The Influence of Subsidence Laws and Regulations on the Underground Bituminous Coal Industry in the Commonwealth of Pennsylvania over the Last 25 Years

by

Taylor DaCanal

B.S. in Civil Engineering, University of Pittsburgh, 2017

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2019

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Taylor DaCanal

It was defended on

July 9, 2019

and approved by

Luis E. Vallejo, Ph.D., Professor, Department of Civil and Environmental Engineering

Daniel Bain, Ph.D., Assistant Professor, Department of Geology and Environmental Sciences

Thesis Advisor: Anthony T. Iannacchione, Ph.D. P.E. P.G., Associate Professor, Department of Civil and Environmental Engineering

Copyright © by Taylor DaCanal

2019

The Influence of Subsidence Laws and Regulations on the Underground Bituminous Coal Industry in the Commonwealth of Pennsylvania over the Last 25 Years

Taylor DaCanal, M.S.

University of Pittsburgh, 2019

Pennsylvania is currently the third leading state in coal production. The first underground coal mines in Pennsylvania were formed in the late 1700s by mining the outcrops of the Pittsburgh coalbed on the hillsides of Mount Washington. For over 200 years in Pennsylvania, there has been an evolution of both underground coal mining and the laws and regulations that govern it.

Room-and-pillar and longwall mining methods have been used in Pennsylvania. Though more efficient and safer for miners, the longwall mining technique, introduced in the late 1960s, elevated both the number and intensity of subsidence related impacts to surface features. The 1966 Bituminous Mine Subsidence and Land Conservation Act was the first state law advocating for the protection of surface structures from subsidence. In 1994, Pennsylvania amended the outdated 1966 law with the formation of Act 54 for additional protection of structures, watersources, lands, and streams from mine subsidence. Act 54 requires all impacts due to mining be recorded and analyzed on a five-year basis. Between 1993 and 2018, there have been 2,222 impacts to structures, land, and watersources for which the mining companies were responsible for repairing or fairly compensating the property owner for damages. The data collected from the 25-years of Act 54 enables an investigation of how the country's strictest subsidence regulations have impacted Pennsylvania's mining industry.

This study used data collected through Act 54 to identify trends in mine characteristics and surface impacts to spot significant changes in mining. Subsidence prediction models were compared with the recorded field impacts to observe when impacts occurred in expected areas and, more importantly, when they appeared far beyond the predicted influence zone of the models. Case studies of far field effects were studied to determine why these impacts are occurring past the expected prediction limit. The recognized trends and characteristics of impacts aided in the review of the standards and guidelines set by Act 54. Overall, this study found Act 54 to be an evolving law that has contributed to protection of the communities and environmental resources of the Commonwealth of Pennsylvania.

Table of Contents

Acknowledgements xxxi

1.0 Introduction 1

1.1 Underground Bituminous Coal Mining 1

1.2 Origins of Subsidence Law and Regulations 6

1.3 Research Aim 12

2.0 Literature Review 14

2.1 Final Subsidence Basin Characteristics 14

2.2 Dynamic Subsidence Basin Characteristics 19

3.0 Method of Study 23

3.1 Data Sources 23

3.1.1 Site Visits 24

3.1.2 Mapping 27

3.2 Data Analysis 28

3.3 Limitations 29

4.0 25-Year Review of Pennsylvanian Underground Bituminous Coal Mining 30

4.1 Types of Mining Operations 30

4.2 Acres Mined 32

4.3 Mining Characteristic 36

4.4 Mine Locations 41

4.5 Future Mining 45

5.0 Impact Review 49

5.1 Watersource Impacts ... 53

5.2 Structures Impacts ... 58

5.3 Land Impacts ... 64

6.0 Subsidence Modeling and Impact Prediction ... 68

6.1 Empirical Formula Subsidence Prediction ... 69

6.1.1 Empirical Method Case Study ... 71

6.2 Subsidence Deformation Prediction Software ... 74

6.2.1 Subsidence Prediction Model Case Study ... 75

6.2.2 Panel Characteristics ... 75

6.2.3 Bailey 2L Panel ... 77

6.2.4 SDPS Assumptions ... 78

6.2.5 SDPS Outputs ... 79

6.2.6 Subsidence Impacts ... 84

6.3 Mitigation Strategies ... 85

7.0 Far Field Effect Case Studies ... 89

7.1 Chapel Hill Property Case Study ... 91

7.2 Morris Township Case Study ... 99

7.3 Bailey Streams Case Study ... 107

8.0 Discussion ... 114

9.0 Summary ... 121

10.0 Conclusion ... 124

Appendix A ... 127

Appendix B ... 131

Bibliography **436**

List of Tables

Table 1. Act 54 assessment period and assessment team 12

Table 2. Subsidence Categories 17

Table 3. Lists of office visits to mining companies active during the 5th assessment 25

Table 4. List of impact site visits during the 5th assessment period 26

Table 5. Visits to active mine workings during the 5th assessment period 27

Table 6. Extraction ratio by mining method 31

Table 7. Number of mines per mining type over the last five Act 54 assessment periods... 32

Table 8. Acres mined per mine type over the five Act 54 assessment periods 33

Table 9. Overburden categories per the last three assessment periods 39

Table 10. Overburden statistics per assessment period 40

Table 11. Coalbeds mined per Act 54 assessment period.. 44

Table 12. Unmined longwall permit area of the Pittsburgh coalbed overburden statistics. 47

Table 13. Number of total impacts and the percent of total impacts over the four assessment periods.. 50

Table 14. Total company liable impacts per assessment period.. 51

Table 15. Percent of impacts determined to be company liable 51

Table 16. Acres mined per assessment period and impacts per assessment.......................... 52

Table 17. Location of watersource impacts 54

Table 18. Locatin of the company liabel impacts over room-and-pillar mines during the 5th assessment... 55

Table 19. Total structures impacts by mine type over the last three assessment periods.... 59

Table 20. Company liable impacts over longwall mines 60

Table 21. Percent of strucures located directly over longwall panels that were company liable 61

Table 22. Land during the 5th assessmend by mining type and their liability 65

Table 23. Equations for prediciton of subsidence profile for the Pittsburgh Coalbed......... 70

Table 24. Subsidence featrues for Enlow Fork Case Study 73

Table 25. Average characteristics of completely mined panels during the 5th assessment period. 76

Table 26. Bailey 2L longwall panel dimensions.. 77

Table 27. Assumed values and setting in SDPS.. 79

Table 28. List of far field impacts to streams over the Bailey mine prior to the typical 14 day before undermining observing period... 109

Table 29. Elevation change of the Pittsburgh coalbed across the longwall panels to impacted areas 117

Table 30. Impacts recorded in BUMIS from August 21, 2013- August 20, 2018................ 127

Table 31. Mine codes used by the University for active mines during the 5th assessments 131

List of Figures

Figure 1. Classic room-and-pillar mining method (Lehmann et al., 2015) 2

Figure 2. Place change room-and-pillar mining operation with a continuous haulage machine (Sammarco, 1996) 4

Figure 3. Pillar recovery of a room-and-pillar mine, the gob area represents the area where the pillars have already been extracted (Mark et al., 2016)... 5

Figure 4. Longwall mining technique (figure sourced from U.S. Engergy Information Administration) 6

Figure 5. Example of the angle of support required by BMSLCA (1996) (Iannacchione et al., 2011) 8

Figure 6. Kendorski's diagram of the zones above a subsided mine (Kendorski, 1993)...... 10

Figure 7. Four zones of strata movement above a longwall panel (Peng, 1992) 16

Figure 8. Surface deformation distribution on a major cross section (Peng and Chiang, 1984) 19

Figure 9. Zones of compresion and tension during dynamic subsidence (Peng, 1992) 20

Figure 10. Advancing of the final subsidnce basin to the finals subsience basin (Peng, 1992) 21

Figure 11. Acres mined vs the total number of mines per Act 54 assessment period.......... 34

Figure 12. U.S. coal production from 2008-2018 from the U.S. Energy Information Administrarion (Woodward et al., 2019).. 35

Figure 13. Number of mines closed per assessment period.. 36

Figure 14. Total Extent of Emerald mine, the area circled in red shows examples of older mining 37

Figure 15. Year panel was completed vs the width of the panel 38

Figure 16. Panel overburden per year from 1994 to Present 40

Figure 17. Counties that have had active underground bituminous mining during the last five assessment periods 42

Figure 18. Stratigraphic sections of the (a) Allegheny and (b) Pittsburgh formations and the minable coalbeds contained in them (Edmunds et al. 1999) 43

Figure 19. Trendline showing the advances in longwall panel width with advancing mining technology 45

Figure 20. Map of the longwall mines in the Pittsburgh Coalbed and overbuden depths ... 46

Figure 21. Location of unmined Pittsburgh coalbed in southwestern Pennsylvania 48

Figure 22. Diagram of the cracks and fissures formed duirng minib and the disruption of ground water 53

Figure 23. Knob Creek mining extent from the 5th assessment period and the impacted watersource loaced 7,000-ft from mining 57

Figure 24. Population density map with the longwall mining in the 3rd, 4th, and 5th assessments (U.S. Census Bureau et al., 2017) 62

Figure 25. Damage to a dwelling located over an Enlow Fork panel (photographs courtesy of the PA DEP) 63

Figure 26. Location of land impacts over longwall mines 65

Figure 27. Mass wasting occurring over the Harvey mine during the 5th assessment (Photographs from the PADEP files) 66

Figure 28. Impacted garage that was surveyed to compare the deformation of the garge with the predicted subsidence basin 72

Figure 29. Predicted subidece versus measured subsidence basin of the Enlow Fork E27 panel 74

Figure 30. Map of Bailey 2L panel 78

Figure 31. A. Vertical Subsidence of the 2L panel B. Ground Strain of the 2L panel. 80

Figure 32. SPDS vertical subsidence prediction for the 1L and 2L panels 81

Figure 33. Strain predictions for the 1L and 2L panels 82

Figure 34. 3D vertical subsidence prediction model for the 1L, 2L, and 3L panels 83

Figure 35. Stain prediction for the 1L, 2L, and 3L panels 84

Figure 36. Location of all reported effects over the Bailey 1L, 2L, and 3L panels 85

Figure 37. Bracing of an undermined structure in the 3rd Act 54 assessment (Photograph courtesy of N. Evanek) 86

Figure 38. Trenching of an undermined structure in the 5th Act 54 assessment 87

Figure 39. Timber cribbing to support an outbuilding during the 5th Act 54 assessment (Photograph courtesy of the PA DEP) 88

Figure 40. a.) Damage the driveway b.) roll forming in the hillside across from the property 92

Figure 41. Map of Enlow Fork F25 panel with fair field impact property 93

Figure 42. Location of the F25 longwall panel when the first impact was noted 93

Figure 43. Angle of deformation of far feild effect* 94

Figure 44. Topography of impacted area 95

Figure 45. Elevation of the Pittsbrugh Coalbed 96

Figure 46. Ancient landslide outlined on the hill adjacent to the impacted property 97

Figure 47. Distance from longwall face posistions and the areas of longwall panel extraction as of August 2019, the face positions during impacts are shown in blue. 100

Figure 48. 3A panel of the Harvey Mine and far feild effects... 101

Figure 49. a.)Crack in the wall of the community center b.) Compression hump in the yard (Photographs courtesey of the PA DEP files) 102

Figure 50. a.) Angle of deformation of the first far field effect* b.) Angle of deformationof of refollowing far feild impacts* 103

Figure 51. Topography map of the Harvery Mine... 104

Figure 52. Elevation of the Pittsburgh Coalbed.. 104

Figure 53. Location of natural gas wells from impacted properties 106

Figure 54. Ariel view of the impacted properties and the location and size of the natural gas well located 900-ft from the impacts 106

Figure 55. Map of streams with far feild effects over the Bailey mine 110

Figure 56. Topography of the Baily Mine and impacted streams 111

Figure 57. Elevation of the Pittsburgh coalbed across the Baily mine during the 5th assessment period.. 113

Figure 58. Punch longwall layout (Martin et.al, 2018) 118

Figure 59. A.) Longwall panel mining the same elevation in flat terrain B.) Longwall panel incrasing in elevation mining in a area of hills and vallies....................................... 119

Figure 60 Bailey Mine total extent of mining 133

Figure 61. Bailey mining extent for the 3rd, 4th, and 5th assessment periods 134

Figure 62. 200-ft interval overburden contour map for the total mining extent of Bailey Mine 135

Figure 63. Bailey Mine 5th assessment 200-ft buffer and structures* 136

Figure 64. Bailey Mine 5th assessment water supplies and RPZ*.. 137

Figure 65. Properties associated with the 5th assessment period over the Bailey Mine...... 138

Figure 66. Cumberland total extent of mining... 139

Figure 67. Cumberland mining extent for the 3rd, 4th, and 5th assessment periods......... 140

Figure 68. 100-ft interval overburden contour map for the total mining extent of Cumberland Mine.. 141

Figure 69. Cumberland Mine 5th assessment 200-ft buffer and structures*....................... 142

Figure 70. Cumberland Mine 5th assessment water supplies and RPZ 143

Figure 71. Properties associated with the 5th assessment period over the Cumberland Mine 144

Figure 72. Emerald Mine total extent of mining... 145

Figure 73. Emerald mining extent for the 3rd, 4th, and 5th assessment periods 146

Figure 74. 100-ft interval overburden contour map for the total mining extent of Emerald Mine.. 147

Figure 75. Emerald Mine 5th assessment 200-ft buffer and structures*.............................. 148

Figure 76. Emerald Mine 5th assessment water supplies and RPZ 149

Figure 77. Properties associated with the 5th assessment period over the Emerald Mine . 150

Figure 78. Enlow Fork Mine total extent of mining 151

Figure 79. Enlow Fork mining extent for the 3rd, 4th, and 5th assessment periods............. 152

Figure 80. 100-ft interval overburden contour map for the total mining extent of Enlow Fork Mine 153

Figure 81. Enlow Fork Mine 5th assessment 200-ft buffer and structures* 154

Figure 82. Enlow Fork Mine 5th assessment water supplies and RPZ 155

Figure 83. Properties associated with the 5th assessment period over the Enlow Fork Mine 156

Figure 84. Harvey Mine total extent of mining 157

Figure 85. Harvey mining extent for the 3rd, 4th, and 5th assessment periods 158

Figure 86. 100-ft interval overburden contour map for the total mining extent of Harvey Mine 159

Figure 87. Harvey Mine 5th assessment 200-ft buffer and structures 160

Figure 88. Harvey Mine 5th assessment water supplies and RPZ 161

Figure 89. Properties associated with the 5th assessment period over the Harvey Mine 162

Figure 90. Monongalia County Mine total extent of mining 163

Figure 91. Monongalia County mining extent for the 3rd, 4th, and 5th assessment periods 164

Figure 92. 100-ft interval overburden contour map for the total mining extent of Monongalia County Mine 165

Figure 93. Monongalia County Mine 5th assessment 200-ft buffer and structures 166

Figure 94. Monongalia County Mine 5th assessment water supplies and RPZ 167

Figure 95. Properties associated with the 5th assessment period over the Monongalia County Mine 168

Figure 96. Tunnel Ridge Mine total extent of mining. 169

Figure 97. Tunnel Ridge mining extent for the 5th assessment period 170

Figure 98. 100-ft interval overburden contour map for the total mining extent of Tunnel Ridge Mine 171

Figure 99. Tunnel Ridge Mine 5th assessment 200-ft buffer and structures 172

Figure 100. Tunnel Ridge Mine 5th assessment water supplies and RPZ 173

Figure 101. Properties associated with the 5th assessment period over the Tunnel Ridge Mine 174

Figure 102. Acosta Deep Mine total extent of mining 175

Figure 103. Acosta Deep Mine mining extent for the 5th assessment period 176

Figure 104. Fifty-foot overburden contour intervals for the Acosta Deep Mine 177

Figure 105. Acosta Deep Mine 5th assessment 200-ft buffer and structures* 178

Figure 106. Acosta Deep Mine 5th assessment water supplies and RPZ* 179

Figure 107. Properties associated with the 5th assessment period over the Acosta Deep Mine 180

Figure 108. Barbara No. 2 total extent of mining 181

Figure 109. Barbara No. 2 mining extent for the 5th assessment period 182

Figure 110. Barbara No. 2 mining extent for the 4th and 5th assessment periods* 183

Figure 111. Fifty-foot overburden contour intervals for the Barbara No. 2 Mine 184

Figure 112. Barbara No. 2 Mine 5th Assessment 200-ft buffer and structures 185

Figure 113. Barbara No. 2 Mine 5th assessment water supplies and RPZ* 186

Figure 114. Properties associated with the 5th assessment period over the Barbara No. 2 Mine 187

Figure 115. Barrett total extent of mining 188

Figure 116. Barrett mining extent for the 4th and 5th assessment periods 189

Figure 117. Fifty-foot overburden contour intervals for the Barrett Mine........................ 190

Figure 118. Barrett 5th assessment 200-ft buffer and structures... 191

Figure 119. Barrett 5th assessment water supplies and RPZ 192

Figure 120. Properties associated with the 5th assessment period over the Barrett Mine.. 193

Figure 121. Beaver Valley total extent of mining.. 194

Figure 122. Beaver Valley mining extent for the 3rd, 4th, and 5th assessment periods........ 195

Figure 123. Fifty-foot contour intervals for the Beaver Valley Mine.................................. 196

Figure 124. Beaver Valley 5th assessment 200-ft buffer and structures.............................. 197

Figure 125. Beaver Valley 5th assessment water supplies and RPZ 198

Figure 126. Properties associated with the 5th assessment period over the Beaver Valley mine 199

Figure 127. Brubaker total extent of mining... 200

Figure 128. Brubaker mining extent for the 5th assessment period 201

Figure 129. Brubaker's mining extent for the 4th and 5th assessment periods* 202

Figure 130. Fifty-foot overburden contour intervals for the Brubaker Mine.................... 203

Figure 131. Brubaker 5th assessment 200-ft buffer and structures..................................... 204

Figure 132. Brubaker 5th assessment water supplies and RPZ 205

Figure 133. Properties Associated with the 5th Assessment Period over the Brubaker Mine 206

Figure 134. Brush Valley total extent of mining 207

Figure 135. Brush Valley mining extent for the 5th assessment period............................... 208

Figure 136. Fifty-foot overburden contour intervals for the Brush Valley Mine.............. 209

Figure 137. Brush Valley 5th assessment 200-ft buffer and structures 210

Figure 138. Brush Valley 5th assessment water supplies and RPZ 211

Figure 139. Properties associated with the 5th assessment period over the Brush Valley Mine 212

Figure 140. Cass No. 1 total extent of mining 213

Figure 141. Cass No. 1 mining extent for the 5th assessment period 214

Figure 142. Fifty-foot overburden contour intervals for the Cass No. 1 Mine.................... 215

Figure 143. Cass No. 1 Mine 5th assessment 200-ft buffer and structures* 216

Figure 144. Cass No. 1 Mine 5th assessment water supplies and RPZ 217

Figure 145. Properties associated with the 5th assessment period over the Cass No. 1 Mine 218

Figure 146. Cherry Tree total extent of mining 219

Figure 147. Cherry Tree mining extent for the 3rd, 4th, and 5th assessment periods........... 220

Figure 148. Fifty-foot overburden contour intervals for the Cherry Tree mine 221

Figure 149. Cherry Tree 5th assessment 200-ft buffer and structures* 222

Figure 150. Cherry Tree 5th assessment water supplies and RPZ* 223

Figure 151. Properties associated with the 5th assessment period over the Cherry Tree mine 224

Figure 152. Clementine total extent of mining 225

Figure 153. Clementine mining extent for the 3rd, 4th, and 5th assessment periods............. 226

Figure 154. 100-ft overburden contour intervals for the Clementine Mine Lower Kittanning coal seam 227

Figure 155. Clementine 5th assessment 200-ft buffer and structures* 228

Figure 156. Clementine 5th assessment water supplies and RPZ* 229

Figure 157. Properties associated with the 5th assessment period over the Clementine Mine* 230

Figure 158. Coral Graceton total extent of mining.. 231

Figure 159. Coral Graceton mining extent for the 5th assessment period 232

Figure 160. Fifty-foot overburden contour intervals for the Coral Graceton mine 233

Figure 161. Coral Graceton 5th assessment 200-ft buffer and structures 234

Figure 162. Coral Graceton 5th assessment water supplies and RPZ 235

Figure 163. Properties associated with the 5th assessment period over the Coral Graceton mine 236

Figure 164. Cresson total extent of mining.. 237

Figure 165. Cresson mining extent for the 5th assessment period 238

Figure 166. Fifty-foot overburden contour intervals for the Cresson Mine...................... 239

Figure 167. Cresson Mine 5th assessment 200-ft buffer and structures 240

Figure 168. Cresson 5th assessment water supplies and RPZ 241

Figure 169. Properties associated with the 5th assessment period over the Cresson Mine 242

Figure 170. Crooked Creek total extent of mining 243

Figure 171. Crooked Creek mining extent for the 5th assessment period......................... 244

Figure 172. Fifty-foot overburden contour intervals for the Crooked Creek Mine Upper Freeport coal seam.. 245

Figure 173. Fifty-foot overburden contour intervals for the Crooked Creek Mine Upper Kittanning coal seam 246

Figure 174. Crooked Creek 5th assessment 200-ft buffer and structures 247

Figure 175. Crooked Creek 5th assessment water supplies and RPZ.............................. 248

Figure 176. Properties associated with the 5th assessment period over the Crooked Creek Mine 249

Figure 177. Darmac No. 2 total extent of mining 250

Figure 178. Darmac No. 2 mining extent for the 3rd, 4th, and 5th assessment periods 251

Figure 179. Fifty-foot overburden contour intervals for the Darmac No. 2 Mine 252

Figure 180. Darmac No. 2 Mine 5th assessment 200-ft buffer and structures 253

Figure 181. Darmac No. 2 Mine 5th assessment water supplies and RPZ* 254

Figure 182. Properties associated with the 5th assessment period over the Darmac No. 2 Mine 255

Figure 183. Dutch Run total extent of mining 256

Figure 184. Dutch Run mining extent for the 3rd, 4th, and 5th assessment periods 257

Figure 185. Fifty-foot overburden contour intervals for the Dutch Run Mine 258

Figure 186. Dutch Run 5th assessment 200-ft buffer and structures* 259

Figure 187. Dutch Run 5th assessment water supplies and RPZ* 260

Figure 188. Properties associated with the 5th assessment period over the Dutch Run Mine 261

Figure 189. Gillhouser Run total extent of mining 262

Figure 190. Gillhouser Run mining extent for the 3rd, 4th, and 5th assessment periods 263

Figure 191. Gillhouser Run mining extent for the 3rd, 4th, and 5th assessment periods* 264

Figure 192. Fifty-foot overburden contour intervals for the Gillhouser Run mine 265

Figure 193. Gillhouser Run 5th assessment 200-ft buffer and structures 266

Figure 194. Gillhouser Run 5th assessment water supplies and RPZ 267

Figure 195. Properties associated with the 5th assessment period over the Gillhouser Run Mine.. 268

Figure 196. Harmony total extent of mining 269

Figure 197. Harmony mining extent for the 4th and 5th assessment periods 270

Figure 198. Fifty-foot overburden contour intervals for the Harmony Mine 271

Figure 199. Harmony 5th assessment 200-ft buffer and structures.................................... 272

Figure 200. Figure B-Hy-5. Harmony 5th assessment water supplies and RPZ* 273

Figure 201. Properties associated with the 5th assessment period over the Harmony Mine 274

Figure 202. Heilwood total extent of mining 275

Figure 203. Heilwood mining extent for the 4th and 5th assessment periods....................... 276

Figure 204. Fifty-foot overburden contour intervals for the Heilwood Mine Brookville Coal Seam 277

Figure 205. Fifty-foot overburden contour intervals for the Heilwood Mine Lower Kittanning Coal Seam.. 278

Figure 206. Heilwood 5th assessment 200-ft buffer and structures 279

Figure 207. Heilwood 5th assessment water supplies and RPZ 280

Figure 208. Properties associated with the 5th assessment period over the Heilwood Mine 281

Figure 209. Horning Deep total extent of mining.. 282

Figure 210. Horning Deep mining extent for the 4th and 5th assessment periods................ 283

Figure 211. Fifty-foot overburden contour intervals for the Horning Deep Mine 284

Figure 212. Horning Deep 5th assessment 200-ft buffer and structures.............................. 285

Figure 213. Horning Deep 5th assessment water supplies and RPZ 286

Figure 214. Properties associated with the 5th assessment period over the Horning Deep Mine 287

Figure 215. Knob Creek total extent of mining.. 288

Figure 216. Knob Creek mining extent for the 4th and 5th assessment periods.................... 289

Figure 217. Fifty-foot overburden contour intervals for the Knob Creek Mine 290

Figure 218. Knob Creek 5th assessment 200-ft buffer and structures.................................. 291

Figure 219. Knob Creek 5th assessment water supplies and RPZ* 292

Figure 220. Properties associated with the 5th assessment period over the Knob Creek Mine 293

Figure 221. Kojancic total extent of mining 294

Figure 222. Kojancic mining extent for the 5th assessment period....................................... 295

Figure 223. Fifty-foot overburden contour intervals for the Kojancic Mine 296

Figure 224. Kojancic 5th assessment 200-ft buffer and structures 297

Figure 225. Kojancic 5th assessment water supplies and RPZ*.. 298

Figure 226. Properties associated with the 5th assessment period over the Kojancic Mine299

Figure 227. Logansport total extent of mining.. 300

Figure 228. Logansport mining extent for the 3rd, 4th, and 5th assessment periods 301

Figure 229. Fifty-foot overburden contour intervals for the Logansport Mine.................. 302

Figure 230. Logansport 5th assessment 200-ft buffer and structures* 303

Figure 231. Logansport 5th assessment water supplies and RPZ 304

Figure 232. Properties associated with the 5th assessment period over the Logansport Mine 305

Figure 233. Lowry total extent of mining ... 306

Figure 234. Lowry mining extent for the 4th and 5th assessment periods ... 307

Figure 235. Fifty-foot overburden contour intervals for the Lowry Mine ... 308

Figure 236. Lowry 5th assessment 200-ft buffer and structures* ... 309

Figure 237. Lowry 5th assessment water supplies and RPZ ... 310

Figure 238. Properties associated with the 5th assessment period over the Lowry Mine ... 311

Figure 239. Madison total extent of mining ... 312

Figure 240. Madison mining extent for the 3rd, 4th, and 5th assessment periods ... 313

Figure 241. Fifty-foot overburden contour intervals for the Madison Mine ... 314

Figure 242. Madison 5th assessment 200-ft buffer and structures ... 315

Figure 243. Madison 5th assessment water supplies and RPZ ... 316

Figure 244. Properties associated with the 5th assessment period over the Madison Mine 317

Figure 245. Maple Spring total extent of mining ... 318

Figure 246. Maple Spring mining extent the 5th assessment period ... 319

Figure 247. Fifty-foot overburden contour intervals for the Maple Spring Mine ... 320

Figure 248. Maple Spring 5th assessment 200-ft buffer and structures ... 321

Figure 249. Maple Spring 5th assessment water supplies and RPZ ... 322

Figure 250. Properties associated with the 5th assessment period over the Maple Spring Mine ... 323

Figure 251. Mine 78 total extent of mining ... 324

Figure 252. Mine 78 mining extent for the 3rd, 4th, and 5th assessment periods ... 325

Figure 253. Fifty-foot overburden contour intervals for the Mine 78 Mine ... 326

Figure 254. Mine 78 5th assessment 200-ft buffer and structures ... 327

Figure 255. Mine 78 5th assessment water supplies and RPZ* 328

Figure 256. Properties associated with the 5th assessment period over the Mine 78 Mine 329

Figure 257. North Fork total extent of mining 330

Figure 258. North Fork mining extent for the 5th assessment period 331

Figure 259. Fifty-foot overburden contour intervals for the North Fork Mine 332

Figure 260. North Fork 5th assessment 200-ft buffer and structures................................. 333

Figure 261. North Fork 5th assessment water supplies and RPZ 334

Figure 262. Properties associated with the 5th assessment period over the North Fork Mine 335

Figure 263. Ondo total extent of mining 336

Figure 264. Ondo mining extent for the 3rd, 4th, and 5th assessment periods...................... 337

Figure 265. Fifty-foot overburden contour intervals for the Ondo mine 338

Figure 266. Ondo 5th assessment 200-ft buffer and structures* 339

Figure 267. Ondo 5th assessment water supplies and RPZ.. 340

Figure 268. Properties associated with the 5th assessment period over the Ondo mine 341

Figure 269. Parkwood total extent of mining 342

Figure 270. Parkwood mining extent for the 4th and 5th assessment periods 343

Figure 271. Fifty-foot overburden contour intervals for the Parkwood Mine.................... 344

Figure 272. Parkwood 5th assessment 200-ft buffer and structures 345

Figure 273. Parkwood 5th assessment water supplies and RPZ... 346

Figure 274. Properties associated with the 5th assessment period over the Parkwood Mine 347

Figure 275. Penfield Mine total extent of mining.. 348

Figure 276. ***Penfield Mine mining extent for the 3rd, 4th, and 5th assessment periods*******.......... 349**

Figure 277. Fifty-foot overburden contour intervals for the Penfield Mine 350

Figure 278. Penfield Mine 5th assessment 200-ft buffer and structures............................... 351

Figure 279. Penfield Mine 5th assessment water supplies and RPZ* 352

Figure 280. Properties associated with the 5th assessment period over the Penfield Mine 353

Figure 281. Roytown total extent of mining 354

Figure 282. Roytown mining extent for the 3rd, 4th, and 5th assessment periods................ 355

Figure 283. Fifty-foot overburden contour intervals for the Roytown mine....................... 356

Figure 284. Roytown 5th assessment 200-ft buffer and structures 357

Figure 285. Roytown 5th assessment water supplies and RPZ*... 358

Figure 286. Properties associated with the 5th assessment period over the Roytown mine 359

Figure 287. Starford total extent of mining... 360

Figure 288. Starford mining extent for the 4th and 5th assessment periods 361

Figure 289. Fifty-foot overburden contour intervals for the Starford Mine....................... 362

Figure 290. Starford 5th assessment 200-ft buffer and structures* 363

Figure 291. Starford 5th assessment water supplies and RPZ 364

Figure 292. Properties associated with the 5th assessment period over the Starford Mine 365

Figure 293. TJs No. 6 total extent of mining... 366

Figure 294. TJs No. 6 mining extent for the 3rd, 4th, and 5th assessment periods................ 367

Figure 295. Fifty-foot overburden contour intervals for the TJs No. 6 Mine 368

Figure 296. TJs No. 6 5th assessment 200-ft buffer and structures...................................... 369

Figure 297. TJs No. 6 Mine 5th assessment water supplies and RPZ 370

Figure 298. Properties associated with the 5th assessment period over the TJs No. 6 Mine 371

Figure 299. Tom's Run total extent of mining 372

Figure 300. Tom's Run mining extent for the 3rd, 4th, and 5th assessment periods............ 373

Figure 301. Tom's Run mining extent for the 3rd, 4th, and 5th assessment periods* 374

Figure 302. Fifty-foot overburden contour intervals for the Tom's Run Mine 375

Figure 303. Tom's Run 5th assessment 200-ft buffer and structures* 376

Figure 304. Tom's Run's 5th assessment water supplies and RPZ* 377

Figure 305. Properties associated with the 5th assessment period over the Tom's Run mine 378

Figure 306. Tracy Lynne total extent of mining.. 379

Figure 307. Tracy Lynne mining extent for the 3rd, 4th, and 5th assessment periods.......... 380

Figure 308. Fifty-foot overburden contour intervals for the Tracy Lynne Mine 381

Figure 309. Tracy Lynne 5th assessment 200-ft buffer and structures*.............................. 382

Figure 310. Tracy Lynne Mine 5th assessment water supplies and RPZ 383

Figure 311. Properties associated with the 5th assessment period over the Tracy Lynne Mine 384

Figure 312. Kimberly Run total extent of mining... 385

Figure 313. Kimberly Run mining extent for the 4th and 5th assessment periods.............. 386

Figure 314. Kimberly mining extent for the 4th and 5th assessment periods* 387

Figure 315. Fifty-foot overburden contour intervals for the Kimberly Run mine 388

Figure 316. Kimberly Run 5th assessment 200-ft buffer and structures............................. 389

Figure 317. Kimberly Run 5th assessment water supplies and RPZ 390

Figure 318. Properties associated with the 5th assessment period over the Kimberly Run mine 391

Figure 319. Kingston West total extent of mining 392

Figure 320. Kingston West mining extent for the 3rd, 4th, and 5th assessment periods 393

Figure 321. Fifty-foot overburden contour intervals for the Kingston West Mine 394

Figure 322. Kingston West 5th assessment 200-ft buffer and structures 395

Figure 323. Kingston West 5th assessment water supplies and RPZ 396

Figure 324. Properties associated with the 5th assessment period over the Kingston West Mine 397

Figure 325. Twin Rocks total extent of mining 398

Figure 326. Twin Rocks mining extent for the 3rd, 4th, and 5th assessment periods 399

Figure 327. Twin Rocks mining extent for the 3rd, 4th, and 5th assessment periods* 400

Figure 328. Fifty-foot contour intervals for the Twin Rocks Min 401

Figure 329. Twin Rocks 5th assessment 200-ft buffer and structures* 402

Figure 330. Twin Rocks 5th assessment water supplies and RPZ* 403

Figure 331. Properties associated with the 5th assessment period over the Twin Rocks mine 404

Figure 332. 4 West total extent of mining 405

Figure 333. 4West mining extent for the 3rd, 4th, and 5th assessment periods 406

Figure 334. 4 West mining extent for the 3rd, 4th, and 5th assessment periods* 407

Figure 335. Fifty-foot overburden contour intervals for the 4 West mine 408

Figure 336. 4 West 5th assessment 200-ft buffer and structures 409

Figure 337. 4 West 5th assessment water supplies and RPZ 410

Figure 338. Properties associated with the 5th assessment period over the 4 West Mine... 411

Figure 339. Crawdad Portal B total extent of mining 412

Figure 340. Crawdad Portal B mining extent for the 3rd, 4th, and 5th assessment periods. 413

Figure 341. Fifty-foot overburden contour intervals for the Crawdad Portal B Mine 414

Figure 342. Crawdad Portal B 5th assessment 200-ft buffer and structures* 415

Figure 343. Crawdad Portal B 5th assessment water supplies and RPZ............................. 416

Figure 344. Properties associated with the 5th assessment period over the Crawdad Portal B Mine 417

Figure 345. Nolo total extent of mining.. 418

Figure 346. Nolo mining extent for the 3rd, 4th, and 5th assessment periods 419

Figure 347. Fifty-foot overburden contour intervals for the Nolo Mine 420

Figure 348. Nolo 5th assessment 200-ft buffer and structures.. 421

Figure 349. Nolo 5th assessment water supplies and RPZ* 422

Figure 350. Properties associated with the 5th assessment period over the Nolo Mine 423

Figure 351. Prime No. 1 total extent of mining 424

Figure 352. Prime No. 1 mining extent for the 3rd, 4th, and 5th assessment periods........... 425

Figure 353. Fifty-foot overburden contour intervals for the Prime No. 1 Mine 426

Figure 354. Prime No. 1 5th assessment 200-ft buffer and structures 427

Figure 355. Prime No. 1 5th assessment water supplies and RPZ.. 428

Figure 356. Properties associated with the 5th assessment period over the Prime No. 1 Mine 429

Figure 357. Quecreek No. 1 total extent of mining 430

Figure 358. Quecreek No. 1 mining extent for the 3rd, 4th, and 5th assessment periods...... 431

Figure 359. Fifty-foot overburden contour intervals for the Quecreek No. 1 Mine 432

Figure 360. Quecreek No. 1 Mine 5th assessment 200-ft buffer and structures................... 433

Figure 361. Quecreek No. 1 Mine 5th assessment water supplies and RPZ......................... 434

Figure 362. Properties associated with the 5th assessment period over the Quecreek No. 1 Mine.. 435

Acknowledgements

I would like to thank my advisor Dr. Anthony Iannacchione at the University of Pittsburgh. Dr. Iannacchione was always available to resolve any questions or concerns that I had during both my graduate and undergraduate studies. He shared his wealth of knowledge in engineering and mining related topics with me through class lectures, conversations, and stories of his work in the professional and academic settings. The mentoring that Dr. Iannacchione has given me has not only helped in the completion of my graduate degree but will continue to guide me in my future engineering career.

So many others deserve my deepest gratitude for contributing to my thesis and engineering studies through their support, guidance, and work collaborations including:

- Thesis Committee- Dr. Daniel Bain and Dr. Luis Vallejo
- Engineering Colleagues and Professors- Emily Adelsohn, Jie Yang, Mingzhou Li, Robert Winn, Benjamin Grunauer, Zachary Kaminski, and Dr. Jeen-Shang Lin
- Act 54 Team- Patrick Shirey, Stephen Tonsor, Andrea Kautz, Alan Deglmann, Marja Copeland, Memphis Hill, Sadie Trout, Rachel Dodson, Dolores Sullivan, James Whitacre, John Wenzel
- Family- Mike, Mary, Hayley, Nate and all others
- Friends- Casey, Nicole, Marissa, Bekah, Andrew, Trevor, Dean, James, Grant, Corinne, Tim, Nikki, Haley, Katie Chaz, and James
- The staff at the Pennsylvania Department of Environmental Protection and the California District Mining Office. My graduate studies were funded in part by a contract with the PA DEP.

1.0 Introduction

1.1 Underground Bituminous Coal Mining

Pennsylvania has a plethora of energy resources and is the second leading state in total energy production in the United States. In 2016 Pennsylvania's total fossil energy production was 7,888 trillion BTUs (British Thermal Units), coming from coal, crude oil, and natural gas (U.S. Energy Information Administration, 2019). Currently, Pennsylvania is ranked second in natural gas production, third in coal production, and seventeenth in crude oil (U.S. Energy Information Administration, 2019). Of all energy resources, coal extraction has been part of Pennsylvania's history the longest. Underground coal mining started in Western Pennsylvania in the late 1700's when the Pittsburgh settlement mined the outcrops of the Pittsburgh coalbed on the hillsides of Mount Washington. For over 200 years underground coal mining in Pennsylvania has continued to grow (Department of Environmental Protection, 2019).

There are two types of coal extracted in Pennsylvania. The Eastern part of the state has some of the last remaining anthracite coal mines in the country, many of which are surface mines. Anthracite is the highest rank of coal; it has a high percentage of fixed carbon and a low volatile mater. It burns as very high temperatures and is hard, brittle and appears lustrous (Schwienfurth et al., 2002). The Western part of the state is dominated by deep underground bituminous coal mines. (Department of Environmental Protection, 2019). Bituminous coal has a lower carbon content and is softer than anthracite, it is ideal for electricity and steel production, it is shiny and has a layered texture (Schwienfurth et al., 2002). In 2018 bituminous coal accounted for 96% of Pennsylvania's coal production (U.S. Energy Information Administration, 2019).

The most common underground extraction methods used for bituminous coal are the room-and-pillar and longwall mining methods. Room-and-pillar mining was the first mining method in Pennsylvania; it involves extracting a room of coal and then leaving a pillar of solid coal in place to support the ground. The goal of room-and-pillar mining is to leave the smallest pillars possible, while keeping the roof intact. The pillars usually follow a regular pattern and typically have square or rectangular cross sections. The underground bituminous room-and-pillar coal mines of Pennsylvania most often use the classic room-and-pillar method. An example of classic room-and-pillar mining is shown in Figure 1.

The classic room-and-pillar mining method is done in moderate to thick, and flat to moderately inclined coal beds. The coal is mined in horizontal strips starting at the top of the coal seam and benching down towards the mine floor (Hustrulid et al., 2001).

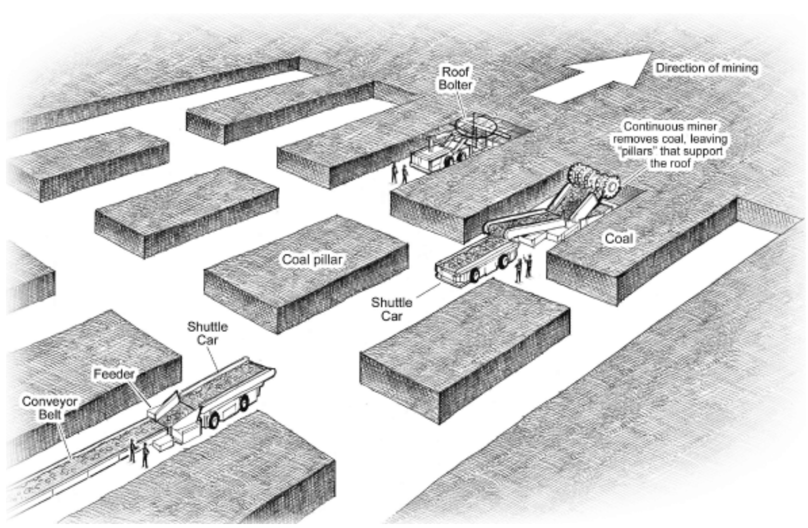

Figure 1. Classic room-and-pillar mining method (Lehmann et al., 2015)

The first Pennsylvania room-and-pillar mines had two main entries were established and wide rooms developed off the sides of the main entries. The rooms were large enough to fit the needed equipment. The coal was extracted from the wide rooms, but the pillars supporting the large wide rooms were often not property sized and could not fully support the roof. The inadequate support lead to roof failures and hazardous conditions for the miners.

Eventually, the place change continuous mining method became the dominate room-and-pillar mining technique. Continuous miners were electrically powered machines with a rotating steel drum containing teeth that could remove coal from the face at a faster rate than previous methods ("Continuous Miners,"). In the place change system, the continuous miner made a cut and was then moved to the other side of the entry while the roof bolter installed support in the recently mined area (Bayer et al., 2000). Roof bolting increased the stability of the rooms. The coal from the place change continuous mining was collected and transported via shuttle cars to a conveyor belt to be brought to the surface (Bayer et al., 2000).

In the most recent years, some Pennsylvania room-and-pillar operations have implemented continuous haulage room-and-pillar mining. The same method of place changing is used with the continuous miner and the roof bolter, but the coal from the continues miner is loaded directly onto a haulage system behind the continuous miner. The continuous haulage system transports the coal to the fixed conveyer belt (Sammarco,1996). The continuous haulage system eliminated the need for loading shuttle cars to transport the coal from the room-and-pillar face. From August 21, 2013 to August 20, 2018 at least 66% of Pennsylvania room-and-pillar mines used the continuous haulage method. Figure 2 shows an example of a continuous haulage in a room-and-pillar mine.

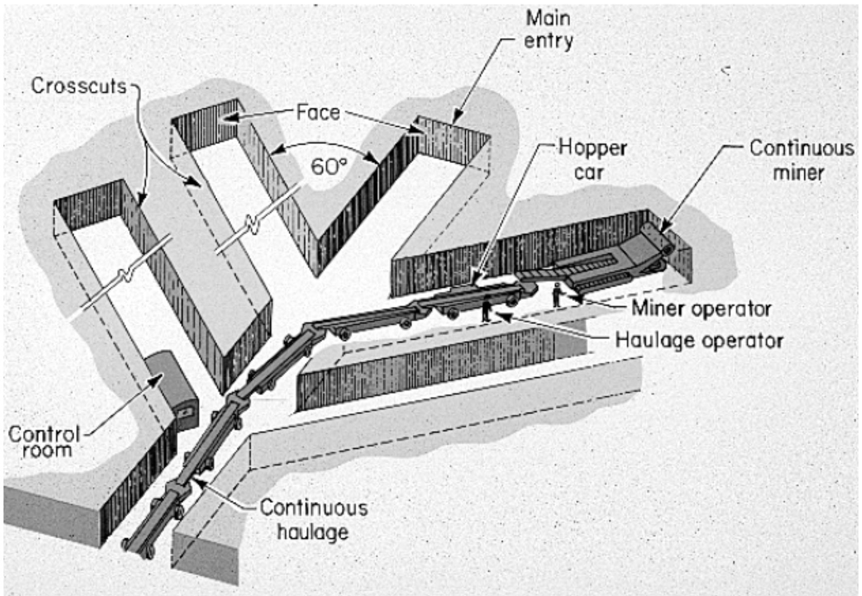

Figure 2. Place change room-and-pillar mining operation with a continuous haulage machine (Sammarco, 1996)

In a limited number of room-and-pillar mines, pillar recovery is implemented. Pillar recovery is the extraction of a coal pillar after the initial room-and-pillar mining has taken place. The extraction of the pillars retrieves additional coal; however, the removal of the pillars decreases the roof support and can cause subsidence to form at the surface (Mark et al., 2016). In Pennsylvania from August 21, 2013 to August 20, 2018 only 11% of room-and-pillar mines used pillar recovery. Figure 3 shows an example of the gob that is formed from the extraction of the supporting pillars.

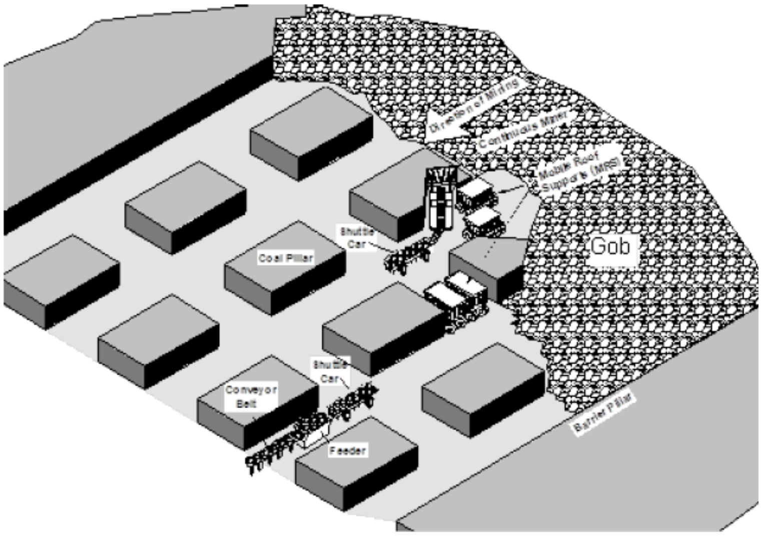

Figure 3. Pillar recovery of a room-and-pillar mine, the gob area represents the area where the pillars have already been extracted (Mark et al., 2016).

Longwall mining was introduced in the late 1960’s and is a form of full extraction mining in which all of the coal is extracted over a large area. From August 21,2013 to August 20, 2018 the longwall mining method Pennsylvania accounted for over 44% of acres mined in Pennsylvania.

Longwall mining is used in coalbeds that have a consistent mineable thickness and large horizontal extents. The coal is completely extracted in large rectangle areas with a machine taking longitudinal cuts across the face of the coal bed. The roof directly above and behind the face is temporally supported but is then allowed to subside once the face has passed. The development of longwall mines relies on head gate and tail gate room-and-pillar mining areas for ventilation and haulage of the mined coal (Hustrulid et al., 2001). Figure 4 shows an example of a longwall mining section.

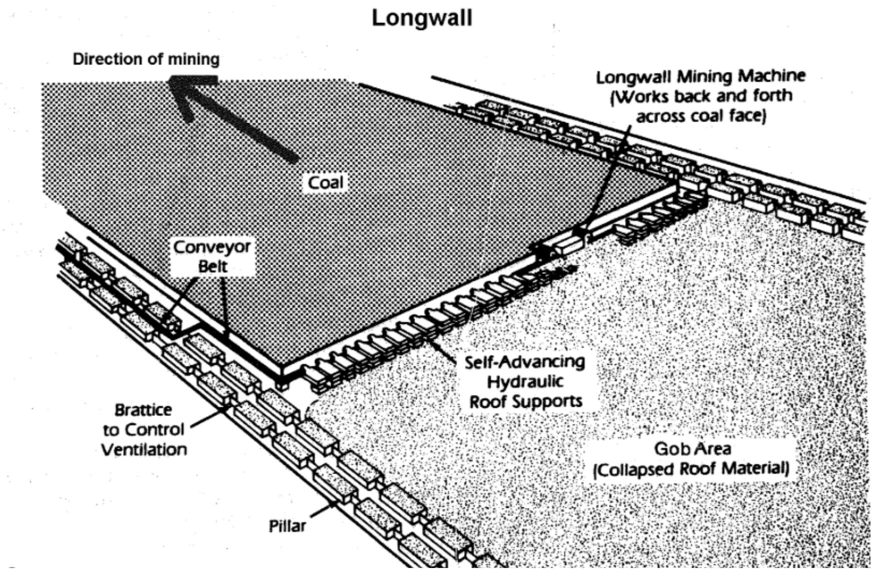

Figure 4. Longwall mining technique (figure sourced from U.S. Engergy Information Administration)

1.2 Origins of Subsidence Law and Regulations

At the beginning stages of coal production environmental stewardship was not heavily emphasized. However, towards the end of World War II in the mid 1940's, Pennsylvania officials realized the need to protect its land and water from the harmful side effects of coal mining. The introduction of full extraction mining, which induced vertical and horizontal movement, and varying levels of strain in the ground above an undermined area amplified the need for protection of surface features.

The first legislative change was implemented in 1945, an amendment to the 1937 Clean Stream Law to include acid mine drainage as a recognized pollution source. After that amendment, also in 1945, the Surface Mining Conservation and Reclamation Act was passed to prevent pollution from surface bituminous coal mining. A similar act for anthracite strip mining was passed in 1947. (Tonsor et al., 2013) Following these acts, new laws and acts focusing on the environmental impacts of deep bituminous coal mines were enacted.

The first state law to focus on subsidence was the 1966 Bituminous Mine Subsidence and Land Conservation Act (BMSLCA). This law was the first to focus on subsidence related damages to structures. It required that only structures built before 1966 be protected from damages caused by mine subsidence, regardless of who owned the coal rights located below the structure. It allowed the state to set guidelines on the extraction ratios that should be used to eliminate structure damages from subsidence, set guidelines for the mapping and permitting of the mines, and the repair of damages caused by subsidence. The repairs were required to be done by the company no more than 6 months after they occurred. Property owners were also permitted to purchase support to mitigate their undermined structures for additional protection from damages, and in some cases the rights to the coal below the structure. There were also structures that were identified that could not be damaged due to subsidence. Those included: certain homes, public buildings, noncommercial structures, and cemeteries.

In 1970, Gray and Meyer developed an angle of support that could be used as a guide to determine a stable area over a mine and reduce subsidence damage. The angle varied from 15 to 25 degrees from the vertical (Figure 5) and relied heavily on the geology of the area. The angle of support was an important contribution to subsidence protection because it showed that even if a structure is directly over solid coal there can still be subsidence effects (Keener, 2014).

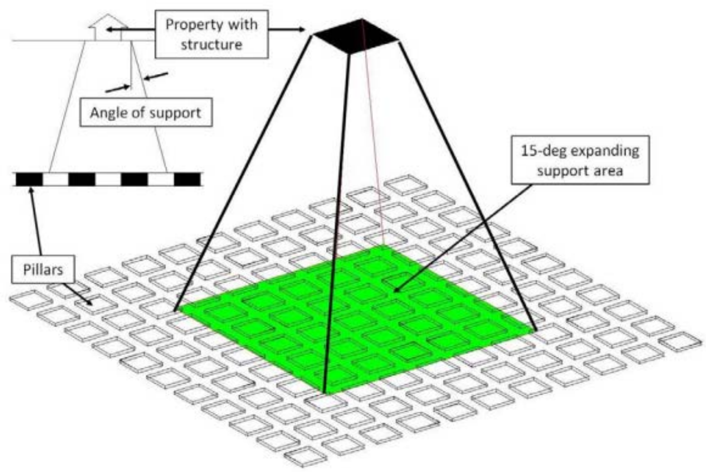

Figure 5. Example of the angle of support required by BMSLCA (1996) (Iannacchione et al., 2011)

After BMSLCA the federal government passed the Surface Mining Control and Reclamation Act of 1977 (SMCRA). SMCRA aided in the creation of the Office of Surface Mining within the Department of the Interior, which supported state regulatory programs. In 1980 Pennsylvania amended BMSLCA so that it met the minimal requirements set by SMCRA. The amendment required that during the permitting process the operator must present measures of how it would prevent subsidence causing material damage to the best practice available and maximize mine stability so that the land value would be preserved for the foreseeable future (Tonsor et al., 2013).

As of 1980, structures were still the only surface feature that were protected from subsidence damage, watersources were not considered in any of the laws. It was not until the mid-1980's through the Deep Mine Mediation Project (DMMP), which orchestrated a discussion among the underground bituminous coal industry, agricultural, and non-governmental organizations (NGOs), that watersources were considered. The outcome from this dialogue was the realizations of the need to replace damaged watersources.

Congruent to the discussion on damaged watersources by the DMMP, research on the potential impacts from mining to waterbodies and groundwater had already began. The effects of mining on large waterbodies on the surface was investigated by Babcock and Hooker (1977) through the U.S. Bureau of Mines. The guidelines that they created for mining near bodies of water included a 200-ft no mining zone in areas that had overburdens less than 350-ft, as well as a 25-degree subsidence protection angle like the angle of deformation discussed above.

Kendorksi played a pivotal role in the initial understands of groundwater movement above a mine. In 1979, he developed a subsidence model that depicted different zones above mined panel. The most important zone dealing with groundwater was the aquatic zone that was located below the zone of increased permeability at the surface. The aquatic zone is an area of low permeability that prevents or limits that shallow groundwater and surface water from entering the mine. In 1993, Kendorksi refined his 1979 model further to include the dilatated zone (Figure 6). The surface and ground waters that drain into this zone can be recovered as the subsidence progresses away from the area by the closing of dilations and or the filling of void space. The bending of the strata increases permeability and storability in the rocks of the dilated zone allowing the water to say in the dilated zone. The zone below it however is fractured and water in that zone will be able to drain to the mine. It was estimated that it could take up to two years for ground water condition to return to a pre-mining state. This zone was extremely important for wells located in it because there was potential for the wells that went dry during mining to recover after mining.

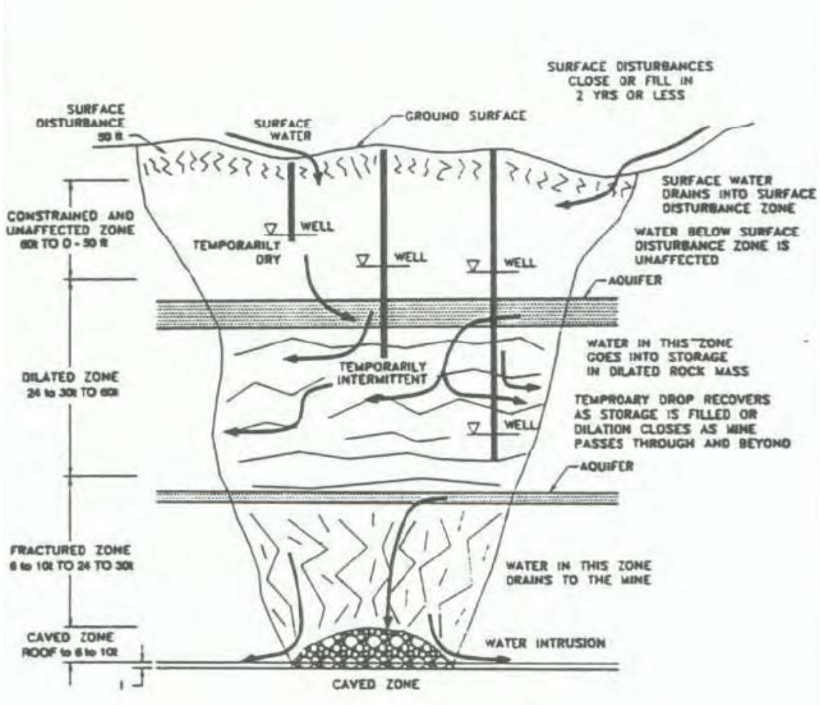

Figure 6. Kendorski's diagram of the zones above a subsided mine (Kendorski, 1993)

In 1994 the state amended BMSLCA again under Act 54 to add protection to structures and watersources affected by underground mining. It held mine operators responsible for damages caused by mine subsidence and required the Pennsylvania Department of Environmental Protection (PA DEP) to track the impacts. The PA DEP determined if an impact was "company liable" the mine operators were required to repair or fairly compensate the damages or "company not liable" where the damages were determined to be not due to mining. The PA DEP was also responsible for mine permitting, enforcing subsidence laws and regulations, and ensuring that pre-mining surveys of areas to be undermined be conducted so that the post-mining changes could be identified.

At the same time in 1994, Carver and Rauch did a case study of mines in West Virginia and discovered that most of the damages to watersources occurred within a 27 to 38-degree angle from the edge of active mining to the ground surface. This angle can be influenced by the topography of the region as well the fractures caused by subsidence. This study, among others, influenced the technical guidance document prepared by the PA DEP that defined a 35-degree angle to determine what is known as the reputable presumption zone (RPZ). Due to this document, Act 54 states that any damaged watersource that falls with the RPZ are the responsibility of the mining company to restore, unless they can demonstrate the impact occurred prior to mining the recorded pre-mining data. The structures and land damages within a 200-ft buffer from the edge of mining were also the responsibility of the mining company, unless they can be demonstrated to exist prior to mining

Act 54 was the first legislation to require the reporting of the surface impacts and extent of underground bituminous coal mining in Pennsylvania. This reporting occurs in five-year intervals. Since 1994, there have been five Act 54 assessments (Table 1). The analysis of the 1st Act 54 assessment period from August 21, 1993 to August 20, 1998 was performed by the PA DEP. The 2nd assessment from August 21, 1998 to August 20, 2003 was done by California State University of Pennsylvania. The 3rd assessment ranging from August 21, 2003 to August 20, 2008, the 4th from August 21, 2008 to August 20, 2013, and most recently the 5th from August 20, 2013 to August 21, 2018 were all completed by University of Pittsburgh.

Table 1. Act 54 assessment period and assessment team

Act 54 Assessment	Assessment Period	Assessment Team
1st	August 21, 1993- August 20, 1998	PA DEP
2nd	August 21, 1998- August 20, 2003	California University of Pennsylvania
3rd	August 21, 2003- August 20, 2008	University of Pittsburgh
4th	August 21, 2008- August 20, 2013	University of Pittsburgh
5th	August 21, 2013- August 20, 2018	University of Pittsburgh

The outline for the Act 54 report continues to evolve. The first and second assessments focused primarily on the structure and watersource impacts. In the third, assessment the impacts to land and streams were add to the discussion and analysis. The 4th assessment focused further on the impacts to streams while looking closely at the biology of the impacted streams. The most recent 5th assessment added more in-depth tracking of wetlands and groundwater aquifers.

1.3 Research Aim

Act 54 is continuing to evolve, to protect more features impacted by underground bituminous coal mining. In doing so, there is evidence that suggests these additional protections impact positively the protection of the communities and environments of the Commonwealth. This investigation examines how the laws have positively impacted undermined communities, the environment, and the local coal mining industry. The data collected by the five Act 54 assessment reports over the last 25 years is used to determine the its effectiveness and to examine several unintended consequences and unseen technical challenges.

Current subsidence prediction models are used to examine expected subsidence associated with longwall mining. The models enable the regulators and operators to have a better understanding of the areas with the most potential impacts, however these predictions must be checked with recorded field data. Tallies of the total acres mined, and the number of impacts reported are compared over the last 25 years. Detailed examples of structure, watersource, and land impacts are used to examine the severity of impacts and how the industry has adapted in repairing and compensating mining induced damages. Lastly, the case studies of reported impacts occurring beyond the scope of current prediction methods, known as “far field effects”, are explored. Forming an understanding of far field effects is important for the protection of the future study of undermined surface features so that the trends discovered amount the impacts can be used to better predict were far field effects will occur and how to mitigate these areas. The outcome of this analysis will provide an assessment of the strengths and weaknesses of Pennsylvania’s strict subsidence laws and examine topics for future research.

2.0 Literature Review

2.1 Final Subsidence Basin Characteristics

Subsidence is the vertical movement of the surface from the formation of the void due to coal extraction. Subsidence can occur in any type of full extraction mining. In Pennsylvania it is most common over longwall mining, but in some cases can occur over pillar recovery and room-and-pillar mining as well. The full extraction leaves a large void in the ground allowing the above strata to move and deform to fill that void. Factors that affect subsidence include, overburden depth, geology, rock characteristics, and orientation of the mine (PA DEP, 1999). Historically the knowledge of the overburden movement has been derived from observation of the surface as well as subterranean investigation of subsidence basins through boreholes and inclinometers (Peng, 1992). Current practice uses the previously mentioned methods, along with GSP and satellite data to monitor subsidence (Iannacchione and Evanek, 2018).

Since the above factors influencing subsidence are specific to the region that the mine is in, the subsidence theory reviewed here focuses on the Northern Appalachian region. The damaged overburden in this region can be divided into four zones: caved zone, fractured zone, continuous bedding (deformation) zone, and soil zone (Figure 7, reproduced from Peng, 1992).

<u>Caved Zone</u>- The caved zone is located directly above the extracted longwall panel. It is characterized by immediate roof completely falling into the open void. This zone can range for two to eight times the mining height (Peng, 1992).

<u>Fractured Zone</u>- The fractured zone is located above the caved zone. In this zone the strata maintains its bedding, but large fractures occur in the rock. The fractures are more prominent

closer to the caved zone and become smaller closer to the surface. The size of this zone is dependent on the rock type. In soft and weak rocks it will be smaller than that in hard and strong rocks. It is generally between 20 and 30 time the mining height (Peng, 1992).

Continuous Bedding (Deformation Zone)- The continuous bedding zone is defined by bending of the strata without breaking. The permeability in this area can increase and can sometimes be recovered after the subsidence has finalized. Some fissures may occur, impacting ground and surface waterflow (Peng, 1992).

Soil Zone- This is the top surface layer consisting of soil and weathered rocks. Surface crack can open and close in this zone dependent of the location of the face of the longwall face is. The cracks will typically open when the face is near and close after the face has passed. Some of the crack may remain open but they are not deep and can be filled in with soil. The size of this zone depends on the location of the mine (Peng, 1992).

Dependent on overburden thickness surface structures, ponds, and some wells are in the soil zone, while deep wells and aquifers can extend to the continuous deformation zone. The soil zone has the least dramatic movement of all the zones but structures and wells in this zone can still be affected by subsidence. The deep wells and aquifer located below the soil zone in the continuous deformation zone are even more likely to be damaged (Keener, 2014).

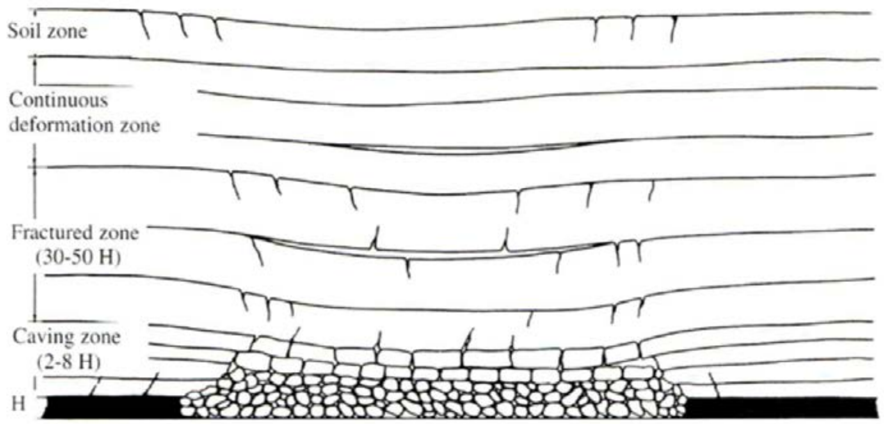

Figure 7. Four zones of strata movement above a longwall panel (Peng, 1992)

When predicting subsidence, Peng defines seven components of surface movement: subsidence, displacement, slope, curvature, horizontal strain, twisting, and shear strain. The first five are the most well defined, and subsidence and horizontal strain are two of the most important factors in subsidence prediction. Subsidence prediction is important when determining the area that are most likely to be impacted by undermining.

The following equation defines subsidence as a function of the mining thickness and subsidence factor which is determined through observed subsidence basins of Appalachian Pittsburgh coalbed (Peng, 1992):

$$S_{max} = a * m$$ **Equation 1**

where:

S_{max}= maximum possible subsidence-ft

a= subsidence factor

m= mining thickness-ft

The subsidence factor of the Pittsburgh coalbed in the Northern Appalachian region be calculated from the equation bellow (Peng,1995):

$$a = 0.6815519 * 0.9997398^{h} \qquad \textbf{Equation 1}$$

where:

a= subsidence factor

h= overburden thickness-ft

Each longwall panel falls in one of three subsidence categories, subcritical, supercritical, or subcritical. These categories are determined by finding the critical width (Wc) (Table 2) of the panels, which is the width of the panel divided by the average overburden of the panel:

Table 2. Subsidence Categories

Panel Category	**Critical Width (width/overburden)**
Subcritical	<1.2
Critical	=1.2
Supercritical	>1.2

A panel that is supercritical has a subsidence basin that has reached its maximum subsidence depth and has a relatively flat bottom, so Equations 1 and 2 above apply. Critical and subcritical panel have not yet reached a final subsidence profile, so the maximum predicted subsidence cannot be predicted with equations 1 and 2 (Peng, 1992). Knowing if a panel has reached maximum subsidence allow operators and property owners to understand the shape of the final subsidence basin. The shape of the basin with respect to the where structures, watersources, and ponds are located can determine the potential for impacts.

The horizontal strain (ε) along the subsidence basin is defined as the difference in horizontal displacement between two points divided between the distance between the two points. The strain can be in tension (positive) or compression (negative) (Peng, 1992). Cracks are attributed to tensile stain, while bumps and heaves are related to compression forces. Some areas of the subsidence basin will undergo tensile forces first causing a crack to form followed by compression forces causing the crack to close and heave. Substantial horizontal strain can even cause vertical fractures (Luo and Peng, 2000).

Figure 8 shows horizontal strain occurring over a supercritical subsidence basin. The highest tensile strain occurs over the gate roads of the panels and the compressional strain occurs a quarter of the length into the panel. The point of zero strain occurs at the inflection point, this is the point in which the curve changes from concave up to concave down, of the subsidence basin.

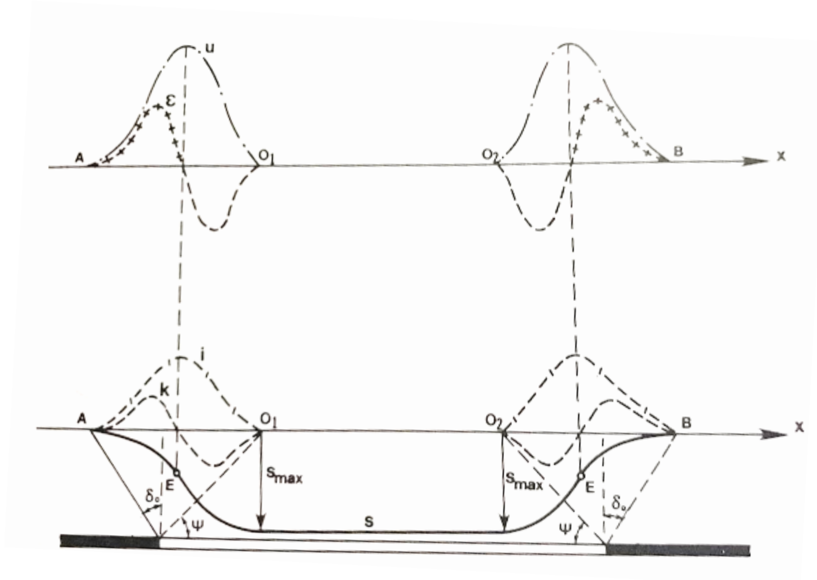

Figure 8. Surface deformation distribution on a major cross section (Peng and Chiang, 1984)

2.2 Dynamic Subsidence Basin Characteristics

Dynamic subsidence occurs while the longwall face is still active, and subjects surface features to changing forces as the face advances (Peng, 1992). The forces alternate between compression and tension. Figure 9 shows that features in front of the longwall face are subject to tension as the ground starts to move into the gob, but once the face has passed the area enters compression (Peng, 1992).

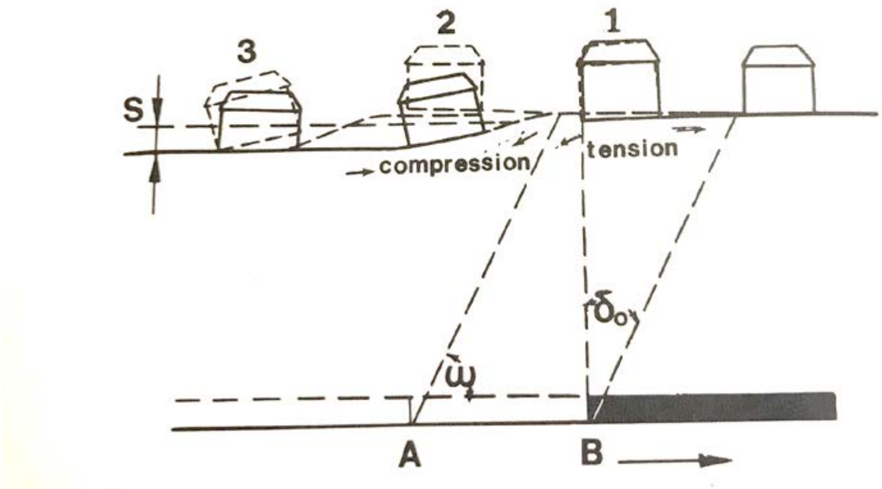

Figure 9. Zones of compresion and tension during dynamic subsidence (Peng, 1992)

A subtle dynamic subsidence basin starts to form when the longwall face moved one sixth to one third the overburden value from the setup of the longwall face (Peng, 1992). As the face continues to advance the depth and length of the subsidence basin expands. Once the face is inactive the subsidence on the face side continues until it becomes stable and final subsidence basin is formed (Peng, 1992). Figure 10 shows the progression of the dynamic subsidence basin to the final one. The final subsidence basin is indicated by S'_7 shown on Figure 10.

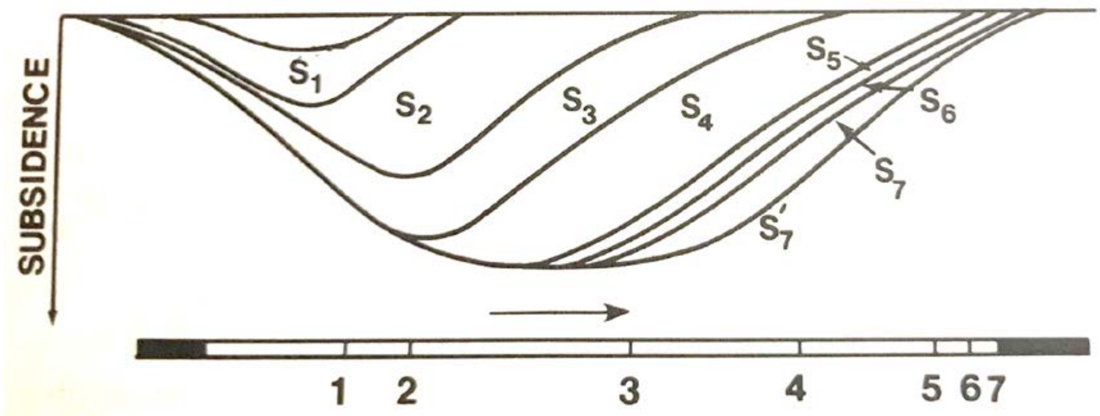

Figure 10. Advancing of the final subsidnce basin to the finals subsience basin (Peng, 1992)

The displacement associated with the dynamic movement has a positive and a negative maximum value. The positive value is on the setup of the face side and moves towards the face as it advances, while the negative is in front of the face but also advances forward with face movement (Peng, 1992). Both the positive and negative displacement values reach a maximum after mining has ceased and remain constant. The dynamic displacement ranges from 60% to 75% of the final displacement (Peng, 1992). The slope of the dynamic subsidence ranges from 50% to 80% of the final slope (Peng, 1992). The curvature of the dynamic subsidence basin continues to increase as the longwall face advances. The curvature generally reaches a maximum at 0.7 to 0.9 the overburden, which is twice the magnitude of the final curvature (Peng, 1992).

The rate of face advance plays a large role in the impact of dynamic subsidence. A study done in West Virginia by Peng shows that the subsidence velocity with increases in the face rate and/or increases in the gob size (Peng, 1992). The maximum subsidence velocity is behind the face of the longwall by a fixed amount (Peng, 1992). In the Appalachian coal field, the subsidence velocity observed by Peng and Geng in 1984 was from 0.2 ft/day to 1-ft/day. The dynamic movement reaches a final subsidence basin when the accumulated subsidence does not exceed 1.2-inches in six months (Peng, 1992).

3.0 Method of Study

Data was collected from multiple sources including the PA DEP, mining companies, and previous Act 54 Reports. The period of study included the analysis of new mining that occurred in the 5th assessment period and the addition of the data previously analyzed in the past four Act 54 assessments. The analysis included site visits with the DEP and mining companies, the mapping of all mining extents, and evaluation of the resolution of impacts to structures, watersources, and land and their locations.

3.1 Data Sources

The data for this study was collected primarily from the PA DEP California District Mining Office and through the mining companies. The PA DEP provided the mining extents for all active mining during the 5th assessment period through the 6-month mine maps submitted by the mining companies. The 6-month mine maps are submitted to the PA DEP from the mine operators every six months as way to show previous mining, monitor current mining, and display projected mining. The 6-month mine maps also include surface features such as structures, wells, springs, ponds, land parcels, and utilities. In some cases, the AutoCAD files of the mining extents and surface features were provided by the mining companies. Mine maps from previous assessments where obtained from files of the University of Pittsburgh.

All structures, watersources, and land impacted by mining were recorded in the PA DEP Bituminous Underground Mines Information System (BUMIS) data base. Field agents, who worked for the PA DEP, were the liaisons between the property owners, the state, and the mining companies.

Additionally, mine permit files stored at the PA DEP CDMO were used for further investigation into specific mining conditions such as the hydrology or geology of a mine. Structural Analysis reports (SA) generated by engineers at PA DEP were used for detailed descriptions of structural impacts that were determined to be company liable.

Data sources outside of those provided by the PA DEP and mining companies included the digitized mining extents of historical mining in Pennsylvania obtained from Pennsylvania Spatial Data Access. Subsidence modeling data was run using Subsidence Deformation Prediction Software (SDPS).

3.1.1 Site Visits

Over the course of this analysis multiple office site and field visits were made to collect new data for the thesis to clarify the 5th Act 54 assessment period. Visits to the mining companies, were done in early stages of the project. Development of good relations with the mining companies allowed for additional information to be collected about the mines to complement data provided by the PA DEP. AutoCAD and ArcGIS maps were obtained for some mines, which made the mapping process more accurate. Discussions with the companies also allowed for the impact data provided by the PA DEP in BUMIS to be checked with company records, and any discrepancies were addressed with both PA DEP and mining companies. Table 3 shows the mining companies that were visited.

Table 3. Lists of office visits to mining companies active during the 5th assessment

Company Name	Date of Site Visit
Rosebud Mining Company Inc.	January 26, 2018 & August 22, 2018
Contura LLC	February 15, 2018
CONSOL Energy	March 5, 2018 (conference call)
Rox Coal Co.	March 13, 2018
Wilson Creek Co.	March 13, 2018
LTC Energy	May 15, 2018
Tunnel Ridge	May 17, 2018
AK Coal Resources	June 6, 2019

Mine permit files and structural analysis reports (SA), performed by the PA DEP, were reviewed during visits to the California District Mining Office (CDMO). The CDMO staff provided information about impacts with detailed investigations and noted impacts that they were looking into with more detail, such as those that occurred outside of the predicted impact area. The PA DEP CDMO staff also made site visits to the University. The visits with the PA DEP CDMO occurred throughout the life of the project.

Field visits were important to see examples of impacts recorded in BUMIS, mitigation techniques, and remediated impacts. Both the PA DEP staff, and mining company staff assisted during field visits. The visits showed the impacts to surface features, but even more importantly prevention and correction techniques. The visits to areas with far field effects allowed collection of data to clarify far field effects. Real time data and photographs were taken during site visits. Table 4 shows the areas that were visited and who accompanied the Act 54 assessment team.

Table 4. List of impact site visits during the 5th assessment period

Field Site	Date	Leader of the Field Visit
Emerald Gate Cut	February 15, 2018	Contura LLC
Enlow Fork	April 19, 2018	Jay Winters
Emerald & Cumberland	July 9, 2018	Rich Kormanik, Valerie Dillie
Bailey & Harvey mines	July 10, 2018	Joseph Laslo
Enlow Fork Gate Cut	July 11, 2018	Josh Silvis
Emerald and Cumberland	August 13, 2018	Contura LLC
Monongalia County	August 14, 2018	Zach Bell
Enlow Fork	August 15, 2018	Anne Hong

Along with field visits the University of Pittsburgh visited active room-and-pillar and longwall face developments (Table 5). Rosebud Mining Company took the team underground at their Brush Valley room-and-pillar mining operation. Tunnel Ridge LLC allowed the team to visit the active longwall face of the Tunnel Ridge mine. The visits to the active mining allowed for a better understanding of how the coal was extracted from the ground, and how the mechanism of coal removal at the face relate to the impacts occurring at the surface.

Table 5. Visits to active mine workings during the 5th assessment period

Active Mine	Date of Active Mine Visit
Brush Valley (room-and-pillar mine)	March 15, 2018
Tunnel Ridge (longwall mine)	May 17, 2018

3.1.2 Mapping

All mines in this study were mapped using a geographic information system (GIS). GIS allowed for the mining extent and surface features associated with the mines to be spatially referenced. The mining extents and surface features for the 5^{th} assessment were converted to GIS from the 6-month mine maps provided by the PA DEP or the AutoCAD from the mining companies. The previous assessments mining extents and surface features, with exception of the 1^{st} assessment, were digitized during the respective assessment period and used here.

Digitized surface features included structures, watersources, land parcels, ponds, and streams. Surface features that had an entry in BUMIS were noted on the maps. The overburden was also mapped using GIS. To determine the overburden the coal contours had to be subtracted from the digital elevation model (DEM) of the area. The coal contours were obtained through the 6-month mine maps, AutoCAD files, or collected from previous assessment periods. The standards and guidelines of Act 54 such as buffers and the RPZ were calculated using ArcGIS. The 200-ft buffer was used to identify structures and land parcels vulnerable to subsidence impacts and the RPZ to identify the watersources vulnerable to subsidence impacts.

3.2 Data Analysis

To complete a full analysis of the underground bituminous coal mining and its impacts on Pennsylvania in the last 25 years, the data collected and mapped during the 5th assessment period was added to that previously reported in the 1st through 4th assessments. First, a thorough examination of the mining and BUMIS database was conducted for the 5th assessment period. The 5th assessment analysis was modeled after the previous assessments so that that they could be easily compiled and compared. The BUMIS database of the 5th assessment included the type of impact that occurred, the property it occurred on, the date it happened on, the date that a final resolution was made, and the type of final resolution and in some cases additional comments about the impacts. It is important to note that BUMIS had not been updated from the last assessment so all data for the 1st through 4th assessment had to be collected from the Act 54 assessments and not BUMIS. Combining the BUMIS database with the mapped surface features in GIS spatial information about the impacts were recorded for each impact.

By combining the data from all five assessment periods, the mining in Pennsylvania was summarized with respect to: the number of mines, total acres mined per mining type, overburden characteristics, mine size, and mine location. The total number of structures, watersources, and land impacts was also compared. Additionally the total impacts the number of company liable and company not liable impacts were tallied. Comparing the summary of mining with the total impacts permitted for a full analysis of how Act 54 has affected the mining of Pennsylvania.

Further case studies in this analysis show examples of when Act 54 worked to protect surface features, and areas that it should be improved. Examples of the property owners being fairly compensated in a timely manner show Act 54 protecting the community and environment;

however, case studies of far field effects demonstrate how the Act must evolve to continue protection.

3.3 Limitations

One of the major limitations of this study is how the data was collected and presented throughout the 25-year study period. While the data from the 5th assessment could be analyzed to answer specific questions, data from previous assessments could not be easily recollected and reanalyzed. Act 54 has evolved over the five assessment periods, so aspects that are important in current assessments were not always tracked in detail in earlier assessments. For example, the first assessment did not have the impacts broken down into the categories of structures, watersources, and land (Pennsylvania Department of Environmental Protection, Bureau of Mining and Reclamation, 1999).

Along with the changes focus of the assessments over the 25-year period, different people have worked on the assessments. Each group had their own specialties and focused on different topics. Therefore, the data collected for the assessment was collected to answer distinct questions. Further, as the BUMIS database did not necessarily have a standard entry, some impacts had more detail than others.

Pre-mining data was important to collect to see how the damages impacted the community and environment. In some cases, the pre-mining data was not available. Therefore, only a certain number of impact case studies could be used as examples of how Act 54 has changed the undermined communities and environment.

4.0 25-Year Review of Pennsylvanian Underground Bituminous Coal Mining

The Act 54 assessment has allowed for a review of more than the impacts to surface features, it enables a review of mining characteristics as well. Including the types of mining operations, number of acres mined, mine size, location of mines, and the mining conditions. The tracking of these features allows for the future mining trends in Pennsylvania to be predicted. The tallies of all impacts from the 5th assessment is shown in Appendix A. The mine maps developed for all active mines during the 5th assessment can be found in Appendix B. The maps contained in Appendix B are a product of the 5th assessment Act 54 team. The review of past mining and the prediction future mining permits for a comprehensive of the fluctuating Pennsylvania underground bituminous coal mining industry.

4.1 Types of Mining Operations

Over the last 25 years of Act 54 assessment periods, the mines have been categorized as: a longwall mine, room-and-pillar mine, or a pillar recovery mine. The mine types can be broken down further to the mining methods used in each type. There are three mining methods, longwall mining, room-and-pillar mining, and pillar retreat mining. The longwall mine type consists of room-and-pillar mining used to for the development of main, gate roads, and bleeder entries and longwall mining used in the panel for full coal extraction. Room-and-pillar mines employs only the room-and-pillar mining method. Pillar recovery mines uses room-and-pillar mining methods to drive the main entries and pillar recovery mining for the extraction of specific coal pillars in production panels. The different mining methods have varying extraction ratios. Longwall mining method has the largest extraction ratio and room-and-pillar has the smallest. The extraction ratios in Table 6 were developed by the University of Pittsburgh during the 4th assessment period through review of the mines during this assessment period (Tonser et al, 2013) Subsidence is most likely to occur with extraction ratios between 0.7 and 1 (Tonser et al., 2013).

Table 6. Extraction ratio by mining method

Mining Method	Extraction Ratio (Re)
Room-and-Pillar Developments	0.4 to 0.7
Pillar Recovery	0.7 to 1.0
Longwall	1.0

Table 7 shows the number of active mines in each mine type over the last five assessment periods. The total number of active mines peaked during the 1st assessment period and reached a low in the 4th, decreasing by 45% from the 1st assessment. The total number of mines increased by 6% from the 4th assessment to the 5th assessment. The mining type that has seen the largest drop in the last 25 years are the pillar recovery mines. From the 1st assessment period to the 5th there has been an 82% decrease in pillar recovery mines. While pillar recovery allows operators added coal production. the pillar recovery process can be time consuming and dangerous. Pillar recovery can also cause localized subsidence in areas that the pillars are extracted, as seen with its elevated extraction ratio. The dramatic decrease in pillar recovery mines shows that the potential consequences of pillar recovery outweighs the added coal production.

Table 7. Number of mines per mining type over the last five Act 54 assessment periods

Mine Type	Act 54 Assessment Period				
	1st	2nd	3rd	4th	5th
Longwall	10	9	8	7	7
Room-and-Pillar	45	58	36	34	37
Pillar Recovery	29	14	6	5	5
Total	84	81	50	46	49

4.2 Acres Mined

While the total number of active mines has decreased over the 25-year period, the acreage mined gives a more detailed description of how the mining industry has changed during this time. Table 8 shows the number of acres mined per mining type and the percent of the total acres mined for that assessment period. In all the assessment periods the longwall mines have accounted for more than 50% of acres mined, while the pillar recovery mines have had the lowest percentage. This shows that the longwall mine production is very important in the total amount of coal mined each year. As a result, while the number of pillar-recovery mines have decreased the most, the total amount of acreages mined is influenced most by the decrease in the number of longwall mines.

Table 8. Acres mined per mine type over the five Act 54 assessment periods

<table>
<tr><th rowspan="2">Mine Type</th><th colspan="5">Act 54 Assessment Period</th></tr>
<tr><th>1st</th><th>2nd</th><th>3rd</th><th>4th</th><th>5th</th></tr>
<tr><td>Longwall</td><td>24,600
(63%)</td><td>27,508
(71%)</td><td>24,607
(64%)</td><td>17,005
(54%)</td><td>17,873
(62%)</td></tr>
<tr><td>Room-and-Pillar</td><td rowspan="2">14,250
(37%) *</td><td>6,975
(18%)</td><td>11,552
(30%)</td><td>12,353
(40%)</td><td>8,842
(31%)</td></tr>
<tr><td>Pillar Recovery</td><td>4,028
(11%)</td><td>2,097
(6%)</td><td>1,984
(4%)</td><td>2,139
(7%)</td></tr>
<tr><td>Total</td><td>38,850</td><td>38,511</td><td>38,256</td><td>31,343</td><td>28,854</td></tr>
</table>

**It is important to note that in the 1^{st} assessment period the acres mined in room-and-pillar mines versus pillar-recovery mines were not differentiated so total acreage for the two mining types are listed under the room-and-pillar mine type.*

The total number of acres mined decreased from the 1^{st} assessment to the 5^{th} assessment by only 25%, while the total number of active mines decreased by 65% from the 1^{st} to the 5^{th} assessment period (Figure 11). Advanced mining technology has allowed for more coal to be produced per mine, especially in the longwall mines.

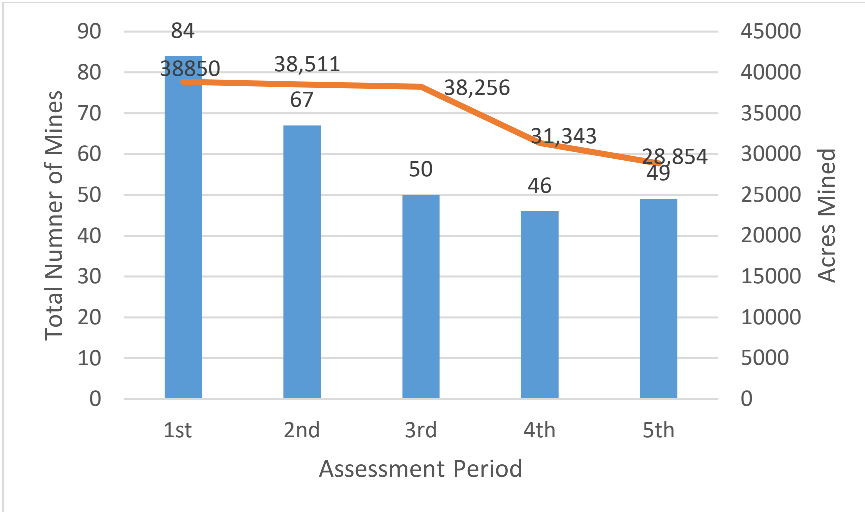

Figure 11. Acres mined vs the total number of mines per Act 54 assessment period

The largest decrease in acres occurred between the 3rd and 4th assessment period, an 18% decrease. Then a 7% decrease occurred from the 4th to the 5th assessment period. The decrease in acres mined in Pennsylvania aligns with the decline in overall coal production in the United States during this period. Figure 12 shows the decline of tons of coal produced by the United States starting in 2008. The decrease can be attributed to the retiring of coal-fired power generation facilities as well as the lower cost of natural gas (Woodward et al., 2019)

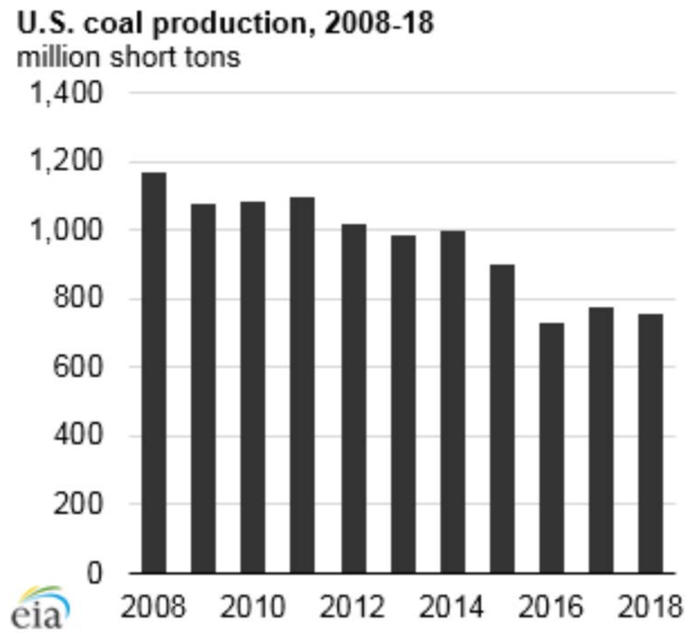

Figure 12. U.S. coal production from 2008-2018 from the U.S. Energy Information Administrarion (Woodward et al., 2019)

Over the last five assessment periods mines have ceased operations and new mines have begun mining.. Figure 13 shows how many mines ceased mining during each assessment period, meaning they were not active in the next assessment period. During the early assessment periods there was a faster turnover with mines; in both the 1st and 2nd assessment period 33 mines were closed. However, even with the large closures rates there were enough new mines opening that the total number of mines each assessment period was still high. The 4th assessment period had the least amount of mine closures of all the assessments. There are also some mines that have idled during one assessment and become active in another.

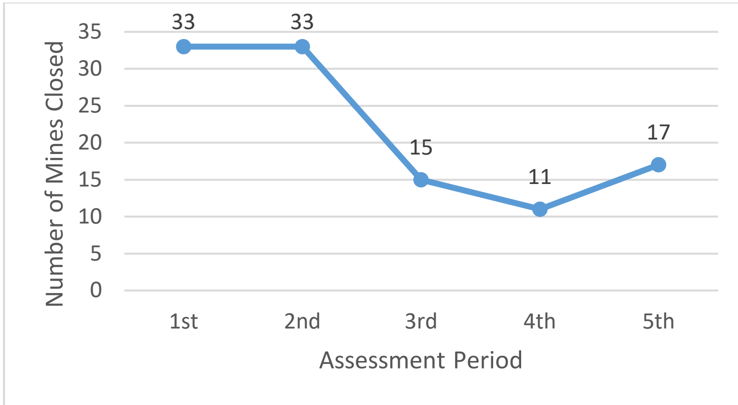

Figure 13. Number of mines closed per assessment period

There were seven mines that have been active for all 25 years of Act 54 reporting. Of these seven mines, five were longwall mines including Baily, Cumberland, Emerald, Enlow Fork, and Monogalia County (previously Blacksville 2). The other two mines that remained open were the room-and-pillar mines Ondo and Tracy Lynne

4.3 Mining Characteristic

Five longwall mines have been active during all five of the Act 54 assessment periods. The Cumberland, Emerald, and Monongalia County mines all opened in 1983, the Bailey mine opened in 1984, and the Enlow Fork mine started production in 1991. Because these mines have been active for the entirety of Act 54, they provide examples of how longwall mining has changed over the lifetime of the Act. Figure 14 below shows the total mining extent of the Emerald Mine from its opening in 1983, until August 2018. The more recent mining can be identified by the larger and more uniform longwall panel size, while the older mining is characterized by smaller panels with erratic size and orientation. The area circled in red indicates area mined prior to the 1994 Act 54.

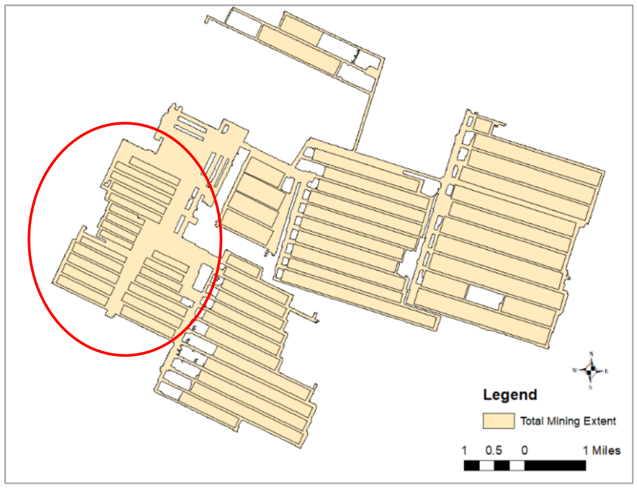

Figure 14. Total Extent of Emerald mine, the area circled in red shows examples of older mining

Since 1994 there have been over 300 longwall panels mined under the regulations of the PA DEP. The panel characteristics did not stop evolving after Act 54 was passed, the longwall panel features continued to change. One of the most notable changes over the Act 54 period is the panel widths. Figure 15 shows the panel width increasing from the 1st assessment to the 5th assessment. The increased widths and lengths of the panels have caused the total acres mined per panel to increase. From the 1990s to the 2000s there was a 22% decrease in number of panels mined but a 26% increase in acreage mined. In the last assessment periods the average ratios of acres mined per panel was 295 acres/panel, while in the 1990s when the largest acreage of coal was mined it was 209 acres/panel. These trends indicate that the advances in mining technologies and changes in the panels has allowed mining companies to extract maximum amounts of coal with minimal development. Changes in room-and-pillar mining characteristics are harder to track because each mine operator has specific layouts and methods that they use, and the design is not as standardized as longwall mines. Although as mentioned in Section 1 the size of the pillars has changed to properly support the roof.

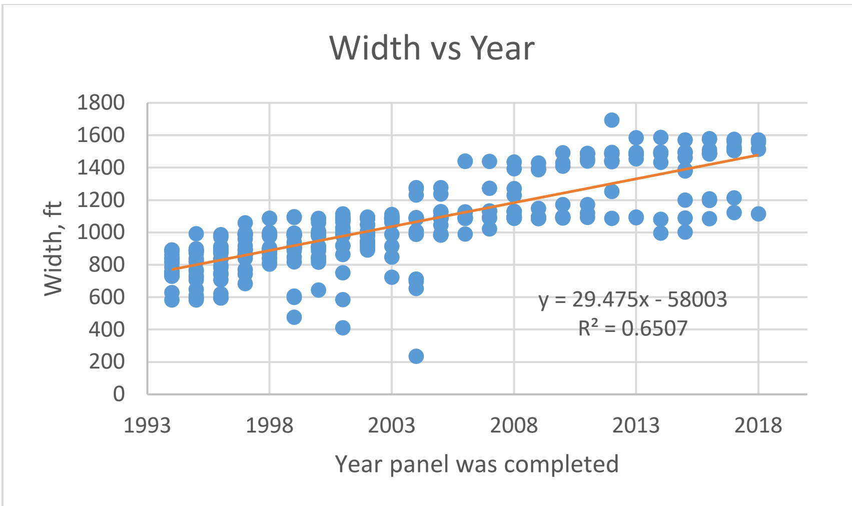

Figure 15. Year panel was completed vs the width of the panel

Along with changing mine characteristics, the conditions that the mines are mining have changed over the life of the assessment as well. The most important mining condition to track is the overburden because of the strong influence it has on subsidence basin formation. In the 3rd, 4th and 5th assessments the average overburden was tracked for each mine type. Table 10 shows how the average has changed over the last three assessment periods. In each of the three assessments the mean, minimum, maximum, and standard deviation of the overburden was calculated for individual mines. The data for the individual mines was used to determine the average range based on the mean and standard deviations in each mine type category. The most notable trend is seen in the shallow overburden category. The thickness for a mine to be considered shallow in all mine type has increased regularly from the 3^{rd} to the 5^{th} assessment period. This increase indicates that the minimum overburden is becoming greater with each assessment period.

Table 9. Overburden categories per the last three assessment periods

Type of Mine	Overburden Category								
	Shallow, ft			Average, ft			Deep, ft		
	3^{rd}	4^{th}	5^{th}	3^{rd}	4^{th}	5^{th}	3^{rd}	4^{th}	5^{th}
Longwall	< 525	< 627	< 705	525 to 850	627 to 939	705 to 907	> 850	> 939	>907
Room-and-Pillar	< 185	< 200	< 295	185 to 397	200 to 562	295 to 425	> 397	> 562	> 425
Pillar Recovery	< 185	< 200	< 432	185 to 397	200 to 562	432 to 552	> 397	> 562	> 552

Overburden increases slightly with time among the over 300 panels mined since 1994. However, when examined by assessment period, the average overburden is highest during the 5^{th} assessment and lowest during the 2^{st} assessment (Table 10). This indicatesa shift in the average depth of the overburden over the last 25 years. The maximum overburden has also increased.

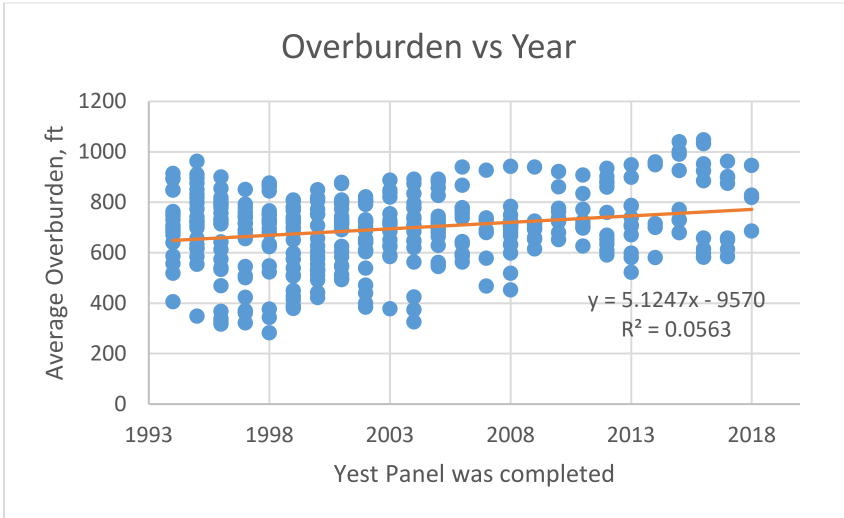

Figure 16. Panel overburden per year from 1994 to Present

Table 10. Overburden statistics per assessment period

Assessment Period	Maximum (ft)	Minimum (ft)	Standard Deviation (ft)	Mean (ft)
1st	1134	226	89	685
2nd	1155	303	85	664
3rd	1218	248	88	698
4th	1197	385	91	736
5th	1293	416	89	810

4.4 Mine Locations

The mine layout and mining characteristic depend largely on where the mine is located. There are three general standards that operators have used over the last 25 years to determine where mines will be placed as cited in the 4th assessment period:

1. The occurrence of bituminous coal thick enough to be extracted with modern mining techniques,
2. The overburden above the minable coalbed greater than 100-ft but less than 1,200-ft. At present there is very little coal mined at depths greater than 1,200-ft in Pennsylvania, and
3. The coal has sufficient quality to compete in either the electric generation or metallurgical markets.

It is assumed that all Pennsylvania counties with mining in them in the last 25 years have these three features in common. Over the last five assessment periods 13 Pennsylvania counties have had underground bituminous coal mining occur in them. All of these counties are located in the southwestern area of the state. There are eight counties that have had mining occur in all five assessment periods. Figure 17 shows what assessments each of the counties have had active mining. All the longwall mines mined in Pennsylvania have occurred in Washington and Greene counties, while the room-and-pillar and pillar recovery mines are distributed among the 13 counties.

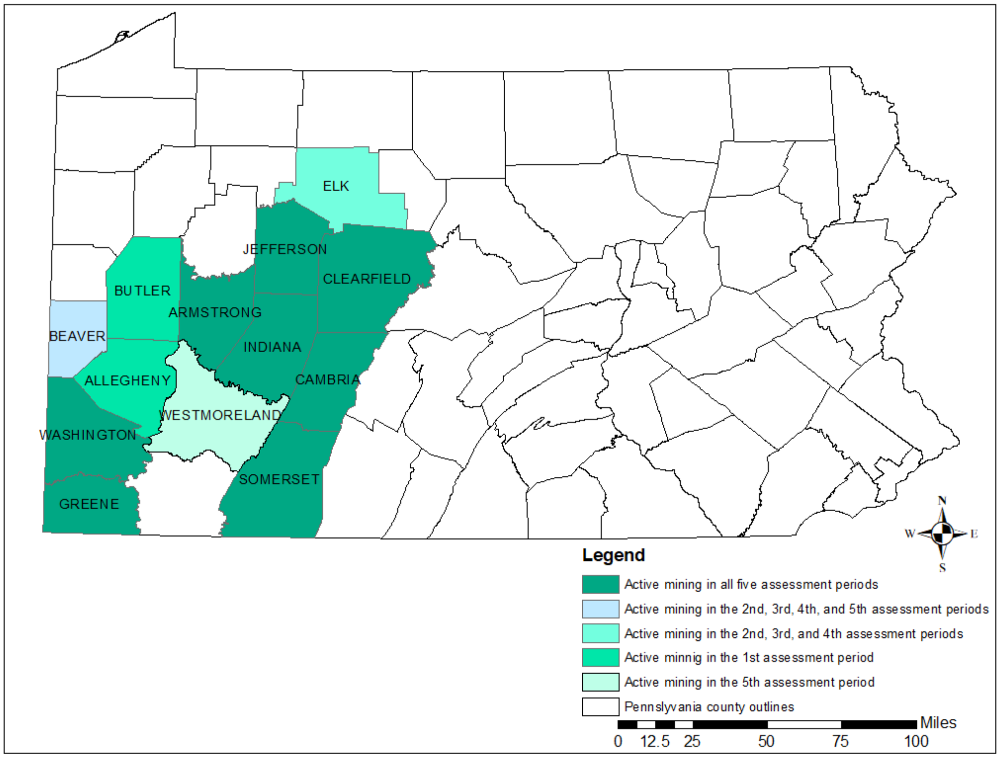

Figure 17. Counties that have had active underground bituminous mining during the last five assessment periods

The geology varies from county to county, but most of the underground bituminous coal mining in Pennsylvania occurs in with in the Pennsylvanian and Permian Geological systems. As seen in the stratigraphic column of the Pennsylvanian system in Figure 18 the most common groups to be mined are the Pittsburgh and Allegheny formations:

Pittsburgh- minable coalbeds, shales, sandstones, and limestones

Allegheny- minable coalbeds, shales, claystones, sand stones, and limestone

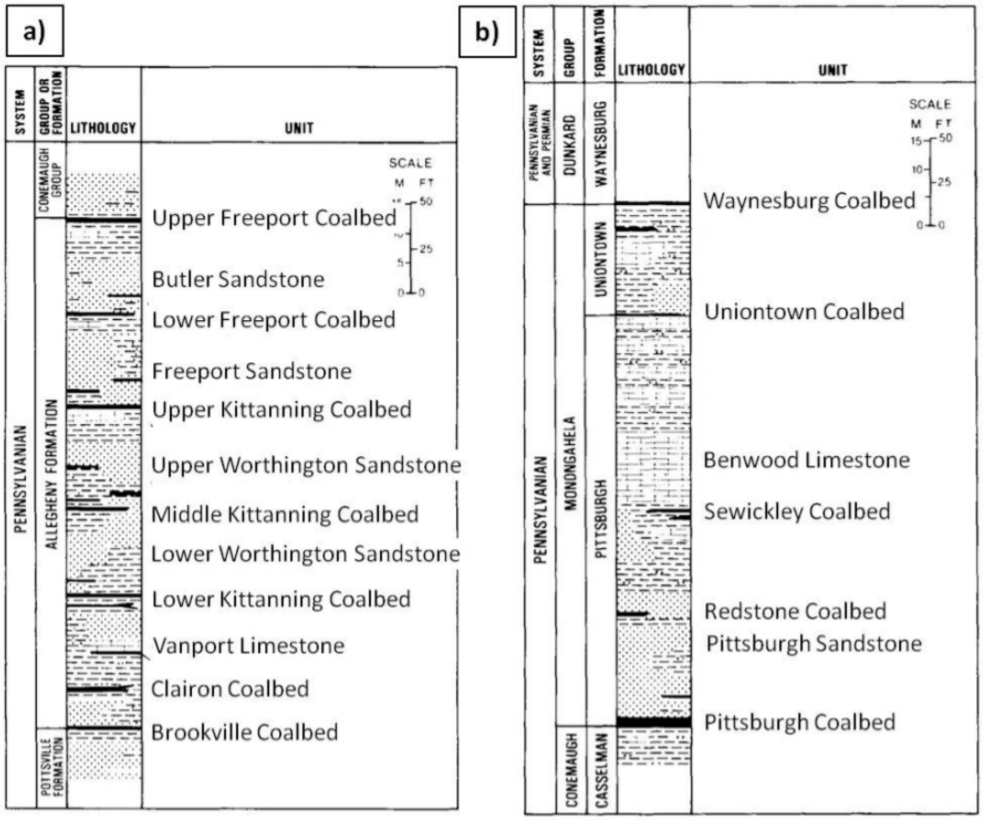

Figure 18. Stratigraphic sections of the (a) Allegheny and (b) Pittsburgh formations and the minable coalbeds contained in them (Edmunds et al. 1999)

All longwall mines in the last 25 years have mined the Pittsburgh coalbed in the Pittsburgh formation. The lateral consistency and thickness of the Pittsburgh coalbed makes it an ideal coalbed for longwall mining. Occasionally a room-and-pillar mine will mine the Pittsburgh coalbed, but generally room-and-pillar and pillar recovery mines operate in the coalbeds in the Allegheny formation. The Allegheny formation is located at shallower overburden making it ideal for room-and-pillar mines because there is no planned subsidence consequences associated with the shallow overburden in room and pillar mining.

Table 11 shows coalbed that all the mines have mined over the last five assessment periods. Several mines have mined multiple coalbeds.

Table 11. Coalbeds mined per Act 54 assessment period

Formation	Coalbed	Number of Mines				
		1st Assessment	2nd Assessment	3rd Assessment	4th Assessment	5th Assessment
Pittsburgh	Sewickley	8	7	5	4	3
	Pittsburgh	14	15	9	7	7
Allegheny	Upper Freeport	24*	16*	14	9	10*
	Lower Freeport	6	6	2	3	6
	Upper Kittanning	12*	8*	8	8	7*
	Middle Kittanning	2*	1	0	0	2
	Lower Kittanning	17*	21*	12	15	15*
	Brookville	1	1	0	0	1*
Clarion		2	1			
Total		84	67	50	46	49

**Multi-seam mining occurred*

4.5 Future Mining

The tracking of previous mining allows for the prediction of future mining. Specifically, predictions can be made for longwall mining in the Pittsburgh coalbed, which is likely to be the dominate mining type in as coal mining continues. As mentioned above, it is assumed that mining technology will also continue to advance and allow for mining to occur at deeper depths and coal be extracted more efficiently with the increase in longwall panel size. The red line in Figure 19 shows the limitation of technology on longwall panel size. However, advancing technology will also compete with geologic anomalies such as sandstone channels, and placement of existing and planned gas wells.

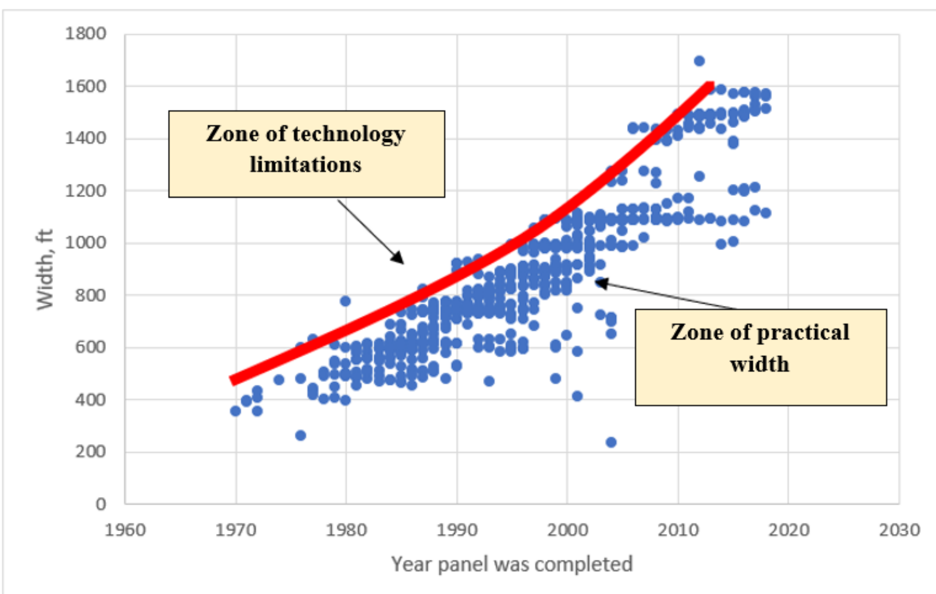

Figure 19. Trendline showing the advances in longwall panel width with advancing mining technology

The outline of the thirteen longwall mines in the Pennsylvania Pittsburgh coalbed longwall mines are shown in Figure 20. This figure also shows the variation in overburden. The northern area of the coalbed has shallower overburden ranging from 100 to 300-ft while the southern area has overburden exceeding 1,000-ft. The average overburden was higher in the 5th assessment than previous assessments. The unmined permit areas shown in tan are all located in areas of deeper overburden, except for the Tunnel Ridge mine, resulting in planned future mining to continue to encounter deeper overburden.

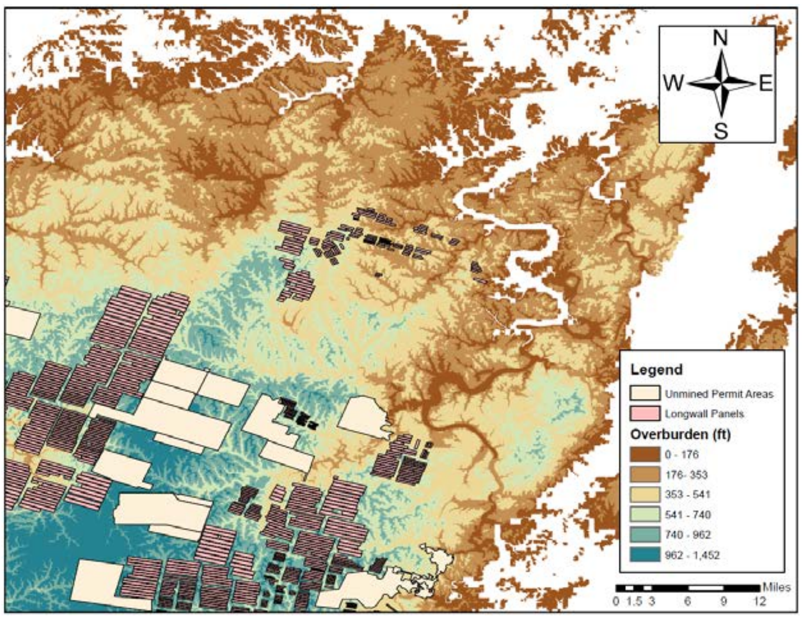

Figure 20. Map of the longwall mines in the Pittsburgh Coalbed and overbuden depths

The unmined permit areas in Figure 20 are areas of future mining that are planned to be mined in the next 5-years. An analysis of the overburden in the unmined permit areas shows that the average depth of these areas will be 858-ft (Table 12). This is a 5% increase in average overburden from the 5th assessment period. The maximum overburden value is also a 5% increase from the deepest mined area of the Monongalia County mine in the 5th assessment period. From this analysis, it can inferred that the longwall mines in Pennsylvania will be subjected to greater overburdens during the next assessment.

Table 12. Unmined longwall permit area of the Pittsburgh coalbed overburden statistics

Average	858-ft
Max	1364-ft
Min	97-ft
Standard Deviation	220-ft

The area depicted in green on Figure 21 is the unmined area of the Pittsburgh coalbed. There are approximately 280,000 unmined acres. The extraction of the unmined coal could range between a conservative 35% and generous 75%. This range of extraction was determined based on trends above, and considers the unexpected circumstances mines could encounter, such as the geology, of the unmined area, and the advances in technology. During the 5th assessment longwall mines had a mining rate of 3,500 acres/year. At the current mining rate and the estimate range of extraction the life of longwall mining in the Pittsburgh coalbed in Pennsylvania is between 28 and 60 years.

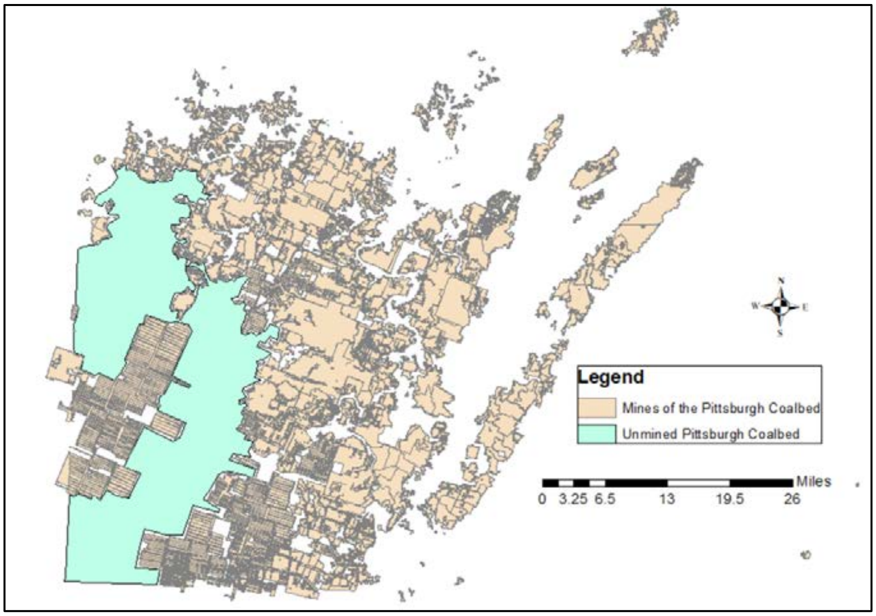

Figure 21. Location of unmined Pittsburgh coalbed in southwestern Pennsylvania

5.0 Impact Review

The data collected in this section is a summary of the structures, watersources, and land impacts previously analyzed Act 54 assessment reports. In the 1st assessment the impact data was not recorded so this analysis will focus on the data recorded in remaining assessments. Examples of how impacts were handled by the mining companies as well as the PA DEP show where the Act is effectively doing its job and where improvements can be made.

Over the last four assessment periods, there has been an overall total of 4,647 reported effects in structures, watersources, and land. Table 13 shows the total number of impacts per categories in each assessment period and the percent of the total impacts. Watersource impacts make up the largest percent of the total impacts and the land impacts account for the smallest percent. The largest drop in the number of watersource impacts occurs from the 4th to the 5th assessment. The 4th assessment had the highest percentage of the overall impacts, 29%.

Table 13. Number of total impacts and the percent of total impacts over the four assessment periods

Assessment Period	Watersource Impacts	% of Total	Structure Impacts	% of Total	Land Impacts	% of Total
2nd	684	16%	348	7%	60	1%
3rd	683	15%	456	10%	108	2%
4th	855	18%	389	8%	106	2%
5th	379	8%	455	10%	124	3%
Total	2601	57%	1648	35%	398	8%

Along with recording all impacts reported by property owners, Act 54 assessments focus on which of the reported effects were determined to be company liable. Tracking the company liable events shows when the operators are fairly compensating or repairing the damages that were caused by undermining. Table 14 breaks down the number of company liable events for each impact category over the four assessment periods. It is important to note that the land impacts were not recorded as company liable and company not liable during the 2nd and 4th assessment period. However, the land impacts were recorded in detail in the 5th assessment this is a good example of the changing and evolving nature of Act 54. Watersources were the category with the most company liable impacts (n=1079). The 4th assessment had the most company liable impacts not including land impacts (n= 709).

Table 14. Total company liable impacts per assessment period

Assessment Period	Company Liable Impacts			
	Watersources	Structures	Land	Total
2nd	247	141	-	*388
3rd	269	301	50	620
4th	371	338	-	*709
5th	192	247	66	505
Total	1,079	1,027	*116	*2,222

**excluding company liable land impacts for the 2nd and 4th assessment period*

As discussed previously, watersources have had the most reported impacts and the largest number of company liable impacts over the last 20 years. This highlights the importance of the addition of the protection of watersources through Act 54. However, the category with the highest percent of impacts that were determined to be company liable was structures. Table 15 shows that mining companies compensated or repaired 62% of the structures that had reported damage.

Table 15. Percent of impacts determined to be company liable

Impact Category	Percent of Impacts Determined to be company Liable
Watersources	41%
Structures	62%

The number of company liable impacts can also be viewed from a standpoint of the acres mined. Table 16 shows the total acres mined each assessment, as well as the number of impacts and company impacts that occurred per acre. While the total acres mined over the last 20 years has decreased by 23%, the impacts per acre, as well as the company liable impact per acre, has increased. Both the impacts/acre and the company liable impacts/acre reached a maximum in the 4th assessment. There as a decrease in the 5th assessment but the 5th assessment values are still larger than the 3rd and 2th assessments. While the area of mining is decreasing the number company liable impacts is not.

Table 16. Acres mined per assessment period and impacts per assessment

Assessment Period	Total Acres Mined	Impact/Acre	Company Liable Impact/Acre
2nd	37,458	0.029	0.010
3rd	38,256	0.033	0.016
4th	31,343	0.043	0.042
5th	28,854	0.033	0.018

5.1 Watersource Impacts

Watersources have the most overall impacts as well as the most company liable impacts (Tables 13 and 14). A watersource is listed as a spring, well, or pond. Watersources do not necessarily need the formation of a subsidence basin to be damaged. Watersource can lose water through small cracks and fissures can occur from small movement in the overburden (Figure 22).

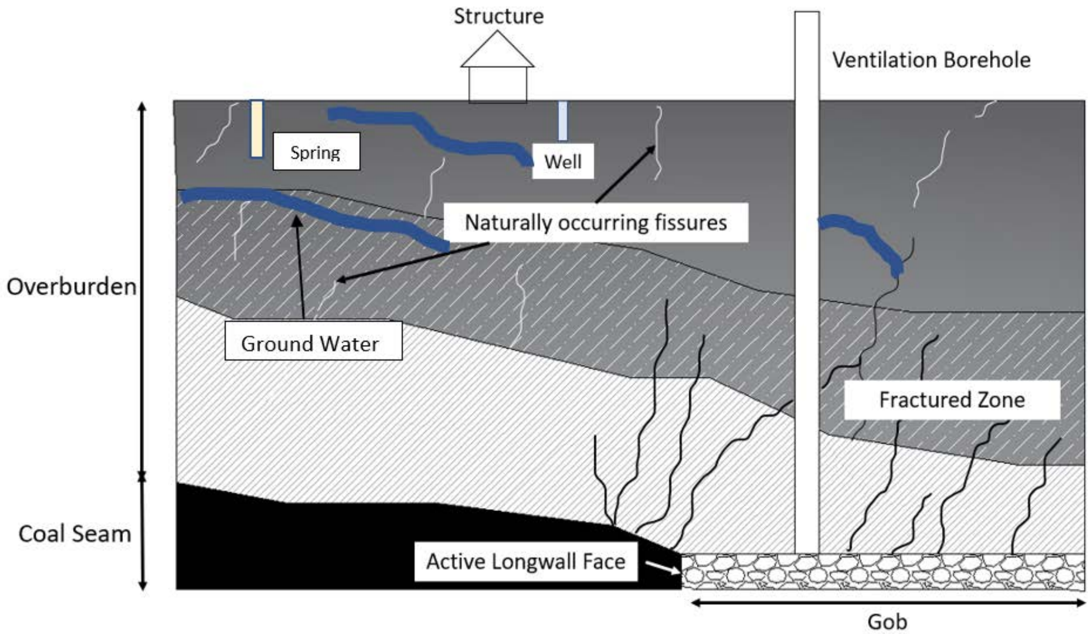

Figure 22. Diagram of the cracks and fissures formed duirng minib and the disruption of ground water

Cracks and fissures can occur over not only longwall mining, but also room-and-pillar mines. They can cause the ground water to be redirected from the wells or springs. The RPZ, described previously, is used to track the impacted watersources. The RPZ is used in all mining types; longwall, room-and-pillar and pillar recovery. The data from the 5th assessment was broken down to show were the watersources with reported effects were occurring for each mine type.

From Table 17 most of the water impacts in the 5th assessment occurred directly over longwall mining. This is expected because of the major ground movement that occurs directly above a longwall mining during subsidence. However, 140 impacts occurred outside of the PRZ with the largest outside of the RPZ attributed to room-and-pillar mining.

Table 17. Location of watersource impacts

Mine Type	Over room-and-pillar mining	Over longwall mining	Over pillar recovery mining	Within RPZ	Outside RPZ
Longwall	23	154	-	29	27
Room-and-Pillar	6	-	-	10	106
Pillar Recovery	1	-	1	1	7
Total	30	154	1	40	140

Table 18 shows the distribution of the 27 company liable impacts associated with room-and-pillar mines. Seventy percent (70%) of the company liable impacts to occur from room-and-pillar mining were outside of the of the RPZ.

Table 18. Locatin of the company liabel impacts over room-and-pillar mines during the 5th assessment

Location	Number Impacts
Over room-and-pillar	3
Within RPZ	5
Outside of RPZ	19
Total	27

Of the 19-company liable impacts that occurred outside of the room-and-pillar RPZ during the 5th assessment period 13 occurred over areas that were mined in previous assessment periods. Impacts over previous mining could indicate that there are still open cracks and fissures in the ground above these mined areas disrupting the flow of ground water. A large amount of impacts over previously mined room-and-pillar mines can, in some cases, indicate failure pillar punching or floor heave, however neither of those two incidents were indicated on the 6-month mine maps or reported by the mining companies. The instances of companies compensating or repairing the 13 watersources outside of active mining in the 5th assessment is an example of Act 54 working and protecting landowners that are affected by mining beyond the mining in the current assessment period.

The remaining six company liable that were outside of the RPZ during the 5th assessment did not occur over mining that had occurred in the last 25-years. These six reported effects generally occurred within hundreds of feet of active mining and may be due to mining as the angle that Carver and Rauch studied in 1994 for affected watersources in West Virginia was not exactly 35-degrees, rather it ranged between 27-38-degrees. There is one company liable impact that occurred in Knob Creek that cannot be reasonably explained with current known mechanics. The impact is located over 7,000 feet from active mining of the 5th assessment period, and the mining located directly below it occurred in the 1930's. Figure 23 depicts a map of Knob Creek 5th assessment mining and the RPZ and the distance to the company liable impact.

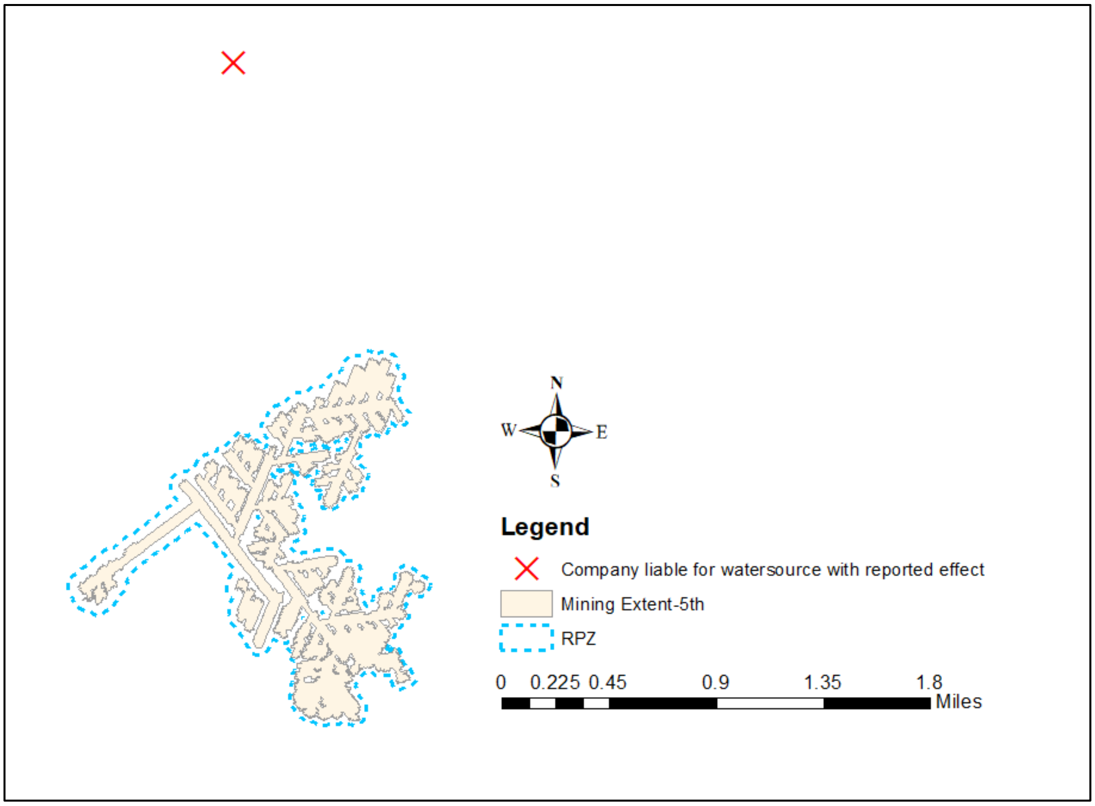

Figure 23. Knob Creek mining extent from the 5th assessment period and the impacted watersource loaced 7,000-ft from mining

The BUMIS entry shows that the well initially started to have a decreased yield in April of 2014, but the state determined that the decrease was not due to mining. Then in November of 2015 the same well was reported to have dried up, and an unspecified agreement was made between the mining company and the well owner. In discussion with the mine operator it was discovered that the well was not operating because of debris in the well so the unspecified agreement was the mine operator cleaning the well for the homeowner. The well is located on a hill side near a stream valley. The mine permit cites that the water table as around 50-ft in the area of the mine. There is no indication of shallow aquifers in the area of the impact listed in the permit. In discussion with the mine operator it was discovered that the well was not operating because of debris in the well so the mine operator cleaned the well for homeowner

Knob Creek is an example of how Act 54 has protected the landowners because the company entered into an agreement so that the well could be fixed even with it being well beyond the RPZ. It can also be cited as an example of how Act 54 has fallen short because more information about why the impact was considered company liable is not recorded. A more detailed account of what was done to determine the companies' liability could be used to update past studies of the effects of mining on watersources.

5.2 Structures Impacts

Structures experience damage from the stress and strain of the ground movement during the forming of the subsidence basin. Over the life of Act 54 there has been fewer structures impacted than watersources. However, structure damage is not expected to over room-and-pillar mining due to the absence of a subsidence basin. Structure damage is generally limited to longwall and other forms of full extraction mining were subsidence occurs. In some cases, failures can occur in room-and-pillar mines causing unplanned subsidence and damages to structures.

In the 3rd, 4th, and 5th assessments the number of impacts for mines active during the assessment period were broken down by mine type (Table 19). In all three assessment periods the longwall mines accounted for over 75% of all the impacted structures. The large percent of impacts occurring over the longwall mines is expected because of the subsidence that occurs from longwall mining. However, it is important to note that while pillar recovery also has subsidence in the areas were the pillars are extracted there are very few structures impacts occurring over these mines.

This is because unlike longwall mining, that extracts a continuous area of coal, pillar recovery mines can decide where it is best for full extraction to take place and avoid the areas with structures. This trend was observed specifically in the 5th assessment period, no structures were located over areas of pillar extraction.

Table 19. Total structures impacts by mine type over the last three assessment periods

<table>
<tr><th>Mine Type</th><th>3rd</th><th>4th</th><th>5th</th></tr>
<tr><td>Longwall</td><td>427 (94%)</td><td>315 (81%)</td><td>345 (75%)</td></tr>
<tr><td>Room-and-Pillar</td><td rowspan="2">29 (6%)</td><td>48 (12%)</td><td>45 (10%)</td></tr>
<tr><td>Pillar Recovery</td><td>7 (2%)</td><td>1 (0.2%)</td></tr>
<tr><td>Total</td><td>456*</td><td>389*</td><td>455*</td></tr>
</table>

**Total including the impacts from inactive mines*

The total percent of impacts occurring over longwall mines has decreased from the 3rd assessment to the 5th assessment. Table 20 shows the number of company liable impacts over the longwall mines per assessment period. While the total number of structures with company liable impacts has decreased over the last three assessment periods, the percentage of the total structures over longwall mines that are company liable has varied. The lowest amount of company liable impacts and lowest percent impacted structures occurred in the most recent assessment period. There was only a combined total of nine reported effects that occurred over the room-and-pillar and pillar recovery mines in the last three assessment periods.

Table 20. Company liable impacts over longwall mines

Assessment Period	Total Longwall Impacts	Company Liable Impacts
3rd	427	300 (70%)
4th	315	230 (73%)
5th	345	229 (66%)

A 200-ft buffer around the furthest extent of mining is used to track the structure impacts for all mining types. In longwall mines the most common place for impacts to occur is within the subsidence basin over the longwall panels. The percent of structures located over the panels that had impacts determined to be company liable decreased from the 3rd to the 4th assessment period but increased from the 4th to the 5th assessment. In the 3rd assessment period there were 1069 structures over the longwall panels and 24% of them were company liable, in the 4th assessment period there were 1210 structured undermined by panels and 17% of them were determined to have impacts that were company liable, and in the 5th assessment there were only 583 structures over the panels, but 28% of them were company liable.

Table 21 shows the percent of structures located directly over the longwall panels that were company liable in the 3rd, 4th, and 5th assessment periods. It is important to note that the percentage of total structures over longwall panels that were company liable decreased in the 5th assessment from the 4th assessment in all mines active in the 5th assessment, expect for the Enlow Fork mine.

Table 21. Percent of strucures located directly over longwall panels that were company liable

Mine Name	Assessment Period		
	3rd (%)	4th (%)	5th (%)
Bailey	24.3	17.0	15.2
Monogalia County (Blacksville No. 2)	11.7	24.4	0
Cumberland	17.5	16.8	15.7
Emerald	20.8	16.8	5.2
Enlow Fork	28.4	16.8	46.7
High Quality	40.0	Not Active	Not Active
Mine 84	25.3	0	Not Active
Harvey	Not Active	Not Active	10.4
Tunnel Ridge	Not Active	Not Active	12.5
Shoemaker	0.0	Not Active	Not Active

Figure 24 shows that the Enlow Fork mined in an area of higher population density in the 5th assessment than it had in the past two assessments and compared to other mines in the 5th assessment period. Which explains the increase in company liable events directly over the longwall panels. It also is an example of how Act 54 has worked to protect the landowners, while allowing the mining companies to extract the maximum amount of coal. Before Act 54 it would have been difficult for the mining companies to undermine a highly populated area because of the subsidence damages that could occur to the surface, and the damage that did occur because of mining was not guaranteed to be compensated or repaired.

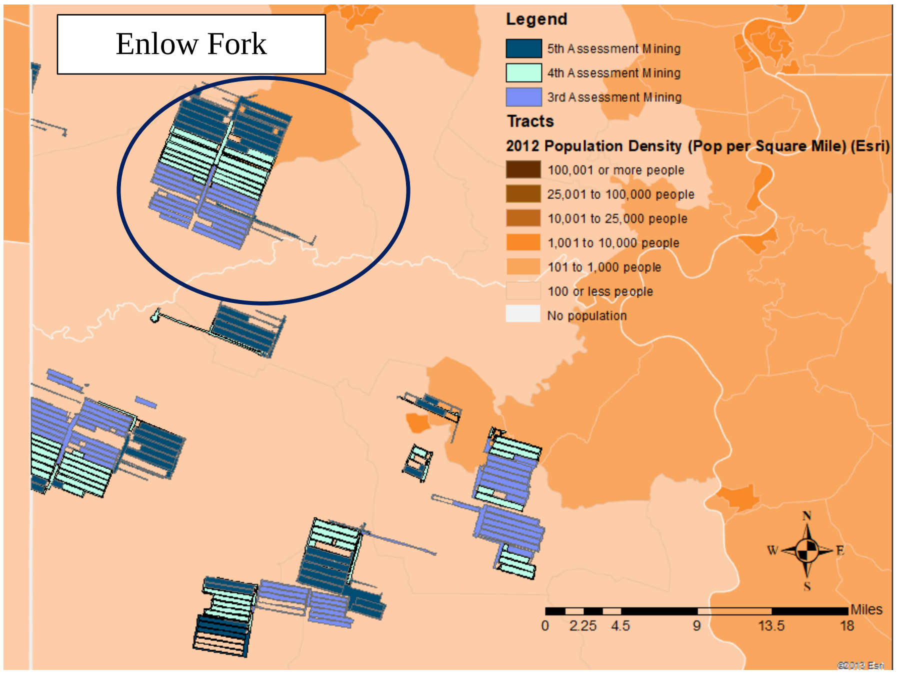

Figure 24. Population density map with the longwall mining in the 3rd, 4th, and 5th assessments (U.S. Census Bureau et al., 2017)

An example of structure damage that occurred over the Enlow Fork mine is shown in Figure 25. A crack developed along the basement floor of the dwelling and into the brick walls. This structure was located above a panel, slightly off center of the panel, so the damage was undisputedly due to underground mining. The landowner and the mining company entered into an unspecified agreement six months after the damage occurred

Figure 25. Damage to a dwelling located over an Enlow Fork panel (photographs courtesy of the PA DEP)

While the example above is another demonstration of Act 54 protections for landowners, in recent years there have been several structure impacts related to longwall mines that are occurring at distances further from the panels than predicted by current subsidence modeling practices. One of these “far field” impacts occurred at the Enlow Fork mine. Damage to the house occurred when the longwall panel face was still 700-ft from the property, well beyond the 200-ft buffer that the PA DEP uses as a guideline for structures impacts. The details of this example and others like it will be discussed in more detail in the Section 7. Far field structure impacts are examples of when the scope of Act 54 must be updated so that the far occurring impacts can be understood and structures better protected.

5.3 Land Impacts

Land impacts can be harder to track and report because if the impact happens in a remote area, it could go unnoticed. When land is impacted by mining it can be in the form of, landslides, ground cracks, heaves and bumps, and the release of methane. Of all the impact categories the land subsection has the fewest impacts. The land impacts were only broken down by company liable and company not liable during the 3rd and 5th assessment periods. Like structure impacts, land impacts are most likely to occur over subsided areas, i.e. full extraction mining. Data from the 5th assessment breaks down the land impacts to show what mine types the land impacts were distributed over and how many were company liable (Table 22). In the 5th assessment 79% of land impacts occurred over longwall mines and 94% of the company liable impacts were over longwall mines.

Table 22. Land during the 5th assessmend by mining type and their liability

Mining Type	Reported Effects	Company Liable
Room-and-Pillar	8 (6%)	0 (0%)
Pillar Recovery	3 (2%)	0 (0%)
Longwall	99 (79%)	63 (94%)
Total	124*	67*

**Total including the impacts from inactive mines*

Figure 26 shows the location of the land impacts over longwall mines. Seventy-two percent (72%) of the impacts occurred directly over the longwall panels, aligning with the subsidence basin.

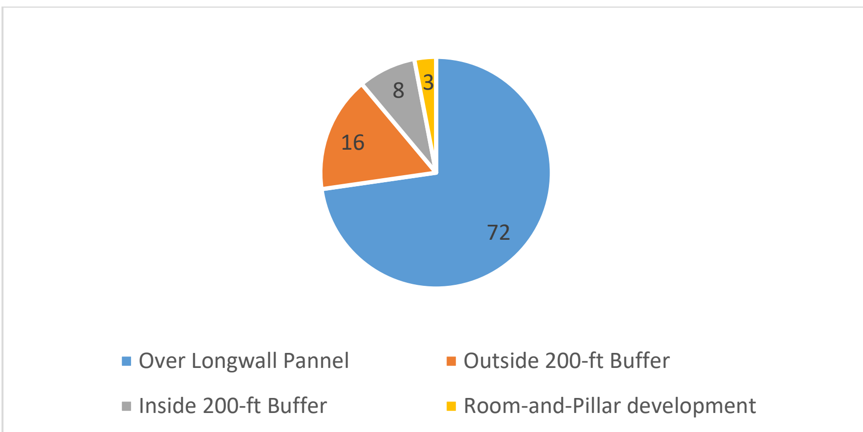

Figure 26. Location of land impacts over longwall mines

A unique concern with land impacts is that mining can induce the reactivation of historical or pre-historical landslides. In the Allegheny and Washington county areas, there are estimated to be 15,000 recent and historical landslides. (Pomeroy, 1982). Ancient pre-existing landslides that developed after the last retreat of the glaciers in the Pleistocene Era can reactivated from the changing ground deformations associated with the subsidence basin. Large landslides that occurred during the glacial periods have been mapped over Western Pennsylvania (Southwestern Pennsylvania Commission, 2017). These slopes may have been semi-stable for hundreds to thousands of years but mining induced movement can cause landslide reactivation.

In the 5th assessment there were 46 instances of landslides or mass wasting, it was the most common land impact in the assessment period. Figure 27 is an example of mass wasting occurring over the Harvey mine. This was a company liable impact that occurred over the corner of a panel and was repaired.

Figure 27. Mass wasting occurring over the Harvey mine during the 5th assessment (Photographs from the PADEP files)

In the 5th assessment methane related impacts were tracked as part of the land impacts. There were two methane impacts over the longwall mines. Low concentrations of methane released from the coal and surroundings area (5% to 15%) can be explosive, making this impact extremely dangerous. Certain coal seams are known to have higher methane concentration than others (McCulloch, 1975). The methane gas migrates from the gas bearing coalbeds into the broken strata associated with the longwall panel were gas is free to flow from these areas of elevated pressure to the atmospheric conditions on the surface through connecting fracture systems. All mines have a mechanical ventilation system capable of removing methane from the underground workings. The additional analysis of methane impacts added to the 5th assessment is an example of how Act 54 has changed to investigate conditions landowners face due to mining.

6.0 Subsidence Modeling and Impact Prediction

The prediction of longwall mining subsidence is important in the permitting, planning, and monitoring of mining operations (Karmis et al., 2008). The prediction models allow both the state and operators to gain a better understanding on where the most substantial damages are likely to occur. Identifying the areas with the highest chance of impact allows controls to be implemented to help reduce or eliminate the damages. However, as mentioned, these models are only predictions so there is still a degree of uncertainty that remains and not all impacts will be able to be accurately predicted. In the cases where damage occurs from mining in unexpected areas it is important to understand how these damages fit in with the prediction models, or how they can be used to improve current prediction models. The accuracy of the prediction model can improve with the collection of measured subsidence data (Karmis et al., 2008).

There are numerical, empirical, and semi-empirical prediction models. Finite element, finite difference, and discrete element methods are used in the numerical modeling of subsidence. These methods rely heavily on detailed data about site conditions, such as geology and complex mechanical properties of the subsurface and overburden. Along with the comprehensive site investigation, numerical models also require a great computational effort (Saeidi et al., 2012).

Empirical and semi-empirical methods include graphing methods and profile and influence functions. These models rely on a many case studies in specific regions to identify patterns in the specified area. Therefore, these methods are precise to the region that the case studies draw from and not necessarily applicable to a broader area. Profile functions are one of the most popular subsidence prediction method. They fit a predicted profile with a measured profile based on mathematical functions via the curve fitting process (Saeidi et al., 2012). The influence functions use the sum of displacements of induvial points and superposition to determine the total subsidence at one point. Influence functions can be used on complex mine geometries and are able determine not only vertical and horizonal movements but also strain (Saeidi et al., 2012). As will be discussed below, identifying areas of high strain is significant in subsidence damage control.

6.1 Empirical Formula Subsidence Prediction

One of the most basic form of subsidence prediction is the use of empirical formulas developed for a specific region. There is a set of empirical formulas that can be used to manually plot the predicted subsidence basins that will occur in the Pittsburgh coalbed in the Appalachian Region. The empirical formulas rely on manual entry of the panel characteristics and the assumed values of subsidence features. The features that are needed to construct the predicted profile include:

- Overburden (h)
- Panel width (L_2)
- Mining height (m)
- Rock Property Coefficient (c)
- Angle of Draw (δ_0)
- Subsidence Factor (a)
- Maximum Predicated Subsidence (S_0)
- Inflection point
- Distance from edge of mining to inflection point (d)

- Half the width of the predicted subsidence basin (R)

The overburden, rock property coefficient, panel width, and mining height are all constants. The overburden, panel width, and mining height are measurements taken form the longwall panel, and the rock property coefficient is a factor of location of the mine. The larger the rock property coefficient the harder the rock surrounding the mine (Peng, 1992). Table 23 displays the equations used in the Pittsburgh coalbed to define the remaining subsidence features:

Table 23. Equations for prediciton of subsidence profile for the Pittsburgh Coalbed

Feature	Equation for the Pittsburgh Coalbed
δ_0	$3.05 + 0.00023 * h + 4.607 * 10^{-6} * h^2$
a	$0.6760821 * 0.9997678^h$
S_0	$a * m$
$Inflection\ Point$	0.5*S_0
d	$0.45439 * h * e^{-0.000914*h}$
R	$\frac{L_2}{2} + h * \tan(\delta_0 * \frac{\pi}{180})$

There are two methods that rely on the calculation of the previously listed features for the empirical calculation of the predicted final subsidence basin. In both methods the subsidence basin is a function of the horizontal distance from the center of the panel (x).

Negative Exponential Function Method: This method is used best for panels that are critical or supercritical because of the asymmetry about the inflection point (Peng and Cheng,1981).

$$S(x) = S_0 * e^{-c*\left(\frac{x}{R}\right)^d} \qquad \textbf{Equation 2}$$

Hyperbolic Tangent Function Method: This method is used best for panels that are critical or supercritical because of the symmetry about the inflection point (Peng and Cheng, 1981).

$$S(x) = \frac{S_0}{2} * (1 - \tanh\left(\frac{c * x}{h}\right)) \qquad \textbf{Equation 3}$$

6.1.1 Empirical Method Case Study

In the 5th assessment period there was an impacted garage located at the edge of a panel of the Enlow Fork mine. The damage of the impacted garage included the uneven settlement of the concrete garage floor. The University was able to survey the damages to the garage floor to obtain the total vertical drop across the garage. Because of the location of the garage, shown in Figure 28, the profile of the sloping garage floor was able be compared to the predicted subsidence profile developed by empirical methods.

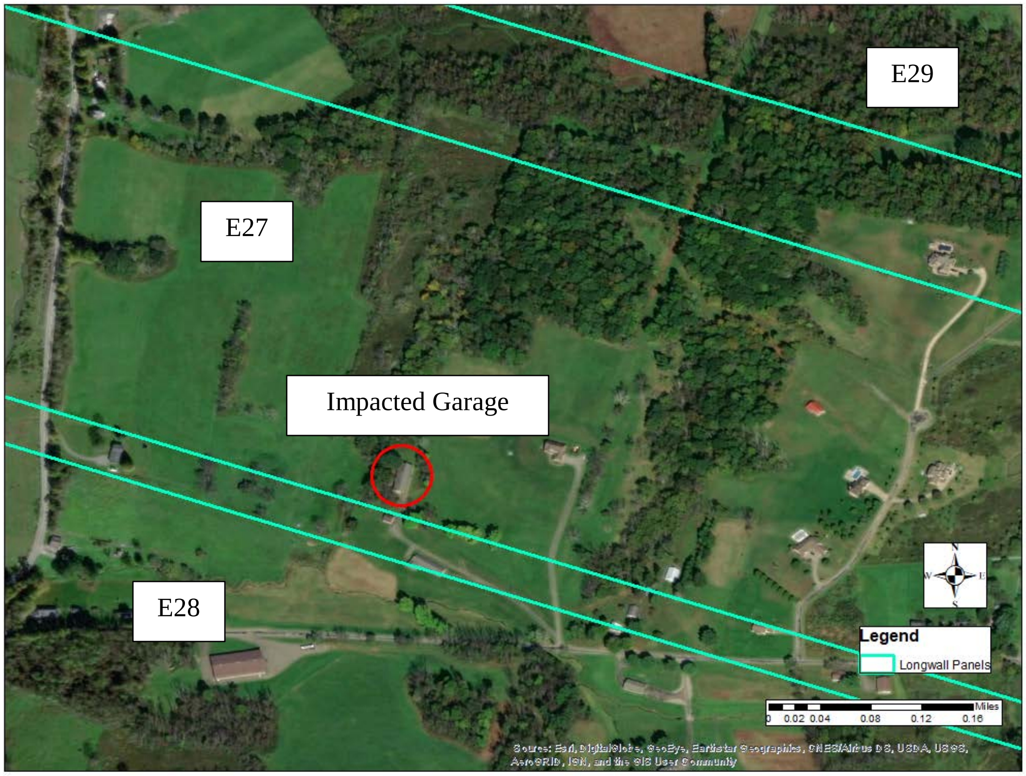

Figure 28. Impacted garage that was surveyed to compare the deformation of the garge with the predicted subsidence basin

The E27 panel of Enlow Fork was a supercritical panel so the hyperbolic tangent function method was used to predict the subsidence basin. Table 24 shows the mine and subsidence features that were used in the hyperbolic tangent function equation, all were collected from the mine or derived from the equations shown in Table 23 above for the Pittsburgh coalbed. The rock property coefficient was assumed to be high because of the sandstone that is abundant in the Enlow Fork Mine area (Su et al., 2012).

Table 24. Subsidence featrues for Enlow Fork Case Study

Feature	Equation for the Pittsburgh Coalbed
L_2	1520-ft
h	550-ft
m	7.33-ft
c	11
δ_0	21-degrees
a	0.615
S_0	4.5-ft
$Inflection\ Point$	2.25-ft
d	151.1-ft
R	971.3-ft

The survey points of the garage were plotted versus half of the predicated subsidence basin of the E27 panel. The profile of the garage floor is assumed to be the profile of the actual subsidence basin because the garage is located at the edge of the panel where the subsidence profile is expected to most prominent. The predicted profile is shown in blue and the field profile as assumed by the slope of the garage floor is displayed in orange in Figure 29. The profile of the garage floors matches that of the predicated subsidence basin almost exactly. This case study is an example of when the empirical formulas can accurately predict the actual subsidence profile that occurred.

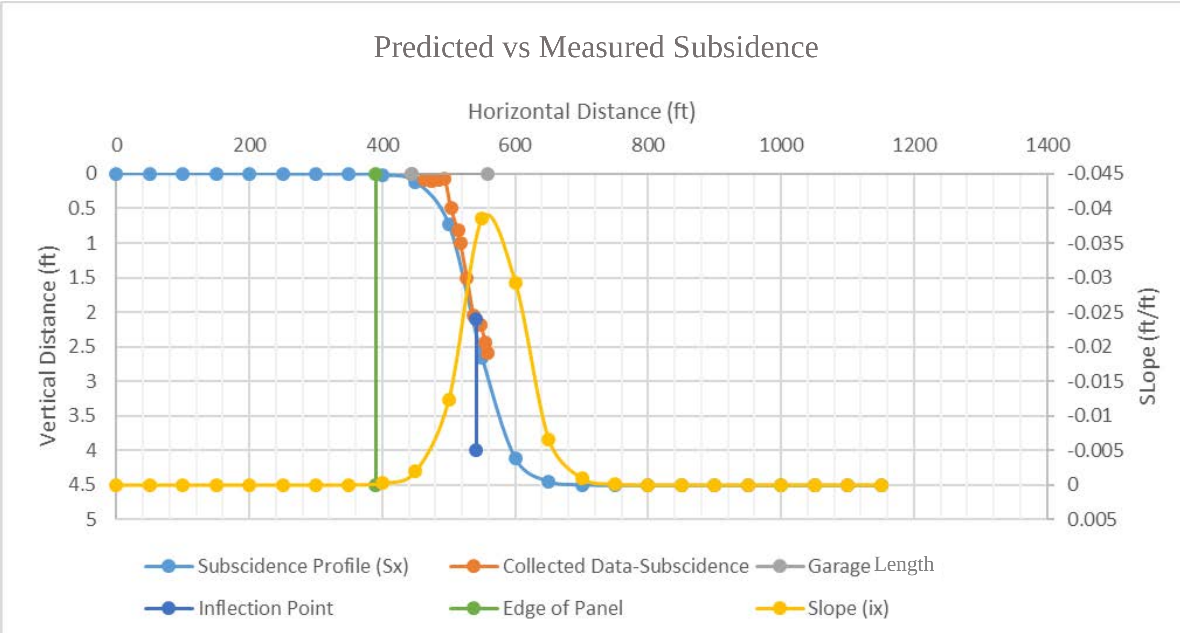

Figure 29. Predicted subidece versus measured subsidence basin of the Enlow Fork E27 panel

6.2 Subsidence Deformation Prediction Software

The PA DEP and mine operators in the northwestern region of Pennsylvania often use the Subsidence Deformation Predication Software (SDPS) developed by Michael Karmis of Virginia Polytechnic Institute & State University that is currently maintained by Zach Agioutantis of the University of Kentucky. In SDPS both the profile function and influence functions can be used to create prediction models. In this research the influence function was used with parameters set for the Eastern area of the United States. SDPS outputs the graphs of the vertical and horizontal movement, and ground strain induced by mining.

6.2.1 Subsidence Prediction Model Case Study

The outputs of SDPS can aid in the successful aim of Act 54 by allowing operators to identify areas of concern prior to mining. To gain a better understanding of how SDPS outputs can be used a longwall panel mined during the 5th assessment period was modeled in SDPS and the impacts that occurred were retroactively compared to the SDPS model.

6.2.2 Panel Characteristics

To identify a panel that would be modeled all panels mined in the 5th assessment were analyzed to determine the average characteristics of the 5th assessment panels. There were 49 total panels mined in the 5th assessment. However, panels that were still active as of August 20, 2018, as well as panels that were only partially mined in Pennsylvania were eliminated. These panels were eliminated because the width, length, and overburden recorded for the panel in Pennsylvania was not representative of the whole panel; there were 13 panels were eliminated. The average characteristics shown in Table 25 were used to detect a panel that best represented the average features of the 36 completely mined panels.

Table 25. Average characteristics of completely mined panels during the 5th assessment period.

Panel Characteristic	Average	Standard Deviation
Width (ft)	1,450	149
Length (ft)	10,515	1,600
Overburden (ft)	819	156
Critical Width (ft)	1.84	0.447

Using conditional formatting in Microsoft Excel, all panels that had a width, length, overburden, and critical width within one standard deviation of the average were identified. There were 14 panels whose four characteristics were all within one standard deviation of the average length, width, and overburden. Of the 14 panels pervious identified the Baily 2L panel was selected for the SDPS case study because both the width and the overburden of the 2L panel are less than a seven percent difference from the average. The width and overburden were specifically examined because they are two of the most important characteristics in subsidence prediction modeling. Table 26 shows the exact dimensions of the Bailey 2L panel.

