A new hybrid framework of site selection for groundwater recharge

Javadi, S., Saatsaz, M., Shahdany, S. M. H., Neshat, A., Milan, S. G., & Akbari, S. 2021. A new hybrid framework of site selection for groundwater recharge. *Geoscience Frontiers*, **12**, 101144

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Date : 2024/06/07

Out line

1 Introduction

2 Material and methods

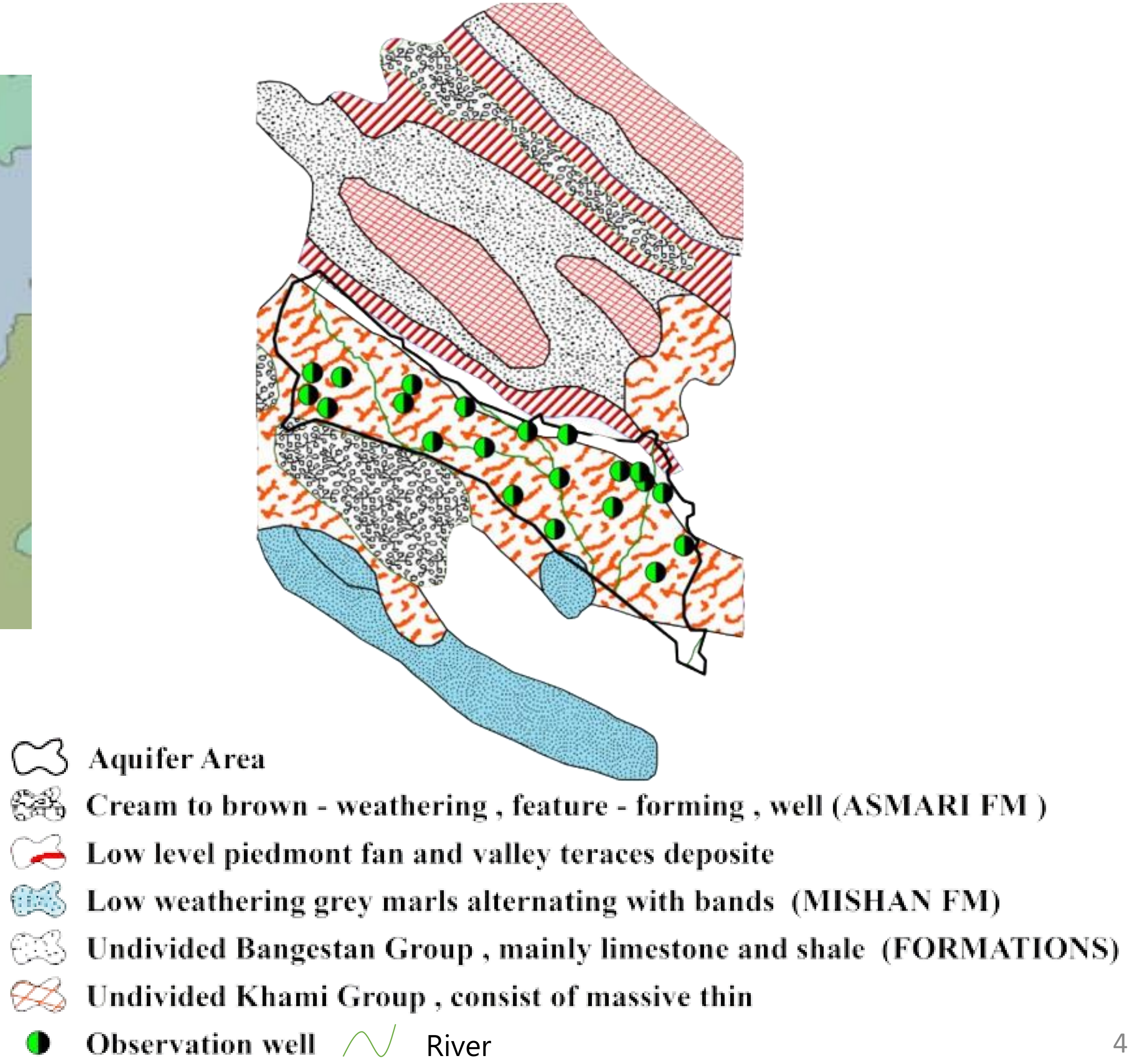
3 Result

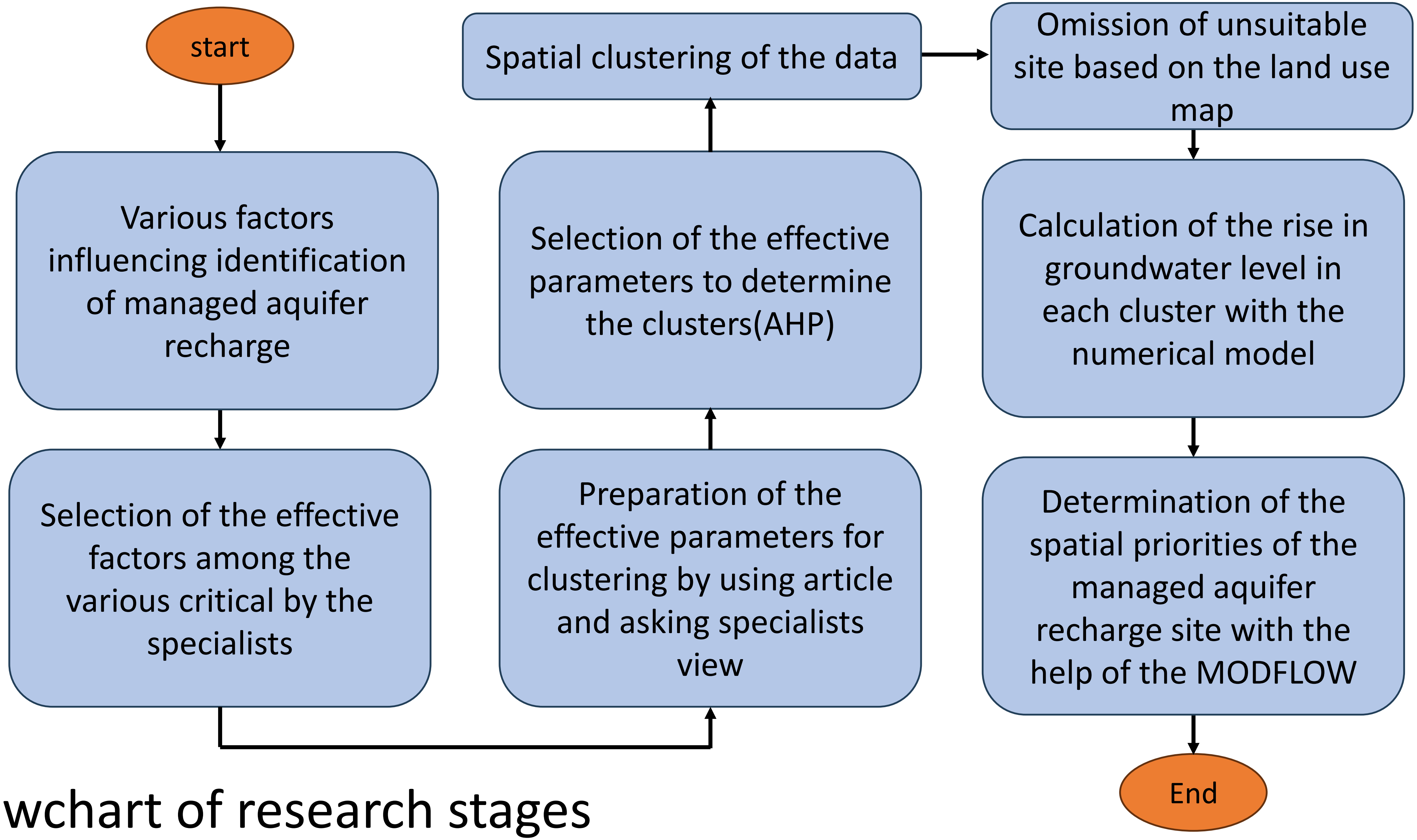
4 Conclusion

- Population growth followed by increased agricultural, industrial, and urban water consumption, on the one hand and limited surface water resources on the other, have caused irreparable damages to the aquifers in Iran during the past two decades.
- Artificial recharge (AR) is one of the effective methods for increasing aquifer reserves.
- The Clustering techniques are among the methods that take into account several criteria to identify the most suitable sites that have standard features
- MODFLOW was used to simulate the groundwater level and cluster the sites selected, with regards to increase in groundwater level

- Study area


Azerbaijan
Turkmenistan
Uzbekistan
Iraq
Iran
Iran
Afghanistan
Kuwait
Pakistan
Saudi Arabia
Bahrain
United Arab Emirates
Qatar
Oman


Aquifer Area
Cream to brown - weathering , feature - forming , well (ASMARI FM)
Low level piedmont fan and valley teraces deposite
Low weathering grey marls alternating with bands (MISHAN FM)
Undivided Bangestan Group , mainly limestone and shale (FORMATIONS)
Undivided Khami Group , consist of massive thin
Observation well
River



- Flowchart of research stages

- AHP technique

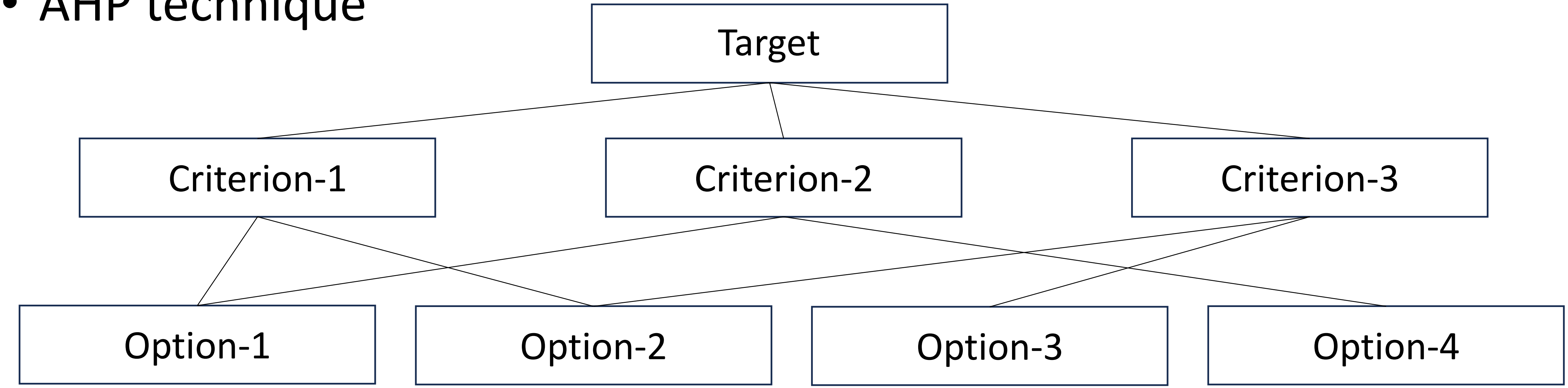
$$\lambda_{\max} = \frac{1}{N}\sum_{i=1}^{n}\frac{\hat{a}\cdot w_{(j,j)}}{w_{(i,j)}}$$

$$CI = \frac{\lambda_{\max} - n}{n-1}$$

$$CR = \frac{CI}{RI}$$

$\lambda_{\max}$: average value of the consistency vector
$\hat{a}$: matrix geometric mean
W(i. j) : alternative weight or priority
