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Corrosion Risk Assessment for Illinois Alluvial Regional Water Company Project

Below-grade Corrosion Mapping and Soil Analysis Report

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TABLE OF CONTENTS

SYNOPSIS

The objective of this project is to collect and analyze pertinent geographical and soil data for the purpose of developing a high-resolution below-grade corrosion risk assessment map for a water main project in western Illinois, owned by the Illinois Alluvial Regional Water Company. In addition to remote assessment by corrosion mapping, soil samples collected from twelve (12) boreholes are tested in Matergenics Soils Lab to investigate their chemical composition and corrosivity level. The pipeline route, and location of boreholes drilled during a geotechnical study by Terracon, are shown in Figure 1. The water main is 48.3 miles (77.8 km) long and is constructed of ductile iron[1].

As the result of these assessment efforts, areas with high corrosion risk are highlighted along the water main route so that specific recommendations for asset maintenance and corrosion risk mitigation can be planned. This may include pipe material selection, sacrificial steel thickness consideration, protective coating application, and cathodic protection system installation in order to protect the pipeline in highly corrosive soil service environments.

CORROSION MAPPING

The data sets used for corrosion mapping in this project are obtained from reliable sources such as databases from the Natural Resources Conservation Service (NRCS), the United States Geological Survey (USGS), the Soil Survey Geographic (SSURGO), the US EPA EnviroAtlas, and the US Department of Agriculture (USDA). All relevant data are analyzed and compiled on the ESRI ArcGIS platform to generate the required maps with regard to the project objectives.

To present maps for soil properties along the pipeline, a 0.62-mile (1,000 m) wide buffer strip is considered along the line; 0.31 miles (500 m) on each side of the pipeline. Most of soil properties presented in the maps represent averaged values from grade-level to 6.5 ft (2 m) below the grade line.

Multiple soil property maps are compiled and combined in the ArcGIS platform to develop a final corrosion map. As shown in Figure 14 red, yellow, and green colors in the final soil corrosion map correspond to high-corrosivity, moderate-*corrosivity*, and *low-corrosivity* soil service environments, respectively.

The following datasets are used in the development of the soil corrosivity map.

Data Set 1: Pipeline Route, Soil Sampling Locations, and Mapping Territory

In Figure 1, the red line presents the water main route, and twelve (12) yellow pins indicate boring locations for the geotechnical study and soil sampling (conducted by others). A buffer zone with 0.31 miles (500 meter) width is considered on each side of the pipe as the territory for soil mapping. The pipeline is approximately 48 miles (78 km) in length.

Data Set 2: Physiochemical Properties of Soil

Physiochemical properties of soil describe the corrosivity of the liquid phase in the soil. The key parameters in this category are:

- **Soil pH:** Soil pH determines the capacity of soil to support underground corrosion processes by supplying the required reactants for cathodic reactions. Acidic soils with low pH values correspond to soils with a high concentration of hydrogen ions. The excessive presence of hydrogen ions in the soil promotes cathodic reactions which in turn increases the demand for the formation of anodic areas where the material loss and corrosion pitting occur. For the selected territory, a map for soil pH is presented in Figure 2. The level of soil corrosivity based on pH level is presented in Table 1. The most acidic soils are present on the west side of the pipeline; however, the acidity level is not critical, as the most acidic soil has the pH value of 5.5.

[1] In similar corrosive environments, corrosion rates for steel and ductile iron is considered the same in our analysis.

- **Soil electrical conductivity (inverse of electrical resistivity):** Soil electrical conductivity is a property that determines the ability of soil to support electrolytic corrosion currents. Electrical conductivity strongly depends on the soil moisture content and concentration of soluble salts. Soils with higher electrical conductivity generally correspond to soils with higher soil moisture and higher concentrations of salts, which provide a perfect environment for the advancement of underground corrosion. In the AWWA C105 standard, soil resistivities lower than 1,500 ohm-cm are considered as "severe risk" for ductile-iron pipes.

  For the selected territory, a map for soil electrical conductivity is presented in Figure 3. The level of soil corrosivity based on electrical conductivity values is presented in Table 2. The soil resistivity in most areas along the pipeline is less than 1,500 ohm-cm which falls within the high-corrosivity category.

- **Soil salinity:** The soil salinity represents the concentration of soluble salts such as chlorides, sulfates, and sulfides in the liquid phase of the soil. Detailed soil salinity data for the considered territory is not available; however, information regarding surface salination risk is available as shown in Figure 4. For soil surface salination risk, only qualitative descriptions are available in soil databases.

Table 1: Soil corrosivity based on pH level.

pH Value	Corrosivity Level for Steel
Less than 4.0	Regressively High
4.1 – 5.0	
5.1 – 5.5	
5.6 – 6.0	Steadily Moderate
6.1 – 6.5	
6.6 – 7.3	
7.4 – 7.8	
7.9 – 8.4	
8.5 – 9.0	
9.1 – 12.0	Regressively Low
More than 12.1	

Table 2: Soil corrosivity based on resistivity/conductivity value.

Soil Resistivity (ohm-cm)	Soil Conductivity (dS/m)	Corrosivity for Steel
Less than 500	More than 2	Severe
500 – 2,000	0.5 – 2	High
2,000 – 5,000	0.2 – 0.5	Moderate
5,000 – 10,000	0.2 – 0.1	Mild
10,000 – 25,000	0.1 –0.04	Poor
More than 25,000	Less than 0.04	Negligible

x (dS/m) = 1000/x (ohm-cm)
In the AWWA C105 standard, soil resistivities lower than 1,500 ohm-cm are considered as "severe risk" for ductile-iron pipes.

Data Set 3: Geological Information

Selected geological information describes the capacity of the soil to retain moisture. The main parameters in this category are parameters that define soil material/composition, soil texture/particle size, and surface topology. To investigate the effects of geological parameters, the following maps are considered:

- **Soil organic matter content:** Organic matters in soil include bacteria, micro-organisms, and mostly plant and animal residues at various stages of decomposition. The presence of organic matter in soils can result in accelerated corrosion due to microbiologically induced corrosion (MIC), increase in soil acidity, and prolonged time-of-wetness. For the selected territory, a map for organic matter content is presented in Figure 5.

- **Soil clay/silt/sand content:** A detailed dataset for clay, silt and sand content of the soil is available for the considered soil service area. The data is presented in Figure 6, Figure 7, and Figure 8. As demonstrated in the soil wetness triangle, in Figure 9, soils with a high percentage of clay and/or silt have a poor drainage capability and, as such, retain the moisture for longer time; thus, are potentially more corrosive.
- **Soil drainage class:** Soil drainage depends not only on the soil type but also on land use and surface topology. A map for soil drainage is presented in Figure 10. Soils with poor drainage capability are more prone to corrosion activities at grade level and shallow burials due to the possibility of flooding, the formation of water ponds, and frequent wet-dry cycling. For soil drainage, only qualitative descriptions are available in soil databases.
- **Surface topology:** A digital elevation map (DEM) along the line is presented in Figure 11. Pipeline sections located in valleys and low elevation areas are prone to prolonged wetting and a higher risk of corrosion. The maximum elevation variation along the pipeline route is low and around 660 ft (200 m). The lowest section of the pipe is located close to the east end.
- **Other parameters:** In Figure 12 and Figure 13 maps for the soil *bulk density* and *water table* are depicted. The relationship between soil bulk density and corrosion is indirect and often influenced by factors such as moisture content, oxygen availability, and soil composition. In general, soils with lower bulk density values correspond to clay soil and are more corrosive. The water table data represents the depth at which the ground is saturated with water. The water table map is fairly consistent with the drainage class map in Figure 10.

Data Set 4: Stray Current Corrosion Sources

Stray current corrosion can cause significant material loss over a short period of in-service life. Sources of stray current include substation grounding systems, buried electrical equipment, cathodically protected pipelines (mostly oil and gas), ground beds in industrial areas (electroplating and welding facilities in particular), and electric railways.

Maps for other buried assets in the proximity of the water main are not available in public databases. Once the pipeline is commissioned, pipe-to-soil potential measurements during field investigations can confirm if a section of the pipe is affected by stray current or not. Considerable potential fluctuations or potential variations between different pipe sections are signs of DC current interference which can cause stray current corrosion.

CORROSION RISK ASSESSMENT MAP

The final "Soil Corrosion Map" is developed by combining the relevant information from individual maps. This map, shown in Figure 14, highlights areas with low to high corrosion risk. The corrosive soil service environments are mostly identified in the pipe section between boring sites 8 and 10. Soil parameter for boring sites, extracted from soil maps, are summarized in Table 3.

LABORATORY ANALYSIS OF SOIL SAMPLES

Soil Samples

A geotechnical study was conducted (by other contractors) that involved drilling at 12 locations along the pipeline; boring locations are shown with yellow pins in Figure 1. Soil samples of at least 10 liters in volume were collected from each borehole and shipped overnight in sealed 5-gallon buckets to Matergenics' laboratory in Pittsburgh for laboratory analysis. As-received photographs of the twelve (12) soil samples are provided in Figure 15 through Figure 26.

In-Lab Corrosivity Testing

Per the client's request, six (6) soil corrosivity tests listed below were performed:

1. Resistivity test per ASTM G57: *Standard Test Method for Measurement of Soil Resistivity Using the Wenner Four-Electrode Method.* For soil samples, both **as-received** and **saturated** resistivities will be measured.
2. Chlorides contamination test per AASHTO T291: *Standard Method of Test for Determining Water-Soluble Chloride Ion Content in Soil*.
3. pH test per ASTM G51: *Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing* and/or ASTM D4972: *Standard Test Methods for pH of Soils.*
4. Moisture content per ASTM D2216: *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.*
5. Oxidation-reduction potential test ASTM G200: *Standard Test Method for Measurement of Oxidation-Reduction Potential (ORP) of Soil*.

Based on our experience in corrosion inspection and risk assessment of buried assets, chlorides content in soil is a critical factor for soil corrosivity. This parameter is not included in the AWWA C105 standard; however, it is investigated in our lab analysis.

Table 6 to Table 17 present the test results for all twelve (12) soil samples for tests (a) to (e) listed above. For each sample the tests were performed four (4) times to ensure consistency of the data. Soil corrosivity levels corresponding to each tested parameter are tabulated in Table 1, Table 2, Table 4, and Table 5.

Table 3: Soil data for boring location extracted from soil maps.

ID	Water Table (cm)	Bulk Density (gr/cm^3)	Organic Matter (%)	Sand Content (%)	Silt Content (%)	Clay Content (%)	Elec. Cond. (ohm-cm)	Drainage	pH	Corrosivity (based on the map)
Site 1	201	1.45	0.32	4.0	69.4	26.6	1.0	Well	5.9	Moderate
Site 2	46	1.20	1.41	3.0	69.8	27.2	1.0	Poor	6.5	High
Site 3	84	1.40	1.34	14.0	70.0	16.0	0.0	Well	6.7	Moderate
Site 4	46	1.20	1.41	3.0	69.8	27.2	1.0	Poor	6.5	High
Site 5	46	1.30	0.73	8.0	64.6	27.4	0.0	Poor	5.8	Moderate
Site 6	46	1.38	1.28	17.4	59.5	23.1	0.2	Poor	6.9	Moderate
Site 7	46	1.36	0.90	6.6	62.4	31.0	1.0	Poor	6.2	High
Site 8	46	1.38	1.28	17.4	59.5	23.1	0.2	Poor	6.9	Moderate
Site 9	46	1.36	0.90	6.6	62.4	31.0	1.0	Poor	6.2	High
Site 10	38	1.41	0.63	9.80	76.2	14.0	0.0	Poor	6.4	Moderate
Site 11	46	1.40	0.68	9.6	64.3	26.0	0.0	Poor	6.0	Moderate
Site 12	38	1.41	0.63	9.8	76.2	14.0	0.0	Poor	6.4	Moderate

Table 4: Soil corrosivity based on chlorides content.

Chlorides Concentration (ppm)	Corrosivity Level for Steel
Less than 50	Negligible
51 to 200	Moderate
201 to 500	Severe
More than 501	Extreme

Table 5: Soil corrosivity based on redox potential.

Soil Redox Potential (mV-SHE)	Corrosivity Level for Steel
More electro-positive than 401	Non-corrosive
201 to 400	Slight
101 to 200	Moderate
Less electro-positive than 100	Severe

6. Microbiologically Induced Corrosion (MIC) testing: MIC refers to corrosion caused by the presence and activities of microorganisms that can accelerate the corrosion processes. MIC tests, with bacteria specific media, were performed on four (4) selected samples (B1, B4, B8, and B12) collected from 8 feet depth of corresponding boreholes. The bacteria specific media was inoculated by serial dilution and the data were collected after a fifteen-day incubation period. Table 18 to Table 21 summarize the MIC test results for the selected soil samples. Photos showing test results are shown in Figure 27 to Figure 46. MIC tests include the following five (5) tests:
    - Low nutrient bacteria
    - Iron-related bacteria
    - Anaerobic bacteria
    - Acid-producing bacteria
    - Sulfate reducing bacteria

Table 6: Soil corrosivity analyses for Sample 1 – 15235232 B1.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
1	15235232 B1	1	Out of Range	1,691	19.10	6.35	2	661.4
2	15235232 B1	2	Out of Range	1,712	19.50	6.11	2	623.2
3	15235232 B1	3	Out of Range	1,990	19.80	6.16	2	663.6
4	15235232 B1	4	Out of Range	1,845	20.50	6.19	2	675.1

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 7: Soil corrosivity analyses for Sample 2 – 15235232 B2.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
5	15235232 B2	1	Out of Range	1,968	6.91	7.06	2	756.1
6	15235232 B2	2	Out of Range	1,265	7.35	7.21	2	785.1
7	15235232 B2	3	Out of Range	1,097	7.24	7.15	2	714.7
8	15235232 B2	4	Out of Range	1,123	7.28	7.10	2	743.8

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 8: Soil corrosivity analyses for Sample 3 – 15235232 B3.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
9	15235232 B3	1	1,747	1,723	63.20	8.01	16	403.9
10	15235232 B3	2	2,075	1,821	64.70	8.19	15	437.8
11	15235232 B3	3	1,871	1,680	62.90	8.10	15	420.2
12	15235232 B3	4	1,781	1,789	62.70	8.39	15	411.7

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 9: Soil corrosivity analyses for Sample 4 – 15235232 B4.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
13	15235232 B4	1	Out of Range	1,191	119.00	7.31	2	504.7
14	15235232 B4	2	Out of Range	1,220	110.00	7.32	2	637.9
15	15235232 B4	3	Out of Range	1,201	115.00	7.20	2	622.6
16	15235232 B4	4	Out of Range	1,150	109.00	7.37	2	626.8

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 10: Soil corrosivity analyses for Sample 5 – 15235232 B5.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
17	15235232 B5	1	Out of Range	2,232	10.90	6.95	23	600.9
18	15235232 B5	2	Out of Range	2,218	10.40	6.47	23	582.8
19	15235232 B5	3	Out of Range	2,149	10.20	6.84	24	590.3
20	15235232 B5	4	Out of Range	2,225	10.50	6.87	26	567.5

