Site selection using multi attribute decision analysis in GIS - A case study on brownfields of Minnesota

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Abstract

Minnesota is the seventh largest agricultural exporting state in the U.S. For Class I railroads grain and grain related food products accounted for 7.9% of carloads, 11.3% of tons hauled and 12.2% of revenues. Much of the grain exported, has to travel long distances (more than 1,000 miles) to reach U.S. ports. These increasing volumes of grain are being shipped in containers because Containers offer opportunities to lower logistics costs and to broaden marketing options. Consequently, exporters are put at a competitive disadvantage when they are unable to obtain containers at a reasonable cost for their exports and new market entrants experienced threat to their new markets. This situation has increased the desire with inland, small market shippers for more and closer container terminals for shorter truck hauls and increased access to empty containers.

The objective of this research is to prepare a comprehensive database of Brownfield sites and find the optimal locations amongst them in order to establish new container depots in the state of Minnesota. Geographic Information Systems (GIS) with multi attribute Weighted Linear Combination (WLC) that is based on weighted average, are the tools used to conduct the analysis. The criteria that were used to select suitable sites are Grain elevators, highways, railroads terminals, port terminals, social and economic factors. The result of the study showed that there are 90 locations that are potentially feasible for the development of new container depots in the state of Minnesota.

Brownfields

The increased costs in the redevelopment of a site due to unknown or actual environmental pollution of land that is redundant, unexploited, or neglected within viable and industrial locations are known as Brownfield (Davis, 2002). Brownfield are commonly linked to metropolitan locations that were once industrialized and evacuated. A Brownfield can range from a small deserted filling station to a large steel mechanized operation. The definition of

Brownfield on certain instances may be the opposite of “Greenfields” which is a location reputed to be free from contagion, and had not been previously utilized for industrial or commercial reasons. The pollution levels at Brownfield locations can vary from soil fragments to widespread contagion of ground water. The counteractive costs of a Brownfield can be as little as a few thousand to millions of dollars depending on the project’s level of cleanup and pollution levels (Reddy et al., 1999).

Brownfields have been in existence for many years. This has led to a Superfund program that was first launched in 1980 by the United States Congress to offer monetary aid for the overhaul of perilous locations. Additionally, the remediation sought to improve sites that had been established to pose risks in safety and public health as well as degrade the quality of an environment. The U.S. Environmental Protection Agency (U.S. EPA) took charge over the Superfund program. A National Priority List (NPL) was created, a catalog of hazardous locations that qualify for the Superfund program and need a widespread remediation This list made it easier to rank locations entitled to the Superfund program. The reformation of Brownfields was one of President Bush’s main agenda which was reflected by allocation the EPA a budget of $38 million in April 2001 to enable ninety communities to clean up the land (Davis, 2002). Furthermore, the President also sanctioned a program that would help in decreasing the liabilities in the Superfund as well as increase funds on cleanup and appraisal called S 350. Despite these efforts, there are about 500,000 polluted industrial and commercial sites as stated by the office of U.S. Government Accounting. It would be very beneficial for the country to have computer-based tools to help in the effective location, monitoring and updating of records on Brownfield locations.

Minnesota Brownfields

The characteristics of brownfield properties exist in most parts of Minnesota, presenting an opportune time to improve the state’s economy, reduce carbon emissions, better the environmental health, and free communities from their distress. There are about 425,000 brownfields in the U.S (https://portal.hud.gov/). The metropolitan and industrial locations in Minnesota are brownfields mostly found and few in the rural areas. Since 1995-2014 the Minnesota Pollution Control Agency (MPCA) listed, more than 8000 brownfields in the state that required clean up. By September 2014, more than 63,828 acres had been registered. Additionally, more than 13, 674 acres were registered via the Petroleum Brownfields program. The locations total up to 77, 502 acres space that is larger than St. Paul and the cities of Minneapolis combined.

Benefits of Brownfield Cleanup and Redevelopment

The revitalization of the sites will bring about social, fiscal, and environmental benefits to the people living in the area.

1. *Job Retention and Creation*

The revitalization of brownfield enables people in a community to obtain and retain jobs. For every $ 10,000- $ 13, 000 invested in brownfield recovery one permanent job is created, showed a national study in 2008 (Evans Paull, 2008).

