

Risk-Based Prioritisation of Closed Mine Waste Facilities Using GIS

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Abstract Recent EU legislation and relevant guidance documentation requires inventories of closed mine sites to be prepared and recommends a risk-based approach to the pre-screening of sites related to environmental and human health criteria. In this study, a geographical information system (GIS) was assembled to combine available data from five catchments in south west England, an area with a high density of abandoned metal mines. A series of risk factors was selected and risk classified according to their respective magnitude. Relative weightings for each risk factor were assigned within an analytical hierarchy procedure by applying expert knowledge and literature information. The model output provided a priority list for further investigation by the responsible statutory body. The GIS model is adaptable, in particular with respect to expert opinion and inclusion of additional risk factors and therefore showcases the application of ArcGIS software for processing readily obtainable data to produce rapid and flexible environmental risk assessments.

Key Words Mine waste, mining waste directive, risk assessment, GIS

Introduction

Directive 2006/21/EC on the Management of Waste from the Extractive Industries (Mining Waste Directive, MWD) requires all member states to produce an inventory of closed waste facilities by 01 May 2012. Furthermore, a pre-screening methodology has to be developed that identifies sites that pose a risk to human health or have the potential to cause negative environmental impacts (Stanley *et al.* 2010), whereby guidance documentation recommends the use of available data and a GIS system.

In England and Wales, the Environment Agency (EA) is responsible for the management of pollution resulting from historical metal mining. However, the spatial resolution of the EA's regular monitoring programme of watercourses is insufficient for the identification of individual pollution sources, which are often diffuse in nature and can be highly elevated in dissolved metals and metalloids compared to water quality standards. European member states are legally bound to meet such standards as part of European Water Framework Directive 2000/60/EC (WFD). This paper describes the design of a GIS based tool used to prioritize mine waste tips as potential pollutant sources in five river catchments of south west England. The work incorporates data on the location of abandoned mine sites collated by the EA into a GIS in a model that is based on three key attributes of mine waste tips. The methodology serves as a systematic and rapid screening tool. but it does not consider the concentrations of toxic metals and metalloids in the waste, since such information is only obtainable after site specific intrusive investigations.

Methods

The scope of the study was defined by the requirements of the EA and included the five management catchments shown in Figure 1. The input parameters of interest to this model were proximity of each waste tip to the nearest watercourse or body, the area occupied by the waste tip and the slope of the drainage pathway. The latter was defined for each waste tip from digital terrain model DTM (5 m resolution) using ArcHydro (Version 1.4) software. All other operations and output maps were created using ArcGIS (Version 9.3) in conjunction with XTools (Version 7.1).

Determination of Area and Proximity

Digitized hydrological information comprising catchment boundaries, a detailed river network (DRN), lakes and estuary outlines were provided by the EA. Catchment boundaries were extended by 50 m using the buffer tool, to prevent mine waste tips close to catchment boundaries being split between catchments. A database of mine features was provided by the EA as a polyline feature class, with unique identification (ID) codes. Poly-lines relating to areas of mine waste were selected using the select by attributes tool and saved to a new file. The new data set was divided into the five management catchments, shown in Figure 1, using the clip tool.

For each catchment, polyline features were converted to polygons using the convert polylines to single polygon tool (XTools). Polygons were sorted based on ID code and duplicate codes merged to construct individual polygons for each mine waste tip. The mine polygon files were inspected for errors caused by the conversion process, such

