Paper for ISMAR10 symposium. **Topic No: 4 (125#)**

Site selection for underground dams using spatial multi-criteria evaluation in the semi-arid region of the state of Alagoas, Brazil

Daniel Webber*, Flávio Marques, Manuel de Oliveira Neto, Alexandre Hugo and Maria Sonia da Silva

Brazilian Agricultural Research Corporation.
*Correspondence: daniel.webber@embrapa.br; Tel.: +55 - 813-198-7840

Abstract: A spatial multi-criteria evaluation is proposed to identify suitable locations for underground dams (UD) in the semi-arid state of Alagoas, Brazil. This is a strategic program, which involves a national agency, Embrapa, and the State Government of Alagoas. Suitable areas are identified by combining spatial information on topography, hydrography, pedology, and geology. The topography (slope) and hydrography line vectors were extracted treating a Digital Elevation Model. The pedological data were classified using soil attributes including salinity and sodicity. The geological data were classified according their origin and structural/tectonic factors. The pluviometry data from 78 stations were classified and, subsequently, interpolated. Each map following a basic Geographic Information System analysis was divided into three categories. The "High suitability" category was given to locations that contain ideal conditions; the "Moderate" category indicates suitable regions, but may require further analysis focused on the element which indicated a low rating note, and finally, the "Low Suitability" category, indicates environmental limitations under the criteria presented here, although may still be considered if a more detailed investigation is performed. The methodology proved to be accurate for the scale of investigation as the results coincided well with the areas where the most efficient UDs are already in operation.

Keywords: Underground Dam; Site selection; Geographic Information System; Multi-criteria Evaluation

---

1. Introduction

The Brazilian semi-arid region has a severe scarcity of water, reaching 200mm to 800mm of rainfall per year and irregular frequency, possibly showing a lack of rainfall during 2 or 3 months in sequence. These climate conditions results put at risk the success of many agricultural and livestock activities and the live standard of rural families. Consequently, this situation enhances migration to the big cities or to other regions causing a social problem. Nevertheless, the region has a potential to capture 3,780 m^3 / habitant / year, which is equivalent to 400 water trucks / habitant / year [1]. Thus, the problem, at least in some locations, may be overcome through a proper management of water resources.

Rainwater harvesting during the drought period became a priority when designing and implementing public policies. In order to promote the efficient use and maintenance of water resources, the governmental programs and private initiatives have been increasing the deployment of social technologies for rainwater harvesting. Some examples include underground dams, little dams, cisterns for human consumption, cisterns for food production and watering (boardwalk cistern and storm cistern), “barreiro” trenches, stone tanks, among others.

The UDs offer capturing and rainwater storage in the ground. They consist mainly of a dam body (cut-off wall), which is constructed on a relatively impermeable formation under the ground in the transverse direction of descending water. Thus, a groundwater flow in the porous medium is restrained and as the groundwater level rises, it increases a volume of water stored underground. The structures proved to help the local communities with water provision enabling regular and permanent production of crops and livestock and, consequently, offering the resilience of the families to the adversities of the climate, and contributing to the sovereignty, nutritional and food security of the agricultural families of the region [2-4].

There are many advantages of the UDs in comparison to the conventional surface dams, such as, (a) evaporation losses are low; (b) there is no reduction in storage volume due to silting and absence of the accumulation of sediments in reservoirs; (c) the stored water is less susceptible to pollution and health hazards due to mosquito breeding; (e) the land above the underground dam can be utilized as it was before the construction of the dam; (f) potential disasters caused by the collapse of dam walls are non-existent; among others [5].

The Brazilian Agricultural Research Corporation - Embrapa has been researching UD (submersible model) for agricultural purposes in the Brazilian semi-arid since 1982. The Embrapa has been developing agricultural research projects and technology transfer actions among universities, the State Government of Alagoas, Articulação do Semiárido Brasileiro (ASA Brasil), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ), Banco do Nordeste, and Institutos Federais de Educação, Ciência e Tecnologia.