N : number of compared alternatives
n : matrix size
CI : consistency index
CR : consistency rate
RI : inconsistency index of the random matrix

- AHP technique



1. Preparing the paired comparison matrix for each level of the hierarchy starting from the top and continuing downward
2. Calculating a weight for each element of the hierarchy
3. Estimating the consistency rate (CR)

- CR < 0.1 indicate a consistent matrix
- CR > 0.1 indicate a discontinuous matrix

- AHP technique

Table 1
Previous research on selecting suitable AR sites.

Research	Country	Parameters considered in the identification of AR sites
Chenini et al. (2010)	Tunisia	Rainfall, watershed drainage density, surficial geology and aquifer boundary conditions
Valverde et al. (2016)	South America	The slope of the land, soil texture, irrigation network density, and hydraulic characteristics
Amineh et al. (2017)	Iran	Depth, runoff as the water resource, morphology, geology, geomorphology, land use, land cover, drainage density, aquifer characteristics, and aquifer quality
Senanayake et al. (2016)	Sri Lanka	Rainfall, lineations, slope, drainage, land use/cover, lithology, geomorphology, and soil characteristics
Prabhu and Venkateswaran (2015)	India	Geologic parameters, geomorphology, lineation, lineation density, drainage density, and land use/cover
Singh et al. (2013)	India	The geomorphological layer, geology, land use, drainage network density, slope, soil texture, aquifer transmissivity, and specific yield
Singh et al. (2017)	India	Runoff coefficient, slope, drainage density, and rainwater harvesting
Manap et al. (2013)	Malaysia	Lithology, slope, land use, lineation density, soil texture, precipitation, drainage density
Sargaonkar et al. (2010)	India	Porosity, land use, slope, topography, soil depth, and water-level fluctuations

1. slope
2. specific yield
3. depth to groundwater
4. aquifer thickness
5. qualitative land use and hydraulic conductivity

