Comparing Different Spatial Decision Making Models Performance in Siting a Nuclear Power Plant

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Gulf Cooperation Council countries recently announced their intent to start a peaceful nuclear energy program. With fossil fuel reserves in high demand worldwide, it is safe to assume that more and more countries around the world will turn to nuclear power as the only feasible alternative for energy-hungry economies. The increase in global demand for energy combined with the race to cut hydrocarbon emissions to half by 2050, will put tremendous pressure on renewable energy sources, however, the only other alternative that can currently guarantee large supply of energy is the nuclear option. The negative aspect of this type of energy lies in the risks involved in its operation which are far greater than those associated with hydrocarbon-based plants. In the race to provide new such plants, health, and other safety risks might be compromised in this era of profit driven economies, and private sector control. The choice of the best location for each of the expected hundreds of new nuclear power plants on top of the available 439 operational ones worldwide is a necessary step towards safeguarding public health and safety, as well as ensuring cost effectiveness. This paper reviews the application of different spatial decision making models in a GIS environment to select the optimum sites for nuclear power plants using a case study in Saudi Arabia. The results of the case study and discussed and compared.

Keywords: GIS, Nuclear Reactors, Facilities Siting, Multi-Criteria Decision Making

Introduction - Why go nuclear?

The combined production of electricity in the GCC countries is 273 kWh/year [2]. This is expected to grow exponentially over the next decade due to the high rate of population increase, and the increase of living standards. This demand can currently be met using hydrocarbon-based energy sources for the next decades, however, beyond that, the growing demand will require many countries to start building Nuclear Power Plants (NPP) at least to prepare its workforce for future needs. While renewable sources of energy provide a good alternative from an environmental perspective, they are by no means an efficient source of energy to cover the needs of major cities let alone countries using the currently available technologies. This is due to multiple factors such as cost, practicality, and other factors. A medium sized city would require thousands of acres of exposed solar panels to cover its energy needs. The combined cost of solar panels, their maintenance and the land they require, significantly exceeds the cost of other sources of energy including the nuclear option. There are currently 30 new countries considering starting a new peaceful nuclear power program to generate electricity including most Arab and Middle Eastern countries.

In addition to above mentioned reasons, there is a need to start building the local capacities in designing, building, and operating such plants. This will require accelerating the process of owning such installation sooner rather than later, even though energy shortage doesn't seem to be forecasted for a region with abundant supply of hydrocarbon deposits. While establishing and nuclear physics, and nuclear engineering departments at local universities is required, it is by no means enough to cover for practical, hands on experience that can be gained from working on local installations.

Objectives

As identified in the introduction, there is a dire need in the world to increase power production generating facilities, and especially NPPs. While NPPs would provide the most feasible energy supply option, there are numerous concerns of the environmental, health, and other risks expected to be posed by such installations. Choosing the most feasible sites to locate such installations would significantly reduce such risks. This paper aims to review and compare spatial decision making techniques to site a Nuclear Power Plant through the review of available literature. In addition, the authors will use a case study region in Eastern Saudi Arabia to identify the proposed site for a joint Gulf Cooperation Council NPP installation.

Methodology

The authors have conducted a thorough literature review of similar work done in the past covering site selection methodologies for power installations in general, and other types of installations. In parallel, similar review was conducted to cover work done in the decision making field to identify available models that can be implemented in such endeavor. In addition, the authors drew from their own experience in the fields of GIS Analysis, Remote Sensing, and Geological Mapping which combined spans over 50 years.

Review of Available Models

Traditionally, site suitability problem has been the classic problem to deal with since the early implementation of grid-based analysis models during the early sixties [10]. However, as models started to mature, and the technology advanced, attempts to model more complex models started to take into consideration that in real life, suitability problems do not only take into account more than one criteria, but also more than one objective. This is especially true in the case of land-use planning where several conflicting land-use elements are competing for the same land. The degree of complexity of the model increases with the increase of the number of criteria and/or objectives. Figure 1 illustrates the increase of model complexity in relation to the number of objectives and criteria. The NPP siting problem is one of multi-Criteria, but single-objective decision making, which makes it less complicated than another problem where more than one land-use is required to be sited such as in the case of regional or local land-use plan preparation.

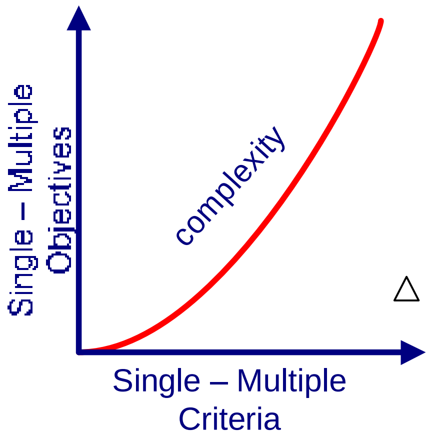


Figure 1: Relation between model complexity and objectives and criteria

In the following discussion, the authors examine the available multi-criteria, single-objective models for the siting application from the review of the available literature.

