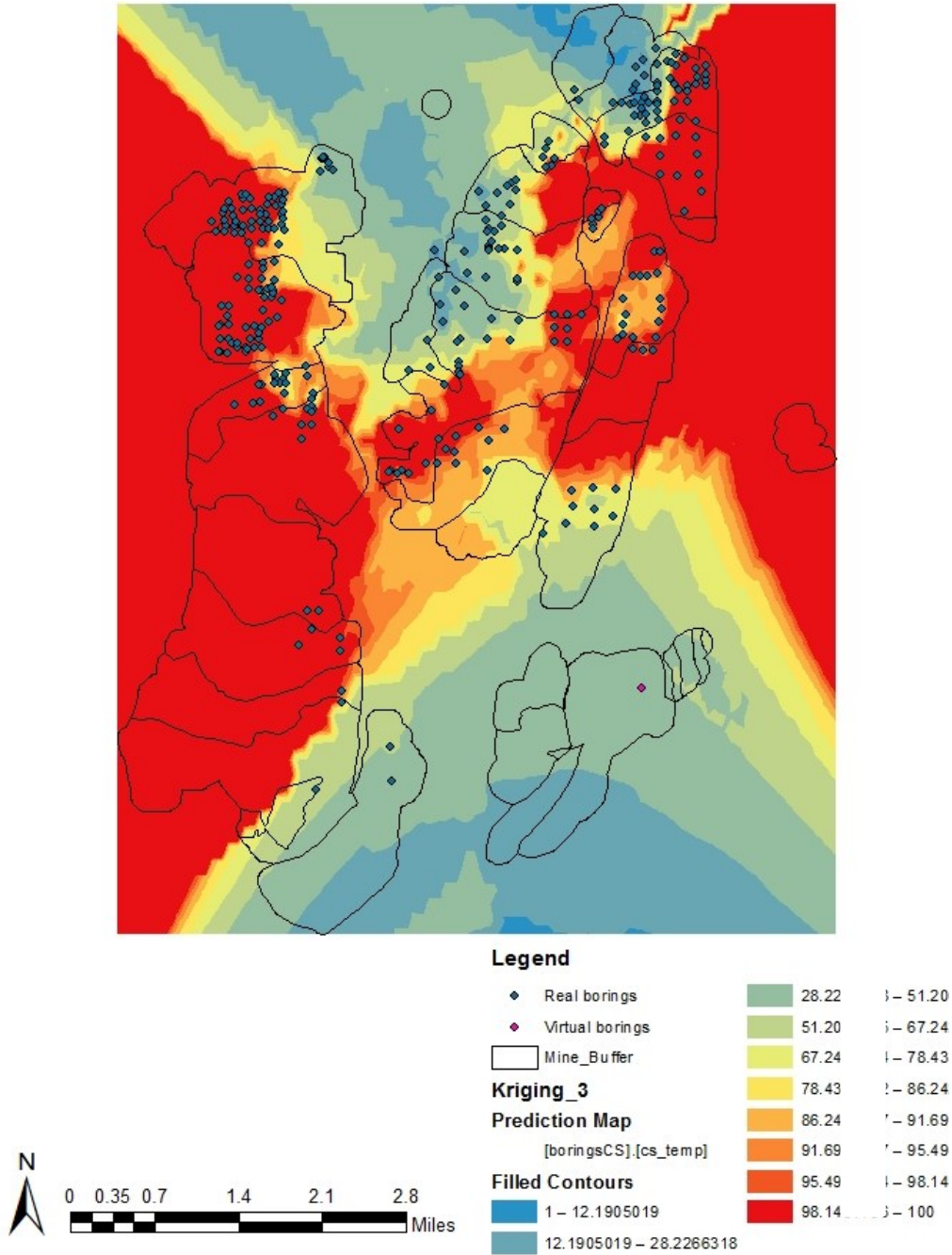


Figure 3.2: Percent claystone within 50 feet above the mined interval interpolated using ordinary Kriging. Areas outside the mine polygons are invalid.

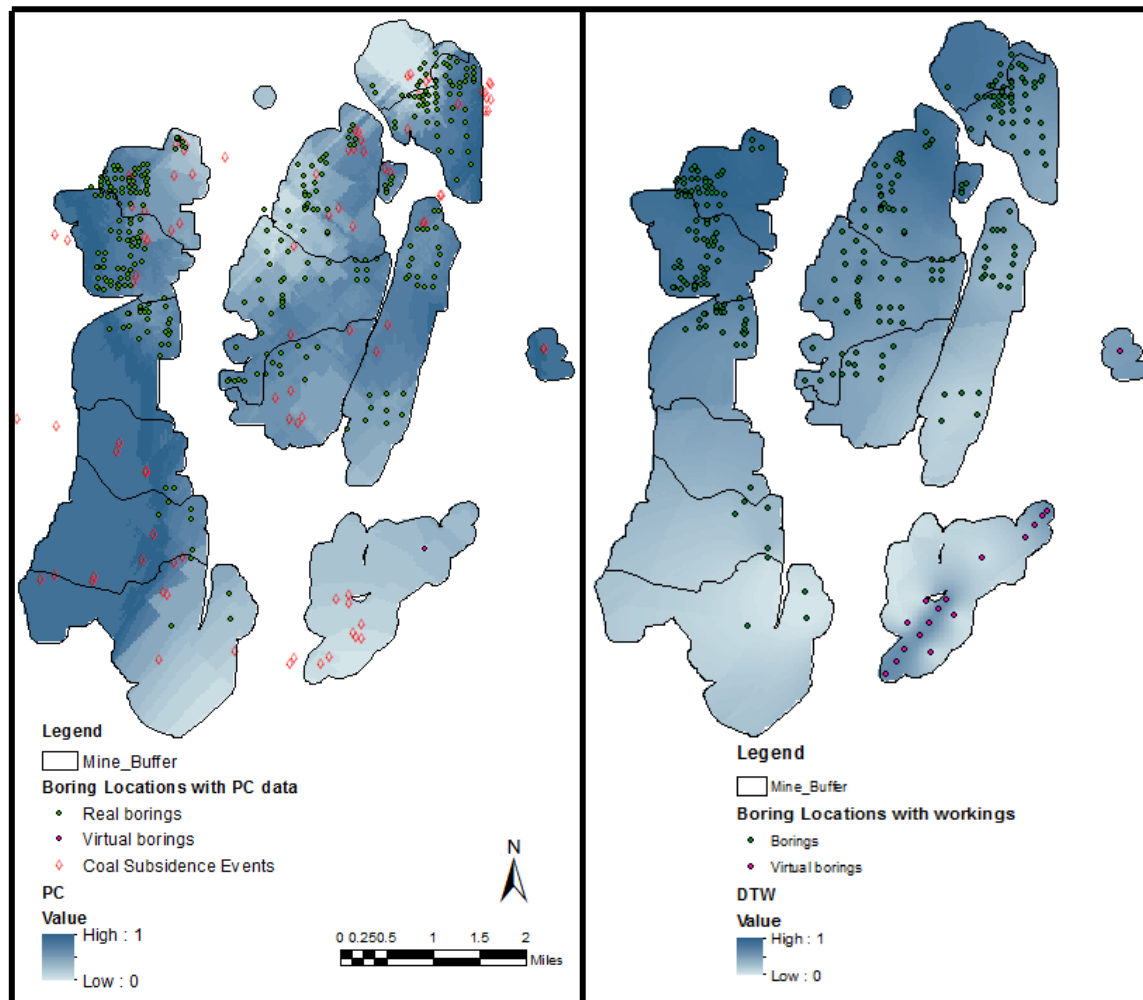


Figure 3.3: Adjusted percent claystone surface (left) and adjusted depth to workings surface (right). “High” correlates to the representative hazard. Note the subsidence events shown on left have not yet been evaluated, nor has the percentage of claystone associated with delayed failure. Virtual holes were added to aid in the interpolation.

5. Combine the two extrapolated surfaces using the *Fuzzy Overlay* tool. The “sum” method, in which the combined evidence of the two factors is more important than either factor individually, was specified as it represented a more conservative approach and better accounted for data reliability and quality concerns. The “product” method, in which the combined evidence is less important than any single factor, was also modeled for comparison purposes. The product method shows the critical, non-conservative case where both depth to workings and percent claystone suggest high subsidence potential. The *Mask* tool was used to only show the hazard in the undermined areas, as shown in Figures 3.4 and 3.5.

6. Incorporate multiplication factor adjustments for groundwater pumping and conditions of mine workings. This was accomplished by clipping the conservative fuzzy overlay rasters to each mine section and using the *Raster Calculator* tool to increase the hazard number. The two secondary criteria are used as adjustment factors rather than overlay criteria due to the heavy dependence on limited borehole data with caliper and circulation loss records and the necessity that sections without any available data should not have an effect on the final overlay.

