DOI: 10.1007/s00267-003-3043-1

Prioritizing Abandoned Coal Mine Reclamation Projects Within the Contiguous United States Using Geographic Information System Extrapolation

YURI GOROKHOVICH*
MATTHEW REID
ERICA MIGNONE
Natural Sciences
SUNY, Purchase College
735 Anderson Hill Rd.
Purchase, New York 10577, USA

ANDREW VOROS
Clean Ocean and Shore Trust (COAST)
Department of Earth and Environmental Engineering
Columbia University
918 Mudd Building
New York, New York 10027, USA

ABSTRACT / Coal mine reclamation projects are very expensive and require coordination of local and federal agencies to identify resources for the most economic way of reclaiming mined land. Location of resources for mine reclamation is a spatial problem. This article presents a methodology that allows the combination of spatial data on resources for the coal mine reclamation and uses GIS analysis to develop a priority list of potential mine reclamation sites within contiguous United States using the method of extrapolation. The extrapolation method in this study was based on the Bark Camp reclamation project. The mine reclamation project at Bark Camp, Pennsylvania, USA, provided an example of the beneficial use of fly ash and dredged material to reclaim 402,600 sq mi of a mine abandoned in the 1980s. Railroads provided transportation of dredged material and fly ash to the site. Therefore, four spatial elements contributed to the reclamation project at Bark Camp: dredged material, abandoned mines, fly ash sources, and railroads. Using spatial distribution of these data in the contiguous United States, it was possible to utilize GIS analysis to prioritize areas where reclamation projects similar to Bark Camp are feasible. GIS analysis identified unique occurrences of all four spatial elements used in the Bark Camp case for each 1 km of the United States territory within 20, 40, 60, 80, and 100 km radii from abandoned mines. The results showed the number of abandoned mines for each state and identified their locations. The federal or state governments can use these results in mine reclamation planning.

Abandoned mine land (AML) features are physically and environmentally dangerous sites. The remnants of surface and deep-mining operations, they consist of often massive pits and underground voids, shafts, cliffs, and mine pools. Not only do they regularly result in falling and drowning fatalities, but they hold the potential for underground mine fires, surface subsidence, stream diversions, and the generation of acid mine drainage. Over 560,000 AML features have been cataloged in 29 states by the Department of the Interior's Bureau of Land Management, and their reclamation offers multiple logistical obstacles.

In the Commonwealth of Pennsylvania, with its valuable anthracite deposits, over 10 billion cubic meters of coal have been removed. This has resulted today in 9000 abandoned mines, 145 underground mine fires, 800 annual incidents of surface subsidence, and 3000 miles of acid mine drainage-impacted rivers and streams. In 1995 these massive remediation requirements led the Pennsylvania Department of Environmental Protection (PADEP) Bureau of Abandoned Mine Reclamation to partner with the NY/NJ Clean Ocean and Shore Trust (COAST), a bistate marine resources commission, in an effort to demonstrate the use of dredged materials amended with coal fly ash at the Bark Camp Demonstration Project in Huston Township, Clearfield Country, PA, USA (Voros and others 2002).

Since 1998 about 420,000 tons of dredged materials from the Hudson–Raritan estuary were transported by rail to Bark Camp, amended with a similar volume of coal fly ash and waste lime products, and placed in compacted lifts along 3.4 km of a 36.6 m high wall created by strip mining, to recreate the sloped contour that existed before mining began 75 years ago.

While the Bark Camp site was chosen for scientific and not logistical reasons, the success and economy of any future applications of this concept require the cor-

KEY WORDS: Abandoned mines; abandoned mine lands; Planning; Spatial analysis; GIS; Raster modeling

---

*Author to whom correspondence should be addressed.

relation of mine sites, dredging projects, fly ash generators and the rail connections among them. The method selected for this examination combines raster-based analysis provided by geographic information systems (GIS) and method of extrapolation.

Raster data in GIS consist of simple grids of regular pixels (or cells) arranged in rows and columns. The simplicity and efficiency of raster operations depend on this format and allow software to move on a pixel-by-pixel basis through the whole grid and fulfill one or several available functions along the way. All data for this analysis were obtained from Internet sources from various governmental agencies, assigned standard geographic projection and units, and converted into one raster data set, covering the contiguous United States as a grid with a pixel size of 1 × 1 km.