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 11: Soil corrosivity analyses for Sample 6 – 15235232 B6.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
21	15235232 B6	1	2,532	2,193	10.80	7.30	33	501.1
22	15235232 B6	2	3,162	2,651	11.00	7.51	31	526.0
23	15235232 B6	3	2,829	2,479	10.50	7.33	35	510.6
24	15235232 B6	4	2,278	2,207	9.90	7.69	32	514.4

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 12: Soil corrosivity analyses for Sample 7 – 15235232 B7.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
25	15235232 B7	1	Out of Range	1,683	9.89	7.45	1	794.1
26	15235232 B7	2	Out of Range	1,740	9.90	7.42	1	778.1
27	15235232 B7	3	Out of Range	1,672	8.21	7.39	1	788.6
28	15235232 B7	4	Out of Range	1,728	8.32	7.43	2	803.9

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 13: Soil corrosivity analyses for Sample 8 – 15235132 B8.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
29	15235232 B8	1	Out of Range	2,320	15.50	6.81	2	768.0
30	15235232 B8	2	Out of Range	2,423	14.70	6.94	2	736.7
31	15235232 B8	3	Out of Range	2,411	16.90	6.98	2	739.8
32	15235232 B8	4	Out of Range	2,476	15.20	6.97	2	763.9

Table 14: Soil corrosivity analyses for Sample 9 – 5232 B9 BULK.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
33	5232 B9 BULK	1	689	551	66.50	7.33	19	542.4
34	5232 B9 BULK	2	1,056	699	67.20	7.63	19	488.6
35	5232 B9 BULK	3	1,011	728	78.40	7.72	19	549.6
36	5232 B9 BULK	4	1,051	797	68.30	8.09	19	483.5

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 15: Soil corrosivity analyses for Sample 10 – 5232 B10 BULK.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
37	5232 B10 BULK	1	7,560	3,619	4.28	7.85	12	558.0
38	5232 B10 BULK	2	7,780	4,544	3.01	7.97	11	576.4
39	5232 B10 BULK	3	6,040	4,118	4.19	8.02	11	590.4
40	5232 B10 BULK	4	7,080	4,667	3.75	8.18	11	567.9

Table 16: Soil corrosivity analyses for Sample 11 – 5232 B11 BULK.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
41	5232 B11 BULK	1	15,970	3,131	13.20	8.10	8	545.2
42	5232 B11 BULK	2	14,310	2,888	15.40	8.47	8	529.5
43	5232 B11 BULK	3	15,540	2,944	16.00	8.30	8	538.5
44	5232 B11 BULK	4	16,300	3,093	15.90	8.43	7	523.0

Table 17: Soil corrosivity analyses for Sample 12 – 5232 B12 BULK.

Item	Sample ID	Run	As Received Resistivity (ohm-cm)	Saturated Resistivity (ohm-cm)	Chlorides (ppm)	pH	Moisture (%)	Redox (mV-SHE)
45	5232 B12 BULK	1	4,105	2,265	18.00	8.05	16	544.0
46	5232 B12 BULK	2	4,109	2,309	25.50	8.12	17	540.7
47	5232 B12 BULK	3	3,720	2,180	24.10	8.16	16	548.1
48	5232 B12 BULK	4	3,870	2,244	24.00	8.09	16	545.5

Background colors of purple, red, orange, and yellow indicate the order of severity for critical corrosivity parameters in soil samples

Table 18: MIC test results for Sample 1 – 15235232 B1.

Microbiological Test	Results	Range of Viable Bacteria per mL of Slurry
LNB (Low Nutrient Bacteria)	Positive	1,000 to 10,000
IRB (Iron Related Bacteria)	Positive	10 to 100
ANA (Anaerobic Bacteria)	Positive	1,000 to 10,000
APB (Acid Producing Bacteria)	Positive	1,000 to 10,000
SRB (Sulfate Reducing Bacteria)	Positive	1 to 10
Test Start Date: Jan 25, 2024 **Test End Date:** Feb 9, 2024		

Table 19: MIC test results for Sample 4 – 15235232 B4.

Microbiological Test	Results	Range of Viable Bacteria per mL of Slurry
LNB (Low Nutrient Bacteria)	Positive	≥100,000
IRB (Iron Related Bacteria)	Positive	1 to 100
ANA (Anaerobic Bacteria)	Positive	10 to 100
APB (Acid Producing Bacteria)	Positive	1,000 to 10,000
SRB (Sulfate Reducing Bacteria)	Positive	1 to 10
Test Start Date: Jan 25, 2024 **Test End Date:** Feb 9, 2024		

Table 20: MIC test results for Sample 8 – 15235232 B8.

Microbiological Test	Results	Range of Viable Bacteria per mL of Slurry
LNB (Low Nutrient Bacteria)	Positive	≥100,000
IRB (Iron Related Bacteria)	Positive	10 to 100
ANA (Anaerobic Bacteria)	Positive	≥100,000
APB (Acid Producing Bacteria)	Positive	≥100,000
SRB (Sulfate Reducing Bacteria)	Positive	1 to 10
Test Start Date: Jan 25, 2024 **Test End Date:** Feb 9, 2024		

Table 21: MIC test results for Sample 12 – 5232 B12.

Microbiological Test	Results	Range of Viable Bacteria per mL of Slurry
LNB (Low Nutrient Bacteria)	Positive	≥100,000
IRB (Iron Related Bacteria)	Positive	1,000 to 10,000
ANA (Anaerobic Bacteria)	Positive	≥100,000
APB (Acid Producing Bacteria)	Positive	≥100,000
SRB (Sulfate Reducing Bacteria)	Positive	1 to 10
Test Start Date: Jan 25, 2024 **Test End Date:** Feb 9, 2024		

CONCLUSIONS

A high-resolution corrosion map for below-grade service environment is developed that highlight areas with high, moderate, and low corrosion rates. Several soil properties are collected, reviewed, and complied to generate the map, including:

1. Soil pH,
2. Soil electrical conductivity,
3. Soil surface salination risk,
4. Soil organic matter content,
5. Soil clay content,
6. Soil silt content,
7. Soil sand content,
8. Soil drainage class,
9. Soil bulk density,
10. Water table, and
11. Surface topology.

Based on field experience obtained during many corrosion inspection projects, among above-listed parameters, electrical conductivity, clay content, and corrosive salt contents are key parameters in determining soil corrosivity. Accordingly, in the construction of the corrosion map we have assigned the highest weight factor to these parameters. Comparison between lab data on collected soil samples and the prediction of the corrosivity map indicates a fair consistency. The most corrosive soil samples are related to Site #9, followed by Site#4, Site #3, Site #2, Site #1 and Site #7. Among these, Site #9, Site#4, Site #2, and Site #7 are also ranked as Highly Corrosive in the corrosion map; see Table 3.

In addition to soil properties listed above, stray current corrosion due to external factors can influence the corrosion rate on the water main. Unfortunately, public data regarding other buried assets in proximity to the pipeline are not available. To address the stray current corrosion, close-interval surveys must be conducted to map the pipe-to-soil potential along the pipe. These measurements can indicate, with high certainty, if a section of the pipe is affected by stray current.

Finally, bacteria tests conducted on soil samples indicate positive results for all five (5) types of tested bacteria. Considering the depth of the pipeline, moisture accumulation around the pipe and type of bacteria, the risk of biofilm formations and bacterial corrosion is considerably high along the pipeline.

Based on experimental studies by USA National Bureau of Standards, as shown in Table 22, soil corrosiveness can be related to uniform (general) and localized (pitting) corrosion rates. The corresponding corrosion rates for low, moderate, and highly corrosive soils are summarized in Table 23. The provided corrosion rates in this table can be used as estimated corrosion material loss for the Illinois Alluvial Regional Water Company water main during its in-service life.

Corrosion mitigation efforts, in particular cathodic protection, can be considered once accelerated corrosion in highly corrosive soils is detected on the pipeline during future field investigations.

Table 22: Effects of environmental factors on corrosion rate (mm per year) of steel in soil.

Soil Environment Parameters	Uniform Corrosion Rate (mm/yr)			Maximum Pitting Rate (mm/yr)		
	Max.	Min.	Ave.	Max.	Min.	Ave.
Resistivity (ohm-cm)						
< 1,000	0.063	0.018	0.033	0.31	0.11	0.20
1,000 – 5,000	0.058	0.006	0.017	> 0.45*	0.05	0.14
5,000 – 12,000	0.033	0.005	0.018	0.23	0.06	0.14
> 12,000	0.036	0.003	0.014	0.26	0.03	0.11
Drainage						
Very Poor	0.058	0.038	0.046	> 0.45*	0.16	0.28
Poor	0.037	0.010	0.024	0.23	0.05	0.14
Fair	0.063	0.018	0.022	0.31	0.08	0.16
Good	0.022	0.003	0.010	0.18	0.03	0.11
Air-pore Space (%)						
< 5	0.033	0.010	0.021	0.20	0.05	0.13
5 – 10	0.063	0.009	0.024	0.31	0.10	0.17
10 – 20	0.037	0.006	0.017	0.26	0.05	0.15
20 – 30	0.058	0.012	0.025	> 0.45*	0.10	0.20
> 30	0.038	0.004	0.013	0.23	0.03	0.09

* Perforated coupon
Reference: NACE Corrosion Engineer's Reference Book, Third Edition, p. 188.

Table 23: Classification of soil corrosivity based on general and pitting corrosion rates (mils per year, mpy).

Corrosivity Level	Uniform Corrosion Rate	Corresponding Max Pitting Rate
Low	< 0.5 mpy	< 4 mpy
Moderate	0.5 to 1.5 mpy	4 to 8 mpy
High	> 1.5 mpy	> 8 mpy

APPENDIX A: MAPS & PHOTOS

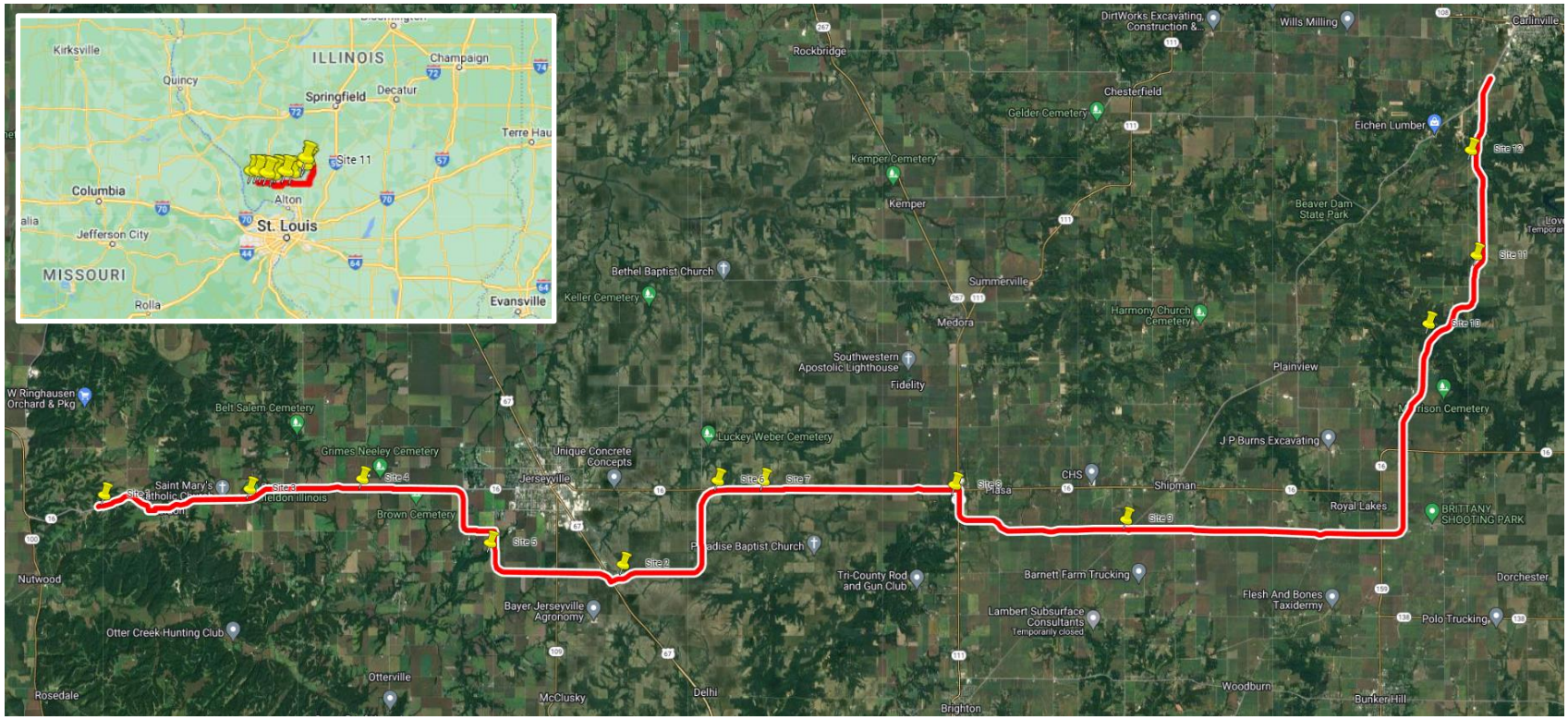

Figure 1: The water main route (red line) and drilling locations (twelve yellow pins) are shown in the map.