Since the condition of the mines is unknown in many areas and boreholes have a high probability of missing important mine features, the mine conditions were estimated on a mine by mine basis rather than as an interpolated surface. If circulation was lost in boreholes within a mined interval but theoretical voids were not encountered, it is assumed the zone has fully collapsed or rubble-sized and future failures are unlikely. In this case, the mine conditions have no weight and the raster overlay is multiplied by 1.0, indicating no change in hazard values. Likewise, if insufficient data is available to change the hazard rating of an area, it is multiplied by 1.0. If voids less than 2 feet are encountered within a mine section and circulation is lost, then the hazard is increased by 10 % and the raster overlay is multiplied by 1.1. This accounts for partial mine collapse and the ability for future collapse to still occur. Likewise, voids between 2 to 5 feet and voids greater than 5 feet had multiplication factors of 1.2 and 1.3, or increased hazardous void propagation of 20 % and 30 %, respectively. Values were chosen based on preliminary estimates by Sherman, Carlson, and the author and are to be calibrated in the final project phase.

Similarly, mine sections with completed groundwater extraction wells in the mined interval were multiplied by 1.2, or a 20 % increase in hazard potential. Wells with low extraction rates, less than 50 gallons per minute, were not included. The maximum the percent claystone/depth to workings overlay hazard rating can currently be increased by is 50 %. The factor weights were increased and decreased by 50 % in order to calibrate the weights to within a narrower range and evaluate the importance of the multiplication factors in predicting subsidence potential. The multiplication factor values are given in Table 3.2.

Consequently, four separate hazard overlays and models were created in this step in order to calibrate and compare the effect of the multiplication factors: a base model with no incorporated factors, and three different model iterations with different multiplication factor values.

7. Merge the adjusted mine section raster clips into a comprehensive map for each situation – a conservative overlay with no incorporated factors (Base Model), a conservative overlay with the initial assumed weights (Model I), a conservative overlay with reduced factor weights (Model II), and a conservative overlay with increased factor weights (Model III). This was accomplished by using the

Mosaic to New Raster tool, which merges the individual raster clips into a single raster, and specifying the adjusted raster clips to take precedence over the conservative fuzzy overlay values. The hazard values then ranged from 0 to 1.5 instead of 0 to 1.0.

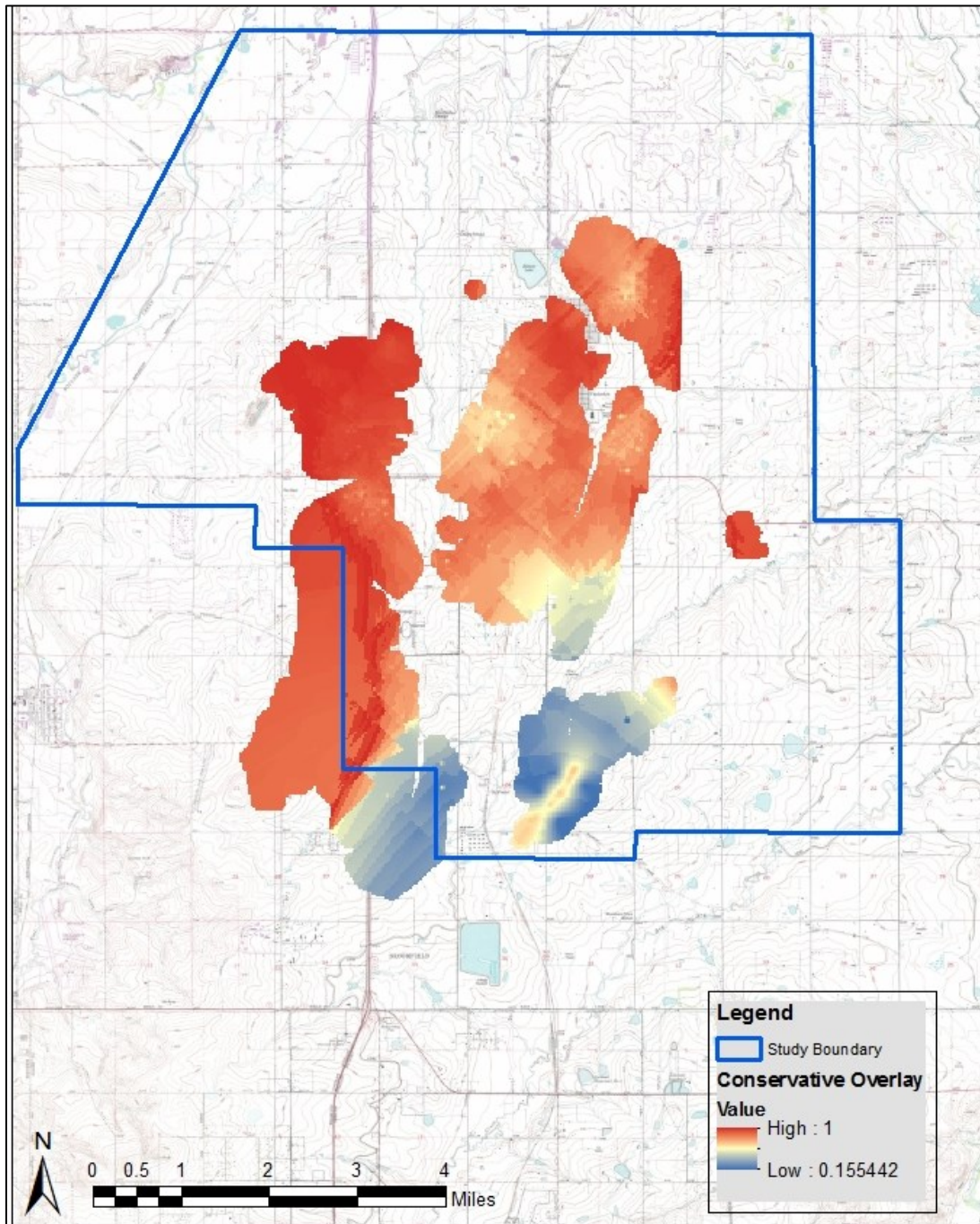


Figure 3.4: Fuzzy overlay with percent claystone and depth to workings. This is the conservative case where the combined evidence is more important than any single factor. The method compensates for data reliability and availability concerns.

