GIS Based Site Ranking using Neighbourhood Analysis and Comparison

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***Abstract*—This paper presents a Geographical Information Systems (GIS)-based toolkit, developed for site comparison and ranking that can be used to facilitate the decision making process in second stage of the site selection process. The toolkit has been developed as an analytical component of a multi-criteria spatial decision support system for geoenvironmental and geoenergy applications. The methodology adopted to develop this analytical module is based on a systematic comparison of the surrounding areas of each site in accordance with key environmental, socio-economic and public-health indicators. The sites are ranked based on the most favorable key indicators using a Criterion Sorting Mechanism (CSM) or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). An application of the site selection toolkit is presented in relation to an unconventional geoenergy development. The application exercise deals with the ranking of a number of potential sites for coalbed methane recovery in Wales, UK. The locations of potential sites are first selected with respect to the gas resource (techno-economic viability). The toolkit is then used to select and rank the potential sites based on key environmental indicators, in the site's neighbourhood. The results of the site ranking using CSM and TOPSIS methods are compared and a number of scenarios are discussed. This approach of using a combination of site ranking methods along with the neighbourhood analysis reduces the risk of personal judgment and choice. The decisions on site selection can thus be evidenced on a quantified logic.**

Keywords-neighbourhood analysis; spatial decision support system; site selection; site ranking; coalbed methane.

I. INTRODUCTION

This paper describes the development of a Geographical Information Systems (GIS)-based toolkit for site ranking, based on an analysis of the surrounding areas. The toolkit can be used in the "second phase" of a site selection process, where the decision maker may need to choose from a number of potential sites or from a large suitable area.

The problem considered is one where after applying the "first phase" of a GIS-based site selection process, the decision maker is left with multiple choices either in the form of more than one equal potential sites (in vector format) or very large areas (in raster format).

Different GIS modelling techniques have been suggested in the literature for site selection process. These techniques are collectively known as Spatial Multi Criteria Decision Analysis (S-MCDA). For example, a combination of Analytical Hierarchy Process (AHP) and TOPSIS method has been suggested for municipal solid waste landfill site selection with a case study of Thrace region in Greece [1]. Weighted Linear Combination (WLC) in combination with fuzzy set theory has been applied for decisions on wind farm sites selection in Northwest Ohio [2]. AHP, fuzzy membership functions and Simple Additive Weighting (SAW) has been used together in a study to find the most suitable site for a tourist building a in the rural landscape of Hervás in Spain [3]. Similarly, a spatial decision tool for managed aquifer recharge has been presented in [4] that combine AHP, WLC and Ordered Weighted Averaging (OWA). A case study of this tool has been presented for the site selection of managed aquifer recharge in the Algarve Region of Portugal [4].

As described previously, at this stage, multiple sites may be obtained with equal potential. The suitable areas obtained in these studies are in the form of a raster map with relatively large areas, suitable for siting. For example, the area highlighted as a suitable area for aquifer recharge in [4], constitutes about 11.2% of the entire study area. Then, the suitable area was ranked on the basis of suitability score and the most highly suitable class reduced the area under consideration to 1% of the entire study area. At this stage the sitting decision is mainly based on the choice and expert knowledge of the decision maker(s).

To facilitate the decision making in the second phase, under the conditions described above, site ranking using neighbourhood analysis is presented in this paper. This approach can provide a quantified logic to select and rank the best site(s) from several candidate sites identified in the first level of the site selection process. Using the approach presented, inputs required from the decision maker and the risks associated with personal judgement and choice can be minimized.

An overview of neighbourhood analysis for site comparison and methods for site ranking is presented in Section II. In Section III, a description of the toolkit development and analytical components is presented. Tools and technologies used for the development of the toolkit are also highlighted. In Section IV, an application of the toolkit is presented which deals with the ranking of a number of hypothetical Coal Bed Methane (CBM) sites in Wales (UK). The toolkit has been used to rank the suitable sites in terms of key environmental indicators using both CSM and TOPSIS ranking methods. In Section V, the results of the application of the toolkit are discussed. Ranks generated from both the techniques are also compared. Conclusions drawn from this work are presented in Section VI.