1- Binary Suitability Mapping

The most famous effort in this direction -although not the first one, was conducted by Ian McHarg[12], in his 1968 immortalizing book "Design with Nature". McHarg used a manual technique of overlaying transparencies each representing certain criterion in which data is divided into good areas, and bad areas; the good areas are left transparent, while the bad areas are blackened. At end, photocopying the overlaid transparencies to generate a final map where clear areas yielded the best sites. The same model is adopted in early grid analysis systems using an AND function to combine the binary scores of different criteria, hence eliminating any cells that didn't score 'good' in all criteria.

Later efforts used an OR function to allow for minimum risk approach where all cells that scored 'good' in at least one criterion are selected as suitable. Below is an illustration to the product of combining of the value of cells from three layers; the first option is the High Risk (HR) approach in which the logical AND operator is used to determine the outcome of the combination. The result is no matter how good the site has done in all layers, it takes only one 'bad' value to eliminate the site. The second option is the Low Risk (LR) approach, in which a logical OR operator is used, and in that application, it is enough for a candidate site to score only one 'good' in any of the criteria to included in the selected sites.

1 AND 1 AND 0 = 0 (High Risk Approach)
1 OR 1 OR 0 = 1 (Low Risk Approach)

This technique in both variations is clearly handicapped in two ways; the first is that it doesn't allow for any tradeoffs; an area will be deemed unsuitable if it fails to achieve a full score of suitability in each criterion which doesn't reflect any flexibility in the model or the other way around if we are following the LR approach. The second problem with this model is that it doesn’t allow for altering the relative importance of any criteria against the other criteria since the output is always binary.

2- Weighted Overlays

Weighted overlay techniques use a continuum of values that range from good to bad for each criterion represented by shades of colors on each grid. The generic form of the weighted overlay technique uses Equation 1 to extract the value of each cell in the resulting grid.

$$Suitability = \sum_{i=1}^{n} W_i V_i * \prod c_j$$ **Equation 1**

Where: Suitability= combine suitability score for certain cell;
V_i = criterion score for factor i; and
W_i = weight of factor i
$\prod$ = Product
C_j = Criterion score of constraint j

The analyst can apply preferential weights to different criteria in order to emphasis the importance of certain criteria versus other criteria. The weights are then multiplied by the values each cell scores in each criterion. The sum of scores for each cell determines if the cell has scored above or below certain threshold that determines whether or not it belongs to the suitable areas. There are many technical points to be discussed in this model configuration; 1- determining the weights of criteria, 2- comparing different criteria, 3- overlay function.

Weighted Linear Combination (WLC)

This technique uses equation 1 by combining the sum of all layers representing how well different sites have performed against different criteria. The different criteria have to be "Normalized" first, which means that they have to be reclassified to the same evaluation scale, then weights are established using one of different techniques to differentiate between different criteria based on their relative importance, then, these weights are multiplied by the normalized scores in each criteria, the output is then combined in a simple addition operation. This is the most commonly used method to perform Weighted Overlay. It is usually associated with the Analytical Hierarchy Process (AHP), which is a decision making technique first discussed by Saaty[10], and in which pair wise comparison is conducted between each two criteria as shown in Figure 2 using AHP Weight module of Idrisi Andes software package.

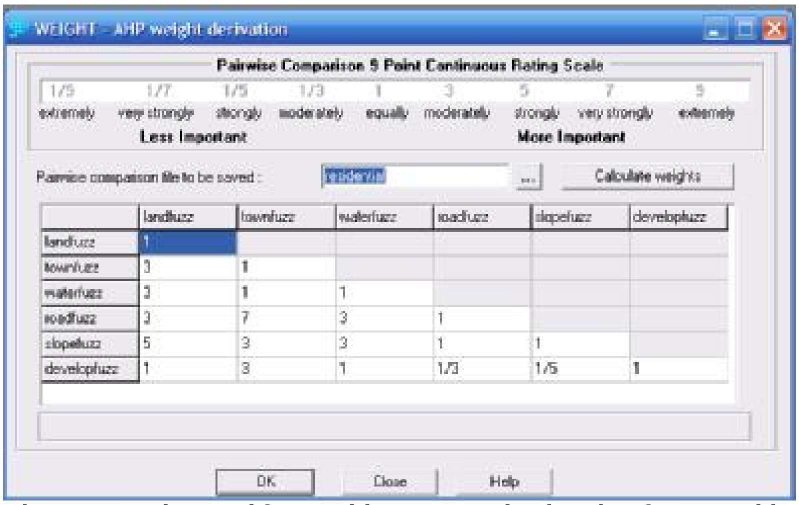


Figure 2: Pair wise comparison table used in AHP Method as implemented in Idrisi

Further mathematical operation is required to reach the actual weight of each criterion; first, each value in the table is divided by the total value of the column, then all rows are summed to yield the final criterion weight. The pair wise comparison is conduced using the Delphi technique, where experts in different domains discuss the relative importance of each criterion.