Extrapolation employs the application of specific parameters, identified in a particular case, to find similar combinations outside of the spatial boundary of the original study area. This is why it is used mainly for purposes of prediction and evaluation. The technical implementation of the extrapolation technique requires the selection of a spatial method that would be able to work across a geographical area and map or code results in each spatial element. Primarily because of its ability to work quickly on continuous (interpolated) surfaces, this task can be done most effectively with the GIS raster analytical technique described in Longley and others (2001), Burrough and McDonnell (1998), and Tomlin (1990).

Extrapolation techniques have been used in many studies dealing with spatial problems, such as the extrapolation of agricultural technology (Minh and Singh 2002), predicted quantity of deforestation (Pontius and others 2000), terrain modeling (Kidner and others 1999), location of dairy farms in Africa (McCarl and others, 1999), habitat suitability (Rogala and Soballe 1998), and predictive vegetative models (Zimmermann and Kienast 1995).

The present extrapolation analysis takes into account the four elements that contributed to the success of the Bark Camp project: abandoned mines, sources of fly ash, dredging projects, and railroad transportation. Combined into one spatial data set, these factors can provide a basis for the GIS software function to do a systematic search within specified distances on places outside the original Bark Camp location, where all four factors would be available.

This GIS based extrapolation analysis consisted of the coding, ranking, and combination of data sets, and use of the "focalvariety" analytical GIS function to locate areas where the four project factors were within user defined neighborhood (or window). "Focalvariety" is one of several focal functions for raster data developed earlier for GIS by Tomlin (1990) and implemented in many GIS packages, including Idrisi, ArcInfo, pMap, and PC Raster, among others. The function uses a pixel neighborhood that moves along each row in the grid, pixel by pixel. Within each step, the software calculates the number of various pixel values within the window and assigns a value to the current pixel. Therefore, at the end of the analysis, the final grid contains unique occurrences of pixel values within the neighborhood. The neighborhood in this analysis consisted of pixels within 20, 40, 60, 80, and 100 km of the analyzed grid cell.

The results of this extrapolation analysis showed that West Virginia, Pennsylvania, and Alabama are the most likely candidates for the type of mine reclamation that was implemented in Bark Camp. The number of sites within each state varies. All potential reclamation sites are geocoded for future investigations of this project's feasibility.

Bark Camp Project

Currently, efforts are being made nationally to reclaim abandoned mine lands and to mitigate their associated affects. Not only are millions of acres of land useless moonscapes, but their associated hazards, notably acid mine drainage, affect thousands of miles of waterways. Acid mine drainage is the single largest source of water contamination in every Appalachian coal mining state. In many instances only the symptoms can be treated, for instance, by channeling acid-impacted streams through limestone drains while the long-term causes go unabated. Such acid-generating mining waste is expected to continue unabated for 800–3000 years. This is why the method examined—sealing the mining waste of geological materials causing acid mine drainage with an impermeable fill material, while restoring megavoids—holds great potential. The main high wall has been restored to its original contours, covered with a manufactured soil, and planted. Monitoring of groundwater and monitoring wells indicate that the area water supply is improving since the initiation of this project (PADEP 2002).

The Bark Camp Mine Reclamation Laboratory was opened in 1980 to test various methods of reclamation, including the treatment of acid impacted streams with artificial wetlands, and the use of fly ash grouts to backfill stripped high-walls. Coal fly-ash is the mineral remnant of coal combustion, often containing large amounts of lime added to reduce sulfuric acid emissions, and usually having pozzolonic or cementitious properties. Since coal combustion is responsible for

50% of US electricity generation, over 130,000,000 tons of fly ash is produced annually, posing a major disposal problem.