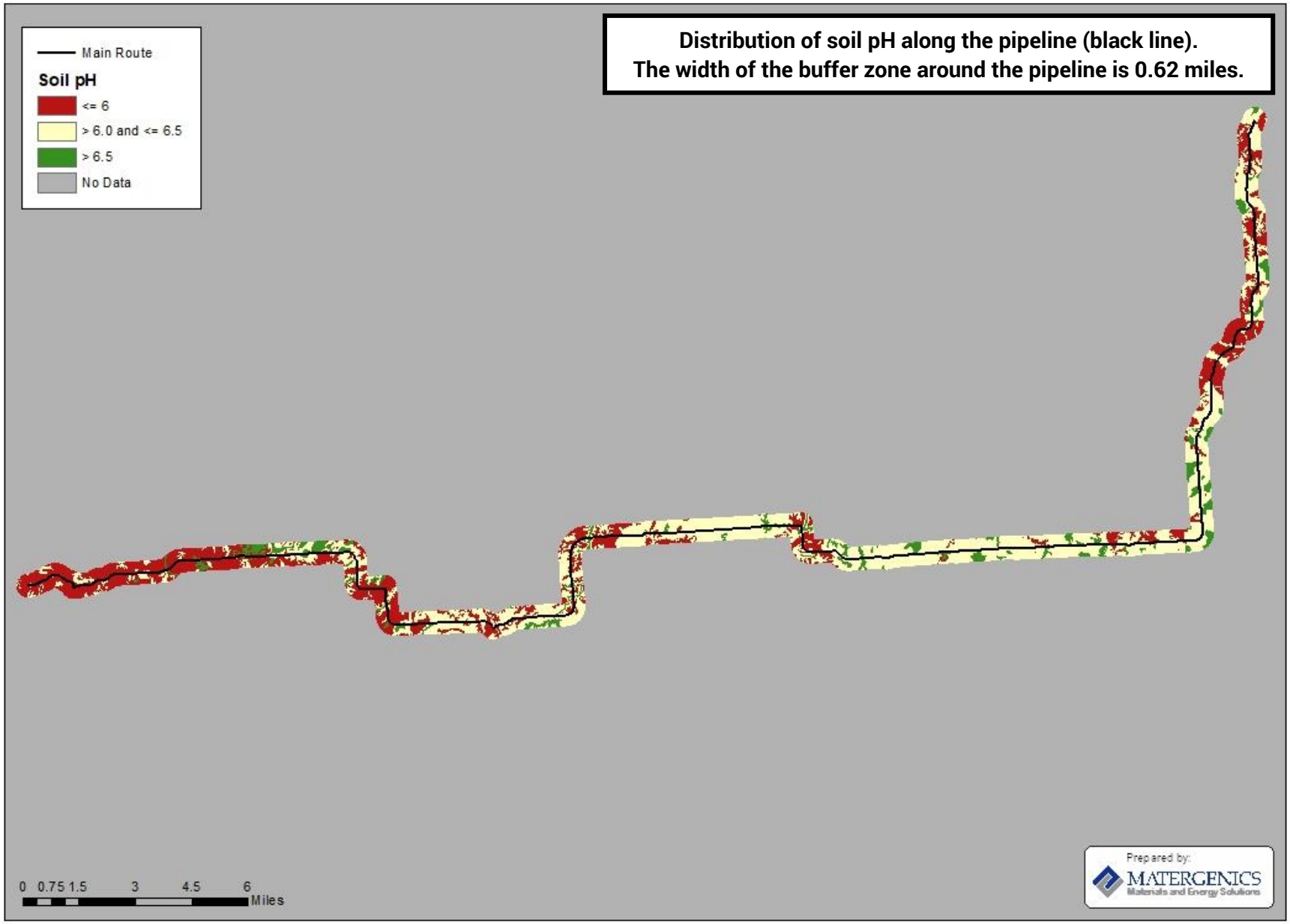

Figure 2: Map of soil pH. Min and Max values are 5.5 and 7.1.

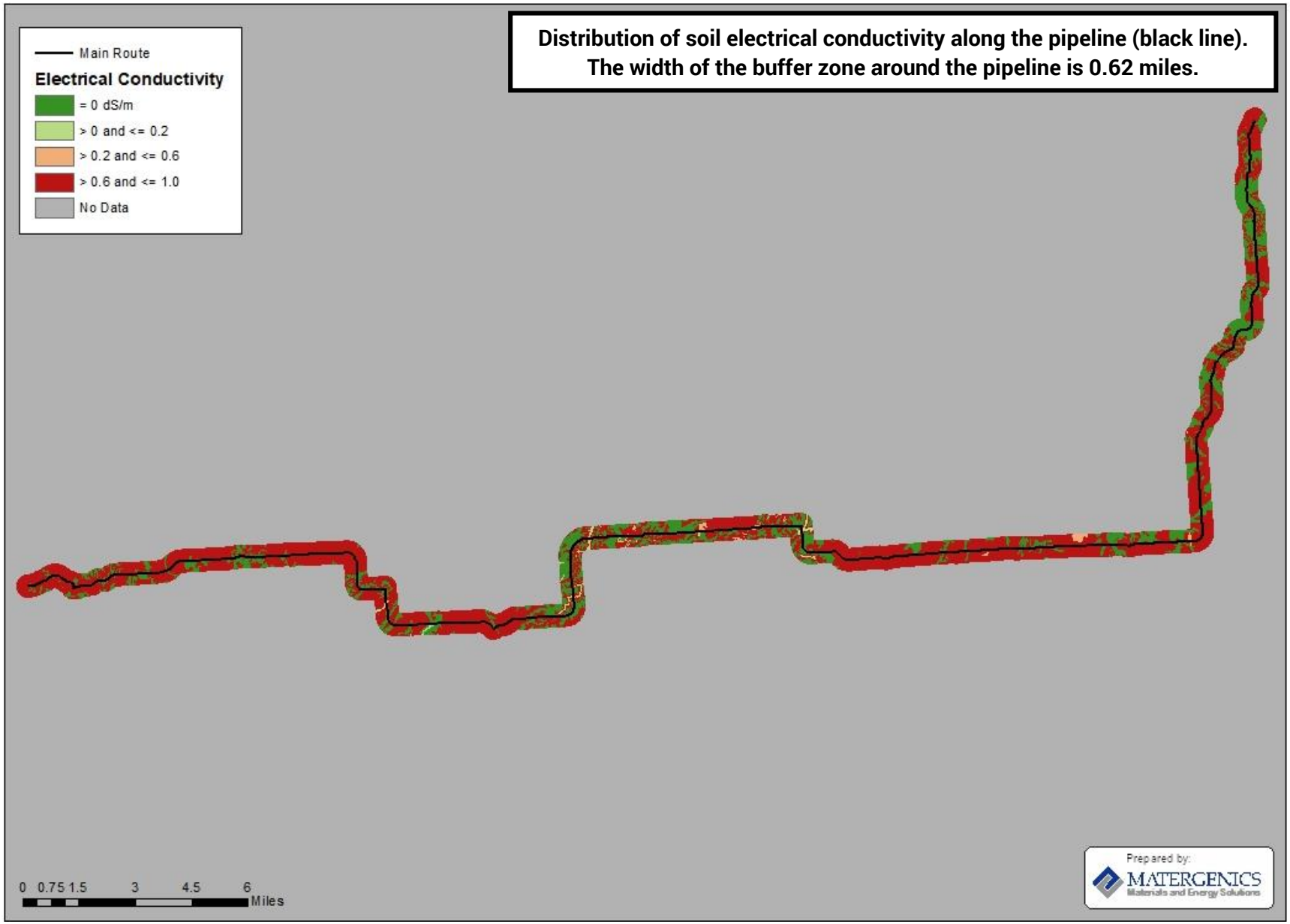

Figure 3: Map of soil electrical conductivity (in dS/m). Min and Max values are 0 and 1 dS/m.

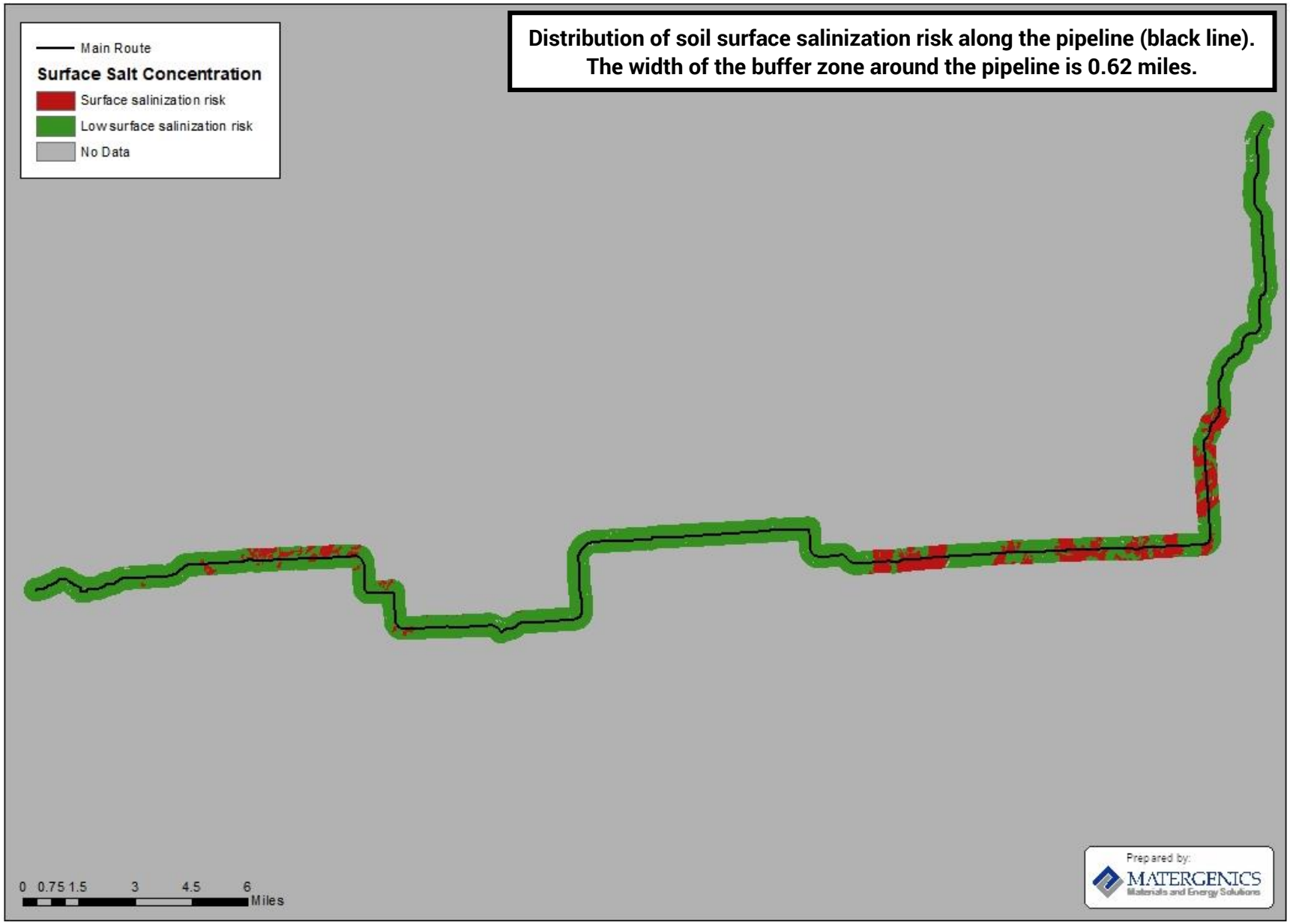

Figure 4: Map of soil surface salinization risk.

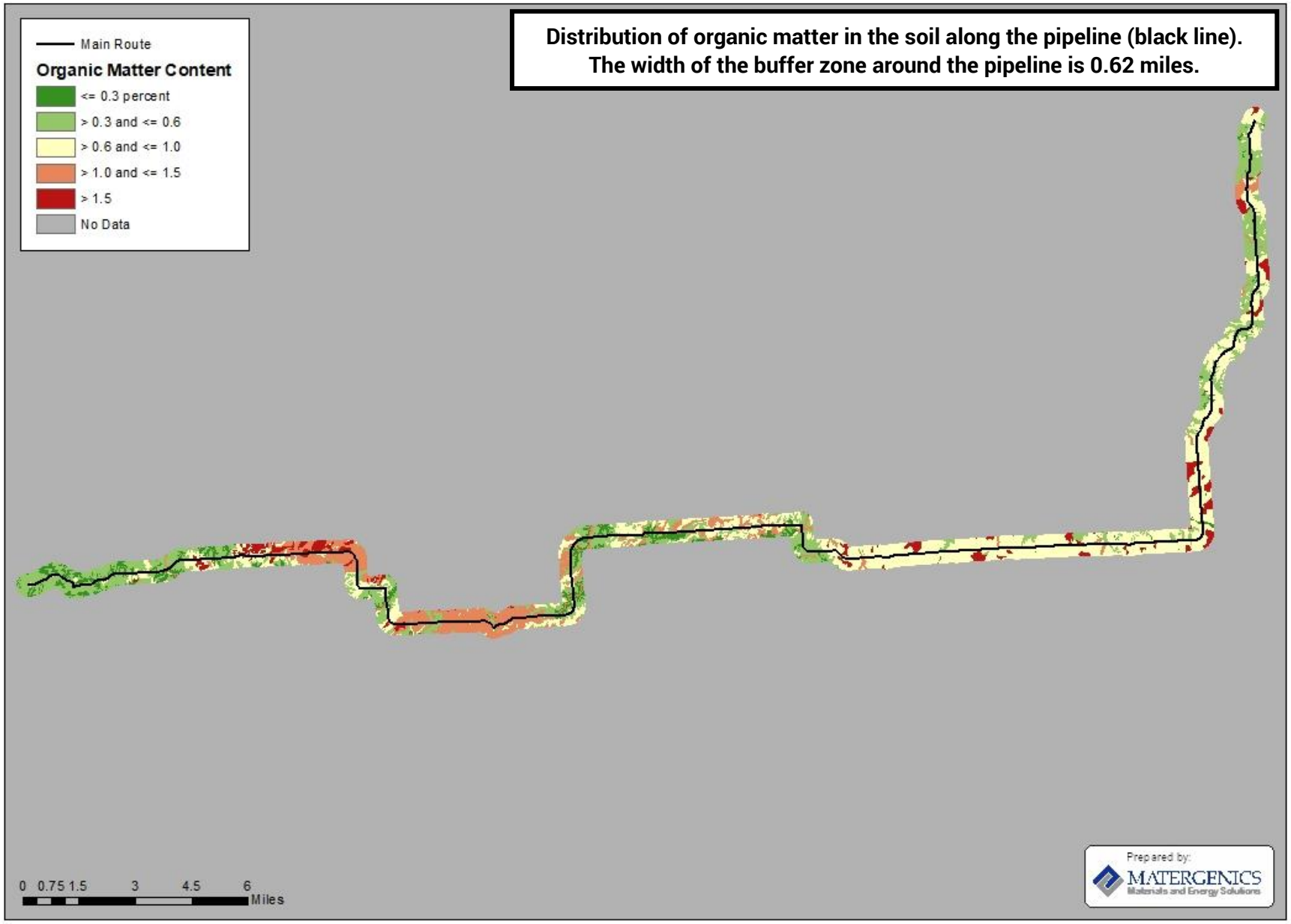

Figure 5: Map of soil organic matter content (in %). Min and Max values are 0 and 3.3%.