- K-means clustering

$$J(X;V) = \sum_{i=1}^{c} \sum_{k \in i} \left\| x_k^{(i)} - v_i \right\|^2$$

$$v_i = \frac{\sum_{k=1}^{N_i} x_k}{N_i}, x_k \in A_i$$

V = {v_i | i = 1,…,c} : cluster centers
$x_k^{(i)}$: the k[th] object belonging to the i[th] cluster
$\left\| x_k^{(i)} - v_i \right\|^2$: distance measure norm indicating the distance between data points and their respective cluster centers.
A_i : set of N_i objects belonging to the i[th] cluster

- Davies-Bouldin Index (DBI)

$$R_{jk} = \frac{\sigma_j + \sigma_k}{\left\|\mu_j - \mu_k\right\|}, j, k = 1,2, \ldots, g \; ; \; k \neq j$$

$$\sigma_j = \sqrt{\frac{1}{n_j} \sum_{x_i \in C_j} \left\|x_i - \mu_j\right\|^2}$$

$$R_j = \max_{k=1,2,\ldots,g; k \neq j} R_{jk}$$

$$I_{DB} = \frac{1}{g} \sum_{i=1}^{g} R_j$$

μ_j : mean of all the objects in cluster j

σ_j : the within class scatter of the j^{th} cluster

C_j : associated with the cluster j

n_j : number of objects in j^{th} the cluster.

R_j : maximal pair score with the cluster j

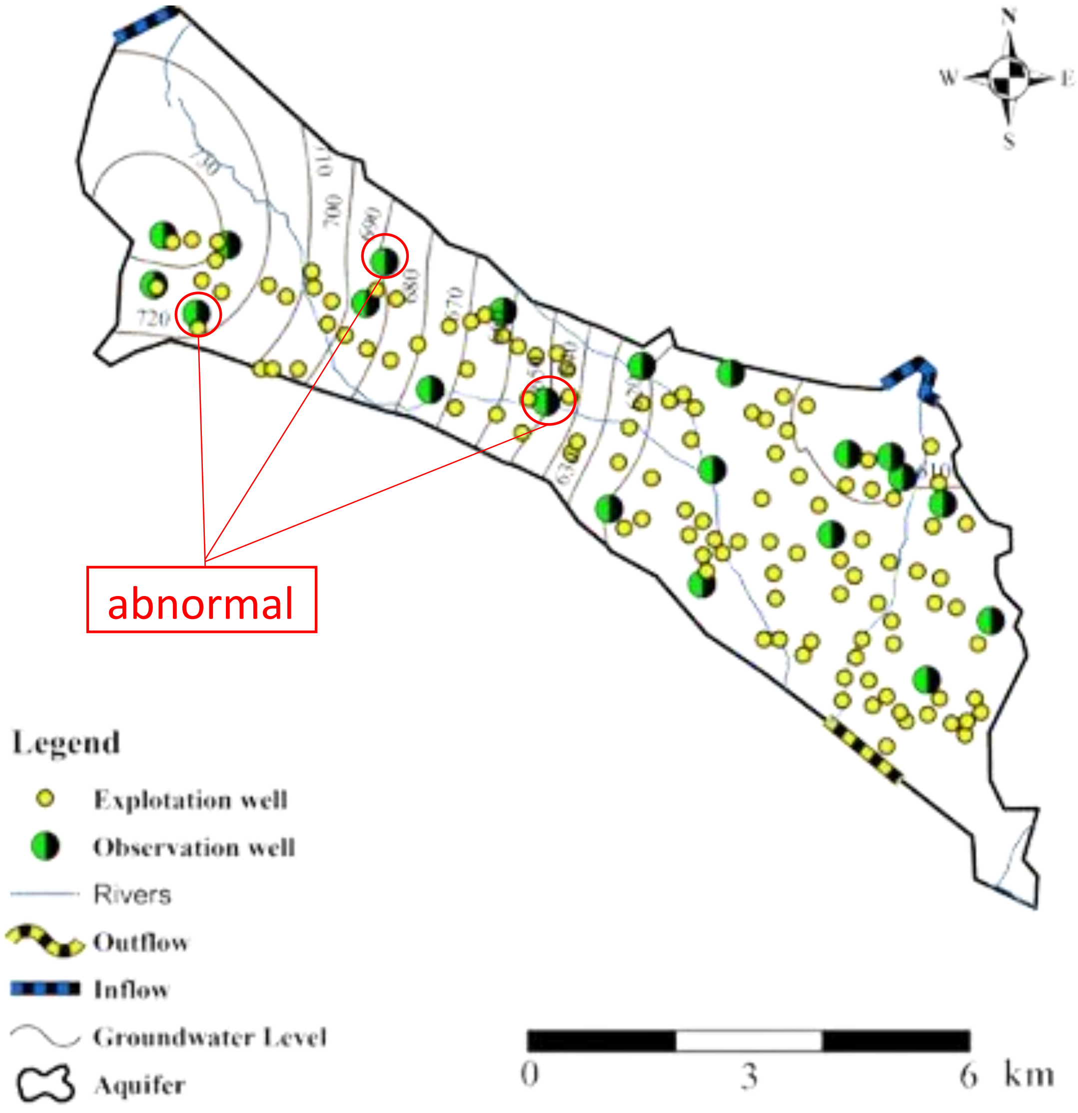
R_{jk} : the score for all the possible pairs of clusters

- Groundwater level simulation of Yasouj aquifer by MODFLOW

$$
\begin{aligned}
& CR_{i,j-\frac{1}{2},k}\left(h_{i,j-1,k}^{m} - h_{i,j,k}^{m}\right) \\
& + CR_{i,j+\frac{1}{2},k}\left(h_{i,j+1,k}^{m} - h_{i,j,k}^{m}\right) \\
& + CC_{i,j-\frac{1}{2},k}\left(h_{i,j-1,k}^{m} - h_{i,j,k}^{m}\right) \\
& + CC_{i,j+\frac{1}{2},k}\left(h_{i,j+1,k}^{m} - h_{i,j,k}^{m}\right) \\
& + CV_{i,j-\frac{1}{2},k}\left(h_{i,j-1,k}^{m} - h_{i,j,k}^{m}\right) \\
& + CV_{i,j+\frac{1}{2},k}\left(h_{i,j+1,k}^{m} - h_{i,j,k}^{m}\right) \\
& \quad + P_{i,j,k} h_{i,j,k}^{m} + Q_{i,j,k} \\
= \; & SS_{i,j,k}\left(DELR_{i,j,k} \times DELC_{i} \times THICK_{i,j,k}\right) \frac{h_{i,j,k}^{m} - h_{i,j,k}^{m-1}}{t^{m} - t^{m-1}}
\end{aligned}
$$

