<paper review>

Subsurface temperature trends in response to thermal water exploitation in the Jiashi Hot Spring, northeastern Taiwan

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Outline

- Introduction
- Hydrogeological background
- Research methods
- Results and discussion
- Conclusions

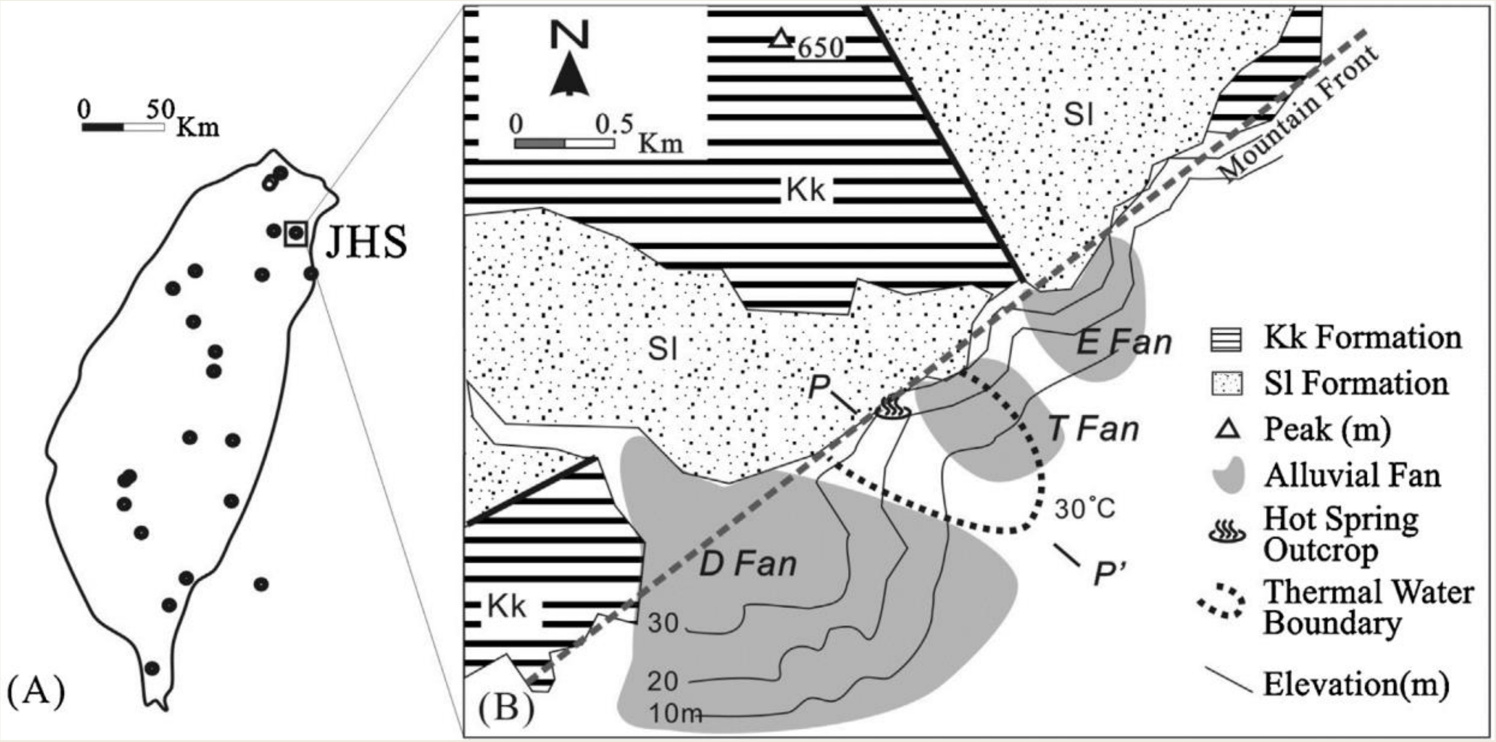
Introduction

- Temperature monitoring provides important information for the sustainable management of a geothermal field.
- Initial subsurface temperatures are basically determined by local hydrogeology and the flow field of groundwater/thermal water.
- Using the Mann–Kendall (MK) method to identified the trends in subsurface temperature changes (Helsel and Hirsch, 2002; Helsel et al., 2006).
- The goal was to detect trends in subsurface temperature changes, as well as the relationship between temperature change and the location and depth of production wells.

Hydrogeological background

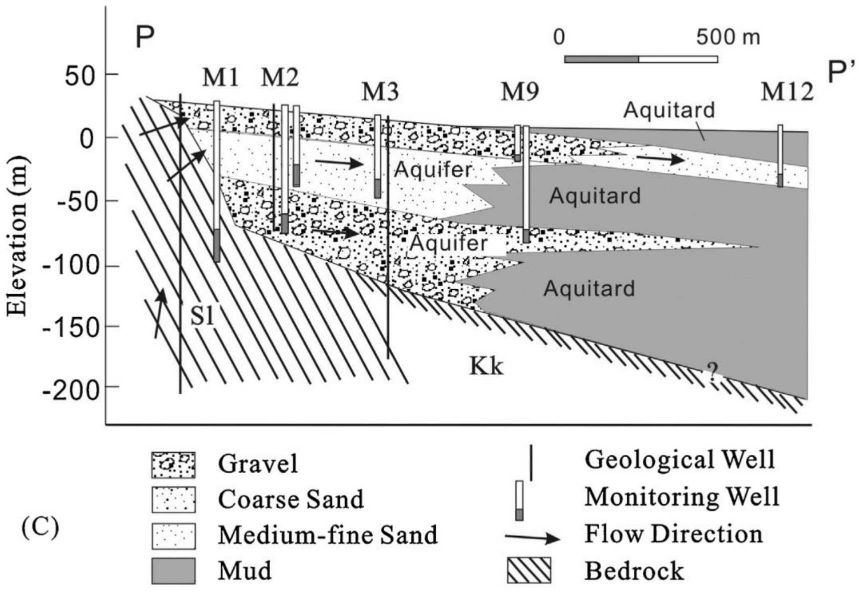
- Over 100 production wells and approximately 14,000 m^3 per day of thermal water are utilized (Yilan County, 2010).