Table 26. Bailey 2L longwall panel dimensions

Width (ft)	1,495
Length (ft)	11,890
Overburden (ft)	886
Critical Width (ft)	1.69

6.2.3 Bailey 2L Panel

The Bailey mine is in the Pittsburgh coalbed in Greene County and is operated by CONSOL Energy. Between August 21, 2013 and August 20, 2018 Baily mined seven total panels completely, and one panel was being actively mined at the conclusion of this assessment period. The 2L panel is located between the 1L and 3L panels and was completed in 2016. Figure 30 shows the location of the 2L panel. It can be noted that the panel does not undermined a heavily populated as per Figure 24, which is an important factor when estimating structure and watersource impacts due to undermining.

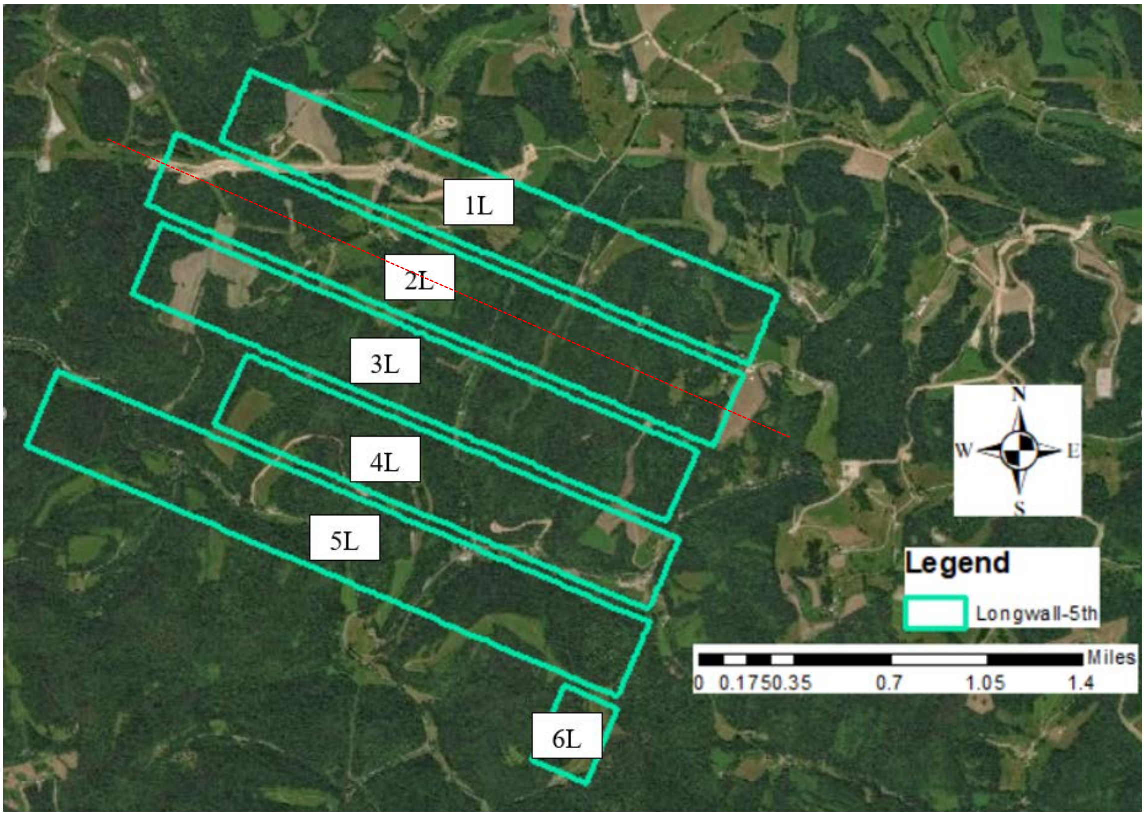

Figure 30. Map of Bailey 2L panel

6.2.4 SDPS Assumptions

As mentioned above the SDPS model was set to the parameters of the Eastern United States. The percent hard rock was set to 20% after consulting the Bailey Mine Permit Module 7 in which it was noted that the mine is overlain mainly by a sandstone unit of the Pittsburgh Formation (Bailey Permit File Module 7). The extraction height was set at the average of 5.8-ft based on the average mining height recorded in the 2017 US Longwall Census (Fiscor, 2018). The edge effects were enabled in SDPS and set as rigid because the gateroads between the 2L panel and the 1L and 3L panels were an average of 220-ft wide. Table 27 shows all assumed values and settings.

Table 27. Assumed values and setting in SDPS

Region	Eastern United States
Percent Hard Rock	20%
Mining Height	5.8-ft
Edge Effects	Enabled; Rigid

6.2.5 SDPS Outputs

The first SDPS model was simplified to only model the 2L panel, and it did not account for the mining of the 1L and 3L panels. This was done to gain a basic understanding of the SDPS outputs and the model of a single subsidence basin. Figure 31 shows the predicted vertical subsidence (A.) and strain (B.). The dashed red line indicated the center of the 2L panel. The maximum vertical subsidence occurs in the middle of the panel with a maximum value of 3.97-ft. The flat bottom of vertical subsidence basin indicates that the panel has reached it maximum subsidence and is a supercritical panel.

The horizontal strain on the ground is zero at the center of the panel and reaches its maximums at the edge of the subsidence basin. Where the vertical subsidence is the greatest the strain is at a minimum because the center of the panel dropped evenly in elevation. The areas of highest strain are where slope of the vertical subsidence is greatest because in these areas the ground is subject to the most change, and strain is defined as the change in length over the original length. There are areas of positive and negative strain indicating areas of tension and compression.

The areas of positive tension are zones of the ground that are being pulled into the subsidence basin. The areas of highest strains are often the best indicator for predicting subsidence damage (Karmis et al., 2008). So, if 2L was a single panel the damage from the subsidence would be predicted to be the most substantial around the edge of the panel, not directly in the middle of the panel.

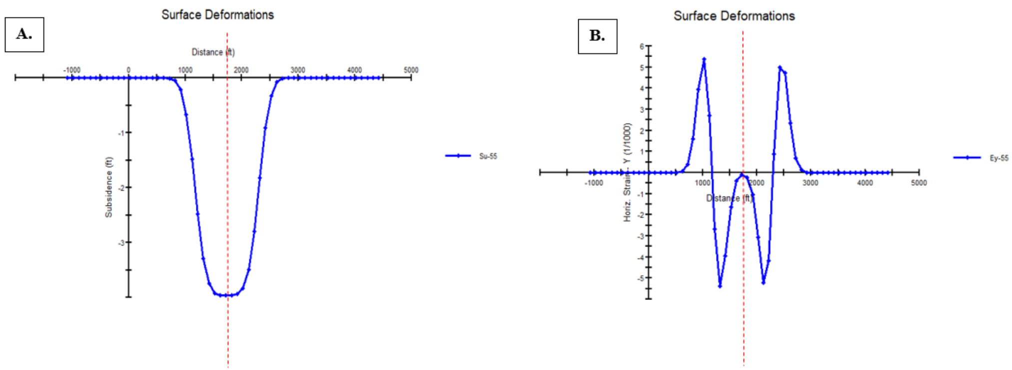

Figure 31. A. Vertical Subsidence of the 2L panel B. Ground Strain of the 2L panel.

The next SDPS model was run with the influence of the mined 1L panel on the 2L panel. A previously mined panel can have influence on the subsidence basin of the panel adjacent to it. Figure 32 shows the vertical subsidence of the 1L and 2L panels. The overall vertical subsidence is not noticeably different. However, there is a slight subsidence over the gate road between the two panels. Both panels have reached their maximum predicted subsidence.

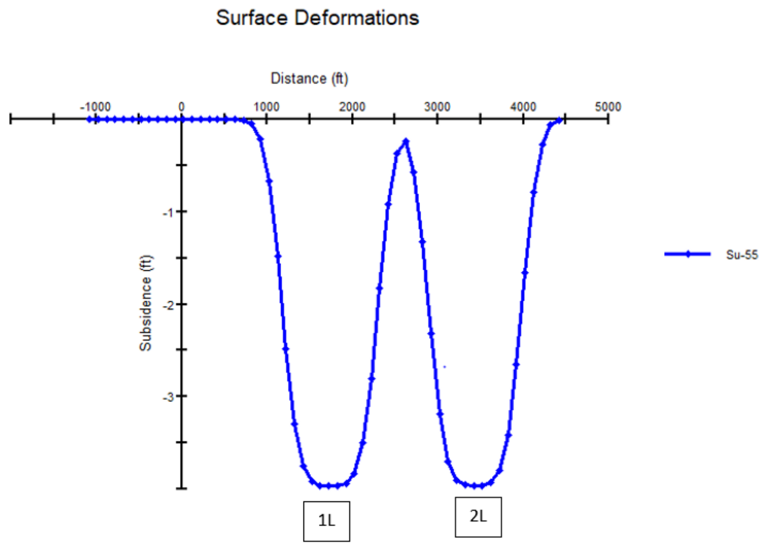

Figure 32. SPDS vertical subsidence prediction for the 1L and 2L panels

The stain induced from the mining of the two panels is shown in Figure 33. As with the modeling of a single panel the strain is highest over the gate roads and approaching zero at the middle of the panels. The maximum stain occurs along edge of the gateroad located between the 1L and 2L panels. This strain value is larger than the maximum over the single panel. This indicates that operators must be more aware when they are mining consecutive panels because the forces are predicted to be larger and therefore have the potential to cause more damage.

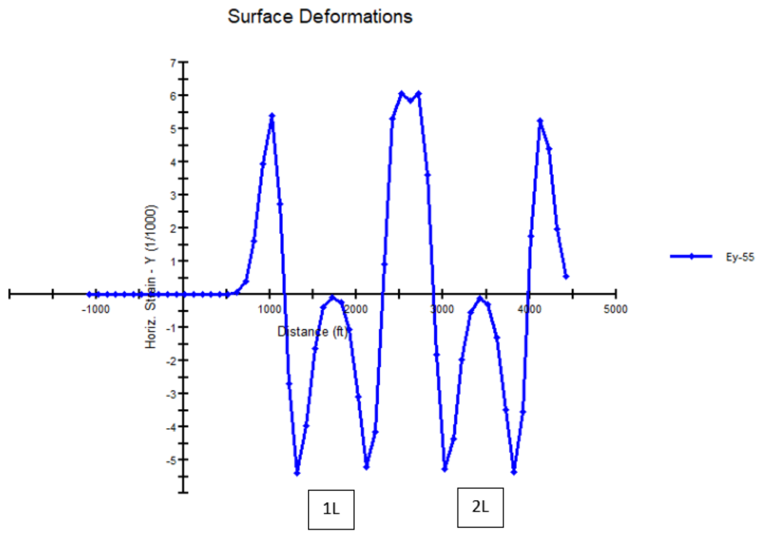

Figure 33. Strain predictions for the 1L and 2L panels

The final SDPS model run was after the 1L, 2L, and 3L panels were mined. This is the most realistic prediction of the final subsidence basin and horizontal strain of the 2L panel because the mining on each side of the panel has been completed. Figure 34 is a 3-D model of the final predicted subsidence basin. Once again, the maximum vertical subsidence at the middle of each of the panels does not vary drastically, and the maximum of each panel is the same. There is very minimal subsidence over gateroads between the 1L and 2L panels as well as the 2L and 3L panels.

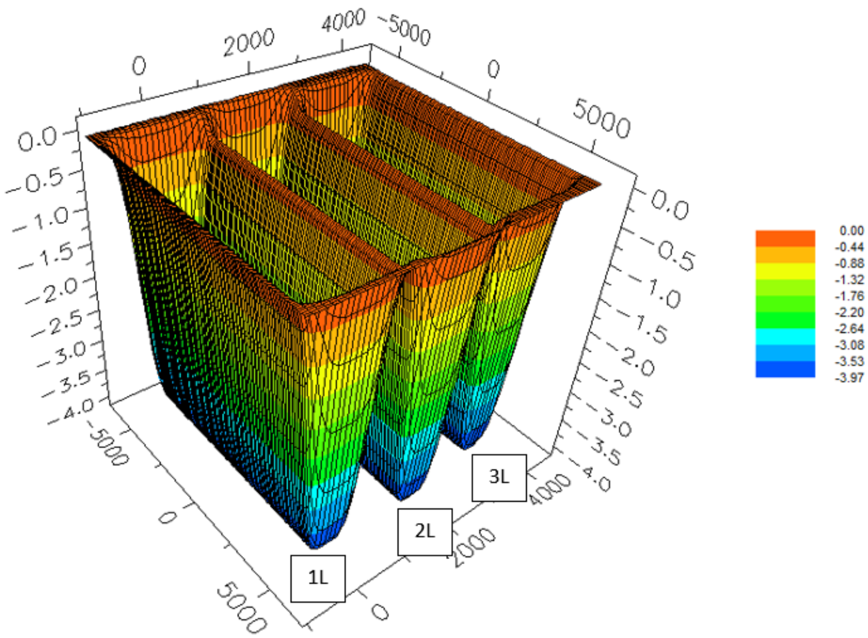

Figure 34. 3D vertical subsidence prediction model for the 1L, 2L, and 3L panels

Lastly the stain over the three panels is seen in Figure 35. The stains once again line up with the area of the largest slope for the vertical subsidence. In the case of three consecutively mined panels, both gate roads on the side of the 2L panels have maximum stains, greater than just one mined panel. The strain is less on the sides that do not have a panel next to it. This shows that in a line of consecutive panels the middle panel is predicted to see the most impacts from subsidence.

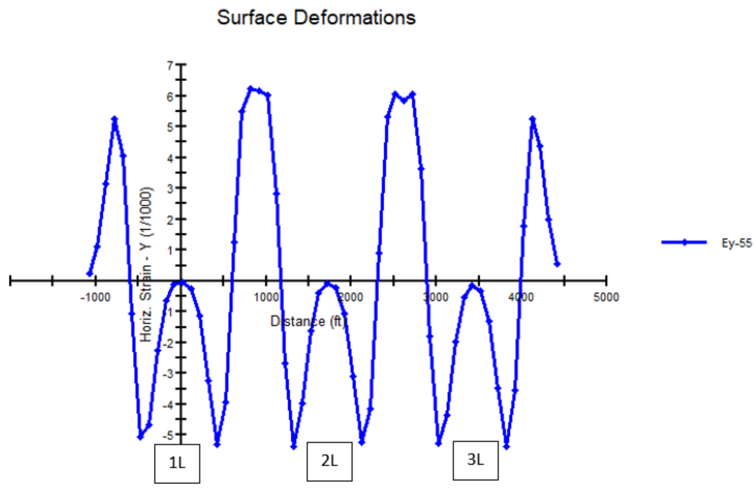

Figure 35. Stain prediction for the 1L, 2L, and 3L panels

6.2.6 Subsidence Impacts

The above SDPS models showed that the highest strains occurred around the edges of the panels in tension and at the end of the sloping subsidence basin in compression. These are the areas that the damage is predicted to be the most extreme. Figure 36 shows all reported effects over the 1Lthrough 6L Bailey longwall panels. The impacts are recorded as company liable or company not liable.

Looking particularly at the 1L, 2L, and 3L panels it is important to take note of where the company liable impacts are occurring. Over the 1L panel there are five company liable structures along the edge of the panels, three of which are located near the gateroad connecting the 1L panel with the 2L panel where the SDPS models showed the highest strain. In the 2L panel there are five watersources that are company liable around the edge of the panel. Indicating that structures are not the only impact occurring in areas of elevated strain. The deforming ground along the edges can cause the previous mentioned cracks and fissures to form redirecting the flow of water. The company liable land impacts are also predominately along the edges of the panels. In all three panels the company liable impacts were located an average of 211-ft from the edge of the panels.

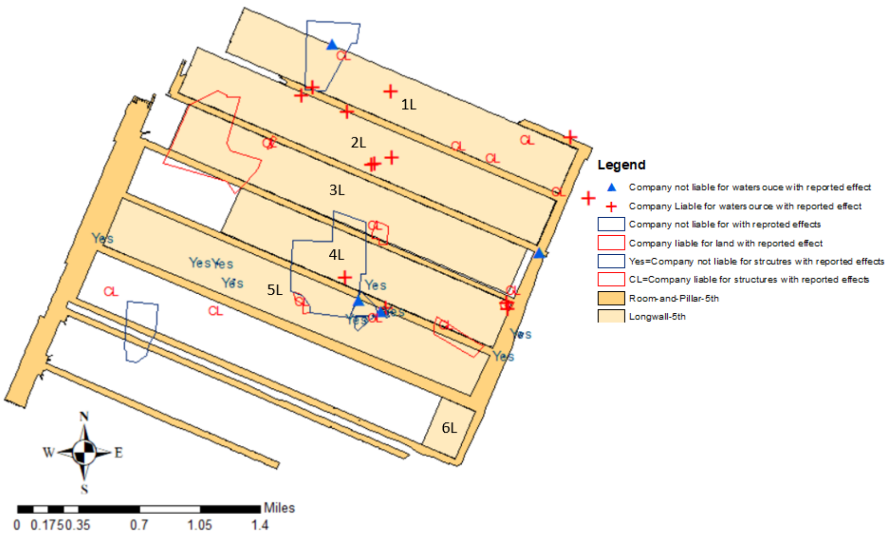

Figure 36. Location of all reported effects over the Bailey 1L, 2L, and 3L panels

6.3 Mitigation Strategies

While the above map shows the location of the impacts, it is unknown if mitigations were done to all the structures or watersources over the 1L, 2L, and 3L panels in areas of high predicted strain. Mitigation techniques are most often used on structures that will experience future undermining. There are some companies that rely on mitigation techniques, while other would rather compensate the owner for damages (Tonsor et al., 2013). Examples of structure mitigation include:

Banding- Banding involves the wrapping of tensioned steel cables or nylon or polypropylene rope around typically the foundation of the structures. At the corners of the structures wood boards are placed between the ropes and structures to distribute the forces (Tonsor et al., 2013).

Bracing- Bracing is typically wood, or metal placed diagonally across an opening in the structure (Figure 37). The bracing helps to stiffen the structure (Tonsor et al., 2013).

Figure 37. Bracing of an undermined structure in the 3rd Act 54 assessment (Photograph courtesy of N. Evanek)

Bridging- Bridging is also used to stiffen a structure and protect it from differential settlement and is often applied in the attic (Tonsor et al., 2013).

Trenching- Trenching is when a trench is excavated to the bottom of the foundation (typically around 2-ft in depth) all the way around the structure. This is the most effective way to absorb the horizontal strain surrounding a structure (Figure 38) (Tonsor et al., 2013).

Figure 38. Trenching of an undermined structure in the 5th Act 54 assessment

Cribbing- Cribbing is when a structure is placed on wooden crib to aid in vertical movement and uneven settlement (Tonsor et al., 2013). The crib's elevation can be adjusted so that the structures above them stay level. Figure 39 shows cribbing applied to a house located on a slope.

Figure 39. Timber cribbing to support an outbuilding during the 5th Act 54 assessment (Photograph courtesy of the PA DEP)

Mitigation of watersource and land impacts can be harder to achieve. In some cases, water and gas lines can be excavated and placed on the surface so movement within the ground surface is less likely to affect them. When on the surface they can also be inspected for damages more regularly. A more flexible piping can also be used in place of the rigid pipe, allowing for more movement. While mitigation strategies can be helpful to reduce damages, damage can still occur even with mitigation strategies.

7.0 Far Field Effect Case Studies

As described in Section 6, models are used to predict the vertical subsidence and strain that are expected to occur from underground bituminous coal mining. These models aid in the prediction of impacts occurring to surface features and are also used as guide by the operators and PA DEP to determine if an impact is mining related. However, in recent years there has been an increase in literature discussing impacts that are occurring outside of this predicted region, and whose expected cause is underground mining (Hebblewhite et al., 2000). These unexpected impacts are referred to as "far field effects." There has been recording of far field effects on structures, watersources, and land features over the last 25-years in the United States and in Australia (Hebblewhite and Gray, 2014).

In 2000, Hebblewhite, Waddington, and Wood noted that high topographical relief in mining areas in Australia can result in unexpected subsidence behavior. These behaviors include, gorge closure, gorge base uplift, and large-scale regional mining induced horizontal displacement. Subsidence events were noted up to 5000-ft from mining in the direction of the gob. In creek beds where there is high relief, large compressive strains and bumps occurred. The "Valley Notch Effect" was defined by mining induced stress changes that unlock strata and can result in the closure of gorges, valley bulging, and/or base uplift. Gorge closures have been recorded up to 1500-ft before the longwall face passing beneath it. They also note that massive cantilevering of the gob can cause far field effects of subsidence and uplift (Hebblewhite et al., 2000).

Hepplewhite compares the far field effects recorded in Australia with those occurring in the United States, specifically at the far field effects at Ryerson Station dam. Like the Australian terrain, Ryerson Station dam is in an area of steep hills. The compression bump in the road and uplift in the flat region are consistent with the valley closure (Hebblewhite and Gray, 2014).

In 2005, a 45-year-old concrete gravity dam in Ryerson Station State Park was breached due to the deteriorating conditions of the dam. At the time mining from the Baily mine was 900-ft from the damn, the angle of draw being over 66-degrees. A PA DEP report shows that, prior to mining in the area, the Ryerson Station dam had been inspected and was noted to be in relatively good condition. There had been a crack noted in the dam prior to the mining occurring, but the leaking increased in July 2005 before the beach occurred. Along with the damage to the dam, buckling occurred on a nearby road where the dam extends under the road. There was also vertical uplift in a flat area near the dam. Extreme loading conditions on the dam and the stability of the hill slopes surrounding the damn where checked, but the damages observed could not be attributed to either of these factors.

The PA DEP has recorded five other notable times that impacts that occurred There were stream impacts that have occurred 1,200-ft from mining of the Maple Creek mine (Pennsylvania Department of Environmental Protection California District Mining Office, 2010) and structure damage that has occurred over 1,000-ft from the Emerald mine (Pennsylvania Department of Environmental Protection California District Mining Office, 2010). Far field effects are also noted in the most recent Act 54 assessment, with notable far field effects occurring within the Enlow Fork, Harvey, and Bailey mines.

7.1 Chapel Hill Property Case Study

Data recorded by the landowner and the PA DEP agent for the far field effect at the Enlow Fork Mine allows for a detailed timeline of the damages that occurred to the Chapel Hill property versus the distance of mining. The impacts occurred over the F25 panel that was mined from February 2015 to April 2016. The mining company was determined to be liable for the impacts to the land and structures. The list below shows approximate distance from mining and the descriptions of the impacts that were being observed on the property. This timeline was recorded by the landowner and was reconstructed from the PA DEP inspector’s notes.

- Mining is about 690-ft on the week of October 25, 2015 and the landowner starts to note small signs of damage
- Mining is about 480-ft away on the week of November 9, 2015 and the house is noted to be out of level, i.e. the doors are not closing, and stove is tilting. The homeowner also starts to hear cracking and popping in the house.
- Mining is about 330-ft away on November 17, 2015 and the landowner is provided a methane detector by the mine operator and notes the roof, patio, and driveway have noticeable damages to them and a roll is forming in the field across from the home.
- Mining is about 330-ft away on November 18, 2015 and well that supplies the property starts to run back.
- Mining is about 100-ft away on November 23, 2015 and the roll that had developed in the field has extended to reach the front yard through the backyard as well as through the patio. The damages to the driveway and patio are becoming a heave feature, another roll formed in the back of the house.

The images in Figure 40 show examples of the impacts that occurred. The photograph of the damage to the driveway was taken on November 19, 2015. The photograph of the roll in the hillside across from the property was taken on November 23, 2015.

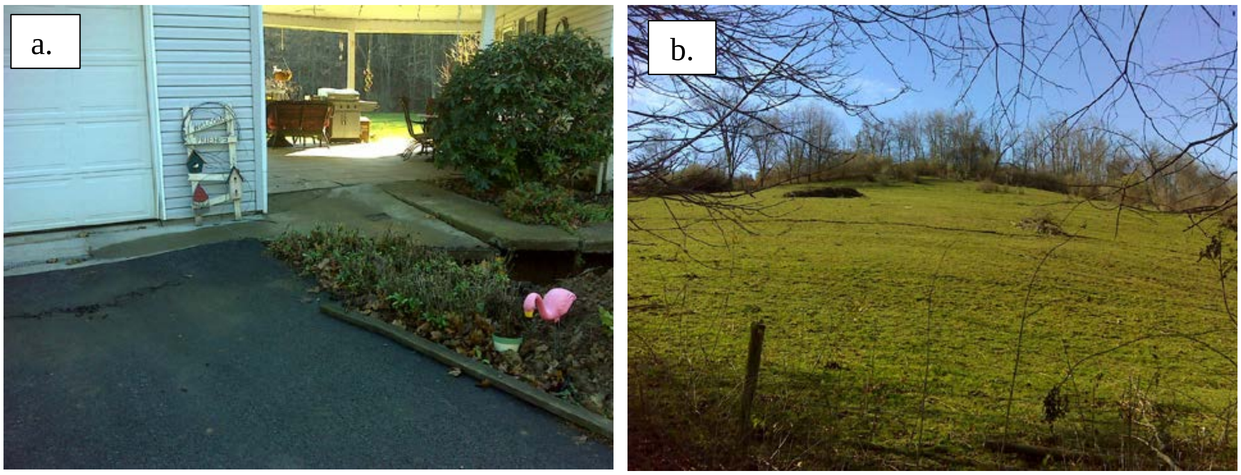

Figure 40. a.) Damage the driveway b.) roll forming in the hillside across from the property

The furthest distance from mining that damage was noticed was 690-ft, this is well beyond the limits of predications using current modeling techniques. When the damage to the well occurred, the well was located within the RPZ of the F25 panel, and the property was eventually directly undermined by the F25 panel on December 3, 2015. The F24 panel had previous mined approximately 610-ft to the southwest of the property from February 2013 to January 2014 but there no impacts to the property noted in that time period. The maps in Figures 41 and 42 shows the location of the property with respect to 5th assessment mining and the location of the active longwall face from the property when the first impacts were recorded.

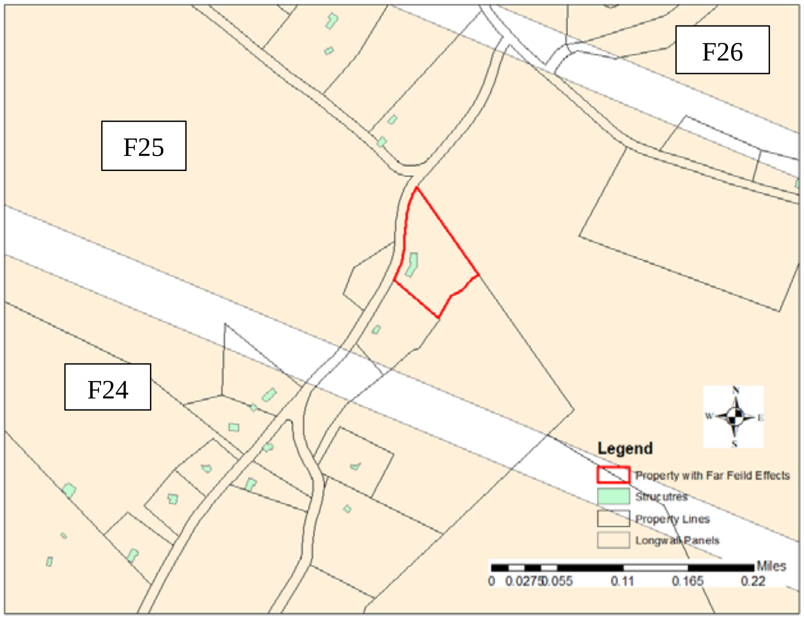

Figure 41. Map of Enlow Fork F25 panel with fair field impact property

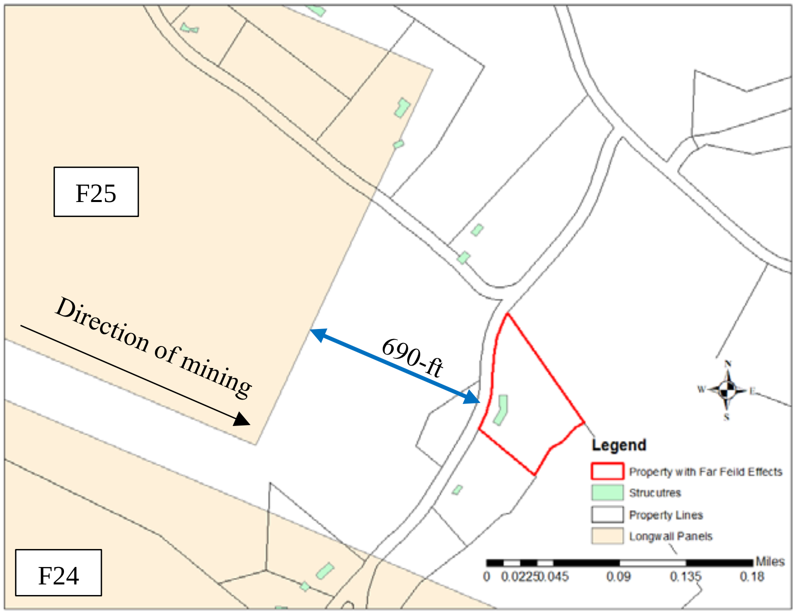

Figure 42. Location of the F25 longwall panel when the first impact was noted

The angle of deformation was calculated for the impact that occurred 690-ft from the edge of mining. The critical angle of deformation for the Pittsburgh coal bed in the Appalachian region was defined by Peng in 1992 as generally 10-degrees less than the 45-degree angle of draw. The calculated angle of deformation was determined to be 47-degrees, when the first impact was noted (Figure 43). This is larger than the 35-degrees predicted by Peng (Peng, 1992).

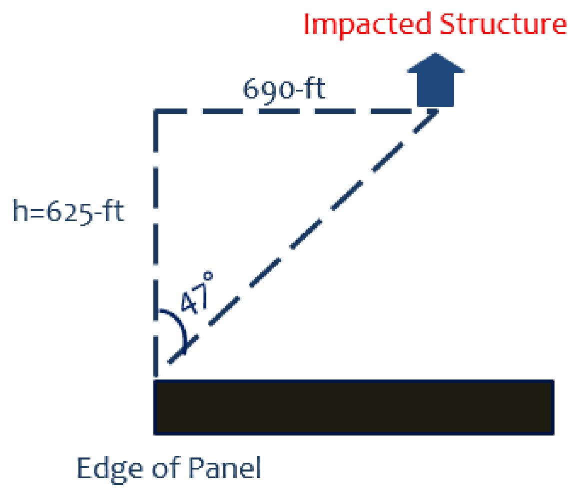

Figure 43. Angle of deformation of far feild effect*

Note distance not to scale

The topography of the area surrounding the far field impact is defined by steep hills and stream valleys. The impacted property is located at the bottom of a hillside to the east and west, with a creek located at the back of the house. The hillside to the west of the property had a maximum elevation of approximately 1,200-ft and the property was located at an elevation of 1,000-ft. The hillside slopes perpendicular to the direction of mining of the F25 panel (Figure 44).

The elevation of the Pittsburgh coalbed is shown in Figure 45, in this area of Enlow Fork the coalbed has a slight increase in elevation south of the impacted property.

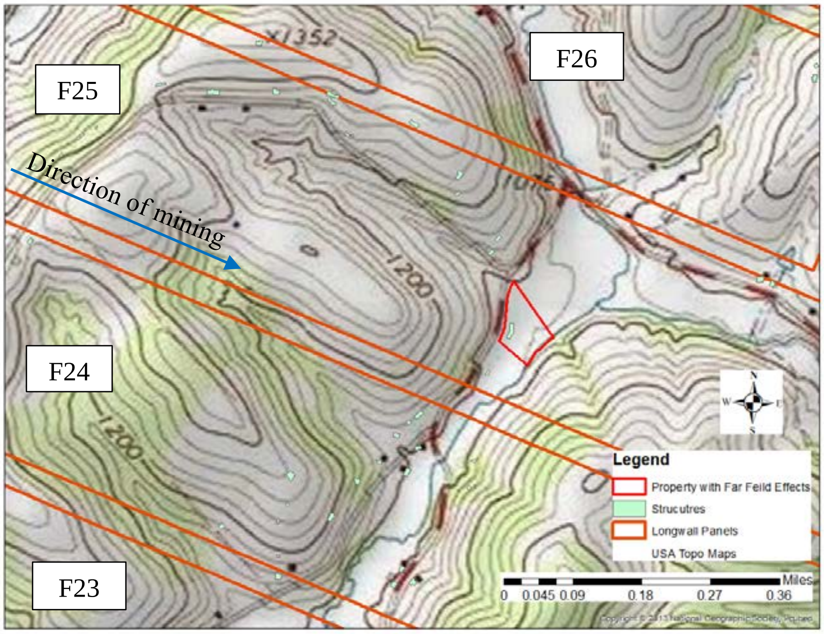

Figure 44. Topography of impacted area

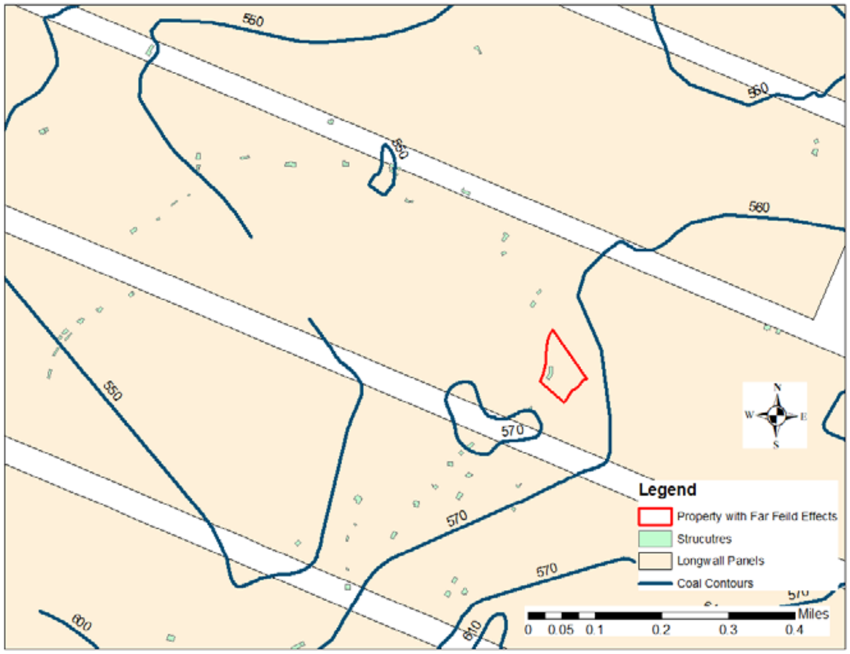

Figure 45. Elevation of the Pittsbrugh Coalbed

As explained in Section 5.3, the area over the Enlow Fork mine has many ancient landslides due to its rugged topography and geologic materials. A review of the mapped landslides believed to have occurred during peri-glacial conditions associated with the last glaciation indicates an ancient landslide on the hillside perpendicular to mining and across from the property were the roll was first noticed (Figure 46). A study was done using the RocScinece program SLIDE to determine if the hillside could have failed in naturally occurring conditions or extreme saturation or seismic events. If the ancient landslide was naturally reactivated, this could have been the cause of the impacts to the property and hillside.

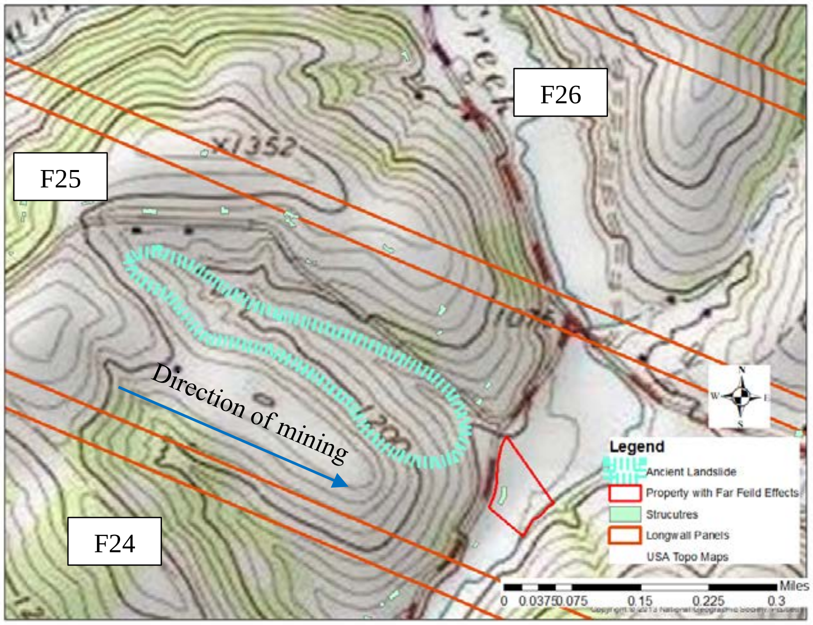

Figure 46. Ancient landslide outlined on the hill adjacent to the impacted property

The SLIDE analysis was performed by collecting the soil information for the area and running the program under varying soil saturation conditions. The soil in the area is defined by loam deposits and the distance from the soil and regolith to the bedrock ranges between 19-ft to 78-ft. When no water is present on the hillside the program output a factor of safety of 1.78 indicating that the slope would not fail under these conditions. The factor of safety was 1.48 when there was no water and a seismic event occurred. The hillside did not fail until the soil was fully saturated the slope had a factor of safety of only 0.43 and indicated a small failure in the surface soil at the toe of the slope across from the property. When the fully saturated slope was subjected to seismic activity the factor of safety dropped to 0.4, but the indicated failure was still a small surface soil failure away from the house. These small predicted failures were not considered large enough to cause the damages seen to the property. So, by this analysis, it was determined the reactivation of the landslide through extreme saturation or seismic activity could not be cited for the events that occurred prior to undermining.

After eliminating the cause of the impacts to be the natural reactivation of the ancient landslide by saturation and seismic activity, mining related causes were investigated. The topography is like that near the Ryerson Station Dam, steep hillsides with stream valleys at the bottom. As Hebblewhite compared the Ryerson Station dam with the valley closure characteristics happening in Australia, so can the far field effects that occurred in this case study. The house becoming out of level when the mine was 480-ft away indicates the uneven movement of the ground. And the heave that is described in the driveway and porch are consistent with those that occurred in the flat areas of Ryerson Station.

Along with the valley closure theory the dynamic subsidence wave was examined. With the dynamic subsidence wave the ground alternates between tension and compression. The damage to the driveway was first seen as a crack but it is noted that it later turned into a heave. The crack is indication of tension while compression causes the ground to heave.

The property owner filed an impact claim to the state on November 18, 2015 and a final resolution was reached on December 9, 2015. The landowner and company entered into an unspecified agreement, so no additional information about the damages or repairs were recorded by PA DEP.

7.2 Morris Township Case Study

Far field effects occurred during the 5th assessment period over the Harvey Mine as well. These impacts happened even further from mining than the Chapel Hill property case study, and they have not yet reached a final resolution. The impacts occurred to the Morris Township Community center and surrounding structures during the mining of the of the 3A and 4A Harvey panels when the mine was located as distant as approximately 3,720-ft from the nearest active longwall mining. The 3A panel was mined first from January 2017 to December 2017 followed by the 4A panel which was started in February 2018 and finished in January 2019. The far field impacts occur over a four-month period. The timeline below describes the impacts that occurred to a township community center and the surrounding land and structures. The timeline was developed from the information provided in BUMIS and the 6-month mine maps.

- Longwall mining from the 3A panel is approximately 3,700-ft from the town community center and a dwelling, located on the same block, on December 11, 2017 and cracks in the plaster and basement are cited for both structures.
- On February 9, 2019 there was structure damage reported approximately 800-ft from the gob of the 3A panel. The damage was cited as cracks to the foundation, ceiling, and floors of two structures as well as the doors sticking. During this time there was no active mining as the longwall face was being moved from the end of the 3A panel to the start of the 4A panel.
- On February 19, 2018, the gob of the 3A panel was still 800-ft away and the 4A panel had just started active mining over 3 miles away the when a structure and land impacts occurred. The doors in the basement were sticking and sink holes had developed in the yard.

- Once again, on March 1, 2018 when the gob of the 3A panel was 800-ft away and the active 4A mining was 3 miles away damage was reported to a structure and land. The structure had leaks in the basement allowing for water to enter and a hump formed in the back yard.

The map of the Harvey mine during the 5th assessment in August 2018 in Figure 47 shows the location of the properties that were damaged from December 11, 2017 to March 1, 2018. The blue lines on the longwall panels indicated the position of the face and gob when the damages occurred, and the distance that they were from the impacted properties. It should be noted that none of the properties were directly undermined by the longwall panels but were undermined by development room-and-pillar mining in December of 2014.

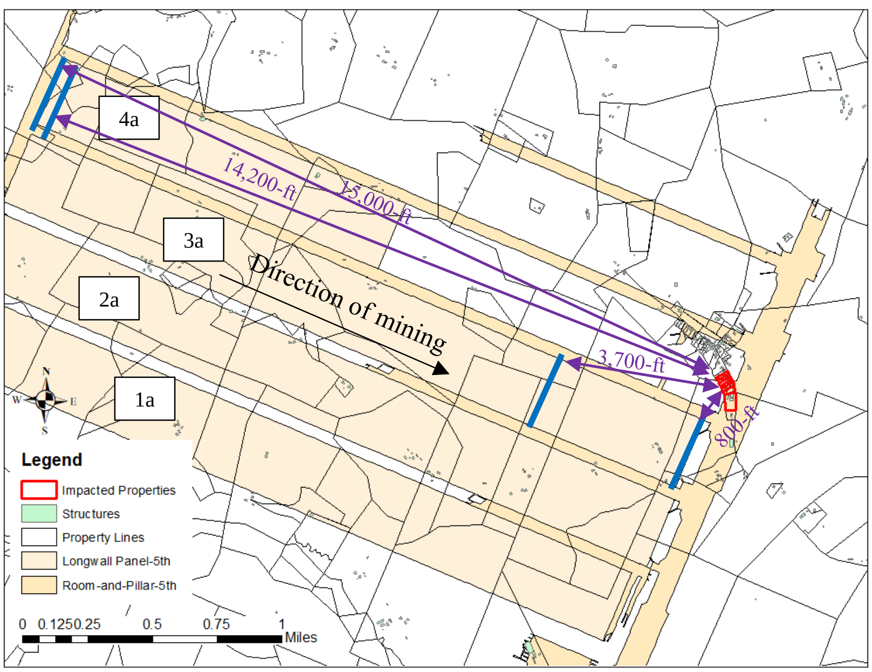

Figure 47. Distance from longwall face posistions and the areas of longwall panel extraction as of August 2019, the face positions during impacts are shown in blue.

Figure 48 shows a zoomed in image of the 3A panel and the properties impacted by mining. The blue lines represent were the face or gob of the 3A panel was located when the impacts to the property occurred.

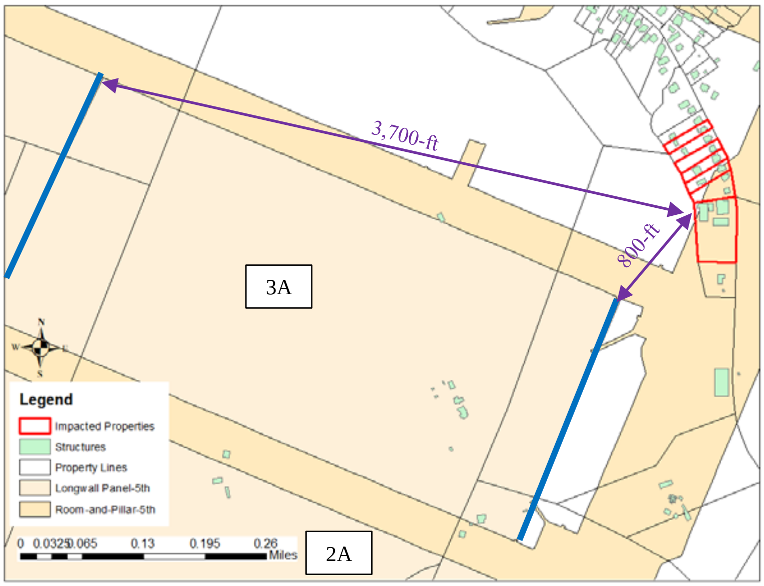

Figure 48. 3A panel of the Harvey Mine and far feild effects

Examples of the damages that occurred from December 11, 2017 to March 1, 2018 are shown in Figure 49. The most notable damage is the crack that arose in the township community center and the hump the formed in the back yards of the properties.

Figure 49. a.)Crack in the wall of the community center b.) Compression hump in the yard (Photographs courtesey of the PA DEP files)

The angle of deformation was calculated for all the far field impacts with respect to the 3A panel (Figure 50). As mentioned above the expected angle of deformation in the area is 35-degrees. To calculate the angle of deformation the overburden and distance the impact was from mining were used. The first impact occurred 3,700-ft from the edge of mining and the angle of deformation was 77-degrees. The impacts that were located 800-ft from the gob of the 3A panel had an angle of deformation of 44-degrees. This showed that the impacts occurring 800-ft from the 3A panel had an angle of deformation more reasonable in the Pittsburgh coalbed than the first impact observed. The overburden depth of the Harvey mine is deeper than the previous case study in Enlow Fork.

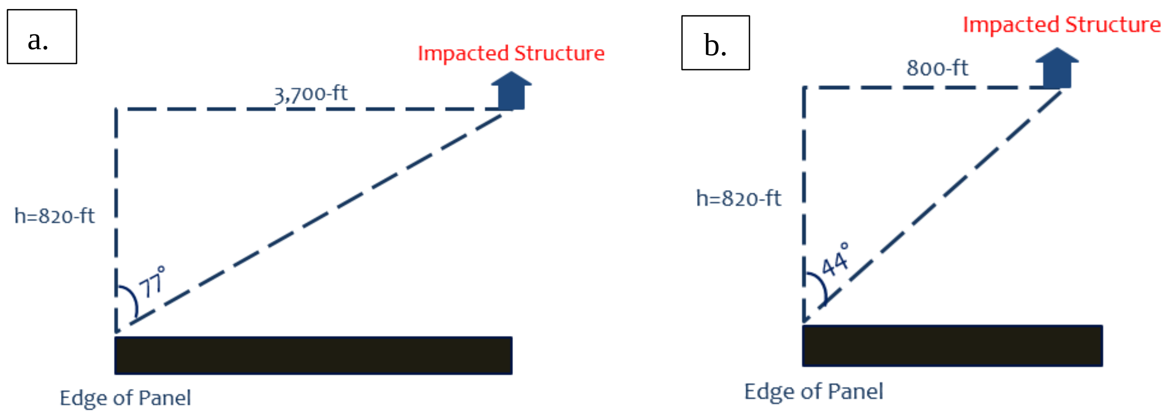

Figure 50. a.) Angle of deformation of the first far field effect* b.) Angle of deformationof of refollowing far feild impacts*

**Note distances not to scale*

The terrain surrounding Morris Township is like that of the Steel property and Ryerson Station Dam. It is defined by steep rolling hills and valleys with streams running through them. The impacted properties are located at the toe of the slope. The top of the slope has an elevation of 1,300-ft and the properties are located at about 900-ft. There are slopes to the east and to the west of the properties perpendicular with the direction of mining (Figure 51). The elevation of coal from the Pittsburgh coal bed can be seen in Figure 52. The coalbed elevation increases at it approached the impacted properties.

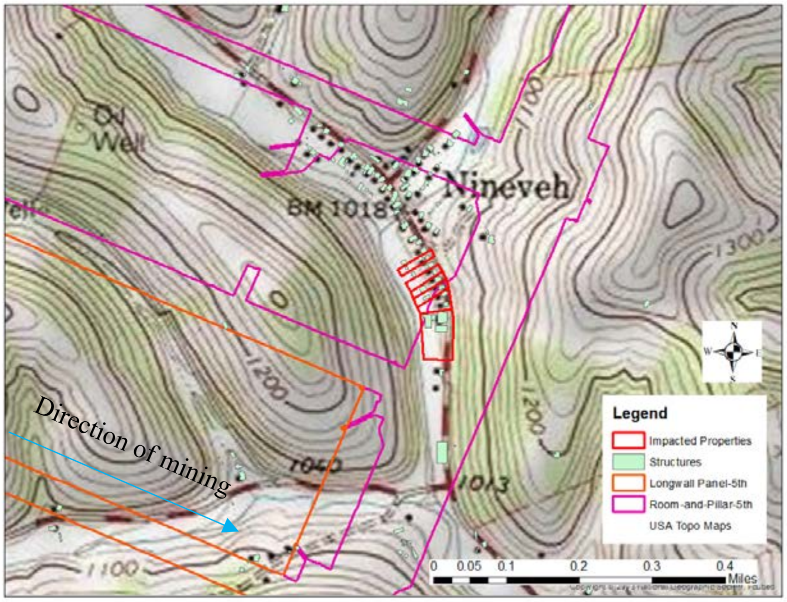

Figure 51. Topography map of the Harvery Mine

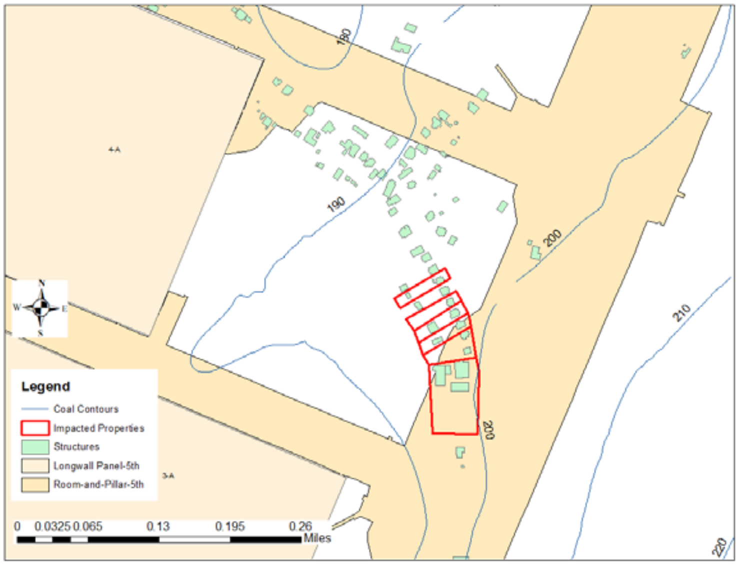

Figure 52. Elevation of the Pittsburgh Coalbed

Unlike the Chapel Hill property, there are no significant ancient landslides mapped over this area that could be investigated as the cause for these impacts. Although it is important to note that because there are no significant historical landslides that are currently mapped over the area does not mean none have occurred. Because of the mine location in Greene County another factor that was investigated was the plethora of natural gas wells operating in Greene County. In Greene County, natural gas is extracted from the Marcellus Shale rock formation located approximately 7,000-ft below the surface. The extraction is done using the hydraulic fracturing technique in which water a high pressure fractures the rock layer and sand or other medium fills the fracture and the gas is extracted (Soeder & Kappel).

There was a natural gas well pad with 12 wells on it developed in 2014 only 900-ft from the impacted structures. The location of the wells and the well pad construction was also the reason that the 4A panel stops before the impacted properties. The wells were drilled in 2014 and the hydraulic fracturing occurred between July of 2014 and October of 2016. Figure 53 shows the location of the wells with respect to the impacted properties, and Figure 54 shows the aerial view of the cite in October of 2016. While the damages to the properties occurred from December 2017 to February 2018, there are no current studies of ground movement data associated with hydro fracturing.

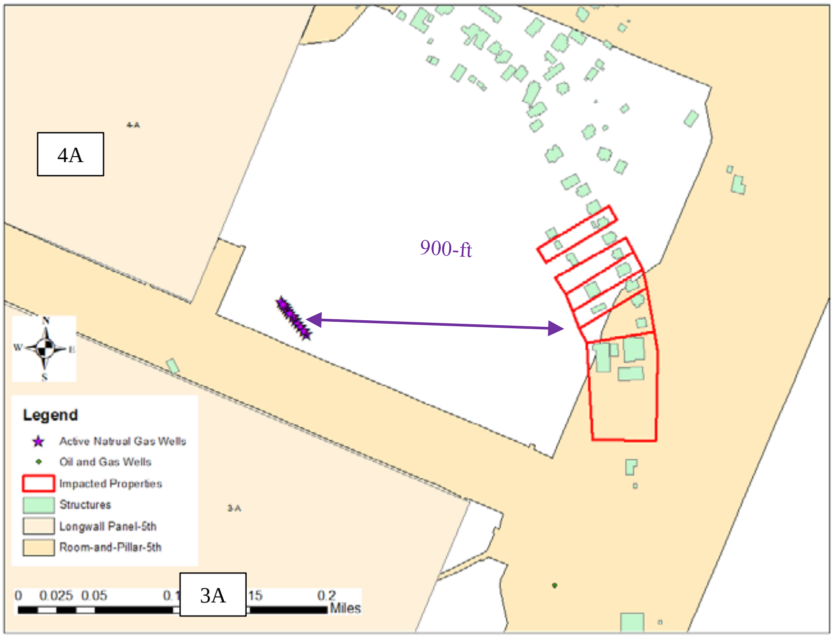

Figure 53. Location of natural gas wells from impacted properties

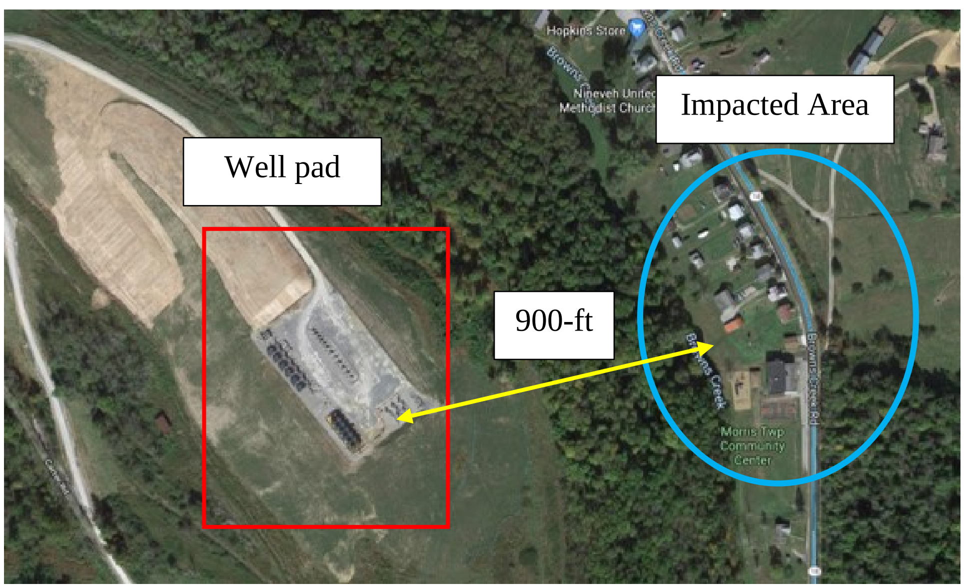

Figure 54. Ariel view of the impacted properties and the location and size of the natural gas well located 900-ft from the impacts

In this case study, the distance of the first impacts at over 3,700-ft is difficult to explain with the current knowledge and examples of far field effects. The impacts that are closer at 800-ft from 3A gob are more comparable to the impacts that occurred at the Ryerson Station Dam and the Chapel Hill property. The steep terrain and nature of the damages that occurred are consistent with the valley closure theories, i.e. unlevel ground and structures and heaves. The possible relationship of the impacts and the natural gas wells in the area cannot yet be concluded. There is no current research showing the impacts that hydrofracturing has on surface movements, or if impacts can occur for a time after fracturing occurs.

There were two land impacts and six structure impacts reported by the landowners to the PA DEP and tracked in BUMIS. None of the impacts have reached a final resolution yet, the mining company and the state are still determining the cause of the impacts and who will be held responsible.

7.3 Bailey Streams Case Study

Far field impacts were detected to streams over longwall panels of the Bailey mine. Typically, a stream flow is measured daily by the operator beginning two weeks prior to its undermining. Because the Bailey mine had previous far field impacts at the Ryerson Station Dam streams overlaying the longwall panels were observed well in advance by the surface subsidence agent. The additional observation identified far field impacts that occurred over three of the Bailey panels mined during the 5th assessment period.

The far field impacts that were observed occurred both directly above panels that were actively being undermined and adjacent to panels that were actively mining. Table 28 indicates the stream that was impacted, the panel that was actively mining, the distance to the longwall face at the time of the impacts, and how many days prior to undermining the stream was impacted (directly under the impact and panels adjacent to the impact). The longest distance from mining, 1,500-ft, occurred in Whitethorn Run over the 2L panel. In Australia, the furthest far field effect to streams was recorded as 1,300-ft (Kay et al., 2006).

Table 28. List of far field impacts to streams over the Bailey mine prior to the typical 14 day before undermining observing period

Active Panel	Stream	Longwall Face Distance from Stream	Days from impact until stream was undermined by panel
1L	Kent Run	610-ft	14 days
2L	Kent Run	1,300-ft	42 days
3L	Polen Run	1,400-ft	28 days
2L	32620	550-ft	20 days
2L	Whitethorn Run	635-ft	17 days
2L (damage over 3L)	32605	900 -ft	431 days(3L)
1L (damage over 1L)	32618	400-ft	16 days (1L) 323 days (2L)
2L (damage over 3L)	32618	1,450-ft	32 days (2L) 353 days (3L)
2L (damage over 3L)	32618	1,450-ft	13 days (2L) 334 days (3L)
2L (damage over 3L)	Whitethorn Run	1,150-ft	38 days (2L) 342 days (3L)
2L (damage over 3L)	Whitethorn Run	1,500-ft	17 days (2L) 321 days (3L)

Figure 55 is a map of the Bailey mine during the 5th assessment period and the streams that had a far field effect as reported in the table above. All the far field impacts were cited as heaves or cracks in the stream beds. All the impacted streams run perpendicular to the direction of mining. It is important to note that the horizontal stress in this area is north 60-degrees east (Peng, 2008). The longwall panels are aligned perpendicular to the horizontal stress field to eliminate unfavorable ground control conditions while mining (Peng, 2008). However, the streams are more parallel with the horizontal stress field, which can cause unfavorable mining conditions and stress concentrations (Peng, 2008).

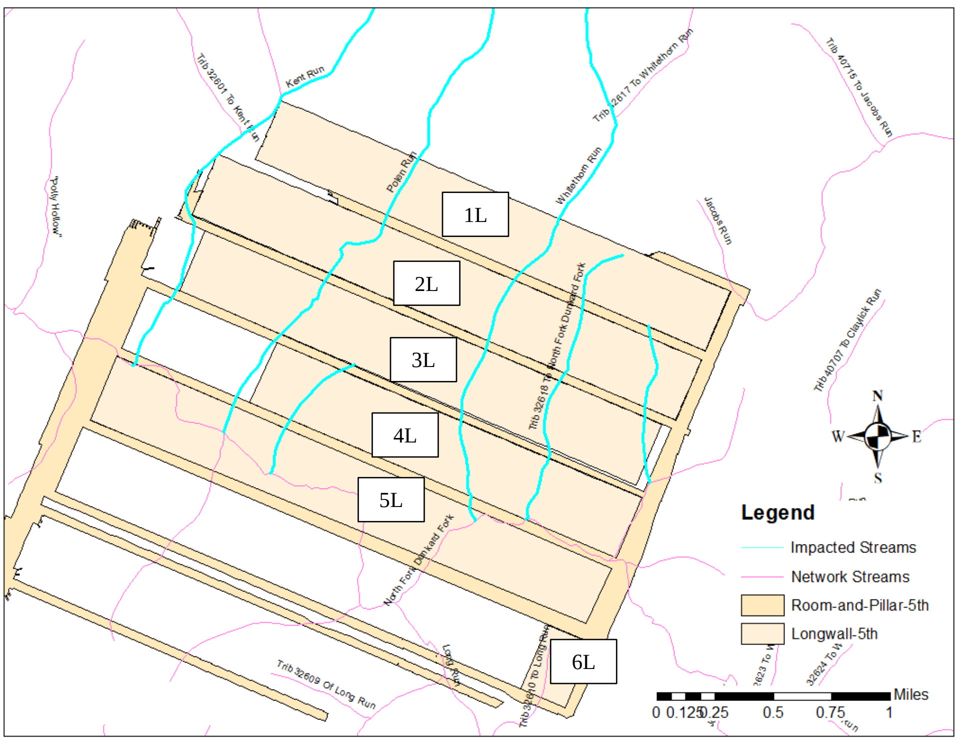

Figure 55. Map of streams with far feild effects over the Bailey mine

The area of the Bailey mine were the far field effects occurred is defined by steep hills and valleys. There is a 300-ft drop in elevation from the top of the slopes to the stream valleys. The map in Figure 56 shows the changes in elevation across the panels. This area is heavily forested and not densely populated. If the streams had not been observed prior to the 14 day required periods, the impacts to the streams may not have been recorded when they occurred.

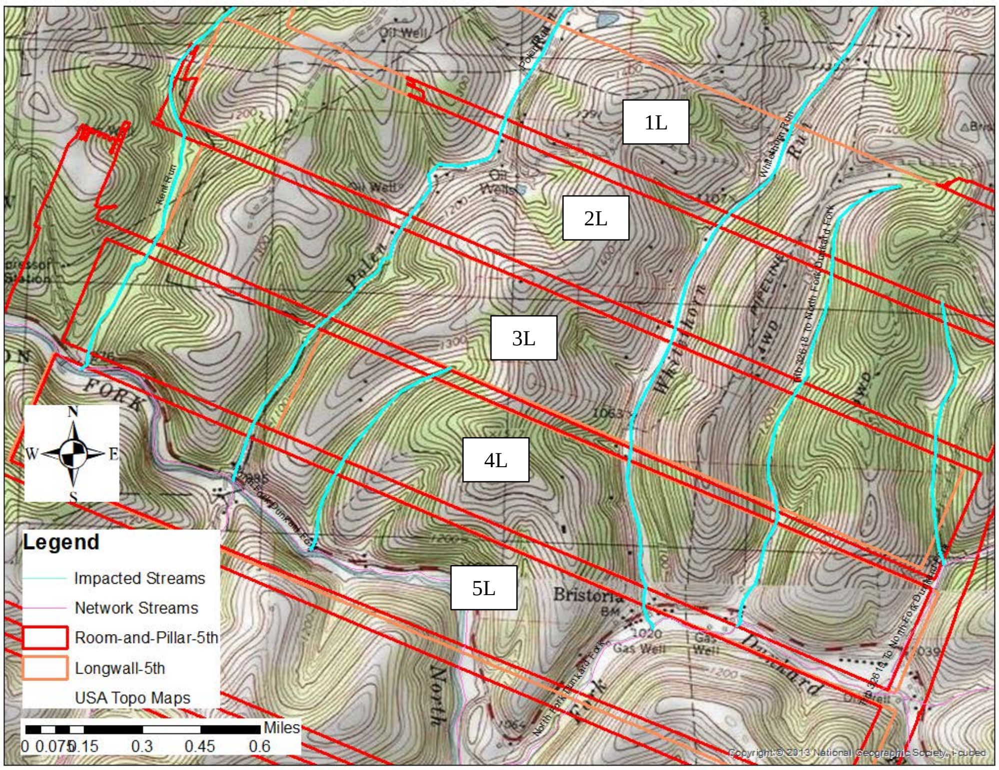

Figure 56. Topography of the Baily Mine and impacted streams

Previous investigations of mining under stream valleys (Molinda et al., 1992) catalog the difficult ground control conditioned faced when undermining stream valleys. The damages occurring to the Bailey Mine streams are like those observed by Molinda, and the impacted streams are parallel with the horizontal stress field of the region. Molinda cites a clear correlation between the roof instability in the mines with proximity to stream valleys (Molinda et al., 1992). The cause of failures in the mine roofs were a result of stress relief in the strata known as “valley effect”. This is like the stress relief theory suggested by Hebblewhite in the Australian fields. The valley effect can be seen at the surface due to the buckling of the valley floor form high horizontal stresses (Molinda et al., 1992). High horizontal stresses can be assumed in stream valleys of the Bailey mine due to the orientation of the valleys with respect to the horizontal stress field. Case studies of the Tahoma mine in Pennsylvania the roof failure in the mine was due to the poor rock mass quality due horizontal stress failures caused by valley stress relief (Molinda et al., 1992).

The mining of the Bailey mine happened in an east to west direction. In this direction the Pittsburgh coalbed has a slight increase in elevation. The figure below shows the coal contours of the Pittsburgh coalbed and the direction of mining. In all the panels the elevation of the Pittsburgh coal increases from the start of the panel to when it reaches the gateroads. The average elevation gain in the coalbed across the panels is 200-ft.

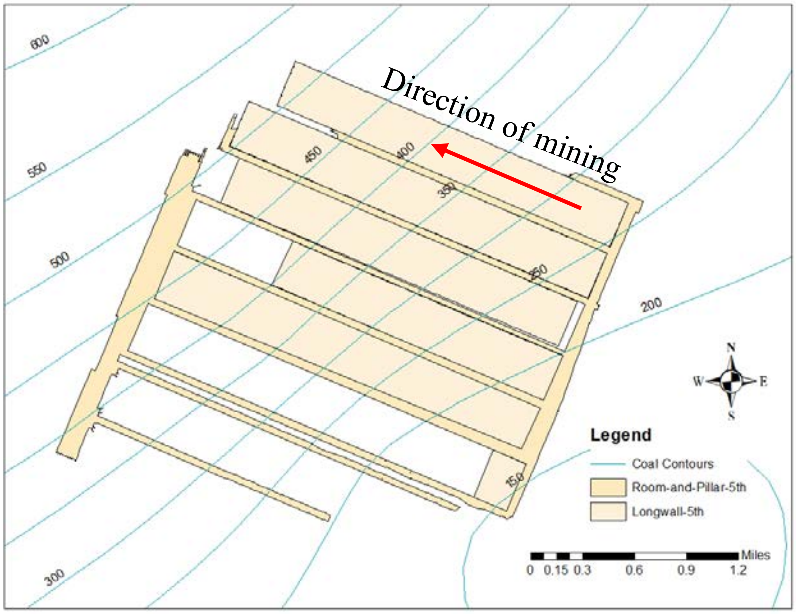

Figure 57. Elevation of the Pittsburgh coalbed across the Baily mine during the 5th assessment period

8.0 Discussion

This discussion will focus further on far field impacts and the implication that they have on the laws and regulations protecting the communities of the Commonwealth of Pennsylvania. The 5th assessment is not the first time that far field effects were discovered. However, the analysis done in Section 7 allowed for a more comprehensive analysis of far field effects occurring in Pennsylvania.

The current empirical and analytical modeling practices, by their nature, are designed to replicate expected or normal conditions associated with the formation of subsidence basins. So, they are incapable of predicting anomalous behavior/conditions that can sometime occur during subsidence basin formation. This manuscript has provided examples of these anomalous conditions. What most often distinguishes them from conditions 'normally encountered' is the distance well beyond those predicted by both empirical and analytical models. Currently, little pre-mining data is being collected more than a few hundred feet from future mining areas. In the absence of data, consensus opinions as the cause of far field subsidence impacts are lacking. Add this lack of data to the infrequent nature of anomalous subsidence basin formation has led to our current inadequate level of understanding. These conditions have inhibited efforts to recognize far field effects and, as a result, inadequately compensate people impacted by this phenomenon. There are no accepted guidelines on how to address far field effects, the PA DEP deals with these cases individually, relying on the expertise of its agents. Agents must rely heavily on the effect of the location and timing of the nearby mining. This research has attempted to identify important trends in the data and factors thought to be the most important contributors to far field effects.

These factors are used to develop a conceptual model that will help explain the origin of far field effects.

The furthest impact occurred over 3,700-ft from active mining, while the other ranged from 1,500-ft to 690-ft. The impacts occurring at ranges of 1,500-ft to 3,700-ft were more difficult to associate with undermining than the later impacts. It is important to note that the lack of recorded cases at this distance may be associated with impacts occurring outside the areas predicted by limited capabilities of our current subsidence models. The practice of overlooking an impact because of the distance to active mining is not sustainable for the increased understanding of why surface features are damaged from mining.

All the far field impacts studied in this analysis were land, structures, and stream impacts. Watersource can have far field effects, but there are no substantial cases noted in the 5th assessment. The first notable trend was the land heaves that formed in all the cases. Eleven agent records described heaves within stream beds, especially when strong strata were present, and the streams channels oriented in a northerly direction. In these cases, streams were generally oriented perpendicular to the direction of mining, and parallel with the horizontal stress field. Three of the cases also had damages to structures that included uneven settlement and the formation of cracks. The description of these land and structures impact matched many accounts of impacts that occurred when mining was close to or directly under the impact area. So, although the impacts described in Section 7 are far from mining their appearances are not uncommon. Other reasonable accounts for how these impacts could have formed could not be found in the PADEP files. Reactivation of the ancient landslide, adjacent to the Chapel Hill property, due to full saturation of the slope or seismic activity could not have impacted the property, and there is no current research describing how hydro fracturing may impact the ground surface. Future research on far field effects should gather pertinent information about large-scale construction projects and pay close attention to the stability of the slopes, especially in areas where past landslides have been identified

Similarities in surface topography of far field impacts were observed. In all four cases, the longwall panel associated with the impact was advancing up in the direction of a steep slope, and the damage occurred at the bottom of the slope. The topography of these locations aligns with the case studies presented by the Australian researchers (Hebblewhite and Gray, 2014). Hebblewhite observed that impacts to land occurred when the longwall face was as much as 5,000-ft from a surface feature. The Harvey mine example was approximately 3,700-ft from mining, although it should be noted that this event is currently classified as an interim resolution. The valley closure theory and gorge uplift were described by Hebblewhite, Waddington, and Wood in 2000, and the impacts were similar to those that occurred in Pennsylvania, i.e. heaves and uneven settlement.

Another interesting trend among the far field effects in this study is the increase in elevation of the Pittsburgh coalbed as the longwall panel mined towards the main entries close to where the longwall face would be recovered. Table 29 shows the average elevation change in the direction of mining across the panels to the impact area. There was an increase in elevation in the panels near Morris Township as well as the Chapel Hill property, but the Bailey streams has the largest elevation increase over the panels. The increased angle that mining occurs when the elevation increases, potentially causing the subsidence basin to form further in advance of the longwall face.

Table 29. Elevation change of the Pittsburgh coalbed across the longwall panels to impacted areas

Far Field Impacts	Coalbed Elevation Increase Across Panels
Chapel Hill Property	100-ft
Morris Township	50-ft
Bailey Streams	300-ft

An Australian study looked at the subsidence effects on highwall stability during punch out longwall mining when mining a steeply dipping surface (Figure 58) (Martin et al., 2018). The highwall was expected to be pulled towards the longwall gob as the strata strains in the direction of the void; however, the survey data indicated that the highwall was being pushed out away from the gob (Martin et al., 2018). It was proposed that the open cut of the highwall (like that of stream valleys) could not contain massive push forward from the subsiding ground normally confined by solid ground. The hypothesized formation of the subsidence basin further in advance of the longwall mine due to sloped coalbeds can be compared to the outward push seen in the Australian highwall. Future studies on far field effects in the United States should focus on the correlation of sloped coalbeds and the outward movement of open cut areas.

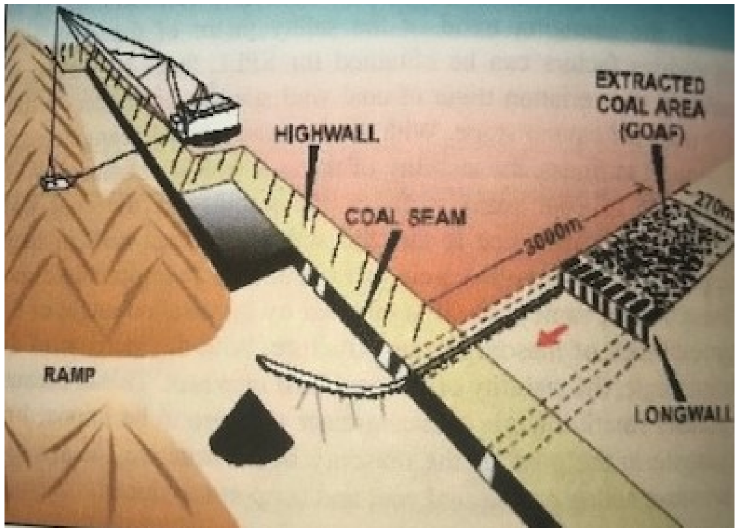

Figure 58. Punch longwall layout (Martin et.al, 2018)

Figure 59 shows an example of a longwall mine undermining a flat surface with no elevation change in the coalbed versus a panel increasing in elevation located in a valley. As described by Martin in the highwall example the valley is not able to contain the push from the bulking of the broken strata causing an outward push into the valley. However, when there is no valley the intact strata is able to contain the bulking of the broken strata and resist the outward push.

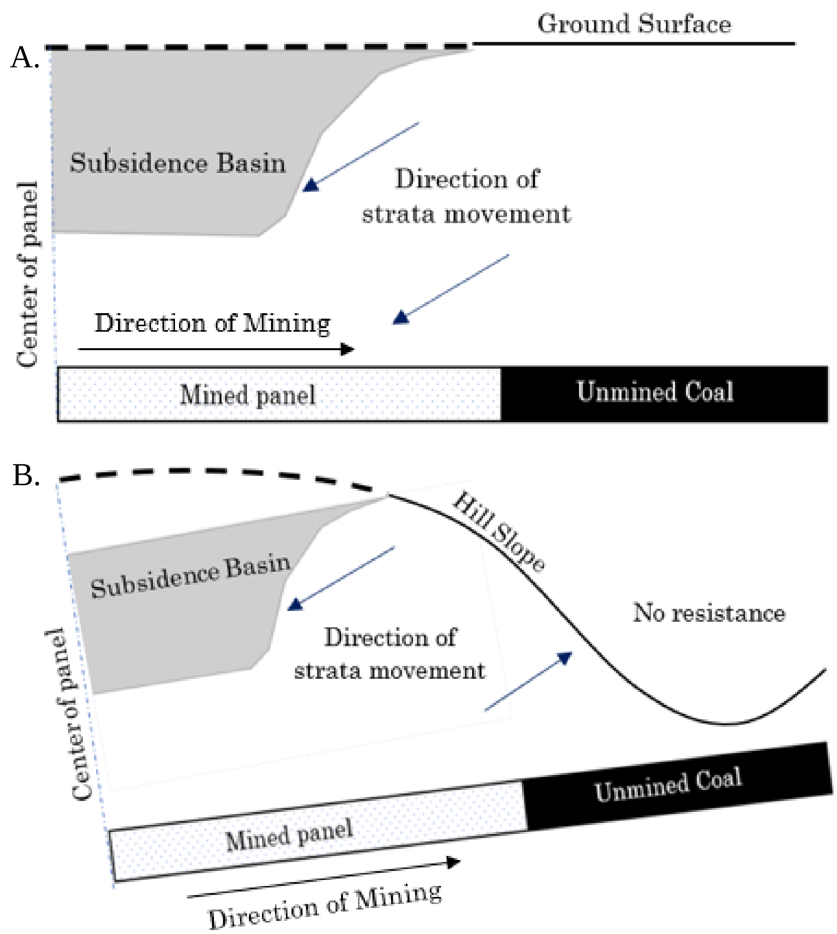

Figure 59. A.) Longwall panel mining the same elevation in flat terrain B.) Longwall panel incrasing in elevation mining in a area of hills and vallies

The study of far field effects brings into question the guidelines set by Act 54 to determine if an impact is company liable within the 200-ft buffer for structure and land impacts, and if 14-day observation period prior to mining is soon enough for stream observations. The frequency of these events is significant enough to consider adjusting existing guidelines to better accommodate far field impacts. It is possible that enhanced awareness will identify more far field impacts. This study suggests the factors of topography, the tendency of the elevation of the coalbed, ancient landslides and any other major construction projects surrounding far field impacts be used to develop the conceptual model. The conceptual model on far field effects will allow better guidance in Act 54 for the protection of the Commonwealth.

The impacts to Ryerson Station Dam and the Chapel Hill property were determined to be company liable, but the final liability has not yet been decided for any of the impacts to Morris Township. Damaged streams over the Bailey mine were mitigated as needed. The study of far field effects brings into questions the guidelines set by Act 54 to determine if an impact is company liable or not. If the current 200-ft buffer is not enough, what is? Does buffer need to be extended or do the characteristics of the areas being mined such as the tendency of the elevation of the coalbeds, the topography, and location of ancient landslides need to be considered more vigilantly? With continued tracking more trends can be determined to understand favorable conditions for far field impacts to occur. More trends will allow for more detailed strategies for handling far field effects and increased protection for communities and environments undermined in the Commonwealth.

9.0 Summary

The information recorded from Act 54 has allowed for an all-inclusive analysis of the underground bituminous mining done in in the last 25 years. There was a total of 175,814 acres mines in over 100 mines in 13 counties. The following are key observations made over the 25-year period.

- During the 25-year period the total acres mined, and active mines have decreased by 65% from the first to the 5th assessment period but the acres mined only decreased by 25%. The largest decrease in acres mined occurred during the 4th assessment period, which aligns with the increased retiring of coal fired energy production facilities and the decrease in natural gas prices.
- The larger the extraction ratio the more likely there is to be subsidence and subsidence related impacts. Longwall mines had the largest extraction ratio and the most company liable impacts and room-and-pillar has the least.
- There was a total of 4,647 impacts reported in BUMIS for watersources, structures and land and 47% of these impacts were determined to be company liable. Watersources were the most impacted features and had the most company liable outcomes. Watersource impacts occurred over all three mining types while structure and land impacts occurred mainly over longwall mining.
- During the 3rd, 4th, and 5th assessments an average of 18% of structures located directly above longwall panel had a company liable impact. The average percent of company liable impacts over the three assessment periods has decreased from the 3rd to the 5th assessment period.

- The state and the mine operators can use current prediction techniques and the impact data collected over the last 25 year to better understand how the mining of longwall panels will affect surface. The empirical formulas used to predict subsidence in the Pittsburgh coalbed have been verified by field data collected from the 5th assessment period. The subsidence prediction software shows the mining of consecutive panels causes higher strains over the internal panels. The recorded impacts of Bailey mine during the 5th assessment align along the edges of the panels in the areas of highest strain.
- Land impacts have not been tracked as consistently throughout the 25 years; they can go unnoticed if they are in remote areas. In all the assessment periods 94% of the company liable land impacts were associated with longwall mines.
- Impacts are occurring that are beyond the realm of the current prediction methods, these are referred to as far field effects. The Ryerson Station Dam impact is a far field effect that has been extensively studied. During the 5th assessment, notable far filed effects occurred over the Enlow Fork, Harvey, and Bailey mines to land, structures, and streams. Similar features observed form all the impacts indicated trends in topography and changing coalbed elevations.
- Factors identified in this study for the conceptual model of far field effects include: topography, the tendency of the elevation of the coalbed, ancient landslides and any other major construction projects surrounding the area.
- Advancing technology has dominated how the mine layouts have changed, and how future mining will advance. The widths of the longwall panels and the maximum overburden encountered has increased over each assessment period. Future longwall mining is projected to mine overburdens an average of 5% deeper than the 5th assessment.

- At current mining rates and conditions there is an estimated 28-60 years remaining of longwall mining in the Pittsburgh coalbed in Pennsylvania.

The observations made show the importance of the continued analysis of the Act 54 data. The analyzed data demonstrations the strengths that the strict laws and regulations have with protecting the communities and environment of the Commonwealth of Pennsylvania. The attention to notable and unexpected issues over the last 25-years will allow for the guidelines set by the laws and regulations and the mining industry to adapt to future circumstances.

10.0 Conclusion

The purpose of this study was to analyze the affects that mining laws and regulations have had on the communities and environments of the Commonwealth of Pennsylvania. The emphasis on environmental stewardship and sustainable mining practices in the Pennsylvania has evolved over the 250-year history of Pennsylvania mining. The current requirements of the PA DEP Act 54 set Pennsylvania's underground bituminous coal mines' regulating and reporting standards as some of the strictest in the county. With 25 years of data collected through Act 54 tendencies were identified to study the impact of the strict laws.

The resolution of 4, 647 reported impacts to watersources, structures, and land shows how Act 54 has worked to protect Pennsylvania's features and advance its mining industry. In the last 25 years the mining companies have been responsible for 47% of all the impacts. When the company is held liable, they are required to fairly compensate or repair the damages cause. As a result, without Act 54 there would be over 2,222 impacts from due to mining that would have been the total responsibility of the property owner to repair.

The amount of underground bituminous coal mined has decreased by 25% since the enactment of Act 54, but this decease cannot be directly attributed to the Act 54 and the mining laws. It is associated rather with the decrease in demand for coal nationally for energy production. While acres mined has decreased each assessment period the company liable impact per acre did not decrease with the acreage. This shows that mining is occurring over more populated areas. Before Act 54 and previous regulations, the mining under heavily populated areas would be difficult for the mining company and property owners. But with Act 54 both the mining company and landowner can be assured that the impacts will be repaired or compensated if they are due to mining. This assurance allows for mining companies to mine more of their reserves and continuing good environmental stewardship practices.

Other examples of Act 54 improving the mining industry include the mining companies agreeing to repair a damage for the sake of being a “good neighbor”. It has also allowed for the identification of impacts that are happening beyond the limit of expected impacts. The study of the far field effects questions the proposed guidelines and standards of the current laws. The improvement of the standards and guidelines calls for detailed studies of mining methods and the reexamination of current impact mechanisms. The examination of impacts in this study allowed the factors of topography, the tendency of the elevation of the coalbed, ancient landslides and any other major construction projects surrounding the area be identified as important features in the conceptual model of far field effects. With continued data collection and more complete information the factors and conceptual model of far field effects will be an aid to those determining the liability of the impacts. Additional data permits for more informed decisions and the better protection of the landowners.

It is concluded that the laws and regulations placed on Pennsylvania’s underground bituminous coal mine industry have had a positive impact on the communities of the Commonwealth. The laws hold the mining companies responsible for damages they cause and assure that communities that are undermined are not adversity impacted. The law also gives the companies the opportunities to continue to mine in Pennsylvania and contribute to local economy and jobs. It is advantageous to have the data from Act 54 continue to be collected so that the trends described in this study can be elaborated further. Future investigation on the trends described in this analysis are imperative to the continued success of the protection of the citizens, communities, and environment from the underground bituminous mining industry in the Commonwealth of Pennsylvania.

Table 30. Impacts recorded in BUMIS from August 21, 2013- August 20, 2018

Mine Name	Type of Mine**	Mining Method (Acres)			Total (Acres)	Structures				Watersources				Land				Streams Undermined (Miles)
		Room-and-pillar	Pillar Recovery	Longwall		RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	
Acosta	RP	45			45	0	0	0	0	3	0	1	2	0	0	0	0	0.00
Barbara 2	RP	32			32	0	0	0	0	6	3	3	0	0	0	0	0	0.00
Barrett	RP	381			381	0	0	0	0	0	0	0	0	0	0	0	0	0.56
Beaver Valley	RP	138			138	0	0	0	0	2	0	2	0	0	0	0	0	0.06
Brubaker	RP	361			361	0	0	0	0	2	0	2	0	0	0	0	0	0.00
Brush Valley	RP	548			548	0	0	0	0	1	0	1	0	0	0	0	0	2.00
Cass 1	RP	244			244	2	0	2	0	4	0	2	2	0	0	0	0	0.50
Cherry Tree	RP	158			158	1	0	1	0	3	0	3	0	0	0	0	0	0.36
Clementine 1	RP	118			118	5	2	3	0	23	8	15	0	2	0	2	0	0.08
Coral Graceton	RP	59			59	0	0	0	0	0	0	0	0	0	0	0	0	0.03
Cresson	RP	5			5	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Crooked Creek	RP	351			351	0	0	0	0	0	0	0	0	0	0	0	0	0.93
Darmac 2	RP	180			180	0	0	0	0	3	0	1	2	0	0	0	0	0.23
Dutch Run	RP	225			225	2	0	2	0	6	2	3	1	0	0	0	0	0.40
Gillhouser	RP	146			146	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Harmony	RP	339			339	0	0	0	0	5	0	4	1	0	0	0	0	0.47
Heilwood	RP	261			261	4	0	4	0	4	2	2	0	0	0	0	0	0.61

Table 30. (continued)

Mine Name	Type of Mine**	Mining Method (Acres)			Total (Acres)	Structures				Watersources				Land				Streams Undermined (Miles)
		Room-and-pillar	Pillar Recovery	Longwall		RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	
Horning	RP	5			5	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Kimberly	RP	267			267	0	0	0	0	5	1	4	0	0	0	0	0	0.04
Kingstonwest	RP	69			69	0	0	0	0	0	0	0	0	0	0	0	0	0.05
Knob Creek	RP	339			339	0	0	0	0	3	1	2	0	0	0	0	0	1.10
Kojancic	RP	256			256	0	0	0	0	0	0	0	0	0	0	0	0	0.38
Logansport	RP	206			206	4	0	4	0	4	2	2	0	2	0	2	0	0.28
Lowry	RP	118			118	5	0	1	4	0	0	0	0	0	0	0	0	0.48
Madison	RP	800			800	2	0	1	1	4	0	4	0	1	0	0	1	0.41
Maple Springs	RP	123			123	1	0	0	1	6	0	3	3	0	0	0	0	0.35
Mine 78	RP	688			688	6	0	6	0	3	1	2	0	2	0	2	0	3.27
North Fork	RP	540			540	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Ondo	RP	105			105	3	0	3	0	2	0	2	0	0	0	0	0	0.50
Parkwood	RP	387			387	0	0	0	0	8	1	6	1	0	0	0	0	1.26
Penfield	RP	393			393	0	0	0	0	11	1	7	3	0	0	0	0	0.94
Quecreek 1	RP	355			355	0	0	0	0	0	0	0	0	0	0	0	0	1.60
Roytown	RP	1			1	0	0	0	0	1	0	1	0	0	0	0	0	0.00
Starford	RP	28			28	1	0	1	0	0	0	0	0	0	0	0	0	0.07
TJS 6	RP	15			15	0	0	0	0	0	0	0	0	0	0	0	0	0.06

Table 30. (continued)

Mine Name	Type of Mine**	Mining Method (Acres)			Total (Acres)	Structures				Watersources				Land				Streams Undermined (Miles)
		Room-and-Pillar	Pillar Recovery	Longwall		RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	
Toms Run	RP	228			228	2	0	2	0	6	3	3	0	0	0	0	0	0.53
Tracy Lynne	RP	220			220	4	1	3	0	5	2	3	0	1	0	1	0	0.03
Twin Rocks	RP	108			108	3	0	3	0	2	0	2	0	0	0	0	0	0.00
Subtotal	*RP*	*8842*			8842	*45*	*3*	*36*	*6*	*122*	*27*	*80*	*15*	*8*	*0*	*7*	*1*	*17.58*
4 West	PR	1577	137		1714	1	0	1	0	2	1	1	0	1	0	1	0	5.90
Crawdad	PR	150	85		235	0	0	0	0	0	0	0	0	0	0	0	0	0.27
Nolo	PR	156	14		170	0	0	0	0	6	3	3	0	2	0	0	2	0.03
Prime 1	PR	2	18		20	0	0	0	0	2	2	0	0	0	0	0	0	0.00
Subtotal	*PR*	*1885*	*254*		*2139*	*1*	*0*	*1*	*0*	*10*	*6*	*4*	*0*	*3*	*0*	*1*	*2*	*6.2*
Bailey	L	717		2265	2982	40	26	2	12	22	16	3	3	21	11	5	5	11.31
Cumberland	L	1081		2507	3588	24	8	7	9	22	14	1	7	11	6	0	5	10.69
Emerald	L	96		523	619	24	5	16	3	10	5	3	2	11	3	7	1	1.71
Enlow Fork	L	2115		4071	6186	222	180	12	30	135	100	8	27	37	31	1	5	22.30
Harvey	L	455		1759	2214	22	7	1	14	24	13	0	11	9	5	1	3	8.60
Monongalia County	L	580		1474	2054	5	0	5	0	6	1	3	2	5	4	1	0	7.94
Tunnel Ridge	L	111		120	231	8	3	0	5	14	9	1	4	5	3	0	2	0.14
Subtotal	*L*	*5154*		*12719*	*17874*	*345*	*229*	*43*	*73*	*233*	*158*	*19*	*56*	*99*	*63*	*15*	*21*	*62.69*
Inactive Mines during the 5th Assessment Period***						64	15	19	30	14	1	11	2	14	4	6	4	

Table 30. (continued)

Mine Name	Type of Mine	Mining Method (Acres)			Total (Acres)	Structures				Watersources				Land				Streams Undermined (Miles)
		Room-and-Pillar	Pillar Recovery	Longwall		RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	RE*	CL*	CNL*	I*	
Total		*15881*	*254*	*12719*	*288854*	*455*	*247*	*99*	*109*	*379*	*192*	*114*	*73*	*124*	*67*	*29*	*28*	*86.47*

*-RE= Total Reported Effects, CL=Company Liable Effect, CNL= Company Not Liable Effect, and I= Effect in Interim Resolution.

**-RP-Room-and-pillar mining, PR-Room-and-pillar with pillar recovery, and L=Longwall mining.

***-Inactive mines include: Augustus, Barbara 1, Blacksville 1, David Dianne, Emilie1&2, Geronimo, High Quality, Keystone East, Long Run, Mine 84, 3 Deep, Ridge, Rossmoyne, Stonycreek, TJS 1, Urling 1& 3

Appendix B

Table 31. Mine codes used by the University for active mines during the 5th assessments

Mine	Mine Code
Longwall Mines	
Bailey	By
Cumberland	Cu
Emerald	Em
Enlow Fork	Ef
Harvey	Hr
Monongalia County	Mo
Tunnel Ridge	Tu
Room-and-Pillar Mines	
Cherry Tree	Ch
Clementine 1	Cl
Coral Graceton	Co
Cresson	Cr
Crooked Creek	Ck
Darmac 2	Dm
Dutch Run	Dr
Gillhouser	Gh
Harmony	Hy
Heilwood	Hw
Horning	Hd
Knob Creek	Kc
Kojancic	Kj

Table 31. (continued)

Logansport	Lg
Lowry	Ly
Madison	Ma
Maple Springs	Ms
Mine 78	M7
North Fork	Nf
Ondo	Od
Parkwood	Pa
Penfield	Pf
Roytown	Rt
Starford	St
TJS 6	T6
Toms Run	Tr
Tracy Lynne	Tl
Twin Rocks	Tw
Kimberly	Kr
Pillar Recovery Mines	
Kingstonwest	Ki
4 West	Fw
Crawdad Portal B	Cd
Nolo	No
Prime 1	Pr
Quecreek 1	Qc

Longwall Mines

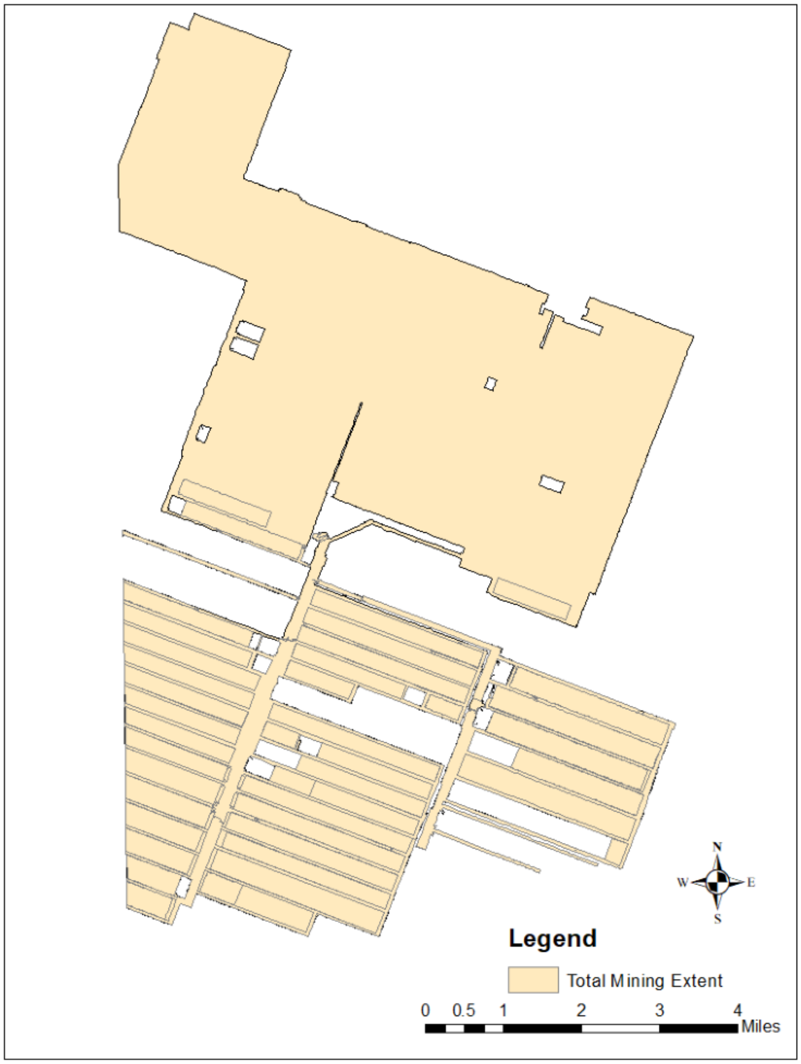

Figure 60 Bailey Mine total extent of mining

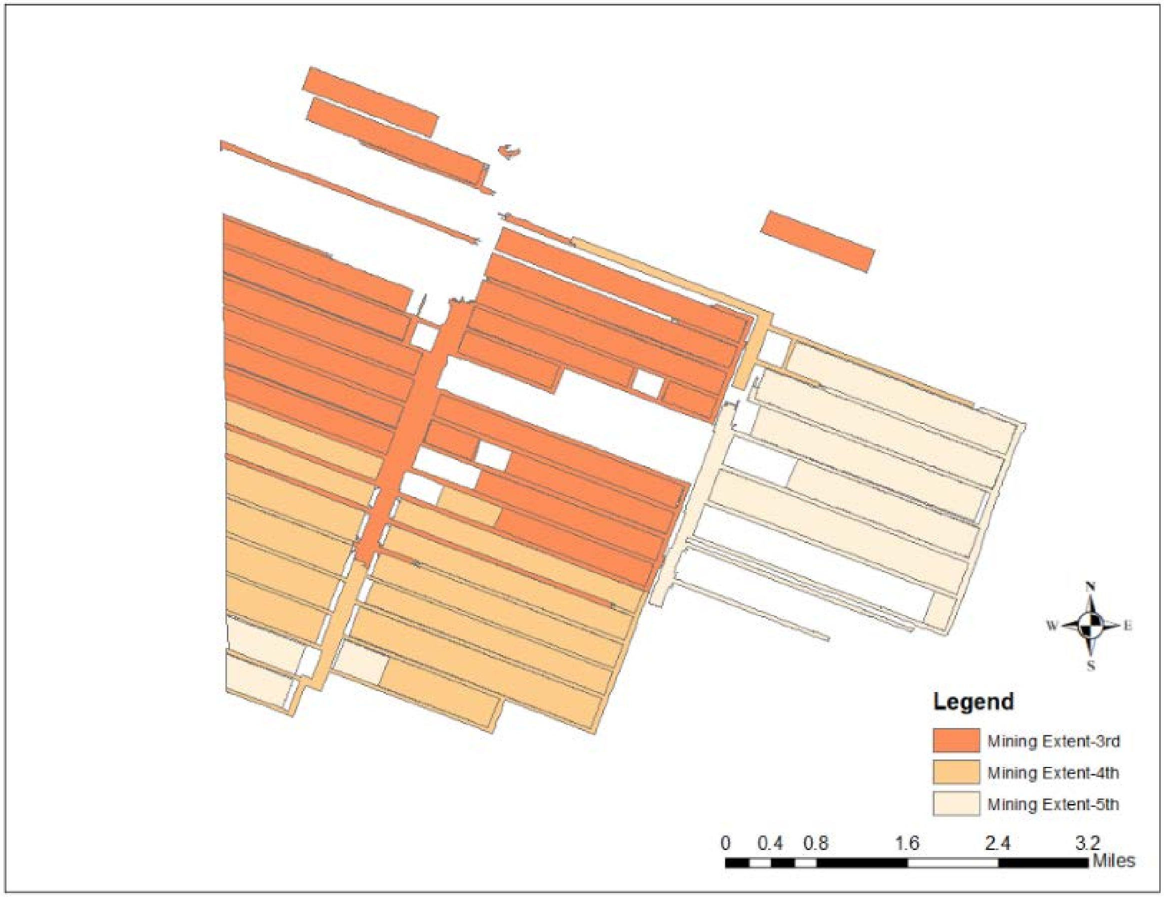

Figure 61. Bailey mining extent for the 3rd, 4th, and 5th assessment periods

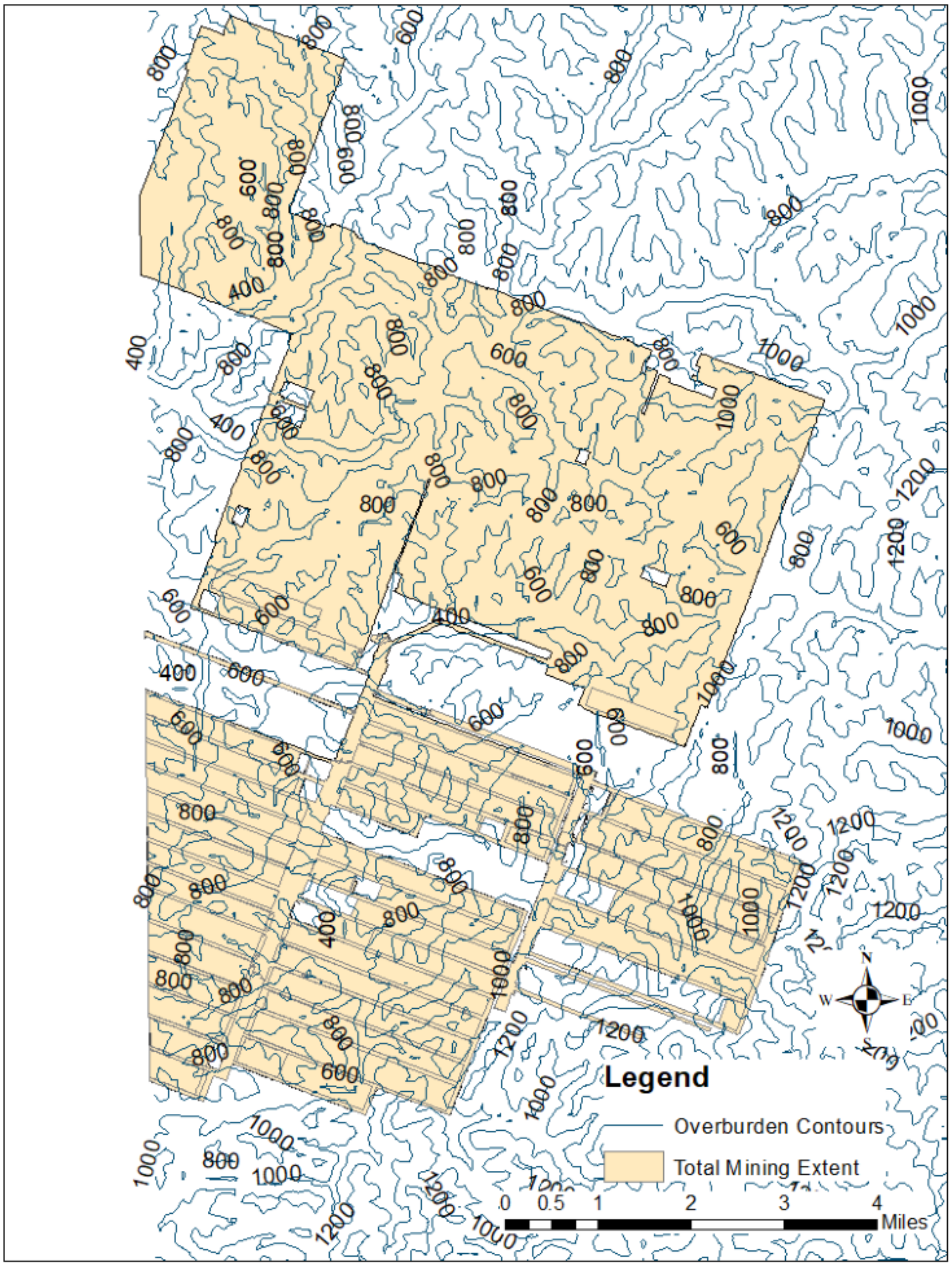

Figure 62. 200-ft interval overburden contour map for the total mining extent of Bailey Mine

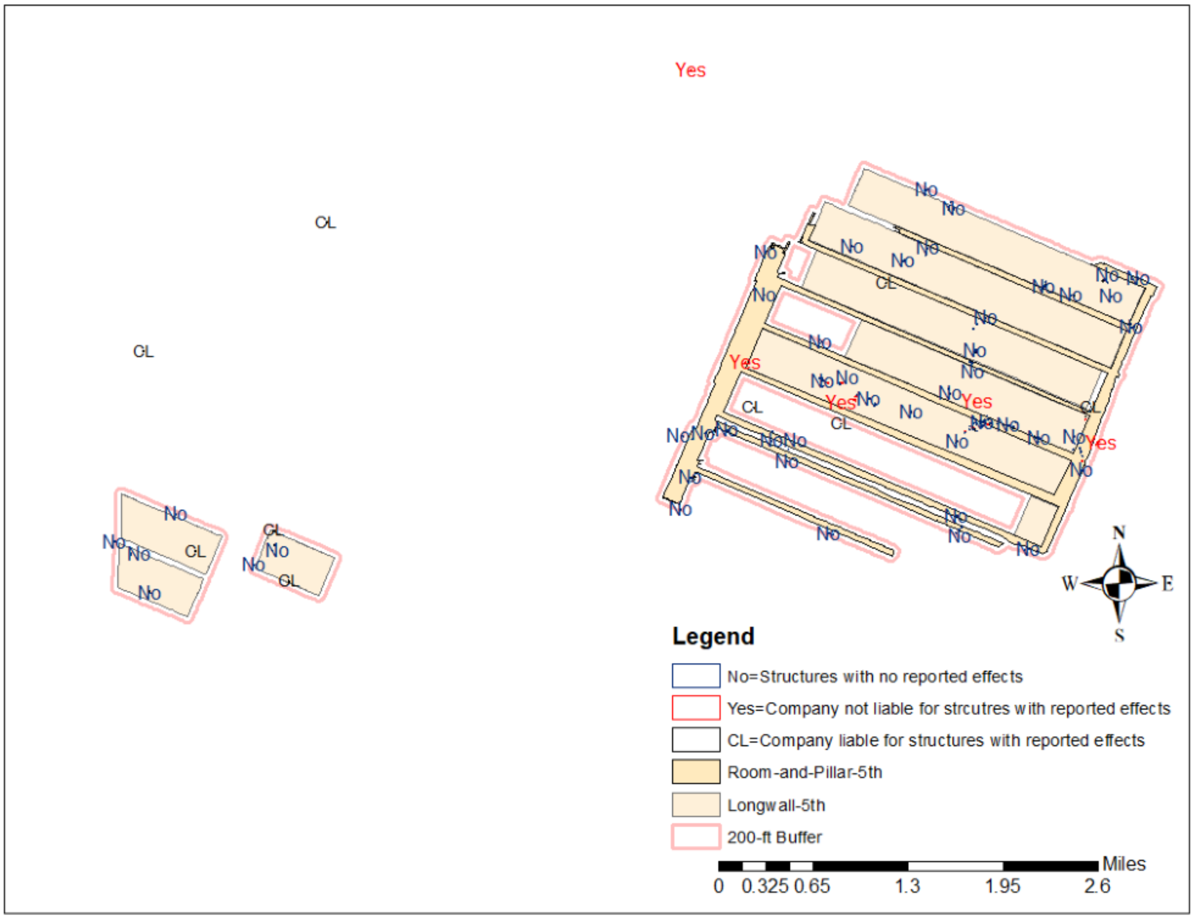

Figure 63. Bailey Mine 5th assessment 200-ft buffer and structures*

*****_Note there are four structure with reported effects determined to be company liable that are not shown here for display purposes._

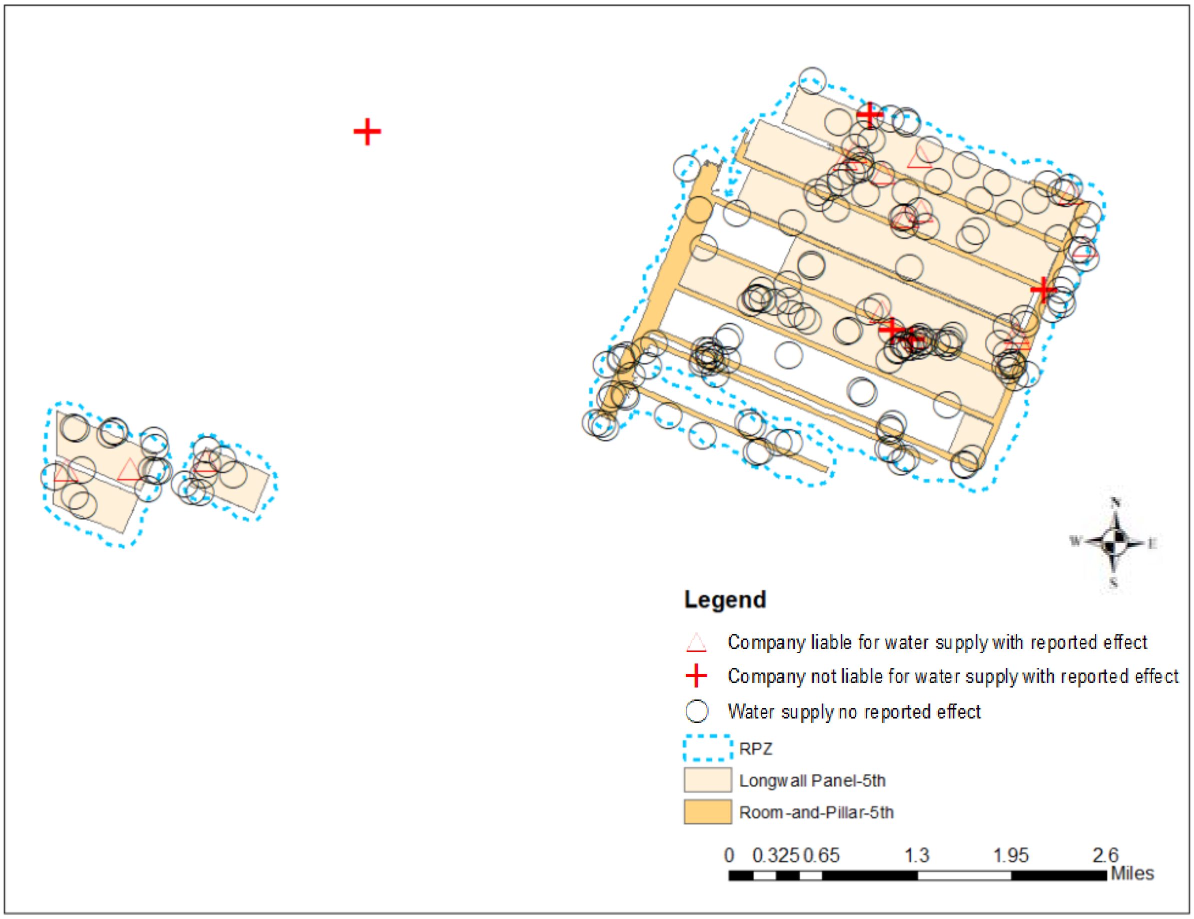

Figure 64. Bailey Mine 5th assessment water supplies and RPZ*

***Water supplies with reported effect was determined to be not company liable is not shown.**

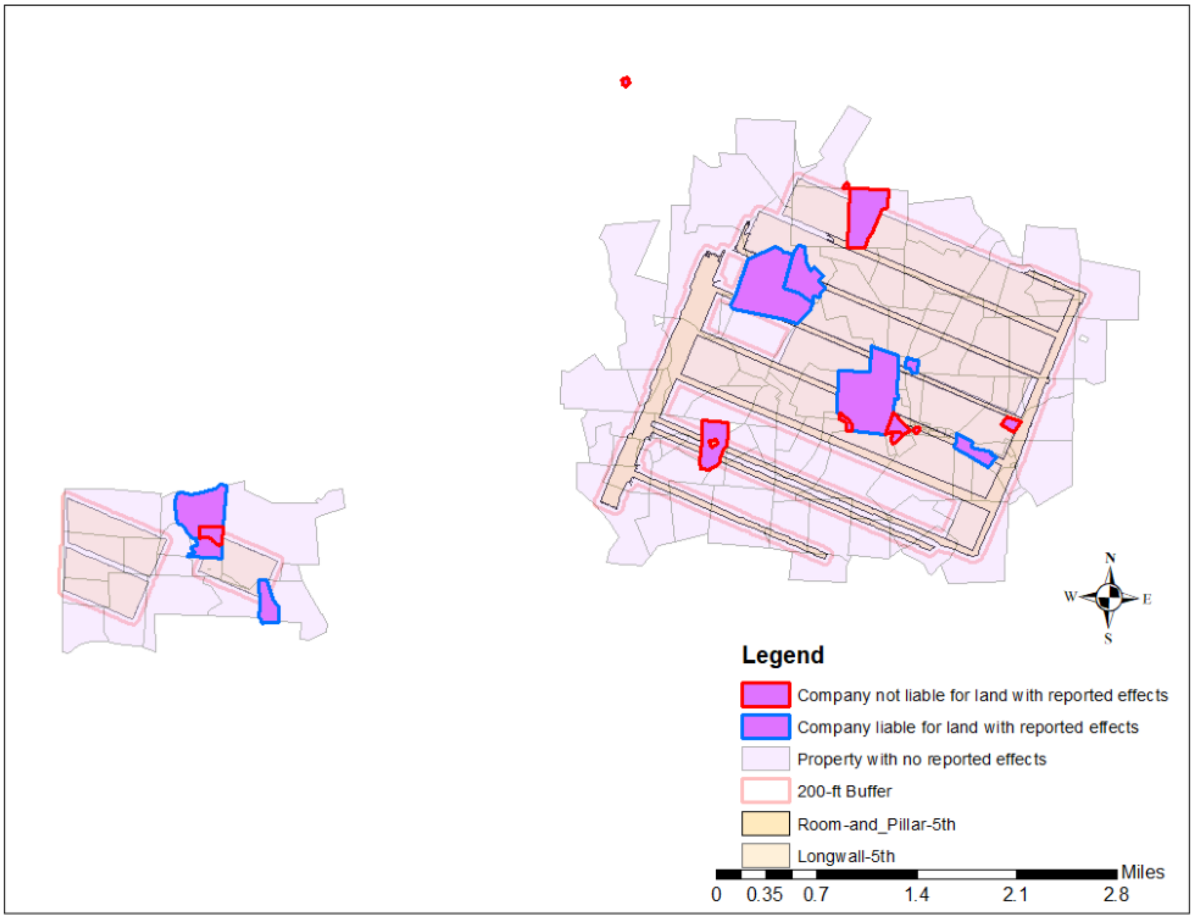

Figure 65. Properties associated with the 5th assessment period over the Bailey Mine

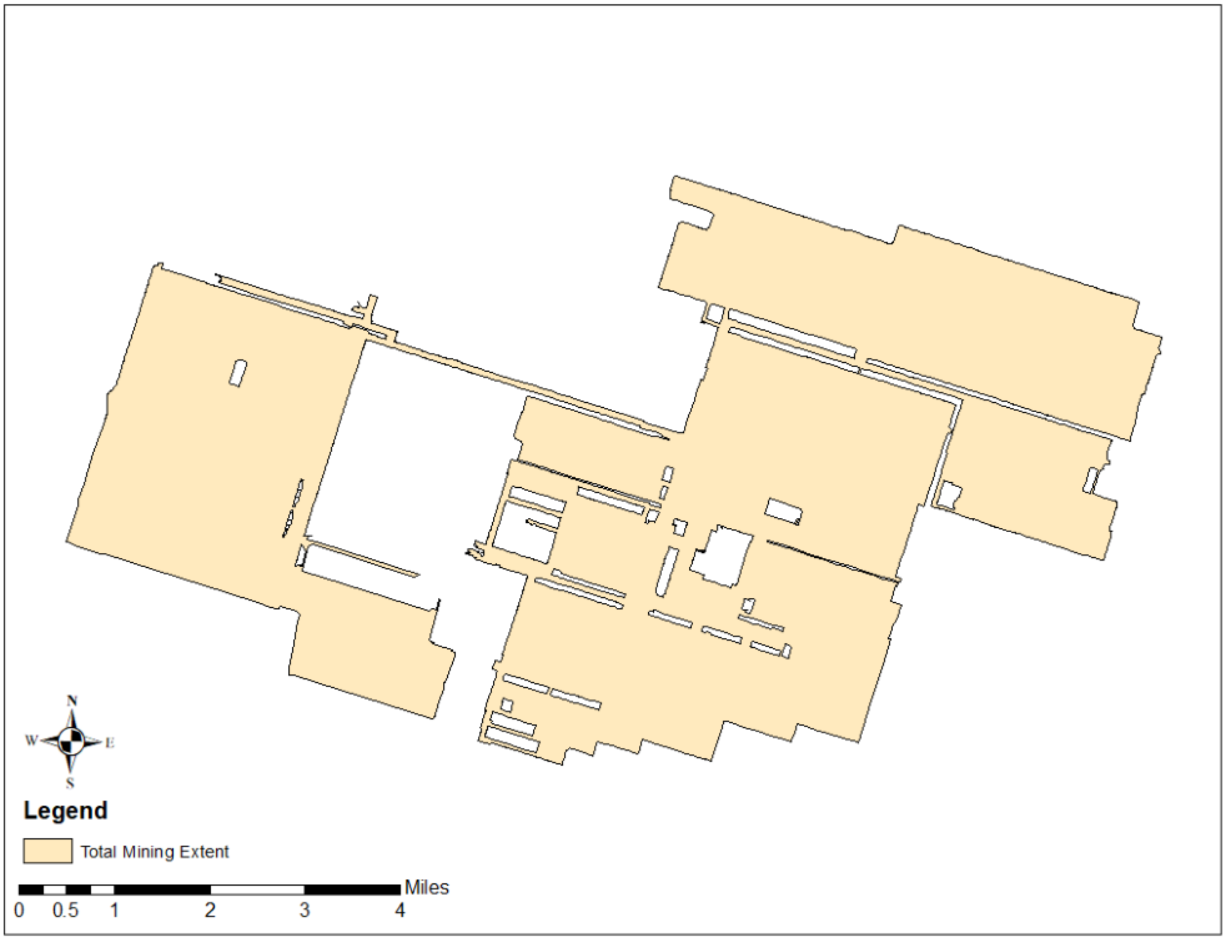

Figure 66. Cumberland total extent of mining

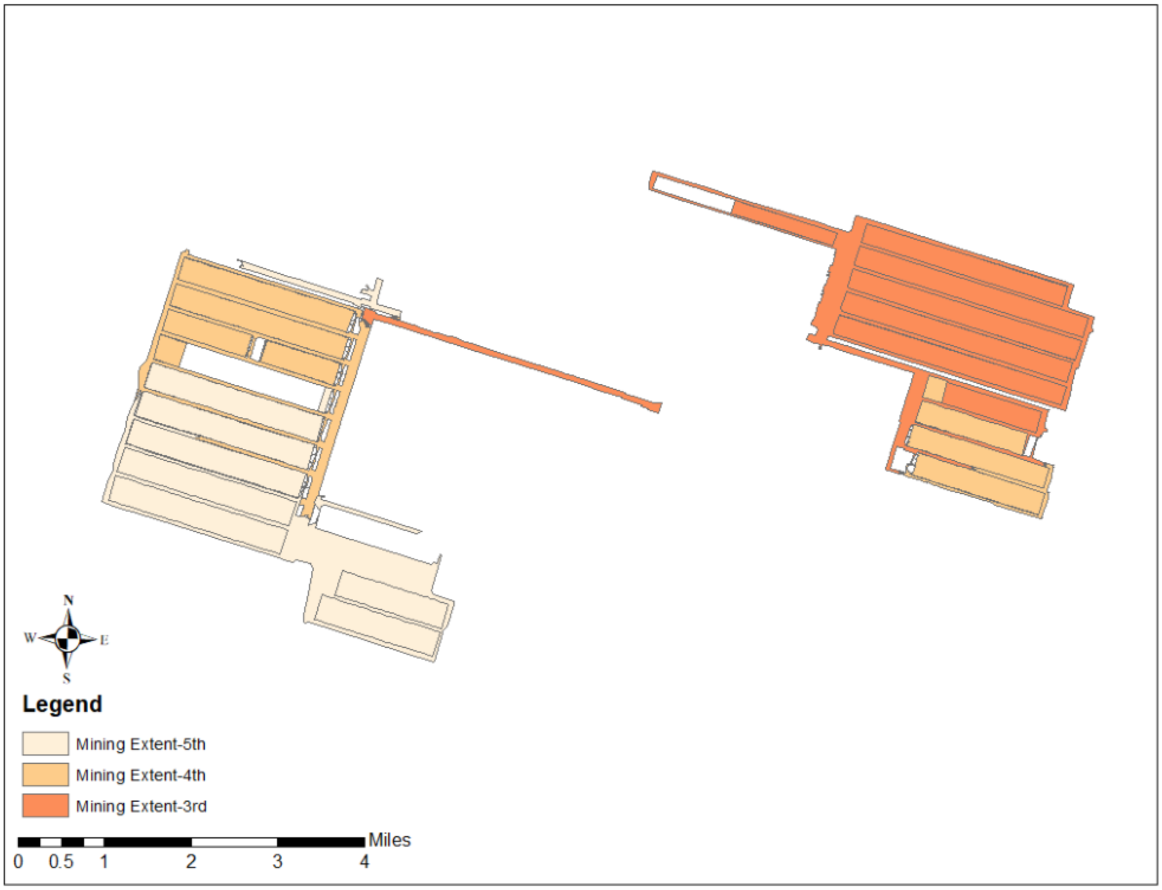

Figure 67. Cumberland mining extent for the 3rd, 4th, and 5th assessment periods

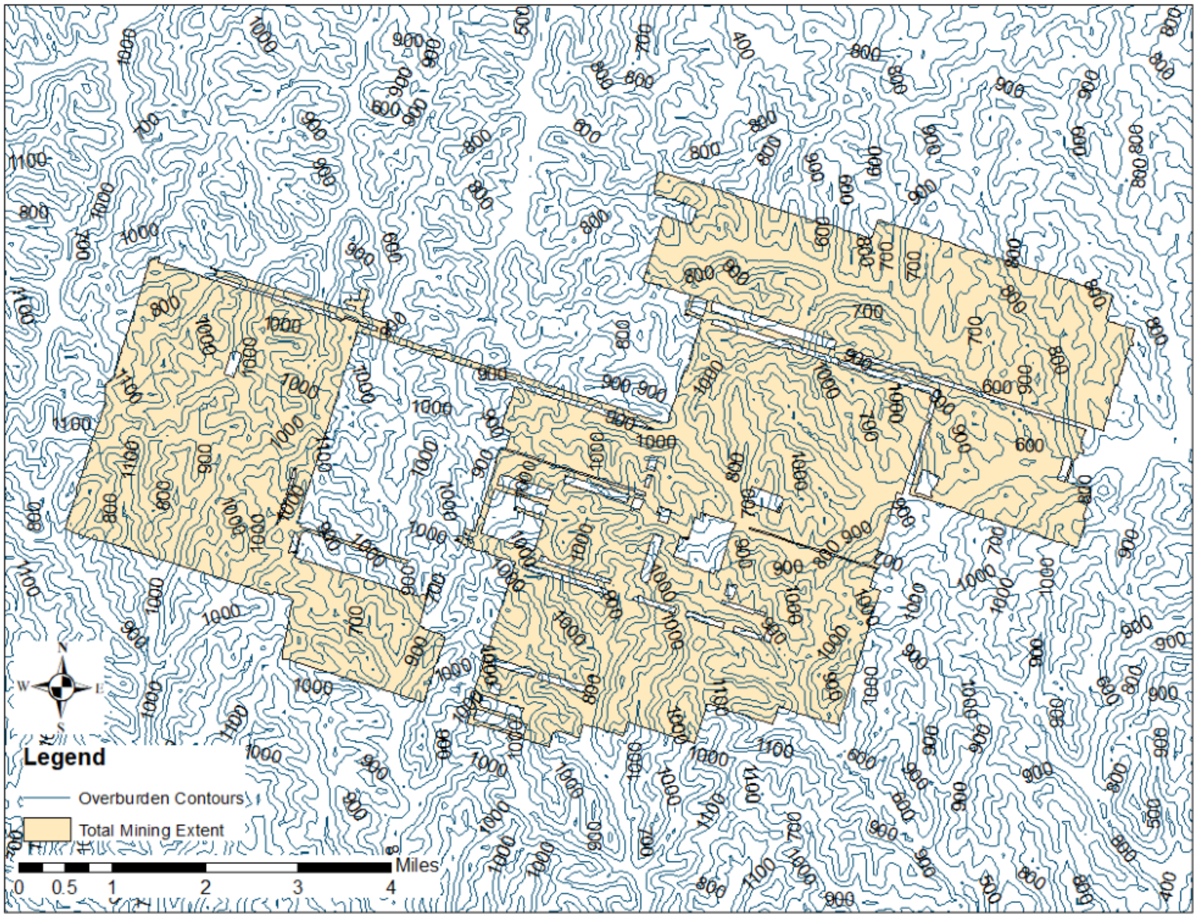

Figure 68. 100-ft interval overburden contour map for the total mining extent of Cumberland Mine

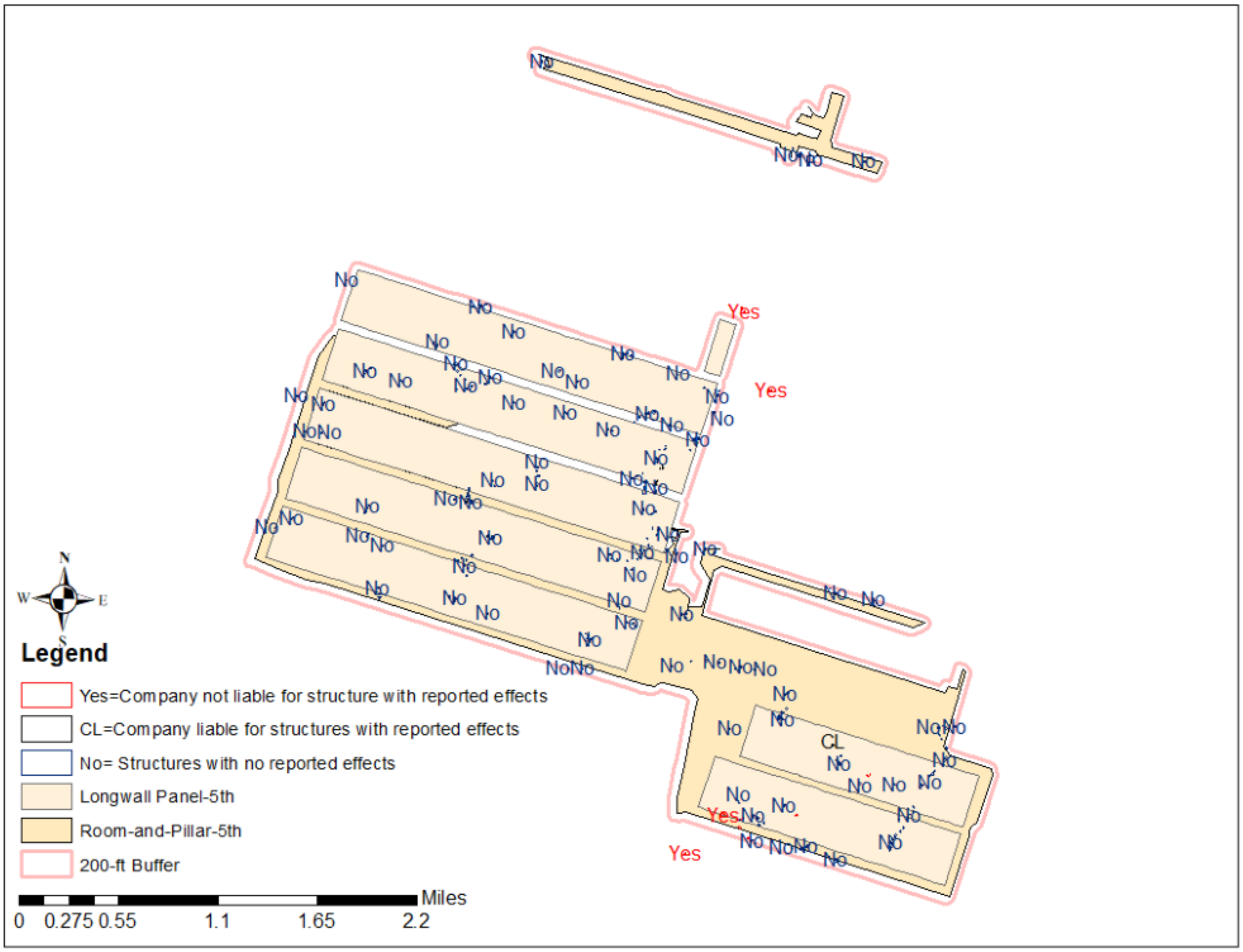

Figure 69. Cumberland Mine 5th assessment 200-ft buffer and structures*

**Note there are two structures with a reported effect that are far from mining that were determined to be company not liable that are not included here for display purposes.*

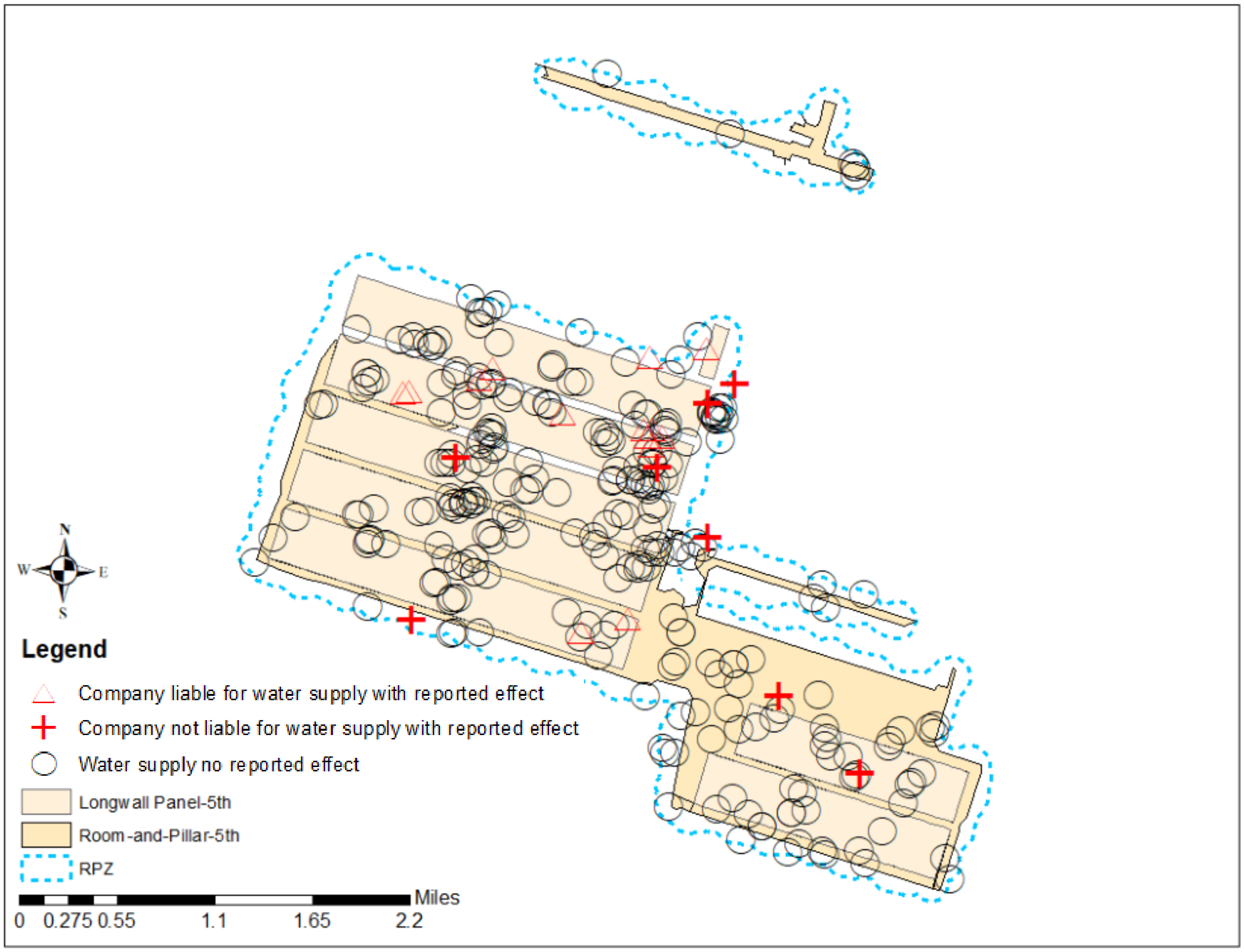

Figure 70. Cumberland Mine 5th assessment water supplies and RPZ

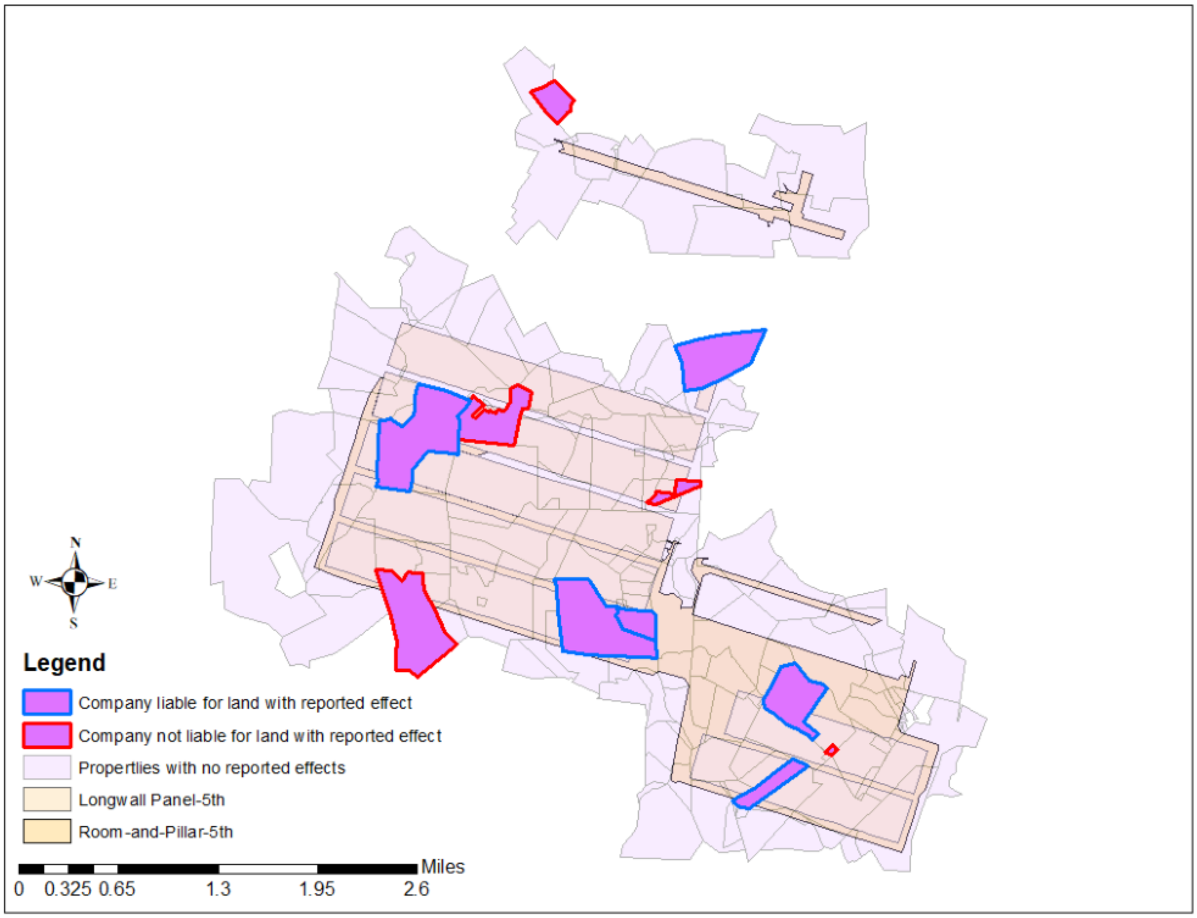

Figure 71. Properties associated with the 5th assessment period over the Cumberland Mine

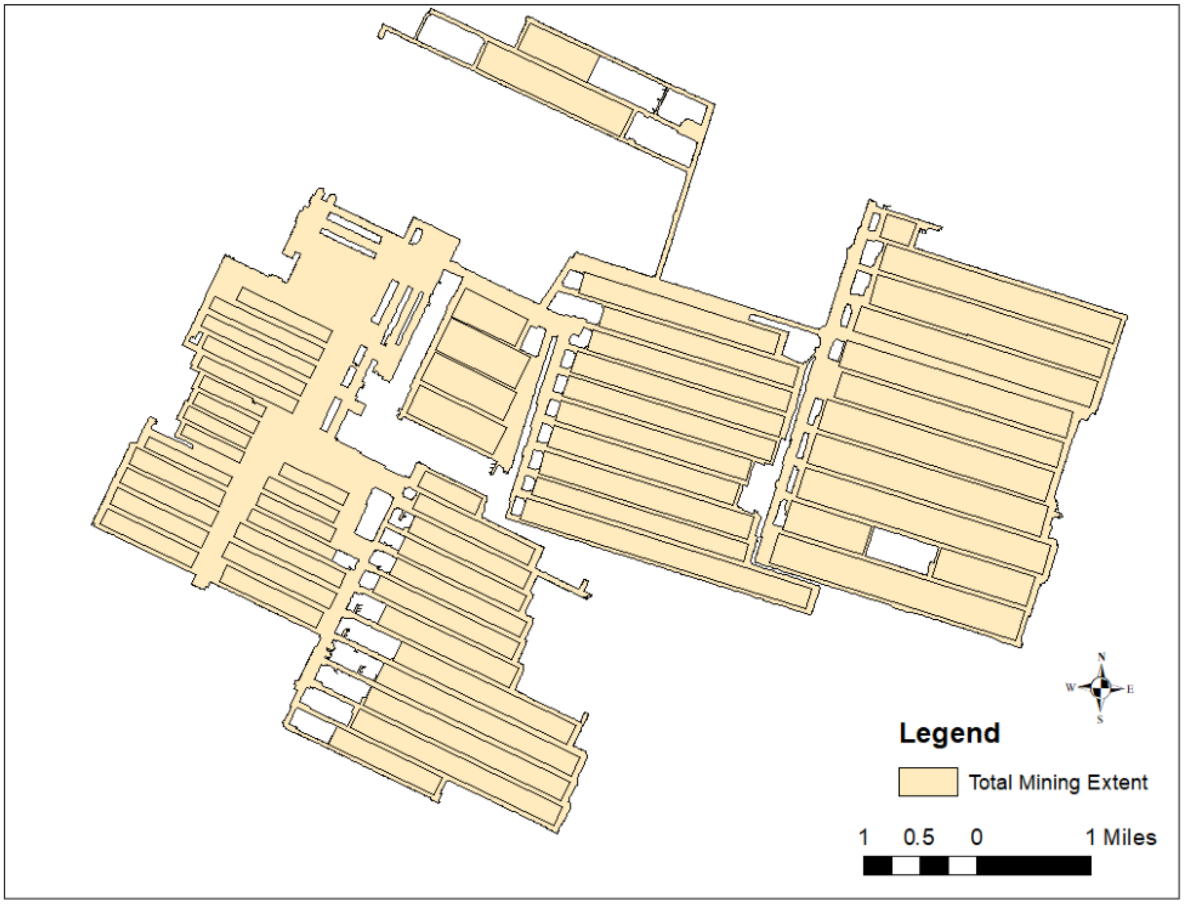

Figure 72. Emerald Mine total extent of mining

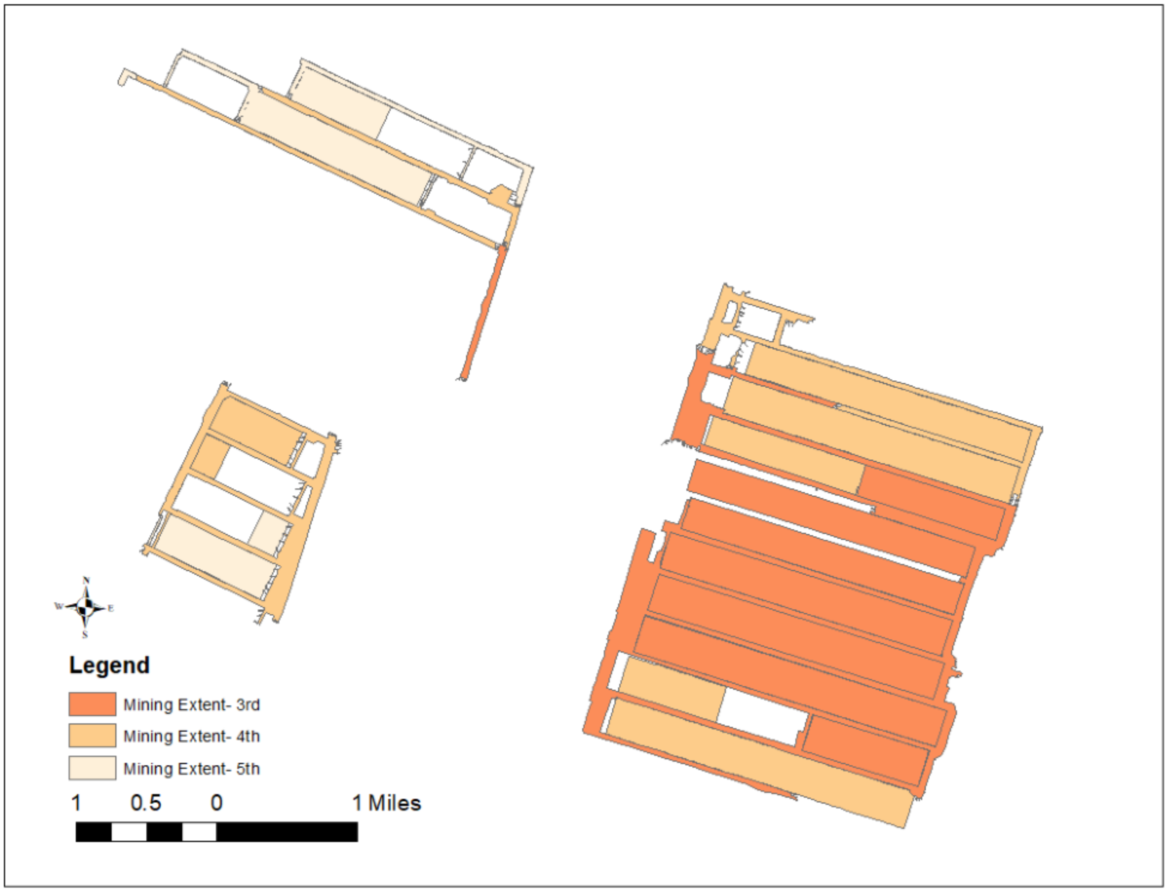

Figure 73. Emerald mining extent for the 3rd, 4th, and 5th assessment periods

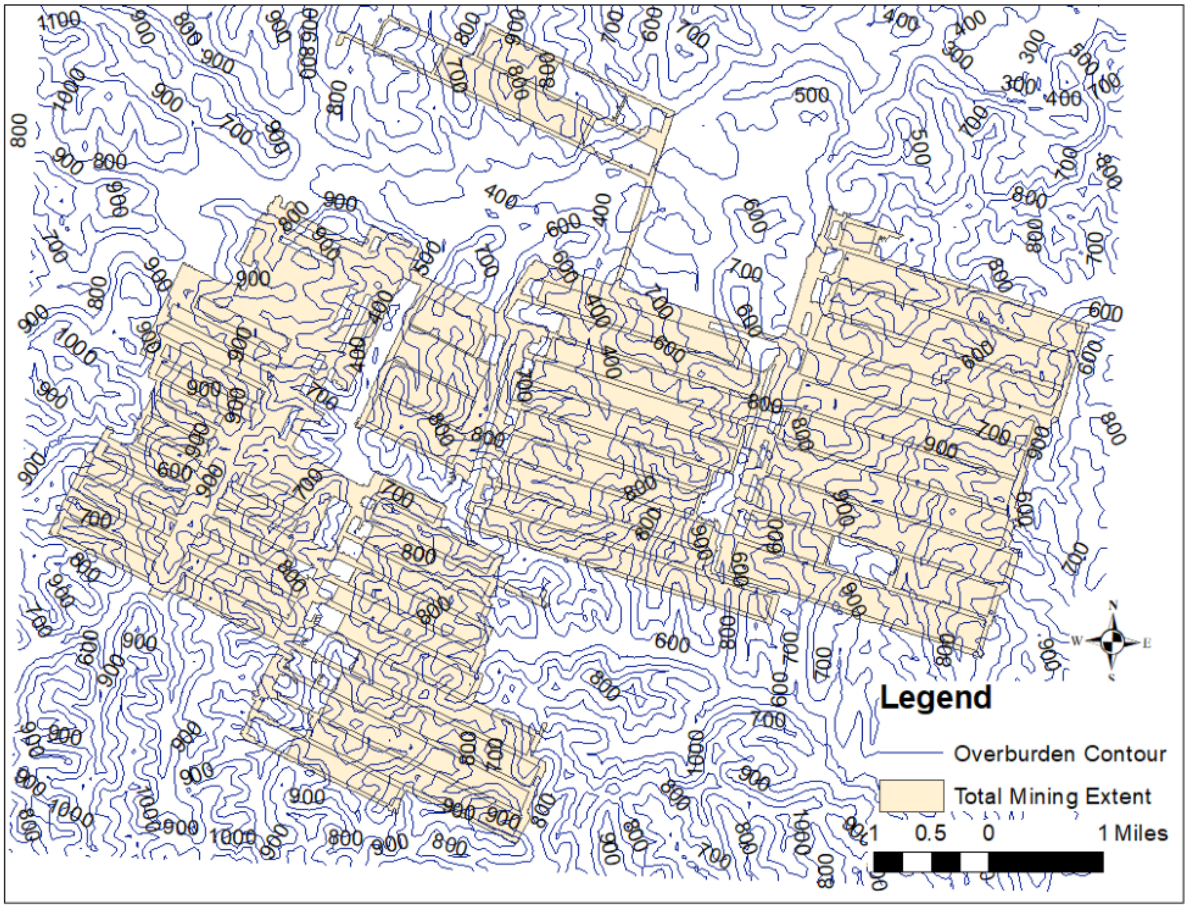

Figure 74. 100-ft interval overburden contour map for the total mining extent of Emerald Mine

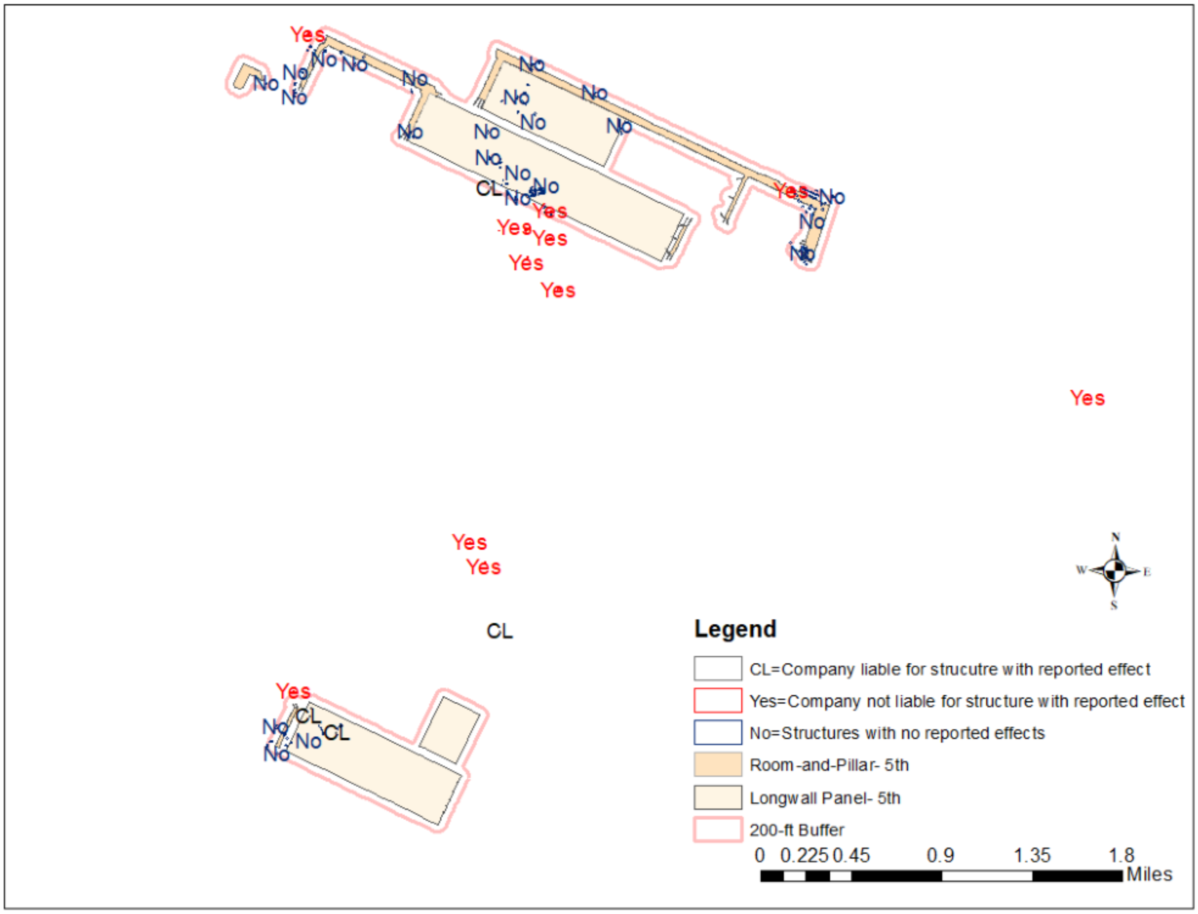

Figure 75. Emerald Mine 5th assessment 200-ft buffer and structures*

**Note there is one structure with a reported effect that is far from mining and is not included here for display purposes.*

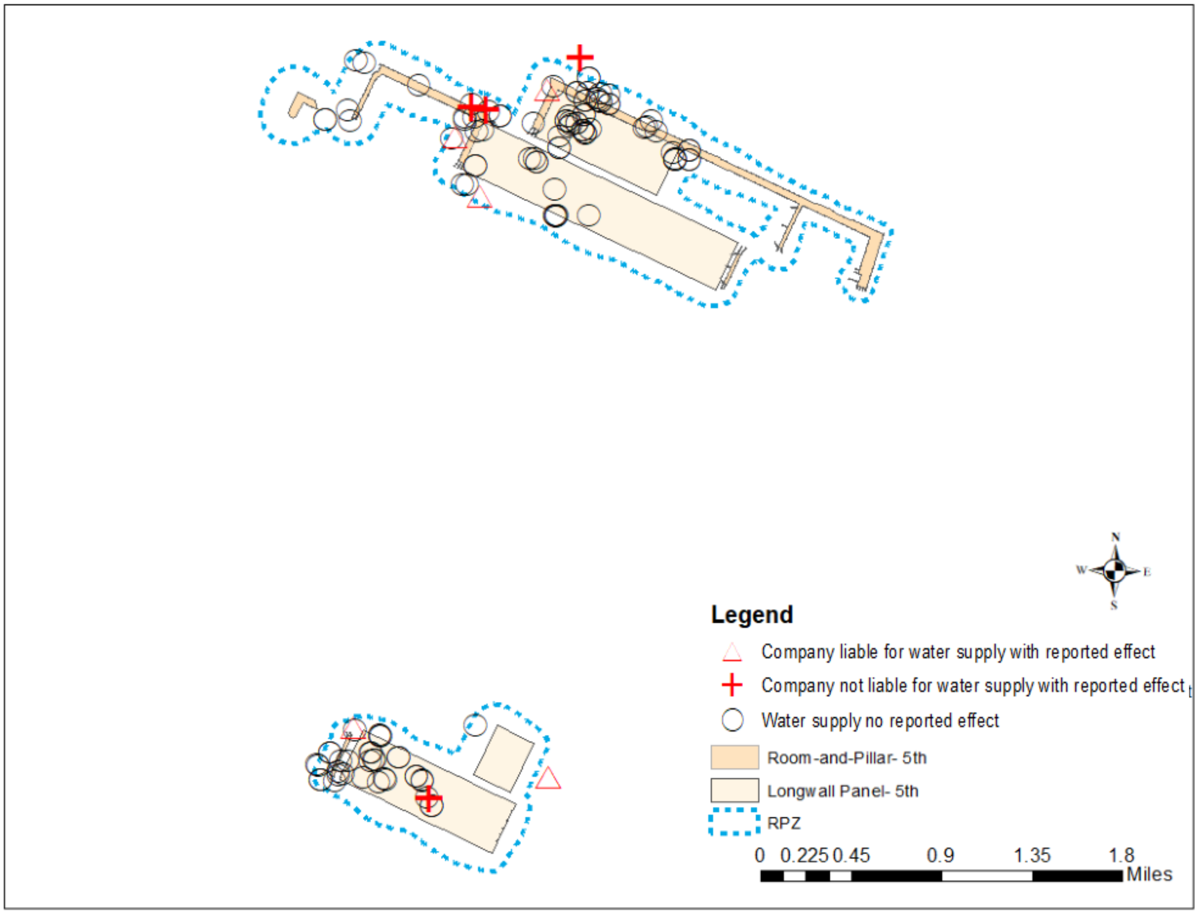

Figure 76. Emerald Mine 5th assessment water supplies and RPZ

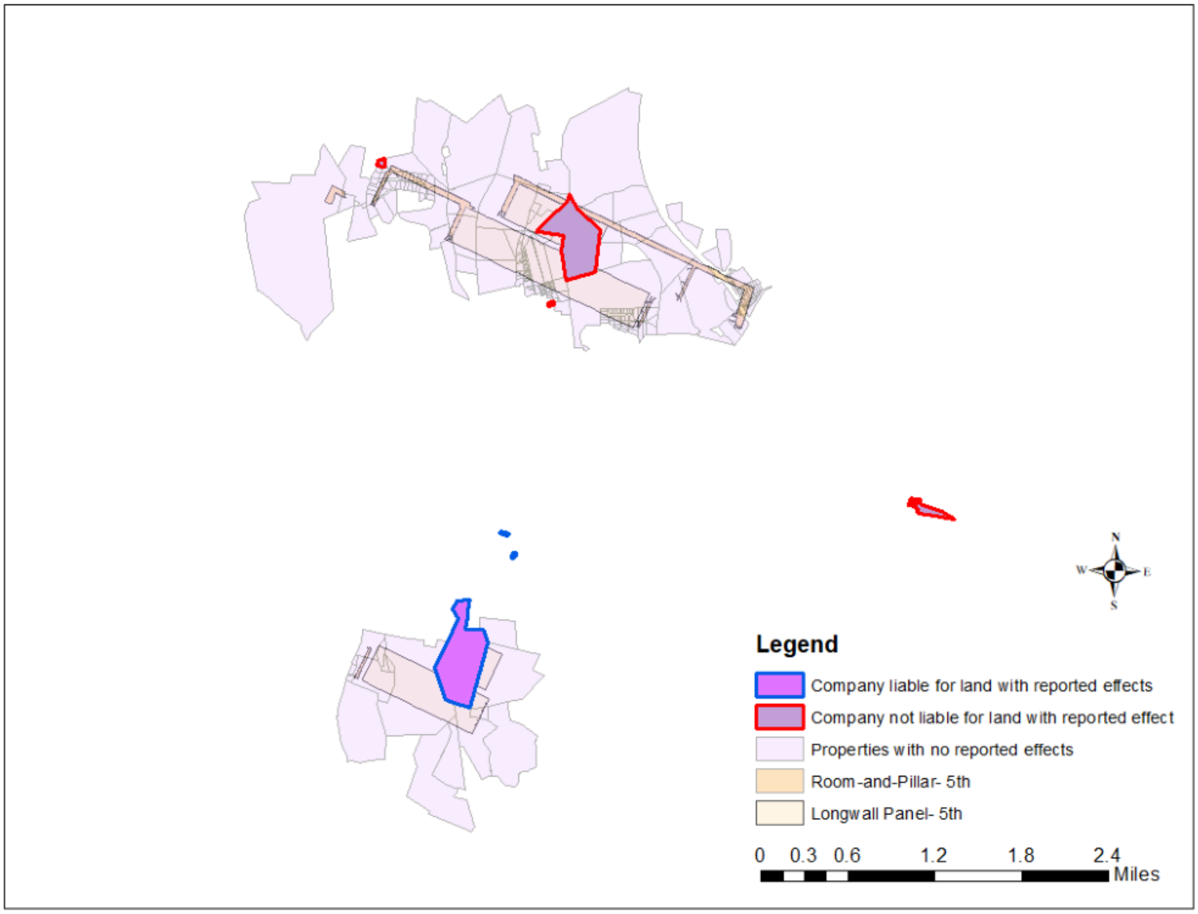

Figure 77. Properties associated with the 5th assessment period over the Emerald Mine

