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Research Paper

A Method to Assess Groundwater Vulnerability to depletion in Alluvial plain, Jilin, China

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Abstract: *The Quantitative Groundwater Vulnerability Assessment (GVA) method was developed and tested to provide vulnerability index maps to groundwater depletion. GIS technique was used to create these maps. A numerical ranking scheme is used to assess groundwater risk in varying geologic settings. The parameters used for vulnerability assessment of groundwater quantity in the Songhuajiang river valley, China, are aquifer thickness, drawdown, groundwater pumping density and net recharge. The GVA method was manipulated by using percentage ratio parameters and separated parameters to create two quantitative groundwater vulnerability assessment index maps and to choose which is the best method should be adopted to evaluate the quantitative groundwater vulnerability assessment (GVA). The percentage ratio parameters index map classifies 27% (score 0~5) of the study area as more safe and having least vulnerability to depletion, 46% (score 5~11) as having moderate vulnerability to depletion, whereas 27% (score 11~16) as having most vulnerability to depletion. The separated parameters index map classifies 25% (score 7~14) of the study area as having least vulnerability, 49% (score 14~20) as having moderate vulnerability whereas 26% (score 20~27) as having most vulnerability to depletion.*

Keywords: Vulnerability, ranking, index map, groundwater, aquifer.

Introduction

The Quantitative Groundwater Vulnerability Assessment (GVA) is an idea based on the fundamental concept that some land areas are more vulnerable to groundwater depletion risks than others [1]. Hence, spatially delineation of groundwater quantity risks (groundwater overdraft or aquifer depletion) can be considered as a function of geologic, hydrologic, hydrogeologic characteristics and intensive water utilization of the area, those were varied drastically from place to another [2, 3,4]. The heterogeneity of aquifer characteristics has great impacts on the groundwater assessment maps. The main purpose for demonstrating groundwater vulnerability to depletion or water quantity risk, is to formulate a convenient approach to create an index map that provides information on the relative occurrence and distribution of groundwater, presents the basis for understanding the relationship between groundwater and geological and hydrological environment and delineates areas where can relatively be recommended for safe groundwater abstraction from areas those are very sensitive to groundwater pumpage and create water depletion hazards. The general criteria for application were developed to encourage a consistent approach to groundwater quantity assessment. This approach was intended to be used in mapping application techniques such as a Geographic Information System (GIS). In fact initial application of related approaches employed a manual map overlay and computational procedure [5,6].

Merchant[7] was, probably, the first to use GIS to implement drastic techniques for groundwater vulnerability to contamination. Data from multitude of sources can be transformed to digital spatial information. Data can be manipulated with varieties of GIS softwares as those used for vulnerability to contamination [8,9]. Most of the previous groundwater vulnerability assessment approaches were used for groundwater contamination risk. It is a curial task to create a method for groundwater quantity distribution to reveal a quick picture of relative groundwater quantity regions in the area of concerned. However, the prepared maps are interpretations of known or estimated subsurface conditions. Groundwater maps, in contrast to most other maps, deal with transient, rather than essentially constant phenomena. Transient data can be shown on maps in two very different ways. One shows essentially static conditions on the basis of totals or averages for specific time span and the other shows conditions at a particular moment or during a short interval of time. The primary objective of groundwater vulnerability index map is to define the physical characteristics of the groundwater system. Various natural and artificial physical processes that operate in the saturated zones may cause the aquifer to change its hydraulic behavior.

To define more meaningful groups of vulnerability and to determine which processes are most important to be incorporated into quantitative groundwater vulnerability assessment, a method was developed, concerning groundwater quantity risk, based on geographic information system (GIS) to combine and display many layers of spatial data into different formats for results to be more easily interpreted. GIS has been used in many aspects of groundwater management and modeling [10, 11,12]. Hence, spatial evaluation of groundwater vulnerability to depletion or overdraft risk can easily implement in GIS than any other single groundwater related model. The quantitative groundwater vulnerability assessment (GVA) depends on the use of commonly available groundwater related data for evaluating quantitatively groundwater depletion or overdraft risk. Although most of the previous researches concerning the groundwater vulnerability assessment with respect to the pollution hazards, this is one of the new approach tackled the vulnerability assessment of groundwater quantity.