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II. Overview: Site Neighbourhood Analysis and Site Ranking

As discussed in Section I, the GIS-based site selection process can result in a number of potential sites or a relatively large potential area that meets the basic criteria, set in the first stage of selection process. In the second stage of site selection, it is important to reduce and prioritise the equal potential sites identified for further investigation and final selection. Some of the spatial multi criteria decision analysis techniques described earlier, may also involve the user's judgments and preferences over the relative importance of key indicators. Site neighbourhood comparison and ranking can be useful in a logical ordering of the available options based on only the analysis of the key indicators in the site neighbourhood. Once key indicators are defined and the effective neighbouring region is selected around the sites identified in the first stage of selection process, an appropriate ranking method can then be used to prioritise the alternatives.

Site neighbourhood analysis has been adopted in identifying potentially suitable sites for storm water harvesting in an urban area [5] in which a similar two-stage approach for site selection and ranking was adopted. The application of the site neighbourhood analysis has also been reported in selection of temporary municipal storage waste sites in Sweden using buffer analysis [6]. In the mentioned application, key demographic metrological indicators were analysed in these buffers around the sites [6].

For ranking the alternates or equal potential sites, different ranking techniques can be applied. Some commonly used ranking techniques are: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [7], Superiority and Inferiority Ranking (SIR) [8] and Weighted Linear Combination (WLC) [9]. TOPSIS is among widely adopted methods for ranking. In the toolkit presented in this paper, TOPSIS method has been adopted along with a new approach which is based on a criterion sorting mechanism.

III. Development of the Toolkit

As described previously, a site neighbourhood comparison approach has been adopted after a first phase site selection process has been completed. Using the appropriate logic in the toolkit, suitable areas are narrowed down into the most suitable site, considering additional criteria. The following steps are adopted in the toolkit to analyse the information and generate the results:

- First, the user provides two GIS layers to the toolkit and related data are loaded in the memory. One layer holds all potential sites whereas the other layer presents information of the neighbourhood of each site for the analysis. It is noted that this information could vary from problem to problem, e.g., socio-economic indicators or environmental indicators in the surrounding regions.
- The toolkit then scales all the indicators between 0-1(where 0 is the minimum value and 1 is the maximum value of each indicator in the layer). During the scaling process, i.e., commensuration, the user defines whether a particular indicator is Benefit (the more, the better) or Cost (the less, the better) in nature. The user can use either original values or scaled values. For scaling, the toolkit provides Maximum Score Procedure and Score Range Procedure, as in [10] and [11]:
  a. Maximum Score Procedure:

  $$\text{(Benefit)} \quad X'_{ij} = \frac{X_{ij}}{X_{j.max}} \tag{1}$$

  $$\text{(Cost)} \quad X'_{ij} = 1 - \frac{X_{ij}}{X_{j.max}} \tag{2}$$

  b. Score Range Procedure:

  $$\text{(Benefit)} \quad X'_{ij} = \frac{X_{ij} - X_{j.min}}{X_{j.max} - X_{j.min}} \tag{3}$$

  $$\text{(Cost)} \quad X'_{ij} = \frac{X_{j.max} - X_{ij}}{X_{j.max} - X_{j.min}} \tag{4}$$

  where X_{ij} is the value of the i^{th} location (potential site) for the j^{th} criterion. X'_{ij} is the scaled (standardized) value of X_{ij}. $X_{j.min}$ and $X_{j.max}$ are the minimum and maximum values of the j^{th} variable in the entire dataset [11].

  c. Using original values: This is the case when all indicators have same unit of measurement and they are either cost or benefit in nature. In such scenarios, decision maker can keep them in original units.
- The toolkit then selects the neighbouring areas of each potential site based on criteria specified by the user. This is done by applying buffers around the candidate sites and selecting the intersecting regions in indicator layer.
- The toolkit calculates the minimum, maximum and average values of each indicator in the selected neighbourhood of each site. Either of these average, maximum or minimum values can be selected to rank the sites.
- The final step is to assign ranks to the sites. User can choose the ranking either based on CSM or the TOPSIS method. The toolkit generates the results and visualises them in decision assistive graphs and tables.

