Application of GIS Multi-Criteria Decision Analysis for Managed Aquifer Suitability Mapping in China

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Abstract

China's freshwater resource is 2.8 trillion m^3, however, due to high population water resource per capita is limited. Also because of the uneven distributed water resource and water demand, some parts of China are under severe water stress. Based on this fact, managed aquifer recharge (MAR) is being considered to replenish groundwater storage of the country, slow down land subsidence and also prevent and retard sea water intrusion. The present study used GIS multi-criteria decision analysis (GIS-MCDA) method to identify suitable sites for implementing MAR type spreading method. Suitable sites were identified by constraints and alternatives. Aquifer type, land use, slope and national reserve zones were used as constraints to single out the unavailable sites. Aquifer type, soil texture, land use, slope, groundwater quality were used as alternatives to create a final suitability map. Among different alternatives, step-wise function was used for standardization, pairwise comparison was used for criterion weighing as well as weighted linear combination was used as decision rules. The results show that 82% of the feasible area is suitable for implementing spreading MAR. The highly suitable areas locate in the north part of China. Most areas are moderate suitable and distribute throughout the country. The areas with low suitability are mainly in North China Plain and northeast part of China, due to the limitation of aquifer type. 25 existing spreading MAR sites are plotted in current study and 43% of them are in highly suitable area, the result shows a good fit for the suitability map and existing sites.

Keywords: Managed aquifer recharge (MAR), GIS, Spreading method, Suitability mapping.

1 Introduction

China is located in the eastern part of the Asian Continent and at the west coast of the Pacific Ocean. With a mean annual precipitation of 660mm and an area of approximately 9.6 million km^2, China has a total water resource of 2.8 trillion m^3 (Ministry, 2016). However water resources are distributed very unevenly in both time and space.

Due to the water stress caused by the unevenly distributed water resources and the imbalance between water resources and water consumption, groundwater is being overexploited. Methods to solve the growing water demand need to be implemented. Managed aquifer recharge (MAR) is being considered as a possible solution. MAR is a powerful groundwater manager's tool, which may be useful for replenishing aquifers to oppose declining yields, saline intrusion or land subsidence (Gale 2005). Hence, managed aquifer recharge, as one possible solution, is discussed in this study.

The purpose of the present study is developing a method to obtain a suitability map for implementing surface MAR systems in China. To achieve this, geographical information system (GIS) is used as a tool to get the basic condition maps to generate the suitability map. For MAR systems, only spreading methods are discussed. Furthermore, the generated suitability map is compared with the existing MAR sites in China to check the compliance. This study can be used as a reference for MAR site selection for further research and construction.

2 Methods

In the methods part, an introduction of all techniques used in this study is provided. It offers a definition of MAR system, different MAR types, GIS and its benefits; also an introduction to multicriteria decision analysis (MCDA) and its procedure is discussed.

2.1 Managed Aquifer Recharge

Managed aquifer recharge, which is defined as recharge of an aquifer using a source of water (including recycled water) under controlled conditions to store it for later use or for defined environmental benefit (Dillon, 2009). MAR types can be divided by two main purposes: one is primarily to provide excessive storage of water and the other is primarily for water treatment. In this case, MAR is mainly use to replenish aquifer to store excessive water and slow down land subsidence and saline intrusion, it is clear that it serves for the first purpose.

2.2 Multicriteria Decision Analysis (MCDA)

Generally speaking, multicriteria decision making (MCDM) problems contain a set of alternatives that are evaluated on the basis of conflicting and incommensurable criteria (Malczewski, 1999). Decision making is a process that contains a series of activates starting with decision problem recognition and ends with recommendations. First recognize the problem that needed to be solved, specify the purpose. Once the problem is defined, find the set of evaluation criteria. The criteria should contain the objectives that reflect all concerns relevant to the decision problem and the measures for achieving those objectives. Then alternatives are chosen. The MADM approaches assume that the alternatives are specified and explicitly. The alternatives are represented by a set of pixels in a raster GIS database or a set of points, lines or/and polygons in a vector GIS. Each alternative is described by its locational attribute (coordinate data) and attribute data (criterion values) (Malczewski, 1999). Constraints are presented by points, lines, polygons and/or rasters characterized by certain attributes and certain values of attributes. Next, as all the alternatives are not equally important, different weights should be assigned to them, so the next process is called criterion weighting. At this stage, decision maker's preference is expressed by a higher weight for relative high importance and a lower weight for relatively low importance. Later, all the alternatives should be combined together to get a final map. The way to combine them is called decision rules. Furthermore, sensitivity analysis should be performed to determine robustness. Finally recommendations are given for future actions.