Creation of the index map implies manipulation of appropriate data in various ways to provides quantitative assessments of groundwater depletion at any point in the study area and creating the critical depletion groundwater index map. It would be possible to overlay all the polygons associated with the indicator parameters, according to location in the resulting polygons, and calculate statistics on those groups.The accuracy of composite map products is generally less than the accuracy of the least accurate map layer used in the analysis [13]. As the number of layers increases, the number of possible errors combinations increases rapidly. Thus, there are potential advantages in using the fewest number of factors required to produce an acceptable results particularly when one is employing data having varying scales and often unknown level of accuracy and precisions [14].

In Songhuajiang river valley (Figure 1), the system involves two components, designation of mappable hydrogeologic settings and superposition of relative rating system of parameters. A numerical ranking scheme is used to assess groundwater risk in varying geologic settings. The system contains three significant parts: weights, ranges, and ratings. In developing the method, each parameter will be evaluated with respect to the others (weighting) to determine the relative importance of each factor. The most significant start point in quantitative groundwater vulnerability assessment is the assigning of the most effective parameters to the groundwater quantity such as net recharge(R), pumping rate density (Q), drawdown (D) and thickness of aquifer (H). Ranges, ratings and weights for these parameters comprise a geographic information system (GIS) map layers. Overlaying maps of the most risk zones with maps showing the location of each potential risks of water quantity generates map of potential problem (Index map). Each parameters' map will be divided into either ranges or significant media types that have important impact on the quantitative vulnerability assessment. Each range for any parameter will be evaluated with respect to the others (ratings) to determine the relative significance for each range with regard to the risk (Table 1 and 2). Moreover, this approach determines a numerical value for any hydrogeologic setting by using a linear combination equation.

$$Depletion\quad Index = D_r D_w + R_r R_w + H_r H_w + Q_r Q_w \ldots \ldots\ldots\ldots\ldots..(1)$$

where the subscripts *r* and *w* denote the rating and weighting of each parameter respectively.
Since all parameters have the same weight and equal unity the above equation can be rewritten as:

$$Depletion\quad Index = D_r + R_r + H_r + Q_r \ldots..\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Once the index map has been computed, it is possible to identify areas that are more likely risk relative to others.

Material and Methods

The method of groundwater vulnerability assessment (GVA) consists on creation of a multi-layered geographic database (Mappable units) and creation of groundwater vulnerability index map based on overlay and ranking processes. The data based creation contained various layers including: Net recharge(R), pumping rate density (Q), drawdown (D) and thickness of aquifer (H) (Figure 2). Among above parameters, groundwater recharge is generally not directly measured, but rather inferred from more easily measurable physical parameters, often with the help of models with varying complexity [15, 16 ,17]. Arc-GIS software was used to overlay and evaluate these layers of spatially oriented data to determine the most affected sites location in the study area. Each item of information used in this approach should be in form of hydrogeologic and hydrologic map to be entered into a computer for subsequence spatial analysis. Once maps for the study area have been prepared, information will enter into the computer by geocoding the data. The specific x, y-coordinates for each parameter on a given map will maintain the spatial relationships between adjacent map parameters and referencing the map parameters to a common geographic coordinate system. The aforementioned parameters were manipulated into two ways to achieve a best result with reference to field check (Figure 2). First by using the range and rating for each parameter separately, considering the same weight as unity for all parameters (Table 1, Figure 3) and further overlaid these individual maps to create a vulnerability to depletion index map (Figure 5). The other, by using the percentage ratio of the pumping rate density to net recharge and drawdown to aquifer thickness and creating two percentage ratio maps (Figure 4) which further were overlain to develop the groundwater vulnerability to depletion index map (Figure 6).