The toolkit has been developed using Microsoft .Net C# programming language and an open source .Net spatial library, i.e., DotSpatial [12]. The toolkit uses Shapefiles, which is a "de facto" data type standard for vector data in GIS. The toolkit can also work on layers from an open source spatial database, namely SpatiaLite [13]. The problem is presented to the toolkit through two information layers (Shapefiles or SpatiaLite layers).

Figure1 presents the Geographical User Interface (GUI) of the toolkit. User can provide the necessary information using this interface. The user can also assign the buffer radius in map units to define the surrounding areas of each site to be included in the analysis. The toolkit first generates the buffer polygons around each site according to the user defined buffer size. Then the second layer containing indicators is intersected with these buffer polygons. If the buffer option is unused, only those areas are selected from the indicator layer that directly intersects with the sites without using any buffer. The toolkit can rank the sites based on the average, maximum or minimum value of each indicator in the given surrounding regions of each site.

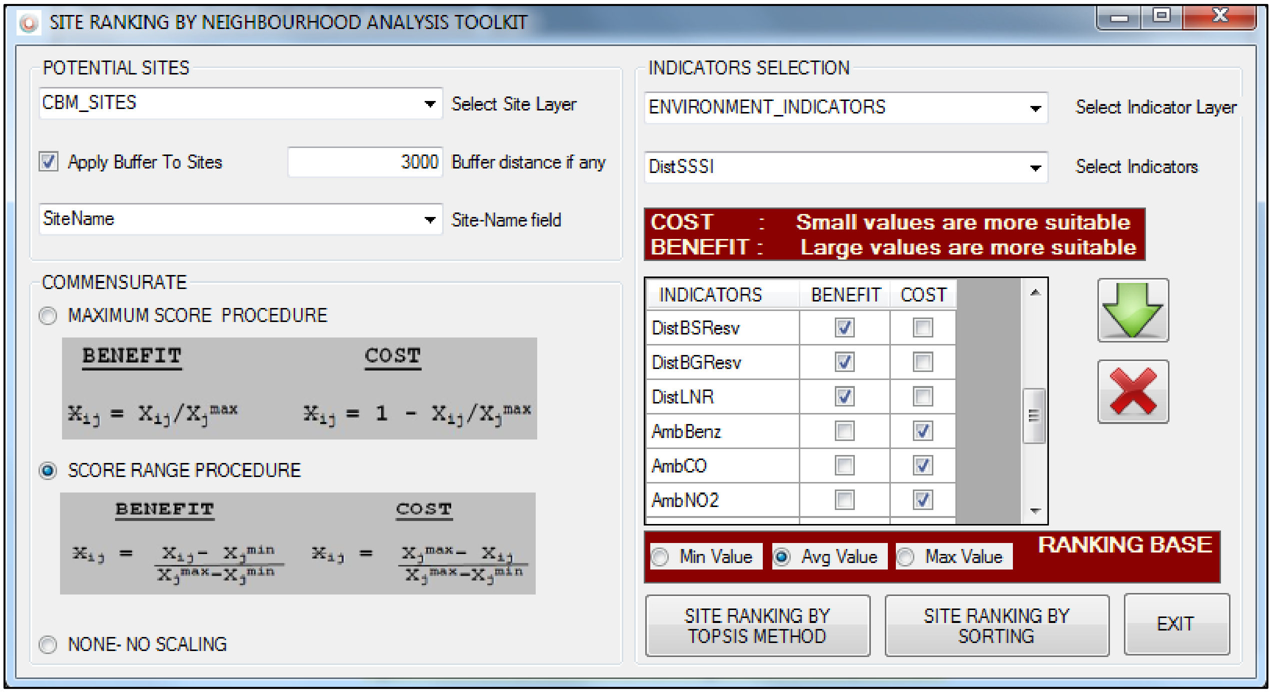

Figure 1.The user interface of the site neighbourhood analysis toolkit.