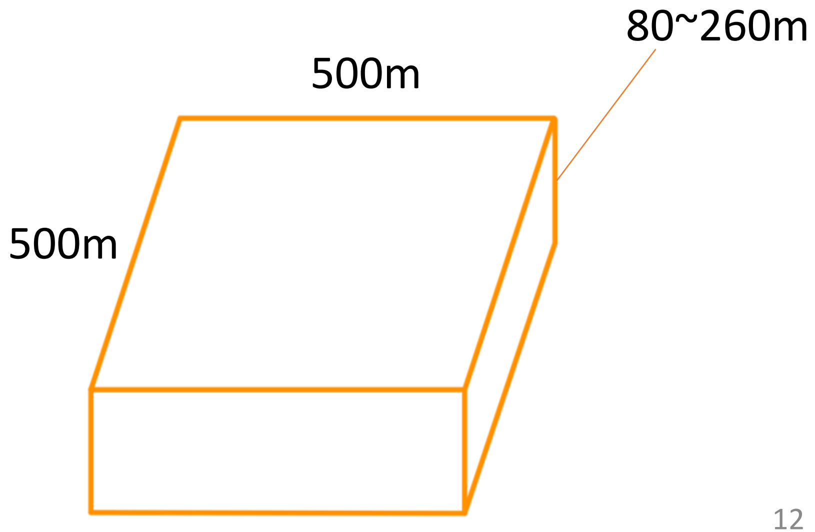
$h_{i,j,k}^{m}$: head at cell i,j,k at time step (L);
CV, CR, CC: hydraulic conductance, or branch conductance, between node i,j,k and a neighboring node (L^2/T)
$P_{i,j,k}$: sum of coefficients of head from source and sink terms (L^2/T)
$Q_{i,j,k}$: sum of constants from source and sink terms, with $Q_{i,j,k}$ < 0.0 for flow out of the ground-water system, and $Q_{i,j,k}$ > 0.0 for flow in (L^{33}/T)
$SS_{i,j,k}$: specific storage (L^{-1})
$DELR_{i,j,k}$: cell width of column j in all rows (L)
$DELC_{i}$: width of row i in all columns (L)
$THICK_{i,j,k}$: vertical thickness of cell i,j,k (L)
t^m : time at time step m (T).

- Groundwater simulation

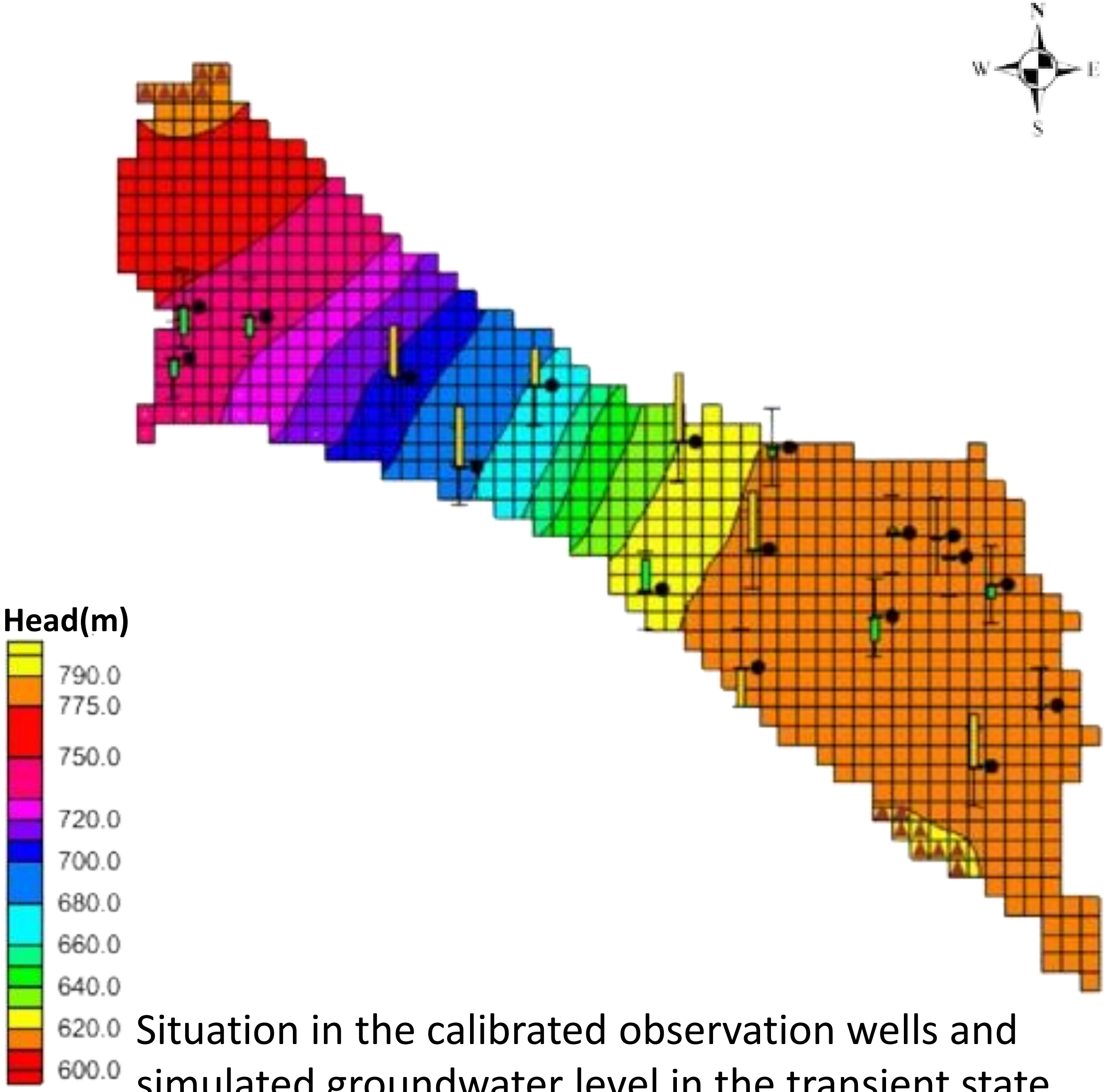


Locations of the observation wells, exploitation wells, input flow, and output flow in the Yasouj aquifer