Accordingly, the main steps of the method implementation can be summarized as:

- Construction of a model area map
- Entering Information for each parameter into a separate map indicating different regions, each of particular range and relative rate.
- Four individual parameter maps encompassing, drawdown (D), aquifer thickness (H), pumping rate density (Q) and net recharge (R) were constructed
- Two other percentage ratio maps were created encompassing the percentage ratio of drawdown to aquifer thickness and percentage ratio of pumping rate density to net recharge
- These maps were overlain and summed to develop the quantitative groundwater vulnerability assessment index maps of the study area.

It is important to lump generalities and not to split unnecessary regions by customizing the equal ranges (classes). The map produced using this procedure is one, which outlines areas of hydrogeologic settings and variable groundwater vulnerability assessment (GVA) indices. However, it should also be noted that the numbers are not contoured. Contour lines imply a sequential progression between each line. The GVA numbers are comparative and not sequential. This means that each individual index value is not related to the adjacent value but only a mean of comparison.

Results and Discussion

The assumptions made for the method formulation include the availability of the required data and their sufficient precision, resolution and accuracy for assignment of ranking the data according to their significant to determine the spatial distribution of groundwater depletion and overdraft sites in Songhaujaing river valley.

It is evident that all of the parameters used are interacting and dependent variables. The selection is based on available data quantitatively developed and rigorously applied.

The selected parameters include the *drawdown* which represents an important parameter for quantitative groundwater vulnerability assessment. *Drawdown* can be described in form of a map that shows its spatial variation in the study area. It varies from 1 to more than nine meters. The maximum drawdown was assigned in the pumping centers at Jiuzhan, Hadawan, Songyuanhada and at the southern part of model domain, where heavy groundwater abstraction generates cones of depression at these sites. Most parts of the area characterized by drawdown vary from 2 to 4 meters (Figure 3). The *aquifer thickness* is very significant parameter used to evaluate the quantitative groundwater vulnerability assessment in Songhuajiang river valley (Figures 3 and 4 ,Table 1). The *aquifer thickness* can be derived from the aquifer bottom elevation and water level elevation grid-cell data. The necessary information may be obtained from well 1ogs, geologic cross sections or maps of the elevations of the bedrock surface. The aquifer thickness in the study area varies from 15 to more than 60 meters in increasing order from the south to the north of the Songhuajiang river valley (Figure 3). Large aquifer thickness implies high groundwater potentiality whereas thin aquifer thickness is more subjected to groundwater depletion or overdraft depending on the pumping rate.

The *pumping rate density* is significant parameter used to evaluate the quantitative groundwater vulnerability assessment in Songhuajiang River Valley. Withdrawal carried out by means of numerous well fields results in forming cones of depression, changes of groundwater flow direction, and transformation of discharge areas into recharge areas. The groundwater abstraction for irrigation, industrial and domestic purposes is centered in well fields at Gudainzi, Jiuzhan, Hadawan, and Songyuanhada. The pumping rate density in the study area is calculated as million cubic meters per year per square kilometers (mcm/y.Km^2). The pumping rate density at Gudainzi, Jiuzhan, Hadawan, Songyuanhada and other part of the area were found to be 0.5, 0.8, 1.5, 3.4 and 0.05 mcm/y.km^2 respectively. *Net recharge* represents the total quantity of water, which is applied to the ground surface and infiltrates to reach the saturated zone. Because net recharge values are less precise and less easily obtained than values for other parameters, the ranges for net recharge are intentionally broad. These broad ranges afford the flexibility in choosing a range, which is representative of the amount of recharge for the area. The average annual net recharge in Songhuajiang River valley varies from 72.24 to 137.16 mm distributed into different sited regions each of particular values and rate used in quantitative evaluation of groundwater vulnerability.