Each site may obtain different ranks for different indicators. A cumulative rank is then constructed by the toolkit using a Criterion Sorting Mechanism (CSM). If CSM is used, this cumulative rank is based on the individual ranks for each indicator. For this purpose, a rank sum is constructed for each site by summing up individual ranks of all the indicators. Sites are sorted in ascending order in terms of this rank sum. The site with lowest rank sum gets the overall Rank 1.

In order to compare the results of CSM technique, TOPSIS method is also incorporated within the toolkit. TOPSIS is selected because it is a commonly used ranking method in MCDA problems [14] [15]. It ranks the sites based on their distances from the most ideal and the least ideal solution [7].

If TOPSIS method is used, the cumulative site ranks are constructed using the empirical formulation of TOPSIS method. The procedure adopted in TOPSIS approach follows the steps provided in [7]. The detail of the calculation and procedure is therefore not provided here. The closer the rank is to 1, the priority of the alternate is higher as it is closer to the ideal solution and far from the worst solution [7]. It is a matter of sorting all the alternatives on the basis of these values and then assigning ordered ranks between 1-m, where 1 is the highest rank and m is the lowest rank.

The results are generated in the form of a report containing charts and a table, which provide the ranks of each site with respect to the indicators and also present the cumulative rank produced by CSM and TOPSIS. For charting, Microsoft chart control is used under the Microsoft Public Licence (Ms-PL) [16]. Polar chart scheme is also used to show the area covered by each potential site over different axis (indicators).

IV. APPLICATION CASE STUDY

An application of the toolkit for the site neighbourhood analysis of six potential sites for CBM recovery in Wales, UK is presented. Using CBM technology, the gas contained in deep and un-minable coal seams can be exploited [17]. The gas recovery can also be enhanced by injecting carbon dioxide into coal seams (ECBM) [17].

A number of potential areas for CBM have been identified and reported in the North and South Wales coalfields [18]. Estimations have been carried out based on parameters, such as coal seam thickness, clean coal thickness (total thickness minus 15% ash and dirt allowance), density and gas content [18].

Two areas in Wales have been selected, one in the South coalfield (CBM area 4) and one in the North coalfield (CBM area 3). The areas have been selected among the potential CBM areas identified and reported in [18] based on “resource” capacity consideration. It is noted that the selected regions are not necessarily the most suitable areas for CBM in Wales. However, according to the CBM resource assessment figures given in [18], these areas may also contain a considerable CBM resource potential. The major characteristics of these two CBM areas are shown in Table 1.

Six 500m×500m squared areas have randomly been selected within the two regions mentioned (3 in each region). Figure 2 presents the coal resources in Wales and the potential CBM sites selected for this study. Since the area and properties of all the six sites are similar, it was assumed that the sites are equal potential candidates for CBM.

TABLE 1. ANALOGOUS CBM AREAS IN NORTH AND SOUTH COALFIELDS [14].

Properties	**South Wales (Area 4)**	**North Wales (Area 3)**
Coal thickness (m^3/t)	23.8	23
Clean coal thickness (m^3/t)	20.23	19.55
Coal density (g/cm^3)	1.33	1.26
Gas content Ave (m^3/t)	8.5	8