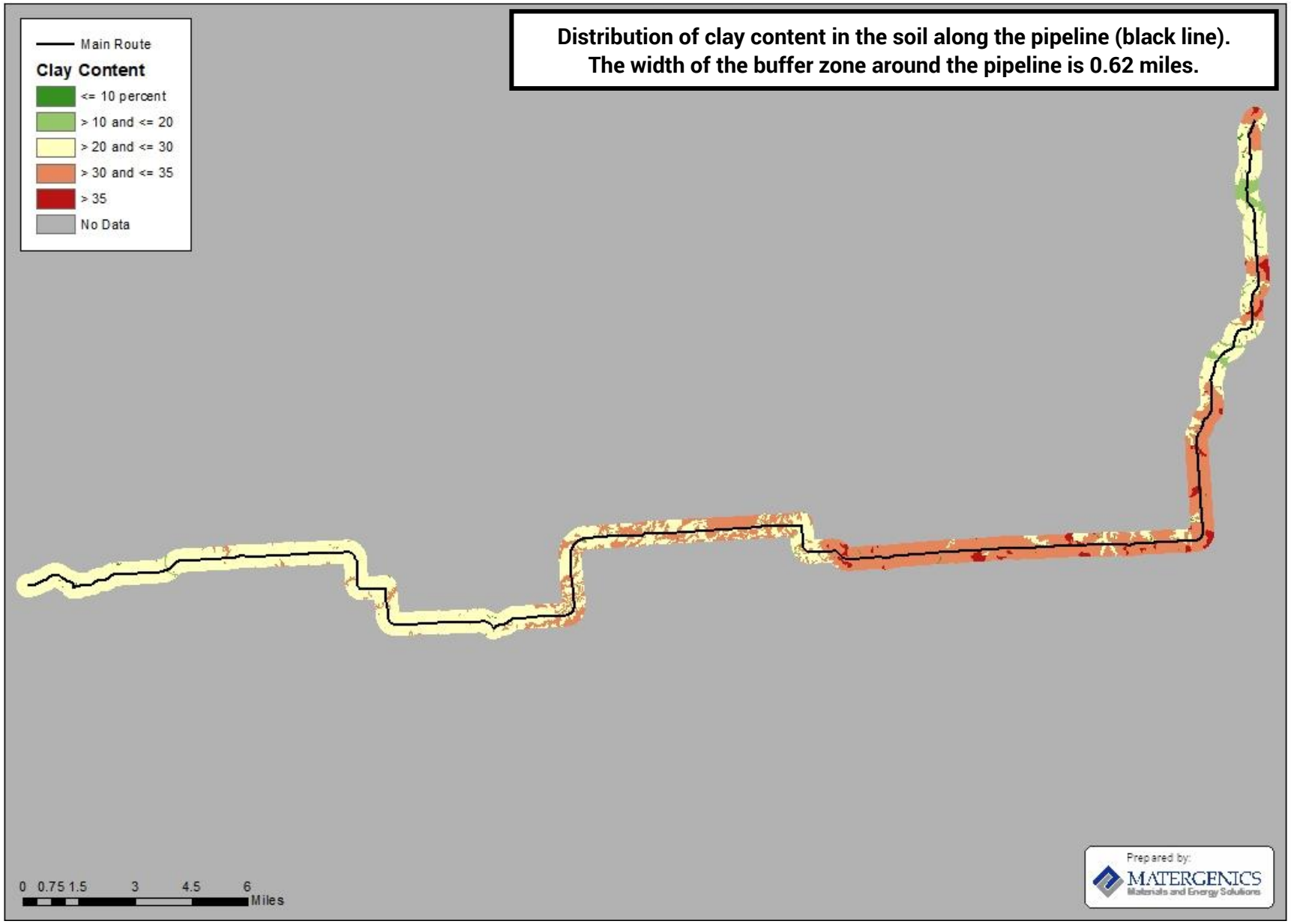

Figure 6: Map of soil clay content (in %). Min and Max values are 0 and 40.3%.

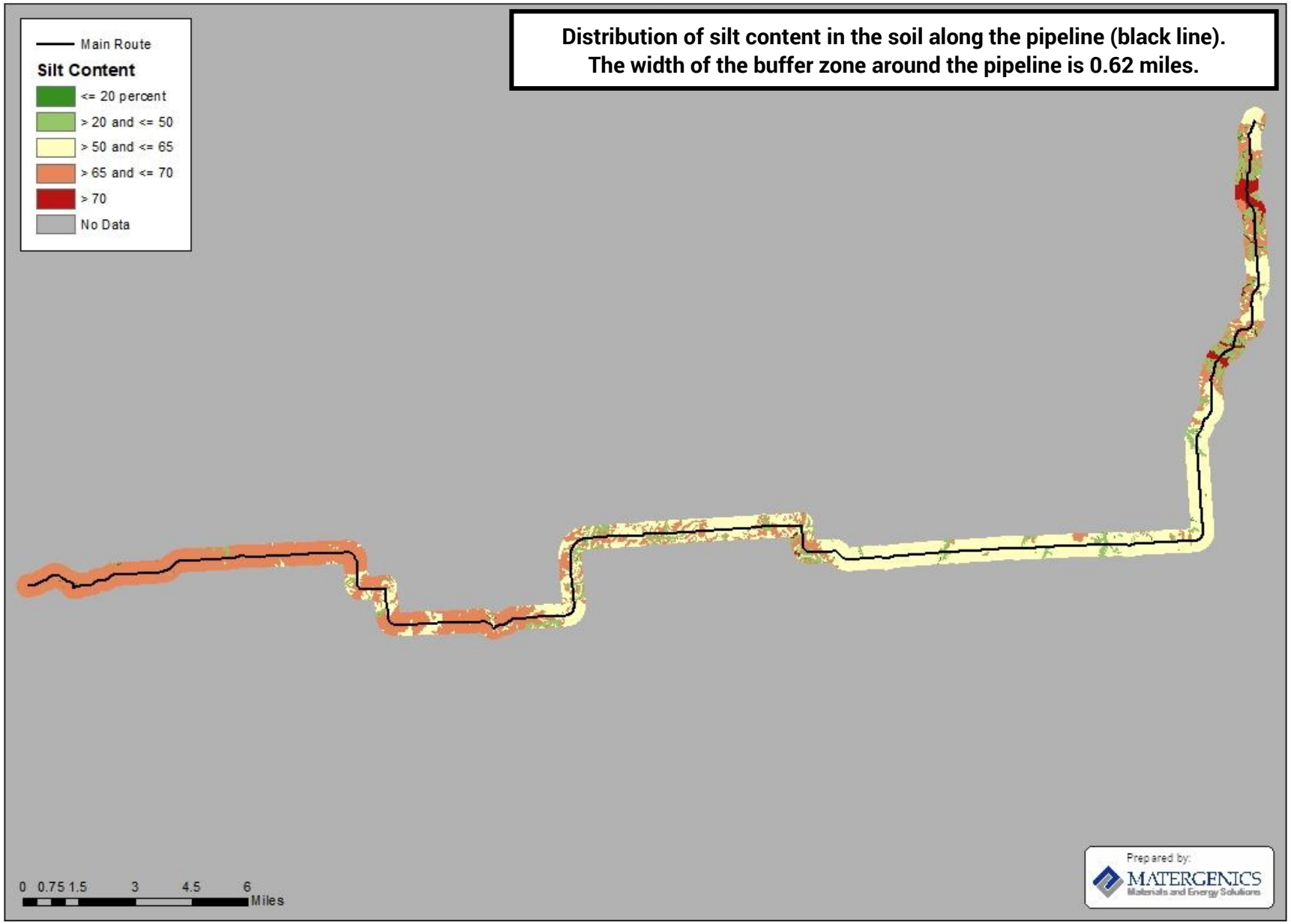

Figure 7: Map of soil silt content (in %). Min and Max values are 0 and 76.19%.

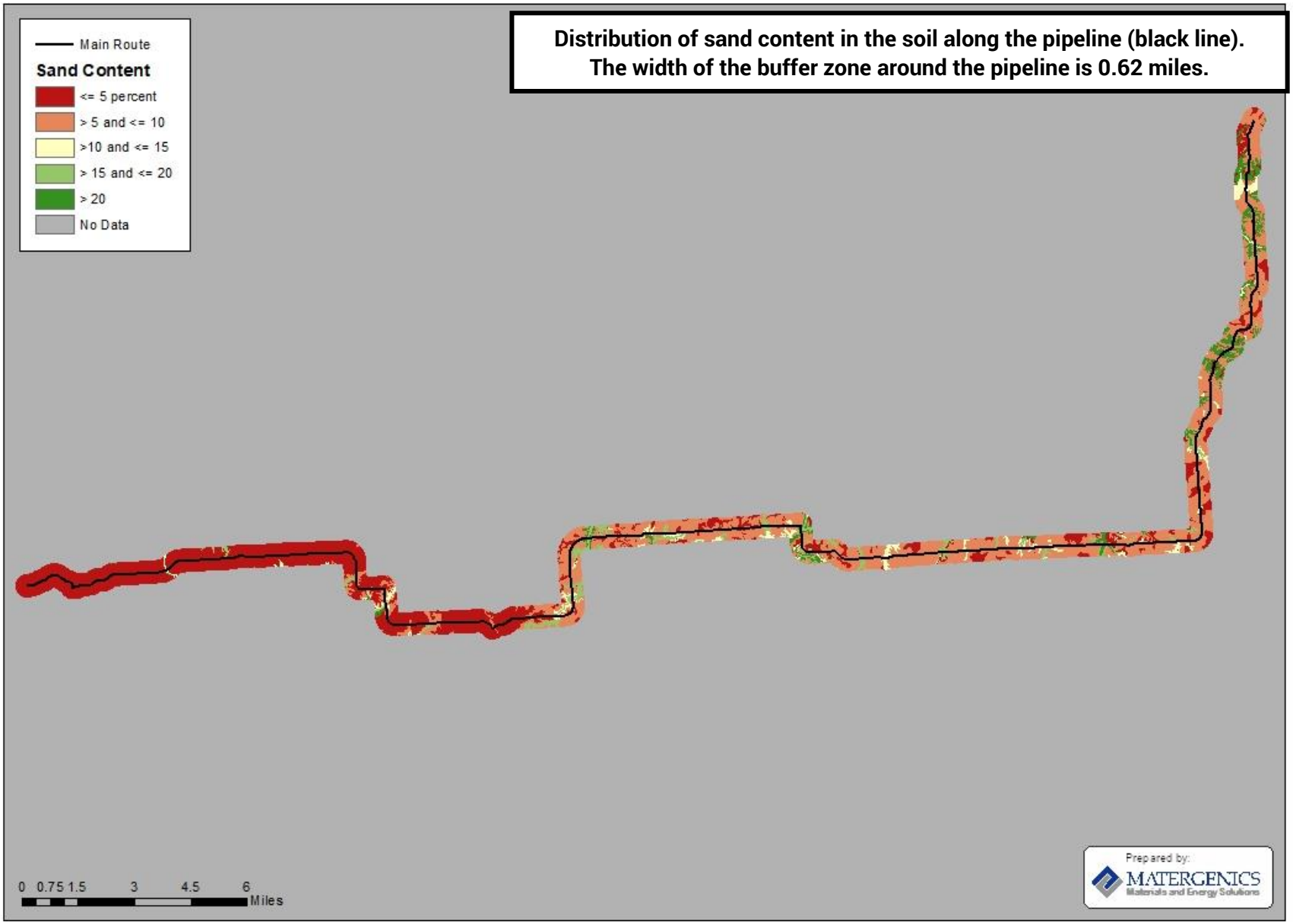

Figure 8: Map of soil sand content (in %). Min and Max values are 0 and 61%.

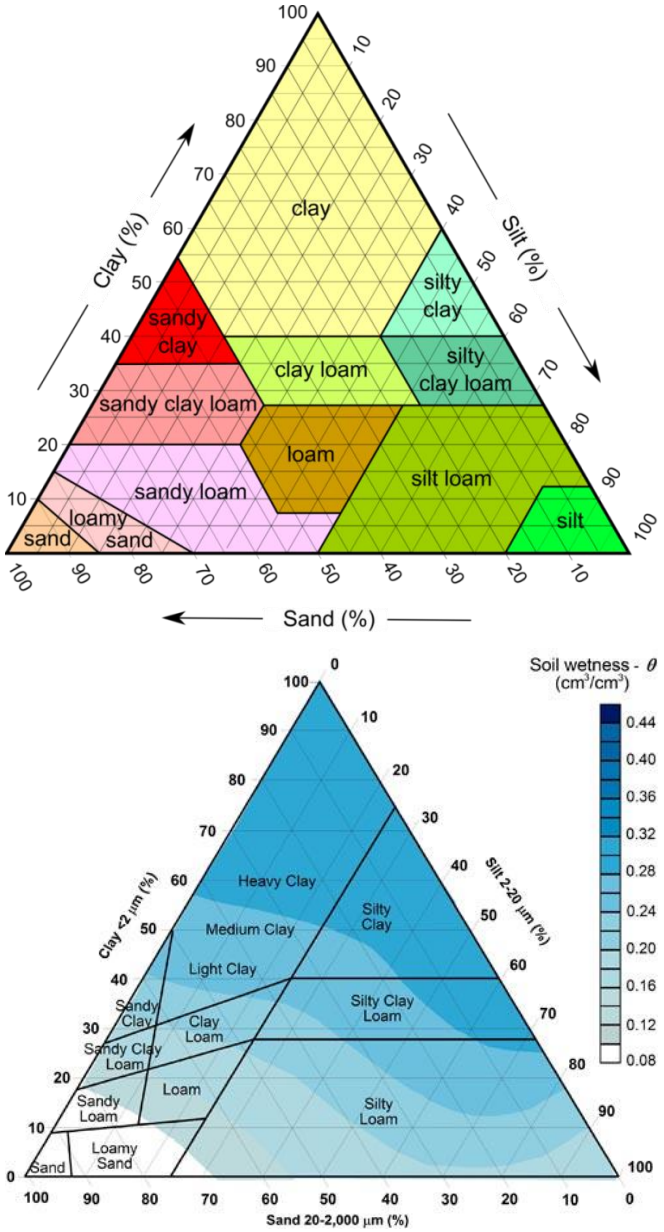

Figure 9: (Top) USDA textural classification triangle for soil; (bottom) soil wetness (capacity to retain water) based on soil texture.