After all the information had been gathered and analyzed, a conceptual hydrogeologic model that best fits the observed data was developed. The separated and percentage ratio parameters manipulation were used to select which is the convenient way that can be used to create the quantitative groundwater vulnerability assessment index map. Aquifer thickness were used in conjunction with zones of significant drawdown, and pumping rate density data were used in conjunction with net recharge distribution from the direct precipitations on one hand, and using these parameters separately on the other hand for developing the index maps. These maps differentiate sites of relatively overdraft to be avoided from sites of relatively high potentiality to be strongly recommended for further groundwater development. The drilling and testing of exploratory wells can easily be directed to locations recommended for groundwater development and/or monitoring. Information obtained from these exploratory wells will be used to calculate aquifer characteristics as well as to provide optimum well design for long-term aquifer development, monitoring and groundwater protection. The preparation of a detailed quantitative groundwater vulnerability map will describe the existing groundwater regime with particular reference to groundwater potential, long-term safe yield and aquifer protection. Mapping of statistically analyzed results makes spatial patterns in detection of risk zones very evident. This visualizes considerable variations in water quantity through the study area. Maps and statistics form a complementary description of the hydrologic and hydrogeologic setting. As with the maps, the ease of interpretation comes at the expense of a loss of detail. The parallel between the maps and statistics can be extended further by analogy: Summary statistics reduce large amounts of data to a few meaningful numbers, and maps reduce large amounts of data to a few meaningful images. Proper interpretation of the index map requires an understanding of the physical processes under study. The maps best serve to identify regions where consistently low or high probabilities are found, aiding in, but not replacing the interpretation of statistical analyses.

As a result of this method, the depletion risk index map generated from the percentage ratio parameters overlay technique (Figure 6) seemed to be more suitable compared to that generated from the overlay of the separated parameters (Figure 5). The former classes index map, classifies 27% (score 0~5) of the study area as more safe and having least vulnerability to depletion, 46% (score 5~11) as having moderate vulnerability to depletion, whereas 27% (score 11~16) as having most vulnerability to groundwater depletion. The separated parameters classes index map, classifies 25% (score 7~14) of the study area as having least vulnerability, 49% (score 14~20) as having moderate vulnerability whereas 26% (score 20~27) as having most vulnerability to groundwater depletion. When comparing these results with those from water level contour map, there are very close acceptable match of the groundwater vulnerability assessment generated from the percentage ratio parameters compared to that generated from the individual parameters.

The main differences between these two maps is that the separated parameters overlay map assigned the lower western part of the area as having high groundwater vulnerability to depletion (Figures 4 and 6), whereas this area was assigned by the percentage ratio parameters overlay map as having moderate groundwater vulnerability to depletion (Figure 6). The latter index map suggested that the northern part of the area is safer for further groundwater development and assigned by the method as least vulnerability to groundwater depletion or overdraft. This is in conformable with water level contour map that assigned this area as of high productivity from the negligible drawdown values and widely spaced equipotential lines. Most of the study area (49%) in Songhuajiang river valley was classified as having medium groundwater vulnerability to depletion or overdraft. Small areas (26%) at Jiuzhan, Hadawan, Songyuanhada and small pockets at the southern part of the area are relatively most vulnerable to groundwater depletion (Figure 6). Concordantly these areas also assigned by water level contour map as of maximum drawdown and of high pumping rate density and are the main groundwater pumping centers in the study area. Accordingly this confirmed that the quantitative groundwater vulnerability assessment (GVA) method is more convenient to produce a quick assessment of hydrogeologic processes that prevail in the area. The percentage ratio index map (Figure 6) fairly represents the present natural situation of the hydrogeologic system in the study area and strongly recommended to be the best quantitative groundwater vulnerability assessment method for the study area and other similar systems.

Model verification: This method provided an acceptable results as it is compared with the results of groundwater flow modeling and seemed to be the best method for assessing groundwater vulnerability to depletion risk and can established a greater confidence to be applied to similar system.

Conclusion

The quantitative groundwater vulnerability assessment (GVA) technique was developed and tested to provide vulnerability index maps to groundwater depletion. Two quantitative groundwater vulnerability index maps by using separated parameters and percentage ratio parameters were constructed. The index map produced from the percentage ratio parameters overlay technique, suggested that the northern part of the area is safer for further groundwater development and assigned by the method as least vulnerable to groundwater depletion or overdraft. This is in agreement with model simulation that assigned the same area as of high productivity. Hence, it confirmed that the percentage ratio index map fairly represents the present natural situation of the hydrogeologic system in the study area and strongly recommended to be the best quantitative groundwater vulnerability assessment method for the study area and other similar systems and can also be used for evaluating the quantitative groundwater vulnerability assessment and protection plans as policy analysis.