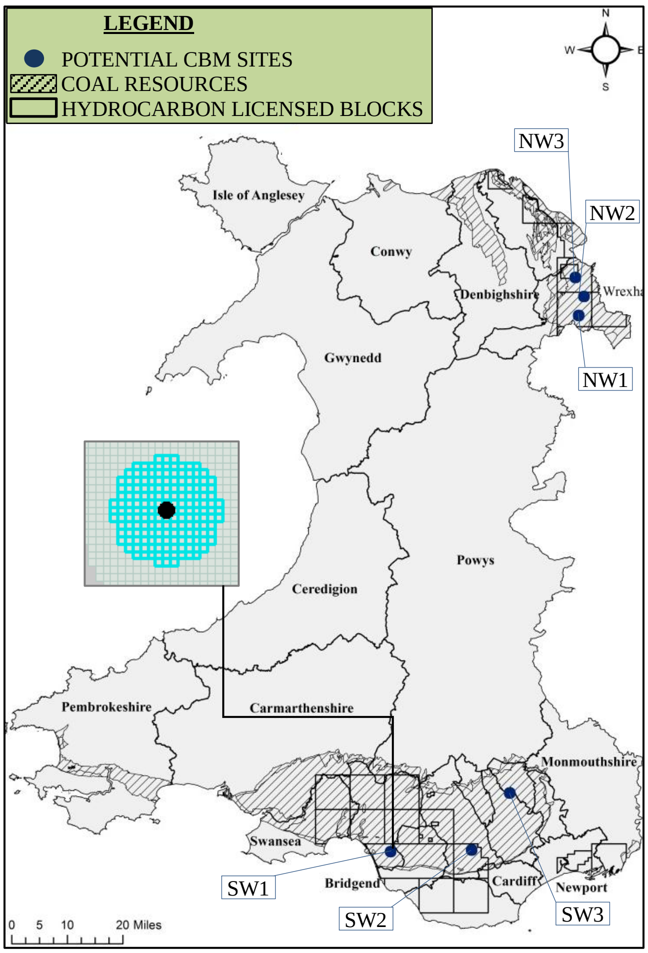

Figure 2. Coal resource map in Wales and selected potential CBM sites with 3 km buffers.

In the example provided, multiple sites exist with similar suitability, which is the same as the site suitability problem discussed in section two. The site neighbourhood analysis tool has therefore been applied, using some key environmental indicators. Some of these indicators were taken from the Department for Environment Food and Rural Affairs (DEFRA). The indicators are the background air pollution maps used for the ambient air quality assessment [19], which have also been adopted in the construction of the environmental deprivation within the Welsh Index of Multiple Deprivation 2011 (WIMD) [20]. Other environmental indicators used are the distance of each potential site from the protected areas in Wales, which was taken from datasets managed by the Countryside Council for Wales (CCW) [21].

The Intrinsic Evaluation Matrix of LandMap (Visual Sensory) dataset developed by CCW was also used for aesthetic coverage across Wales. This data set contains records of the ordinary and spectacular landscapes and information about the physical, ecological, visual, historical and cultural landscape of Wales [21]. The Intrinsic Evaluation Matrix covers scenic quality, integrity, character and rarity of the area and an "overall" index, which divides the Welsh landscape into Outstanding, High, Moderate and Low values [21]. These qualitative values were converted to numerical values of 1.0, 0.75, 0.50 and 0.25 respectively, to be used in the analysis. Table 2 shows the datasets used in neighbourhood assessment of the six potential sites for CBM exploitation.

All these environmental indicators were combined together into one GIS layer. For this a grid of 500m×500m area was generated across Wales using ArcGIS software. Using "near" and "spatial join" tools of the ArcGIS, these cells were then populated with the indicators data. The six potential sites were then saved in another vector layer. The site neighbourhood tool was applied with a buffer of 3 km around the sites (as shown in Figure 2) and ranking of the sites was carried out using both CSM and TOPSIS methods.

In the TOPSIS method used in this study, a relative weight of the criterion is also provided by the user to emphasize the importance of one over the other [7]. In simple cases, the weights can be directly applied and in cases, where uncertainty exists about the individual weights, pairwise comparison method is implied to find the relative weights [22]. In both cases the sum of all the individual weights should be equal to 1. To simplify the procedure in the example provided, it is assumed that the selected environmental indicators are equally important in the CBM site ranking process therefore an equal weight is assigned to every indicator for the construction of the TOPSIS ranks.

V. RESULTS AND DISCUSSION

The results of the analysis are presented in Table 2. The ranking analysis has been carried out on the basis of the average values of each indicator in the given neighbourhood (3km in this case). The overall rank for the six potential sites was constructed using both CSM and the TOPSIS methods. In CSM, final ranks are constructed by summing up the individual ranks for each site and then sorting in ascending order. The site with the lowest rank sum was assigned the overall rank 1 whereas the site with highest sum was assigned rank 6 accordingly.

The TOPSIS method calculates a distance of each potential site (alternate) from the most ideal and least ideal solution and the final ranks are constructed using (5).

Figure 3 shows the neighbourhood analysis results for each site considering key environmental indicators. The area covered under each polar graph is reflected in the ranks produced by the tool. The scale on the polar graphs is shown between 0-1 as the score range procedure, defined by (3) and (4), was used to scale the indicators.

