2023 FECM / NETL Spring R&D Project Review Meeting

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

A Data-driven Multiscale Phytotechnology Framework for Identification and Remediation of Leached-Metals-Contaminated Soil Near Coal Ash Impoundments

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VIRGINIA TECH

Background: Coal Combustion Product Impoundments

- Many older impoundments are not lined.

Asheville Power Station
Arden, NC 28704
Owned and Operated by Duke Energy Corporation

Hazard Rating: High

Contamination

BORON, CHLORIDE, CHROMIUM, IRON, MANGANESE, SELENIUM, TOTAL DISSOLVED SOLIDS, NITRATE, SULFATE AND THALLIUM, ARSENIC, LEAD, AND PH.

Unlined Impoundment	
Impoundment Name	1964 Ash Pond
Hazard Rating	High
Capacity	72,664,773 gallons
Ash	2,535,600 tons
Wastewater	9,776,000 gallons
Dam Height	100
Active	Yes

Unlined Impoundment	
Impoundment Name	1982 Ash Pond
Hazard Rating	High
Capacity	290,007,390 gallons
Ash	686,000 tons
Dam Height	95
Active	Yes

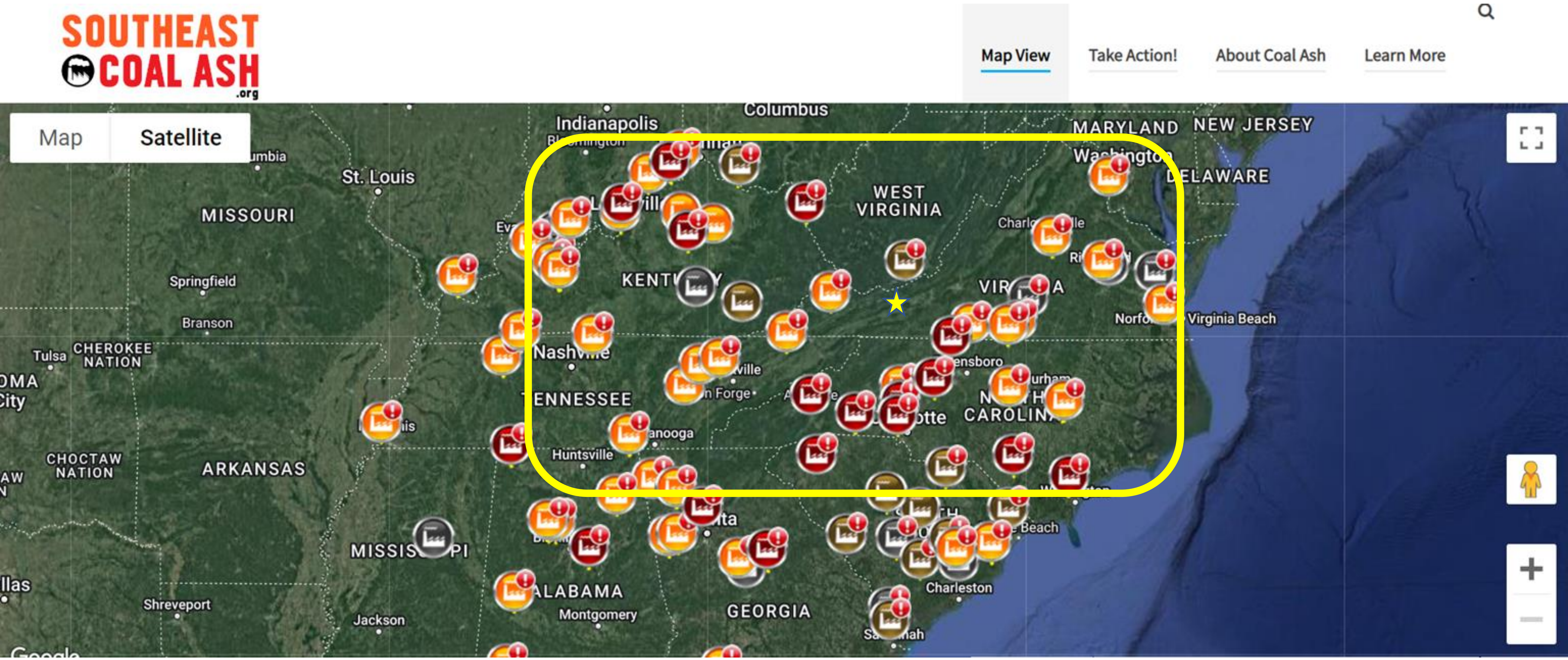
Unlined Impoundment	
Impoundment Name	Stilling Pond
Hazard Rating	Not Rated
Active	Yes

http://www.southeastcoalash.org/plant-page/?id=44

Phytotechnology Development for Identification and/or Remediation of Sites Exhibiting Soil Contamination via Groundwater Transport of Metals from Coal Combustion Product Impoundments

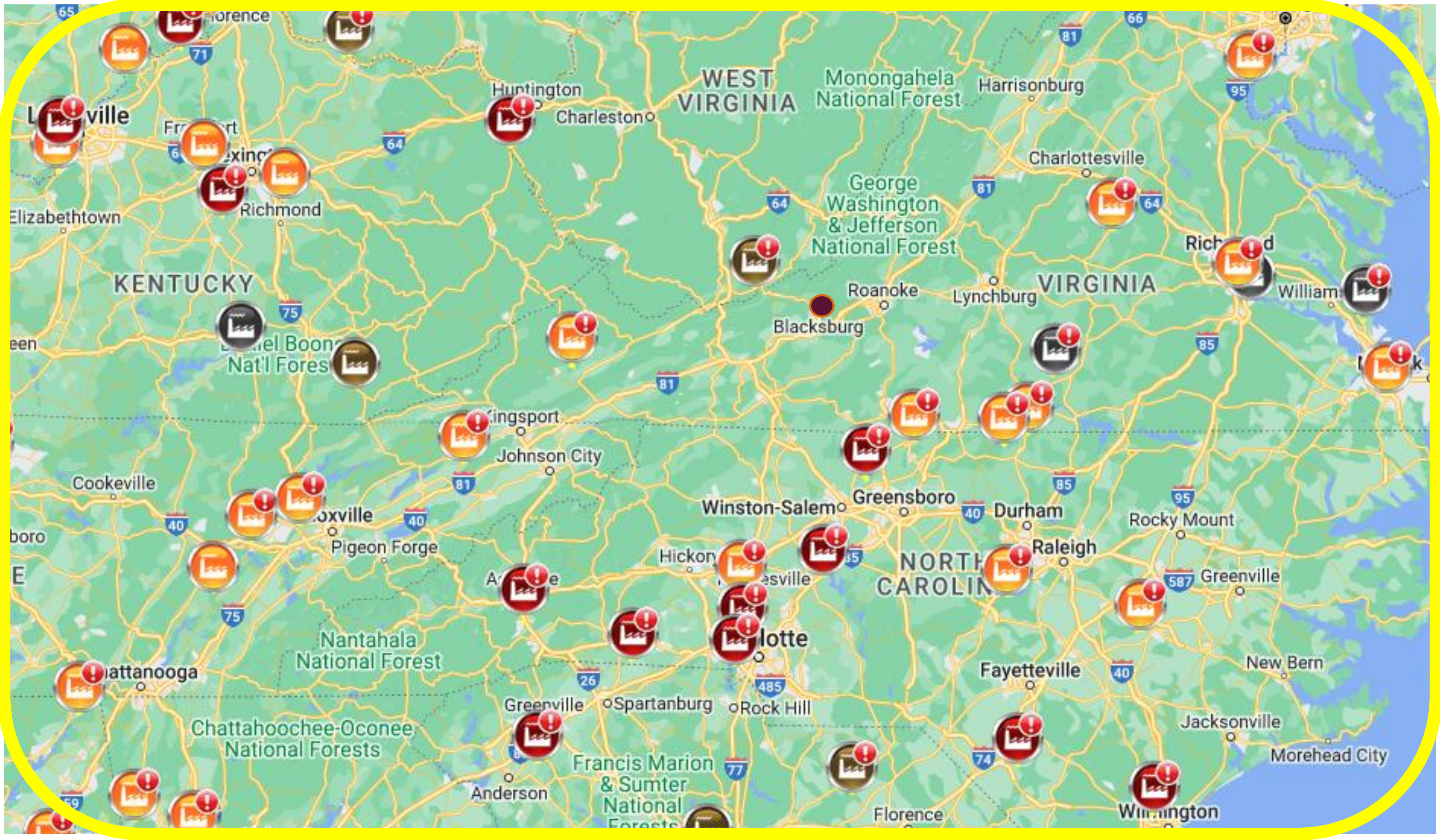
- Identification of sites that need more aggressive monitoring and remediation
- Low-cost technology is needed to screen sites
- Facilitate a treatment development and deployment
- No removal of the affected soils or groundwater

Coal combustion product impoundments in the region



http://www.southeastcoalash.org/

Sites selection: coal ash impoundments in the region



Available data

Primary goals

- Using **phytotechnology** to identify leached-metal contamination
- **Not being limited to a few sites** (site identification should be the outcome, screening is important)
- **Not being limited to a few number of metal-leached contaminants**
- Facilitate (future) **development of phytoremediation**

Remote sensing: Satellite imagery

Benefits:

- Low-cost technology
- Searching for visual ques
- Extended coverage over multiple states
- No site access needed.

Challenges:

- What kind of visual ques we are searching for?
- Low resolution
- What type of metal-leached contamination we are looking for?

Image processing: searching for abnormalities

Lack of a reference point to distinguish metal-stressed plants from those unstressed. We don’t know what the visual ques are!

Examples of contamination bio-indicators:

- Cadmium-induced stress for rice crops, indicator: color change (Liu et al., 2018)
- Cement dust pollution, indicator: effect on plant species density and diversity (Bayouli et al., 2021)
- Mercury in fly ash, indicator: presence in soil and vegetation samples (Huang et al., 2017)

→ **Search for both temporal and spatial abnormalities**

Factoring out other influencers

A Data-driven Smart Search!

- Climate and environmental conditions
- Soil type and properties, pH, moisture
- Structural conditions: underground geological features

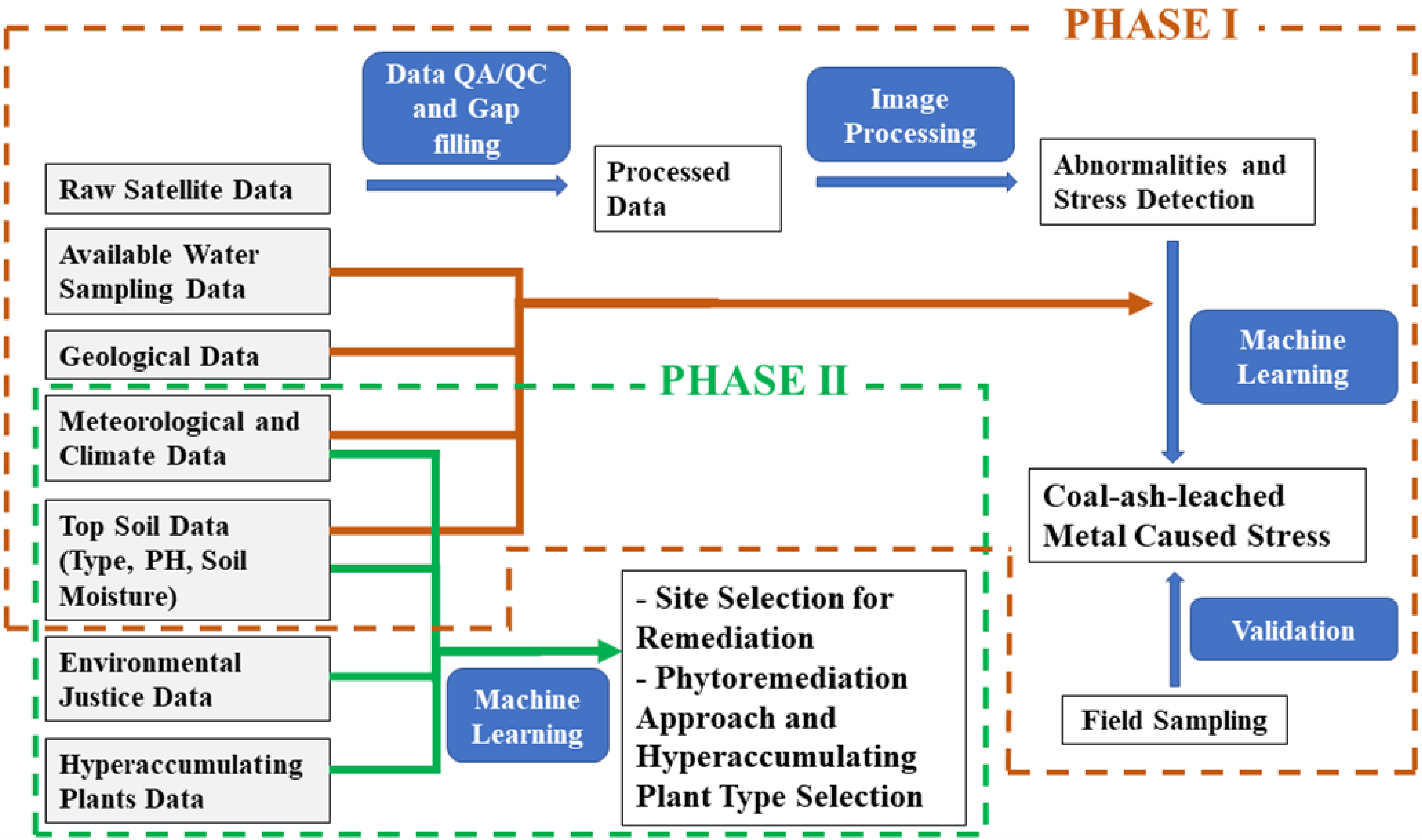
How to validate our model?

- Soil sampling
- Vegetation sampling
- Geological modeling

Phytoremediation

- Database of hyperaccumulating plants is available.
- How to select a site as a phytoremediation candidate? How can we rank them?
- What are the factors we should consider in order to select plant species?

Multiscale data-driven phytoindication and phytoremediation framework

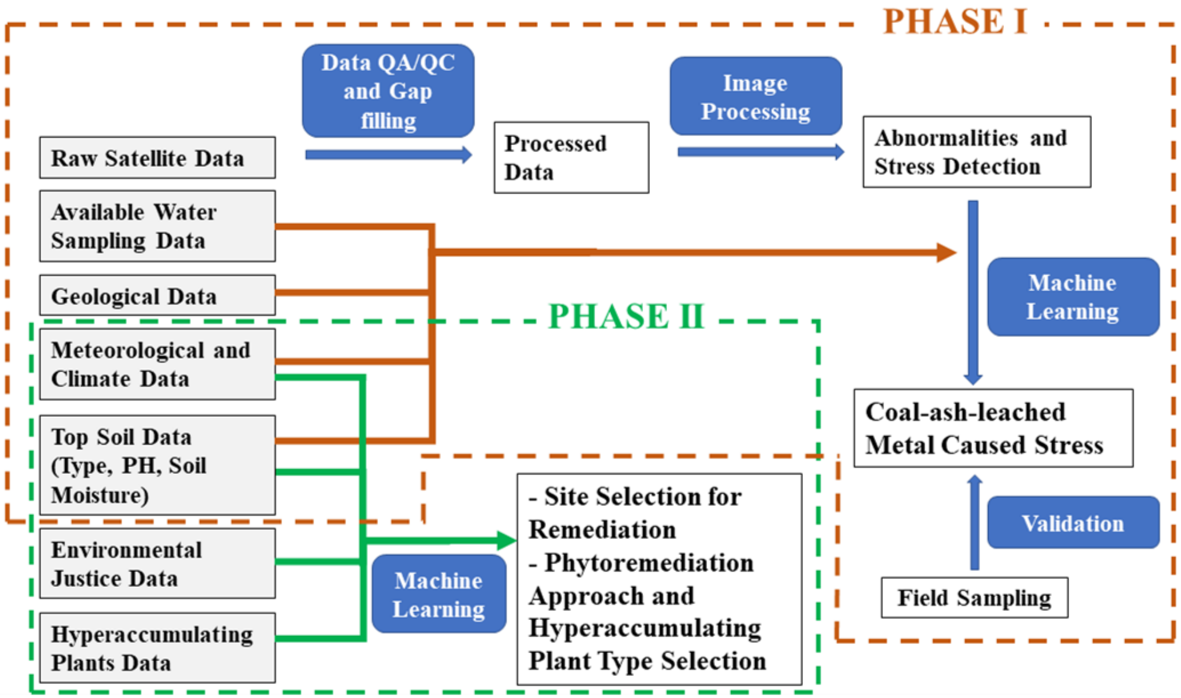


Main project objectives

- Process and analyze multi-year satellite retrievals to find vegetation-related abnormalities.
- Develop a model correlating the leached-metal contamination and the above-mentioned abnormalities.
- Validate our data-driven model through soil and vegetation sampling for a limited number of sites.

