A GIS-based Landfill Site Suitability Model for Monongalia County, WV

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Introduction

Municipal solid waste remains a primary concern. Landfilling is the last critical step of waste management process which compresses waste yield into minute volumes and covers it with a soil layer (Sumathi et al., 2008). Landfill site selection is governed by several multidisciplinary parameters. It should minimize environmental, economic, health and social costs under governmental regulations. It should consider geologic, hydrological, and present natural land use of the target area. Economic factors include cost of site construction, operation, management, maintenance, and the traveling cost for waste to be transported to the site (Wu et al., 2011). It should not lead to negative impacts on residential surroundings. The NIMBY (not in my back yard) phenomenon has become an important factor to be considered in the siting process (Kao & Lin, 1996).

Manually handling such huge amounts of information is challenging. Geographic information systems (GIS) is a powerful tool to automate the analysis process, allowing for the integration of multiple criteria and multiple data sources in a predictive model that simulates various scenarios and temporal analysis of trends (Berry, 1995; Wu et al., 2011). Advantages of using a GIS in siting landfills include, but not limited to, map display, automated and fast screening process, performing "what if" analysis for different scenarios where criteria change, route planning for transporting the waste, long-term monitoring of the site (Kao & Lin, 1996; Sumathi et al., 2008). As satellite landcover products with fine resolution become widely available and integrated into GIS, spatial impact of each potential site can be assessed at a fine scale in a timely manner (Krometis et al., 2017).

As a major tool for supporting landfill site decision making, multiple criteria decision analysis (MCDA) has been integrated with GIS, enabling decision makers' preference of manipulating each spatial/aspatial criteria. Consider a GIS-based MCDA model as a hierarchical problem-solving process. As the siting question is broken down into many sub-questions, the GIS model is broken down into corresponding modular components. Each sub-question/component is analyzed independently. The sub-questions at the same level of the hierarchy are overlaid to answer the next-level question, until the ultimate question is solved. In solving each-level question, different map algebra operations/functions are applied based on decision makers' requirements (Demers, 2002).

A critical issue in MCDA is selecting contributing criteria and the establishment of relative weights of the criteria. Analytical Hierarchy Process (AHP) is a common MCDA framework integrated into the GIS for determining and ranking the relative priority for each criterion/sub-criterion in the decision hierarchy. It combines multiple ideas from a group of people to a consolidated outcome that all participants agree to be plausible. It also uses the pairwise comparison matrix for assessing the weights of criteria and calculates a consistency ratio index to uncover the subjectivity in the weighting. Bunruamkaew & Murayam (2011) used AHP to calculate the relative importance of the contributing factors and classes in their ecotourism site suitability model. However, AHP does not eliminate subjectivity from the human dimension in selecting the criteria and deciding their importance along the 9-point scale.

In this study we created a raster-based GIS MCDA model for identifying the most suitable landfill site in Monongalia County that generates the lowest traveling cost to Morgantown. This is of great practical importance for Monongalia county since no landfill is present in this area but a solid waste transfer station that transfers trash to landfills in other countries such as Ohio or in Harrison (Monongalia County Solid Waste Authority, 2016). The criteria included landcover, distance to waterbody, minimum area of the site, slope and road. We first identified all candidate sites based on limiting the distance to waterways, landcover types and the minimum area of the site. We performed the cost distance analysis with slope and road as the input to estimate the traveling cost of all candidate sites and identified the site with the lowest cost as the optimal site. We ran the model twice for comparison with modified parameters (transportation input, classification schemes for distance to waterbody, and classification schemes for slope steepness). This can be related to the concept of dynamic simulation that allows the model parameters to be changed systematically and tracks the results to find the importance of each variable (Berry, 1995).

Study Area and Datasets

Monongalia county sits in North-Eastern West Virginia with its county seat at Morgantown (Figure 1). As of census of 2010, it covers 360.06 square miles and has a population of 267.1 per square mile (U.S. Census Bureau, 2020). There are many hydrological features including Monongahela River, Cheat Lake and Decker's Creek. Surface water from the Monongahela River supplies 82.4% of Morgantown's drinking water. Close proximity of any landfill to the river can result in elevated toxicity of surface water thus threatens human health (Samadder et al., 2017). Topography is also challenging with steep slope throughout the county, which constrains development and should be considered in siting a landfill. Flood hazard is another threat in the area thus a big obstacle for development (Curtis, 2012).