As described previously, some of the indicators are *"cost"* in nature, such as the air pollution or the aesthetic maps whereas others are *"benefit"* in nature, such as the distance from protected areas. By using the appropriate equations for scaling the data, it was ensured that all *"cost"* and *"benefit"* indicators were scaled between 0-1, where 0 is the least favourable and 1 is the most favourable value.

The results indicate that by using the CSM in ranking procedure, the site SW3 is overall the most suitable site in terms of the indicators used in the analysis (TABLE 2). However, using TOPSIS method, the site SW3 has been ranked as the third most favourable site. The site SW3 is ranked as the best site based on only two individual indicators, i.e., Distance from Ramsar Sites (DistRamsar) and PM10 (AmbPM10). It has been ranked as the least suitable site based on only one indicator, i.e., DistLNR. The TOPSIS takes into account the distance of the site from the most and least ideal solutions. Therefore the SW3 has not been ranked as the most suitable site using TOPSIS.

The site NW1 has been ranked as the most suitable site by TOPSIS and second most suitable site by the CSM technique. Exploring the individual ranks assigned by the CSM, it can be observed that the site NW1 has been ranked as the most suitable site based on eight different individual indicators and as the least suitable site based on seven individual indicators. As a result, this makes the NW1 less suitable site compared to the SW3 using the CSM. From the results obtained, it can be deduced that the outcomes from CSM technique are less affected by the extreme values of criterion, compared to the results obtained from TOPSIS.

The TOPSIS method assigns an overall Rank 2 to the site NW2 without it having top ranks for any of the individual indicators. Exploring the individual ranks further, it can be observed that almost all of the indicators ranks are in the middle of ranking scheme (1-6), i.e., taking the mean values. Considering the less deviated conditions of all indicators from the average values, the TOPSIS has ranked the site as the second most suitable alternative.

Both SW3 and NW1 are in the top three most suitable sites by using any of the two ranking methods described. The NW1 can overall be considered as the most suitable site with more confidence as it was rated as the top two sites by both ranking methods. Further confidence has been achieved by using the two methods of ranking together for the identification of the most suitable site, described in this application. It is noted that, once ranks are assigned to the sites, top ranked sites can be further investigated for environmental, health and socio-economic risks.

TABLE 2. ENVIRONMENTAL INDICATORS USED AND SITE RANKING RESULTS OBTAINED.

	INDICATORS			**RANKS**					
		Units	**Abbreviation**	**SW1**	**SW2**	**SW3**	**NW1**	**NW2**	**NW3**
1	Distance from SSI (Site of Special Scientific Interest)	m	DistSSSI	1	5	2	6	3	4
2	Distance from SAC (Special Areas of Conservation)	m	DistSAC	3	1	2	6	5	4
3	Distance from SPA (Special Protection Areas)	m	DistSPA	1	3	2	6	4	5
4	Distance from Ramsar Sites (Wetlands of International Importance)	m	DistRamsar	3	2	1	4	5	6
5	Distance from NNR (National Nature Reserves)	m	DistNNR	6	2	5	4	3	1
6	Distance from MNR (Marine Nature Reserves)	m	DistMNR	6	5	4	3	2	1
7	Distance from AONB (Areas of Outstanding Natural Beauty)	m	DistAONB	4	1	2	3	5	6
8	Distance from Heritage Coasts	m	DistHC	6	5	4	1	2	3
9	Distance from Biospheric Reserves	m	DistBSResv	2	1	3	6	5	4
10	Distance from - Biogenetic Reserves	m	DistBGResv	2	1	3	6	4	5
11	Distance from LNR(Local Nature Reserves)	m	DistLNR	4	3	6	1	2	5
12	Visual and Sensory Landscape overall Evaluation	-	Intrinsic	4	1	5	6	3	2
13	CO	mgm^{-3}	AmbCO	6	5	2	1	3	4
14	Benzene	μgm^{-3}	AmbBenz	5	3	2	1	4	6
15	NO_2	μgm^{-3}	AmbNO2	5	6	2	1	3	4
16	NOX	μgm^{-3}	AmbNOX	5	6	2	1	3	4
17	PM2.5(Particulate matter < 2.5 microns)	μgm^{-3}	AmbPM25	2	6	3	1	4	5
18	PM10 (Particulate matter < 10 microns)	μgm^{-3}	AmbPM10	3	4	1	2	5	6
19	SO_2	μgm^{-3}	AmbSO2	6	3	2	1	4	5
20	Ozone	μgm^{-3}	AmbOzone	1	3	5	6	4	2
	SITE RANK (CSM)			**5**	**3**	**1**	**2**	**4**	**6**
	SITE RANK (TOPSIS)			**6**	**5**	**3**	**1**	**2**	**4**