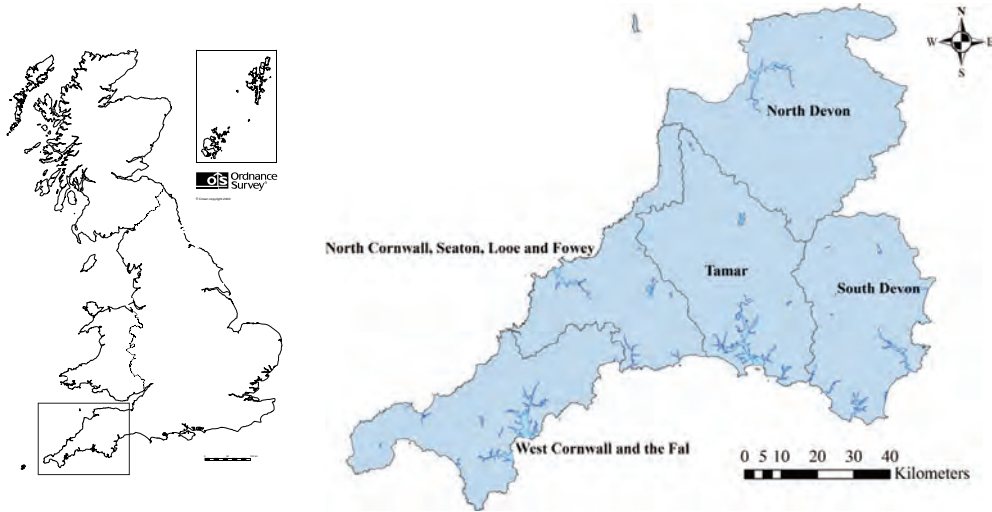


Figure 1 Map showing the five management catchments subject to the model. Created in ArcMap, data supplied by the Environment Agency and used under license.

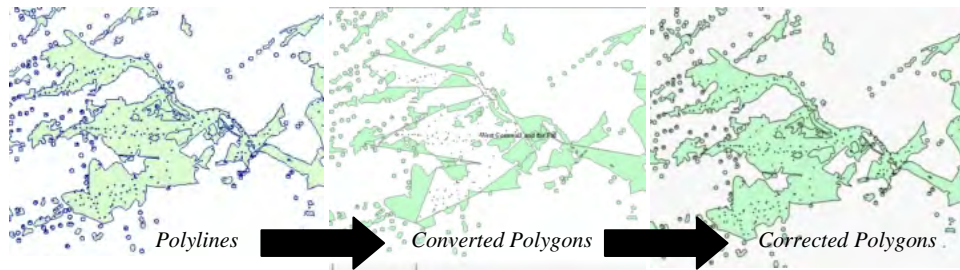


Figure 2 Self intersection errors shown in polygon file (centre), caused by conversion process of polyline features (left) to polygon features. Corrected polygon features shown on right.

as self intersections, and corrected as shown in Figure 2.

An additional field was added to the attribute table of each mine waste polygon file and was populated with the area of each polygon using the calculate geometry tool. Small areas of 1963 m^2 (for example the 25 m^2 default areas assigned to mine shafts by the EA in the original database) were re-

moved, leaving 1894 areas of waste. The remaining areas were statistically divided into six categories and assigned a risk score from 6 (largest), to 1 (smallest) (Table 1), which were, for each catchment, added to the attribute table in a new field.

The DRN polyline file provided accurate locations of rivers and streams, which were isolated for each management catchment by using the clip

Weighting	Nominal Risk Classification	Upper Threshold Areas (m^2)					Combined
		SD	ND	Tamar	NC	WC	
6	Extreme	93185	16968	36781	176795	2510815	2510815
5	Very High	12601	10997	18048	12016	16920	15862
4	High	7266	5460	7534	6283	7778	7528
3	Moderate	5936	4571	4818	4356	5044	4951
2	Moderate -Low	3925	3519	3653	3519	3790	3747
1	Low	2986	3285	2778	2756	3019	2946
Number of waste tips > 1963 m^2		130	23	309	184	1248	1894 (Total)

Table 1 Table showing the upper threshold for area of mine waste in each risk category for each of the five catchments subject to model: South Devon (SD), North Devon (ND) Tamar, North Cornwall (NC) and West Corn (WC). Also show, are upper thresholds if data for all catchments is combined and classified (rightmost column).

Table 2 Distance to nearest watercourse (stream/lake/estuary) and number of waste tips in each category for South Devon (SD), North Devon (ND) Tamar, North Cornwall (NC) and West Cornwall (WC).