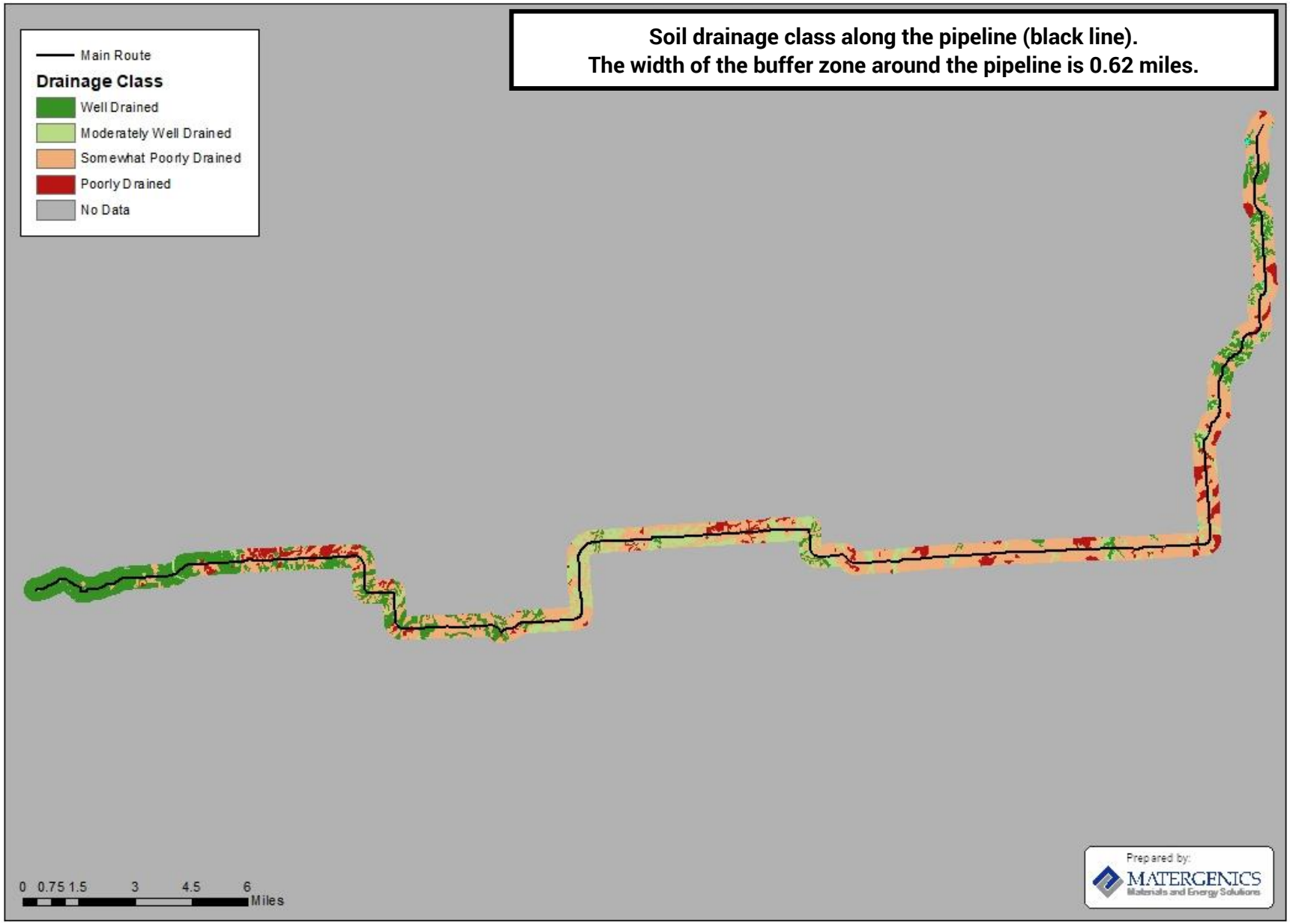

Figure 10: Map of soil drainage class.

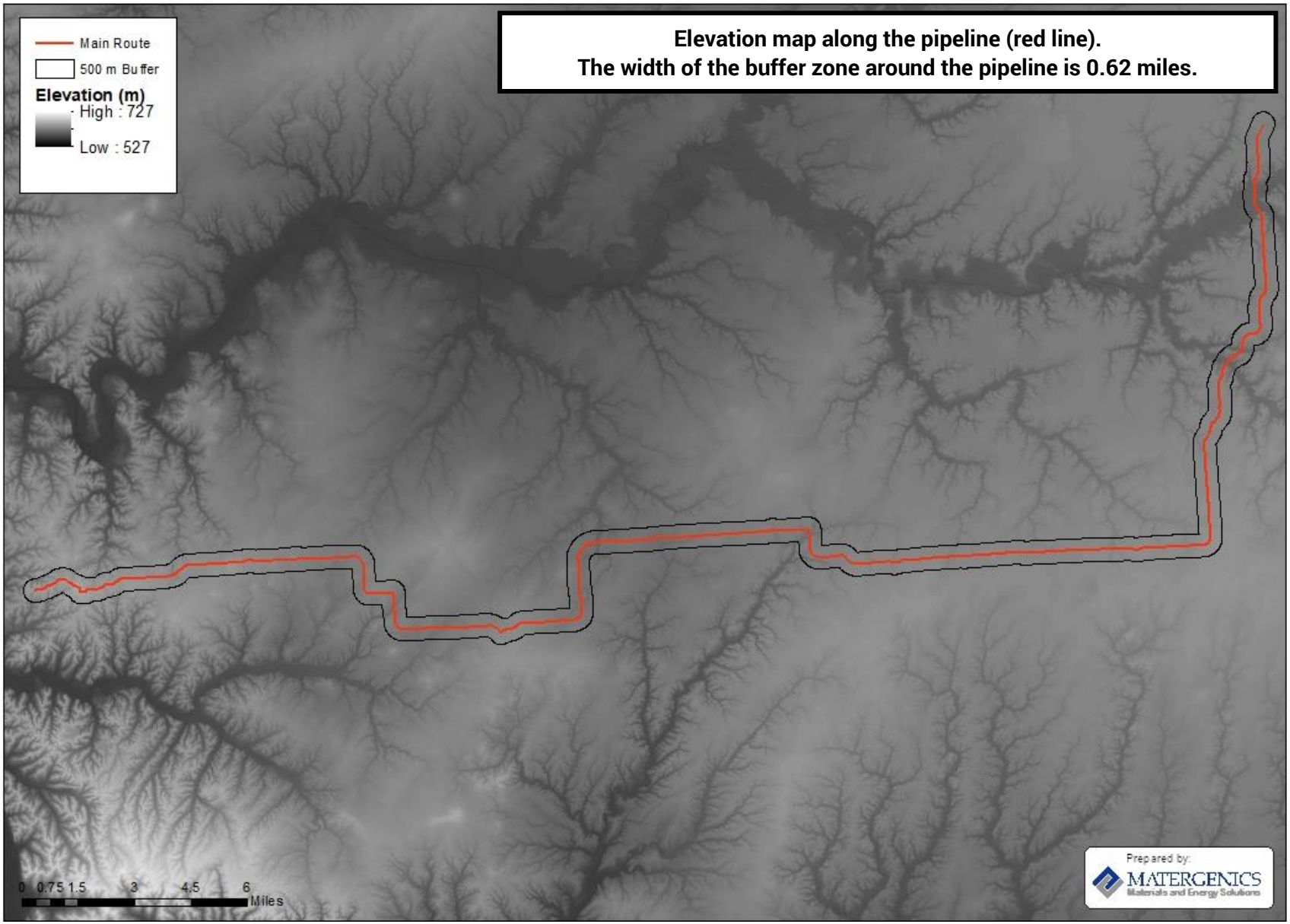

Figure 11: Digital elevation map (DEM) for surface topology. Min and Max elevation along the pipe are 527 and 727.

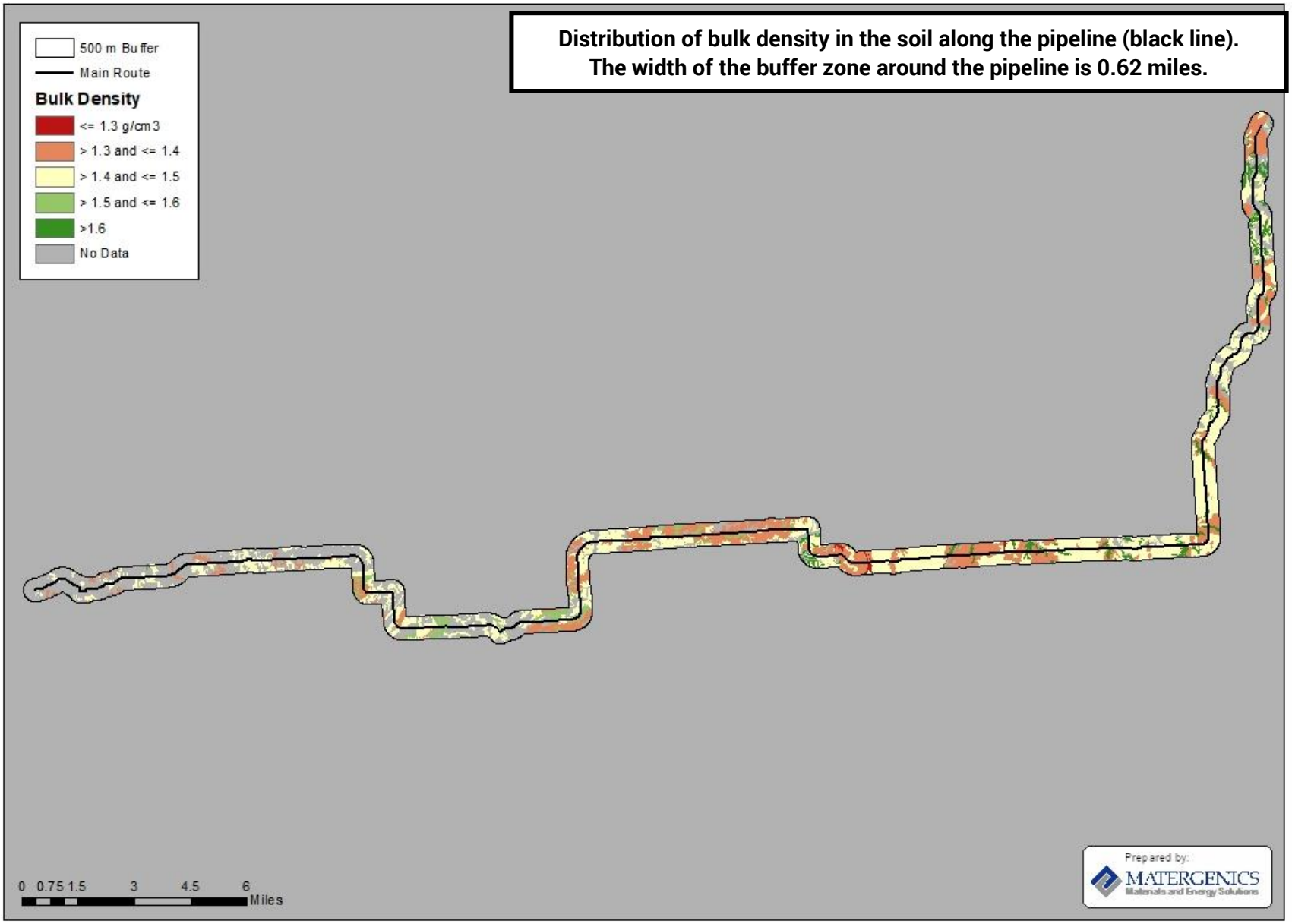

Figure 12: Map of bulk density distribution (in g/cm^3). Min and Max values are 1.2 and 1.7 g/cm^3.

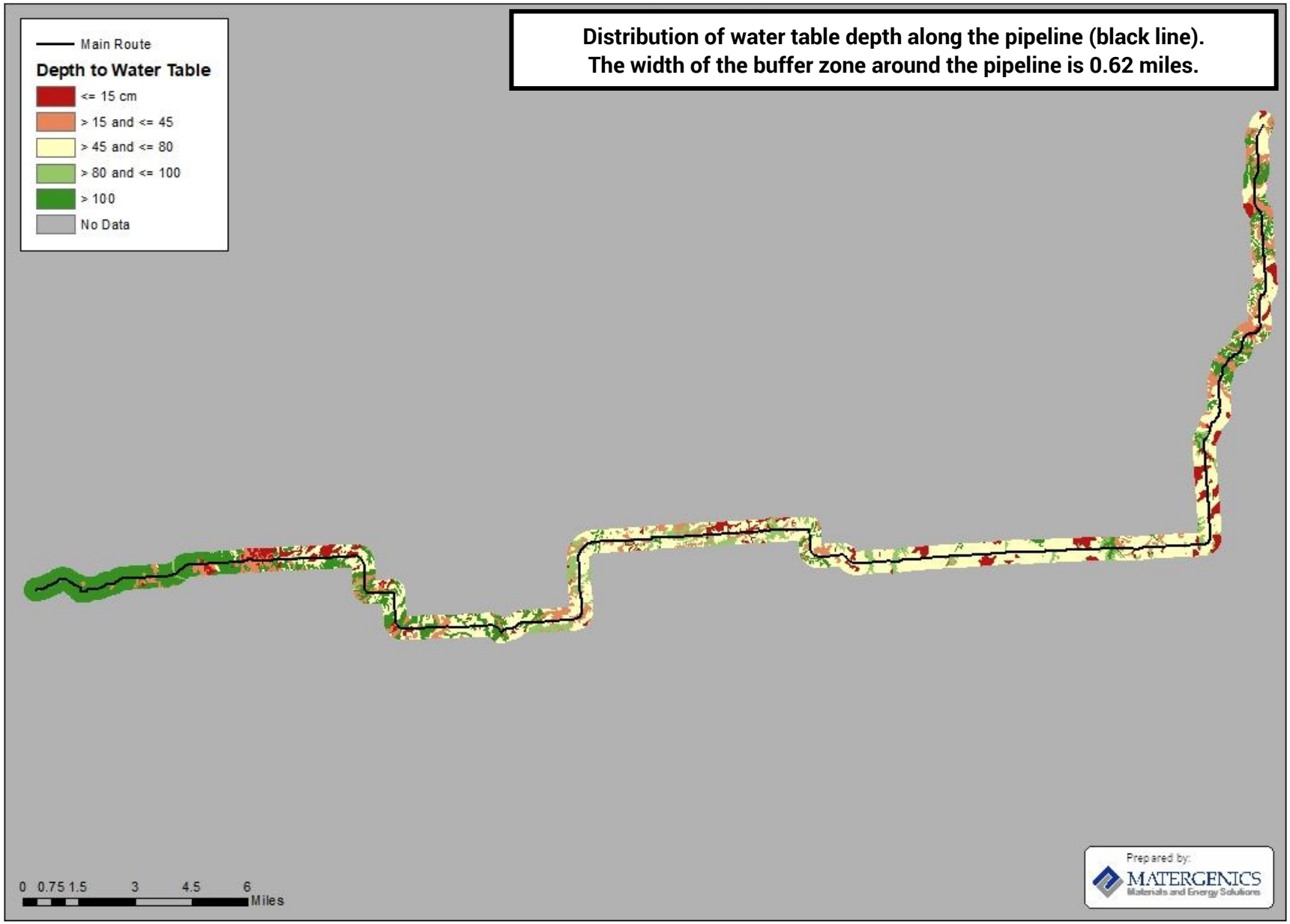

Figure 13: Map of water table (in cm). Min and Max values are 15 and 201 cm.