The Bark Camp project sought to combine the massive fill requirements of mine reclamation with another volume related issue; the removal of 500,000,000 tons of dredged materials from US navigation channels annually. The size of today's shipping fleets requires the creation of channels in excess of natural depths. Erosion, sedimentation, and tidal processes make maintenance dredging unavoidable. Much of this vast amount of material had previously been disposed of in the near-shore and marine environment, but increasing sentiment against such disposal methods due to traces of agricultural and industrial contaminants has instigated a drive for beneficial upland uses. Upland placement of dredged mud consolidated with pozzolonic materials does not pose the problem of direct ingestion by mud-dwelling organisms, and this was the hypothesis tested at Bark Camp.

The Bark Camp Mine Reclamation project has been deemed extremely successful. The final report detailing this project is scheduled to be released in 2003.

Data Collection and Sources

Abandoned Coal Mines

Locations of the abandoned coal mines can be obtained from the US Geological Survey (USGS) at *http://nationalatlas.gov/atlasftp.html* (last time accessed January 2003). It is distributed by US Office of Surface Mining, Reclamation and Enforcement. This data set identifies those mines that pose problems to public health, safety, and welfare at the national level on a 1:2,000,000 base map. Total number of sites is 22,143, geographic coordinates for this data set are in decimal degrees (NAD83, GRS1980) and the dataset is available in vector format for free download.

Dredge Sites

Locations of the dredge sites can be obtained from the US Army Corps of Engineers (USACE). This data set represents the locations of executed dredging projects between the years 1994 and 1999 (US Army Corps of Engineers 2001). There is very little metadata associated with this data set. This point data set is in vector format. This information is available at *http://www.wrsc.usace.army.mil/ndc/drgmatdisp.htm* (US Army Corps of Engineers 2001).

Fly Ash

Fly ash is a by-product of coal-burning power plants. Locations of electrical producing power plants can be obtained from the Department of Energy (DOE). The information from the "2000 Annual Electric Utility Report" includes the utilities' name, address, energy source, and zip codes of all electricity-producing facilities in the United States. This information is available at both of the following websites, *http://www.eia.doe.gov/cneaf/electricity/page/eia861a.html* and *http://www.eia.doe.gov/cneaf/electricity/page/eia861.html* (US Department of Energy 2003). This data set is incomplete and has to be modified by independently verifying address information of selected power plants. Because of the absence of spatial information such as latitude and longitude, the power plant facilities were geographically coded by their zip codes. After conversion from PDF format to the text comma-delimited file, it was linked then to the zip code GIS data obtained from the Environmental Systems Research Institute (ESRI) data set distributed with the software. Therefore zip code polygons contain at least one electric producing facility. Apparently, security restrictions do not allow for a resolution finer than the zip code level for the representation of power plant sites.

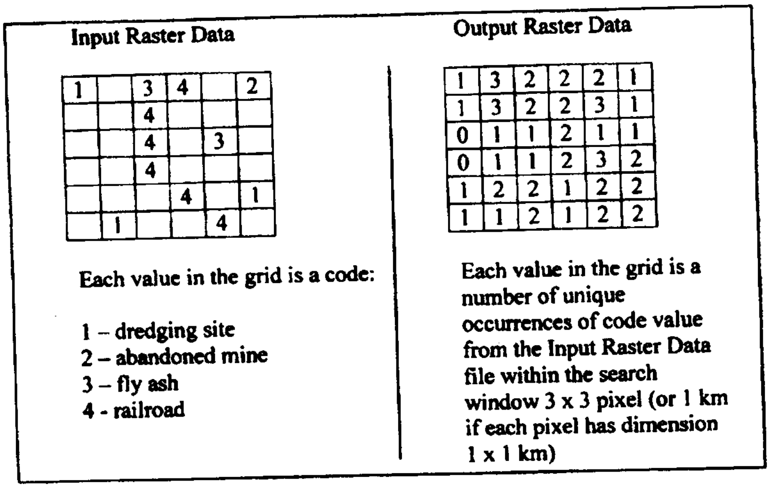
Rail Roads

Locations of railways can be obtained from the USGS website *http://nationalatlas.gov/atlasftp.html* (US Geological Survey 2003). This data set represents the locations of railroad lines within the continental United States and Alaska in 1998 at the national level on a 1:2,000,000 base map. The geographic coordinates for this data set are in decimal degrees (NAD83, GRS1980) and dataset is available in vector format for free download.