- Propose a phytoremediation approach based on the specifics of hyperaccumulator plants, sites, and environmental and geological conditions.
- Select and rank site candidates for phytoremediation based on environmental and meteorological conditions, soil type and condition, severity of contamination, and environmental justice metrics.

PHASE I



PHASE II

Our team

- **Bahareh Nojabaei (PI)**

Mining and Minerals Engineering, fluid transport in porous media, underground multiphase multicomponent flow simulation

- **Hosein Foroutan (Co-PI)**

Civil and Environmental Engineering, Atmospheric science and remote sensing

- **Hoda Eldardiry (Co-PI)**

Computer Science, Artificial Intelligence and Machine Learning

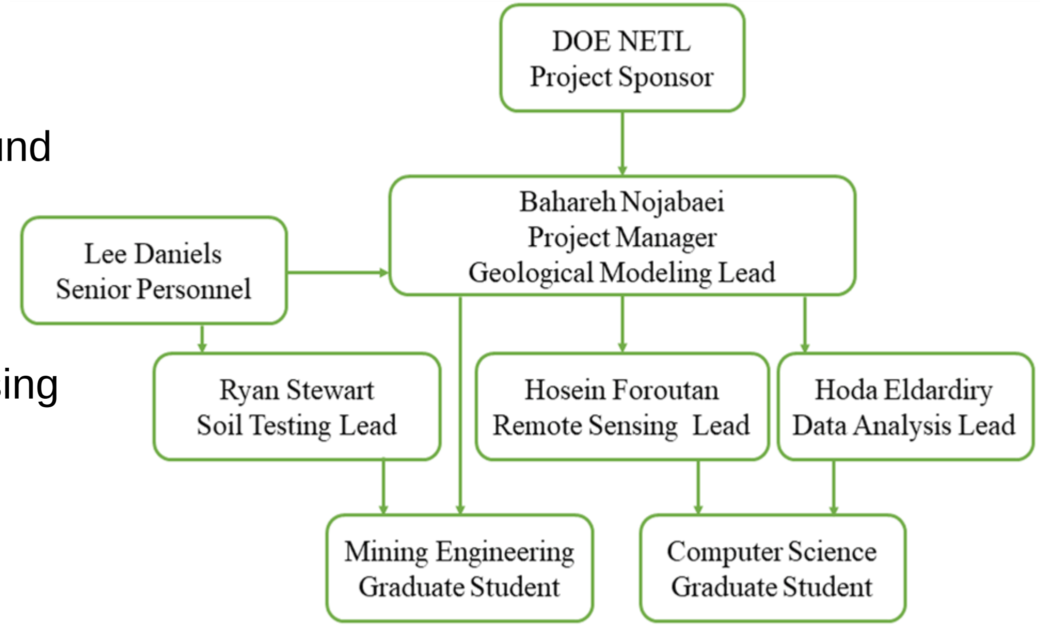
- **Ryan Stewart (Co-PI)**

School of Plant and Environmental Sciences, Quantifying interactions between water, soil, and plant communities

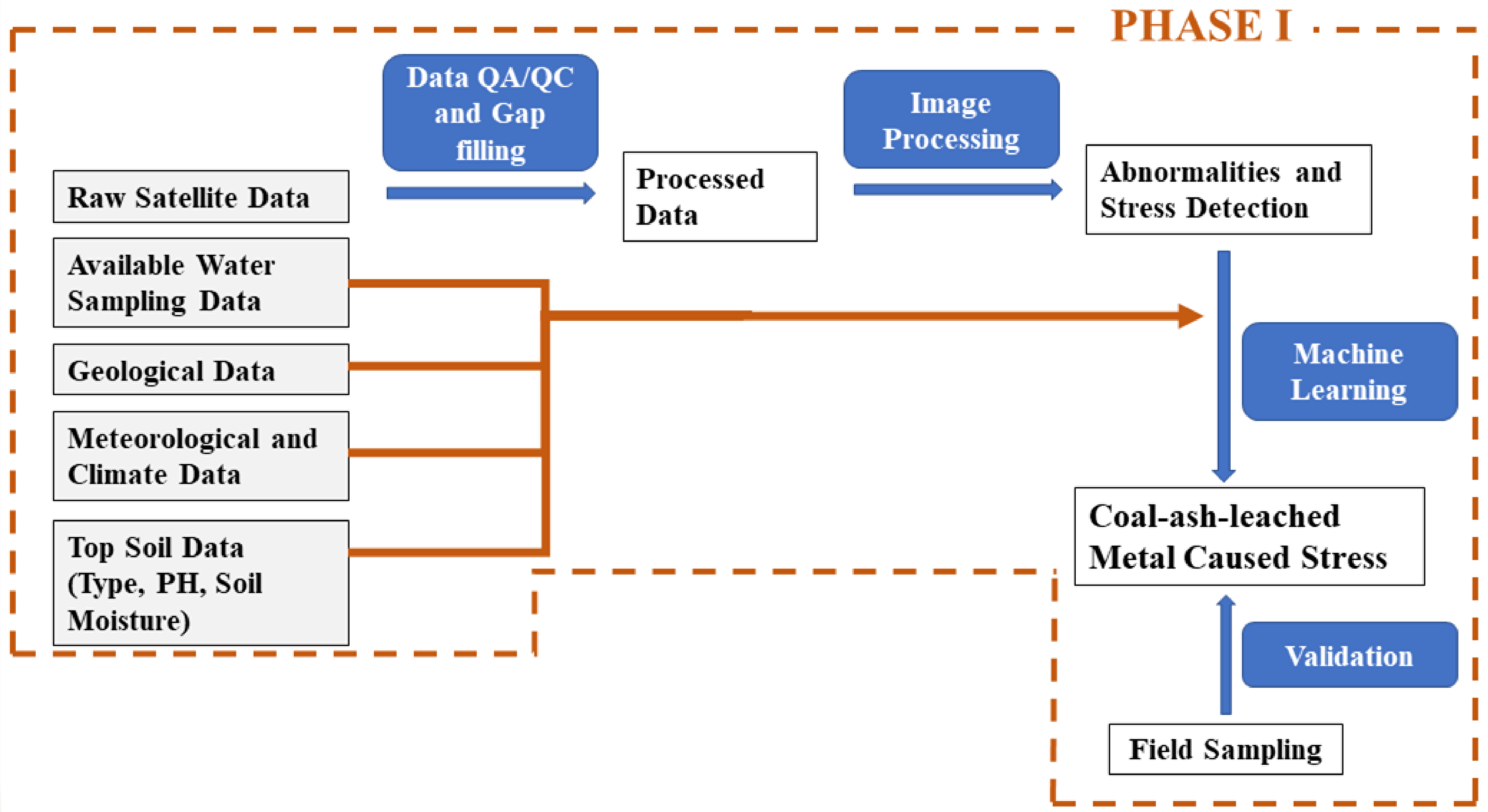
- **Lee Daniels (senior personnel)**

School of Plant and Environmental Sciences , Rehabilitation of drastically disturbed soils

- **Mining Engineering Graduate Student: Salman Karim**
- **Computer Science Graduate Student: Hongjie Chen**



Phase I: Identify leached-metal contaminations from coal combustion products impoundments



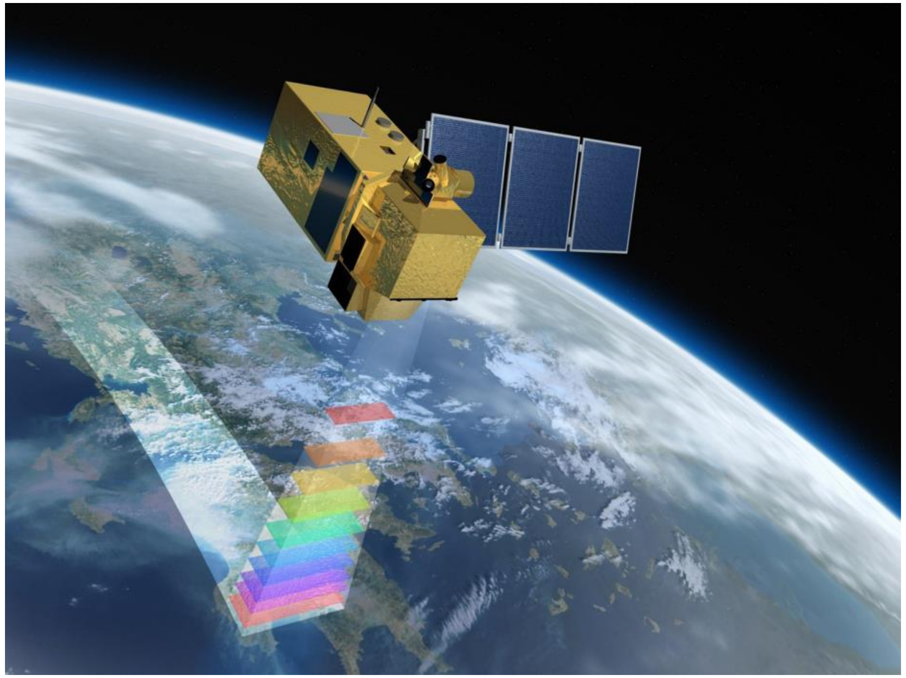
Multiplatform satellite observations

- **Landsat 8 OLI (Operational Land Imager)**
  - Launched in 2013
  - Resolution : 30 m
  - Revisit cycle : 16 days
  - Number of bands : 9

- **Landsat 7 ETM+ (Enhanced Thematic Mapper Plus)**
  - Launched in 1999
  - Resolution : 30 m
  - Revisit cycle : 16 days
  - Number of bands: 8

- **Sentinel-2**
  - Launched in 2015
  - Resolution : 10-20 m
  - Revisit cycle: 10 days
  - Number of bands: 13

Landsat 8

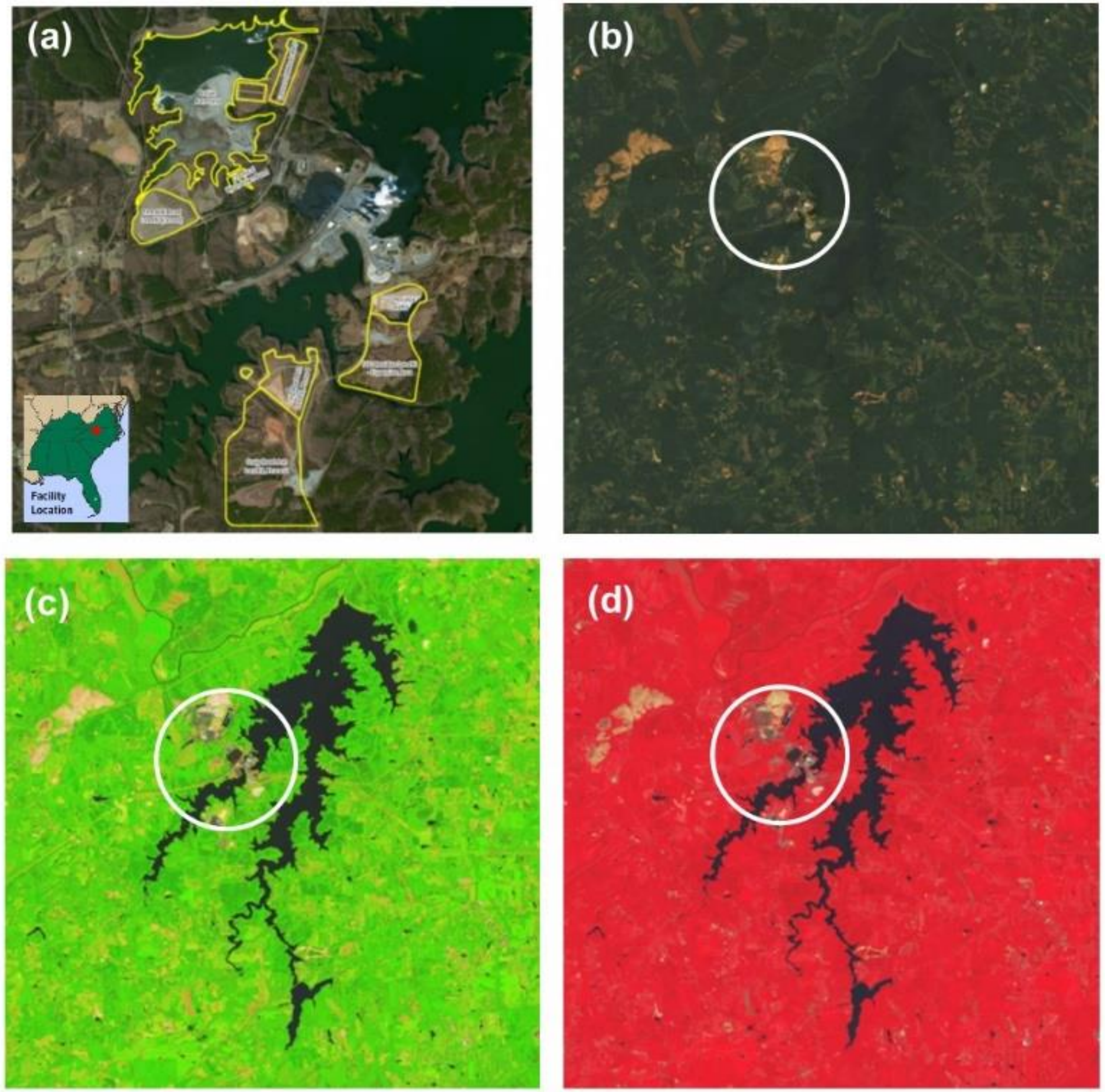


Sentinel-2

Multiband Capability of Landsat 8 OLI

Belews Creek Stream Station in Walnut Cove, NC that has a “high hazard” rating

Satellite view with natural color



Satellite view with false color (combination of bands 4, 5, and 6)

Satellite view with color infrared (combination of bands 3, 4, and 5)

Satellite data post-processing

Raw Satellite Data

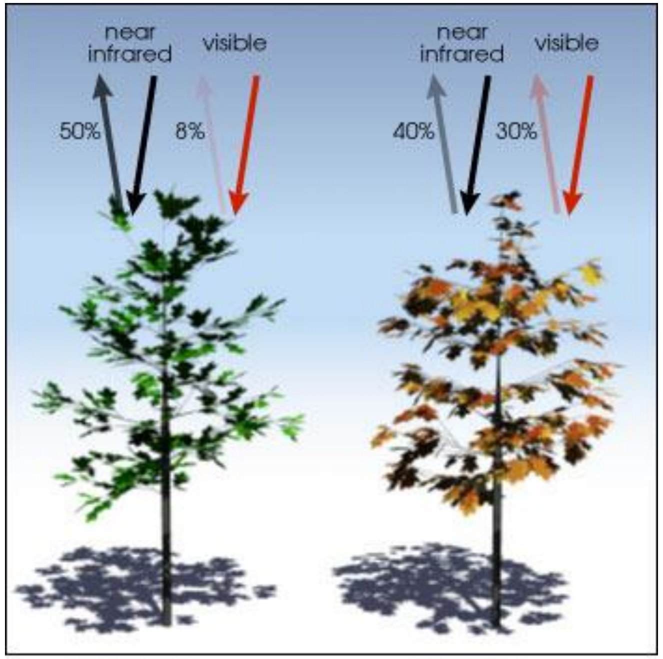
- Landsat 7 & 8
- Sentinel-2

Data Post-Processing

- QA/QC
- Filter out clouds
- Gap-fill
- Atmospheric correction

Vegetation Indices

- NDVI
- EVI
- NDWI1 & NDWI2
- CIRE
- REP
- MTCI
- NDRE1 & NDRE2



$$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72 \qquad \frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$$