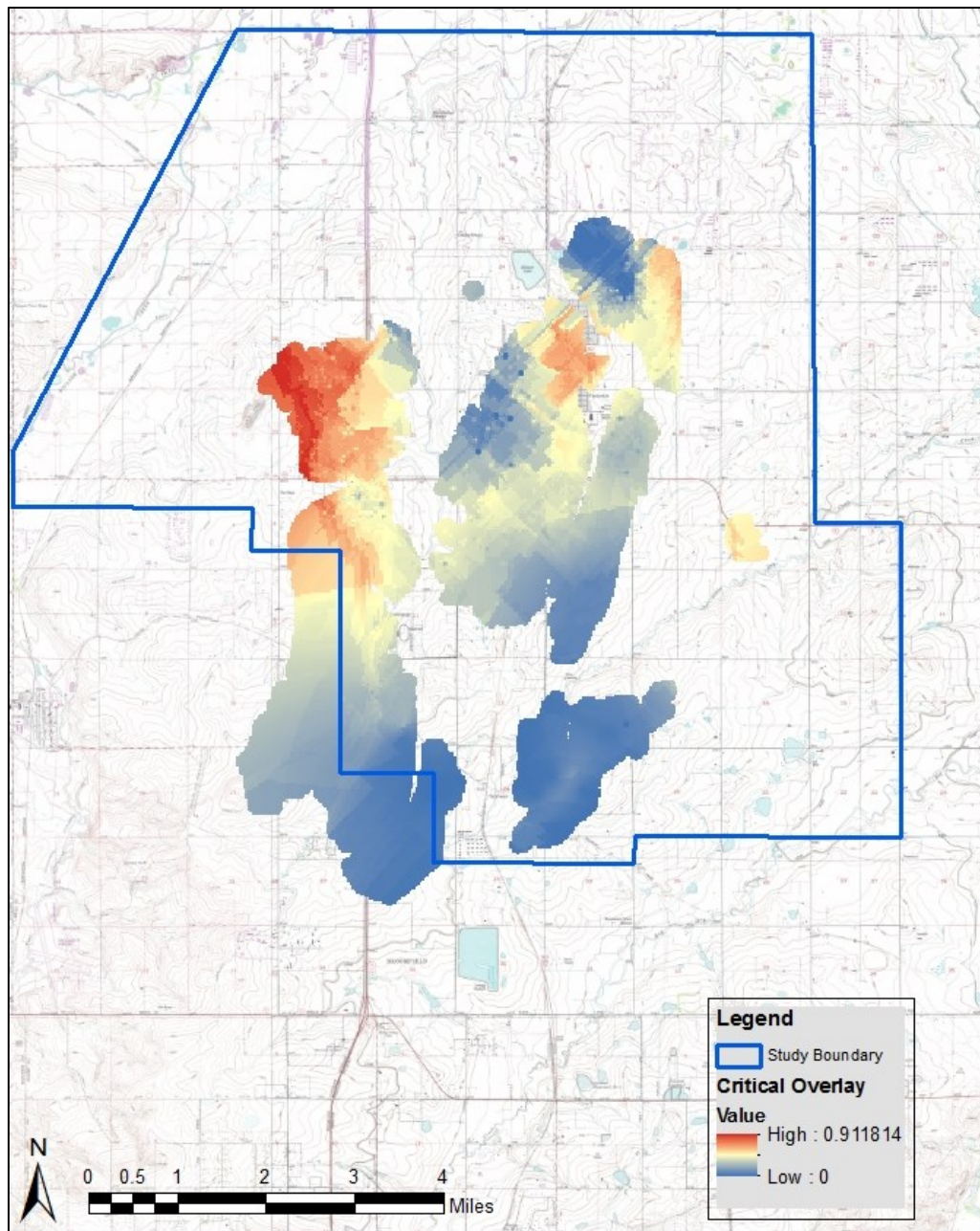


Figure 3.5: Fuzzy overlay with percent claystone and depth to workings. This is the non-conservative, critical case where the combined evidence is less important than any single factor. The method displays where subsidence is most likely, given low depth to workings and high percent claystone with cantilevering sandstone.

Undermined regions without any borehole data available within 200 feet of the undermined location were hachured to indicate a lack of data. The geology and overall conditions may change significantly over that interval. The predicted hazard in these locations may not be as conservative as

Table 3.2: Mine section multiplication factors. All mine sections are assigned an initial susceptibility weight of 1.0. The weight is increased with the presence of voids and groundwater withdrawal. The susceptibility values of the combined claystone and depth to workings model are multiplied by the initial, reduced, and increased factors. The mine sections associated with the assigned ID can be viewed in Figure 3.1.

ID	Mine(s)	Depth Range (ft)	Voids Factor	Pump Factor	Prelim. Factor	-50%	+50%
1	Eureka#3/Shamrock	50-100	0.3	0.2	1.5	1.25	1.75
2	Davis/Evans Jones	50-100	0.0	0.0	1.0	1.0	1.0
3	Puritan/Whitehouse	100-150	0.2	0.2	1.4	1.2	1.6
4	Puritan1939/Rock Tunnel	150-250	0.2	0.2	1.4	1.2	1.6
5	Imperial	250-300	0.1	0.2	1.3	1.15	1.45
6	Eagle	300-400	0.1	0.2	1.2	1.1	1.3
7	Washington	350- >400	0.0	0.2	1.2	1.1	1.3
8	Lincoln	150- >400	0.0	0.0	1.0	1.0	1.0
9	Witherbee/Peerless	200-250	0.0	0.0	1.0	1.0	1.0
10	Sterling	250-400	0.1	0.0	1.1	1.05	1.15
11	Graden/Boulder Valley#3	250-350	0.2	0.2	1.4	1.2	1.6
12	Baum/Evans	150-250	0.2	0.0	1.2	1.1	1.3
13	Warwick	50-150	0.1	0.0	1.1	1.05	1.15
14	Firestone/Frederick	50-200	0.2	0.0	1.2	1.1	1.3
15	Russell	150-300	0.3	0.2	1.5	1.25	1.75
16	Grant/Emerson	50-150	0.2	0.0	1.2	1.1	1.3

possible due to the lack of data. The predicted hazard might also be overly conservative as the interpolated surface relies on data not in close proximity to the undermined region. Future investigations may be incorporated to better assess hazards in these locations.

8. Apply a relative hazard scale. A linear color scale was applied to display relative low to high hazard. The hazard scale was adjusted once the classification system was implemented in Section 3.6.

9. Prepare maps for print. The final maps were formatted for display. A topographic base was added to the map, as well as verified mine subsidence events, mine extents, and traditional map features. Areas outside of the study area were removed using a *Mask* tool, as were sections mapped as undermined in previous reports but were determined to have no mine workings during prior investigations by Sherman. The unclassified subsidence susceptibility map with preliminary factor weights for void presence and groundwater withdrawal is shown in Figure 3.6.

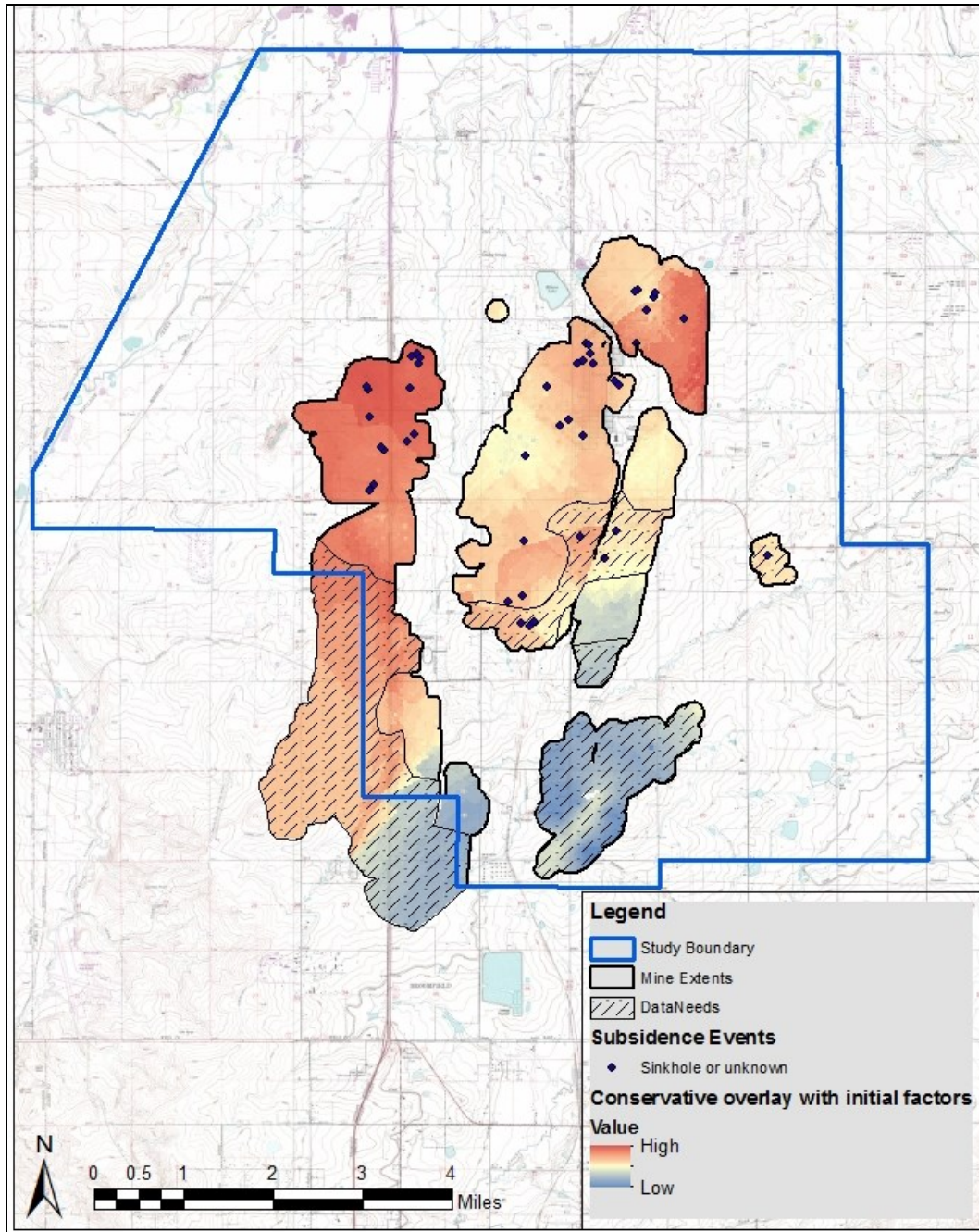


Figure 3.6: Fuzzy overlay with incorporated preliminary factors. The hachured zones should be supplemented additional borehole data nearby to better reflect the actual hazard. The factor weights were adjusted after the development of the classification scheme discussed in section 3.6.