The region classified as semi-arid covers 45% of the territory of the State of Alagoas (1,258,000 hectares) and encompasses 38 municipalities with approximately 30% of the state's population [6]. Data from ASA Brasil point out that there are more than 70 UDs constructed in the semi-arid region of Alagoas [7], which is a significant quantity and a great opportunity for the validating process of the site selection methodology. Identifying suitable locations for the construction of UDs is necessary for its success and requires a multi-criteria evaluation, including pedological, geological, climatic, hydrographic and geophysical data. Since there is a robust number of geospatial data from the semi-arid region of State of Alagoas, available on the 1:100000 scale, Embrapa and the State Government of Alagoas joined efforts to identify which areas have the required characteristics to build sustainable UDs. This contribution proposes a low-cost site selection method for the construction of UDs in the semi-arid of Alagoas using a spatial multi-criteria evaluation.

2. Materials and Methods

2.1 GIS Data Collection

Primary and secondary data of the study area were collected from Brazilian Government [8-13] and from NASA sites [14]. All layers (vectors and raster) were imported to ArcGIS, adopting SIRGAS 2000 as the reference system.

2.2 Exclusion areas

The reservoirs, lakes and urban areas were manually digitalized and vectorized using 5-meter resolution images (GeoEye and other satellite images from ArcGIS basemaps) and, then, converted to raster. Those have reached 1.5% of the total semi-arid region of Alagoas, being defined as exclusion areas in this site selection methodology.

2.3 Evaluation of Slope for UD Construction

A mosaic was created from 30-meter SRTM elevation raster images collected from NASA website using Mosaic to New Raster Tool and, subsequently, converted to the 1.100000 scale (pixel size of 20m). Topography (contour) were extracted from a Digital Elevation Model (DEM) and hydrography line vectors were extracted from a Hydrologically Consistent Digital Elevation Model (HCDEM). The HCDEM is a DEM whose flow direction defines expected flow of water over the terrain (the drainage pattern).

Since there wasn´t a significant number of elevation points available for the study area, a Digital Terrain Model (DTM) could not be created. However, a Triangular Irregular Network (TIN) was built using Delaunay triangulation from contour lines and stream lines in order to get more homogeneity to the model. TINs are a form of vector-based digital geographic data and are constructed by triangulating a set of vertices. The vertices are connected with a series of edges to form a network of triangles.

The outliers (data that was too high or blank) were detected with "Locate Outliers tool" and, after, excluded from TIN. TIN was converted to a raster image (TIN to Raster Tool) and, subsequently, a slope percentage was calculated (Slope Tool). Finally, the slope was classified using a Embrapa method [15], where data from 0 to 3% as "High Suitability" category, 3 to 8% as "Moderate Suitability" and, upper 8% as "Low Suitability".

2.4 Evaluation of Soil-water Conditions for UD Construction

The drainage system was configured to extract pixels that value greater than or equal to 100 considering that many headwater streams or streams in semi-arid regions sometimes run dry. Spring points were identified at the vertices of all tributaries and, after, received 50 meters circular buffers according to the premises of the Brazilian Environmental Laws. These areas were classified as "Low Suitability". As UDs are not recommended to operate on soils with high salinity and sodicity, other buffers measuring 80 meters were defined around the whole drainage system in order to clip this attributes from soil layer.

The pedological data from Embrapa [8] were classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories using soil attributes, such as, effective depth of soil or lithic contact, presence of stony, rocky, erosive and texture. The layer was then merged using 80-meter buffer of the drainage system that contained soil salinity and sodicity.

2.5 Evaluation of Geology for UD Construction

The geological data from CPRM [10] were classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories according to their origin (sedimentary, igneous or metamorphic) as well as structural / tectonic factors, including the presence of faults, fractures and foliation. Hydrogeological conditions require that dams should be located in water transmissive sediments overlying a poorly-permeable formation. For example, permeable fractures in the underlying formation may cause preferential groundwater flow resulting in a risk that the water stored in an UD escapes.

2.6 Evaluation of Climate Conditions for UD Construction

Climate conditions were also included in the multi-criteria evaluation through the pluviometry data, once rainfall is the main source of water recharge in semi-arid regions. Spatial-temporal analysis of pluviometric scenarios are necessary for the identification of areas suitable to the construction of UD. In the present study, 78 pluviometric stations – only those with historical rainfall series over 20 years – were interpolated in three different seasons (dry, rainy and interseasonal) and, classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories. The dry season represents the years where the total rainfall accumulated in the three consecutive rainy months was equal to or less than the value corresponding to the probability of 25%. The rainy season represents those years whose total precipitation, accumulated in the three consecutive rainy months, is higher than the value corresponding to the probability of 75%. The inter-seasonal records refer to years that were not classified in the two previous categories. Areas presenting total annual rainfall over 600 mm were classified as “High Suitability”, those presenting less than 300 mm were classified as “Low Suitability” and, areas presenting between 300 and 600 mm were classified as “Moderate Suitability”.