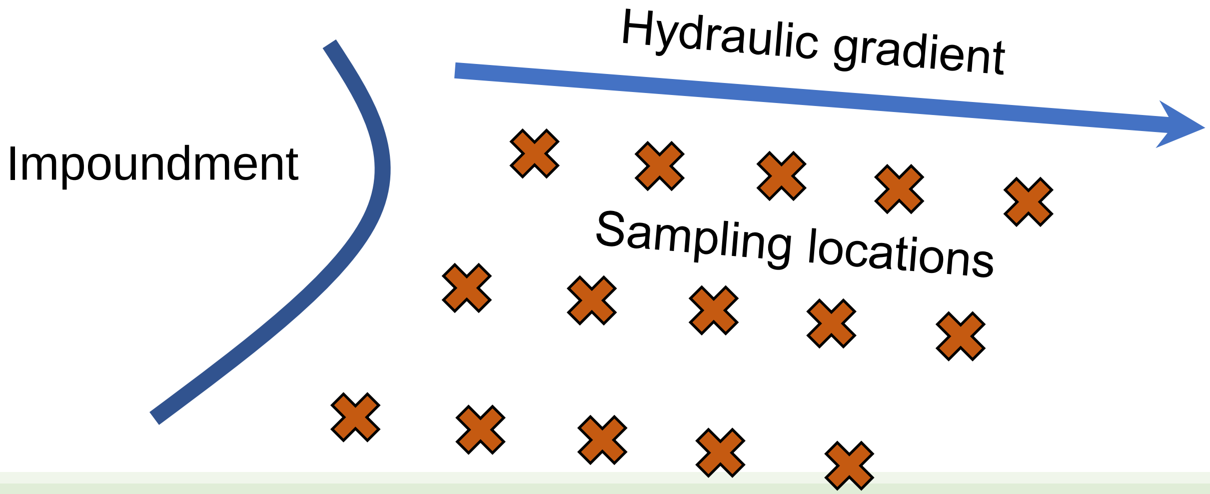
NDVI: Normalized Difference Vegetation Index
REP: Red Edge Position

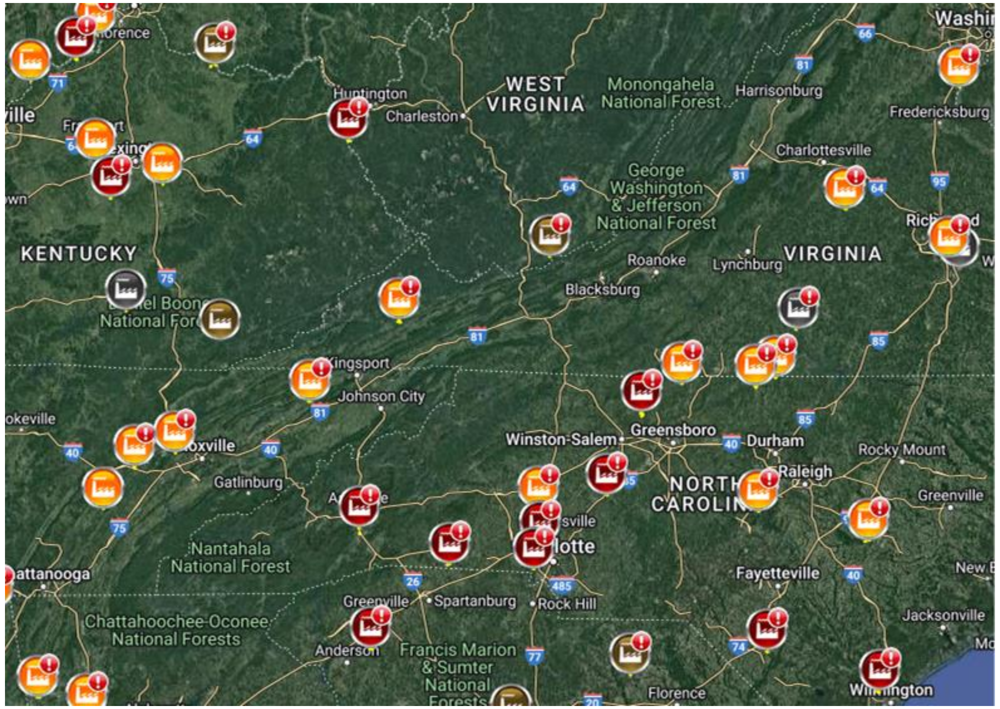
"NDVI is calculated from the visible and near-infrared light reflected by vegetation. Healthy vegetation (left) absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation (right) reflects more visible light and less near-infrared light."

https://earthobservatory.nasa.gov/features/MeasuringVegetation/measuring_vegetation_2.php

Soil sampling

- Select 3 affected sites for field measurements
- Design grid-based sampling scheme
  - 3 transects from each impoundment
  - 10 m sample spacing





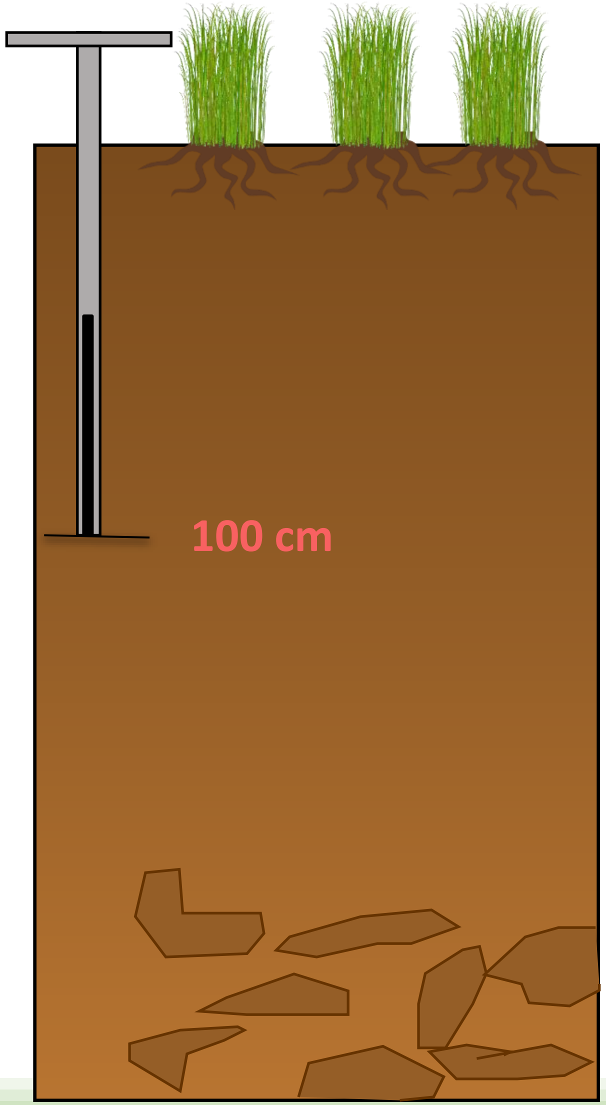
Soil sampling

- Collect unconsolidated samples from 0-100 cm depth

- Subdivide samples by depth increments

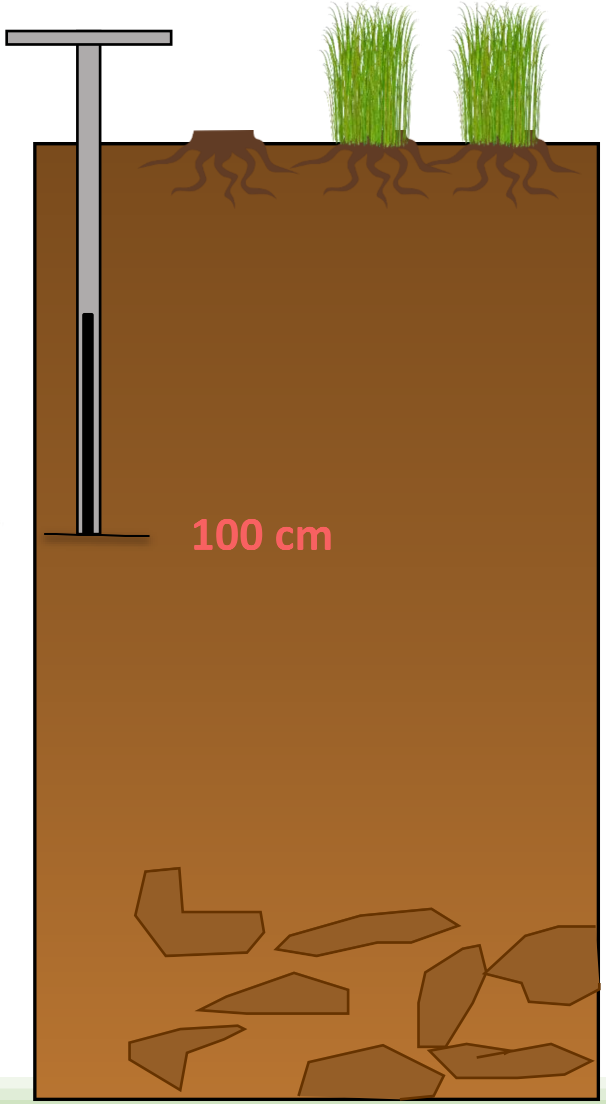
  0-5, 5-10, 10-15, 15-30, 30-60, 60-100 cm

- Oven-dry samples to determine water content and prepare them for metal analysis



Vegetation sampling

- Measure spectral reflectance of living vegetation adjacent to soil samples
- Collect above-ground vegetation samples
- Dry and analyze vegetation samples



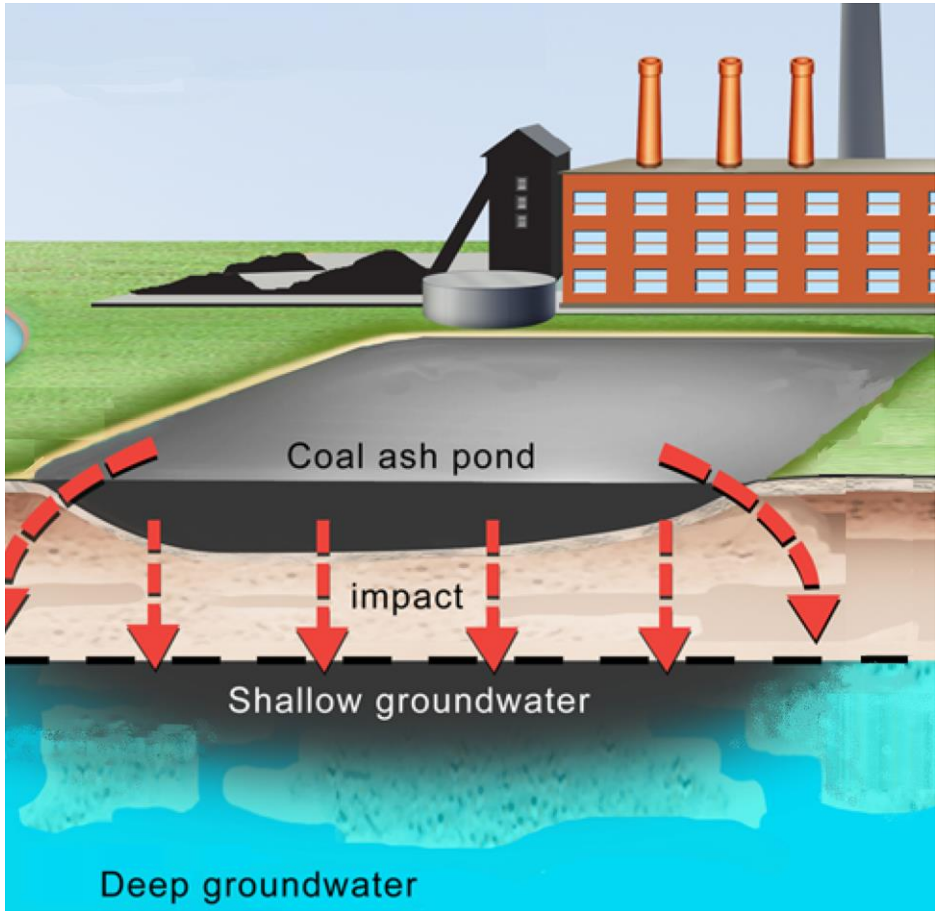
Metal analyses

- Quantify metal concentrations for soil and plant samples
- Inductively coupled plasma mass spectroscopy (ICP-MS)
- Measurements are made of at least Al, As, Cd, Cr, Hg, Mo, Pb, Se.

Contamination transport and leachability of contaminants

- Potential contaminants:

Cadmium, Lithium, Molybdenum, Boron, Arsenic, Manganese, Aluminum, Chromium, Selenium, and Mercury are present in the coal combustion products.



The degree of leachability and diffusion into the ground water system is different!

- Metal type and concentration,
- The aqueous phase pH,
- Soil and underground formation porosity and permeability
- Presence of fractures, faults, or any pathway from the impoundment to the underground water system

Underground hydrological modeling for the sites with abnormalities

Input data:

- Contamination report from monitoring wells
- Geological maps of the flagged impoundments
- Available soil type and properties database from USGS and other federal and private sector databases
- Local hydrological data

- System of equations of mass conservation equation, Darcy-type flow, along with diffusion and solubility of metal contaminants will be solved.

Goal:

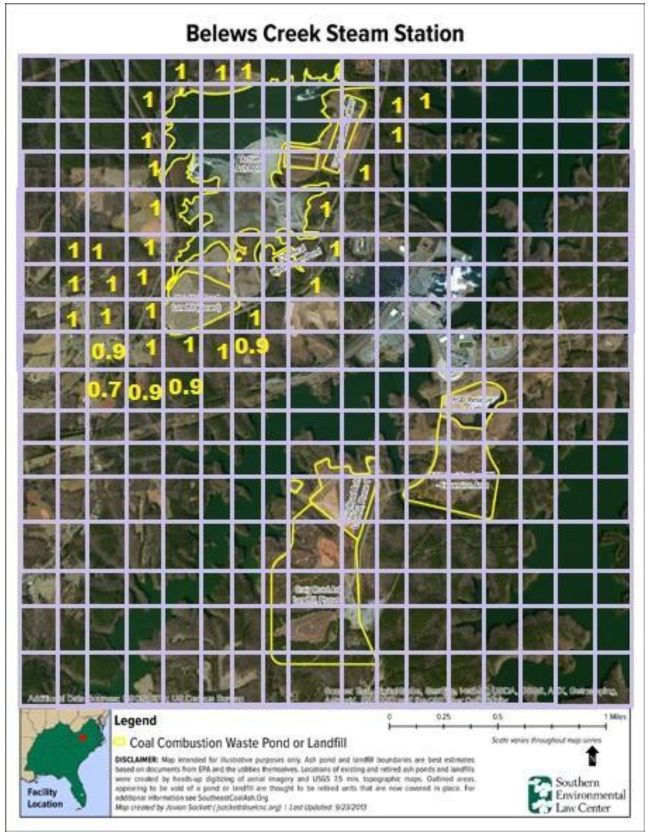
Map a probability function to the studied area

One additional assessment tool to identify:

1) whether the observed abnormality is because of leached metal contamination,

2) the type of leached metal(s) potentially contaminating the soil.