Data Preparation For Analysis

There are two main technical issues associated with data preparation for further analysis: (1) vector-to-raster conversion, and (2) choice of spatial units and projection for selection of the pixel neighborhood for the focalvariety function.

Vector-to-raster conversion is a procedure that is accomplished by converting the spatial extent of the data into the gridded surface with a given pixel size. Pixel size selection depends on the computer power and available memory. Smaller pixel size creates large sizes for the grids and requires a considerable amount of processing time. Large pixel size makes files smaller, but resolution of the data becomes lower at the expense of the quicker data processing. After experimenting with grid pixel sizes, the size of 1 × 1 km was selected as most adequate for the speed and memory of the available computer (Pentium IV, 2 MHz processor, 1



Input Raster Data

1		3	4		2
		4			
		4		3	
		4			
			4		1
	1			4	

Each value in the grid is a code:

1 – dredging site
2 – abandoned mine
3 – fly ash
4 - railroad

Output Raster Data

1	3	2	2	2	1
1	3	2	2	3	1
0	1	1	2	1	1
0	1	1	2	3	2
1	2	2	1	2	2
1	1	2	1	2	2

Each value in the grid is a number of unique occurrences of code value from the Input Raster Data file within the search window 3 x 3 pixel (or 1 km if each pixel has dimension 1 x 1 km)

Figure 1. Explanation of the focalvariety analysis.

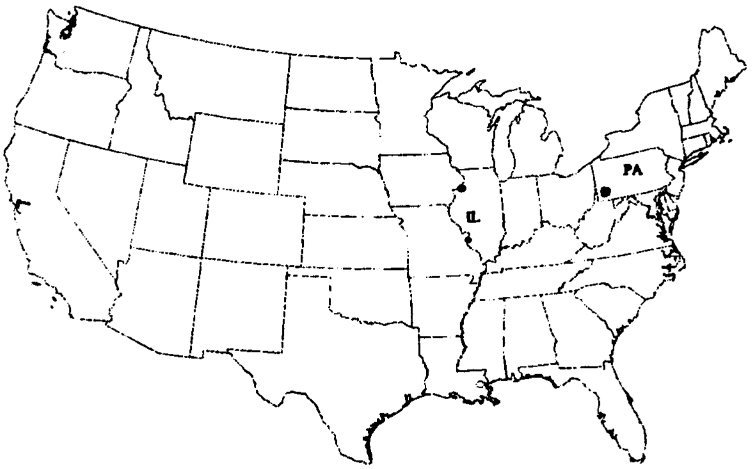


Figure 2. Abandoned mines that can be reclaimed using resources similar to Bark Camp available within the radius of 20 km in Pennsylvania (PA) and Illinois (IL).

Gb RAM). This pixel size places spatial resolution and accuracy of analytical results within 1 km. Results of analysis identify abandoned coal mines that satisfy conditions of the analysis. The geographical location and address for each mine is available from the associated attribute table. Therefore, this seemingly coarse resolution is not critical. If needed, mines can be located precisely according to its address information.

The focalvariety function requires setting of the search window or neighborhood for the analysis with an integer value greater than 1 (i.e., number of pixels). Original units for GIS data in this analysis are decimal degrees. In geographic conversion one degree is equal to 78.85 km (east–west arcs to distance at 45°N latitude); therefore, a 20-km search radius will be equal to 0.25 decimal degrees, and 100 km will be equal to 1.3. These numbers are less than 1 or not integers. To make the search radius in appropriate units, the original GIS data were reprojected into a geographic projection with units defined as meters. After data were reprojected, they were converted into grids with pixel size of 1 km, covering the total area of the contiguous United States.

Focalvariety Analysis

Focalvariety analysis is one of the techniques available in a raster GRID module of ArcInfo GIS software (ESRI, 1992a,b). As was mentioned before, this function exists also in other GIS software packages. Focal analysis is a technique used with raster data that defines a neighborhood or search window and then executes a standard statistical or other technique within the window. Figure 1 shows an example of the focalvariety function.