2.7 Spatial Multi-criteria Evaluation for UD Construction

The raster maps obtained were submitted to basic operations using the GIS raster calculation tool. The numerical grids of each matrix file were multiplied between them. Pixels classified in the “High Suitability” category were represented by the integer number “2”, “Moderate Suitability” category pixels by the integer number “1” and; “Low Suitability” category pixels by the integer number “0”. It is worth mentioning that any number multiplied by zero equals to zero. In the sense of spatial relations, all “Low Suitability” categorical areas of any of the five thematic evaluations will overlap “High Suitability” and “Moderate Suitability” categorical areas that are in the same position. An exception was configured to the spring evaluation which had “High Suitability” category pixels represented by the integer number “1”, considering that this kind of natural resource requires only one restriction area for the structure constructions.

Finally, the map resulted in six products coming from the programmed combinations using a multi-criteria evaluation. As usual, the values were classified into the three categories – “High Suitability” from 5 to 16, “Moderate Suitability” from 1 to 4 and, “Low Suitability” for 0 values of final raster´s pixels. This final raster was converted to a feature (polygon) and symbology of all categories has been chosen according to the following colors: dark green for “High Suitability”, light green for “Moderate Suitability” and, beige for “Low Suitability” areas.

In our approach, the “High Suitability” categorical areas are dedicated for those polygons that contain ideal natural conditions for UD construction. The “Moderate Suitability” categorical areas are suitable, but may require further analysis on variables which low evaluation rates were recognized. The “Low Suitability” categorical areas have natural limitations for the construction of UDs, however they are not prohibited since environmental studies did not indicate any technology that could provide water source in these areas.

In order to check if the site selection methodology and the current strategy of UD construction were matching, the layer of UDs in operation was imported to the GIS project where spatial analyzes could be made with all suitability categorical areas.

3. Results

3.1. Slope Suitability for UD Construction

The slope obtained from TIN showed an adequate homogeneity to the suitability map considering the limitations of SRTM Radar (Shuttle Radar Topology Mission) to penetrate in vegetation (not until the ground). The polygons resulted from the slope evaluation have reached an average size of 63.36 hectares. Table 1 presents some statistics of the areas by classes.

Table 1. Slope classes and respective areas (average and maximum).

Classes	Average Size (hectare)	Max. Size (ha)
High Suitability	84.07	688,750.03
Moderate Suitability	2.23	2,328.88
Low Suitability	103.79	15,893.56
Average	63.36	235,657.49

In the slope evaluation, 67.18% of the study area was classified as “High Suitability” (844,695 hectares), 17.02% as “Moderate Suitability” (213,956 hectares) and, 15.80% as “Low Suitability” (198,662 hectares). Considering that around 84% of the study area presents less than 8% of slope

(Moderate to High Suitability), the state shows adequate slope conditions for the construction of UDs (Figure 1).