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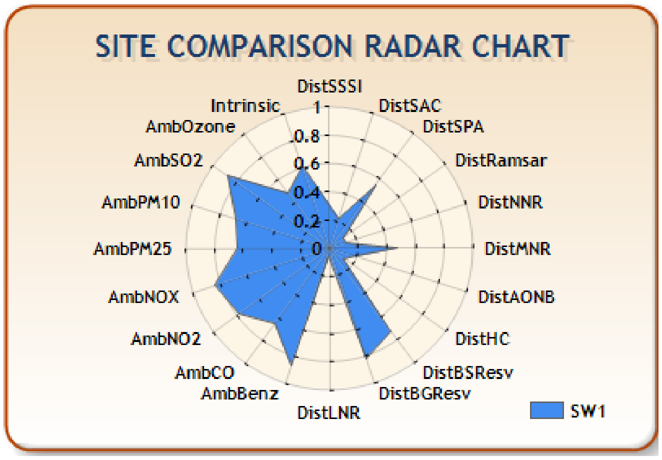
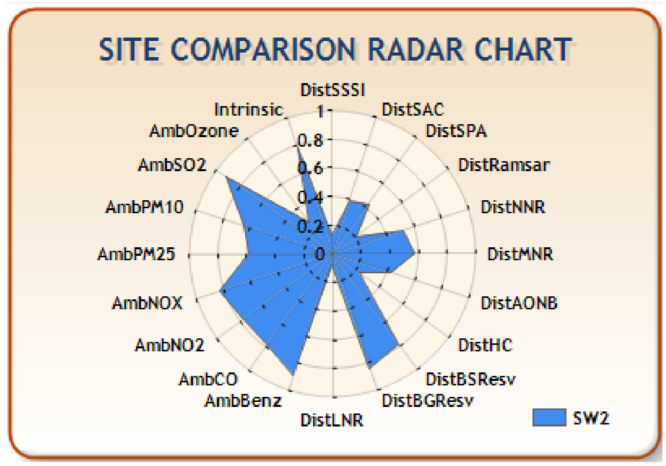
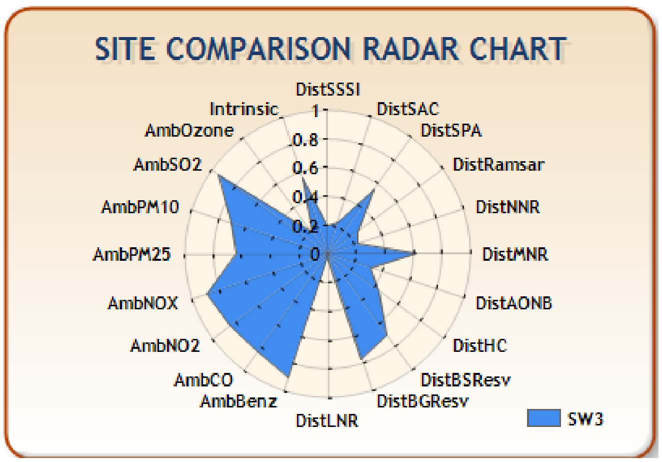


