Seawater Intrusion Vulnerability Assessment using the GALDIT and the modified GALDIT–AHP methods: Application in the coastal Almyros aquifer, Thessaly, Greece

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1. Introduction

- The concept of **vulnerability** is based on the assumption that the natural environment provides a degree of protection to groundwater, (Margat, 1968).

- The assessment of the general vulnerability **aims** at better management of water resources in the area and prevention of further degradation of the aquifer.

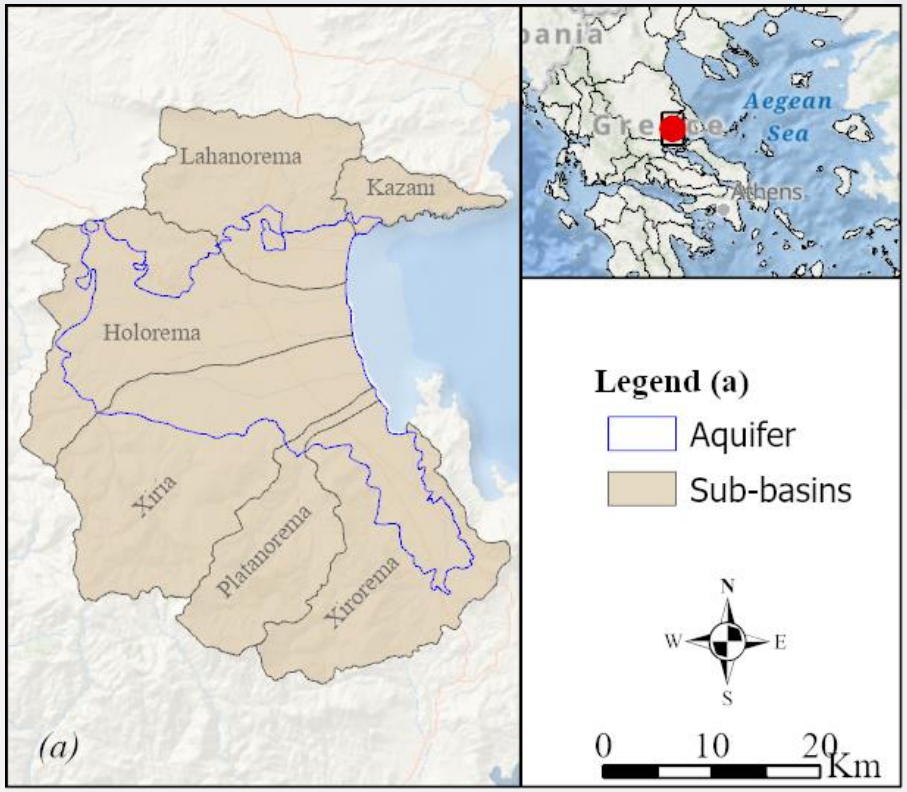
The methods used to assess the groundwater vulnerability are:

- The statistical methods.
- The simulation methods that solve numerically the groundwater motion equations.
- The rating methods.

Also, the above methods can be modified and used together for more reliable results.

1. Introduction

Study Area-Almyros basin



Description	Data
Area (km²)	293
Sub-basins	6
Climate	Mediterranean
Mean annual precipitation	570 mm
Mean annual temperature	15.0 ° C
Main streams	Lahanorema, Holorema, Xirias, Platanorema , Xirorema

1. Introduction

Geology and hydrogeology

- The soil cover is clay loam, clay, and silt loam
- The geological materials of the aquifer system are of Neogene and Quaternary age
- Hydraulic gradients direct the flow from west to east, higher values in the central region
- Hydraulic conductivity varies from 0.1 to 18.7 m/d and has an average of 2.3 m/d
- The hydrogeological zones of the aquifer consist of water-permeable quaternary formations and semi-permeable neonatal formations.

The existing situation

- The agricultural areas occupy 85.12% of the total study area.
- The irrigated areas consist of water-intensive crops, (Lyra et al., 2021).
- Groundwater abstraction to cover irrigation needs have degraded the quality and quantity of the Almyros aquifer.
- The Almyros aquifer faces high nitrate pollution and severe seawater intrusion.