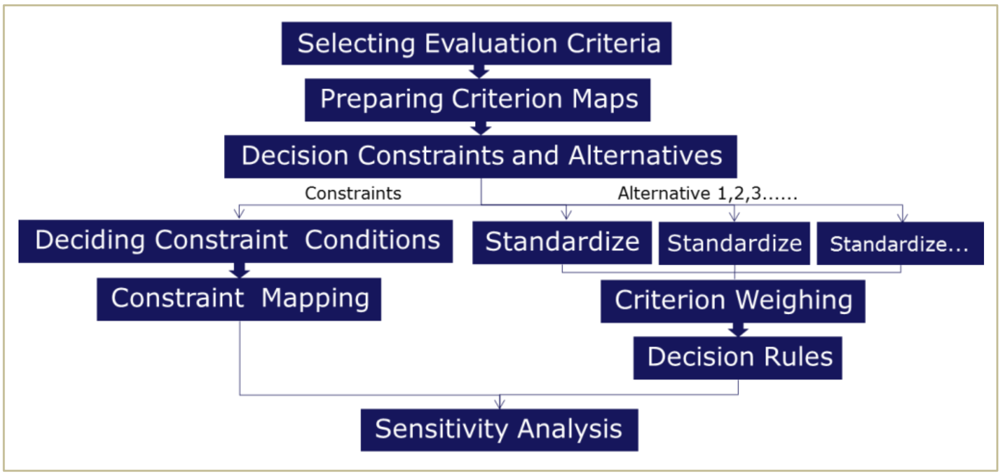

Figure 2.1 Procedure for GIS-MCDA used in present study (modified after Rahman, 2002)

Figure 2.1 shows the procedure that present study follows, method for each part will be discussed separately.

2.2.1 Selecting Evaluation Criteria

For evaluation criteria, as discussed above, it contains the concept of both objective and attribute. The way to select evaluation criteria is to specify the objectives and then achieve the objective by specific attribute. There is no universal technique for selecting evaluation criteria; it is based on specific problem. For the available resources, several authoritative maps were found: DEM map, geology map, aquifer type map, groundwater salinity map, natural reserve zone map, geomorphology map, land use map, soil texture map and soil type map. All of them are considered first and some of them are selected as criteria.

2.2.2 Decision Constraints and Alternatives

Constraints are the criteria that limited by nature or by human where certain actions are not permitted to be taken (Keeney, 1980). The setting of constraints is mainly based on available resources or regulations set by human with certain consideration such as soil water conservation. Constraints stipulate the limitation, so it should be the first one to determine.

2.2.3 Constraint Mapping

Constraint, as discussed before, sets the limitation for all decision alternatives (Malczewski, 1999). Constraint mapping is the procedure that set the feasible areas for further suitability mapping. To be specific, constraint mapping is the procedure that uses Boolean logic to modify each criteria map, assigning value 1 for the areas that are satisfied with its constraint conditions and assigning value 0 for the areas that are unfeasible. As several constraint conditions are set, using AND logic to overlay all the single constraint maps together. After gaining the constraint map, areas that are finally assigned 1 are the feasible areas for further suitability mapping.

2.2.4 Standardizing Criterion Maps

As all the criteria for the alternative are described in its own way and in a linguistic way, they are not able to compare with each other. For ArcGIS, it is not possible to do overlay on different raster layers without values. Therefore, standardizing the alternatives and assign values for each catalog are needed for further steps. Step-wise and linear functions are the two standardization methods (Bonilla, 2016). In current study, step-wise function was used for standardization. In each criterion, the most satisfied alternative catalog is assigned 1, and the rest catalogs are assigned between 0 and 1 according to their satisfactory level. So far, the criteria map is transferred into a digital map that ArcGIS can do further operation.

2.2.5 Criterion Weighing

As different criterion has different importance to the final objective, relative importance of the criteria is required. The procedure of distributing relative importance to different criteria is called criterion weighing. It can be achieve by assigning a value, a weight, to a criterion, indicating its importance comparing to other criteria (Malczewski, 1999). The larger the weight, the more important the criterion is. However, this step also depends and varies according to different decision makers.