2. *Tax Base Expansion and Revitalization*

In more than 50 states, tax worth $ 309 million was collected since 1993 to 2010 for the brownfield redevelopment (The United States Conference of Mayors, 2010). The same research found that cities would collect more than $ 872 million to $ 1.3 billion every year in tax revenue if brownfields were revitalized in about 58 cities. Numerous Brownfield sites can be found within metropolitan locations; therefore, the magnitude of tax collectable provides fiscal stimulus above what a single state or national grant could achieve.

3. *Public Health Improvements*

Places that have numerous brownfields are faced with increasingly high threats to public health due to the exposure to low quality air, harmful chemicals, high asthma occurrences, increased lead levels in blood, and a lack of recreation centers. Negative effects on health include death due to cancer and respiratory diseases. Therefore, the revitalization of brownfields ensure improved health for neighboring communities.

4. *Meeting Increasing Demand for Land Availability*

The recovery of brownfields is a way of saving land especially Greenfield land, which is often habitable and suitable for agriculture. Brownfields also present a chance for the creation of a sustainable environment, as they are located close to canals, railways, and old roads which makes them assessable and thus offers a locational advantage. The changes help in the reduction of emissions and saving energy.

Data Collection

Based on the previous researches and reviewing the objectives of this research we developed the following factors that covered most of the aspects to answer all the research questions for making a location decision to open new depots. Each factor was represented in a geographic information system (GIS) data layer:

- *Physical Factor:*

  Abandoned, idled or underused industrial and commercial sites (Brownfields)

- *Convenience Factor: Grain elevators*

  The use of storage and transport capacity offered by grain elevators requires purposely designed container depots in the proximity, from where the freight can be transferred. The depots should be designed to be commodity specific, like in case of grains these should be designed as bulk terminals used to transport grains to the desired destinations.

- *Proximity Factor: Highways, Railroads and Waterways*

  The complexity of modern freight distribution, the increased focus on intermodal and co-modal transport solutions appears to be main causes of the container capacity issues and thus needs a renewed focus on hinterland logistics. Congestion, energy consumption and empty movements become the driving forces to consider the setting of container depots near the railroad terminals, as the next step in freight planning. Also, due to the massification of flows in networks, through a concentration of cargo on a limited set of ports, there is an intense need for these depot nodes to appear along.

- *Social and Economic Factor (distance for the residential areas, parks and schools etc.*)
  Trucks, trains and ships help moving cargo and surge economic growth but at the same time they also burn fossil fuels that creates air pollution.
  The warehouses, distribution centers, intermodal and other logistic facilities operate 24 hours a day, seven days a week, creating constant noise. Noise pollution, when encountered continuously and at high levels (of over 85 decibels) contributes to permanent hearing loss from trauma to the structures of the inner ear. So, to address this problem, the site for setting up of new depots should be at a safe distance from the population of the city.

Table 1. Data collection from regulatory sources

Data Layer	Format	Source
Brownfields	Recorded in Excel spreadsheets which are readable by ArcMap as .csv files and shapefiles	Minnesota Pollution control Agency (MPCA) https://www.pca.state.mn.us/
Grain Elevators	Recorded in Excel spreadsheets which are readable by ArcMap as .csv files and shapefiles	http://www.bnsf.com/
Port Terminals	Shapefiles	https://www.rita.dot.gov/
Railroad Terminals	Shapefiles	https://www.rita.dot.gov/
Highways	Shapefiles	
Property Statistics	Recorded in Excel spreadsheets which are readable by ArcMap as .csv files and shapefiles	https://beacon.schneidercorp.com/

The intent of this section is to signify the step by step procedure adopted to collect the data for all the factors involved. The structure of the data collection is presented below:

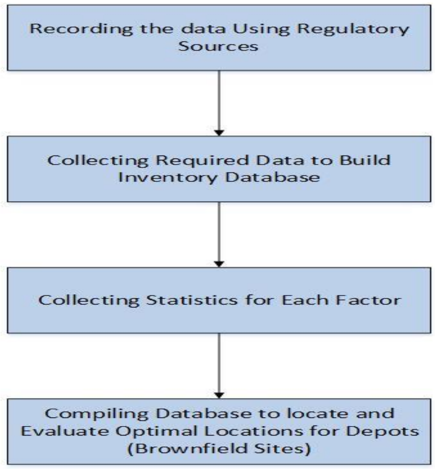

Figure 1. Flow chart for data collection.