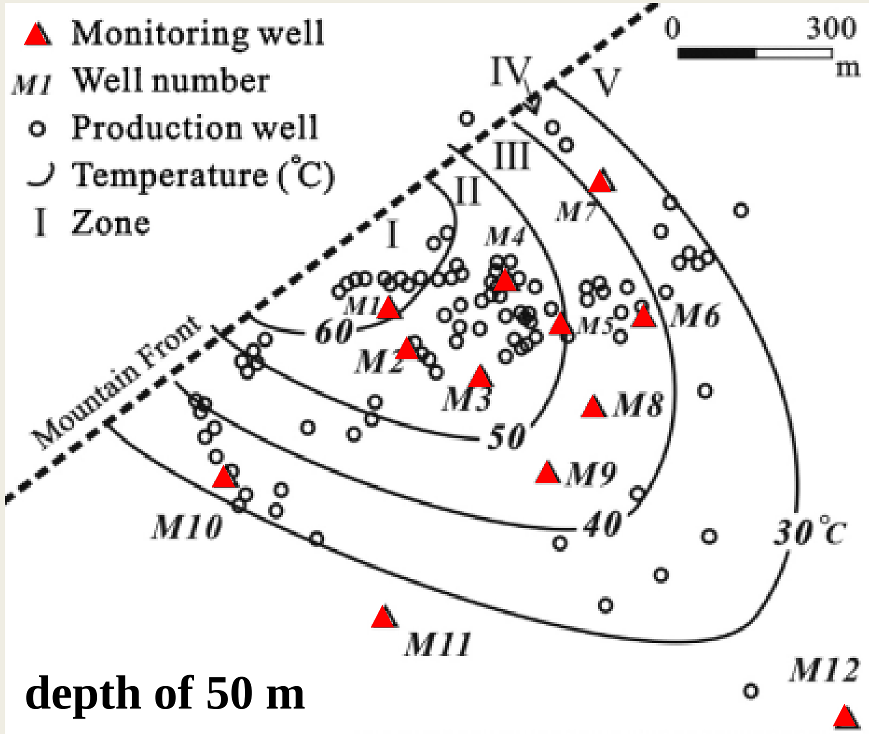
- Along the mountain front, three alluvial fans developed, the rivers flowed southeastward, and hot springs emerged between the T and D fans.



Hydrogeological background

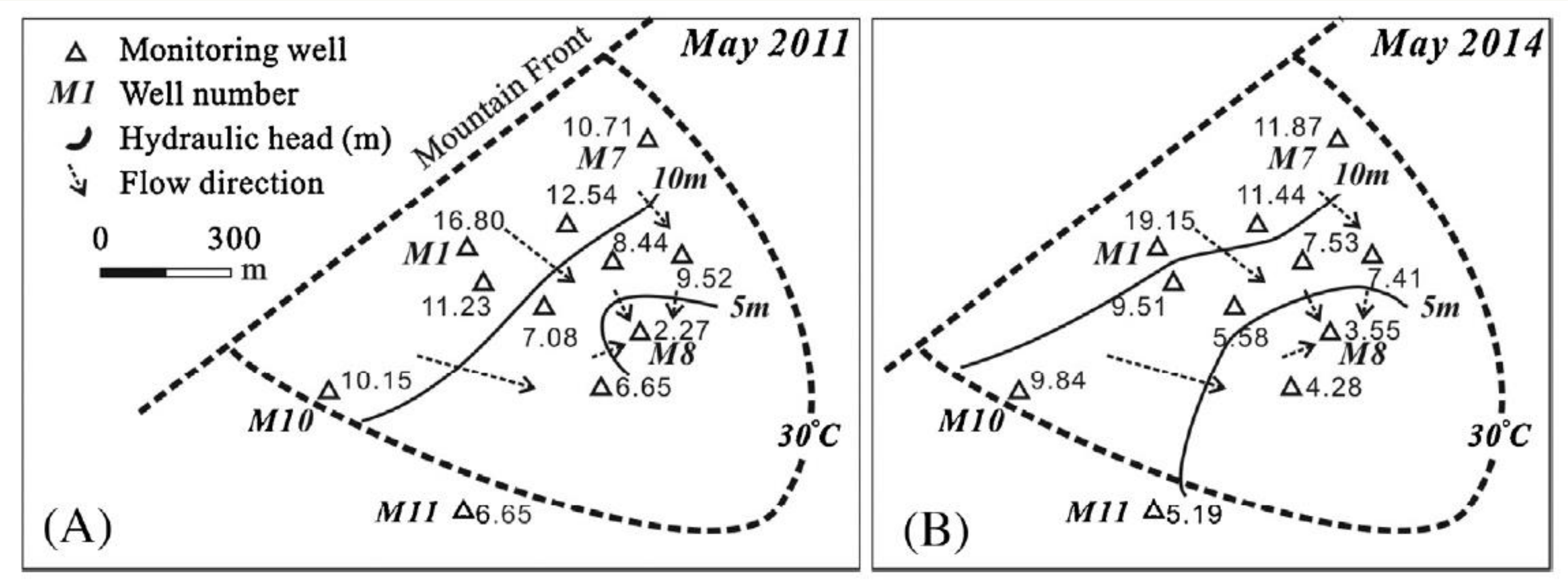
- The bedrock is composed of Sl (quartzite) and Kk (metasandstone and slate) formations.
- Thermal water flows vertically upward from deeper fracture zones within the Sl formations and emerges as hot springs, or horizontally flows to alluvial deposits (Chen and Lu, 2010).
- Subsurface temperatures at a depth of 50 m decrease toward the southeast in the shape of a fan.
- Based on temperature, it can divide into five zones with temperatures of >60°C ~ <30 °C.