Distance to Stream/River/Estuary	Risk Score	Risk Classification	Number of Waste Tips					
			SD	ND	TM	NC	WC	Combined
Direct contact (2 m buffer)	6	Extreme	31	8	89	38	173	339
2 - 50 m	5	Very High	27	5	59	23	133	247
50 - 100 m	4	High	30	2	43	26	107	208
100 - 250 m	3	Moderate	27	4	61	43	292	427
250- 500 m	2	Moderate - Low	1	4	48	43	311	407
> 500 m	1	Low	14	0	9	11	232	266
			1894 (Total)					

tool in conjunction with the catchment polygons (Figure 1). Estuarine areas were defined by modifying catchment polygons to include the estuaries of each river. The Union tool was used to create estuary polygons from the overlapping regions between the modified and original catchment polygons (Figure 3). A polygon file containing known lakes was provided ready to use by the EA. The proximity of each mine waste tip to the nearest watercourse (lake polygon, estuary polygon or river polyline) was determined using the select by location tool. Buffer distances and risk scores were assigned as defined in Table 2.

Determination of Drainage Pathways and Topographical Slope

The EA supplied catchment DTMs as individual raster tiles cataloged by UK Ordnance Survey grid squares. The tiles were combined into a single raster using the Mosaic tool in ArcCatalogue. Individual catchment DTMs were created using the mask tool and the management catchment polygons (buffered to 50 m). To determine surface water flow through the catchments, the DTMs were used to produce a series of hydrogrids in ArcHydro, using the Terrain Preprocessing (TP) tools in accordance with guidance documentation (Djorkic, 2008) as shown in Figure 3. The ArcHydro Watershed Processing toolbar was used to determine the catchment area of a given polygon (e.g. each mine waste tip). The application of the same tool to an inverted DTM allowed drainage areas to be determined (Figure 4).

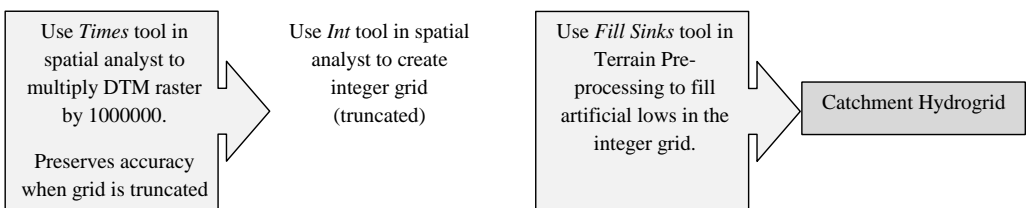


Figure 3 Pre-processing steps required to produce a hydrogrid from a catchment DTM.

The slope (in degrees) for each of the drainage polygons was calculated using the slope tool in ArcHydro. Then steps shown in Figure 5 were followed resulting in the dissolved slope polygon file, indexed and joined to the drainage polygon file by utilizing their common HydroID field in the attribute table. The slope dataset was statistically divided into 6 equal groups, each of which was assigned a risk code (1–6).

Weighting of Input Parameters and Final Combination into Model

The weighting for each of the input parameters was determined using a pairwise comparison matrix first described by Saaty (1980) (Table 3). The matrix scores the relative importance of each input with respect to the other two. A score of one represents equal importance; a maximum score of 9 indicates much greater importance. The reciprocal score is awarded to the partner input for each comparison.

The weight of each layer (w) was calculated by dividing the sum of the row, M_i by the denominator of the matrix (Wang *et al.*, 2010):

$$w = M_i / \sum_{i=1}^n M_i$$

The resulting weightings were multiplied by 100 to avoid the use of decimals, which is favorable in ArcGIS. The weightings were added to the mine waste attribute table as new fields. The total