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References

1. Vrba, J. and A. Zaporozec, Guidebook on mapping groundwater vulnerability. IAH, Int. Contrib. to Hydrogeology, 16 (1994), *Heise, Hannover, 131 p.* **(1995)**

2. Stigter, T.Y., L. Ribeiro, and A. Dill. Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeology Journal* **14(1–2),** 79–99**(2006)**.

3. Frind, E.O., J.W. Molson, and D.L. Rudolph. Well vulnerability: A quantitative approach for source water protection. *Ground Water* **44(5)**, 732–742**(2006)**

4. Liggett, J.E. and A. Gilchrist. Technical summary of intrinsic vulnerability mapping methods in the regional districts of Nanaimo and Cowichan Valley. *Geological Survey of Canada. Open File No. 6168***(2009)**

5. GAO (General Accounting Office) Groundwater Protection: Validity and Feasibility of EPA's Differential Protection Strategy. (GAO/PEMD-93-6) Washington, D.C.: *General Accounting Office* **(1992)**

6. Thirumalivasan, D., M. KarmegamAquifer vulnerability assessment using Analytic Hierarchy Process and GIS For Upper Palar Watershed *,Asian conference on Remote Sensing, Singapore*,**(2001)**

7. Merchant, J.W., GIS-Based Groundwater pollution Hazard Assessment: A critical review o0f the DRASTIC Model. *Photogrammetric Engineering and Remote Sensing,* **60(9),** 1117-1127 **(1994)**

8. Baker, D., L. Wallrabenstein, and R. Richards "Well Vulnerability and Agricultural Contamination: Assessments from a Voluntary Well Testing Program," Proceedings of the Fourth National Conference on Pesticides: New Directions in Research, Development and Policy. D. Weigmann, ed.Blacksburg, Virginia: *Virginia Water Resources Center* **(1994)**

9. Evans B.M., and W.L., Myer, A GIS-Based Approach to Evaluation regional groundwater pollution potential with DRASTIC, *Journal of Soil and Water Conservations pp.* 242-245**(1990)**.

10. Goodchild, M.F., N. Trivedi, and T. R. Smith A Conceptual Framework for Integrated Metadata Management in Very Large Spatial Databases.*NCGIA Technical Paper* 91-2**(1991)**

11. Thapa, K. and J. Bossler Accuracy of Spatial Data Used in Geographic Information Systems. Vol.**58(6)**,835-841**(1992)**

12. Dang, A., H.F. Jia, S.Z. Yi and Z., Lia, Manual of GIS, Arc-GIS 8 Desktop,*Tsinghua University Press, Beijing***(2003)**

13. NRC (National Research Council), Groundwater Vulnerability Assessment, contamination potential under conditions of uncertainty. Committee on Techniques for Assessing Groundwater Vulnerability, Water science and Technology Board, Commission on Geosciences Environment and Resources. *National Academic Press, Washington DC***(1993)**

14. Aller, L., Bennett T., Lehr J., PettyR., and Hackett G.., DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. Ada, Oklahoma: *U.S. Environmental Protection Agency* **(1987)**

15. Crosbie RS, Jolly ID, Leaney FW, Petheram C Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? *Hydrol Earth System Sci* 14:2023–2038. doi:10.5194/hess-14-2023 **(2010a)**

16. Crosbie RS,McCallum JL,Walker GR, Chiew FHS Modelling climate-change Impacts on groundwater recharge in the Murray-Darling Basin, Australia. *Hydrogeology Journal* **18(7),**1639–1656**(2010b)**

17. Szilagyi, J., V. A. Zlotnik, J. B. Gates and J. Jozsa Mapping mean annual groundwater recharge in the Nebraska Sand Hills, USA, *Hydrogeology Journal vol.* **19**, 1503–1513 **(2011).**