Pairwise comparison method was chosen for current study, as it is hierarchical, easy to use, high trustworthiness and quite precise. This method involves pairwise comparisons by creating a ratio matrix. It takes the ratio matrix as input and the relative weights as output (Malczewski, 1999). The procedures for pairwise comparison are: 1. Develop pairwise comparison matrix. 2. Compute criterion weights. 3. Estimate consistency ratio.

2.2.6 Decision Rules

The aim of multicriteria analysis is to get the most preferred alternative, to rank the alternatives from best to worse. There are many decision rules that can be used to solve multiattribute decision making (MADM) problems. The aim for decision rules is to find a procedure to overlay all the alternative maps together considering their relative importance. Current study considered weighted linear combination method for decision rules. The GIS based WLC method can be achieved by the following steps: define the evaluation criteria (map layers) and feasible alternatives; standardize each criterion map; define criterion weights; create weighted standardized criterion maps by multiplying standardized criterion map by its corresponding weights; compute overall score of each alternative by adding (overlay) all the weighted standardized criterion maps; finally rank all the alternatives according to the overall score, the alternative with the highest overall score is the best.

2.2.7 Sensitivity Analysis

For present study, sensitivity analysis was done by ignoring one of the criteria, as some of the criteria are with unsatisfied result or less importance. The procedures for this step are, firstly abandon one of the criteria, recalculate the pairwise comparison matrix of the rest to reallocate criteria weights, use WLC to get new overall values for all alternatives. Comparing the new values with the old values, estimate the percentage of the alternatives that has changes and its changing range, finally do analysis with the results.

2.3 Comparison with Existing MAR Sites

As there are already existing MAR sites in China, based on literature review, several spreading MAR sites are pointed out on the map, comparing the site of existing MAR with the suitability map, analyze the adaptation of the suitability map.

3 Results and Discussions

3.1 Constraint Map

The constraint map contains four constraint criteria: slope, land use, natural reserve zone and aquifer type. Constraint mapping was achieved by ArcGIS. Generate four raster layers, assigning value 0 for constraint areas and value 1 for other areas, then added four layers together using “raster calculator” tool. The final constraint map was conducted by giving 0 for constraint areas and 1 for feasible alternatives.

3.1.1 Slope

Slope is set as one of the constraint since as higher slope will cause more runoff, less infiltration and more soil erosion. The constraint of slope was set by “Technical Specification for Investigation of Land Use Status” (NARC, 1984). It stated that higher than 25° is the limit slope for land reclamation. When slope is higher than 25°, severe water soil erosion will happen with water flushing the area. So 25° was also chosen as the constraint for MAR site selection. After transform degree to percentage, 25° equals to 46.63%, the constraint was done by “reclassify” tool in ArcGIS. Areas with slope higher than 46.63%, a value of 0 is assigned On the contrary, area of slope lower than 46.63%, value 1 is assigned.

3.1.2 Natural Reserve Zone

As discussed before, national reserve zones were fully set as constraint. All six types of reserve zones: water conservation, soil and water conservation, windbreak and sand fixation, flood water storage, marine ecological protection and biodiversity maintenance are set as constraint since all of them are ecological vulnerable or ecological important.

3.1.3 Land Use

Land use was also set as one of the constraints since some kinds of land are not suitable for artificial recharge. These areas mainly include three major types: all water areas, some of construction areas and some of unused land. Water surface areas contain river, lake, reservoir, ice and snow, shoaly land and mudflat. These areas cannot be used for spreading method purposely. For construction areas, special construction lands are excluded. These contain mining area, dense industry area, saltern, oil field, quarry and airport. In these areas, soil surfaces are mainly in use, otherwise water infiltration will cause safety problems for the work underground. Therefore all of these areas were excluded too. For unused land, gobi, wetland, saline and alkaline land, bare rock land, tundra and alpine dessert were excepted since these areas are not suitable for infiltrating.

3.1.4 Aquifer Type

Aquifer type was set as constraint as the aquifers are with frozen layers. All types that are with permafrost layers were excluded as water cannot infiltrate while they are frozen.

Aquifer type is raster file, therefore constraint map can be generate directly using “reclassify” tool, giving 0 to permafrost layers and 1 to all the others.

3.1.5 Final Constraint Map

Final constraint map was conducted by overlaying four sub constraint maps together. It is shown in Figure 3.7. 48.44% of the whole areas are constrained. Most of the constrained areas lie in the west part and northeast part. In central part and southeast part, the constraint areas are mainly caused by natural reserve zones. After making the constraint map, it was also converted to a mask, using “raster calculator” tool to set null for all areas with 0 values, which are the constraint areas, and leave the area with value 1 as mask. Next use “extract by mask” tool in spatial analysis, select the mask layer created before, extract all the maps that are going to use in suitability mapping.