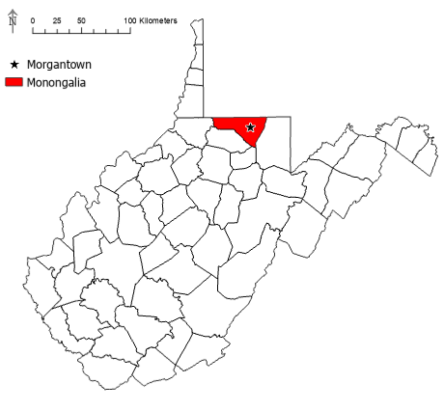


Figure 1. Location map of the study area (Data source: ArcGIS Hub. (2020))

All datasets were downloaded from West Virginia GIS Technical Center:

1) 2000 United States Geological Survey (USGS) Digital Line Graph (DLG) hydrographic data;

2) 1992 30m Landsat-derived landcover raster with 25 landcover codes;

3) 1999 30m-resolution National Elevation Dataset;

4) 1999 USGS DGL transportation data. Primary road and ramp were grouped as "interstate", secondary road and highway as "highway", street as "street" and alley as "no road".

5) 2011 Tiger/line roads data.

Methods

The entire process (Figure 2) was performed in ArcGIS Pro. We preprocessed the 2011 road data to align with the first model, keeping the same road and converted them to a raster layer with the extent masked to Monongalia County boundary. Same road reclassification scheme as the 1999 input was applied.

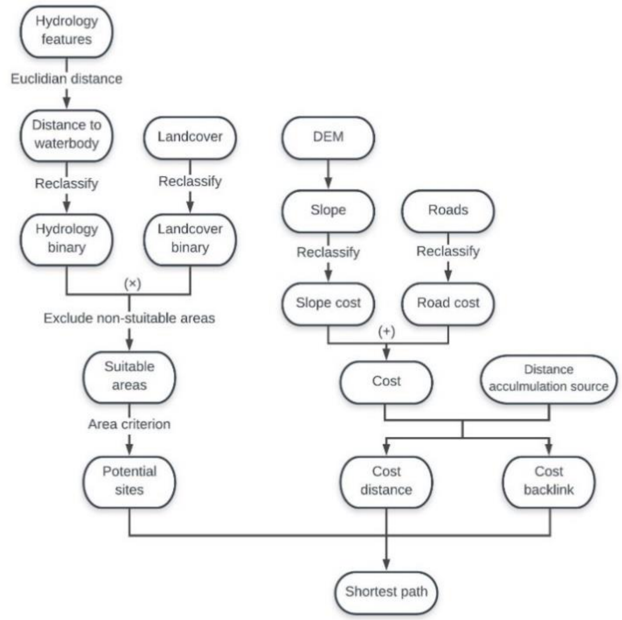


Figure 2. Suitability model to for locating a landfill using MCDA. Candidate sites are identified based on the minimum distance to waterbodies, landcover types and site area. The nearest site to the source location (Morgantown) and the shortest route are found based on traveling cost. Traveling cost is estimated based on slope steepness, road type and distance to the source location.

The modeling process comprises three major tasks:

1. To identify candidate sites for locating a landfill. We reclassified each of landcover and hydrology layer into a binary layer. Pasture, grassland, and reclaimed mine were re-coded as "1" as plausible landcover while others were re-coded as "0". Distance to waterways smaller than 500m were re-coded as "0". We multiplied both binary maps to rule out the non-suitable areas. We also set the minimum size of the landfill site to be 0.04 km^2.
2. To calculate cost distance based on slope cost and road cost. We measured the traveling cost from Morgantown to all the candidate sites by considering slope steepness, road type, and distance. We calculated the slope from the DEM and reclassified the values based on table 1 to estimate slope cost. Cost also varies with road types. Thus, we reclassified roads based on table 2 and estimated the cost of the different road types. We mathematically added both cost maps to estimate the total traveling cost, based on which the cost distance was calculated.
3. To determine the optimal site. We tested all traveling scenarios for each potential site and

identified the optimal site with the least traveling cost and its shortest path to Morgantown.