Ordered Weighted Average (OWA)

This method resembles the previous method in each of the steps discussed above with one exception; it doesn't stop at the criterion importance weights obtained by comparison, but rather, it introduces an additional function that can alter the final score each cell obtains. This function is called "order weight"[10]. The analyst can dictate the way the system will choose the score each cell will ultimately get; suppose for three criteria A, B, and C, the values obtained for one cell were 3, 7, and 9. in OWA, the analyst can choose a Low Risk approach by instructing the model to choose the minimum value among all scores:

Final score = minimum (A, B, C) will result in choosing the value (3).

While a High Risk approach would be to instruct the model to choose the highest scored value as follows

Final score = maximum (A, B, C) will result in choosing the value (9).

Although there are other techniques in the literature covering other types of GIS based decision making for suitability analysis, such as Genetic Algorithms, Neural Networks, and Expert Systems. These techniques will not be discussed in this paper as they were deemed less documented and of little significance in the scientific publications. In order to prepare the model to be followed, the authors conducted a review of the types of NPP to identify the possible type that will be acquired, since that will effect the site requirements.

Case Study

The main objective of the model developed in this case study is to identify the most feasible site that would comply with the IAEA standard requirements, as well as some additional factors set by the authors to differentiate between various sites. These factors are then combined using different methods; Weighted Overlay Techniques using the Analytical Hierarchy Process, and the Binary Overlay Model. The different model outputs are then run, and compared.

Types of Nuclear Power Reactors

There are different types of NPPs. The identification of the expected type is crucial in determining the site requirements, hence the model criteria. The following table is captured from Godoy[6], it illustrates the different types of nuclear power reactors used worldwide, as well as the percentage of their use.

Figure 3: Nuclear power plants in commercial operation (Source [9])

Reactor type	*Main Countries*	*Number*	*GWe*	*Fuel*	*Coolant*	*Moderator*
Pressurised Water Reactor (PWR)	US, France, Japan, Russia	264	250.5	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	43	23.6	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	18	10.8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK)	Russia	12	12.3	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.0	PuO_2 and UO_2	liquid sodium	none
other	Russia	4	0.05	enriched UO_2	water	graphite
	TOTAL	439	384.6			

GWe = capacity in thousands of megawatts (gross).

From the table, it is clear that the most used type of NPPs is the Pressurized Water Reactor (PWR) type which is most likely to be chosen by new, 3rd world energy operators in general, and the GCC countries in particular. As mentioned above, predicting which type of NPP is to be chosen is crucial to the assumptions of the model to be developed since the requirements vary from one type to the other.

Criteria for Siting Nuclear Power Reactors

Godoy[6] discusses the different criteria involved in the decision making process for the objective of siting a Nuclear Power Plant; he identifies twelve criteria as being the major ones when it comes to averting the dangers and negative effects of the new NPP.

Table 1: Main Criteria to be considered when siting a Nuclear Power Plant (after Godoy, 2007)

#	*Factors*	#	**Factors**
1	Seismicity and surface faulting,	7	Dispersion in air and water,
2	Subsurface material,	8	Population distribution,
3	Vulcanism,	9	Emergency planning,
4	Flooding,	10	Land use,
5	Extreme meteorological phenomena,	11	Availability of cooling water
6	Human induced events,	12	Others.

The list in Table 1 is supposed to cover any NPP siting exercise worldwide; he then lists another set which is the set of constraints. These could be looked at as site rejection criteria.

In contrast to fuel/coal thermal plants, were the burning material is a prime factor in locating the plant (more than 3000 tones of coal will be needed for a 1000 MWe plant), raw material is not a concern for shipping. The most urgent criteria is the proximity to a major water surface to draw from and discharge to the cooling water. In the case of Saudi Arabia, this leaves only the two coastal areas East and West with potential candidate sites. In this paper, the case study is only focusing on the Eastern Province; hence, the Arabian Gulf is the only available source of cooling water.

Data Gathering

The authors conducted a thorough search of available data for the case study area. Their efforts resulted in the construction of a GeoDatabase covering the area, and including most of the required data as per the IAEA site evaluation requirements. Table 2 shows the criteria gathered for the sake of implementing the models

Table 2: Criteria gathered for the case study

Type	**Criteria**
Constraints	Existing Agriculture Built-up area Oil fields Pipeline corridor
Factors	Water surface Epicenters Surface cover Accessibility - Roads Accessibility - Airports Distance to population Distance to Agriculture Distance to Aquifers Distance to Wadis Distance to Vulcanoes Topography

Option 1 – Binary Overlay

The first model configuration was that of the Binary overlay using the AND, low risk approach to identify the best site for siting the NPP. This included the production of proximity maps for the quantitative variables (i.e. accessibility), and the reclassification of the nominal variables (i.e. surface geology). The next step was to normalize all maps to reflect the 1/0 dichotomy used in the binary overlay. Figure 4 illustrates the use of the Reclassification tool in ArcGIS Model Builder to achieve this result.