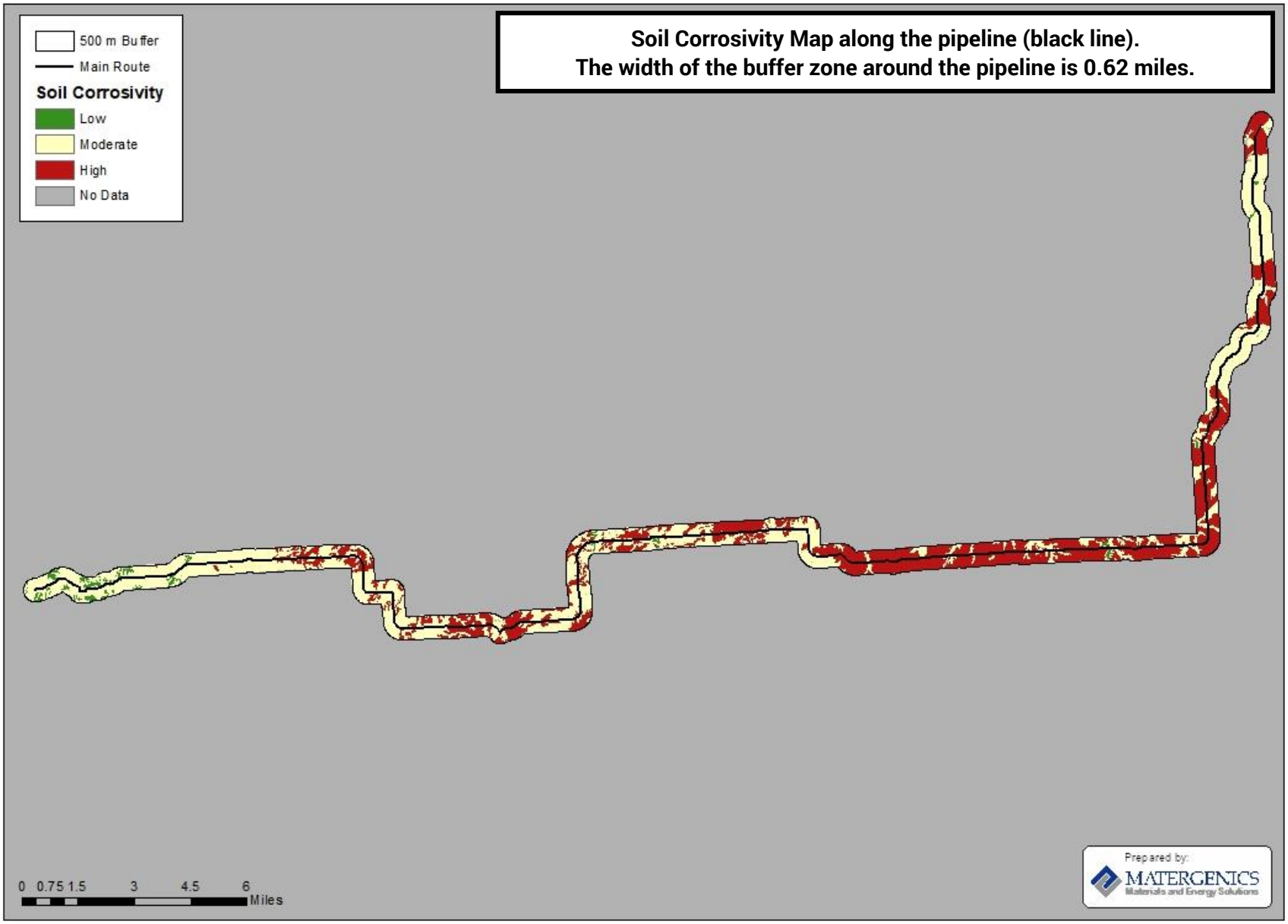

Figure 14: Final soil corrosion map.

Figure 15: As-received photograph of Sample 1 – 15235232 B1.

Figure 16: As-received photograph of Sample 2 – 15235232 B2.

Figure 17: As-received photograph of Sample 3 – 15235232 B3.

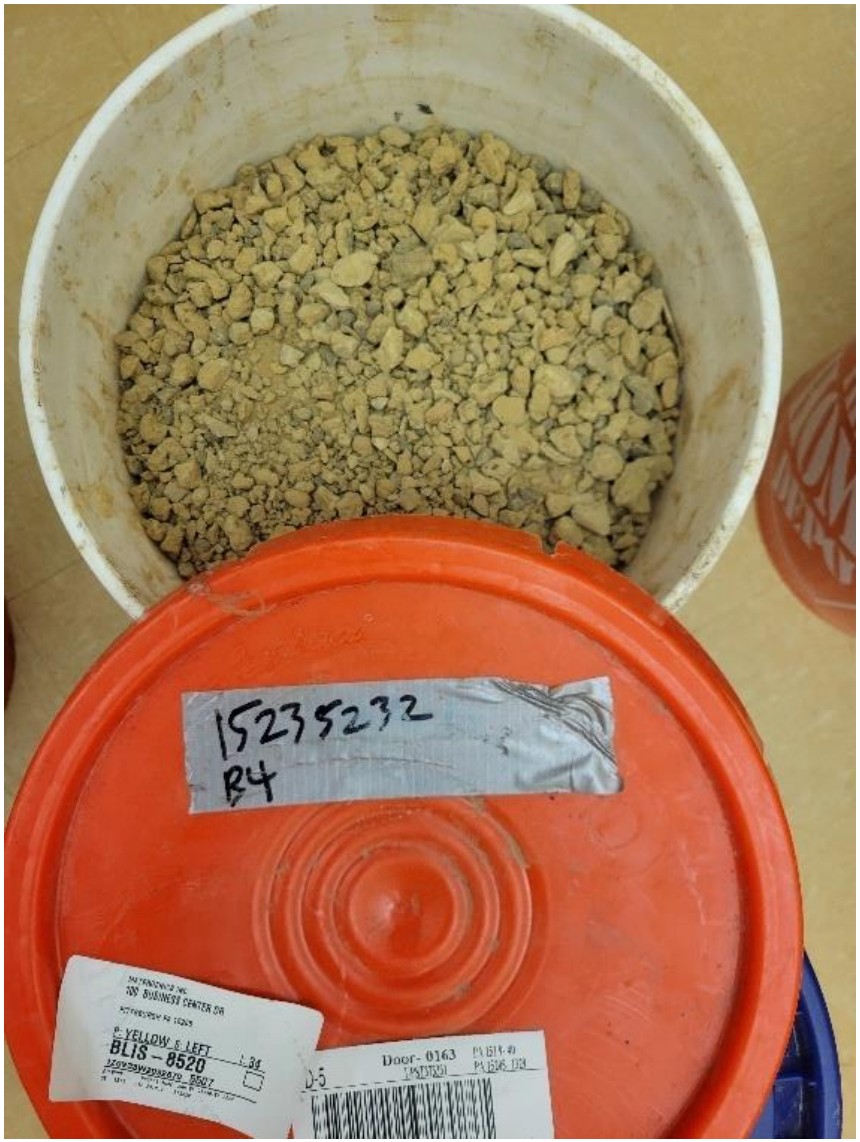

Figure 18: As-received photograph of Sample 4 – 15235232 B4.

Figure 19: As-received photograph of Sample 5 – 15235232 B5.

Figure 20: As-received photograph of Sample 6 – 15235232 B6.

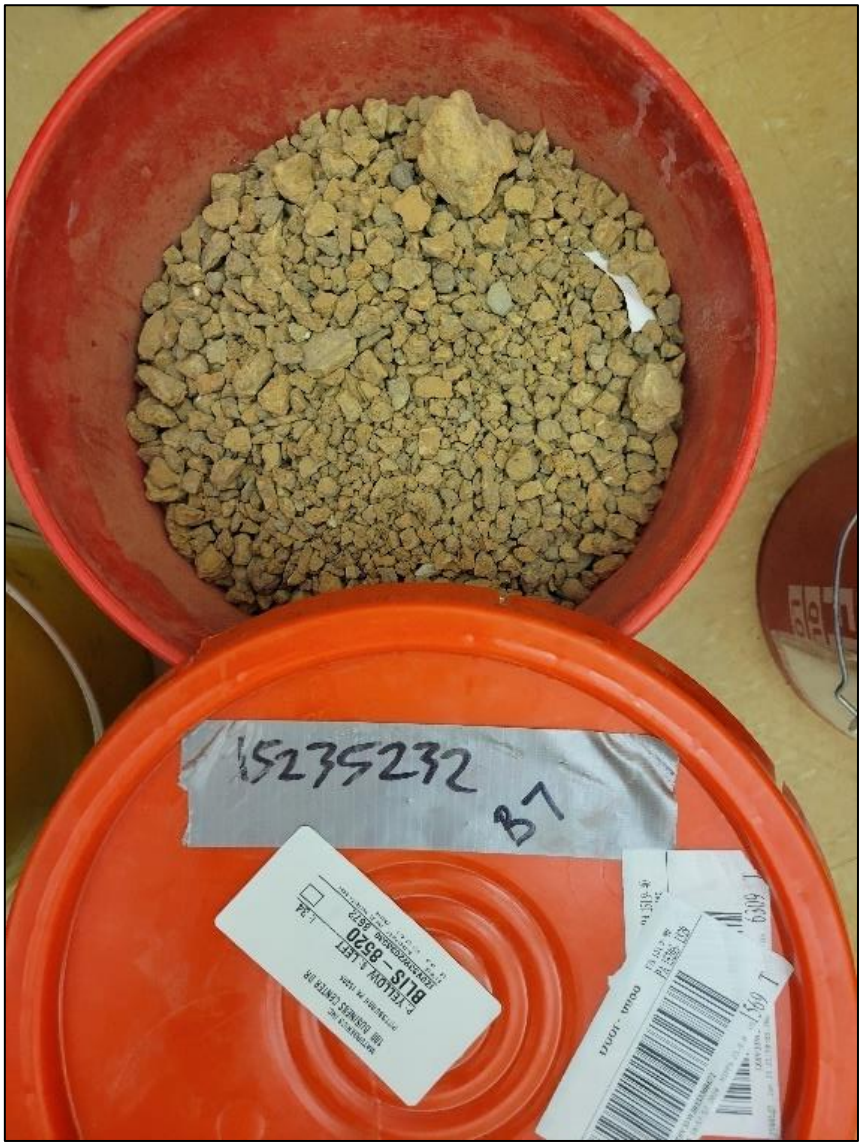

Figure 21: As-received photograph of Sample 7 – 15235232 B7.

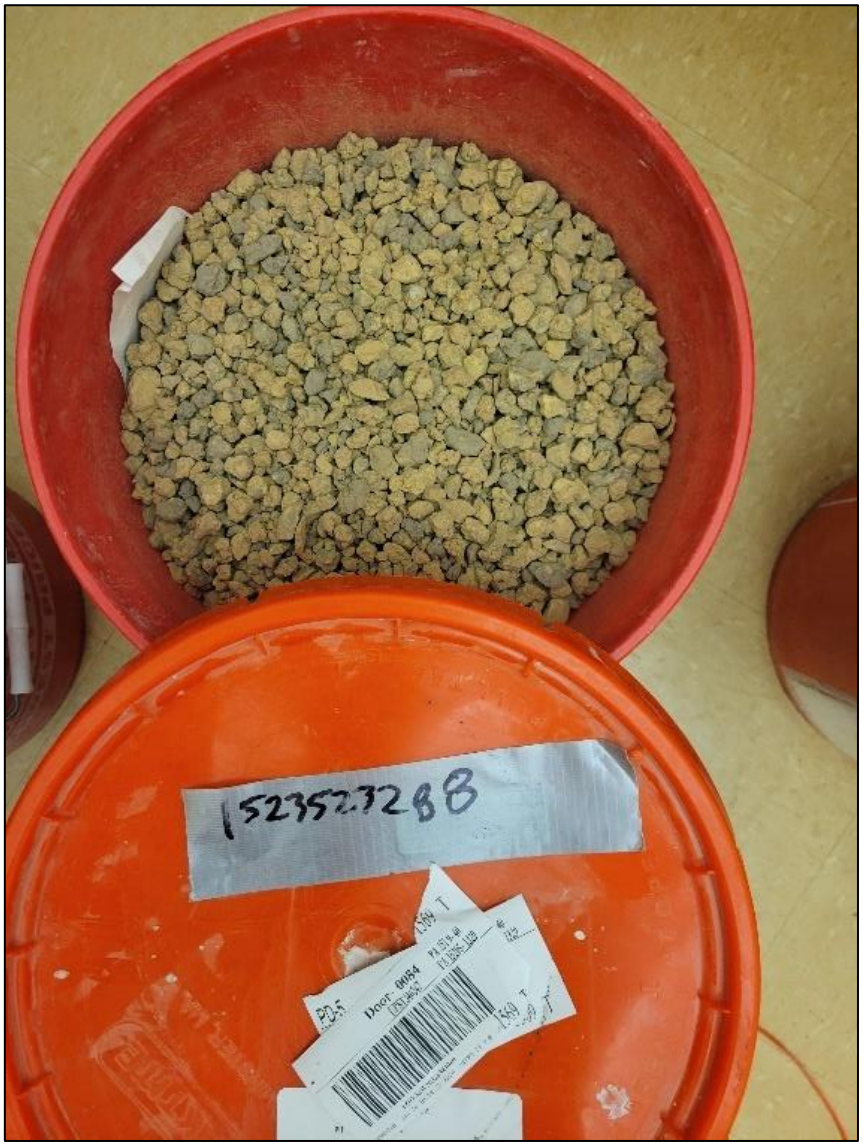

Figure 22: As-received photograph of Sample 8 – 15235232 B8.

Figure 23: As-received photograph of Sample 9 – 5232 B9 BULK.

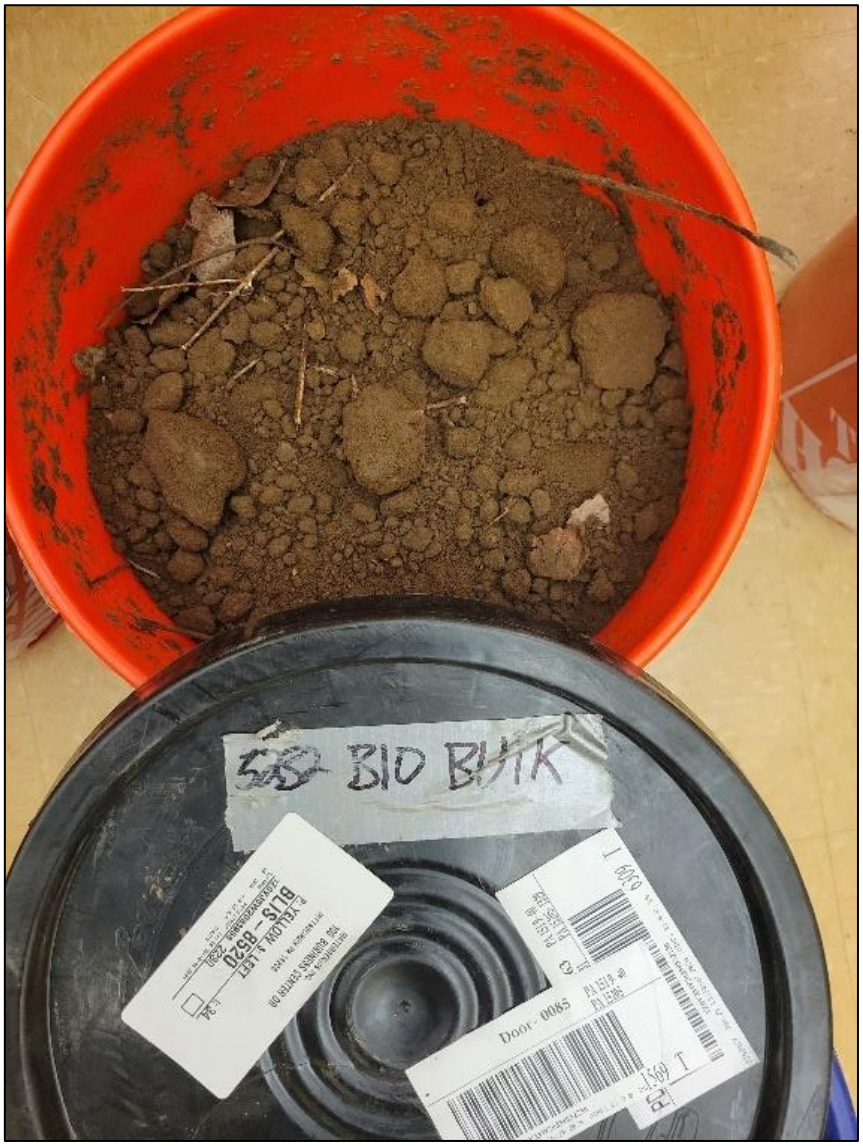

Figure 24: As-received photograph of Sample 10 – 5232 B10 BULK.