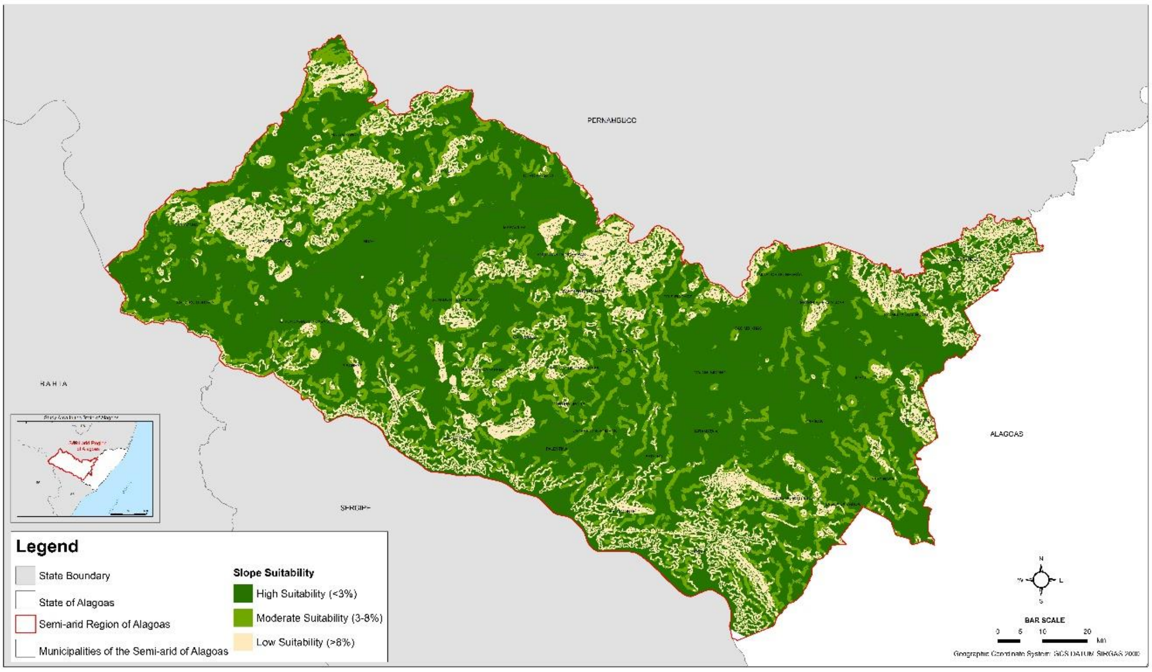

Figure 1. Slope Suitability Map.

3.2. Soil-water Suitability for UD Construction

The evaluation of soil-water conditions was essential to identify more areas with "Moderate" and "High Suitability" classes compared to the isolated pedological classification (Table 2).

Table 2. Classes of Pedological and Soil-water suitability, respective areas and percentages.

Classes	Pedological		Soil-water	
	Area (hectares)	**Area (%)**	**Area (hectares)**	**Area (%)**
Low Suitability	866,721.13	68.89	796,429.88	63.31 ↓
High Suitability	261,713.69	20.8	274,889.99	21.85 ↑
Moderate Suitability	109,069.66	8.67	166,185.27	13.21 ↑
Water bodies	11,333.8	0,9	11.333,80	0.9
Urban Zones	9,233.09	0,73	9.233,09	0.73
Total	1,258072.03	100	1,258072.03	100

The "High Suitability" and "Moderate Suitability" areas were better distributed throughout the semi-arid region from the soil-water point of view than in the single pedological one. It could be noticed clearly in the hinterland region (Figure 2), where the analysis of soil characteristics did not contain conditions conducive to the construction of UD. When overlapped by the soil-water layer, it was possible to identify "High Suitability" and "Moderate Suitability" categorical areas in the surrounding areas of streams where soils do not present salt or sodium.