Table 1. Reclassification scheme for slope. Steeper slopes will have higher traveling cost. Slopes above 15% rise are 1000 time more difficult than slope between 0-5% rise.

Slope (%)	0-5	5-10	10-15	>15
Reclass	1	10	100	1000

Table 2. Reclassification scheme for road type. Highway is 5 times more difficult than interstate. Street is 10 times more difficult than interstate. No road class is weighted 15 times more difficult than interstate.

Road type	Reclass value
Interstate	1
Highway	5
Street	10
No road	15

In the second model version, below modifications were made:

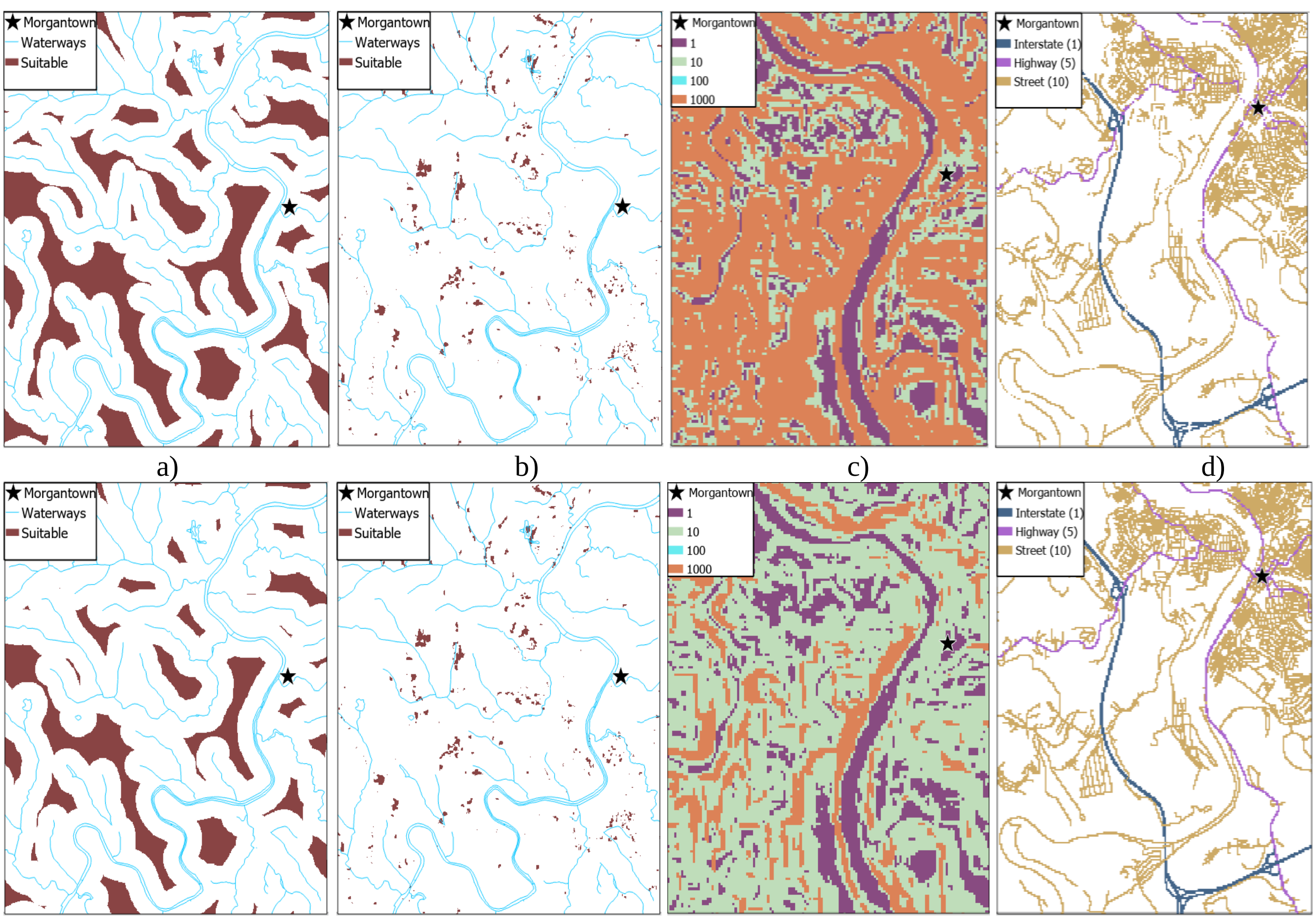
1. We increased the minimum distance to waterways from 500m to 600m, because pathogenic bacteria can travel up to 600m (Ya, et al., 2019).
2. We updated the slope reclassification scheme (table 3) based on the slope gradient established by United States Department of Agriculture (2005). We also replaced the 1999 transportation data with 2011 data. The same reclassification scheme was adopted for both.