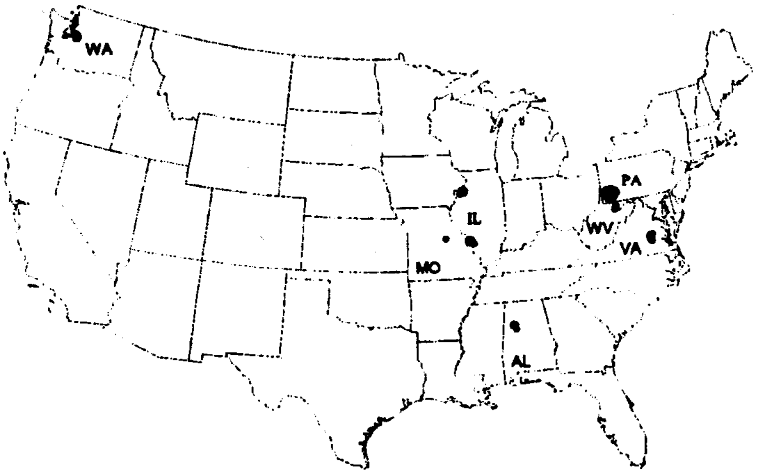


Figure 3. Abandoned mines that can be reclaimed using resources similar to Bark Camp available within the radius of 40 km in Pennsylvania (PA), Illinois (IL), Missouri (MO), West Virginia (WV), Virginia (VA), Alabama (AL), and Washington (WA).

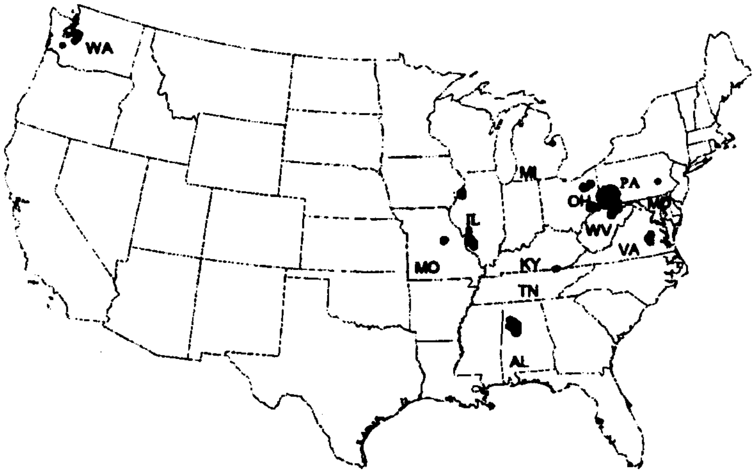


Figure 4. Abandoned mines that can be reclaimed using resources similar to Bark Camp available within the radius of 60 km in Pennsylvania (PA), Illinois (IL), Missouri (MO), West Virginia (WV), Virginia (VA), Alabama (AL), Washington (WA), Michigan (MI), Tennessee (TN), Kentucky (KY), and Ohio (OH).

Analysis with the focalvariety method produces grids with values corresponding to the number of various unique values found within the defined neighborhood. For the analysis we selected five different neighborhoods—20, 40, 60, 80, and 100 km. Upon completion of analysis, each neighborhood within which all four codes (corresponding to dredging sites, abandoned coal mines, fly ash and railroads) existed was mapped.

Results

Figures 2, 3, 4, 5, 6 show maps of the contiguous United States with locations of abandoned coal mines suitable for reclamation projects similar to one in Bark Camp.

Maps (Figures 2, 3, 4, 5, 6) and associated GIS databases display information about location of potential mines for reclamation. These locations have dredging sites, fly ash sources, and railroads within radii of 20–100 km. More comprehensive data on these mines and resources is available in GIS database and corresponding metadata (documentation) files.

Additional analysis should be done to narrow down the list of potential mines for reclamation to mines with geotechnical problems similar to that at Bark Camp. These problems are categorized in the National Association of Abandoned Mine Lands Programs (NAAMLP) database. The Bark Camp project was aimed toward reclamation of the dangerous embankment and highwall created by strip mining.