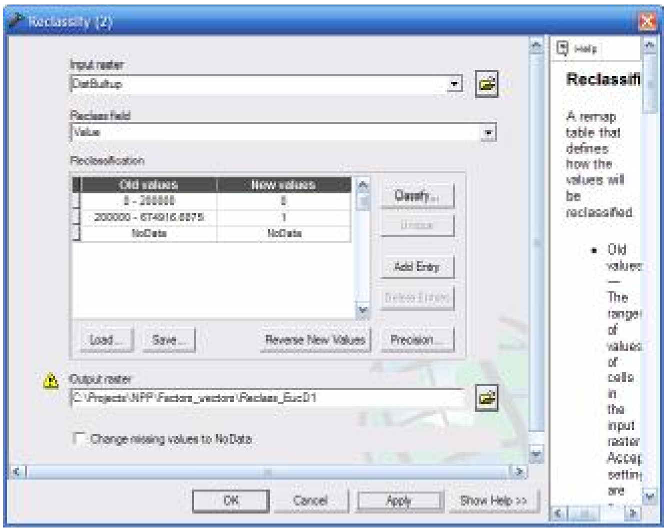


Figure 4: Binary reclassification of the proximity to builtup areas in study region

All constraints were combined, and a masking layer was created to eliminate the lands considered as constraints. These included the current Agriculture, Builtup areas, Oil Fields, and Pipeline Corridors.