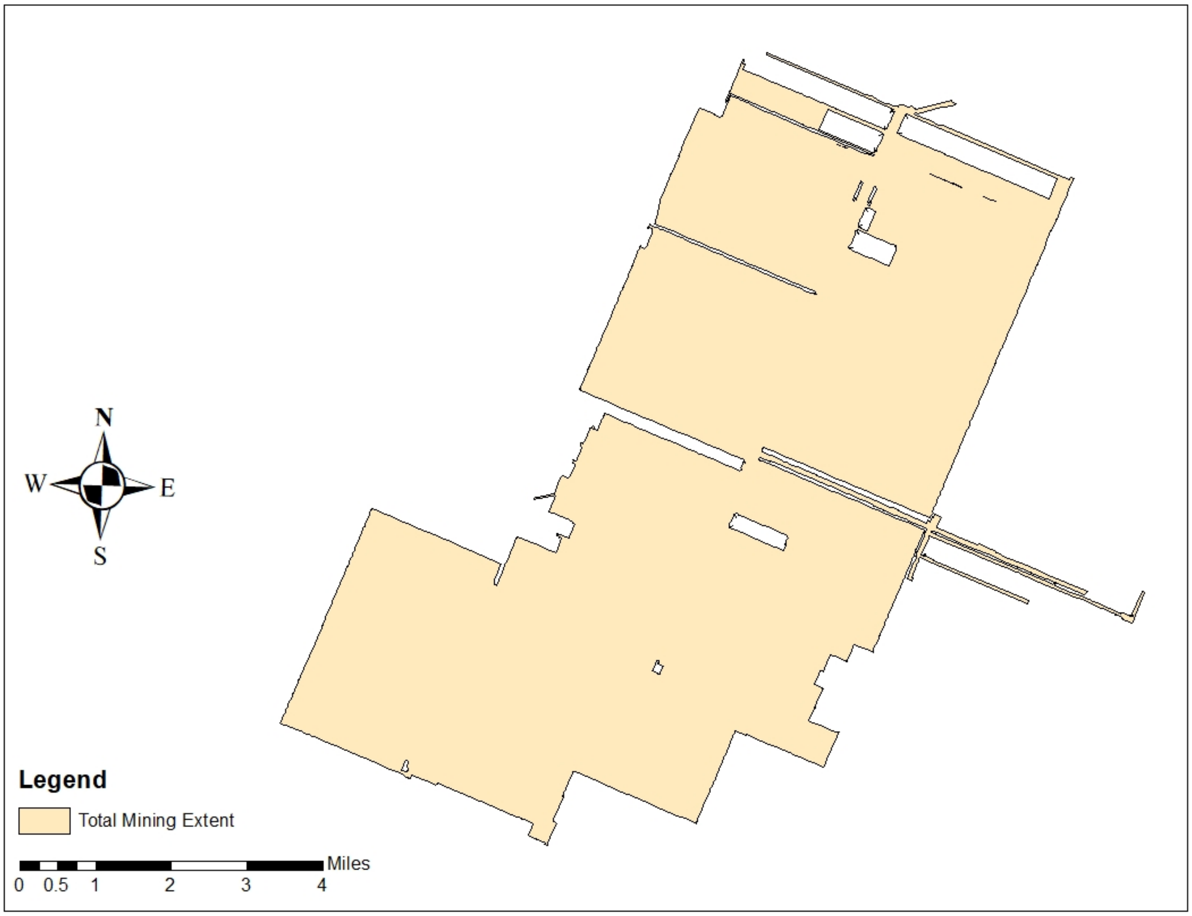

Figure 78. Enlow Fork Mine total extent of mining

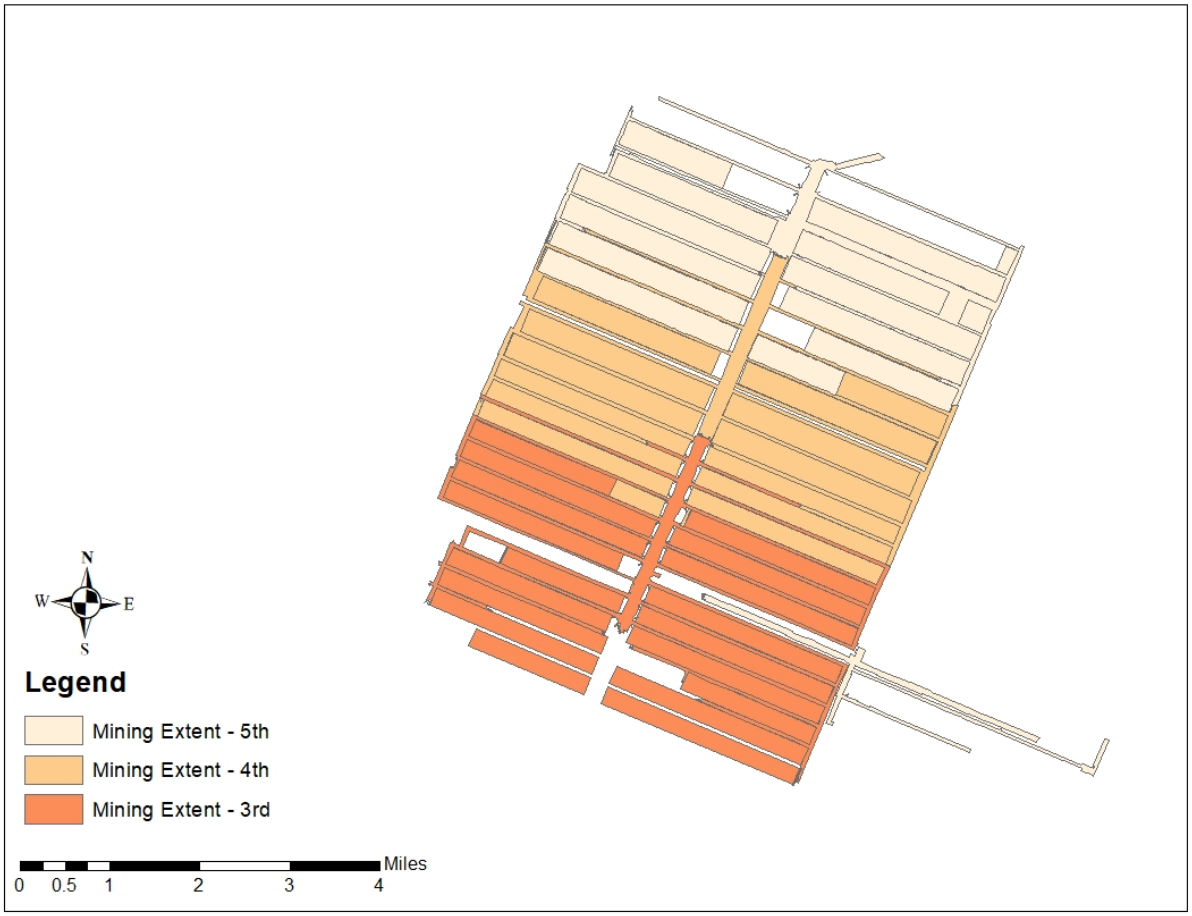

Figure 79. Enlow Fork mining extent for the 3rd, 4th, and 5th assessment periods

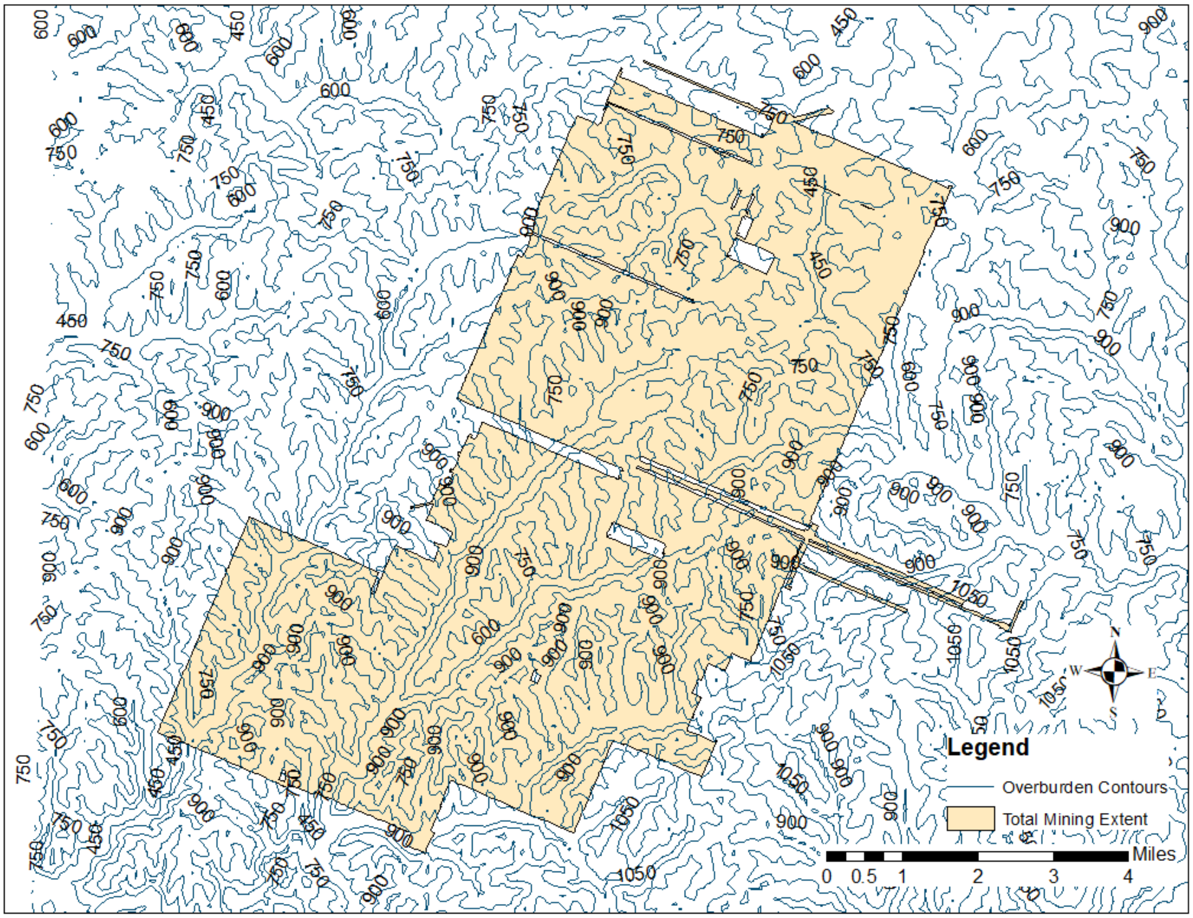

Figure 80. 100-ft interval overburden contour map for the total mining extent of Enlow Fork Mine

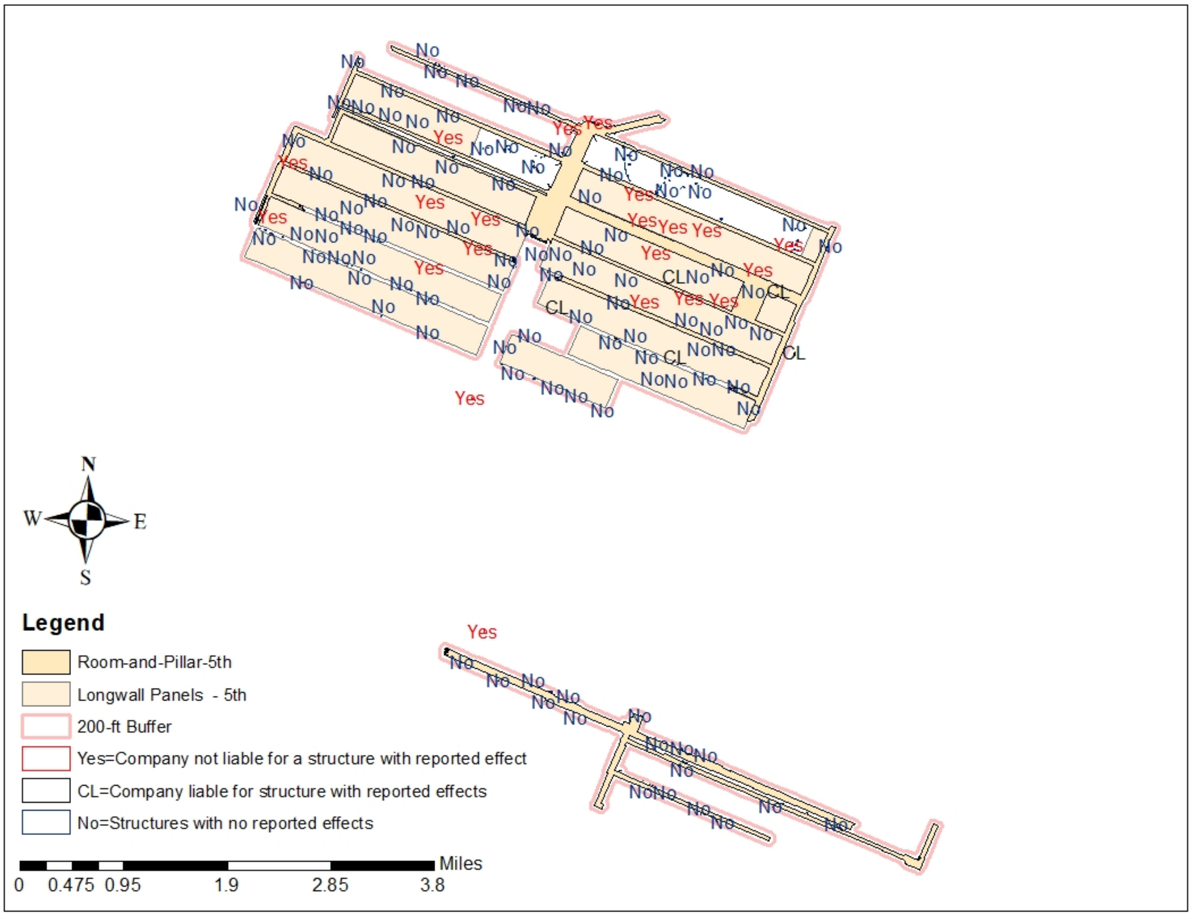

Figure 81. Enlow Fork Mine 5th assessment 200-ft buffer and structures*

***Note there are three structure with reported effects that are company not liable that are far from mining and are not included here for display purposes.**

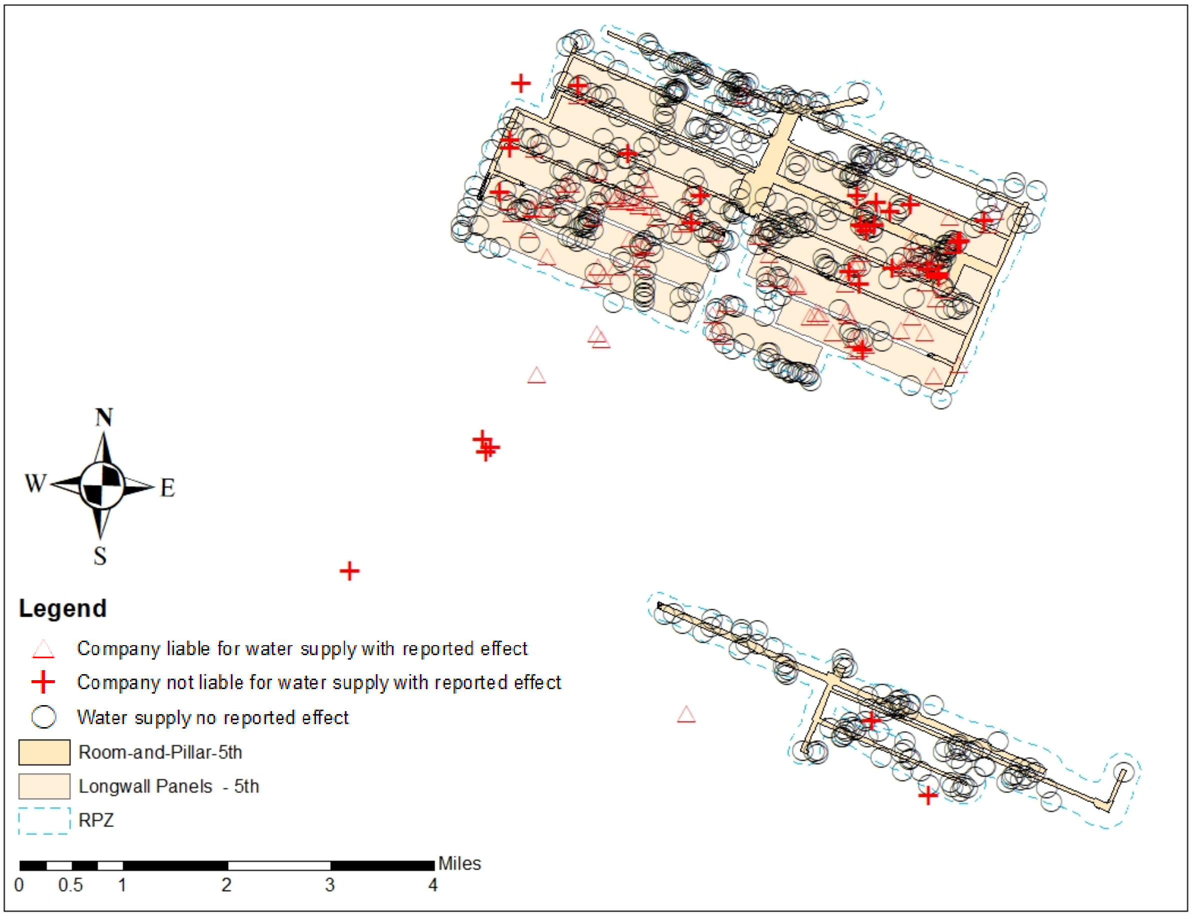

Figure 82. Enlow Fork Mine 5th assessment water supplies and RPZ

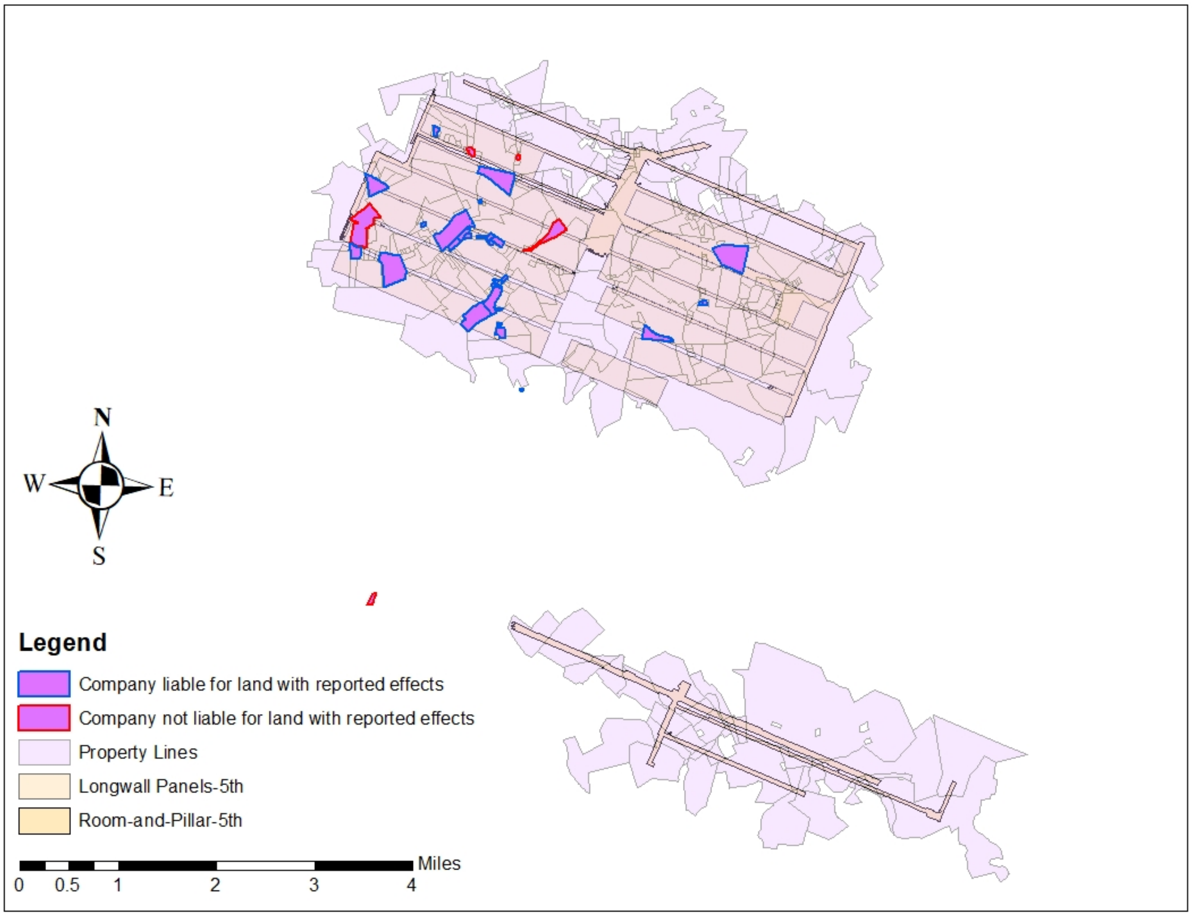

Figure 83. Properties associated with the 5th assessment period over the Enlow Fork Mine

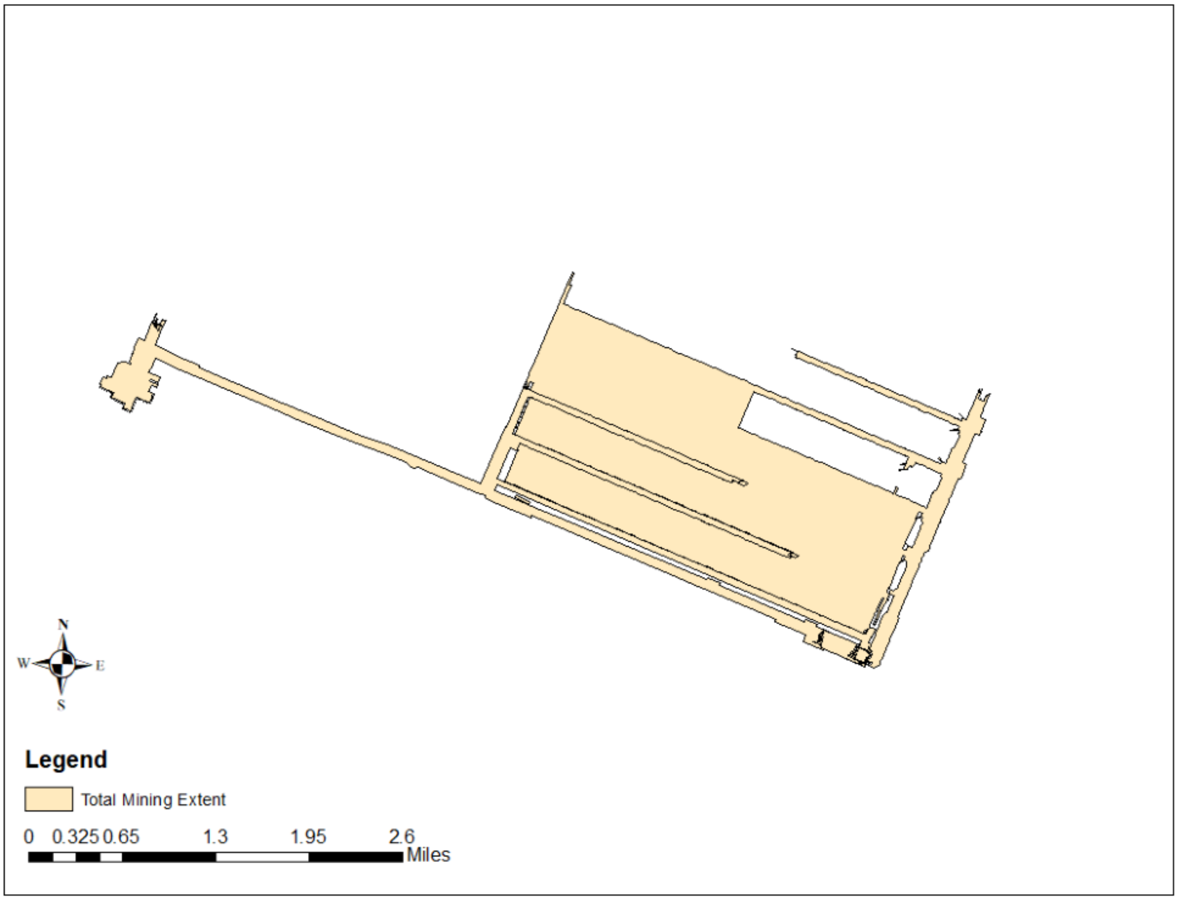

Figure 84. Harvey Mine total extent of mining

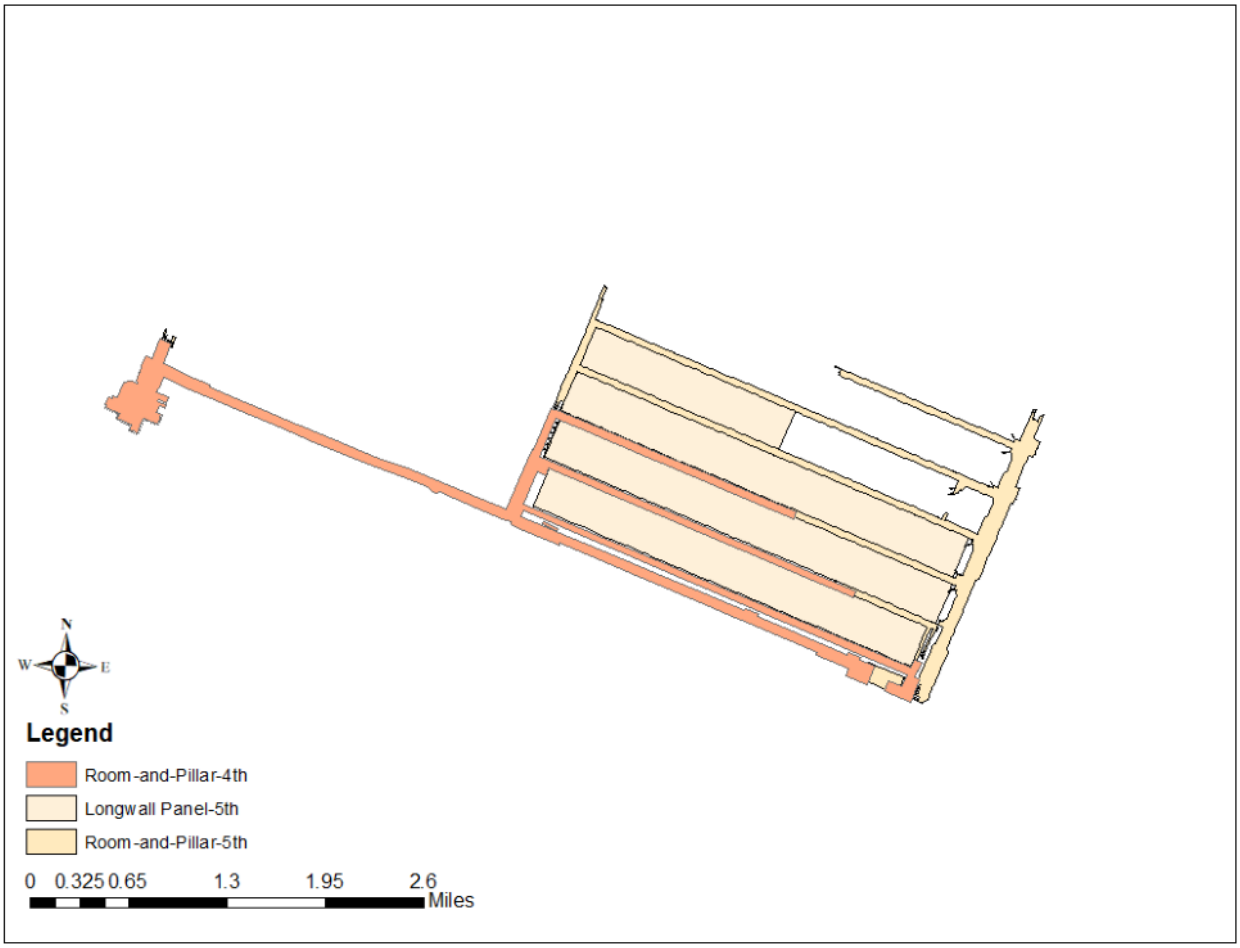

Figure 85. Harvey mining extent for the 3rd, 4th, and 5th assessment periods

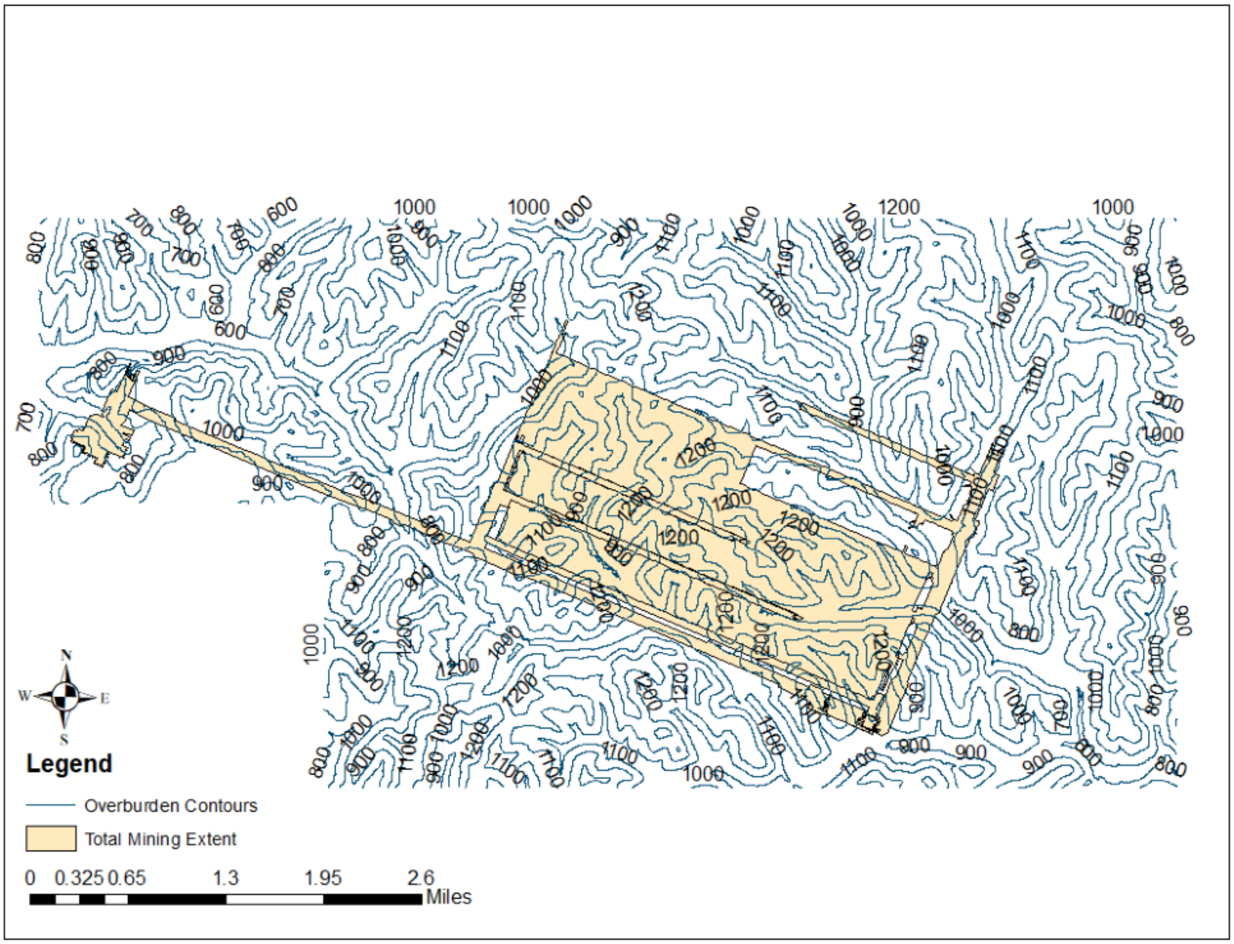

Figure 86. 100-ft interval overburden contour map for the total mining extent of Harvey Mine.

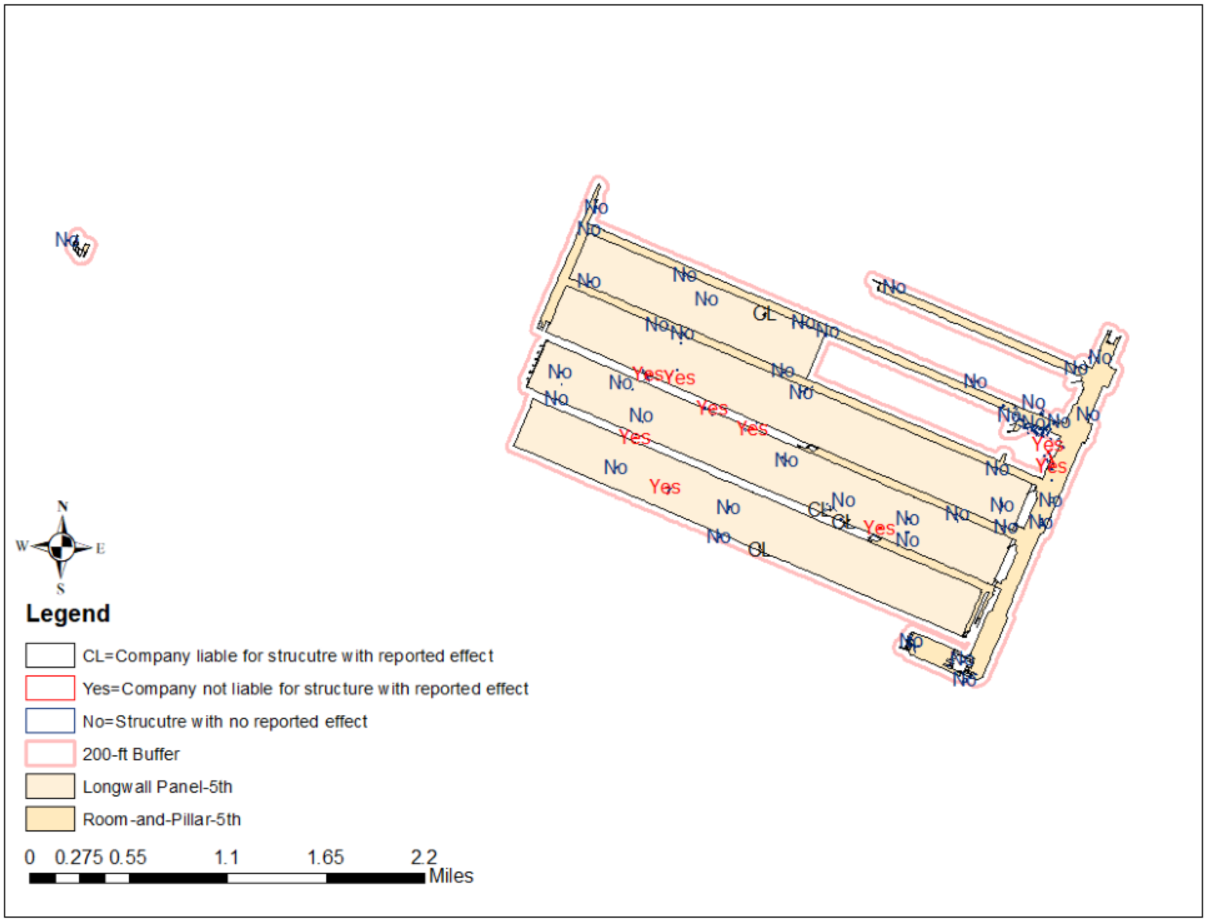

Figure 87. Harvey Mine 5th assessment 200-ft buffer and structures

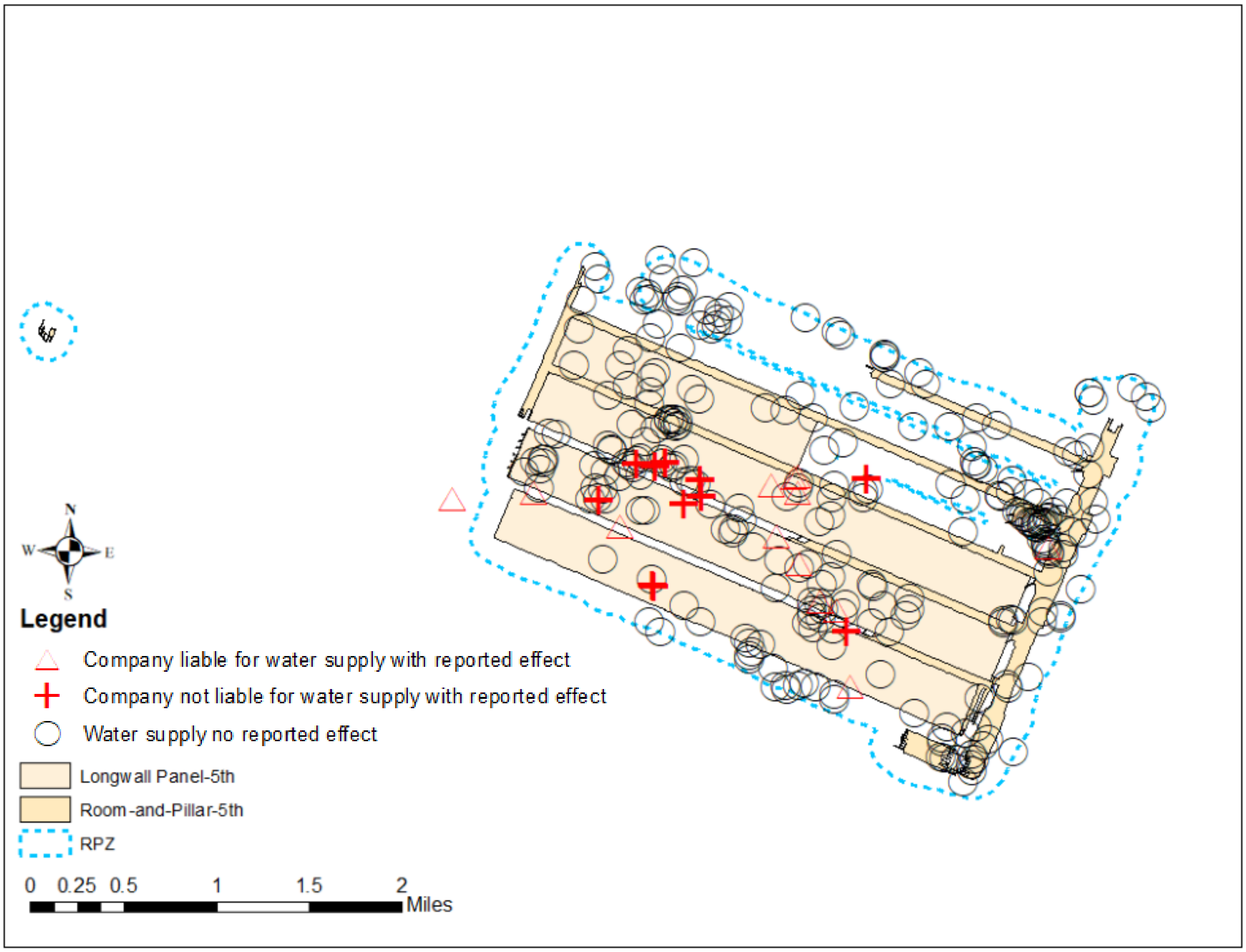

Figure 88. Harvey Mine 5th assessment water supplies and RPZ

Figure 89. Properties associated with the 5th assessment period over the Harvey Mine

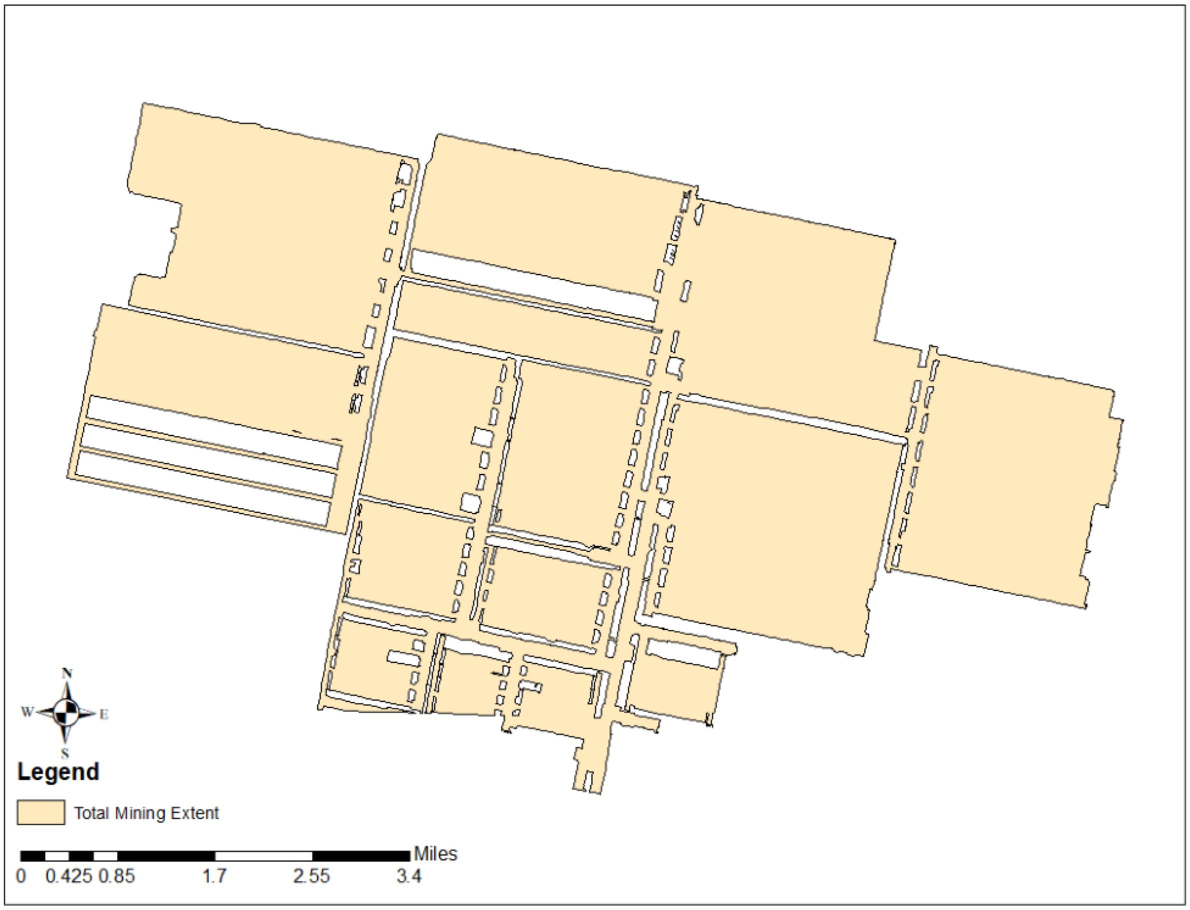

Figure 90. Monongalia County Mine total extent of mining

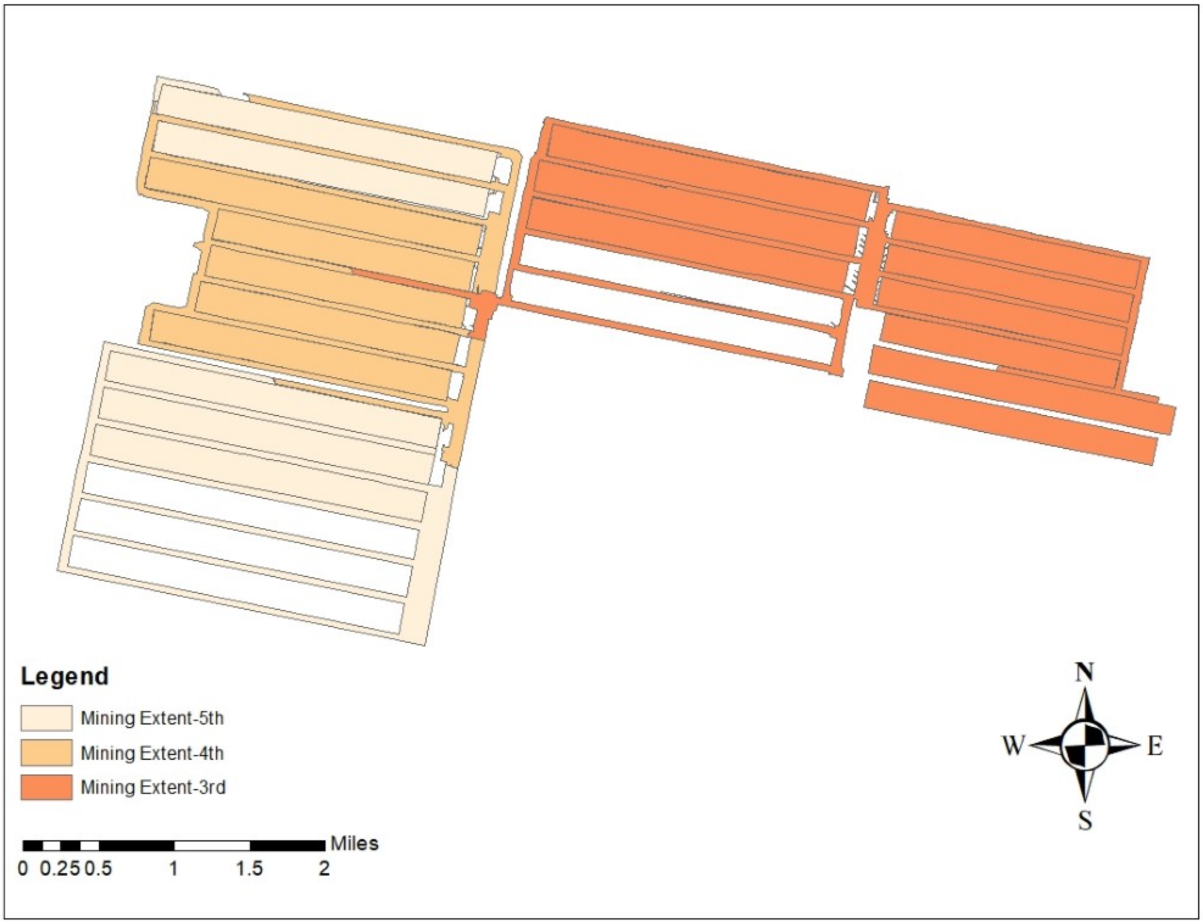

Figure 91. Monongalia County mining extent for the 3rd, 4th, and 5th assessment periods

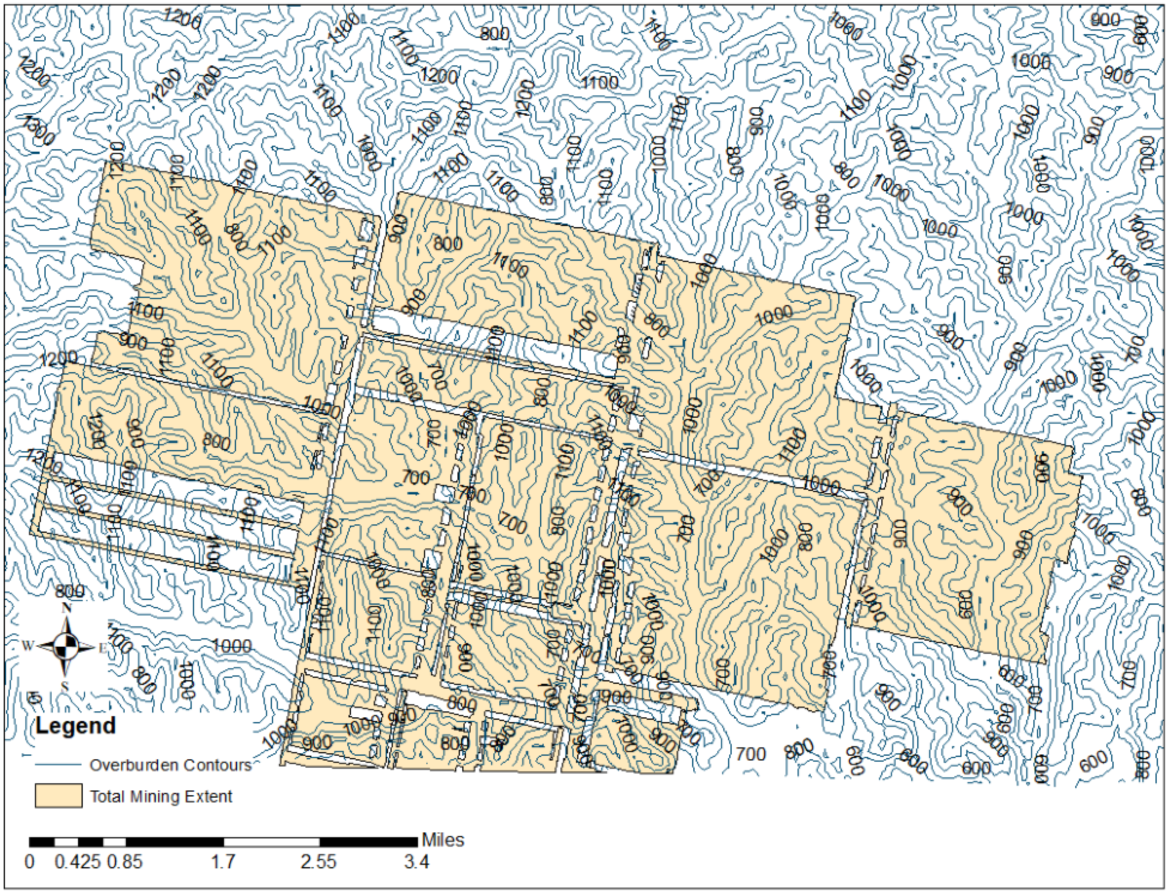

Figure 92. 100-ft interval overburden contour map for the total mining extent of Monongalia County Mine

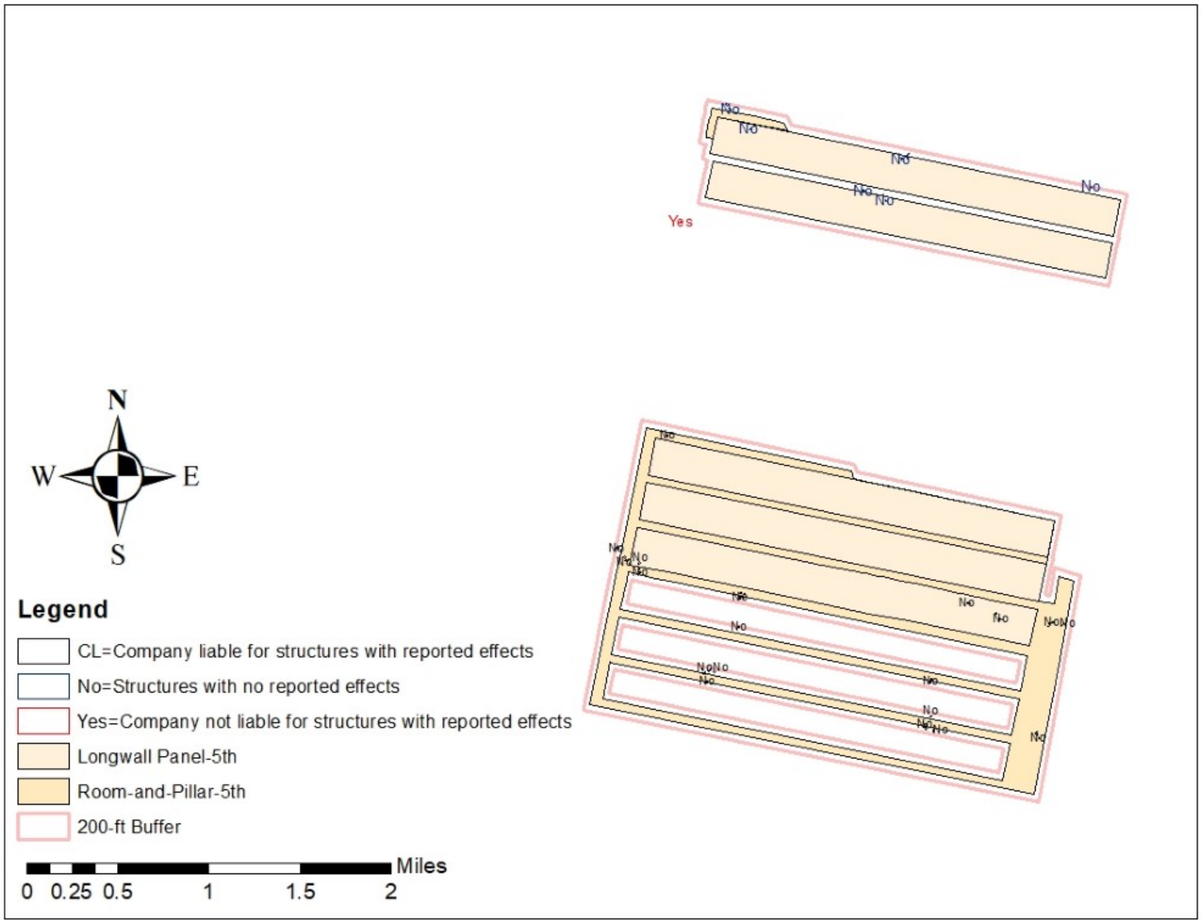

Figure 93. Monongalia County Mine 5th assessment 200-ft buffer and structures

***Note there are four structure with reported effects determined to be company not liable that are far from mining and are not included here for display purposes.*

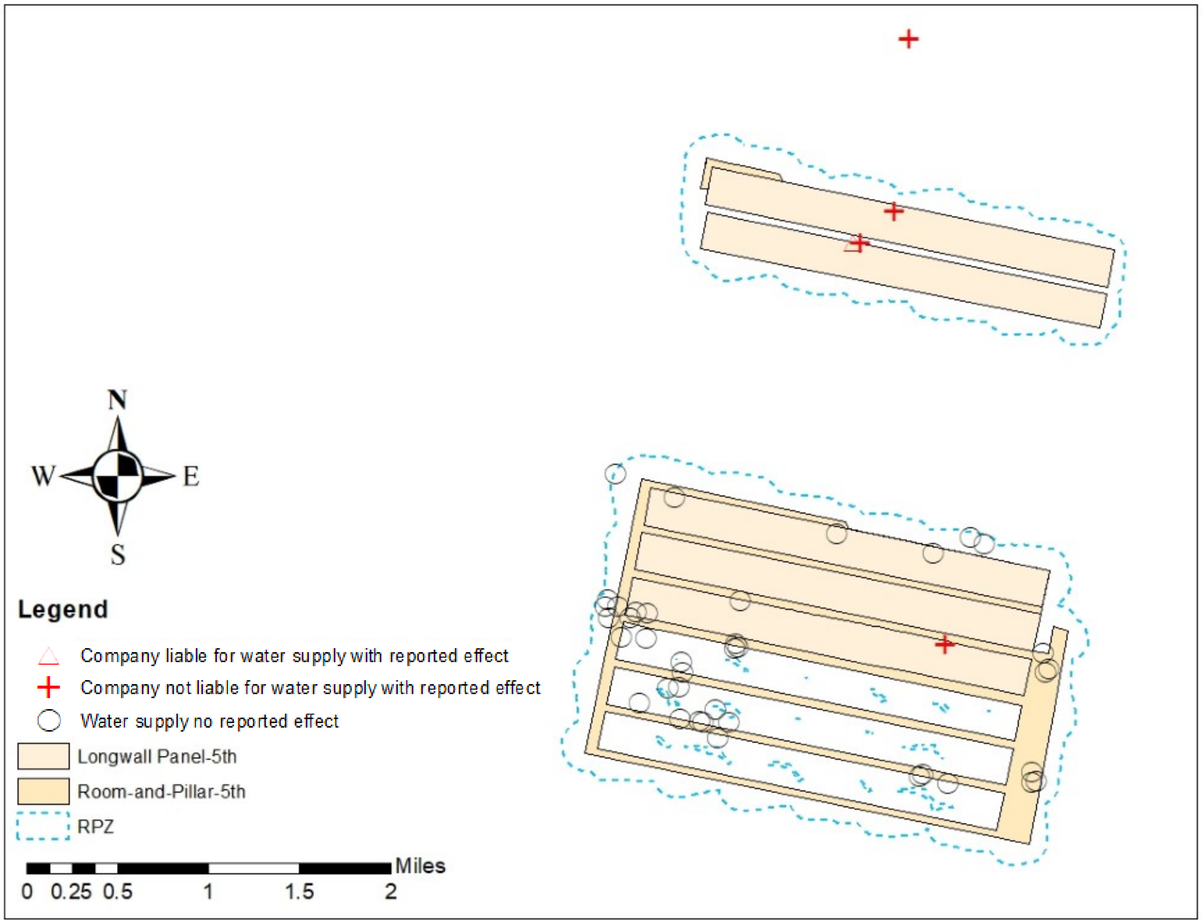

Figure 94. Monongalia County Mine 5th assessment water supplies and RPZ

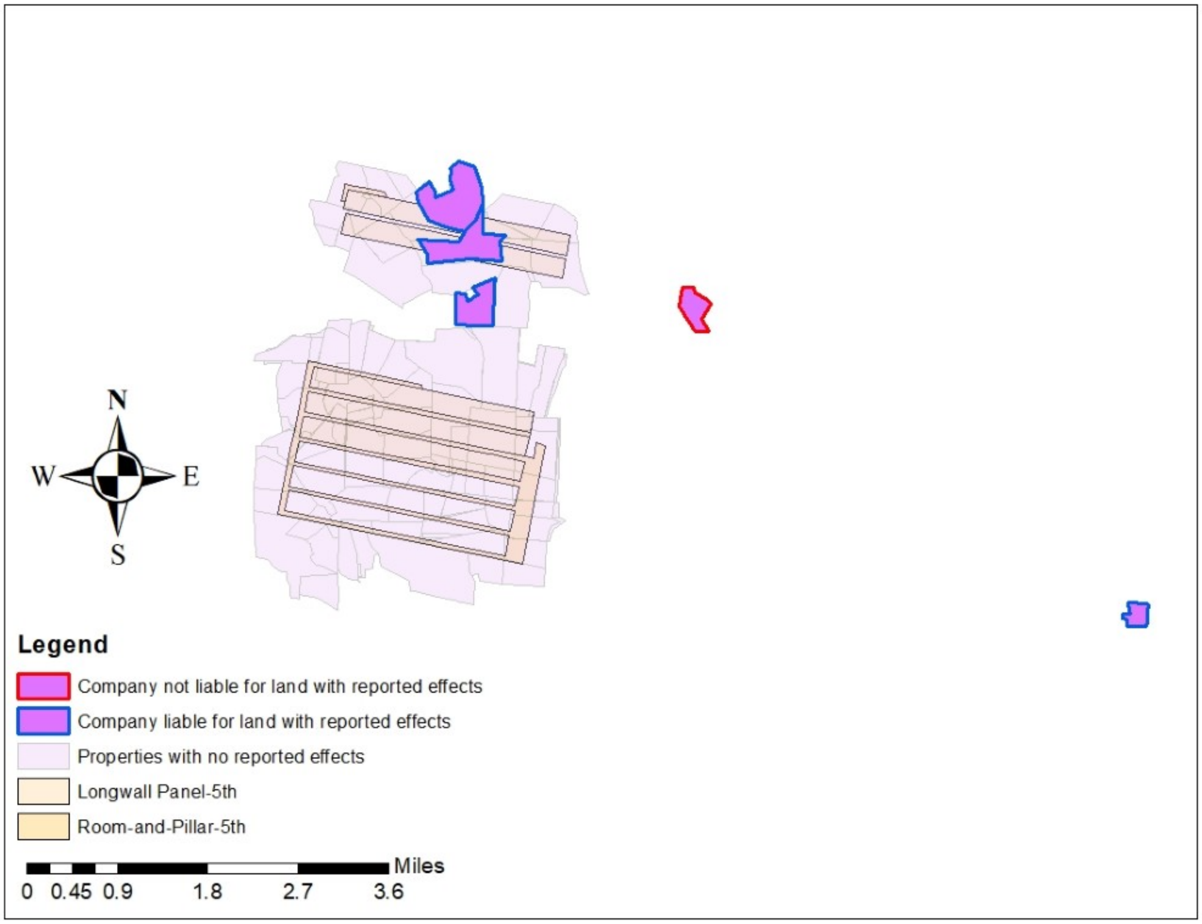

Figure 95. Properties associated with the 5th assessment period over the Monongalia County Mine

Figure 96. Tunnel Ridge Mine total extent of mining.

Figure 97. Tunnel Ridge mining extent for the 5th assessment period

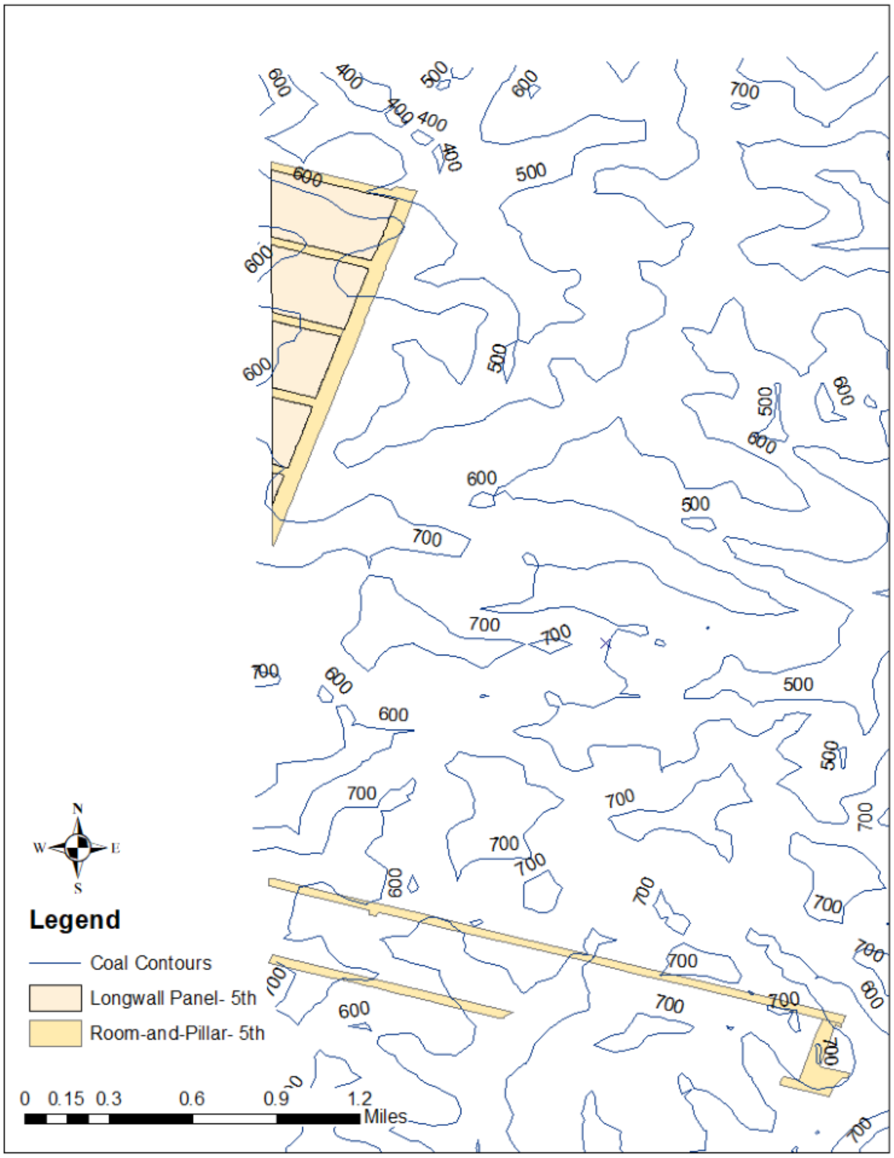

Figure 98. 100-ft interval overburden contour map for the total mining extent of Tunnel Ridge Mine

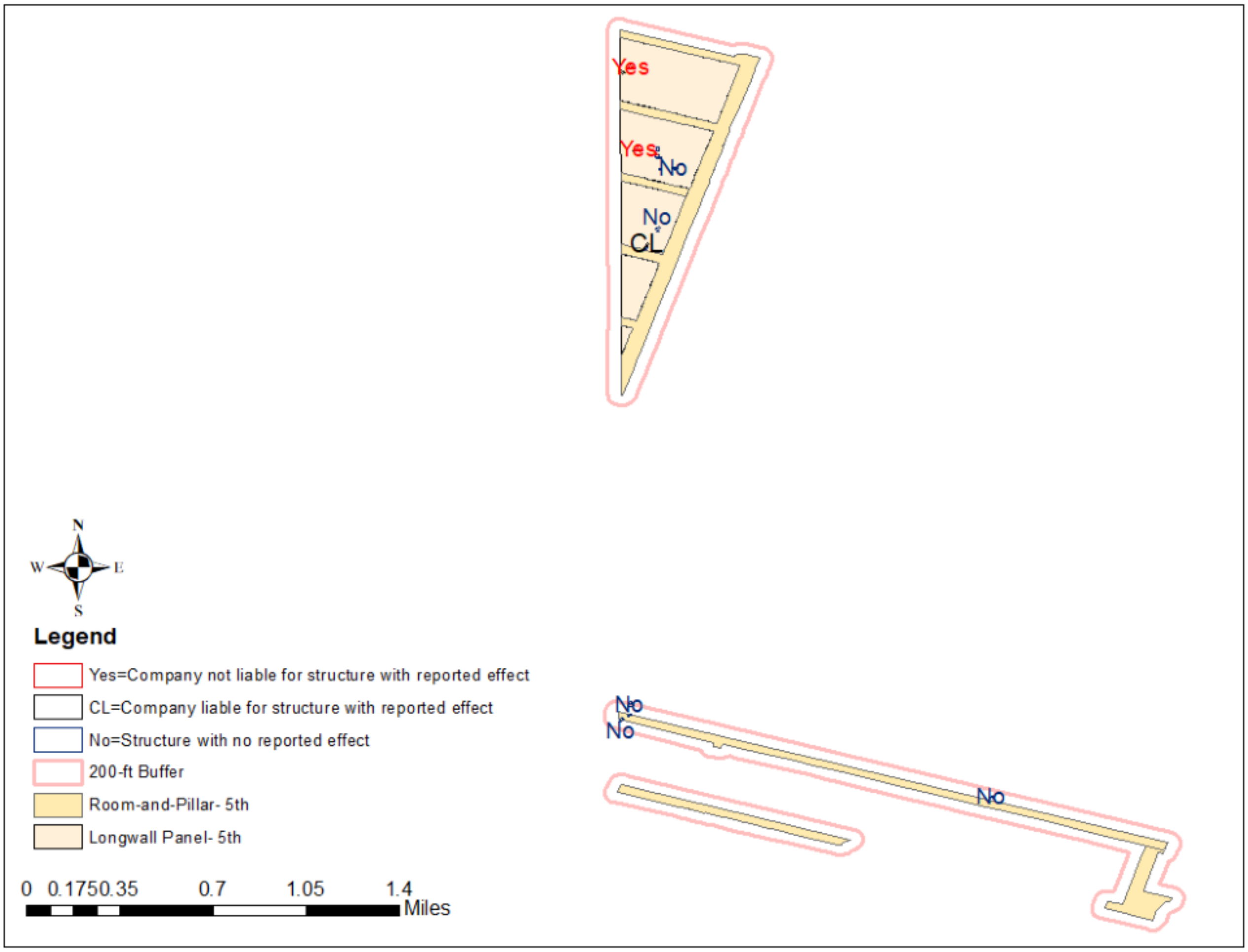

Figure 99. Tunnel Ridge Mine 5th assessment 200-ft buffer and structures

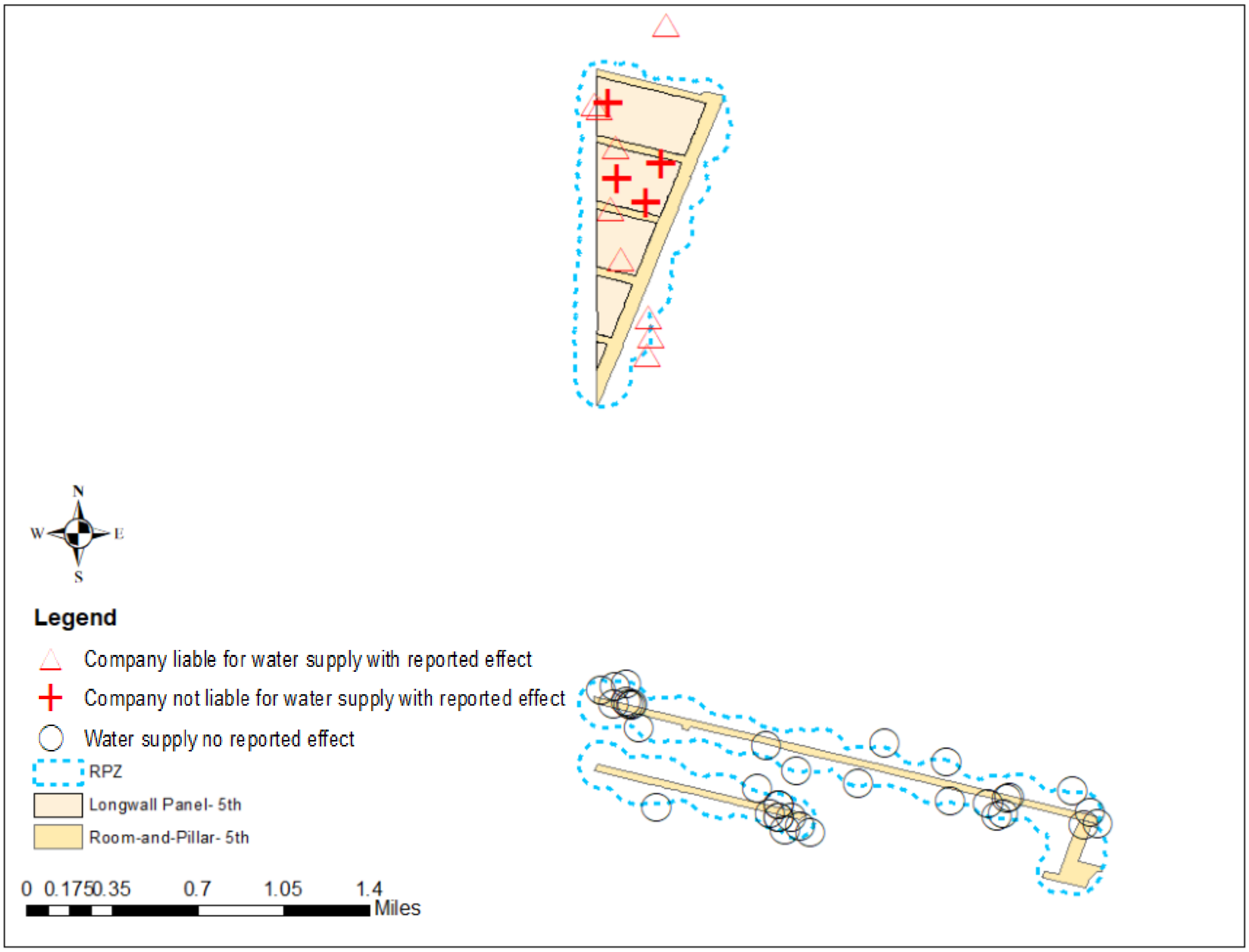

Figure 100. Tunnel Ridge Mine 5th assessment water supplies and RPZ

Figure 101. Properties associated with the 5th assessment period over the Tunnel Ridge Mine

Room-and-Pillar Mines

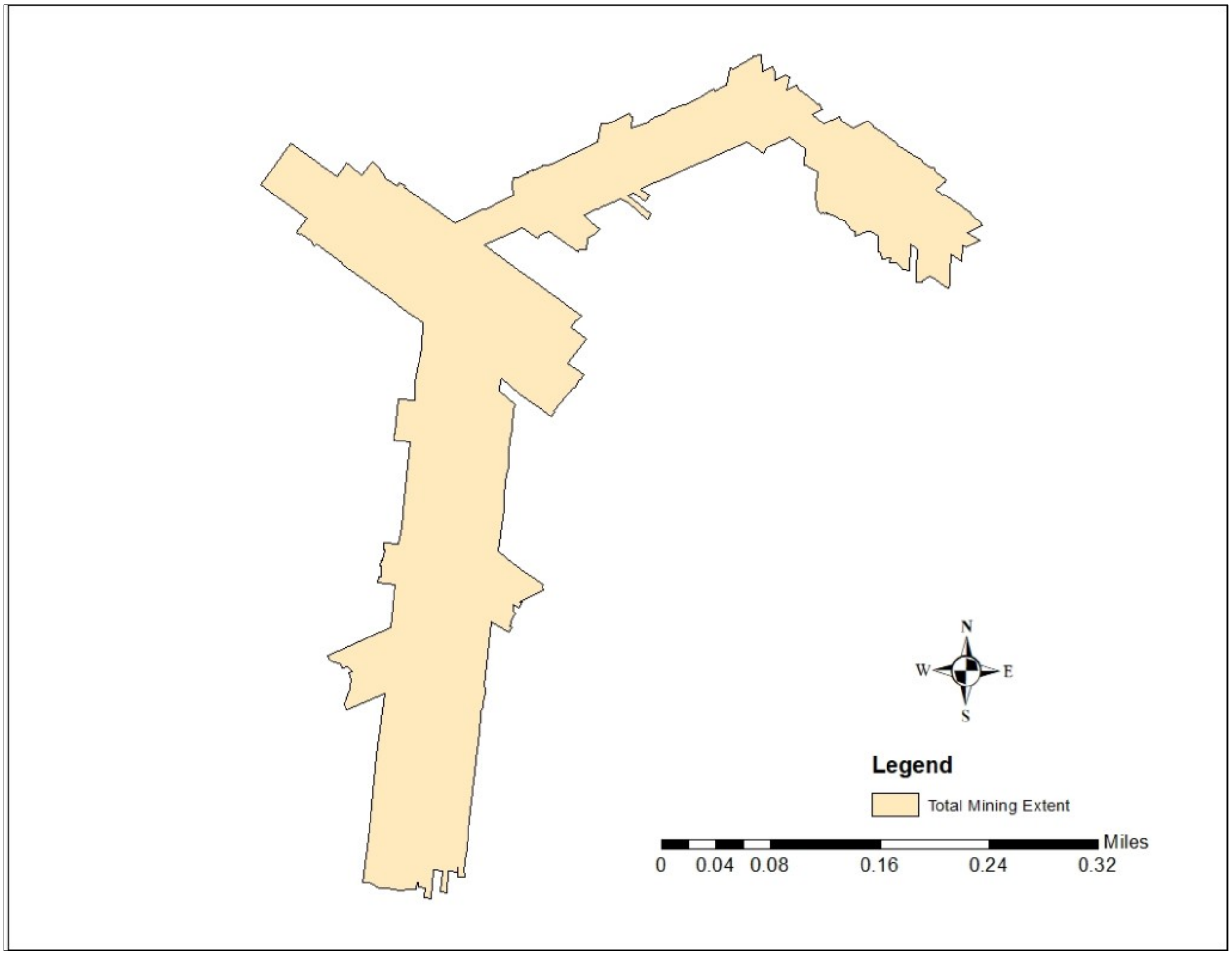

Figure 102. Acosta Deep Mine total extent of mining

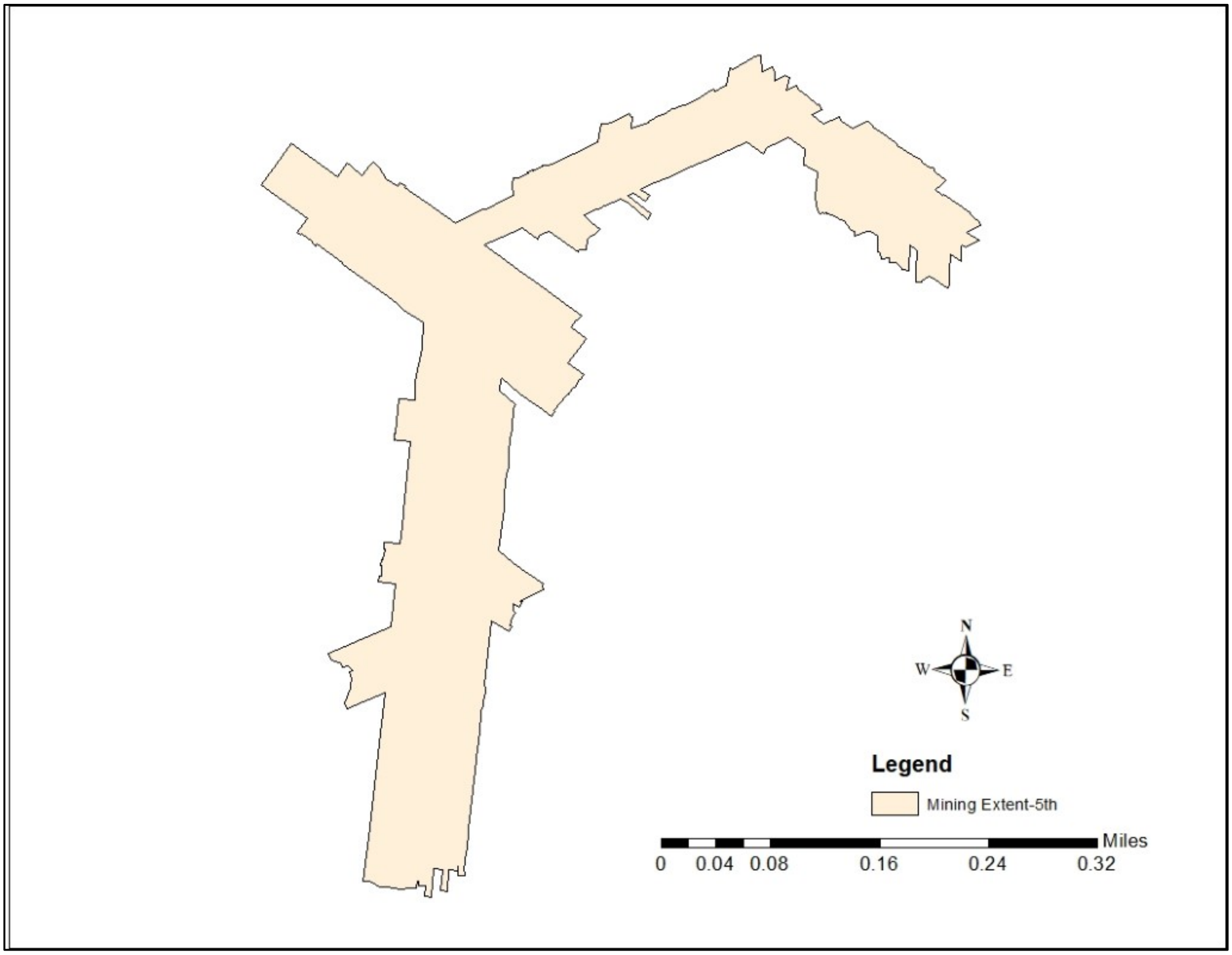

Figure 103. Acosta Deep Mine mining extent for the 5th assessment period

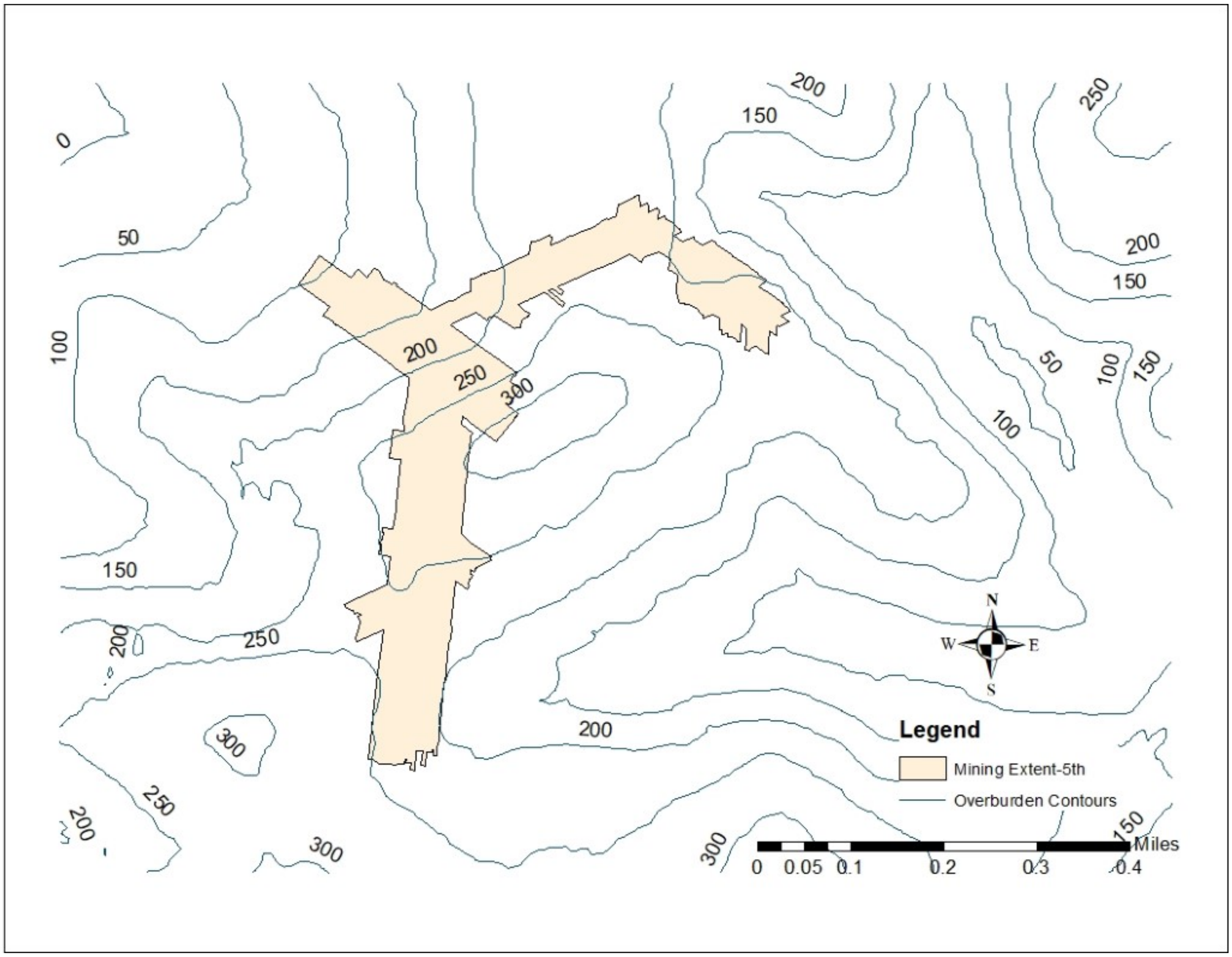

Figure 104. Fifty-foot overburden contour intervals for the Acosta Deep Mine

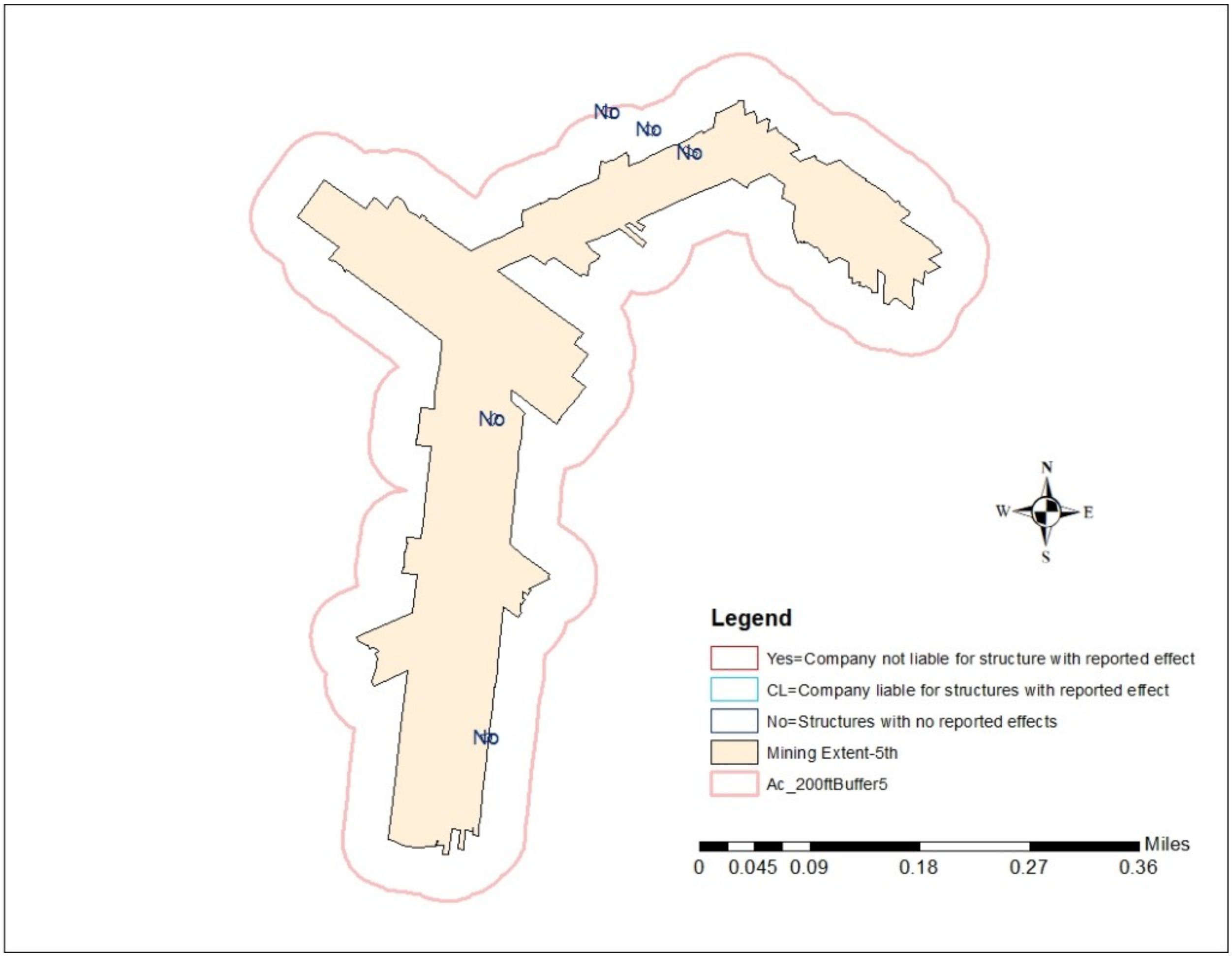

Figure 105. Acosta Deep Mine 5th assessment 200-ft buffer and structures*

Note there are two structures with reported effects that are far from mining and are not included here for display purposes.

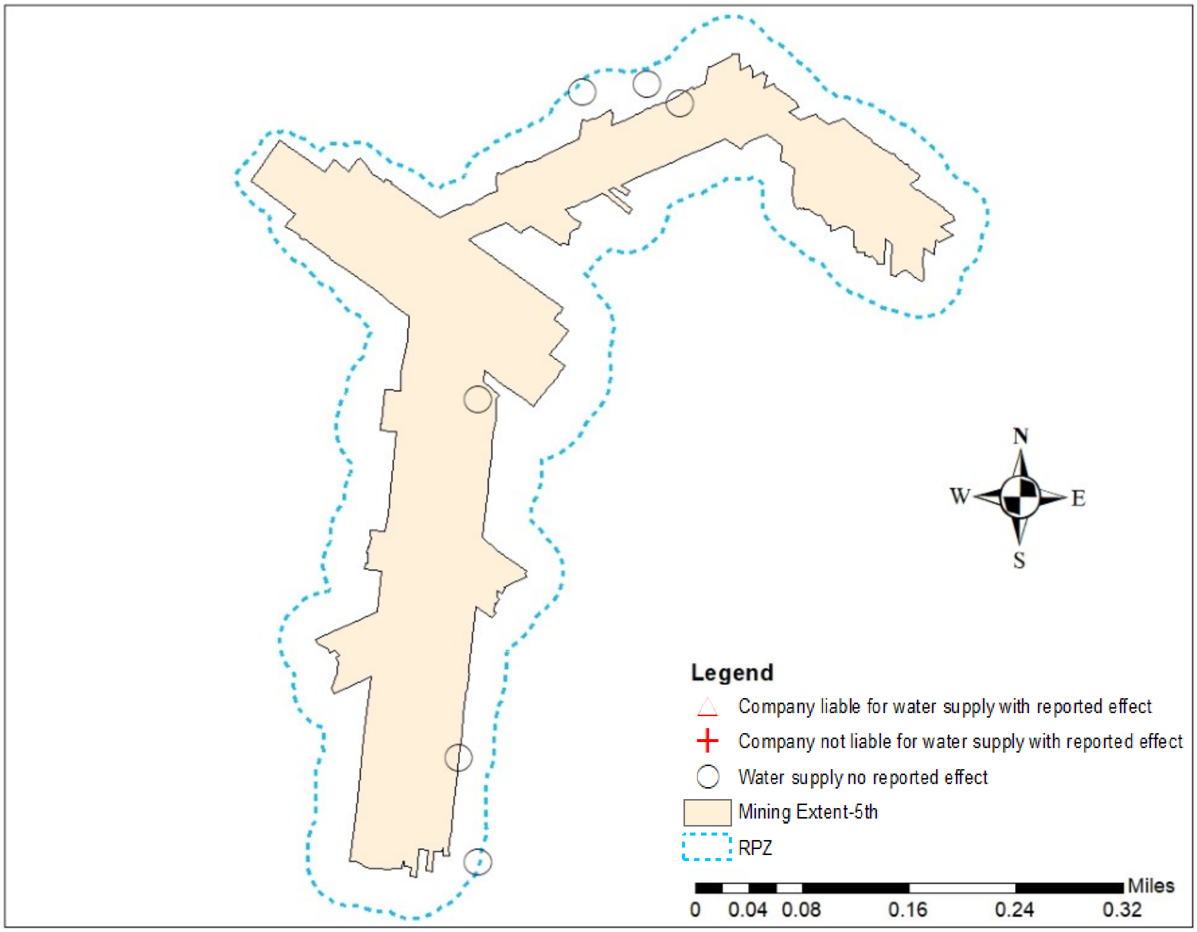

Figure 106. Acosta Deep Mine 5th assessment water supplies and RPZ*

***Note there are three water supplies with reported effects that are far from mining and are not included here for display purposes. One of the water supplies was determined to have no actual problem and the remaining two are in interim resolution.*

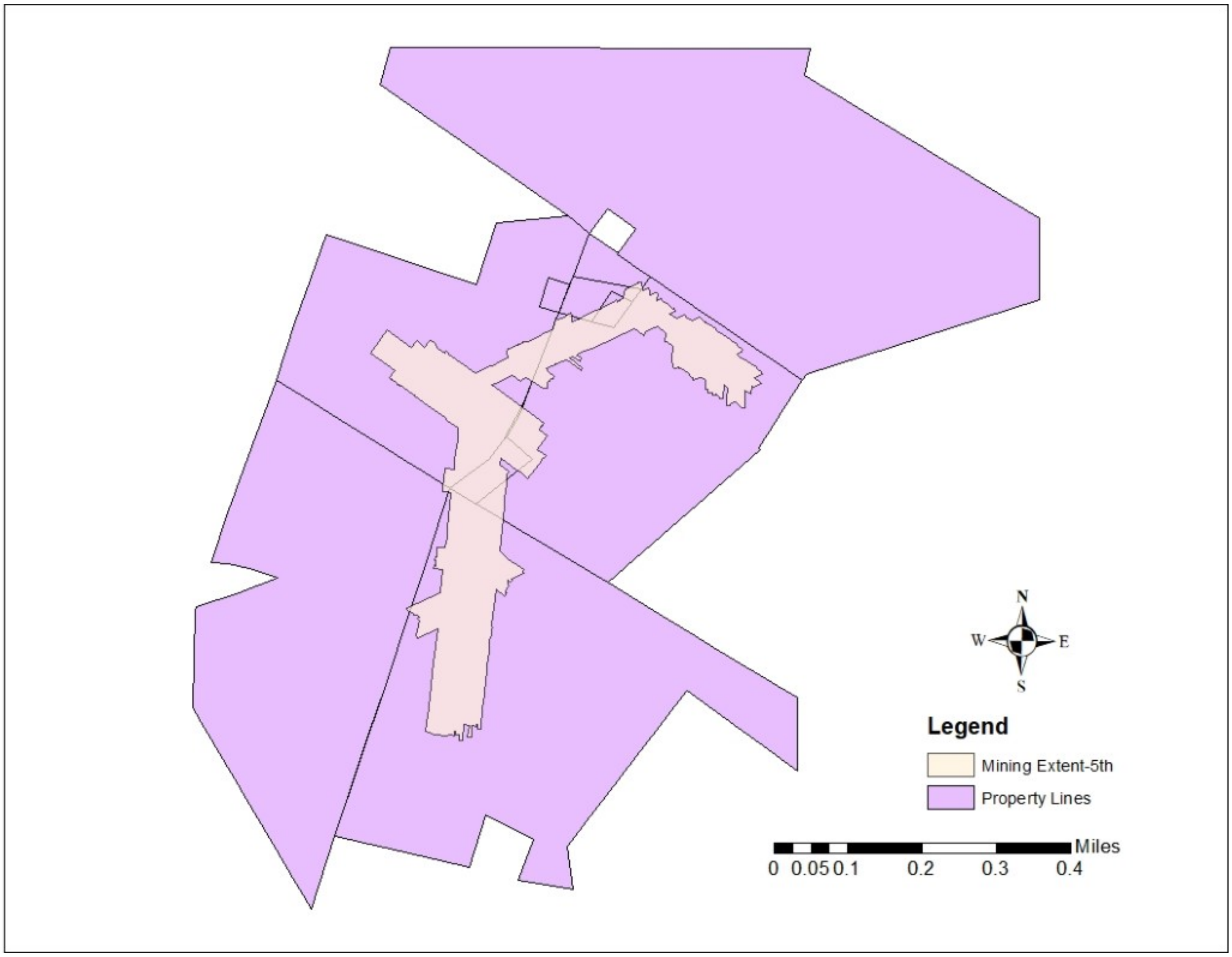

Figure 107. Properties associated with the 5th assessment period over the Acosta Deep Mine

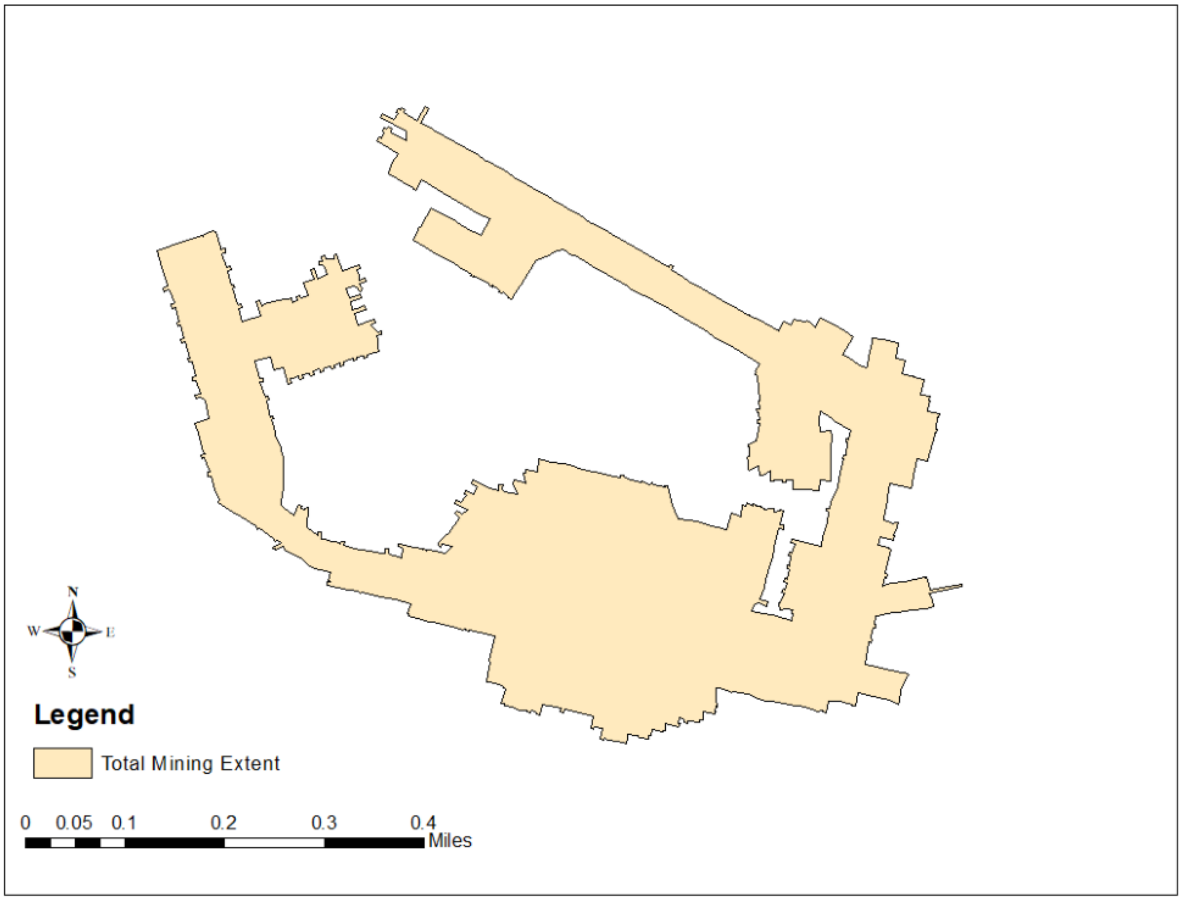

Figure 108. Barbara No. 2 total extent of mining

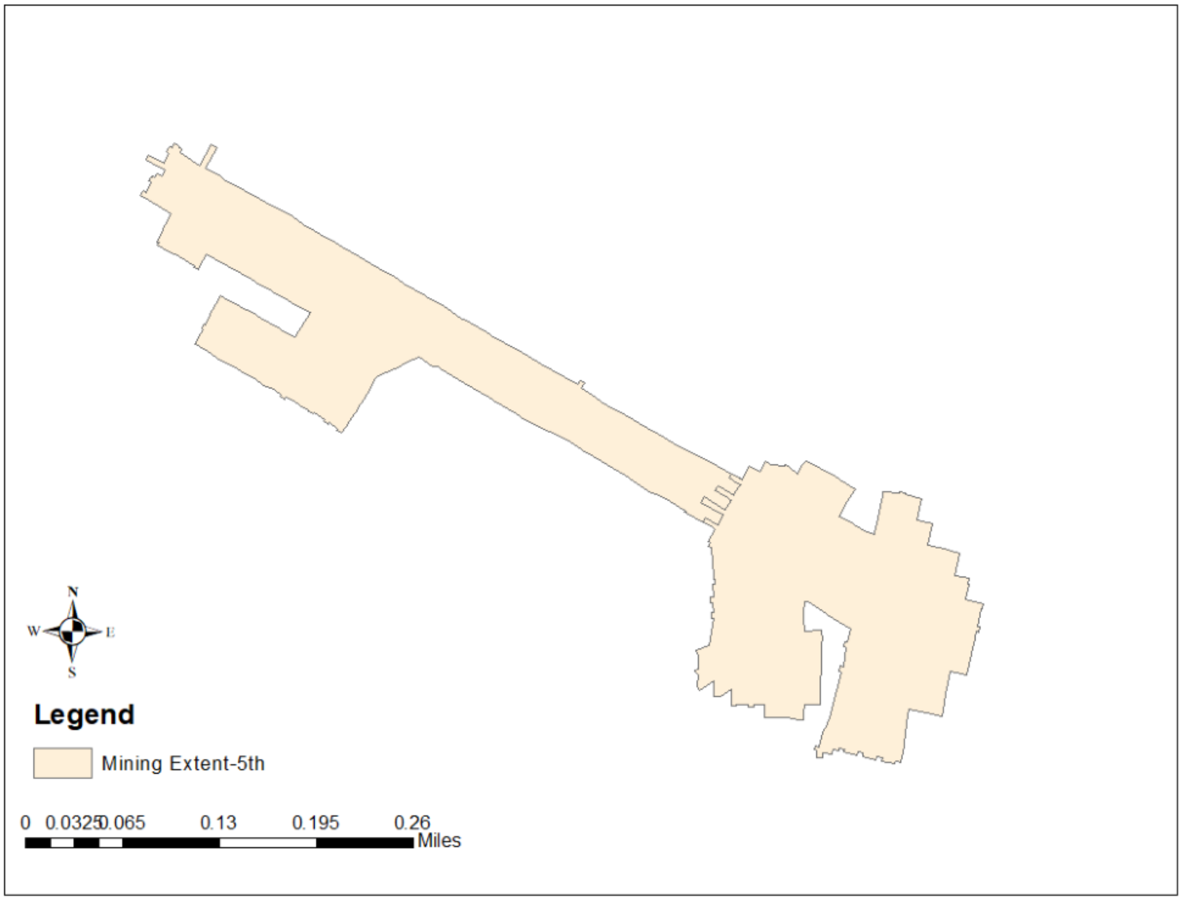

Figure 109. Barbara No. 2 mining extent for the 5th assessment period

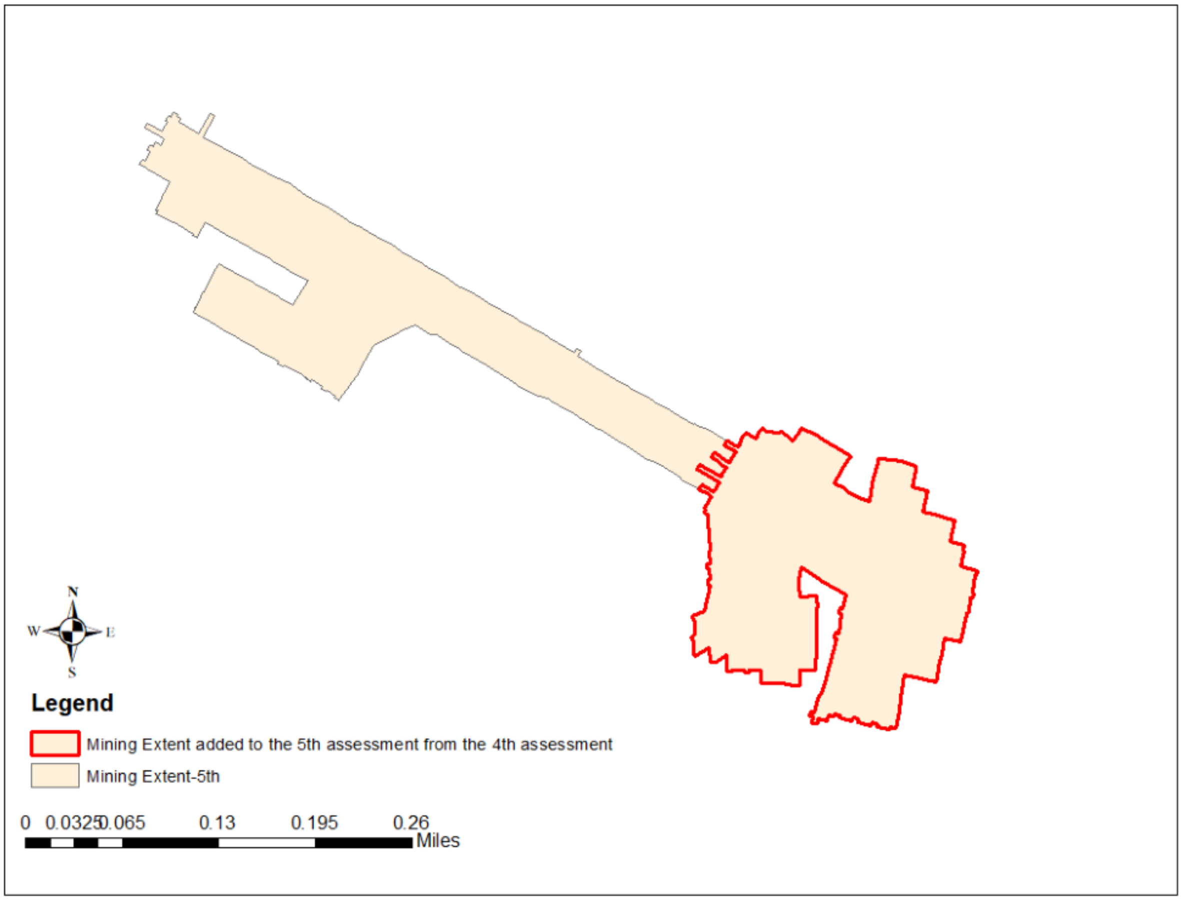

Figure 110. Barbara No. 2 mining extent for the 4th and 5th assessment periods*

***Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined in January 2013 during the 4th assessment period. Due to overlooking of the mining done in the 4th assessment period, this area was not considered during the 4th assessment period. This area is added to the 5th assessment period so that all of the mine area can be analyzed. Only the area of the mining from the 4th assessment, the structures, water supplies, and land with no reported effects are added to this assessment. All structures, water supplies, and land with reported effects were assumed to be accounted for in the 4th assessment.*

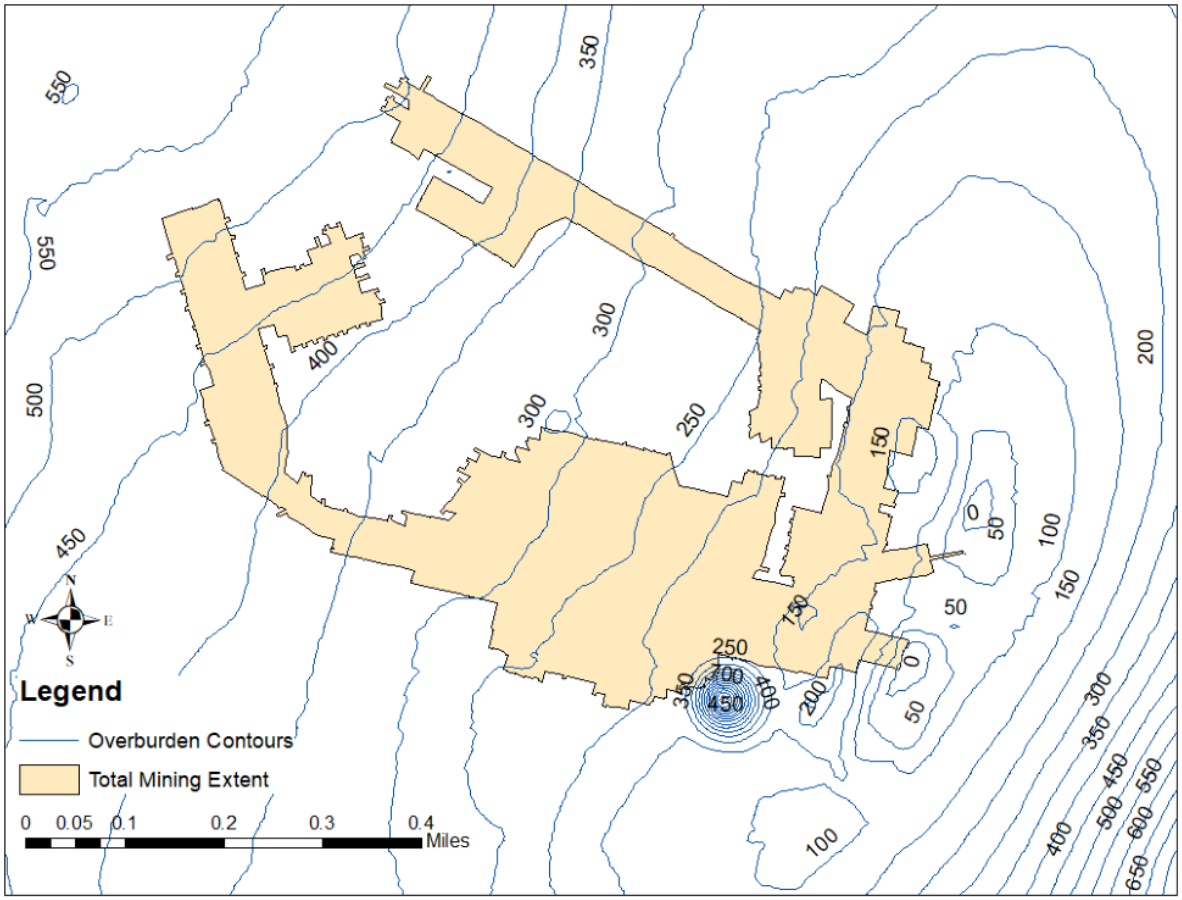

Figure 111. Fifty-foot overburden contour intervals for the Barbara No. 2 Mine

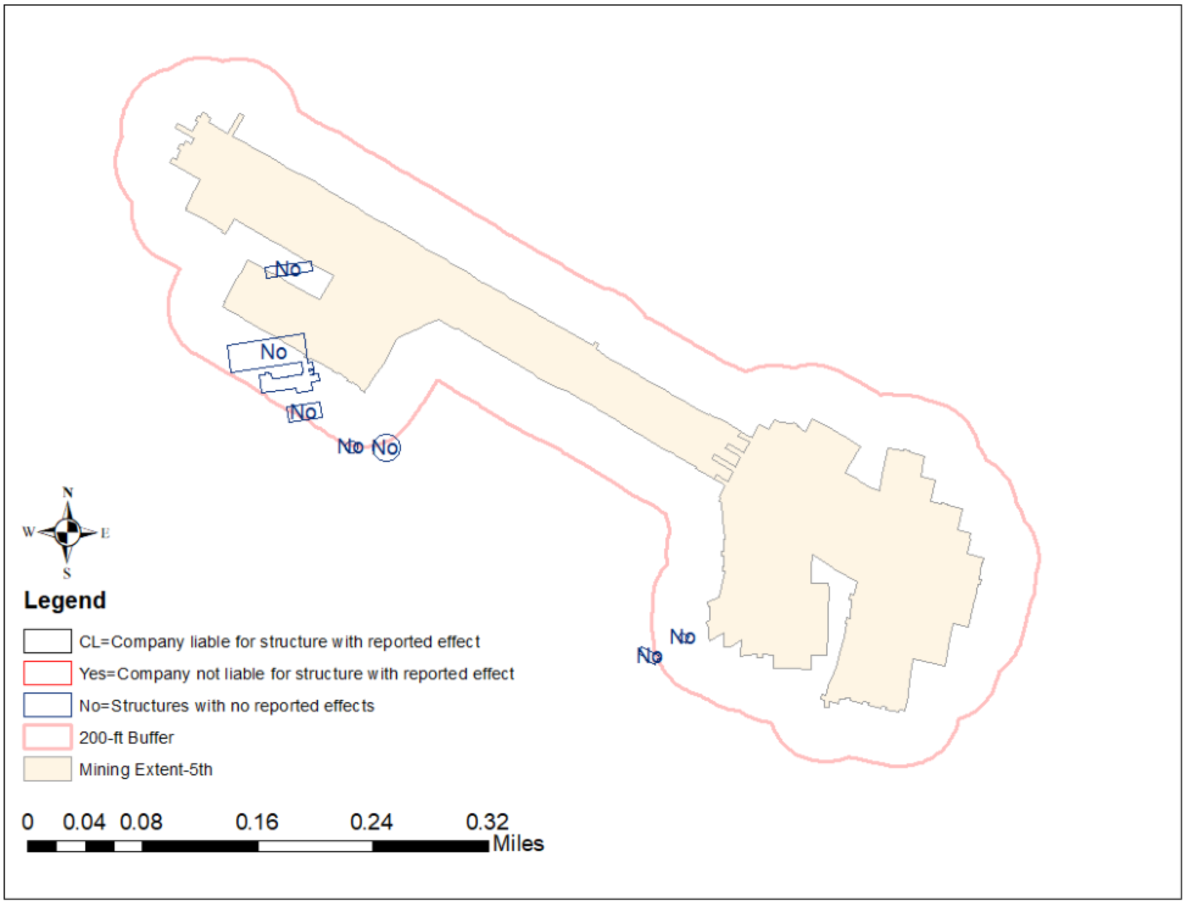

Figure 112. Barbara No. 2 Mine 5th Assessment 200-ft buffer and structures

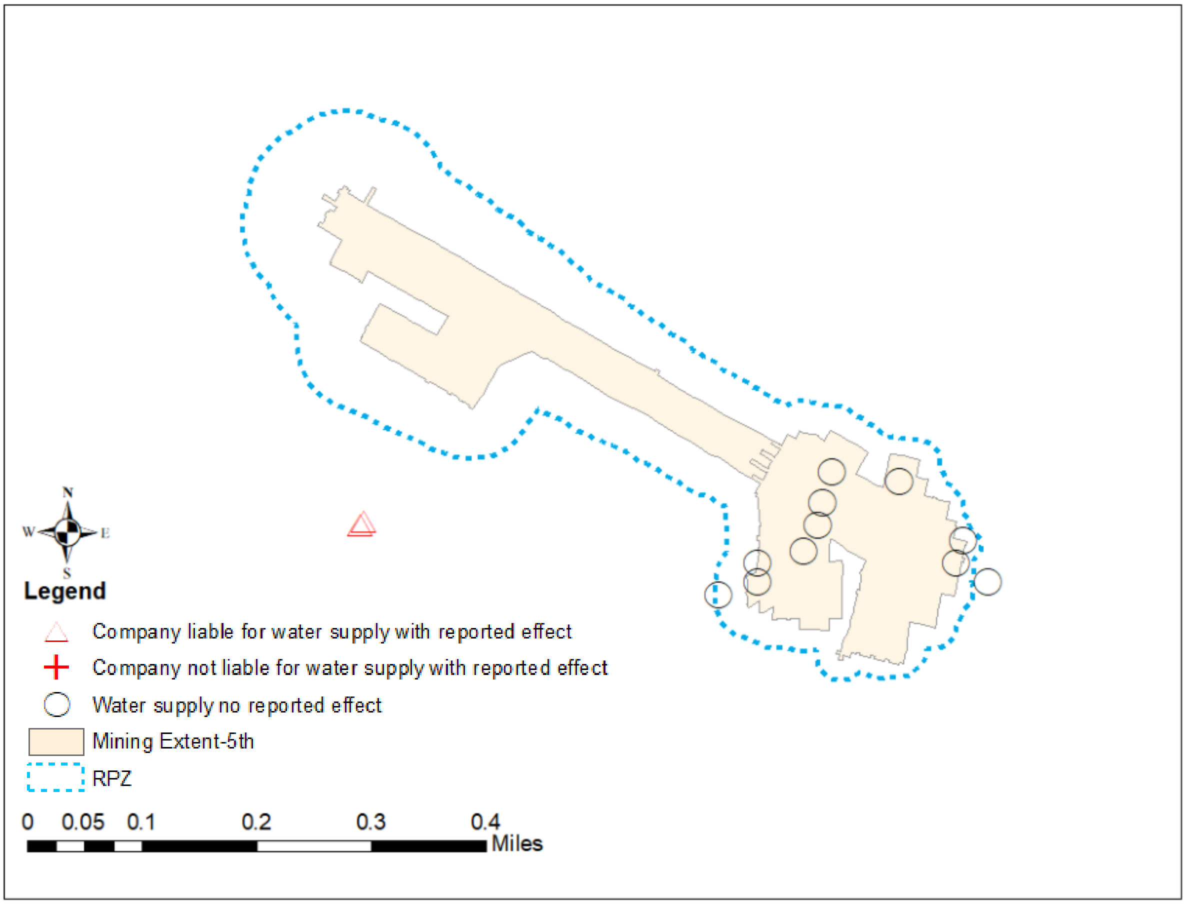

Figure 113. Barbara No. 2 Mine 5th assessment water supplies and RPZ*

**Note there is one water supply with a reported effect that is determined to be company liable and three water supplies with a reported effect determined to be not company liable not shown for display purposes.*

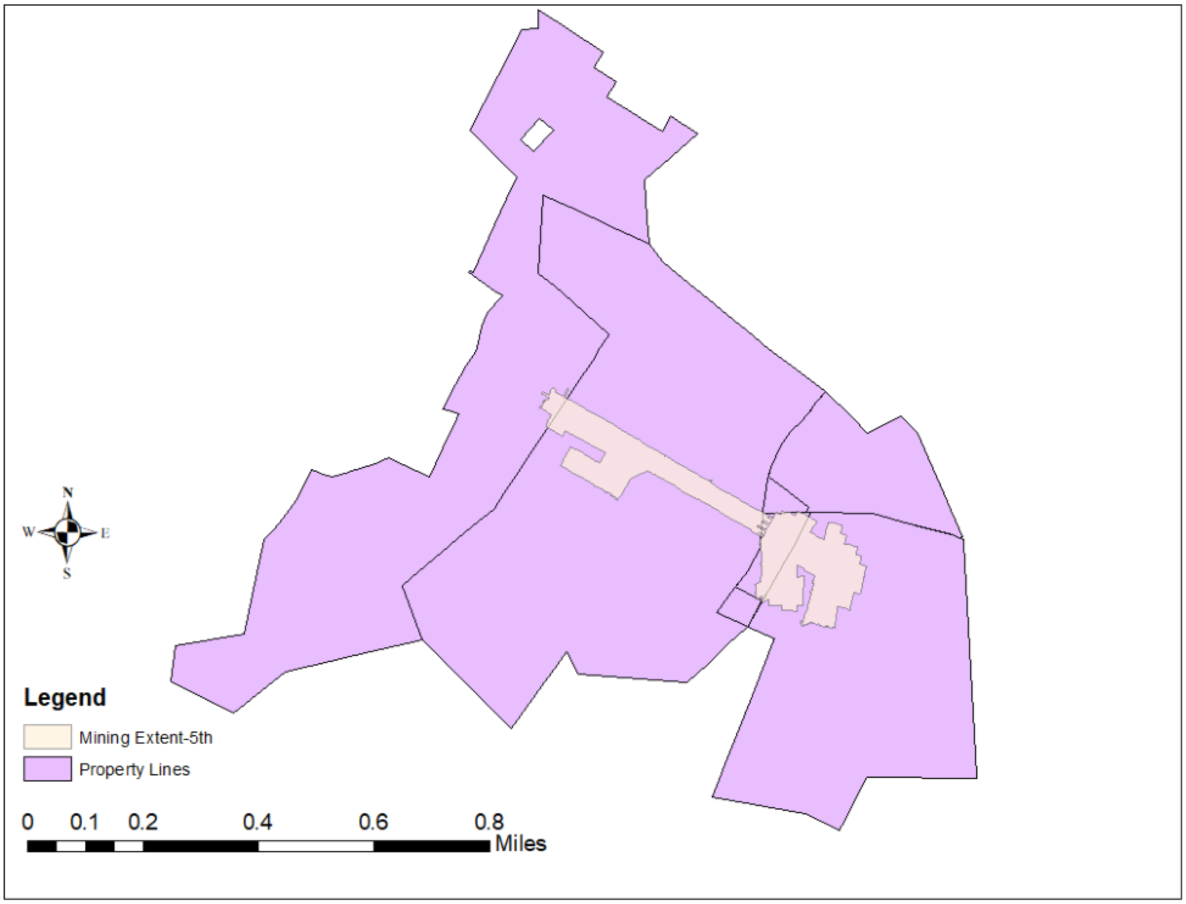

Figure 114. Properties associated with the 5th assessment period over the Barbara No. 2 Mine

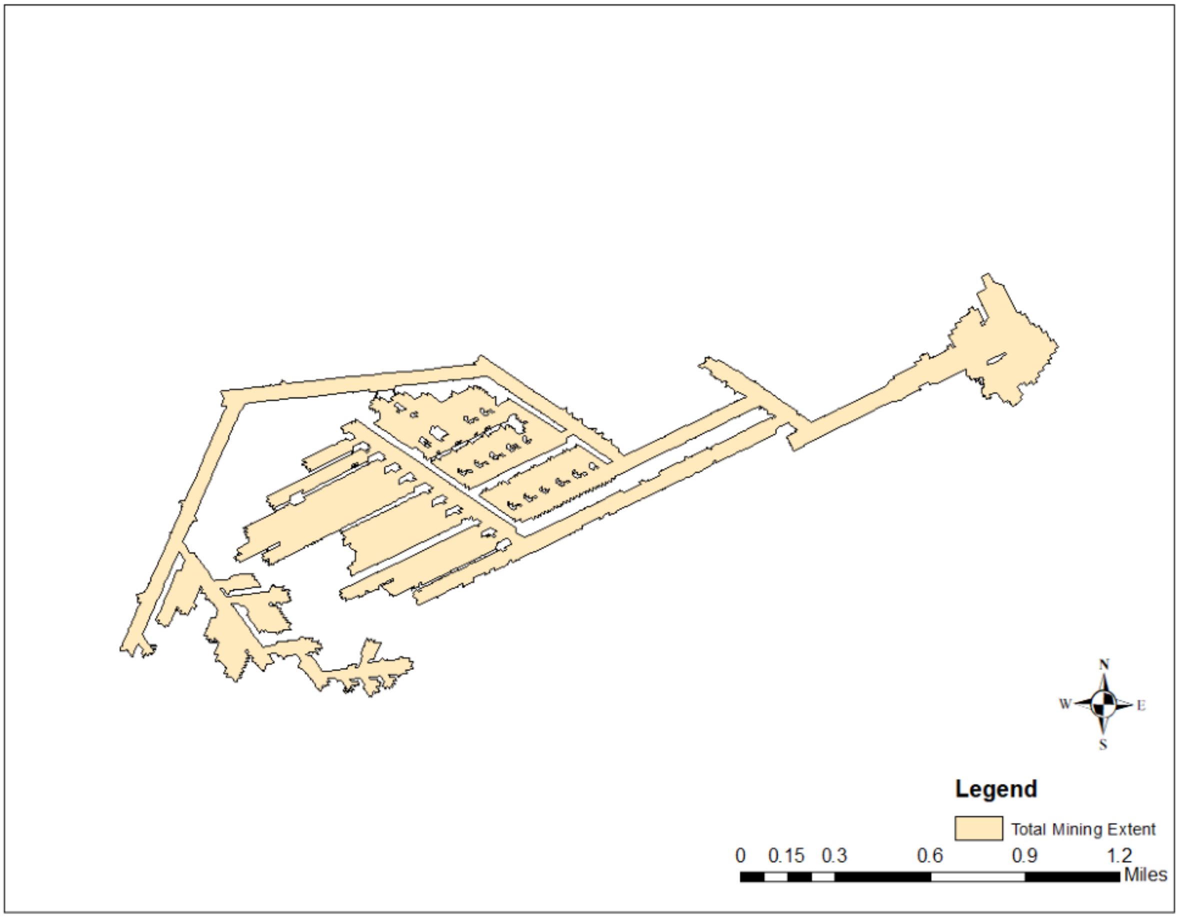

Figure 115. Barrett total extent of mining

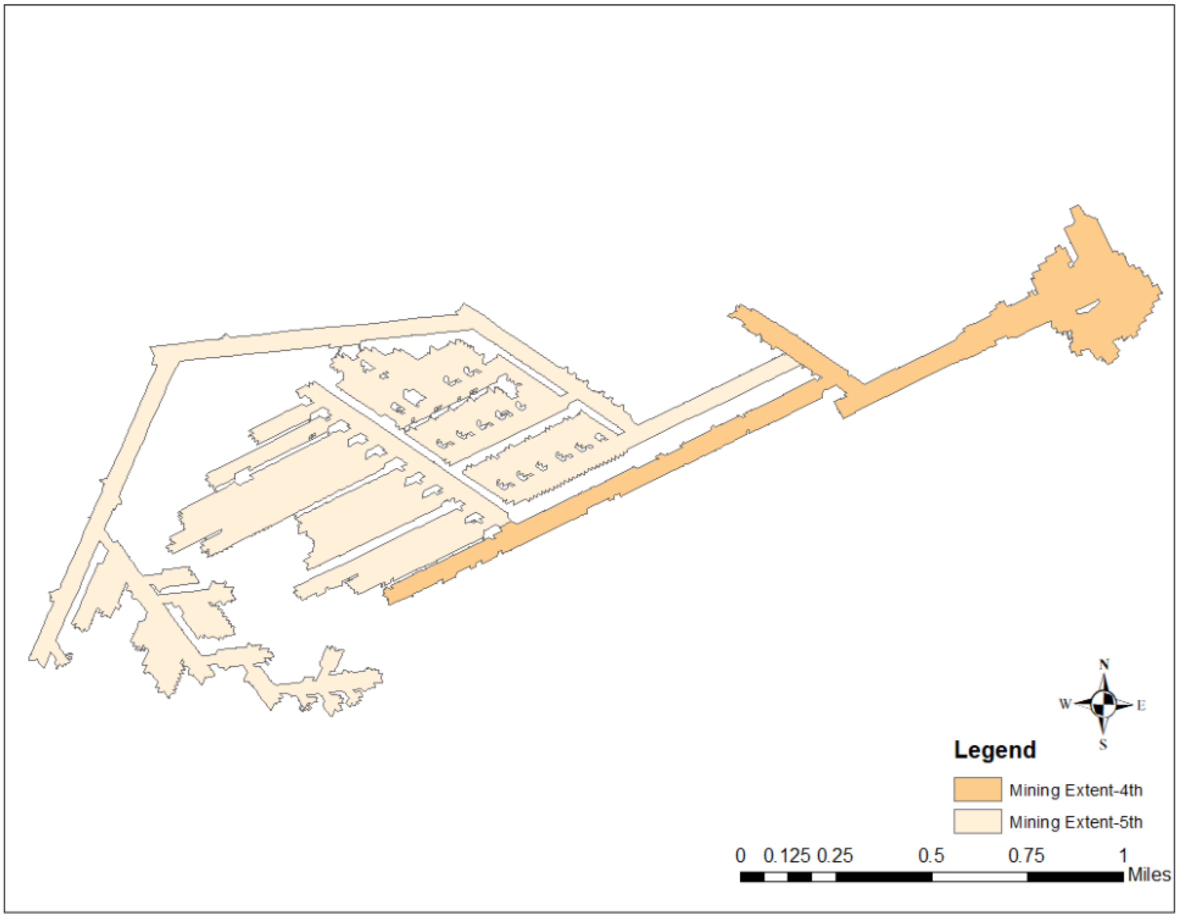

Figure 116. Barrett mining extent for the 4th and 5th assessment periods

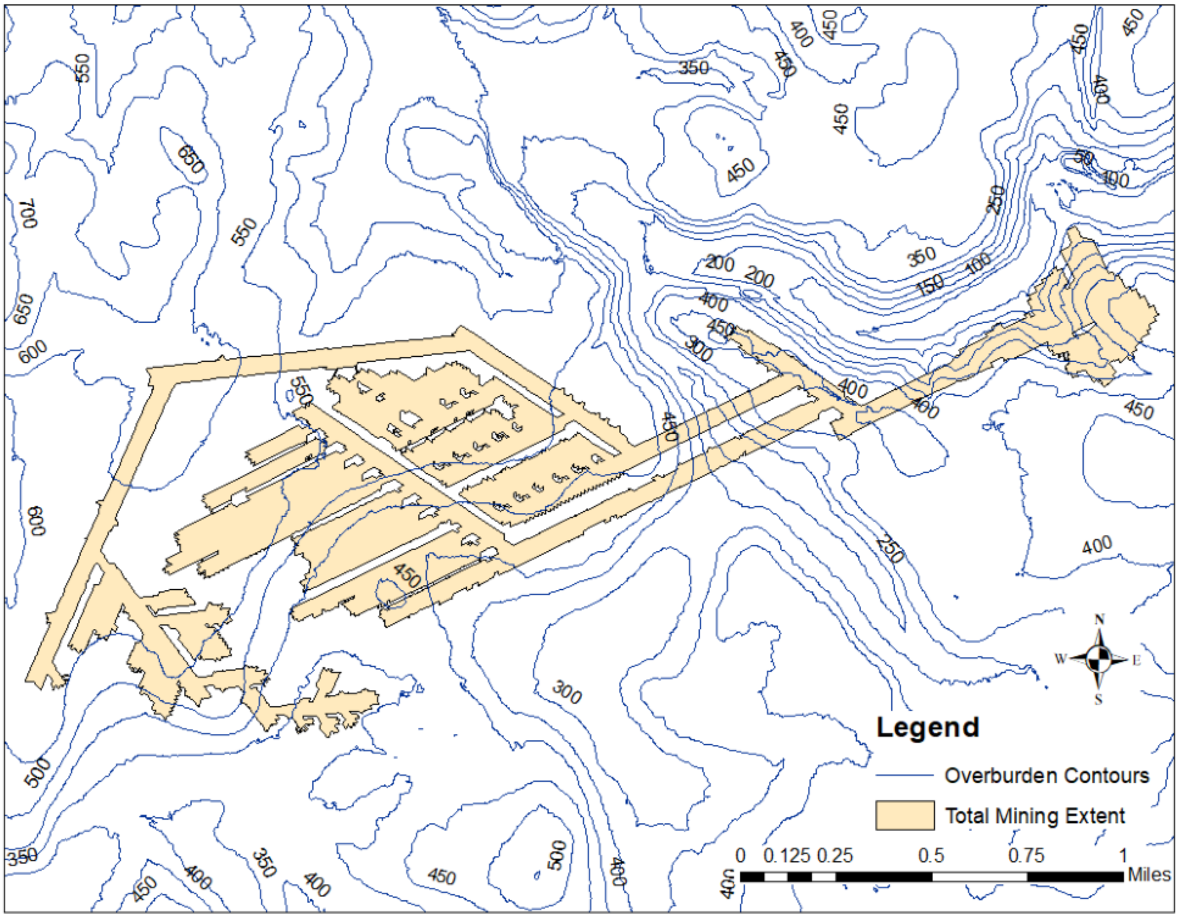

Figure 117. Fifty-foot overburden contour intervals for the Barrett Mine

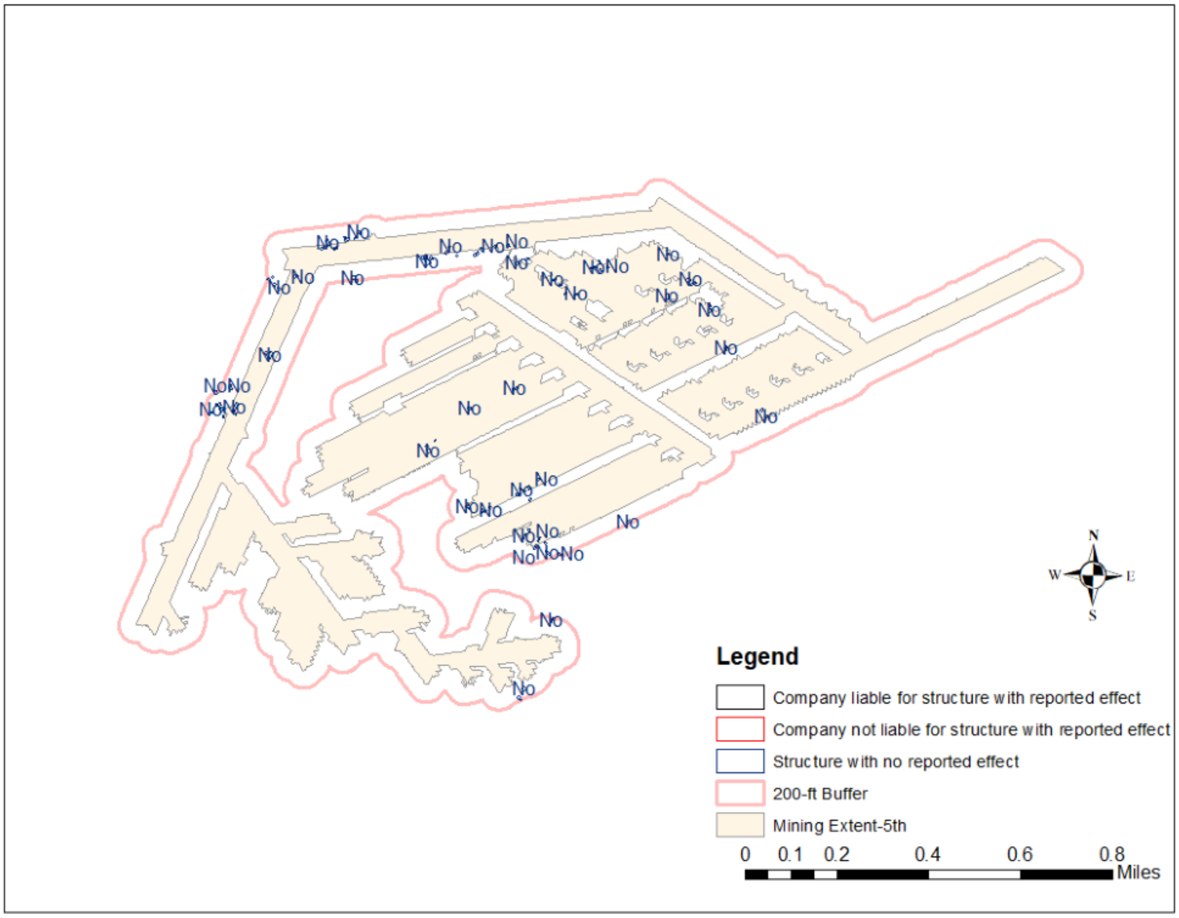

Figure 118. Barrett 5th assessment 200-ft buffer and structures

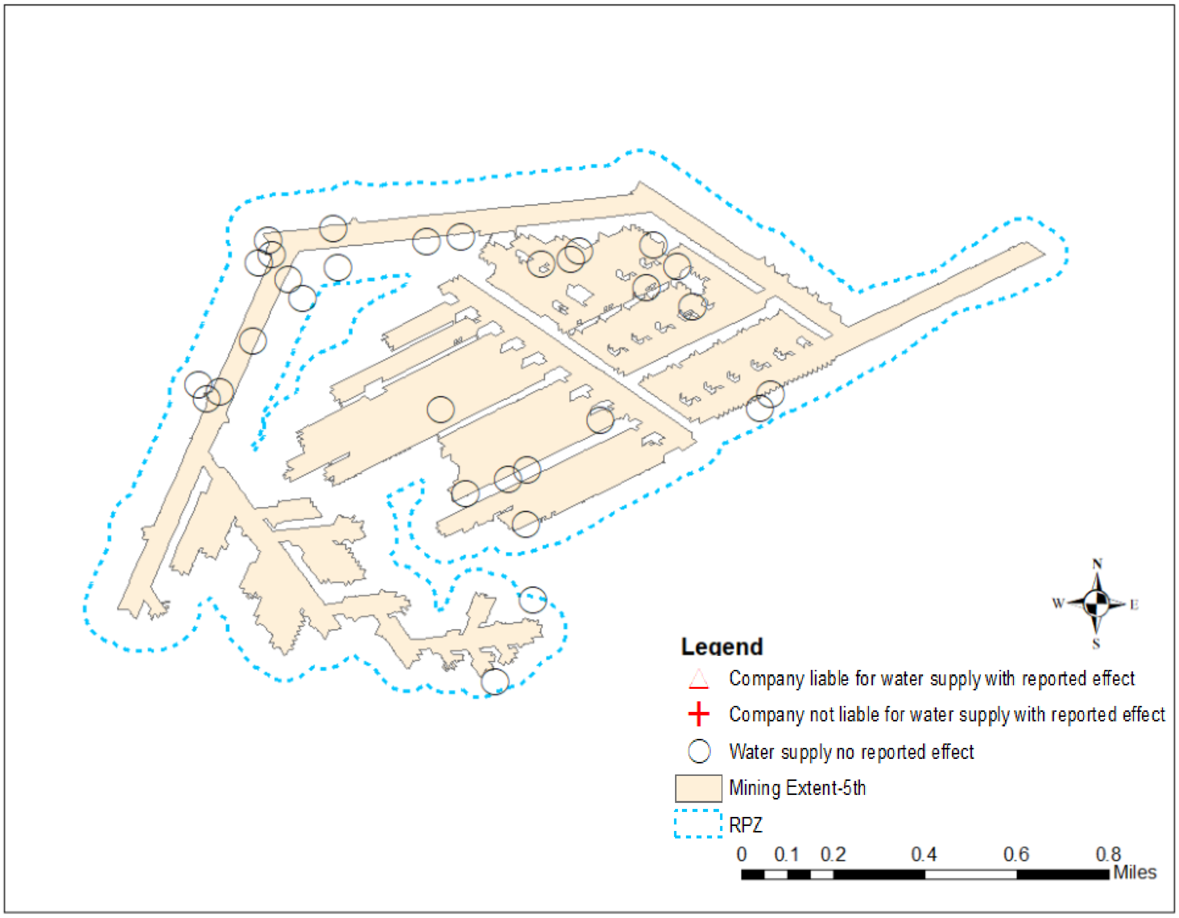

Figure 119. Barrett 5th assessment water supplies and RPZ

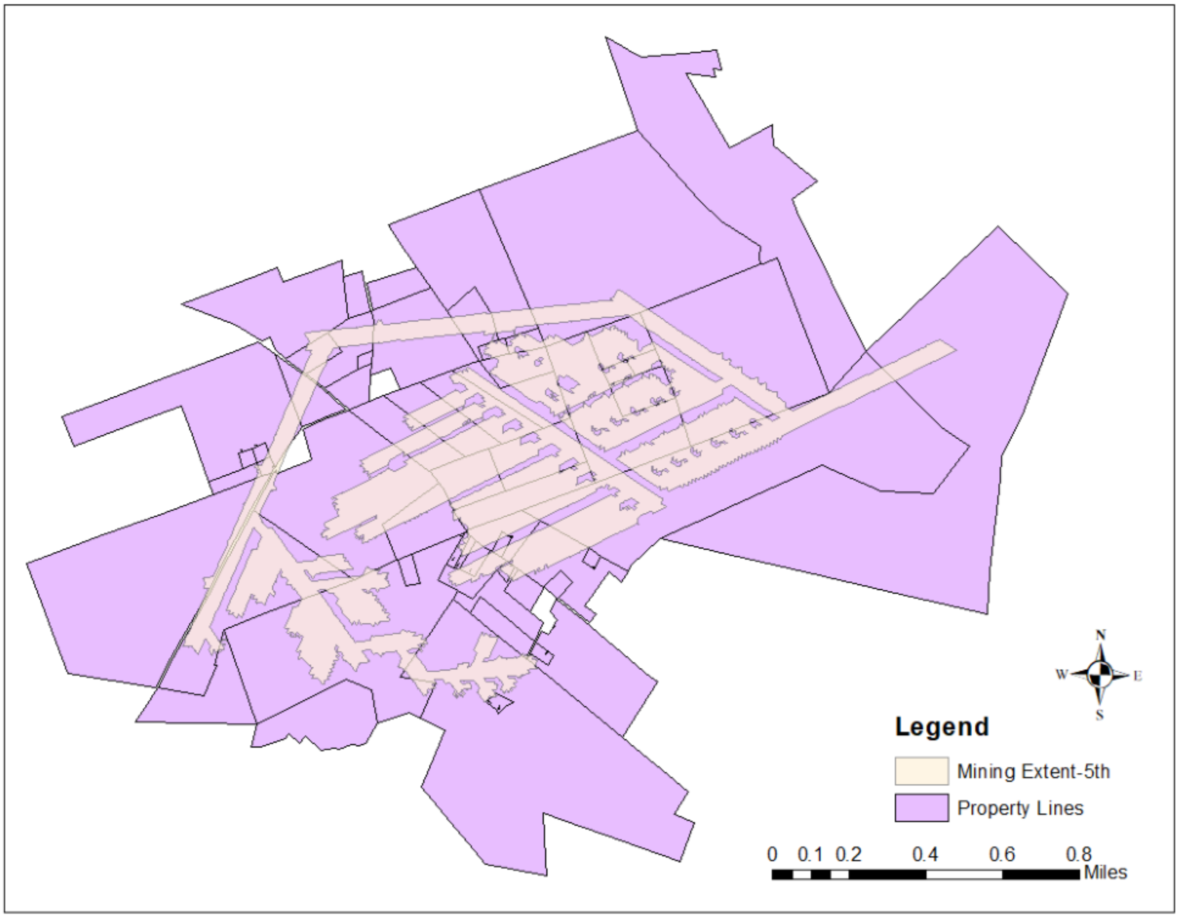

Figure 120. Properties associated with the 5th assessment period over the Barrett Mine

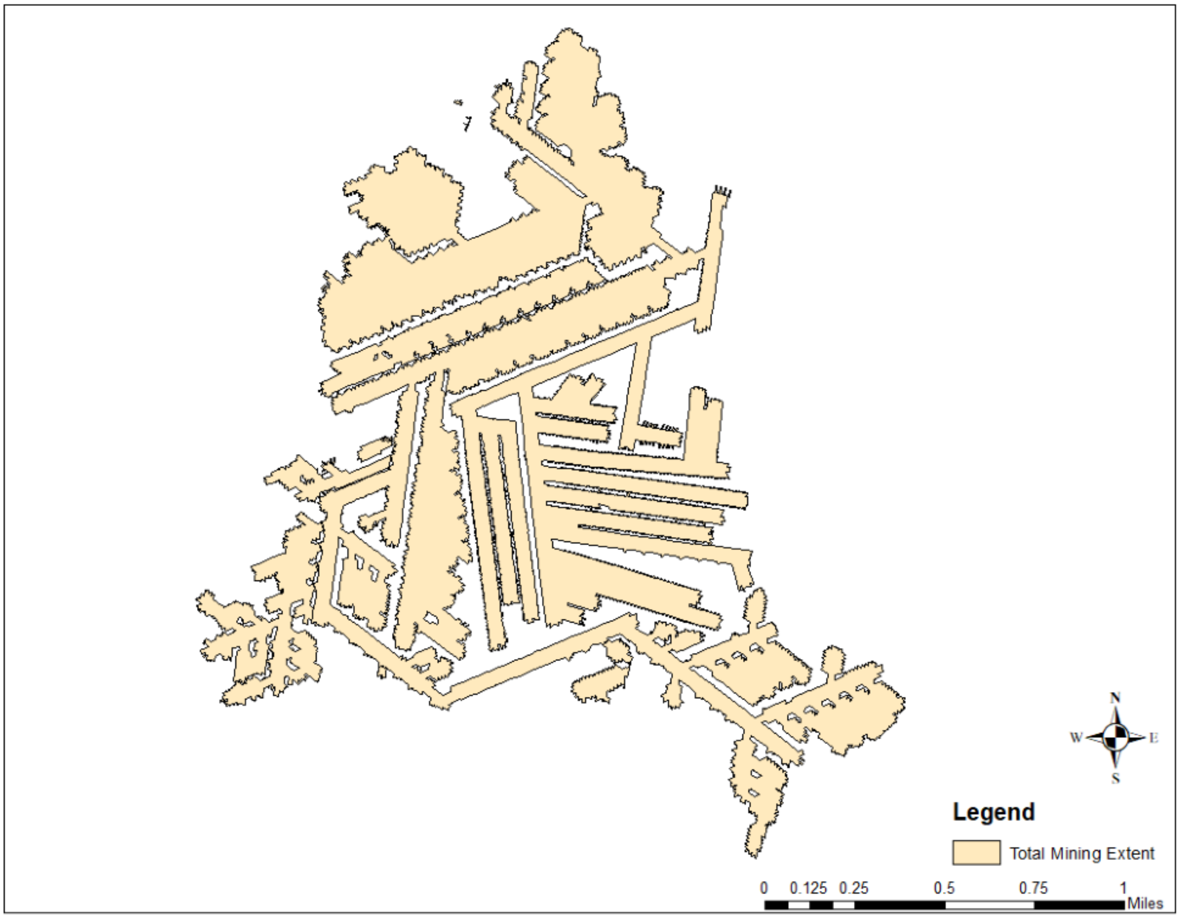

Figure 121. Beaver Valley total extent of mining

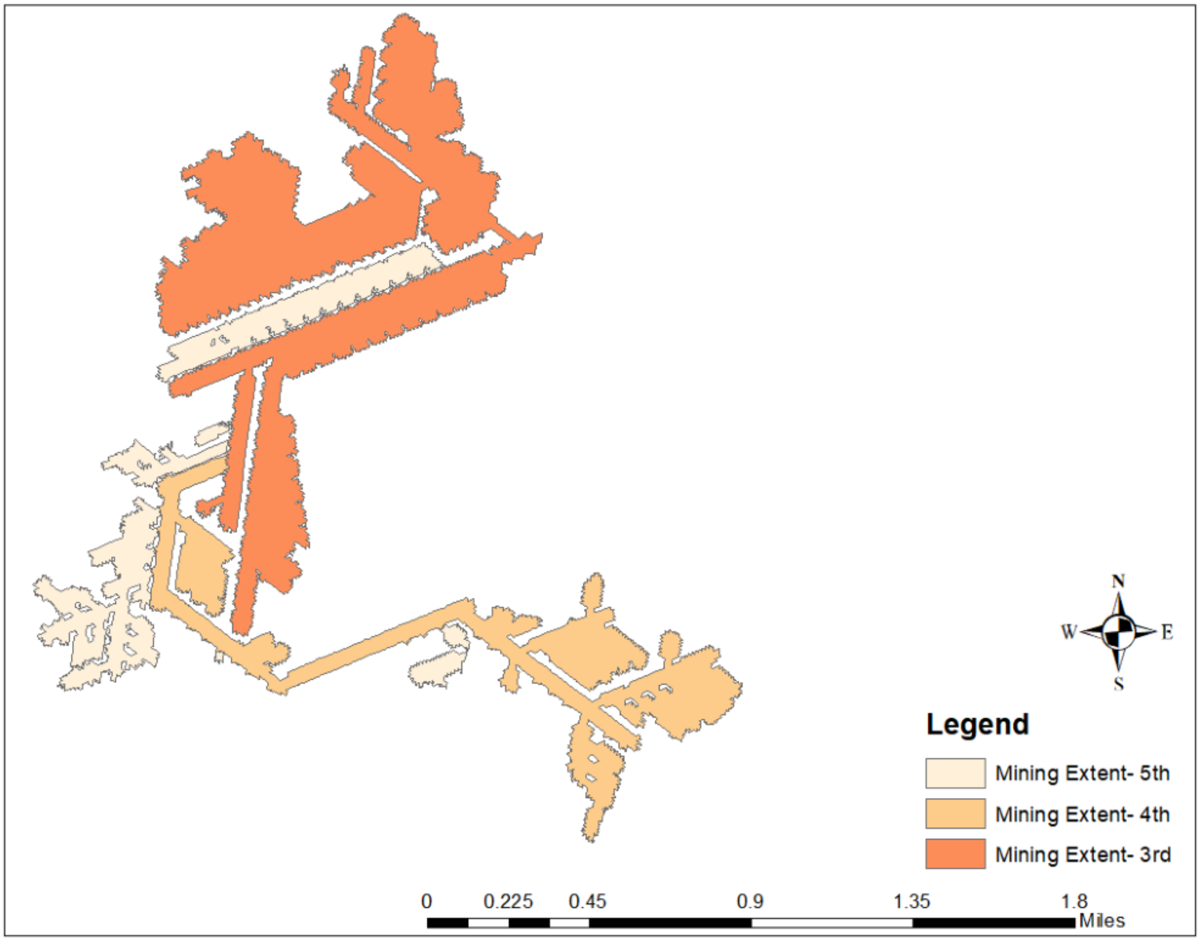

Figure 122. Beaver Valley mining extent for the 3rd, 4th, and 5th assessment periods

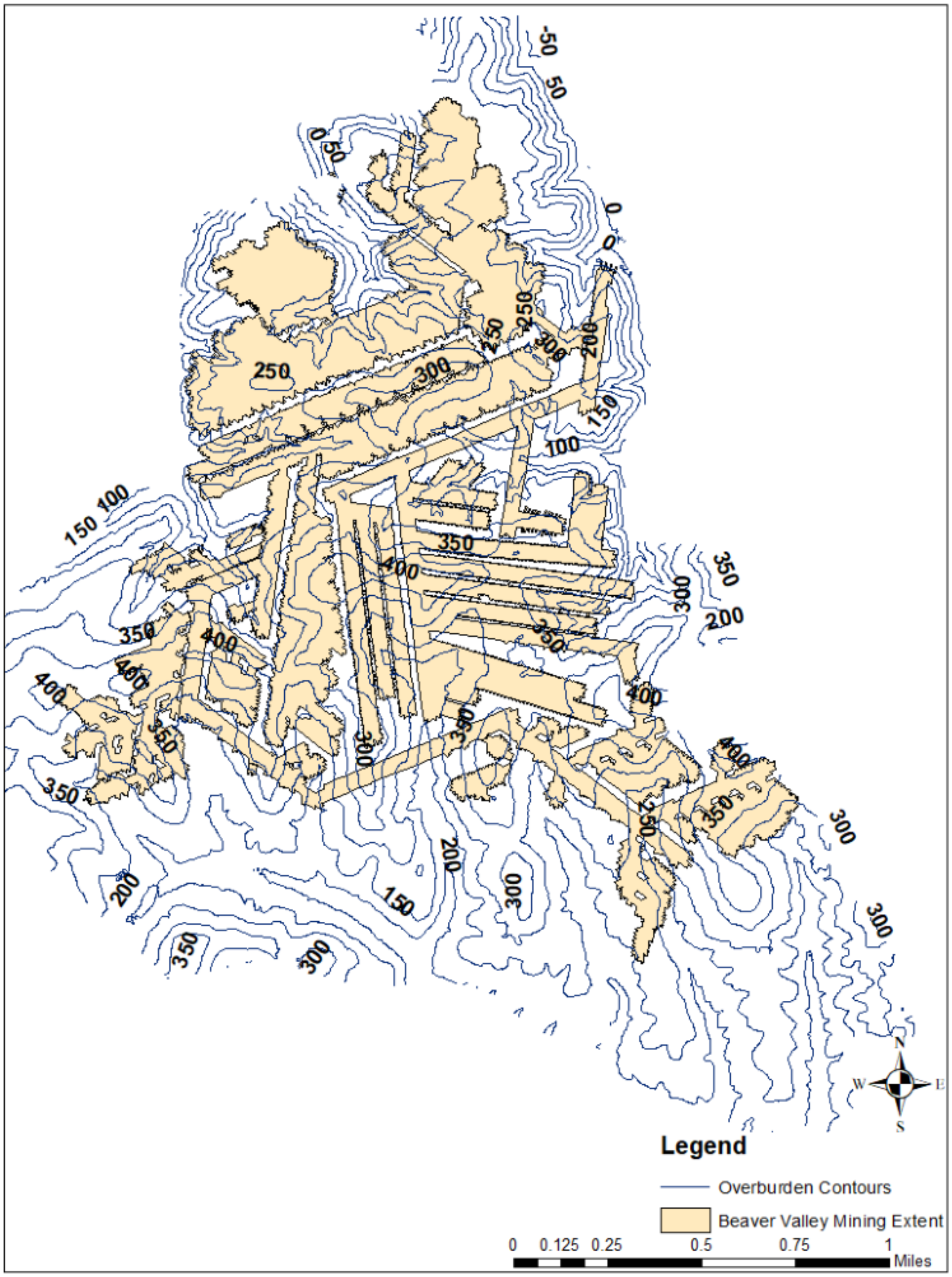

Figure 123. Fifty-foot contour intervals for the Beaver Valley Mine

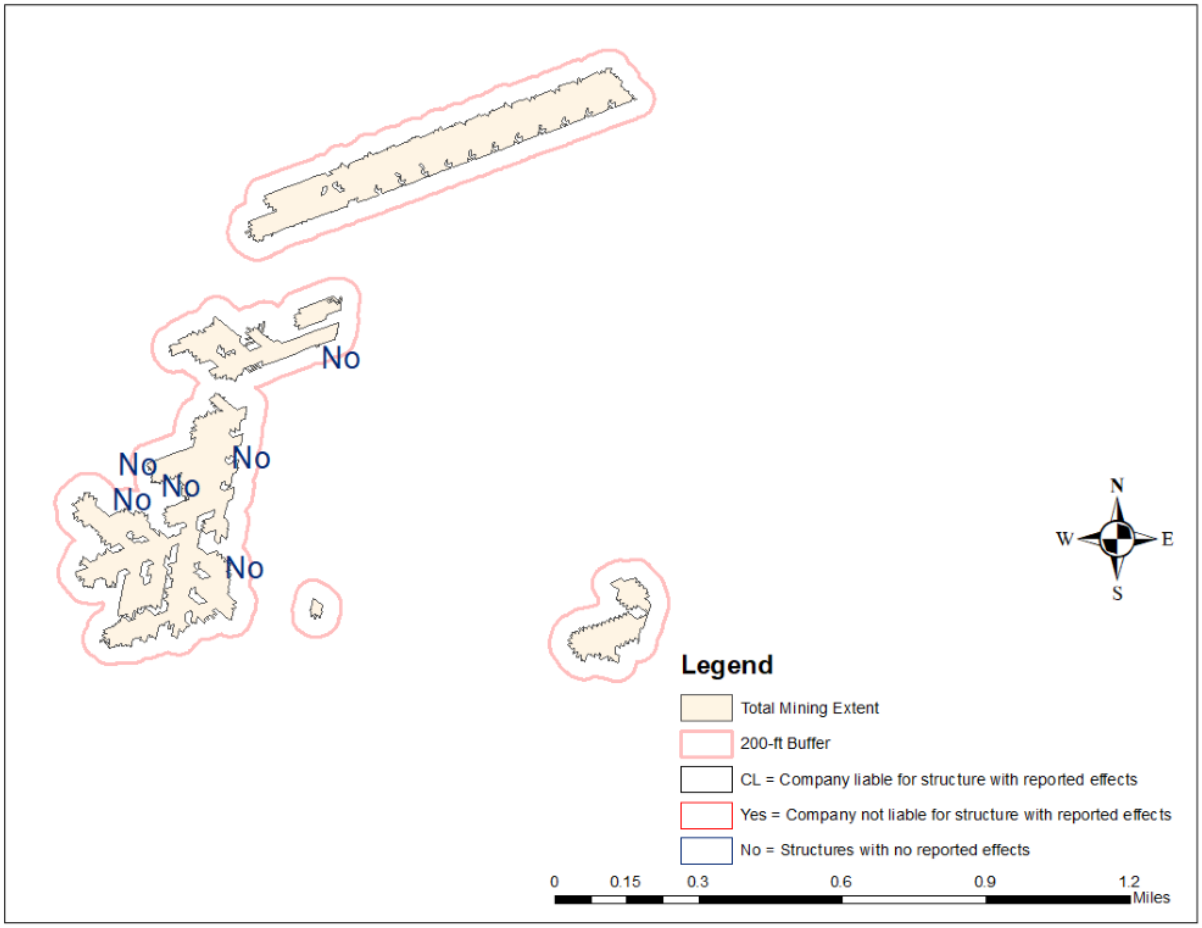

Figure 124. Beaver Valley 5th assessment 200-ft buffer and structures

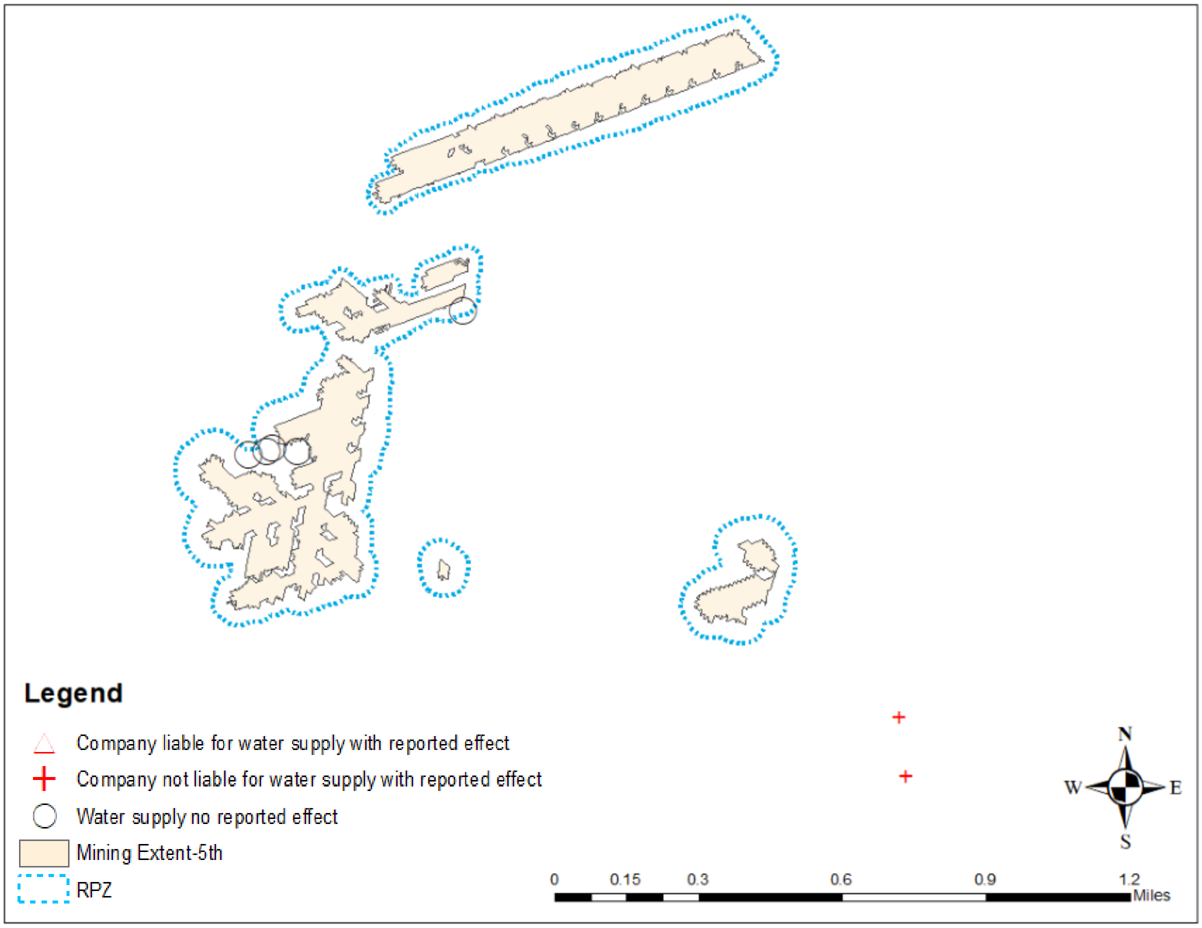

Figure 125. Beaver Valley 5th assessment water supplies and RPZ

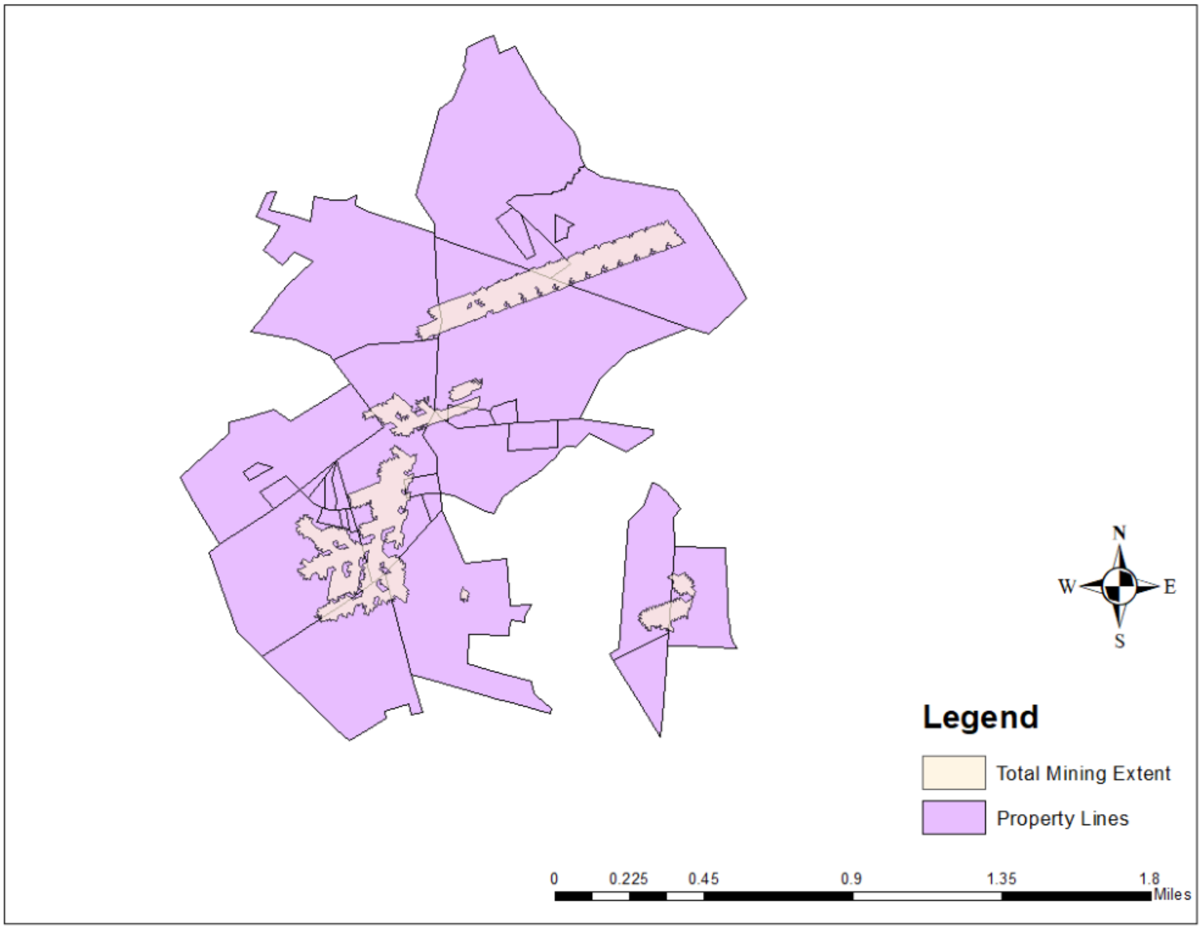

Figure 126. Properties associated with the 5th assessment period over the Beaver Valley mine

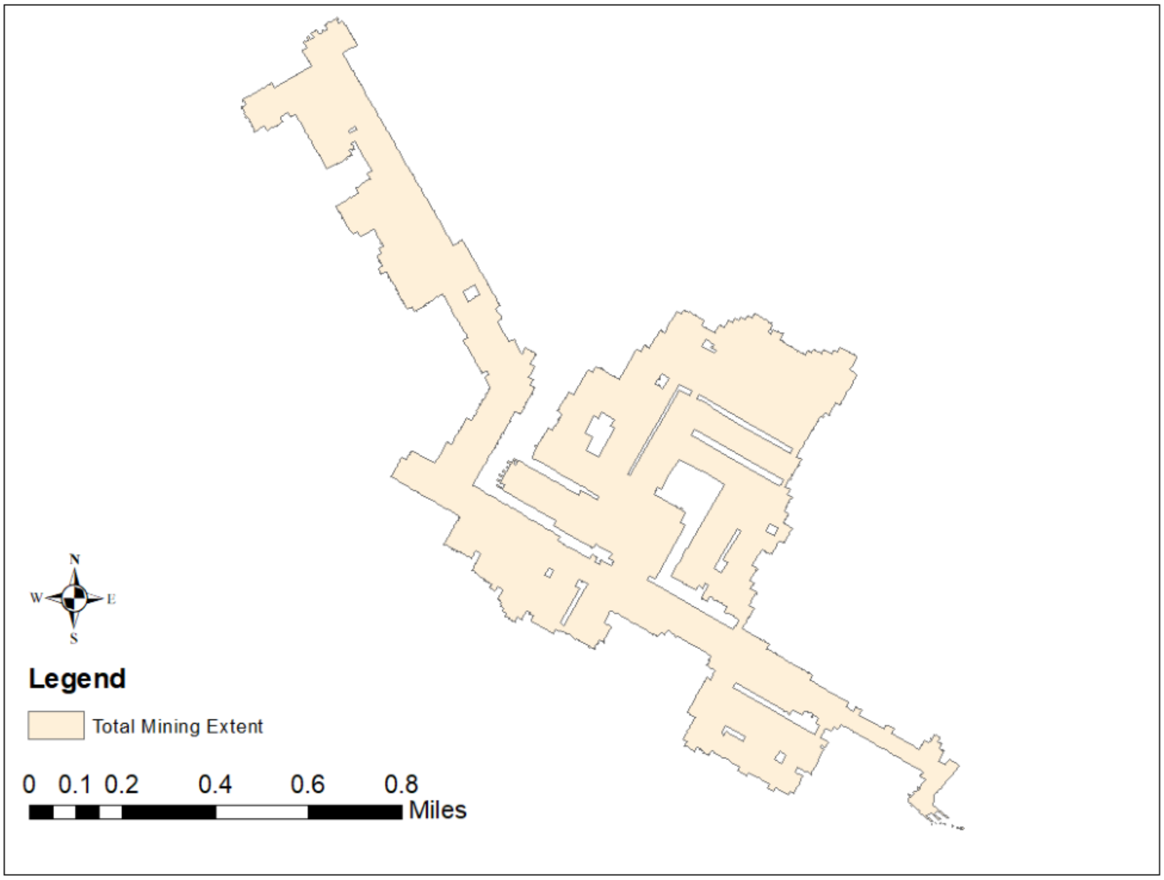

Figure 127. Brubaker total extent of mining

Figure 128. Brubaker mining extent for the 5th assessment period

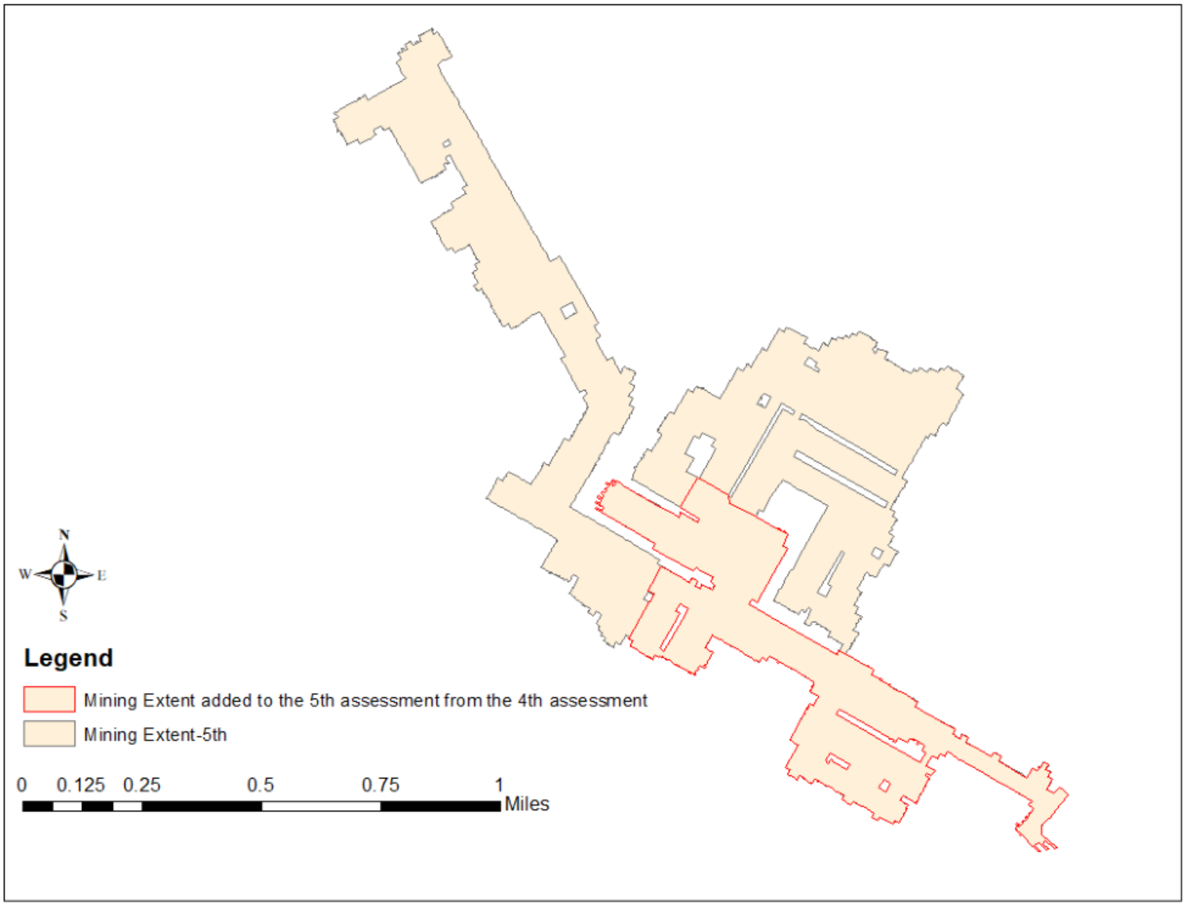

Figure 129. Brubaker's mining extent for the 4th and 5th assessment periods*

Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined before the 4th assessment collection period was finalized. Due to the late submission of this data and the early reporting requirements, this area was not considered during the 4th assessment period. This area is added to the 5th assessment period so that all area of the mine will be analyzed.