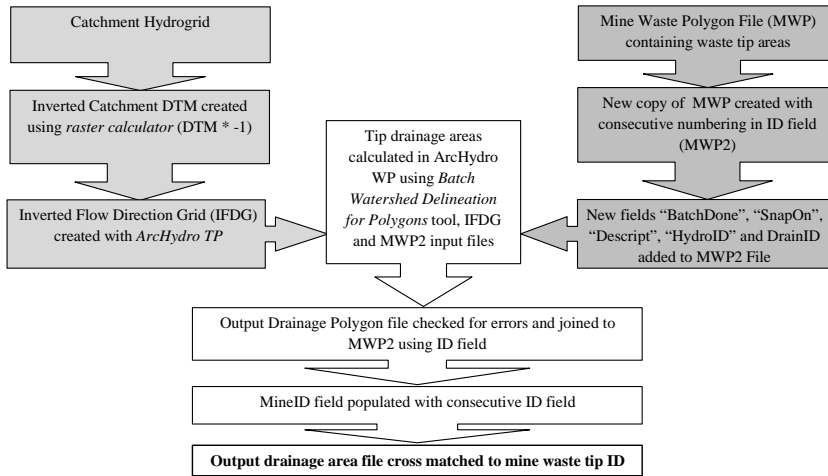


Figure 4 Processes used to: invert the catchment hydrogrid (light grey boxes), sort and prepare mine waste polygon file (dark grey boxes), index drainage polygons to mine waste areas (white boxes). TP = Terrain Preprocessing and WP = Watershed Processing menus in ArcHydro.

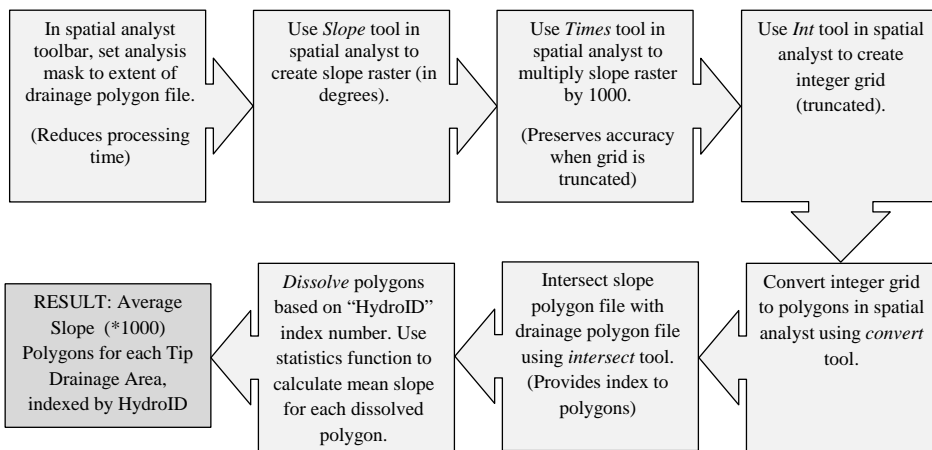


Figure 5 Process steps to produce average slope value (degrees x 1000), for each mine waste drainage polygon. The final slope field may be divided by 1000 to give result in degrees, if required.

Table 3 Pairwise comparison matrix used to calculate input weightings for proximity, area and slope.

	Proximity to Water Body	Area of Waste	Slope of Drainage Pathway	Sum of row	
Proximity to Watercourse	1	2	2	5	
Area of Waste	1/2	1	2	3.5	
Slope of Drainage Pathway	1/2	1/2	1	2	
Sum of Column	2	3.5	5	10.5	Denominator of matrix
Weighting	0.48	0.33	0.19	1.0	Sum of weightings

risk for each mine waste polygon was calculated from:

$$\text{Combined Risk} = \sum w_i \cdot R_i$$

Where *w* is the weighting of each layer and *R* the risk score (1–6). The final total risk field may be sorted to give a prioritisation list for the catchment; a ranking may be added as a new field. The simplest way to populate this field is to export the layer to excel and add the priority number, then import back into ArcMap. The final attribute table for one of the catchments (North Devon) is shown in Figure 6.

Results and Discussion

The attributes of the nearest mine record (EA database of mine names, locations and available data) were joined by location to the results of the prioritisation exercise for each mine tip (Figure 8). The five waste tip/mine site combinations bearing the highest total risk for each of the five catchments are summarized in Table 4 and serve as an example of the output of such a prioritisation exercise, which may be subsequently explored further as site investigations.