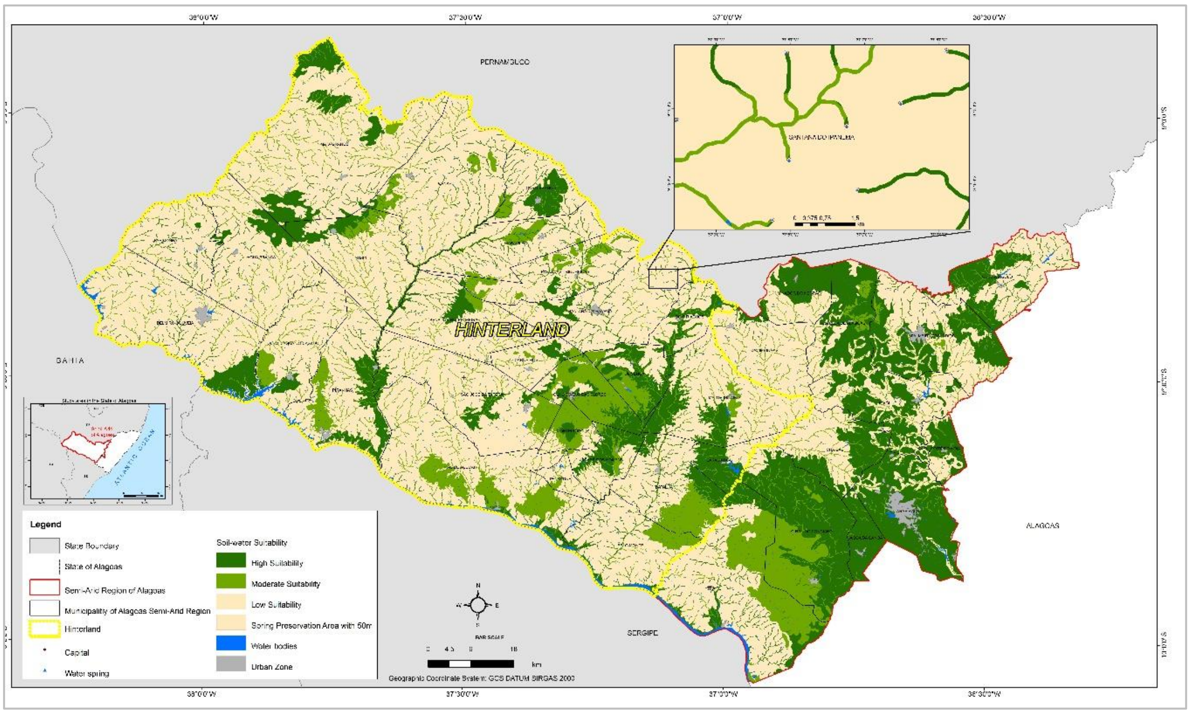

Figure 2. Soil-water Suitability Map.

3.3. *Geological Suitability for UD Construction*

In the evaluation of lithologic units the "High Suitability" categorical areas were predominant, occupying more than half of the entire semi-arid region of Alagoas (62.06%), followed by the "Moderate Suitability" (28.18%) and "Low Suitability" (9.75%) categorical areas (Figure 3).

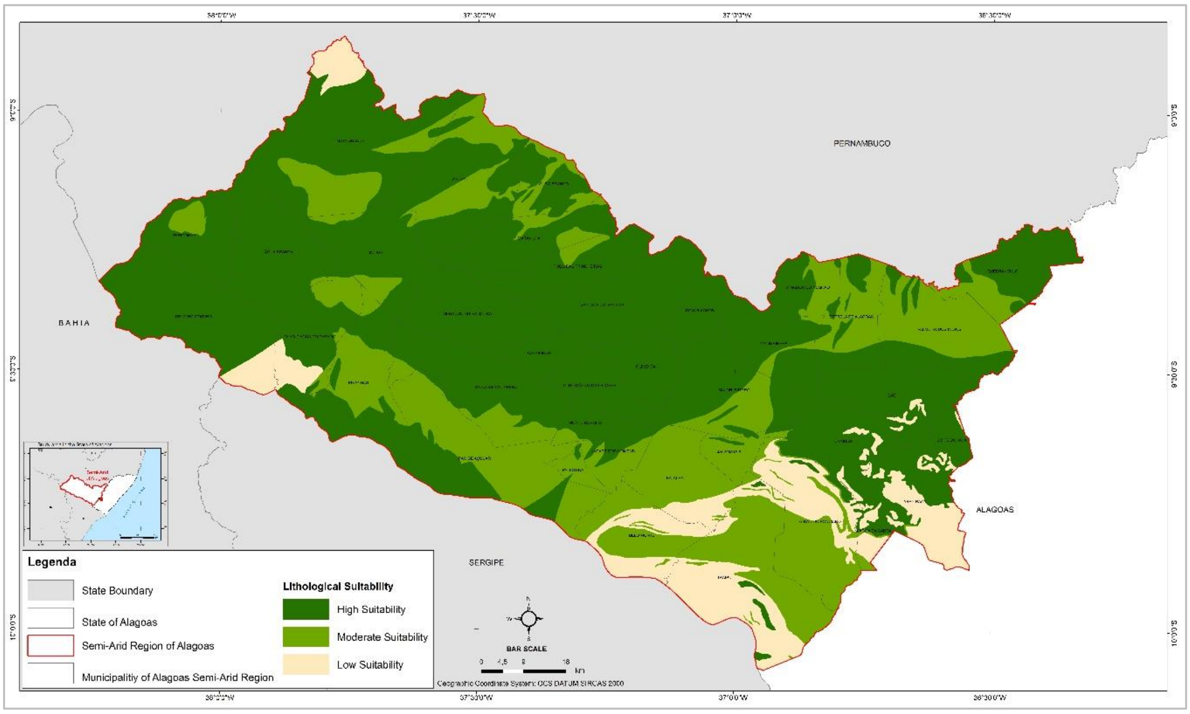

Figure 3. Geological Suitability Map.