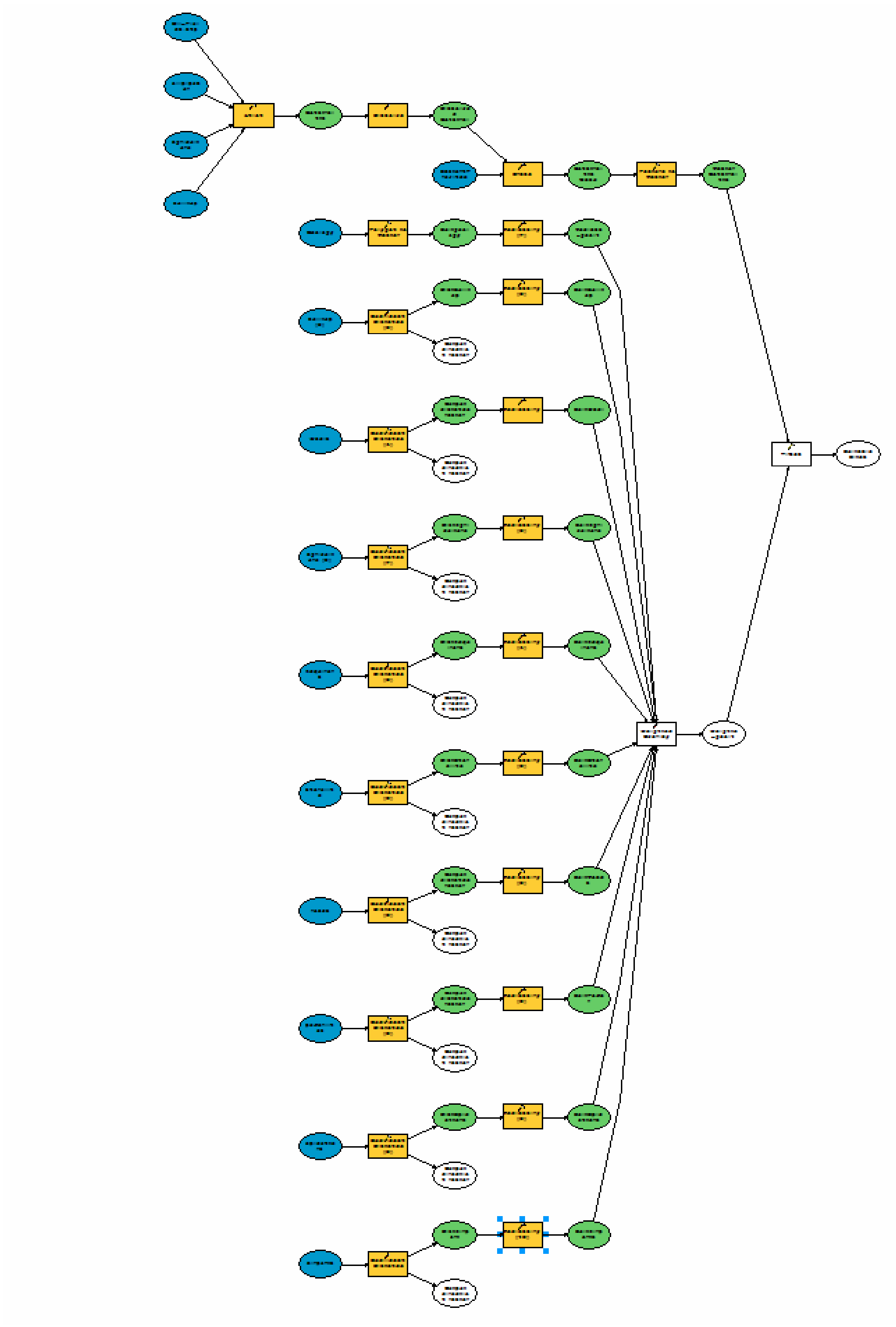


Figure 5: Binary overlay model configuration

Running the Binary Overlay model was a painful experience; the rigidity of the model proved to be a challenge since all 10 factors had to yield positive results in order to be identified as suitable site. The authors had to relax different criteria in order for the model to produce any results although the most important criteria such as proximity to water, and keeping safe distance from population centers, agriculuture, and water sources were not touched.

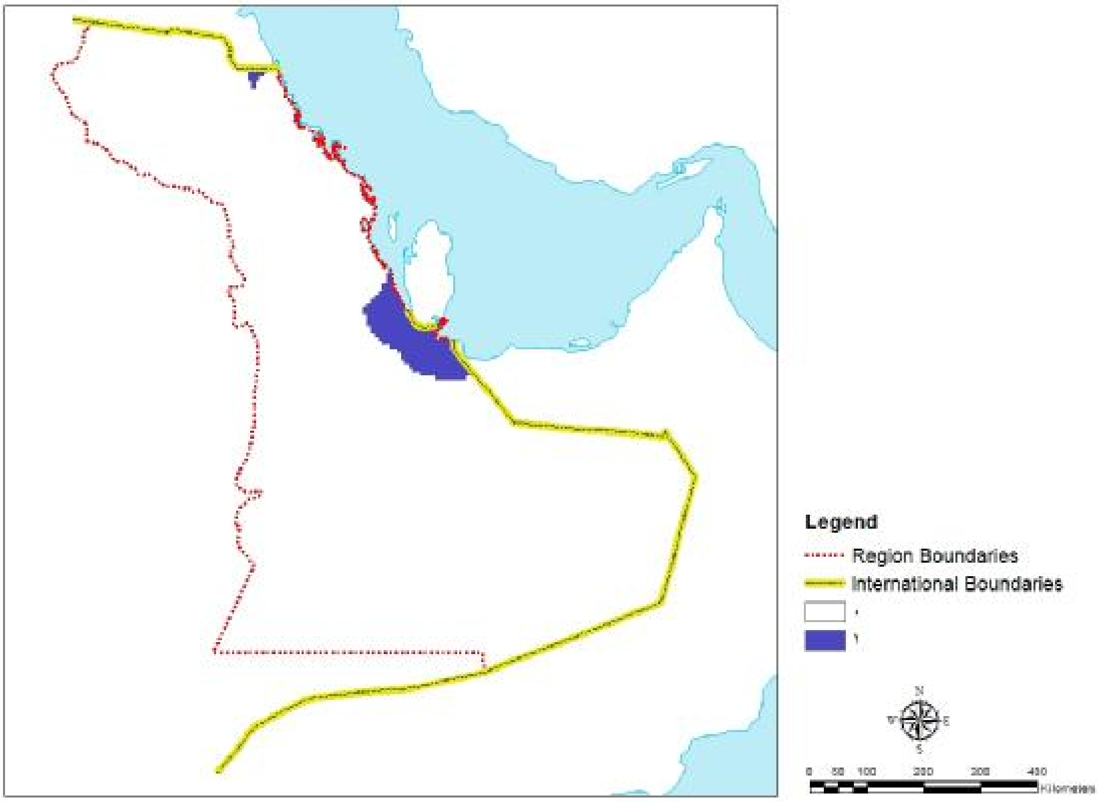
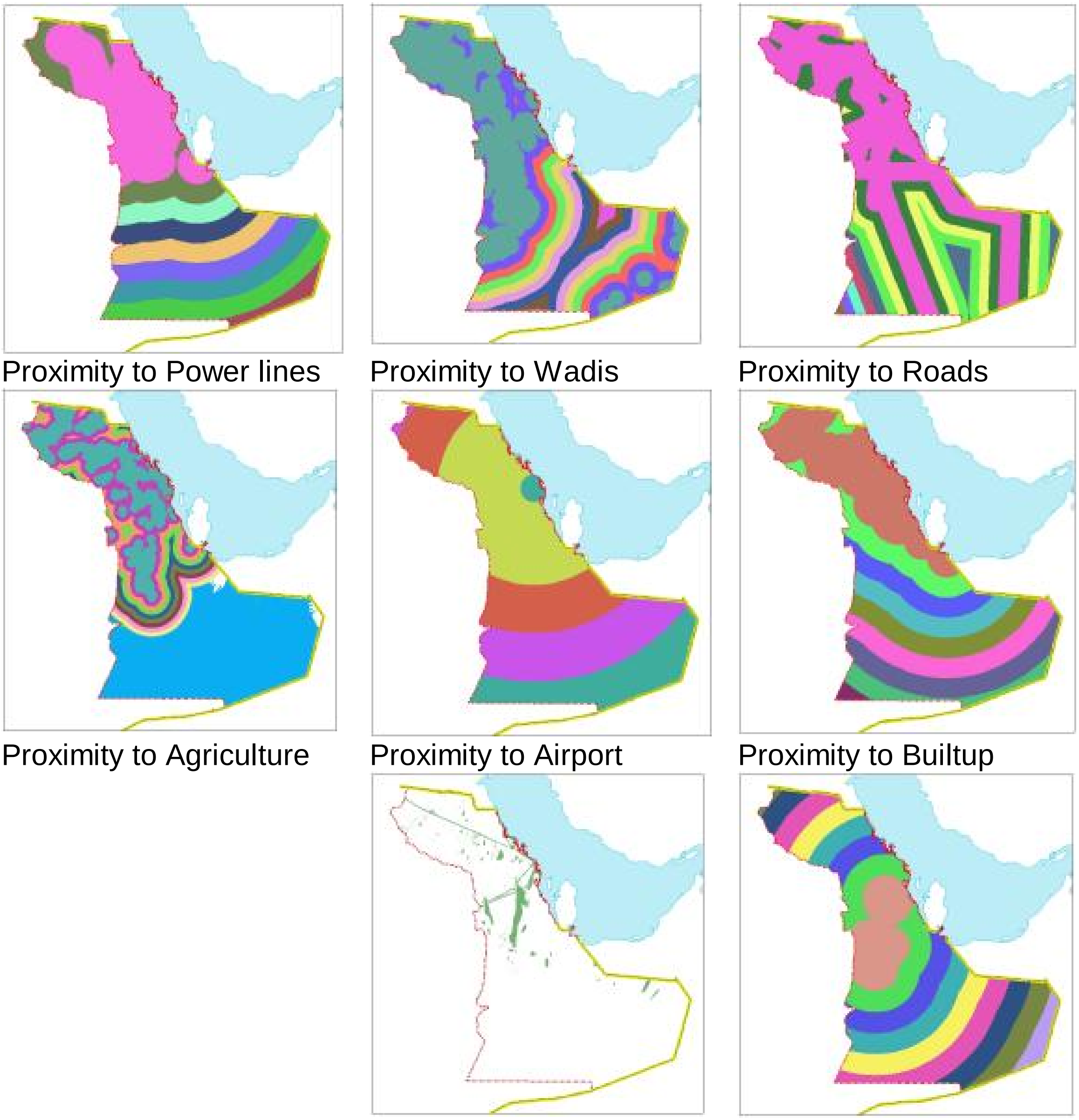