2. Methodology

2.1. GALDIT method

- The aquifer's vulnerability has been estimated for the period 1992-2015 by the calculation of GALDIT index, whose parameter are: a)Groundwater occurrence, b) aquifer hydraulic conductivity, c) depth to groundwater (level above the sea), c) distance from the shore to the beach, d) effects of present seawater intrusion, and e) aquifer thickness.

$$GALDIT = \frac{\sum_{i=1}^{6}\{(W_i)R_i\}}{\sum_{i=1}^{6} W_i}$$

Where, W_i= the weights of the parameters, R_i= the rating of the parameters. The value range of the index is 2.5-10.

2.2. Modified GALDIT method using AHP's statistical indexes

- Statistical GALDIT–AHP indexes, for the median, average and mode values of the pairwise comparison tables filed by 15 experts.
- All pairwise comparison tables have been tested for consistency with the Consistency Ratio (CR) (all tables had CR<0.1)
- The weights of the statistical AHP indexes were used to modify the GALDIT index in order to adjust the GALDIT method to the special hydrogeological conditions of the study area.

2. Methodology

Table 1. The weights of each parameter for the GALDIT method and the modified GALDIT-AHP method.

Parameters	GALDIT	AHP Median	AHP Average	AHP Mode
Groundwater occurrence	0.060	0.276	0.282	0.235
Aquifer hydraulic conductivity	0.200	0.263	0.246	0.235
Level above the sea	0.266	0.190	0.170	0.214
Distance from the shore	0.266	0.118	0.146	0.127
Impact of existing seawater intrusion	0.060	0.081	0.086	0.099
Thickness of the aquifer	0.133	0.072	0.070	0.090

- The rating of the parameters is the same for all the methods.
- The GALDIT method assigns the greatest weights to the parameters of distance from the coast (D) and hydraulic load above the sea (L). The modified GALDIT-AHP assigns the greatest weights to the parameters of the groundwater occurrence (G) and the aquifer hy-draulic conductivity (A).