3.6 DEVELOP CLASSIFICATION SCHEME

The chosen classification scheme, suggested by Carlson, is modified from the previous scheme developed by Hynes (1984). The scheme is intended to aid developers in selecting minimum investigative actions for evaluating abandoned coal mine subsidence under future projects. The relative scale (ranging from 0 to 1.5) from the preliminary factors model (Model I) was divided into five equal-interval zones representative of hazard level. The equal-interval break values were applied to the Base Model and reduced and increased models (Models II and III, respectively). This resulted in four different models with five hazard zones based on the same linear scale. The zones include:

- No Known Hazard – locations outside of the undermined region and the buffer zone. These areas are characterized by no subsidence susceptibility from known mines. In the CGS specifications, no detailed investigations will be required prior to development in these areas.
- Negligible (first fifth) - Locations where subsidence has a low probability of occurring. These locations are above known mines and are susceptible to subsidence; however, geological factors or depth to mining favor stable conditions. A basic mine map review will be required prior to development.
- Slight (second fifth) – Locations with a low to moderate probability of future subsidence events occurring. These locations are above known mines and are susceptible to subsidence; however, geological factors or depth to mining favor stable conditions, though limited subsidence events may occur. A basic mine map and MSIC review is required, as well as a land use assessment.
- Appreciable (third fifth) –Locations with a moderate to high probability of future subsidence events occurring. Depth to mining, unfavorable geology, or additional factors suggest subsidence is a concern. An extensive mine map and MSIC review is required, as well as a detailed borehole investigation and land use assessment. Mitigation and foundation design considerations may be required.
- High (fourth fifth) –Locations with a high probability of future subsidence events occurring. Depth to mining, unfavorable geology, or additional factors suggest subsidence is likely. An extensive mine map and MSIC review is required, as well as a detailed investigation and land use assessment. Mitigation and foundation design considerations may be required.
- Severe (final fifth and values greater than 1.5 in Model III) – Locations with a severe probability of future subsidence events. Extensive mitigation, foundation design considerations, and investigation required prior to development. In addition, recreational or low-risk land use is advised.

The predicted hazard and associated classification in hachured “Data Needs” zones requires further investigation and additional data in order to better estimate the hazard.

3.7 CALIBRATE AND VALIDATE MODEL

The following section discusses model calibration, in which a correlation between the model factors and the observed hazard was sought, and model validation, in which the ability of the model to predict subsidence was considered.

3.7.1 Model Calibration

The model was calibrated by comparing hazard zones with reported subsidence events, existing voids, and consultant expertise. Subsidence events reported within the primary time-dependent failure period 15 years after mine closure were removed from the subsidence dataset in order to focus on the predictive capabilities of the model. This was accomplished by comparing the mine closure dates with the date of the reported subsidence event, when known. In addition, trough subsidence features were identified for comparison purposes. It is difficult to assess the reliability of most reported subsidence events not mitigated by the DRMS.

The model calibration included:

- Quantitatively and qualitatively assessing the percent claystone within 50 feet above the mined interval and comparing the percentage with observed, theoretical voids. A correlation was sought between percent claystone and theoretical voids through the use of statistical analysis. It was expected that a claystone percent from 0 % to 70 % would have limited voids as the rock was too competent to allow failures to propagate to the surface. It was also expected that mines with a high percent of claystone in the overburden, 90 % to 100 %, would have limited voids as the weak rock would have already failed in the primary time-dependent period shortly after mine closure. From 70 % to 90 %, voids were expected as stronger, competent bedrock would delay failure.

Additionally, a maximum value line was created to estimate the maximum theoretical void thickness that may be present given the percent claystone value. The maximum value line included at least 95 % of the data, which allows for ignoring anomalous data. It is expected that a direct relationship between maximum theoretical void size and percent claystone exists.

A qualitative analysis of the results was also conducted due to concerns of limited and unreliable data inhibiting a conclusive statistical assessment. If a statistical assessment failed to correlate the percent claystone most associated with existing voids, then a qualitative assessment could assess whether mine sections identified as high to severe hazard contained existing voids. The assessment was conducted to establish void presence in those susceptibility zones.

- Conducting a sensitivity analysis for the multiplication factors in Table 3.2. Multiplication factors will initially be both increased and decreased by 50% in order to gauge the sensitivity of the model to the factor values. The final multiplication values will be chosen after model validation and it is expected that the multiplication factors will increase the susceptibility near observed subsidence events.

3.7.2 Model Validation

The model validation included comparing the percentage of observed, reasonable subsidence events within each classification zone. The number of subsidence events within each classification zone – no known hazard, negligible, slight, appreciable, high, and severe – was counted for each model case: no factors, reduced factors, initial factors, and increased factors. The model was considered valid if at least 20 % of observed, reliable events were in severe zones, at least 50 % were in high or higher rated zones, at least 90 % were in appreciable or higher rated zones, and less than 10 % were in negligible to slight zones. No verifiable events should be in the “no known hazard” zone. In addition the zones should not be too extensive in that the severe region encompassed all events and confined events as best as possible. The validation process is intended to ensure model results are consistent with the recorded subsidence history. The percentages proposed are reasonable in that the observed subsidence events are concentrated in zones of relatively higher hazard and nearly all observed subsidence events are located in regions where subsidence is predicted by the model.

CHAPTER 4

RESULTS

This section discusses the results obtained from the procedure presented in Chapter 3. Mine subsidence susceptibility maps with the preliminary factors, reduced factors, increased factors, and classification schemes are presented, as well as the model calibration and validation results.

4.1 BASE FACTORS

The Base Model shown in Figure 4.1 is influenced by depth to mining and percent claystone. Additional factors, such as groundwater withdrawal and void space, are not incorporated. The model is based on a classification scale derived from the initial factors model and represents the most rudimentary understanding of the subsidence susceptibility at the project location. The model suggests higher subsidence susceptibility in the north and a lower susceptibility in the south.

4.2 PRELIMINARY FACTORS

Figure 4.2, Model I, displays the combined depth to workings and percent claystone susceptibility map with preliminary factors for groundwater withdrawal and void presence incorporated. The preliminary factor weights are derived from anticipated susceptibility influences as supported by the familiarity of Sherman (2011) and Carlson (2011) with the project location.

4.3 REDUCED FACTORS

Figure 4.3, Model II, displays the combined depth to workings and percent claystone susceptibility map with reduced factors for groundwater withdrawal and void presence incorporated. The preliminary factor weights will contribute to model calibration and validation. The overall predicted hazard is reduced, with limited sections in the north predicted as severe.

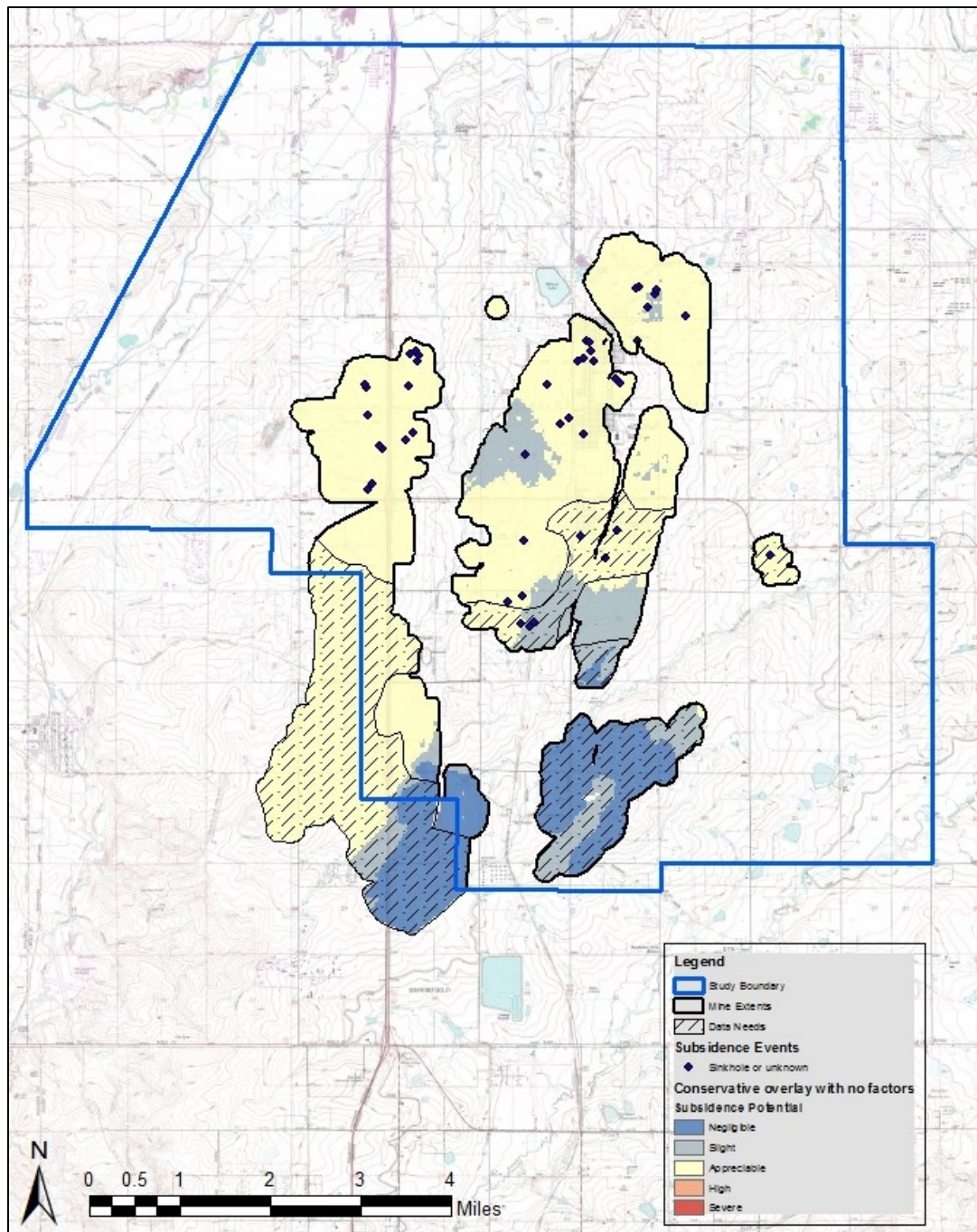


Figure 4.1: Base Model with percent claystone and depth to workings considered. Void presence and groundwater withdrawal are given no weight. In general, the hazard is higher in the north and lower in the south. The classification scale is based on the initial incorporated factors and the hazard should increase as those factors are given more weight. Most subsidence events occur within appreciable zones.