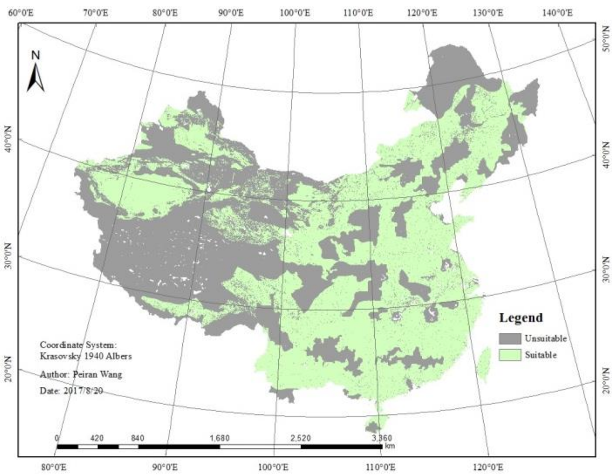

Figure 3.1 Constraint map for MAR suitability mapping in China

3.2 Suitability Map

Suitability mapping, as discussed before, contains following steps: standardizing criterion maps, weighing all the criteria, then set decision rule for overlaying the criterion maps. Use ArcGIS to achieve all the procedures and create final suitability map. Five criteria were chosen for suitability mapping, therefore five map layers need to be standardize. They are aquifer type, soil texture, land use, slope and groundwater salinity.

Table 3.1 Standardization and classification of aquifer type, soil texture, land use, slope, groundwater salinity for MAR suitability mapping

Aquifer Type	Values	Coverage
Confined and unconfined sand-gravel aquifer	10	6%
Confined and unconfined sedimentary aquifer/ Unconfined karst aquifer/ Confined and unconfined basalt fissure aquifer	8	46%
Unconfined sandy aquifer/ Confined and unconfined sandy aquifer	7	11%
Unconfined metamorphic fissure aquifer/ Unconfined igneous fissure aquifer	5	22%
Unconfined silty aquifer	4	1%
Confined sandy aquifer/ Confined sand-gravel aquifer	0	13%

Soil Texture	Values	Coverage
K_{sat} between 10 – 100 µm/s	10	17%
K_{sat} between 1 – 10 µm/s	7	65%
K_{sat} between 0.1 – 1 µm/s	4	18%
K_{sat} between 0.01 – 0.1 µm/s	1	0%

Land Use	Values	Coverage
Pasture land	10	28%
Cultivated land	8	29%
Forest	6	29%
Unused land	3	11%
Residential area	2	3%

Slope	Values	Coverage
≤ 3.5%	10	57%
3.5% to 10.5%	7	25%
10.5% to 26.8%	4	16%
26.8% to 46.6%	1	2%

Groundwater Salinity	Values	Coverage
Fresh water	10	89.8%
Brackish water	7	2.7%
Saline water	4	7.5%

Results for criterion weighing are: Aquifer type 34.4%, soil texture 31.2%, land use 17.9%, slope 10.1% and groundwater salinity 6.4%.

Weighted linear combination (WLC) was chosen as decision rule. WLC can be simply achieve by "raster calculator", using standardized map layer multiply its weight, then simply added all layers together, final map is gained after this.