Aquifer thickness varied from 80 to 260 m
Cell size was considered 500 m × 500 m



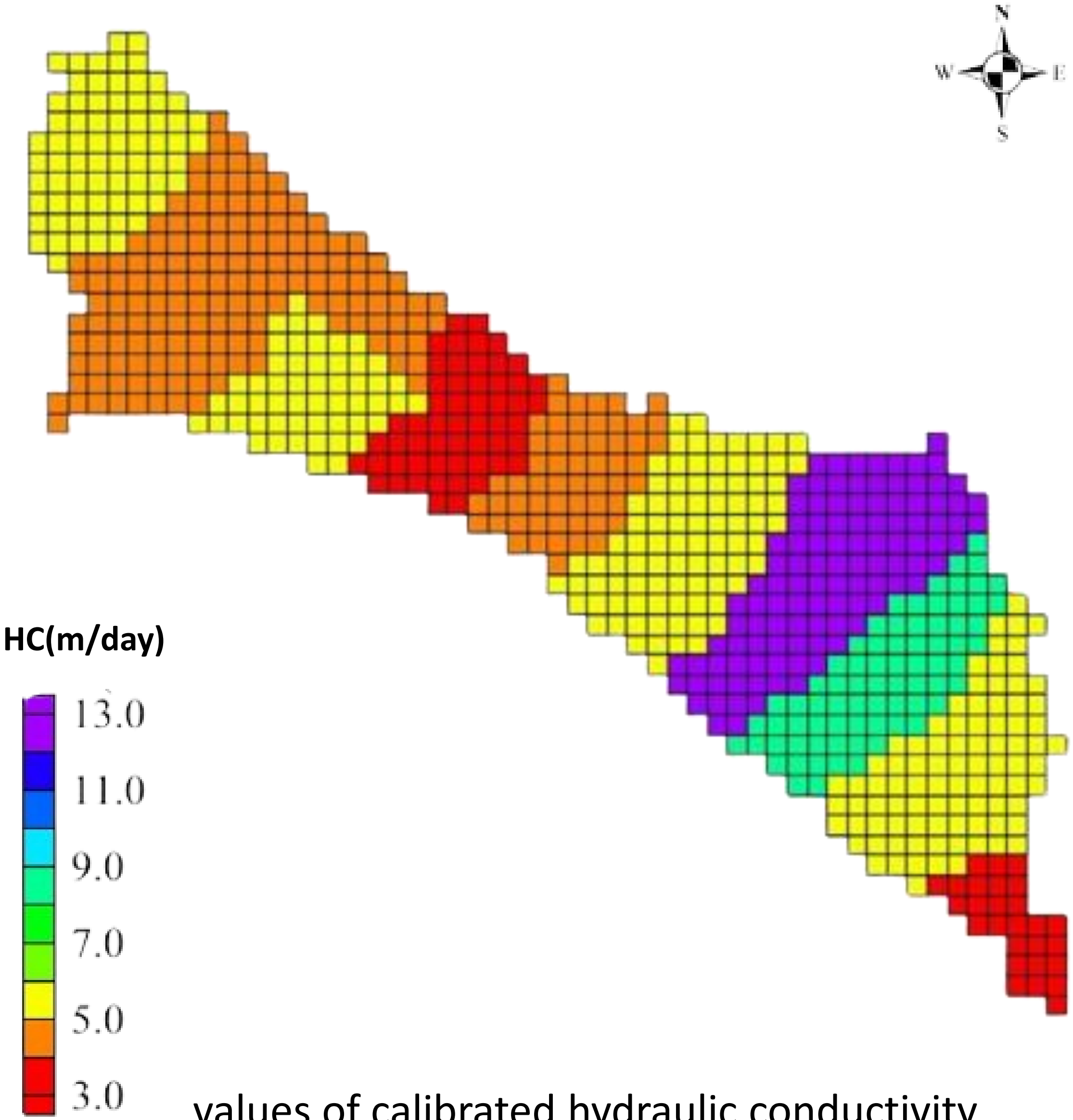
- Groundwater simulation



Situation in the calibrated observation wells and simulated groundwater level in the transient state

Comparing the northern region with the southern parts of the aquifer figure show that the groundwater level in the northern region of the aquifer is higher, which keeps declining as we move towards the southern areas of the aquifer

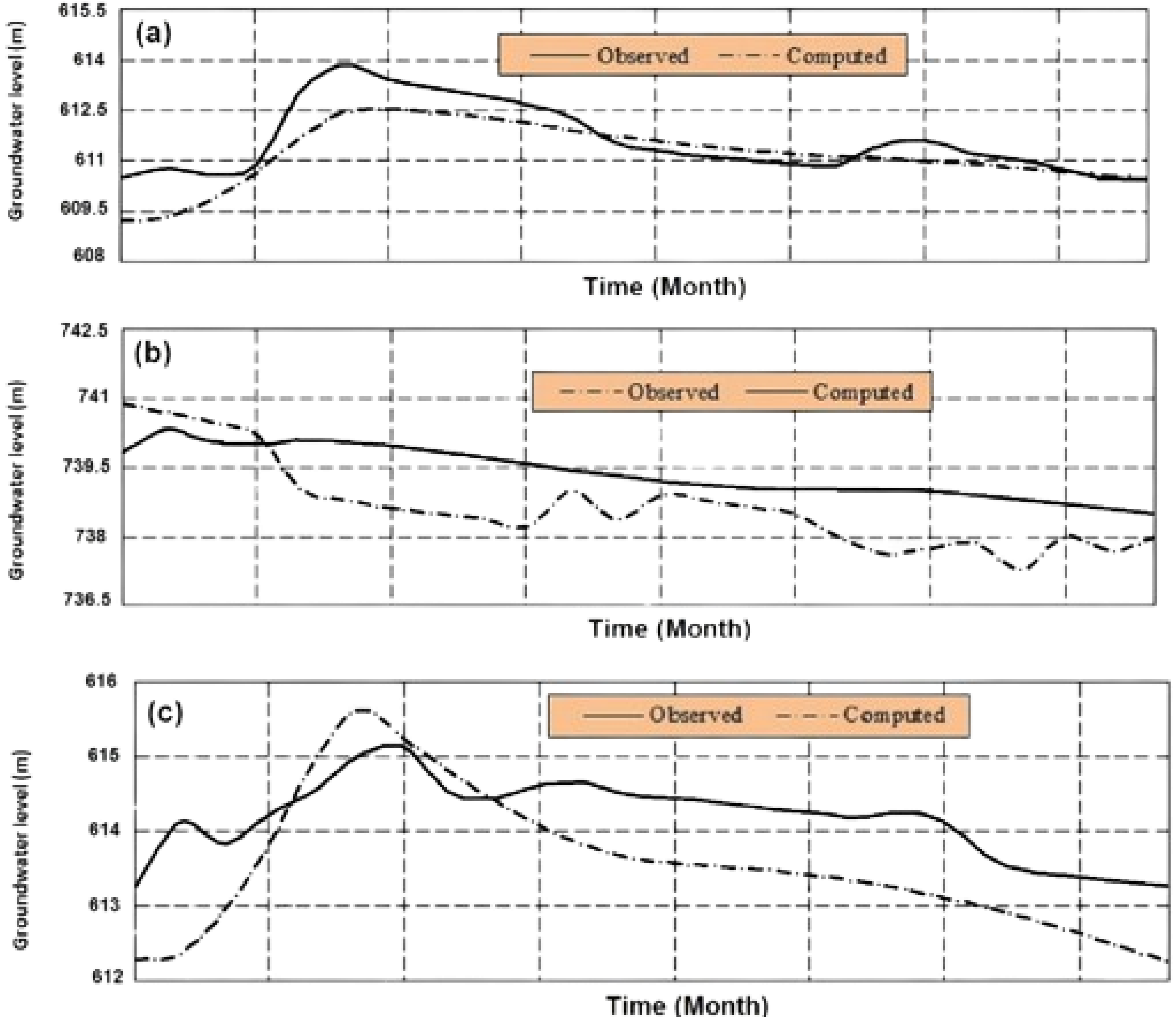
- Groundwater simulation



values of calibrated hydraulic conductivity

The highest value for hydraulic conductivity is 13 m/day, belongs to the central part of the aquifer, and the values for its other regions vary from 3 to 13 m/day