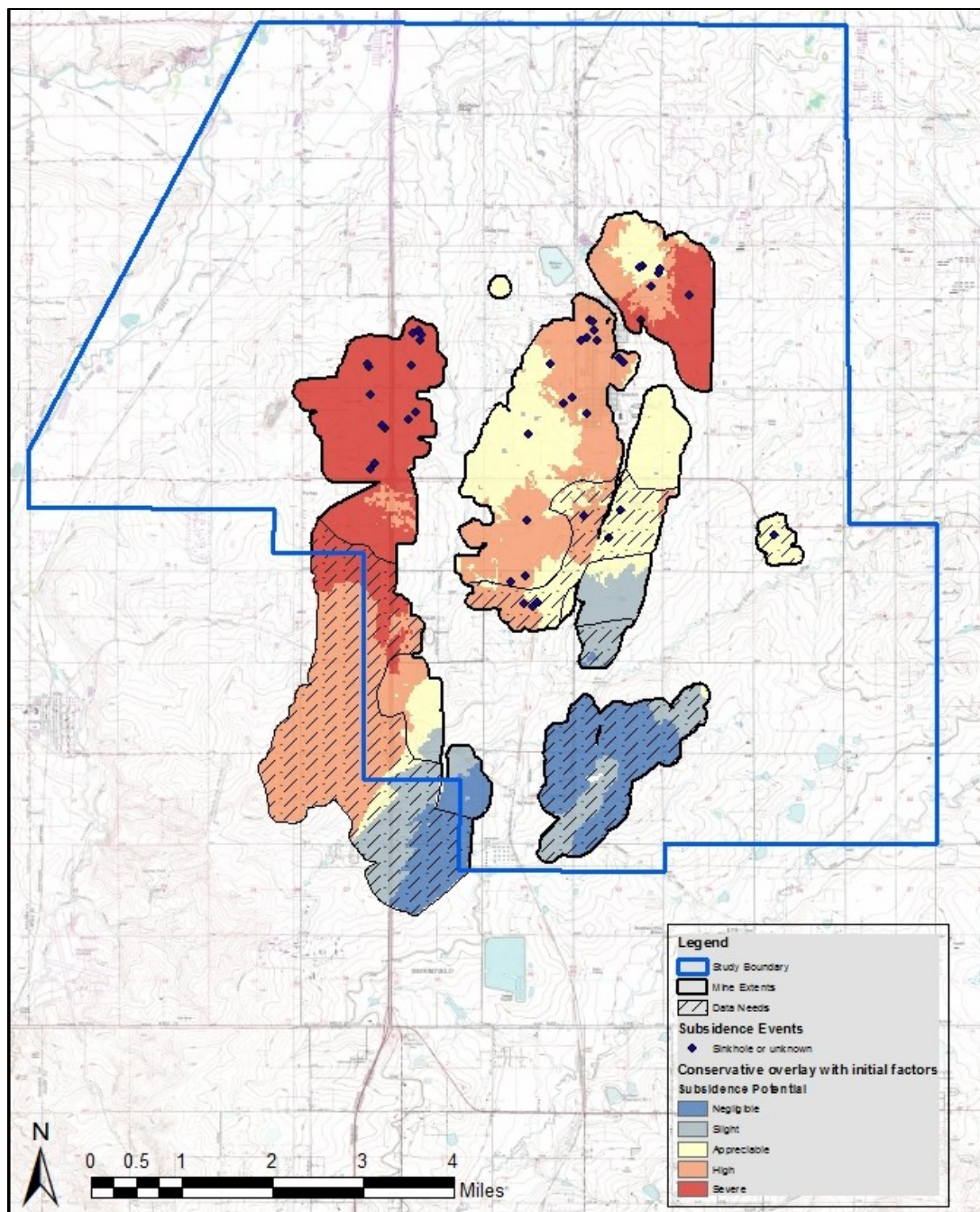


Figure 4.2: Model I with preliminary multiplication factors. Preliminary overlay of the coal mine subsidence hazard in the Tri Towns area with initial factor weights for groundwater withdrawal and void presence. Most subsidence events occur within appreciable to severe zones.

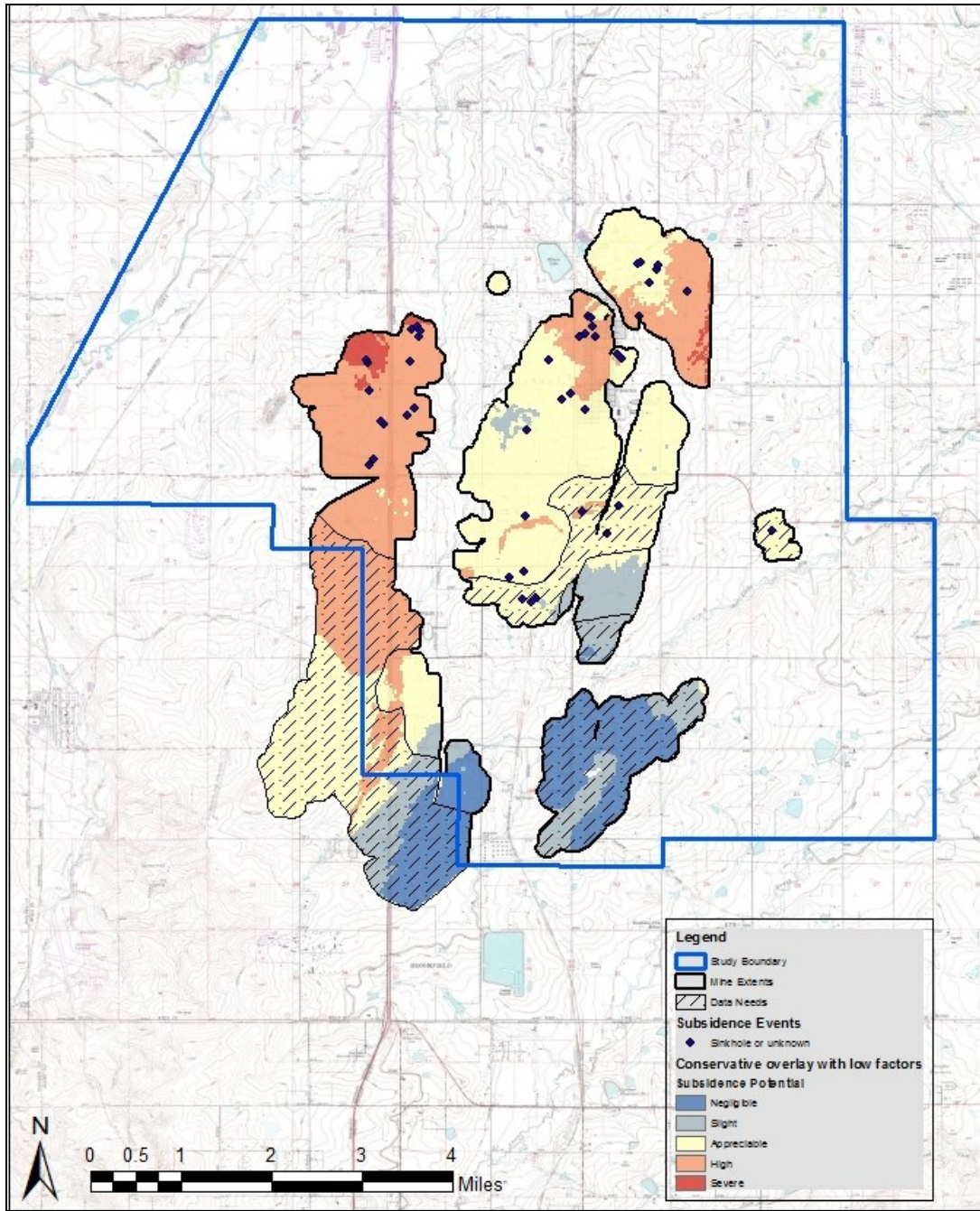


Figure 4.3: Model II with reduced multiplication factors. Overlay of the coal mine subsidence hazard in the Tri Towns area with decreased factor weights for groundwater withdrawal and void presence. Most subsidence events occur within appreciable to severe zones in the northern region of the study.