Figure 25: As-received photograph of Sample 11 – 5232 B11 BULK.

Figure 26: As-received photograph of Sample 12 – 5232 B12 Bulk.

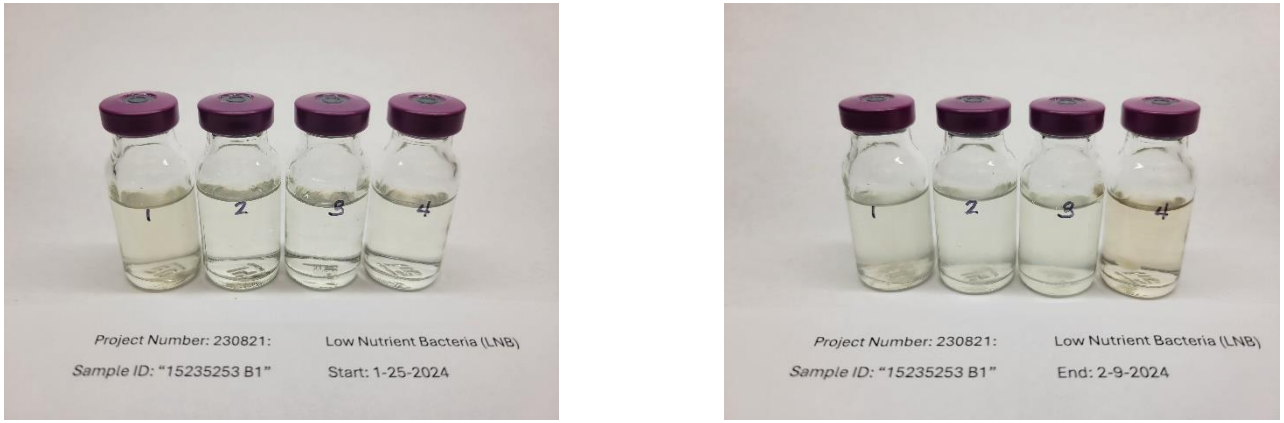

Figure 27: Results of Low Nutrient Bacteria (LNB) for Sample 15235253 B1. A positive result would be indicated by cloudiness with possible slime formation. Bottle number 3 on the right has become cloudy indicating a positive result.

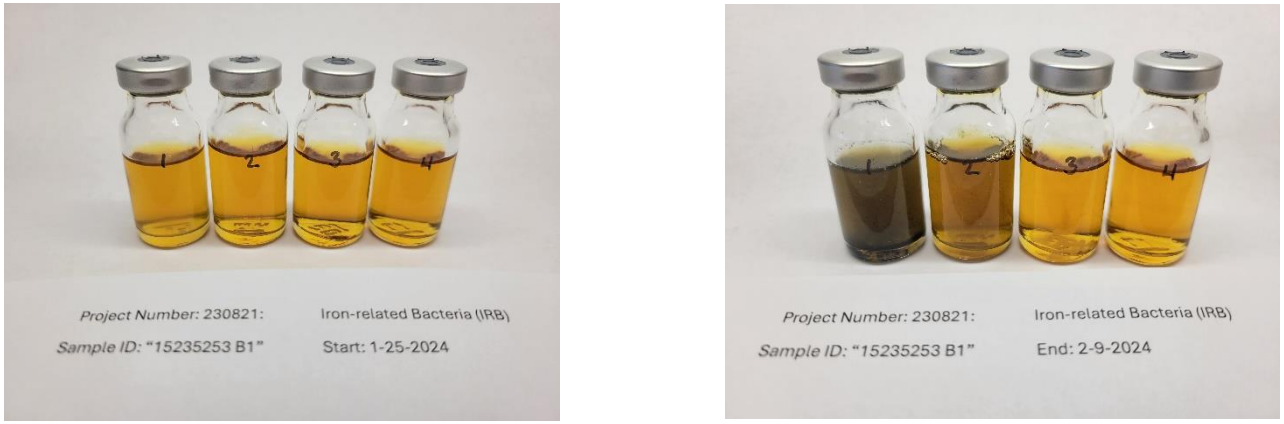

Figure 28: Results of Iron-related Bacteria (IRB) for Sample 15235253 B1. A positive result would be indicated by a dark rust color change. Bottle number 2 on the right has darkened in color indicating a positive result.

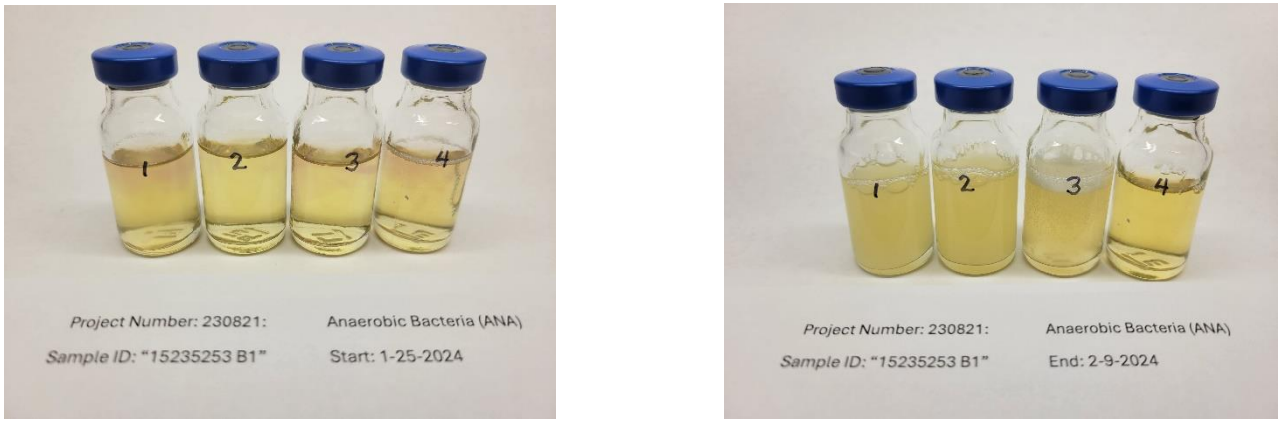

Figure 29: Results of Anaerobic Bacteria (ANA) for Sample 15235253 B1. A positive result would be indicated by cloudiness. Bottle number 3 on the right has become cloudy indicating a positive result.

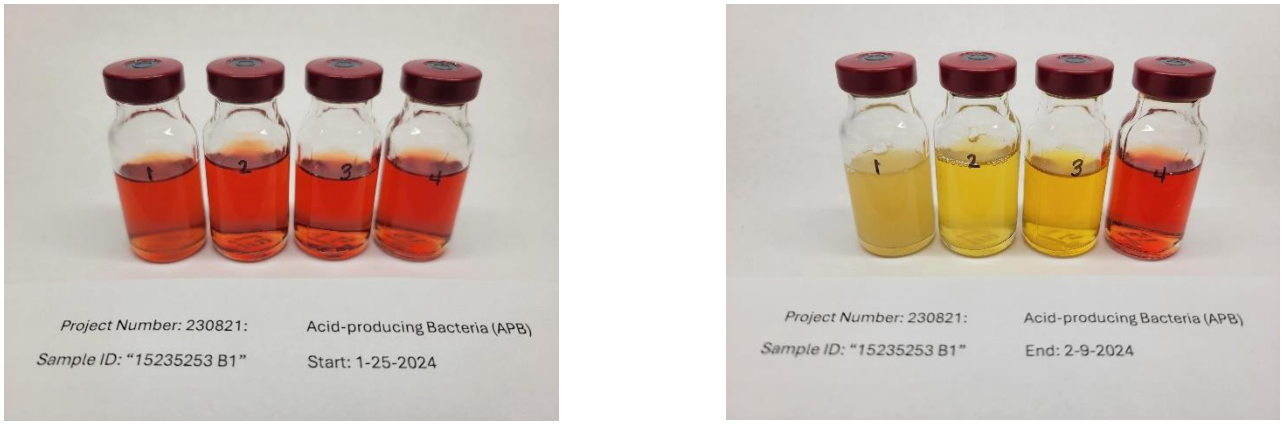

Figure 30: Results of Acid-producing Bacteria (APB) for Sample 15235253 B1. A positive result would be indicated by a cloudy orange or yellow color change. Bottle number 3 on the right has turned yellow indicating a positive result

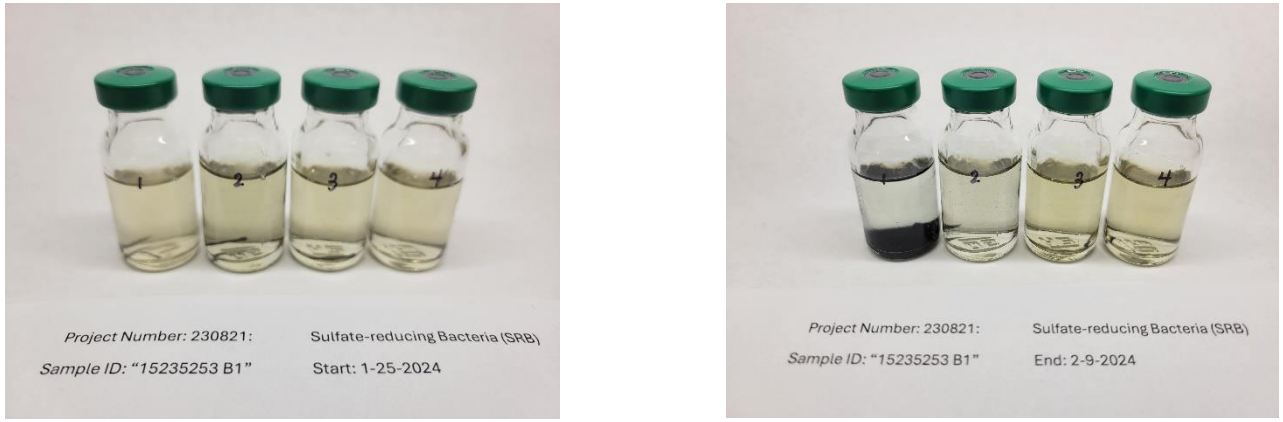

Figure 31: Results of Sulfate-reducing Bacteria (SRB) for Sample 15235253 B1. A positive result would be indicated by a black color change and/or formation of black slime on the iron nail. Bottle number 1 on the right has formed a layer of black slime indicating a positive result.

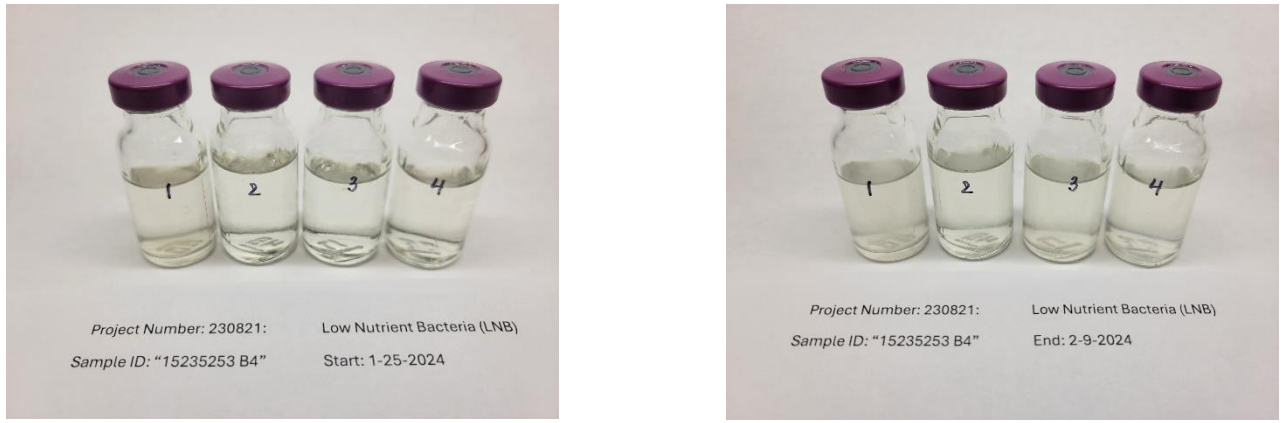

Figure 32: . Results of Low Nutrient Bacteria (LNB) for Sample 15235253 B4. A positive result would be indicated by cloudiness with possible slime formation. Bottle number 4 on the right has become cloudy indicating a positive result.

Figure 33: Results of Iron-related Bacteria (IRB) for Sample 15235253 B4. A positive result would be indicated by a dark rust color change. Bottle number 1 on the right has darkened in color indicating a positive result.

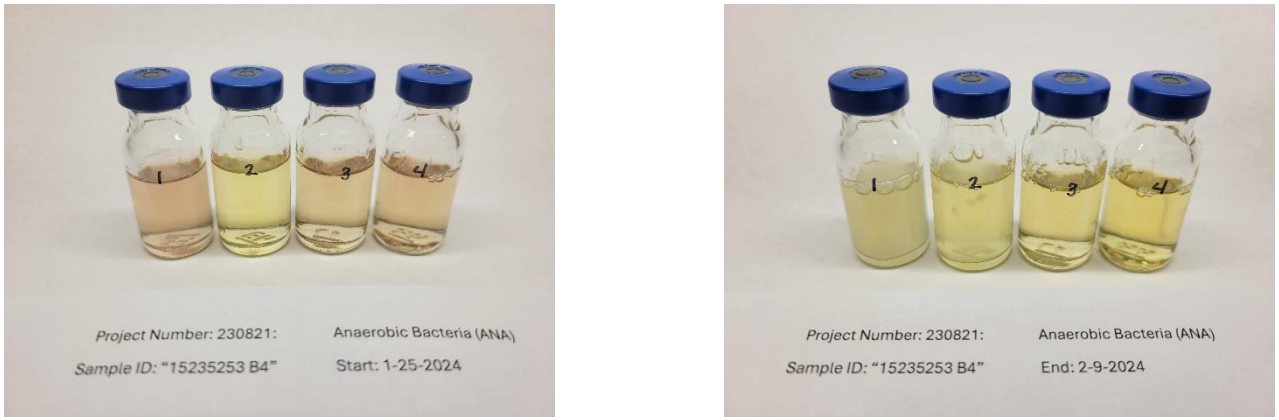

Figure 34: Results of Anaerobic Bacteria (ANA) for Sample 15235253 B4. A positive result would be indicated by cloudiness. Bottle number 2 on the right has become cloudy indicating a positive result.