3.4. Climatic Suitability for UD Construction

Considering the pluviometric scenario of dry years as the most restrictive among the other two (rainy and interseasonal), it was used for the multi-criteria evaluation. During this period the climate conditions for water recharge are limited, with annual rainfall around 300 to 600 mm. Only three small isolated areas were classified as "Low Suitability", with annual rainfall totals lower than 300 mm, which means there is enough rainwater to guarantee at least one period with stored water (Figure 4).

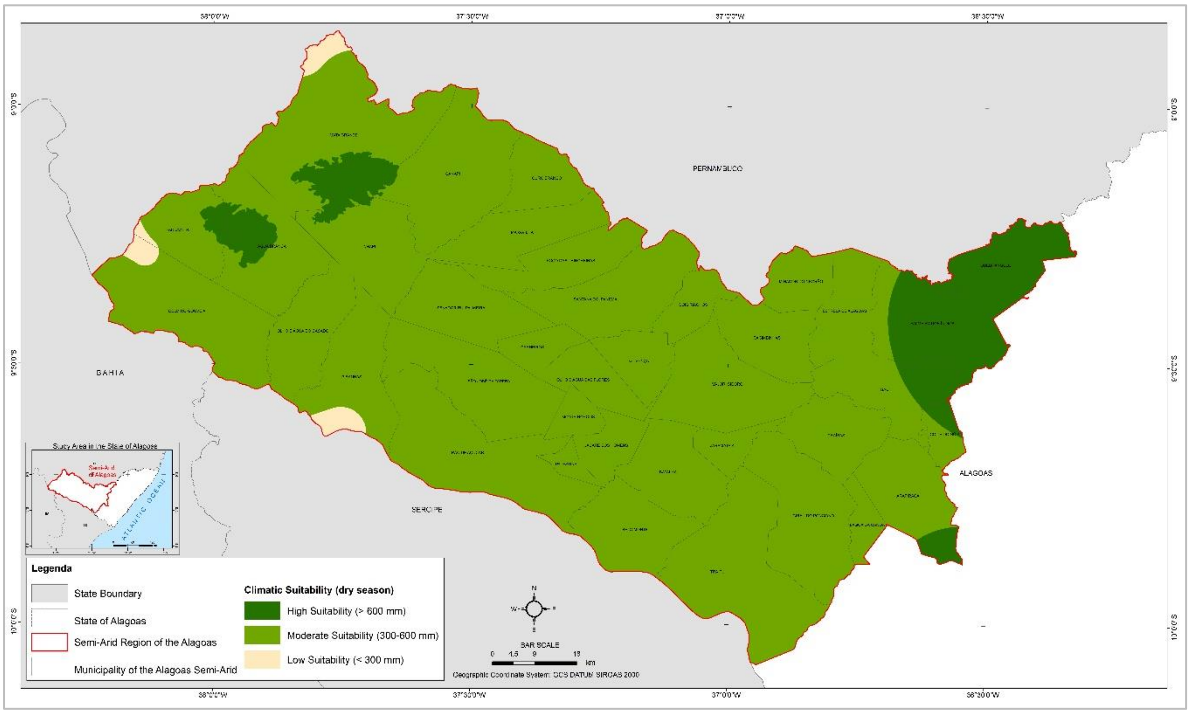

Figure 4. Climatic Suitability Map.

3.5. Site selection for UD using spatial multi-criteria evaluation

The methodology could point out the best sites for UD construction considering five different environmental characteristics in a multi-criteria evaluation. The result of all GIS operations is a layer containing each value of these variables and its respective category. Therefore, it´s possible to identify not only the multi-criteria suitability category, but also analyze which characteristics (geological, slope, climatic and soil-water) were responsible for this condition.

Homogeneous polygons were obtained in the proposed methodology, which are concentrated around the drainage system or along the semi-arid in a set of polygons closely arranged. Average size of high and moderate suitability categorical polygons is 18 ha. This average size of polygon areas is enough to build an UD for agriculture purposes, which is generally two ha.

Visually analyzing the suitability map overlapped by some of the UDs in operation (Figure 5), it´s possible to notice compatibility between the results of the proposed methodology and the current ASA strategy for UD construction. Even so, it´s still not possible to quantify the resulting suitability areas neither do make any statistic with UD´s in operation, once the validation process has not started and changes in the current configuration might happen.