Property Statistics

The online EPA database and Beacon and qPublic.net are interactive public access portals that provides statistics on each property like tax parcel ID, area of the parcel, land use type, previous land use, business name, vacancy of the property etc. The data obtained is stored in excel files and later converted to the ArcMap shapefile. Moreover, the land use type is further divided on the basis of an area, Acreage ≥ 15. Now, the vacancy status of the property can be searched using property tax information and can be added as another new field in ArcMap. Table below shows the different fields of the data that were added for each potential site.

Table 2. Fields for each potential site

Site Number	Field
1	Business Name
2	Street Address
3	Area in Acreage
4	Land use Type
5	Status

Geographical Information Systems (GIS) - Multicriteria Decision Making

GIS - Multicriteria Decision Making can be defined as a process that transforms and combines geographical data (criterion maps) and value judgement to obtain overall assessment of the decision alternatives (Laaribi, 2000; Chakhar and Martel, 2003; Malczewski, 2006; Malczewski and Rinner, 2015). The rationale behind the integrating GIS and MCDM is that these two distinct areas of research can benefit from each other. GIS plays an important role in storing, manipulating, analyzing and visualizing spatial data for decision-making. MCDM provides systematic evaluation procedures and algorithms for structuring decision problems, and designing, evaluating and prioritizing alternatives (e.g., Eastman et al., 1995; Jankowski, 1995; Malczewski, 1999; Thill, 1999; Feick and Hall, 2004; Malczewski and Rinner, 2015).

Geographic Information System based Multicriteria Decision Making has been used for evaluating accessibility to public parks in Calgary, Alberta (Meng and Malczewski, 2015). The approach involves the weighted linear combination with the entropy weighting method for obtaining the criterion (attribute) weights. The results of this research can help the park planning authorities in identifying the needs for improving the accessibility to public parks, monitoring the changes of accessibility patterns over time, and locating new public parks.

GIS-based multicriteria analysis is used to identify the significant opportunities and risks associated with the use of biochar (Lataweic *et al.* 2017). They identified the areas where biochar application could deliver greatest benefit.

The GIS was effectively used to design a model for electing an appropriate landfill site in municipalities (Sureshkumar et al. 2017). The analytical hierarchy process (AHP) is used for calculating the weights for each criterion, such as residential area, road network, Geology, Geomorphology and soil. By using this modelling approach, GIS once again proved to be a valuable tool for evaluating multiple criteria in decision making.

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Fyodorova (2013) performed a research to provide a preliminary wind power suitability analysis for installing medium (100 -1000 kW) and large (1000 - 3000 kW) size wind turbines on abandoned and contaminated urban lands (Brownfields), such as the City of Chicago. Geographic Information Systems (GIS) and a multi attribute Weighted Linear Combination (WLC) method were the primary tools utilized to conduct the analysis. The criteria used to select suitable sites such as wind speeds, historic landmarks, avian and wildlife habitat, conservation lands, proximity to airports, roads, and transmission lines.

Analysis Methods

The most common methods used for locational analysis are Boolean Overlay and Weighted Linear Combination (WLC). Both methods “are often made up of combined approaches as none of the individual approaches provide a comprehensive method for wind energy site suitability analysis" (Moiloa 2009, 38). The Boolean method uses Boolean operation such as intersection, difference, union and other operations for the input layers. However, "Boolean searches are limiting because they provide only "yes" or "no" answers" (Moiloa 2009, 39). On the contrary, the WLC method allows assigning weights according to the relative importance of each layer to the overall suitability measurement, and then combining the map layers to obtain an overall suitability score (Malczewski 2004). According to Rodman and Meentemeyer, this method is flexible and allows different inputs to be used to evaluate a variety of scenarios (Rodman and Meentemeyer 2006).