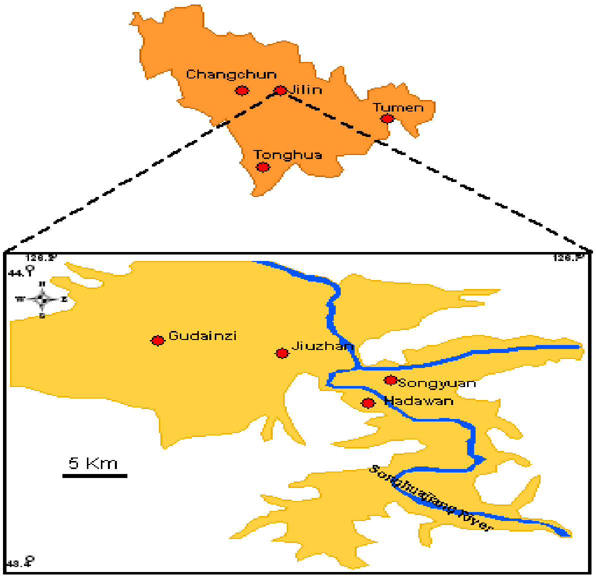

Figure 1: Location map of the study area

Table 1
Ranges and Rating of separated parameters

Drawdown (D)		**Aquifer thickness (H)**		**Pumping rate density (Q)**		**Net recharge (R)**	
Ranges (m)	Rating	Ranges (m)	Rating	Ranges mcm/y.km^2	Rating	Ranges mm/y	Rating
0-1	1	0-10	10	0.0-0.1	1	0-50	10
1-2	3	10-20	8	0.1-0.5	3	50-75	9
2-3	5	20-30	7	0.5-1.0	4	75-100	7
3-4	7	30-40	6	1.0-1.5	5	100-125	5
4-5	8	40-50	4	1.5-2.0	7	125-150	2
5-6	9	50-60	3	2.0-2.5	8	>150	1
>6	10	>60	1	2.5-3.0	9		
				>3.0	10		

Table 2
Ranges and Rating of percentage ratio of parameters

Drawdown/Aquifer Thickness (D/H)		**Pumping rate Density/ Net Recharge (Q/R)**	
Range	Rating	Range	Rating
0-4	1	0-0.01	1
4-8	2	0.01-0.05	3
8-12	3	0.05-0.1	4
12-16	4	0.1-0.5	5
16-20	5	0.5-1.0	7
20-24	6	1.0-1.5	8
24-28	7	1.5-2.0	9
28-32	8	2.0-2.5	10
32-36	9		
>36	10		