3. Results

3.1. The rating of parameters of GALDIT method

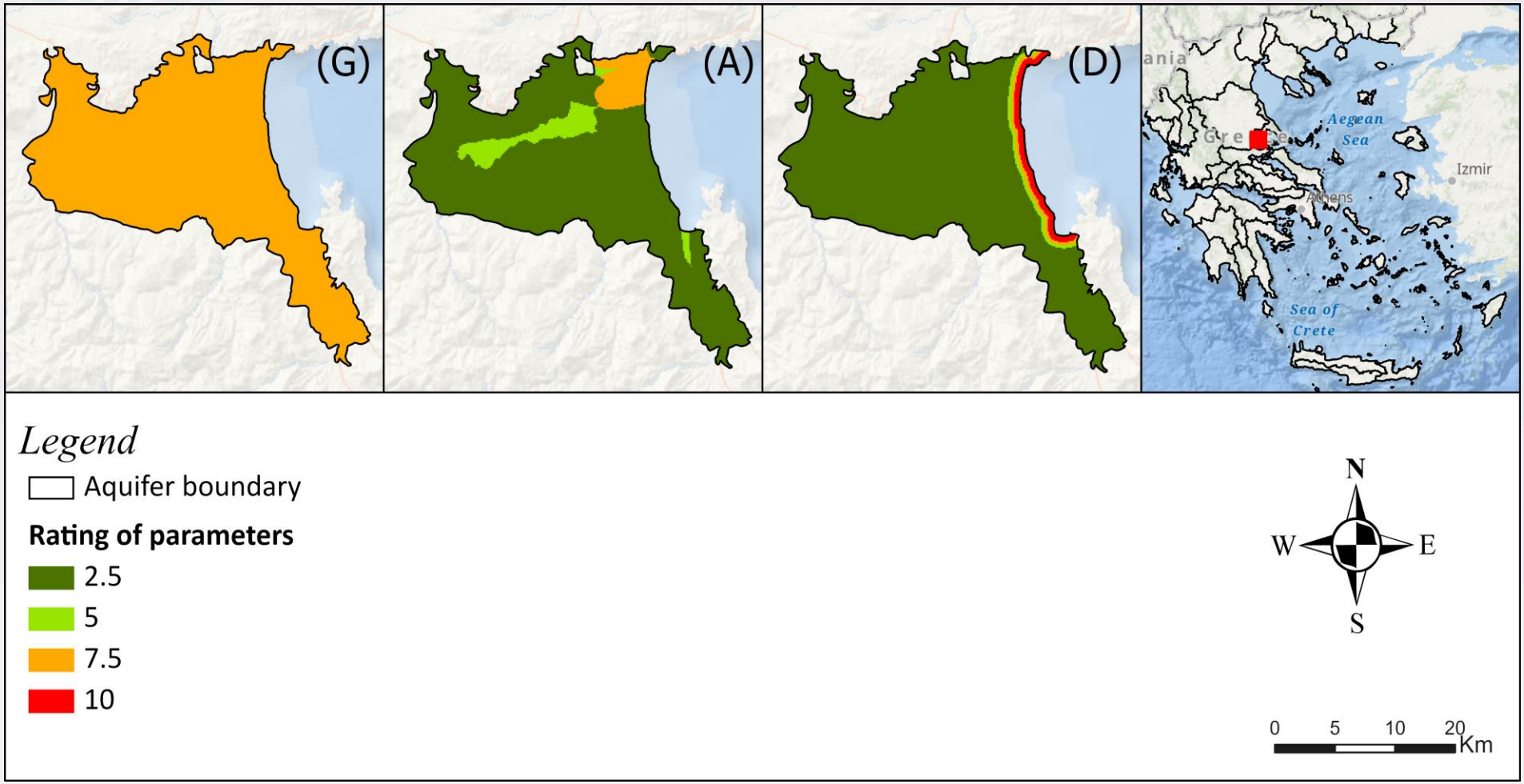


Figure1. Maps of groundwater occurrence ‘s (**G**), aquifer hydraulic conductivity ‘s (**A**) and distance from the shore’s (**D**) ratings according to GALDIT method.