4.4 INCREASED FACTORS

Figure 4.4, Model III, displays the combined depth to workings and percent claystone susceptibility map with increased factors for groundwater withdrawal and void presence incorporated. The preliminary factor weights will contribute to model calibration and validation. Extensive zones are predicted as having a severe mine subsidence hazard.

4.5 MODEL CALIBRATION RESULTS

The model assumes that a percent claystone of 90 % within 50 feet above the mined interval, with 10 % of the overburden composed of more competent materials, represents the highest hazard for delayed failure and the presence of voids. In Figure 4.5, theoretical void thickness was compared with the percent claystone within 50 feet above the mined interval and the relationship between maximum theoretical void and percent claystone was estimated. The correlation coefficient was 0.0006, or no correlation found. While a correlation between average void thickness and percent claystone was not found, a relationship between maximum void thickness and percent claystone was found. The maximum theoretical void showed a direct relationship with percent claystone and a 7.5 feet void was estimated with a maximum of 100 % claystone. The relationship encompasses at least 95 % of the available data and anomalies are not included. The anomalies include 5 feet voids estimated in boreholes with 20 % and 50 % claystone within 50 feet above the mined interval and voids up to 1.5 feet thick with 0 % claystone. In addition, the numbers of borings with voids encountered per selected ranges of percent claystone are presented in Table 4.1.

In Table 4.2, a qualitative analysis was conducted to compare the presence and relative quantity of voids with the classification ranking assigned by the preliminary analysis. In general, mines where boreholes have encountered numerous voids were classified as a higher degree of hazard. The converse was shown as well; locations with a lesser quantity of voids were classified as a lesser hazard.

4.6 MODEL VALIDATION RESULTS

The model validation consisted of analyzing whether or not the model accurately reflects observed, reliable subsidence events recorded in the MSIC and assessing the predictive capabilities of the model. Table 4.3 displays the relative percentages of events for each classification and case and addresses the validity of that model with respect to the aforementioned criteria discussed in Section 3.7.2.

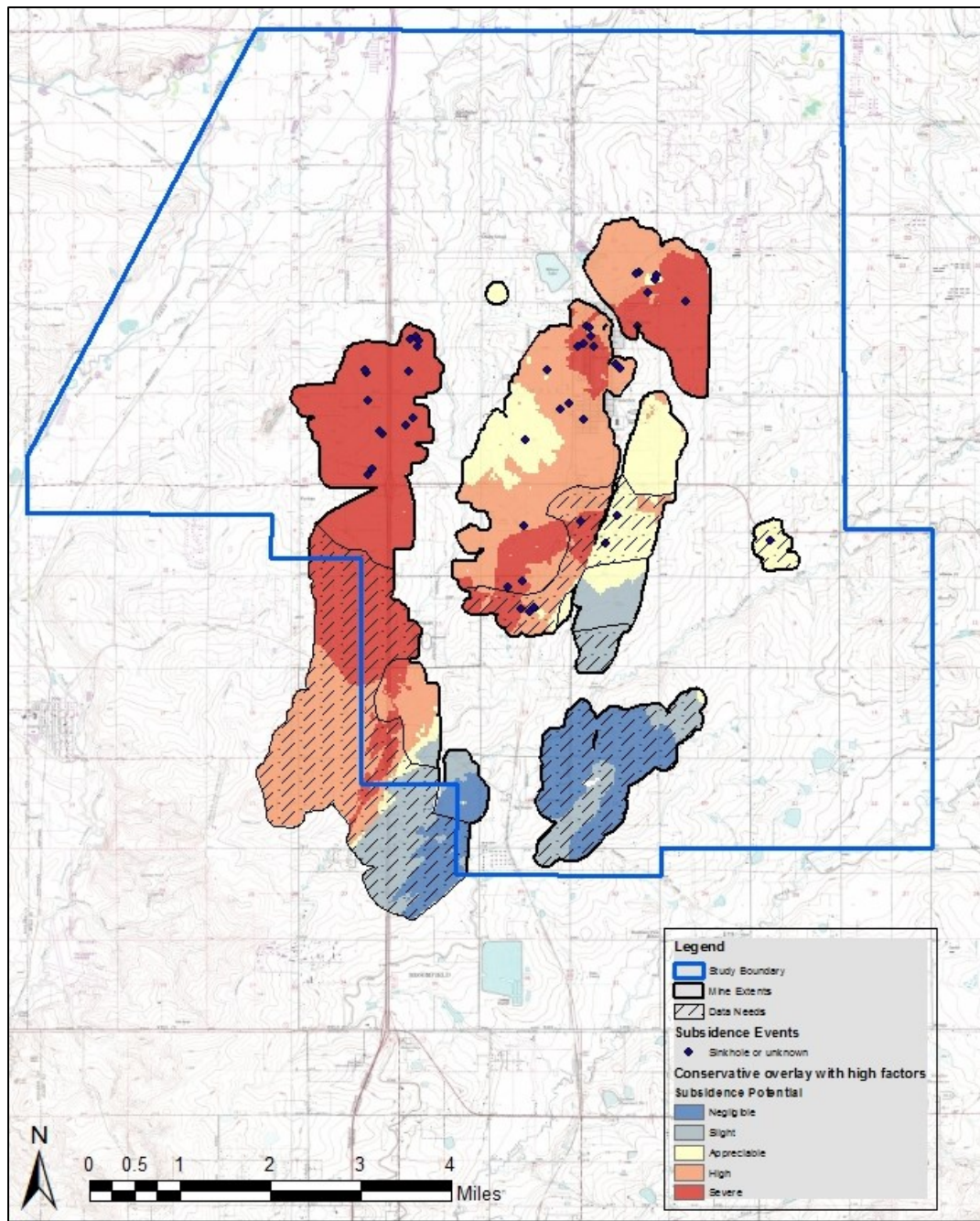


Figure 4.4: Model III with increased multiplication factors. Overlay of the coal mine subsidence hazard in the Tri Towns area with increased factor weights for groundwater withdrawal and void presence. Most subsidence events occur within appreciable to severe zones in the northern region of the study.

Table 4.1: Number of borings with voids encountered per selected ranges of percent claystone. The dataset is positively skewed since claystone is common in the region.

Percent claystone	No. of Borings with Voids Encountered
0-10	5
11-20	1
21-30	2
31-40	0
41-50	8
51-60	6
61-70	6
71-80	13
81-90	18
91-100	58

Table 4.2: A qualitative analysis considering the presence of theoretical voids and the preliminary classification. Data Needs zones were not considered.

ID	Mine(s)	Voids Encountered?	Preliminary classification
1	Eureka#3/Shamrock	In > 5 boreholes with > 5 ft. voids	Severe
2	Davis/Evans Jones	None	Appreciable
3	Puritan/Whitehouse	In > 5 boreholes with 2 to 5 ft. voids	Severe
4	Puritan1939/Rock Tunnel	In < 5 boreholes with 2 to 5 ft. voids	High-Severe
5	Imperial	Not enough data	-
6	Eagle	In < 5 boreholes with < 2 ft. voids	Slight-Appreciable
7	Washington	Not enough data	-
8	Lincoln	Not enough data	-
9	Witherbee/Peerless	Not enough data	-
10	Sterling	In < 5 boreholes with < 2 ft. voids	Slight-Appreciable
11	Graden/Boulder Valley#3	In < 5 boreholes with 2 to 5 ft. voids	Appreciable-High
12	Baum/Evans	In < 5 boreholes with 2 to 5 ft. voids	Appreciable-High
13	Warwick	In < 5 boreholes with < 2 ft. voids	Appreciable-High
14	Firestone/Frederick	In < 5 boreholes with 2 to 5 ft. voids	Appreciable-High
15	Russell	In > 5 boreholes with > 5 ft. voids	High-Severe
16	Grant/Emerson	In < 5 boreholes with 2 to 5 ft. voids	Appreciable-High

Table 4.3: Number and percentage of observed subsidence events per classification region for each model case. The model was considered valid if at least 20 % of observed, reliable events were in severe zones, at least 50 % were in high or higher rated zones, at least 90 % were in appreciable or higher rated zones, and less than 10 % were in negligible to slight zones.