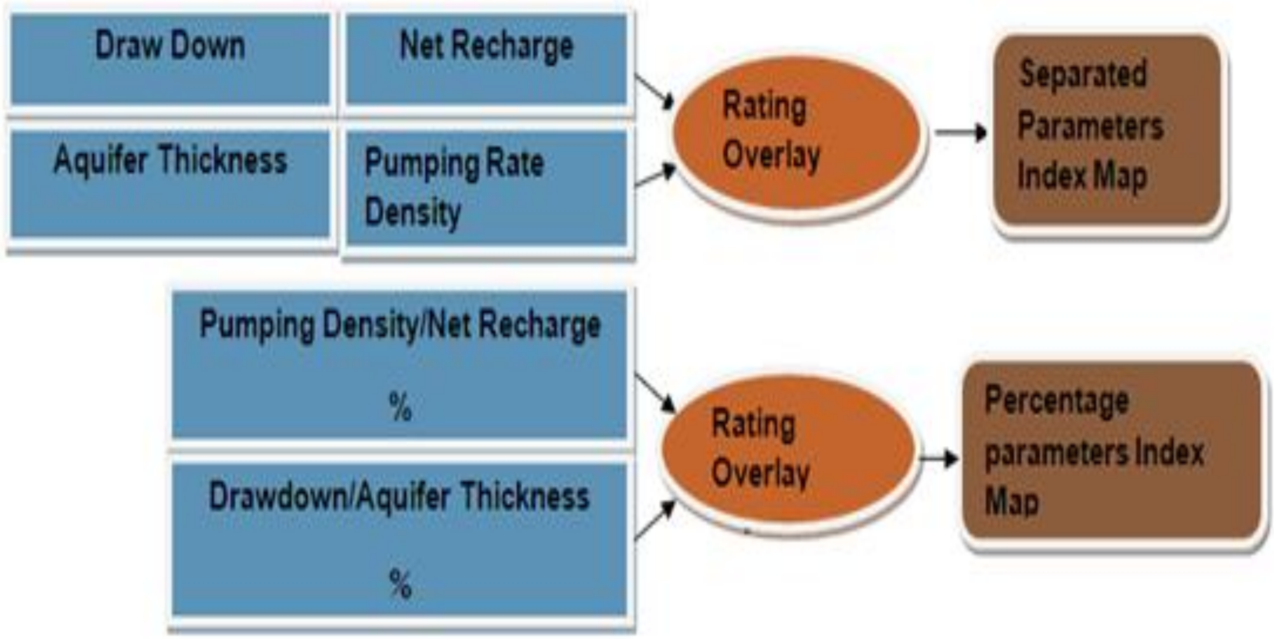

Figure 2: Groundwater Vulnerability Assessment for depletion risk flowchart

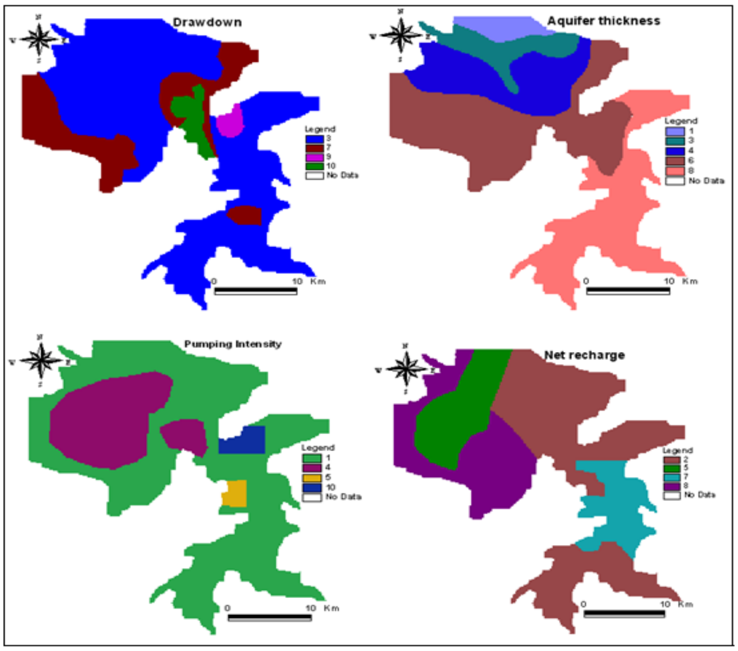

Figure 3: Composites scores of GVA separated parameters

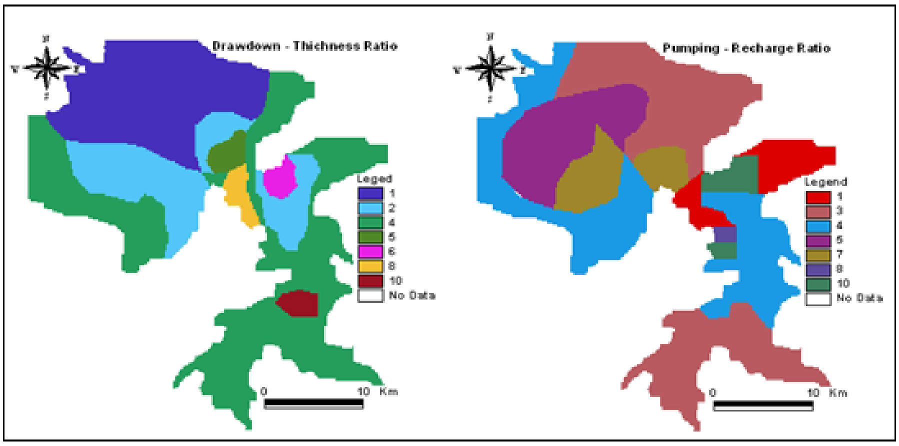