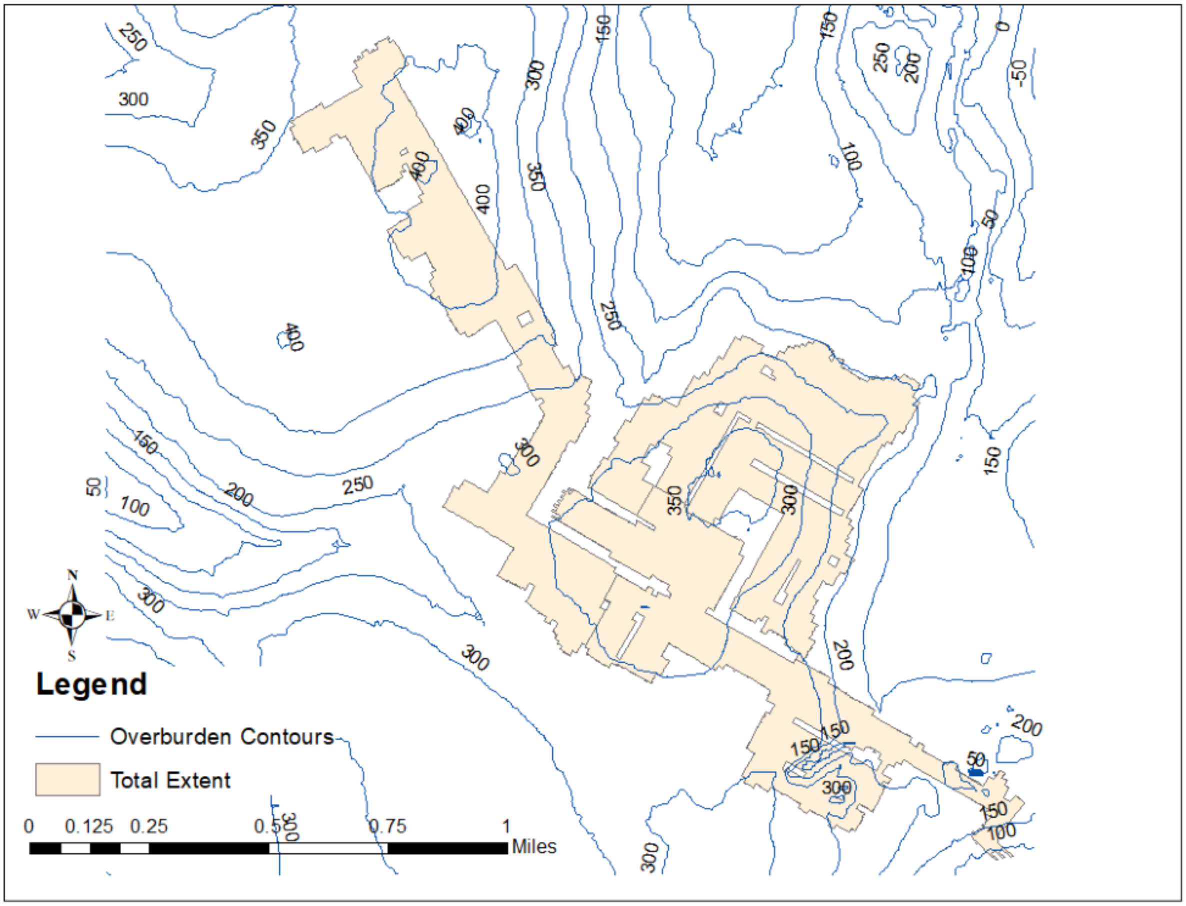

Figure 130. Fifty-foot overburden contour intervals for the Brubaker Mine

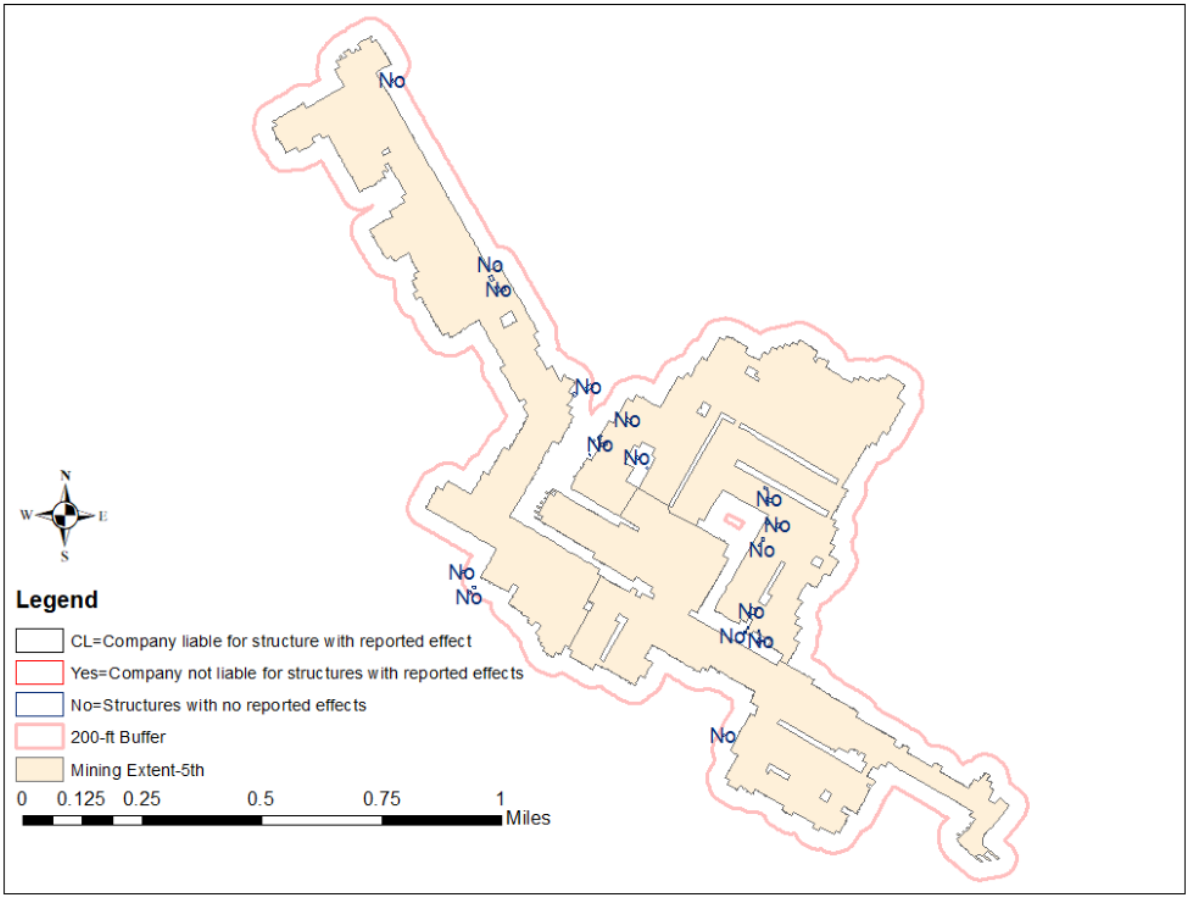

Figure 131. Brubaker 5th assessment 200-ft buffer and structures

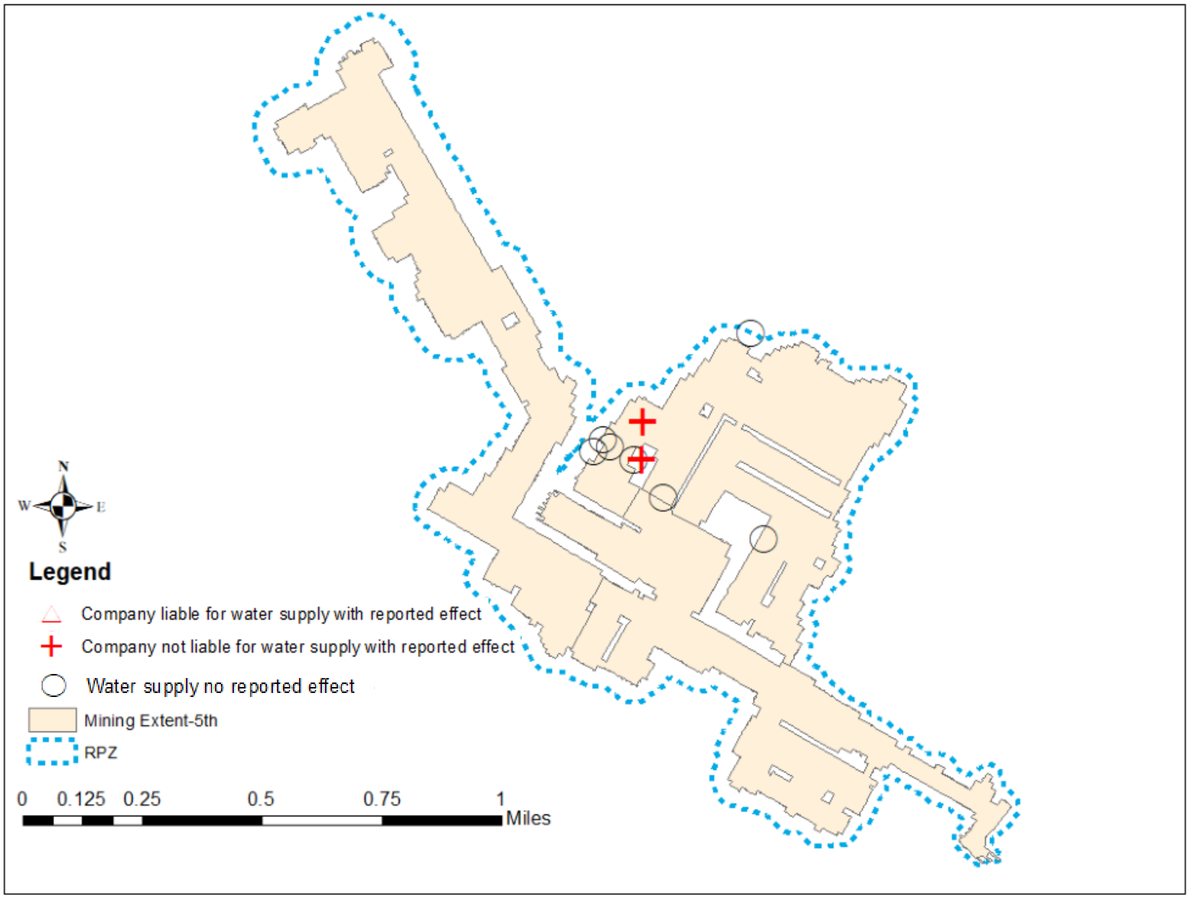

Figure 132. Brubaker 5th assessment water supplies and RPZ

Figure 133. Properties Associated with the 5th Assessment Period over the Brubaker Mine

Figure 134. Brush Valley total extent of mining

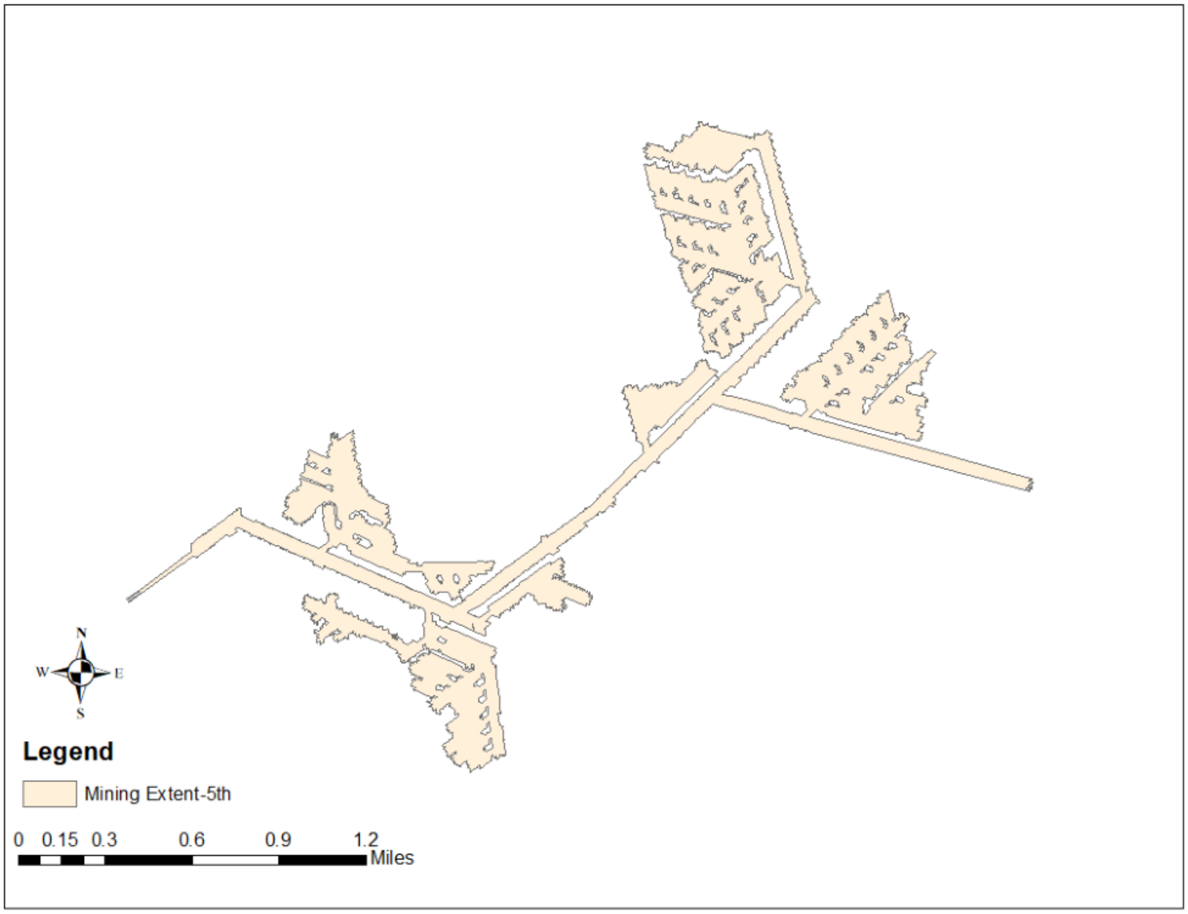

Figure 135. Brush Valley mining extent for the 5th assessment period

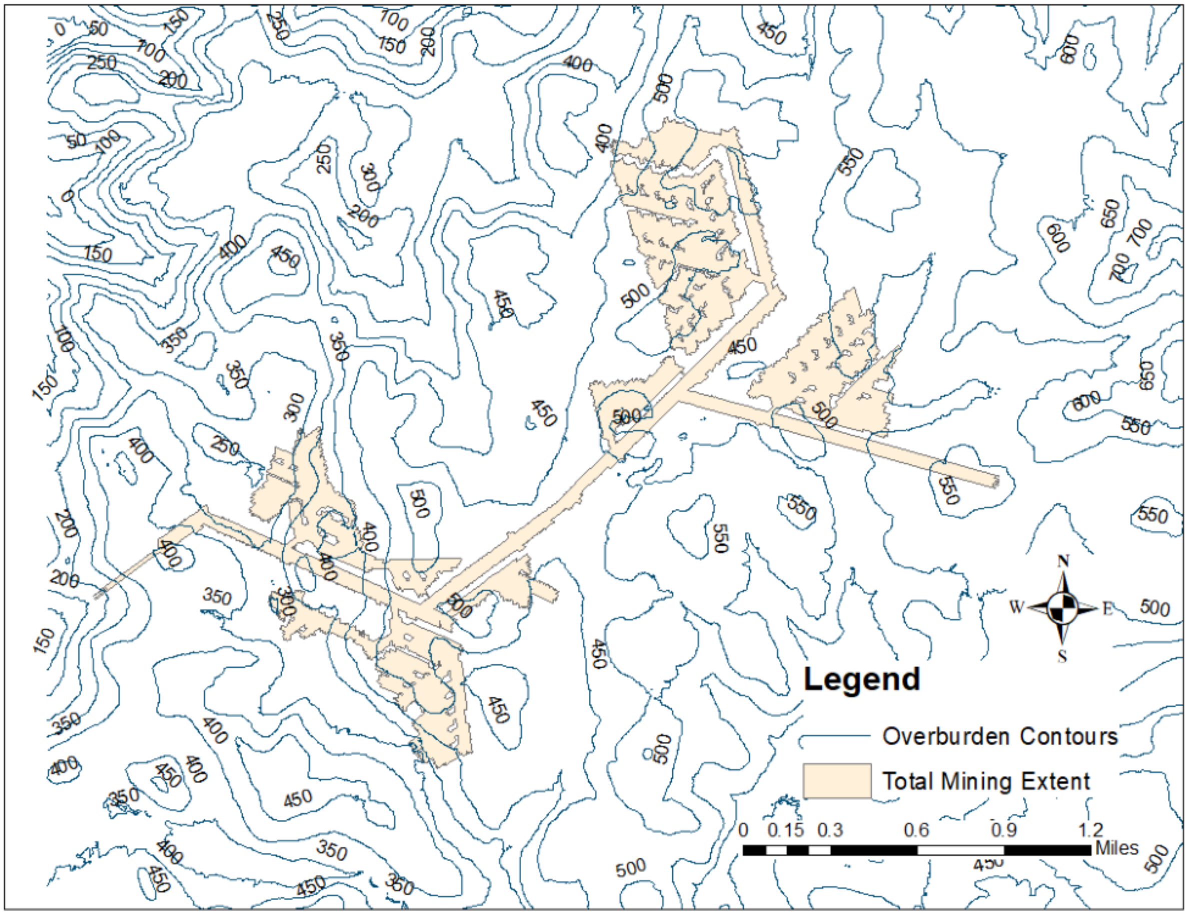

Figure 136. Fifty-foot overburden contour intervals for the Brush Valley Mine

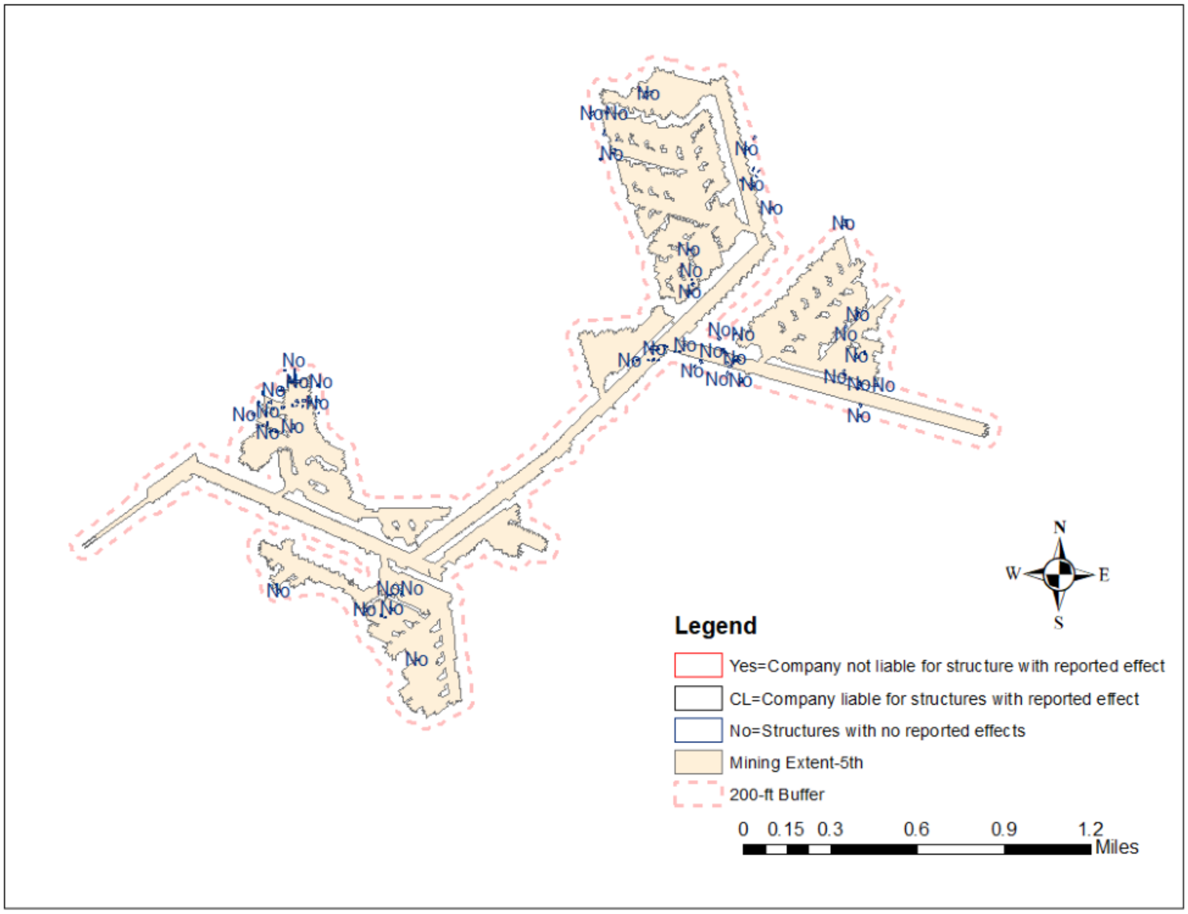

Figure 137. Brush Valley 5th assessment 200-ft buffer and structures

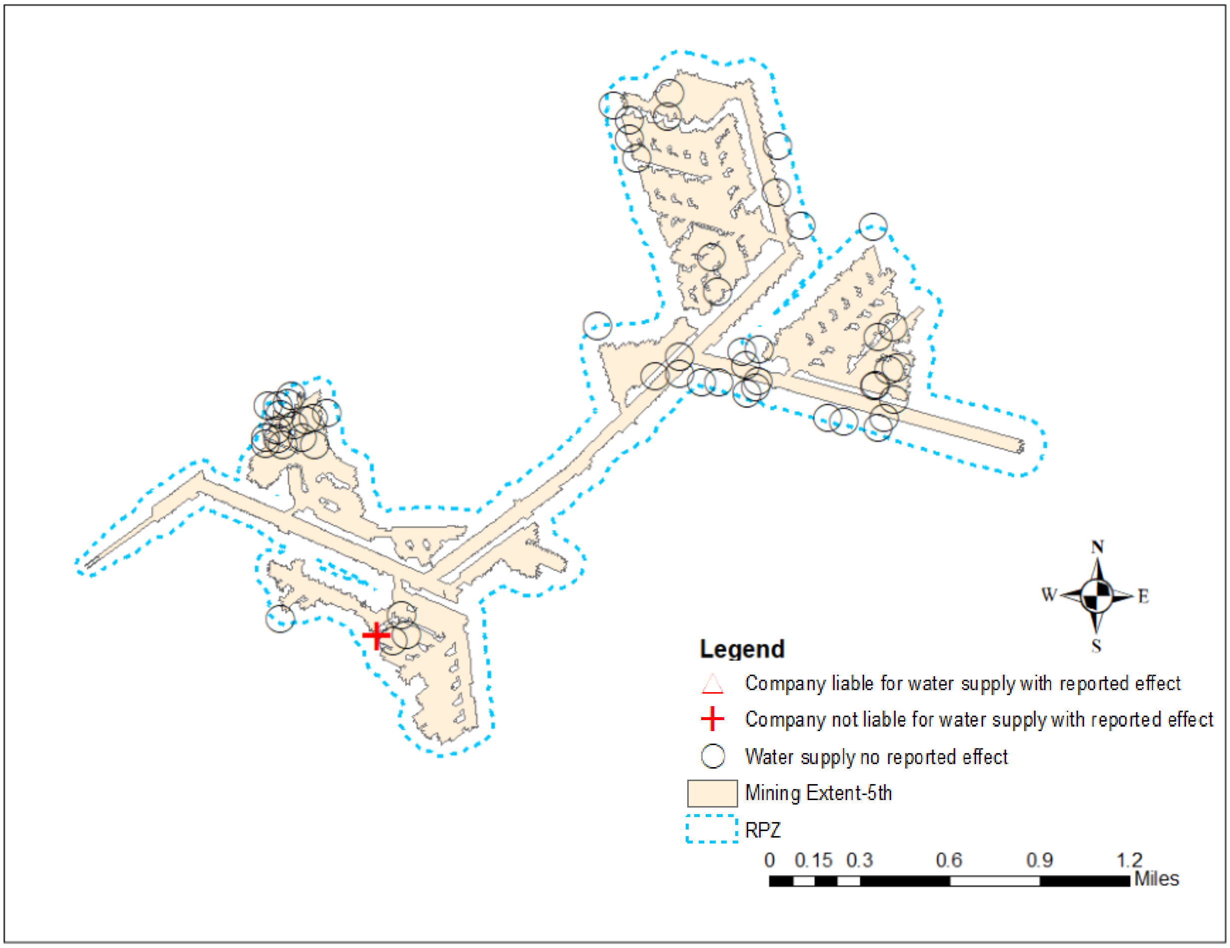

Figure 138. Brush Valley 5th assessment water supplies and RPZ

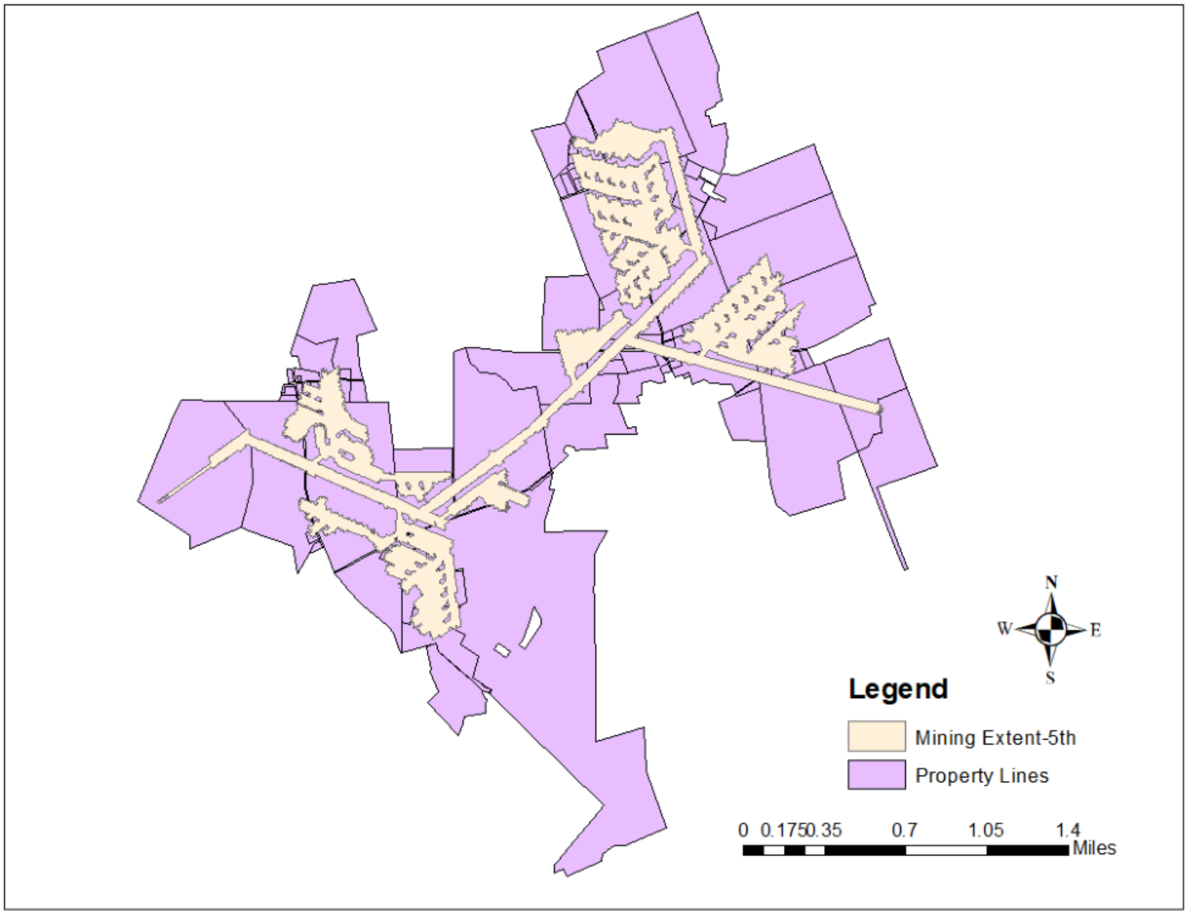

Figure 139. Properties associated with the 5th assessment period over the Brush Valley Mine

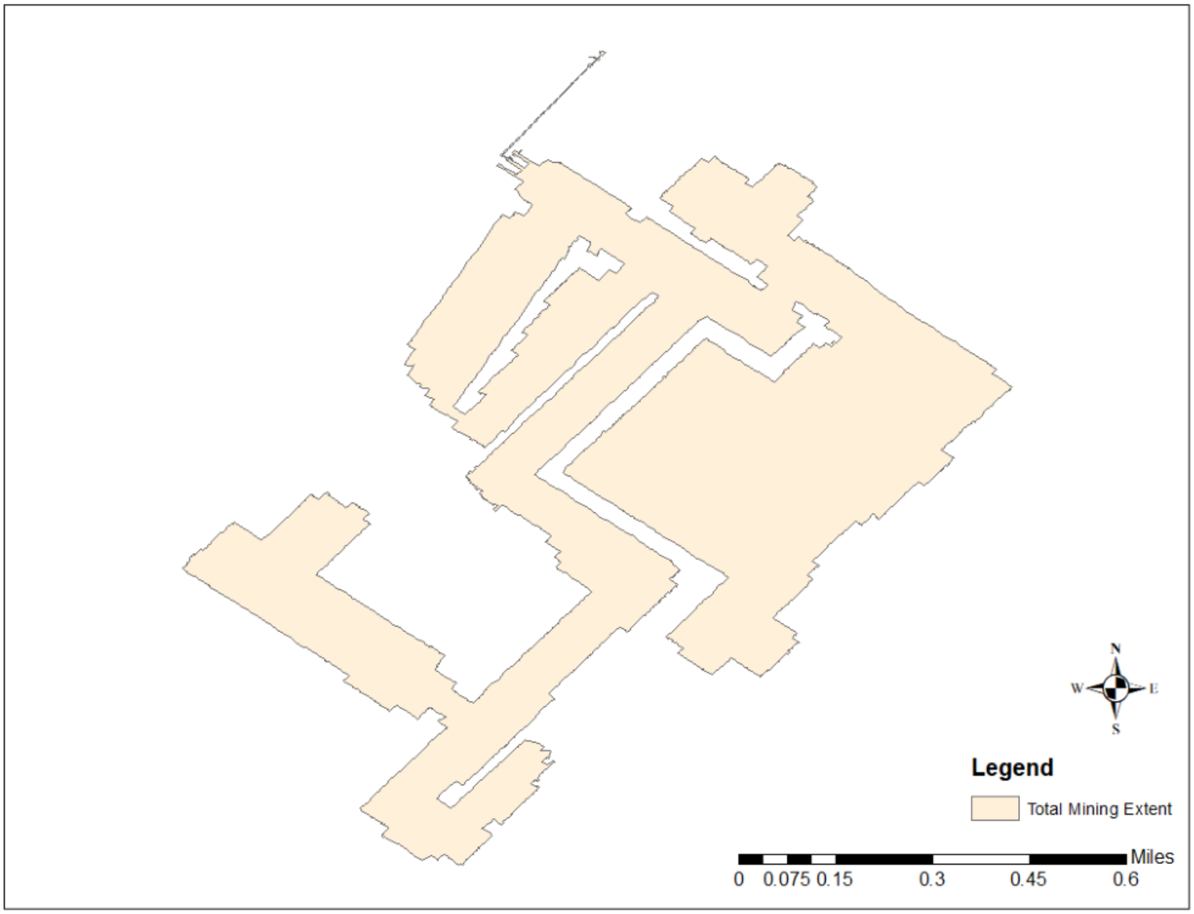

Figure 140. Cass No. 1 total extent of mining

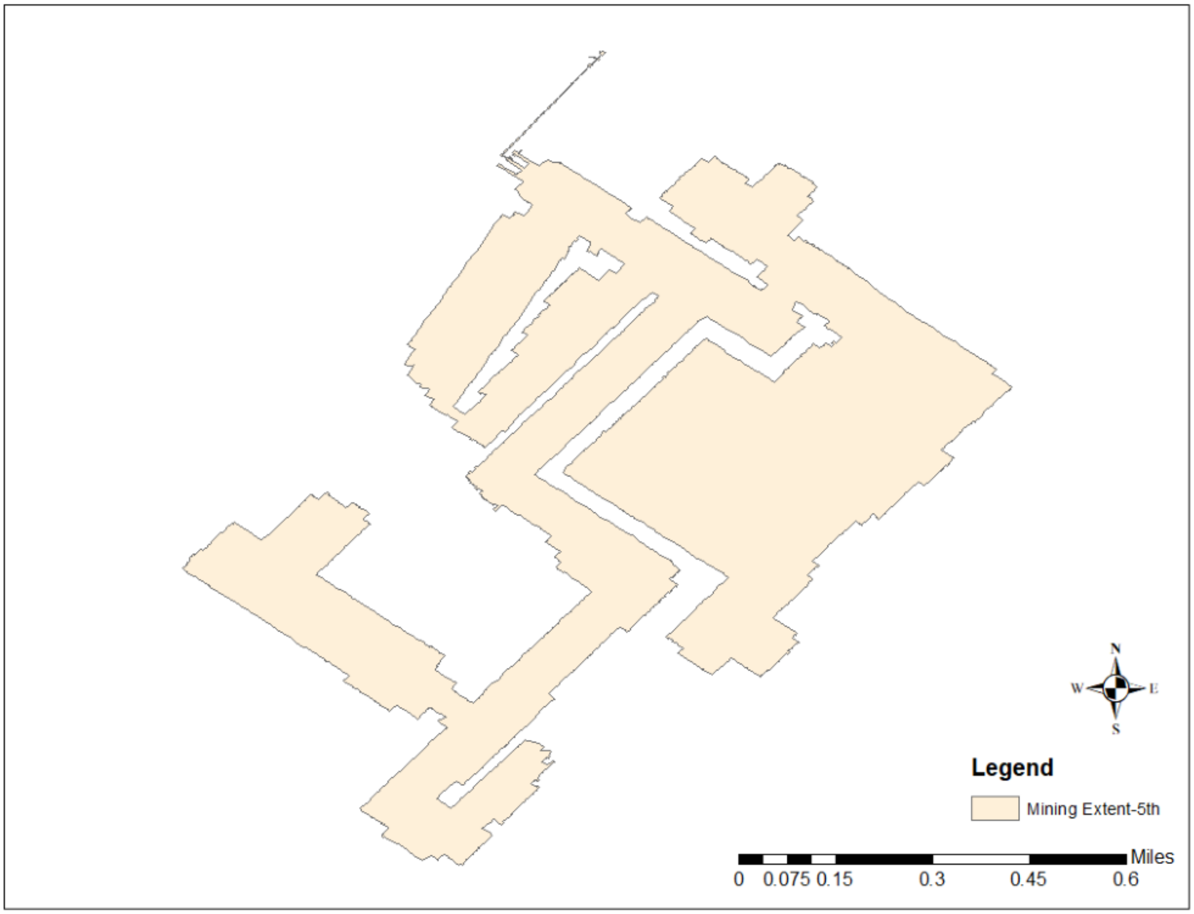

Figure 141. Cass No. 1 mining extent for the 5th assessment period

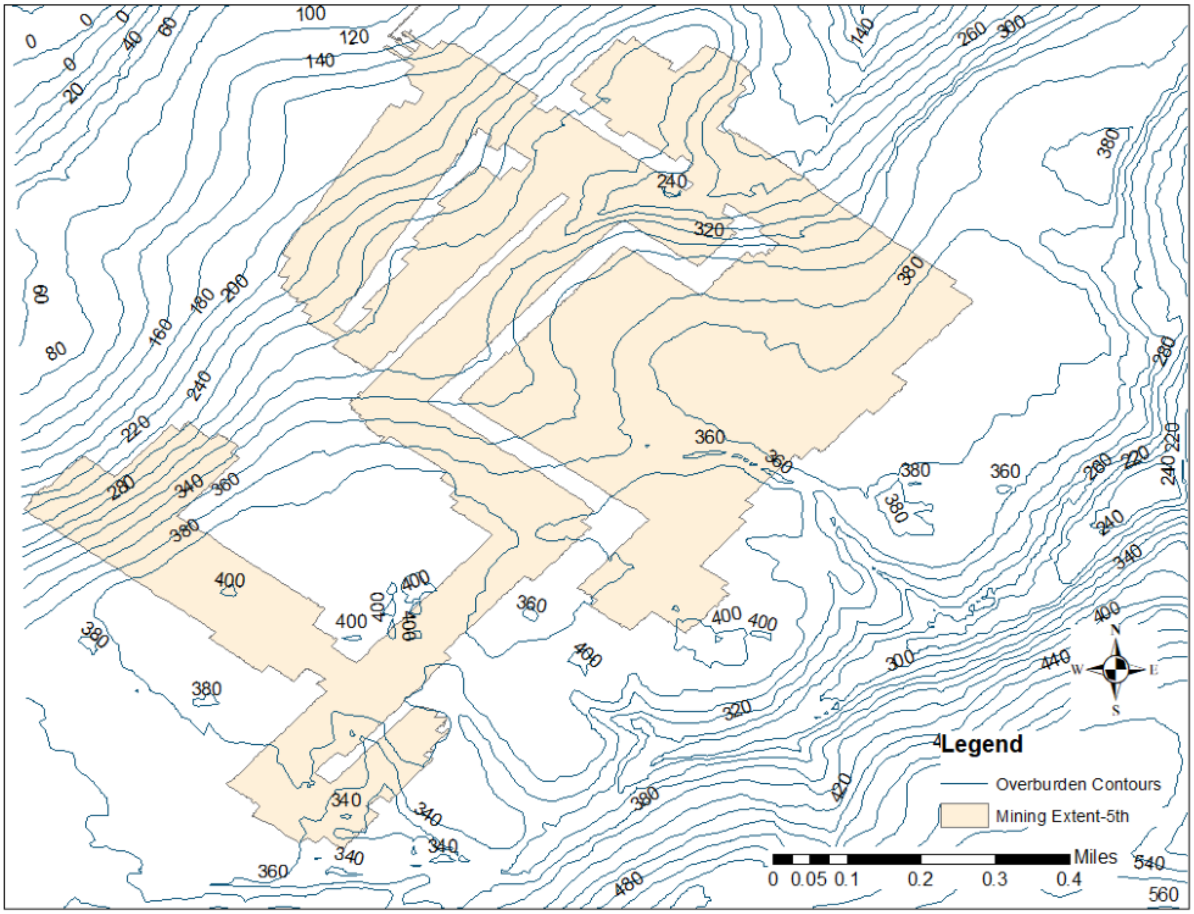

Figure 142. Fifty-foot overburden contour intervals for the Cass No. 1 Mine

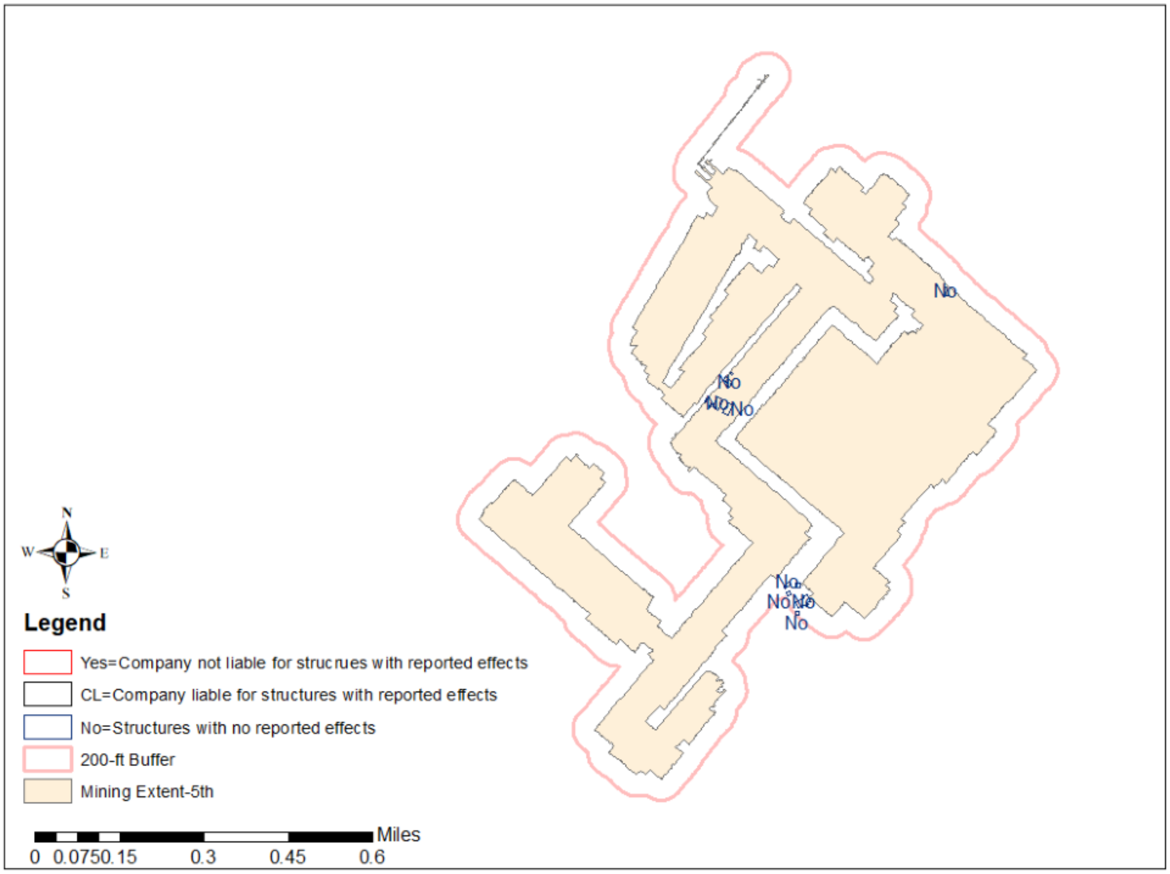

Figure 143. Cass No. 1 Mine 5th assessment 200-ft buffer and structures*

Note there are two structures with reported effects that are not company liable that are far from mining and are not included here for display purposes.

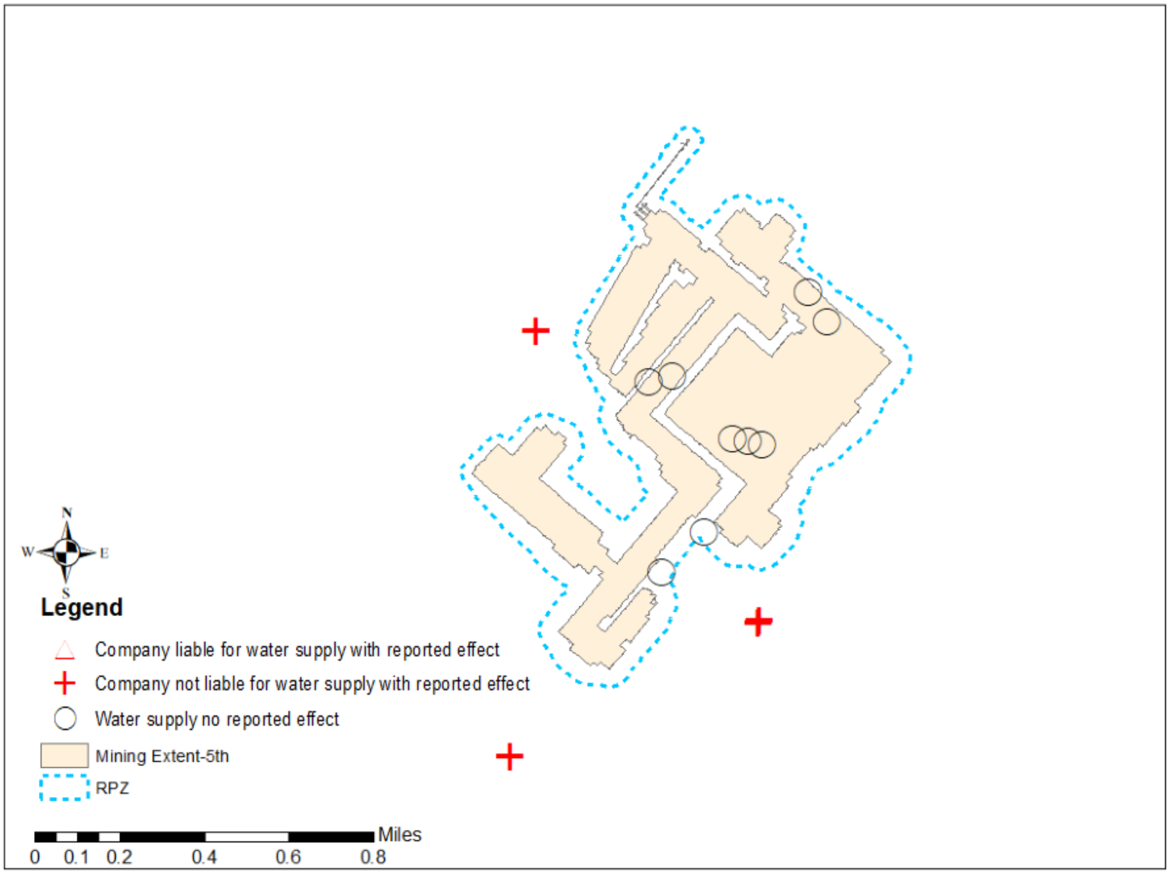

Figure 144. Cass No. 1 Mine 5th assessment water supplies and RPZ

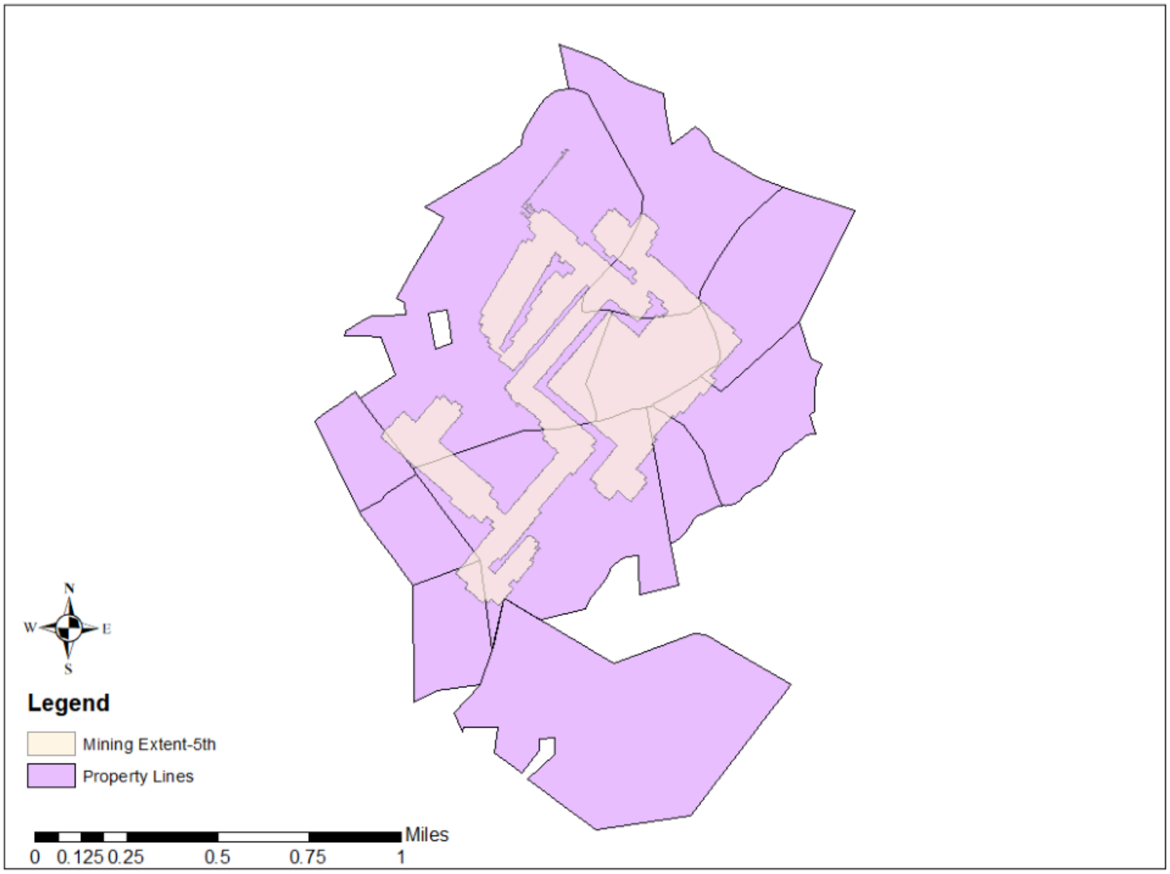

Figure 145. Properties associated with the 5th assessment period over the Cass No. 1 Mine

Figure 146. Cherry Tree total extent of mining

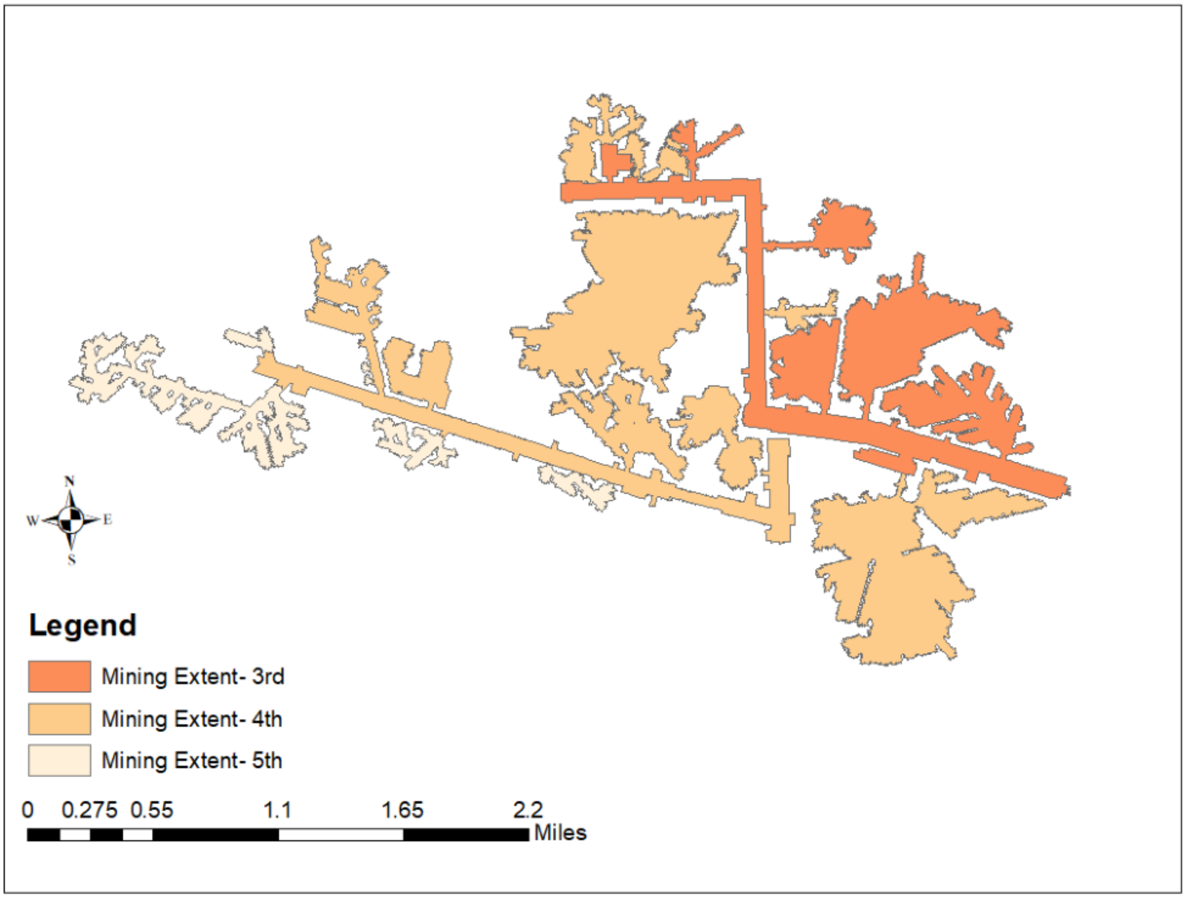

Figure 147. Cherry Tree mining extent for the 3rd, 4th, and 5th assessment periods

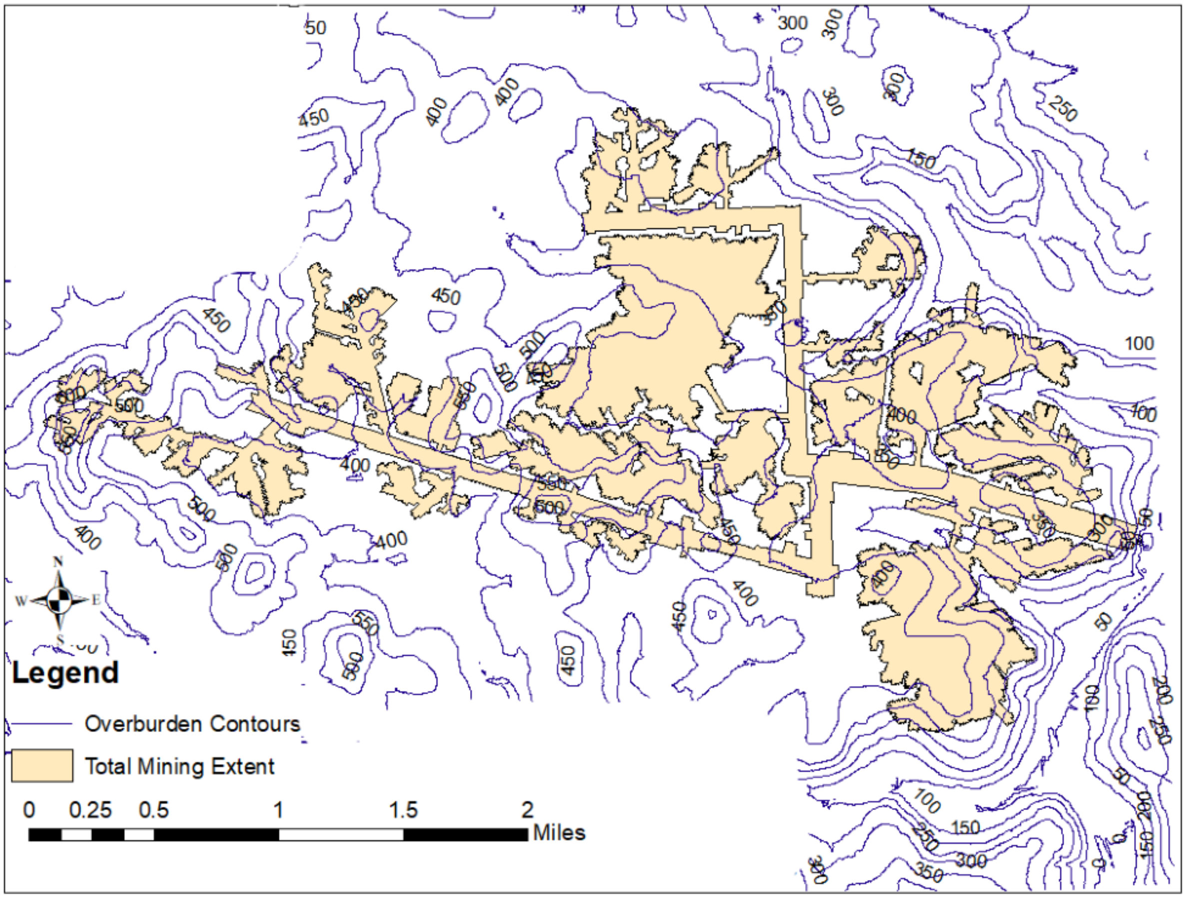

Figure 148. Fifty-foot overburden contour intervals for the Cherry Tree mine

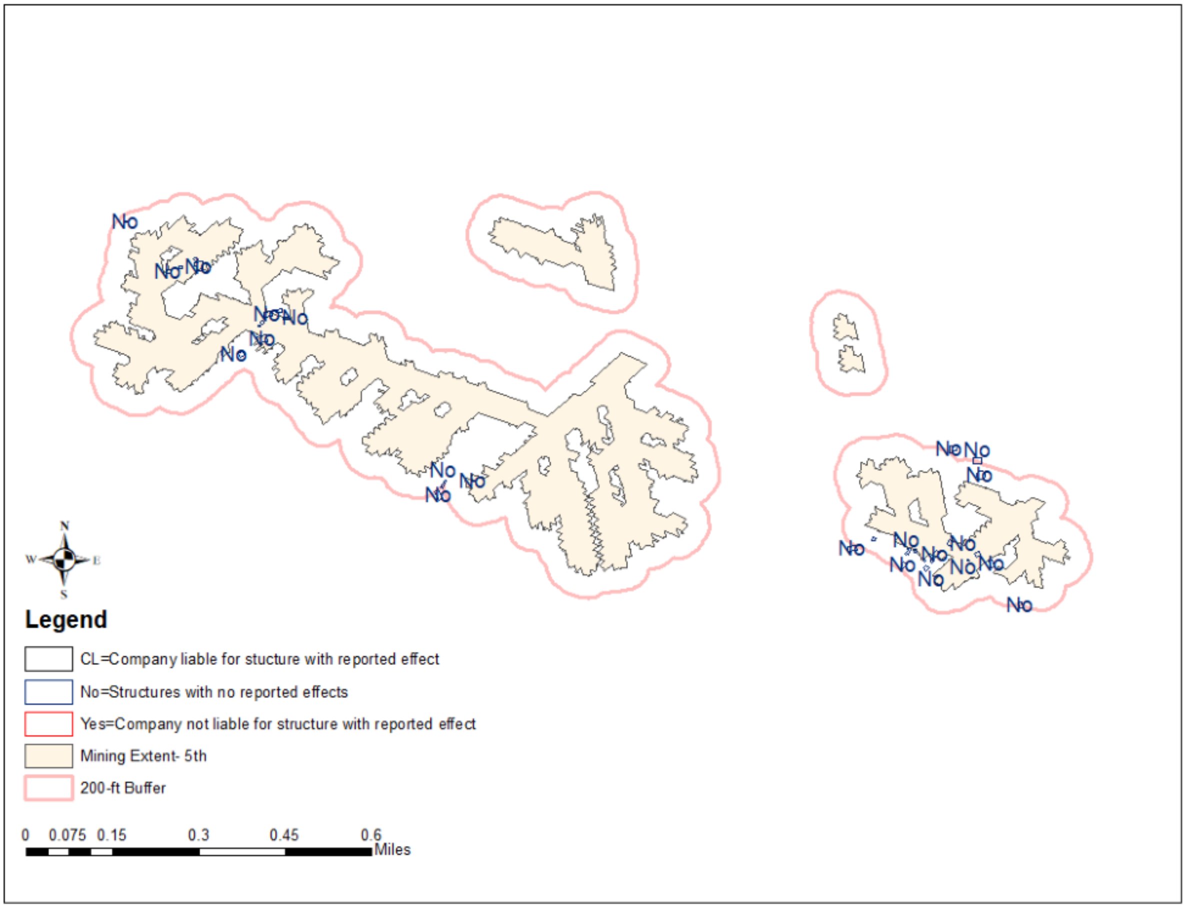

Figure 149. Cherry Tree 5th assessment 200-ft buffer and structures*

Note there are two structures with reported effects that are far from mining and are not included here for display purposes.

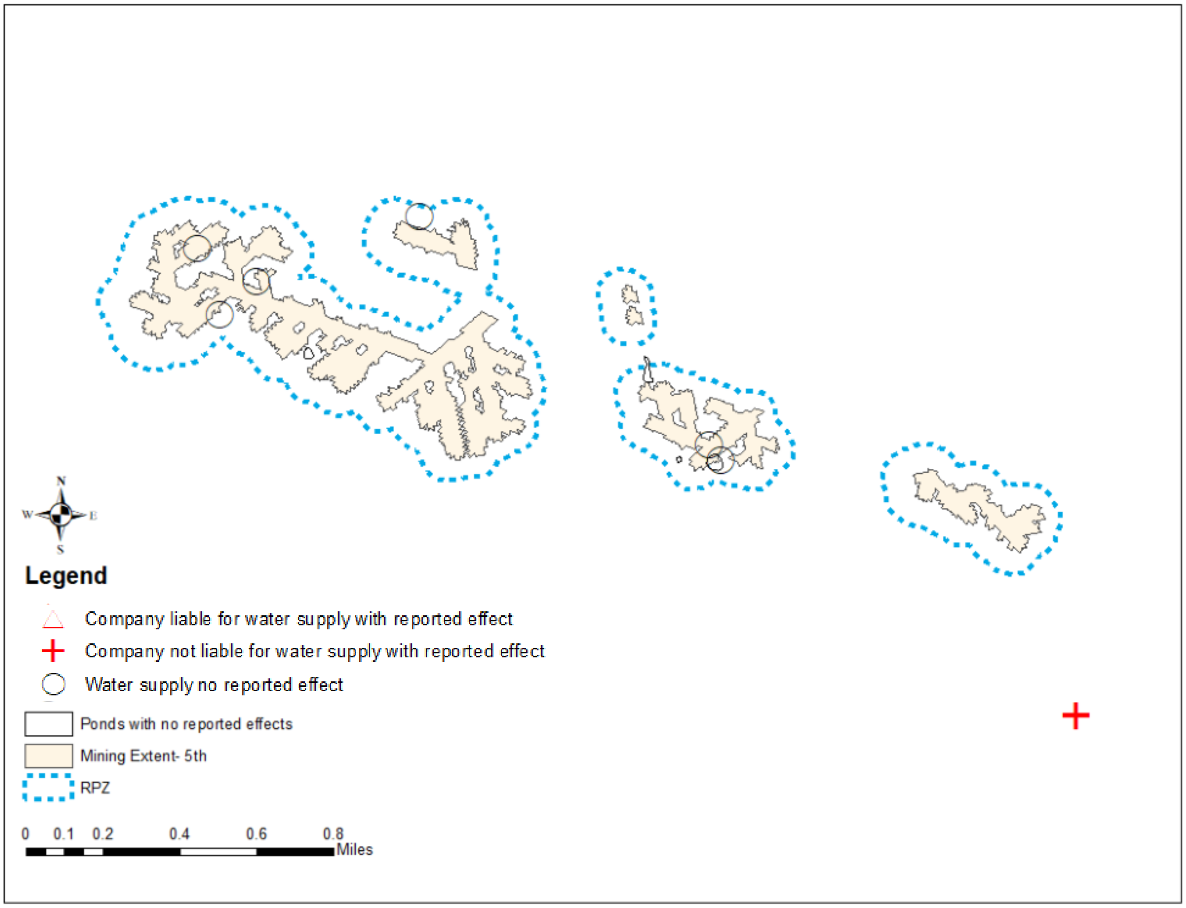

Figure 150. Cherry Tree 5th assessment water supplies and RPZ*

***Note there are two water supplies with reported effects that are far from mining and are not included here for display purposes.*

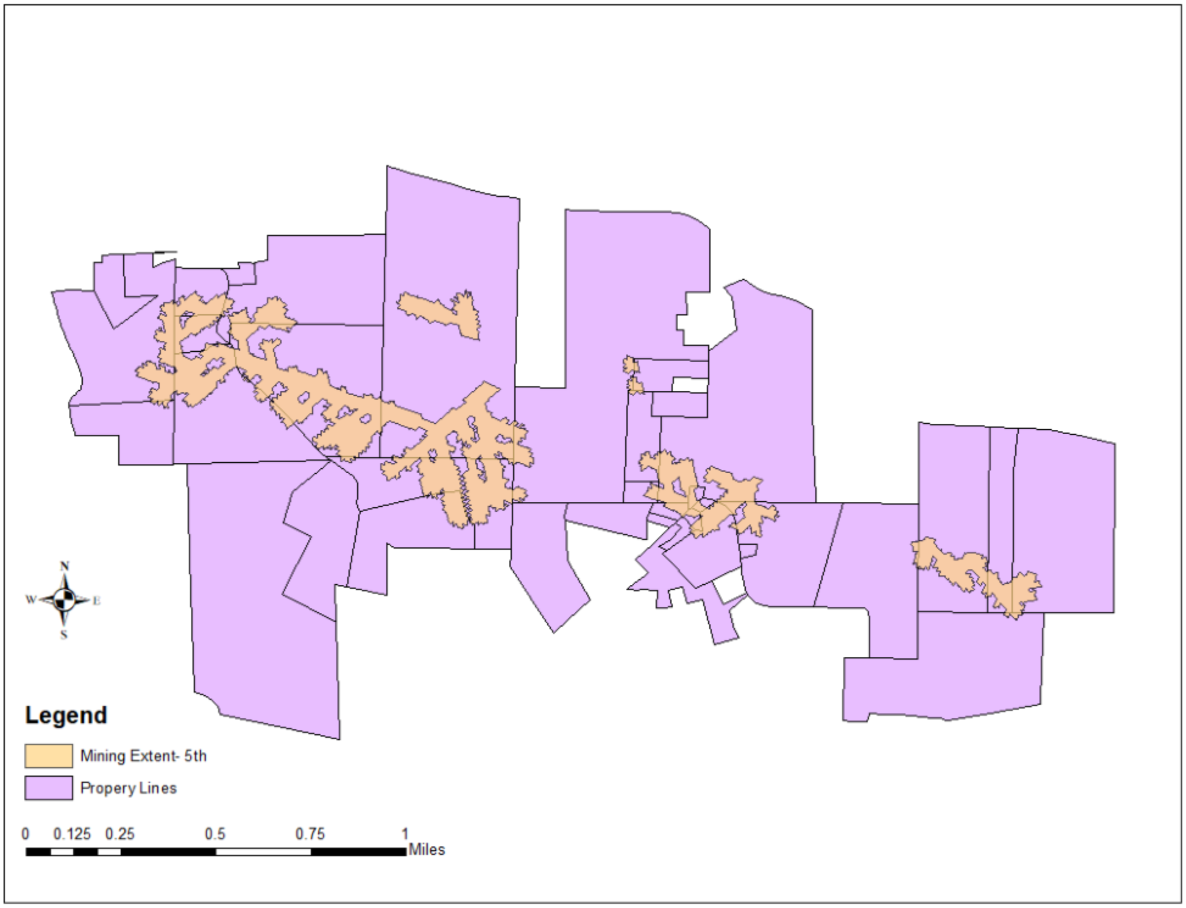

Figure 151. Properties associated with the 5th assessment period over the Cherry Tree mine

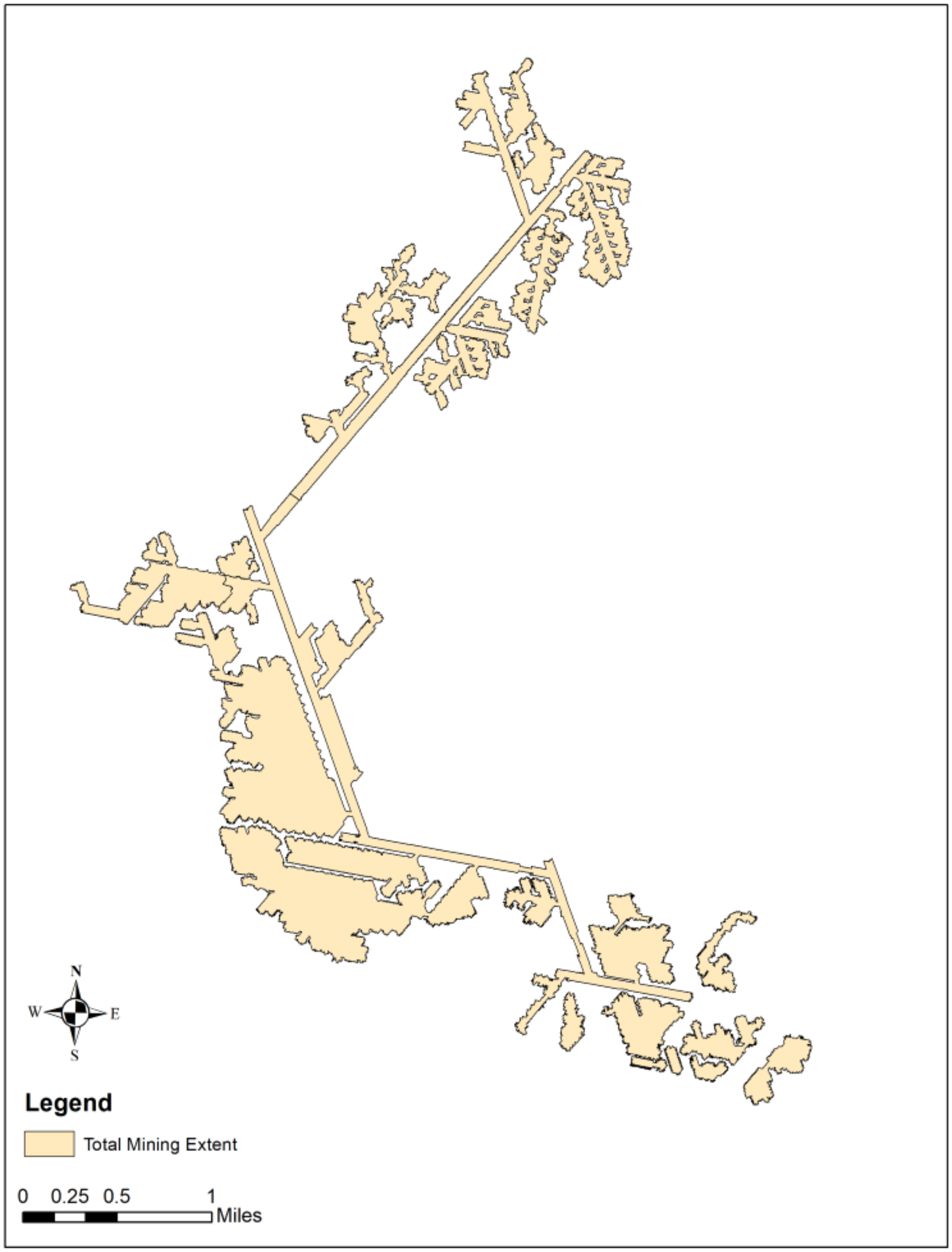

Figure 152. Clementine total extent of mining

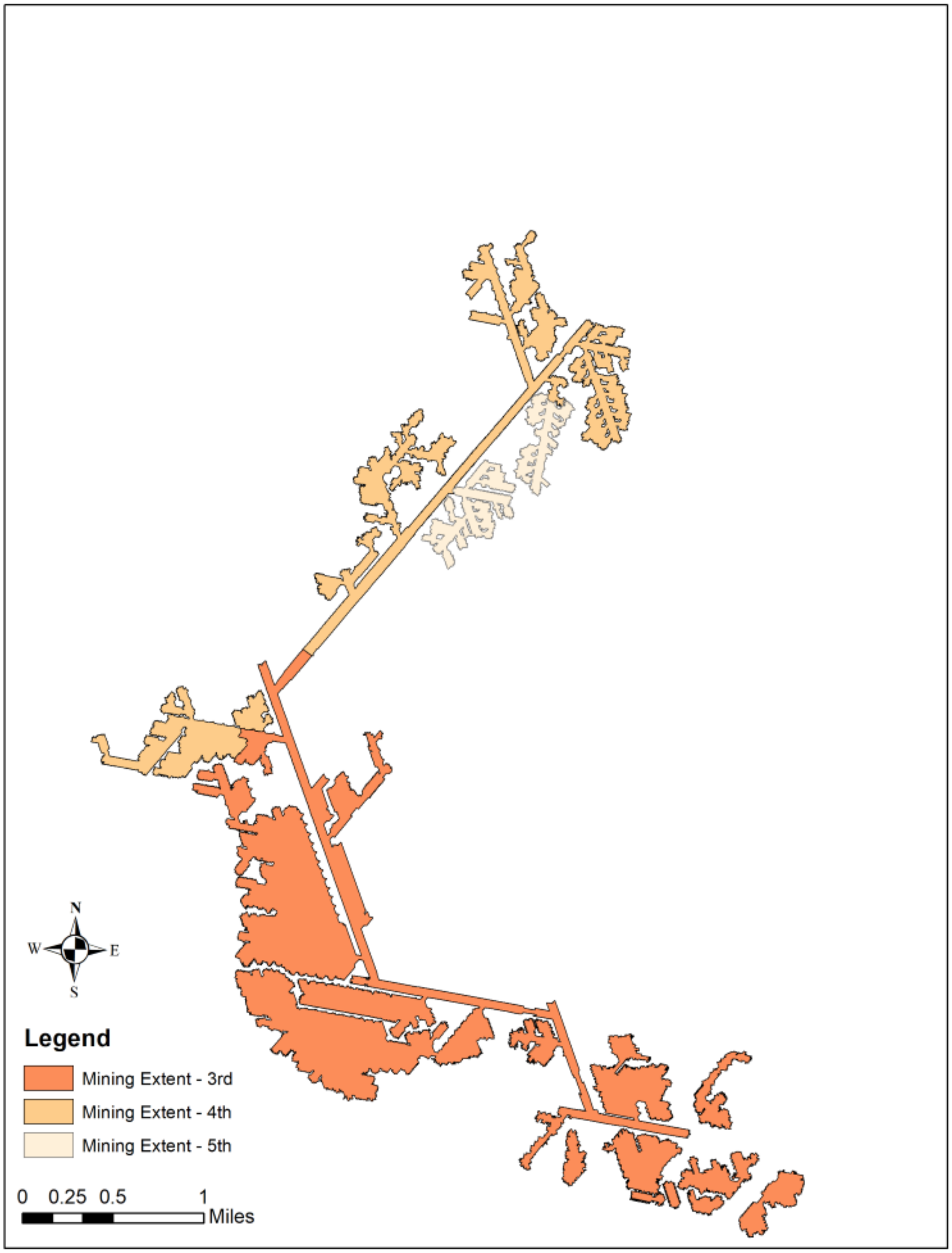

Figure 153. Clementine mining extent for the 3rd, 4th, and 5th assessment periods

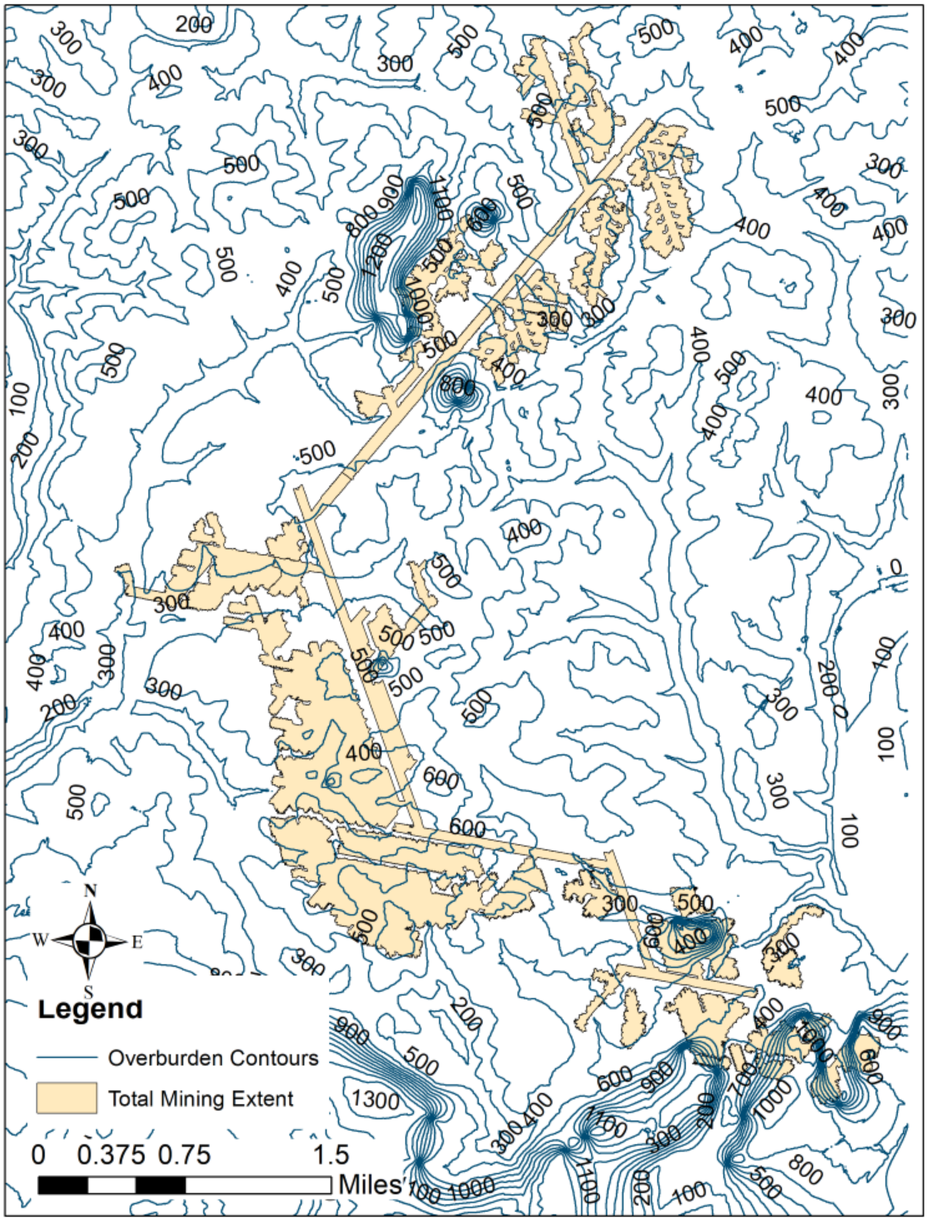

Figure 154. 100-ft overburden contour intervals for the Clementine Mine Lower Kittanning coal seam

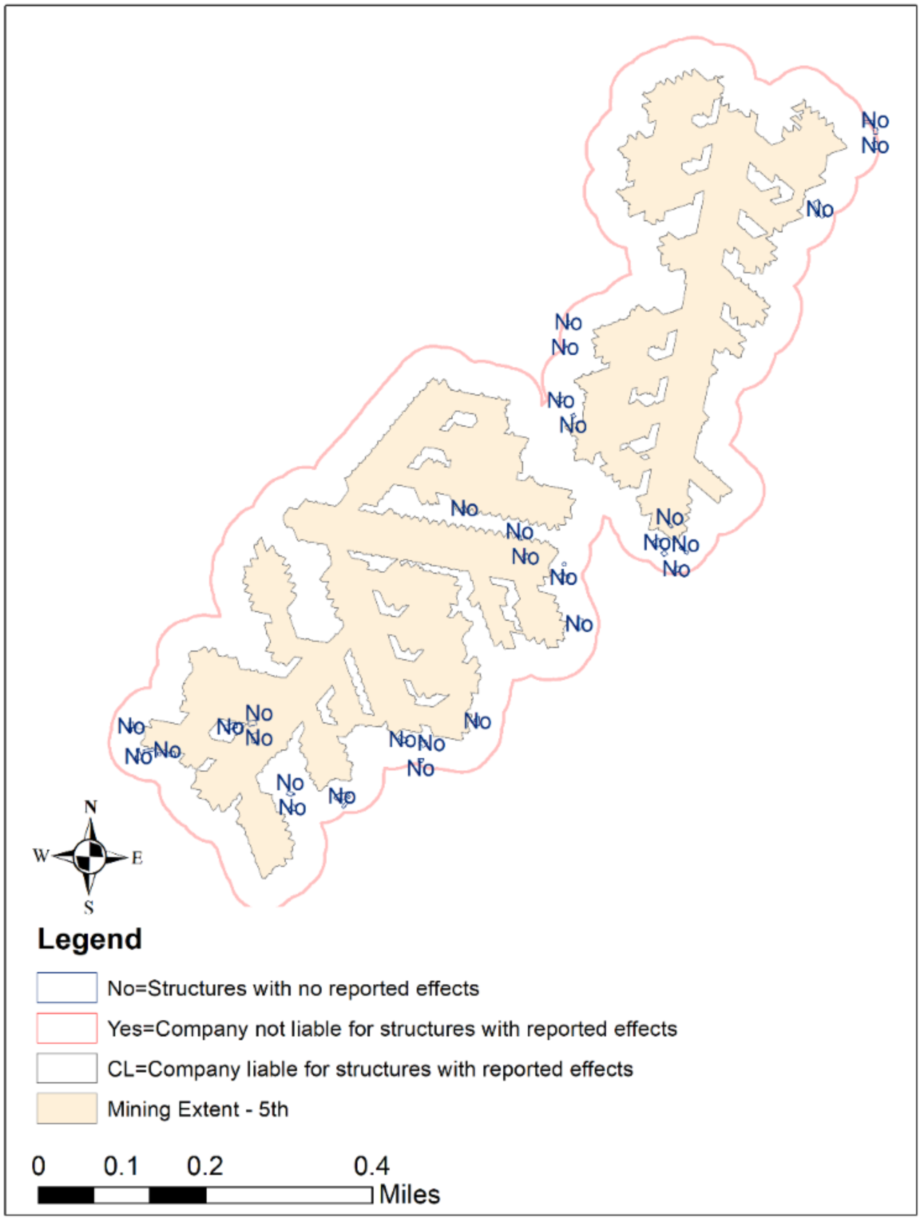

Figure 155. Clementine 5th assessment 200-ft buffer and structures*

***Note** *there are two structures with reported effects that are far from mining and are not included here for display purposes.*

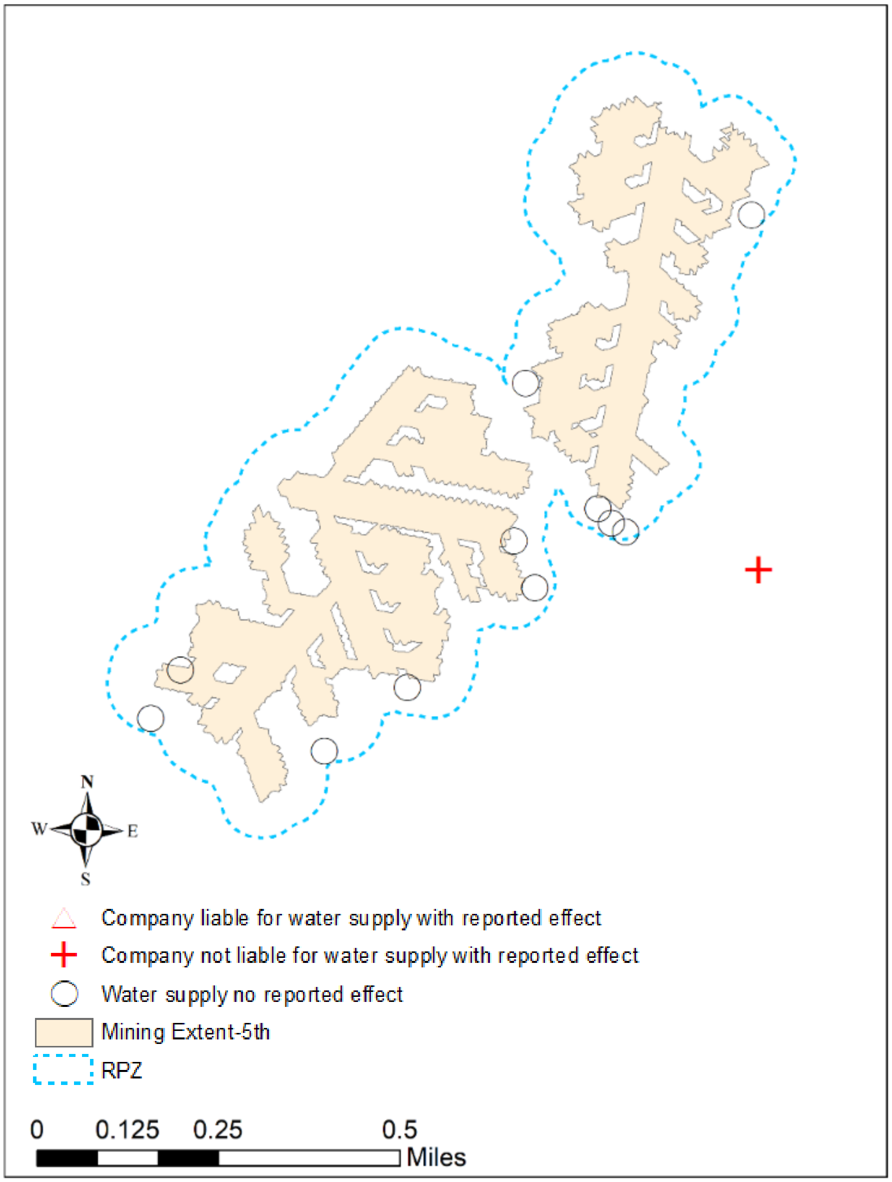

Figure 156. Clementine 5th assessment water supplies and RPZ*

Note there are water supplies with reported effects that are far from mining and are not included here for display purposes.

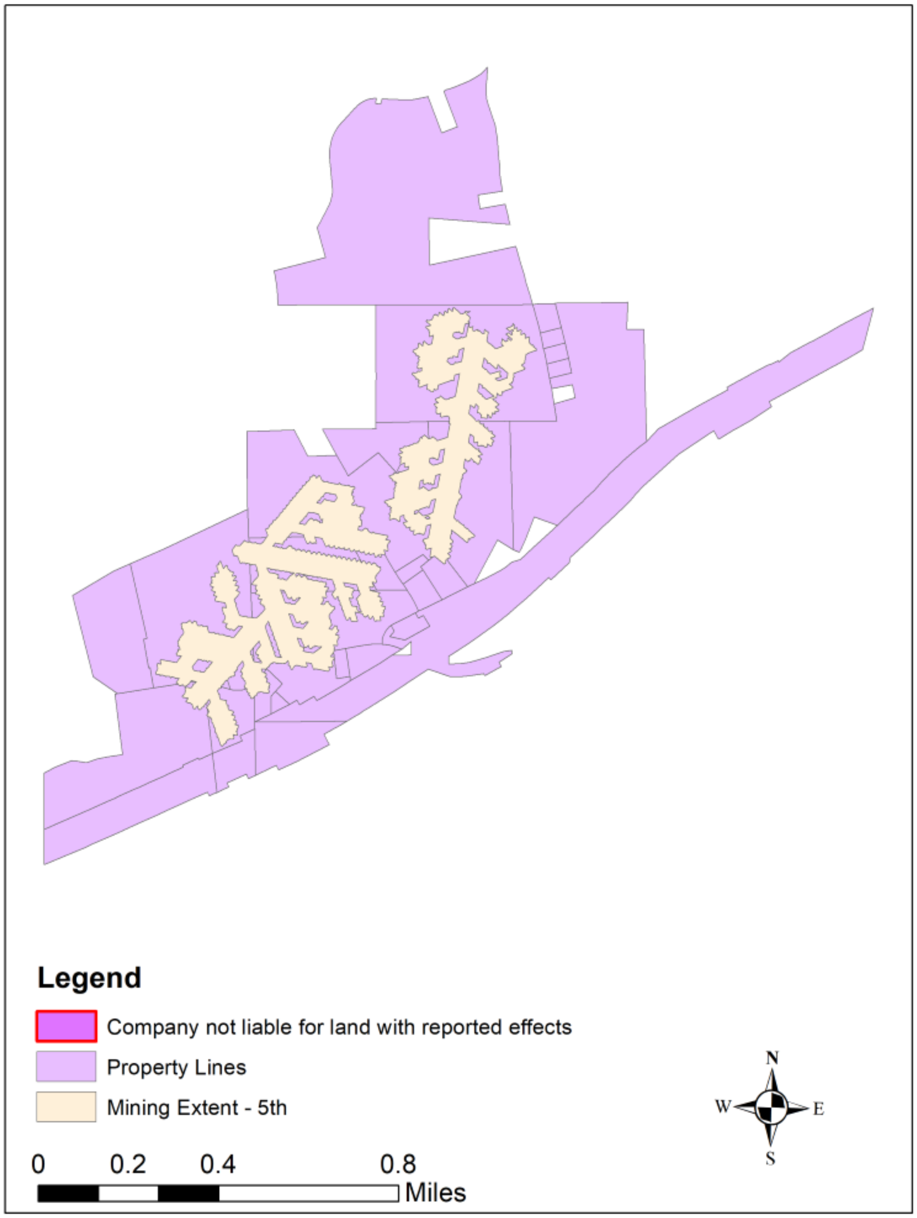

Figure 157. Properties associated with the 5th assessment period over the Clementine Mine*

*****_Note there are properties with reported effects that are far from mining and are not included here for display purposes._

Figure 158. Coral Graceton total extent of mining

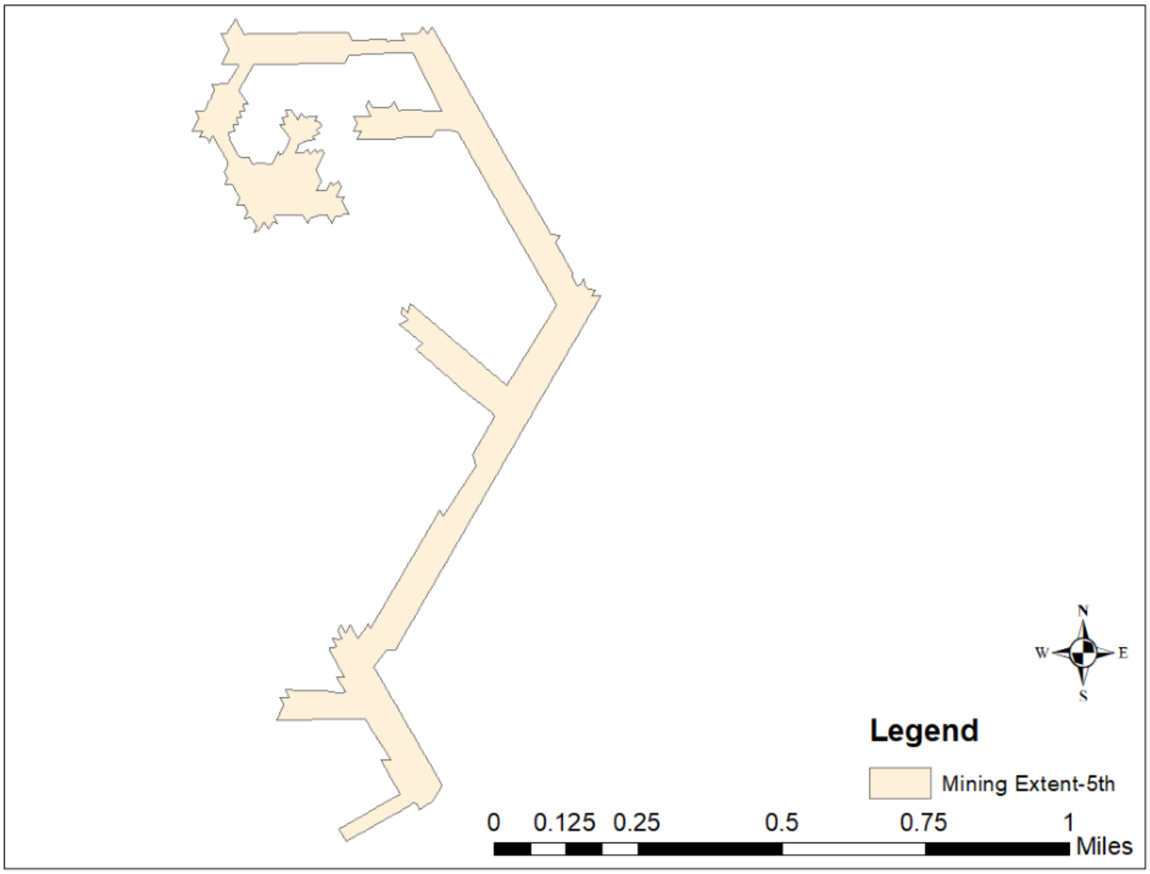

Figure 159. Coral Graceton mining extent for the 5th assessment period

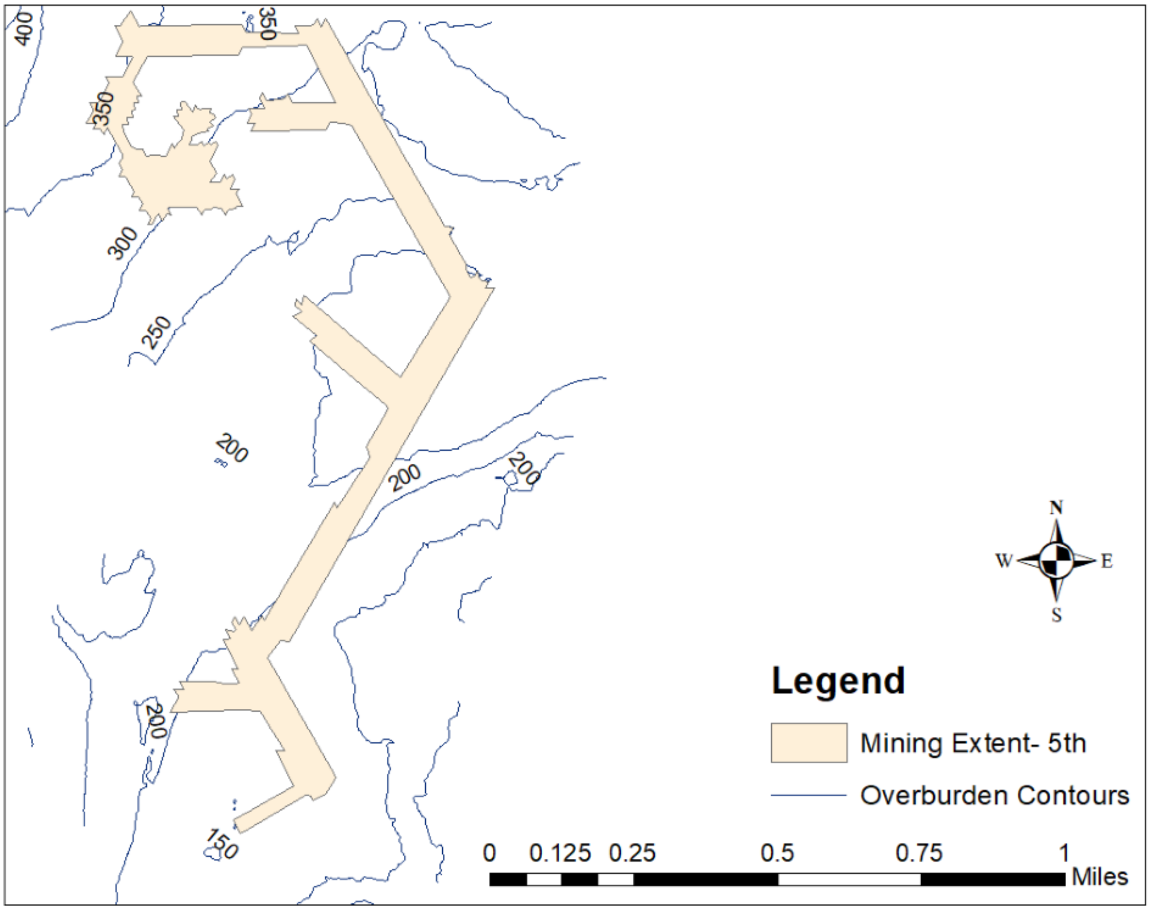

Figure 160. Fifty-foot overburden contour intervals for the Coral Graceton mine

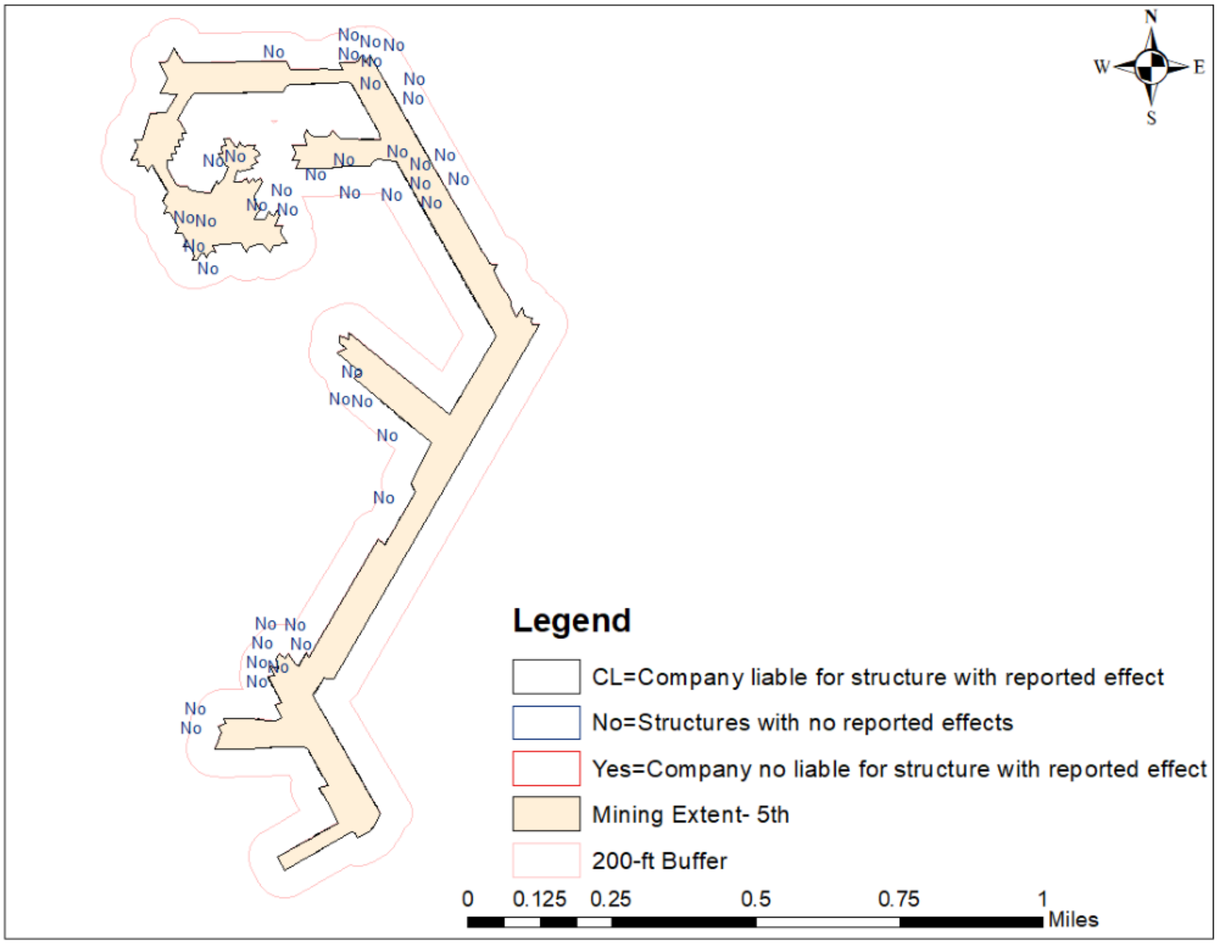

Figure 161. Coral Graceton 5th assessment 200-ft buffer and structures

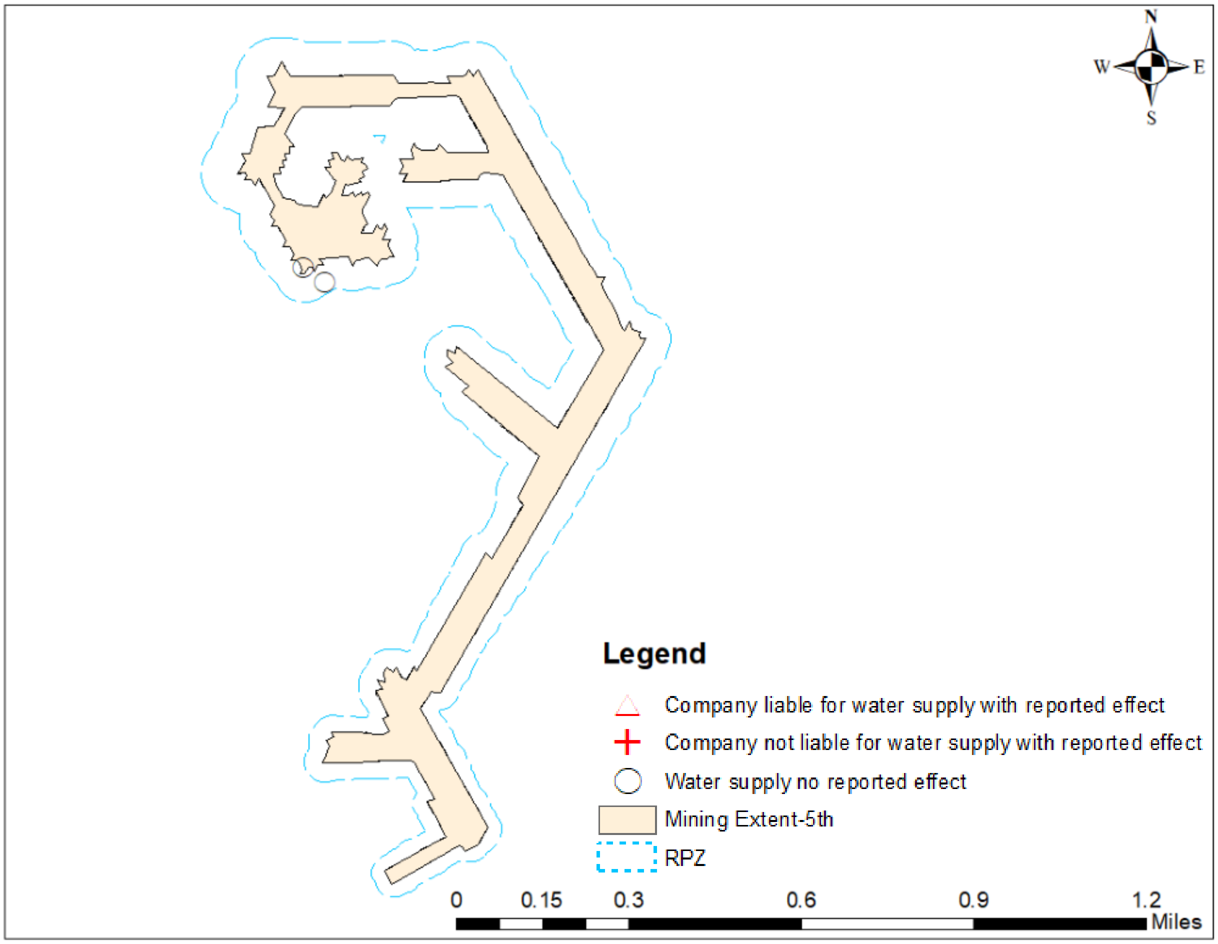

Figure 162. Coral Graceton 5th assessment water supplies and RPZ

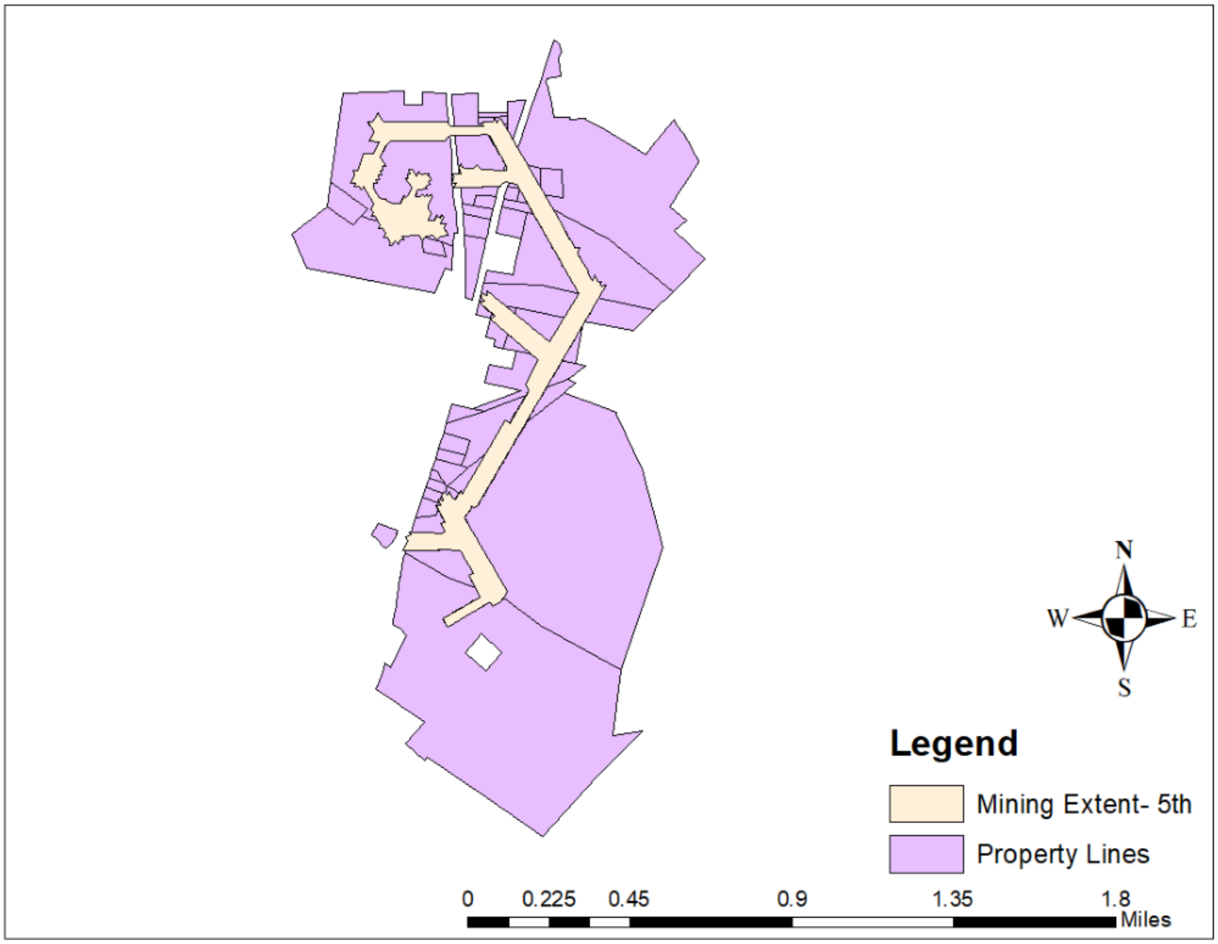

Figure 163. Properties associated with the 5th assessment period over the Coral Graceton mine

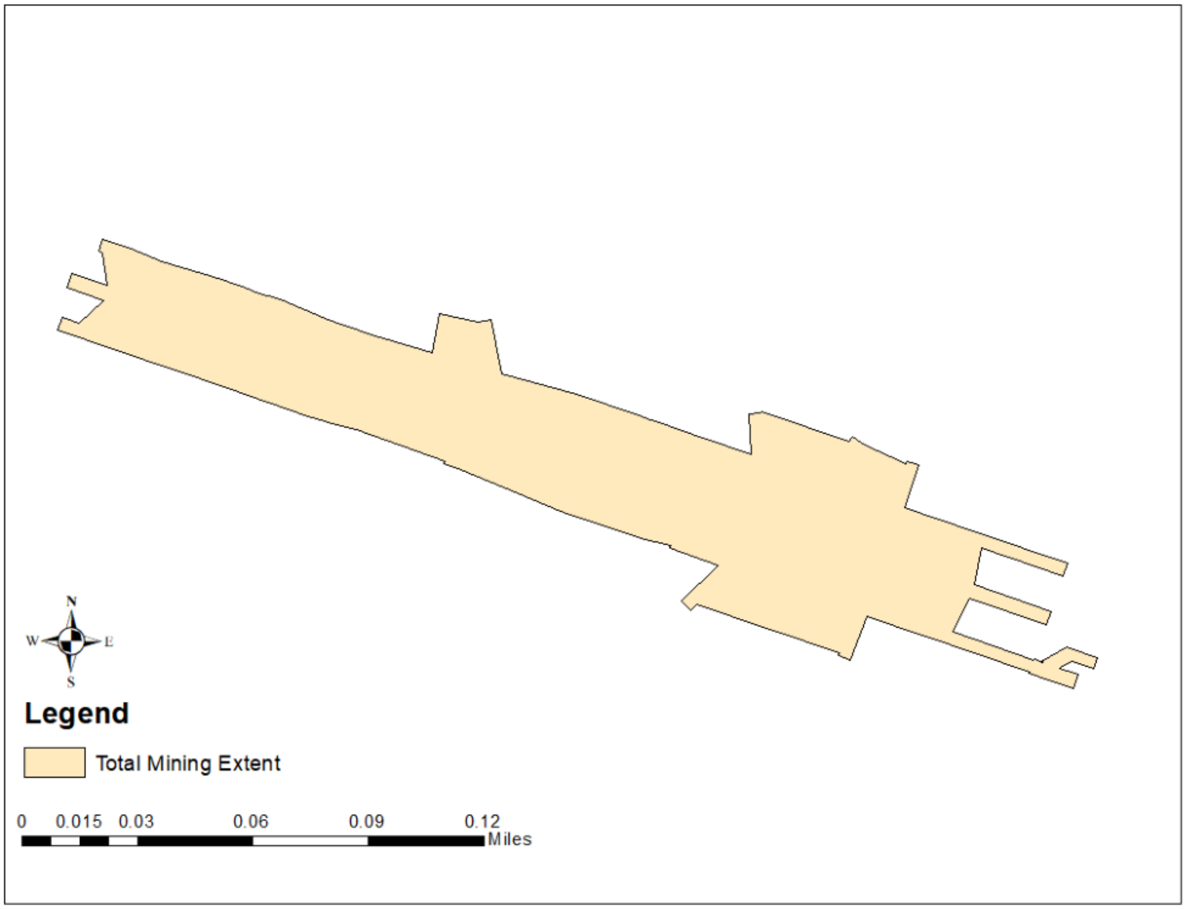

Figure 164. Cresson total extent of mining

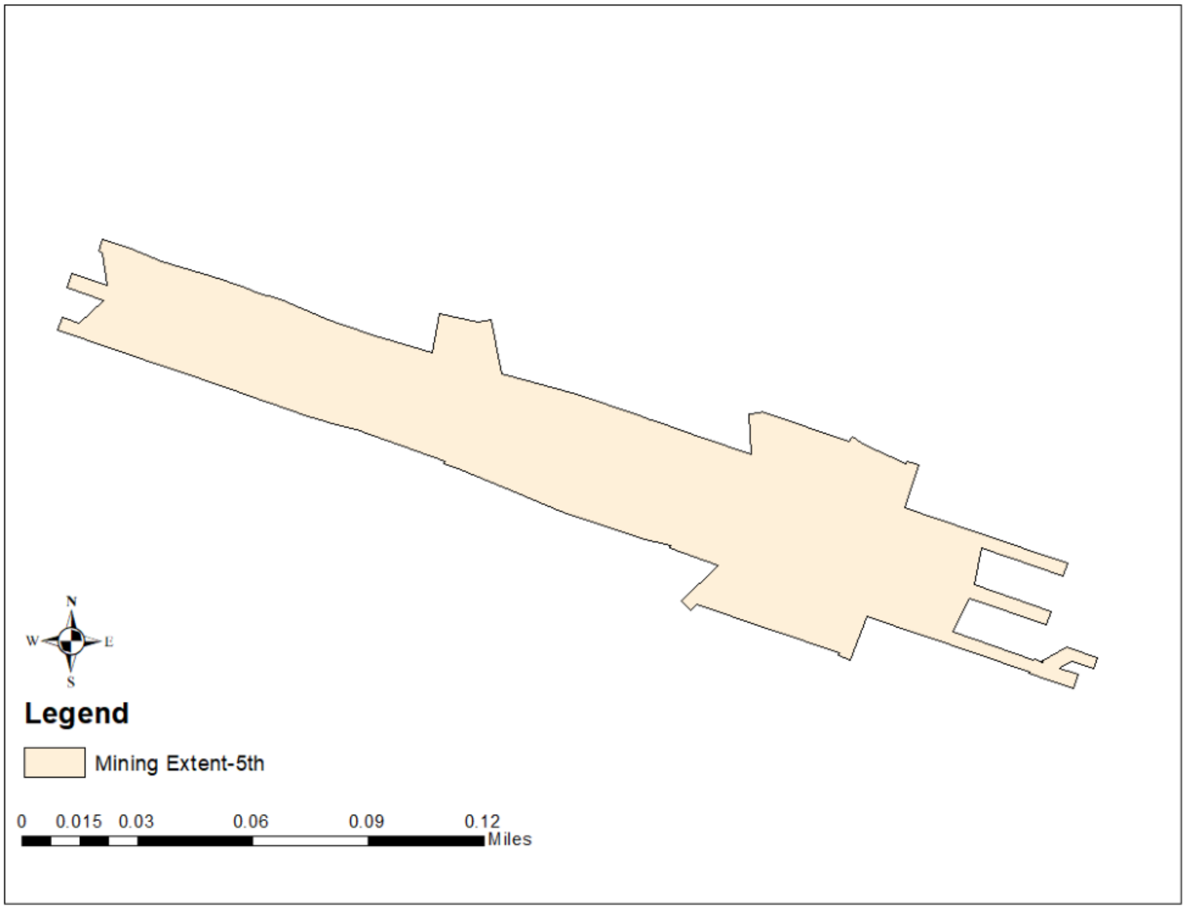

Figure 165. Cresson mining extent for the 5th assessment period

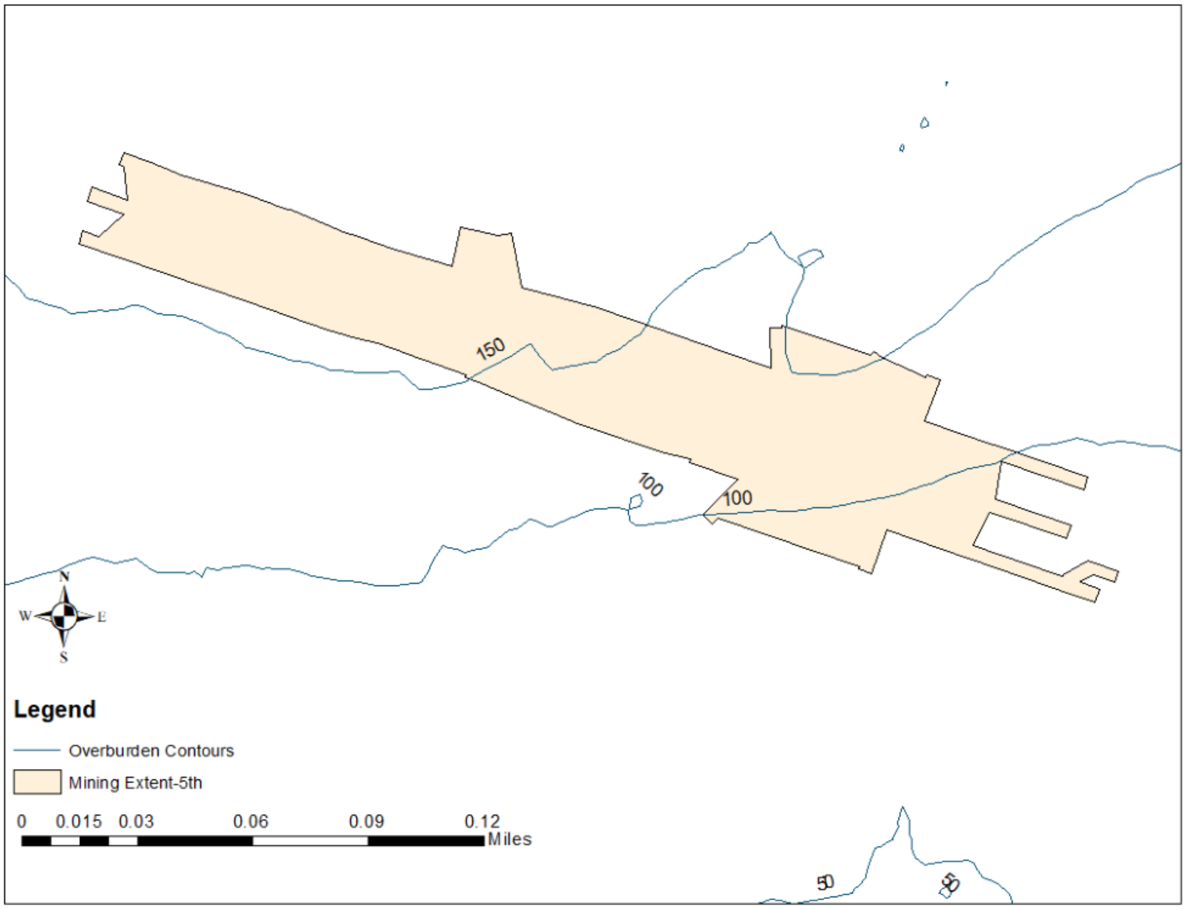

Figure 166. Fifty-foot overburden contour intervals for the Cresson Mine

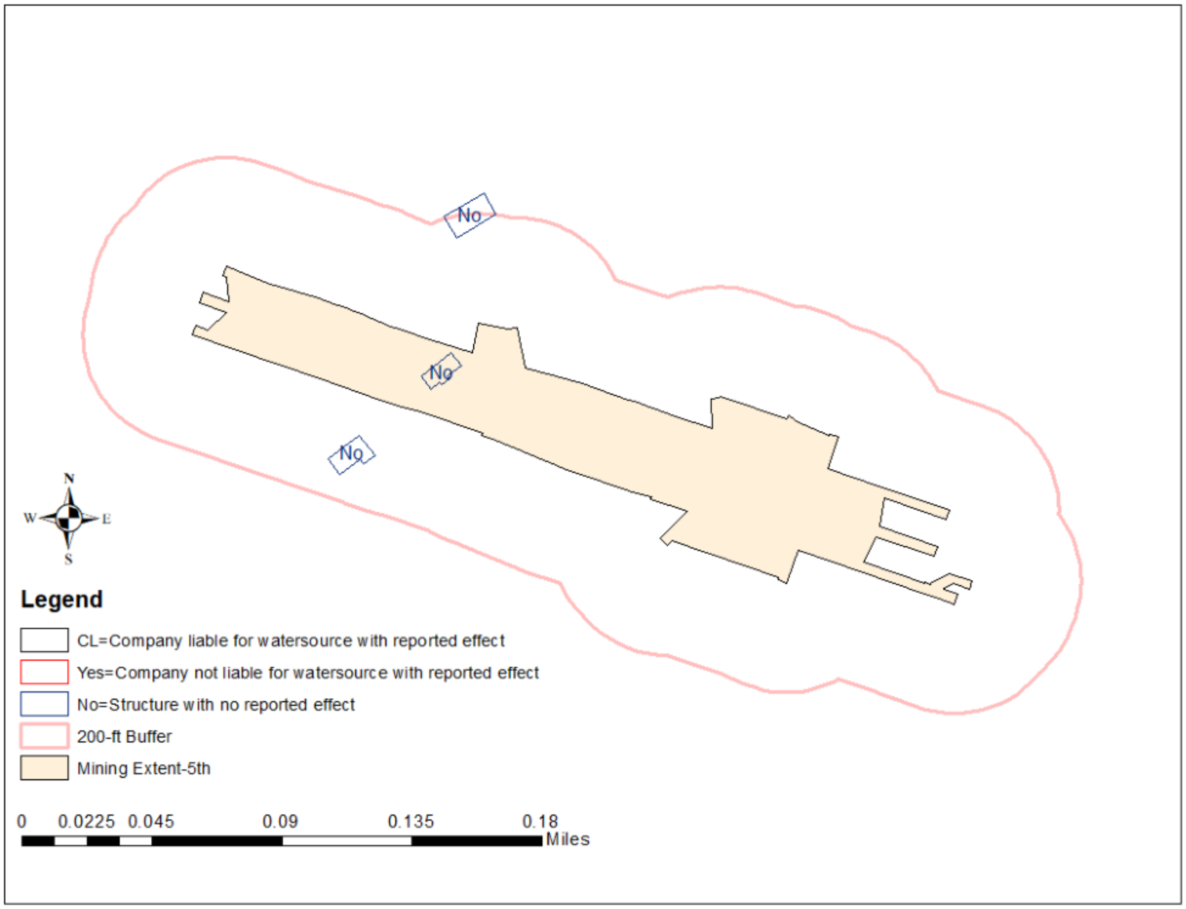

Figure 167. Cresson Mine 5th assessment 200-ft buffer and structures

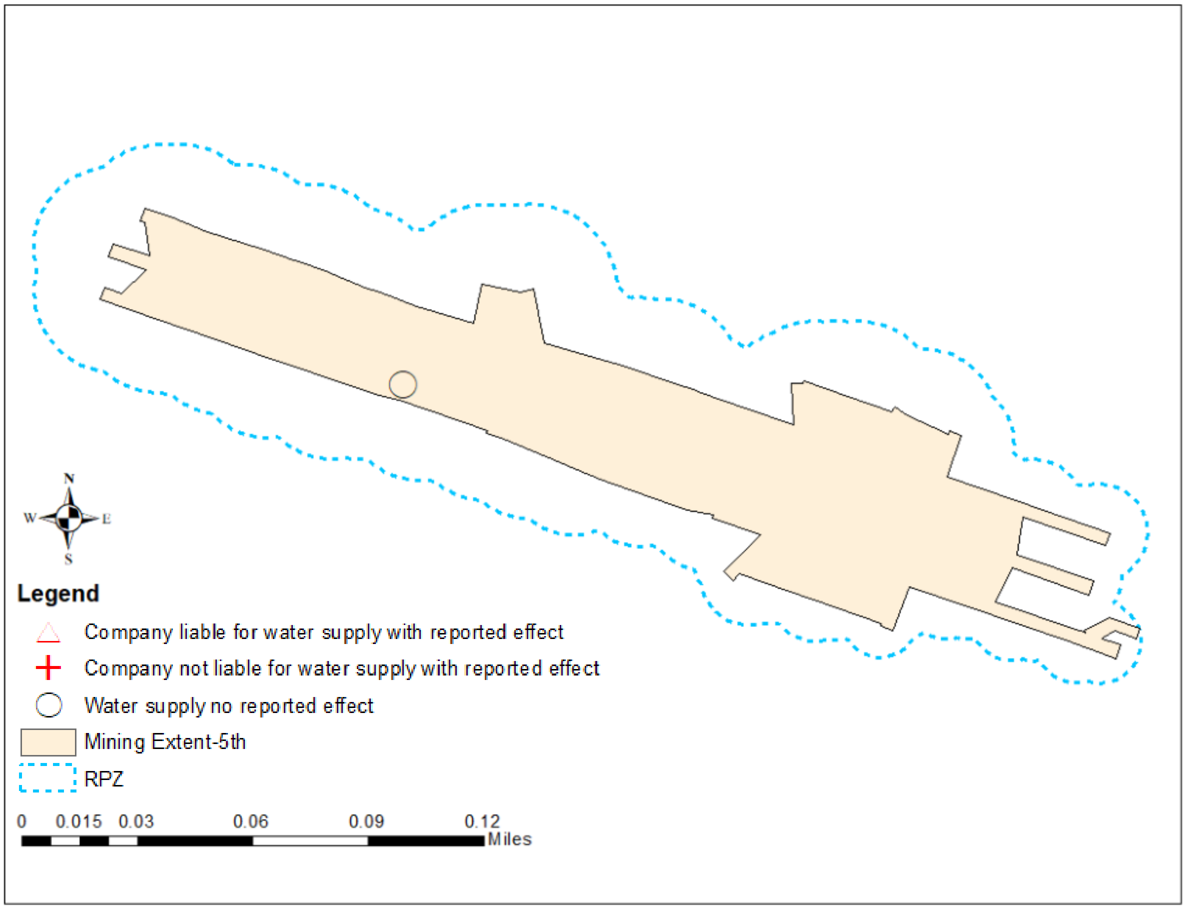

Figure 168. Cresson 5th assessment water supplies and RPZ

Figure 169. Properties associated with the 5th assessment period over the Cresson Mine

Figure 170. Crooked Creek total extent of mining

Figure 171. Crooked Creek mining extent for the 5th assessment period

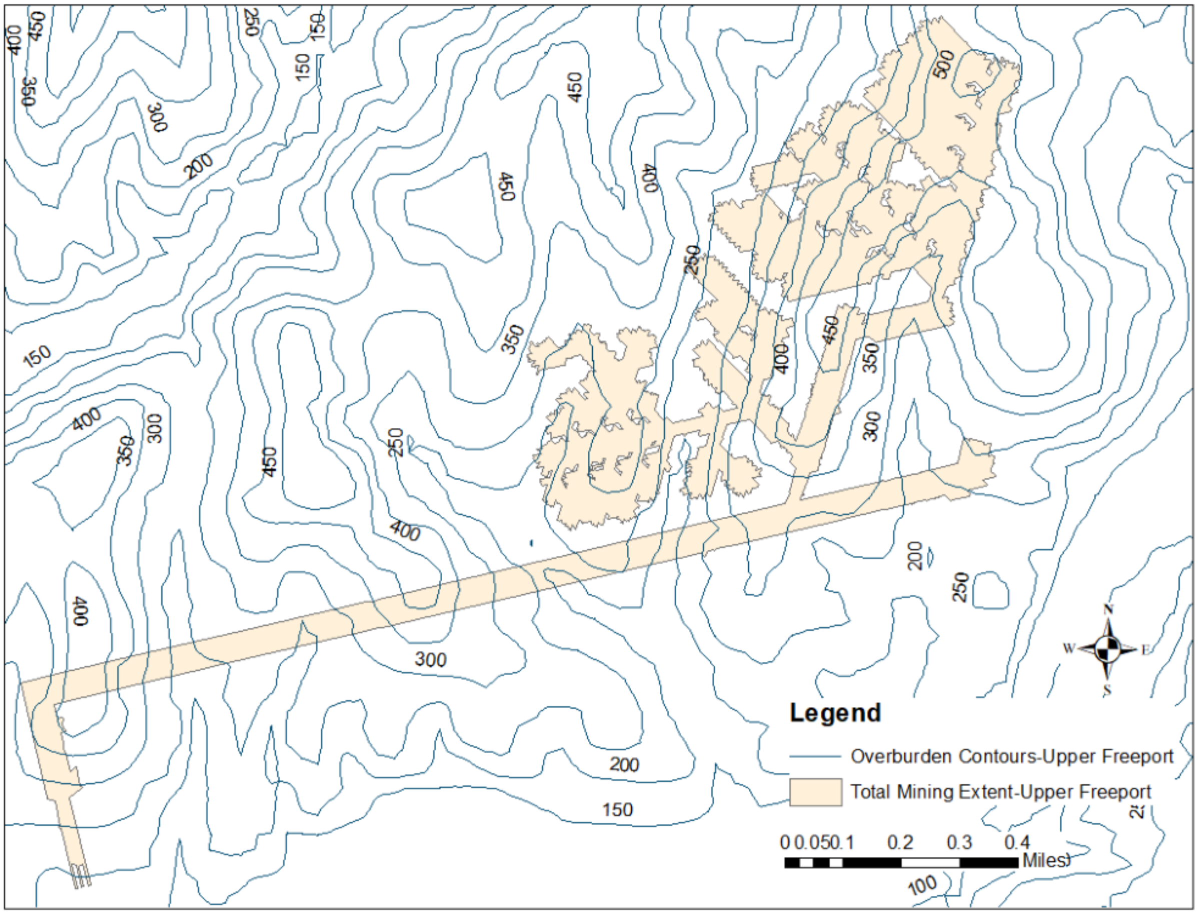

Figure 172. Fifty-foot overburden contour intervals for the Crooked Creek Mine Upper Freeport coal seam

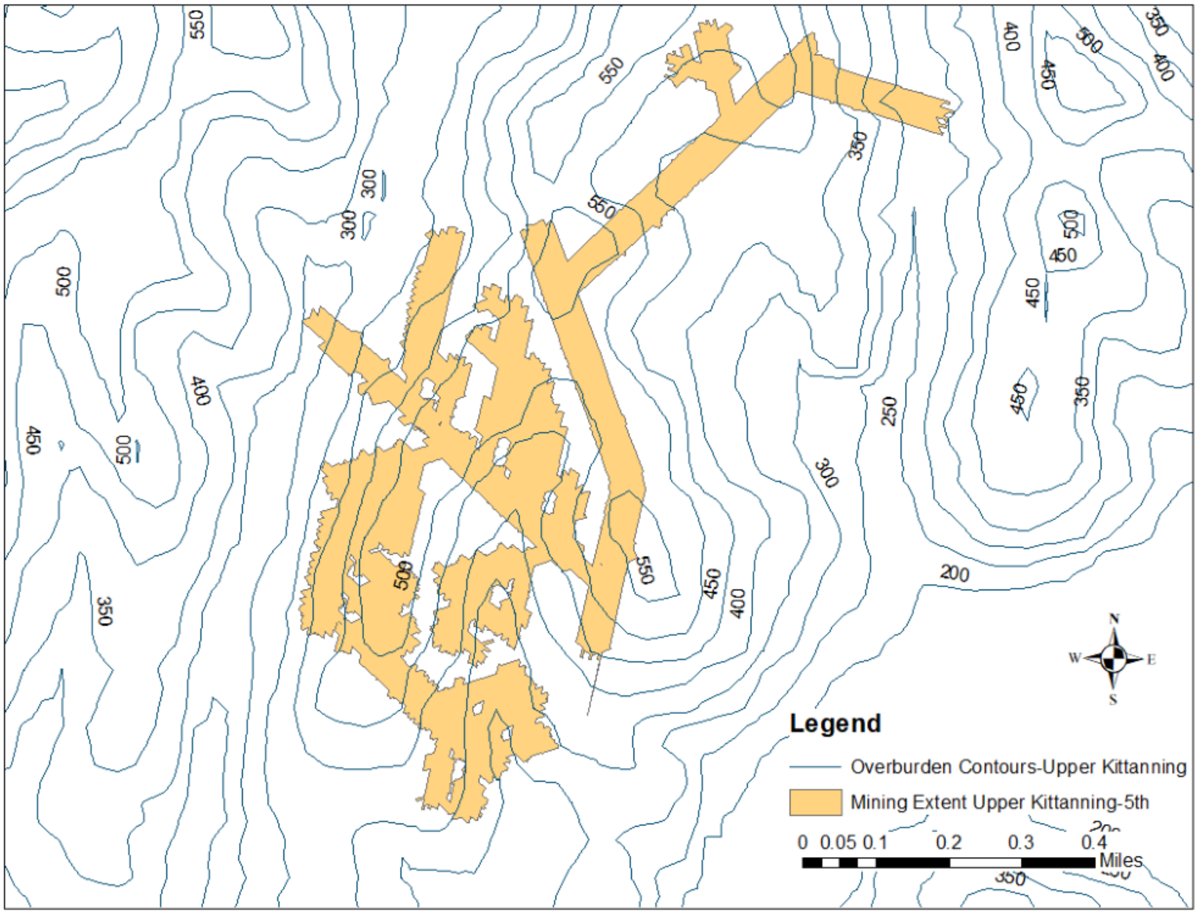

Figure 173. Fifty-foot overburden contour intervals for the Crooked Creek Mine Upper Kittanning coal seam