Case	No. and Percent of 44 Reliable Subsidence Events					Valid?
	Negligible	Slight	Appreciable	High	Severe	
Base factors	5 (11%)	39 (89%)	0	0	0	No
Reduced factors (Model II)	0	0	22 (50%)	20 (45%)	2 (5%)	No
Preliminary factors (Model I)	0	0	10 (23%)	18 (41%)	16 (36%)	Yes
Increased factors (Model III)	0	0	6 (14%)	12 (27%)	26 (59%)	Yes

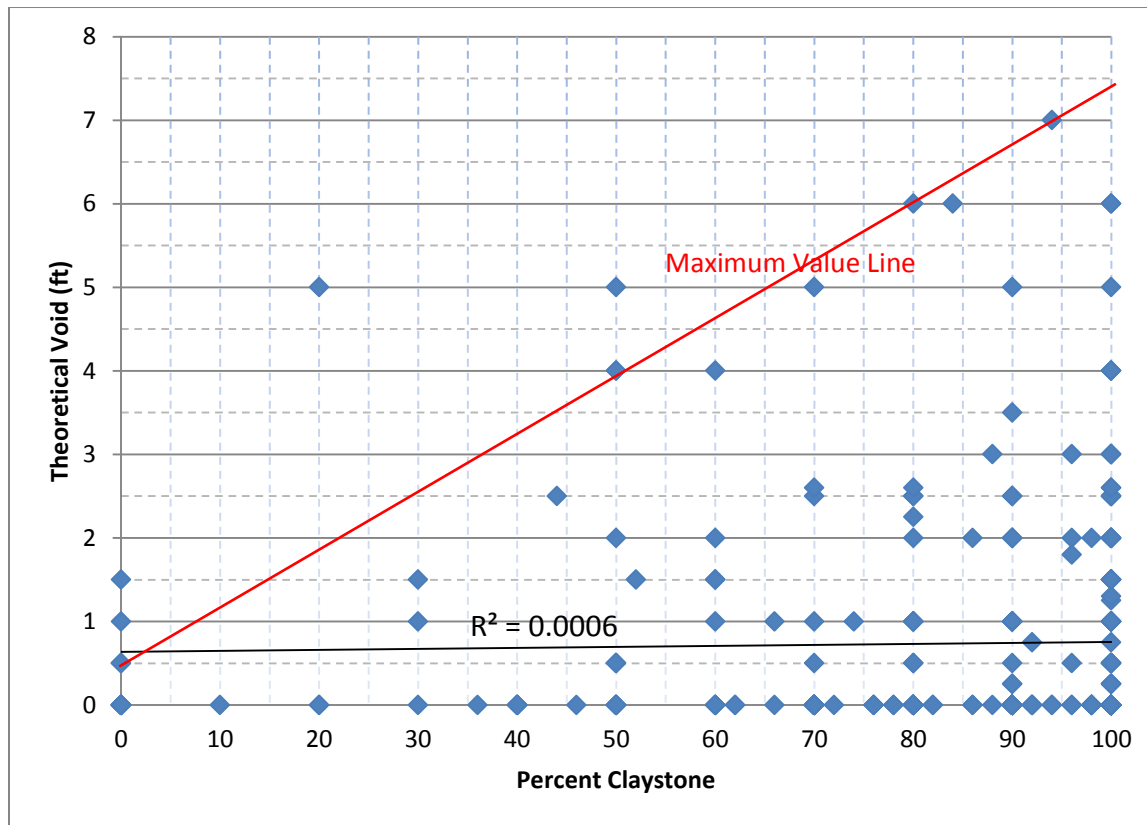


Figure 4.5: Correlation between theoretical void thickness and percent claystone within 50 feet of the mined interval. No correlation was found using the available data. The red line confines 95 % of values and shows the maximum theoretical void expected given percent claystone.

CHAPTER 5

DISCUSSION

This section discusses the accuracy and applicability of the model results in predicting abandoned coal mine subsidence, as well as model limitations. The model results will be discussed in the context of the calibration and validation analyses. Model improvements will also be considered.

5.1 MODEL RESULTS

The purpose of this project was to establish known and previously-correlated subsidence-contributing factors and incorporate the selected criteria and available data into a usable model. However, the influence, or weight, of each factor is not established and is likely to vary on a regional basis. The model attempted to assign weights to each factor and make use of educated assumptions, supported by a qualitative analysis of the results, in order to do so. The model also relies on observed subsidence events to gauge its validity; however, the events themselves are subject to certain biases and unreliability concerns. The model relies heavily on the borehole compilation which is also subject to geographical and reporting biases as a result of residential development, construction practices, hydrology, and training of the observer or driller, among other influences. A portion of the study area is considered invalid due to data needs, or the lack of any available borehole nearby. These regions demonstrate the limitations of the proposed GIS procedure when a normal distribution of data is unavailable. The model attempts to overcome these limitations by conservative practices and the usage of *Fuzzy Overlay* tools, but the uncertainty and irregularity of the data used should be considered when viewing the results.

Overall, each model scenario reflects the observed relative subsidence hazard to some extent – a higher hazard in the north and a lower hazard in the south. This is due to the dependence of the model on two over-arching factors: depth to mining and weak materials, expressed as the percent claystone within 50 feet above the mined interval. The model then attempted to incorporate factors with a lower, yet still-present, correlation to refine the model. These factors included existing voids and groundwater withdrawal. Additionally, mine map analysis, MSIC data-gathering, and a borehole program were used to verify the true extent of mining. The GIS procedure was developed to specifically address the unique information set available through the CGS.

In Figure 4.1, the Base Model is liberal in assigning hazard ratings with the present classification value scheme. Zones generally vary from negligible in the south to appreciable in the north. As the model

only considers depth to mining and lithology, this is expected, though more variability and divisions are desired. Concentrated subsidence events are not predicted as a higher risk zone than locations with fewer events. Additionally, subsidence events occur in negligible to slight zones, which is not a desired model product. In order to show the variability, the model requires adjusting the classification scale to one that favors no additional factors, which would render other models with incorporated factors too conservative. In this model, depths to mining and percent claystone are treated as equal factors where either factor can contribute to the hazard classification. Were the weights of each factor known and widespread data available, the two base factors could be combined in a more accurate manner.

In Figure 4.2, preliminary weights for void presence and groundwater withdrawal are given in Model I. Again, the correlation between the factors and subsidence has been shown but the weight of each factor is not well understood. The model attempts to overcome this limitation by assigning estimated weights, supported by knowledgeable persons, and calibrating those weights to gauge the response of the model. While the weights are still not quantifiable, this allows for model validation. In the preliminary model, most subsidence events are confined to the high and severe zones, with occasional events located in the appreciable zones. No events are located in the negligible to slight zones. This supports the initial assigned weights and lends credence to the two subsidiary factors contributing to the overall subsidence hazard.

In Figure 4.3, the preliminary weights were reduced in order to calibrate their influence on the model. In Model II, the overall hazard was reduced and most subsidence events occur in appreciable to high zones. Clustered events do not occur in severe zones like they do in the preliminary factors model. No events occur in negligible to slight zones. Overall, the model predicts the lower range of hazard level well, but does not accurately display the higher range.

In Figure 4.4, the preliminary weights were increased. Model III is considered too conservative as most subsidence events occur in extensive high to severe zones. The zones do not confine the subsidence event clusters and predict significant hazards in many locations where no subsidence has been observed. This does not render the model invalid as it is a predictive model, but the hazard is likely more localized than the increased factor model suggests.

Model I is the preferred scenario since the Base Model and Model II are not conservative enough and Model III is too conservative. Model I includes the primary subsidence criteria as well as the secondary criteria with the factor weights suggested by experienced researchers. In this model, most observed subsidence events are concentrated in severe hazard zones, as discussed in Section 5.2.

5.2 MODEL ACCURACY

Both model calibration and model validation confirm the correlation between subsidence susceptibility and the contributing factors. However, the models are unable to evaluate the magnitude of those correlations. Preliminary weights, assigned based on estimates by experienced parties and with consideration for the lack of data, were shown to be valid assumptions.

Sections 4.5 and 4.6 attempted to better estimate relationships between various model factors, primarily percent claystone and theoretical voids, and their effects on the model results. Table 4.1 began the semi-qualitative process by considering what claystone percentages were common in boreholes where voids were encountered. Figure 4.5 continued in exploring the relationship by also considering theoretical void size.