Hydrogeological background

- A decreasing trend in temperature is consistent with the direction of thermal water flow, with hydraulic heads decreasing from approximately 20 to 2 m in elevation.
- From 2011 to 2014, despite hot water extraction within the JHS, groundwater flow direction and hydraulic head did not change significantly.



Research methods

Equipment & settings

- In order to ensure balance with borehole ambient temperatures, an automatic probe was placed at each measurement point over a vertical interval of 4 m for at least two minutes.
- Because of air's lower thermal diffusivity, temperature data for the unsaturated zone were discarded (Eppelbaum et al., 2006).
- Long term monitoring for temperature and pressure were recorded using automatic probes over half-hour intervals.

Research methods (The Mann–Kendall statistical test)

- To assess whether or not monotonic upward or downward trends in the variable of interest occur over time (Mann, 1945; Kendall, 1975; Gilbert 1987).

- Data (X_1, X_2,……,X_n) are collected over time (1, 2,......,n).

- Let sign ($X_j - X_k$) be an indicator function. ($j > k$,eg：$X_2 - X_1$, $X_3 - X_1$)

$$\text{sign}(X_j - X_k) = 1 \quad \text{if } (X_j - X_k) > 0$$

$$\text{sign}(X_j - X_k) = 0 \quad \text{if } (X_j - X_k) = 0$$

$$\text{sign}(X_j - X_k) = -1 \quad \text{if } (X_j - X_k) < 0$$

- In this study, they defined 0.2 °C as the threshold required to differentiate the sign ($X_j - X_k$).

Research methods (The Mann–Kendall statistical test)

- The Kendall statistic (***S***)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sign}(X_j - X_k)$$

A positive value for S tends to represent an increasing trend

- The variance **VAR(*S*)**

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)\right]$$

g is the number of tied groups； t_p is the number of observations in the pth group.

- {30,35,32,33,31,35} n=6, g=1, t_1=2 for the tied value 35

Research methods (The Mann–Kendall statistical test)

- The standard normal statistic (**Z**) was computed using the follow equations.

$$Z = \frac{(S-1)}{[VAR(S)]^{(1/2)}} \qquad \text{if } S > 0$$

$$Z = 0 \qquad \text{if } S = 0$$

$$Z = \frac{(S+1)}{[VAR(S)]^{(1/2)}} \qquad \text{if } S < 0$$

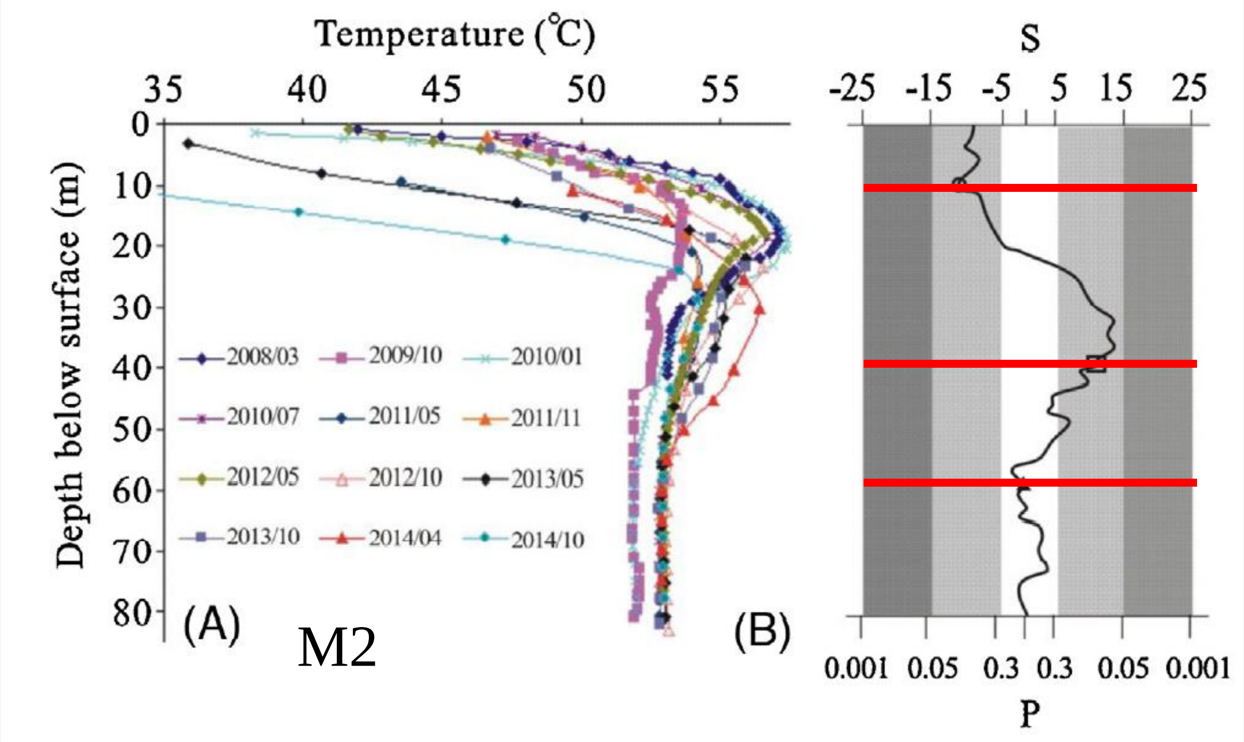
- The probability (***P***) associated with the normalized statistic Z