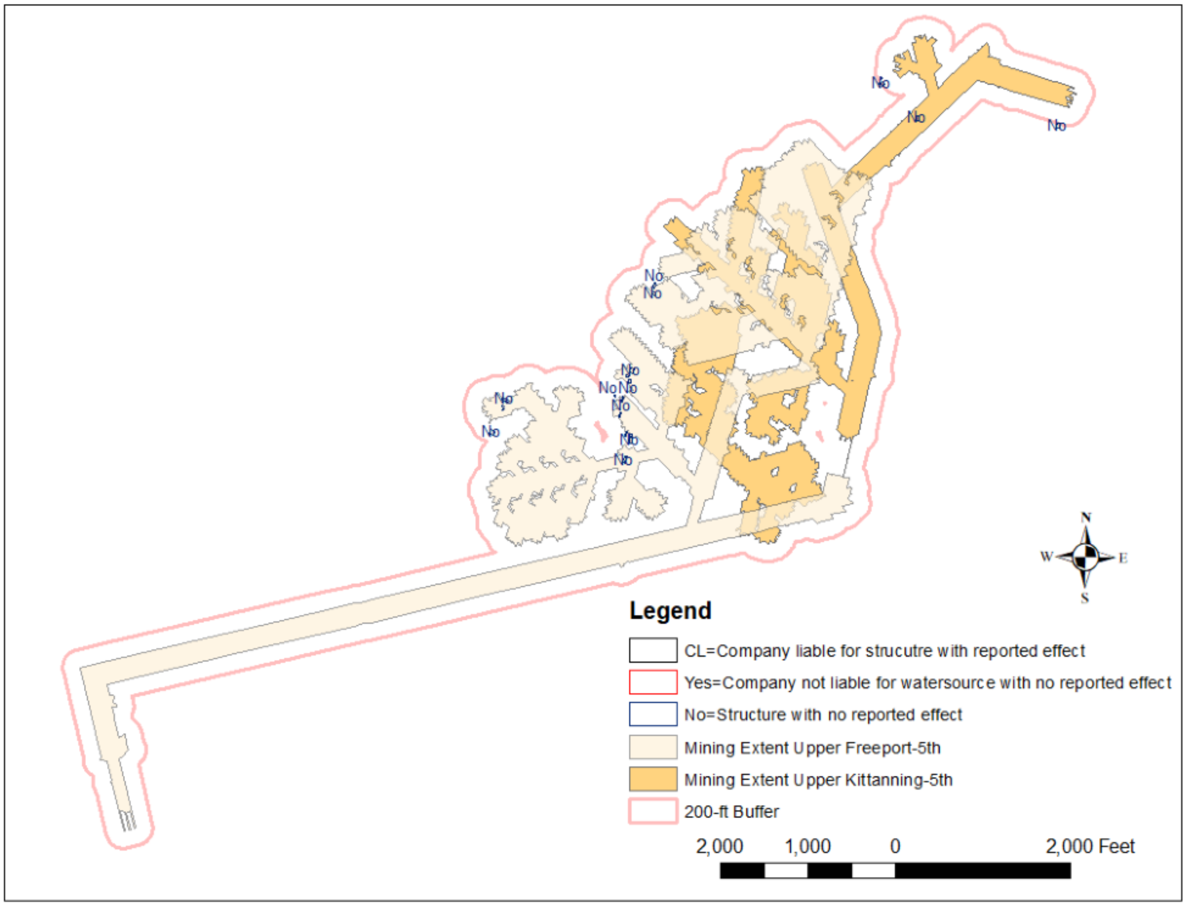

Figure 174. Crooked Creek 5th assessment 200-ft buffer and structures

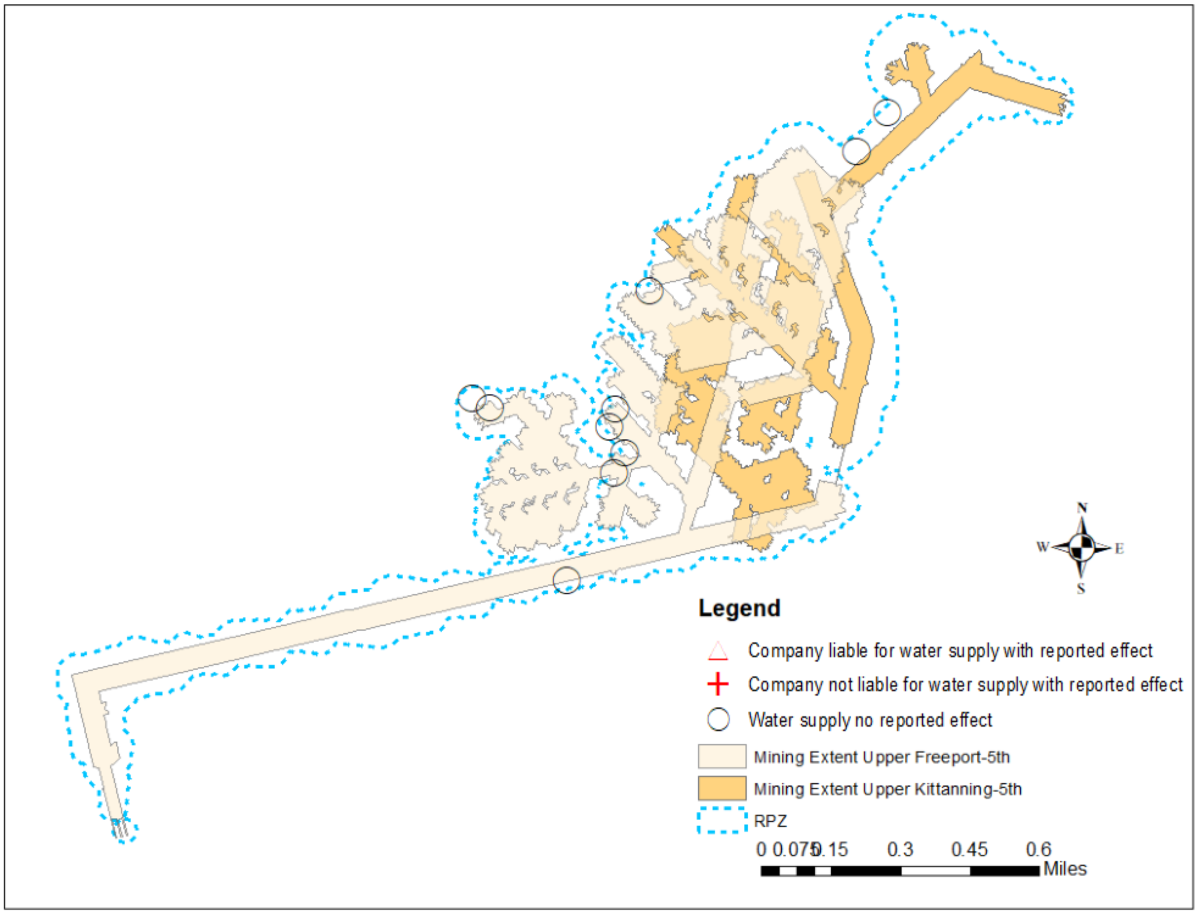

Figure 175. Crooked Creek 5th assessment water supplies and RPZ

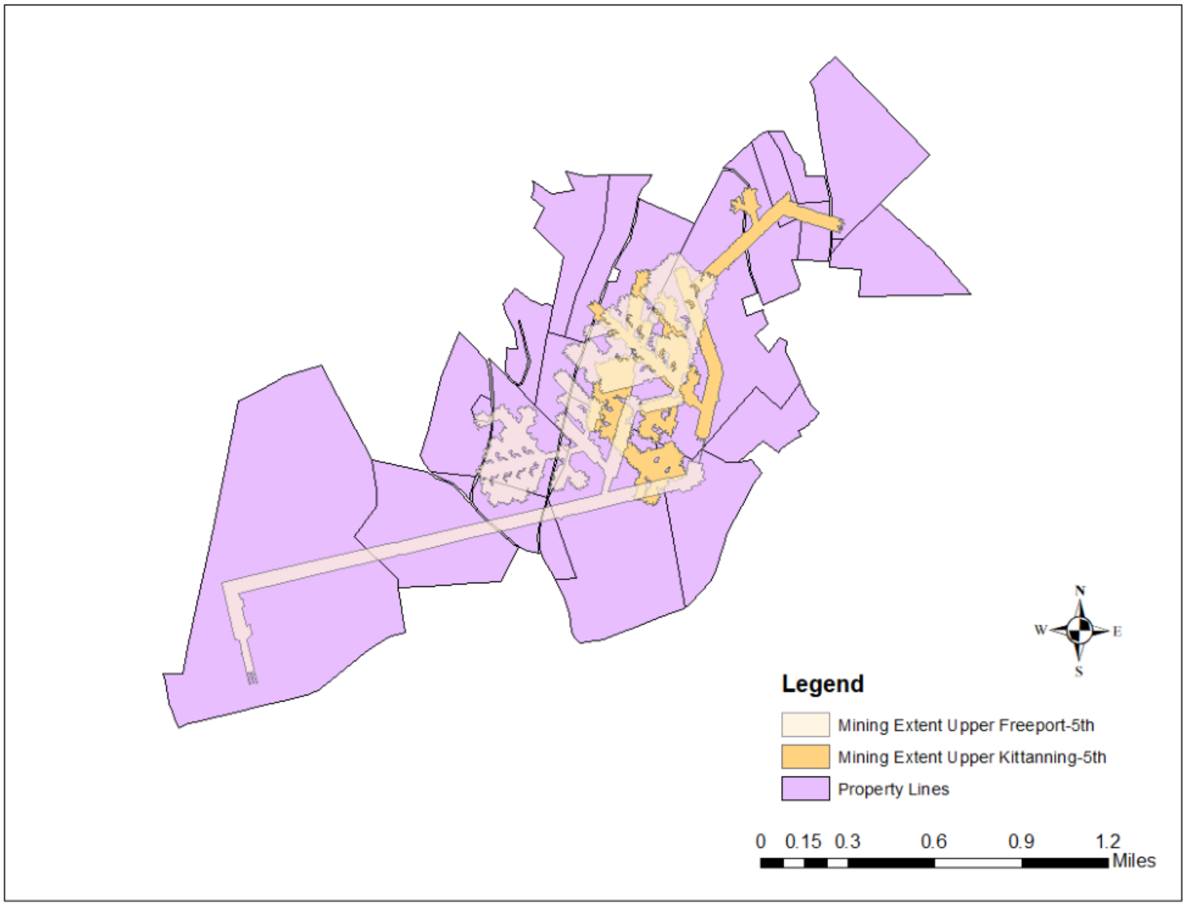

Figure 176. Properties associated with the 5th assessment period over the Crooked Creek Mine

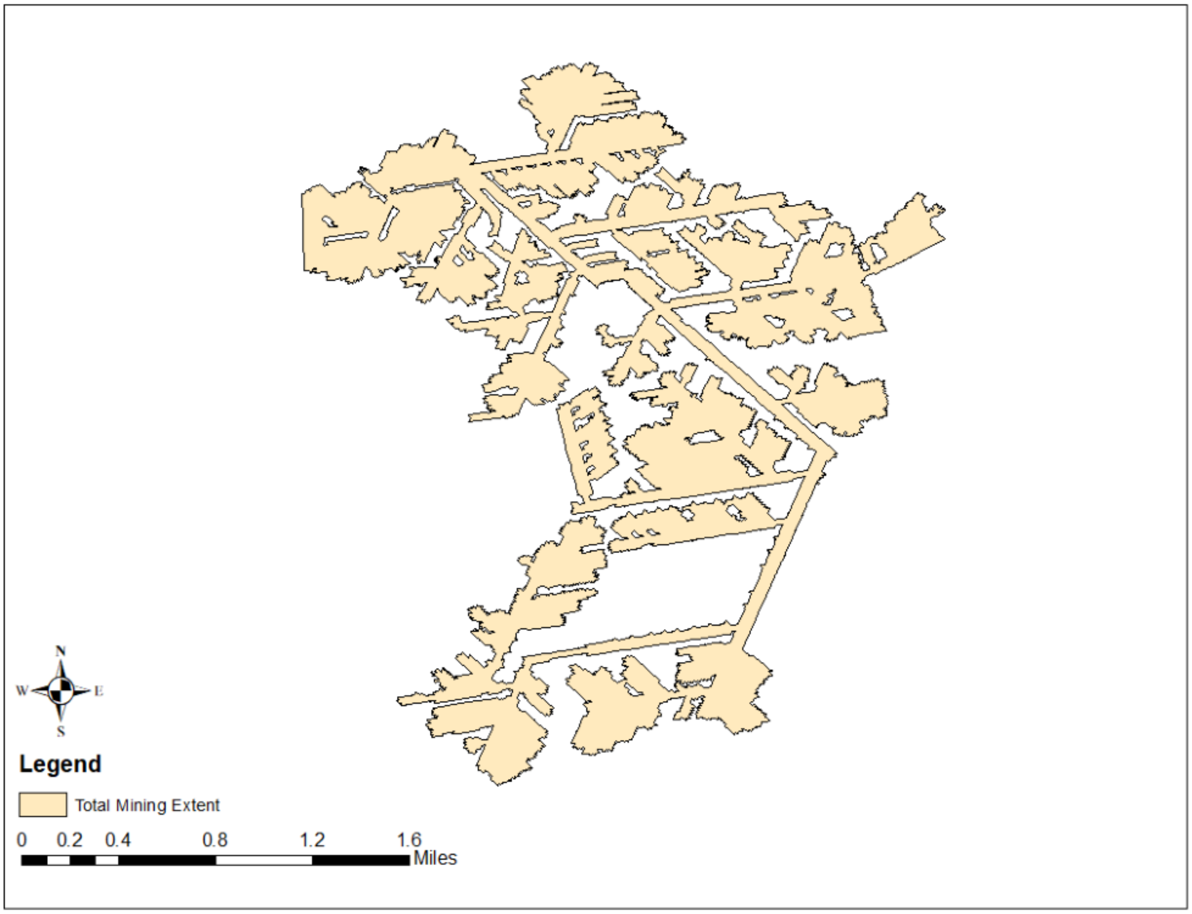

Figure 177. Darmac No. 2 total extent of mining

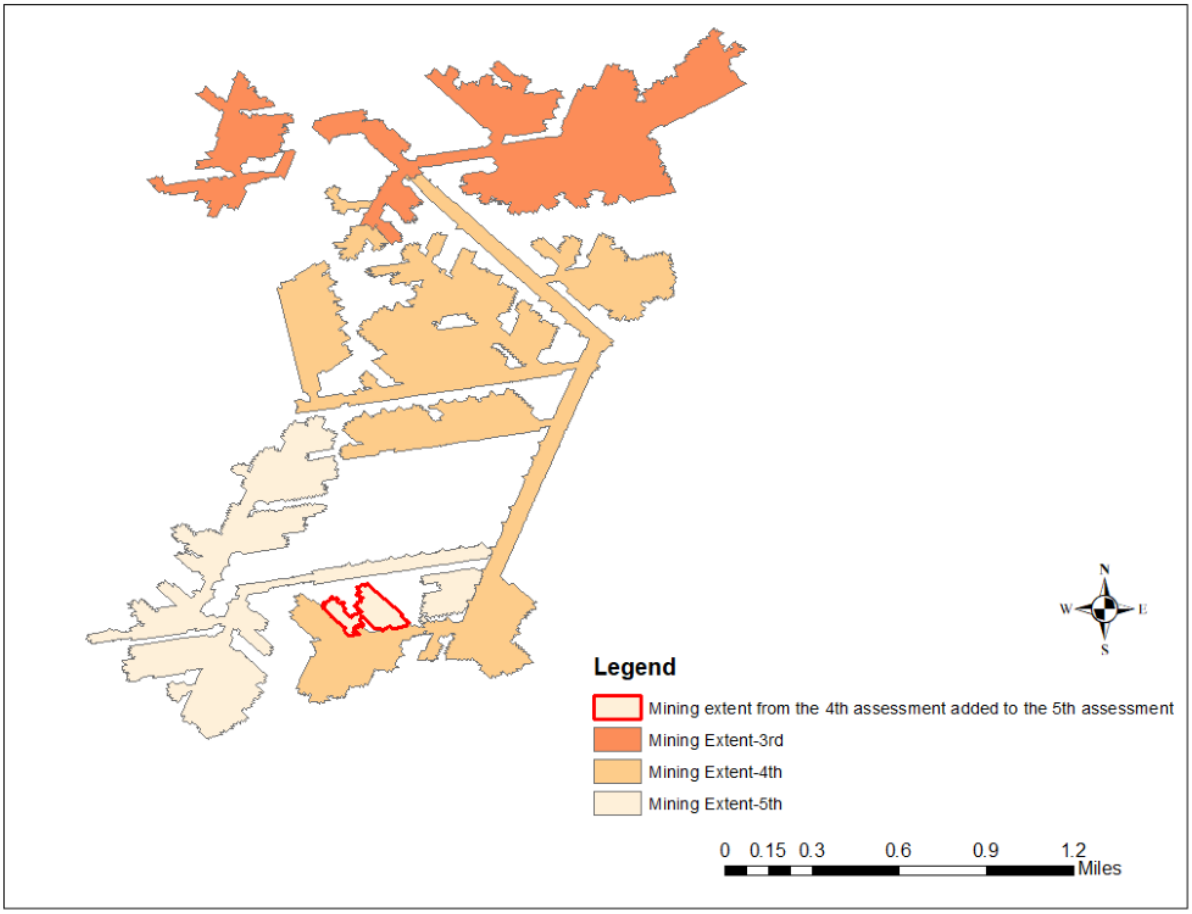

Figure 178. Darmac No. 2 mining extent for the 3rd, 4th, and 5th assessment periods

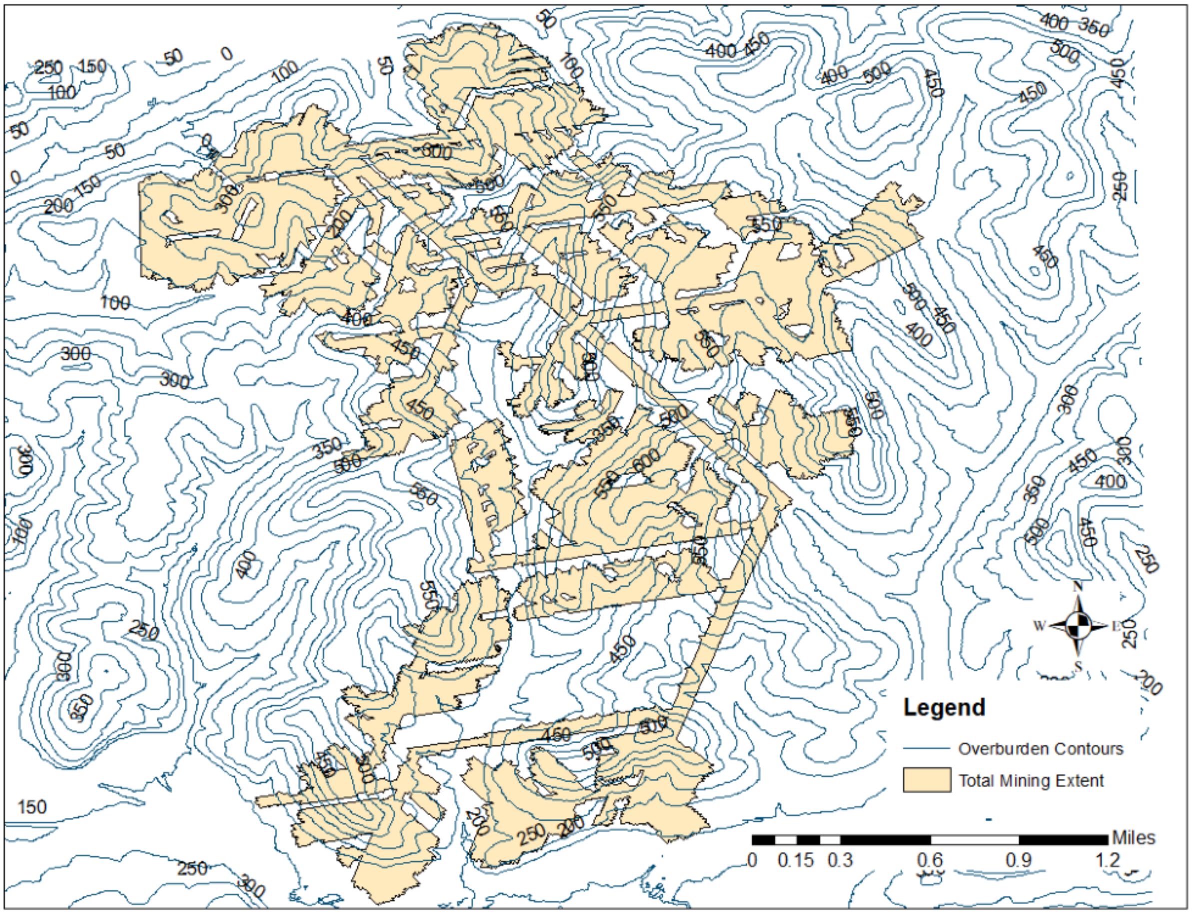

Figure 179. Fifty-foot overburden contour intervals for the Darmac No. 2 Mine

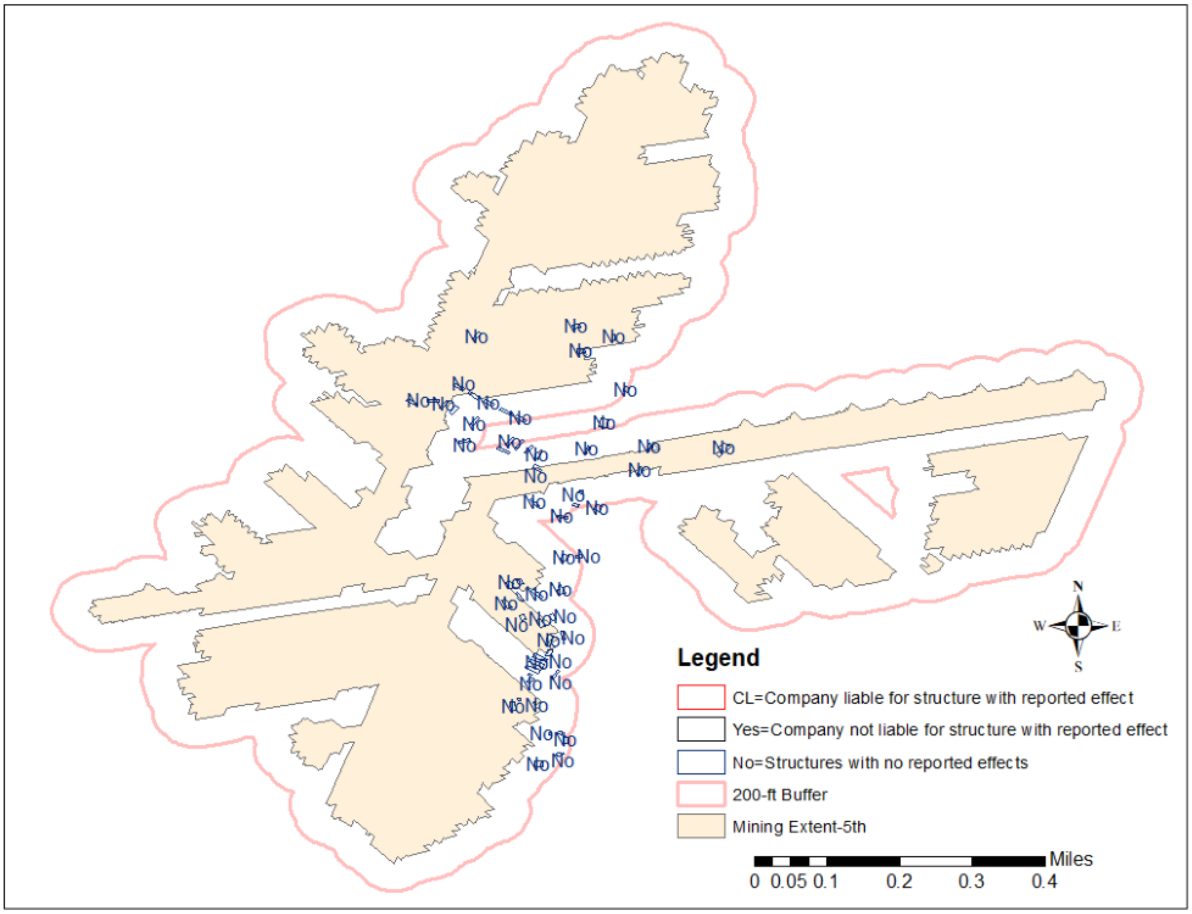

Figure 180. Darmac No. 2 Mine 5th assessment 200-ft buffer and structures

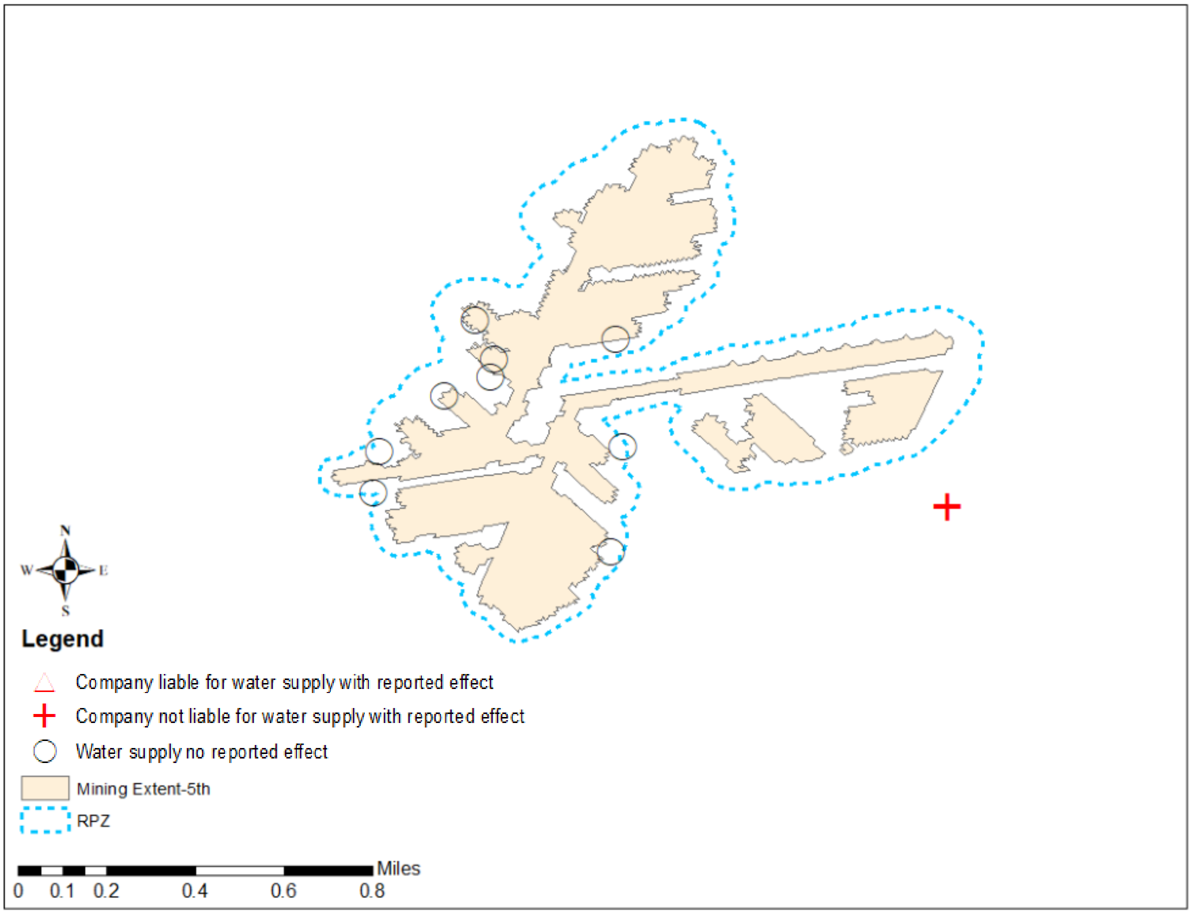

Figure 181. Darmac No. 2 Mine 5th assessment water supplies and RPZ*

**Note there are two water supplies with reported effects that are far from mining and are not included here for display purposes.*

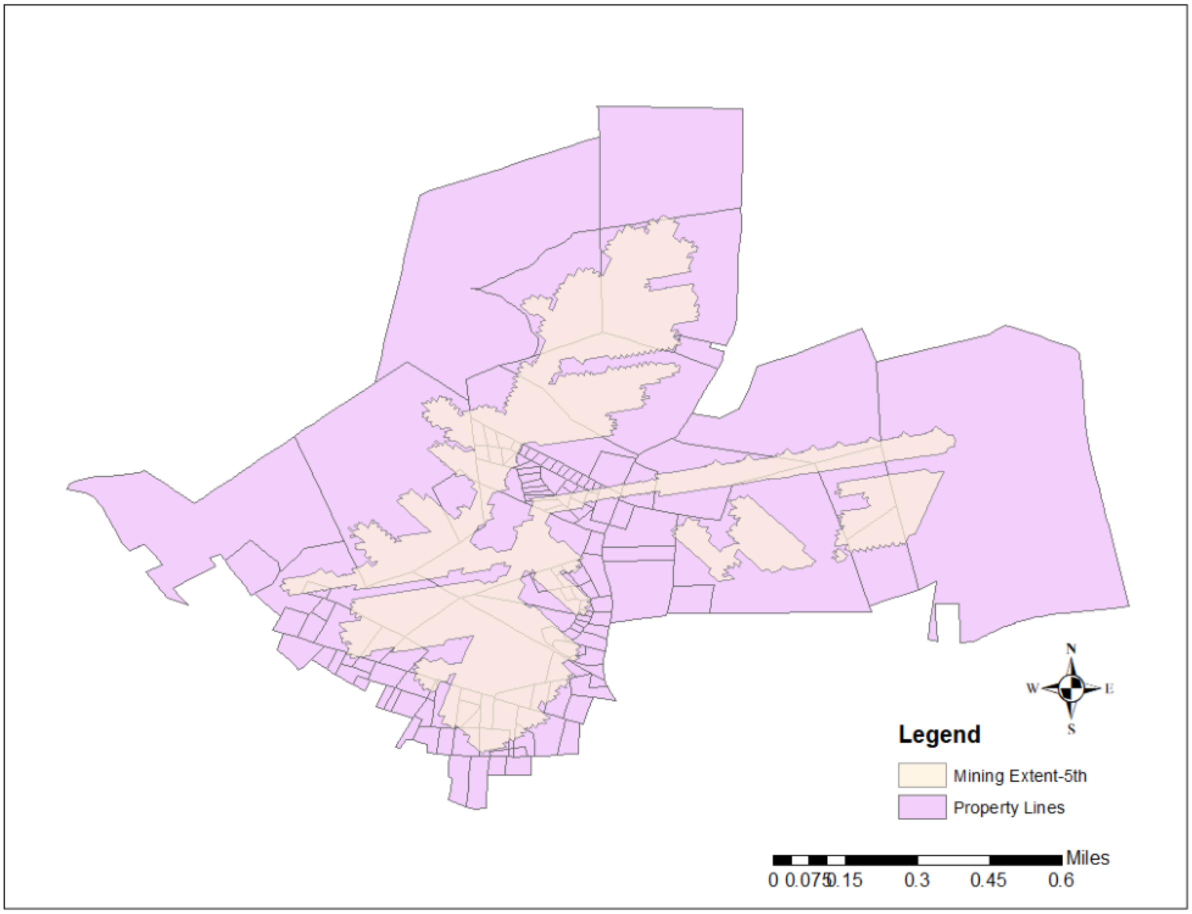

Figure 182. Properties associated with the 5th assessment period over the Darmac No. 2 Mine

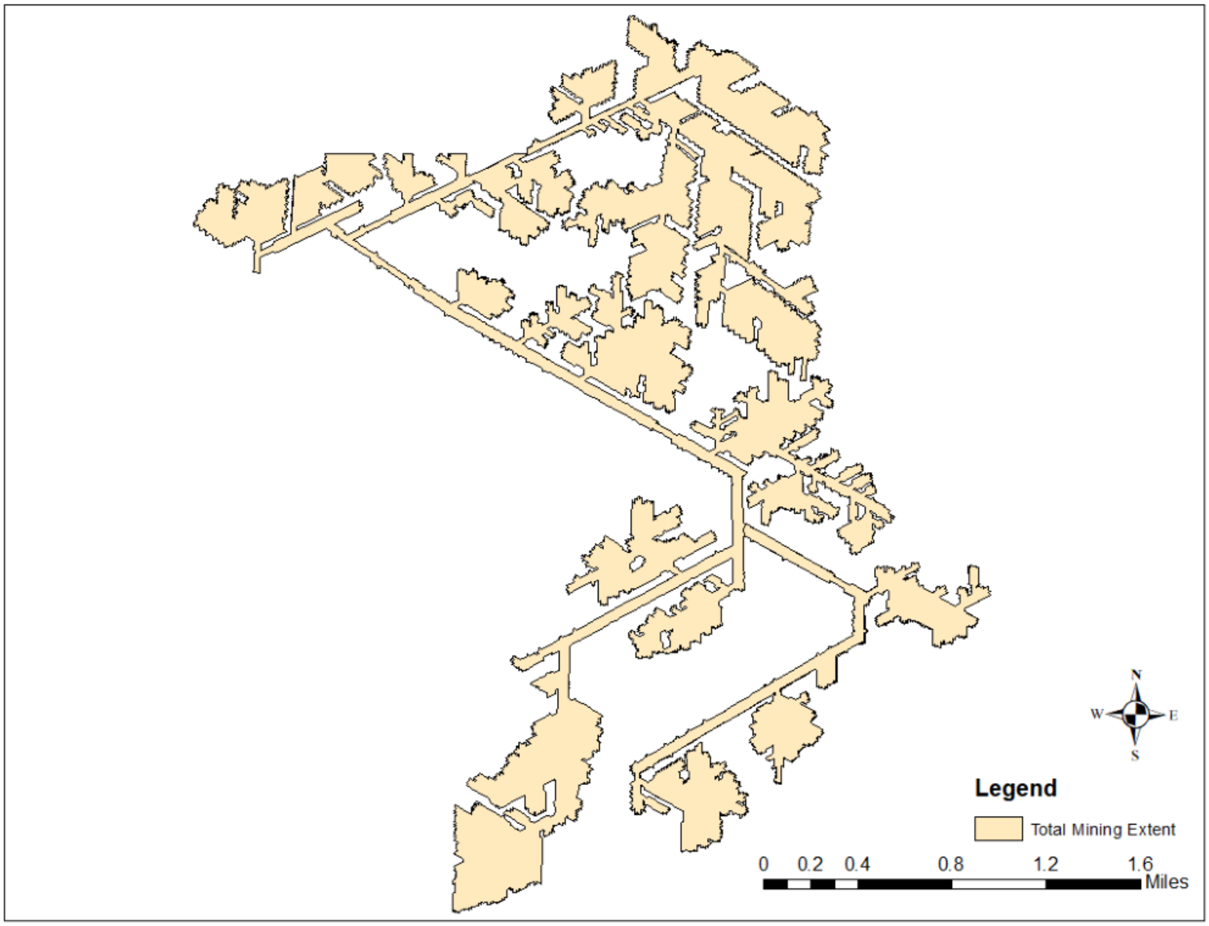

Figure 183. Dutch Run total extent of mining

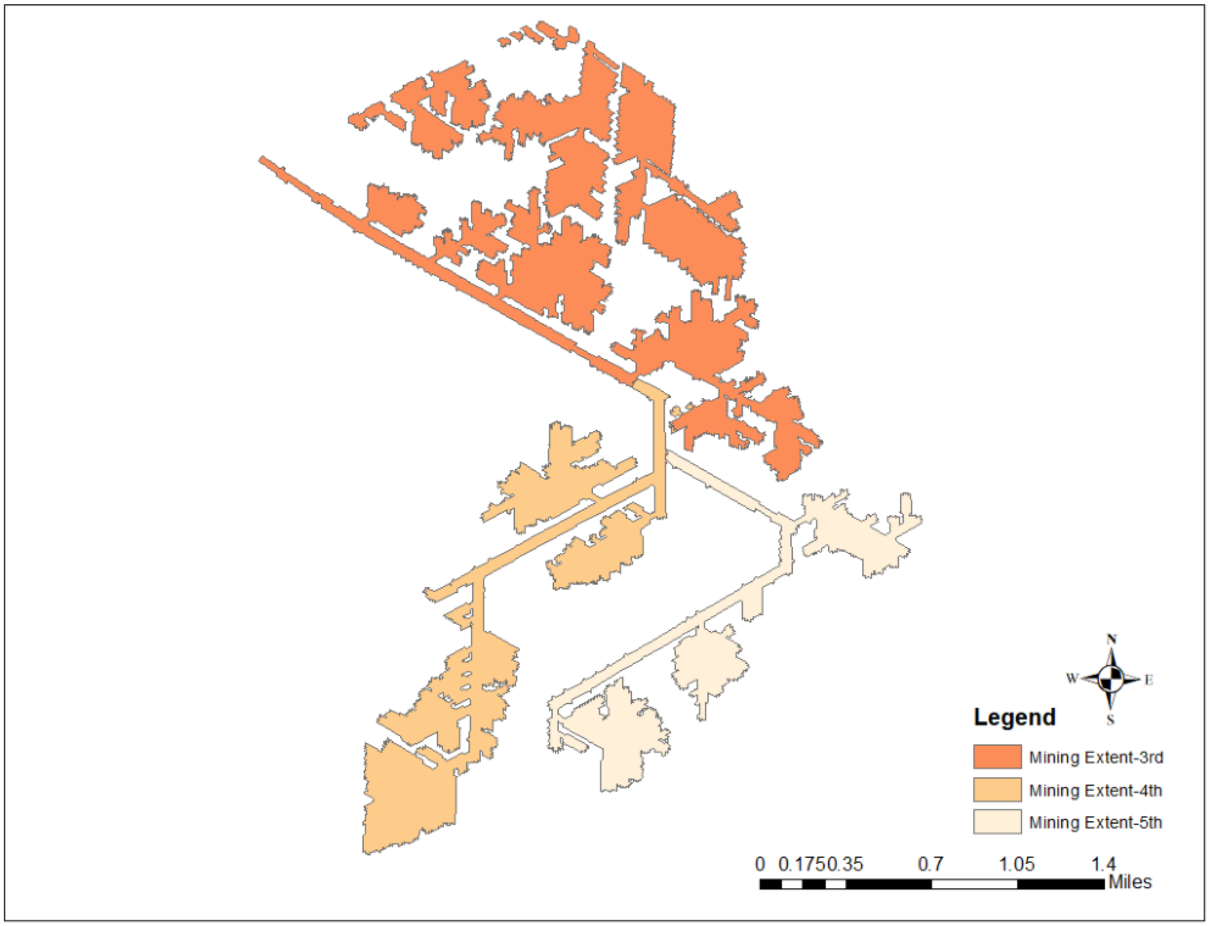

Figure 184. Dutch Run mining extent for the 3rd, 4th, and 5th assessment periods

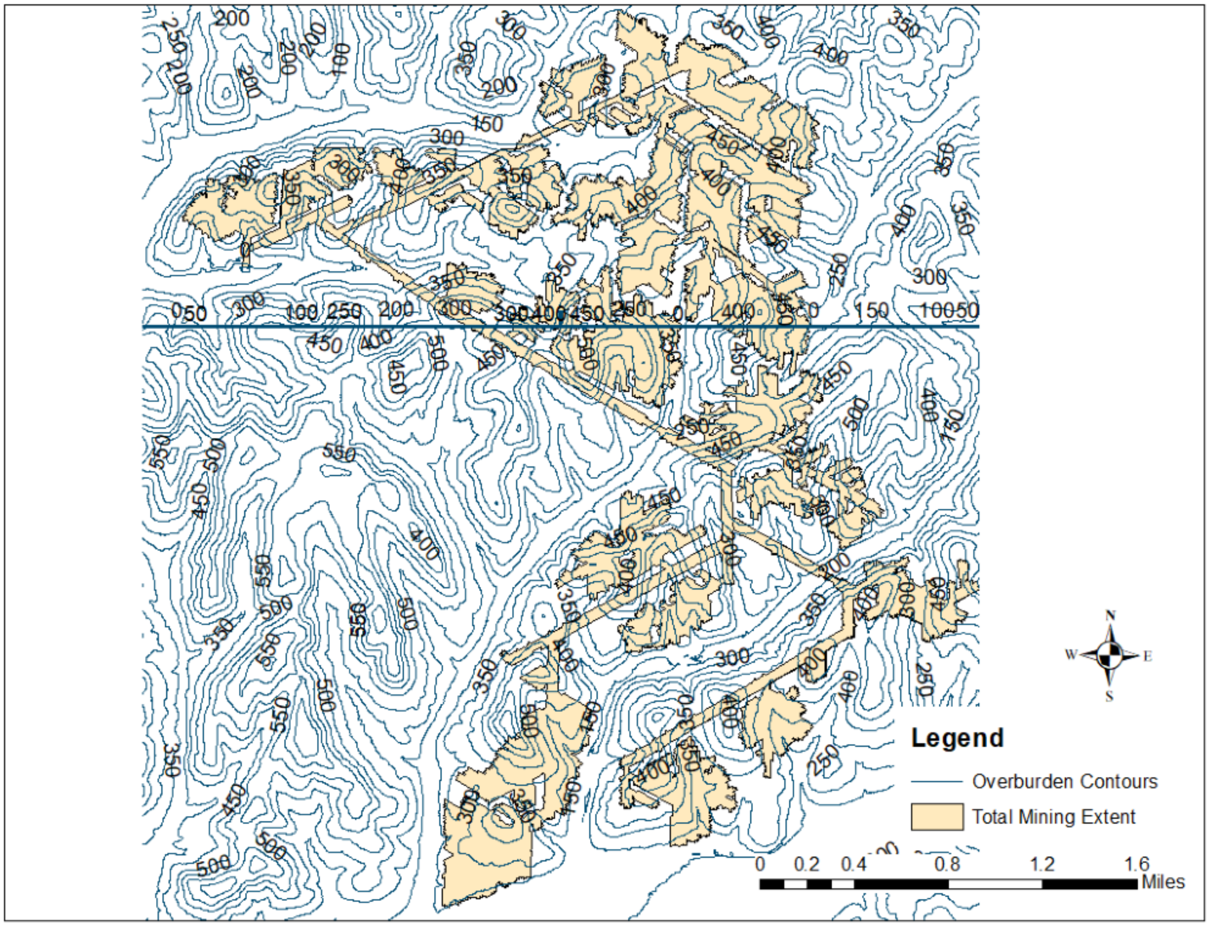

Figure 185. Fifty-foot overburden contour intervals for the Dutch Run Mine

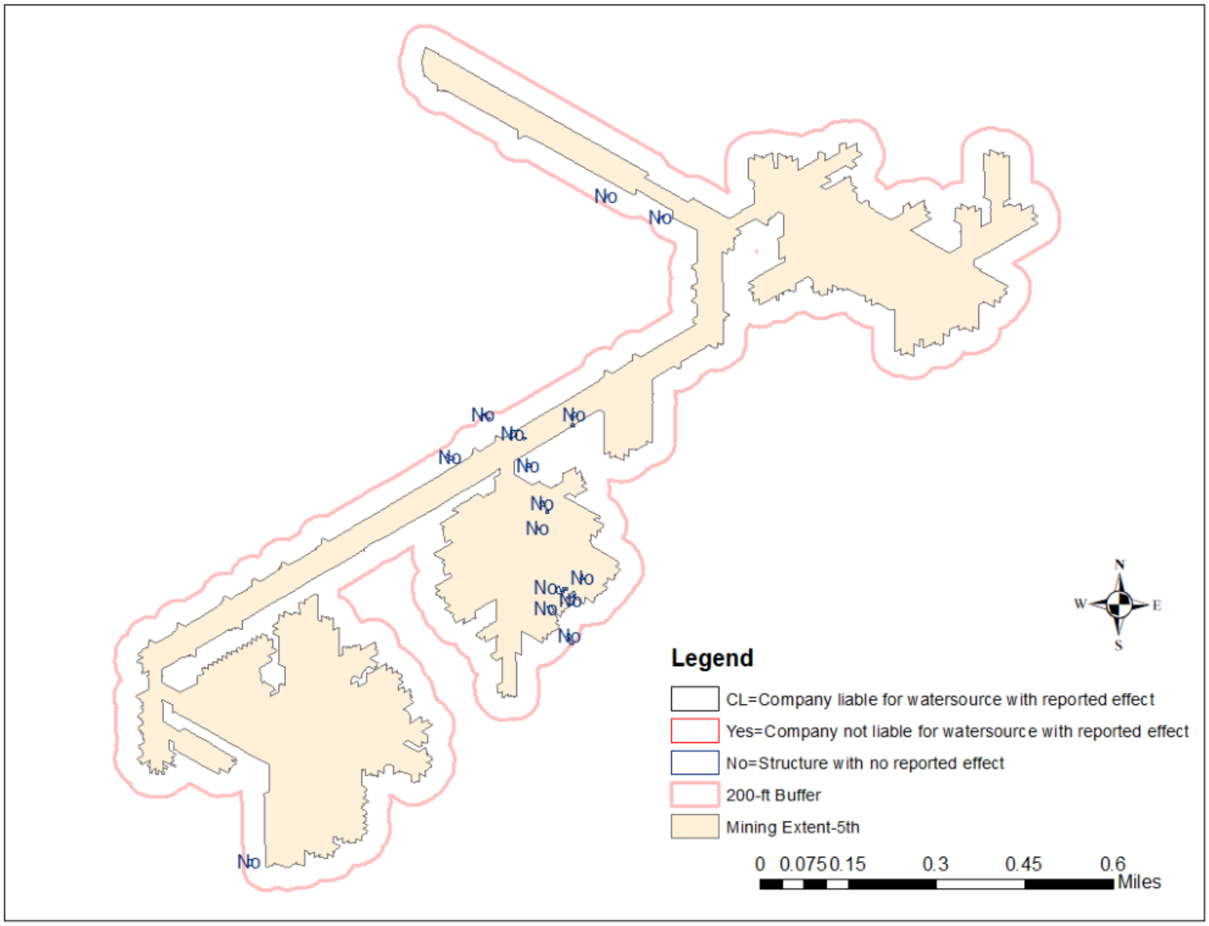

Figure 186. Dutch Run 5th assessment 200-ft buffer and structures*

Note there are two structures with reported effects that are far from mining and are not included here for display purposes.

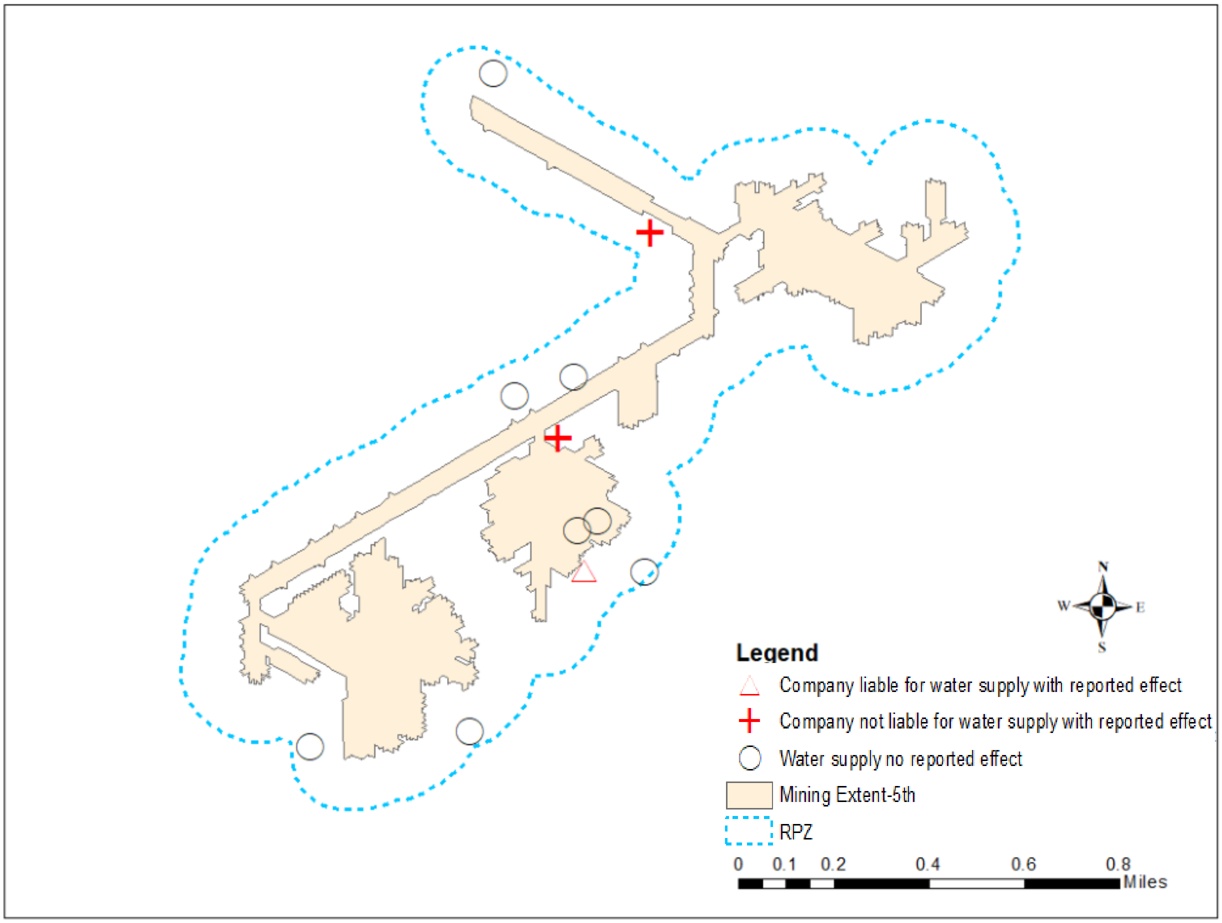

Figure 187. Dutch Run 5th assessment water supplies and RPZ*

***Note there are three water supplies with reported effects that are far from mining and are not included here for display purposes.*

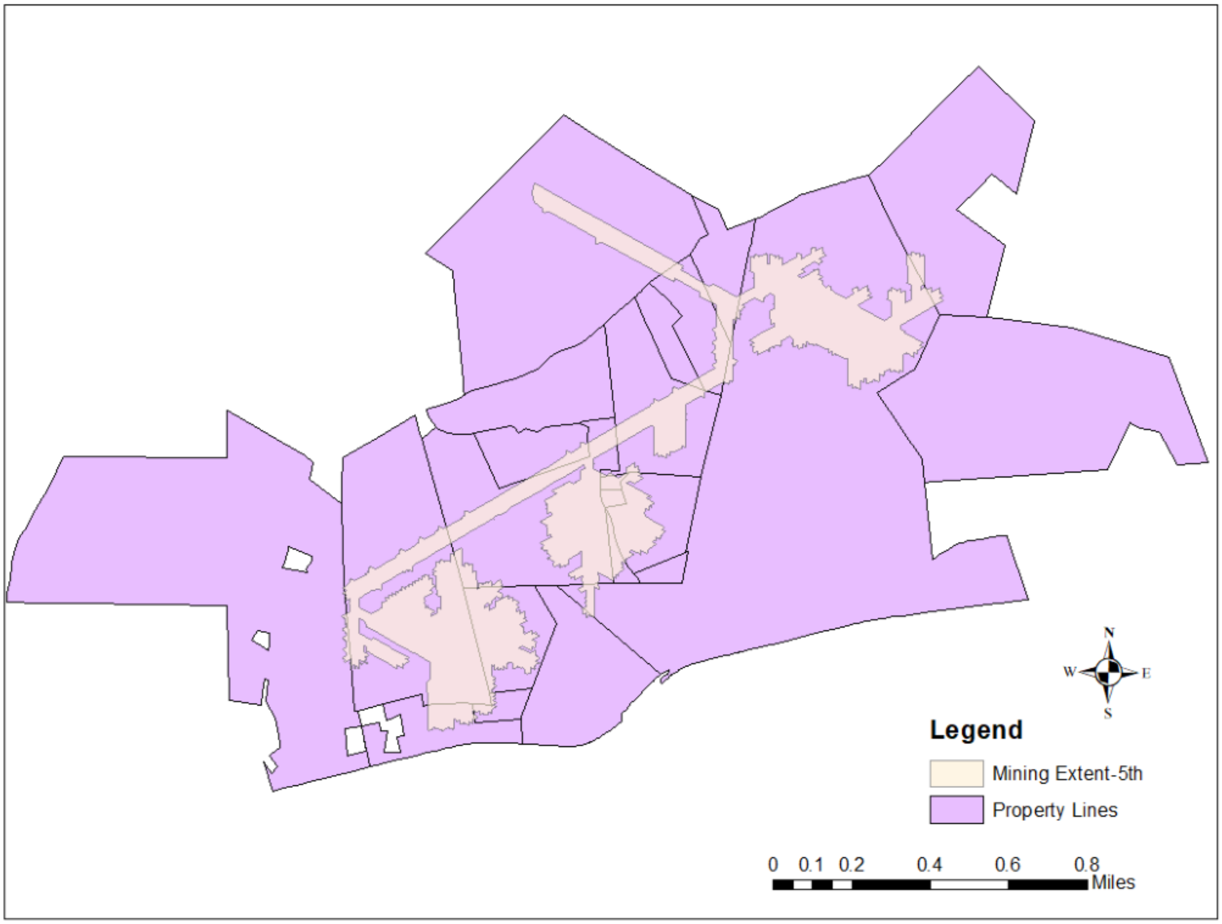

Figure 188. Properties associated with the 5th assessment period over the Dutch Run Mine

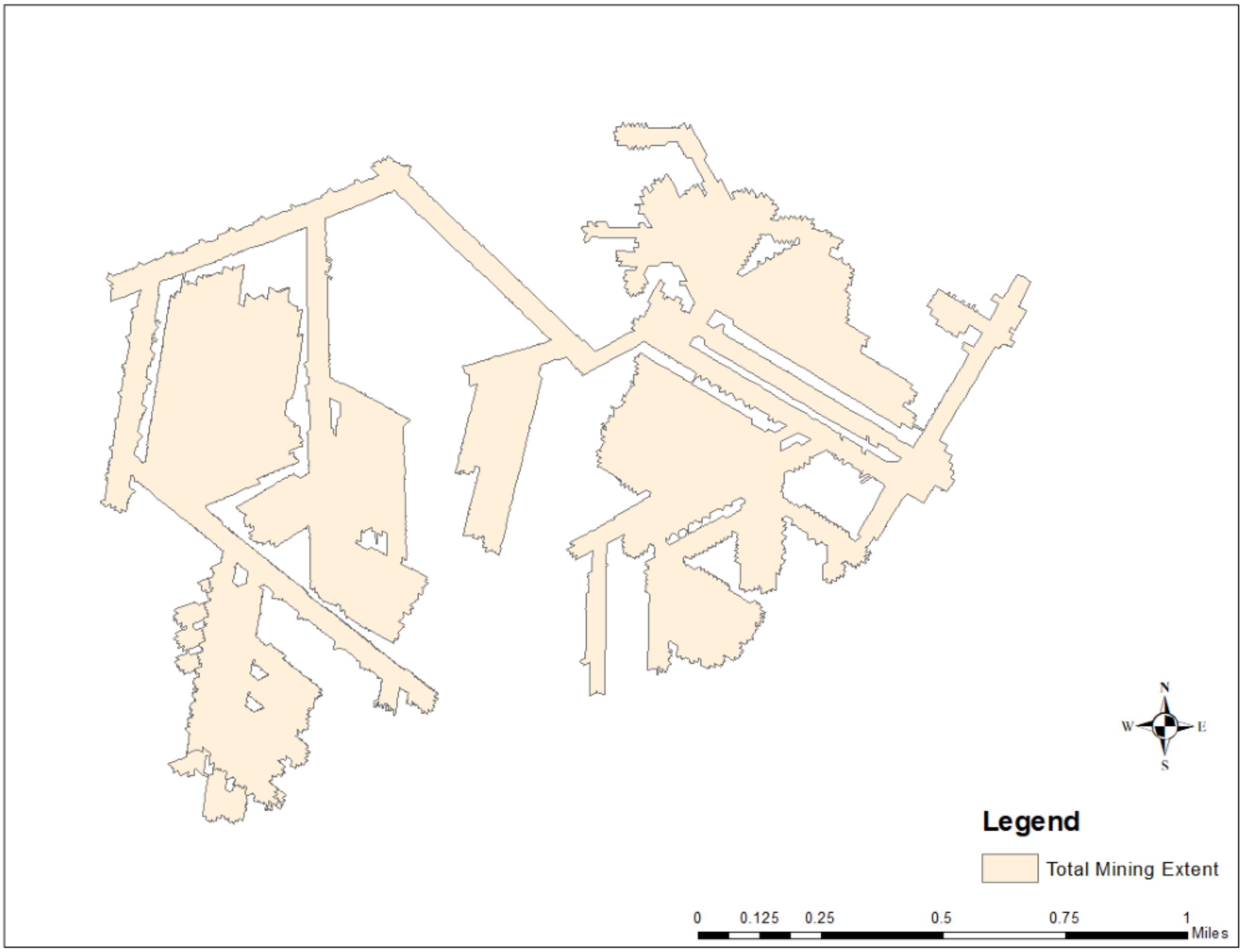

Figure 189. Gillhouser Run total extent of mining

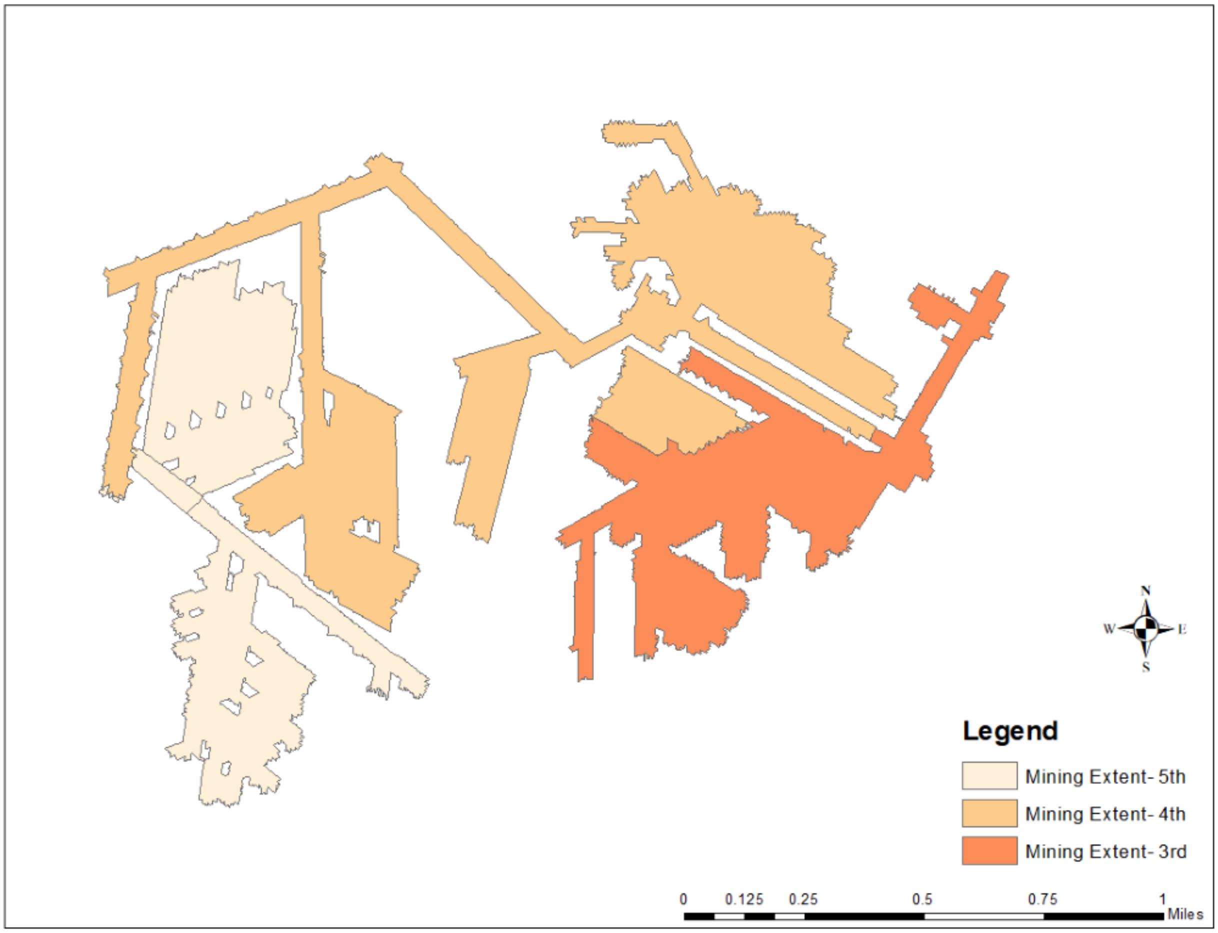

Figure 190. Gillhouser Run mining extent for the 3rd, 4th, and 5th assessment periods

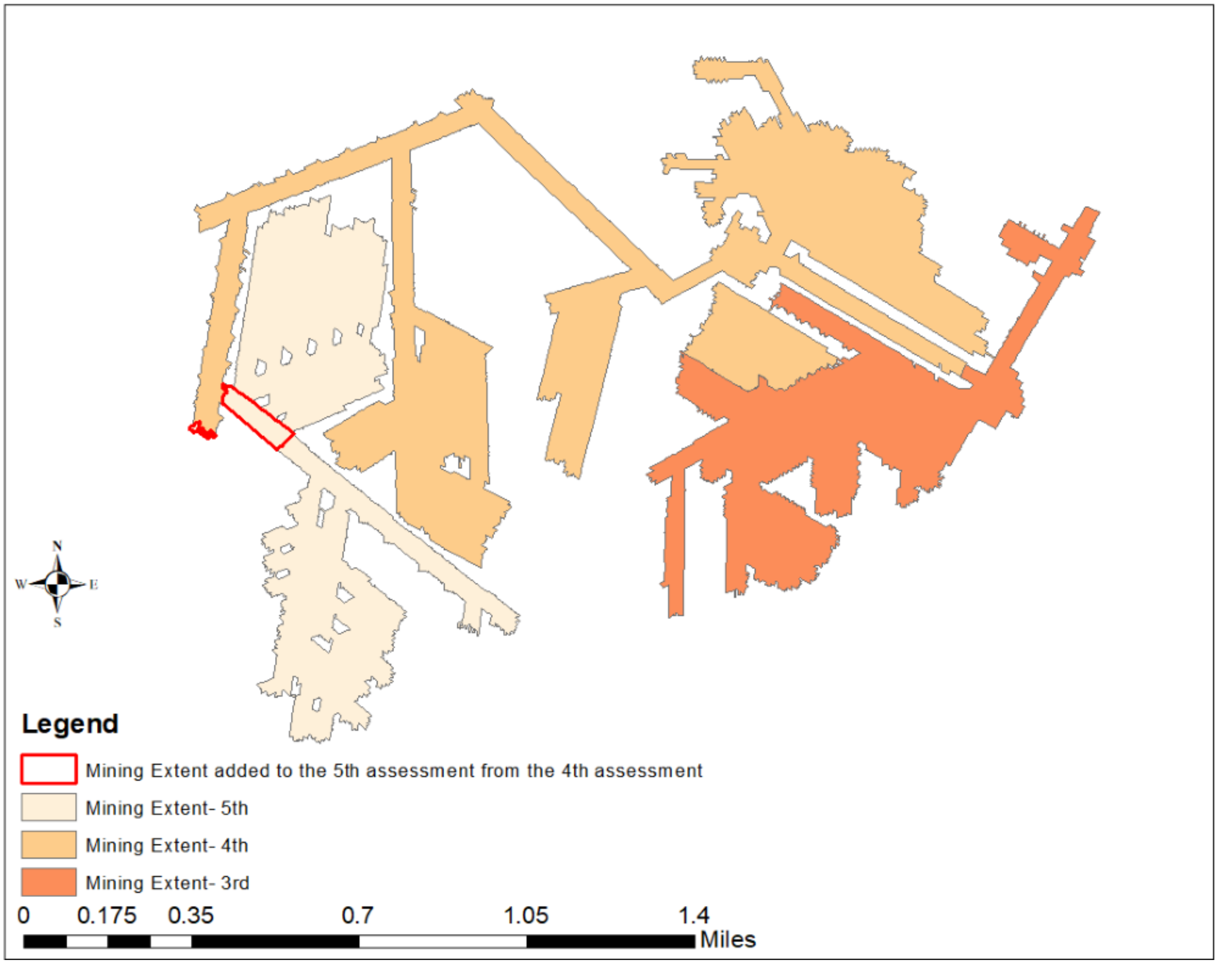

Figure 191. Gillhouser Run mining extent for the 3rd, 4th, and 5th assessment periods*

** Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined in July 2013, a month before the 4th assessment collection period was finalized. Due to the late submission of this data and the early reporting requirements, this area was not considered during the 4th assessment period. This area is added to the 5th assessment period so that all area of the mine will be analyzed.*

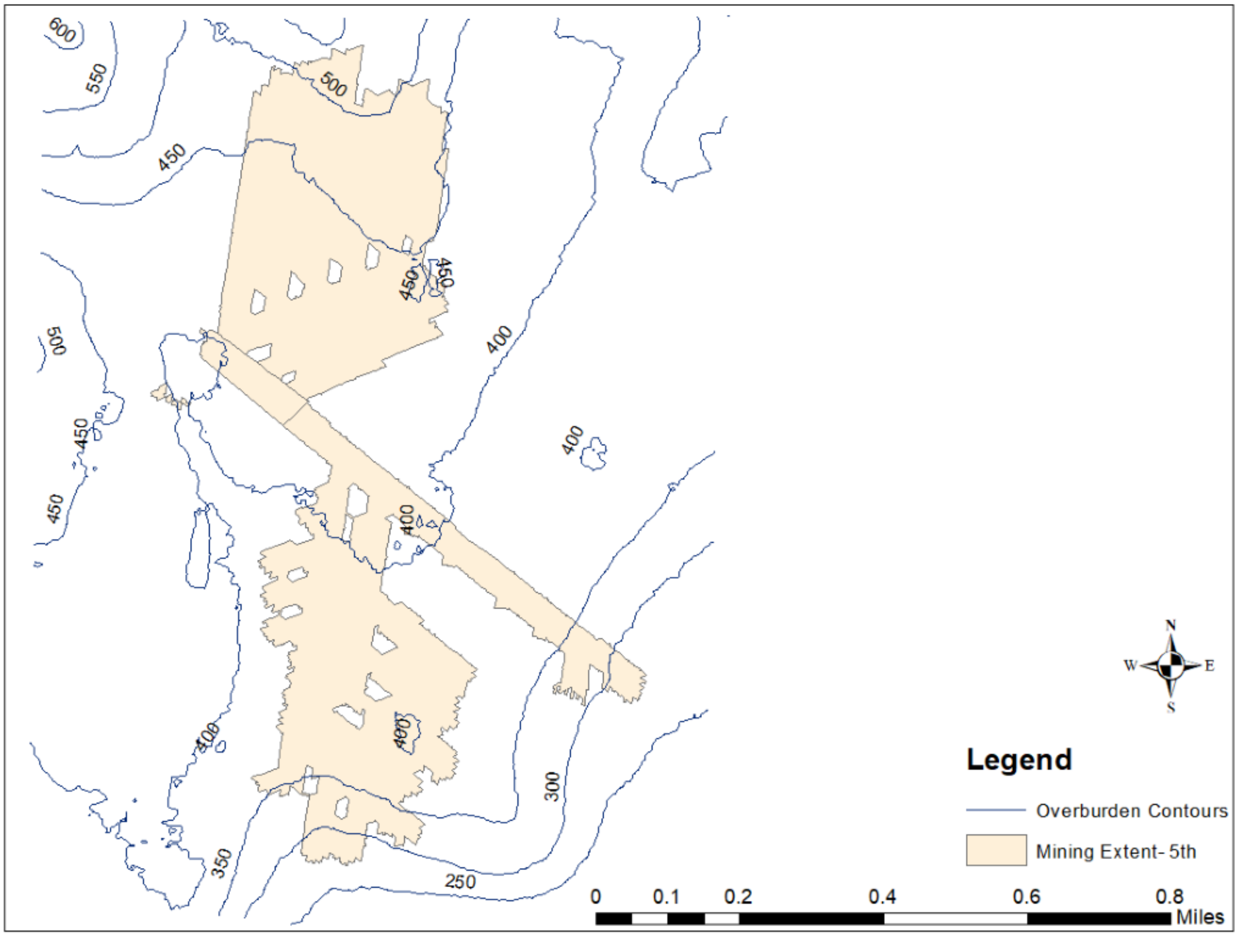

Figure 192. Fifty-foot overburden contour intervals for the Gillhouser Run mine

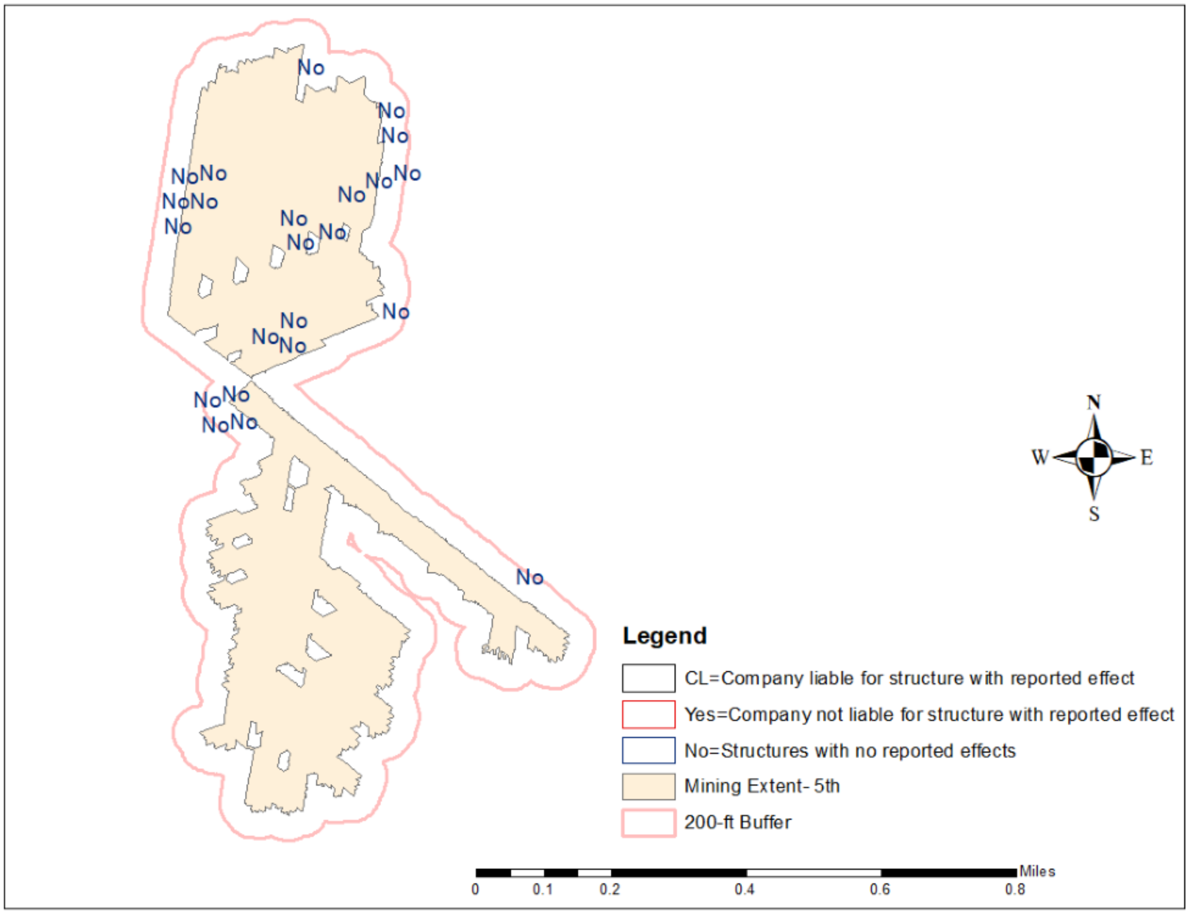

Figure 193. Gillhouser Run 5th assessment 200-ft buffer and structures

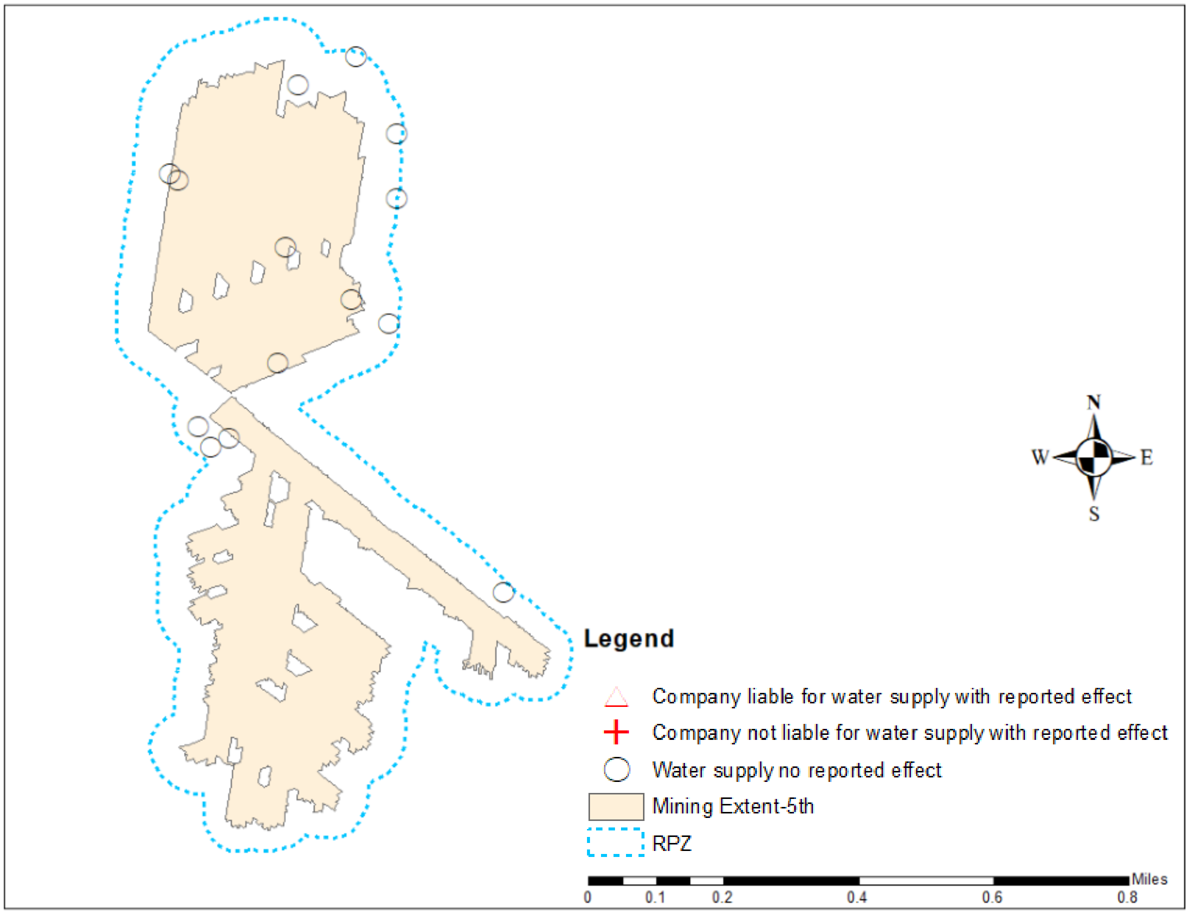

Figure 194. Gillhouser Run 5th assessment water supplies and RPZ

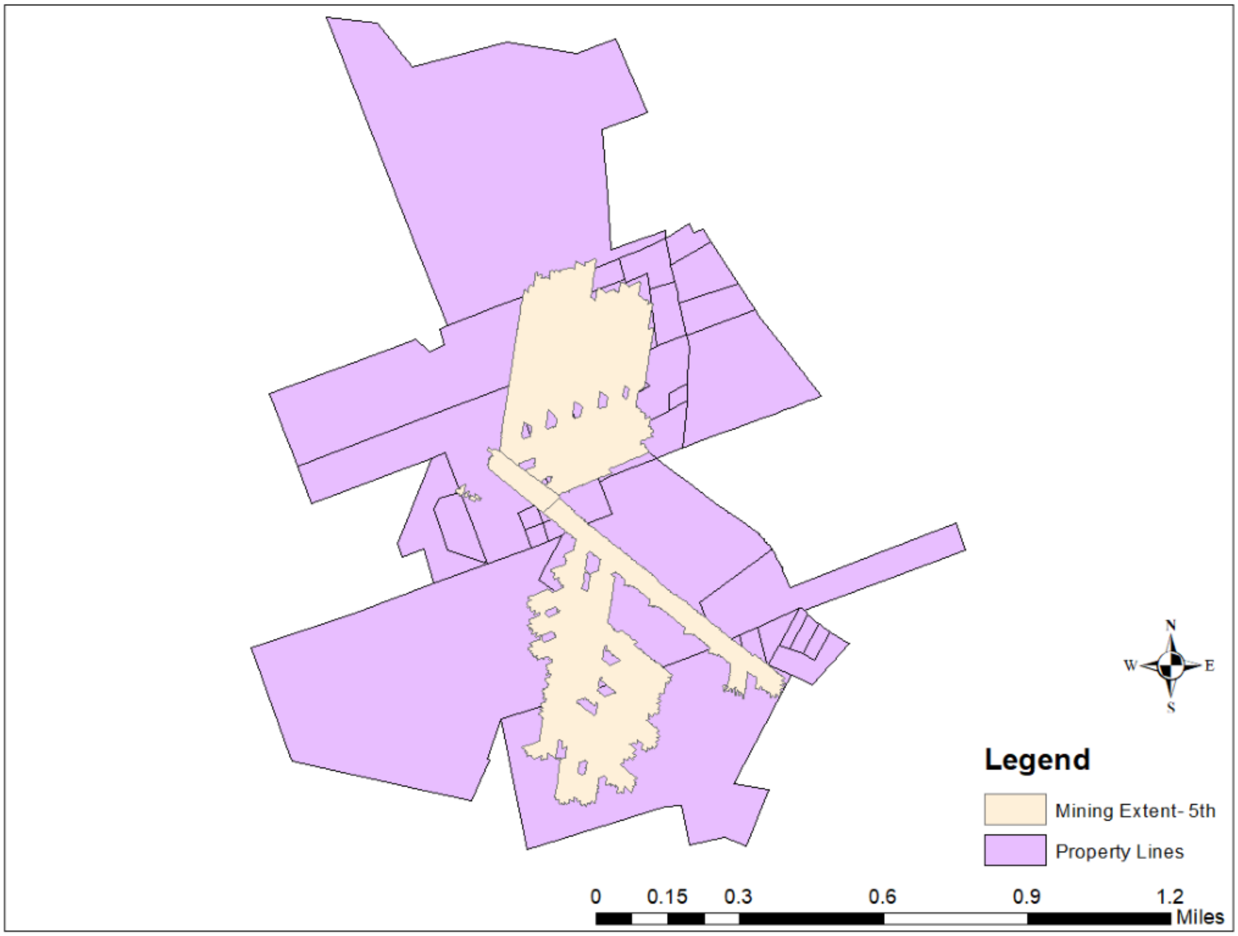

Figure 195. Properties associated with the 5th assessment period over the Gillhouser Run Mine

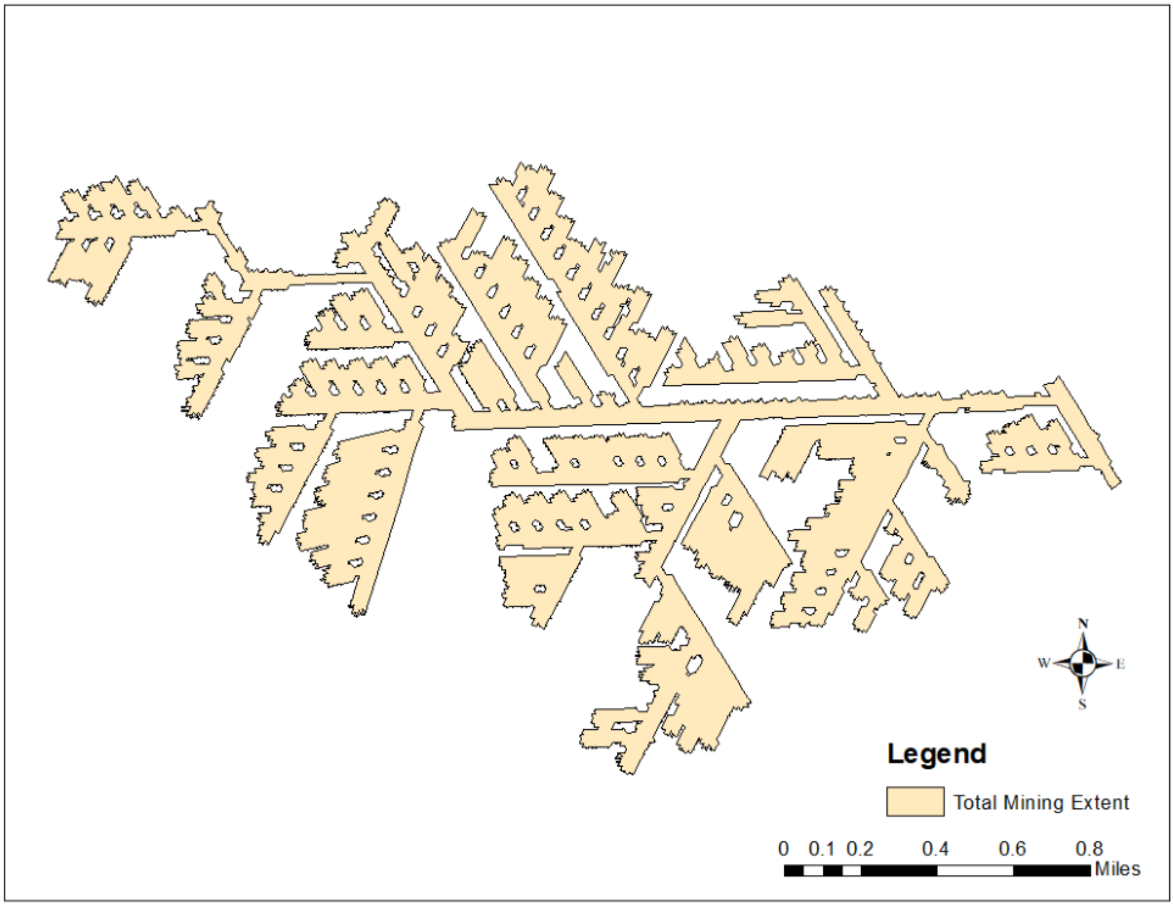

Figure 196. Harmony total extent of mining

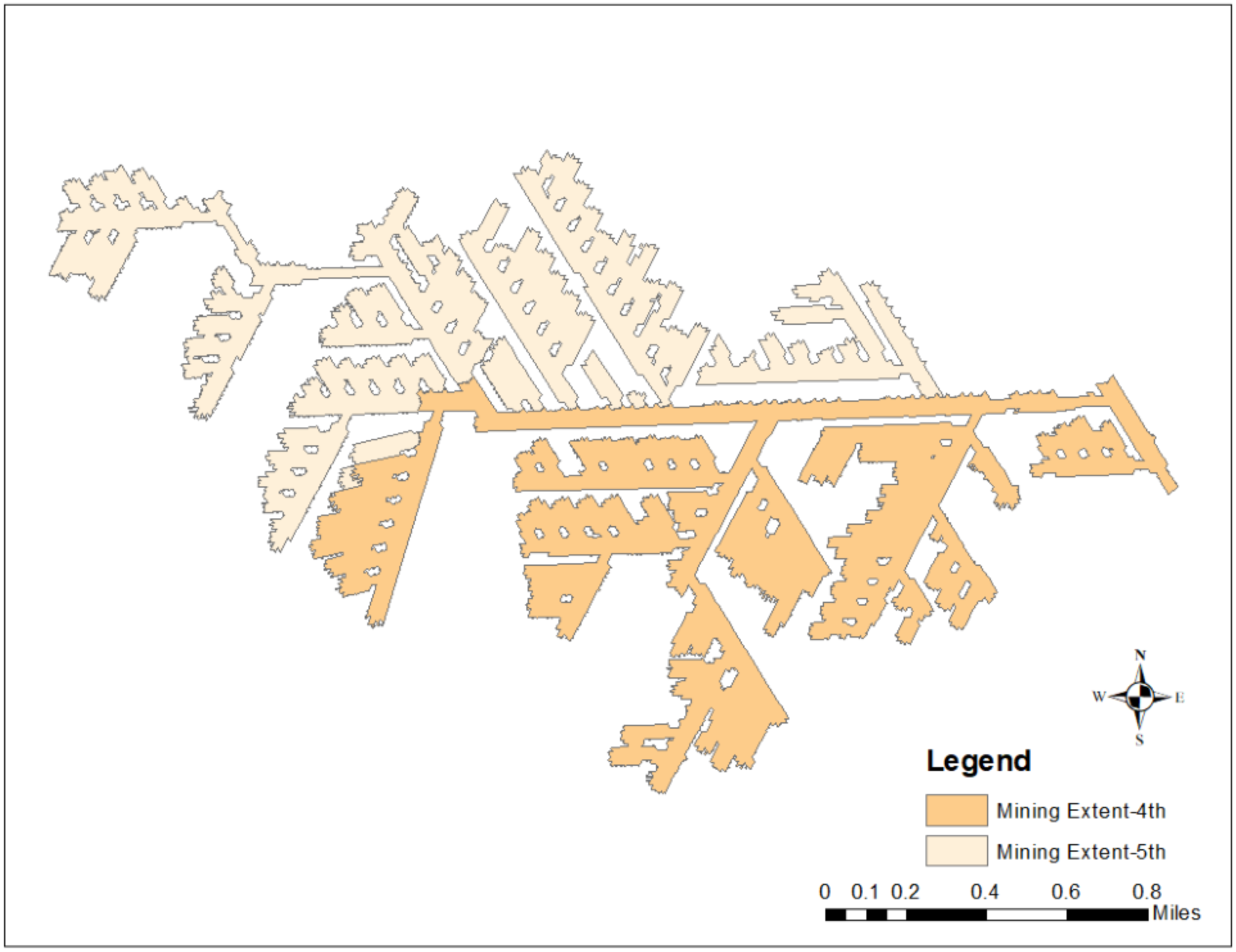

Figure 197. Harmony mining extent for the 4th and 5th assessment periods

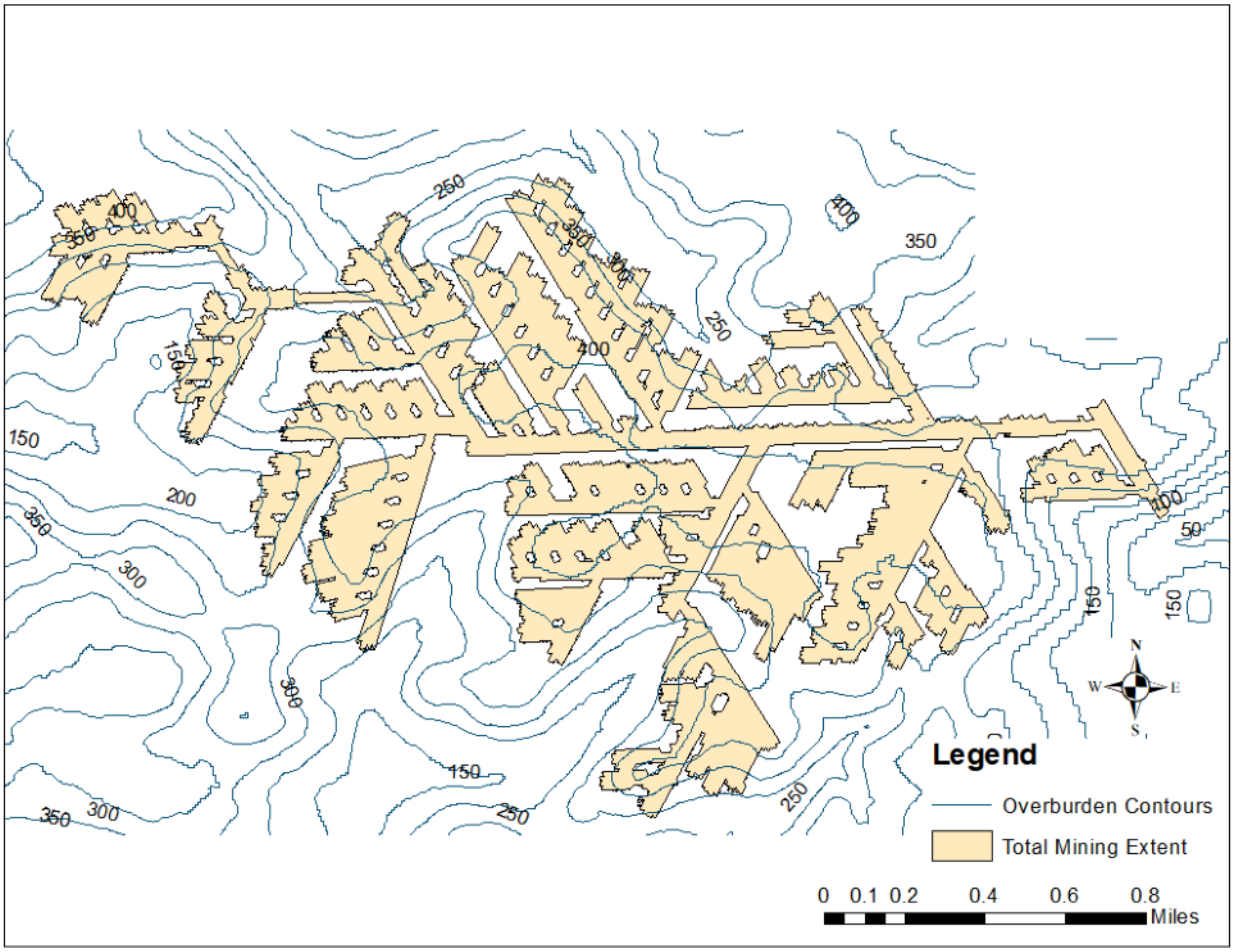

Figure 198. Fifty-foot overburden contour intervals for the Harmony Mine

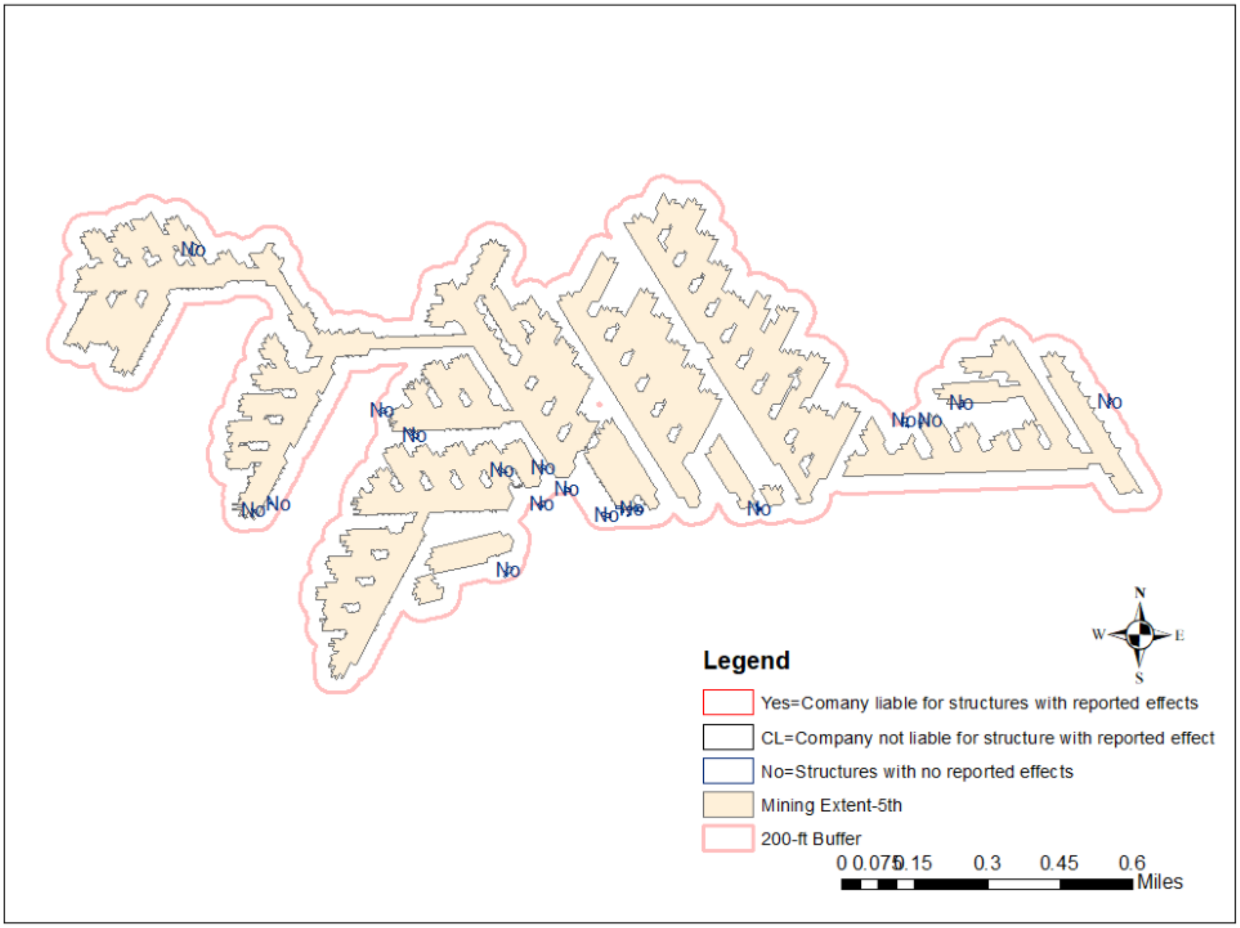

Figure 199. Harmony 5th assessment 200-ft buffer and structures

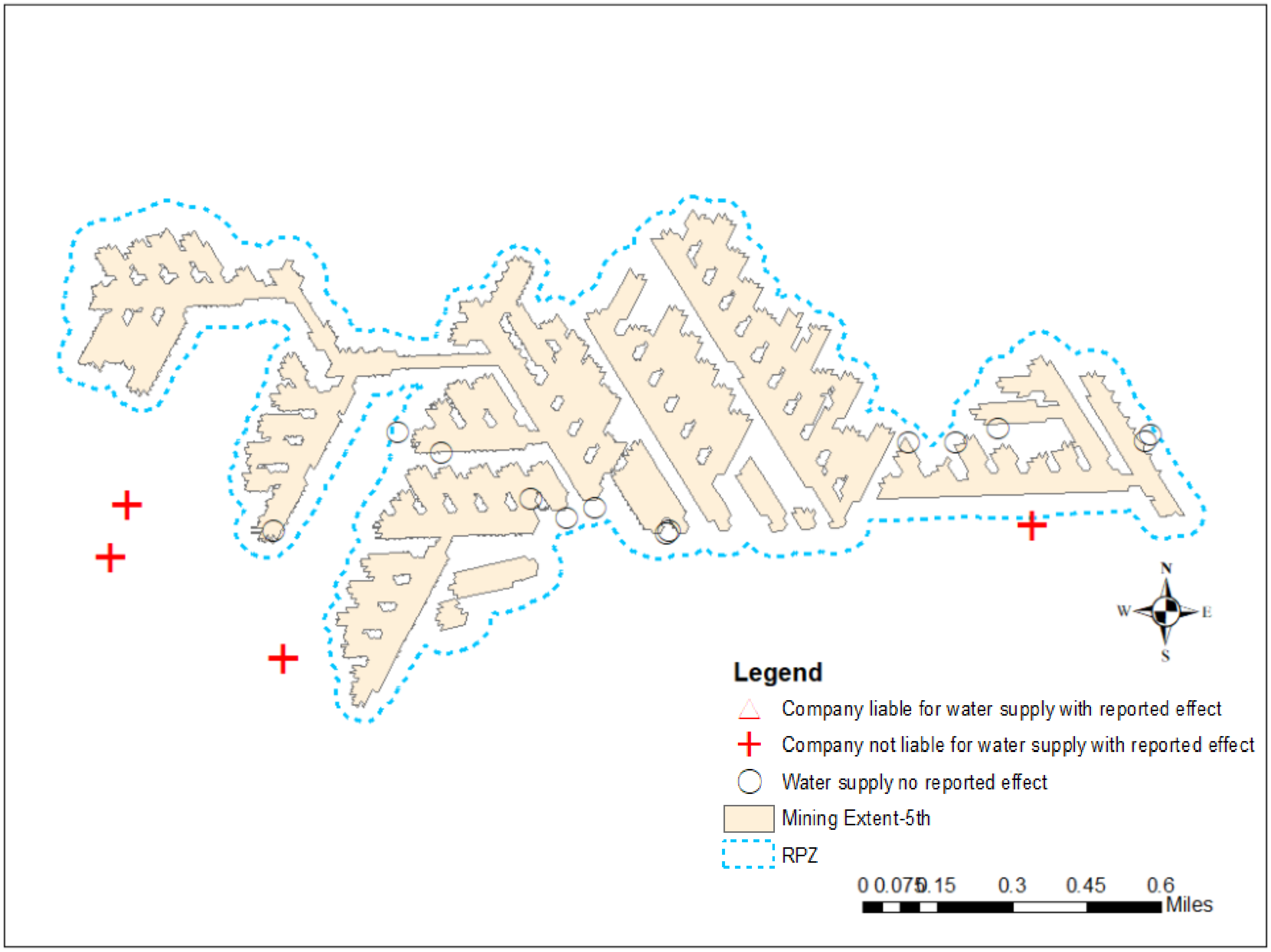

Figure 200. Figure B-Hy-5. Harmony 5th assessment water supplies and RPZ*

****There is one water supply with a reported effect that was determined to be company not liable that is now show on the map for display purposes.*

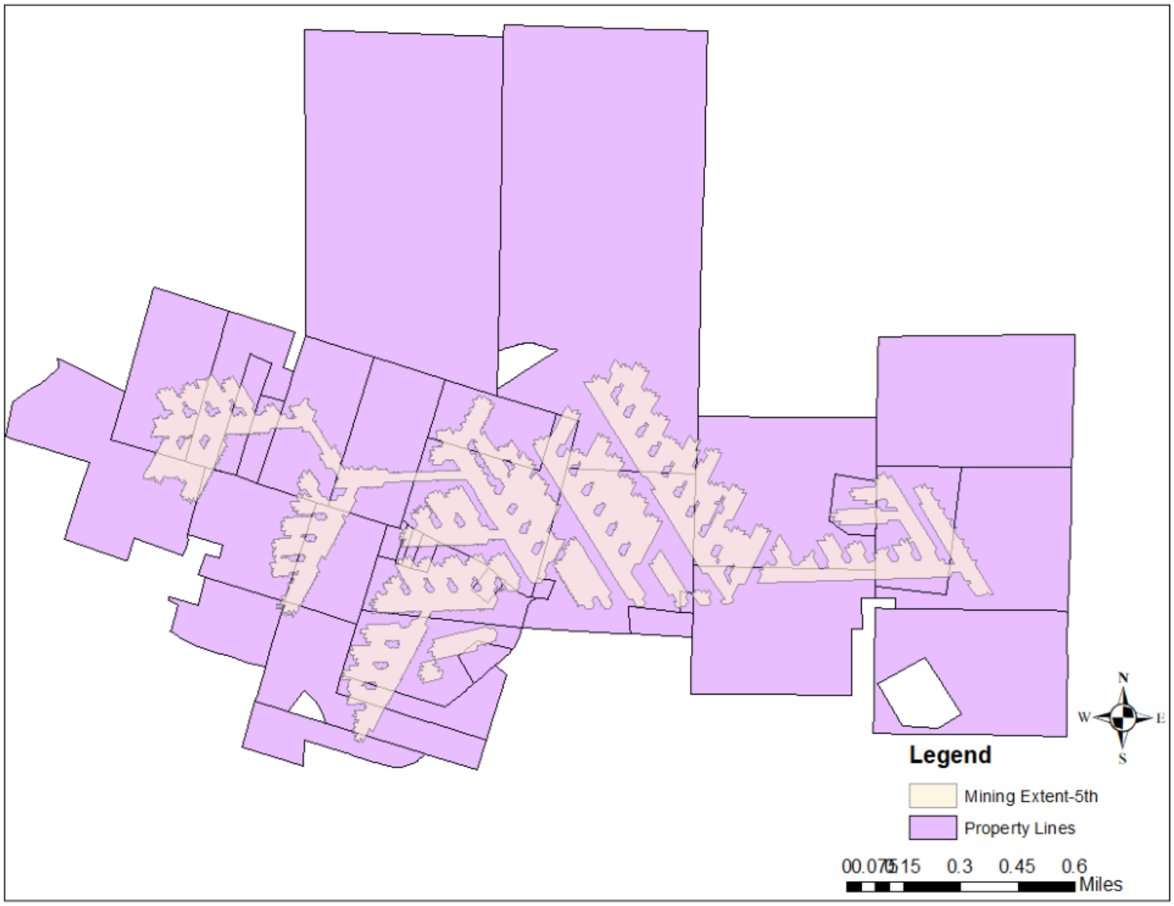

Figure 201. Properties associated with the 5th assessment period over the Harmony Mine

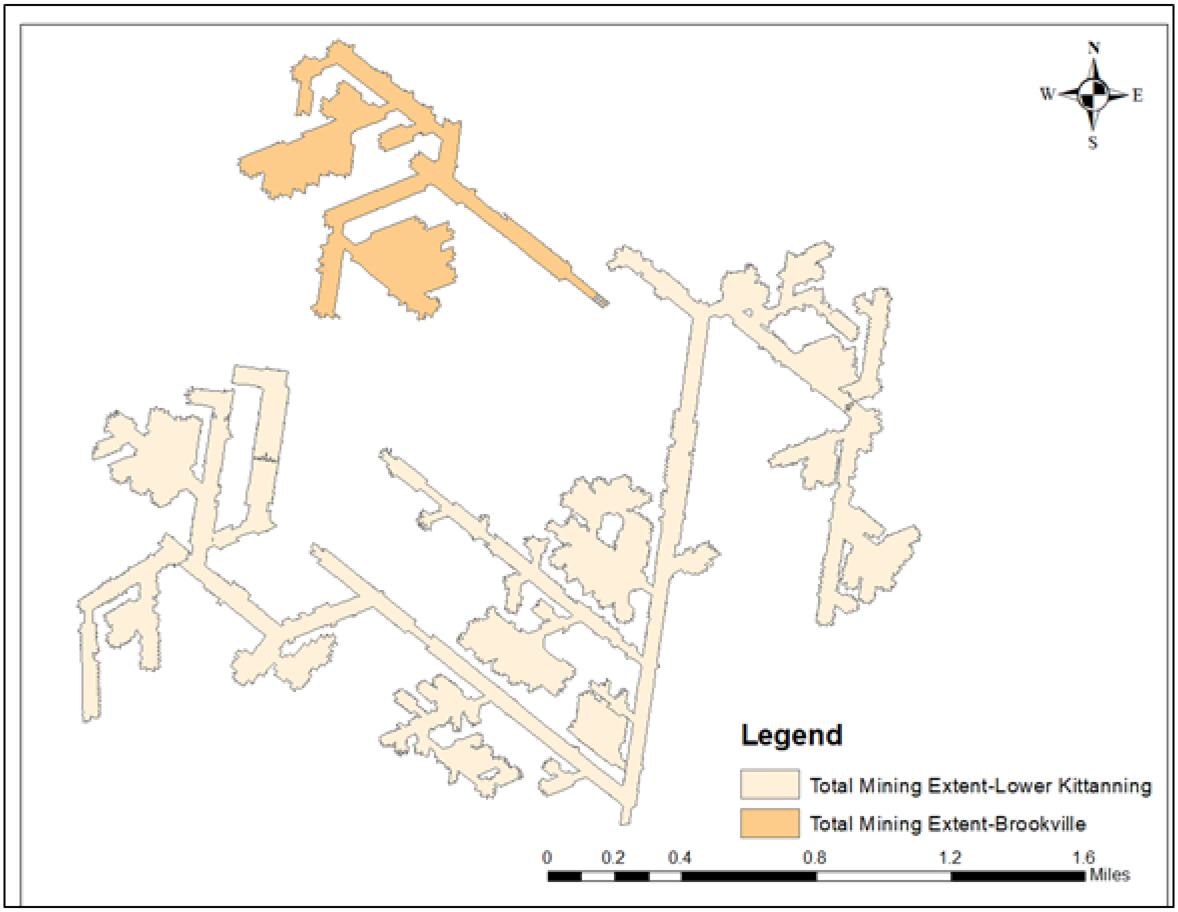

Figure 202. Heilwood total extent of mining

Figure 203. Heilwood mining extent for the 4th and 5th assessment periods

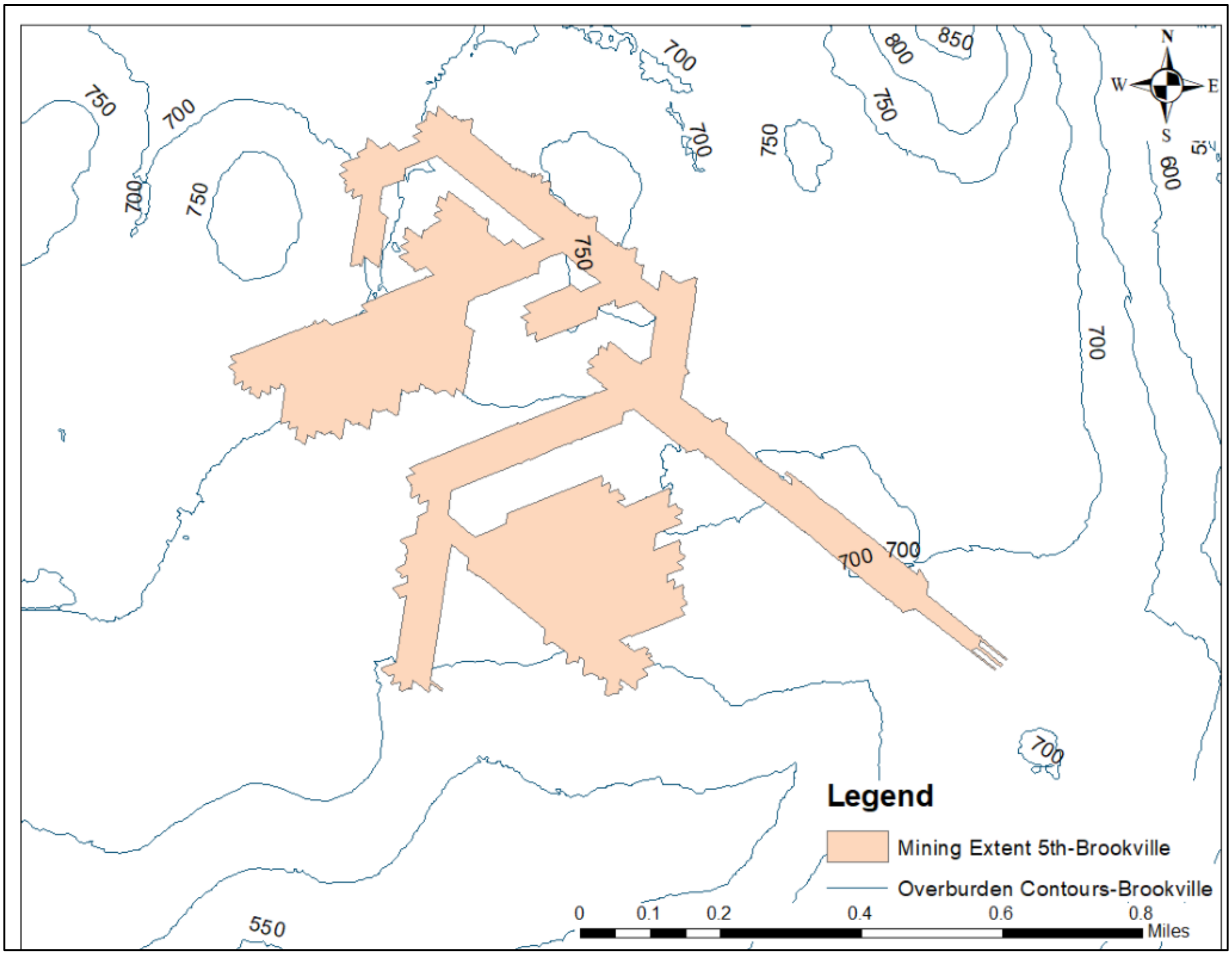

Figure 204. Fifty-foot overburden contour intervals for the Heilwood Mine Brookville Coal Seam

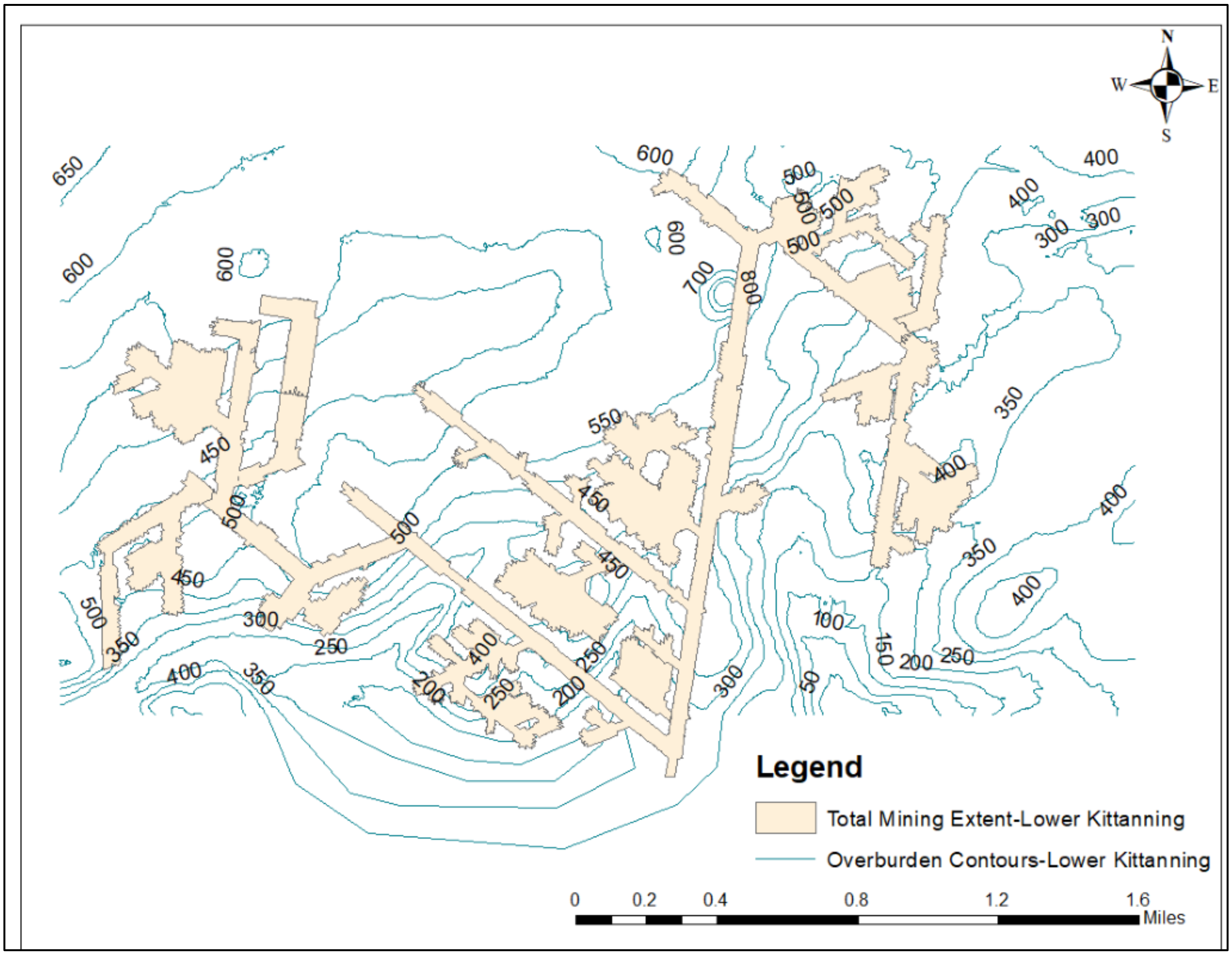

Figure 205. Fifty-foot overburden contour intervals for the Heilwood Mine Lower Kittanning Coal Seam

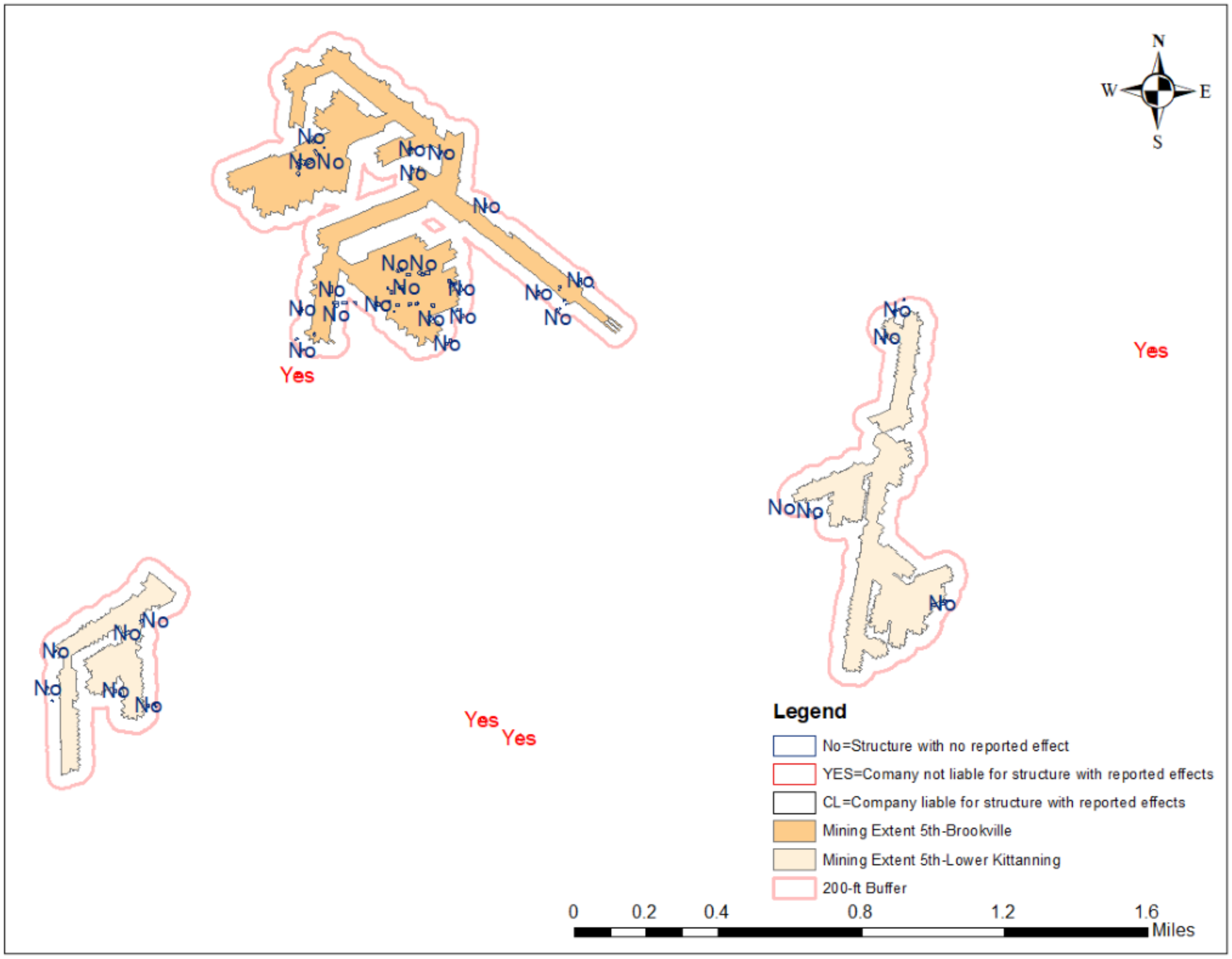

Figure 206. Heilwood 5th assessment 200-ft buffer and structures

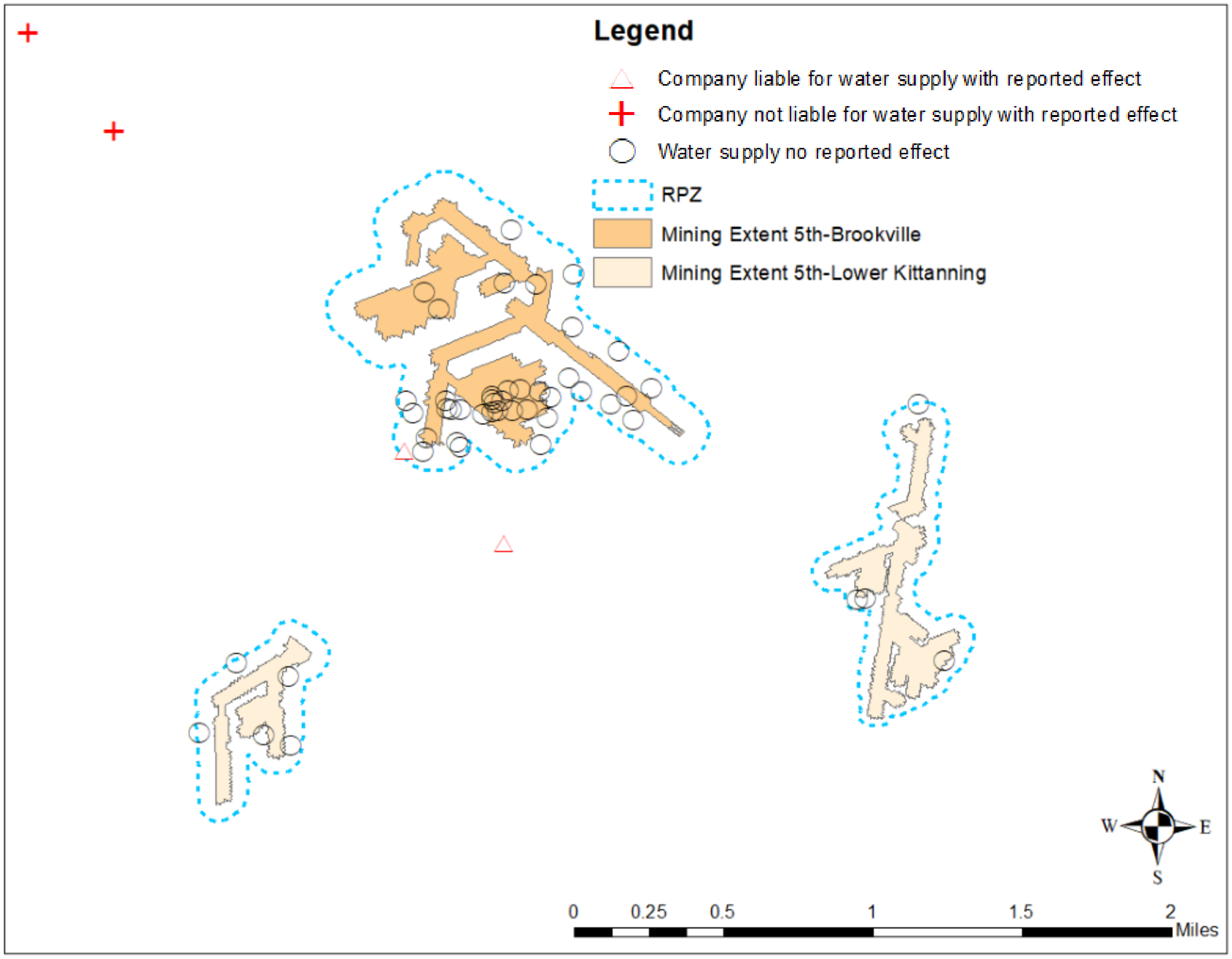

Figure 207. Heilwood 5th assessment water supplies and RPZ

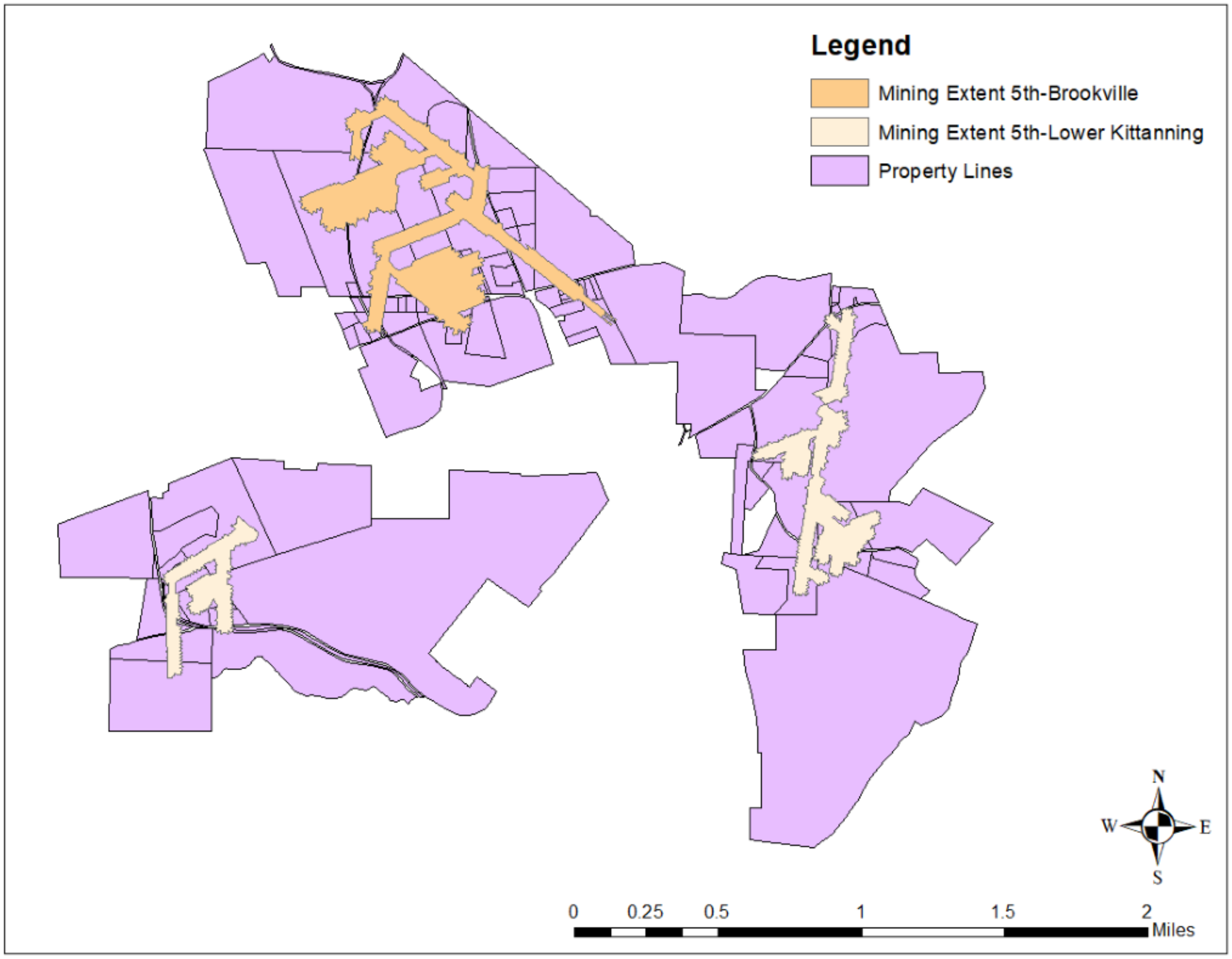

Figure 208. Properties associated with the 5th assessment period over the Heilwood Mine

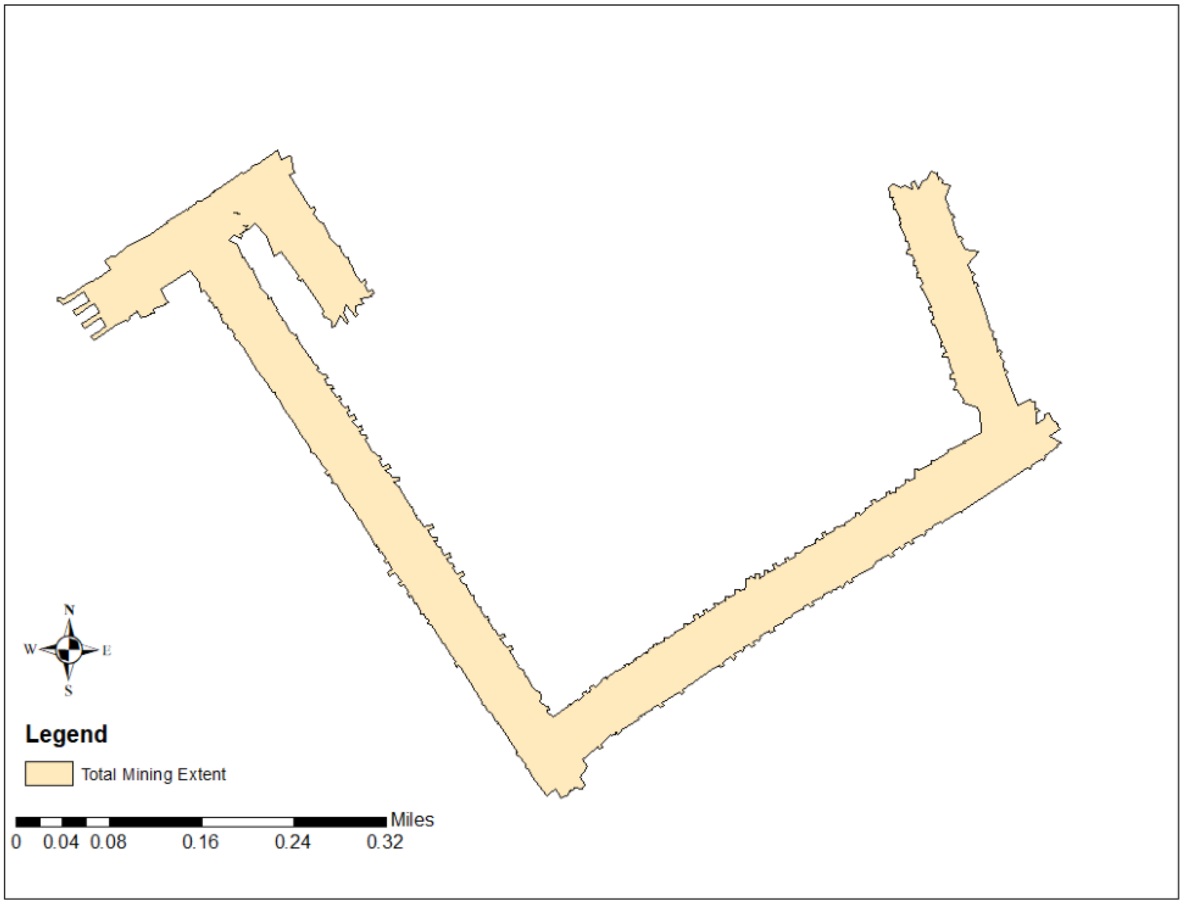

Figure 209. Horning Deep total extent of mining

Figure 210. Horning Deep mining extent for the 4th and 5th assessment periods

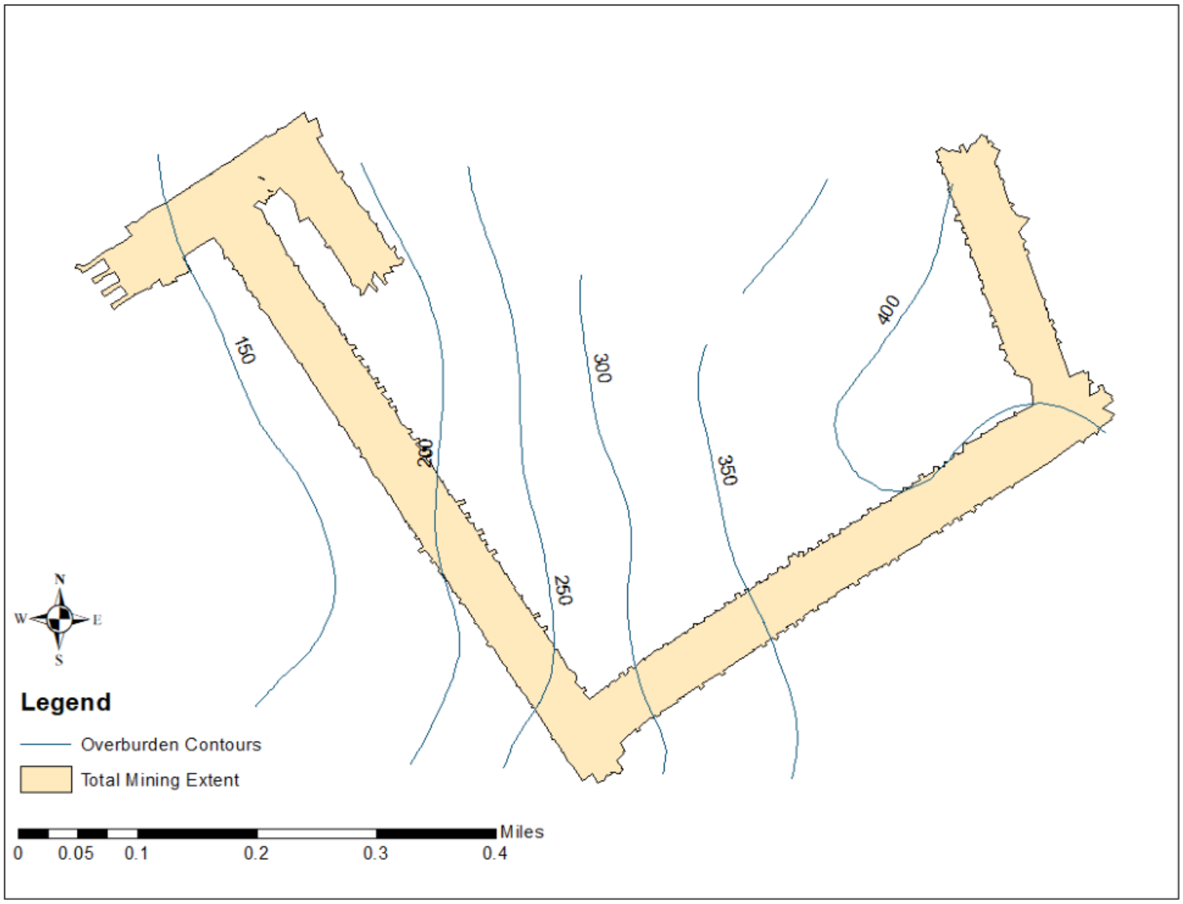

Figure 211. Fifty-foot overburden contour intervals for the Horning Deep Mine

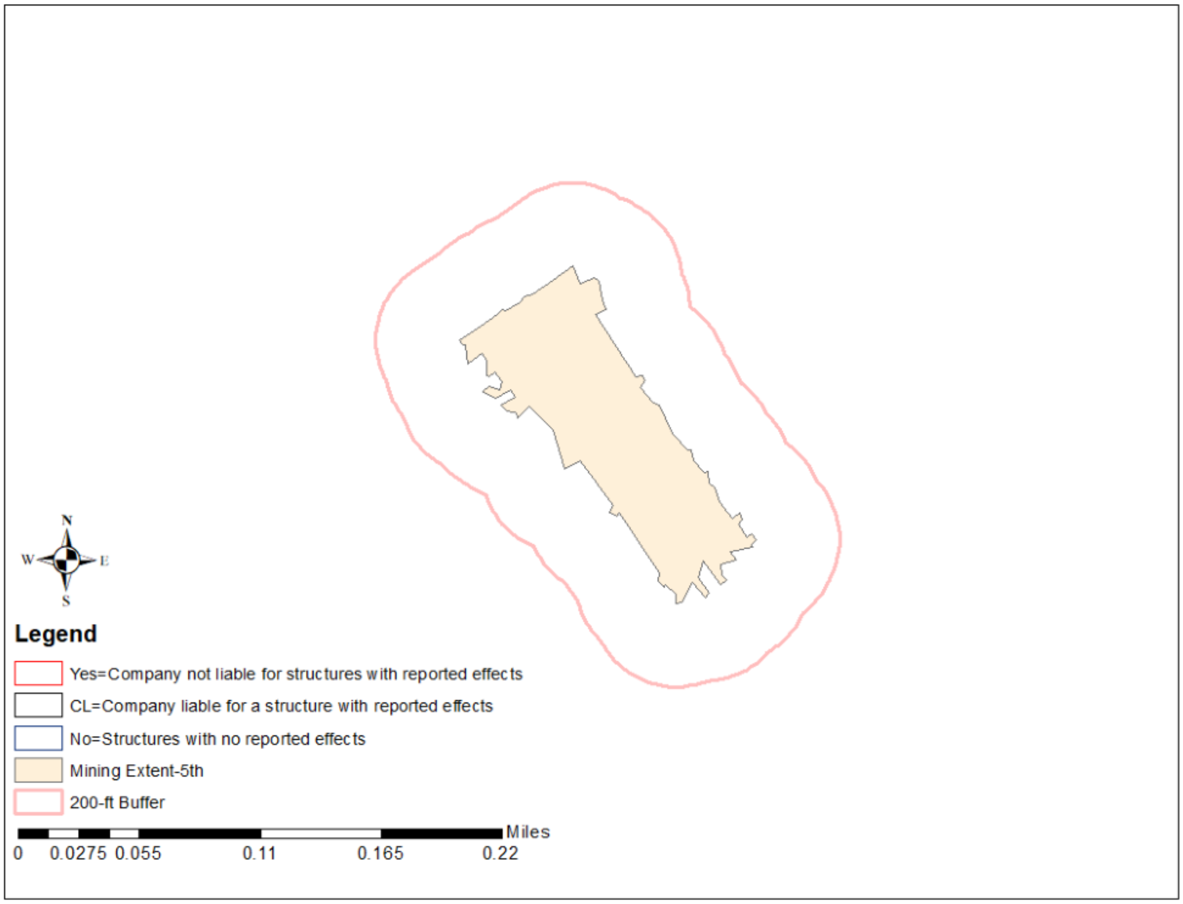

Figure 212. Horning Deep 5th assessment 200-ft buffer and structures

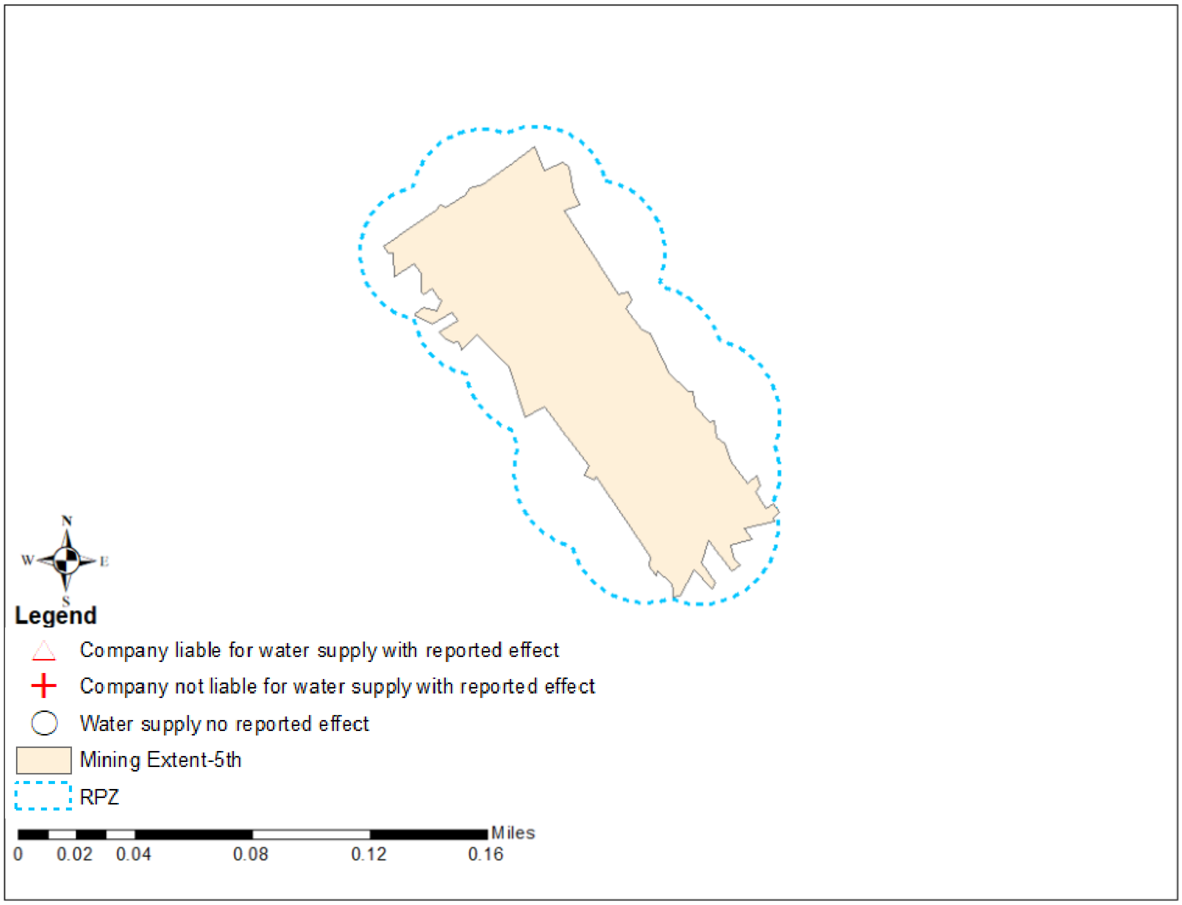

Figure 213. Horning Deep 5th assessment water supplies and RPZ

Figure 214. Properties associated with the 5th assessment period over the Horning Deep Mine

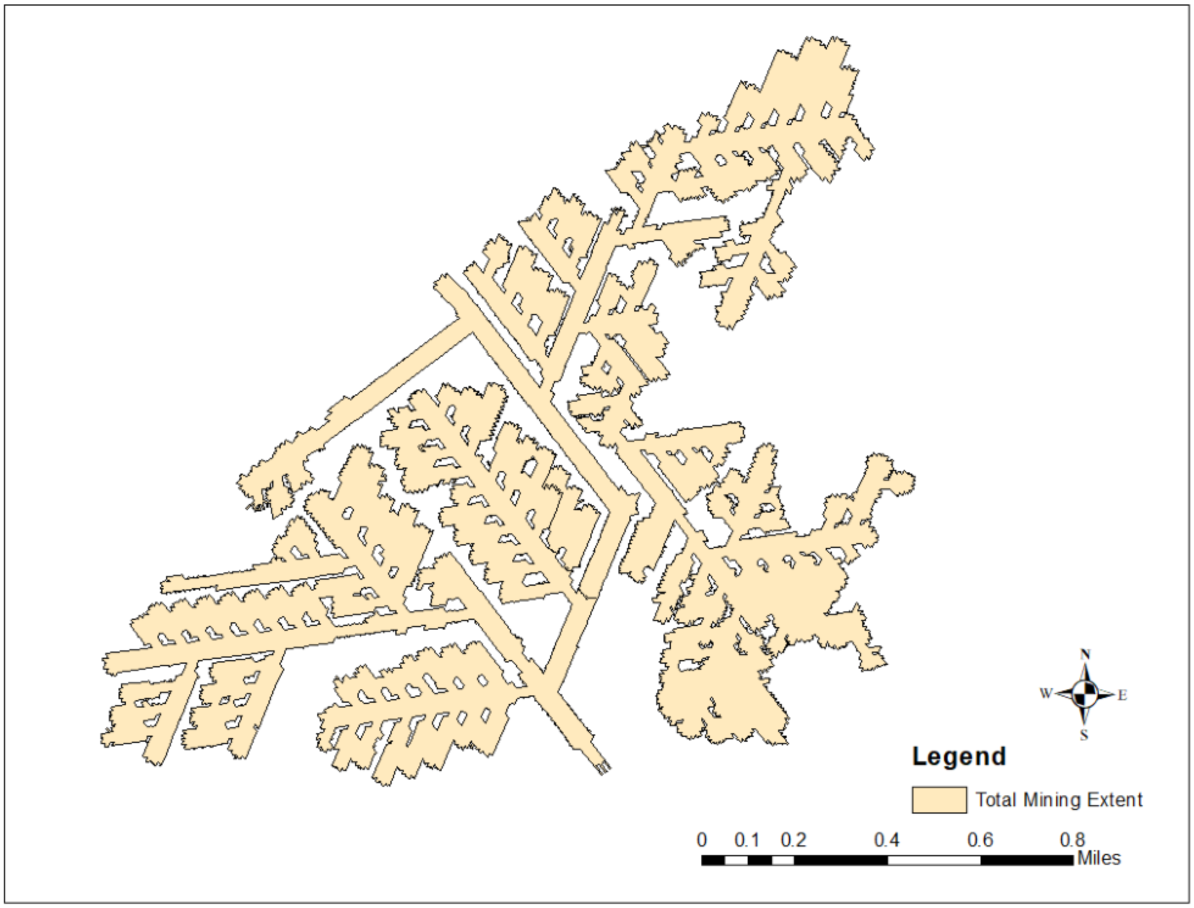

Figure 215. Knob Creek total extent of mining

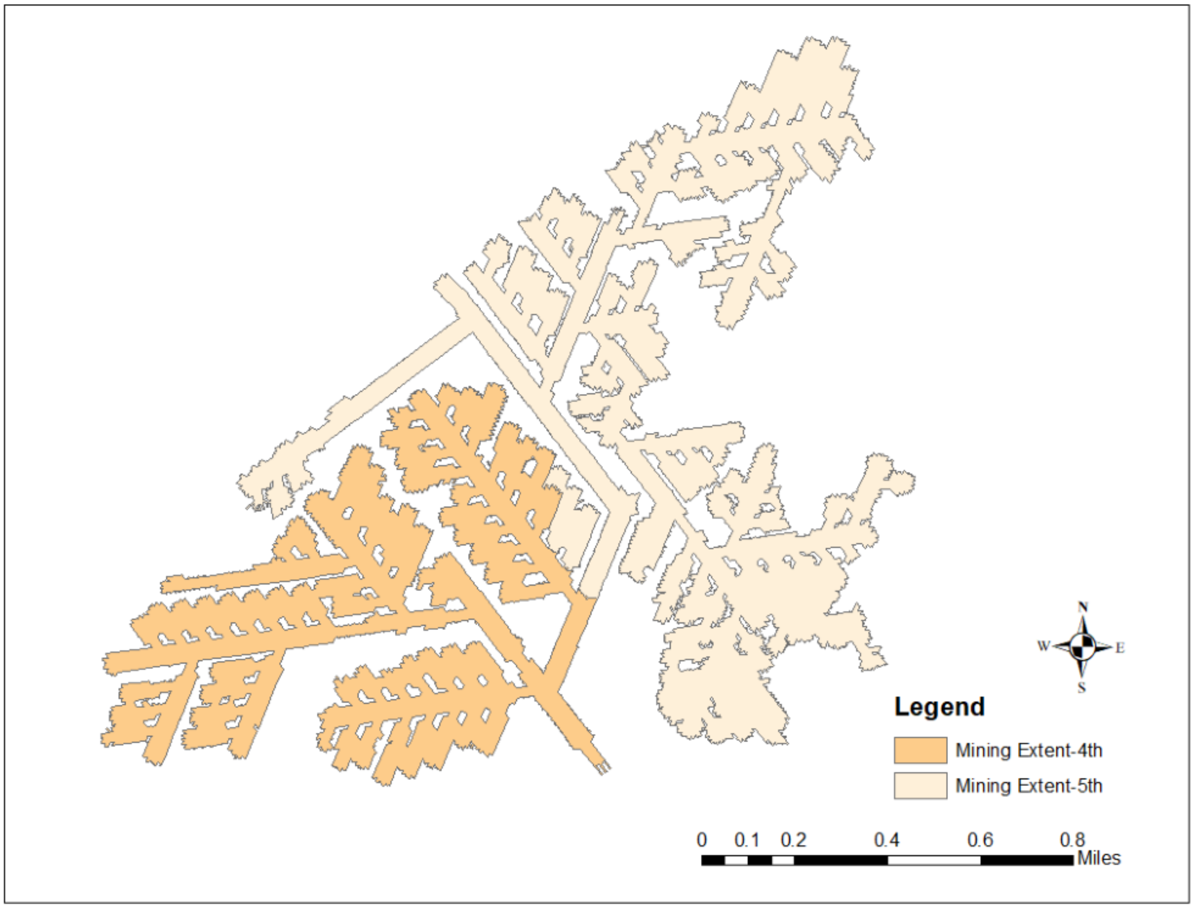

Figure 216. Knob Creek mining extent for the 4th and 5th assessment periods

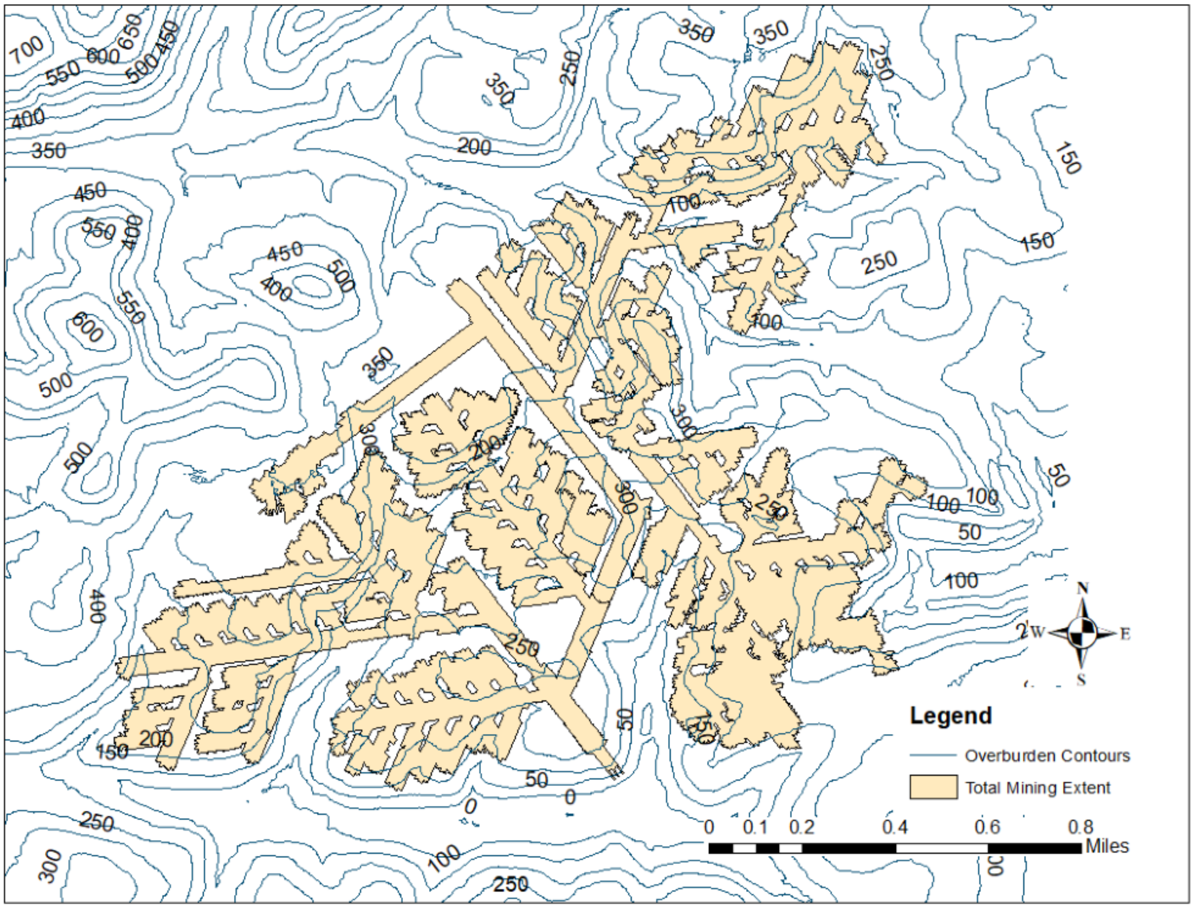

Figure 217. Fifty-foot overburden contour intervals for the Knob Creek Mine

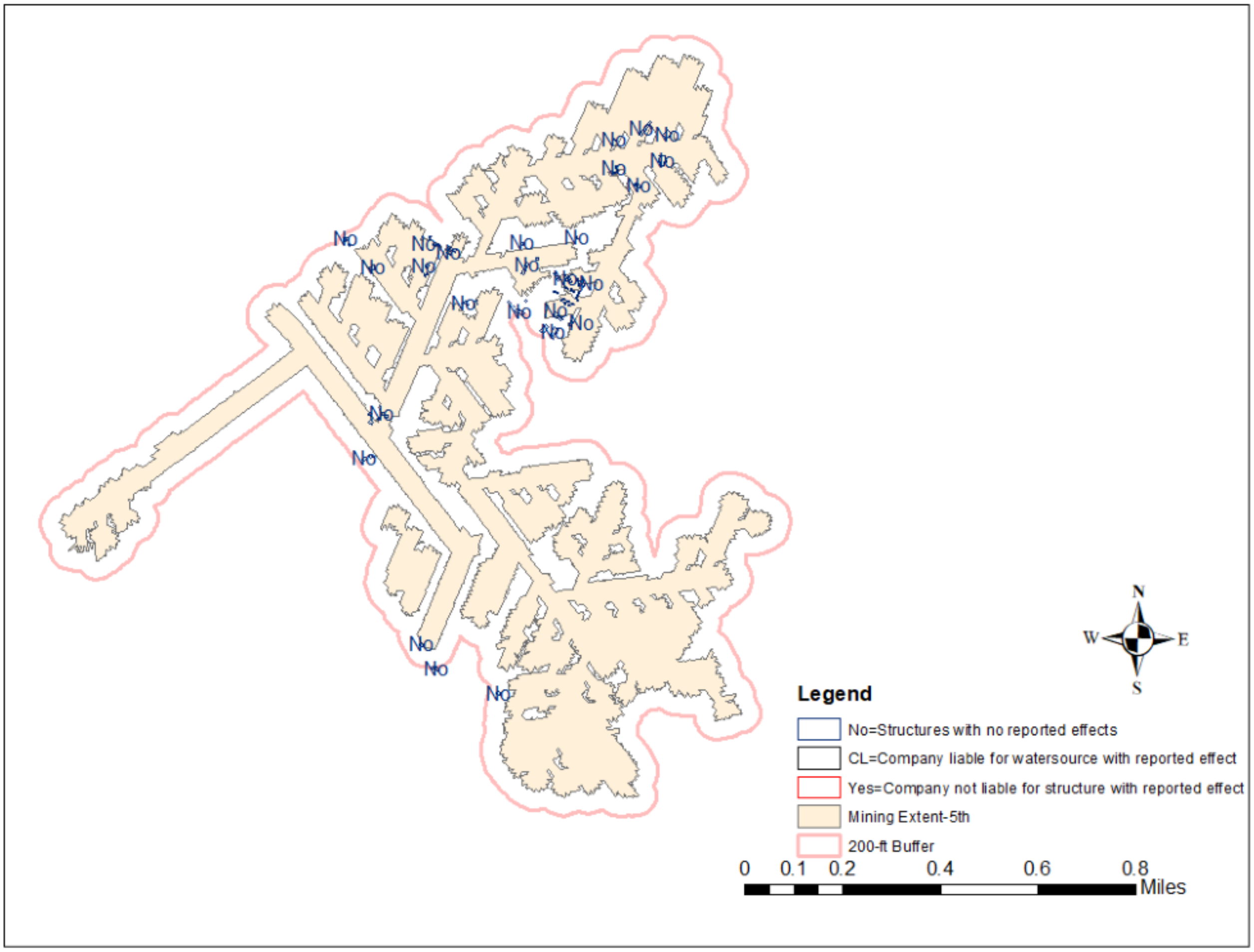

Figure 218. Knob Creek 5th assessment 200-ft buffer and structures

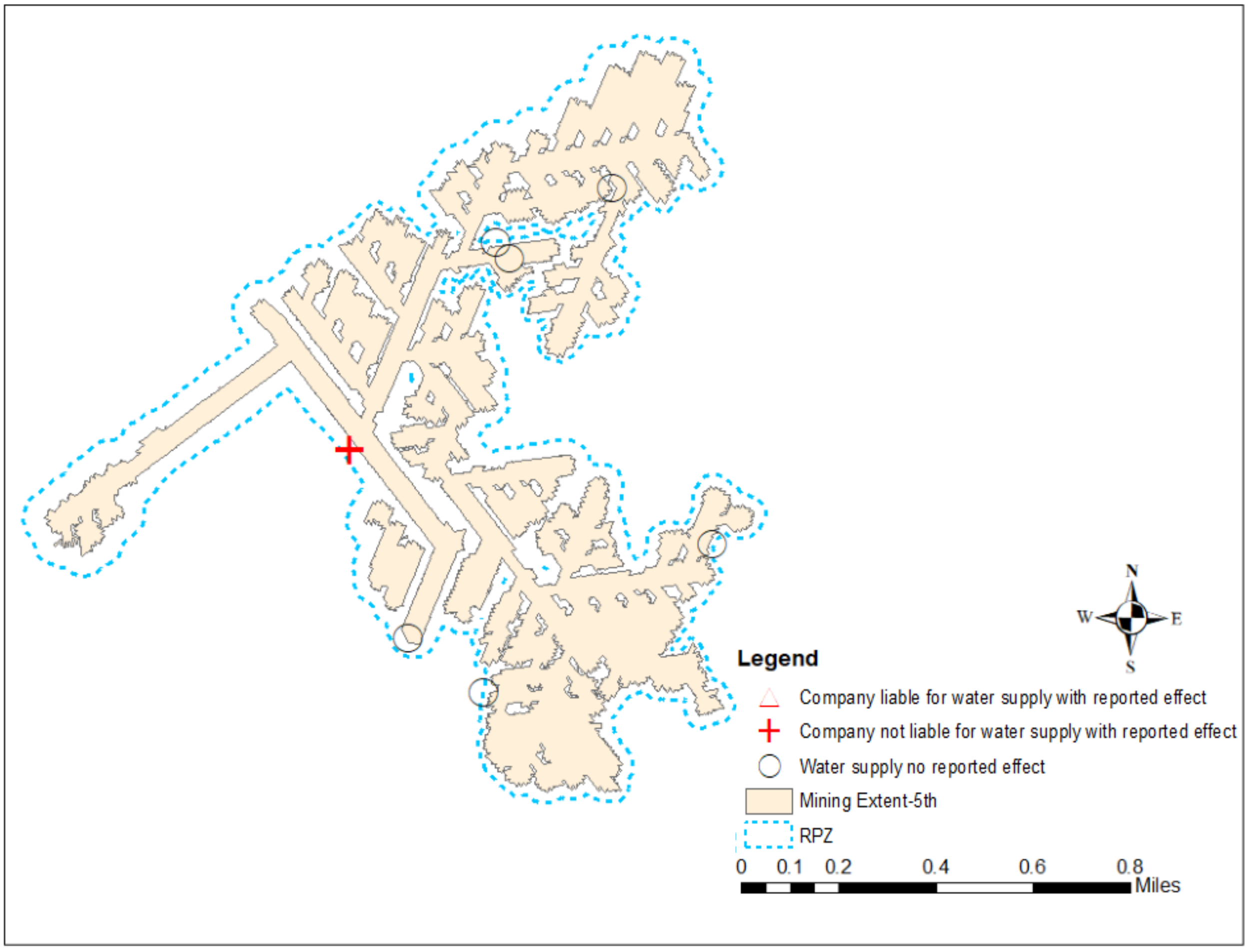

Figure 219. Knob Creek 5th assessment water supplies and RPZ*

Note there are two water supplies with reported effects that are far from mining and are not included here for display purposes.