Figure 6: Selected sites for NPP by Binary Overlay technique

Option 2 – Weighted Overlay

Figure 7 illustrates some of the criteria used in the model. The figure shows the normalized version of the criteria after unifying all of them to 1 – 9 score scale. This unification is intended to be able to measure effect of each criterion in the same way.

Proximity to epicenters Surface suitability Proximity to water



Proximity to Power lines | Proximity to Wadis | Proximity to Roads
Proximity to Agriculture | Proximity to Airport | Proximity to Builtup
Combined Constraints | Proximity to Aquifers

Figure 7: Some of the criteria used in the model

The authors tested the performance of two methods of weighted overlay; the first is the Weighted Linear Combination, and the second is the Ordered Weighted Average (both discussed earlier). In order to derive the importance weights, the authors simulated a Delfi session with multi-discipline experts. A pair wise comparison was conducted and the relative scores were fed into a home made MS Excel macro that runs the Analytical Hierarchy Process. This run yielded the weights used in the model. The best performance of the OWA was generated when using the Average function to collect the average score each cell obtained against different factors. Finally, the result of the combination was multiplied by one masking layer combining all the restricted areas to eliminated the unwanted sites including those of the Agriculture, Urban, Oil Fields, and Oil Pipeline corridors. Figure 8 illustrates the Weighted Linear Combination model configuration as designed in ArcMap's Model Builder.