Figure 4: Composites scores of GWV percentage ratio parameters

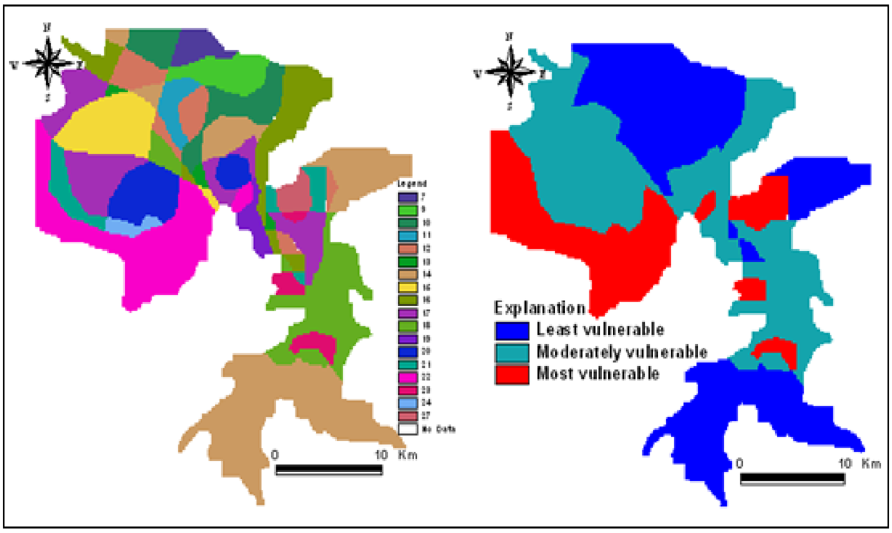

Figure 5: Separated parameters vulnerability Index map

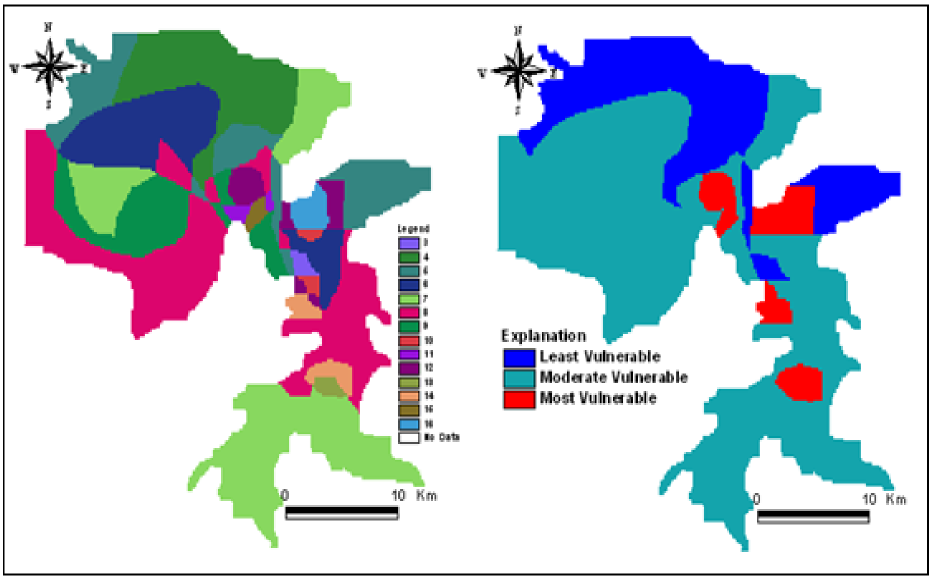

Figure 6: Percentage ratio parameters vulnerability Index map