• Groundwater simulation



■ RMSE(root-mean-square error) :

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} y_i - \chi_i}{n}}$$

Yi : simulation value

Xi : observation value

N : number of consider point

■ MAE(Mean absolute error) :

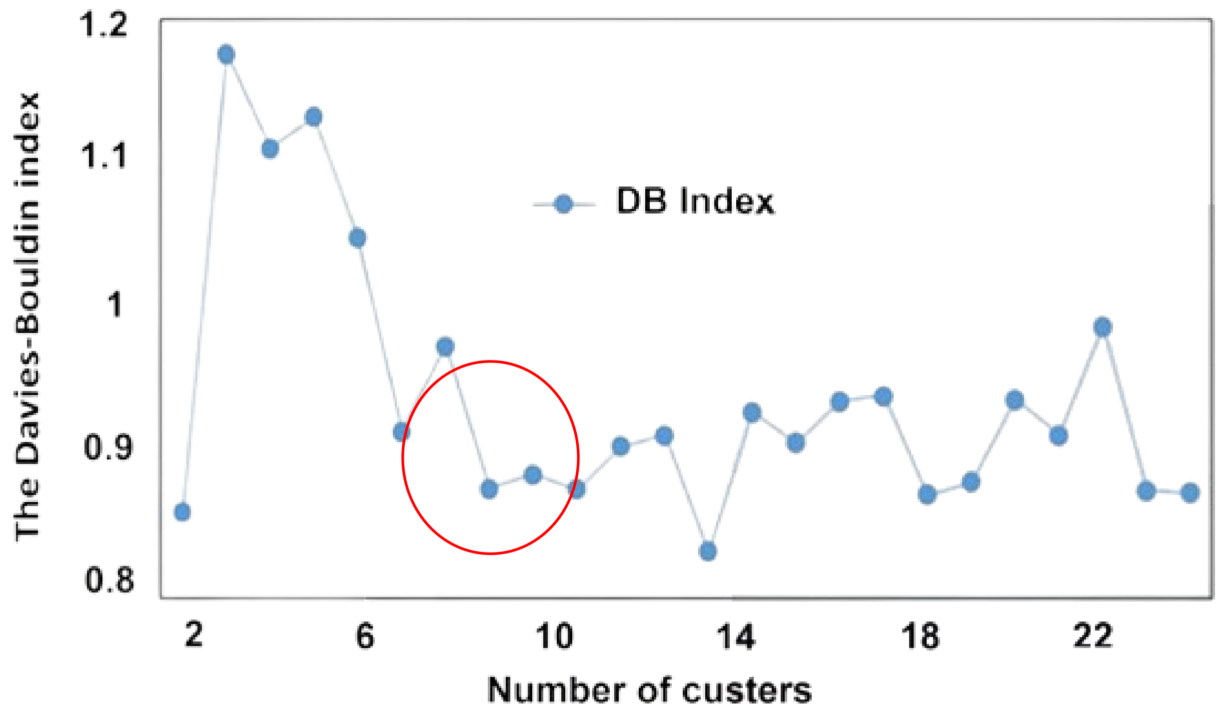
$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |y_i - \chi_i|}{n}$$

Yi : simulation value

Xi : observation value

N : number of consider point

- Aquifer clustering



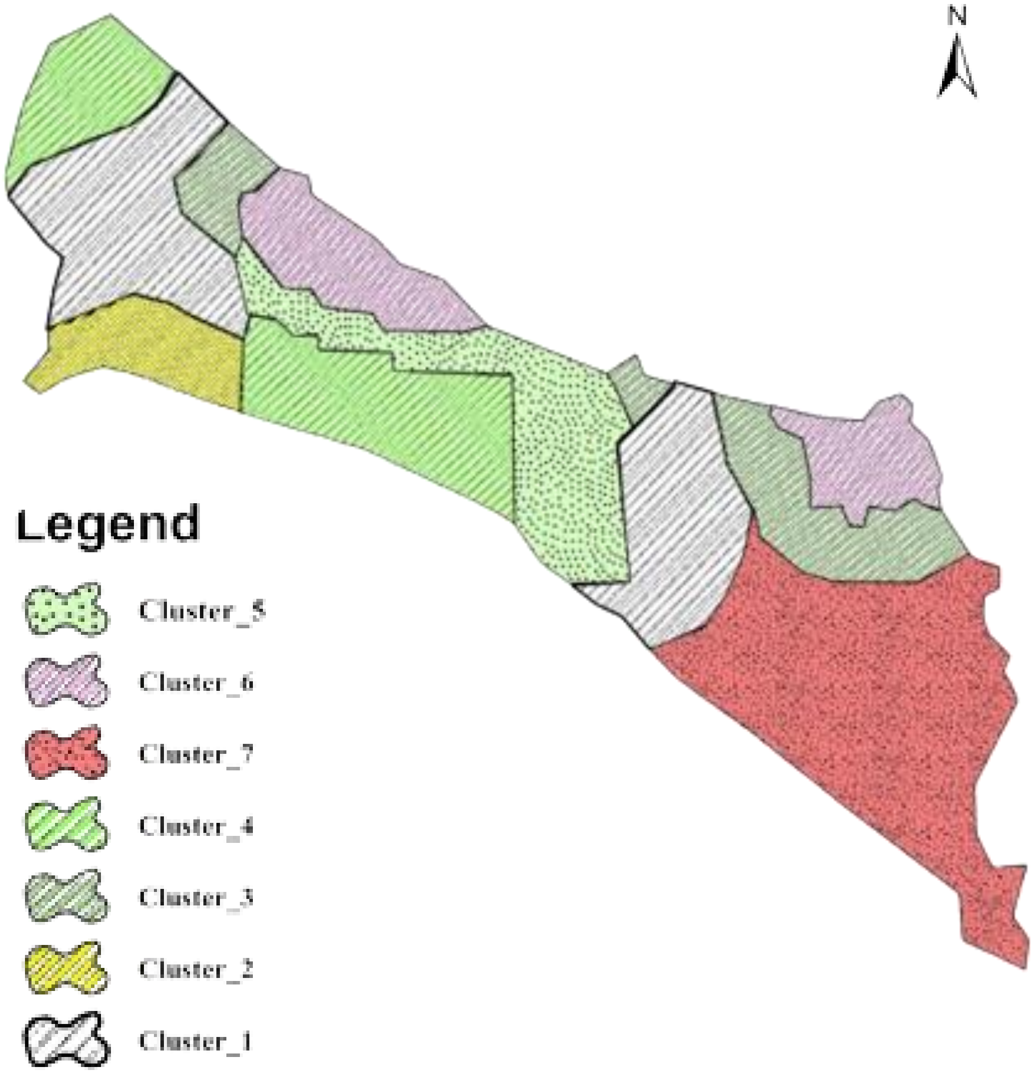
Seven clusters were selected as the optimal clustering, and the entire aquifer area was divided into seven different regions based on these clusters.