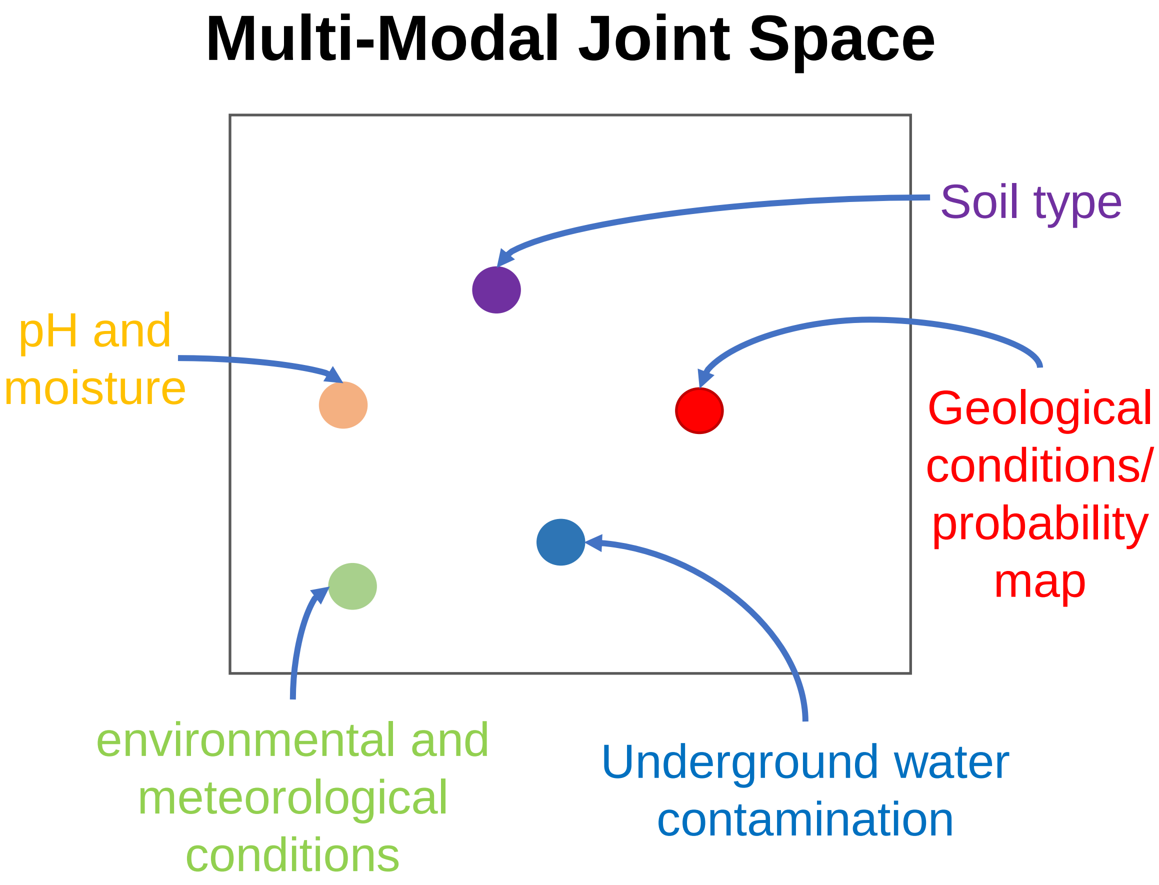
The probability function is a 2D map and provides values from zero to one for each pixel/location, zero being the lowest and one being the highest probability of any specific metal leached from the impoundment to that location's soil.



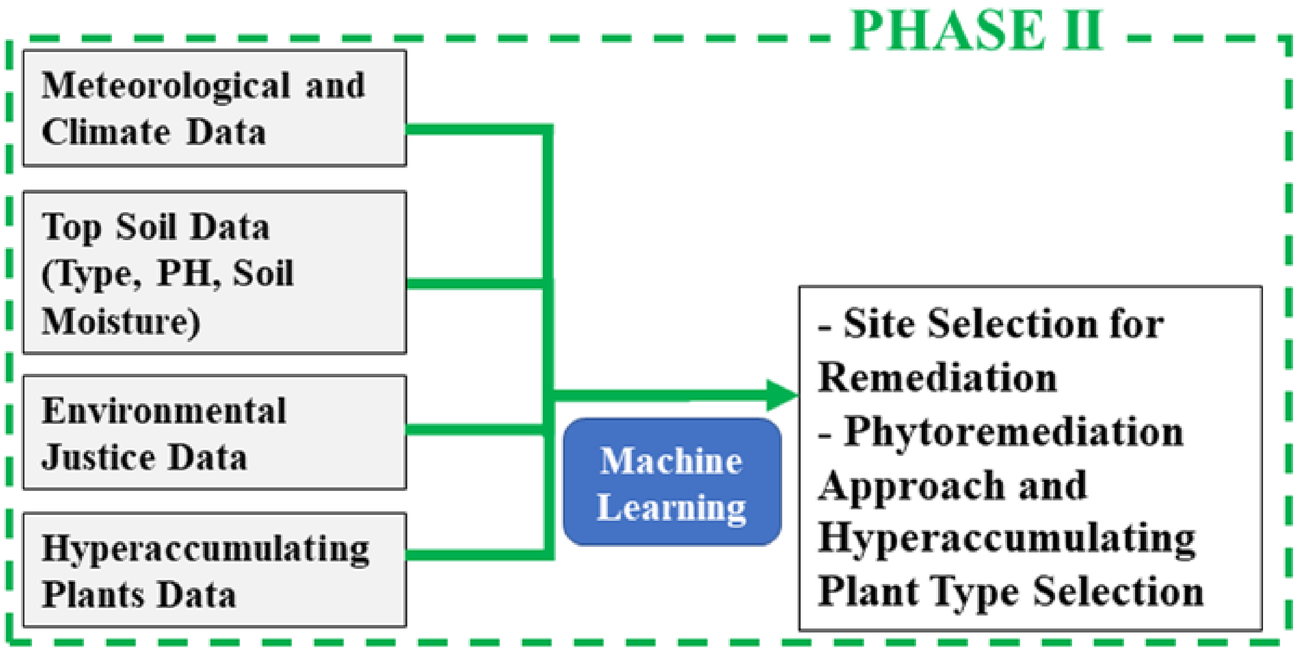
Arsenic, selenium, iron, boron, chlorine, pH, manganese, cadmium, chromium, mercury, lead, antimony, total dissolved solids, thallium, vanadium, nickel and sulfate. a past selenium release from this plant caused local extinction of 80% all fish species in Belews Lake.

Applying machine learning for data correction and classification

- The **different types of input data** are from multiple sources.
- To learn across multiple information sources, different modality of features needs to be projected in the same joint feature space.
- A machine/deep learning-based classifier is implemented to classify whether historical or spatial leached-metal caused abnormalities appear or not.



Phase II: propose locally adaptable phytoextraction approaches to remediate contaminated regions



- A content-based filtering ranking algorithm will be developed for effective and environmentally justified case-specific phytoremediation

Output:

- Ranking phytoremediation candidates
- Suggested plant species to be used for the phytoremediation of candidate sites

Data Acquisition and Classification based on soil type and properties, hyperaccumulating plant types, and metal contamination types

Which plants are a good fit for different sites?

- **Plant type**
- **Soil type**
- **Climate**
- **Native or non-native**

New Phytologist

Letters

A global database for plants that hyperaccumulate metal and metalloid trace elements

Hyperaccumulator plants and the need for a database

Table 1 Hyperaccumulator species in the Global Database (as of September 2017) with the global records that are the highest concentrations reported to date

Element	Threshold ($\mu g\ g^{-1}$)	Families	Genera	Species	Global records
Arsenic (As)	> 1000	1	2	5	*Pteris vittata*[1] (2.3%)
Cadmium (Cd)	> 100	6	7	7	*Arabidopsis halleri*[2] (0.36%)
Copper (Cu)	> 300	20	43	53	*Aeolanthus biformifolius*[3] (1.4%)
Cobalt (Co)	> 300	18	34	42	*Haumaniastrum robertii*[4] (1%)
Manganese (Mn)	> 10 000	16	24	42	*Virotia neurophylla*[5] (5.5%)
Nickel (Ni)	> 1000	52	130	532	*Berkheya coddii*[6] (7.6%)
Lead (Pb)	> 1000	6	8	8	*Noccaea rotondifolia* subsp. *cepaeifolia*[7] (0.8%)
Rare earth elements (lanthanum, La; cerium, Ce)	> 1000	2	2	2	*Dicranopteris linearis*[8] (0.7%)
Selenium (Se)	> 100	7	15	41	*Astragalus bisulcatus*[9] (1.5%)
Thallium (Tl)	> 100	1	2	2	*Biscutella laevigata*[10] (1.9%)
Zinc (Zn)	> 3000	9	12	20	*Noccaea caerulescens*[11] (5.4%)

[1]Ma *et al.* (2001); [2]Stein *et al.* (2017); [3]Malaisse *et al.* (1978); [4]Brooks (1977); [5]Jaffré (1979); [6]Mesjasz-Przybyłowicz *et al.* (2004); [7]Reeves & Brooks (1983); [8]Shan *et al.* (2003); [9]Galeas *et al.* (2006); [10]LaCoste *et al.* (1999); [11]Reeves *et al.* (2001).

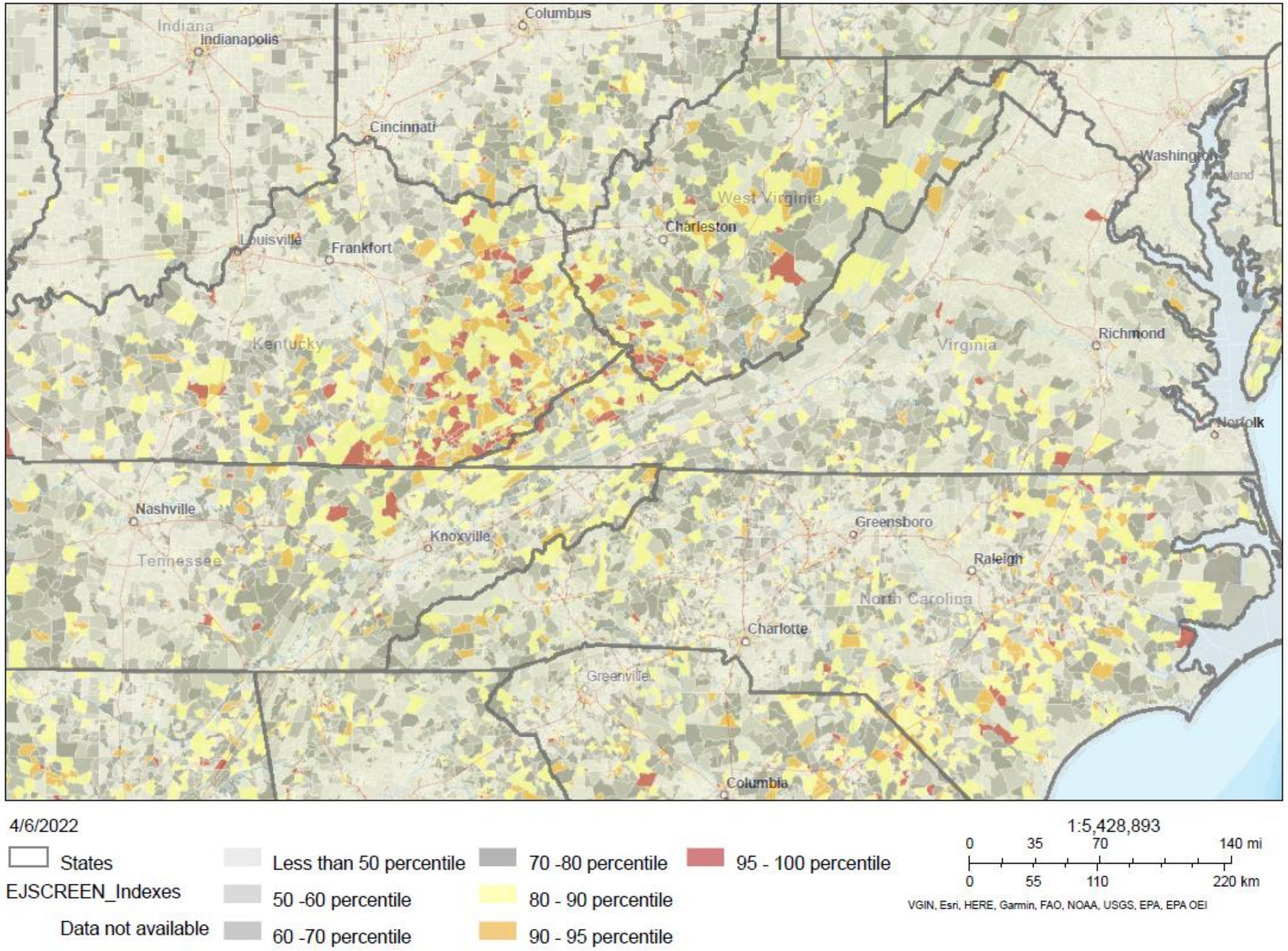
Reeves, R.D., Baker, A.J., Jaffré, T., Erskine, P.D., Echevarria, G. and van der Ent, A., 2018. A global database for plants that hyperaccumulate metal and metalloid trace elements. *New Phytologist*, *218*(2), pp.407-411.

Data acquisition and classification based on environmental justice

Identify priority regions based on the data from **US EPA's Environmental Justice Screening and Mapping Tool (EJSCREEN)**

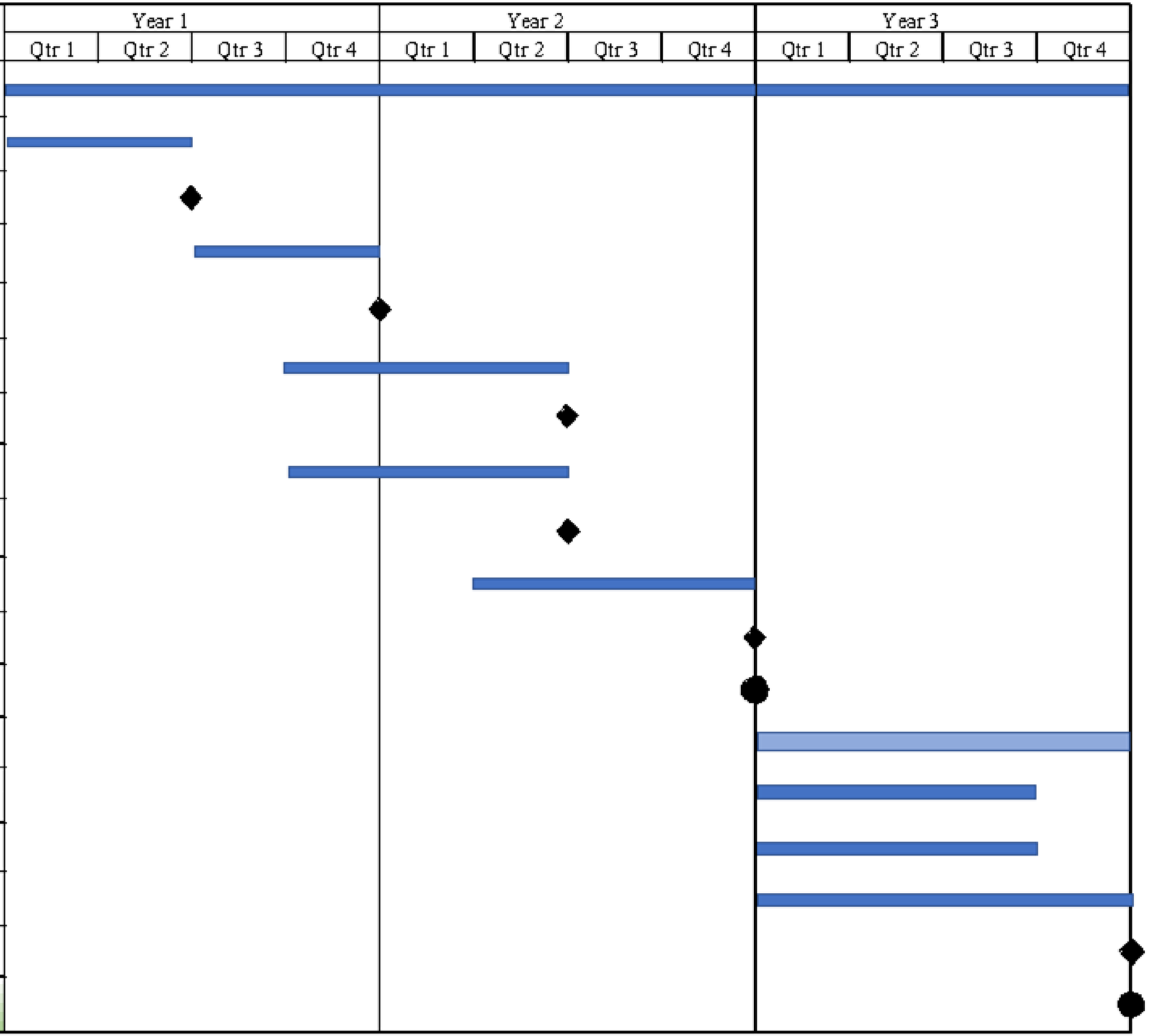
- % Low Income
- % Unemployed
- % Limited English Speaking
- % Less than High School Education
- Low Life Expectancy