Table 3. Updated reclassification scheme for slope

Slope (%)	0-6	6-25	25-40	>40
Reclass	1	10	100	1000

Results

Figure 3 shows all criteria maps of model 1 and model 2. Landcover maps are the same for both models. Figure 4 shows the results of cost distance analysis.



a) b) c) d)

e) f) g) h)

Figure 3. Criteria maps of model 1 (upper) and model 2 (lower): **a)** Hydrology binary map of model 1 showing suitable areas keeping a minimum distance of 500m from waterways; **b)** Landcover binary map of model 1; **c)** Slope cost map of model 1 showing relative cost of slope from 0-5% (1), 5-10% (10), 10-15% (100), and above 15 (1000); **d)** Road cost map of model 1 showing relative cost weightings of traveling on interstate (1), highway (5) and street (10); **e)** Hydrology binary map of model 2 showing suitable areas keeping a minimum distance of 600m from waterways; **f)** Landcover binary map of model 2; **g)** Slope cost map of model 2 showing relative cost weightings of slope from 0-6% (1), 6-25% (10), 25-40% (100), and above 40 (1000); **h)** Road cost map of model 2 showing relative cost weightings of traveling on interstate (1), highway (5) and street (10).

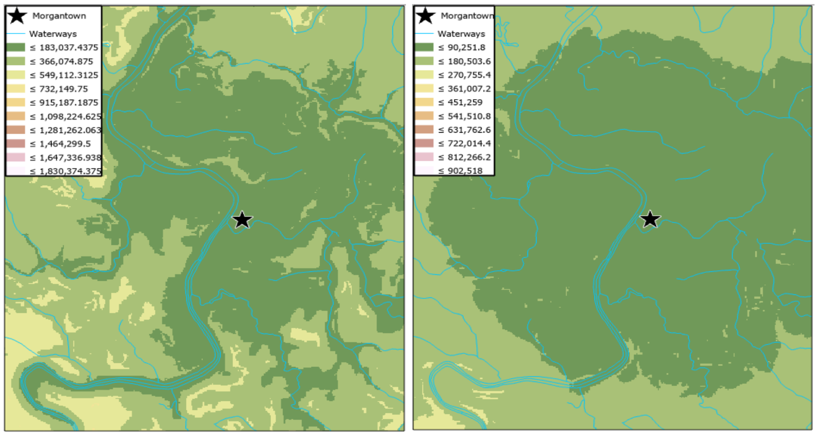


Figure 4. Cost distance maps of model 1 (left) and model 2 (right).

Figure 5 (left) shows the 5 candidate sites generated by model 1. All candidate sites were located west to Morgantown and I-79 and were along Fairmont Road. I-79 is the dark blue interstate line in figure 6, and Fairmont Road as the purple highway line that crosses I-79. Three sites were south to Fairmont Road and the other north to it. Compared with OpenStreetMap, the one to the north of Fairmont Road is located close to Mylan Park in Cassville, WV, while the other three close to Monongahela River in the Little Indian Creek Wildlife Management Area. The cost distance analysis identified the site north to Fairmont Road in Cassville to be the optimal that generates the lowest cost and calculated the most cost-efficient route to Morgantown. Traveling time is about 20 minutes. Model 2 only generated two candidate sites (figure 5 right). Both locate south to Fairmont Road and in the Little Indian Creek Wildlife Management Area. The cost distance analysis found the site located near Glory Barn Road and Wiseman Road to be the optimal site with traveling time about 15 min to Morgantown.