Uncertainty in any GIS model similar to that presented here can arise from three areas, namely: errors in the input data sets, errors in the processing steps within the model, and incorrect assumptions made when designating the risk scores to attributes of an input. The first two may be minor if good quality data can be sourced and are processed by a knowledgeable GIS user. However it must be stressed that the time taken to construct the model is highly dependent on the quality of the input data and the amount of pre-processing required to remove errors. Expert judgement may be tested by testing the model’s sensitivity to differences in relevant parameters, classifications and weightings.

This model considered three physical properties of the mine waste tips only. However a more complex model has been developed and run for the Tamar catchment (paper in preparation). This model followed the same principles outlined here but was extended to include additional input parameters, namely: bedrock geology, superficial geology, annual rainfall, rainfall intensity, vegetation cover and wind exposure. This flexibility, together with the power of GIS to consolidate many sources of information in an easy to access form

Table 4 Results of prioritisation exercise showing nearest mine name to tips scored with highest total risk in each catchment. Likely contaminants identified in EA database shown in parenthesis.

Priority	South Devon	North Devon	Tamar	North Cornwall	West Cornwall
1	Waterhill (Sn)	Fullbrook (Mn, Fe)	Harewood (Cu, As, Fe)	Esther (Sn)	Blue Hills (As, Cu, Fe)
2	Waterhill (Sn)	Ivy Tor (Cu, As, Fe, Bi, Ag)	Betsy (Pb, Ag, Zn, Cd, Fe)	West Caradon (Cu, As, Fe)	Friendly (Pb, Fe, Cu)
3	Hexworthy (Sn)	Bampfylde (Cu, Fe, Ag)	South Devon (Cu)	Penhale (Fe, Cu, Pb, Sb)	Ellen (Cu, Pb, Zn, Ag, Cd?)
4	Crownley Parks (Cu, Ag)	Steeperton (Sn)	Harewood (Cu, As, Fe)	Credis (Cu, Fe)	Carclaze (Zn, Pb, Cd?)
5	Great Eleanor (Sn)	Ramsley (Cu, As, Pb, Fe)	Hawkmoor (Cu, Fe, As)	Trehane (As, Pb, Ag, Cu, Fe, Cd?)	Geevor (Cu, Pb, Zn, As, Sb, Co, Mo, Fe, Ag, Hg, Bi, U, Rn?)

FID	Shape	Id	Area	Area_Risk	Prox_Risk	HydroID	Mean_Slope	Slope_Risk	Area_W	Prox_W	Slope_W	Total_Risk	Priority_N
79	Polygon	157	16152	6	6	80	16	6	33	48	19	600	1
80	Polygon	159	16001	6	6	81	11	5	33	48	19	581	2
28	Polygon	46	12723	6	6	29	9	4	33	48	19	562	3
62	Polygon	129	93185	6	6	63	10	4	33	48	19	562	4
65	Polygon	134	32047	6	6	66	9	4	33	48	19	562	5

Figure 6 Final attribute table for catchment prioritisation. Key to fields: Area = area of waste in m²; (Area/Prox/Slope)_Risk = risk score 1–6, (Area/Prox/Slope)_W = weighting attributed to each layer, Mean_Slope = average slope for drainage area in degrees x 1000; Total_Risk = result of Equation 2 for each object, Priority_N = priority number based on total risk score (and area when tied).

are the main advantages of the GIS models presented here. This preliminary exercise not only directs regulators to sites of potential harm, but may be used to aid the design of site investigations. For example, the modeling of tip drainage pathways can assist in the accurate placing of boreholes and stream samplers to capture drainage waters.

Conclusions

The work presented here represents a principle rather than an absolute approach. The judgments made are flexible and any number of input parameters may be addressed depending on available data and the requirements of the user. The methodology presented here has already played a role delivering the EA's obligations under the WFD

and, with some minor modifications, can meet the requirements of Article 20 of the MWD for pre-selection of potentially harmful abandoned mine sites.

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