% Low Income



Timeline

Task Name	Assigned Resources
Task 1.0 – Project Management and Planning	Bahareh Nojabaei
Task 2.0 – Historical Top-Down Data and Satellite Images Acquisition and Preprocessing	Hosein Foroutan
Milestone A	Hosein Foroutan
Task 3.0 – Image Processing of the Satellite Data and Search for Potential Historical and Spatial Abnormalities	Hoda Eldardiry
Milestone B	Hoda Eldardiry
Task 4.0 – Soil and Vegetation Sampling and Analysis	Ryan Stewart
Milestone C	Ryan Stewart
Task 5.0 – Contamination transport and hydrological modeling	Bahareh Nojabaei
Milestone D	Bahareh Nojabaei
Task 6.0 – Applying machine learning for data correction and classification	Hoda Eldardiry
Milestone E	Hoda Eldardiry
Decision Point 1	Team
Task 7.0 – Locally-Adapted Phytoremediation Design	Team
Subtask 7.1 – Data Acquisition and Classification based on soil, hyperaccumulating plants, and metal contamination types	Bahareh Nojabaei Ryan Stewart
Subtask 7.2 – Data acquisition and classification based on environmental justice	Hosein Foroutan
Subtask 7.3 – Applying machine learning and data analysis to optimize the phytoremediation design	Hoda Eldardiry
Milestone F	Team
Decision Point 2	Team



Milestones

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method
2	**Milestone A: Acquire and process historical top-down data and satellite images**	**6 months after the beginning of the project**	**The availability of acquired data to be used as input for the next task**
3	**Milestone B: Detect historical and spatial abnormalities by image processing of satellite images**	**12 months after the beginning of the project**	**Bioindicators performance**
4	Milestone C: Complete soil and vegetation sampling and testing	18 months after the beginning of the project	Validated phytoindication model
5	Milestone D: Develop a contamination transport and hydrological simulation model	18 months after the beginning of the project	Developed realistic geological model
6	Milestone E: Correct and classify abnormalities data	24 months after the beginning of the project	Bioindicators' performance in detecting contamination
7	Milestone F: Design a locally-adapted phytoremediation system	35 months after the beginning of the project	Developed effective phytoremediation method

Summary of key actions completed

- Data collection of 43 coal power plants within the study area
- Data analysis & visualization of the collected well monitoring data
- Vegetation health monitoring with satellite remote sensing data (LANDSAT 8 and SENTINEL 2)
- Calculation of different vegetation indices and comparative analyses of vegetation indices
- Creating time-series data of different vegetation indices
- Development of toolkit Vegetation Indices Calculator for the VI calculation and analyses which can be used for monitoring of vegetation in different locations.

Overview of study area

- 43 coal power plants spanning in 7 states and owned & operated by 11 different companies.
- Built between 1940 to 1992 and 70% plants are active.
- Generate 36663 MW in total and operate with 133 boilers.
- Only 9% plant status is low in hazard rating.
- 31 different pollutants found (no contamination data is available for 8 plants).
- 100 percent of the plants have one or more associated contamination above safe threshold.
- Total number of known impoundments are 216.
- Total area of these impoundments are 4916 acres (Data found from 39 plants) and have 220,163,869 tons of ash (Data found from 31 plants).
- Total known wastewater 3,437,160,709 gallons. (Data found from 31 plants)
- Total known coal ash and wastewater slurry 997,042,688 gallons.

Data sources

ASHTRACKER.ORG

- Ashtracker provides public access to industry-reported data from state and company records about groundwater contamination at coal ash dumps.
- Ashtracker currently tracks groundwater at 11,727 monitoring wells distributed among 325 sites across the country. 45 percent of wells have been contaminated above safe levels.

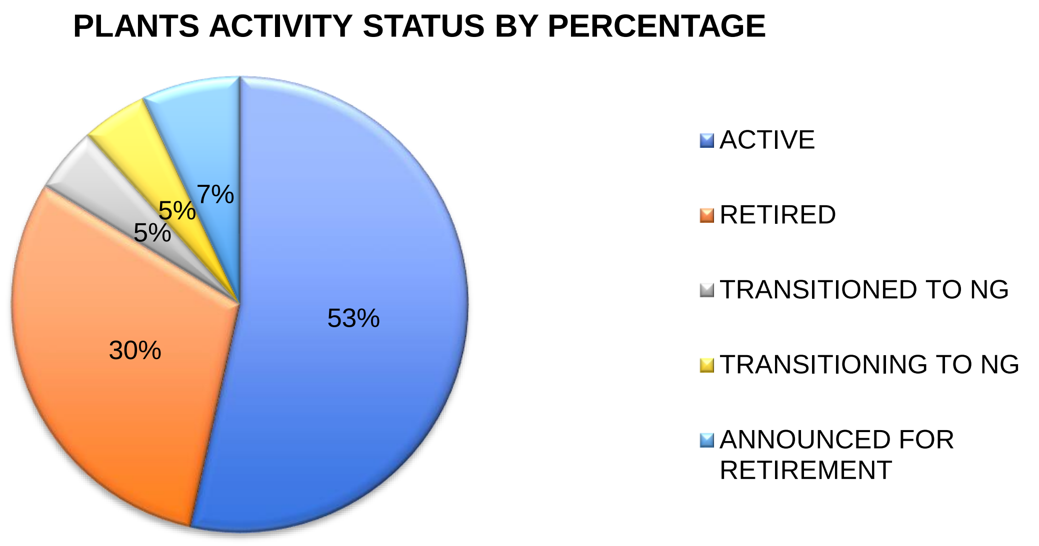
SOUTHEASTCOALASH.ORG

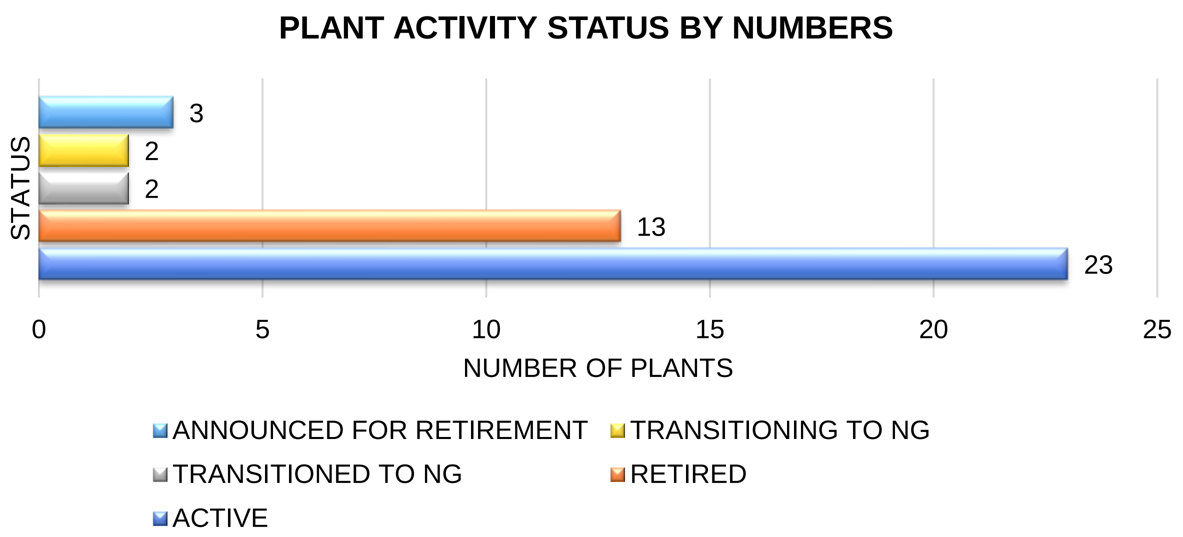
A group of environmental and community organizations in the Southeast working together on three efforts related to coal ash issues:

- The development of this comprehensive website where individuals and groups can get more information on coal ash ponds near them.
- Gathering data and much-needed information on coal ash ponds and water contamination that currently does not exist.
- Collaboratively looking for legal opportunities to hold utility companies in the Southeast accountable for their coal ash pollution.

Plant status by activity

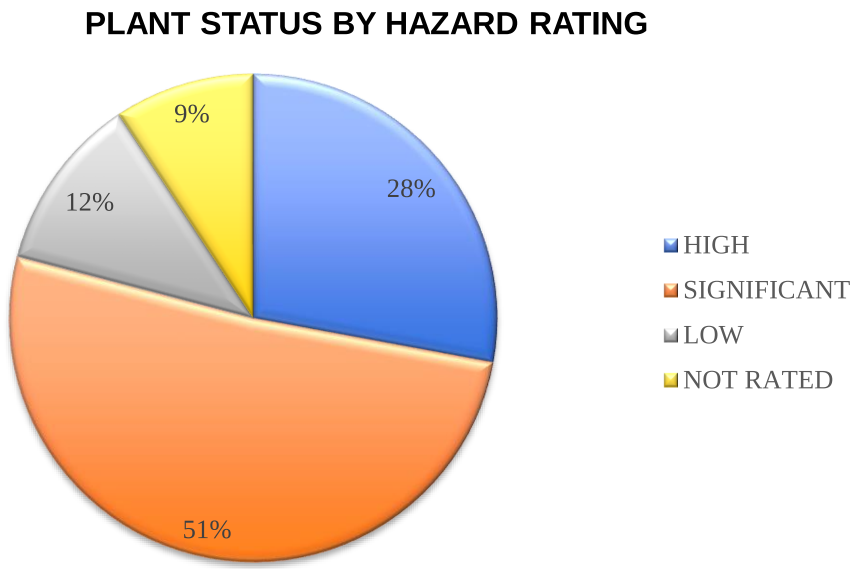
- Active: 23 plants, 53%
- Retired: 13 plants, 30%
- Transitioned to Natural Gas : 2 plants, 5%
- Transitioning to Natural Gas : 2 plants, 5%
- Announced for retirement: 3 plants, 7%

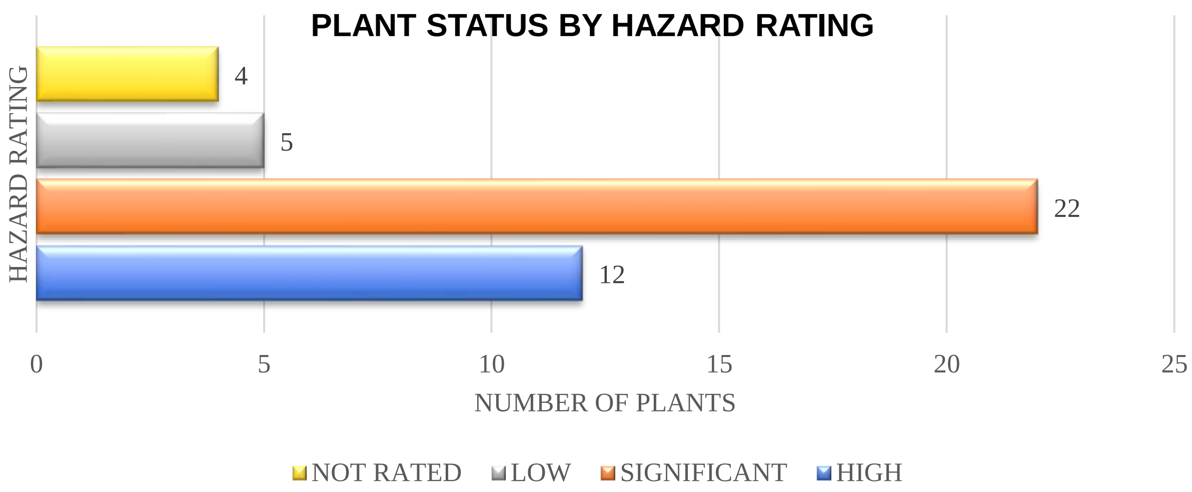




Plant status hazard rating

- High: 12 plants, 28%
- Significant: 22 plants, 51%
- Low: 5 plants, 9%
- Not Rated: 4 plants, 9%

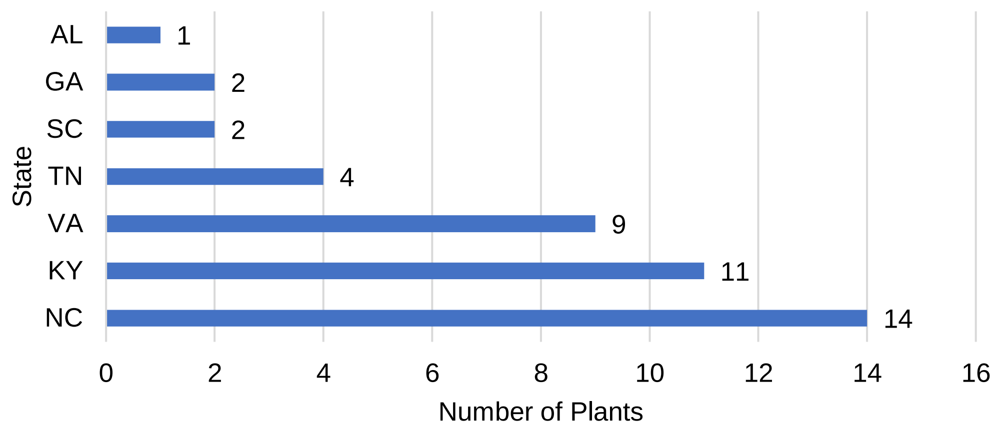




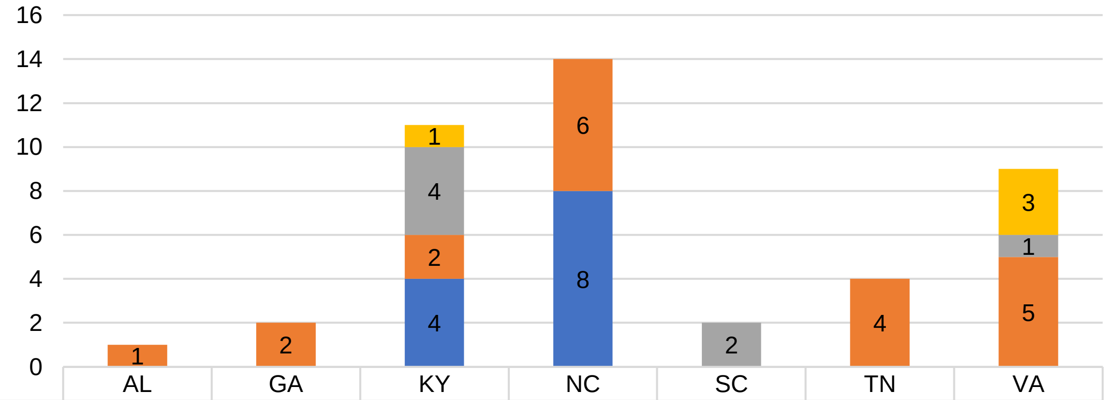
Plants and impoundments in different states

- North Carolina: 14 (High hazard 8, Significant 6), 32%
- Kentucky: 11 (High 4, Significant 2, Low 4, Not Rated 1), 26%
- Virginia: 9 (Rated: Significant 5, Low 1, Not Rated 3), 21%
- Tennessee: 4 Significant Rated, 9%
- South Carolina: 2 Low Rated, 5%
- Georgia : 2 Significant Rated , 5%
- Alabama: 1 Significant Rated , 2%