Weighted Linear Combination Analysis

To identify the appropriate sites for the development of container depots in the study area the Weighted Linear Combination (WLC) approach was used in this research. The factors such as proximity to elevator clusters, proximity to railroad and port terminals and social and economic factors were identified that were used for WLC analysis. ArcGIS Spatial Analyst 10.4 was the primary tool used for data conversion and the WLC and overlay analysis. The complete process is expressed in the flowchart in figure 2:

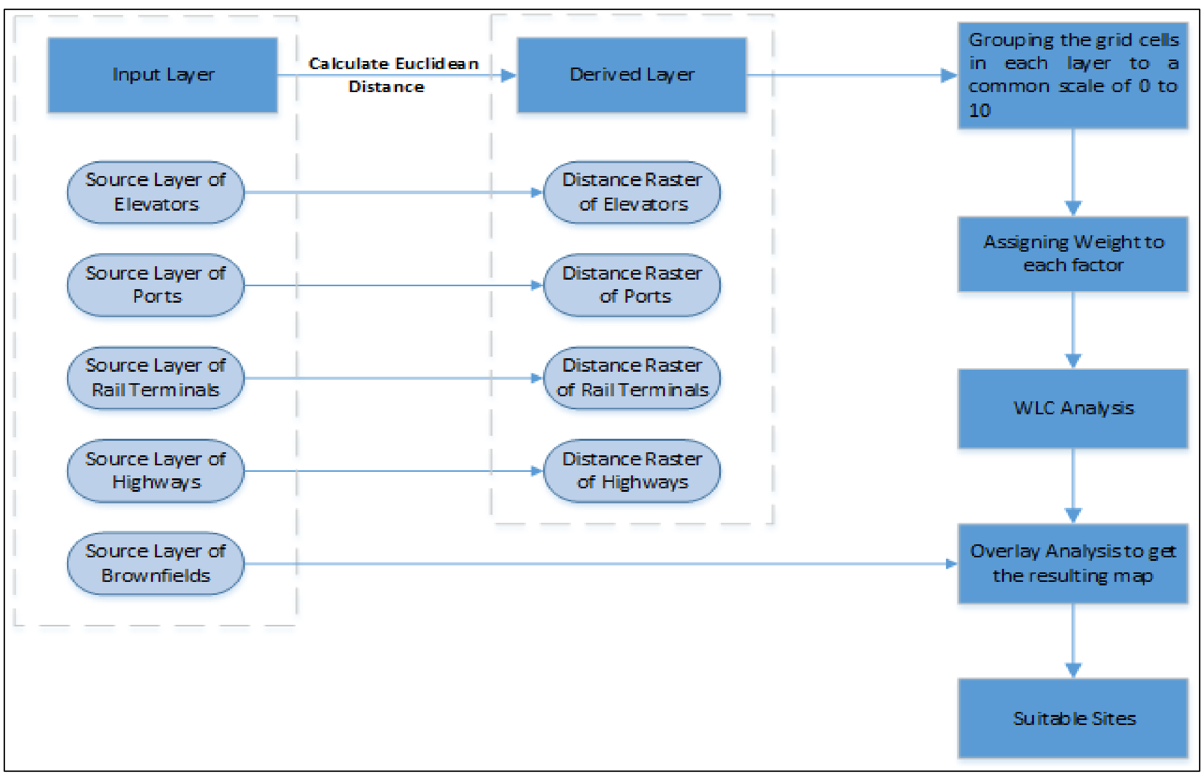

Figure 2. Flow chart for WLC analysis.

1. To begin the analysis all the data were converted to the same projection. All the data were stored in NAD27 Minnesota Project Zones in Central State Plane. The data acquired from other sources were stored in different projections and were reprojected to NAD27 Minnesota Project Zones in Central State Plane using the Arc Toolbox's Data Management Tools >Projections and Transformations >Project, to keep the projection format consistent.
2. The next step was to prepare data for the WLC analysis by converting them to raster format and then reclassifying the grid cells in each raster layer into ten classes and assigning scores to the classes.

First, all map layers (Brownfield sites, elevator clusters, Highway, Railroad terminals, Port terminals) were converted from vector to rasterbased data since all calculations were based on cell values. The Euclidean distance (Spatial Analyst Tools >Distance) was used for conversion because it creates the range of distances (buffer zones) that are calculated from the center of the objects of interest (layer features such as roads, landmark features) while converting vector layers to raster format. The distances are calculated using Euclidean algorithm. The maximum_distance was set to 25,000 meters to consider only grid cells within 25,000 meters from objects of interest as candidates. Grid cells outside of the threshold distance of 25,000 meters were therefore assigned to 'NoData' category in the output. After road data was converted to grid format, all other layers were set to the same extent as the road raster layer before being converted to raster format because it had the largest extent. The extent options were specified via Geoprocessing > Environments > Raster Analysis. Euclidean distance calculations were done in feet by default and Raster calculator (Spatial Analyst Tools >Map Algebra) was used to convert feet to meters.