• Aquifer clustering

Table 2
Ranges of factors based on clusters obtained for the Yasouj aquifer.

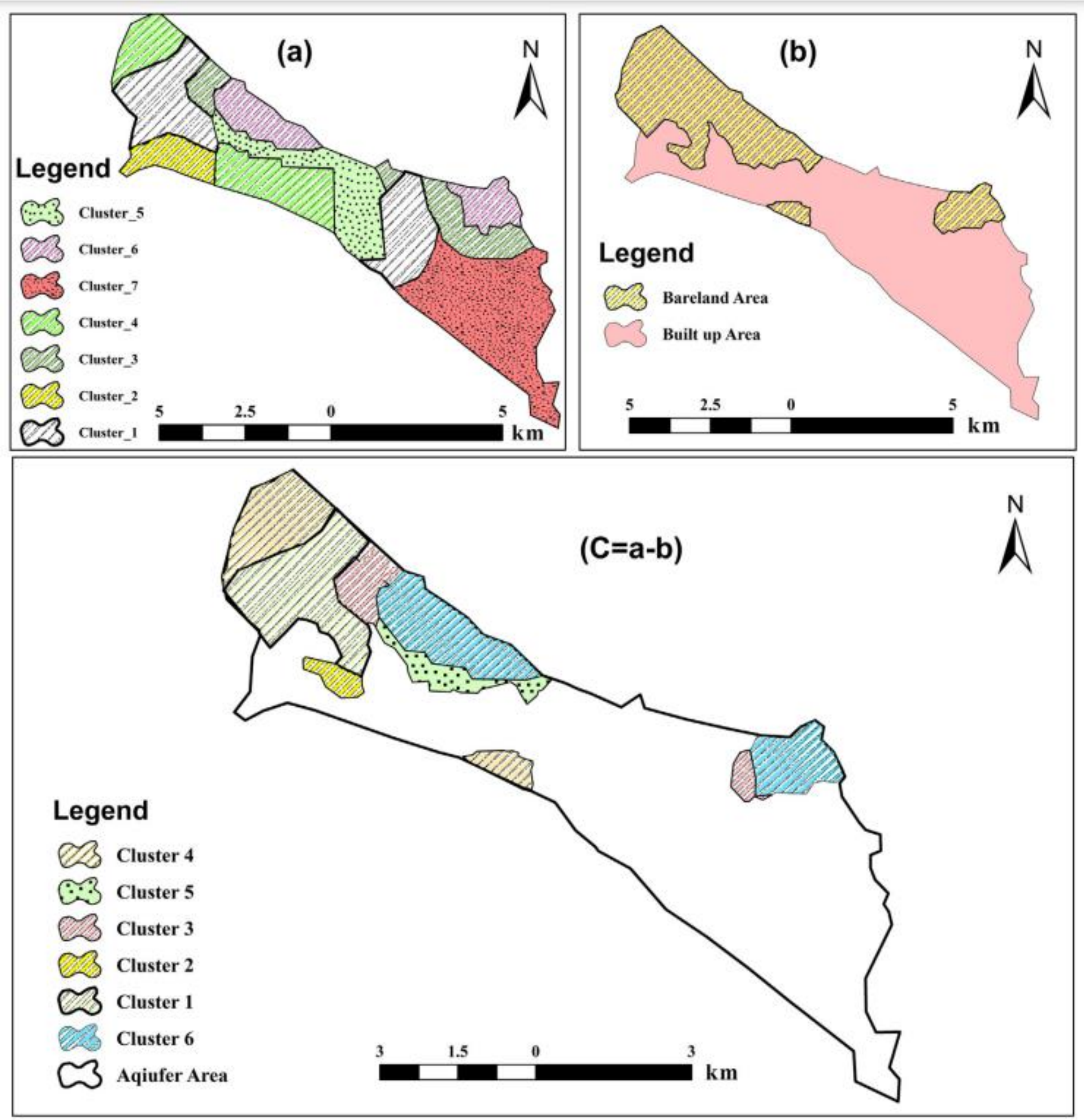
Cluster name	No. of members	Hydraulic conductivity (m/day)		Storage coefficient		Alluvium thickness (m)		Depth to groundwater (m)		Slope	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
C1	119	10.5	13.6	0.12	021	86.4	119.9	33.7	59.8	0.13	3.54
C2	32	6.0	6.5	0.08	0.12	58.5	88.5	1.0	46.4	1.17	4.12
C3	79	8.0	13.6	0.1	0.18	116.9	149.3	45.2	84.7	0.25	3.64
C4	104	4.5	7.0	0.05	0.15	94.6	132.6	0.6	44.2	0.69	3.83
C5	78	5.5	7.0	0.03	0.12	136.9	175.4	33.9	61.0	0.56	4.46
C6	48	4.0	7.0	0.03	0.10	150.6	199.0	56.2	103.5	0.54	4.26
C7	149	1.5	4.0	0.05	0.01	95.0	119.9	39.7	61.2	0.12	1.50