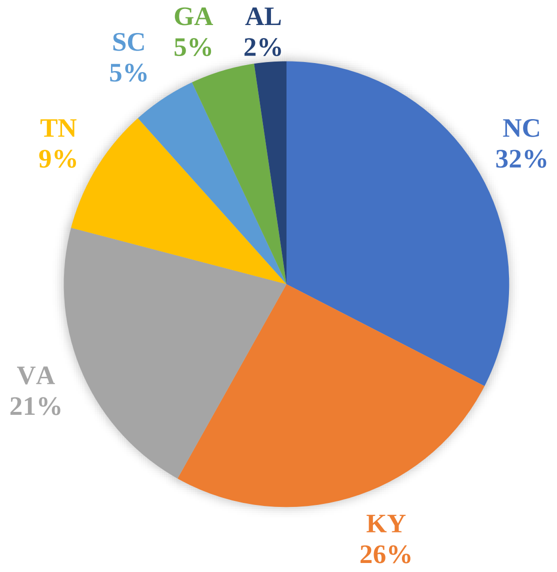
PLANTS BY STATE



PLANTS BY STATE WITH HAZARD RATING

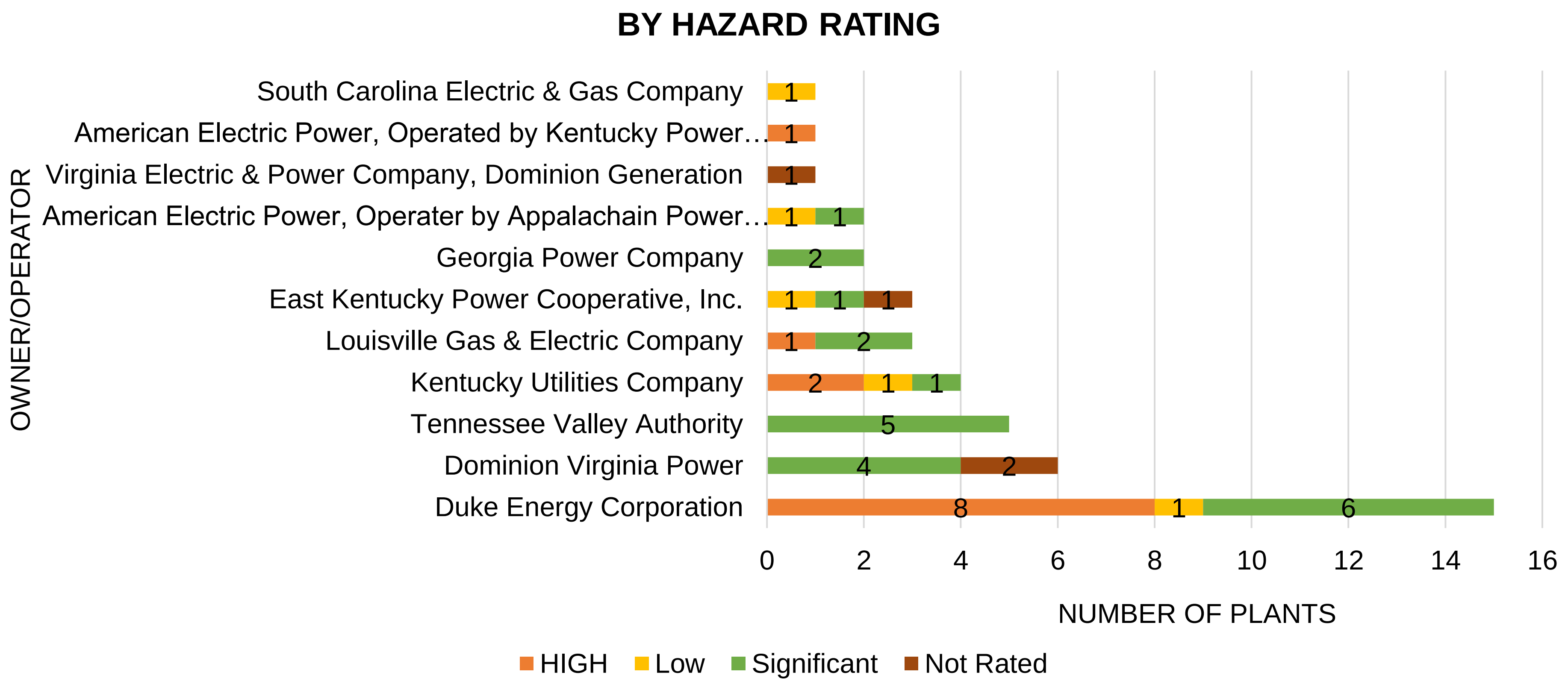


	AL	GA	KY	NC	SC	TN	VA
NOT RATED			1				3
LOW			4		2		1
SINGNIFICANT	1	2	2	6		4	5
HIGH			4	8			



Owner/operator

- Duke Energy Corporation operates 15 plants (14 in NC, 1 in SC), 8 plants rated High, 6 significant,1 Low



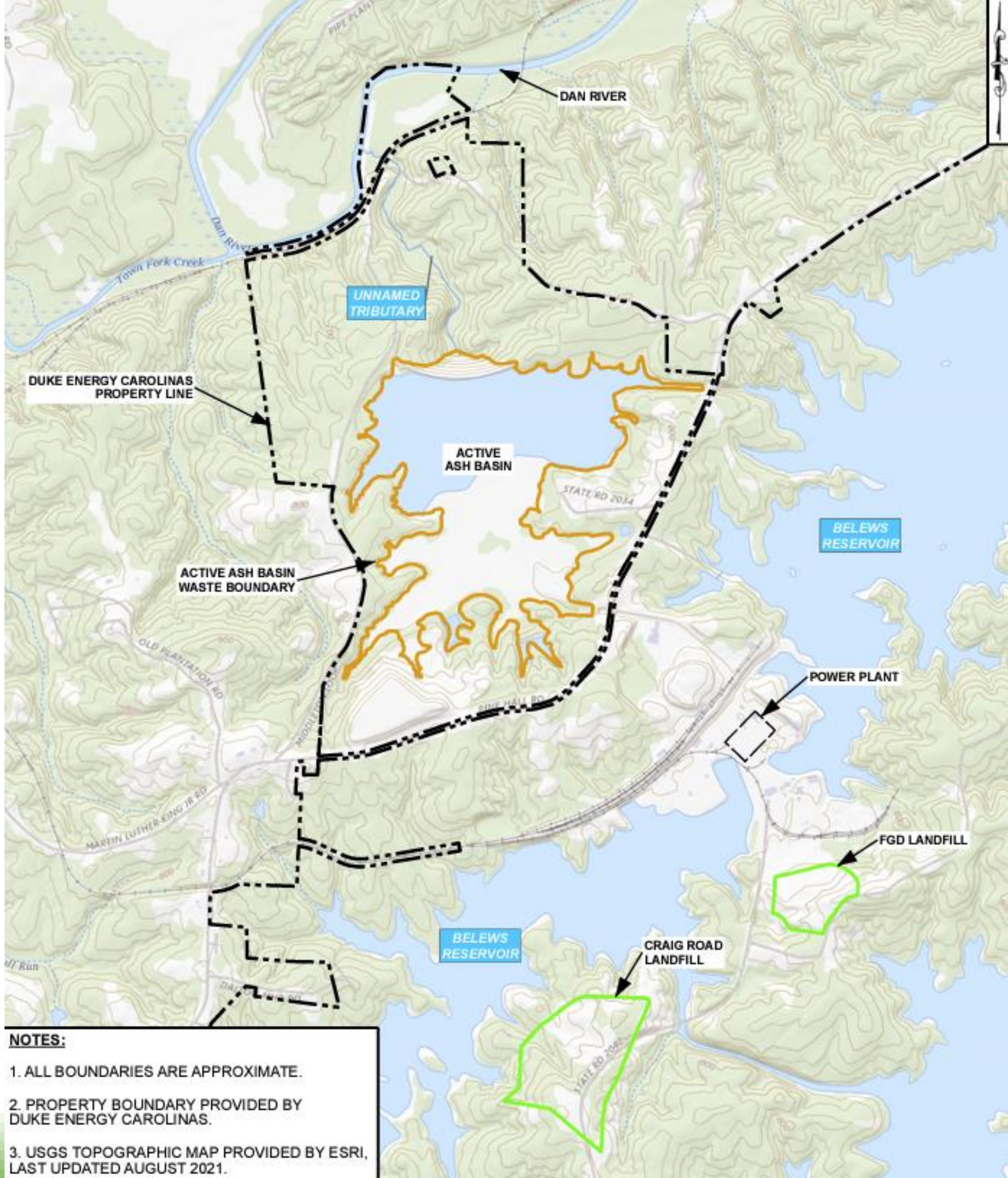
Polluting constituents above safe limit

- Almost all plants have pollutants above safe limit which are required for monitoring for reporting, ruled by EPA.
- 1138 Monitoring wells , 602 wells are polluted with at least one constituent.
- No ground water monitoring data found from 8 out of 43 plants.
- The table shows the percentage and number of plants above threshold limit. (with data from 35 plants)

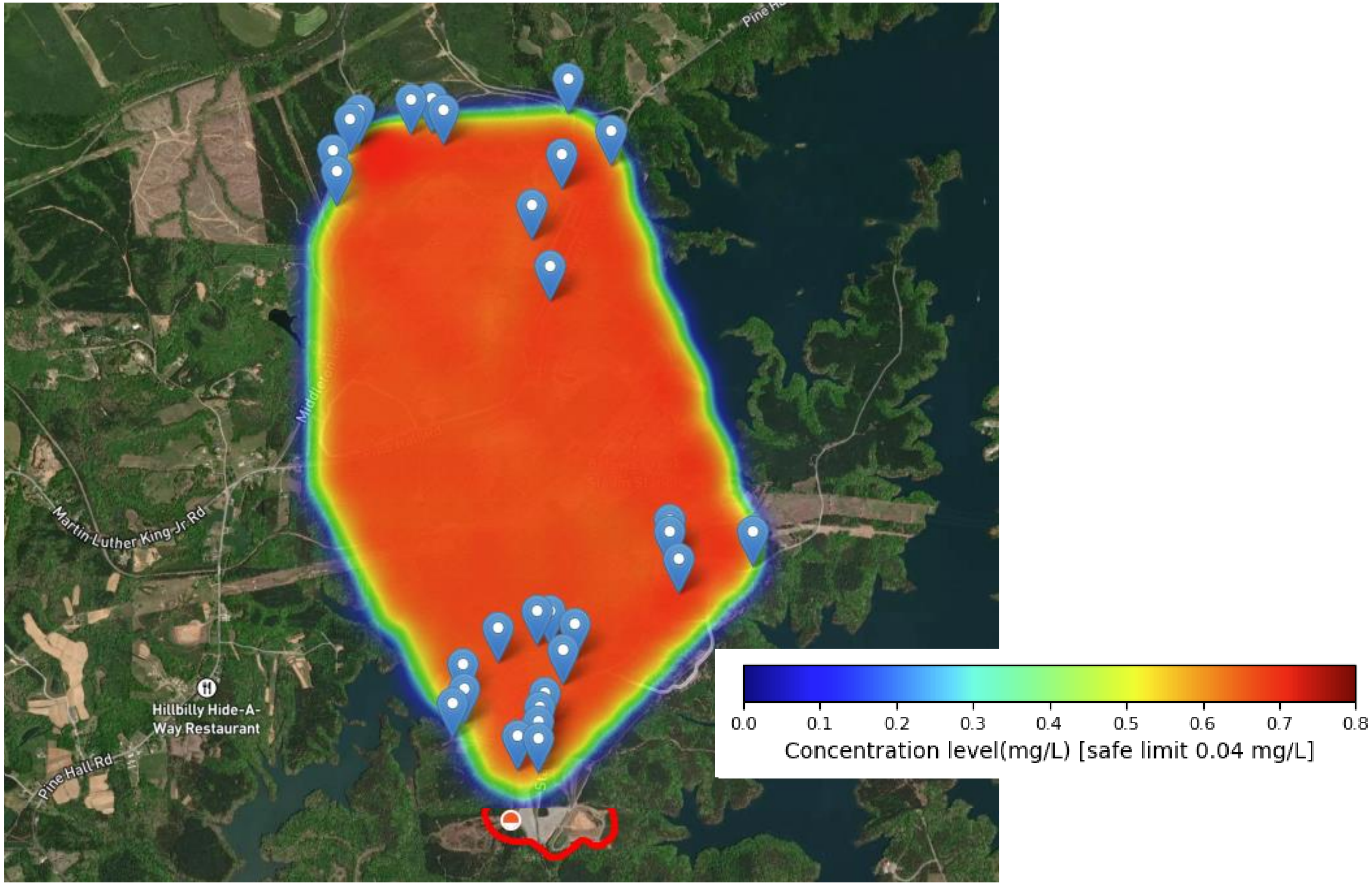
Constituents	Threshold	No of Plants above threshold	% of plants with unsafe levels
Arsenic	0.01 mg/L	27	77%
Cobalt	0.006 mg/L	25	71%
Boron	3.0 mg/L	23	66%
Molybdenum	0.04 mg/L	23	66%
Sulfate	500.0 mg/L	23	66%
Manganese	0.3 mg/L	22	63%
Lithium	0.04 mg/L	19	54%
Lead	0.015 mg/L	16	46%
Radium	0.005 mg/L	15	43%
Beryllium	0.004 mg/L	11	31%
Cadmium	0.005 mg/L	11	31%
Selenium	0.05 mg/L	9	26%
Thallium	0.002 mg/L	9	26%
Chromium	0.1 mg/L	7	20%
Antimony	0.006 mg/L	6	17%
Barium	2.0 mg/L	5	14%
Fluoride	4.0 mg/L	3	9%
Nickel	0.1 mg/L	3	9%
Strontium	4.0 mg/L	3	9%
Mercury	0.002 mg/L	2	6%
Ammonia	30.0 mg/L	1	3%
Nitrate	10.0 mg/L	1	3%

Case study: Belews Creek stream station

- **Owned and operated by Duke Energy**.
- Commercial operations began in 1974 with Unit 1 (1,120 MW), followed by Unit 2 (1,120 MW) in 1975.
- **Hazard rating High**.
- 3 impoundments: FGD Landfill, Craig Road Landfill, and Active Ash Basin.
- Total storage surface area of 324 acres and held approximately 12,654 acre-feet of waste.
- Total known capacity of 2867488800 gallons.
- Total known ash of 14742238 tons.
- Total known wastewater of 99960000 gallons
- From 1974 to 1986, the station discharged wastewater to Belews Lake. As a result, 19 species of fish were eliminated from the lake.
- **104 groundwater monitoring wells**, 54 of which have been polluted above federal advisory levels based on samples collected between January 06, 2011, and April 15, 2019.
- **Groundwater at this site contains unsafe levels of arsenic, beryllium, boron chromium, cobalt, lithium, manganese, mercury, molybdenum, radium, selenium, and sulfate**.
- Pollutants monitored and found below guidelines are antimony, barium, cadmium, copper, fluoride, lead, nickel, nitrate, and thallium.
- Duke Energy announced in 2022 that the facility would be shifted to natural gas by 2035.



Lithium contamination heatmap from monitoring wells



Workflow used for vegetation indices calculation

- Open google earth engine code editor.
- Select region of interest and set map center.
- Load Landsat or Sentinel satellite image collection from google cloud.
- Filter image collection with bands, datetime, cloud cover and region of interest.
- Add visualization parameters to visualize better.
- Add image collection to map.
- Define functions to calculate vegetation indices.
- Add calculated VI to image collection and add to map.
- Chart VI.

A simple code snippet is added here.