Next step is to Reclassify (Spatial Analyst Tools >Reclass) grid cells in each layer to set them to a common scale. The Reclass tool allowed grouping the grid cells on each layer into ten classes and assigning score to each class on a scale of 0 to 10, 0 being the least suitable and 10 being the most suitable (Figure 2).

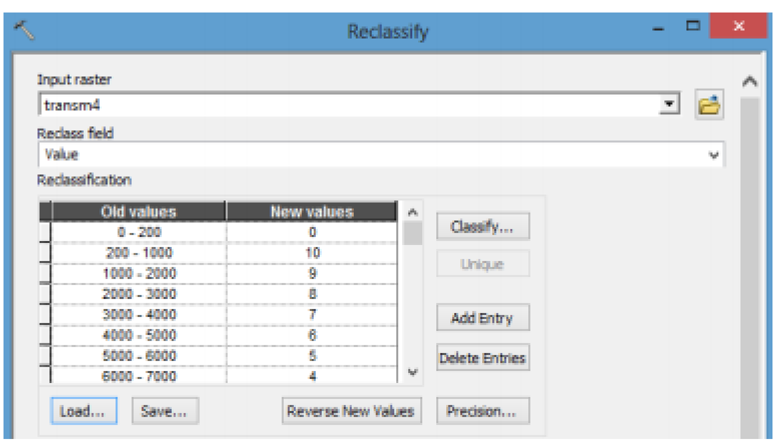

Figure 2. Reclassify tool showing grid layers reclassification

The classes and score categories for all the variables under consideration are shown in Table 3. It should be noted that 'NoData' cells were assigned zero values, because the process of overlaying 'no value' cells with cells containing numerical values would result in a 'no value' grid cells in the output layer.

Table 3. Classses and suitability Score of factors for WLC analysis

Layer	Class	Score	Layer	Class	Score
Grain Elevators	0-200m	1	Ports Terminals	0-3000m	1
	200-400m	2		3000-4000m	2
	400-1000m	3		4000-5000m	3
	1000-2000m	4		5000-6000m	4
	2000-3000m	5		6000-7000m	5
	3000-4000m	6		7000-8000m	6
	4000-5000m	7		8000-9000m	7
	5000-6000m	8		9000-10000m	8
	6000-7000m	9		10000-11000m	9
	7000-10000m	10		11000-12000m	10
	>10000	0		>12000	0
	No Data	0		No Data	0

Rail Road Terminals	0-3000m	1	Highways	0-200m	1
	3000-4000m	2		200-400m	2
	4000-5000m	3		400-1000m	3
	5000-6000m	4		1000-2000m	4
	6000-7000m	5		2000-3000m	5
	7000-8000m	6		3000-4000m	6
	8000-9000m	7		4000-5000m	7
	9000-10000m	8		5000-6000m	8
	10000-11000m	9		6000-7000m	9
	11000-12000m	10		7000-10000m	10
	>12000	0		>10000	0
	No Data	0		No Data	0
Social and Economic Factor	0-200m	10			
	200-400m	9			
	400-1000m	8			
	1000-2000m	7			

	2000-3000m	6	
	3000-4000m	5	
	4000-5000m	4	
	5000-6000m	3	
	6000-7000m	2	
	7000-10000m	1	
	>10000	0	
	No Data	0	

3. Finally, Weighted Overlay tool (Spatial Analyst Tools >Overlay>Weighted Overlay) was used to conduct WLC analysis. During this analysis, each reclassified dataset was multiplied with its associated weight and then all weighted raster layers were combined to produce a composite raster map showing a final suitability score for each grid cell; see Figure 3 for a screenshot of the composite map which is the result of the weighted overlay operation.
   The table 4 shows what weight percentage was assigned to each criterion. The weight represents the relative importance of each layer and can be modified when the criteria importance changes. The importance of each layer was based on personal judgment.

Table 4. Weight assigned to each layer

Elevator clusters	32
	21
	21
	11
	15

The grain elevator cluster is the most important factor in the analysis. The use of storage and transport capacity offered by grain elevators requires purposely designed container depots in the proximity, from where the freight can be transferred. They are the only demand nodes for empty containers in the system. So, they will play a vital role in decreasing the empty miles travelled. Thus, the factor is ranked as most important with the highest weightage.