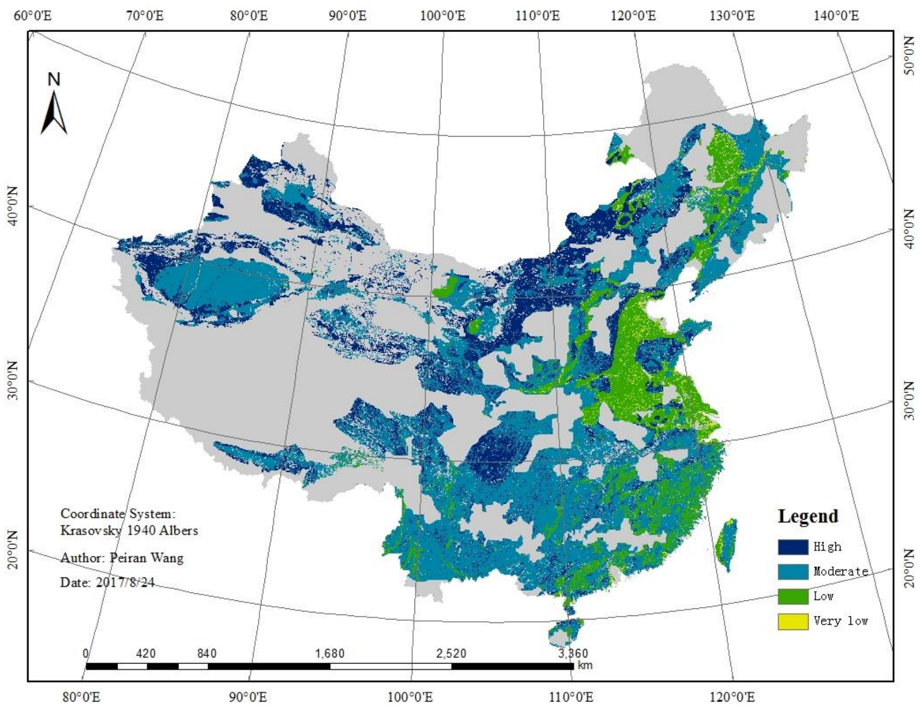

Figure 3.2 MAR suitability map of China

3.3 Comparing with Existing MAR Sites

Based on literature review, 25 locations are found with existing MAR sites (Figure 3.15).

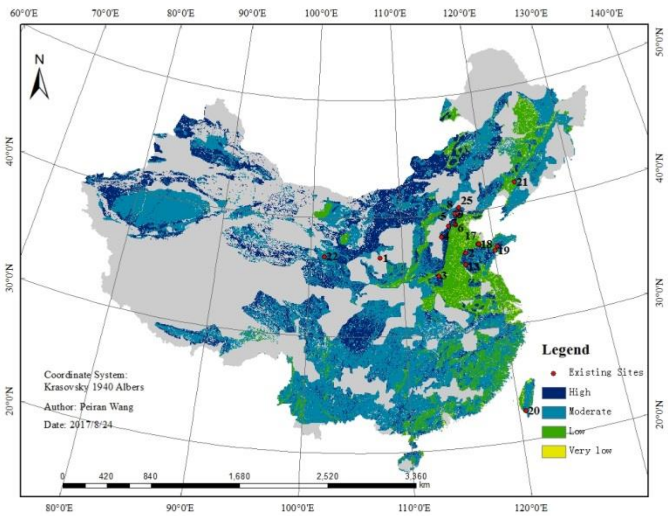

Figure 3.3 Locations of Existing MAR sites in China

Table 3.2 Distribution of existing sites in suitability map

Grade	Number of sites	Percentage
High suitability	11	42.3%
Moderate suitability	6	24.0%
Low suitability	6	24.0%
Very low suitability	0	0%
No data	2	8.0%

4 Conclusions and recommendations

The selection of suitable sites for implementing spreading MAR sites is based on five criteria: aquifer type, soil texture, land use, slope and groundwater salinity. The results gained in this study can be used as an auxiliary for other similar study or other country. However, a lower grade does not mean that the area is totally unsuitable for conducting MAR. Further investigation should be done in actual site survey. And with different criteria, different results can be gained. A higher score in final suitability map only means that it has a higher possibility for better infiltration process in the site.

The areas that are suitable for MAR implementation take up to 82% of the total feasible areas, and the areas locate throughout the country. The suitable areas consist of two groups, the group with high suitability and moderate suitability. 62% of the areas are moderate suitable and they are widespread in the country. The areas that are with high suitability mainly lie in north part of China.

Suitability map shows a good fit with the existing spreading MAR sites. 11 out of 25 sites of existing MAR sites drop in to high suitability area. The two criteria that limit most of the other sites are aquifer type and land use. However, the founded existing MAR sites are too much concentrated in three provinces. This may cause the results not too much representative. More research should be done to find more spreading MAR across China.

In China, most of the population concentrates in the east and south east part of China and main water scarcity happens in these areas. Meanwhile based on the result, there are also sites with high suitability and a lot with moderate suitability stand in water scarcity areas. Spreading MAR can carry out in these areas to better solve or reduce water scarcity problems.

The suitability map can also be considered as one aspect, combining with other aspects, such as population, water demand, and access to water resources, to choose priority for implement MAR sites. Therefore, current study can be used as a general guidance of choosing suitable spreading MAR sites. However for realistic practice, further investigation should be done and more local and detailed information should be gained. Further study can focus more on a local scale with a smaller resolution.