Check the app developed for all the calculation:

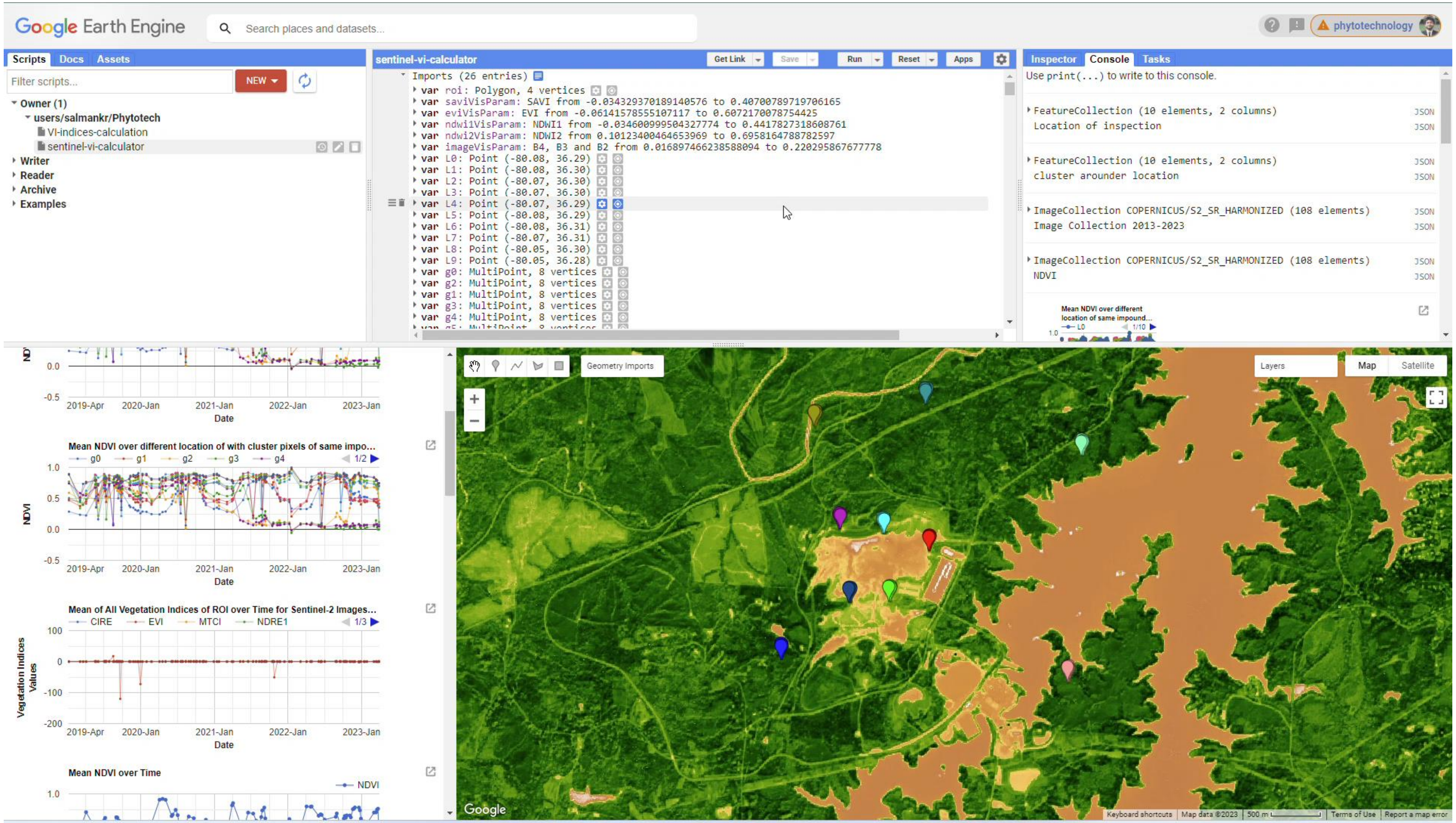
[Vegetation Indices Calculator]

New Script * Get Link Save Run Reset Apps

```
Imports (1 entry)
 var roi: Polygon, 4 vertices
//Select Region of Interest nad add to map
Map.addLayer(roi, {},'ROI', false);
Map.setCenter(-80.0641, 36.2922, 14);
//Load Image collection
var imColl = ee.ImageCollection('COPERNICUS/S2_SR_HARMONIZED')
                  .filterBounds(roi)
                  .filterDate('2017-03-28', '2023-03-28')
                  .select('B1','B2','B3','B4','B5','B6','B7','B8','B8A','B9','B11','B12', 'QA60')
                  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE',30));
// add image collection to map
var visParam ={ bands: ["B4","B3","B2"], gamma: 1, max: 2994.6, min: 198.25714285714287, opacity: 1};
Map.addLayer(imColl.median().clip(roi), visParam,' True Color Image', true);
// Calculate EVI and the calculatd EVI band to image collection
var addEVI = function(image) {
  var calEVI = image.expression(
      '(2.5 * float((B8-B4)/( B8 + (6 * B4)-(7.5 * B2) + 1)))',
      {
        'B8': image.select('B8'),
        'B4': image.select('B4'),
        'B2': image.select('B2'),
      }).rename('EVI');
  return image.addBands(calEVI);
};
var evi = imColl.map(addEVI).select('EVI');
// Chart EVI
var chart_evi = ui.Chart.image.series({
  imageCollection: evi,
  region: roi,
  reducer: ee.Reducer.mean(),
  scale: 30
})
.setOptions({
          interpolateNulls: true,
          lineWidth: 1,
          pointSize: 3,
          title: 'Mean EVI over Time',
          vAxis: {title: 'EVI',titleTextStyle: {italic: false, bold: true}},
          hAxis: {title: 'Date', format: 'YYYY-MMM', gridlines: {count: 20},titleTextStyle: {italic: false, bold: true}}

  });
Map.addLayer(evi.median(), {}, 'EVI', false);
```

Toolkit for vegetation indices calculation



Vegetation indices calculation equations

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} - \text{Red}}$$

$$NDWI1 = \frac{\text{NIR} - \text{SWIR1}}{\text{NIR} + \text{SWIR1}}$$

$$NDWI2 = \frac{\text{NIR} - \text{SWIR2}}{\text{NIR} + \text{SWIR2}}$$

$$NDREI1 = \frac{\text{NIR} - \text{Red Edge 1}}{\text{NIR} + \text{Red Edge 1}}$$

$$NDRE2 = \frac{\text{NIR} - \text{Red Edge 2}}{\text{NIR} + \text{Red Edge 2}}$$

$$EVI = 2.5 * \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + 6 * \text{Red} - 7.5 * \text{Blue} + 1)}$$

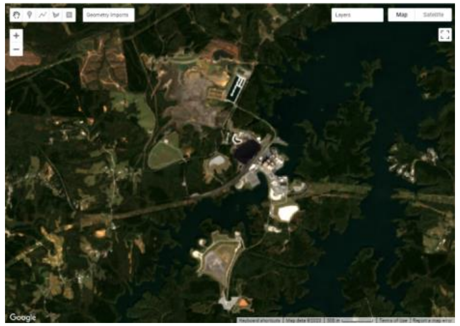
$$SAVI = 1.5 * \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red} + 0.5)}$$

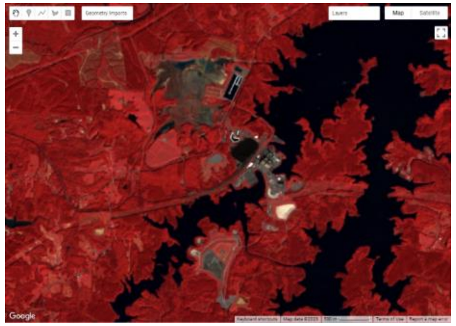
$$REP = 705 + 35 * \frac{\left(\frac{\text{Red} + \text{Red Edge 3}}{2 - \text{Red Edge 1}}\right)}{(\text{Red Edge 2} - \text{Red Edge 1})}$$

$$MTCI = \frac{\text{Red Edge 2} - \text{Red Edge 1}}{\text{Red Edge 1} - \text{Red}}$$

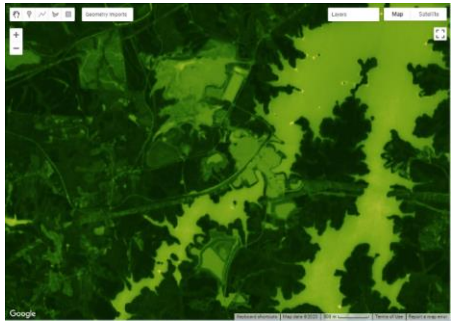
$$\text{CI}_{\text{RE}} = \frac{\text{Red Edge 3}}{\text{Red Edge 1}} - 1$$

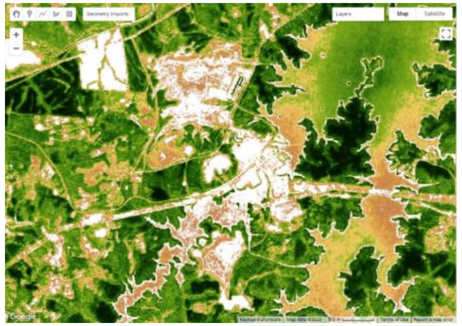
Vegetation indices calculation: visualization

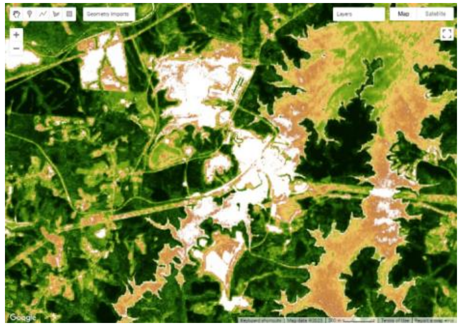

TRUE COLOR

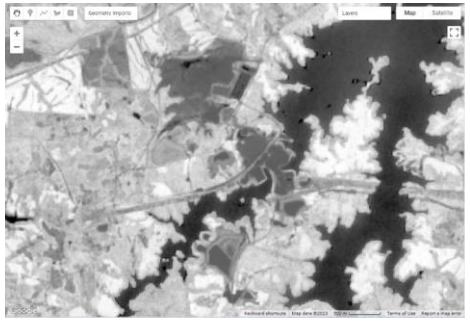

FALSE COLOR

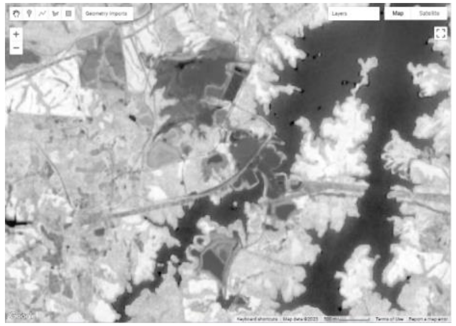

EVI

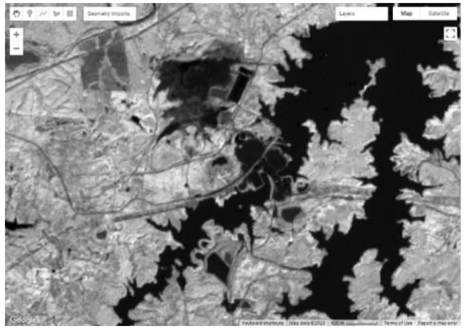

NDVI

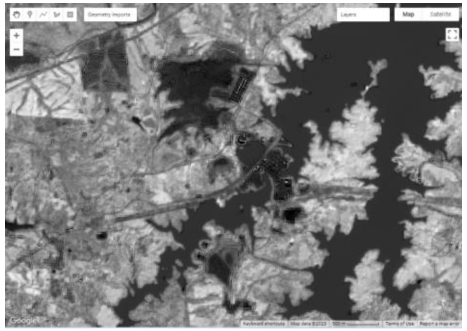

NDWI1

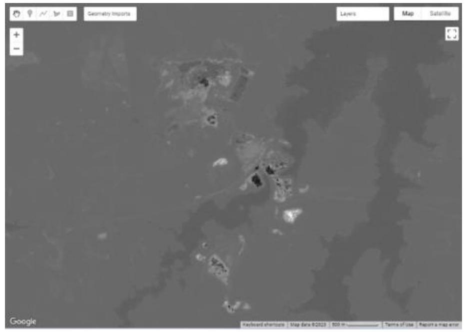

NDWI2


NDRE1


NDRE2

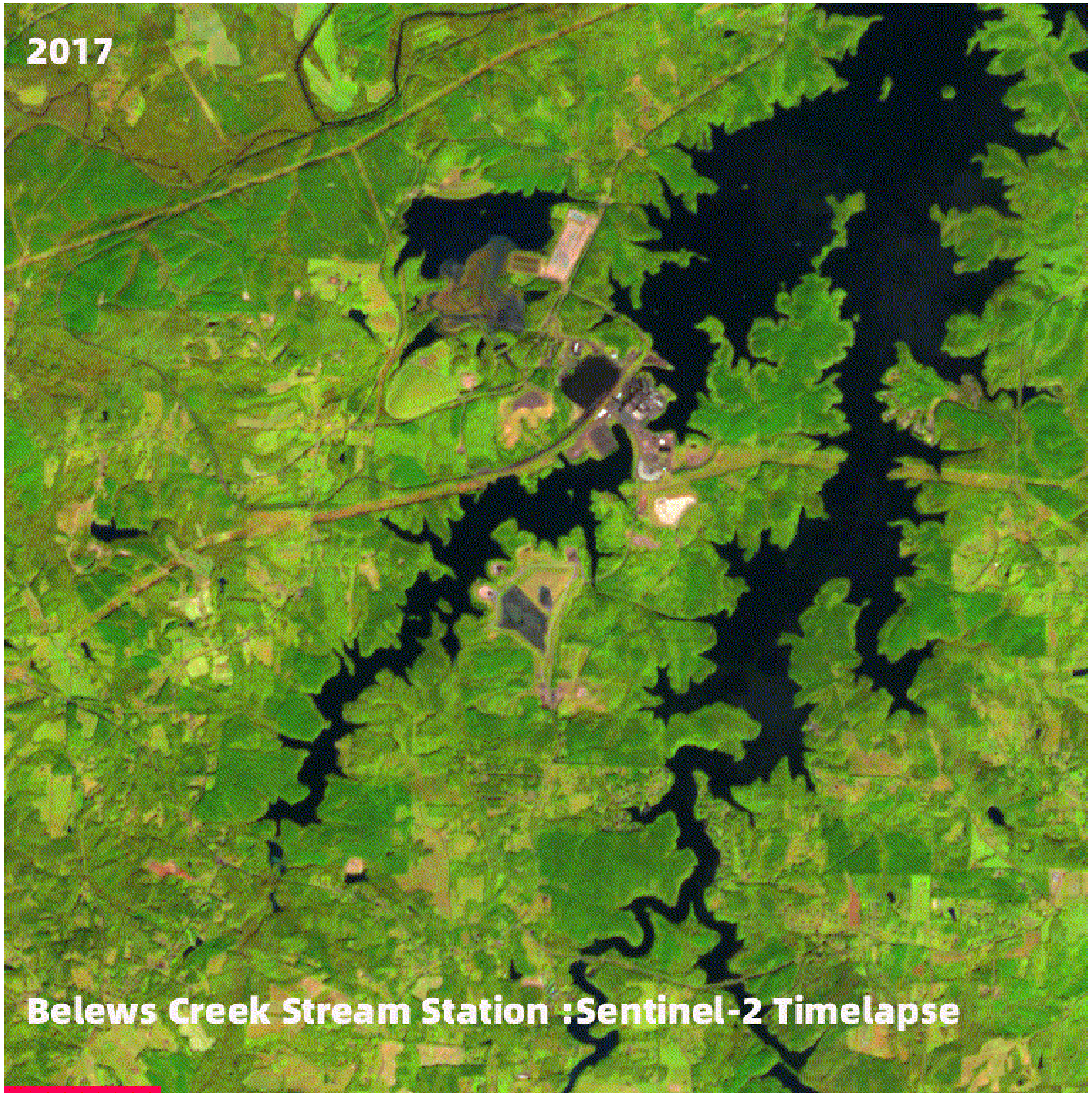

CERI


MTCI


REP


SAVI

Time lapse from sentinel 2 (NDVI)