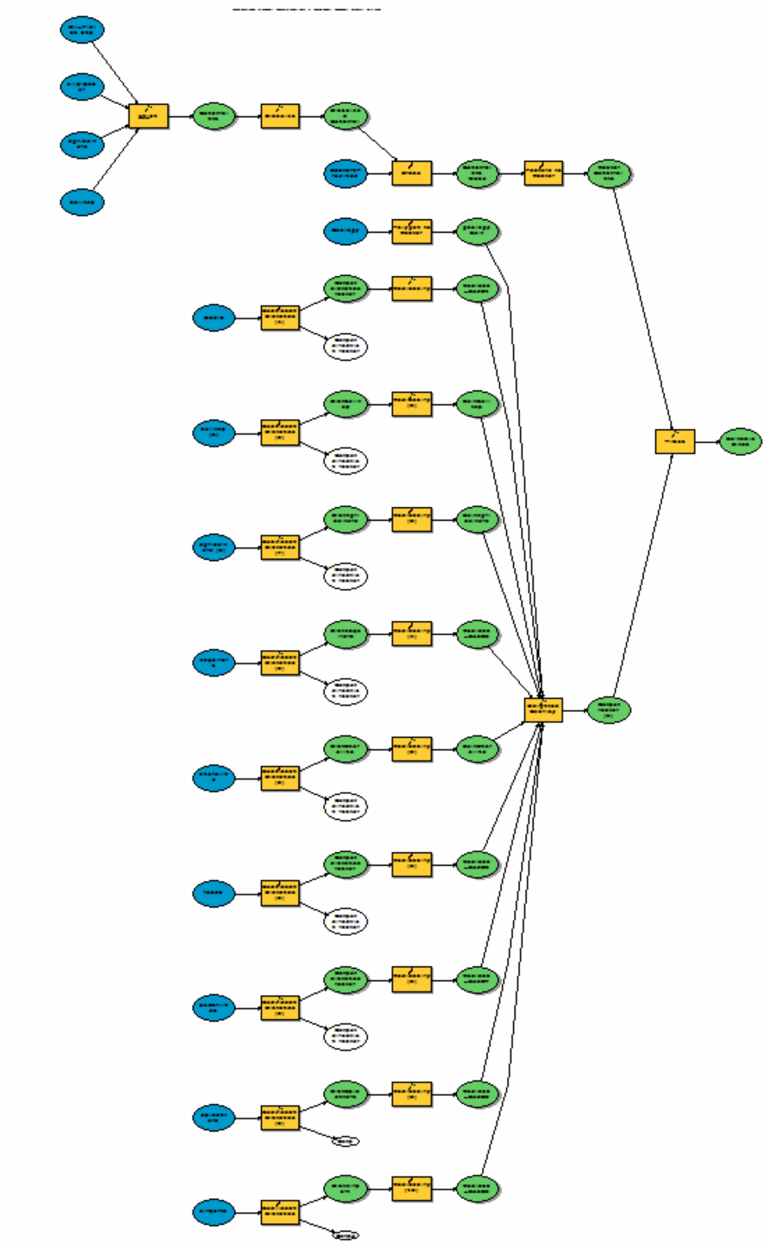


Figure 8: Weighted Linear Combination model configuration

As mentioned, the factor weights obtained using AHP process were then ported to the Weighted Overlay tool in ArcMap Toolbox as shown in Figure 9.