In the freight distribution planning, factors such as congestion, energy consumption and empty movements become the driving forces to consider the setting of container depots near the railroad and port terminals. Here, port and railroads terminals are given intermediate weightage because they are not dispersed throughout the city. Most of them are already located at a safe distance for the city population. Moreover, accessibility and proximity to railroad terminals and port terminals is very crucial because it affects the cost effectiveness of the project.

Social and Economic Factor like distance for the residential areas, parks and schools etc. got the less weightage but still is a very important for the locational analysis. The goods movement industry is heavily reliant upon diesel fuels from ships, trucks, locomotive, forklifts, cranes and more but at the same time Trucks, trains and ships help moving cargo and surge economic growth but at the same time they also burn fossil fuels that creates air pollution. The warehouses, distribution centers, intermodal and other logistic facilities operate 24 hours a day, seven days a week, creating a significant noise pollution. So, the site for setting up of new depots should be at a safe distance from the population of the city.

The function of the road, from a freight perspective, is manifold. Road freight is most often necessary in the beginning and in the end of the multimodal transport chain. Minnesota has a good connectivity of highways, Minnesota Department of Transportation has designated 2,960 miles of roadway outside the Twin Cities area as interregional corridors, that link together the Twin Cities, Rochester, Fargo-Moorhead, Duluth and about 50 other communities. High priority IRCs include Interstates 35, 90 and 94, as well as all or parts of Highways 10, 52, 61, 169 and 212. Medium priority IRCs include all or parts of Highways 2, 8, 10, 14, 23, 34, 53,60, 63, 95, 169, 210 and 371. That being so the factor highways is given the least weightage in the analysis.

The suitable site classes are ranging from 1 to 10. One (red) being the least suitable and 10 (green) being the most suitable sites (Figure 3). The least suitable sites are the sites that are less preferred for the development on new depots.