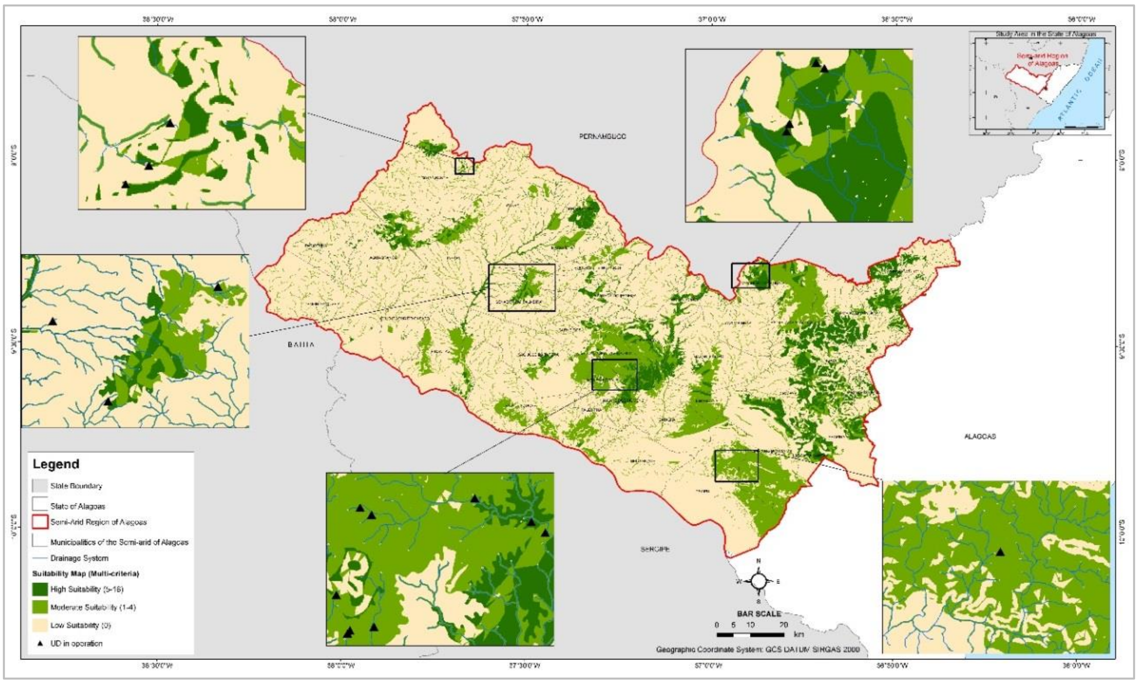

Figure 5. Suitability Map (Multi-criteria) and UDs in operation.

Indeed, this analyzes will be a consistent contribution to the validation map process, which will include survey with farmers, technicians, non-governmental organizations and, rural extension agents, in order to improve and complement the suitability map. It will help decision makers of Embrapa and the State Government of Alagoas to identify potential areas for the construction of pilot technologies and to orient future R&D projects, as well.

4. Discussion

The spatial multi-criteria methodology adopted for underground dam's site selection is simple, but innovative and effective, since existing areas obeyed satisfactorily the multi-criteria evaluation. However, the methodology cannot be replicated in other semi-arid regions since most of them has less accurate cartographic basis, especially in Brazil.

Despite the fact the scale level used in this work (1:100,000) is not the most appropriate for the construction of local structures, this was the most detailed possible considering the cartographic bases available for the Brazilian semi-arid. In addition, the pedological data from Agro Ecological Zoning of the State of Alagoas [8] is the only in 1:100,000 scale which is updated to the Brazilian system of soil classification. Even though, some secondary spatial data used in the multi-criteria evaluation were not in the project target scale (1:100,000), the cell size resample tool and the vectorization process could improve the accuracy of the multi-criteria suitability map. It´s worth mentioning that the geological data used in this study is the most detailed (1:250,000) among the Brazilian states.

It was possible to associate some UDs in operation with their respective categories obtained from the suitability map. These analyses (links) can be considered a reference for the validation process. As soon as the validation process finishes, the suitability map for the UD construction will be available for decision makers from the State Government of Alagoas and other companies in order to select the best areas of the semi-arid to define public policies to this water technology. A detailed investigation is warranted in the selected areas before constructing any kind of hydraulic structure.

Since there are no official procedures of the construction of UDs in the semi-arid of Alagoas, and there is a large number of UDs already in operation, the suitability map becomes an important and strategical tool and should be used as a guidance document to construct and manage UDs.