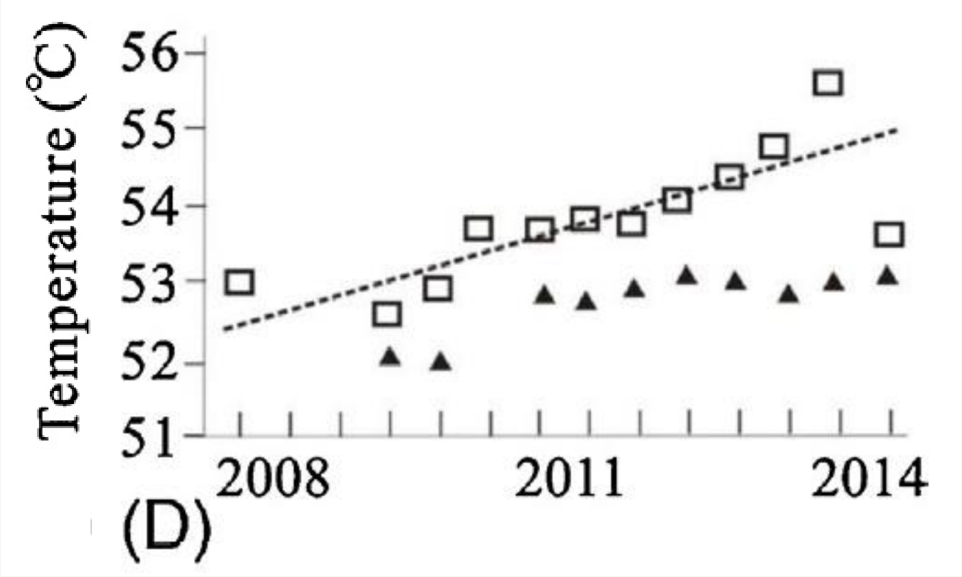
$$P = \frac{1}{\sqrt{2\pi}} e^{\,z^2/2}$$

	0.05		0.3	
Certain	|	Possible	|	No trend

Results and discussion

- Fig (A) provides borehole temperature-depth curves for well M2 from 2008 to 2014.
- The temperature curves indicate shows that dominant flows should occur between 10 and 50 m.
- Fig (B) use MK method to calculate *S* and *P*. (during 2011-2014)