Vegetation indices time series

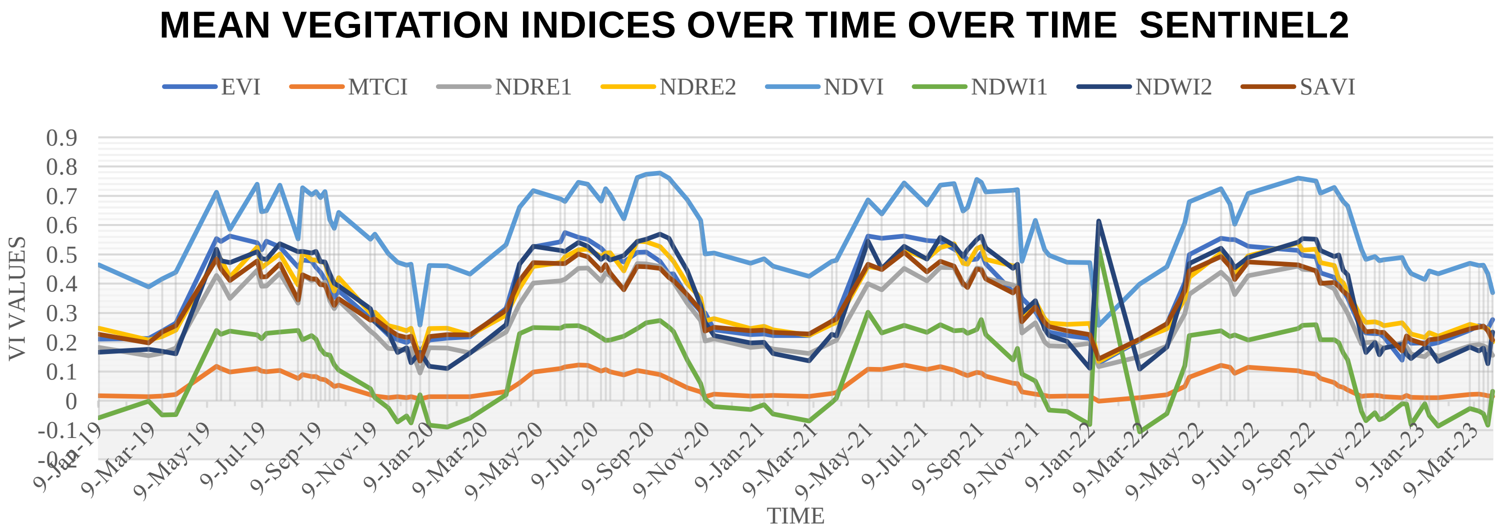
- Various vegetation indices has been calculated from both Landsat 8 and Sentinel-2 satellite with less than 30% cloud cover.
- For Landsat 8:

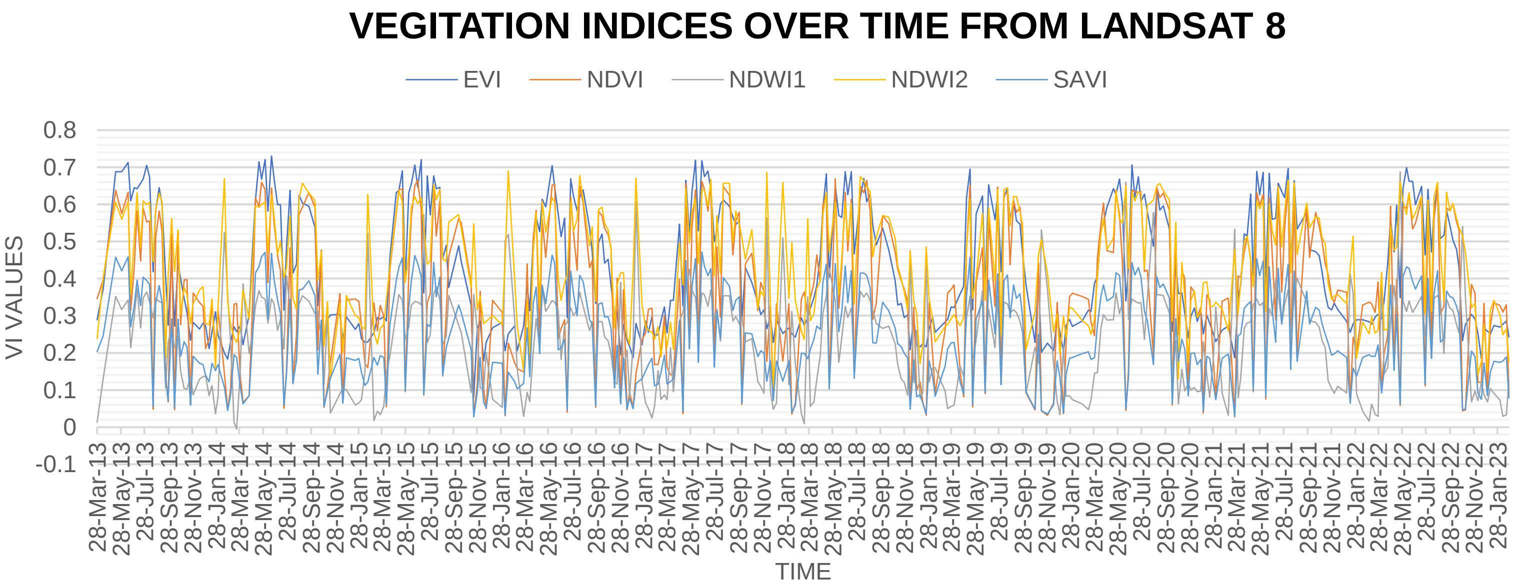
- Image collection from March 2013 to March 2023. (Total filtered images:152)

- For Sentinel 2:

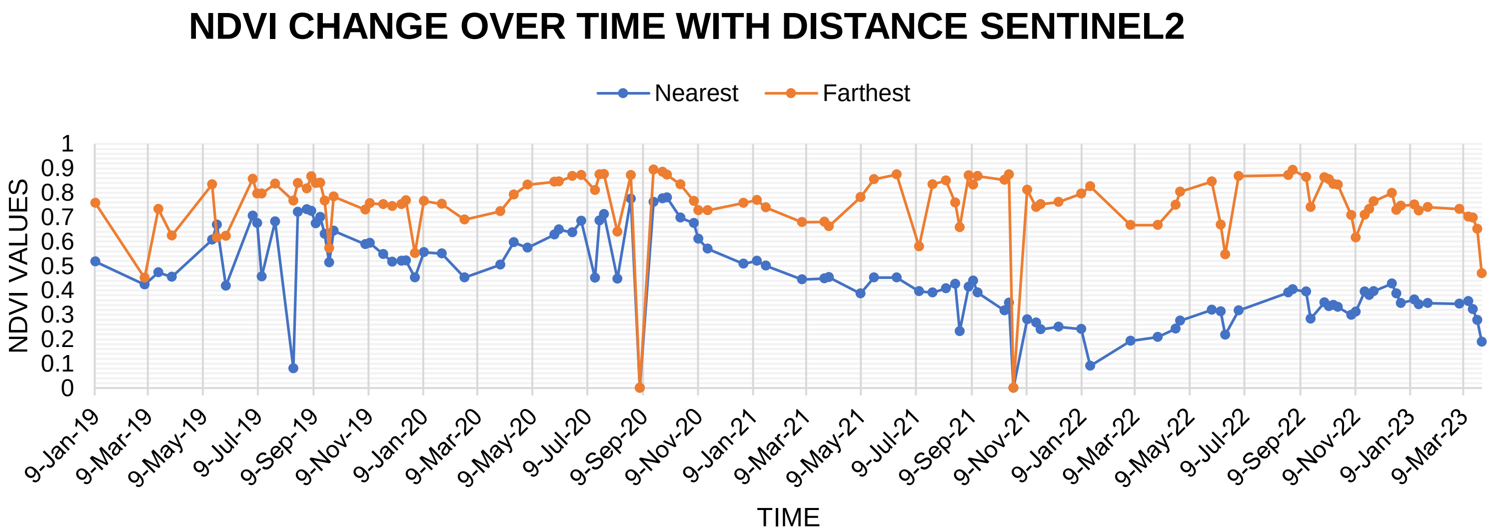
- Image collection from March 2019 to March 2023. (Total filtered images: 108)

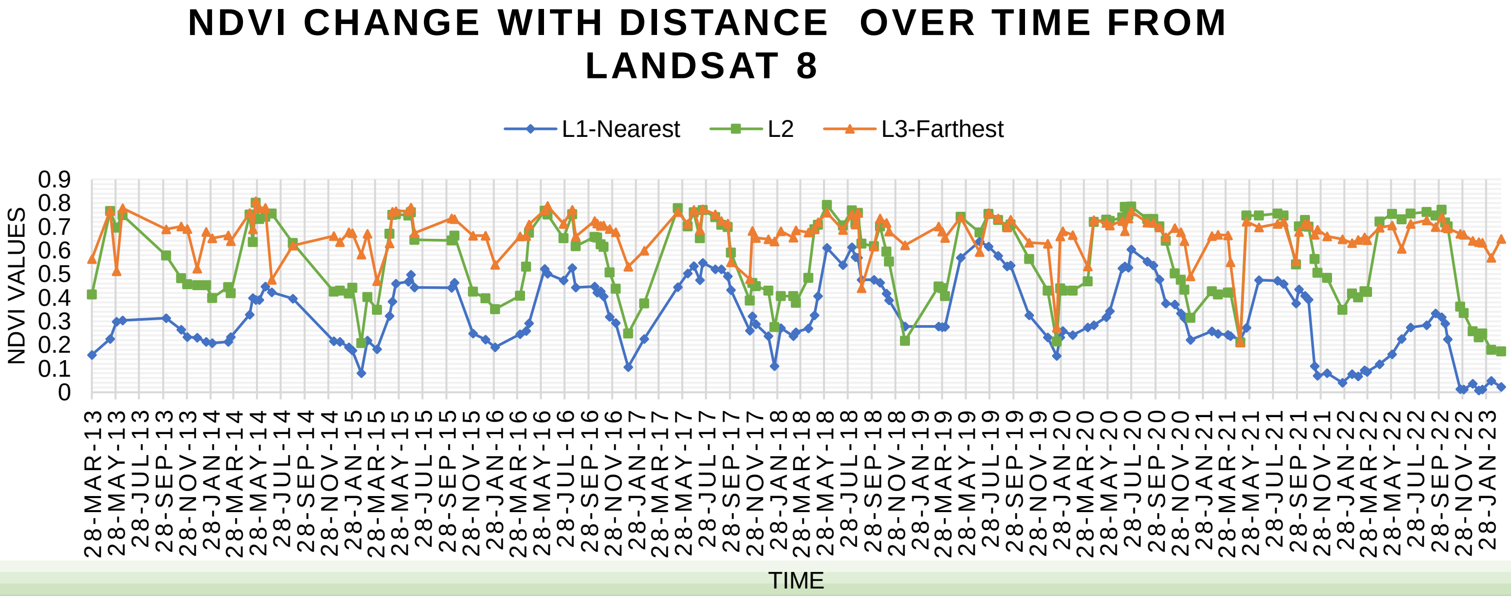
Input for time series analyses: Searching for abnormalities



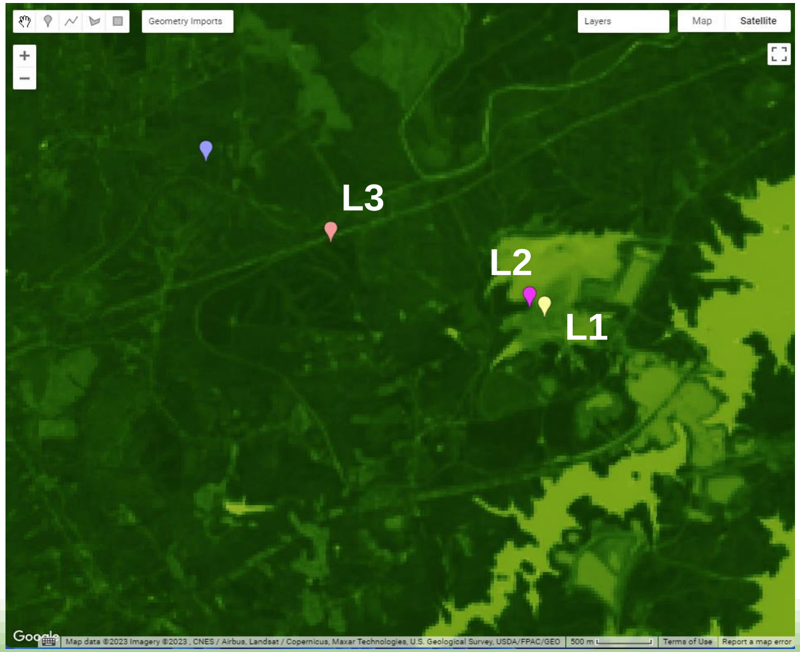


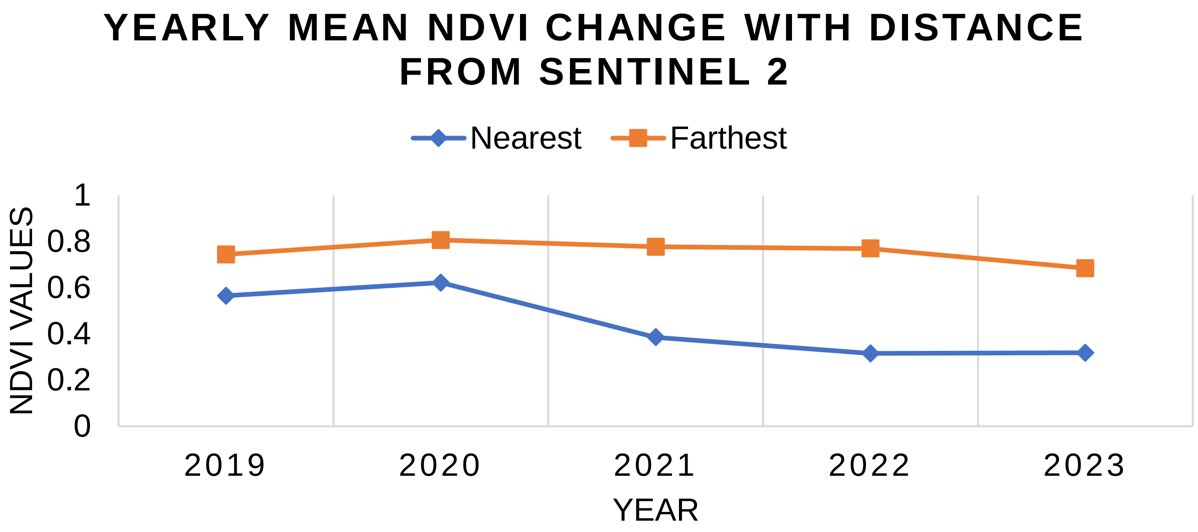
NDVI change with distance

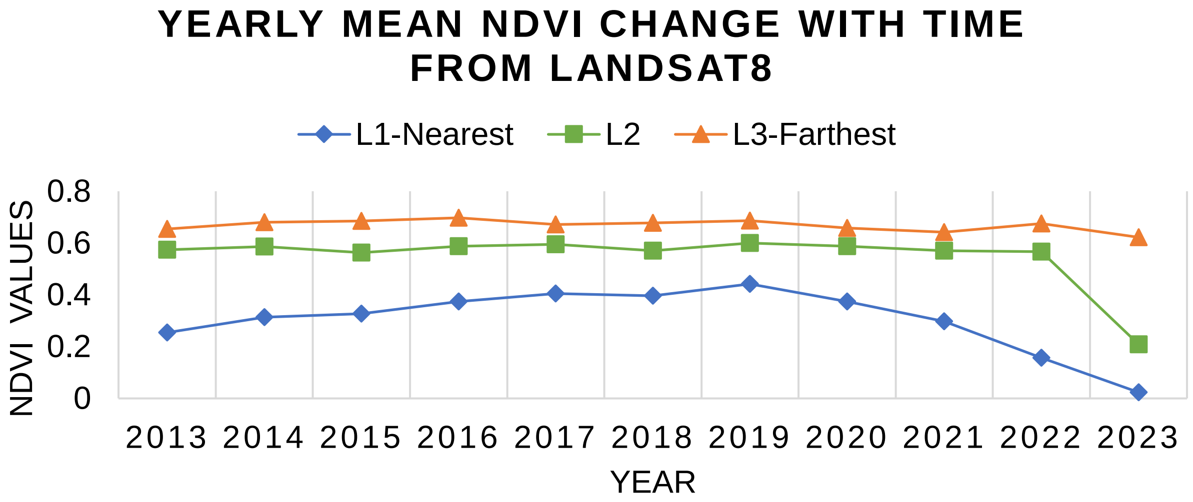




NDVI change with distance







Potential project benefits

- A scalable, low-cost technology to screen a wide range of locations and to identify coal ash-sourced or mine tailings- sourced leached metal-contaminated areas.

- Train and educate students in a multi-disciplinary setting
- Learn about different fields
- Potential application of phytotechnology in other fields (e.g. phyto-mining)
- Phytoremediation pilot design and implementation
- Post phytoremediation monitoring