3. Results

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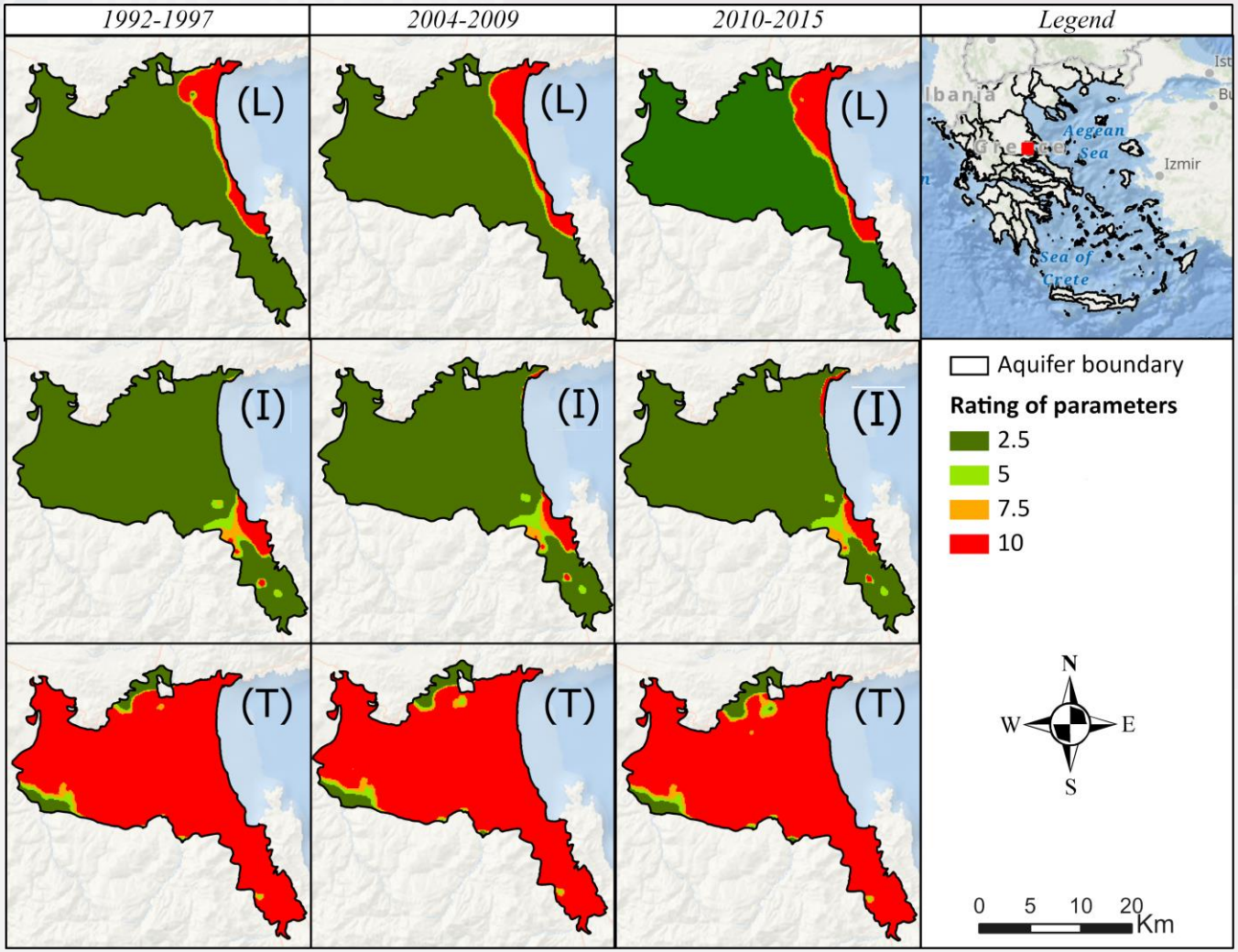
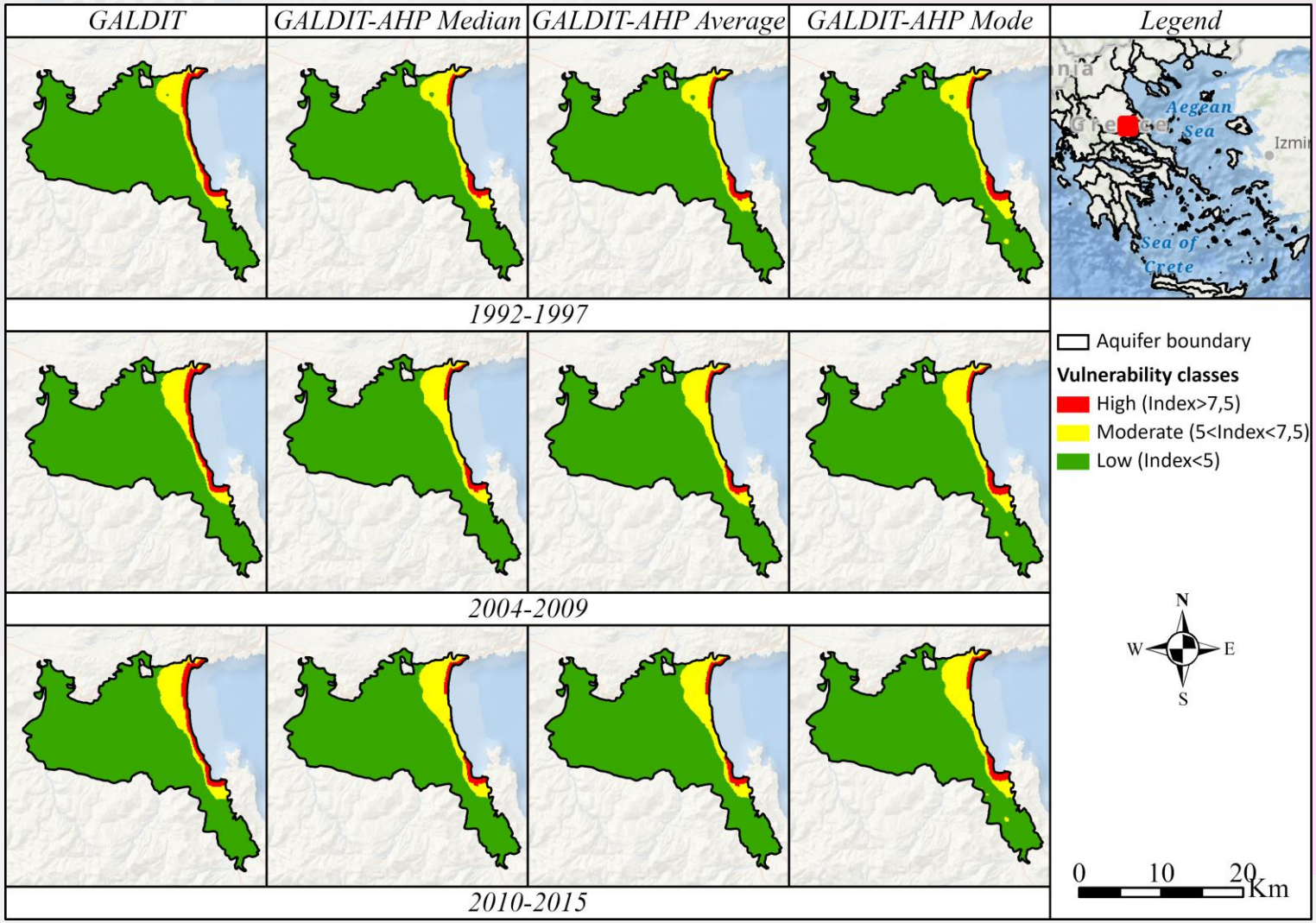