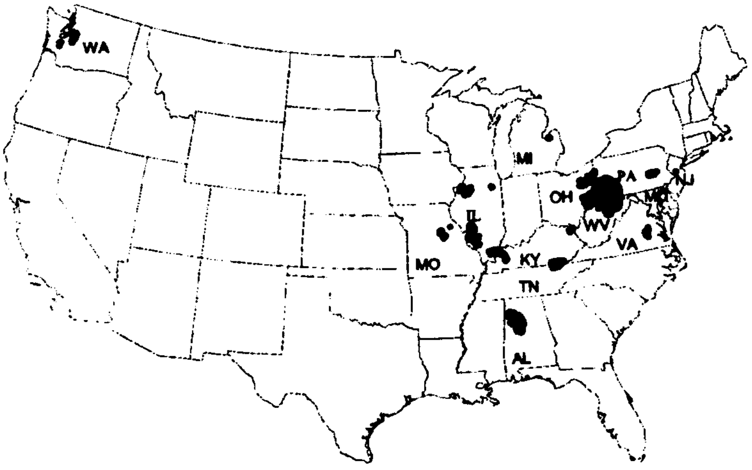


Figure 5. Abandoned mines that can be reclaimed using resources similar to Bark Camp available within the radius of 80 km in Pennsylvania (PA), Illinois (IL), Missouri (MO), West Virginia (WV), Virginia (VA), Alabama (AL), Washington (WA), Michigan (MI), Tennessee (TN), Kentucky (KY), Ohio (OH), New Jersey (NJ), and Maryland (MD).

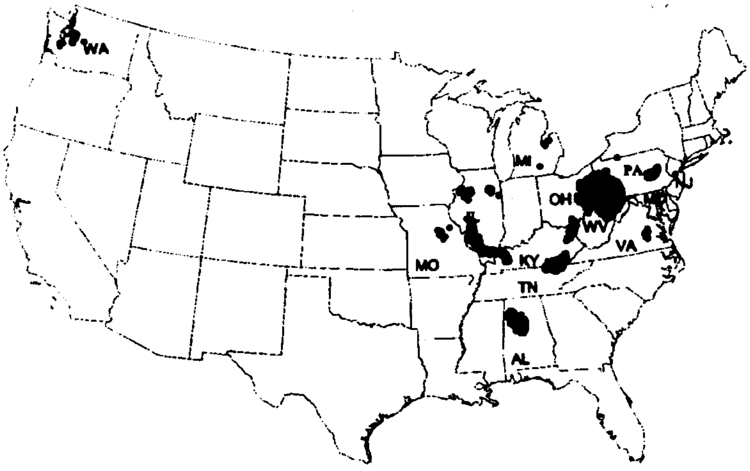


Figure 6. Abandoned mines that can be reclaimed using similar to Bark Camp resources available within the radius of 100 km in Pennsylvania (PA), Illinois (IL), Missouri (MO), West Virginia (WV), Virginia (VA), Alabama (AL), Washington (WA), Michigan (MI), Tennessee (TN), Kentucky (KY), Ohio (OH), New Jersey (NJ), and Maryland (MD).

Upon analysis of the 30 problem codes stored in the NAAMLP database, we found four codes that closely match the problem at the Bark Camp site. These are: "dangerous highwall," "dangerous impoundment," "dangerous slide," and "dangerous pile or embankment." These categories address problems of stability. Engineering remedies include major earth works in addition to installation of fencing and vegetative barriers (Natural Resources Conservation Service 1981). At Bark Camp the earthwork was done with dredged material amended with fly ash.

Additional selection of records from the database reduced the number of selected mines and generated a list of potential mine reclamation projects for mines similar to the Bark Camp geotechnical problem, displayed in Table 1.

Conclusions

- The number of potential reclamation projects for each state from Table 1 informs local state officials and managers of national programs about the number of potential projects for each state.
- The GIS database compiled during research can be used in future reclamation planning:

to identify the location and specific data about each abandoned coal mine in the state [according to NAAMLP (2003) database];expand analysis to include other conditions specified by state officials or land reclamation managers; andprovide web-based mapping and informational portal for the public awareness of