In Table 4.1, the number of borings with voids encountered was compared with the percentage of claystone within 50 feet of the mined interval. The purpose of this table was to attempt to qualitatively calibrate the percentage, or percentage range, of claystone and more competent materials most associated with time-delayed subsidence. The model currently assumes 90 % claystone and 10 % more competent materials, such as sandstone, are most likely to see delayed failures. If the percentage is too high, then failure is likely to have already occurred. If the percentage is too low, then the competent materials and higher bulking factors will bridge the voids and reach a stable state. Determining the critical percentage, which likely varies on a regional basis, would significantly help to improve the model. As shown in the table, 58 boreholes encountered voids when the overburden contained 91 % to 100 % claystone in the 50 feet above the mined interval. For comparison, fewer than nine boreholes encountered voids in each 10 % interval between 0 % to 70 % claystone. From 71 % to 90 % claystone, a slight increase of 13 to 18 boreholes encountering voids was observed, though the quantity is nearly a quarter of what was observed in the 91 % to 100 % range. While this initially suggests the critical percentage range at which cantilevering strata contributes to delayed subsidence is between 91 % and 100 % claystone within 50 feet above the mined interval, it is also important to consider that the local geology is dominated by claystone and boreholes generally encountered significantly more claystone than other rock types. Thus, a positive skew in the sampling data inhibits estimating the percent claystone best associated with delayed failures. Additionally, an estimation of the critical percentage range is affected by reporting irregularities between different samplers or geologists, borehole sampling intervals of 5 feet, and borehole programs geographically concentrated in urbanized locations.

The chart in Figure 4.5 attempted to quantitatively find a relationship between percent claystone and theoretical void size. This would have aided in assigning a weight for percent claystone and reducing

the need for *Fuzzy Overlay* methods. Using both logarithmic and linear statistical methods, no correlation of statistical significance was found with the given dataset. The current dataset inhibits quantitative analysis as the data are positively skewed towards higher percent claystone and are not precise in their sampling measurements. The lithology was described in five foot drilling intervals, leading to error in approximating the percent claystone within 50 feet above the mined interval. Another limiting factor is that spatially uniform data are not available and boreholes are clustered within commercially-developed locations. Finally, the irregularity and unpredictability of encountering measureable open voids in a borehole creates uncertainty in quantitative analyses. Thus, the available data are invalid for establishing a correlation.

Figure 4.5 also sought to estimate the maximum theoretical void that may be present given the percent claystone within 50 feet of the mined interval. The chart was successful in that a direct relationship was observed. Higher percentages of claystone allow for larger theoretical voids. A maximum void thickness of 7.5 feet is estimated for the maximum percent claystone within 50 feet above the mined interval of 100 %. However, the chart was unable to show possible effects of cantilevering strata without including anomalies located above the maximum value line, such as the 5 feet theoretical voids observed with overburdens containing 20 % and 50% claystone. The anomalies suggest void thicknesses greater than the maximum value for a given percent claystone and could possibly represent the effects of cantilevering strata; however, additional data are required to adequately estimate the relationship and effect.

In Table 4.2, another qualitative analysis was conducted to gauge the correlation between void conditions and hazard rating. In general, there is a good correlation between the number of voids encountered in the boreholes in that particular mine section and the preliminary hazard classification. In one case, no voids were encountered in a location rated as appreciable. This is acceptable as the model is predictive in nature and subsidence may not have occurred yet. Conversely, locations with numerous observed voids should be predicted as high or severe zones, as the table confirms. Moderate void quantities are located in slight, appreciable, and high zones. However, as with the other calibration methods, the correlation is shown while the magnitude and weight of the influencing factor in contributing to overall susceptibility is poorly estimated.

Due to the difficulties in quantitatively or qualitatively calibrating the model influences, Table 4.3 addresses whether the models are at least valid and useful in assessing abandoned coal mine subsidence. The model was considered valid if at least 20 % of observed, reliable events were in severe zones, at least 50 % were in high or higher rated zones, at least 90 % were in appreciable or higher rated zones, and less

than 10 % were in negligible to slight zones. Additionally, the zones should not be too conservative so as to classify extensive regions around the cluster of events as a higher-rated hazard than reality or data limitations allow. With the normalized scale applied, the model with no additional factors is not considered valid as it underestimates the hazard. The reduced factors model is not considered valid since too few observed subsidence events occur in high-severe hazard locations. Both the preliminary and increased factors models meet the criteria and are considered valid. The increased factors model is considered too conservative with extensive severe zones.

Since the preliminary factors model is considered valid and the reduced factors model is considered invalid, the true influencing weights of the additional subsidence factors are likely between those of the reduced and preliminary models. While running intermediate model iterations would prove useful in traditional calibration procedures, another model is not appropriate for this case. First, only 44 subsidence events were considered reliable and valid for calibration purposes. This represents 44 point locations in nearly 50 square miles and the events are biased by urbanization and training of the investigator. Additional studies focused on locating subsidence features would aid in the calibration process. Second, the MSIC borehole dataset varies considerably in quality, is subject to driller biases, and is concentrated in urbanized areas. These limitations inhibit an overly-detailed calibration process as concerns about the data quality supersede concerns about precise multiplication values, though the effects of each concern have been mitigated. Finally, even though the validity percentiles were based on reasonable expectations, the percentiles still contain an arbitrary component. The validity percentiles could be varied within a reasonable range and yield similar results; however, this would affect the multiplication factor values significantly, rendering a detailed iteration process unreasonable. Despite the limitations inherent in a calibration process based on questionable data, the GIS methodology presented is receptive of further calibration iterations if the proper data were available.

5.3 MODEL IMPROVEMENTS

The model may be improved by additional borings in the “Data Needs” regions as well as a broad geographical distribution of borings. Additionally, uniform, detailed reporting of geologic materials and conditions encountered in borings would be conducive to a regional-scale GIS model incorporating numerous investigations. These improvements would aid in creating reliable interpolated surfaces for the percent claystone and depth to workings, and help to refine the magnitude of the additional factors. However, this is unlikely to occur without direction provided by a state agency as budget and access concerns inhibit the implementation of a spatially uniform and detailed borehole program.

The GIS procedure may also be improved by further studies focused on establishing the magnitude at which each subsidence factor contributes to the overall hazard. While Matheson (1987) has established a correlation and the GIS procedure presented is considered valid with the incorporated factors, the exact range of factor weights would help to refine the model. In particular, further calibration is needed to determine the percent of claystone and of other materials most associated with subsidence as well as the weight of influence depth to mining, lithology, groundwater withdrawal, and open voids contribute to subsidence.

Finally, the model and GIS procedure can be readily updated as new subsidence investigations and borehole data become available. Thus, the understanding of the hazard in the region can be routinely and flexibly enhanced utilizing the GIS procedure outlined.

CHAPTER 6

CONCLUSIONS

During this project, a GIS procedure was created to predict future abandoned coal mine sinkhole subsidence in the Tri-Towns region of Colorado. The susceptibility map will aid in city planning and provide developers with recommendations for minimum investigation activities. The procedure created was shown to be valid with respect to observed subsidence events.

The preliminary model predicts severe sinkhole subsidence hazard in the north of the site location along Interstate 25 and near the northern Tri Towns city centers. This is validated by numerous observed subsidence events clustered in the area and by shallow mining depths between 0 feet and 150 feet. The hazard generally decreases from severe to high to appreciable towards the southern end of the study boundary, and finally to slight and negligible near the southern terminus where mining depths exceed 350 feet. The hazard generally reflects depth to mining, a strong factor contributing to subsidence propagation.

Reduced and increased factor weights were incorporated in comparative models in order to calibrate the influence of secondary subsidence criteria. The results from the reduced weights were considered invalid, meaning that the predicted subsidence hazard was improperly weighted by secondary factors to match the observed subsidence events. The results from the increased weights were deemed too conservative as it predicted that significant subsidence hazard exists in extensive areas beyond the immediate vicinity of observed subsidence events. The reduced and increased factor weight models supported the preliminary weights given to the contributing subsidence factors.

The subsidence criteria considered are valid and capable of accurately predicting coal mine subsidence. The procedure combines two known factors with a high correlation – depth to mining and weak materials in the overburden – using *Fuzzy Overlay*, a GIS toolset. The overlay was then multiplied by factors representing the presence of voids encountered in boreholes and groundwater pumping when data were available. A borehole investigation and implemented angle of draw buffer zone were utilized to incorporate mining extents. The data were derived from the MSIC database and the data from each investigation had varying levels of reliability. When the dataset is viewed as a whole, the individual biases are reduced and the model gains credibility.

The GIS procedure is not adequate for calibrating the exact weight of factors or for predicting subsidence in locations with limited borehole investigation data. Additionally, no correlation between theoretical void thickness and percent claystone within 50 feet above the mined interval was found;

however, a direct relationship was found between the maximum value for theoretical void thickness and the percent claystone. A maximum void of approximately 7.5 feet was estimated for a mine section with 100 % claystone within 50 feet above the mined interval. The effects of cantilevering strata on maximum theoretical void size were undetermined.

Additional research and data are required to better establish unknown parameters and accurately incorporate them into the model. However, the factor weights and model assumptions were approximated based on the opinions of knowledgeable researchers. The current model uses GIS-based procedures to approximate abandoned coal mine subsidence in the Tri-Towns regions in a valid manner with respect to the data limitations.

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