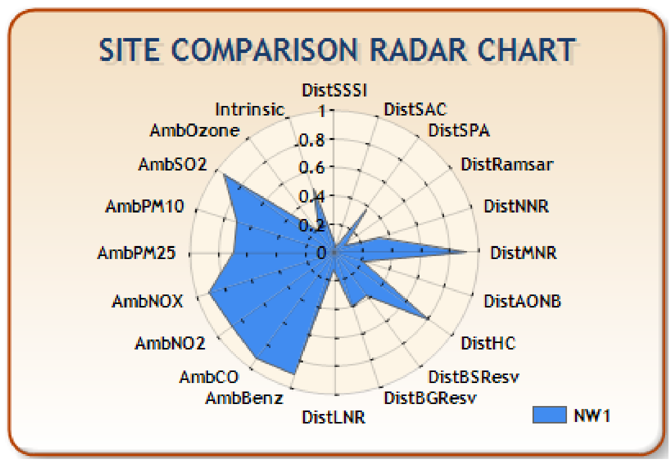
(a) Site SW1



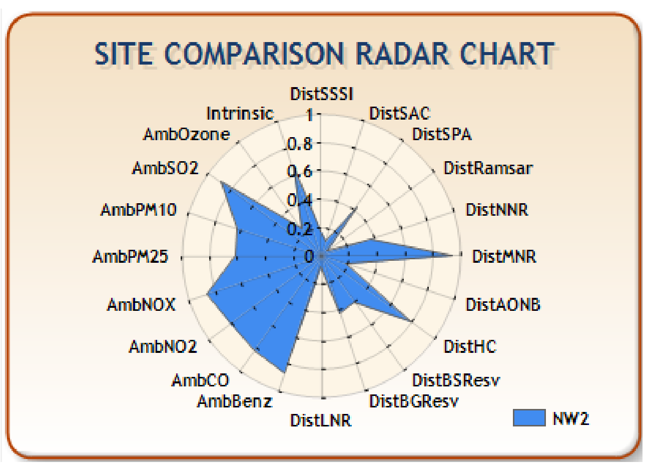
(b) Site SW2



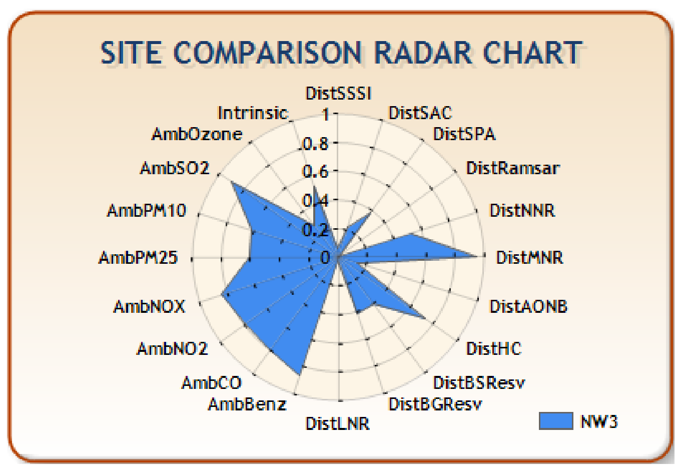
(c) Site SW3



(d) Site NW1



(e) Site NW2



(f) Site NW3

Figure 3. The results of the Site neighbourhood analysis for sites selected in this study.

VI. CONCLUSION

A GIS toolkit to analyse the neighbouring areas surrounding a potential site has been developed, which can be used to facilitate the process of decision making. The tool developed, provides a simple yet effective approach to deal with the ranking of sites based on some key indicators in their surrounding areas. Toolkit provides two different methods of site ranking, i.e., a simple Criterion Sorting Mechanism and the TOPSIS ranking method. This is useful where a number of equal potential sites or a large suitable area is acquired as the result of a GIS based site selection process in first phase of evaluation.

An application of the toolkit for CBM resource exploitation was presented. Six sites were randomly selected in the South and North Wales coalfields with similar resource potential. Based on selected environmental indicators, the potential sites were ranked, considering neighbourhood conditions. The results show the ranks for each site with respect to individual environmental indicators using both the methods.

The toolkit presented is part of a Spatial Decision Support System, developed to support a wide spectrum of geoenvironmental and geoenergy applications, where multiple criteria, such as the environment, public health, socio-economic and technical indicators are of importance in the decision process.

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