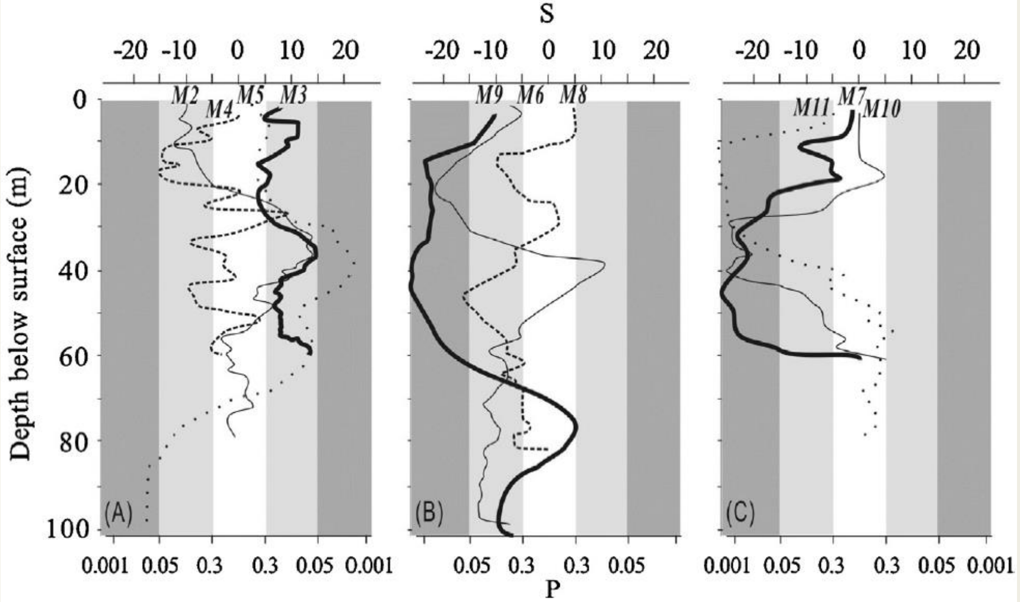


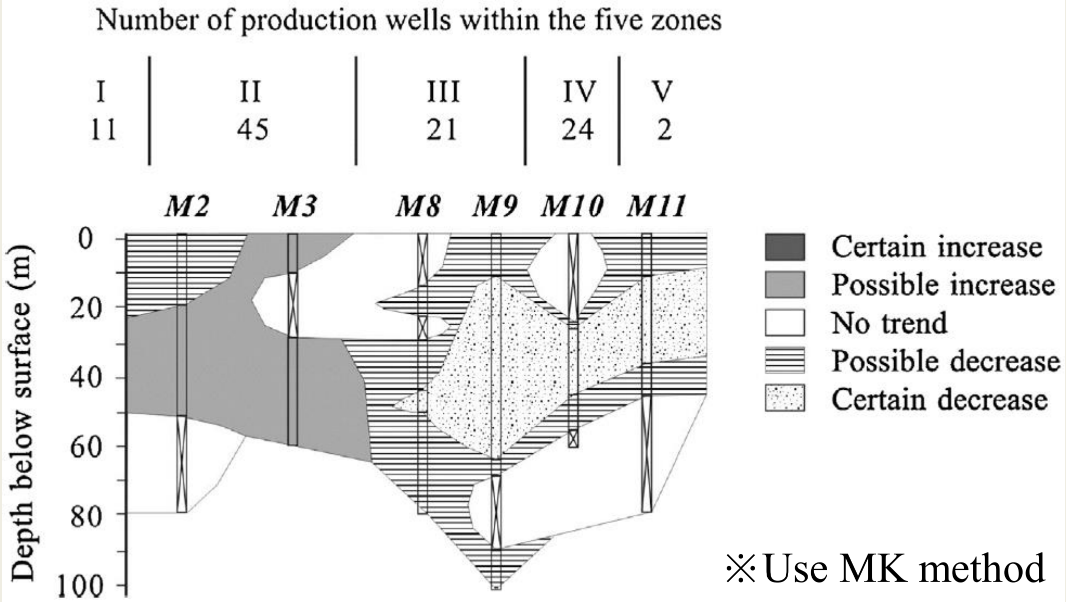


Depth of 40 m(□) (possible increasing trend)
Depth of 60 m(▲) (no trend)

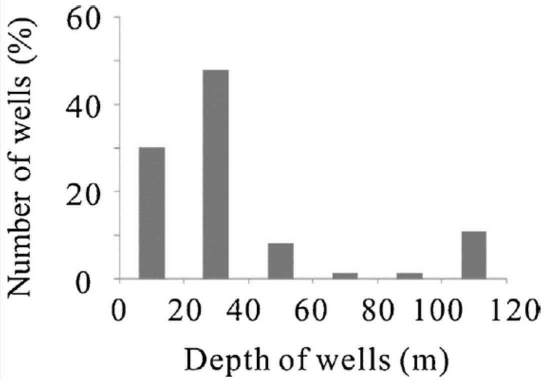
Results and discussion

- *P* and *S* curves for subsurface temperatures for monitoring wells M2–M11 from 2011 to 2014.
- Right figure provides a composite trend profile of subsurface temperatures for monitoring wells based on left figure's data.