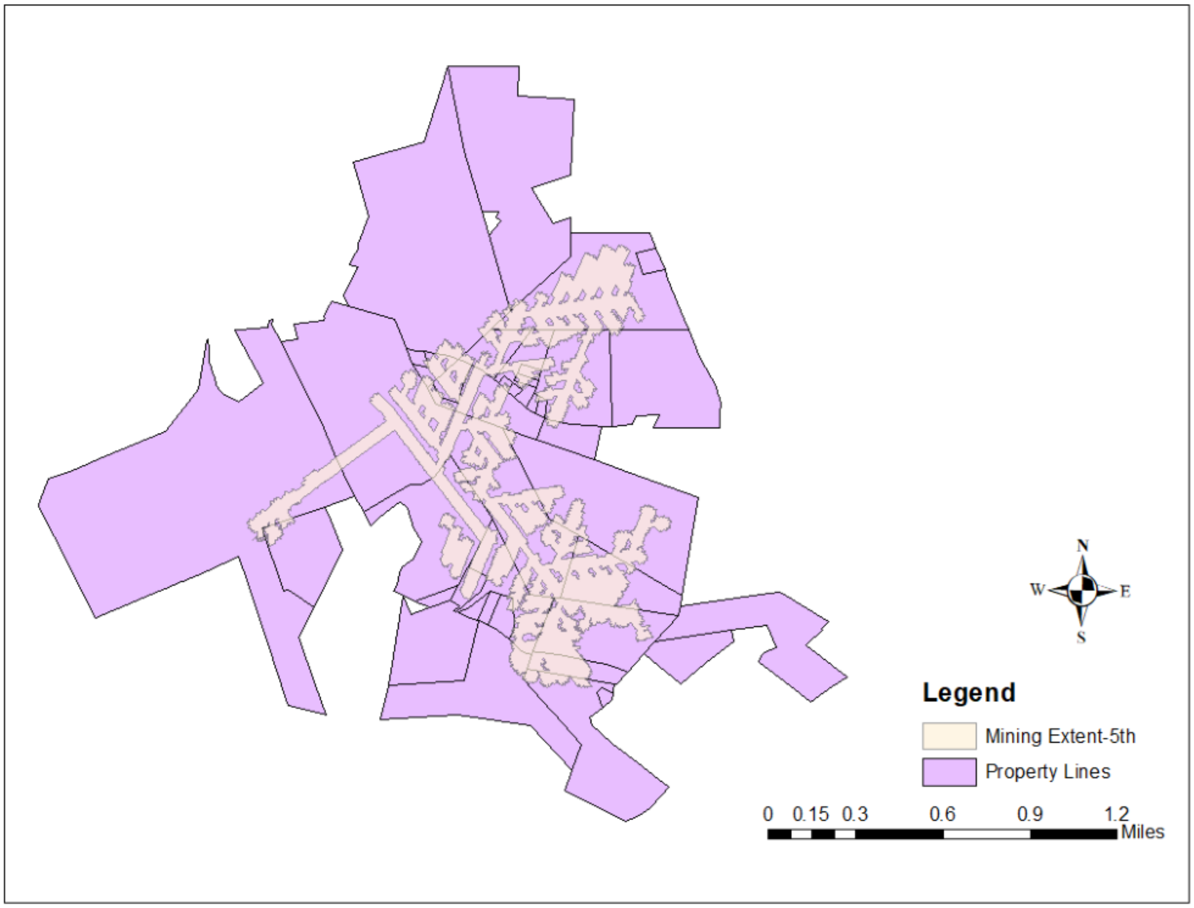

Figure 220. Properties associated with the 5th assessment period over the Knob Creek Mine

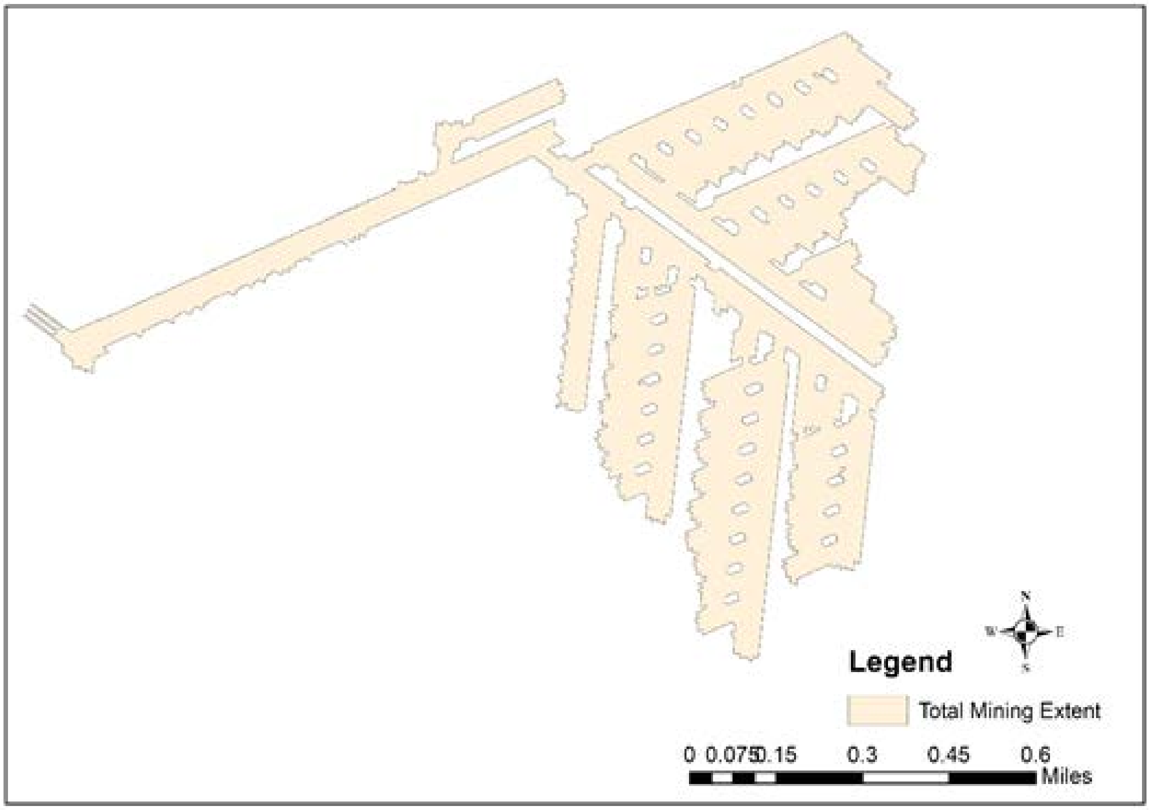

Figure 221. Kojancic total extent of mining

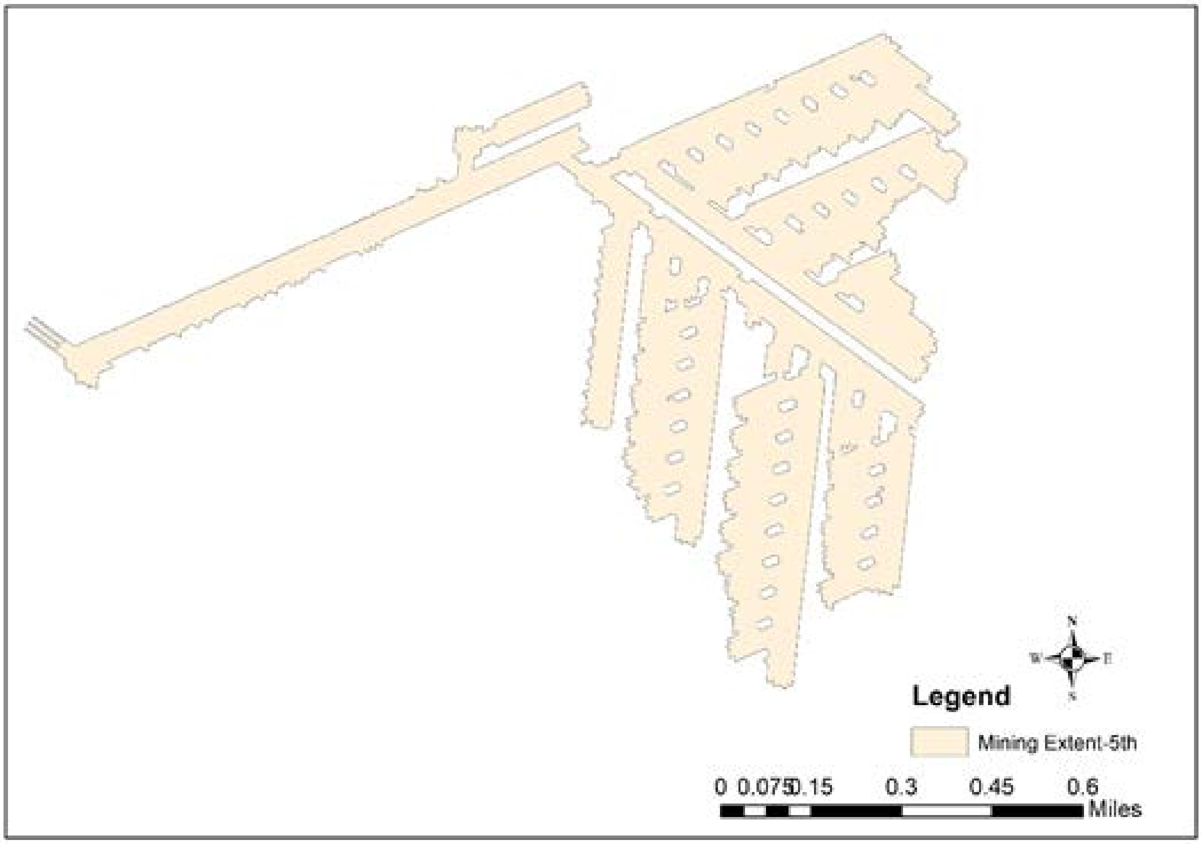

Figure 222. Kojancic mining extent for the 5th assessment period

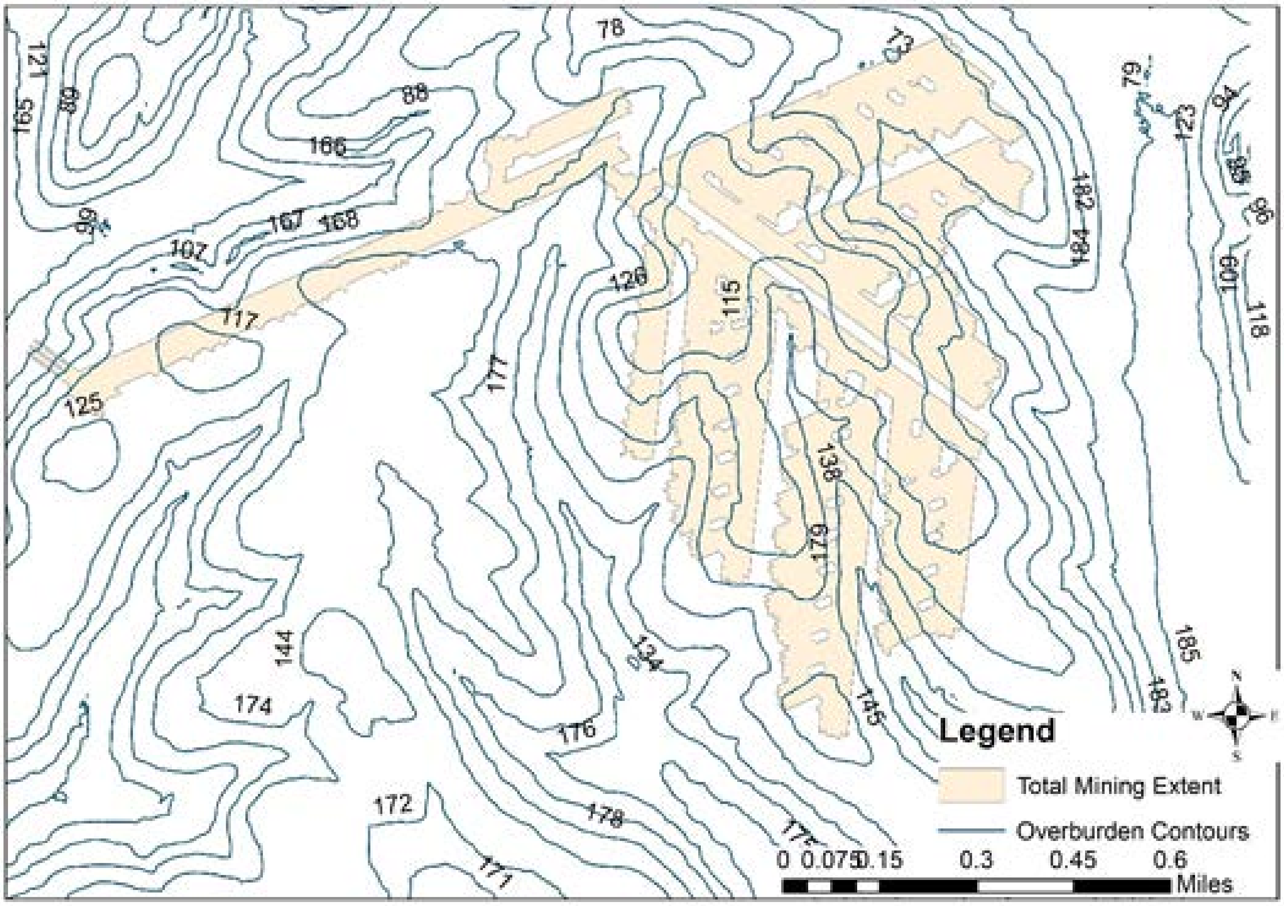

Figure 223. Fifty-foot overburden contour intervals for the Kojancic Mine

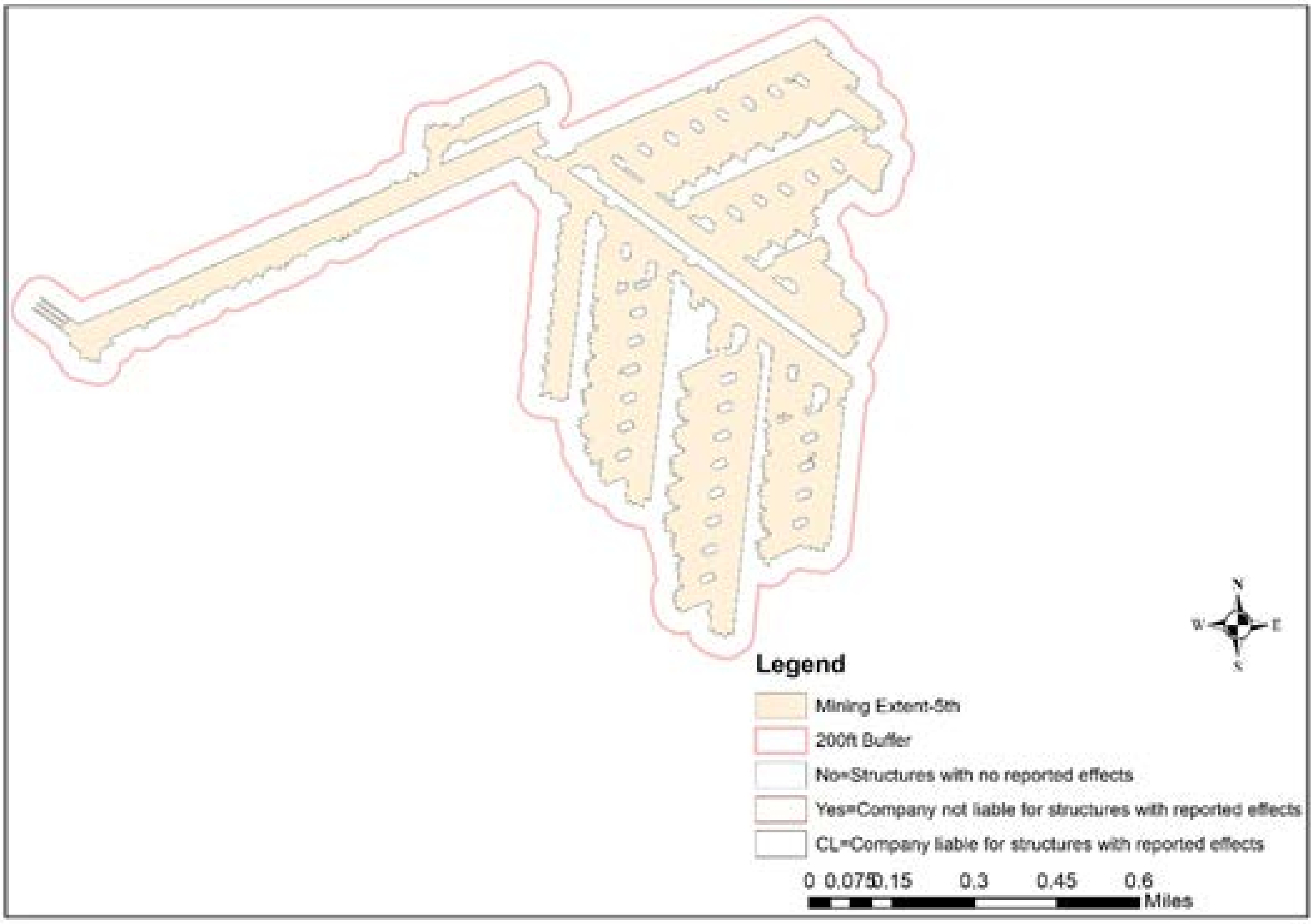

Figure 224. Kojancic 5th assessment 200-ft buffer and structures

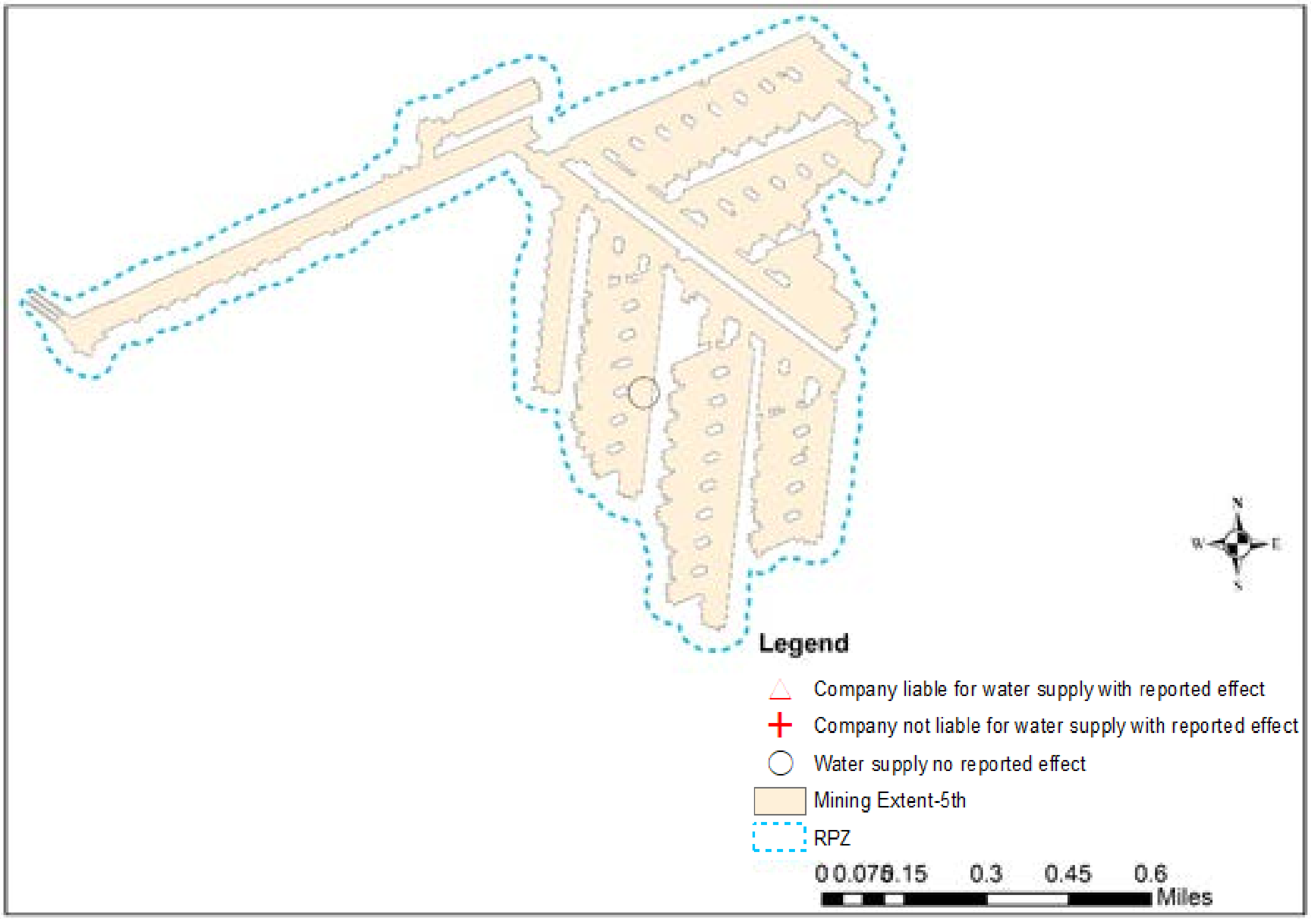

Figure 225. Kojancic 5th assessment water supplies and RPZ*

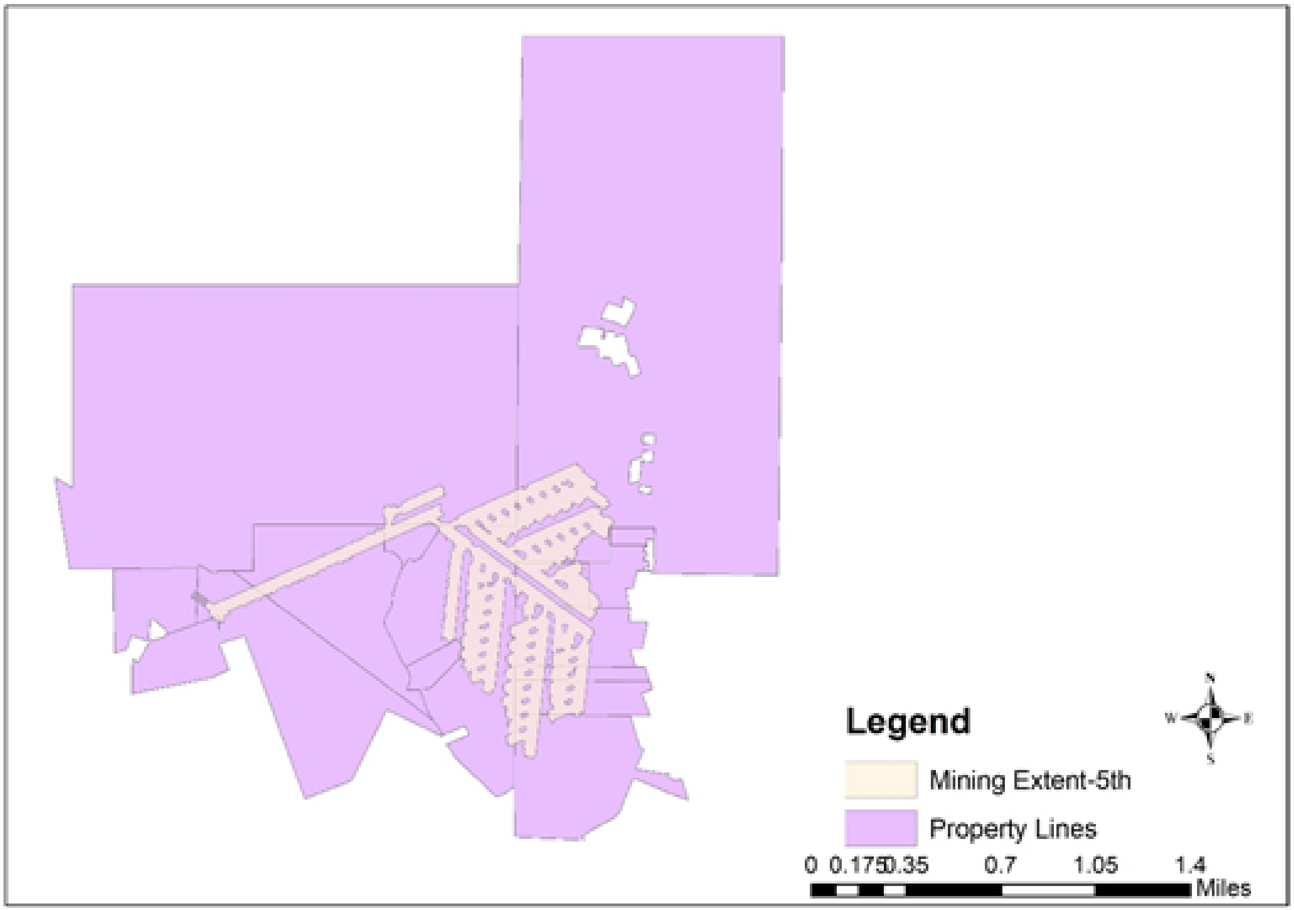

Figure 226. Properties associated with the 5th assessment period over the Kojancic Mine

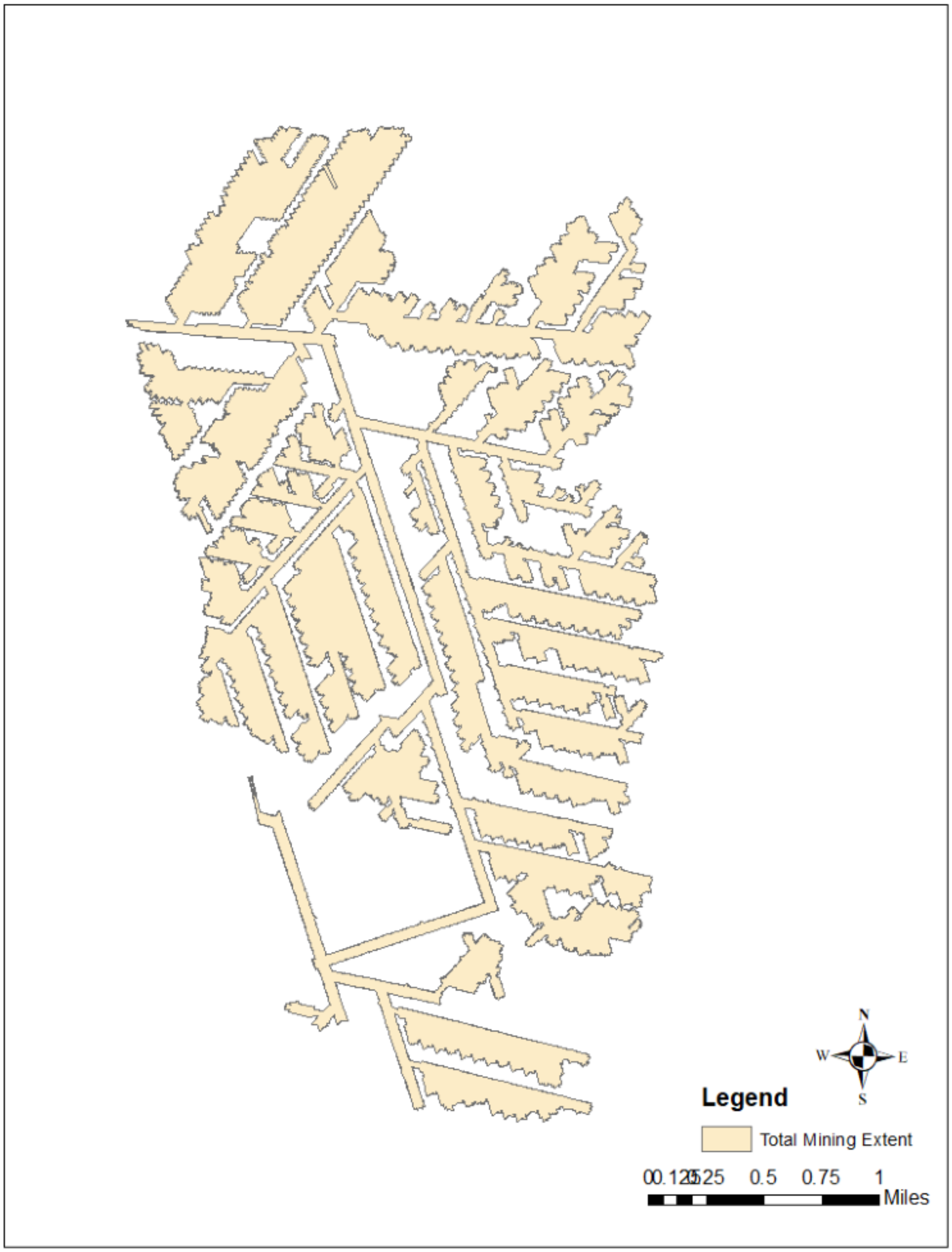

Figure 227. Logansport total extent of mining

Figure 228. Logansport mining extent for the 3rd, 4th, and 5th assessment periods

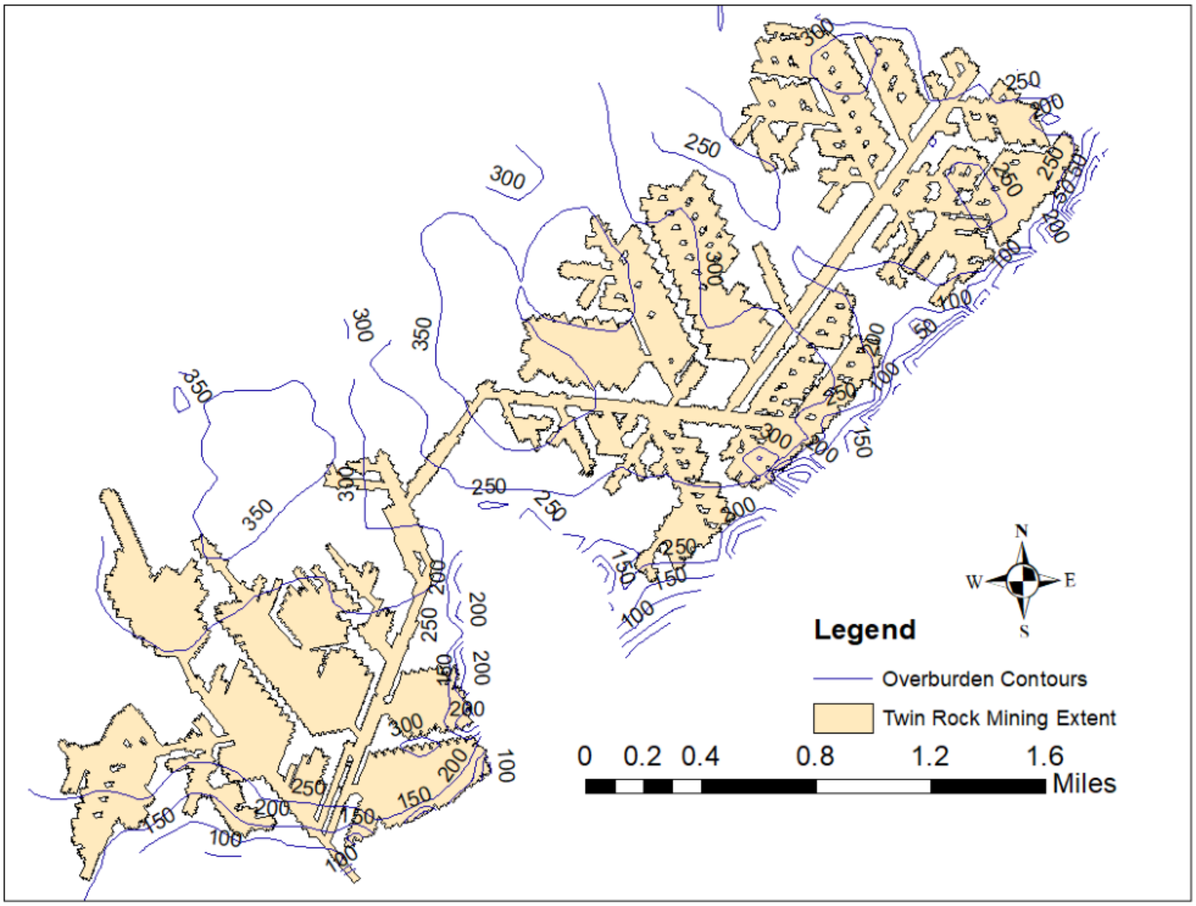

Figure 229. Fifty-foot overburden contour intervals for the Logansport Mine

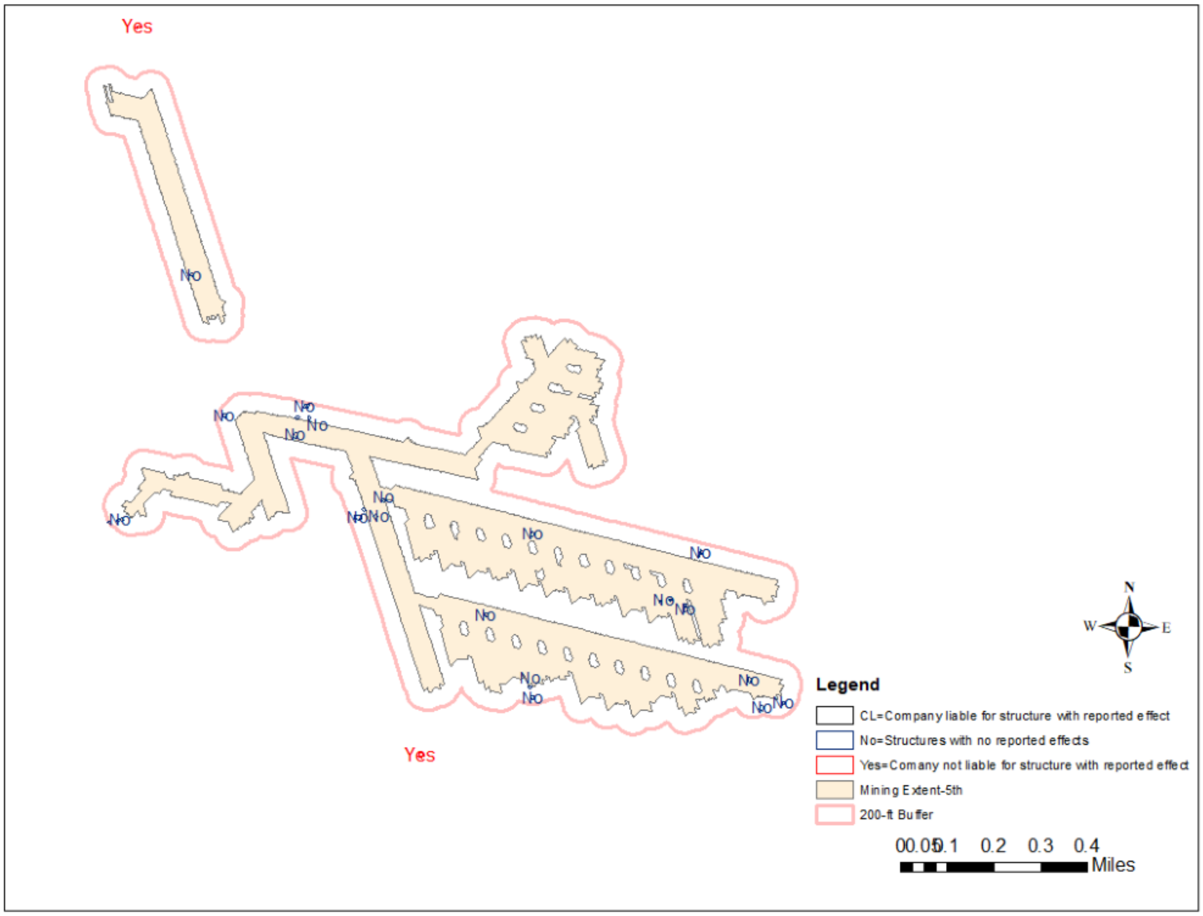

Figure 230. Logansport 5th assessment 200-ft buffer and structures*

Note there are two structures with reported effects that are far from mining and are not included here for display purposes.

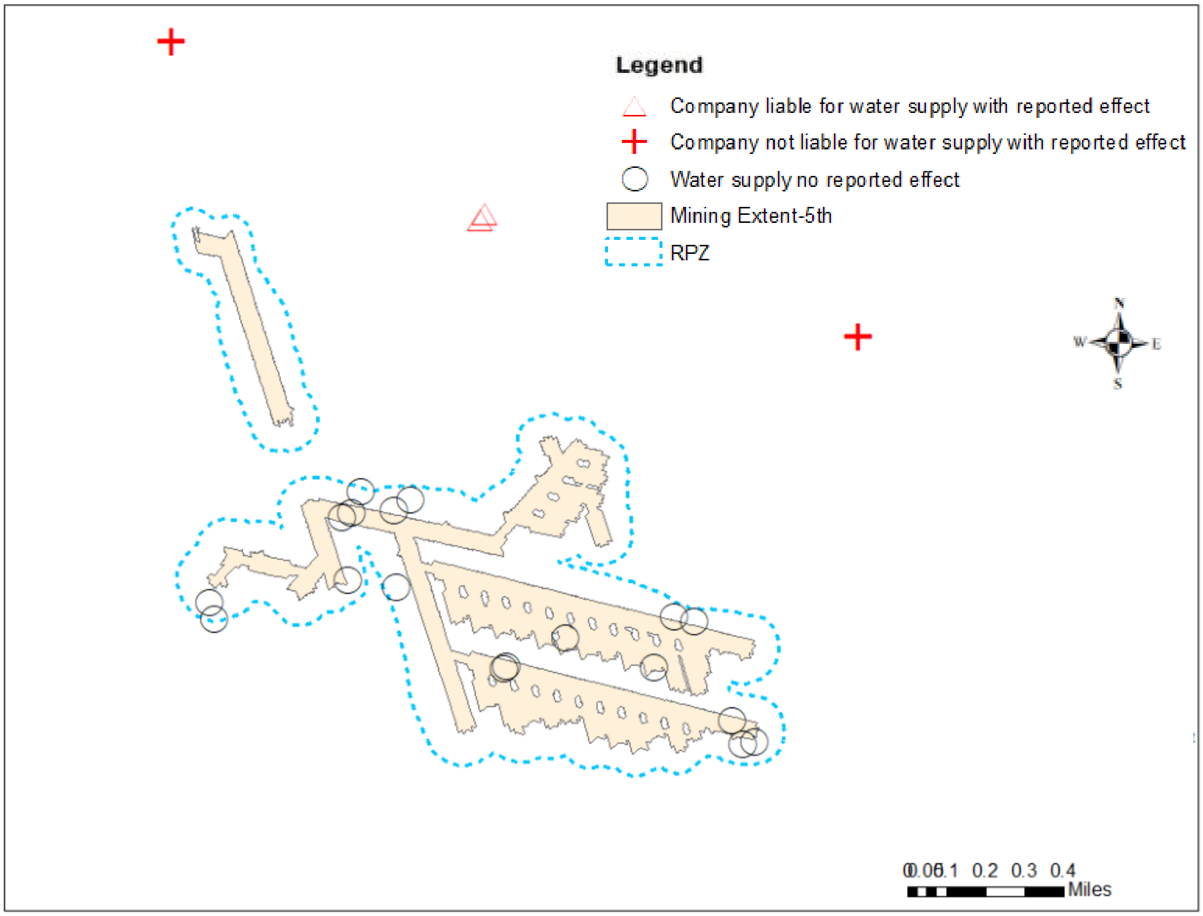

Figure 231. Logansport 5th assessment water supplies and RPZ

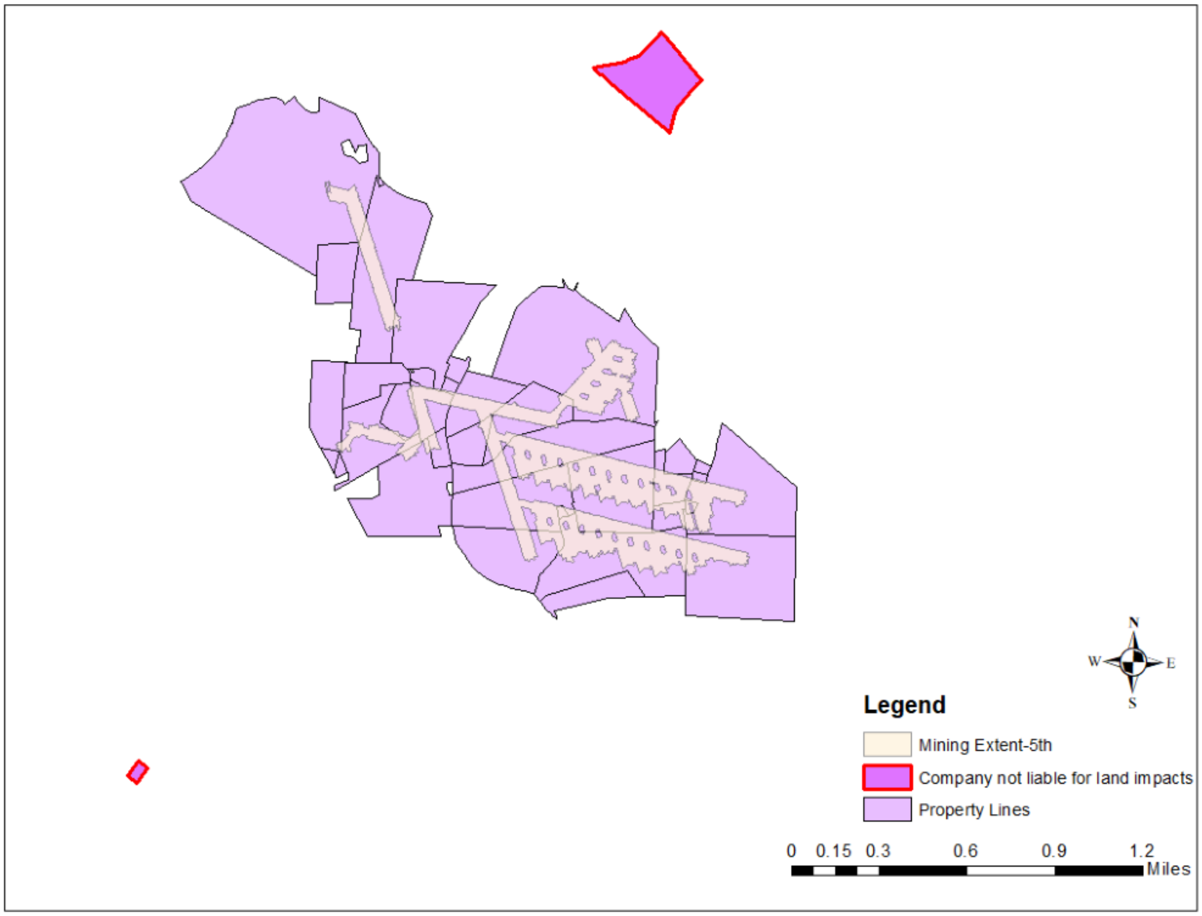

Figure 232. Properties associated with the 5th assessment period over the Logansport Mine

Figure 233. Lowry total extent of mining

Figure 234. Lowry mining extent for the 4th and 5th assessment periods

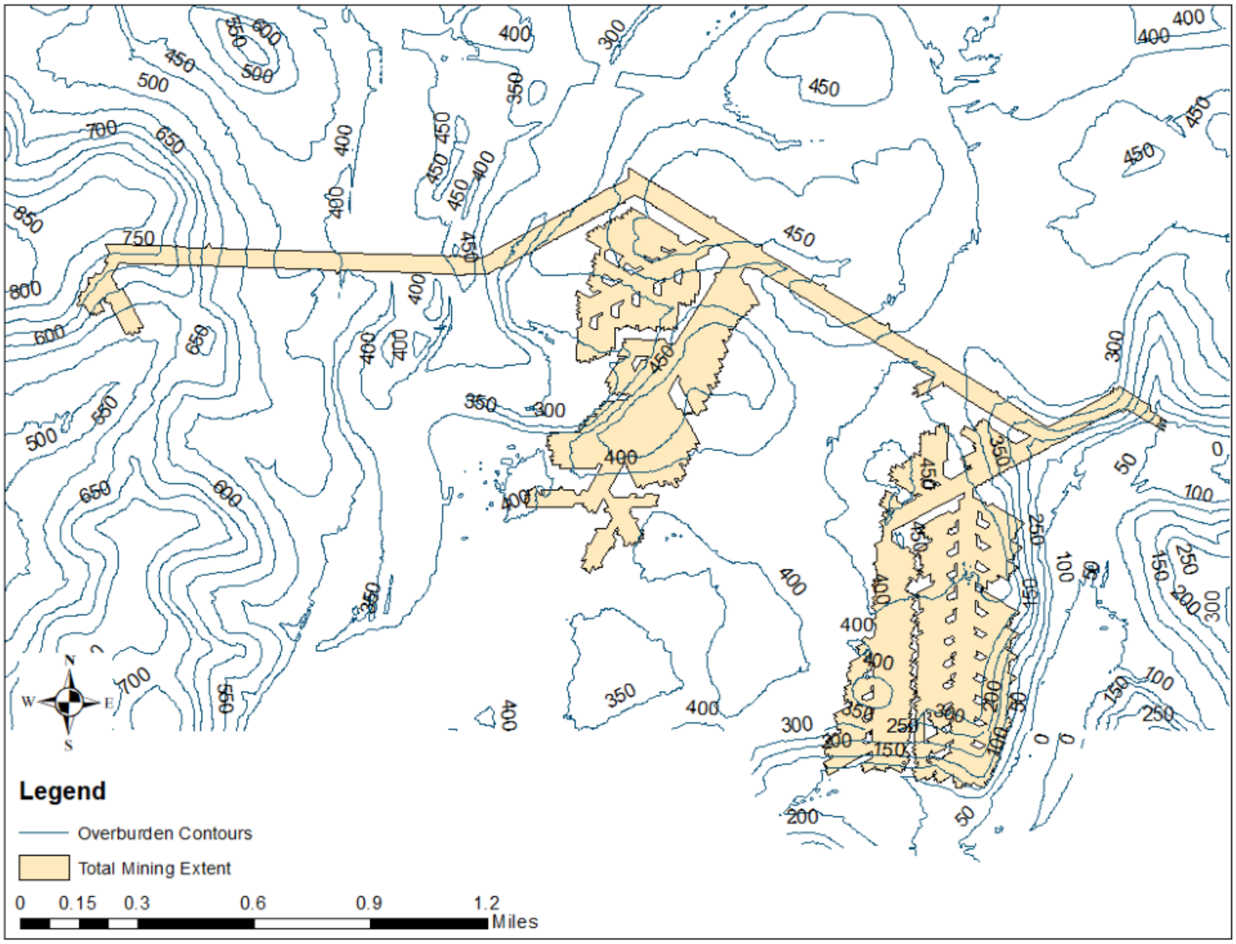

Figure 235. Fifty-foot overburden contour intervals for the Lowry Mine

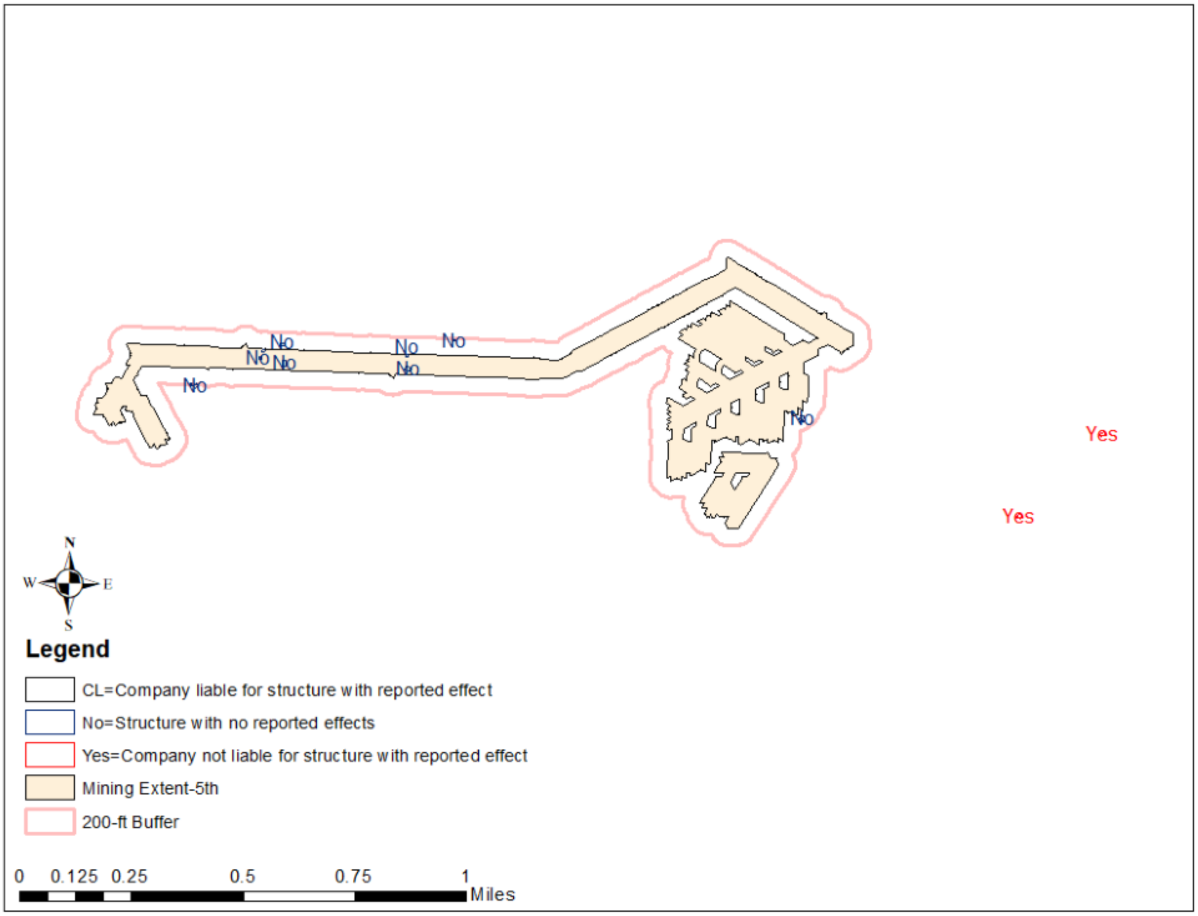

Figure 236. Lowry 5th assessment 200-ft buffer and structures*

**Note there is one structure with reported effect that is not company liable that is far from mining and not included here for display purposes.*

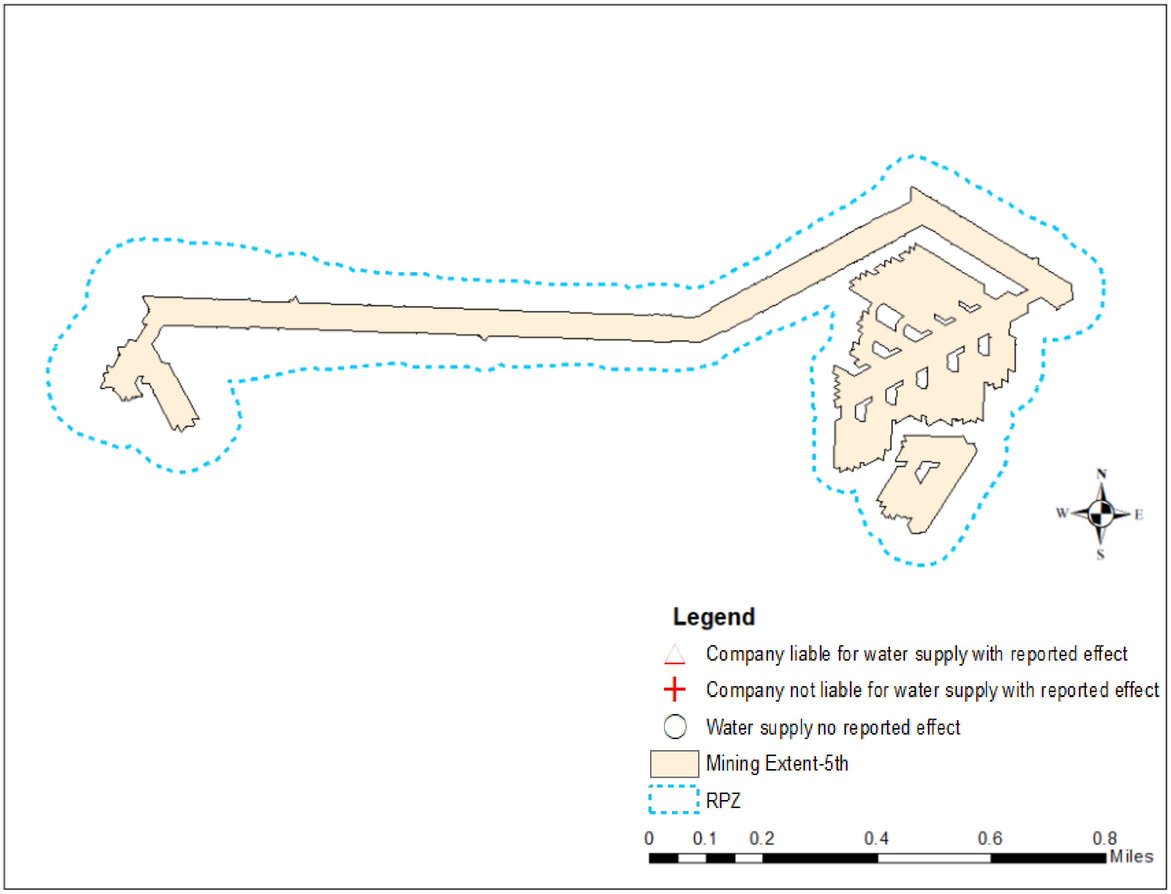

Figure 237. Lowry 5th assessment water supplies and RPZ

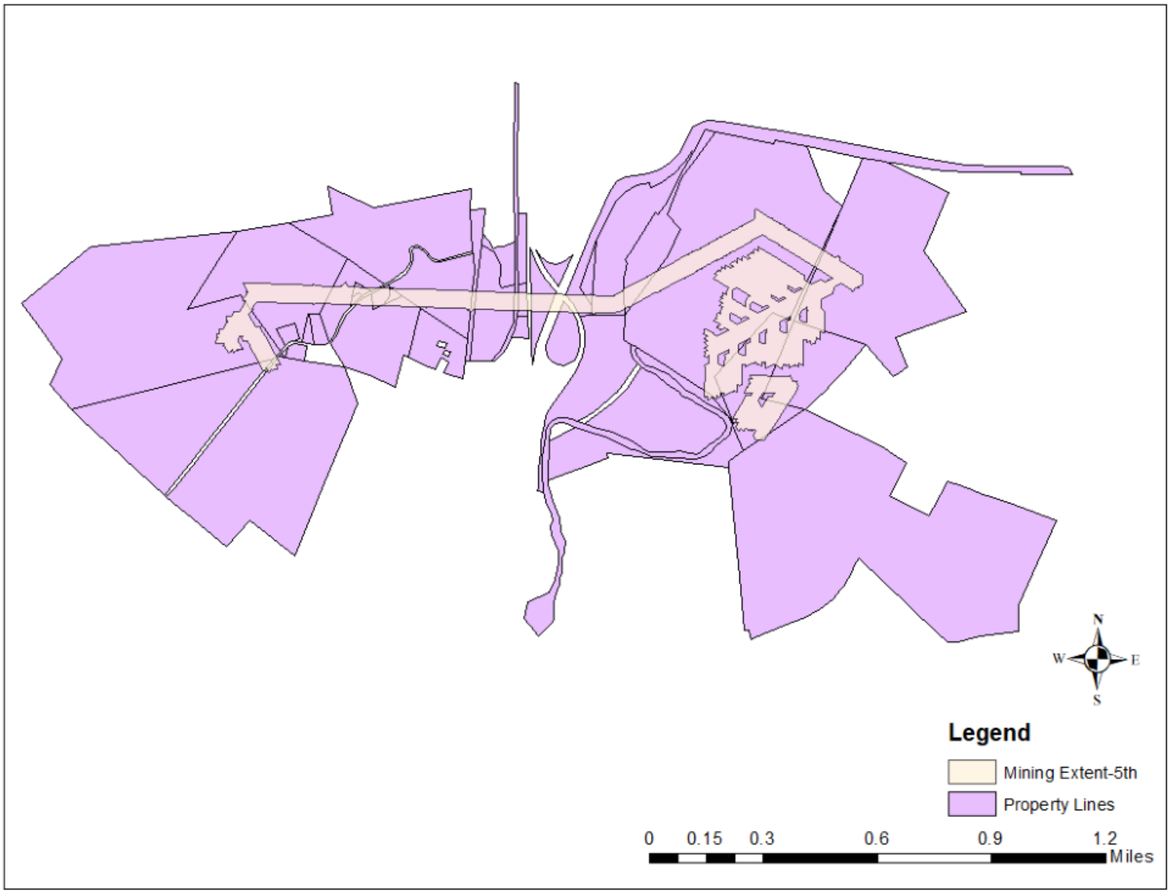

Figure 238. Properties associated with the 5th assessment period over the Lowry Mine

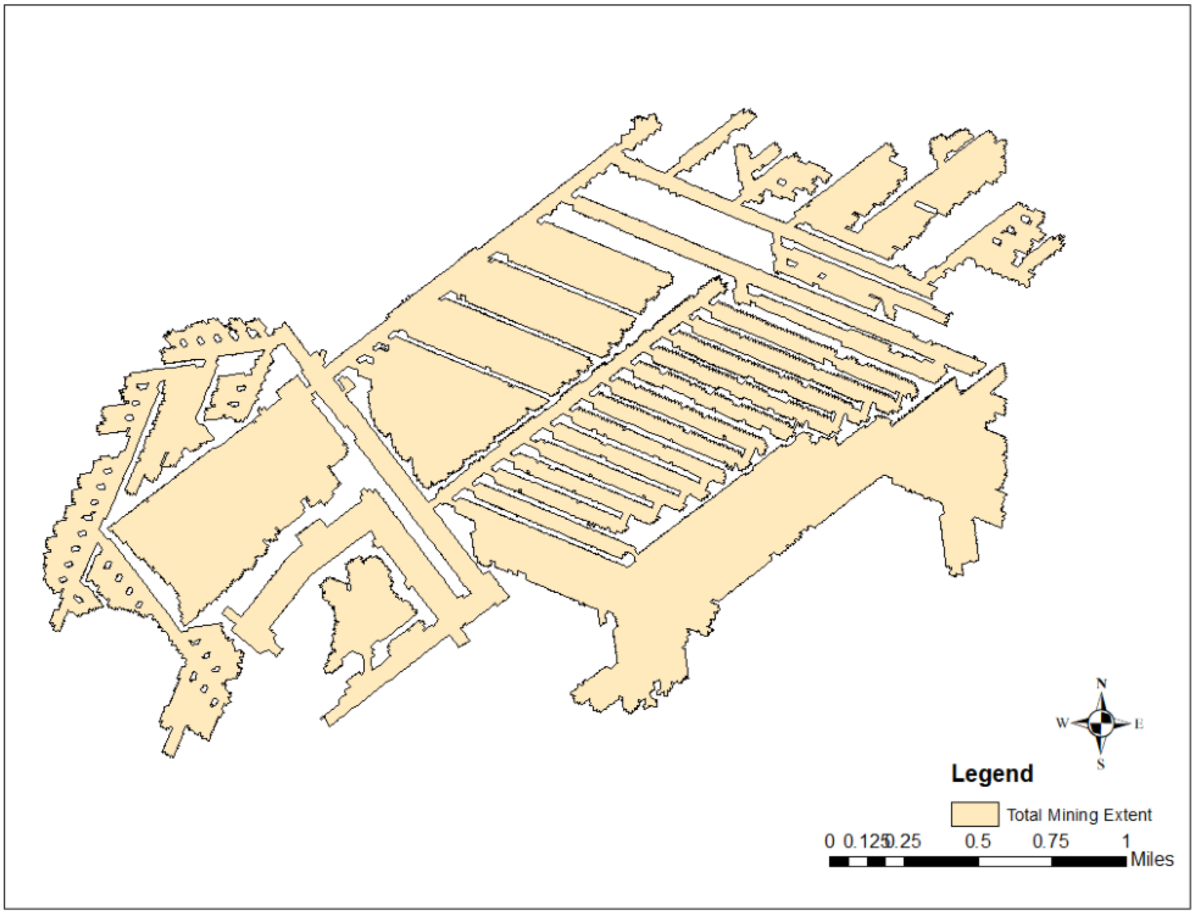

Figure 239. Madison total extent of mining

Figure 240. Madison mining extent for the 3rd, 4th, and 5th assessment periods

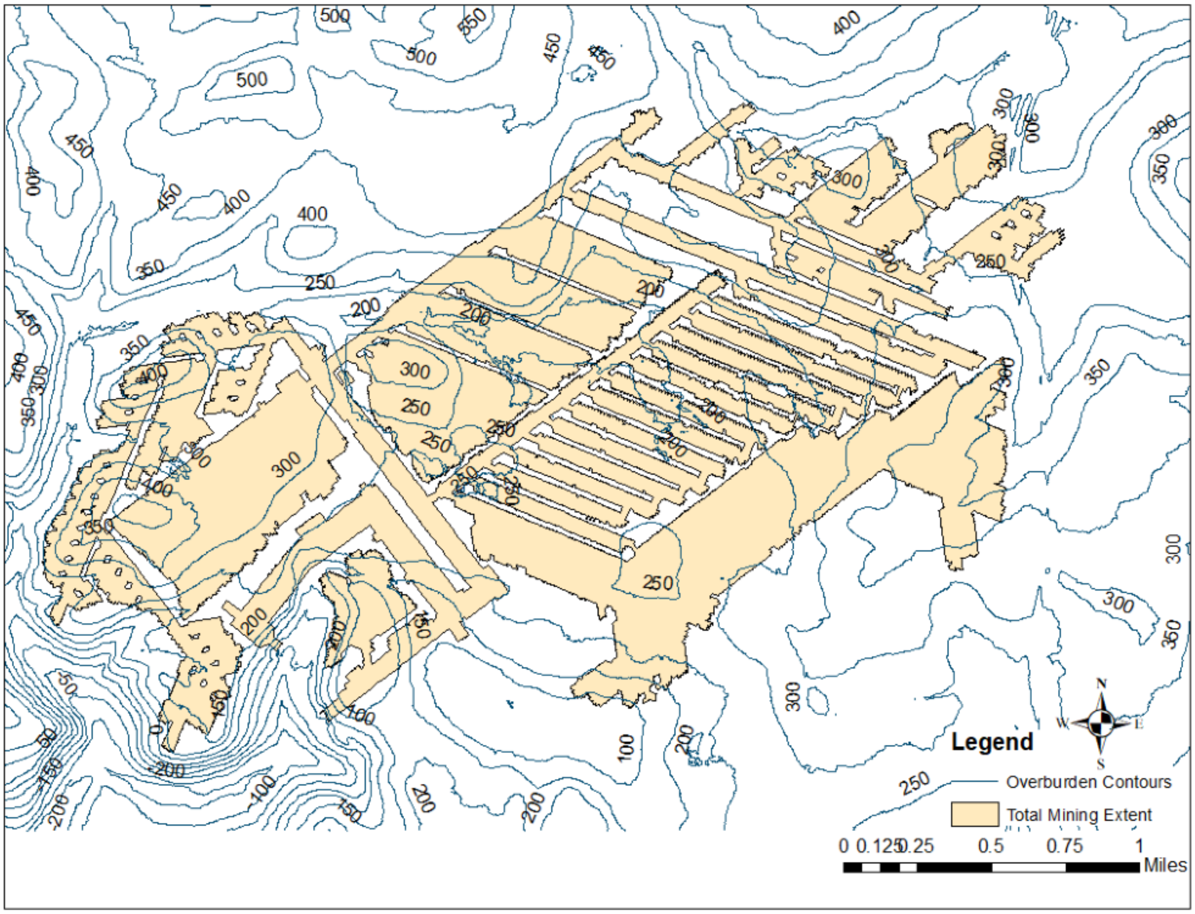

Figure 241. Fifty-foot overburden contour intervals for the Madison Mine

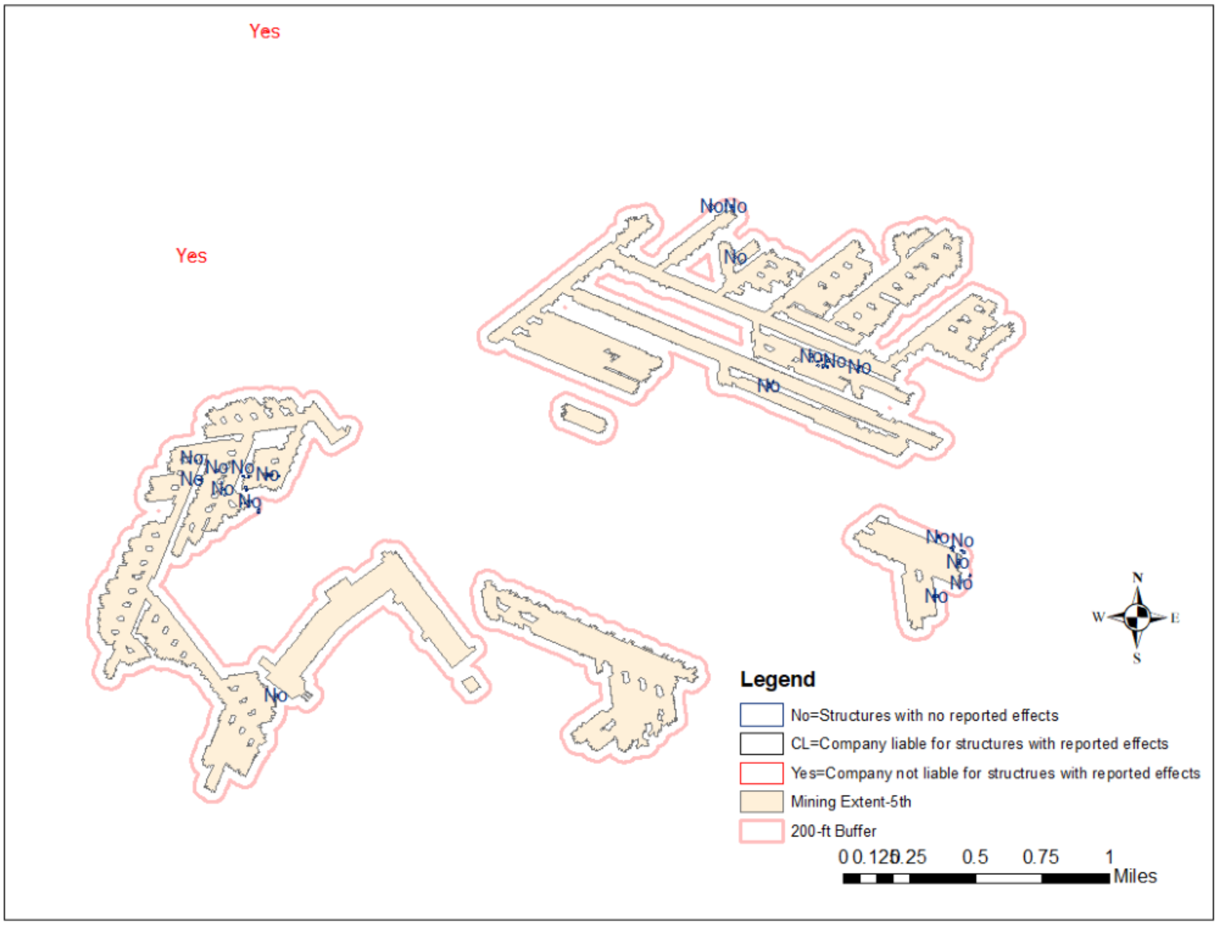

Figure 242. Madison 5th assessment 200-ft buffer and structures

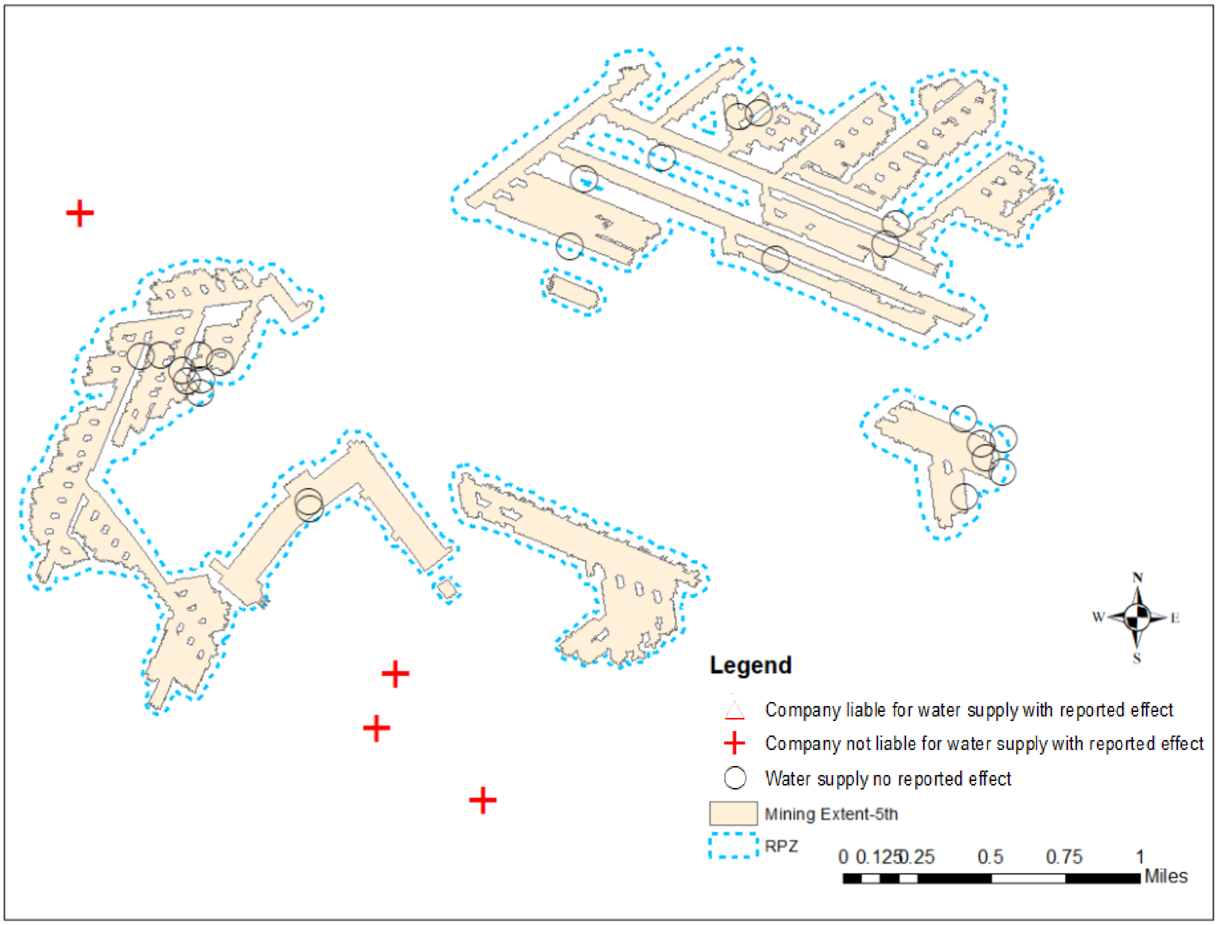

Figure 243. Madison 5th assessment water supplies and RPZ

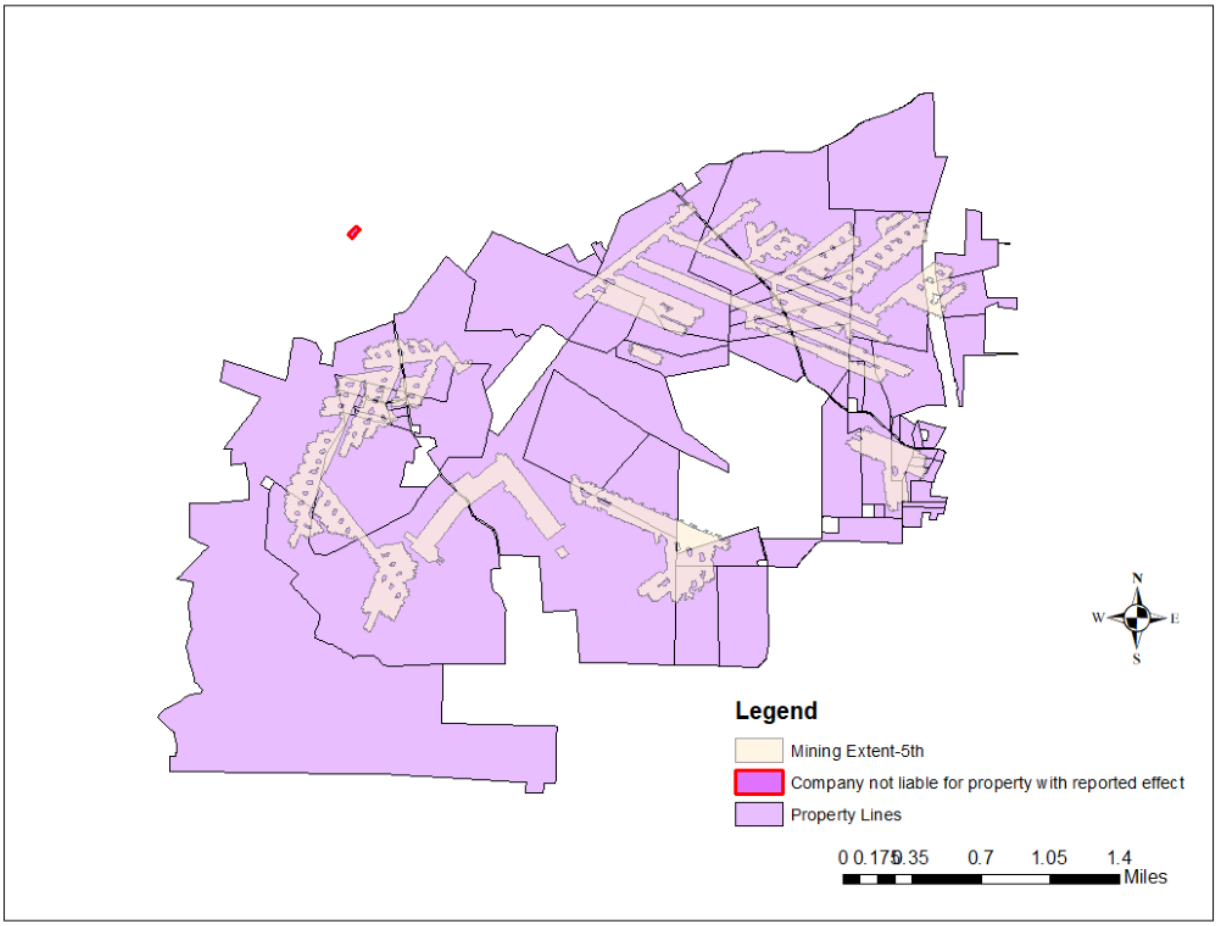

Figure 244. Properties associated with the 5th assessment period over the Madison Mine

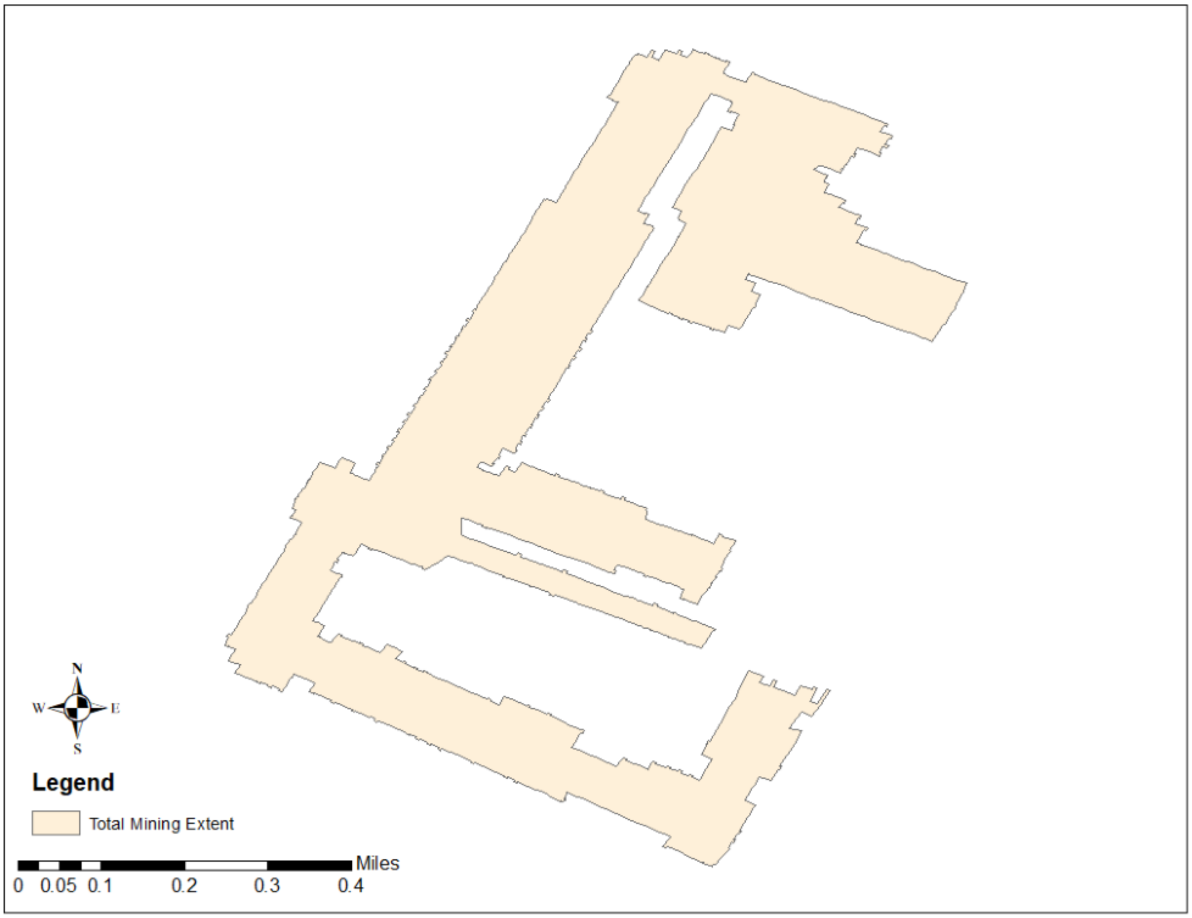

Figure 245. Maple Spring total extent of mining

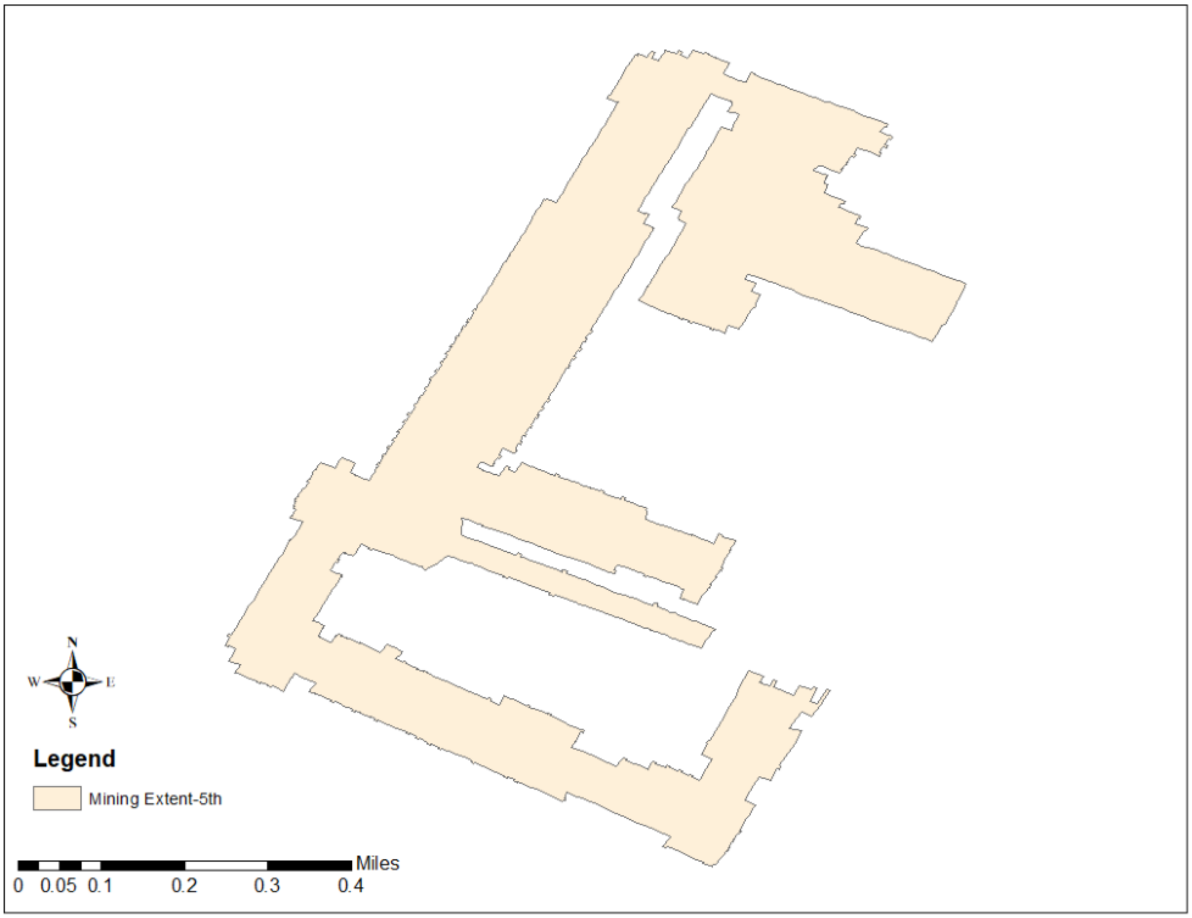

Figure 246. Maple Spring mining extent the 5th assessment period

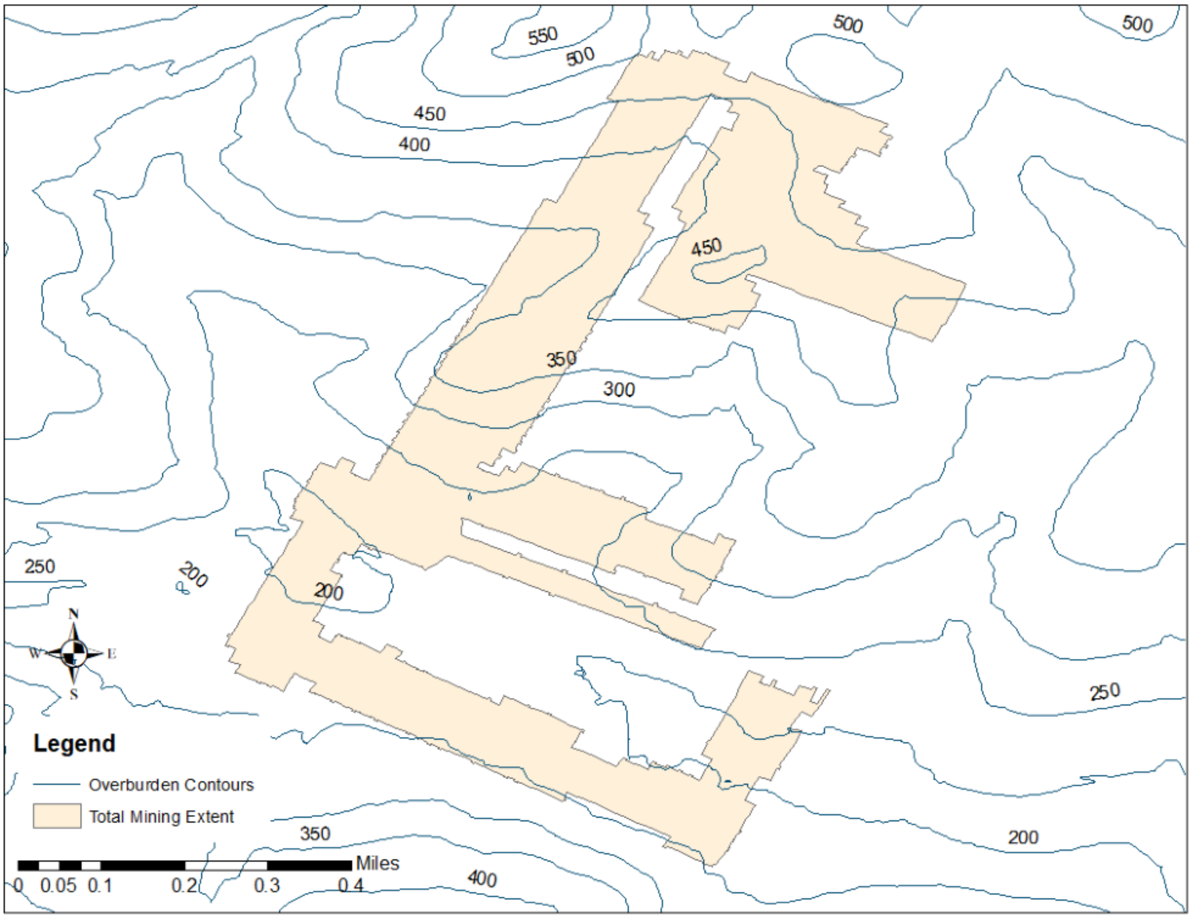

Figure 247. Fifty-foot overburden contour intervals for the Maple Spring Mine

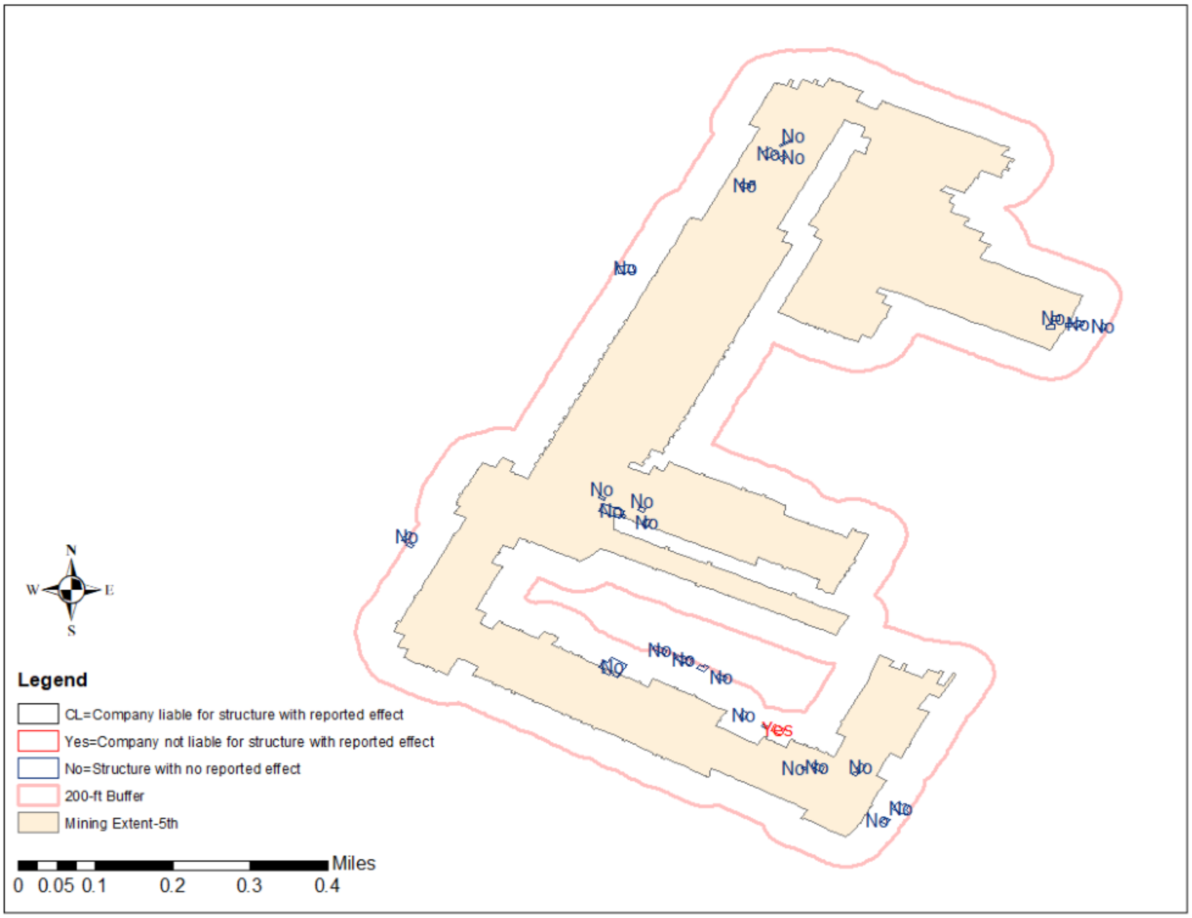

Figure 248. Maple Spring 5th assessment 200-ft buffer and structures

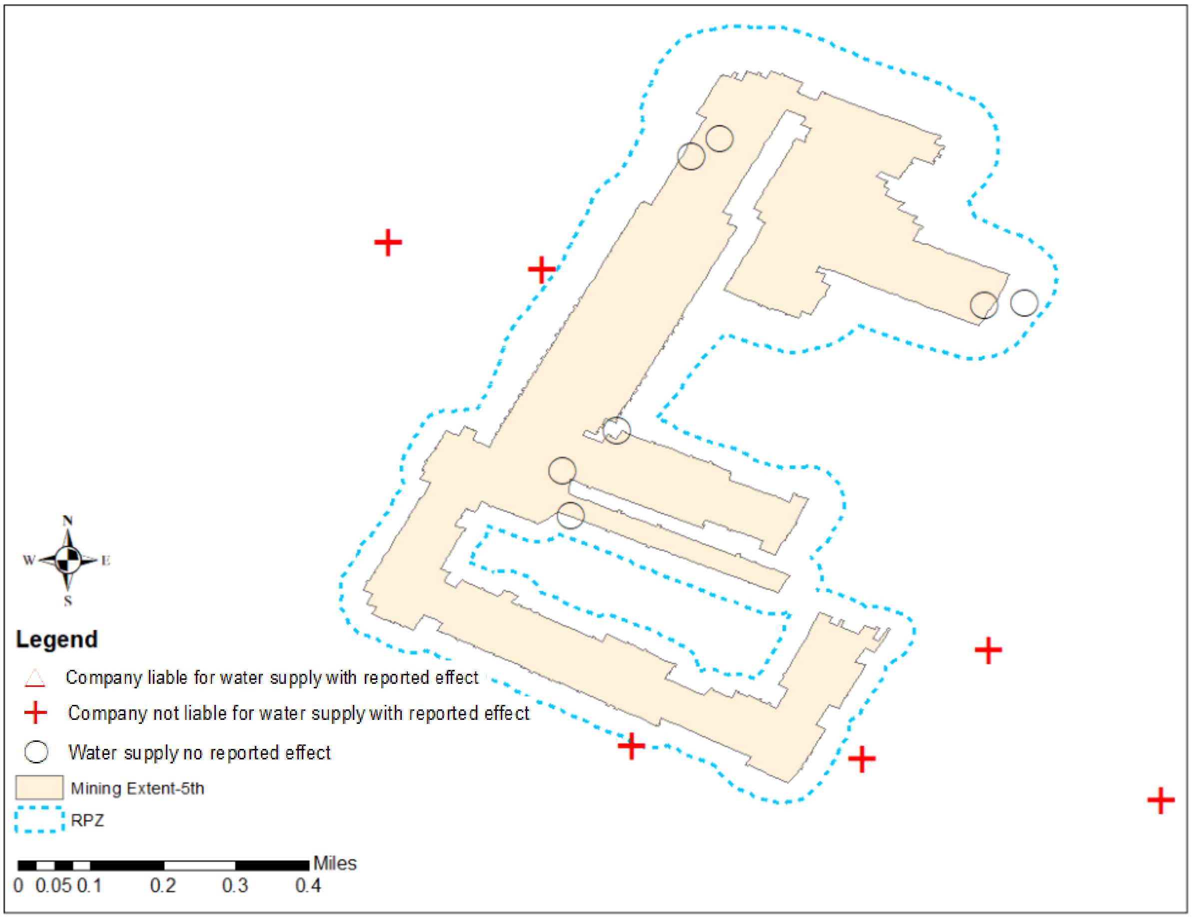

Figure 249. Maple Spring 5th assessment water supplies and RPZ

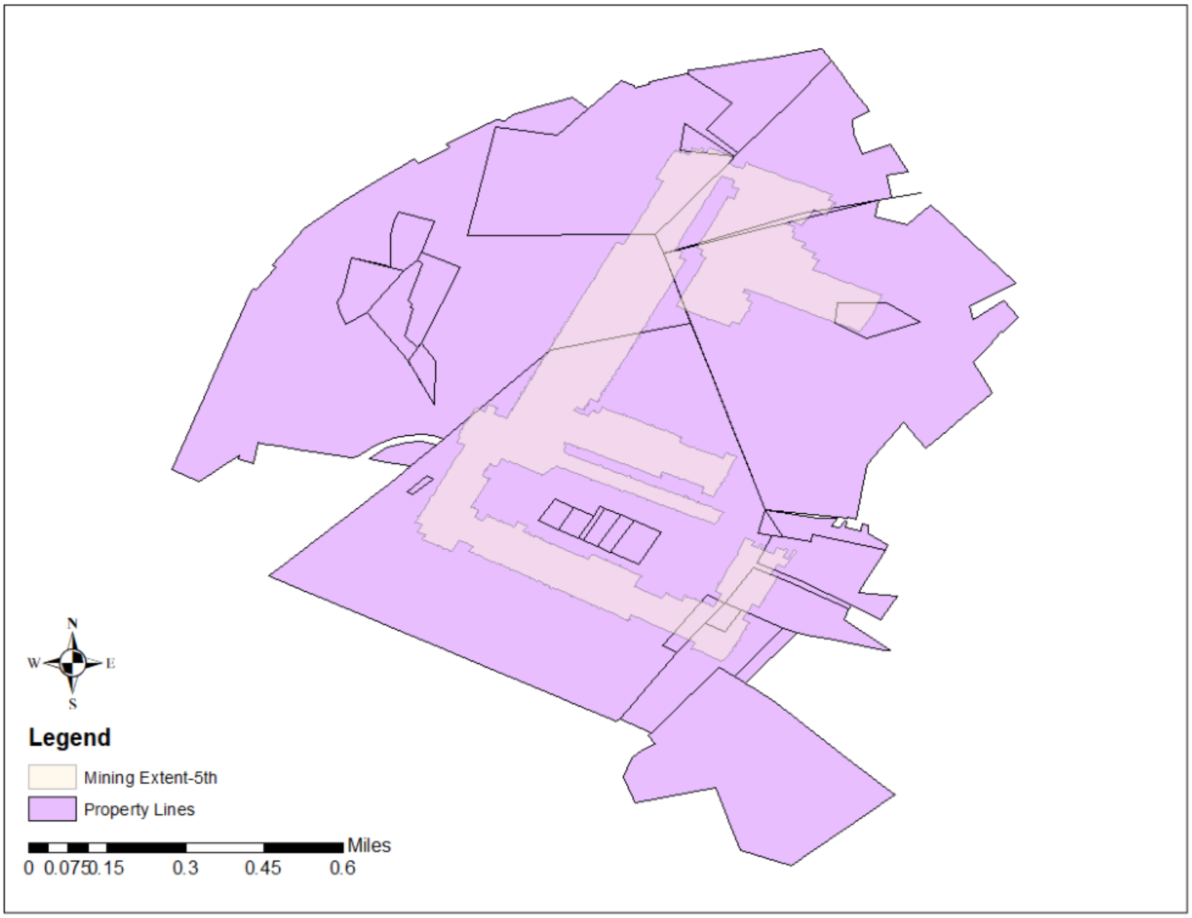

Figure 250. Properties associated with the 5th assessment period over the Maple Spring Mine

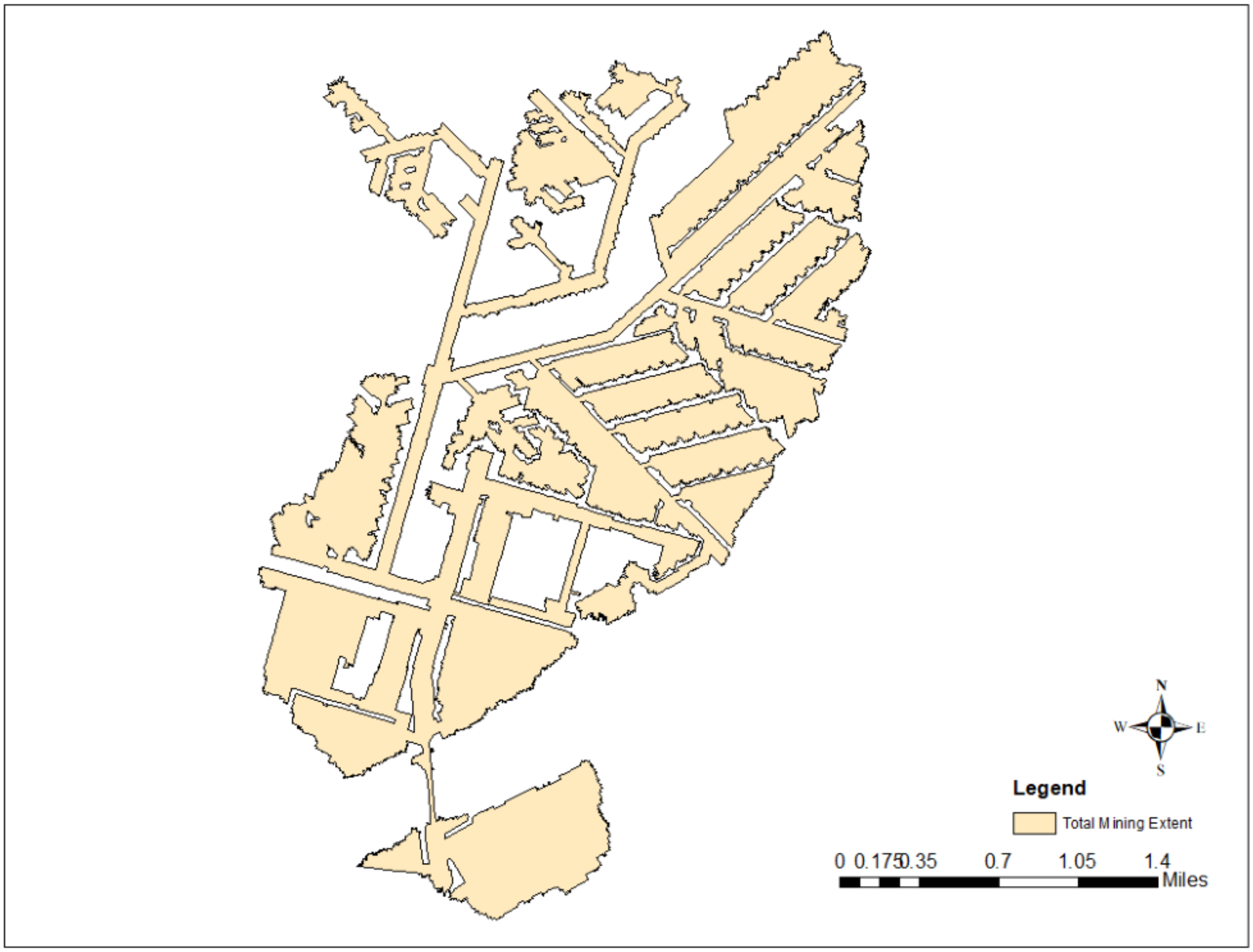

Figure 251. Mine 78 total extent of mining

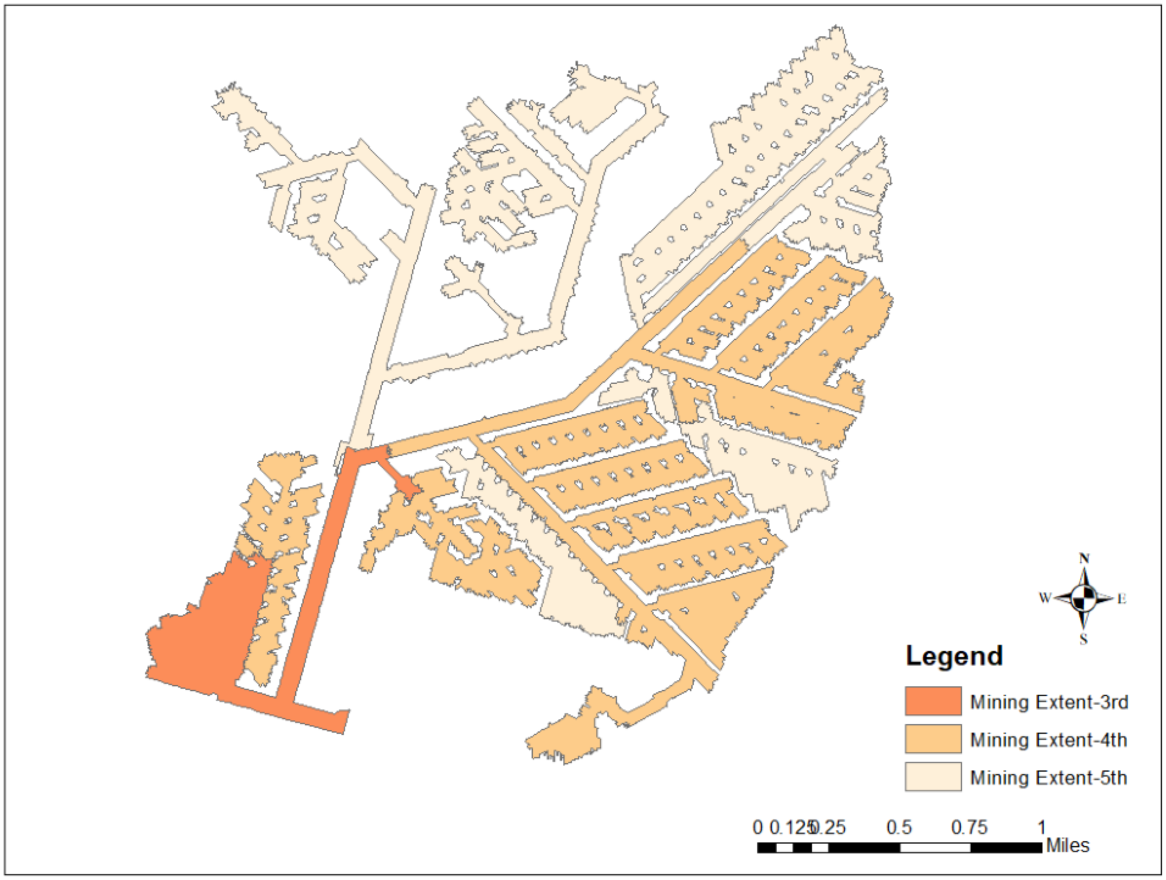

Figure 252. Mine 78 mining extent for the 3rd, 4th, and 5th assessment periods

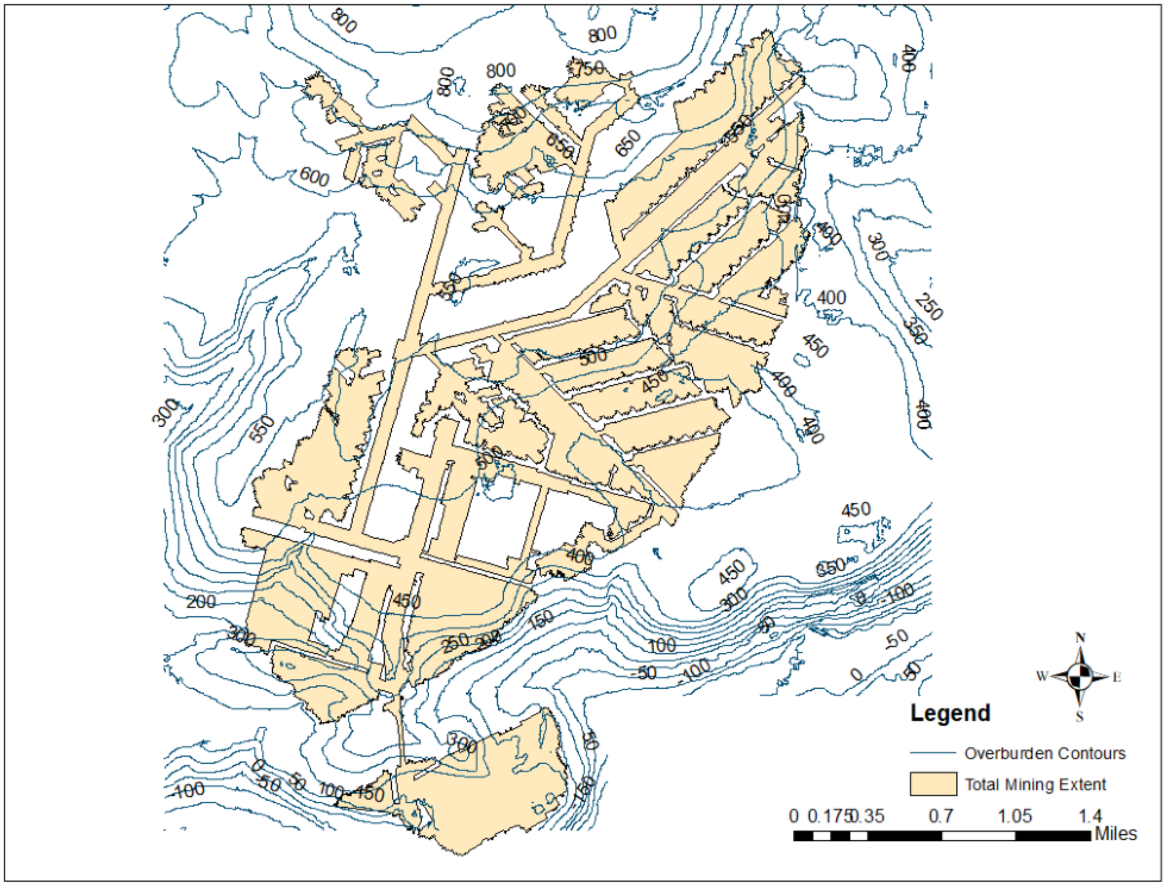

Figure 253. Fifty-foot overburden contour intervals for the Mine 78 Mine

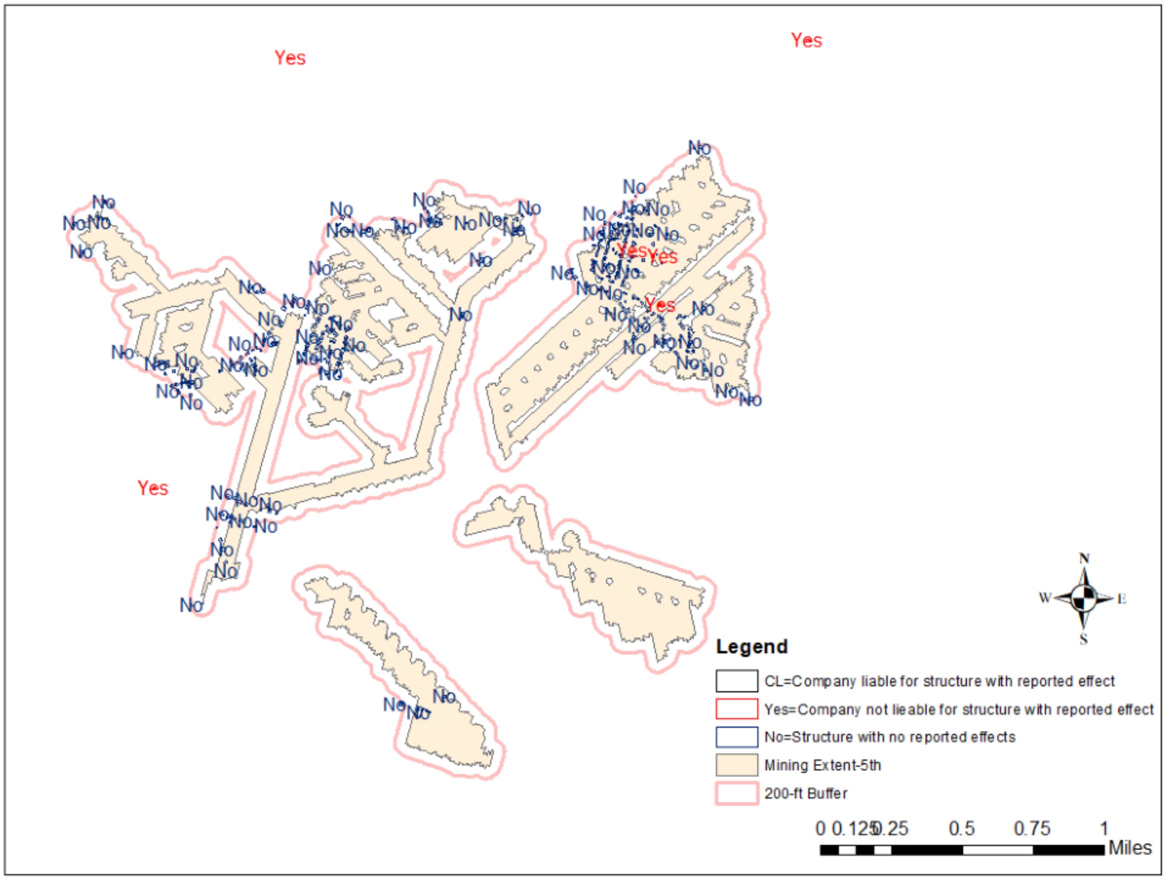

Figure 254. Mine 78 5th assessment 200-ft buffer and structures

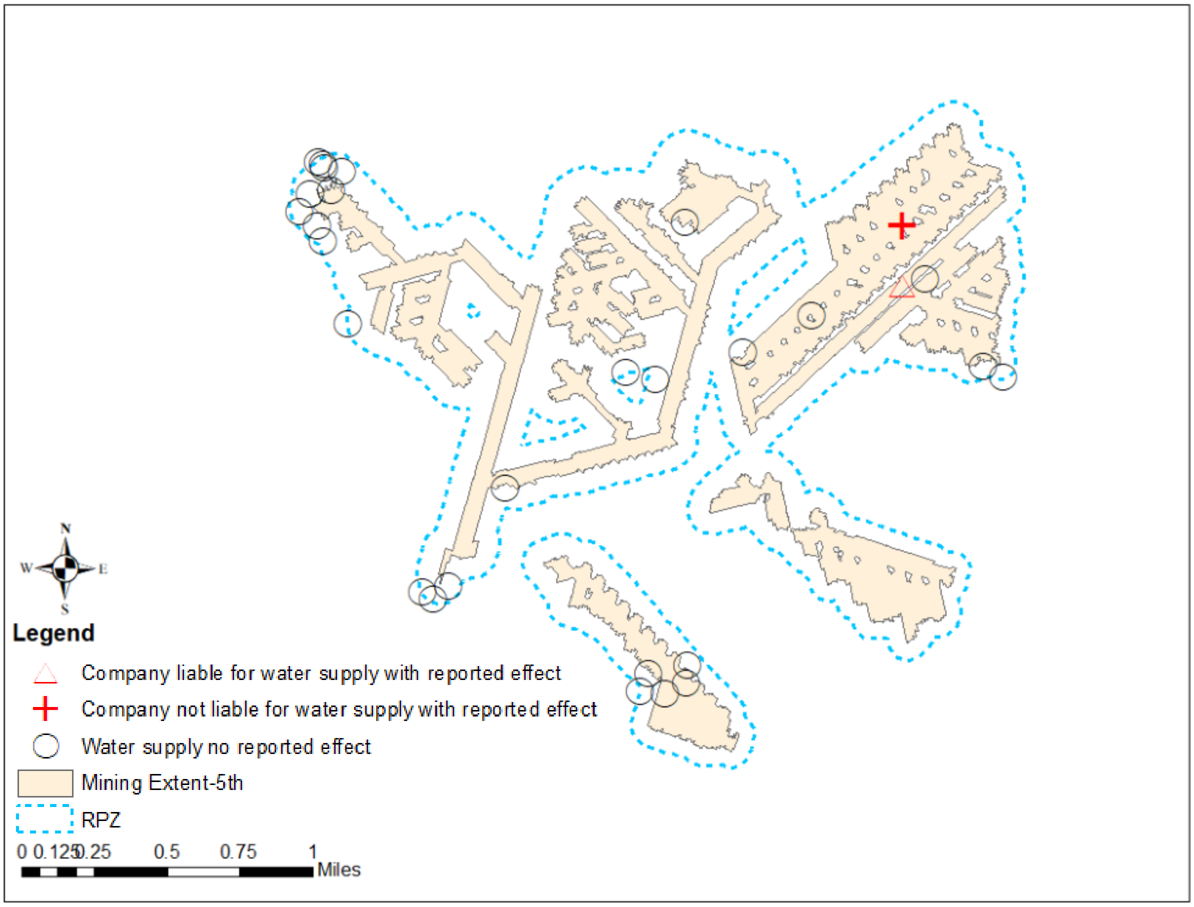

Figure 255. Mine 78 5th assessment water supplies and RPZ*

Note there is one water supply with a reported effect determined to be not company liable that is far from mining and is not included here for display purposes.

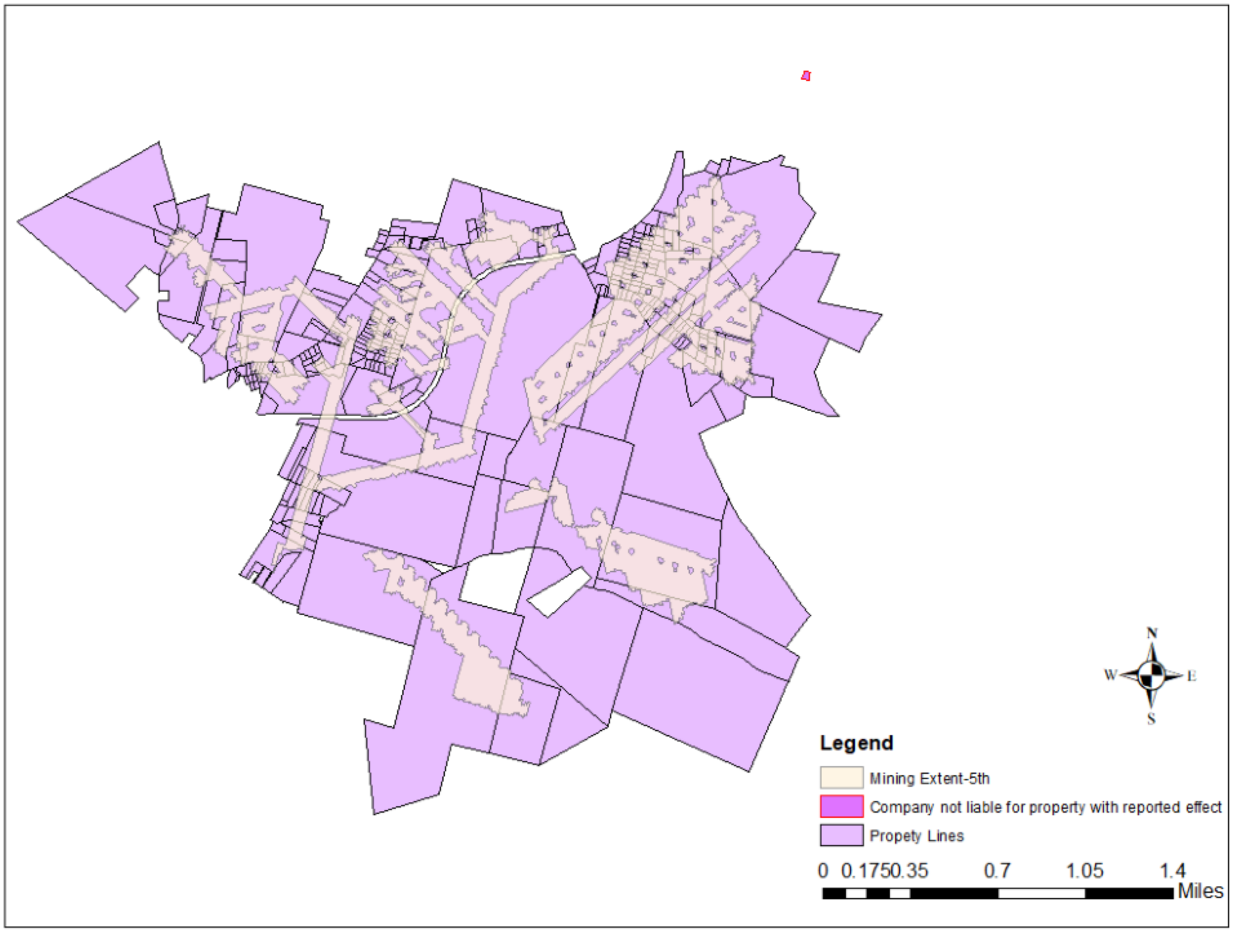

Figure 256. Properties associated with the 5th assessment period over the Mine 78 Mine

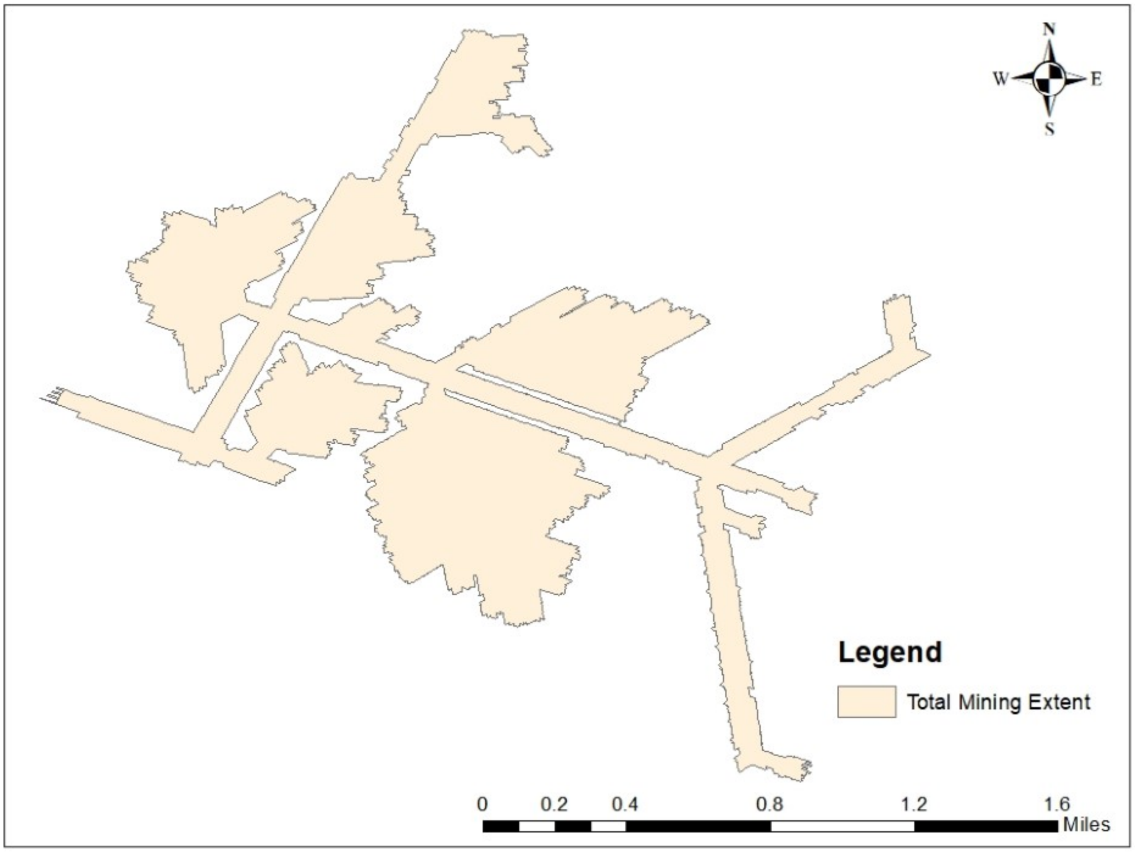

Figure 257. North Fork total extent of mining

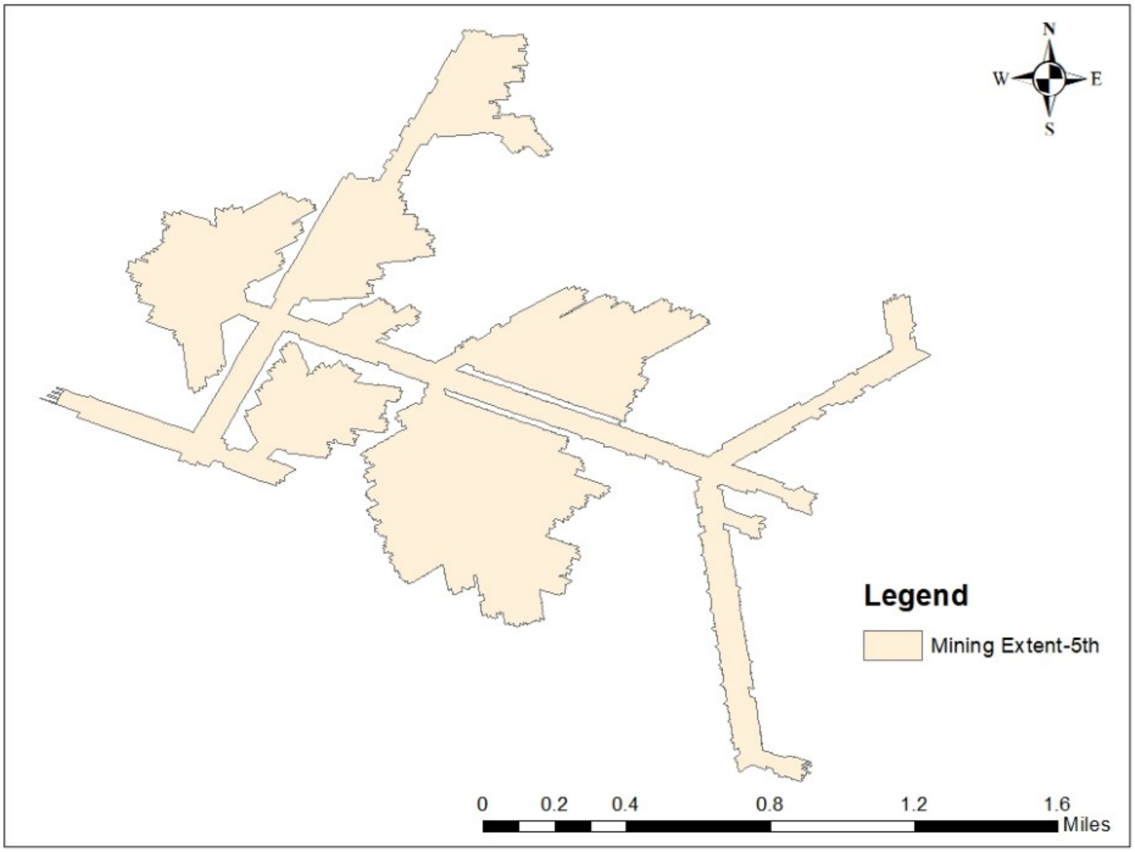

Figure 258. North Fork mining extent for the 5th assessment period

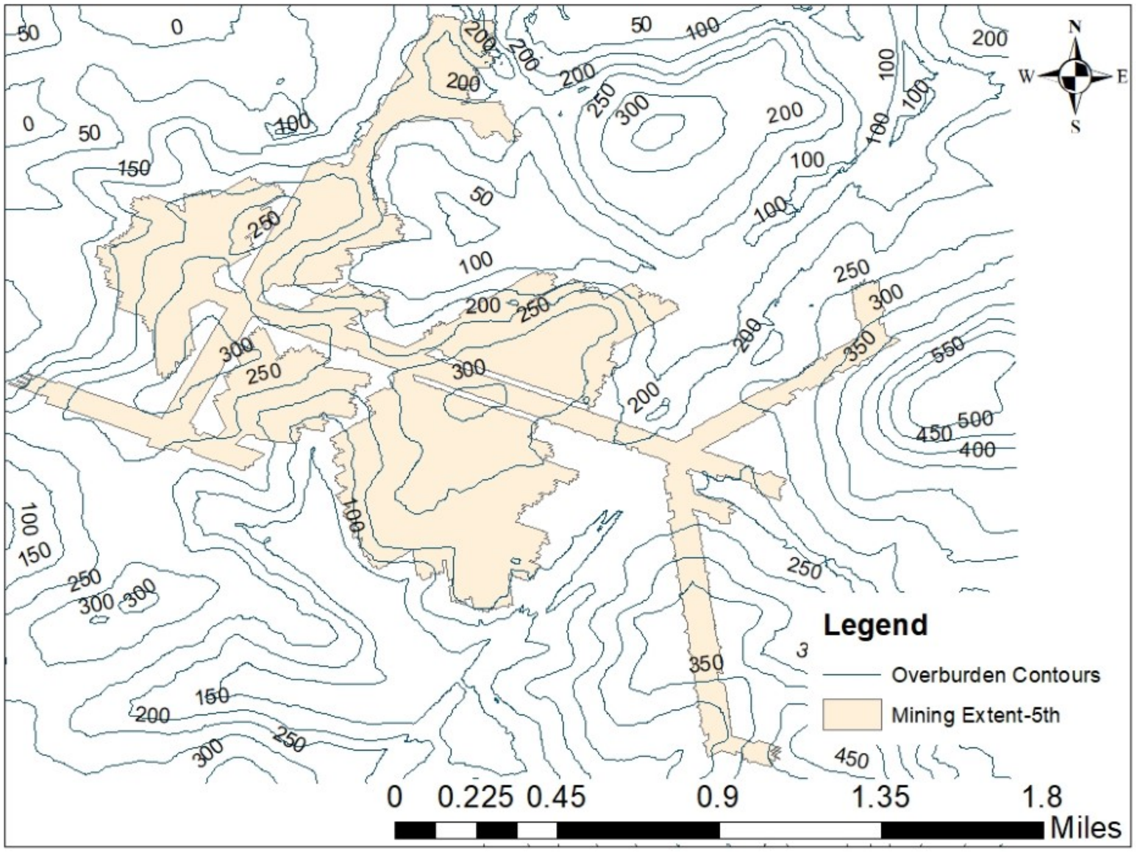

Figure 259. Fifty-foot overburden contour intervals for the North Fork Mine

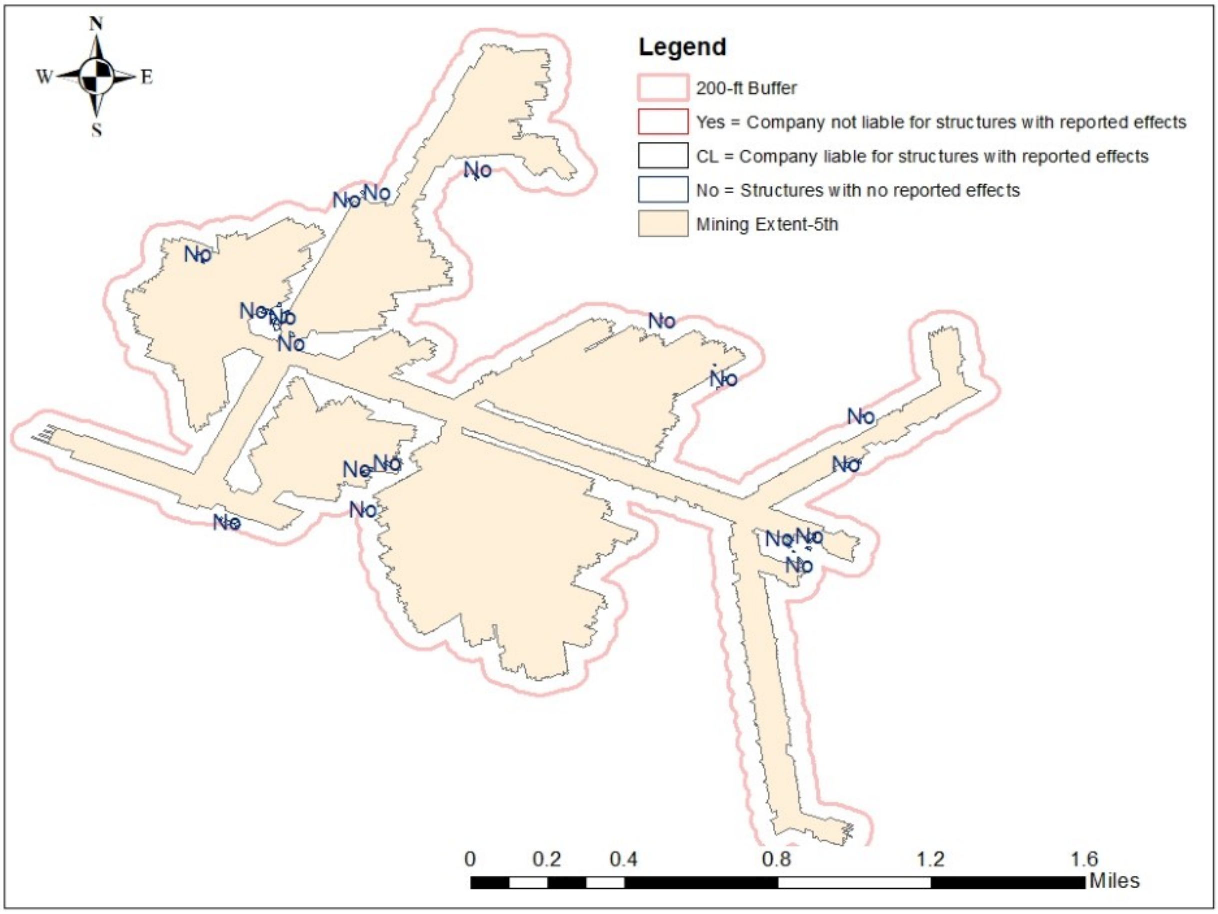

Figure 260. North Fork 5th assessment 200-ft buffer and structures

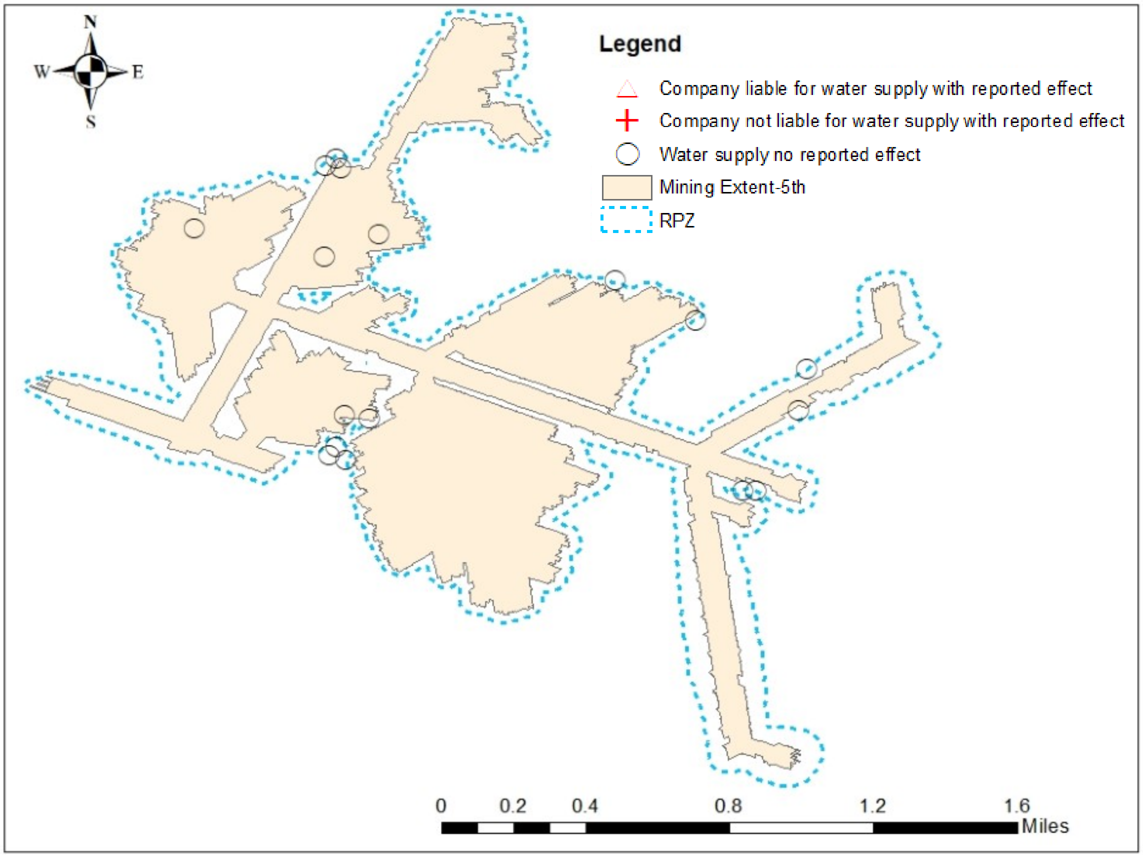

Figure 261. North Fork 5th assessment water supplies and RPZ

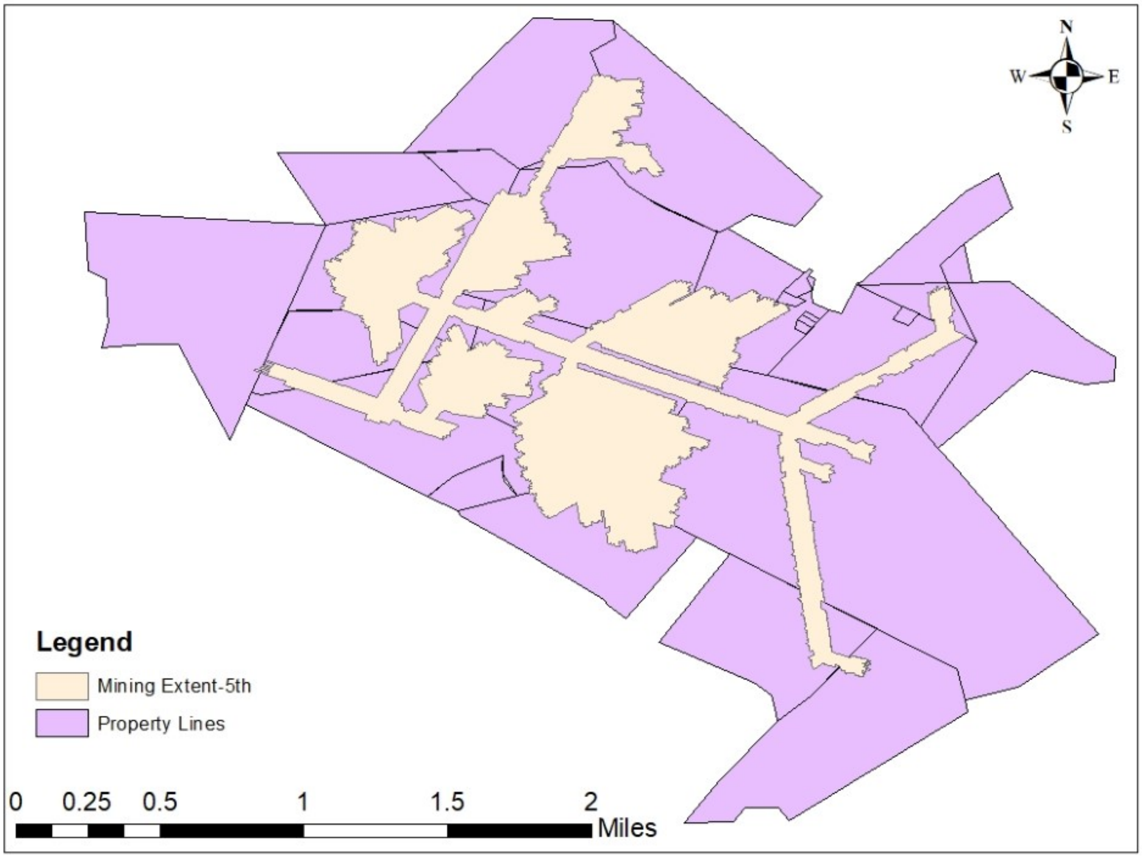

Figure 262. Properties associated with the 5th assessment period over the North Fork Mine