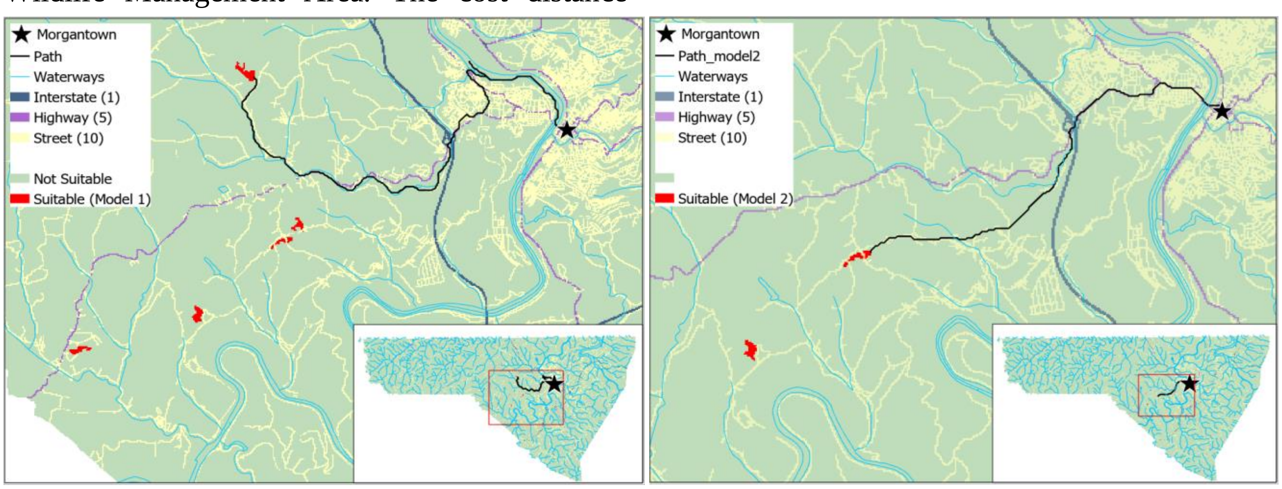


Figure 5. Model 1 result (left) and model 2 result (right). 5 candidate sites were generated by the model 1 at a minimum of 500m from waterways, and sit in pasture, grassland, or reclaimed mine. 2 sites were generated by model 2 at a minimum of 600m from the required landcover. The optimal site and the route to Morgantown are identified based on the cost distance analysis.

Discussion

As we further narrowed down the criteria in model 2, we noticed a shrinkage of the resulting suitable area compared with model 1 (Figure 6).

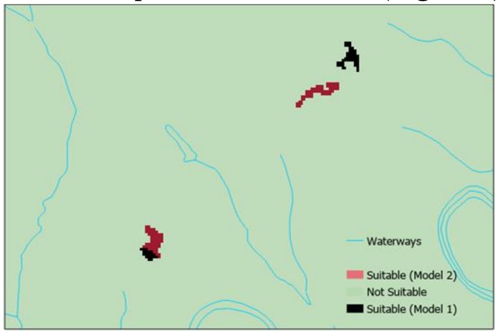


Figure 6. Map showing the two suitable sites identified by model 2 and three of the suitable sites identified by model 1. One of the resulting sites is completely identical. Another site of the model 2 appears to be a subset of a site of model 1.

Based on figure 3 c) and g), we noticed an overall higher slope cost in model 1 result. Slopes above 15% rise (1000× weighted) were the dominant class in the original slope cost map. In model 2, slopes between 6%-40% (10× weighted) were the dominant class. Areas with the lowest slope cost (purple) also shrink slightly from model 1 to model 2. From Figure 3 a) and e) we noticed a decrease of suitable areas from model 1 to 2. We can also see there has been no significant change in the road features though the feature lines have become fuller in the 2011 dataset (Figure 3 b) and f)). In general, we found a much lower cost in the second model version (Figure 4).