- More than 56 production wells (54%) are located within Zones I and II.





Results and discussion

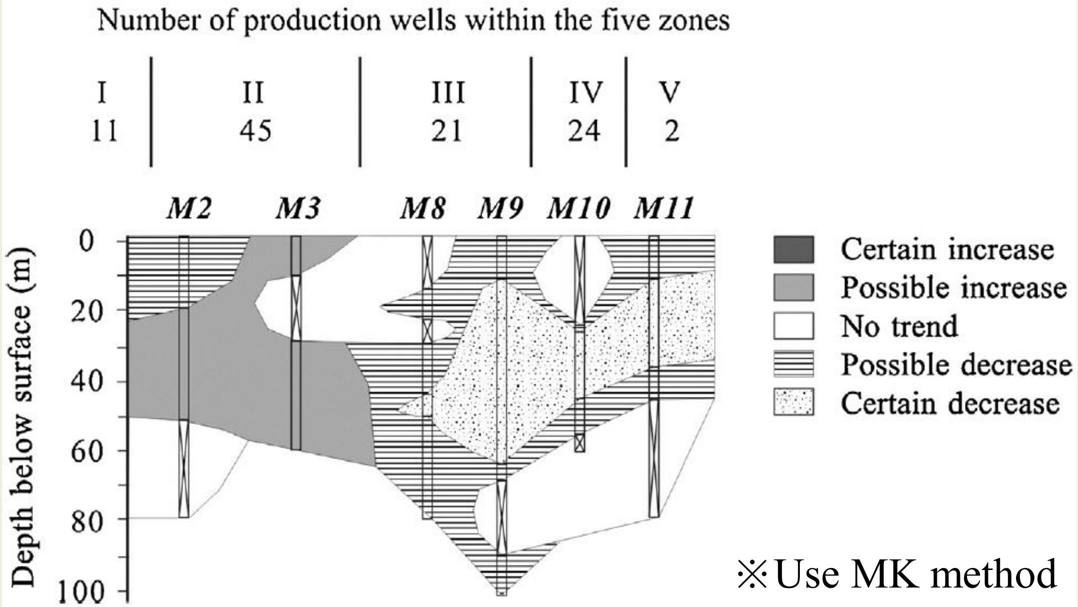


M2 (Zone II)

- A cooling trend from 0 to 26 m and a warming trend from 26 to 46 m.
- Temperatures at 46~80 m remained constant during the period from 2011 to 2014, indicating that there should be no significant flow in this section due to a lack of production wells.