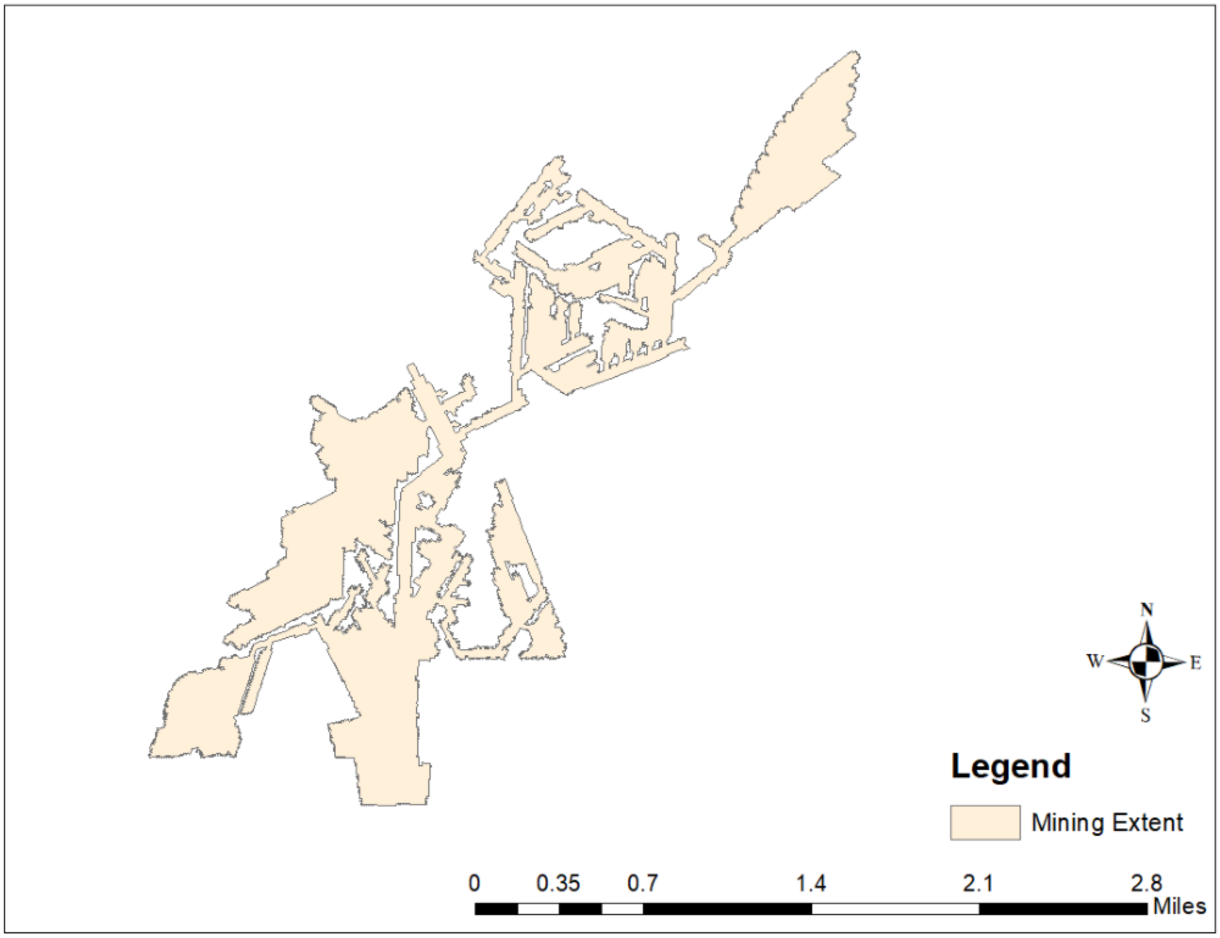

Figure 263. Ondo total extent of mining

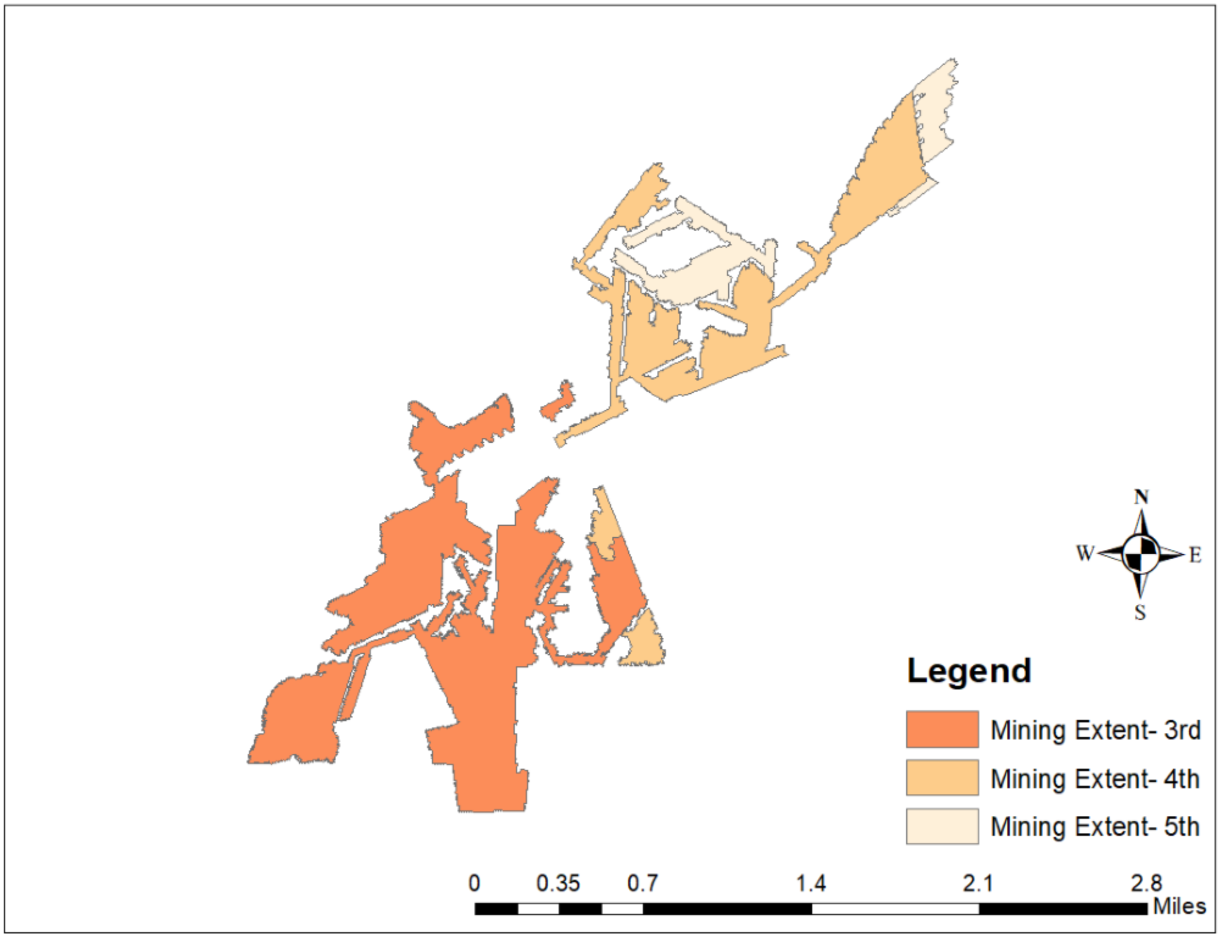

Figure 264. Ondo mining extent for the 3rd, 4th, and 5th assessment periods

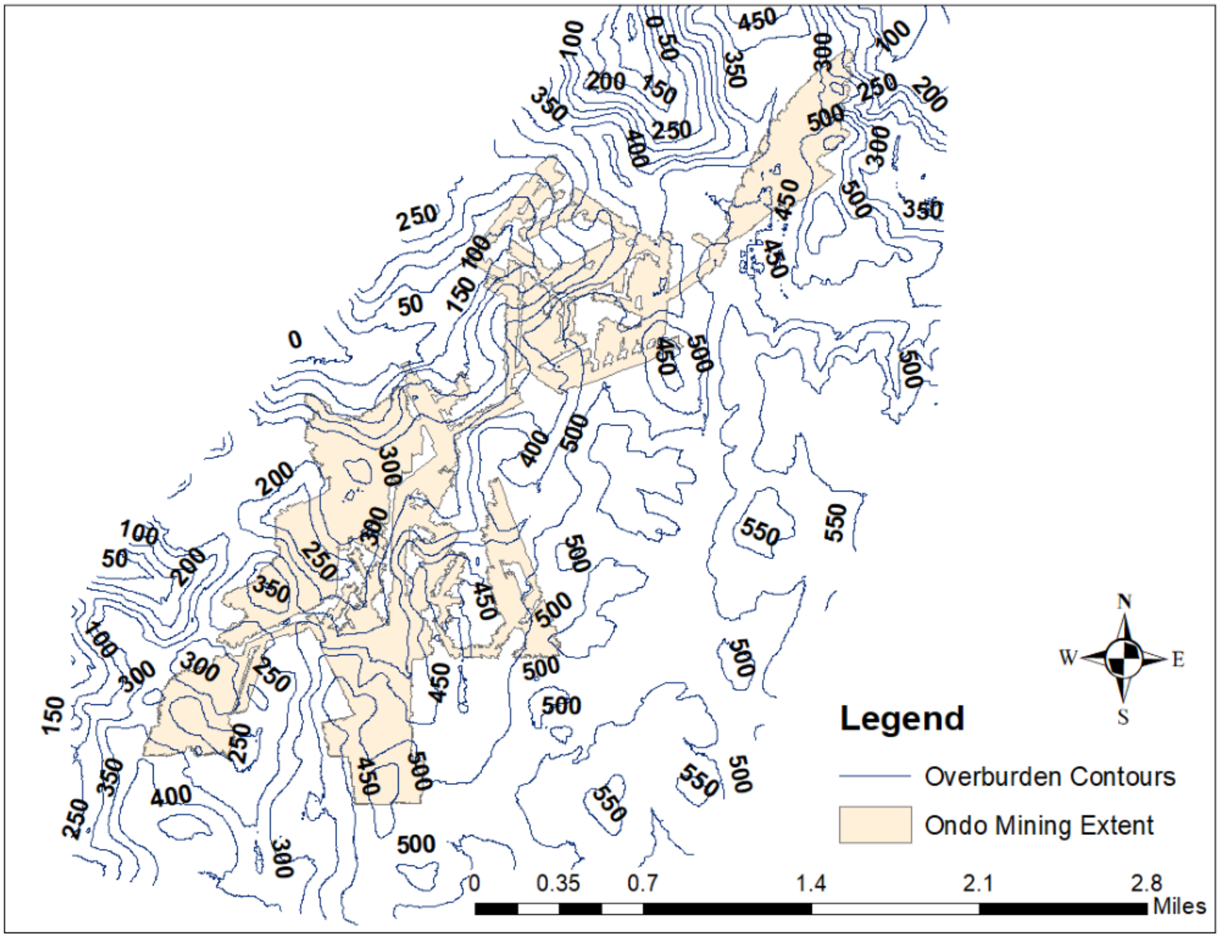

Figure 265. Fifty-foot overburden contour intervals for the Ondo mine

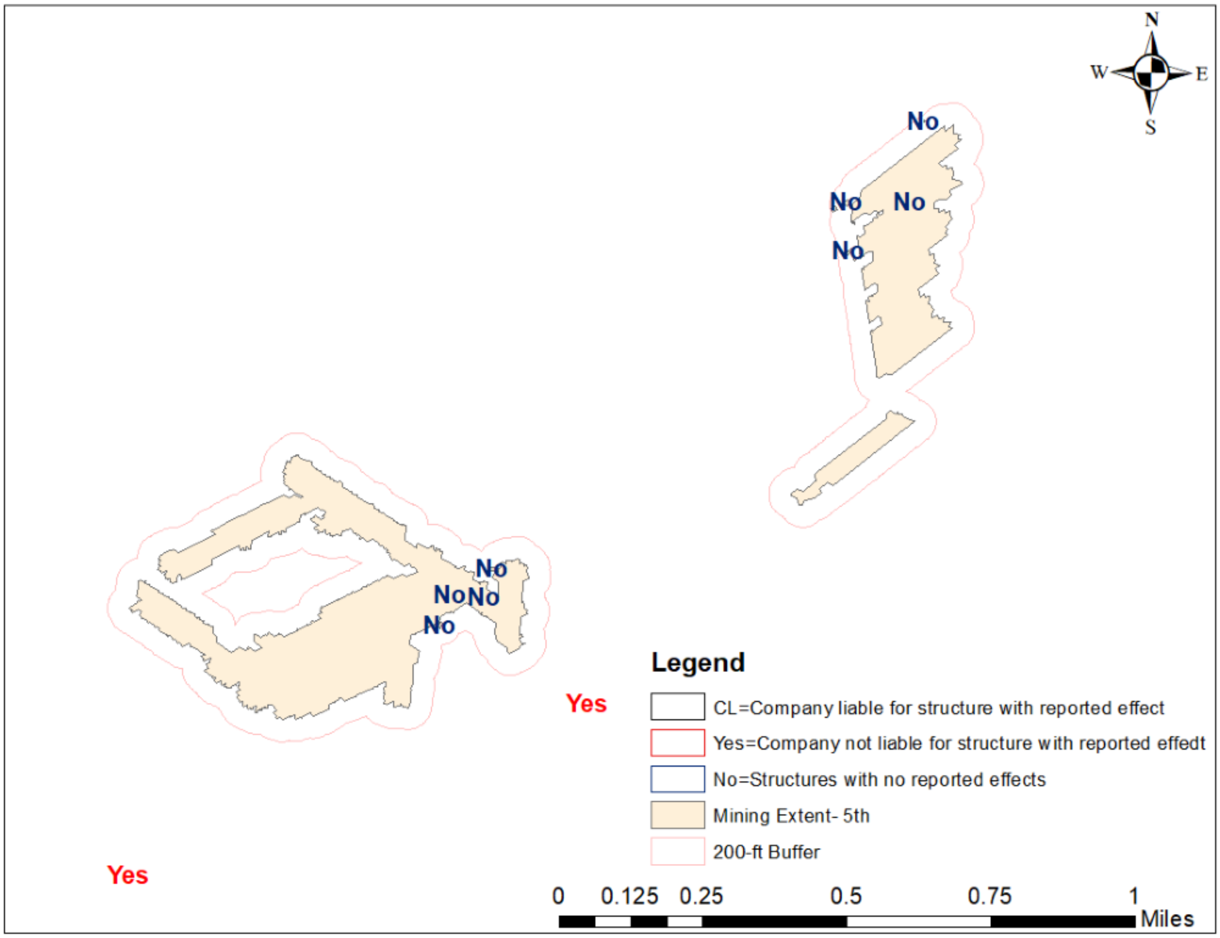

Figure 266. Ondo 5th assessment 200-ft buffer and structures*

*Note there is one structure with reported effects that is far from mining and are not included here

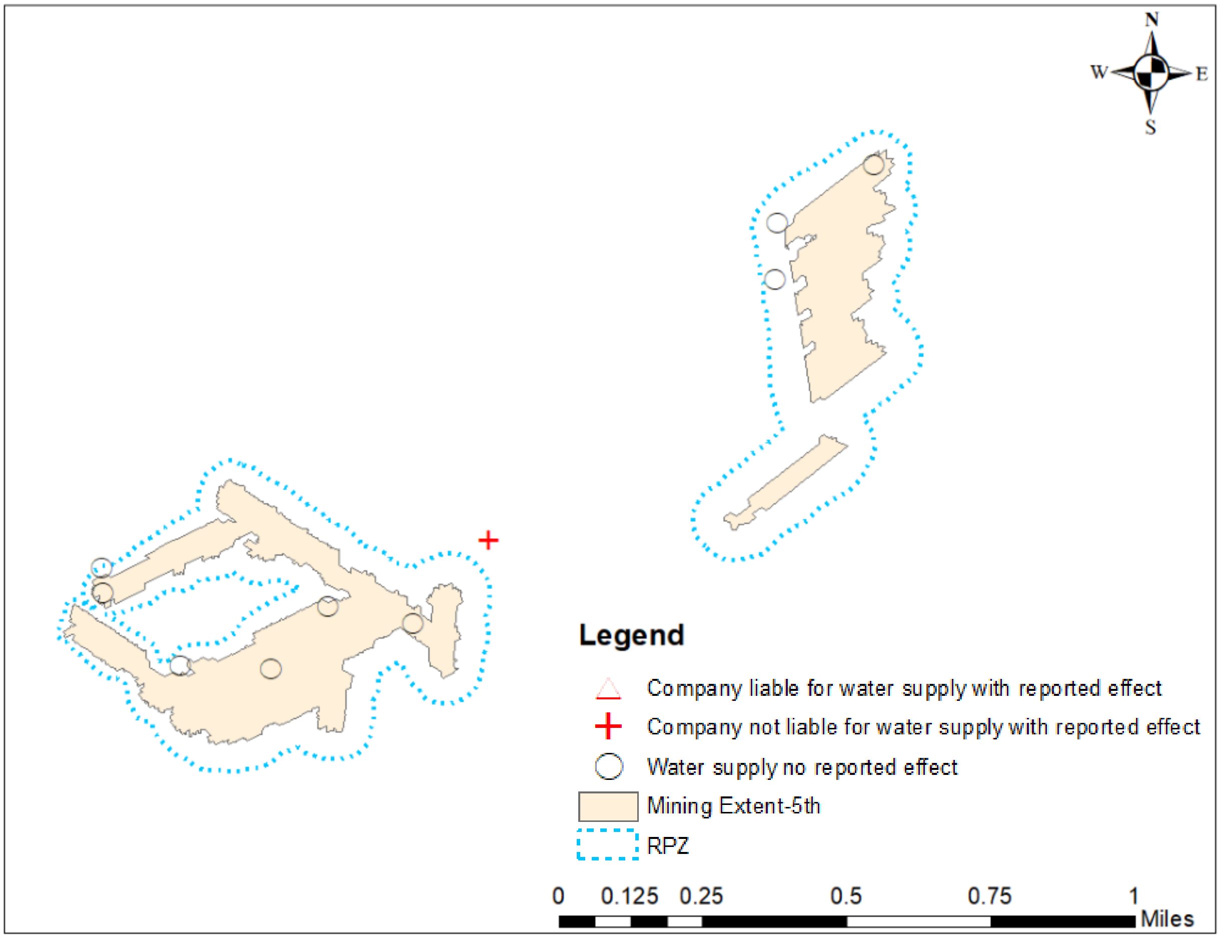

Figure 267. Ondo 5th assessment water supplies and RPZ

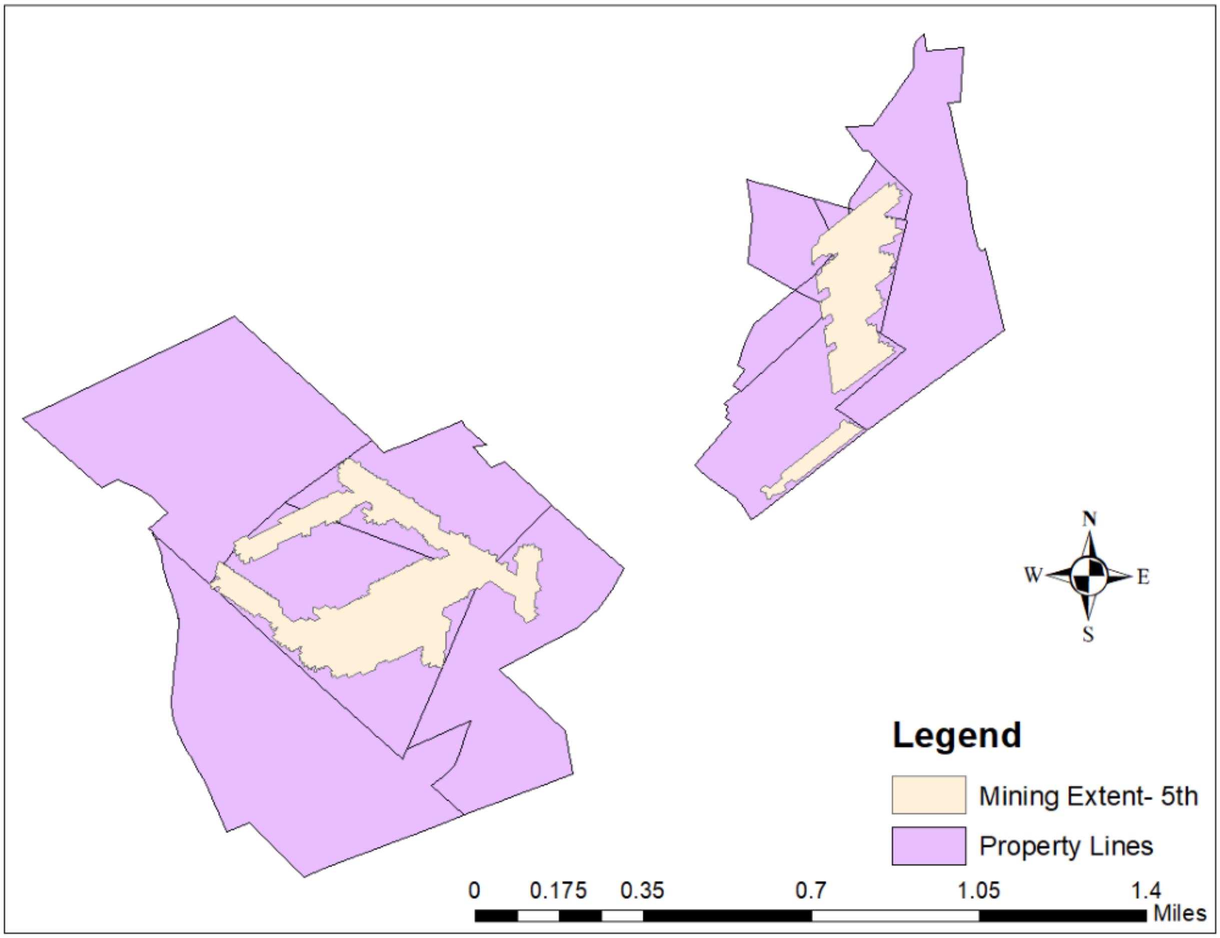

Figure 268. Properties associated with the 5th assessment period over the Ondo mine

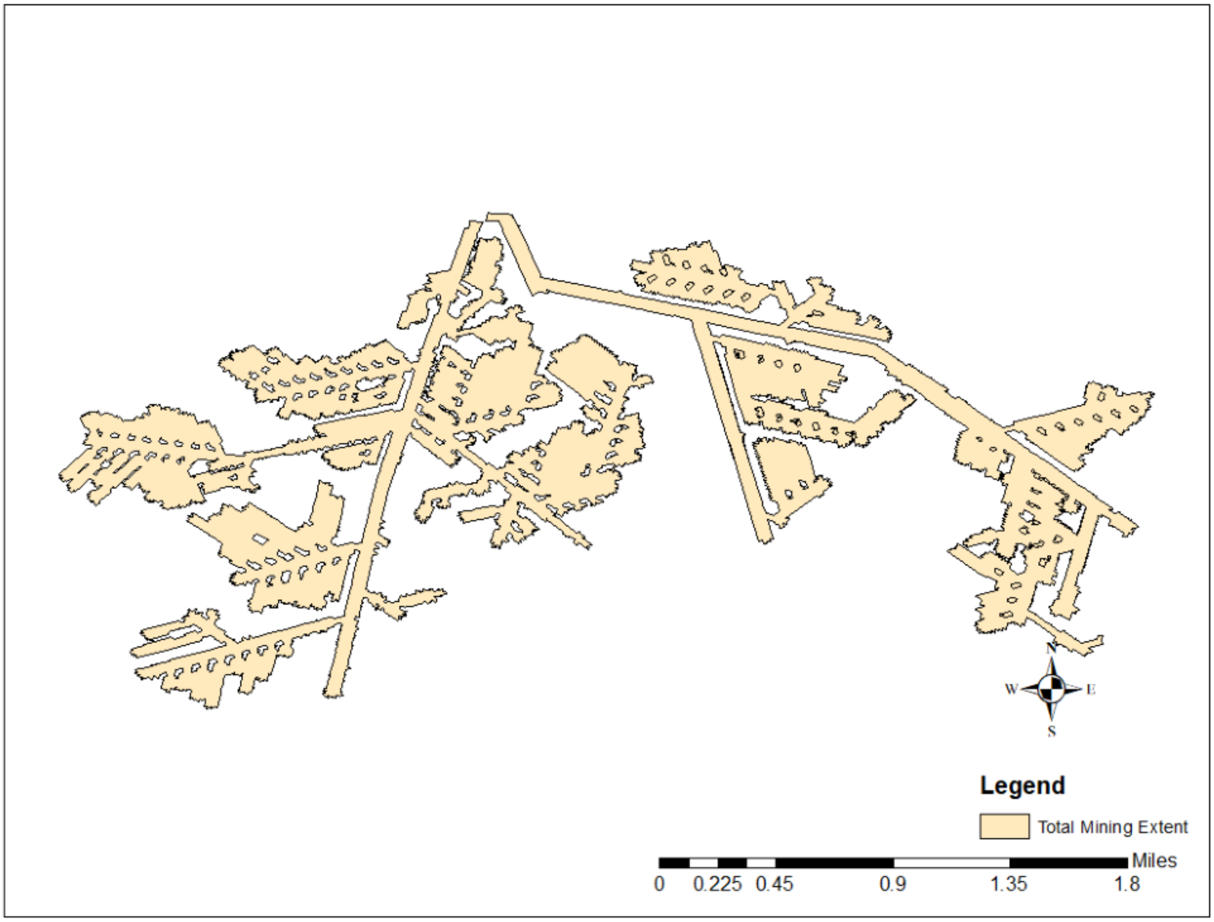

Figure 269. Parkwood total extent of mining

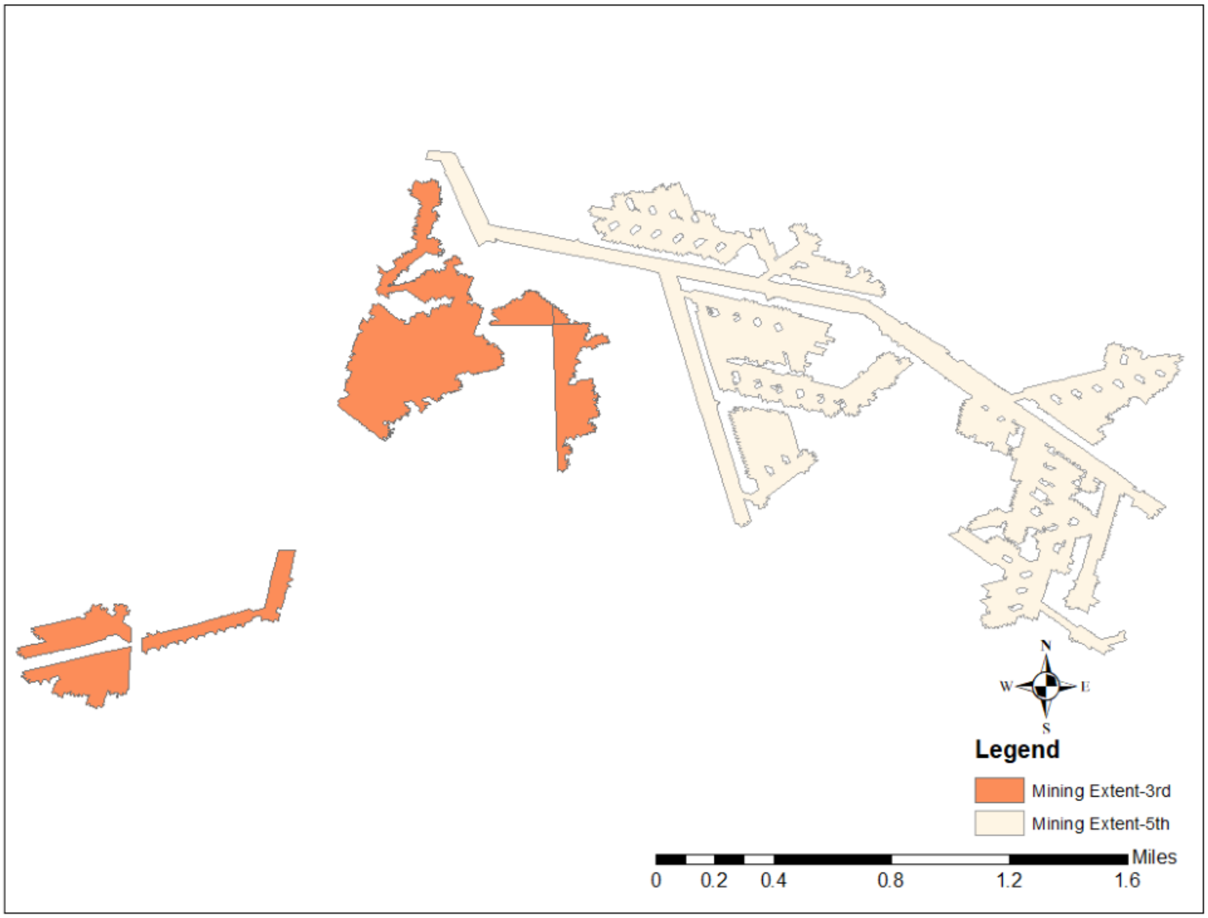

Figure 270. Parkwood mining extent for the 4th and 5th assessment periods

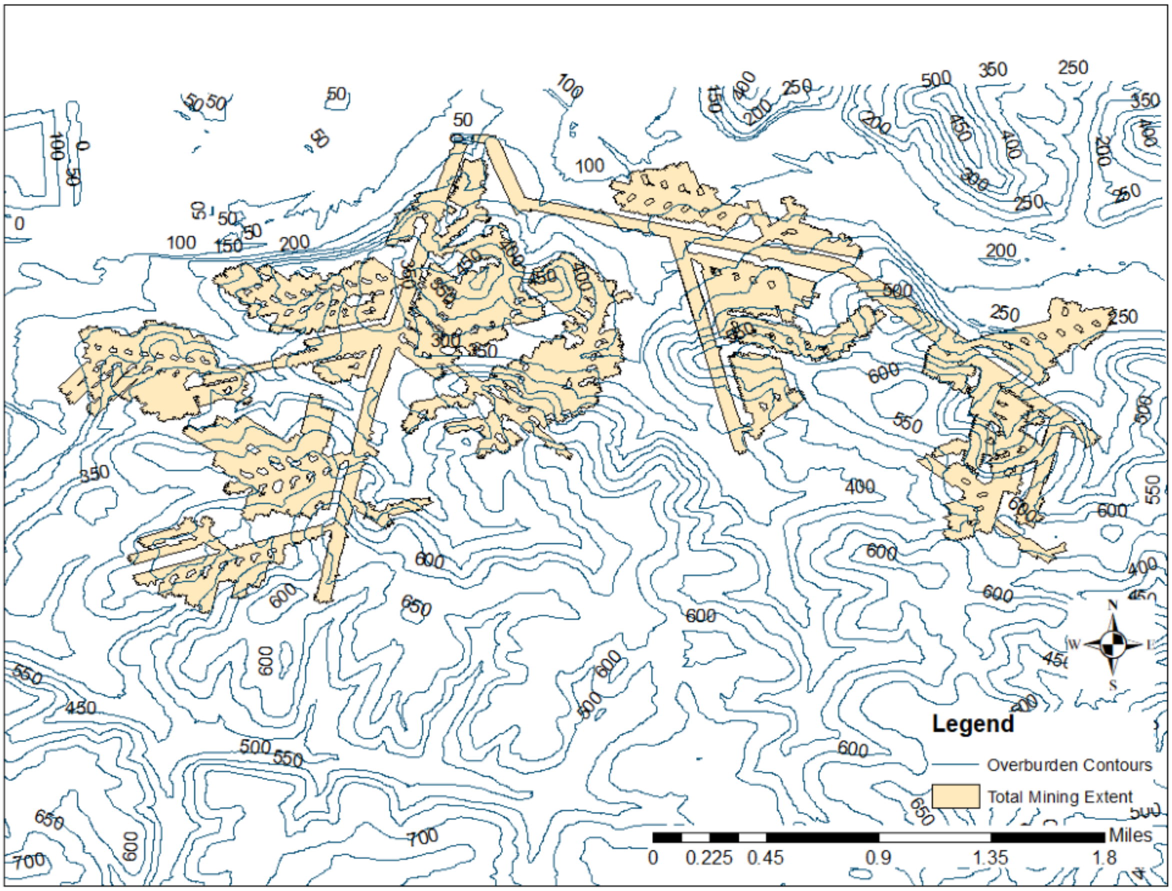

Figure 271. Fifty-foot overburden contour intervals for the Parkwood Mine

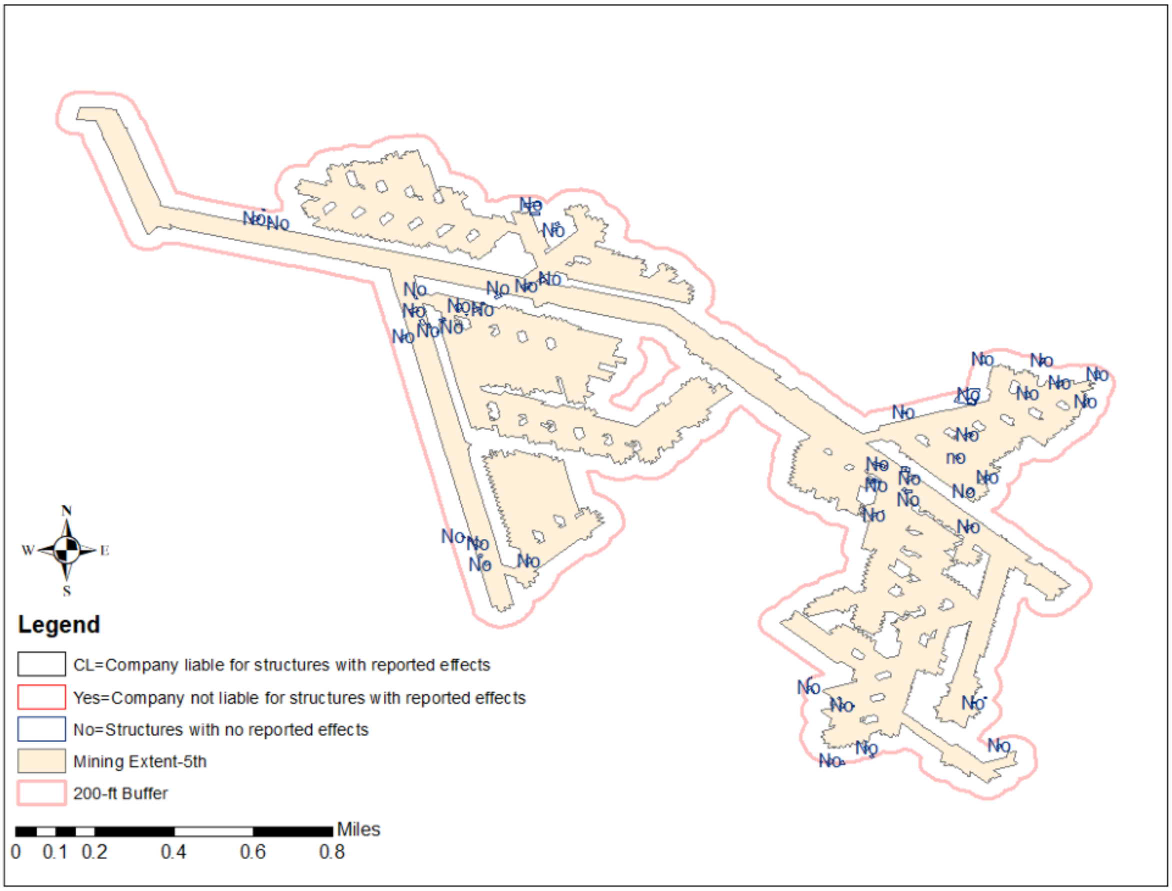

Figure 272. Parkwood 5th assessment 200-ft buffer and structures

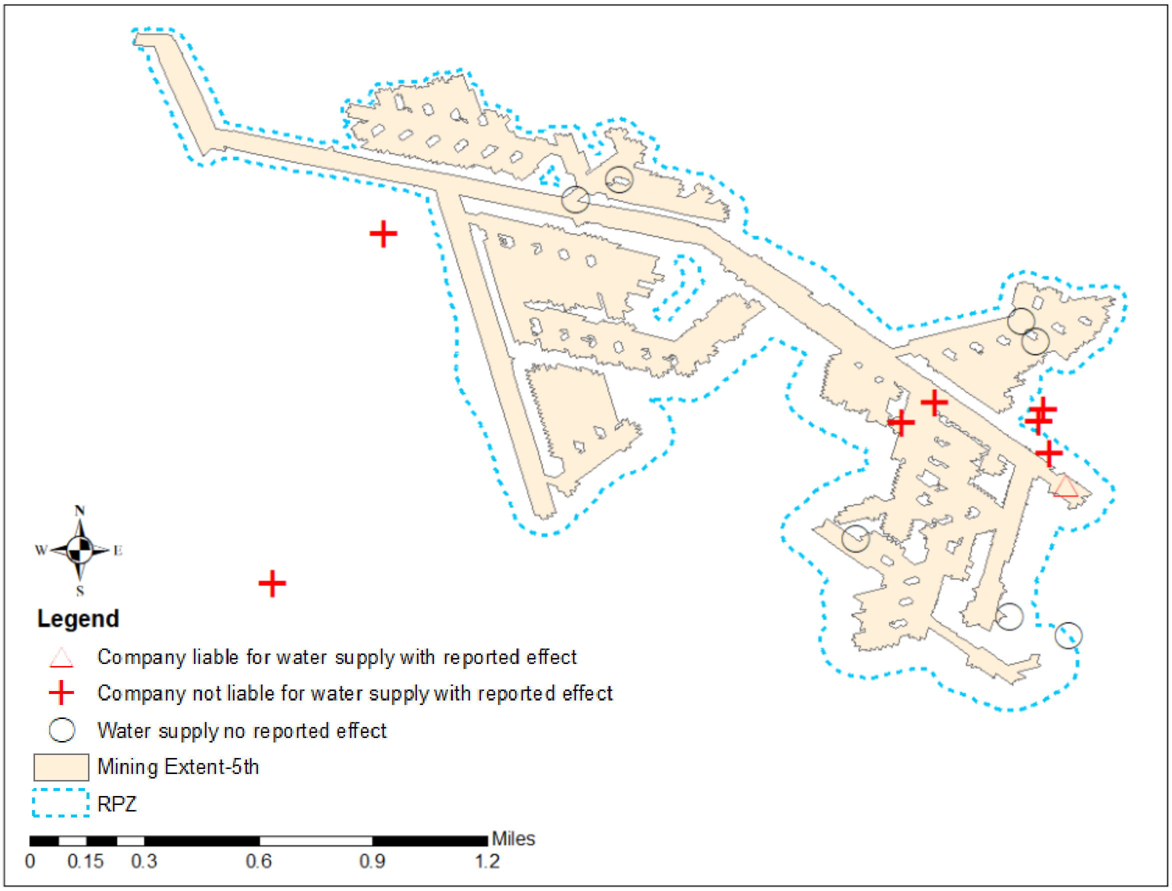

Figure 273. Parkwood 5th assessment water supplies and RPZ

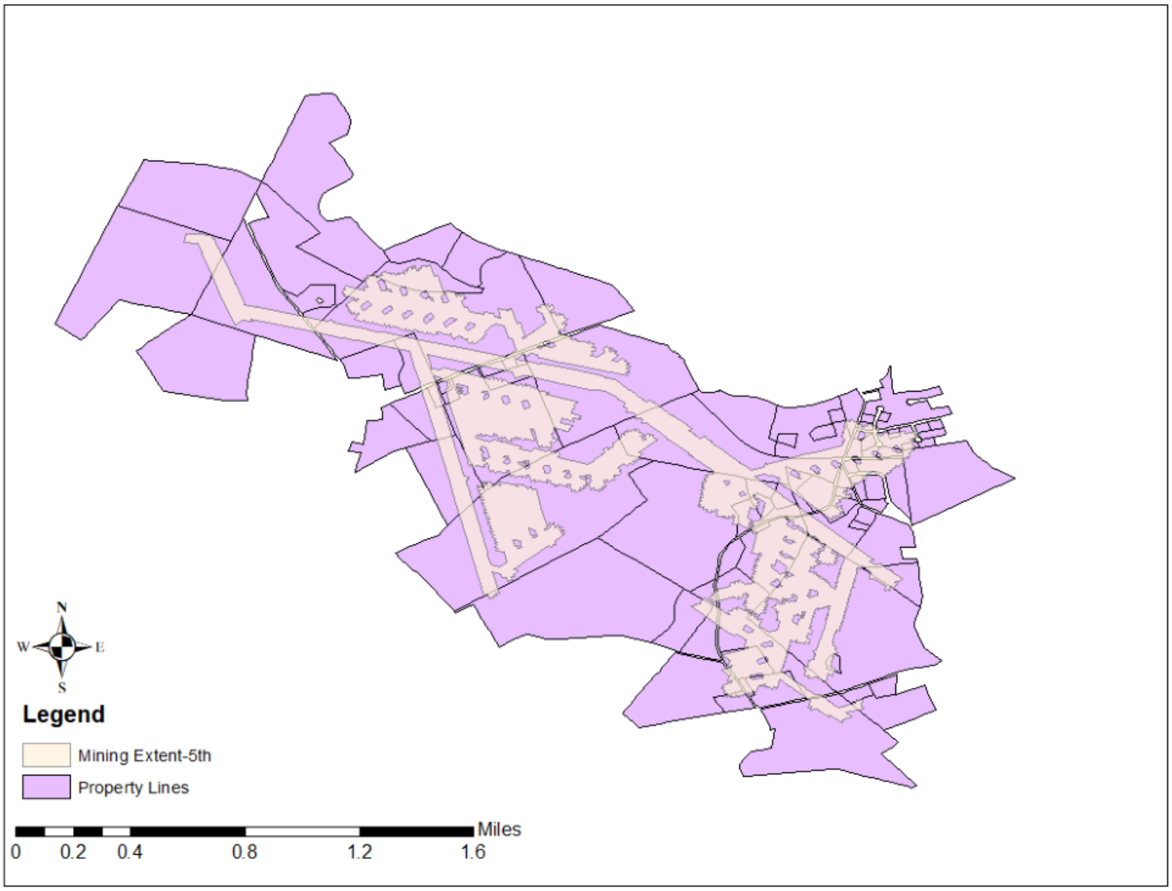

Figure 274. Properties associated with the 5th assessment period over the Parkwood Mine

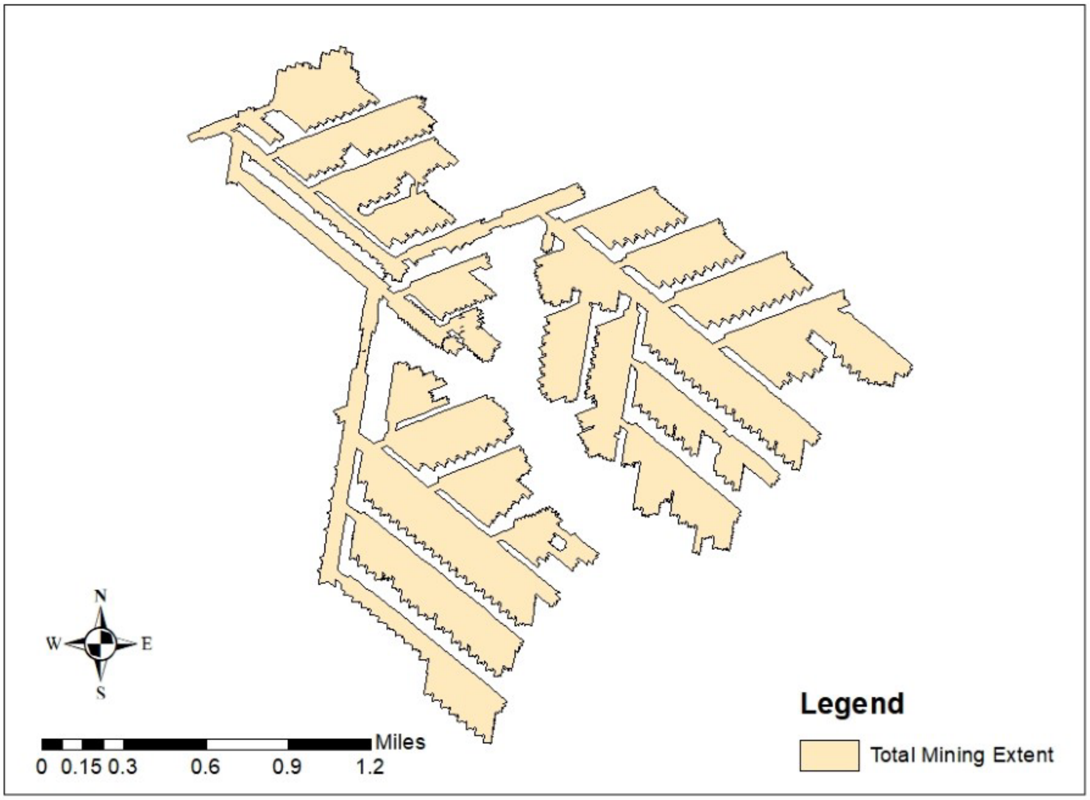

Figure 275. Penfield Mine total extent of mining

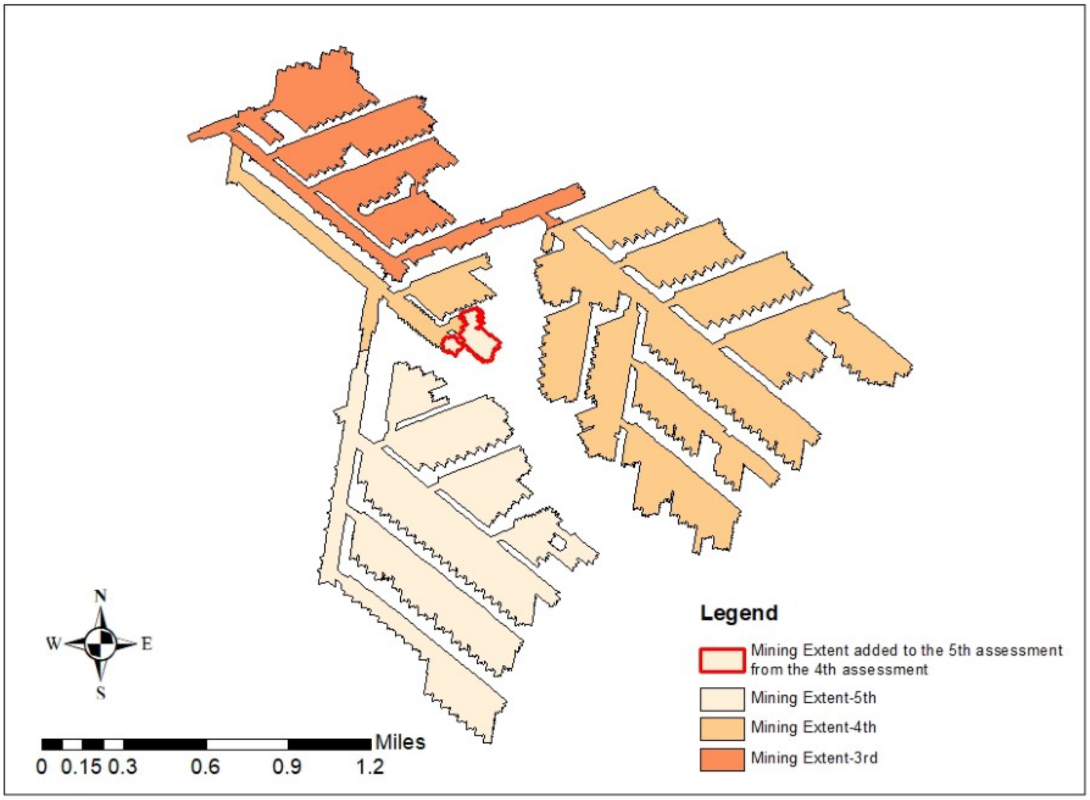

Figure 276. ***Penfield Mine mining extent for the 3rd, 4th, and 5th assessment periods****

***Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined before the 4th assessment collection period was finalized. Due to the late submission of this data and the early reporting requirements, this area was not considered during the 4th assessment period. This area is added to the 5th assessment period so that all area of the mine will be analyzed.*

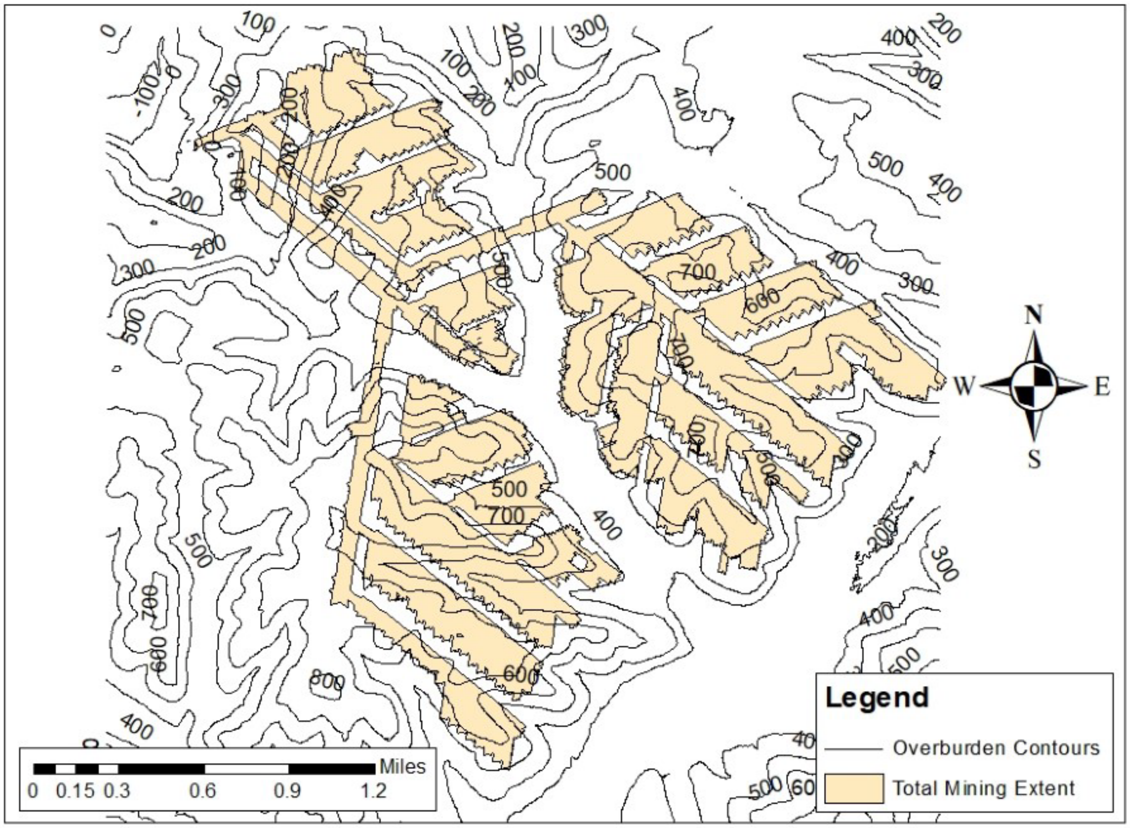

Figure 277. Fifty-foot overburden contour intervals for the Penfield Mine

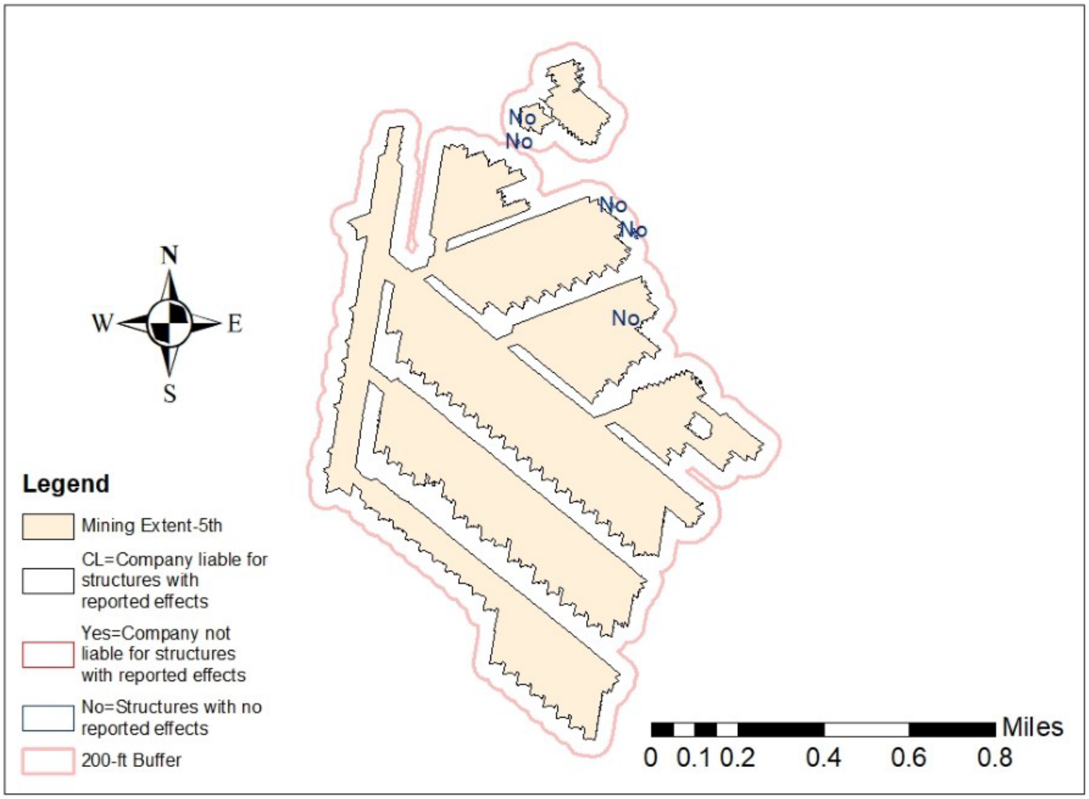

Figure 278. Penfield Mine 5th assessment 200-ft buffer and structures

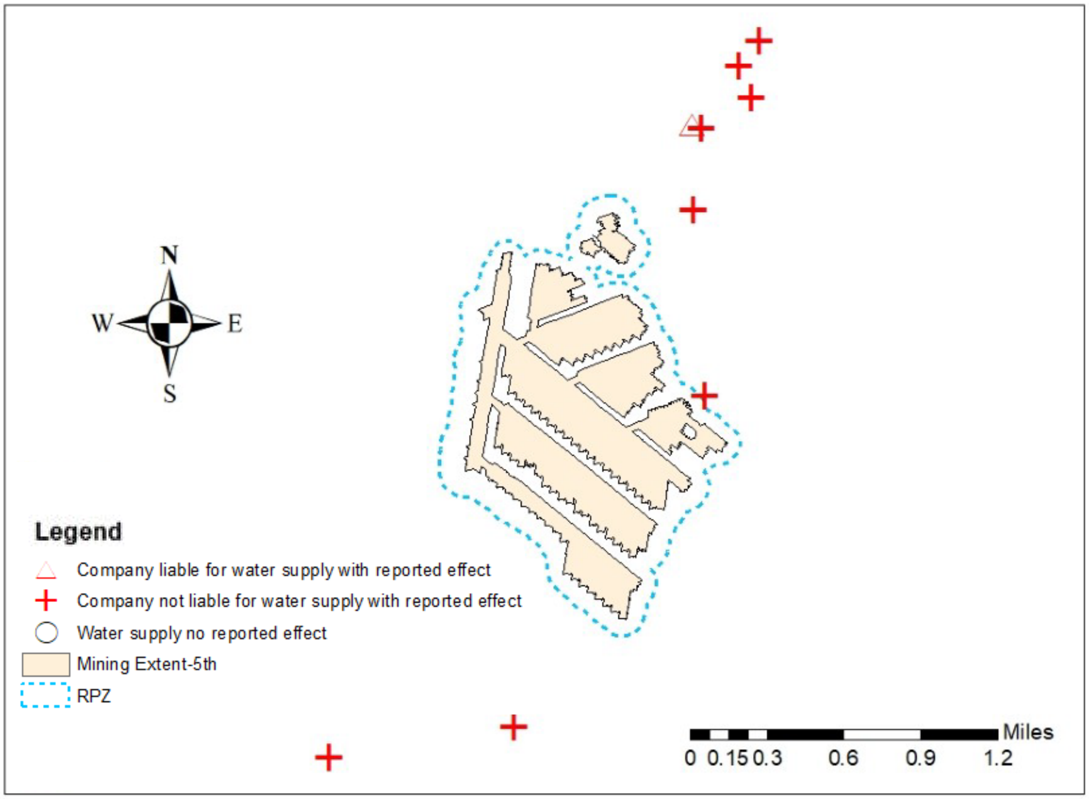

Figure 279. Penfield Mine 5th assessment water supplies and RPZ*

***Note there are two water supplies with reported effects that are far from mining and are not included here for display purposes.*

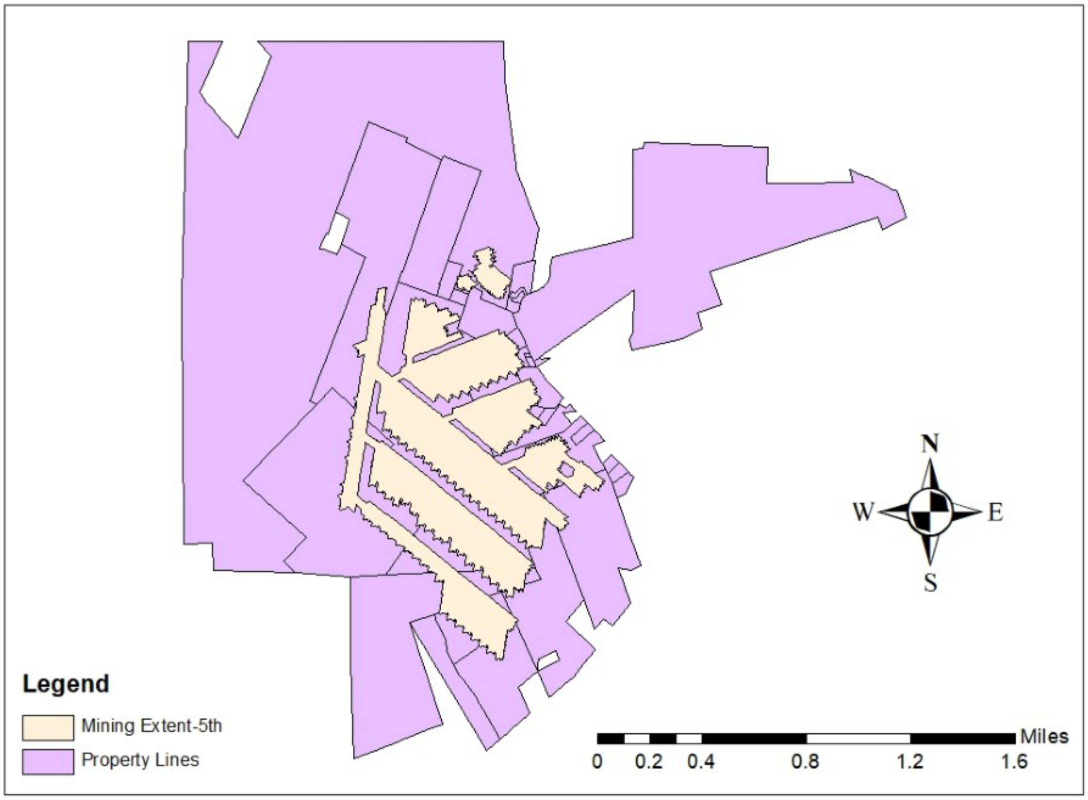

Figure 280. Properties associated with the 5th assessment period over the Penfield Mine

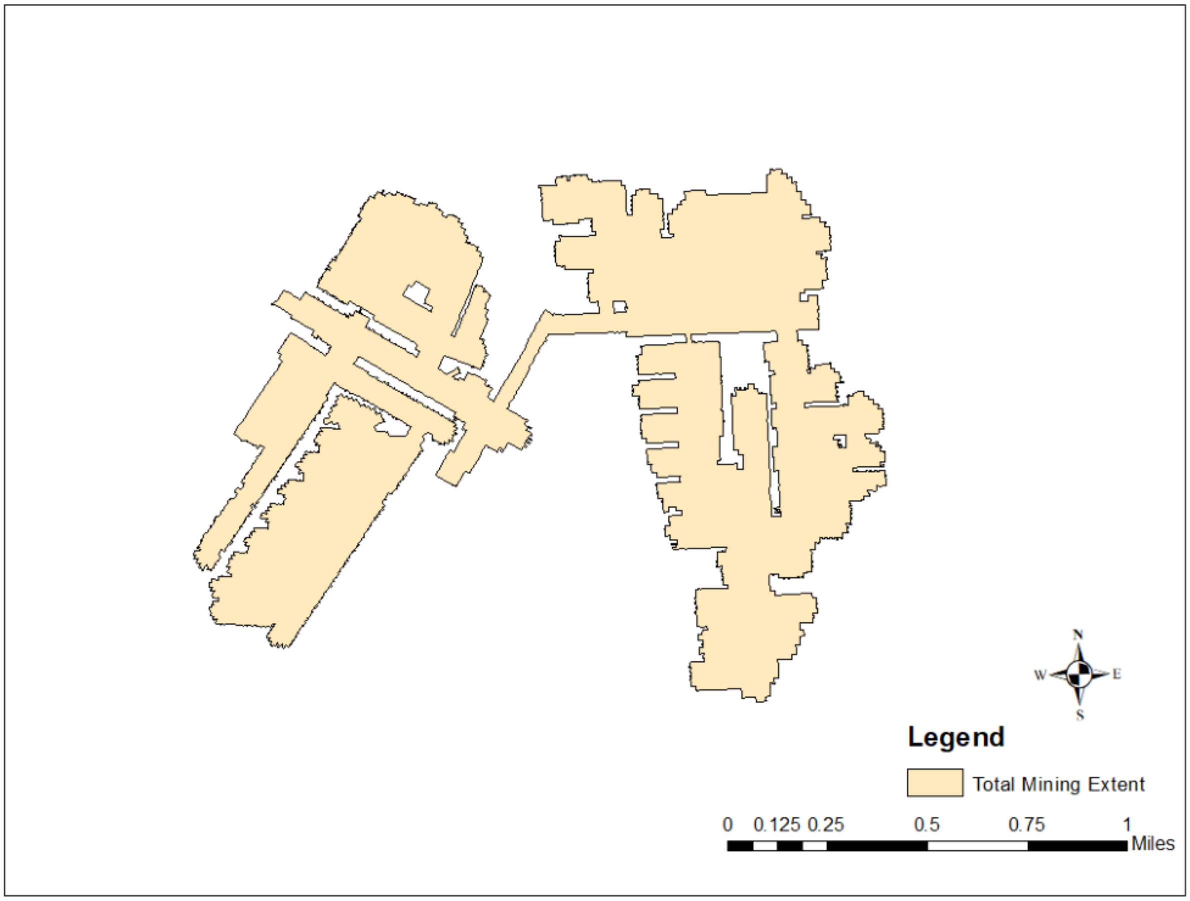

Figure 281. Roytown total extent of mining

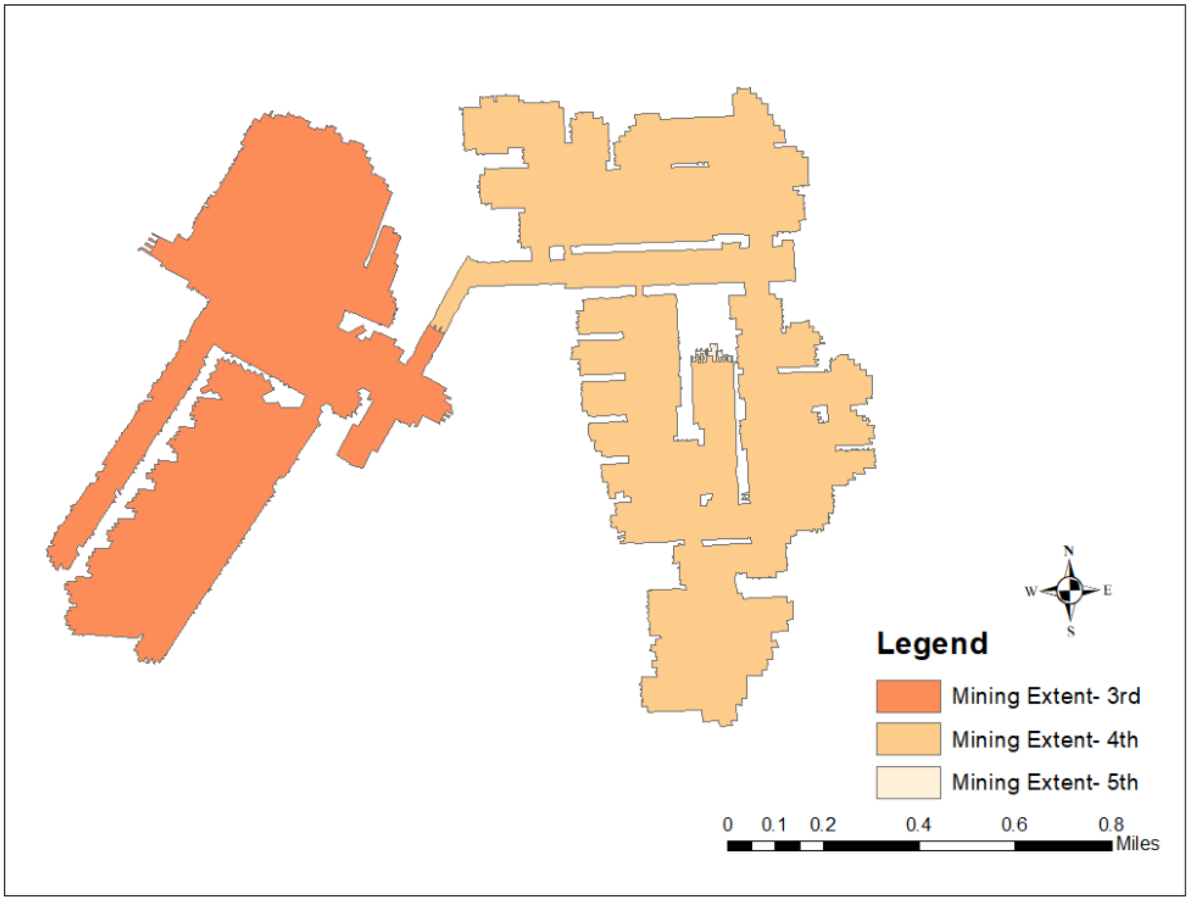

Figure 282. Roytown mining extent for the 3rd, 4th, and 5th assessment periods

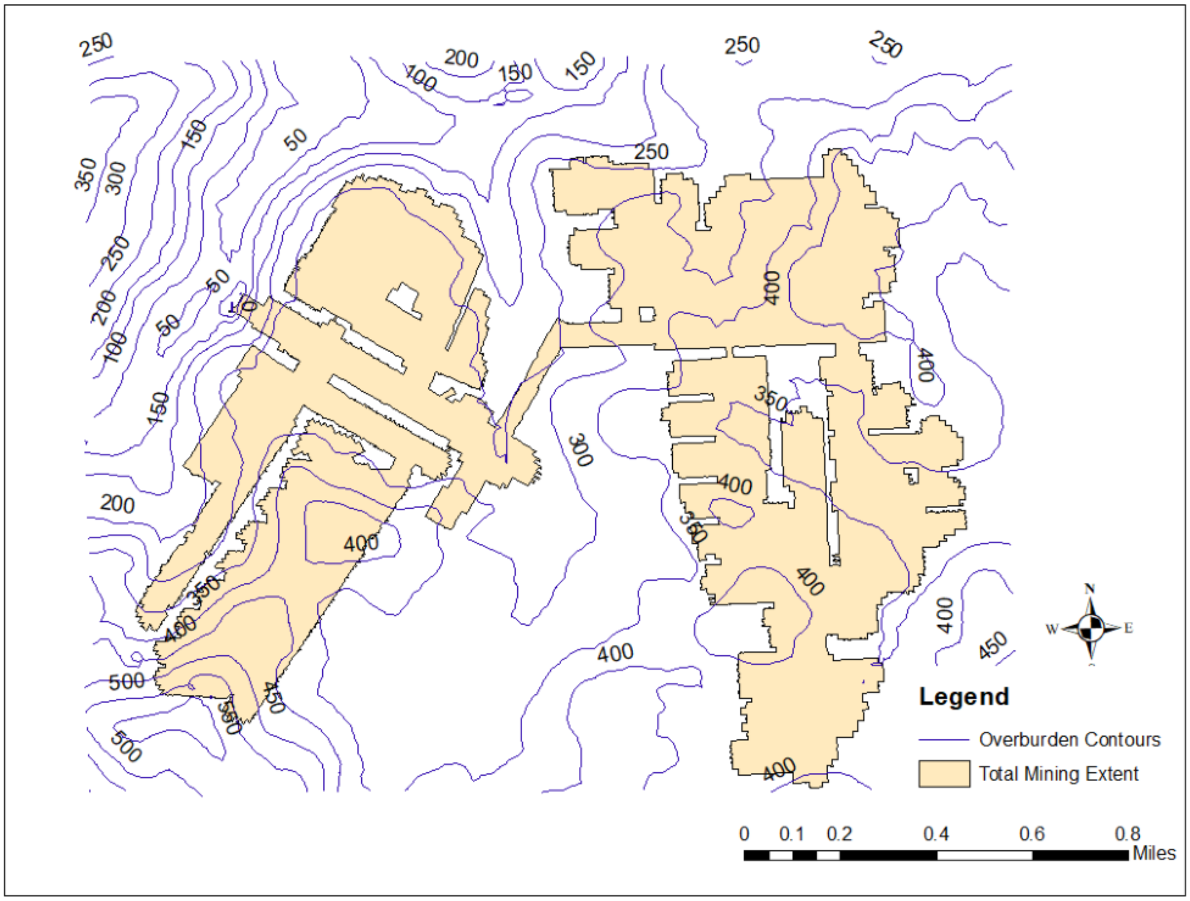

Figure 283. Fifty-foot overburden contour intervals for the Roytown mine

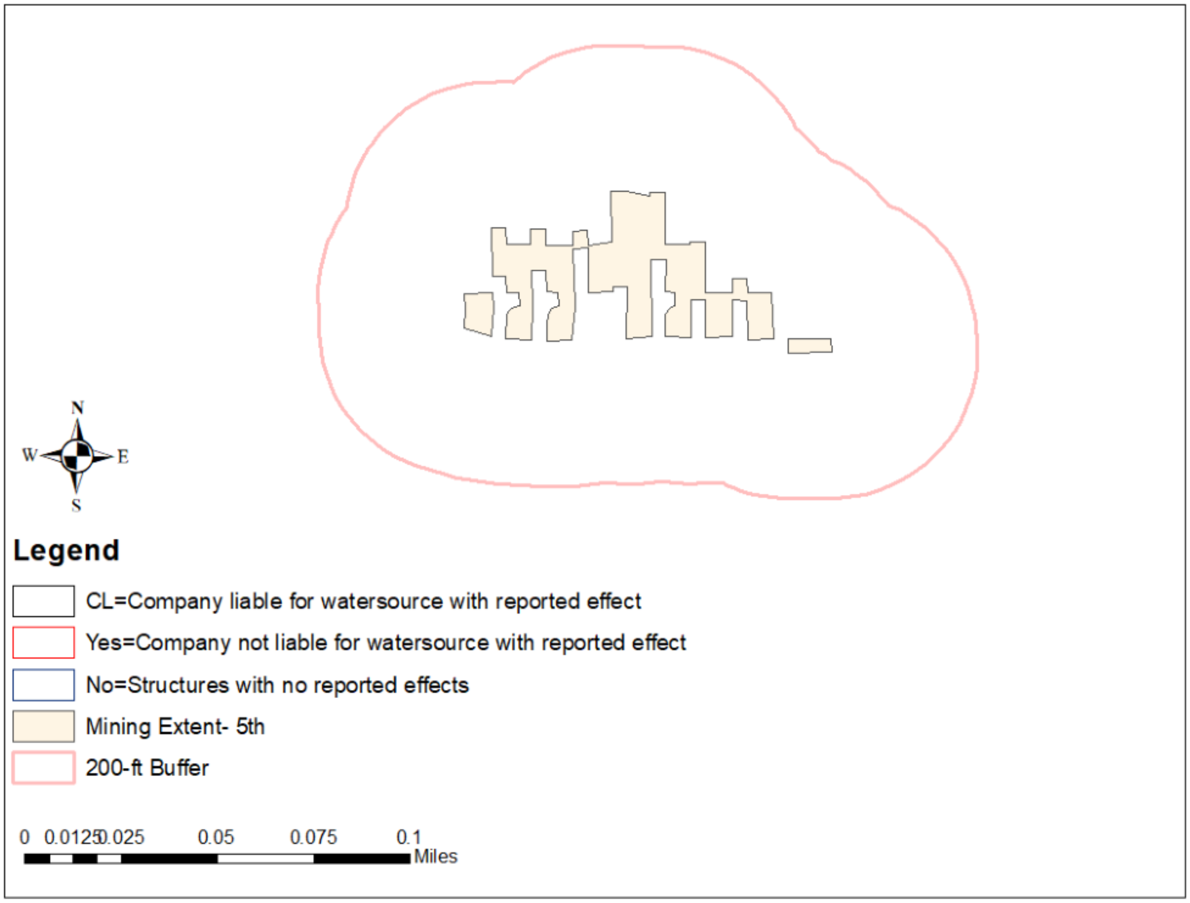

Figure 284. Roytown 5th assessment 200-ft buffer and structures

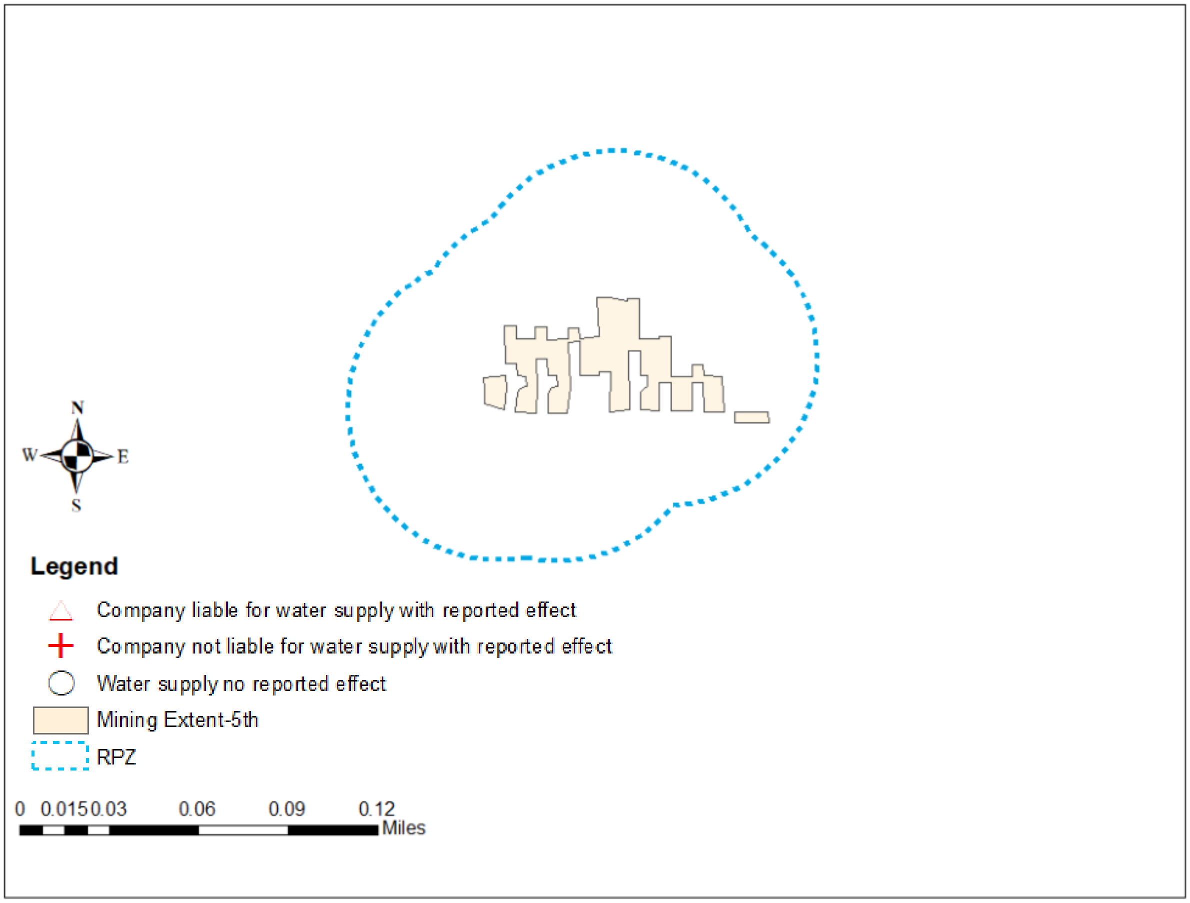

Figure 285. Roytown 5th assessment water supplies and RPZ*

**Note there is one water supply with a reported effects that is far from mining and is not included here for display purposes.*

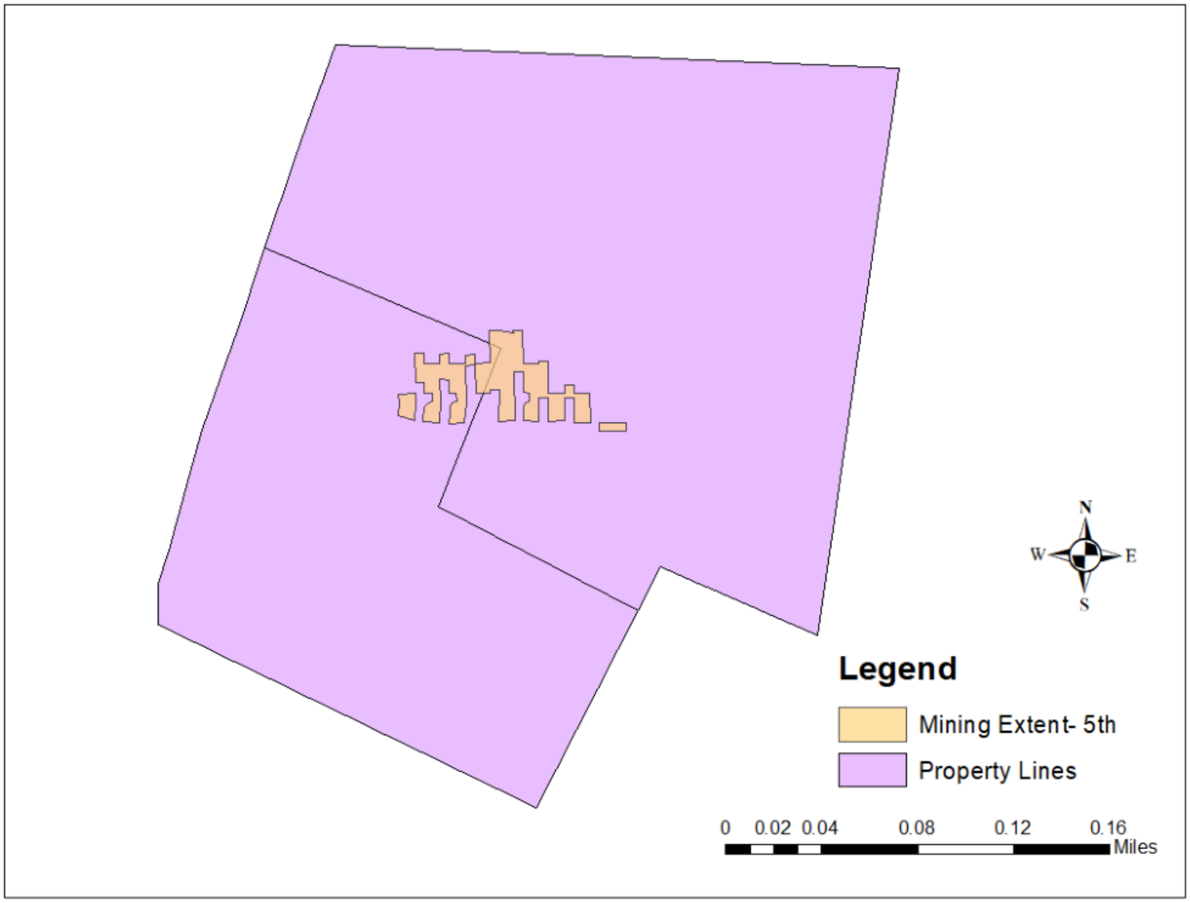

Figure 286. Properties associated with the 5th assessment period over the Roytown mine

Figure 287. Starford total extent of mining

Figure 288. Starford mining extent for the 4th and 5th assessment periods

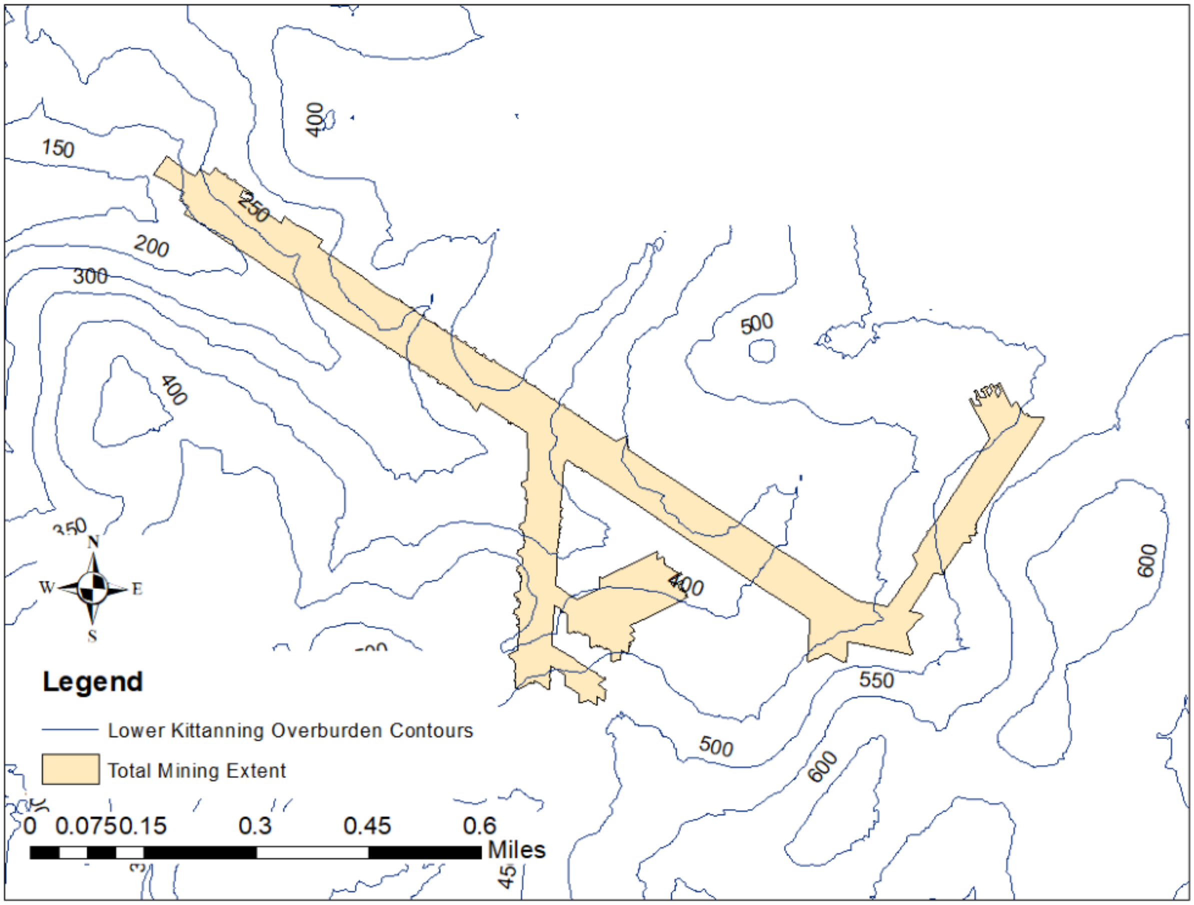

Figure 289. Fifty-foot overburden contour intervals for the Starford Mine

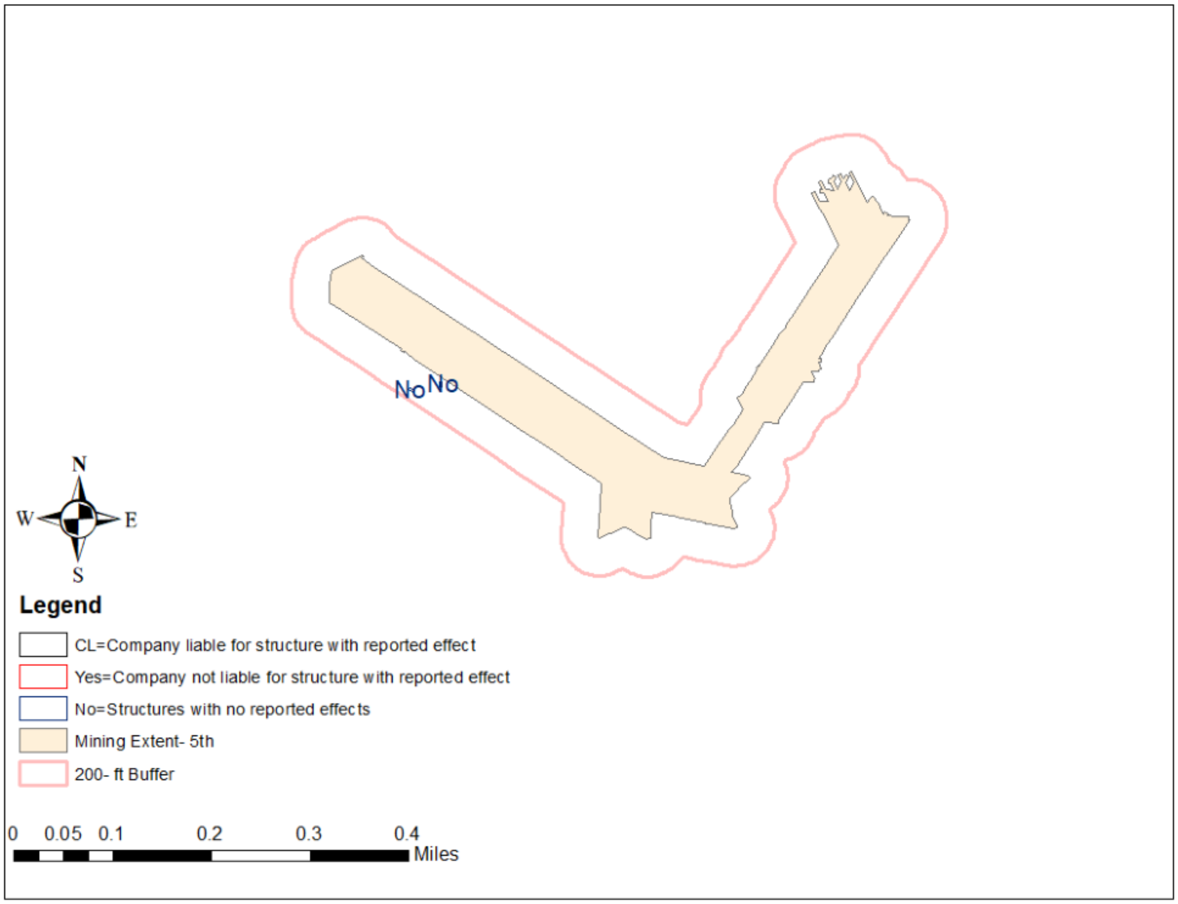

Figure 290. Starford 5th assessment 200-ft buffer and structures*

**Note there is one structure with a reported effect that is far from mining and is not included here for display purposes.*

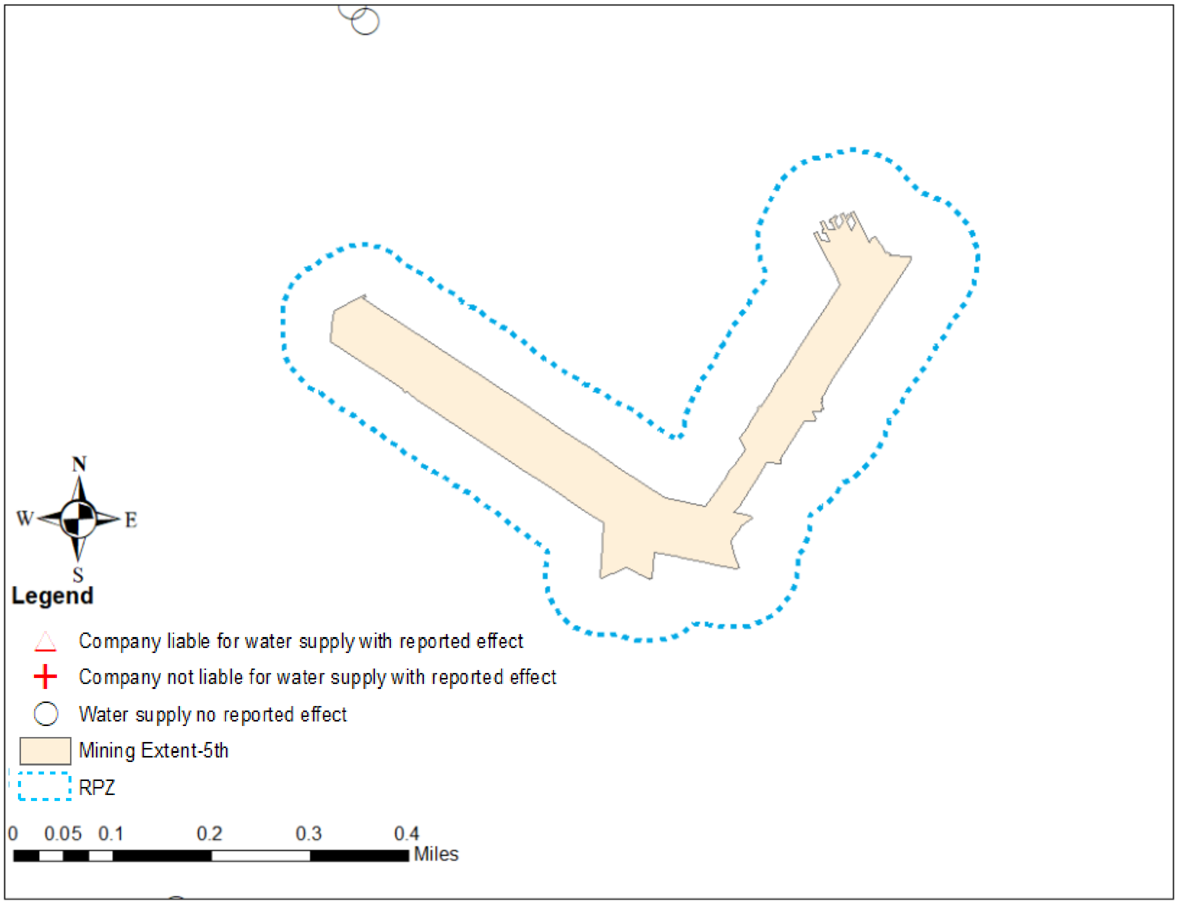

Figure 291. Starford 5th assessment water supplies and RPZ

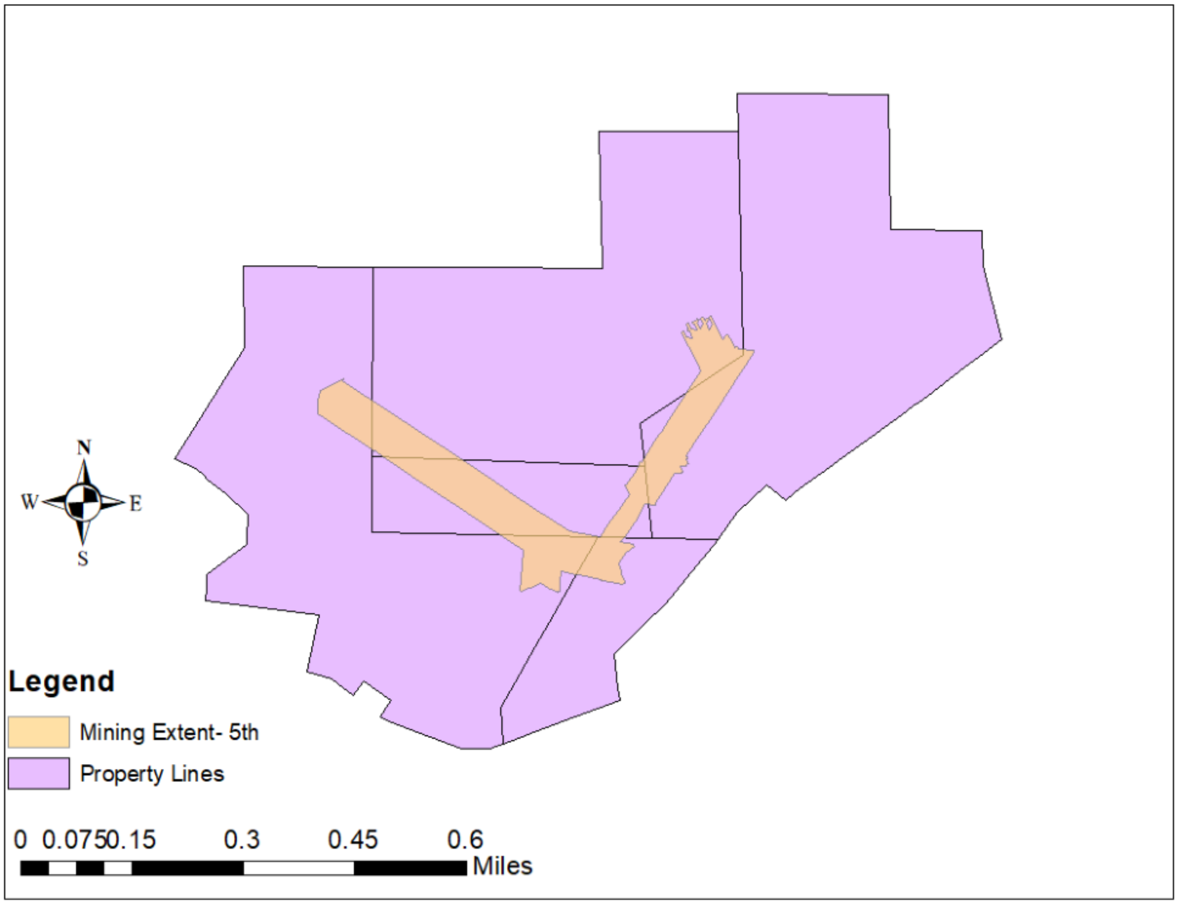

Figure 292. Properties associated with the 5th assessment period over the Starford Mine

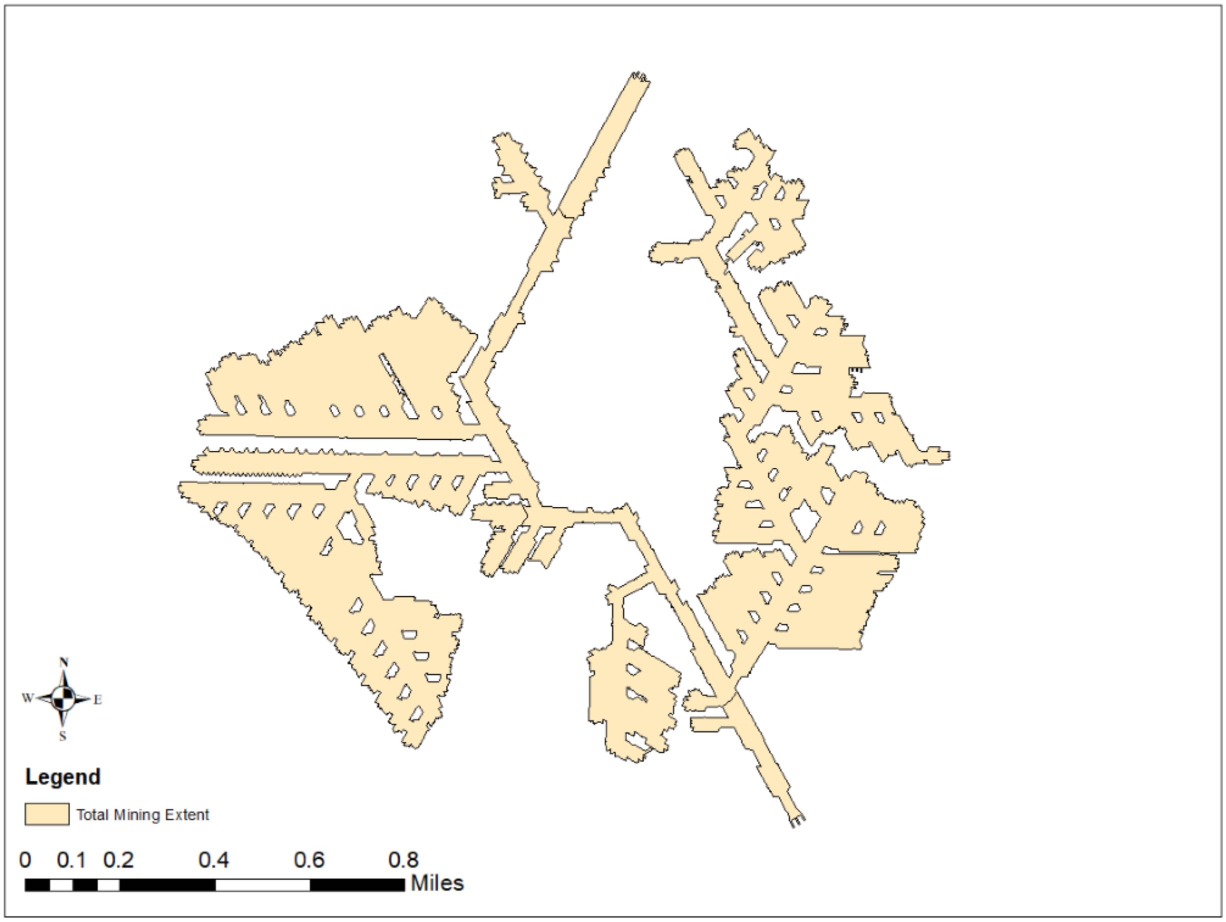

Figure 293. TJs No. 6 total extent of mining

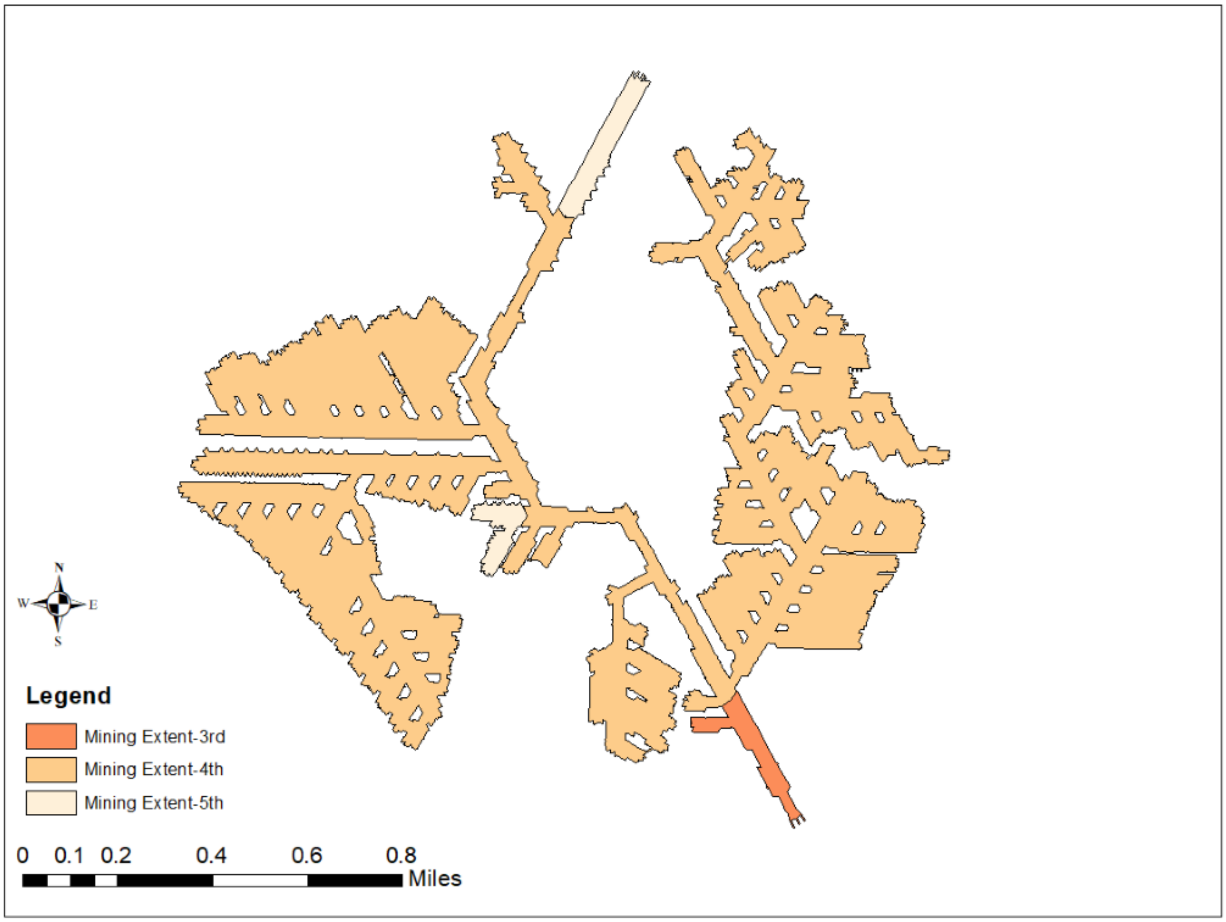

Figure 294. TJs No. 6 mining extent for the 3rd, 4th, and 5th assessment periods

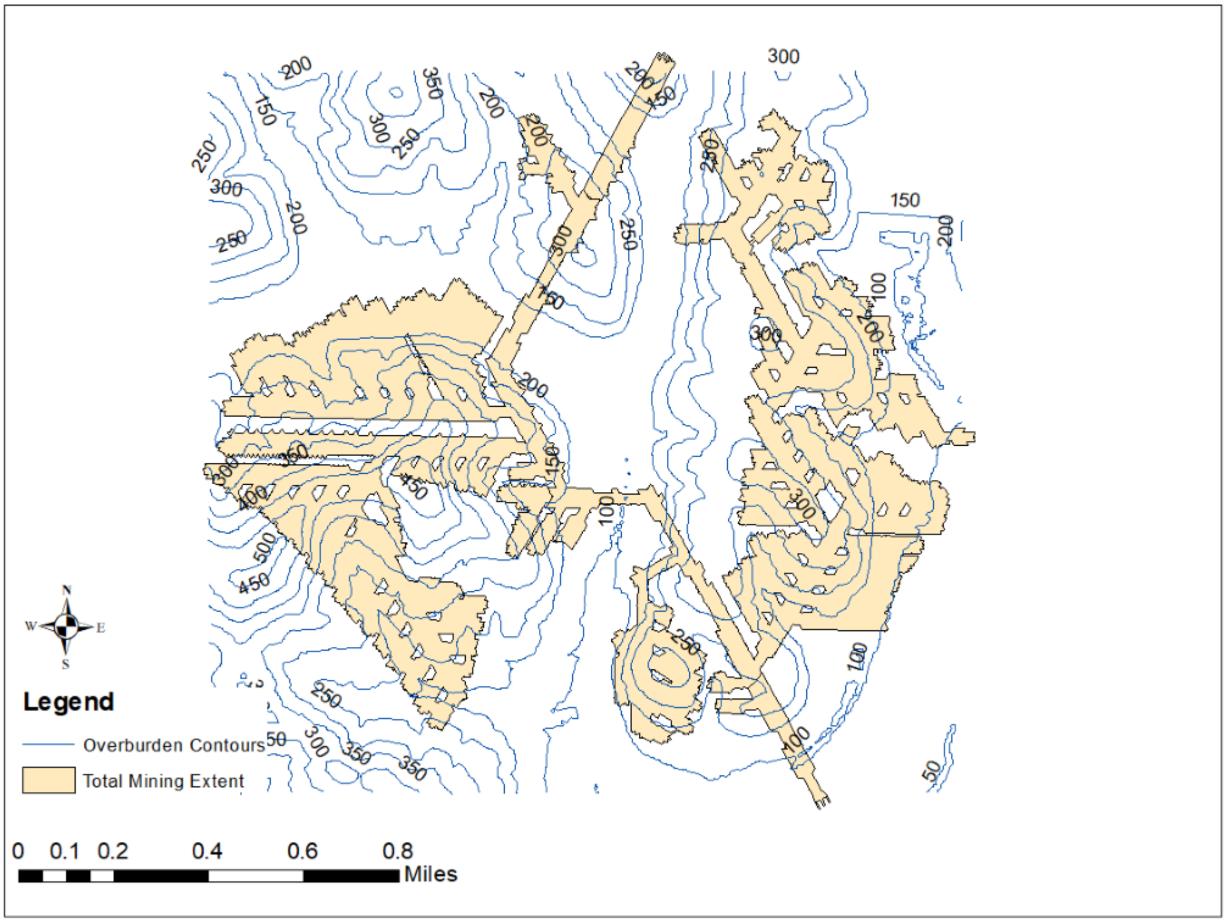

Figure 295. Fifty-foot overburden contour intervals for the TJs No. 6 Mine

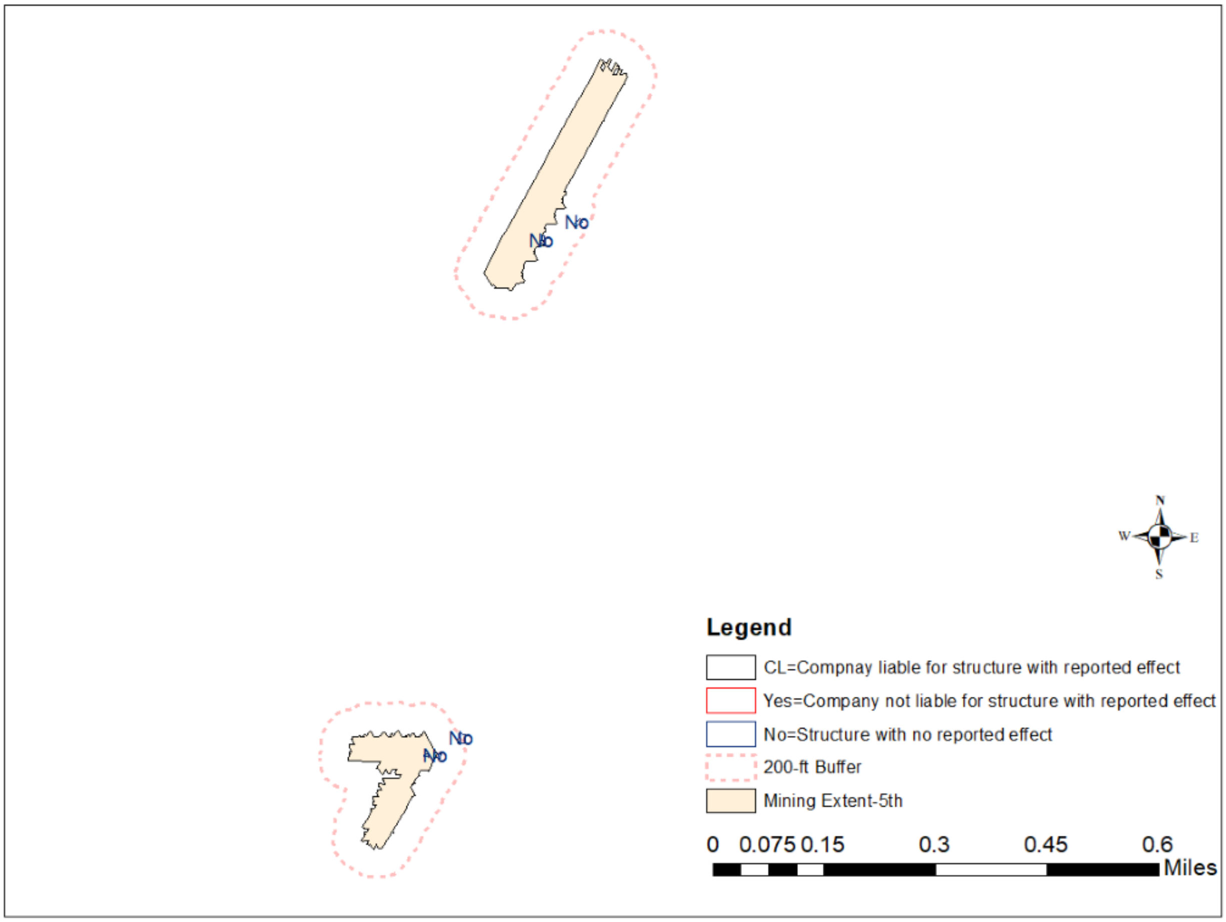

Figure 296. TJs No. 6 5th assessment 200-ft buffer and structures

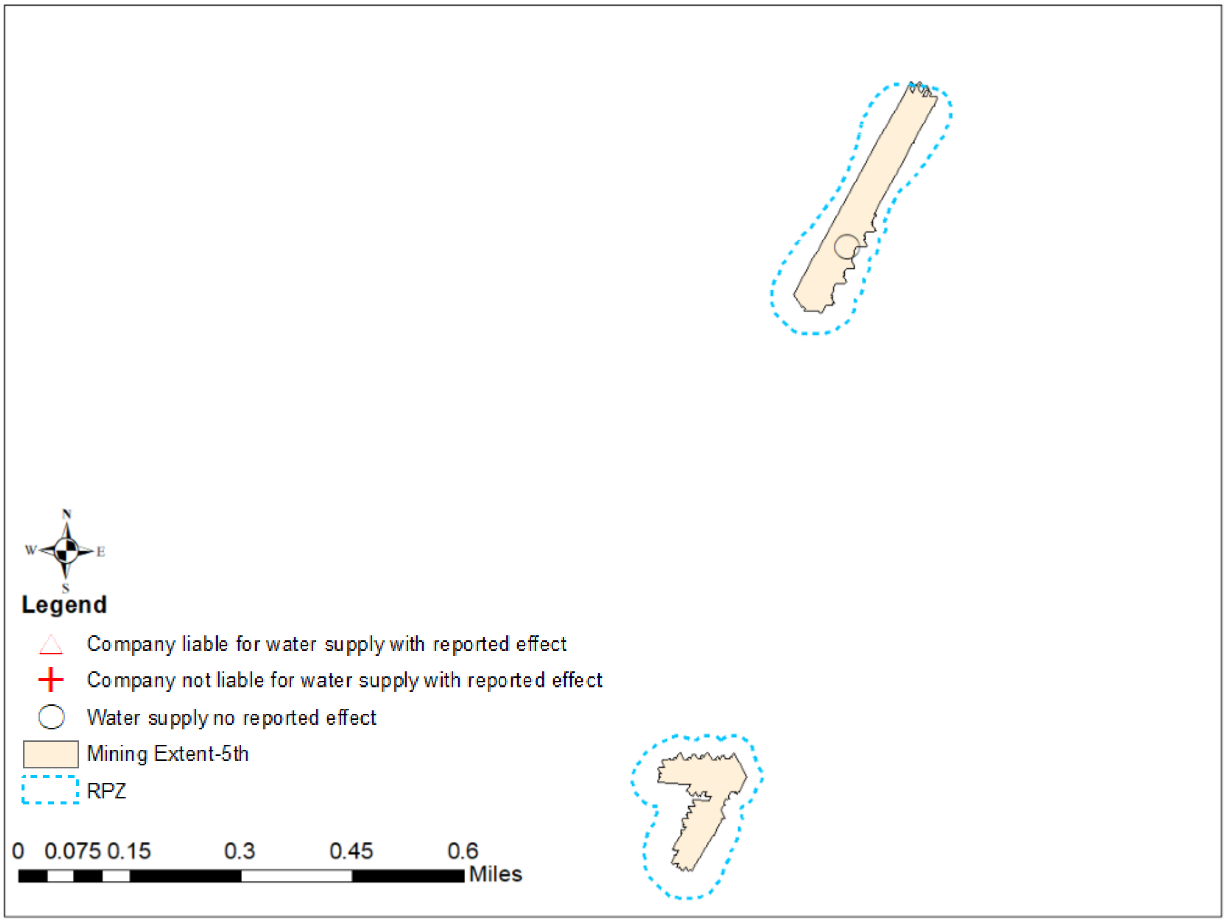

Figure 297. TJs No. 6 Mine 5th assessment water supplies and RPZ

Figure 298. Properties associated with the 5th assessment period over the TJs No. 6 Mine

Figure 299. Tom's Run total extent of mining

Figure 300. Tom's Run mining extent for the 3rd, 4th, and 5th assessment periods

Figure 301. Tom's Run mining extent for the 3rd, 4th, and 5th assessment periods*

***Note the area labeled "Mining Extent added to the 5*th *assessment from the 4*th *assessment" outlined in red was mined in July 2013, a month before the 4*th *assessment collection period was finalized. Due to the late submission of this data and the early reporting requirements, this area was not considered during the 4th assessment period. This area is added to the 5*th *assessment period so that all area of the mine will be analyzed.*

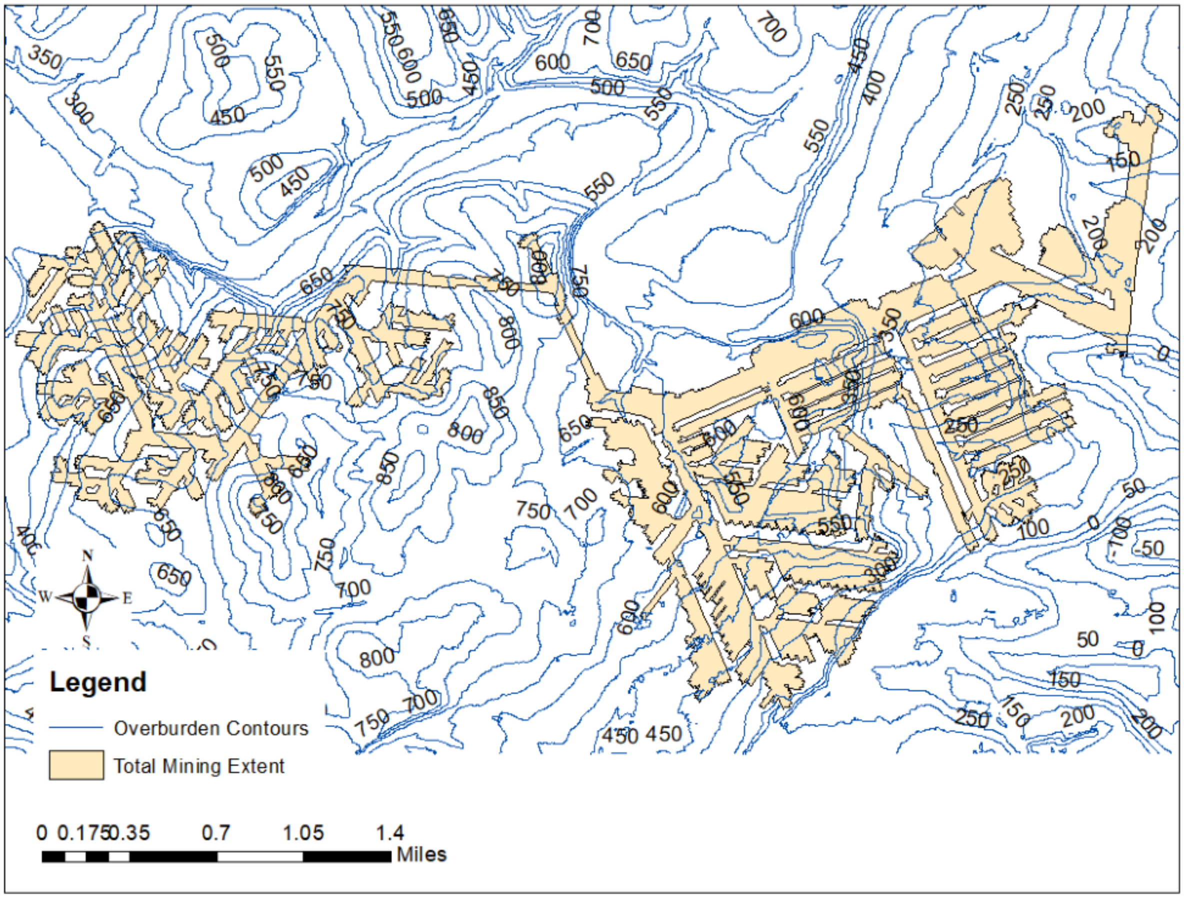

Figure 302. Fifty-foot overburden contour intervals for the Tom's Run Mine

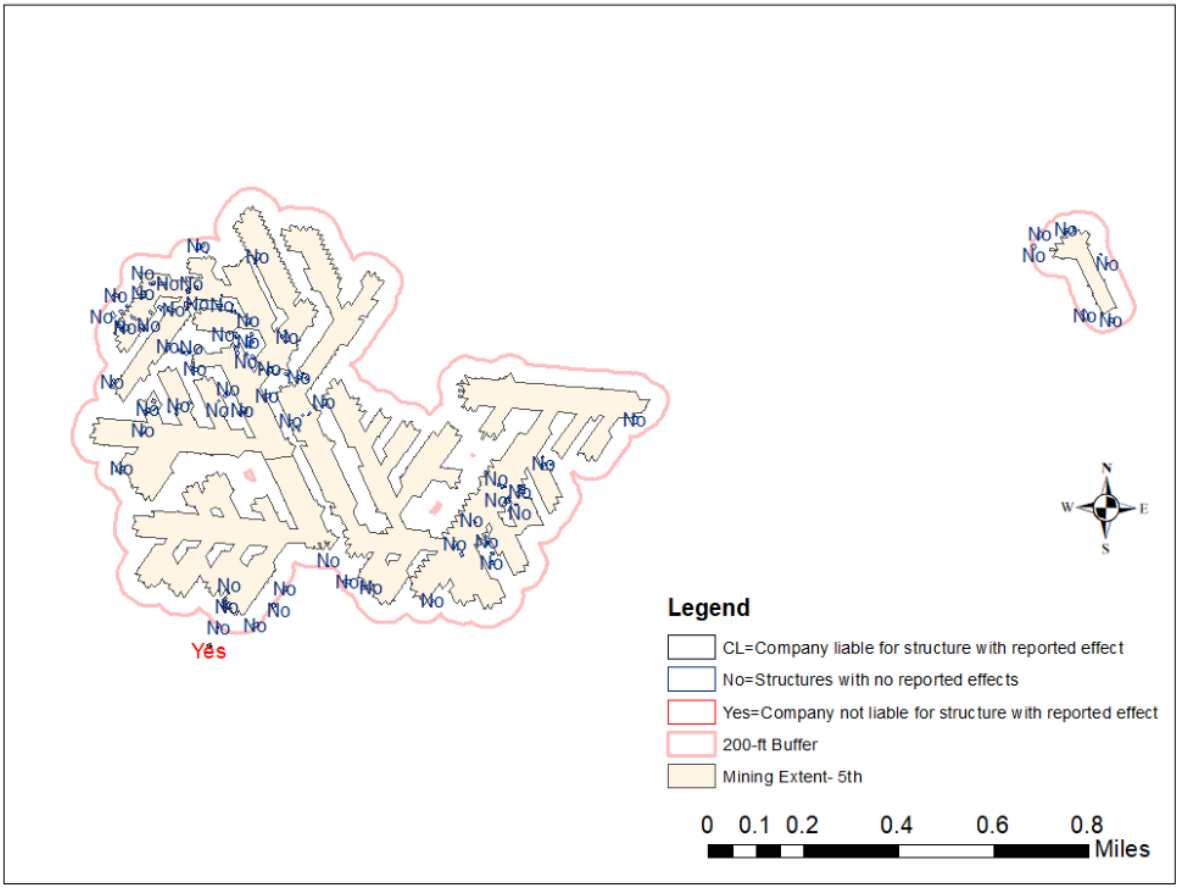

Figure 303. Tom's Run 5th assessment 200-ft buffer and structures*

Note there is one structures with a reported effect that is far from mining and is not included here for display purposes.

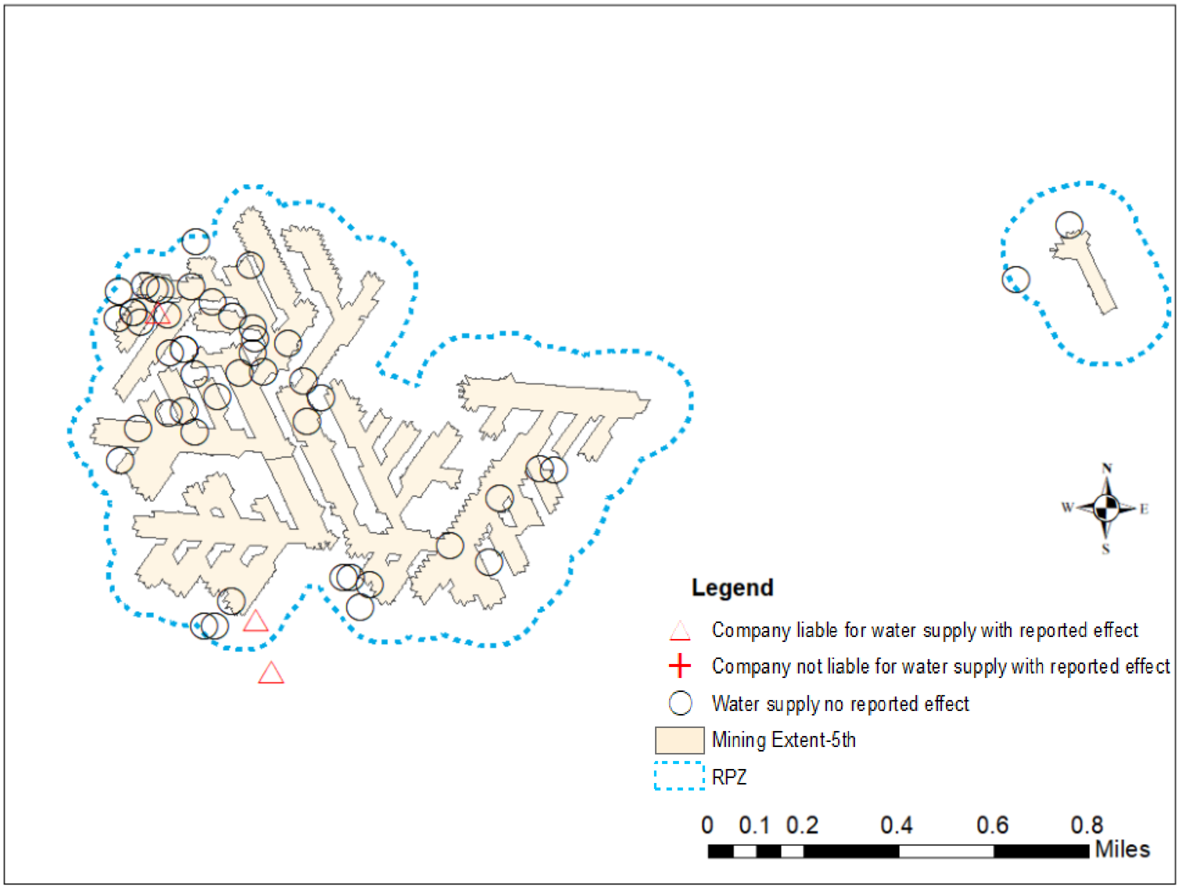

Figure 304. Tom's Run's 5th assessment water supplies and RPZ*

**Note there are three water supplies with reported effects that are far from mining and are not included here for display purposes.*

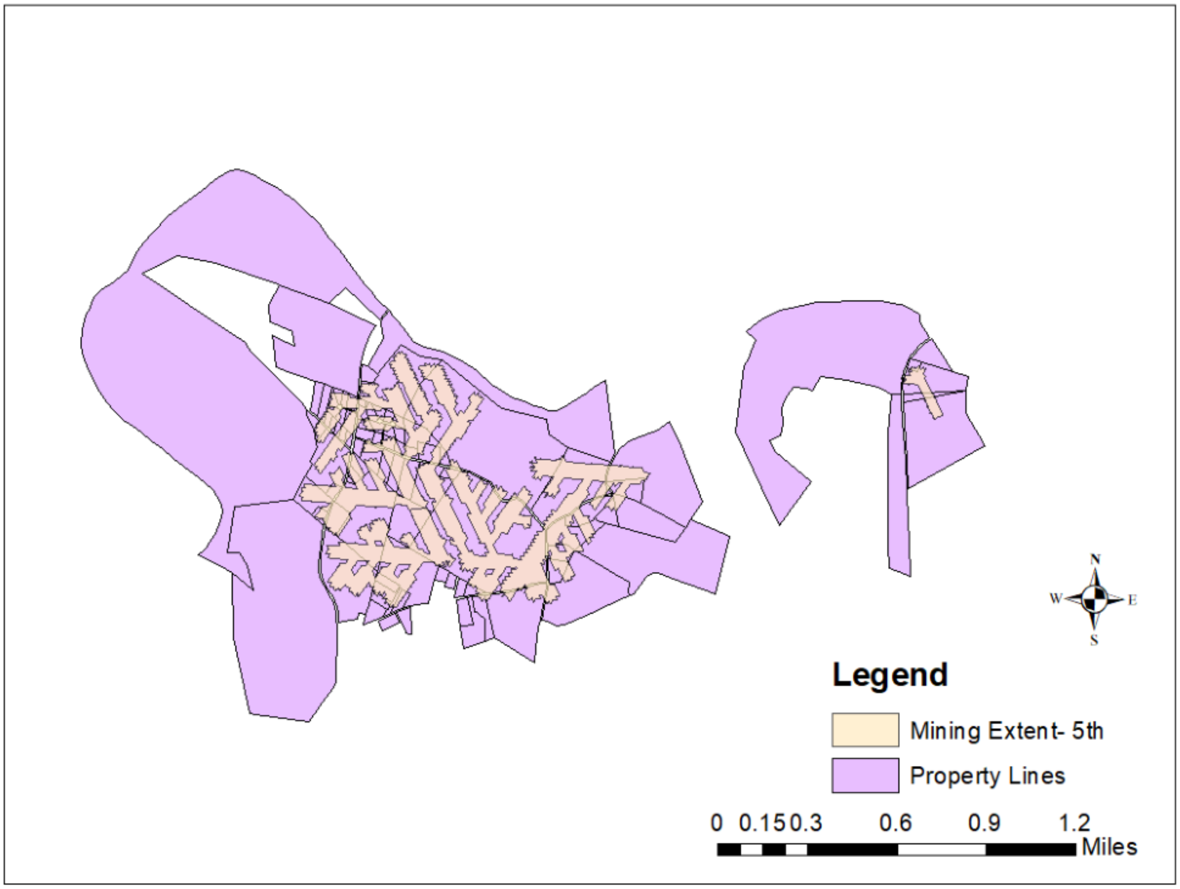

Figure 305. Properties associated with the 5th assessment period over the Tom's Run mine

Figure 306. Tracy Lynne total extent of mining

Figure 307. Tracy Lynne mining extent for the 3rd, 4th, and 5th assessment periods

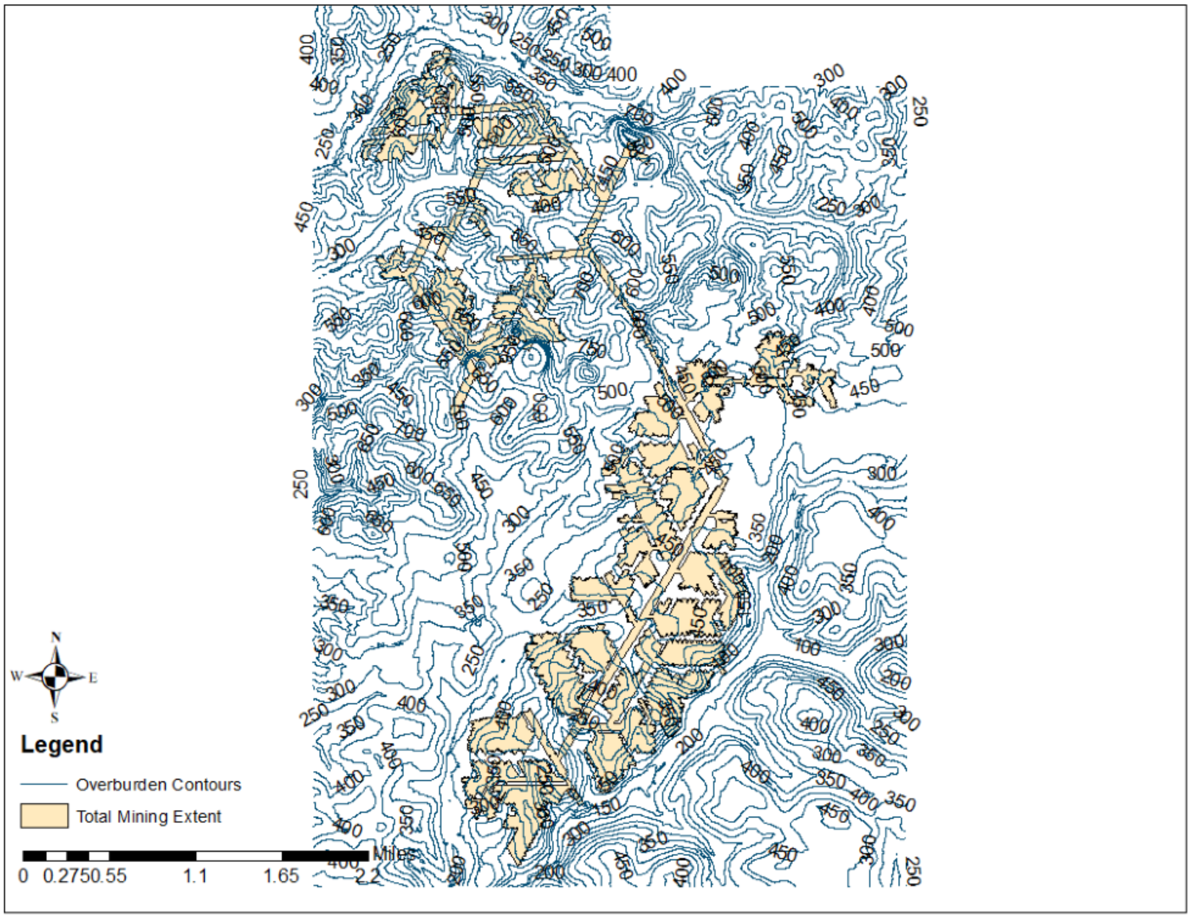

Figure 308. Fifty-foot overburden contour intervals for the Tracy Lynne Mine

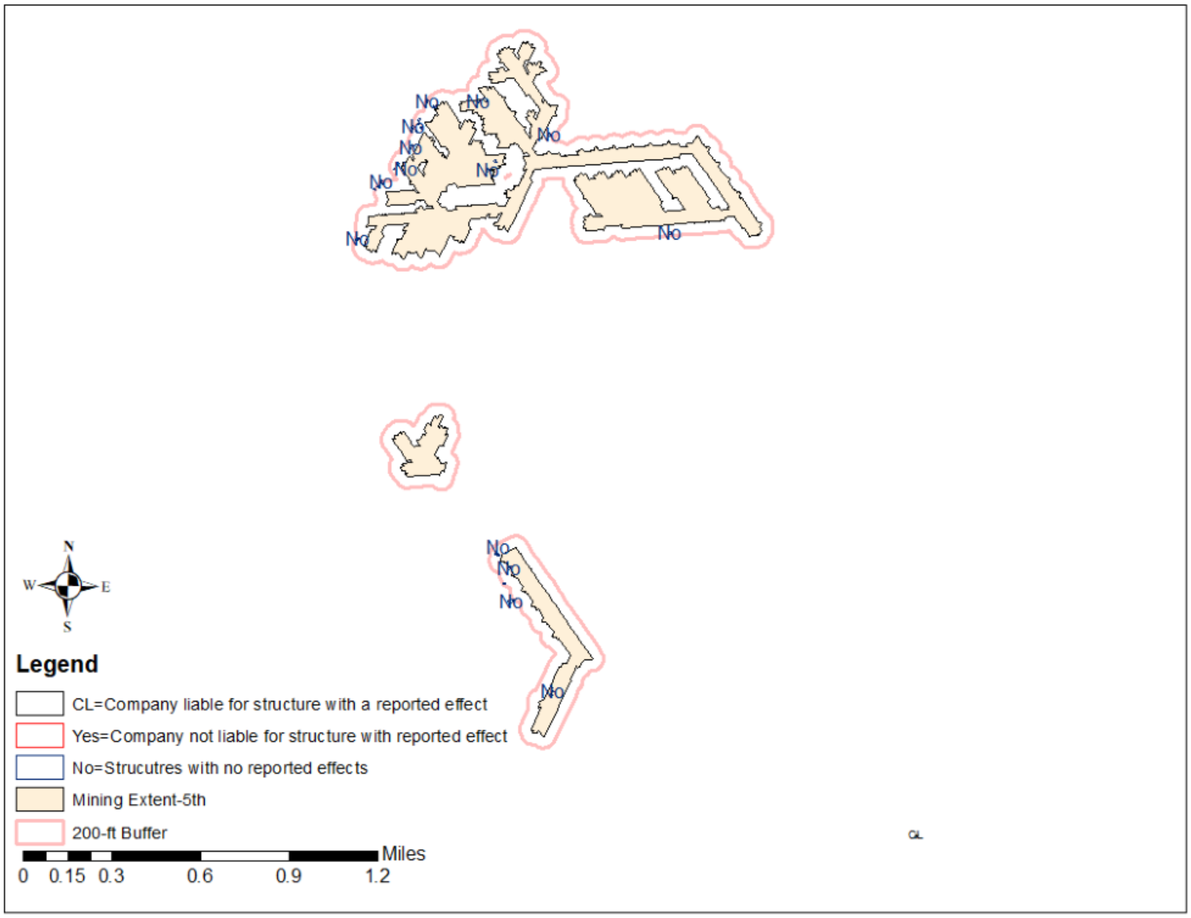

Figure 309. Tracy Lynne 5th assessment 200-ft buffer and structures*

*****_Note there are three structure with reported effects that are far from mining and are not included here for display purposes._

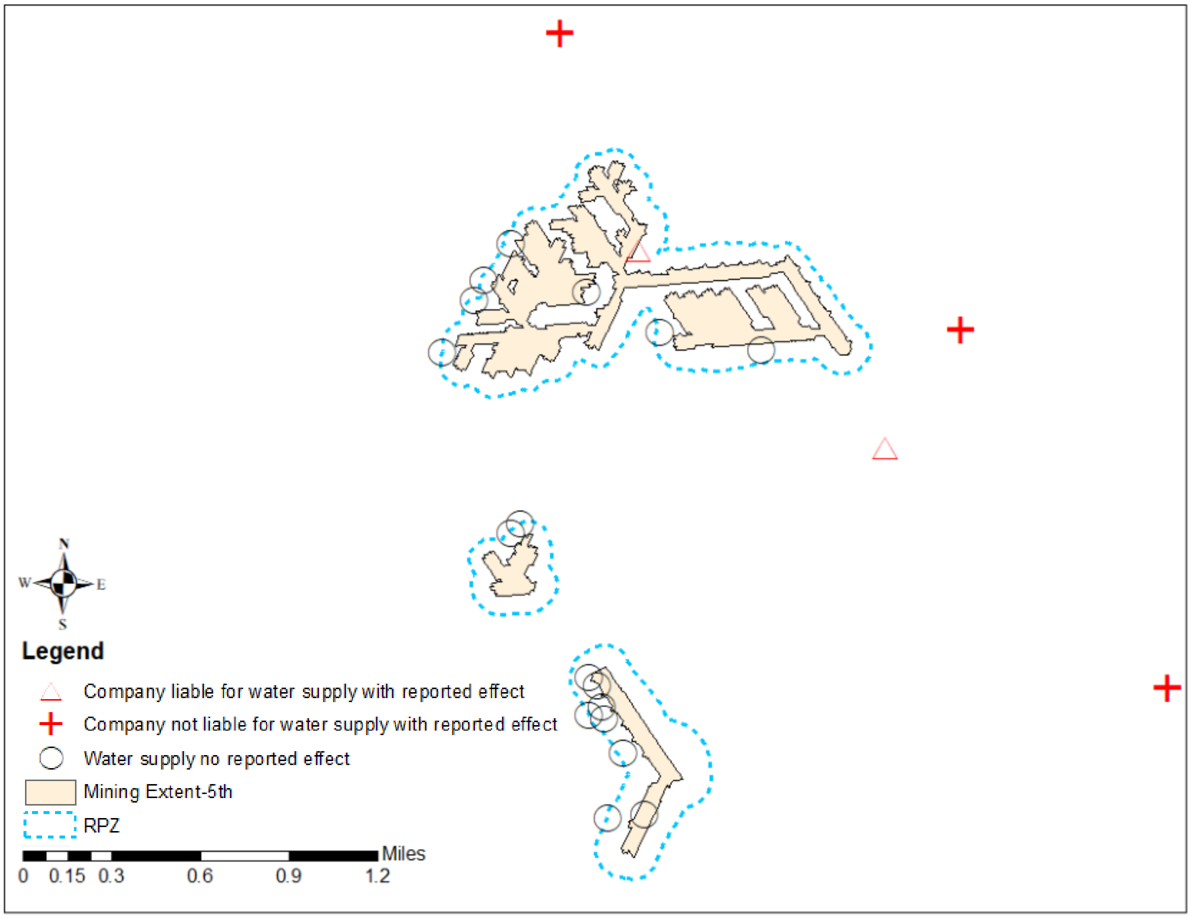

Figure 310. Tracy Lynne Mine 5th assessment water supplies and RPZ

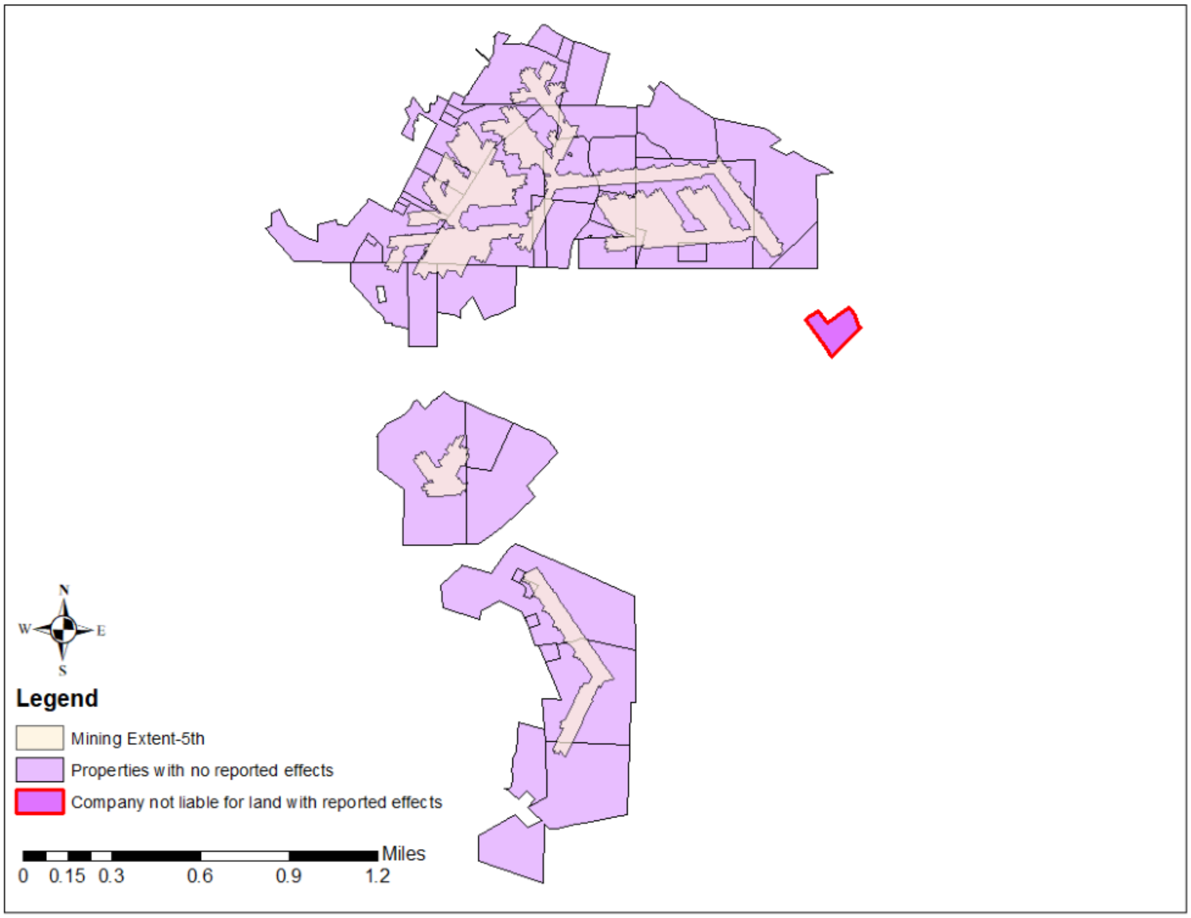

Figure 311. Properties associated with the 5th assessment period over the Tracy Lynne Mine

Figure 312. Kimberly Run total extent of mining

Figure 313. Kimberly Run mining extent for the 4th and 5th assessment periods

Figure 314. Kimberly mining extent for the 4th and 5th assessment periods*

***** *Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined in April 2008- January 2009. Due to overlooking of the mining done in the 4th assessment period, this area was not considered during the 4th assessment periods. This area is added to the 5th assessment period so that all area of the mine will be analyzed. Only the area of the mine from the 4th assessments, the structures, water supplies, and land with no reported effects are added to this assessment. All structures, water supplies, and land with reported effects were assumed to be accounted for in the 4th assessment.*

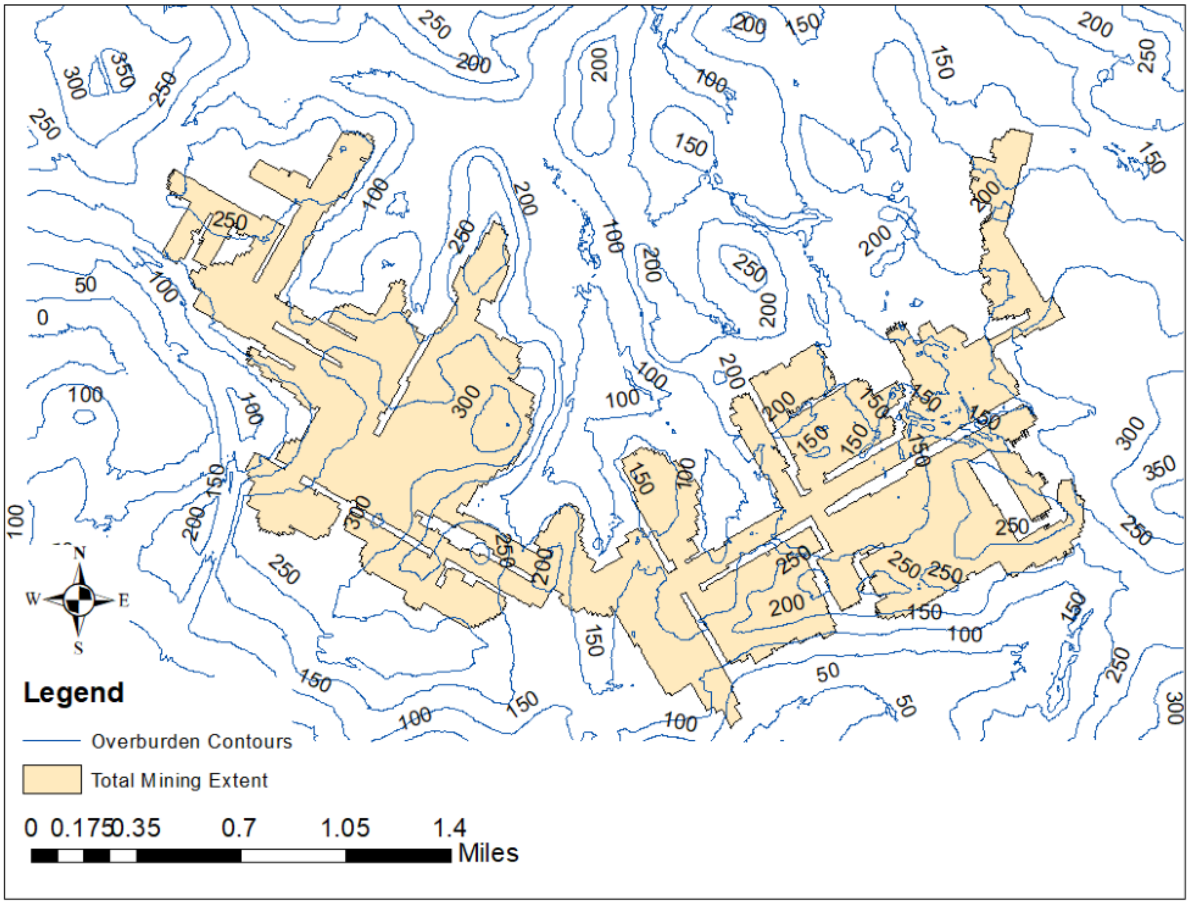

Figure 315. Fifty-foot overburden contour intervals for the Kimberly Run mine

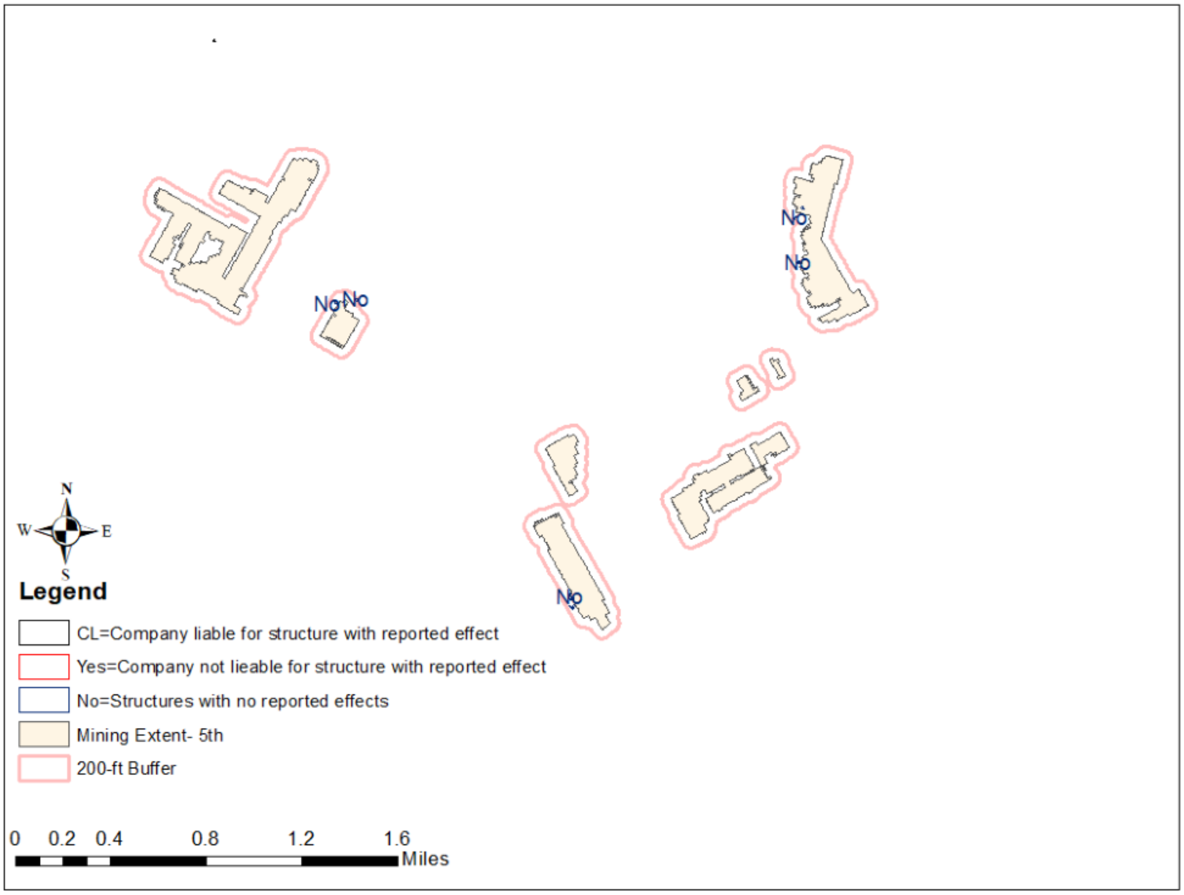

Figure 316. Kimberly Run 5th assessment 200-ft buffer and structures

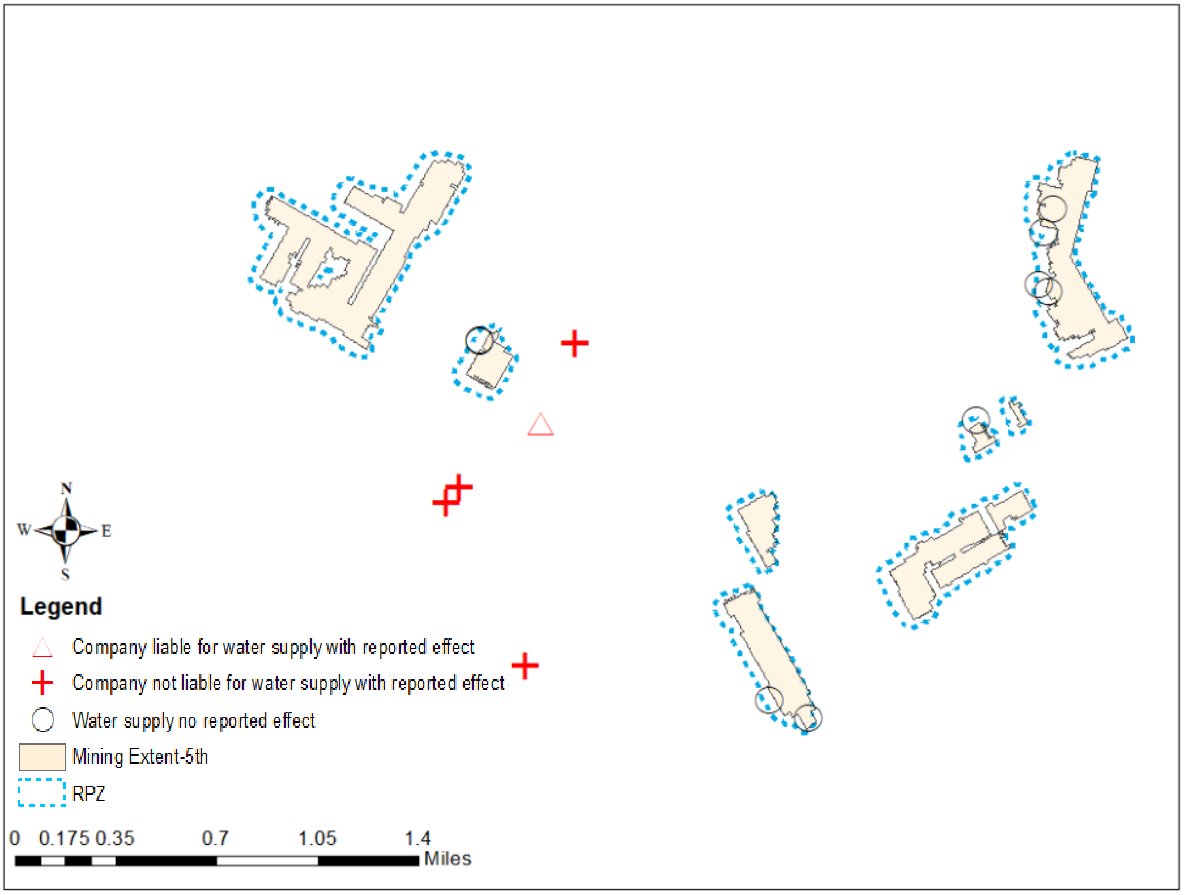

Figure 317. Kimberly Run 5th assessment water supplies and RPZ

Figure 318. Properties associated with the 5th assessment period over the Kimberly Run mine

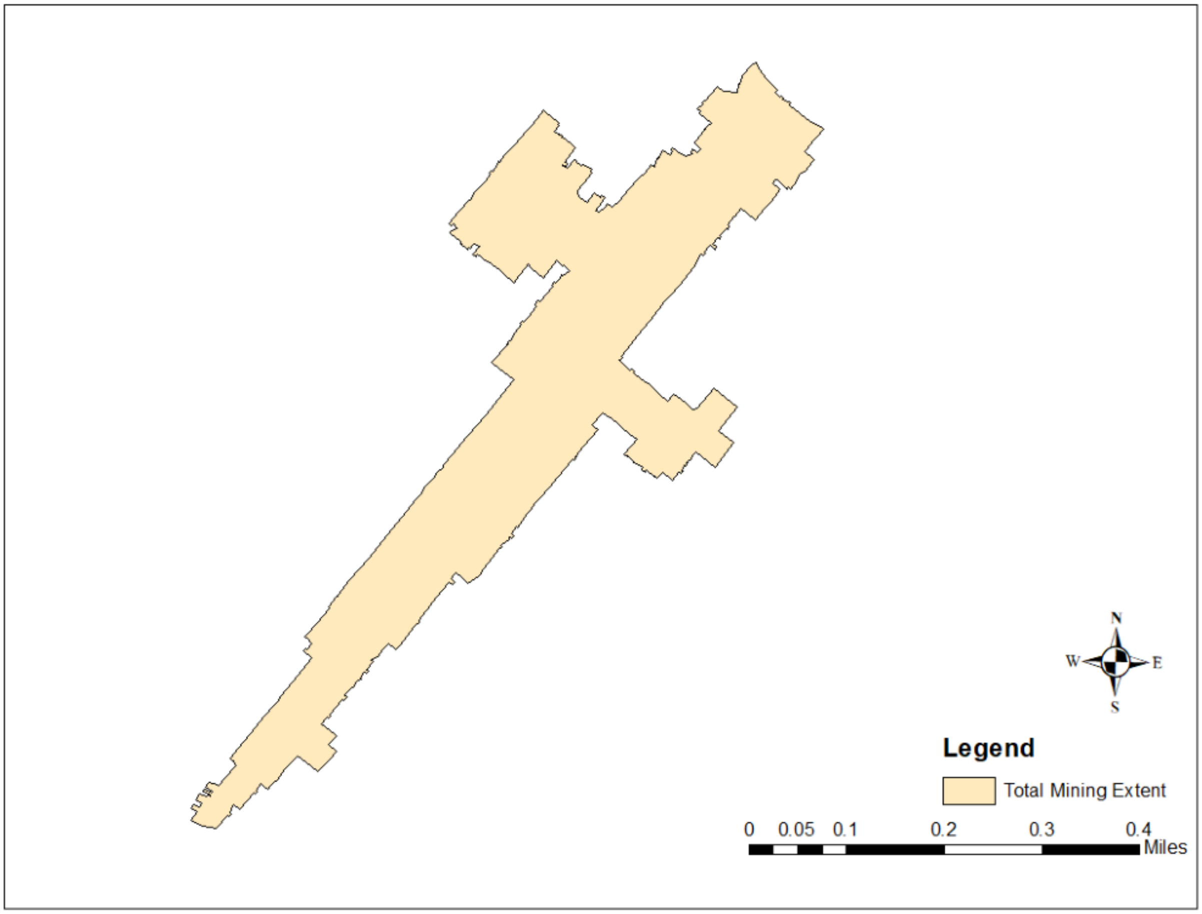

Figure 319. Kingston West total extent of mining

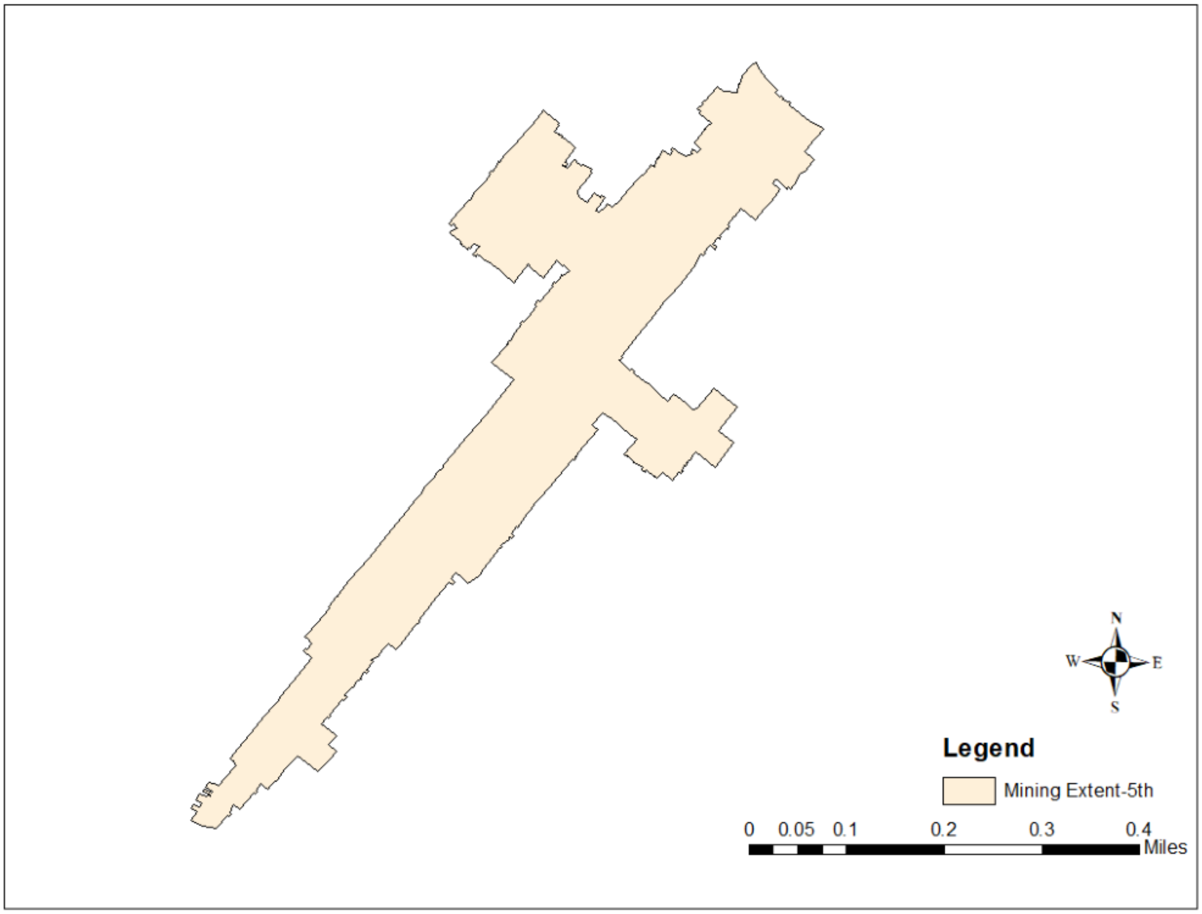

Figure 320. Kingston West mining extent for the 3rd, 4th, and 5th assessment periods