We noticed the established paths not follow actual roads, and there is a divergence in the path calculated by model 1. Timeliness of the input data can contribute to this issue. We suggest using more recent datasets, and the publishing year of each dataset should be as close as possible to avoid possible misalignment. Also, entities with size smaller than the raster cell size (30*30m) could not be adequately represented. This is particularly true when it comes to linear features, resulting in difficulty of establishing network linkage. We also suggest changing of weights or thresholds systematically to find the most plausible route. For example, the area of 0.0405 km^2 can be a source of uncertainty, as a typical landfill site takes up 2.4281 km^2 on average (Corbley, 2011). We should also consider the relative importance of each criteria in addition to the class. However, criteria thresholds and weightings are always sources of uncertainty in MCDA - what criteria/class should be prioritized? What criteria/class should be removed? How should the importance of the criteria/class be ranked? The decision on this should be based on expertise of all related fields and consensus of all participants in the analysis process. We suggest using AHP to account for this.

This is a simplified example of GIS-based MCDA modeling. Many other related important factors were not considered. According to Environmental Protection Agency (EPA), the site must be far away from the flood zone especially with a hundred-year return period. Based on the view of WV Property Assessment (WV Assessment), the candidate sites we found in this study do not sit in the floodplain, however they are close to two flood zones. Likewise, the site should be away from any unstable areas including displacement of rocks, faults or karst, etc. 60 m is specified by EPA as the minimum distance from any earthquake prone areas. Distance to roads, to tourism areas, and to protected land are also important modeling parameters. Another concern is the land ownership. No private/protected land should be considered. This is easily implemented as we rule out the unwanted areas using Parcels and Land Ownership Dataset that is available from USGS Protected Areas Dataset. For this study, we manually checked on the parcels where the optimal sites are located. Half of the optimal site generated by the model 1 sits on an active residential farm thus should be avoided. Another half is on vacant land. However, it can be argued that it is close to the residential land. The optimal site generated by the model 2 is located at a vacant land thus might be considered more plausible. Ya et al. (2019) suggested a minimum of 400m as a conservative distance to residential, while it should go up to 800m if the landfill does not contain heavy metal. We also suggest incorporating geomorphological factors. Cover material/texture varies for different landcover types thus impacts the suitability for siting a landfill.

Conclusions

The study of siting a landfill is multidisciplinary and complex, requiring expertise from a variety of disciplines. The application of the GIS model, like all mathematical models, is limited in predicting all scenarios due to its reductionism. Relating to the state factor model proposed by Amundson and Jenny (1997), the landfill can be considered as the only state factor that will have impacts on the whole ecosystem. The ecosystem here is the multitude of criteria constraining landfill site selection. We want to find out on what condition the landfill has the minimum effect on the ecosystem. The selection of the constraint criteria, the use of map algebra, and the weights assigned to criteria and class, etc. are all sources of bias. Yet “all models are wrong, but some are useful” (Box et al., 1978). To be ideal, a mathematical model may be a comprehensive representation of the reality; but to be clinically “useful”, it should just improve our understanding of the cause effect or the relationship of the factors that we are interested in.

In this study we created a “useful” suitability model for identifying the optimal landfill site Monongalia County that generates the lowest cost traveling to Morgantown. We concluded that the best site is located near Glory Barn Road and Wiseman Road with traveling time about 15 min to Morgantown. Compared the both model versions, we found changing the minimum distance to waterbodies impacts our analysis result most. Thus, we concluded that hydrology distance is the most sensitive variable among all the variable inputs in this model.

This study provides decision makers with a raster-based GIS framework to siting a landfill by combining multiple criteria using basic map algebra operations. The roles of GIS and map algebra in supporting landfill site selection are explained, criteria for the process are reviewed, a case study in Monongalia County is included, limitations are discussed, and future work is suggested.

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