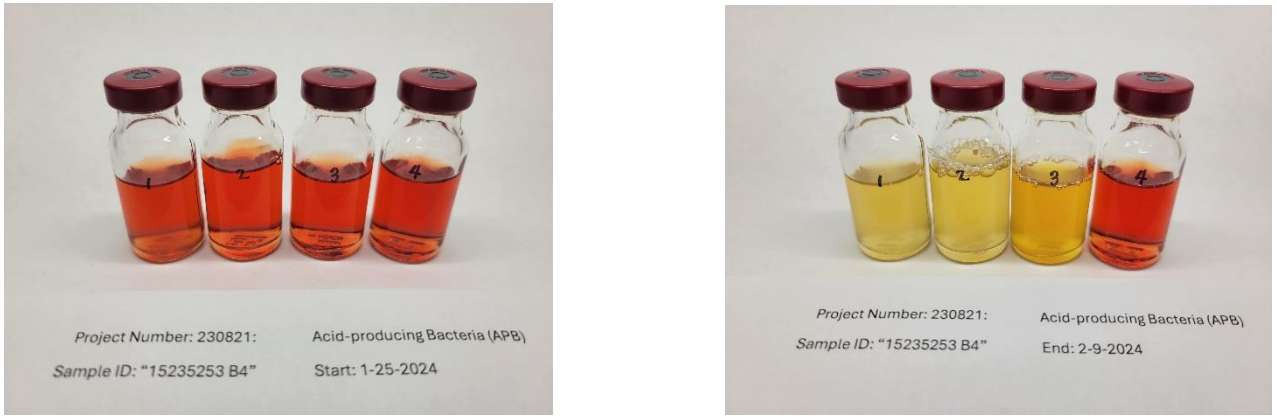

Figure 35: Results of Acid-producing Bacteria (APB) for Sample 15235253 B4. A positive result would be indicated by a cloudy orange or yellow color change. Bottle number 3 on the right has turned yellow indicating a positive result.

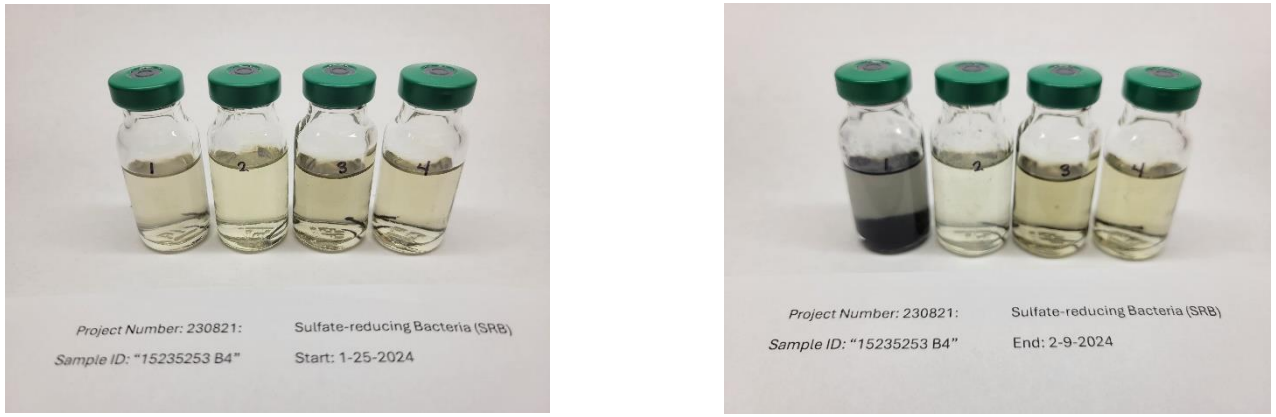

Figure 36: Results of Sulfate-reducing Bacteria (SRB) for Sample 15235253 B4. A positive result would be indicated by a black color change and/or formation of black slime on the iron nail. Bottle number 1 on the right has formed black slime indicating a positive result.

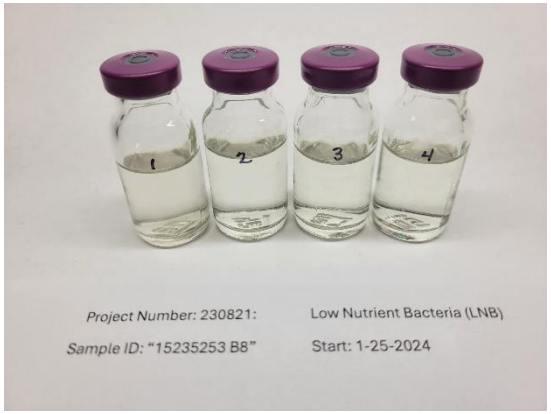

Figure 37: Results of Low Nutrient Bacteria (LNB) for Sample 15235253 B8. A positive result would be indicated by cloudiness with possible slime formation. Bottle number 4 on the right has become cloudy indicating a positive result.

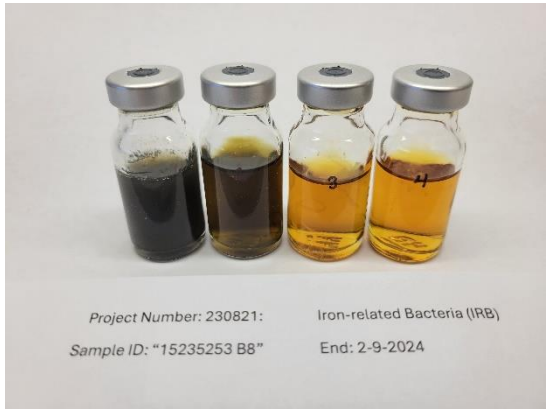

Figure 38: Results of Iron-related Bacteria (IRB) for Sample 15235253 B8. A positive result would be indicated by a dark rust color change. Bottle number 2 on the right has darkened in color indicating a positive result.

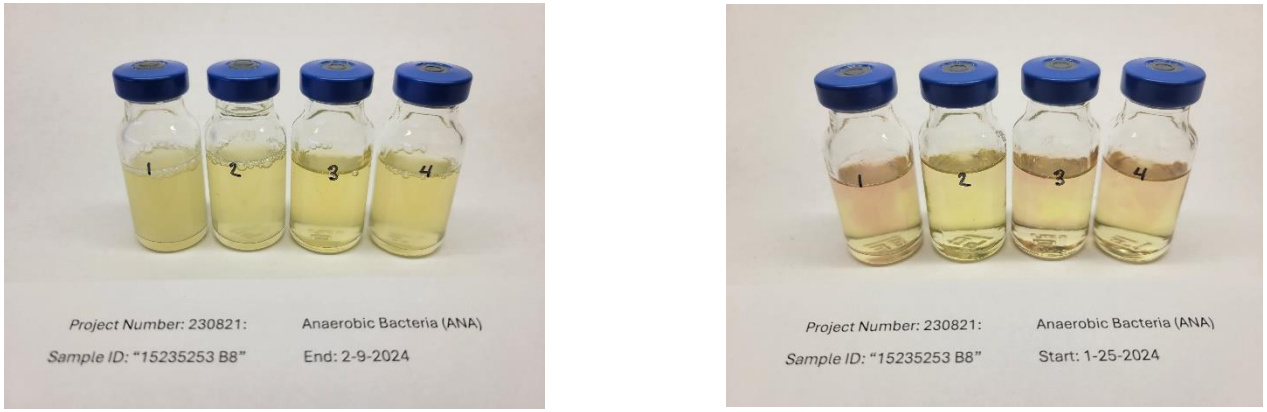

Figure 39: Results of Anaerobic Bacteria (ANA) for Sample 15235253 B8. A positive result would be indicated by cloudiness. Bottle number 4 on the right has become cloudy indicating a positive result.

Figure 40: Results of Acid-producing Bacteria (APB) for Sample 15235253 B8. A positive result would be indicated by a cloudy orange or yellow color change. Bottle number 4 on the right has turned yellow indicating a positive result.

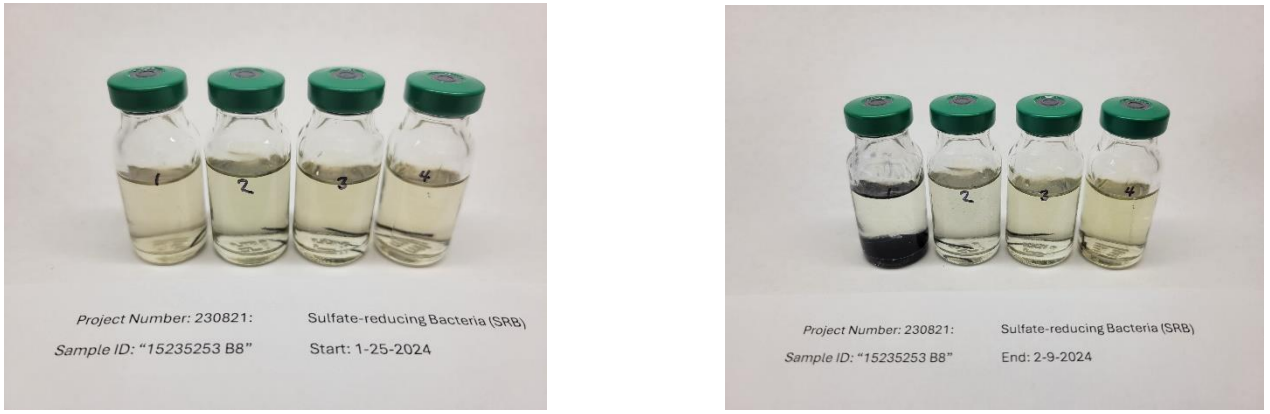

Figure 41: Results of Sulfate-reducing Bacteria (SRB) for Sample 15235253 B8. A positive result would be indicated by a black color change and/or formation of black slime on the iron nail. Bottle number 1 on the right has formed black slime indicating a positive result.

Figure 42: Results of Low Nutrient Bacteria (LNB) for Sample 5253 B12 BULK. A positive result would be indicated by cloudiness with possible slime formation. Bottle number 4 on the right has become cloudy indicating a positive result.

Figure 43: Results of Iron-related Bacteria (IRB) for Sample 5253 B12 BULK. A positive result would be indicated by a dark rust color change. Bottle number 3 on the right has darkened in color indicating a positive result.

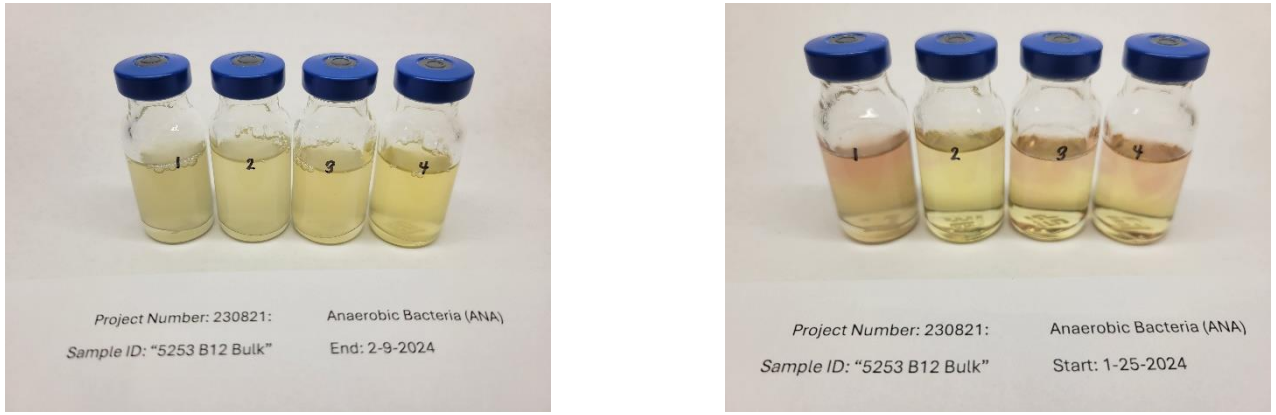

Figure 44: Results of Anaerobic Bacteria (ANA) for Sample 5253 B12 BULK. A positive result would be indicated by cloudiness. Bottle number 4 on the right has become cloudy indicating a positive result.

Figure 45: Results of Acid-producing Bacteria (APB) for Sample 5253 B12 BULK. A positive result would be indicated by a cloudy orange or yellow color change. Bottle number 4 on the right has turned yellow indicating a positive result.

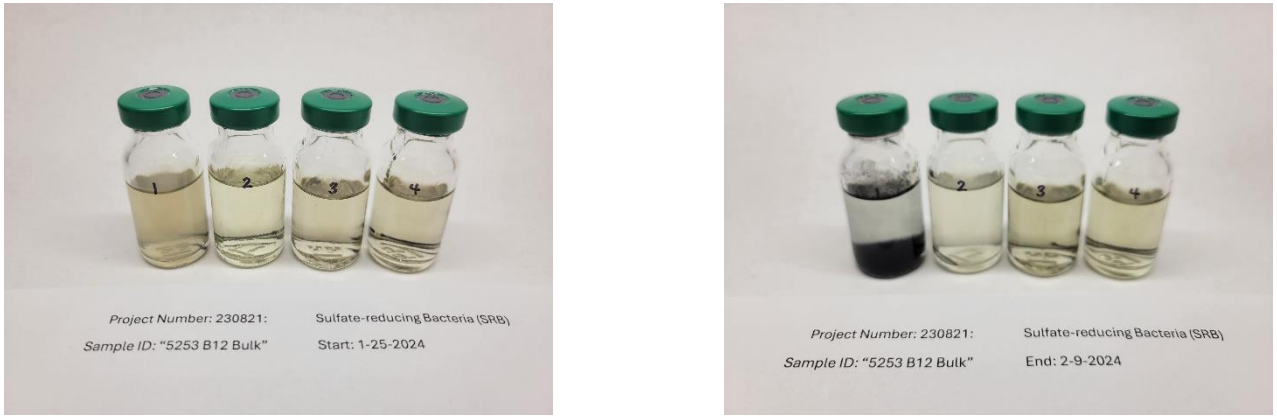

Figure 46: Results of Sulfate-reducing Bacteria (SRB) for Sample 5253 B12 BULK. A positive result would be indicated by a black color change and/or formation of black slime on the iron nail. Bottle number 1 on the right has formed black slime indicating a positive result.