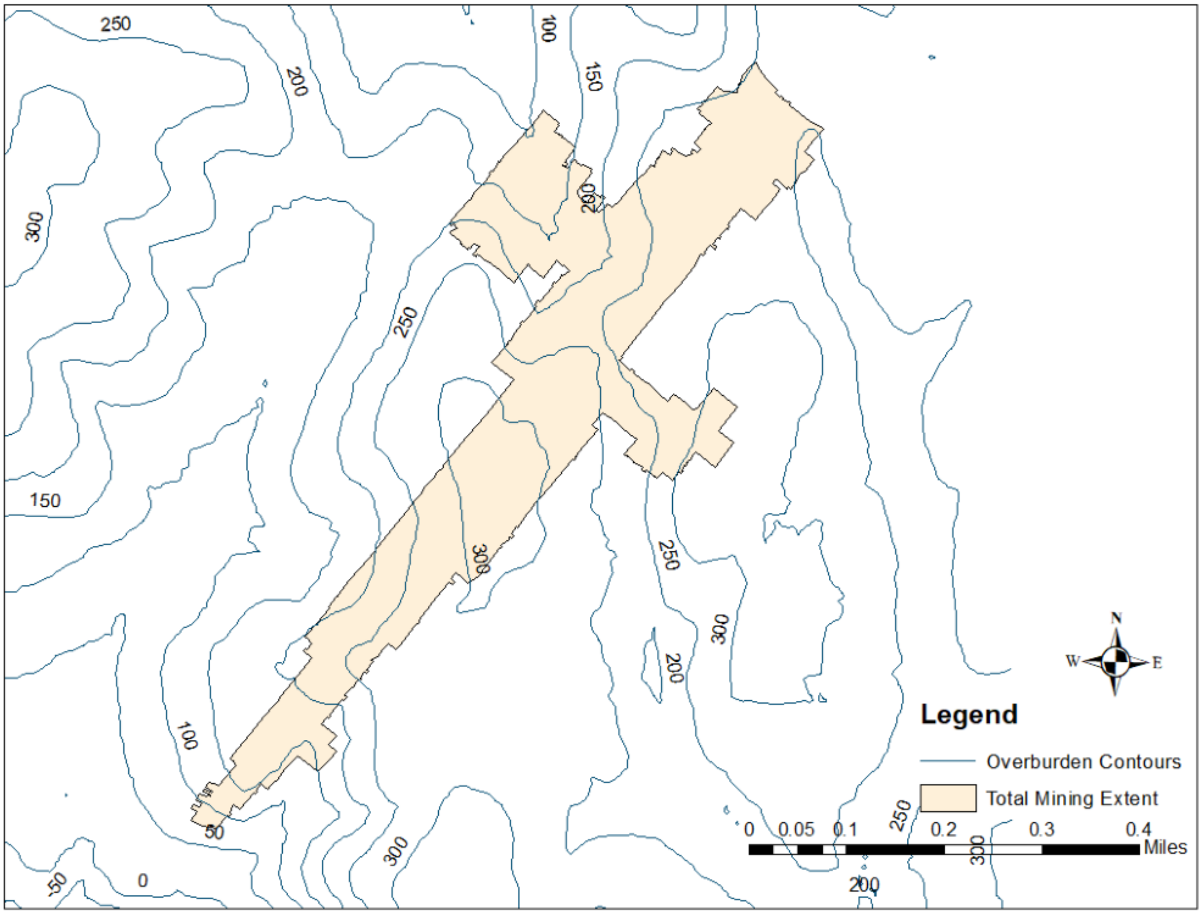

Figure 321. Fifty-foot overburden contour intervals for the Kingston West Mine

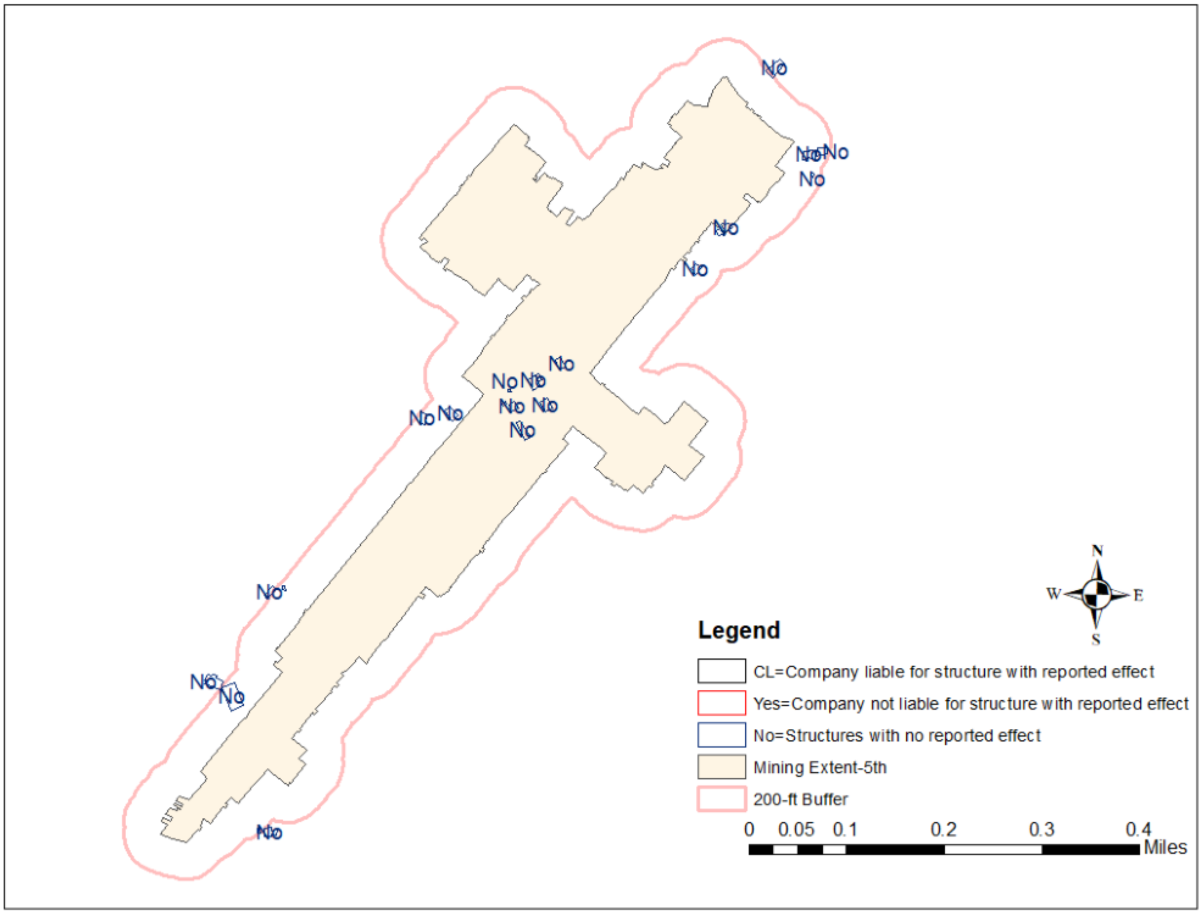

Figure 322. Kingston West 5th assessment 200-ft buffer and structures

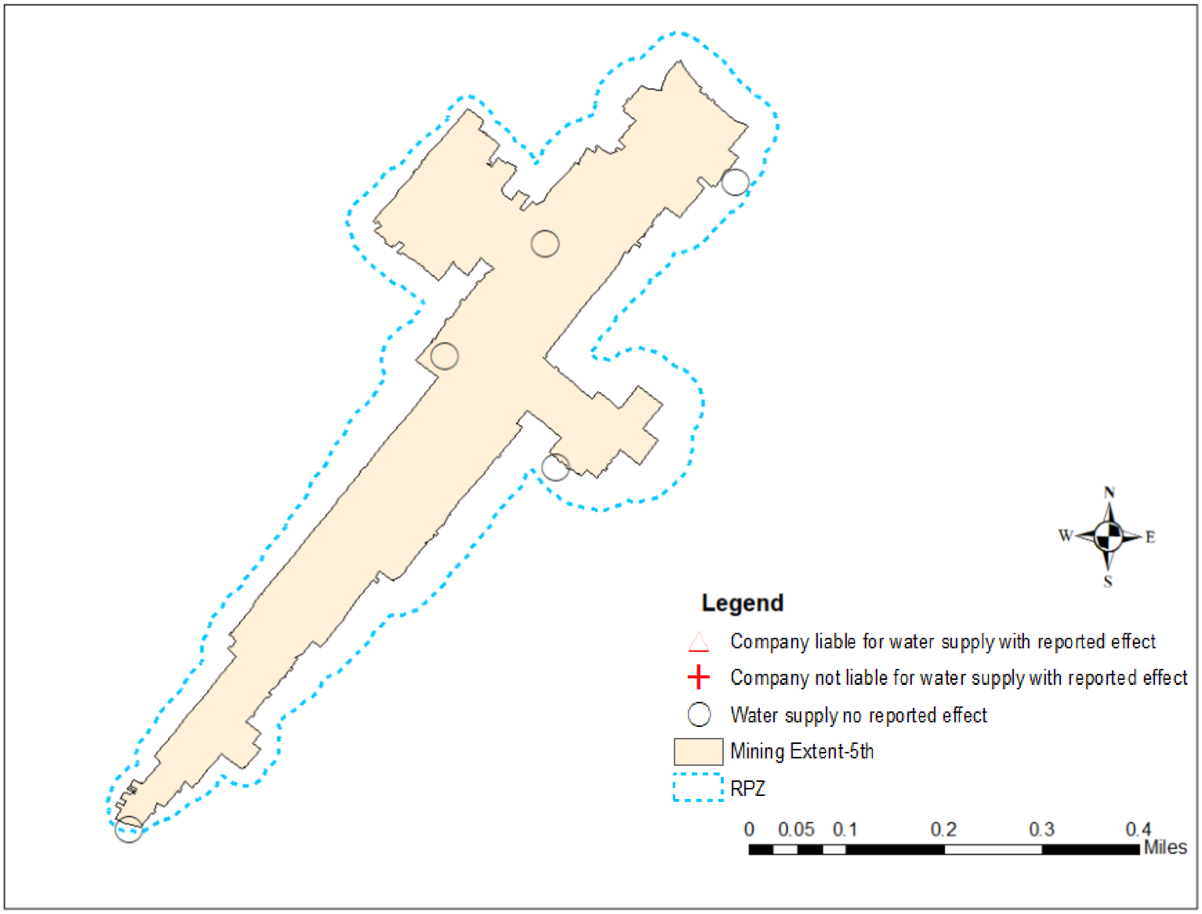

Figure 323. Kingston West 5th assessment water supplies and RPZ

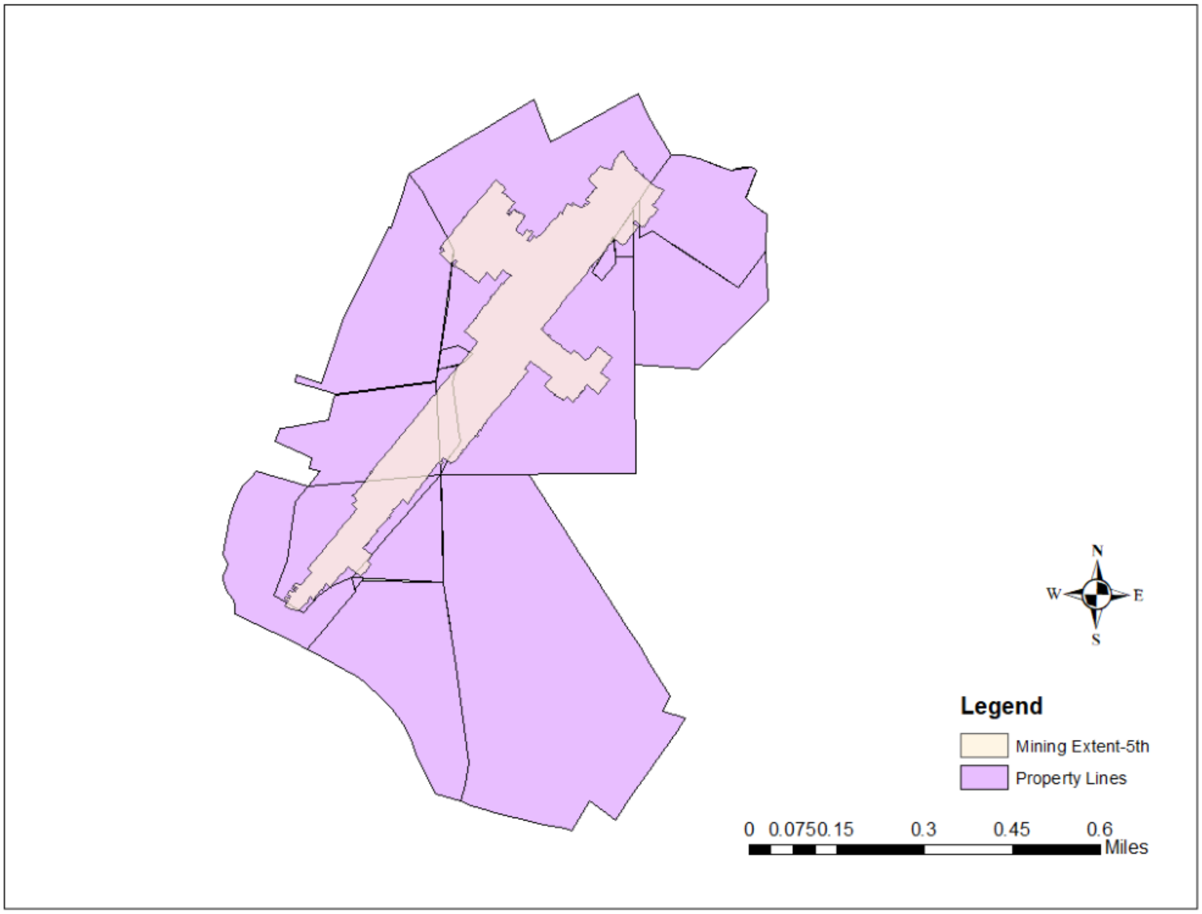

Figure 324. Properties associated with the 5th assessment period over the Kingston West Mine

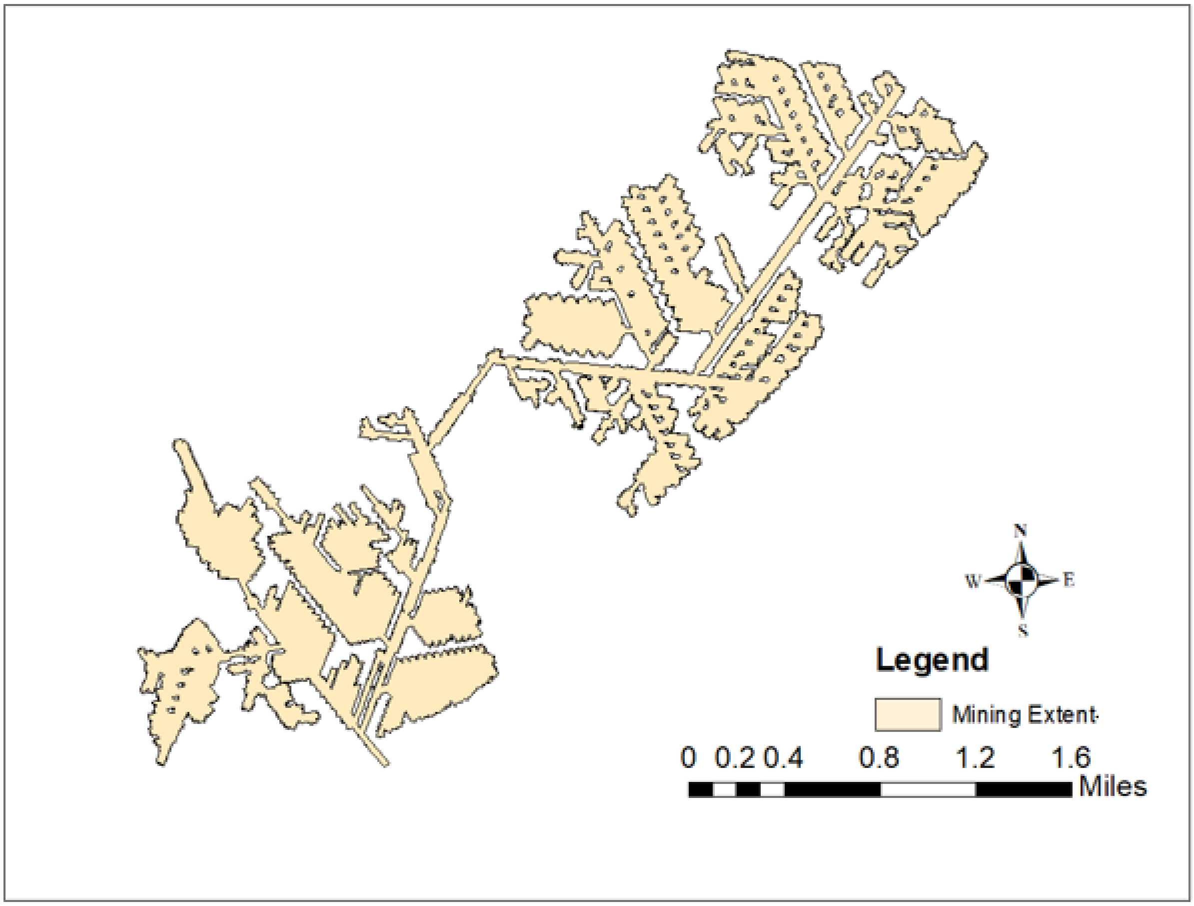

Figure 325. Twin Rocks total extent of mining

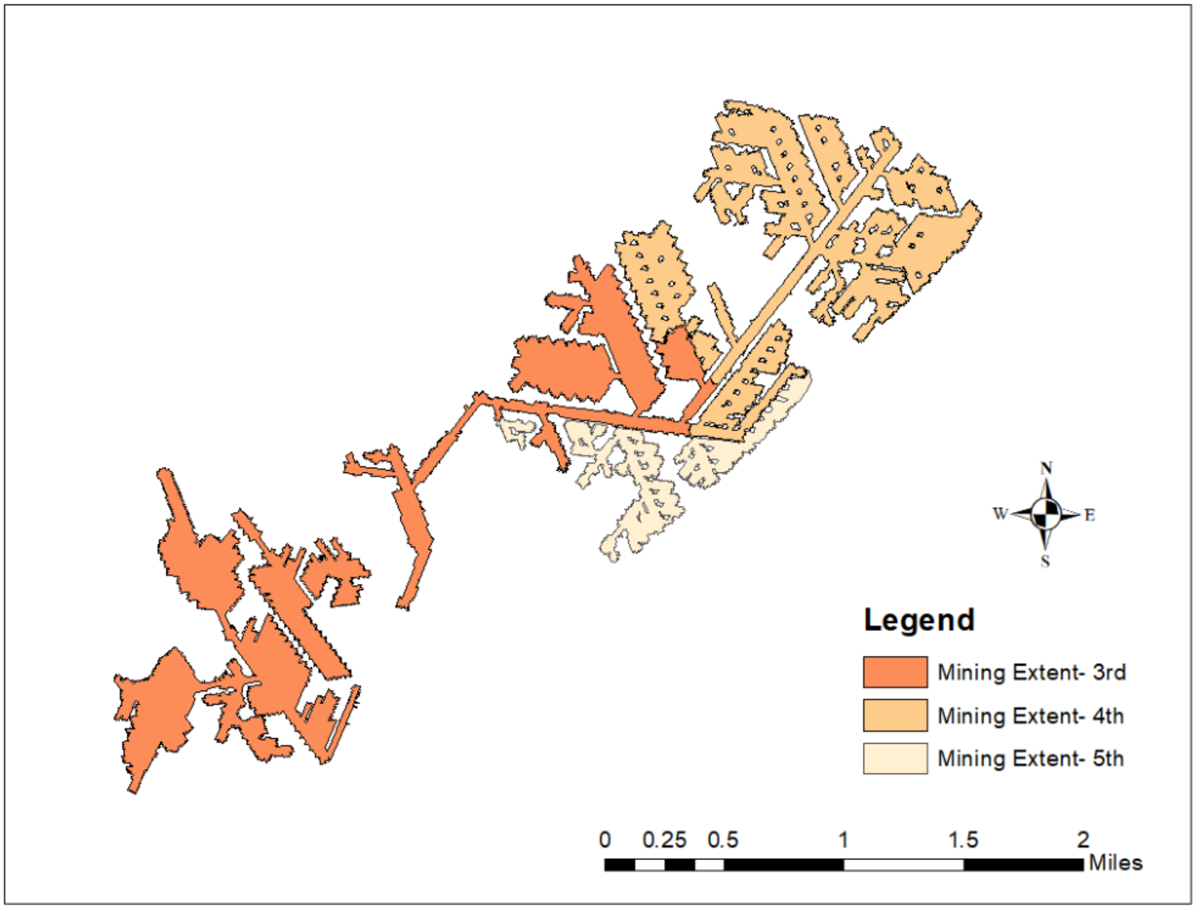

Figure 326. Twin Rocks mining extent for the 3rd, 4th, and 5th assessment periods

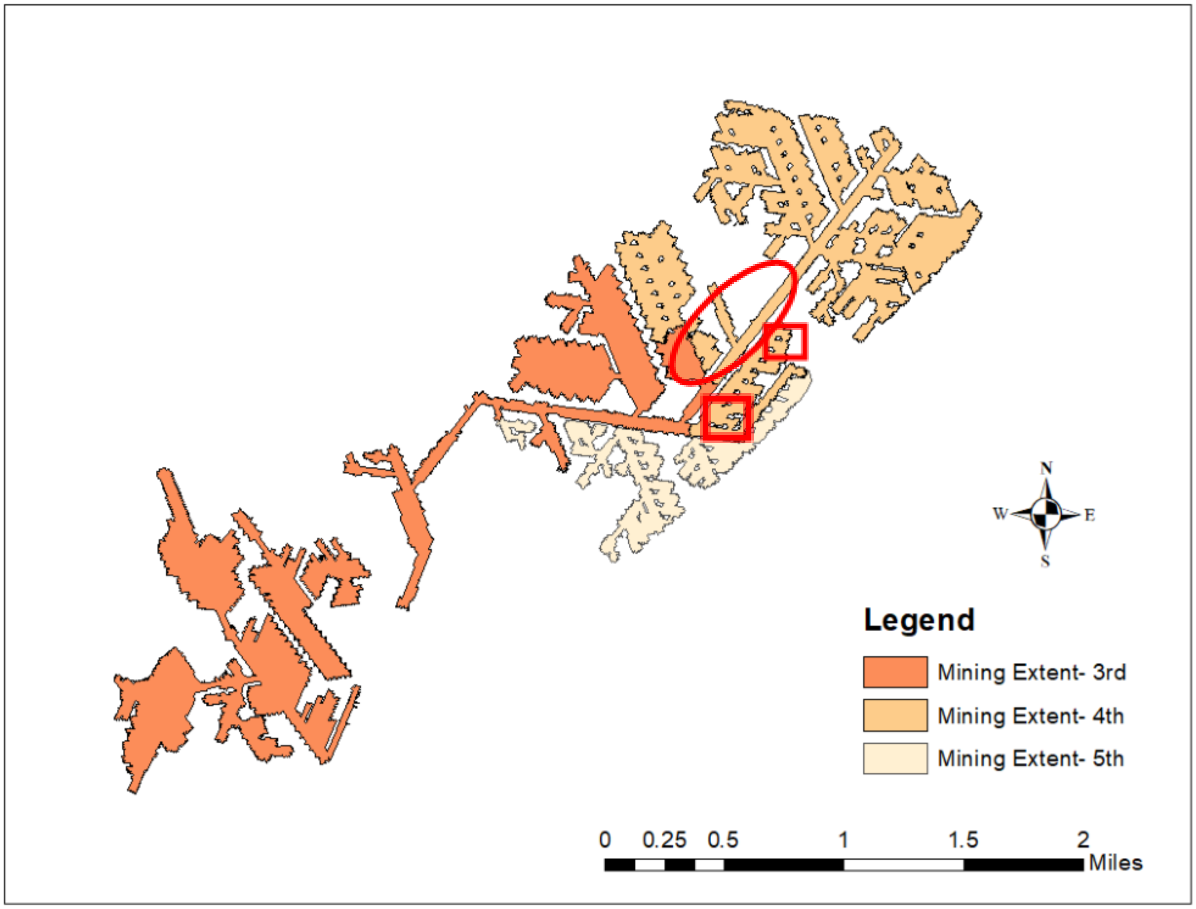

Figure 327. Twin Rocks mining extent for the 3rd, 4th, and 5th assessment periods*

***Note the areas contained in the red squares were mined in July 2013, 20 days before the 4th assessment collection period was finalized, they were not recorded during the 4th assessment period. This area is added to the 5th assessment period so that all area of the mine will be analyzed. The area circled in red was given by Rosebud as having been mined during the 5th assessment period, but was already previously analyzed in the 4th assessment period so it was not included in the 5th assessment period.*

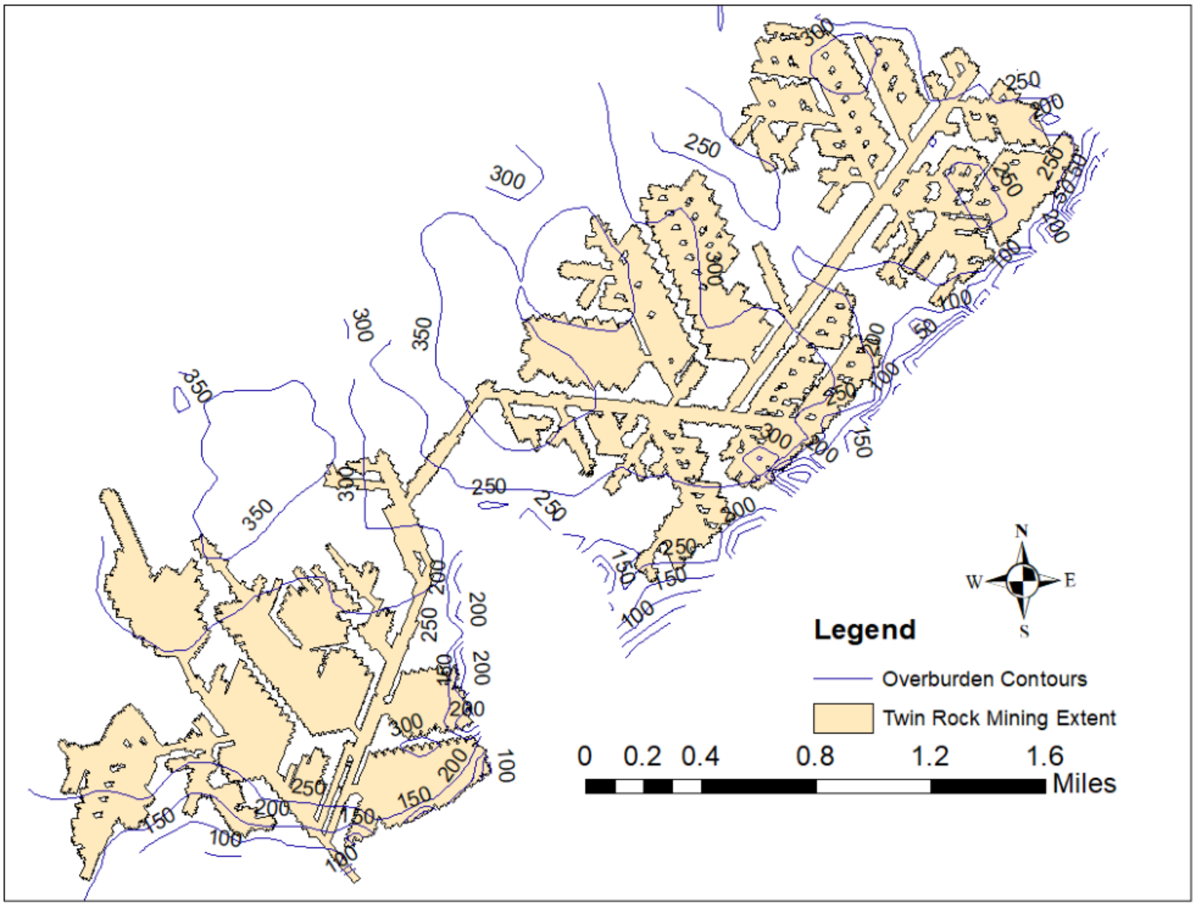

Figure 328. Fifty-foot contour intervals for the Twin Rocks Min

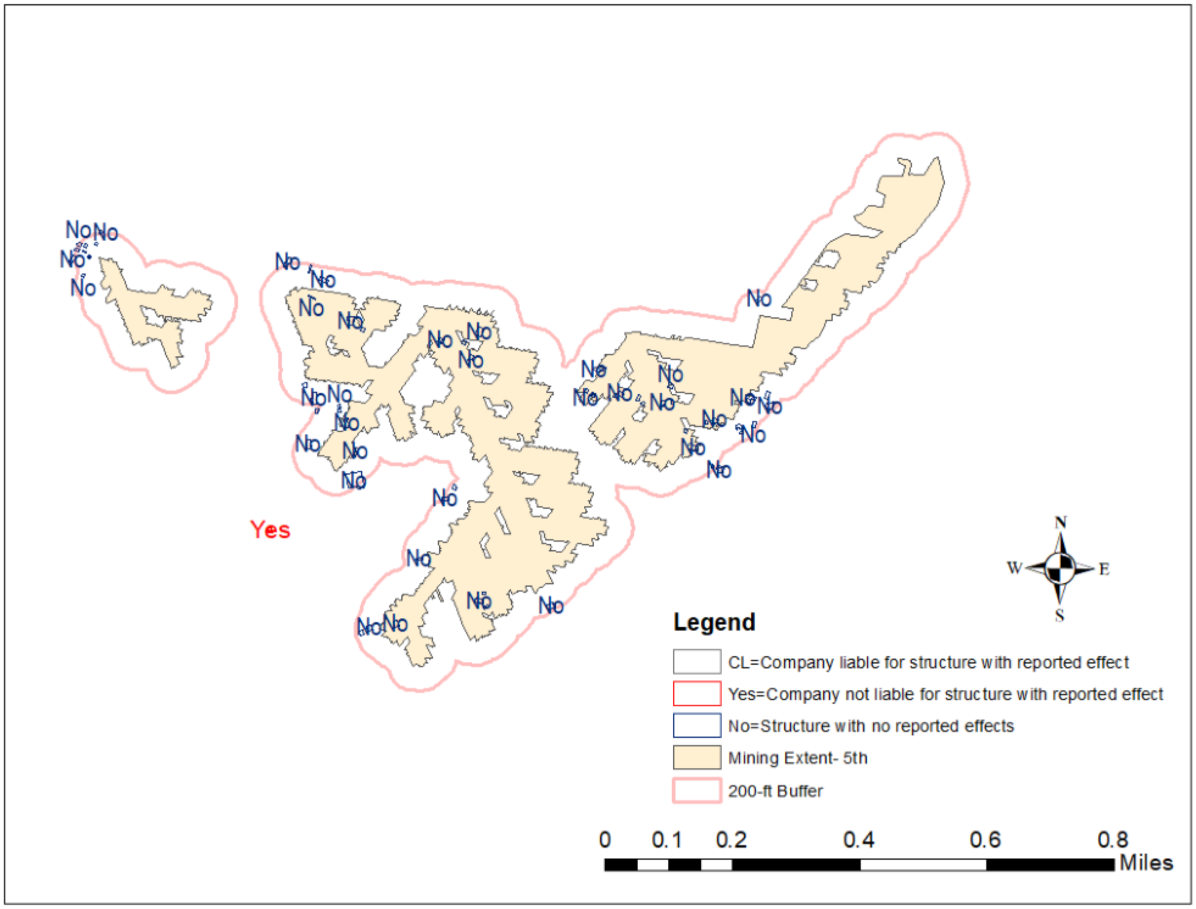

Figure 329. Twin Rocks 5th assessment 200-ft buffer and structures*

**Note there are two structures with reported effects that are far from mining and are not included here for display purposes.*

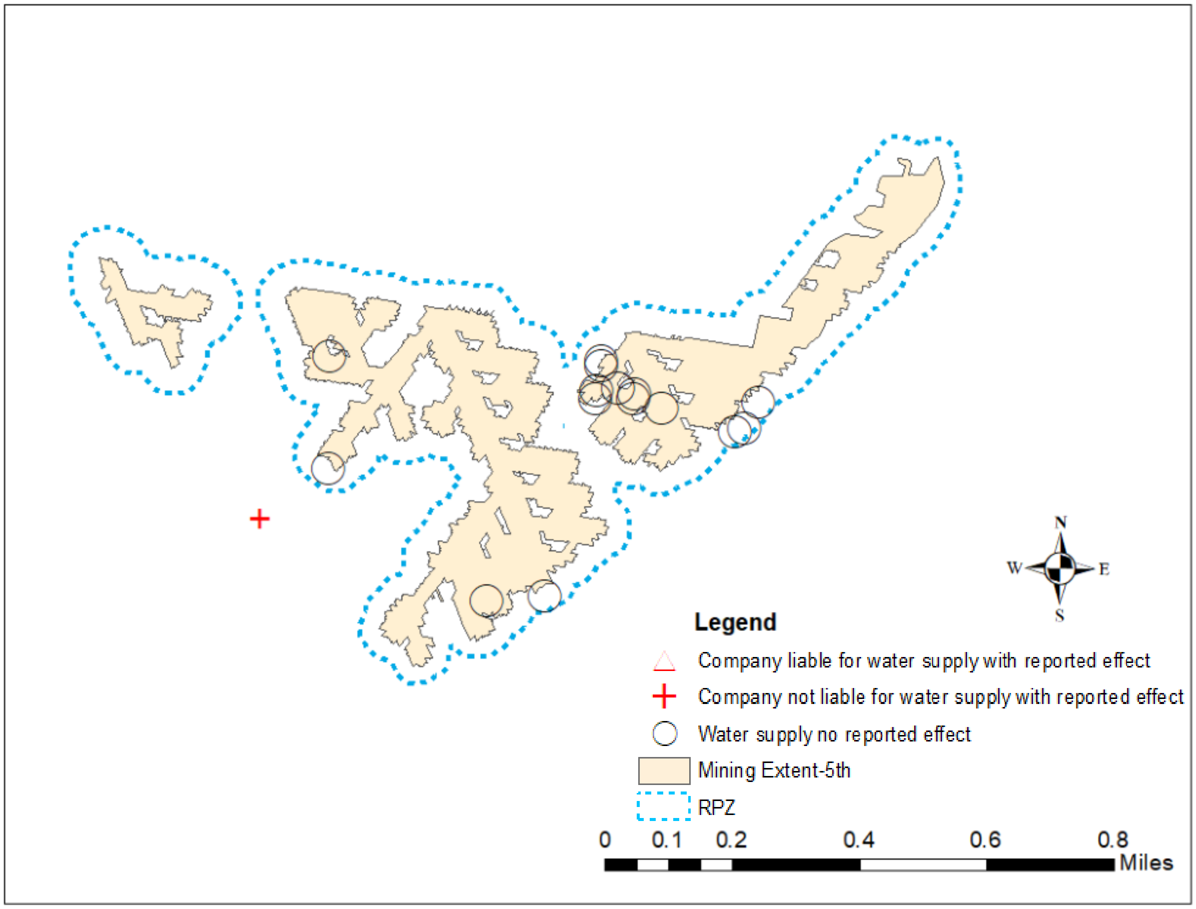

Figure 330. Twin Rocks 5th assessment water supplies and RPZ*

Note there are two water supplies with reported effects that are far from mining and are not included here for display purposes.

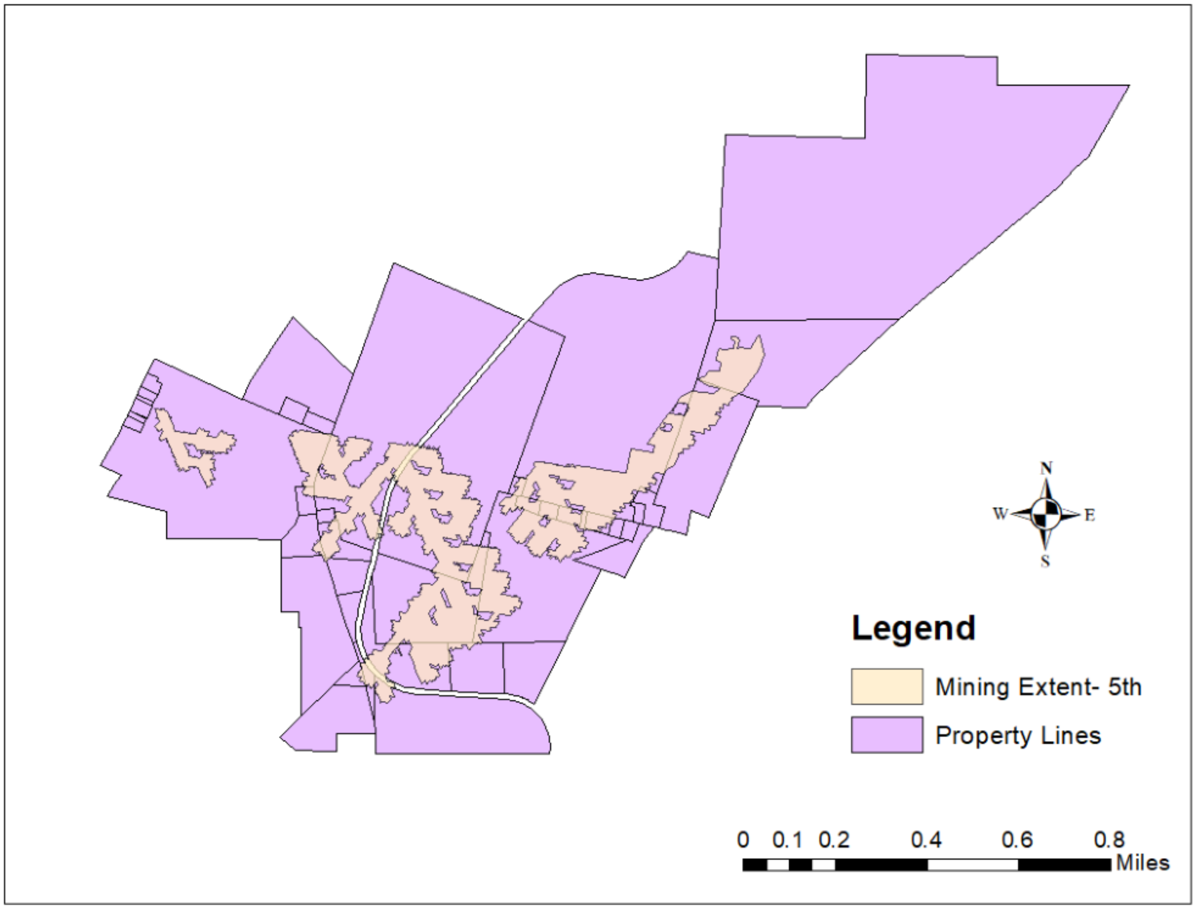

Figure 331. Properties associated with the 5th assessment period over the Twin Rocks mine

Pillar Retreat Mines

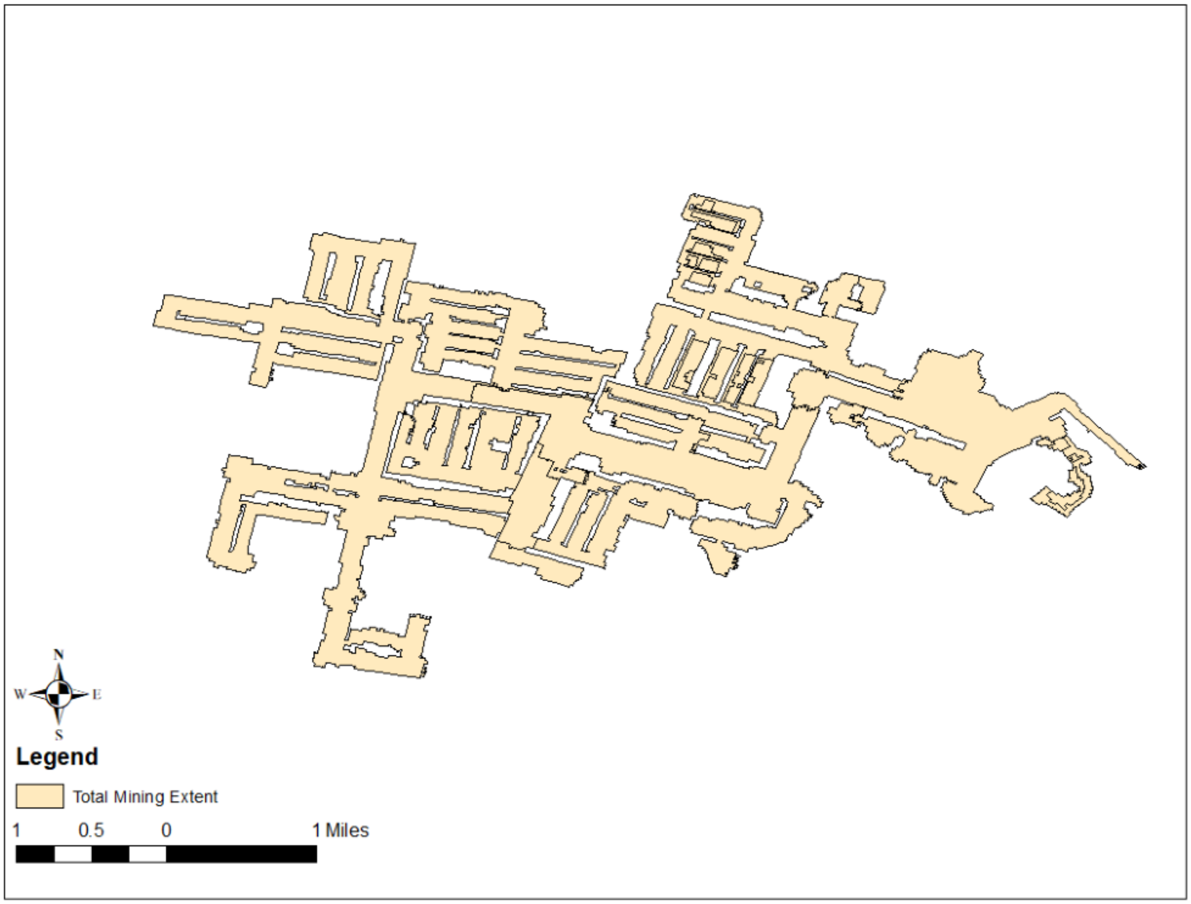

Figure 332. 4 West total extent of mining

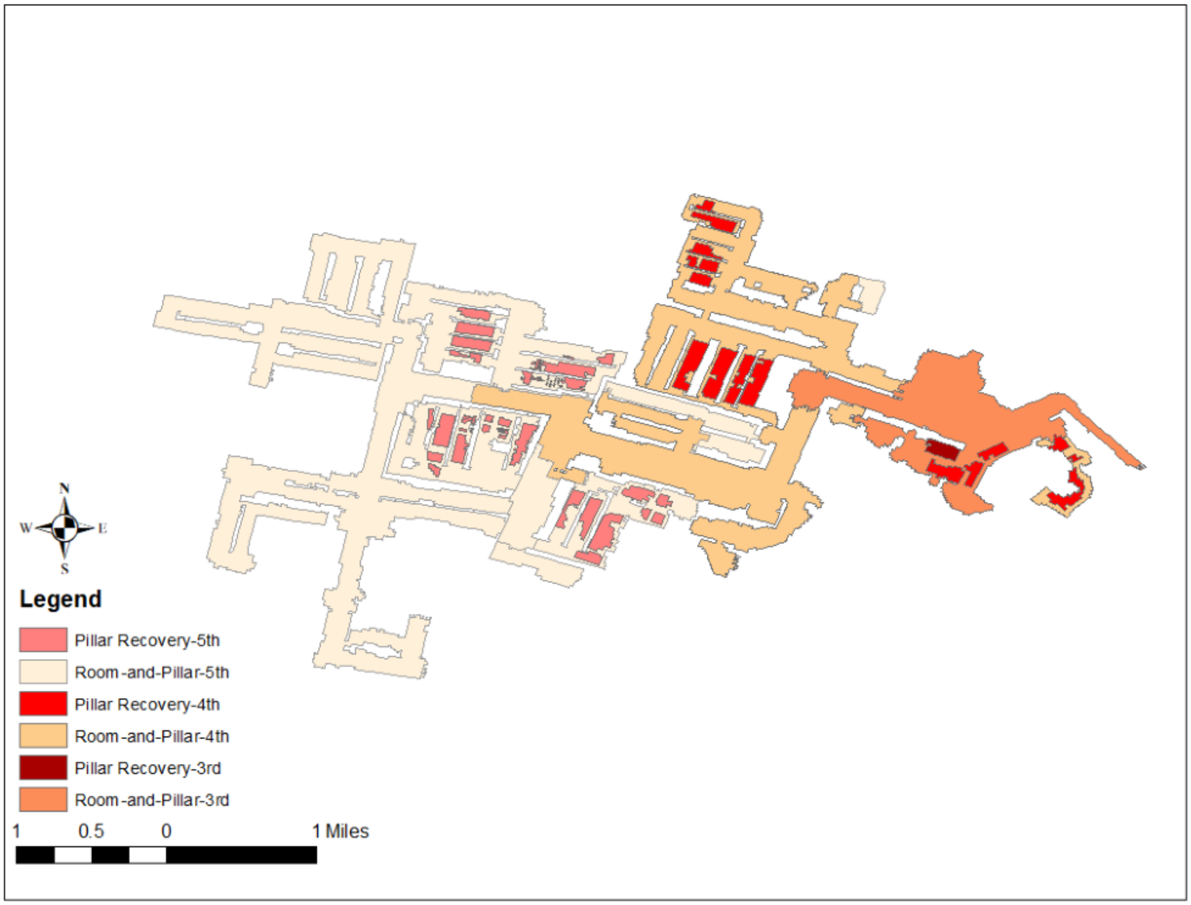

Figure 333. 4West mining extent for the 3rd, 4th, and 5th assessment periods

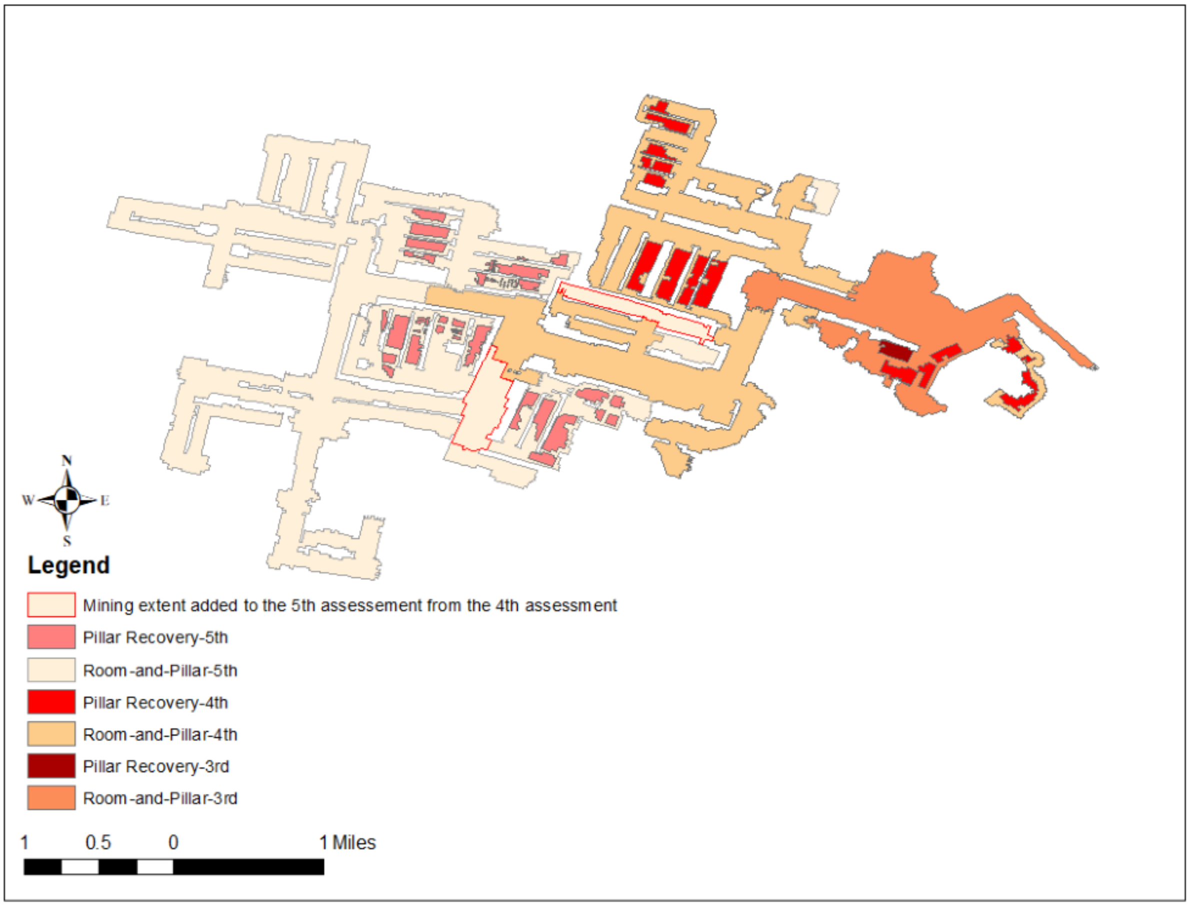

Figure 334. 4 West mining extent for the 3rd, 4th, and 5th assessment periods*

******Note the area labeled "Mining Extent added to the 5th assessment from the 4th assessment" outlined in red was mined before the 4th assessment collection period was finalized. Due to the late submission of this data and the early reporting requirements, this area was not considered during the 4th assessment period. This area is added to the 5th assessment period so that all area of the mine will be analyzed.*

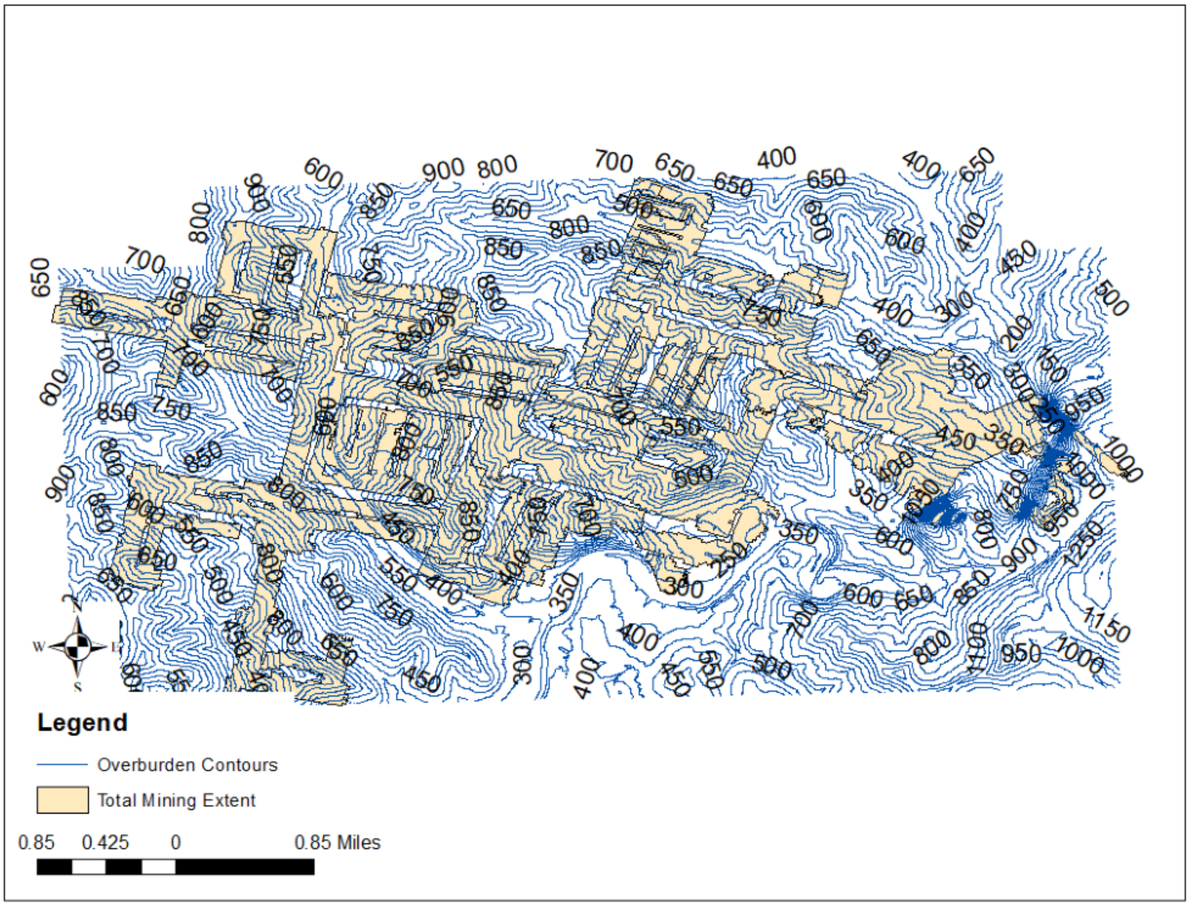

Figure 335. Fifty-foot overburden contour intervals for the 4 West mine

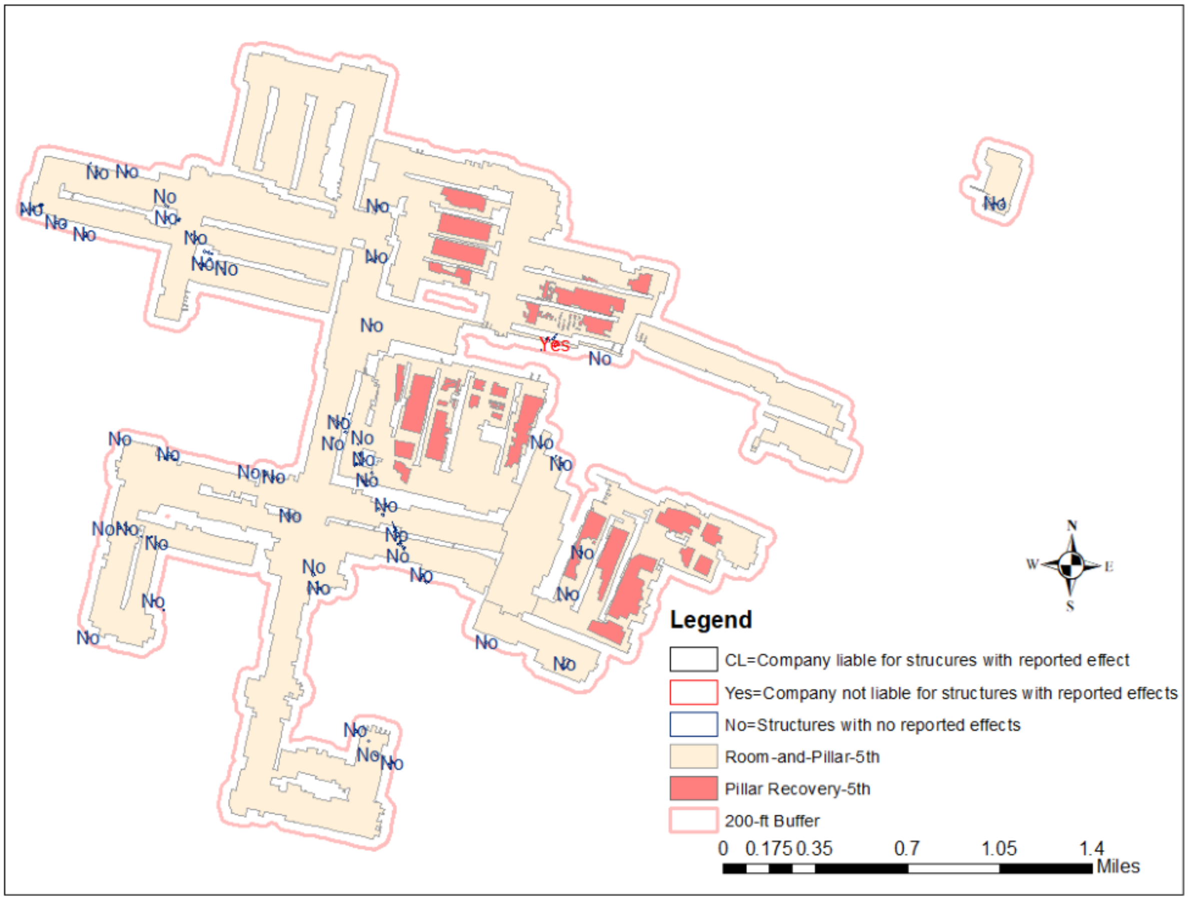

Figure 336. 4 West 5th assessment 200-ft buffer and structures

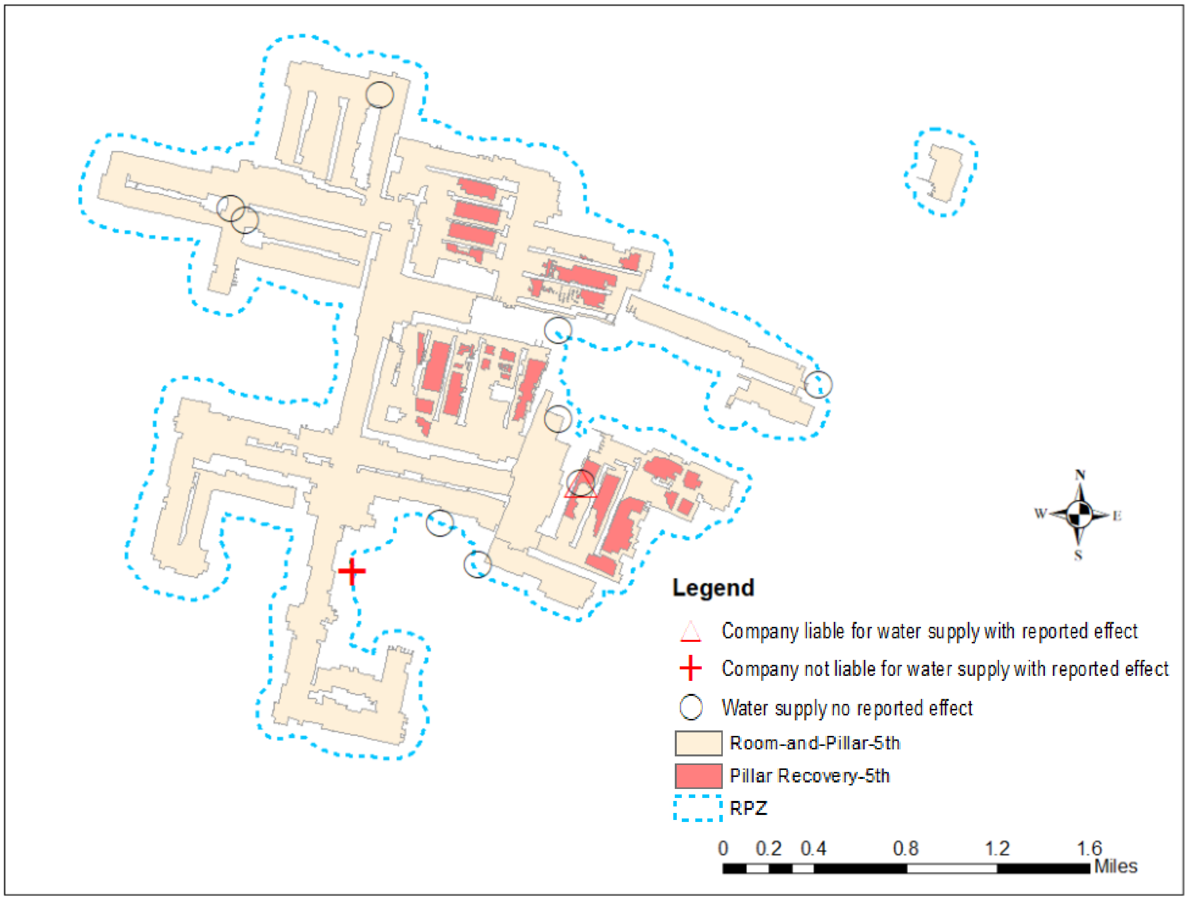

Figure 337. 4 West 5th assessment water supplies and RPZ

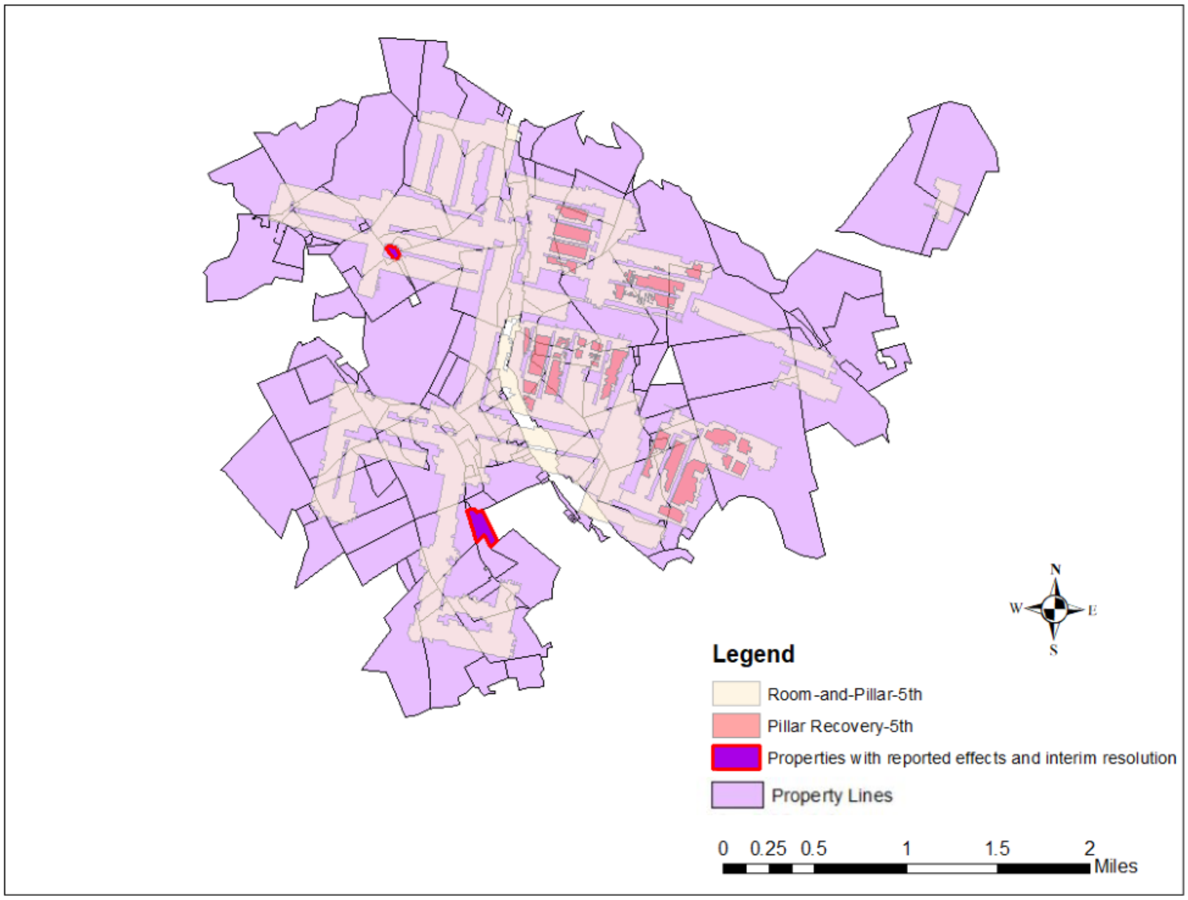

Figure 338. Properties associated with the 5th assessment period over the 4 West Mine

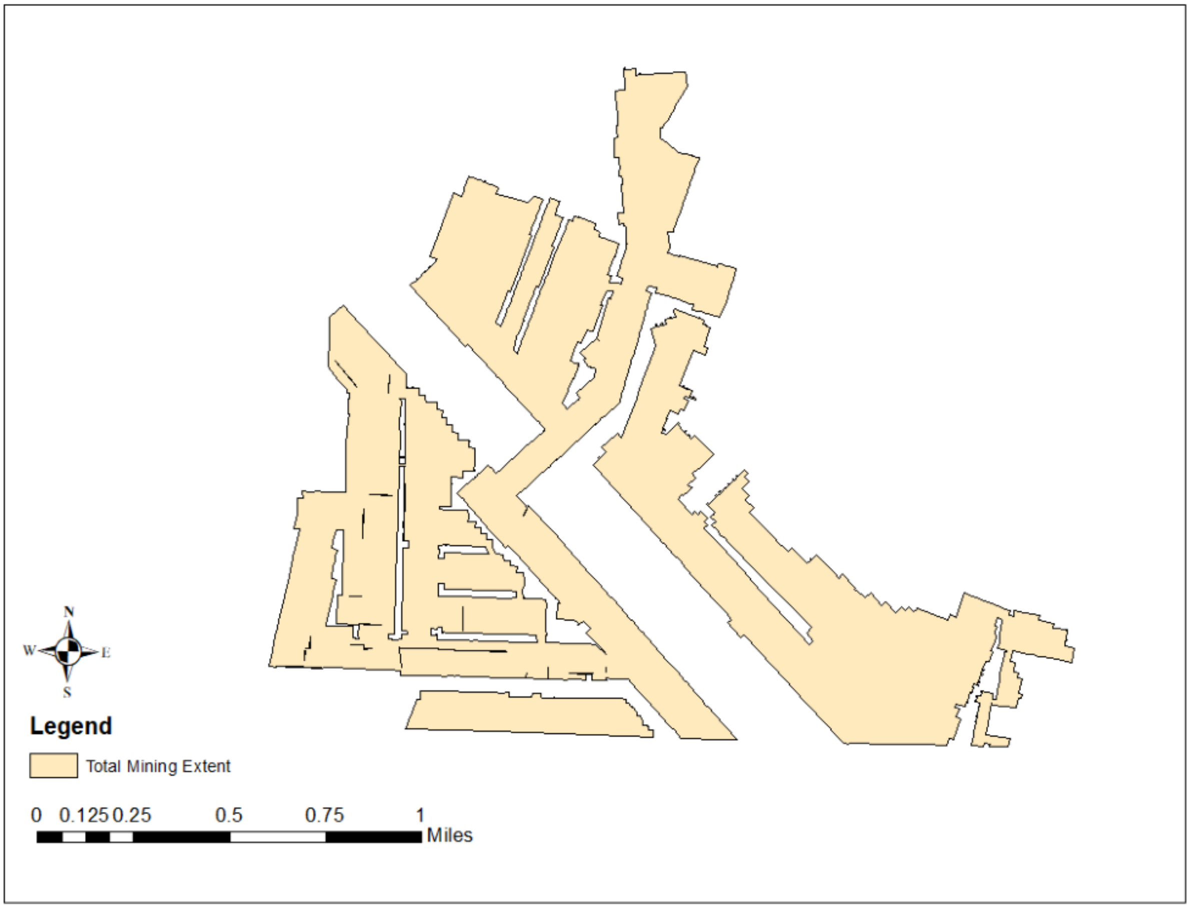

Figure 339. Crawdad Portal B total extent of mining

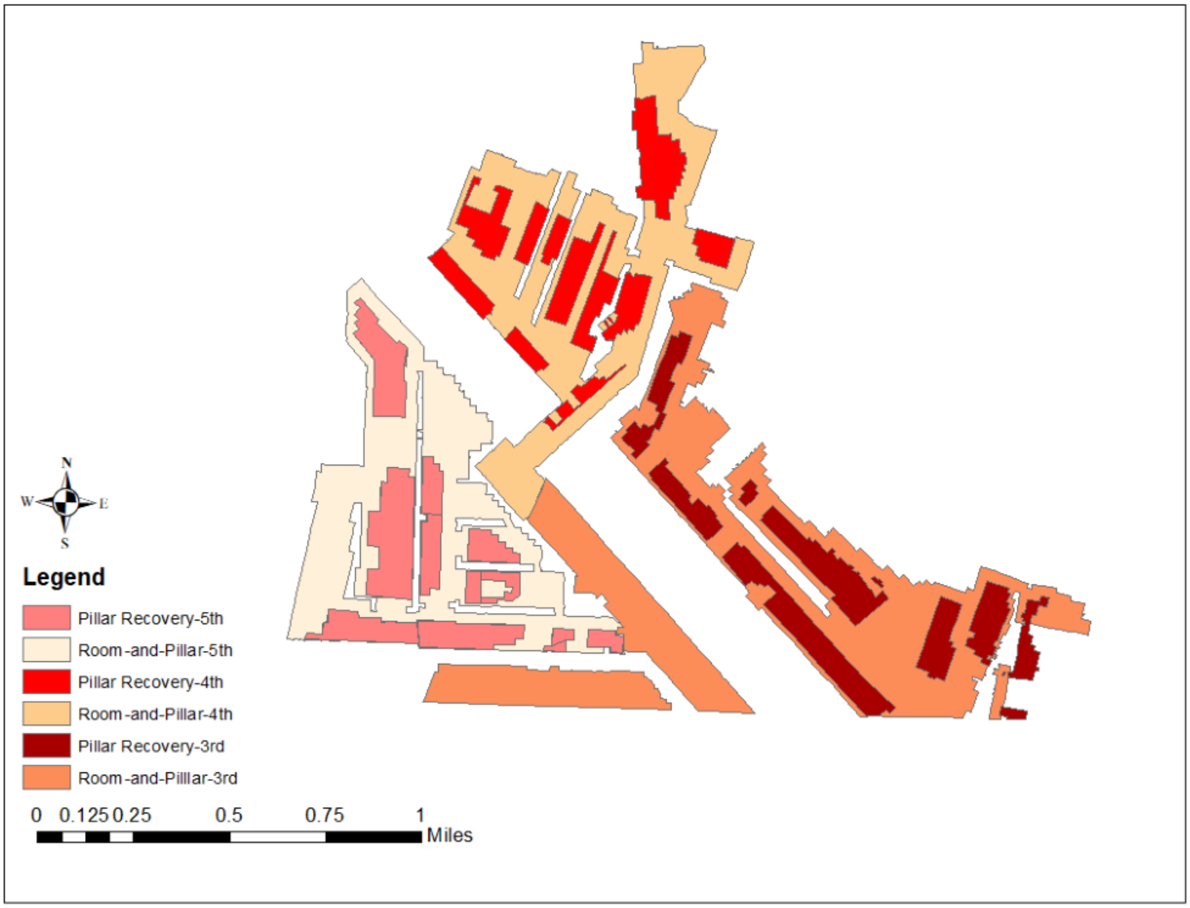

Figure 340. Crawdad Portal B mining extent for the 3rd, 4th, and 5th assessment periods

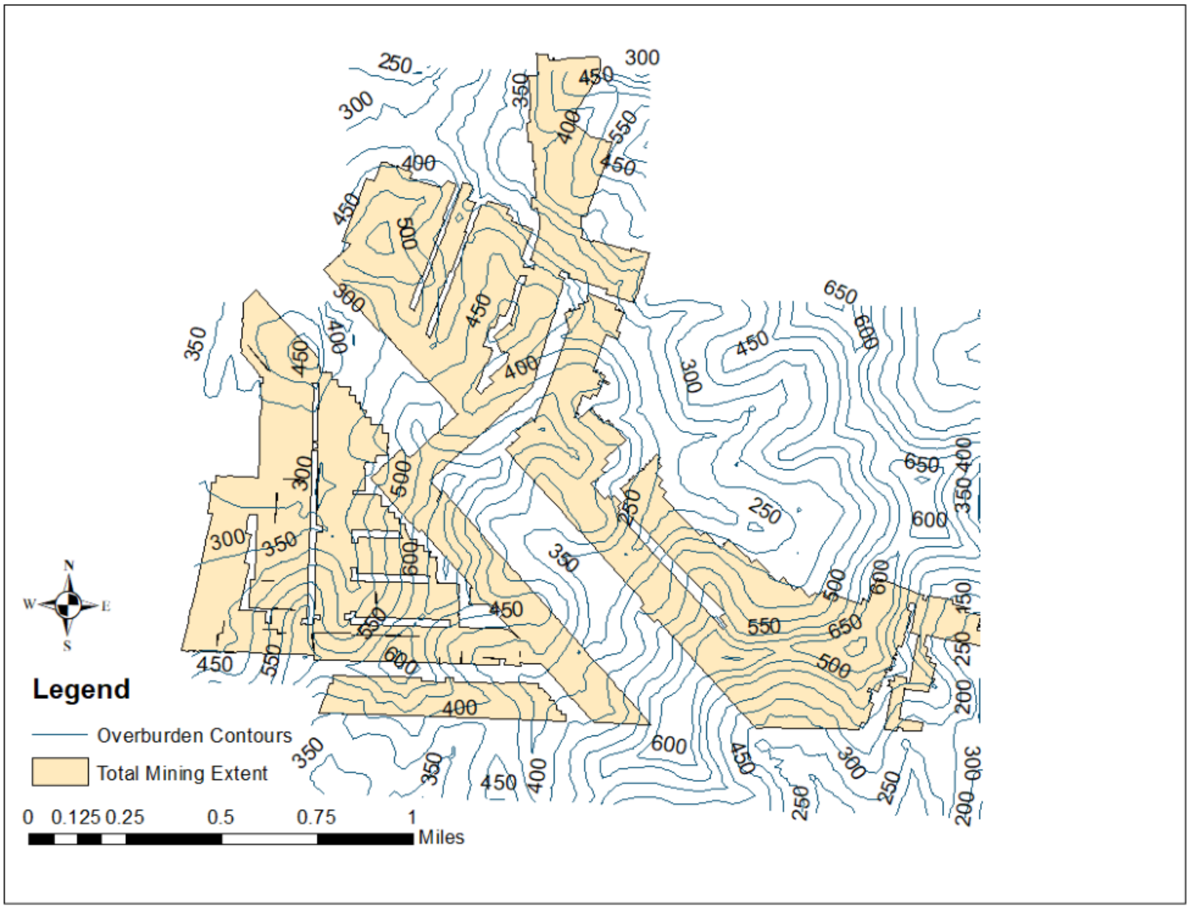

Figure 341. Fifty-foot overburden contour intervals for the Crawdad Portal B Mine

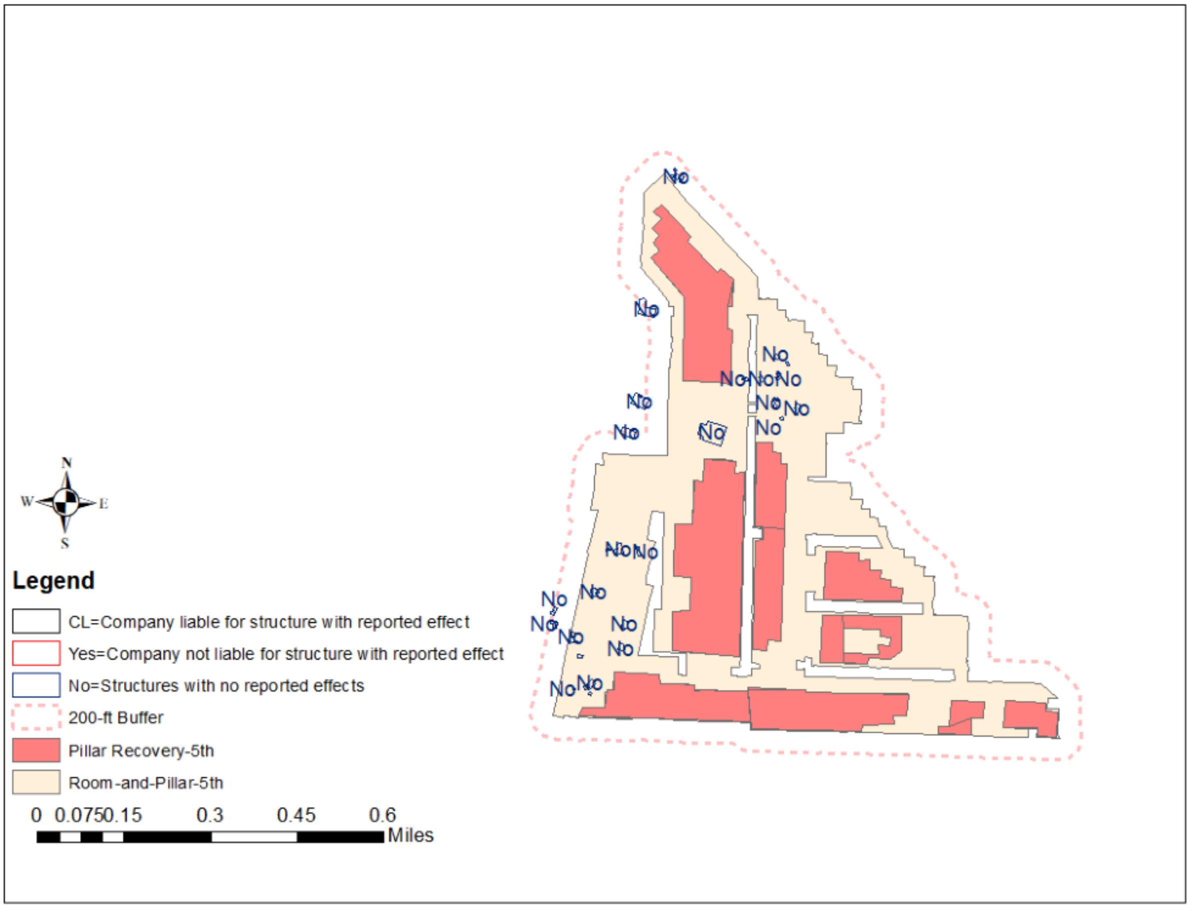

Figure 342. Crawdad Portal B 5th assessment 200-ft buffer and structures*

*****Note there are two structures with reported effects that are far from mining and are not included here for display purposes.*

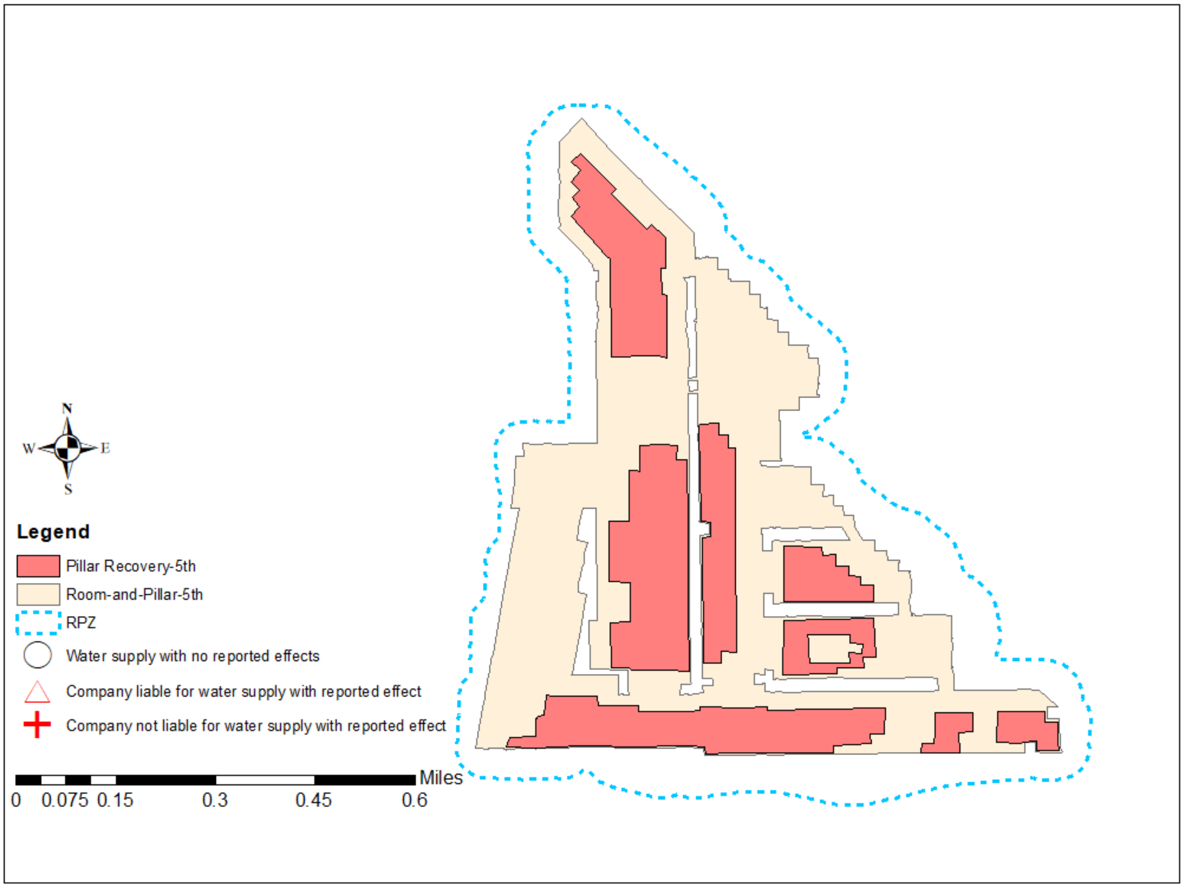

Figure 343. Crawdad Portal B 5th assessment water supplies and RPZ

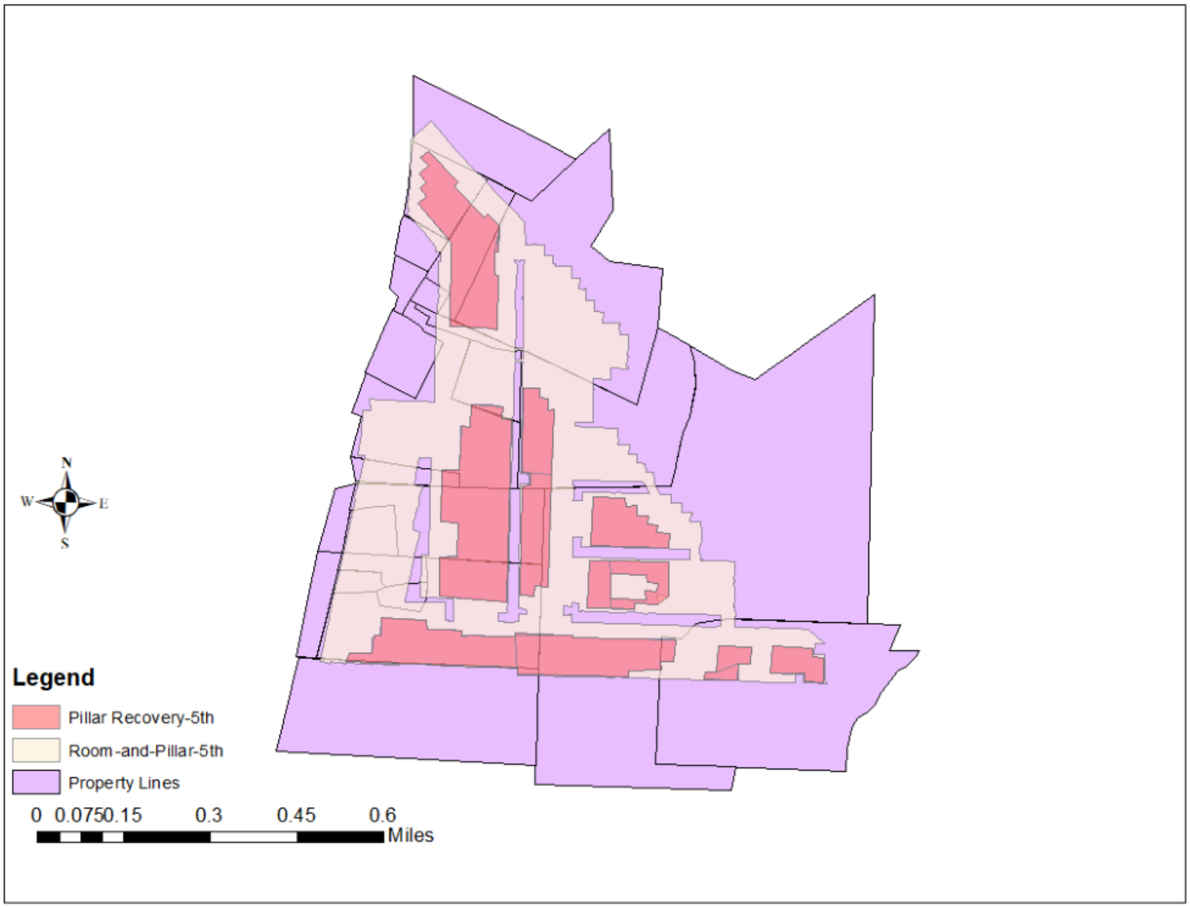

Figure 344. Properties associated with the 5th assessment period over the Crawdad Portal B Mine

Figure 345. Nolo total extent of mining

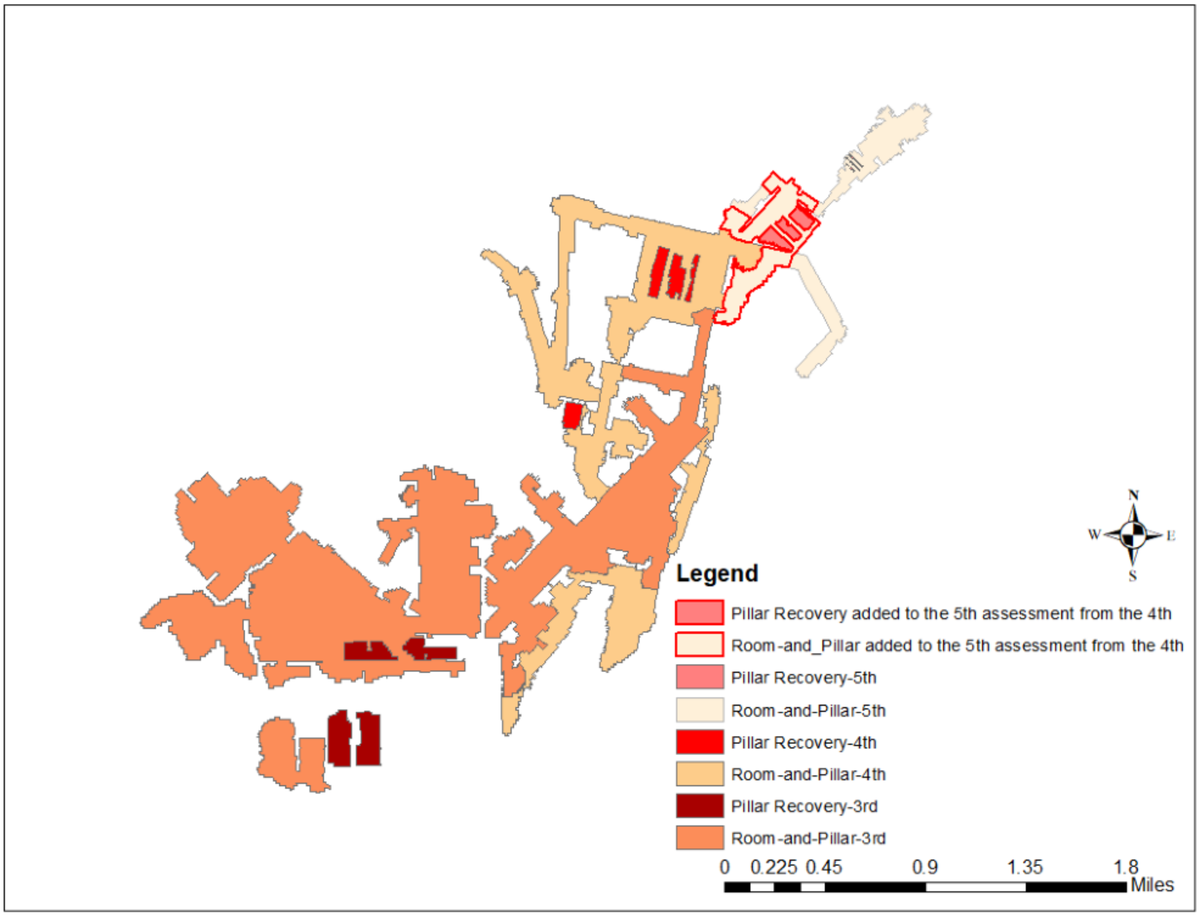

Figure 346. Nolo mining extent for the 3rd, 4th, and 5th assessment periods

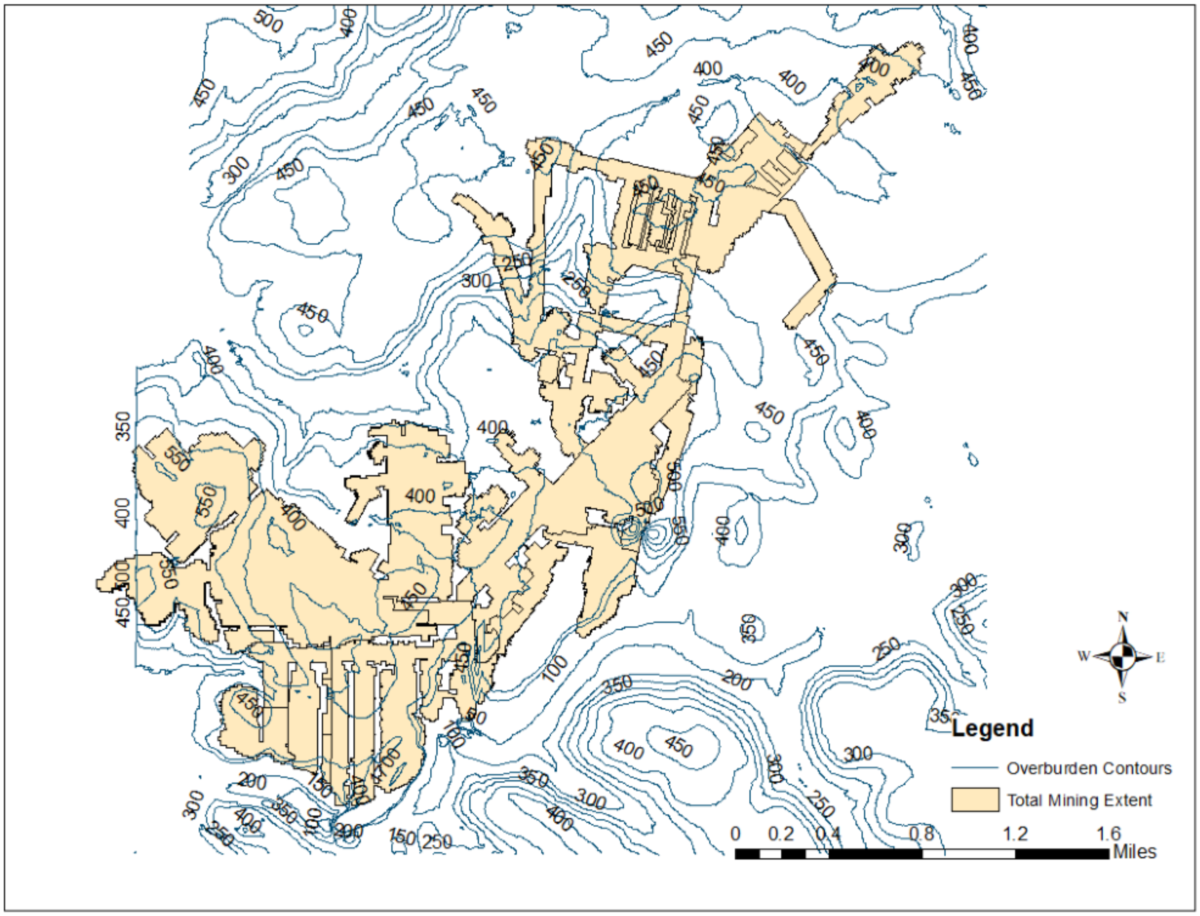

Figure 347. Fifty-foot overburden contour intervals for the Nolo Mine

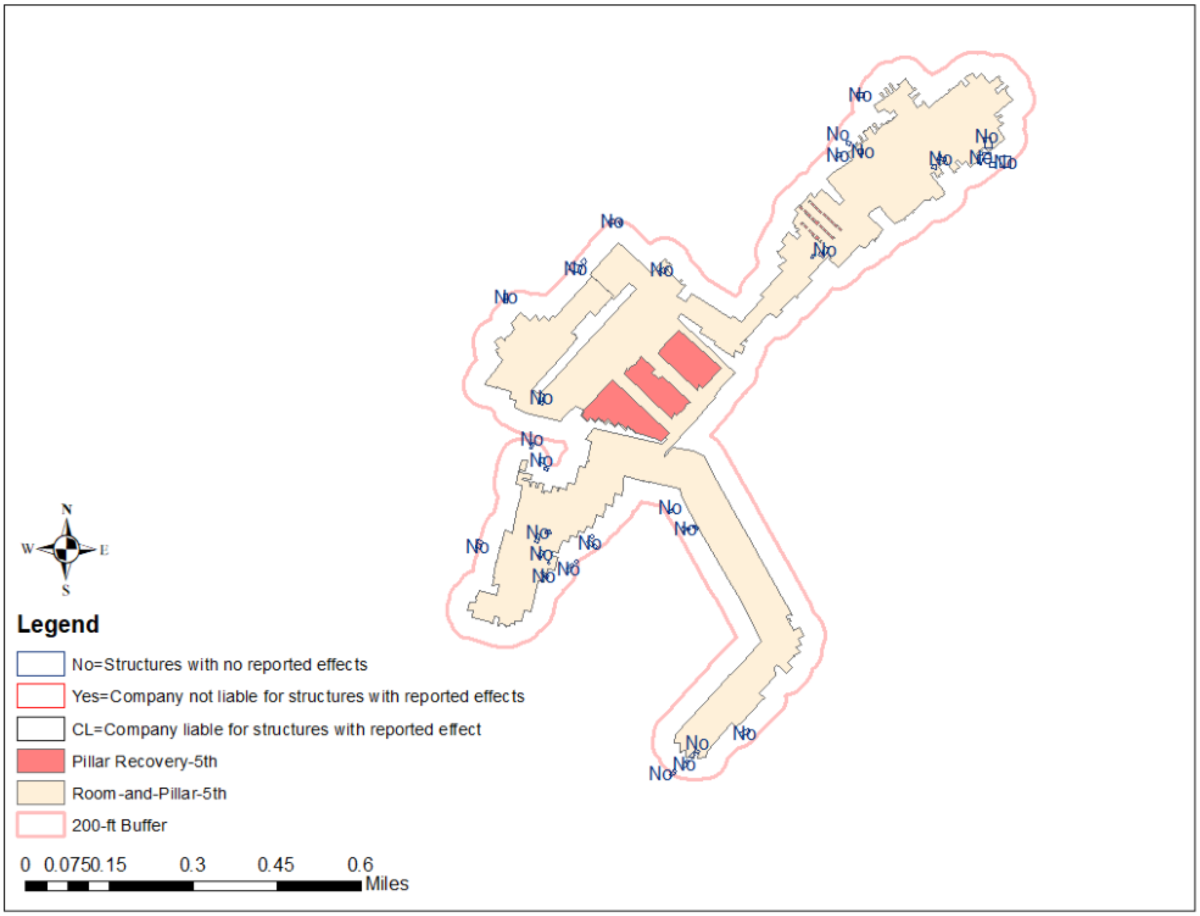

Figure 348. Nolo 5th assessment 200-ft buffer and structures

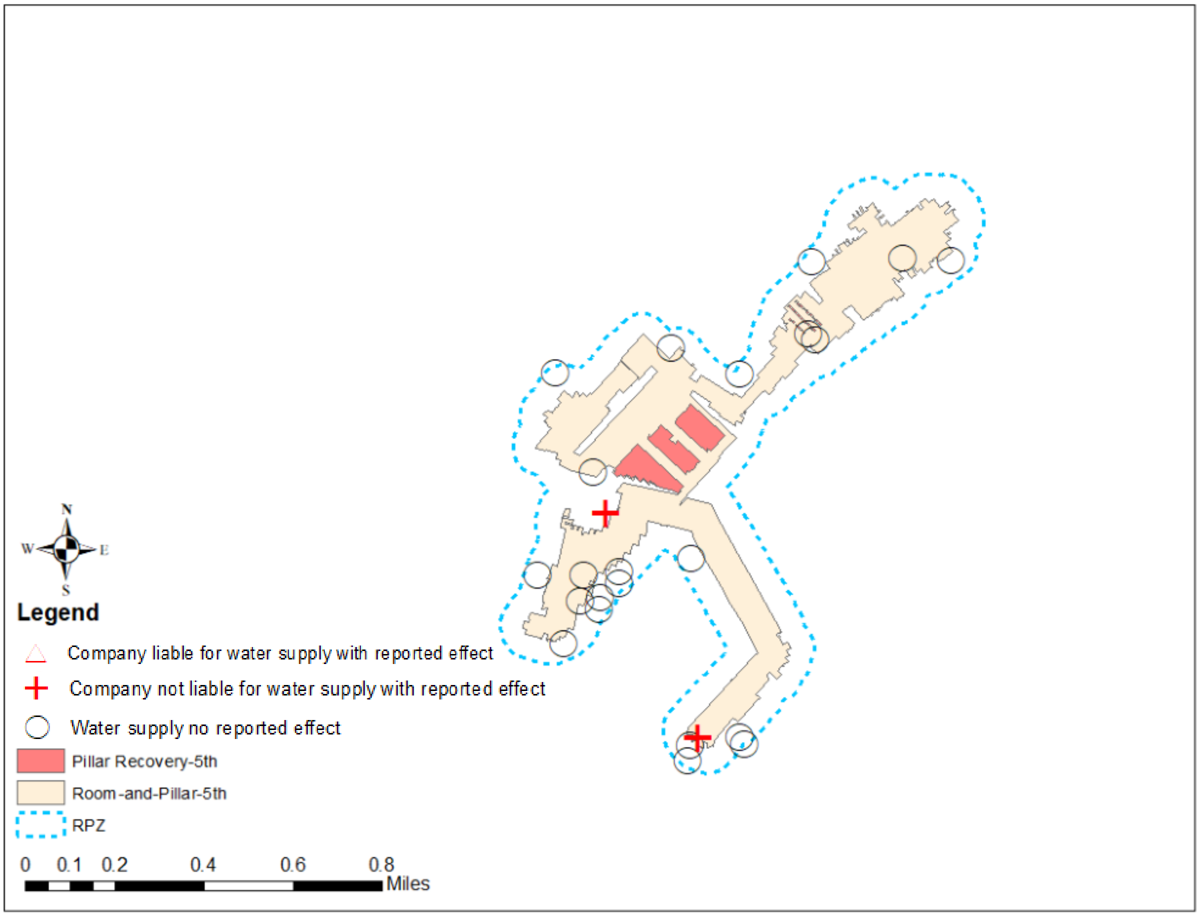

Figure 349. Nolo 5th assessment water supplies and RPZ*

***Note there are three water supplies with reported effects that are company liable and one reported effect that is not company liable that are far from mining and are not included here for display purposes.*

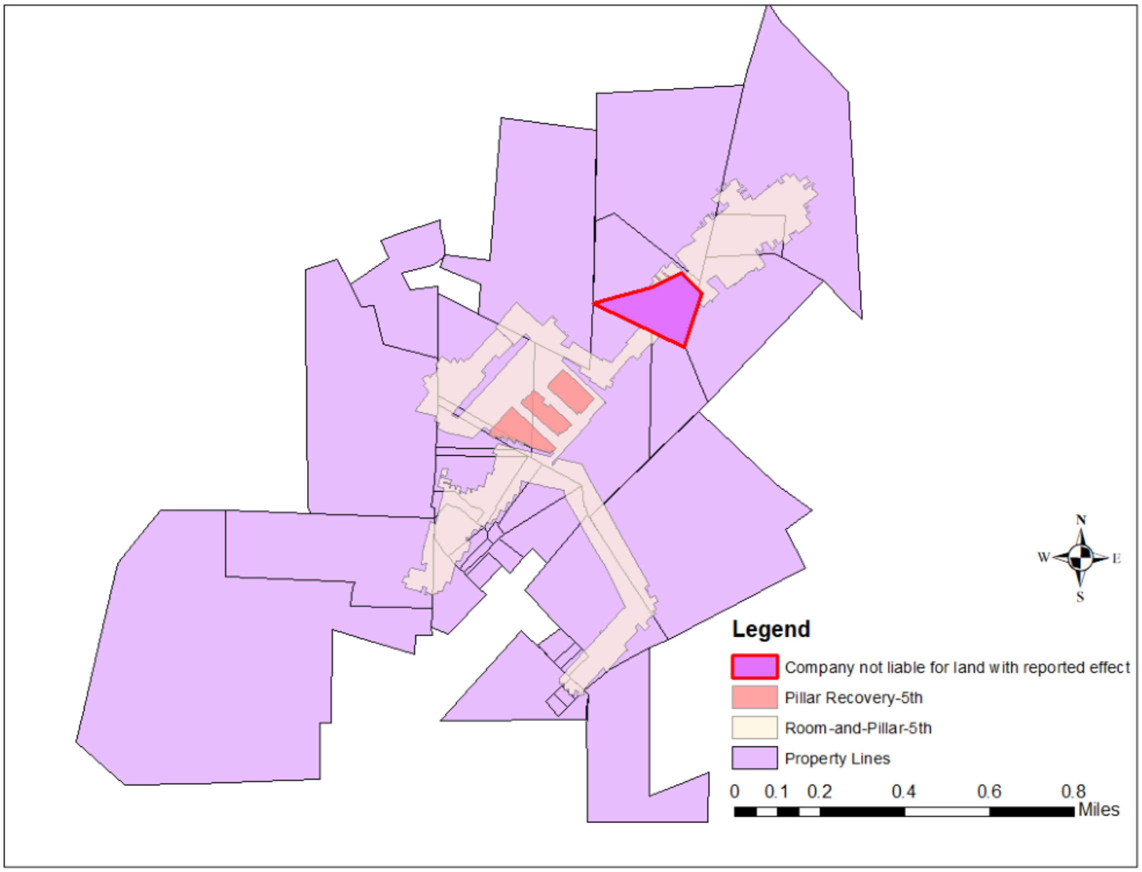

Figure 350. Properties associated with the 5th assessment period over the Nolo Mine

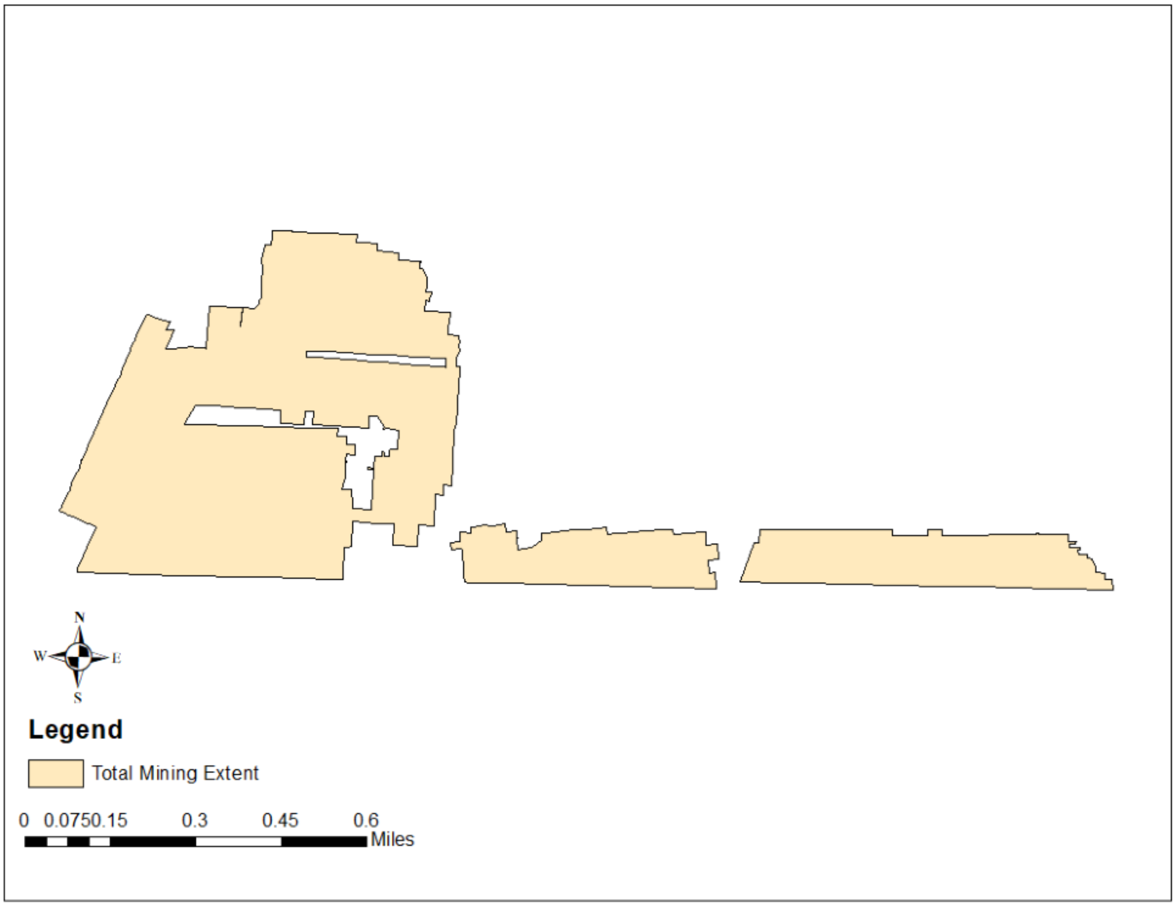

Figure 351. Prime No. 1 total extent of mining

Figure 352. Prime No. 1 mining extent for the 3rd, 4th, and 5th assessment periods

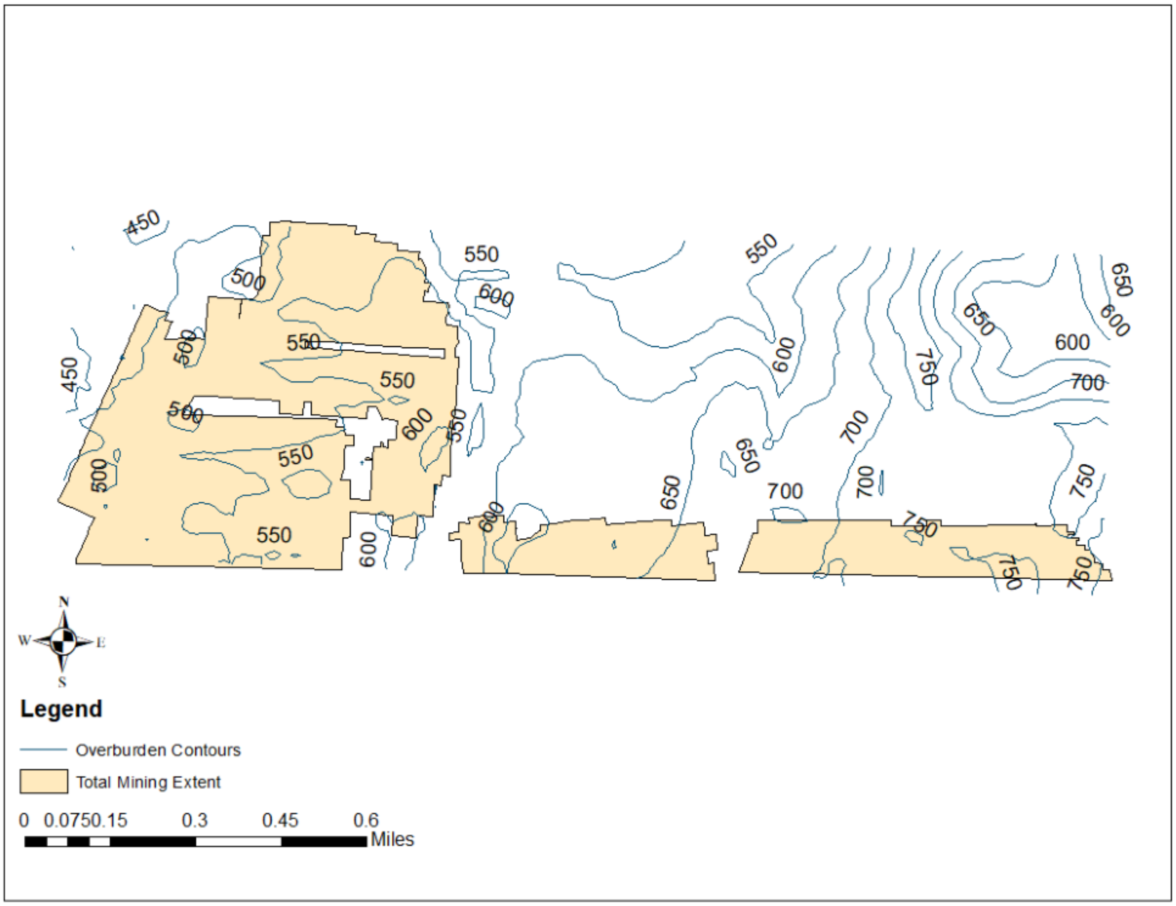

Figure 353. Fifty-foot overburden contour intervals for the Prime No. 1 Mine

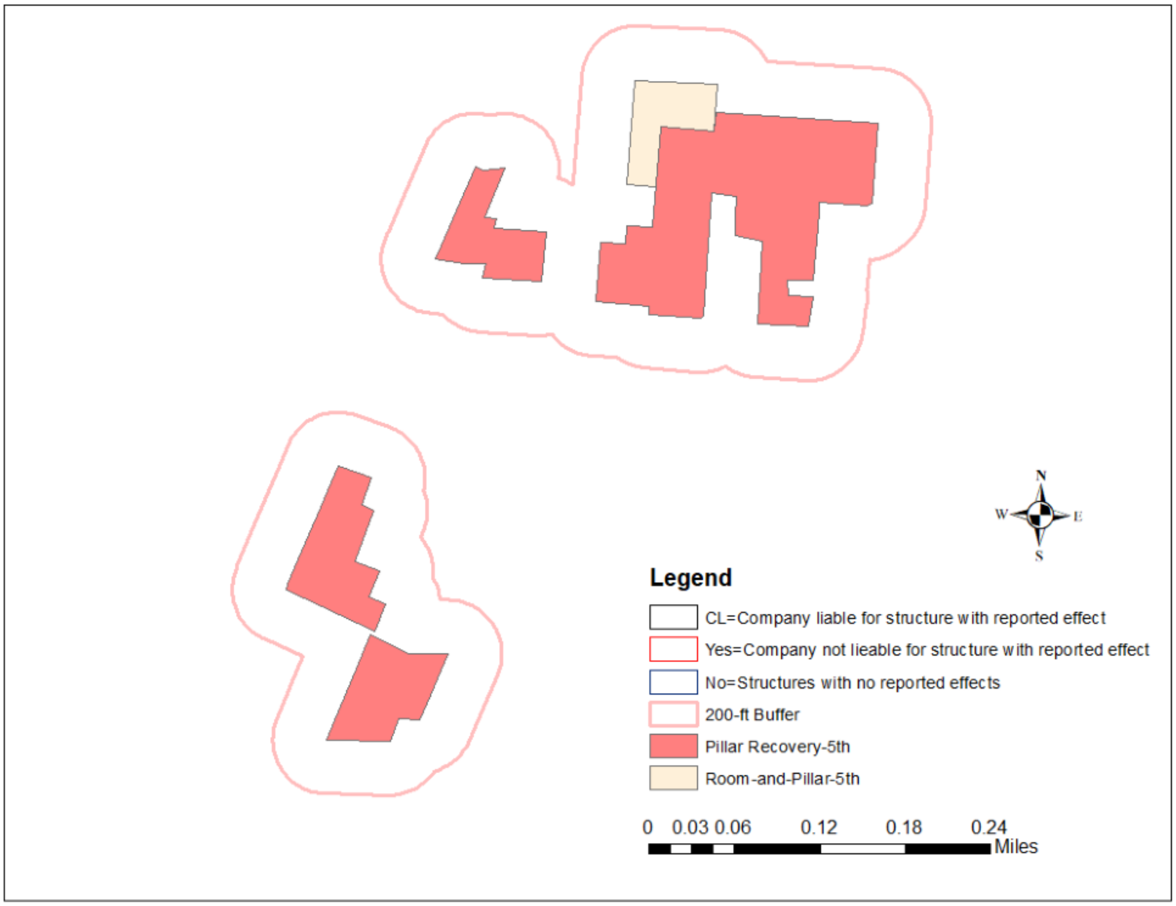

Figure 354. Prime No. 1 5th assessment 200-ft buffer and structures

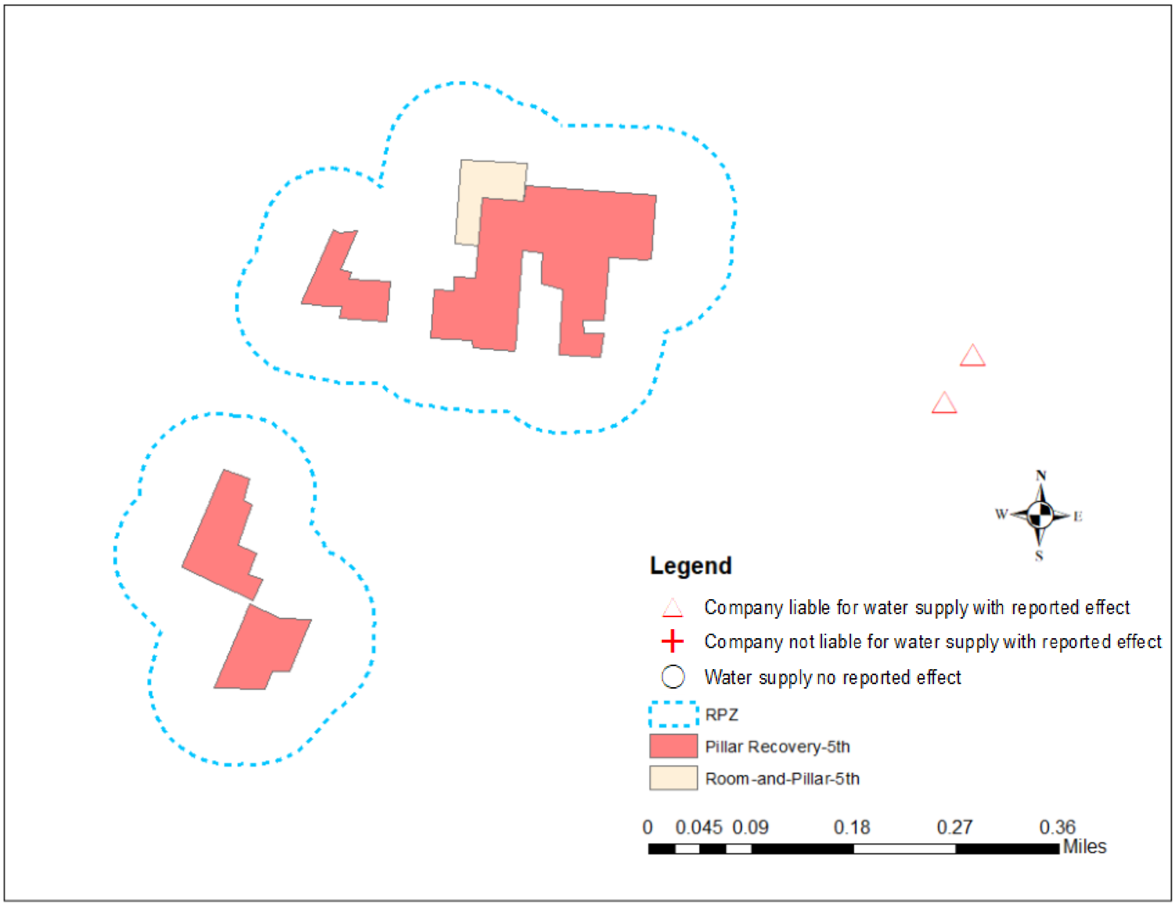

Figure 355. Prime No. 1 5th assessment water supplies and RPZ

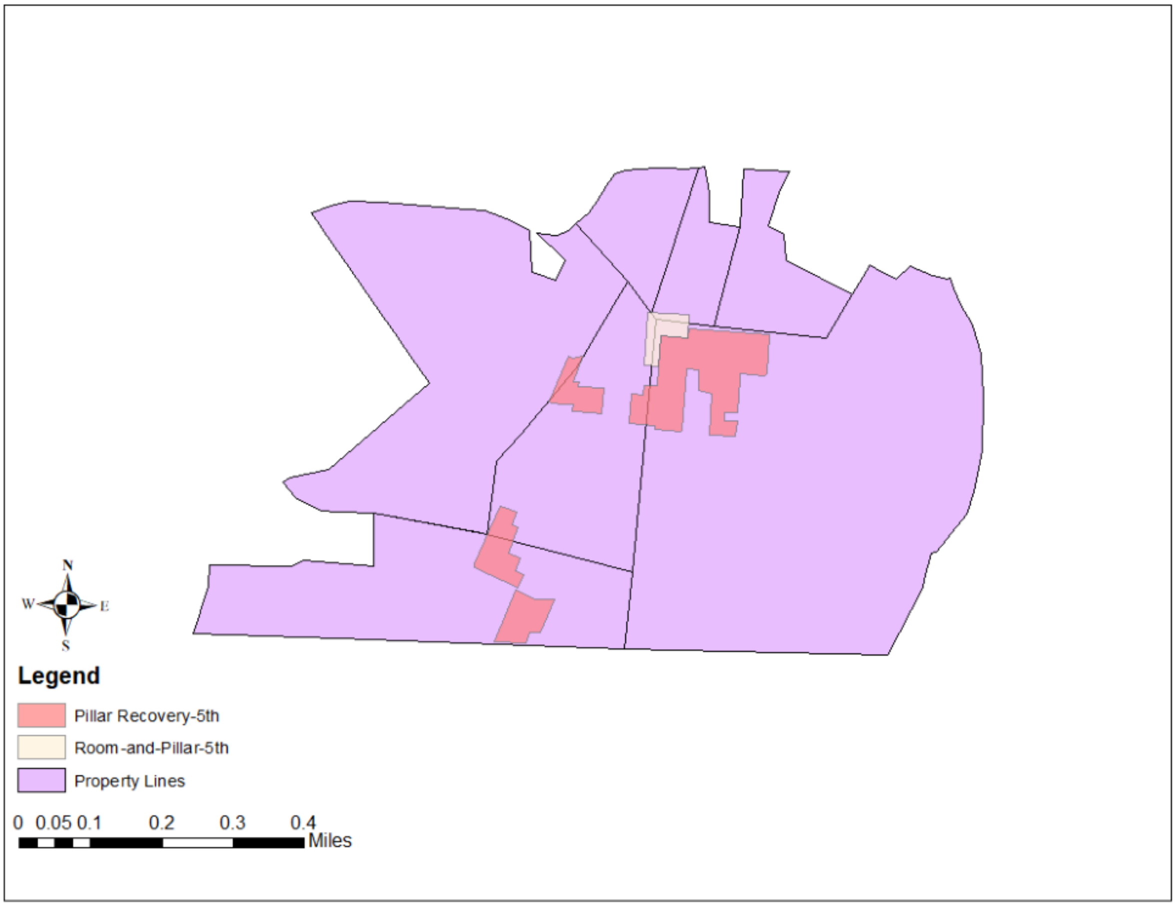

Figure 356. Properties associated with the 5th assessment period over the Prime No. 1 Mine

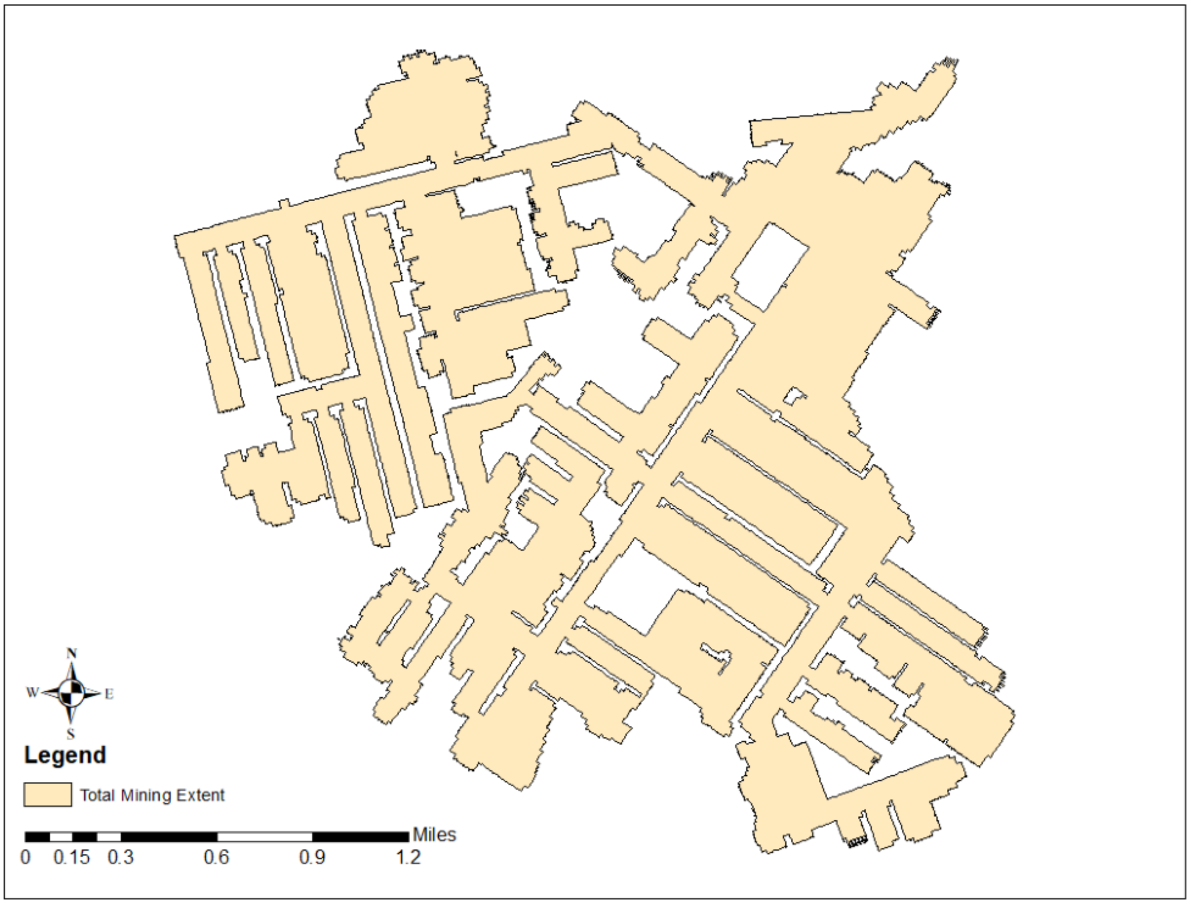

Figure 357. Quecreek No. 1 total extent of mining

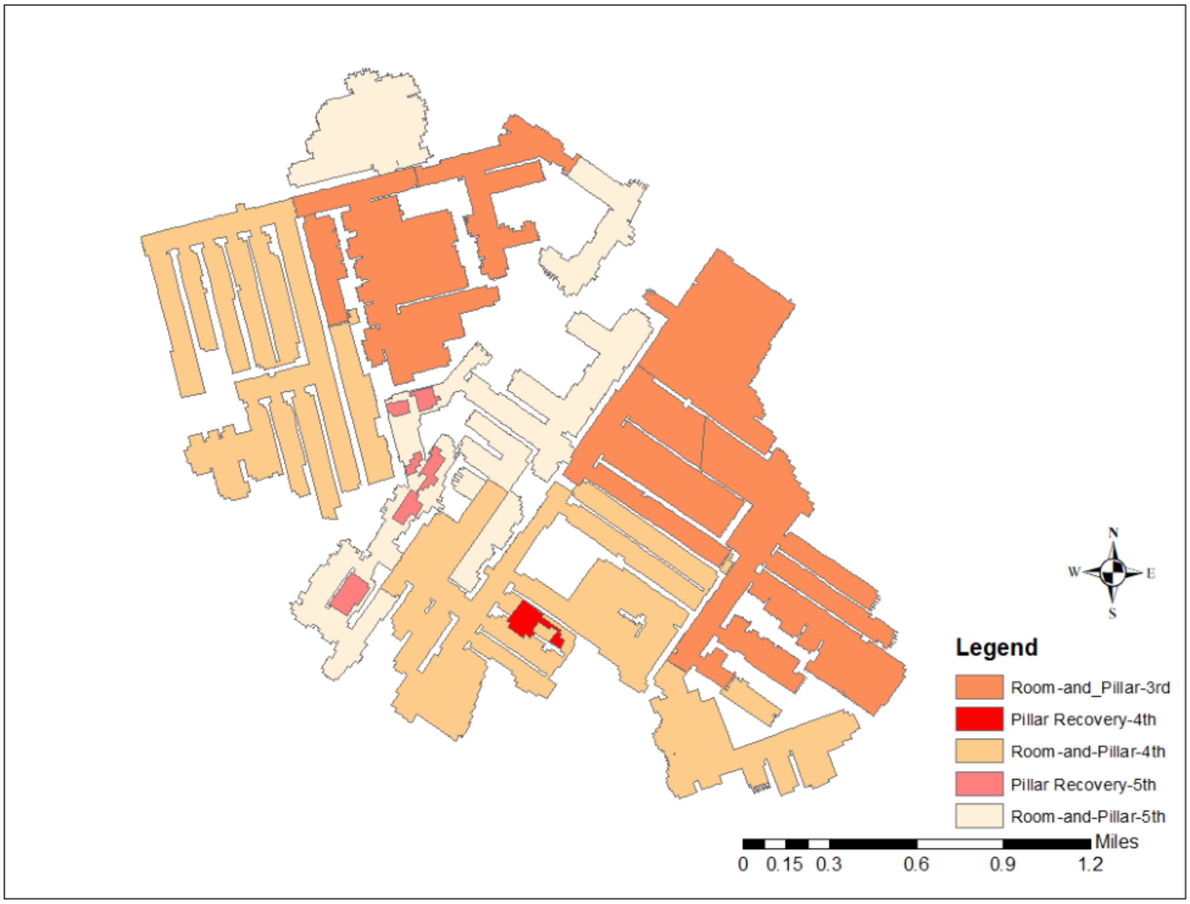

Figure 358. Quecreek No. 1 mining extent for the 3rd, 4th, and 5th assessment periods

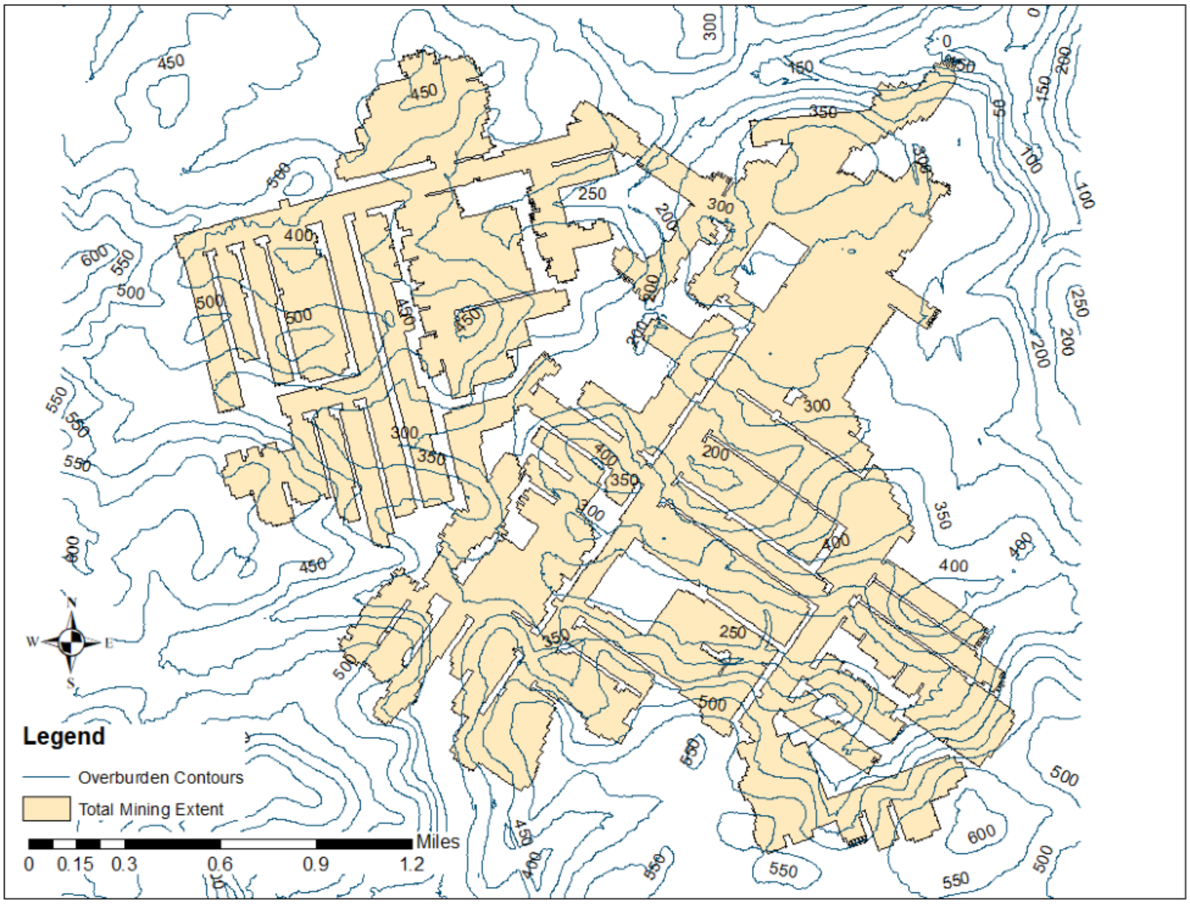

Figure 359. Fifty-foot overburden contour intervals for the Quecreek No. 1 Mine

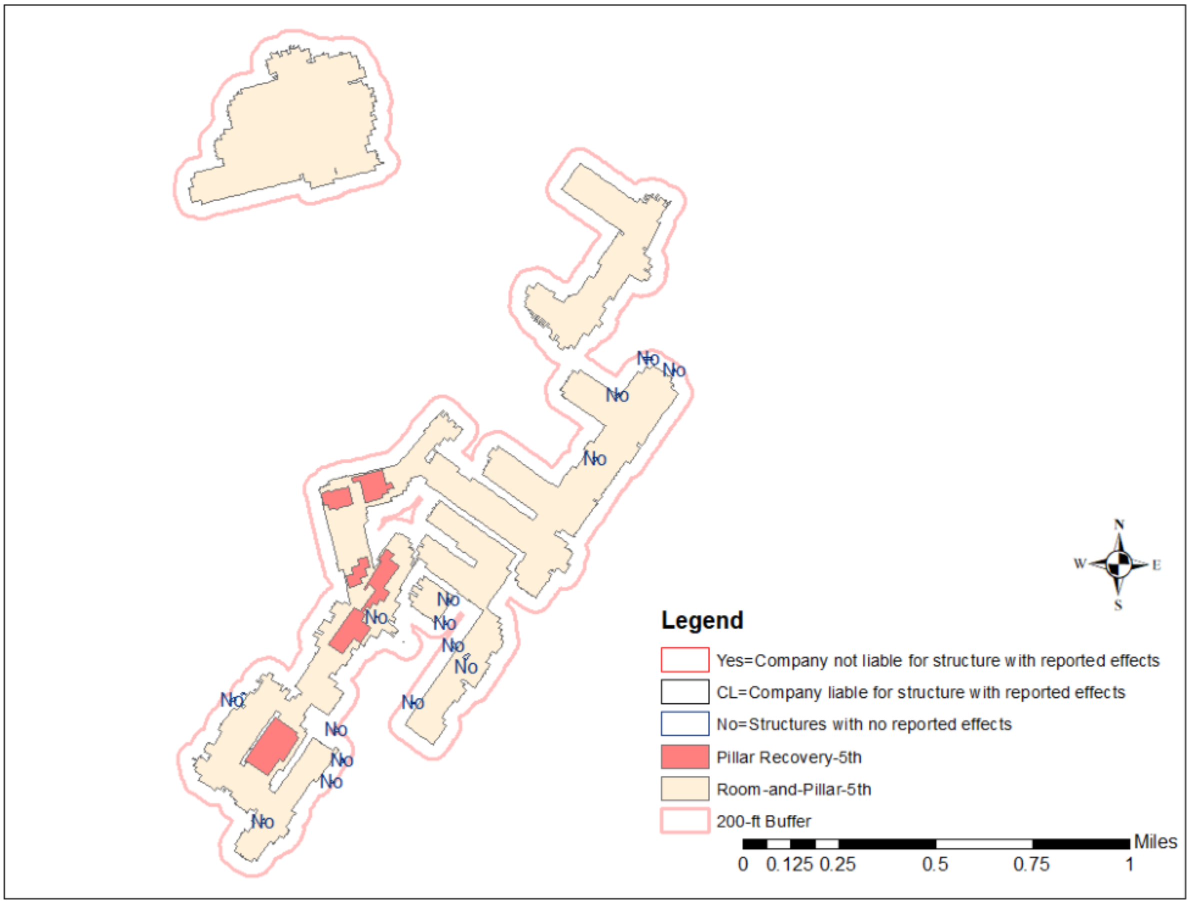

Figure 360. Quecreek No. 1 Mine 5th assessment 200-ft buffer and structures

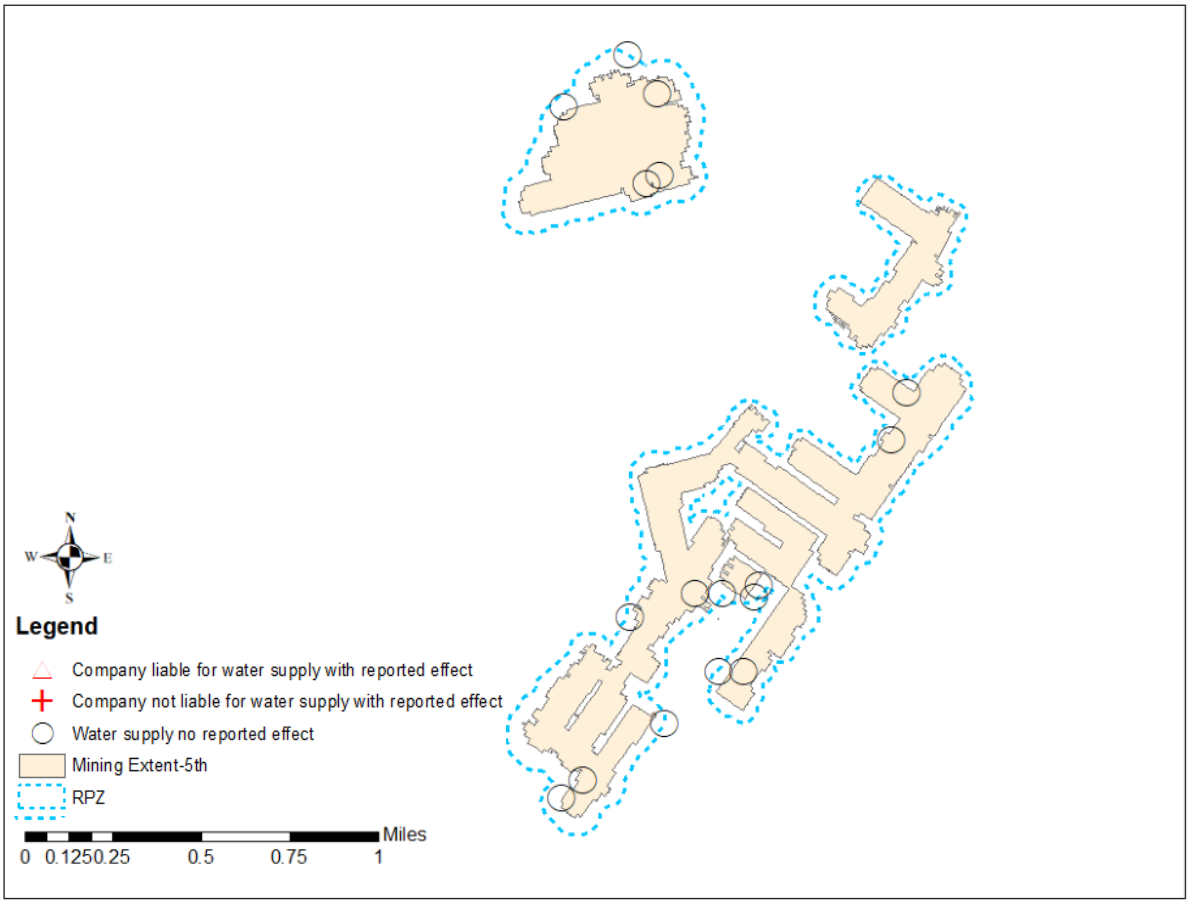

Figure 361. Quecreek No. 1 Mine 5th assessment water supplies and RPZ

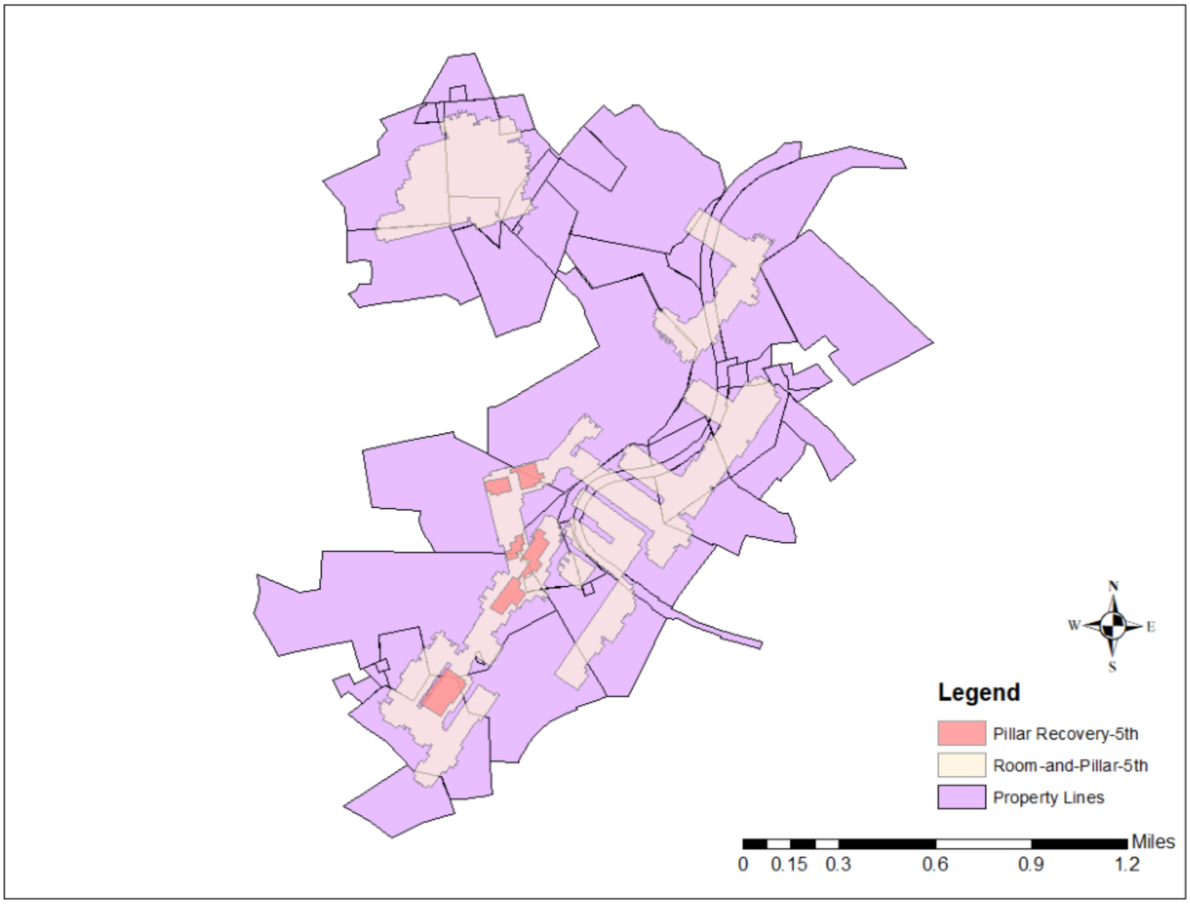

Figure 362. Properties associated with the 5th assessment period over the Quecreek No. 1 Mine

Bibliography

Babcock, C. O. and Hooker, V.E. (1977). "Results of Research to Develop Guidelines for Mining Near Surface and Underground Bodies of Water." U.S. Bureau of Mines Information Circular 8741, pp. 1 – 17.

Bailey Permit File Module 7

Bayer, A. and Nienhaus, K. (2000). Capacity model for room & pillar operations with continuous miners.

Carver, L. and Rauch, H. (1994). "Hydrogeologic Effects of Subsidence at a Longwall Mine in the Pittsburgh Coal Seam." *13th Conference on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 298–307.

Continuous Miners. Retrieved June 18, 2019, from http://www.coaleducation.org/technology/Underground/continuous_miners.htm

Department of Environmental Protection. (2019) "Coal Mining in Pennsylvania." Department of Environmental Protection from https://www.dep.pa.gov:443/Business/Land/Mining/Pages/PA-Mining-History.aspx

Edmunds, W. E., V.W. Skema, et al. (1999) Pennsylvanian - Chapter 10. In: Shutz, C.H., ed. The Geology of Pennsylvania. Pennsylvania Geological Survey and Pittsburgh Geological Society, pp. 149-169.

Fiscor, S. (2018). 2018 U.S. Longwall Census. Coal Age, (Jan-Feb 2018), pp. 24–28.

Gray, R. E. and J. F. Meyers (1970). "Mine Subsidence and Support Methods in Pittsburgh Area." *Journal of the Soil Mechanics and Foundations Division*, Vol. 96, No. 4, July/August 1970, pp. 1267-1287.

Hebblewhite, B., and Gray, D. (2014). "Non-conventional Subsidence Behavior and Impacts-Ryerson State Park Dam, Pennsylvania USA Case Study". *9th Triennial Conference on Mine Subsidence*, pp. 51-61.

Hebblewhite, B.K., Waddington, A., and Wood, J. (2000). "Regional Horizontal Surface Displacements Due to Mining Beneath Severe Surface Topography". *19th Confrence on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 149-157.

Hustrulid, W. A, Bullock, R. L., and Bullock, R. C. (2001). Underground Mining Methods: Engineering Fundamentals and International Case Studies. SME., pp. 1-736.

Iannacchione, A., & Evanek, N. (2018). “36 Years of Subsidence Reporting at the ICGCM.” *37th International Confrence on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 175–182.

Iannacchione, A., Tonsor, S., Witkowski, M., Benner, J., Hale, A., and Shendge, M. (2011). “The Effects of Subsidence Resulting from Underground Bituminous Coal Mining on Surface Structures and Features and on Water Resources 2003 to 2008,” Bituminous Mine Subsidence and Land Conservation Act, Act 54 Amendments, 3rd Five-Year Report, University of Pittsburgh. https://www.dep.pa.gov/Pages/default.aspx

Karmis, M., Agioutantis, Z., and Andrews, A. (2008). “Enhancing Mine Subsidence Prediction and Control Methodologies.” *27th International Confrence on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 136-140.

Kay, D., Barbato, J., Brassington, G., and Somer, K. (2006) “Impacts of Longwall Mining to Rivers and Cliffs in the Southern Coalfield, in N. Aziz” (ed.), Coal 2006: Coal Operators’ Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, pp. 327-336.

Keener, M. (2014). *Factors Influencing the Effects of Underground Bituminou Coal Mining on Water Resources in Western Pennslyvania*. University of Pittsburgh, Pittsburgh, Pennsylvania.

Kendorski, F. S. (1993). “Effect of Full-Extraction Mining on Ground and Surface Waters.” 12th International Conference on Ground Control in Mining, West Virginia University, Morgantown, pp. 412-425.

Kendorski, F. S., Khosla, I., and Singh, M.M. (1979). “Criteria for Determining When a Body of Surface Water Constitutes a Hazard to Mining.” Final Report on U.S. Bureau of Mines Contract No. J0285011, Engineers International, Inc., Downers Grove, IL, August 1979, pp. 364.

Lehmann, C., & Konietzky, H. (2015). Geomechanical issues in longwall mining – an introduction. TU Bergakademie Freiberg, Geotechnical Institute, October 2014, 1-23.

Longwall. U.S. Energy Information Administration.

Mark, C., & Gauna, M. (2016). “Preventing roof fall fatalities during pillar recovery: A ground control success story.” International Journal of Mining Science and Technology, pp. 27.

Martin, M., Payne, D., Coutts, B., & Lync, B. (2018). “Highwall Stability Implications from Longwall Mining at Broadmedow Mine.” *37th International Confrence on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 298–307.

McCulloch, C.M. (1975). “Selected Geological Factors Affecting Mining of the Pittsburgh Coalbed,” US Bureau of Mines Report of Investigations 8093, pp. 72.

Molinda, G. A., Heasley, K. A., Oyler, D. C., and Jones, J. R. (1992). Effects of Horizontal Stress Related to Stream Valleys on The Stability of Coal Mine Operations. U.S. Department of the Interior. Bureau of Mines. Report of Investigations No. 9413; pp. 2–5.

Peng, S. (2008). Coal Mine Ground Control (3rd ed.). Morgantown, West Virginia: West Virgnia University, pp.288-293.

Peng, S. S. & Chiang, H. S. (1984). Longwall mining, Wiley, New York, pp. 708.

Peng, S. S., and Geng, D.Y. (1984) "Surface Subsidence, Overburden Behavior, and Strucutral Damages Due to Longwall Mining-Two Case Studies." *2nd International Confrence on Stability in Underground Mining*. Universtiy of Kentucky, Lexington, Kentucky, pp. 497-523.

Peng, S.S., & Cheng, S.L. (1981). "Predicting Surface Subsidence for Damage Prevention." *Coal Mining and Proccessing*, May. pp, 84-95.

Peng. S. S. (1992). "Surface Subsidence Engineering," Society of Mining, Metallurgy, and Exploration, Inc. pp. 1-66.

Peng. S. S. (1995). "Development of a Subsidence Database and Determination of Subsidence Parameters. In Proceedings." *14th International Conference on Ground Control in Mining*. Morgantown, West Virginia, pp. 226–235.

Pennsylvania Department of Environmental Protection, Bureau of Mining and Reclamation. (1999). "The Effects of Subsidence Resulting from Underground Bituminous Coal Mining on Surface Structures and Features and Water Resources." Bituminous Mine Subsidence and Land Conservation Act, Act 54 Amendments, 1st Five-Year Report.

Pennsylvania Department of Environmental Protection California District Mining Office. (2010) Ryerson Station State Park: Ryerson Station Dam Damage Claim Number SA 1736. Internal Pennsylvania Department of Environmental Protection Interim Report: unpublished.

Pomeroy, J.S., (1982). *Landslides in the Greater Pittsbrugh Regsion, Pennsylvania* [Professional Paper].

Saeidi, A., Deck, O., Al Heib, M., Verdel, T., and Rouleau, A. "Adjusting the Influence function method for subsidence prediction." *International Confrence on Advanced Computational Engineering and Experimentating (ACE-X 2012)*. Istanbul, Turkey, pp. 59–66.

Sammarco, J. J. (1996, November 6). A guidance sensor for continuous mine haulage. vol.4, pp. 2465–2472.

Schwienfurth, S.P. and Finkelman, R.B. (2002). "Coal-- a complex natural resource: an overview of factors affecting coal quality and use in the United States" Circular 1143, pp. 1-55.

Soeder, D. J., & Kappel, W. M. Water Resources and Natural Gas Production from the Marcellus Shale. 6.

Southwestern Pennsylvania Commission. (2017). Previously Active Documented Landslides in Southwestern Pennsylvania. State of Pennsylvania. https://geo.btaa.org/catalog/a1337085-2237-4077-9a31-a161974ad234

Su, D. W., Hasenf, G. J., Kelley, P., & Teeter, D. (2012). "Mitigation of a Massive Sandstone Channel's Impact on a 1,500-Ff-Wide Longwall Face". *31st Conference on Ground Control in Mining*. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration.pp 22-26.

Tonsor, S., Hale, A., Iannacchione, A., Bain, D., Keener, M., Pfeil-McCullough, E., and Garmire, K.2013). "The Effects of Subsidence Resulting from Underground Bituminous Coal Mining, 2008-2013," Bituminous Mine Subsidence and Land Conservation Act, Act 54 Amendments, 4th Five-Year Report, University of Pittsburgh https://www.dep.pa.gov/Pages/default.aspx

U.S. Census Bureau and Esri. (2017). 2017 USA Population Density. Esri. https://.arcgis.com/home/item.html?id=b16d74fba48a4919aacfaac2cd77e5e5

U.S. Energy Information Administration. (2019). "Pennsylvania State Profile and Energy Estimates" U.S. Energy Information Administration from https://www.eia.gov/state/rankings/?sid=PA#/series/47

Woodward, M., Fritsch, D., and Berry, R. (2019) "In 2018, U.S. coal production declined as exports and Appalachian region prices rose." U.S. Energy Information Administration, from https://www.eia.gov/todayinenergy/detail.php?id=38132

Yi Luo, & Syd Peng. (2000). Prediction of Subsurface Subsidence for Longwall Mining Operations. 19th Confrence on Ground Control in Mining. Morgantown, West Virginia: Society for Mining, Metallurgy & Exploration, pp. 163-170.