M8-11 (Zone III ~ V)

- A certain decreasing trend in temperature occurs at depth of 10–60 m.
- The decreasing trend should be caused by decades of thermal water exploitation.



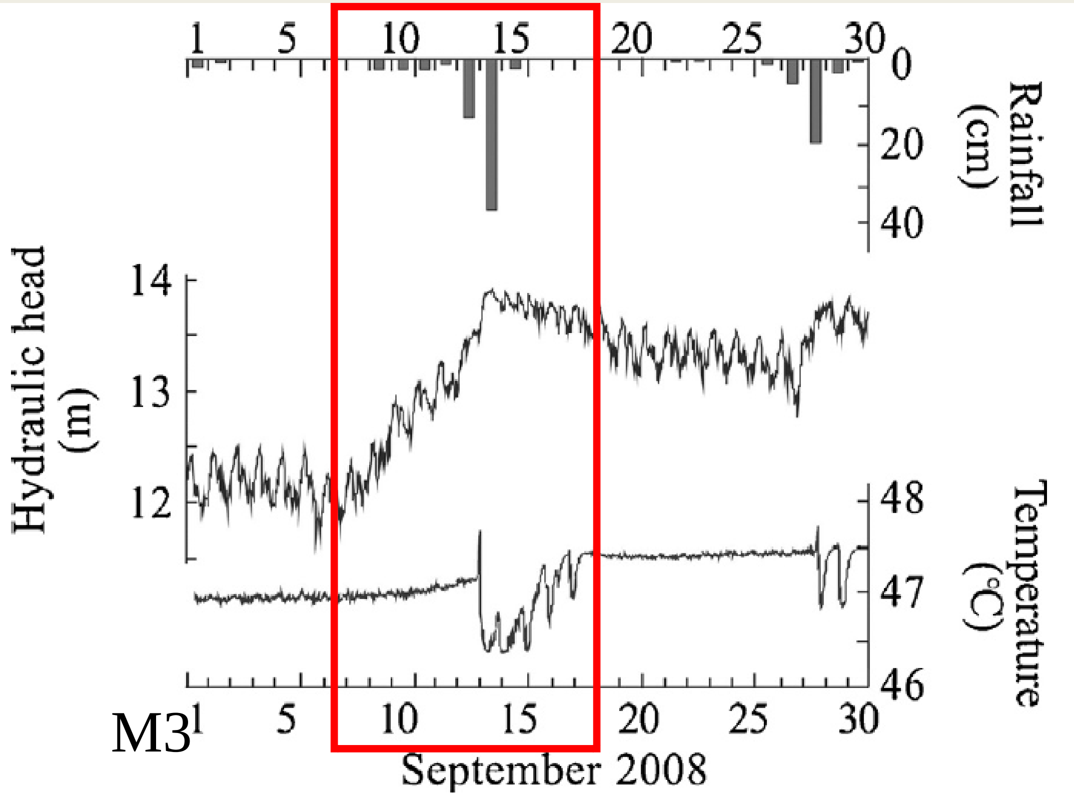
Conclusions

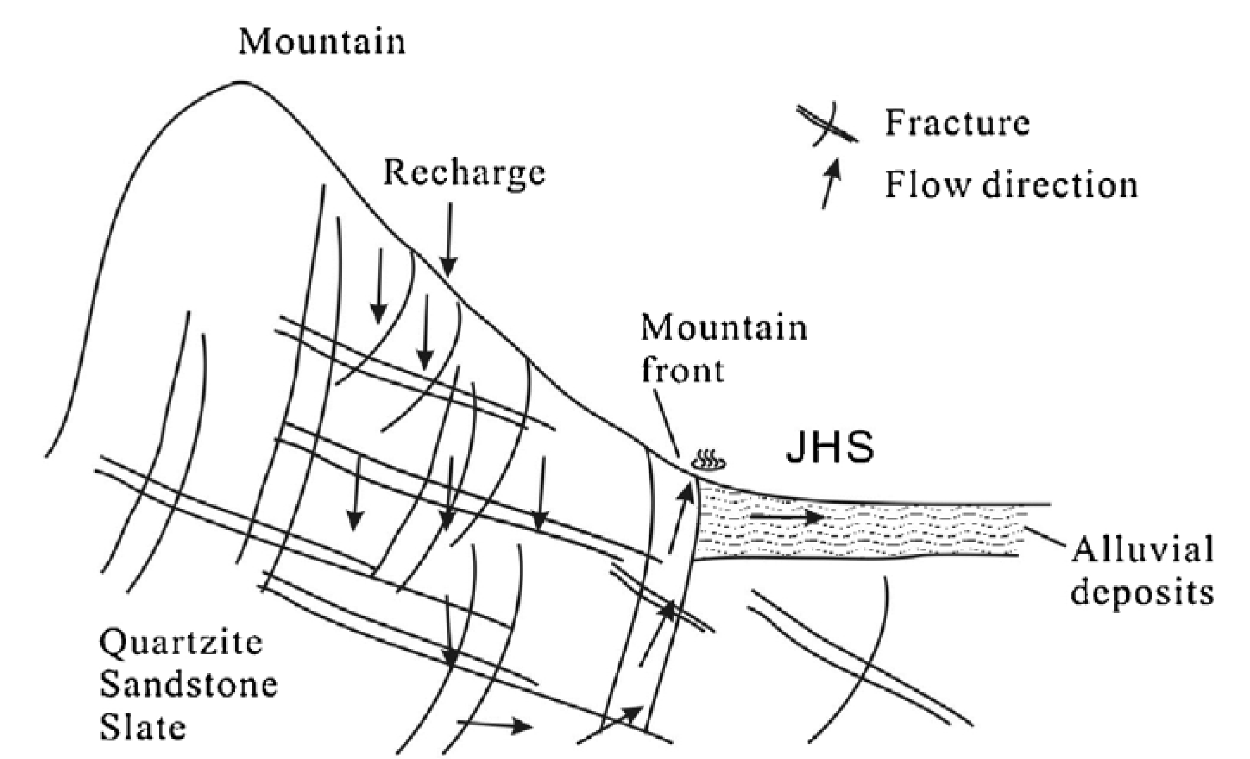
- In this study created borehole temperature-depth curves from 2011 to 2014 for ten monitoring wells within the Jiashi Hot Spring in Taiwan.
- The results indicate that trends for subsurface temperature are related to hydrogeology, the flow field of groundwater, and the depth distribution of production wells.
- Zones I and II：mainly indicated a warming trend. Shallow portions of unconfined aquifers cool due to rainfall and surface water recharge.
- Zones III to V：monitoring data displayed decreasing trends in subsurface temperatures, indicating changes in the groundwater/thermal-water direction.

Thanks for your listening

Hydrogeological background

- The rainfall data we used for our study were obtained from the plain area of the JHS, although the recharge area for thermal water is located in the mountains located approximately 20 km west of JHS.





Research methods

Equipment & settings

- 12 monitoring wells are constructed of stainless steel or polyvinyl chloride, are 4–6 in. in diameter, and have depths to 100 m. Screens of 6–24 m in length were installed in the bottom portion of the wells.
- The probe employed for measurements, the Aqua TROLL 200 of In-Situ Inc., has a working range of −20 to 80 ◦C, an accuracy of 0.1 ℃, a resolution of 0.01 ℃.

The Mann–Kendall statistical test

- Some assumption：
  - Your data isn’t collected seasonally
  - Your data does not have any covariates
  - You have only one data point per time period