Acknowledgement

We wish to thank the following organizations for granting important data to our research: Embrapa, Secretaria de Estado do Meio Ambiente e dos Recursos Hídricos de Alagoas, Articulação do Semiárido Brasileiro, Companhia de Pesquisa de Recursos Minerais, Superintendência de Desenvolvimento do Nordeste, Agência Nacional das Águas and USGS-NASA.

Special thanks should be given to Dr. Antonio Gomes Barbosa, coordinator of the P1 + 2 program and other social programs which ASA Brasil is involved, and Dr. Wilton José Silva, Progestão coordinator from Secretaria de Estado do Meio Ambiente e dos Recursos Hídricos de Alagoas for their valuable technical support on this project; Dr. Konrad Miotlinski, professor of Universidade Federal de Santa Catarina, for reviewing and helping to translate this paper.

References

1. Brito, L.T.; da Silva, M.S.L.; dos Anjos, J.B.; de Oliveira Neto, M.B.; Barbosa, A.G. Tecnologias de captação, manejo e uso da água de chuva no setor rural. In *Captação, Manejo e Uso de Água de Chuva*, 1st ed.; Instituto Nacional do Semiárido, Campina Grande, Brazil, 2015. p. 243-271.
2. Lima, A. de O. Nova Abordagem metodológica para locação, modelagem 3d e monitoramento de barragens subterrâneas no semiárido brasileiro. PhD Thesis, Universidade Federal do Estado do Rio Grande do Norte, Natal, Brazil, 2013.
3. Nascimento, A.F. do; Silva, M.S.L. da; Marques, F.A.; Oliveira Neto, M.B. de; Parahyba, R. da B.V.; Amaral, A.J. *Caracterização Geoambiental em Áreas com Barragem Subterrânea no Semiárido Brasileiro*, Série Documentos, 1st ed.; Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos, Recife, Brazil, 2015, pp. 54p.
4. Silva, M.S.; Parahyba, R.P.; Oliveira Neto, M.B.; Leite, A.P.; Santos, J.C.; Cunha, T.J.; Moreira, M.M.; Ferreira, G.B.; Anjos, J.B.; Melo, R.F. *Potencialidades de classes de solos e critérios para locação de barragens subterrâneas no Semiárido do Nordeste brasileiro*, Circular Técnica, 1st ed. Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos, Recife, Brazil, 2010. Pp. 7p.
5. KanKam-Yeboah, K. Underground dam technology in some parts of the world. *Research Gate* **2004**, *Volume 1*, pp. 113-130p, DOI: 10.5917/jagh1987.46.113. Available online: https://www.researchgate.net/publication276323482 (accessed on 12/12/2018).
6. BRASIL. CONDEL Resolution n° 107, July 27, 2017. Available online: http://sudene.gov.br/images/2017/arquivos/Resolucao-107-2017.pdf (accessed on 2/05/2018).
7. ASA Brasil. Available online: http://www.asabrasil.org.br/mapatecnologias/ (accessed on 13/11/2018).
8. Geoinfo Embrapa. Available online: http://geoinfo.cnps.embrapa.br/layers/geonode%3Aalagoas_zaal_lat_long_wgs84 (accessed on 20/08/2018).
9. SUDENE. http://sudene.gov.br/images/arquivos/semiarido/LIM_Semiarido_Municipal_OFICIAL.zip (accessed 07/06/2018).
10. CPRM. Available online: http://geosgb.cprm.gov.br/downloads/ (accessed on 3/07/2018).
11. ANA. Available online: http://metadados.ana.gov.br/geonetwork/srv/pt/main.home (accessed on 03/07/2018).
12. Agritempo. Available online: https://www.agritempo.gov.br/agritempo-wgis/composer/ (accessed on 20/04/2018).
13. SEMARH-AL. Available online: http://www3.funcate.org.br/geo/available/geoweb-v01-alagoas/src/php/app.php (accessed on 16/02/2018).
14. USGS-NASA. Available online: https://earthexplorer.usgs.gov/ (accessed on 18/03/2018).
15. Embrapa, Serviço Nacional de Levantamento e Conservação de Solos. Súmula da 10 - Reunião Técnica de Levantamento de Solos. In *Embrapa-SNLCS. Miscelânea, 1*. Rio de Janeiro, Brazil, 1979; pp. 83p.