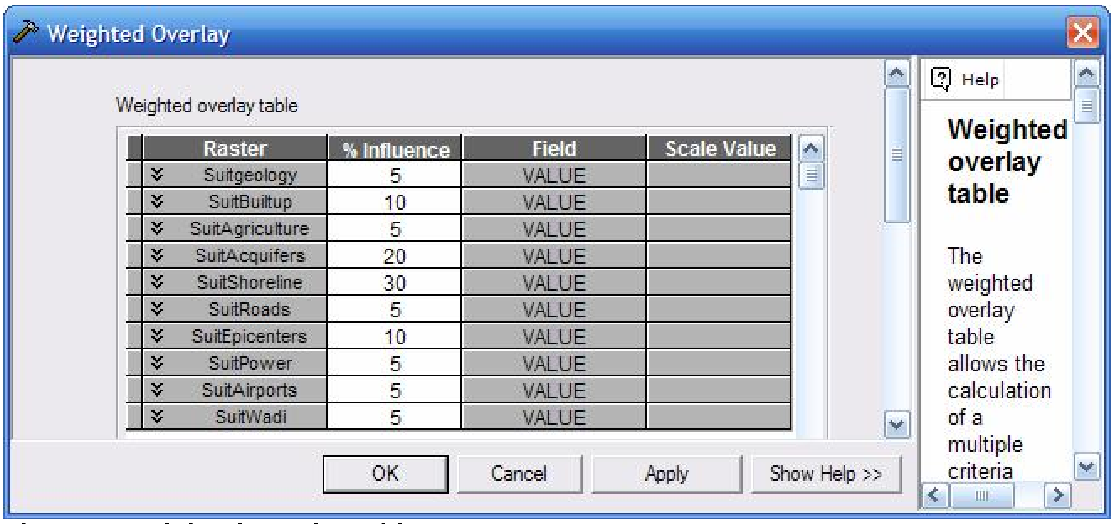


Figure 9: Weighted Overlay table

Finally, running the model yielded several suitable sites as illustrated in Figure 10. while both the Binary and Weighted Overlay methods have reached almost the same conclusion (although in much limited way in the case of the Binary Overlay method), the use of the Weighted Overlay's WLC method proved the most flexible and rewarding. The use of the Ordered Weighted Average proved painful and the results of the low risk approach were close to those obtained by the Binary overlay technique.

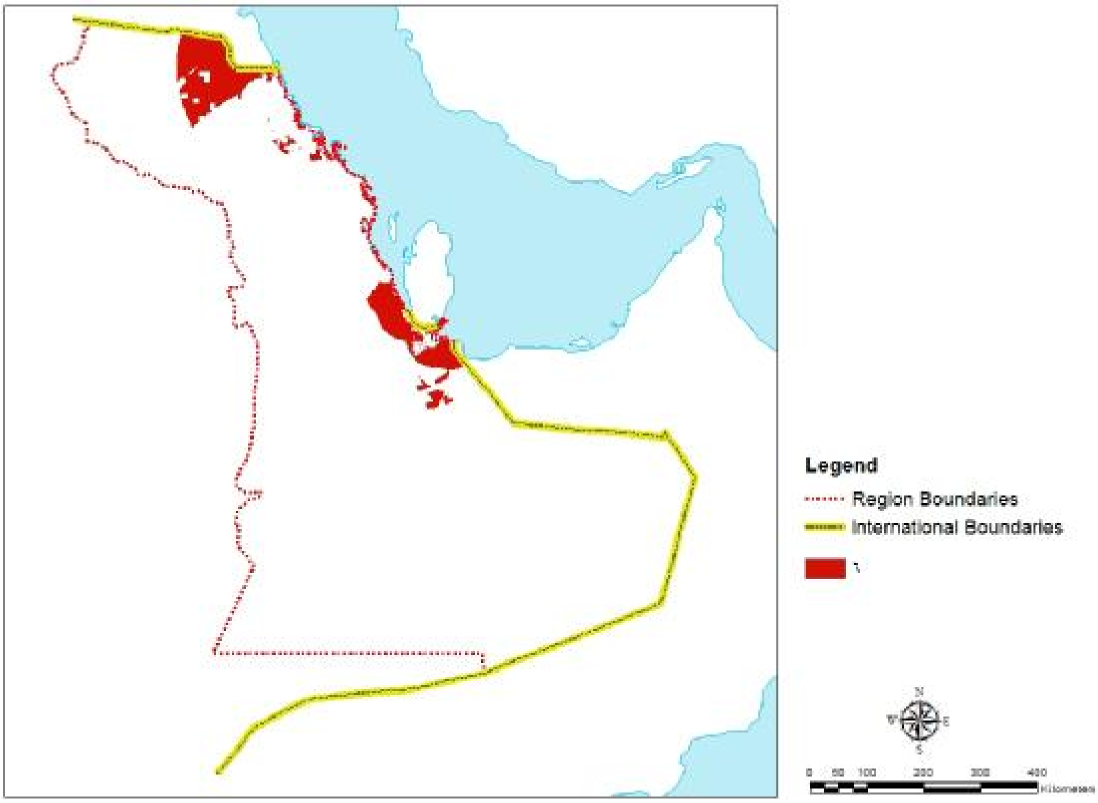


Figure 10: Selected sites by the model for siting NPP using WLC method

Conclusions

This paper discussed the need for Nuclear Power Plants, and in line with the GCC directive, examined the techniques and methods used in siting such a plant. The Binary Overlay technique has shown significant limitations, and had to be adjusted in an iterative way to relax the rules in order to achieve a minimum number of sites. The absence of tradeoff in that model makes it almost irrelevant in real life. The Weighted Overlay techniques examined showed that the Weighted Linear Combination (WLC) method has a lot of flexibility especially when coupled with tools borrowed from decision sciences such the Analytical Hierarchy Process, which helped in determining the weights of the criteria. In this exercise, the authors simulated the presence of multi-discipline team in a Delfi session. In real life situation, such team is irreplaceable. The Ordered Weighted Average OWA technique didn't add much to the performance of the model, and the results were questionable. The main hindrance to the accuracy of such model in real life would be the quality of data. The authors spent extensive time collecting the data, it is hoped that this would not be the case in a real life situation. More research is needed to identify the most suitable way of disposing of nuclear waste in the region, as this is the most important environmental problem to be tackled.

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