- Aquifer clustering



• Aquifer clustering

Choosing the appropriate cluster for AR

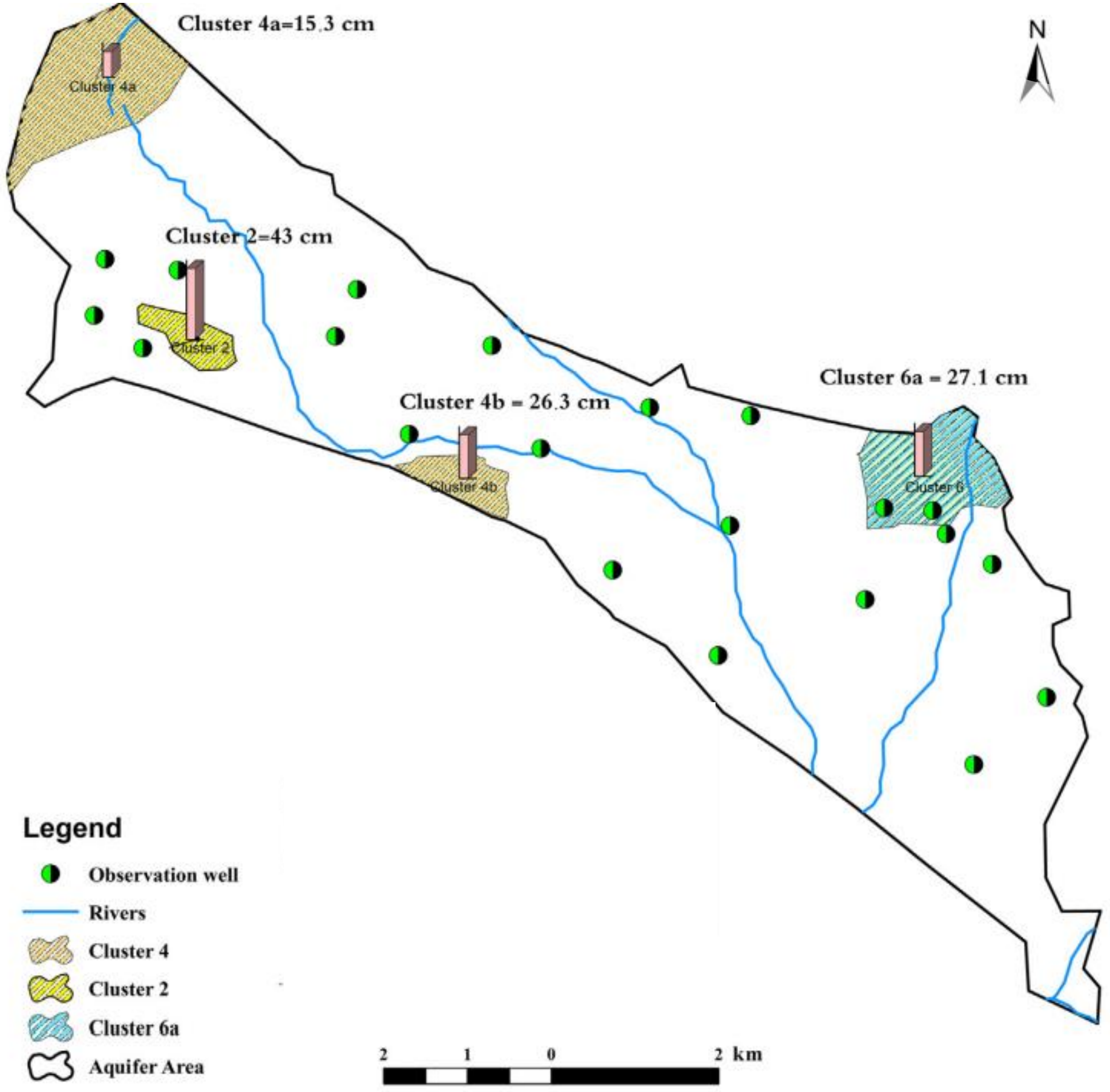


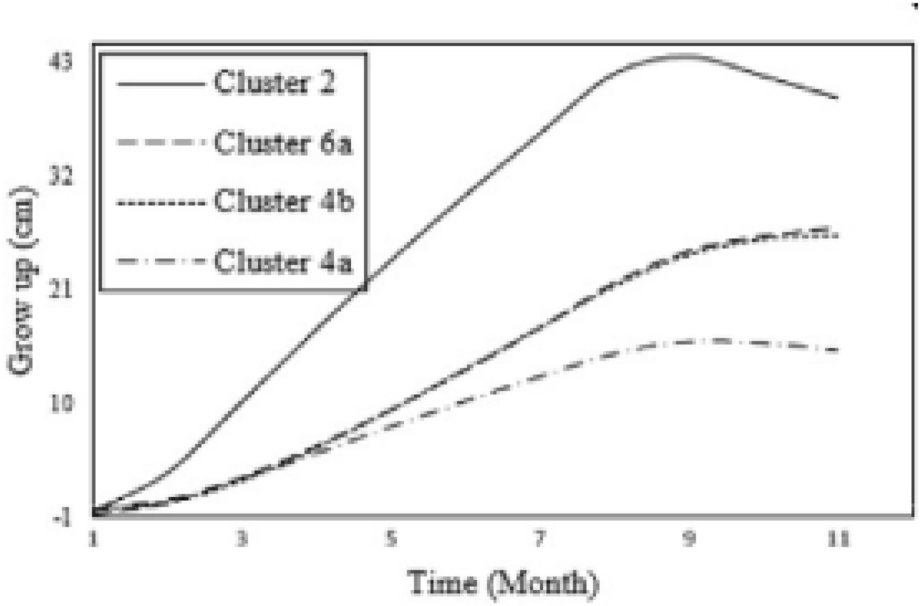
- Aquifer clustering

Table 3
Values of Δh (in mm) for the areas selected in the AR project.

Date	Cluster 1	Cluster 2	Cluster 3-a	Cluster 3-b	Cluster 4-a	Cluster 4-b	Cluster 5	Cluster 6-a	Cluster 6-b
	Δh								
12-Nov	-0.05	-0.46	-0.08	-0.08	-0.16	-0.16	-0.09	-0.01	-0.63
12-Dec	0.62	3.28	0.18	0.48	0.73	0.43	-0.09	-0.01	0.47
13-Jun	1.86	10.19	0.87	1.56	2.77	2.55	-0.05	-0.01	2.90
13-Feb	3.06	17.18	1.85	2.68	5.27	5.69	-0.03	-0.01	5.96
13-Mar	4.14	23.87	2.97	3.78	7.86	9.41	-0.01	-0.01	9.48
13-Apr	5.12	30.19	4.12	4.85	10.36	13.37	0.00	-0.01	13.32
13-May	6.0	36.17	5.26	5.87	12.73	17.35	0.3	-0.01	17.39
13-Jun	6.82	42.00	6.39	6.89	15.00	21.39	0.9	0.00	21.78
13-Jul	6.88	43.67	7.18	7.28	16.19	24.43	1.5	0.01	24.84
13-Aug	6.31	41.79	7.47	7.11	16.04	25.92	2.5	0.03	26.33
13-Sep	5.73	39.68	7.42	6.87	15.30	26.27	3	0.05	27.10

- Aquifer clustering





- Due to limited surface water resources in warm and dry arid regions, the implementation of Aquifer Recharge (AR) projects must be approached with caution

- A brief review of previous studies was conducted to extract criteria influencing the optimal performance of AR projects. The aquifer was divided into various clusters with similar physical characteristics using traditional clustering methods

- Considering the critical situation of aquifers in Iran, the use of clustering and MODFLOW as a numerical modeling tool for aquifers can be applied to prevent cost losses and increase aquifer replenishment

Thanks for your listening

- Groundwater level simulation of Yasouj aquifer by MODFLOW

$$\frac{\partial}{\partial \chi}\left(k_{xx}\frac{\partial h}{\partial \chi}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

k_{xx}, k_{yy}, k_{zz} : values of hydraulic conductivity along the x, y, and z coordinate axes(L/T)

h : potentiometric head (L)

W : volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow in(T^{-1})

S_S : specific storage of the porous material (L^{-1})

t : time (T)