Figure 2. Maps of level above the sea's (**L**), impact of existing seawater intrusion's (**I**) and thickness of the aquifer's (**T**) ratings according to GALDIT method for the periods 1992-1997, 2004-2009 and 2010-2015.

3. Results

3.2. Vulnerability assessment GALDIT and modified GALDIT –AHP methods



- **High and very high values** of vulnerability appear in the **eastern part** of the Almyros basin, the **lowest values** are presented **in the north-western part of the basin**, in the sub-basins of Cholorema and Xirorema.

Figure 3. Vulnerability maps of Almyros aquifer with the methods of a) GALDIT, b) GALDIT- AHP Median ,c) GALDIT- AHP Average, d) GALDIT- AHP Mode for the periods 1992-1997, 2004-2009 and 2010-2015.

3. Results

3.1. Vulnerability assessment GALDIT and modified GALDIT –AHP methods

Vulnerability classes	Typical	AHP Median	AHP Average	AHP Mode
High	3.54%	1.99%	1.99%	2.20%
Moderate	8.16%	9.23%	9.21%	9.57%
Low	88.27%	88.70%	88.80%	88.24%

Table 3. Percentage (%) of the Almyros Aquifer under various classes of vulnerability with the typical GALDIT and GALDIT–AHP methods for the period 1992-2015.

- In all the study periods (1992-1997, 2004-2009 and 2010-2015) a gradual increase of high and medium vulnerability values (0.5-2%) was observed, a fact due to changing parameters such as the hydraulic load above sea level, the existing salinity condition and the aquifer thickness which change with time.
- For the GALDIT index, the standard/typical weights, the weights of the AHP Median and AHP Average statistical indicators showed in all study periods a similar overall rate of high vulnerability with a difference of 0.5%–1%.

3. Results

3.2 The validation of vulnerability maps of the Almyros basin's aquifer

- To test the correlation between salinity concentrations (ppt) and GALDIT seawater intrusion index values for all three time periods, the Spearman correlation coefficient was used.
- The significance (p) value of the correlations is less than 0.05 thus the statistical difference is real and not due to chance. Correlation coefficients range from rho=0.43 to 0.46 per study period.

Table 4. Spearman rank correlation between salinity concentrations and vulnerability indices GALDIT and modified GALDIT–AHP.

Vulnerability indices	1992-1997	2004-2009	2010-2015
GALDIT	0.44	0.45	0.45
AHP Median	0.43	0.44	0.44
AHP Average	0.44	0.44	0.43
AHP Mode	0.43	0.45	0.46

4. Conclusion

- **All methods** agree that the eastern part of the Almyros basin is the most vulnerable, as it generally has high vulnerability values, which is confirmed by comparison with the measured salinity concentrations.
- The differences between the indices in the areas of vulnerability are due to the different weights of the parameters between the vulnerability indices.

- The **vulnerability maps** produced by the GALDIT method can be reliable **tool** for scientists, local government institutions and stakeholders of water resources **for the effective management and protection of water systems**, as long as the adaptation control of the method in the study area has been applied.

Thank you for your Attention