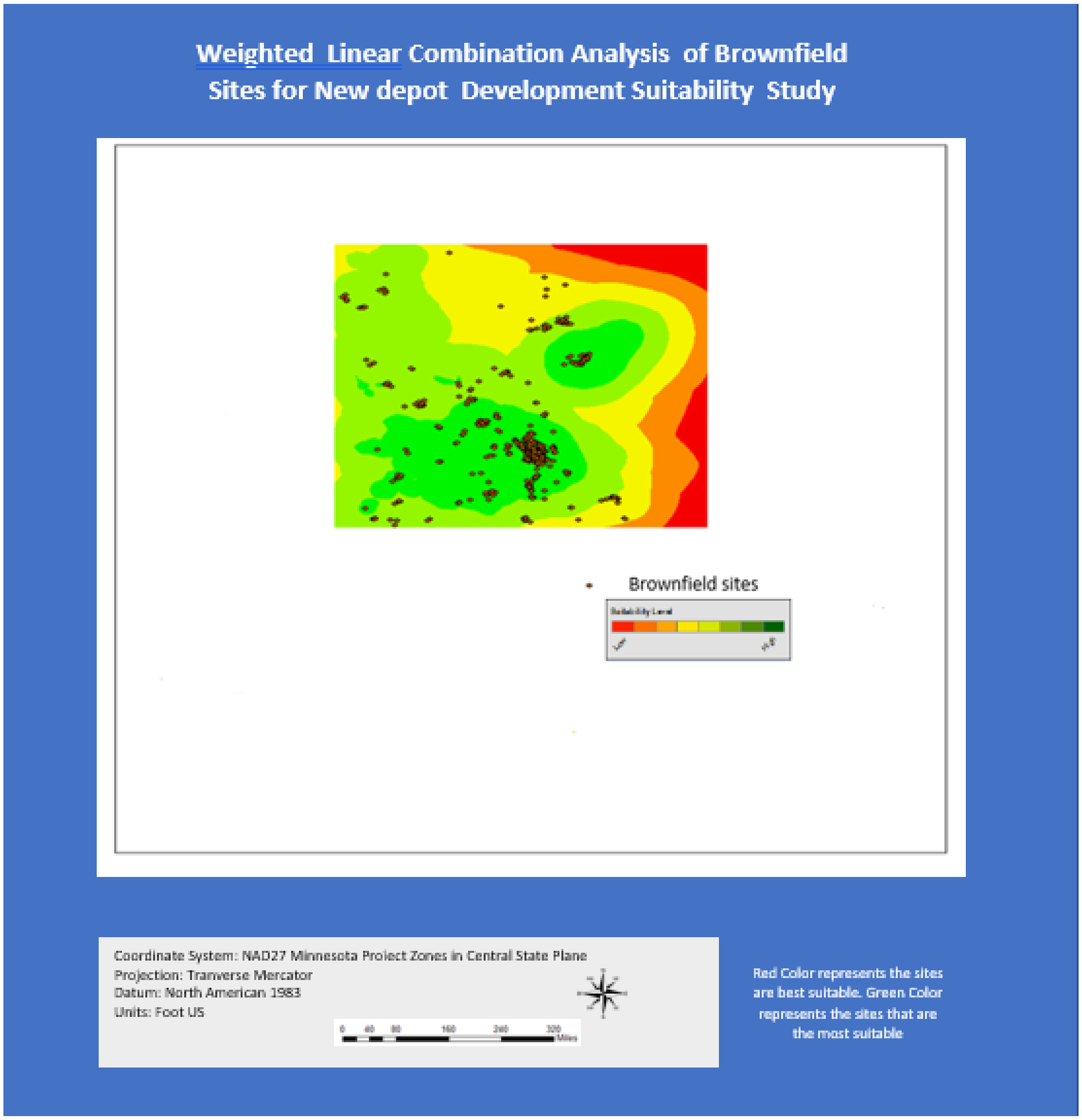

Figure 3. Weighted Linear Combination Analysis Result

Overlay Analysis

Further overlay analysis is done to identify the specific suitable sites and to clean final map. First, the suitability map represented on figure 3, which is a raster layer, was converted to vector format using Raster to Polygon tool (*Conversion Tools>From Raster*), then the sites with suitability scores ranging from 7 to 10 (the most suitable sites) were selected to be overlaid with brownfields layer.

Map in the figure 3 shows the brownfields that meet all the 5 criteria considered in this research for selecting suitable sites for opening new depots in the study region.

Results

The final results of the WLC analysis show that there are 90 potentially suitable sites for the empty container depot development. 31 of the suitable sites have a score 6 and 7, i.e., they are the most suitable sites and other 59 are classified 5 as less suitable sites. The total acreage of suitable sites composes 2050 acres. As can be seen on figure 3, majority of the suitable sites appeared in the south and the north-east region of the study area. Most of these sites in the south are closer to elevators and the ports, which happens to be the high weightage factors. The sites in the north-east region are in proximity to the ports and railway terminals, while keeping a distance from the grain elevator clusters. To identify the sites that are ideally suitable for depot development would require additional and detailed examination.

Conclusions and Recommendations

The development of new depots on the brownfield sites will solve the container availability problem in the portions of the study area, where the exporters are put in competitive disadvantage when they are unable to obtain containers at a reasonable cost for their exports.

Moreover, the opening new inland depots will also reduce the empty container movements between regional importers, marine terminals, empty container depots, and export customers, which is a non-revenue generating exercise.

The recovery of brownfields is a way of saving land especially Greenfield land, which is often habitable and suitable for agriculture. Brownfields also present a chance for the creation of a sustainable environment which could be a vital factor for improved health of neighboring communities. The revitalization of brownfields will also enable people in a community to obtain and retain jobs.

The locational decision making analysis was evaluated using AcrGIS 10.4. Integrating the Weighted Linear Combination into geographic information system (GIS) modeling, this research provides a practical and easy way to select their optimal locations. Comparing to conventional methods, it greatly improves the efficiency of selection and saves time and costs for people. By adding/removing related factors, and adjusting evaluation criteria, the method can be applied in other fields involving spatial decision making and land value evaluating, such as locating commercial and public facilities, city planning, and optimal public transportation routes selection.

This research used a simplified Euclidean distance instead of traveling distance of road networks. Because road networks are extensive in the state of Minnesota, it is assumed it is not significantly different using this method. If this method is applied to other areas with sparse road networks, the results may be less appropriate. The network analysis in geographic information system (GIS) can calculate the shortest routes and shortest travel time for any location to specified facilities. Therefore, in future studies, based on their preference, users can choose to use either the shortest routes or the shortest travel time to evaluate such factors.

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