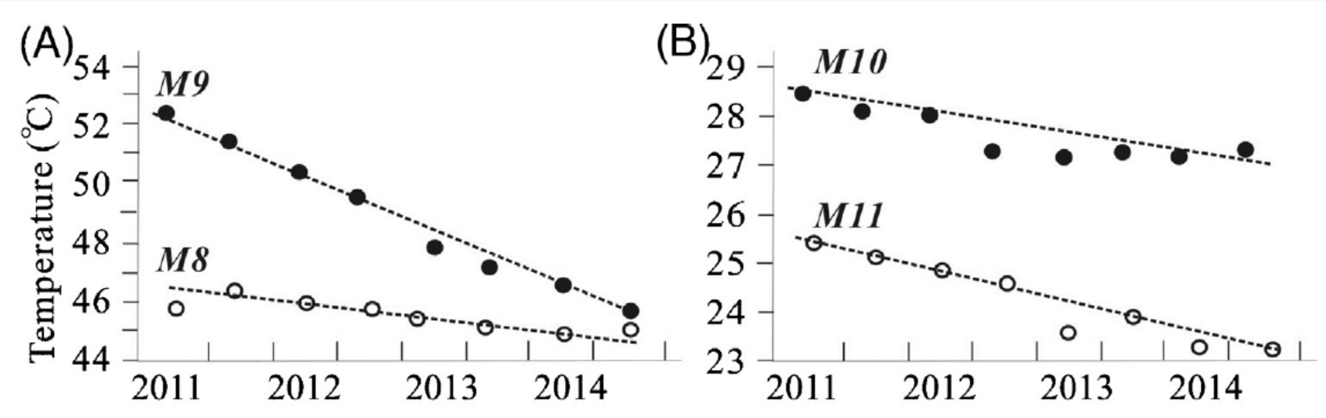
The Mann–Kendall statistical test

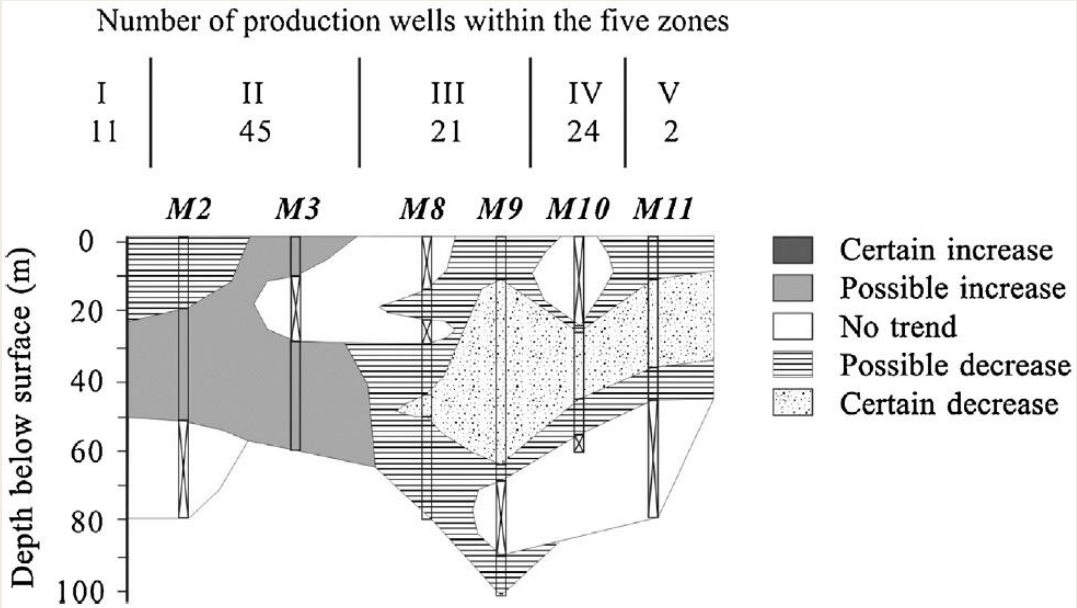
	A	B	C	D	E	F	G	H	I	J
1	data			2	3	4	5	1	3	
2	2		2							
3	3		3	1						
4	4		4	1	1					
5	5		5	1	1	1				
6	1		1	-1	-1	-1	-1			
7	3		3	1	0	-1	-1	1		
8										
9										
10	g	1								
11	t1=3	2	18	=+B11*(B11-1)*(2*B11+5)						
12	n	6	510	=+B12*(B12-1)*(2*B12+5)						
13	VAR	27.33333								
14	S	2		=(1/18)*(C12-C11)						
15	Z	0.191273		=(B14-1)/SQRT(B13)						
16	P	0.40641		=(1/SQRT(2*3.14))*EXP(B15*B15/2)						
17										
18	no trend									
19										
20										

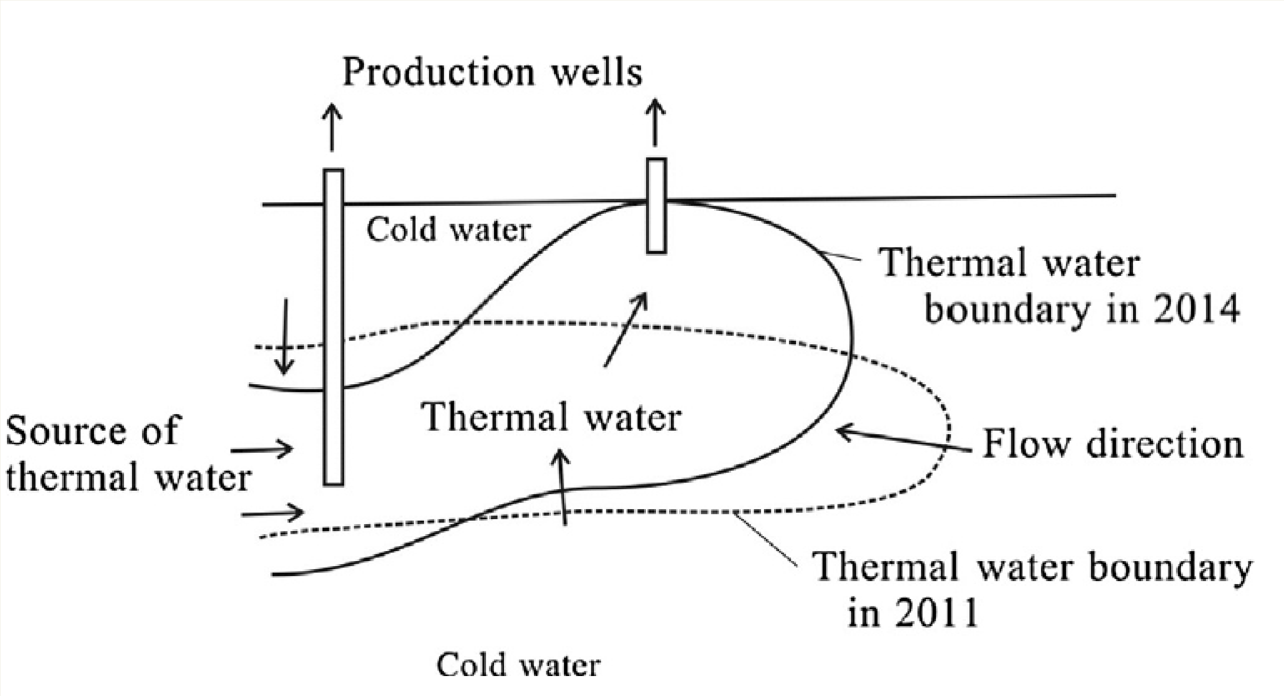
Results and discussion

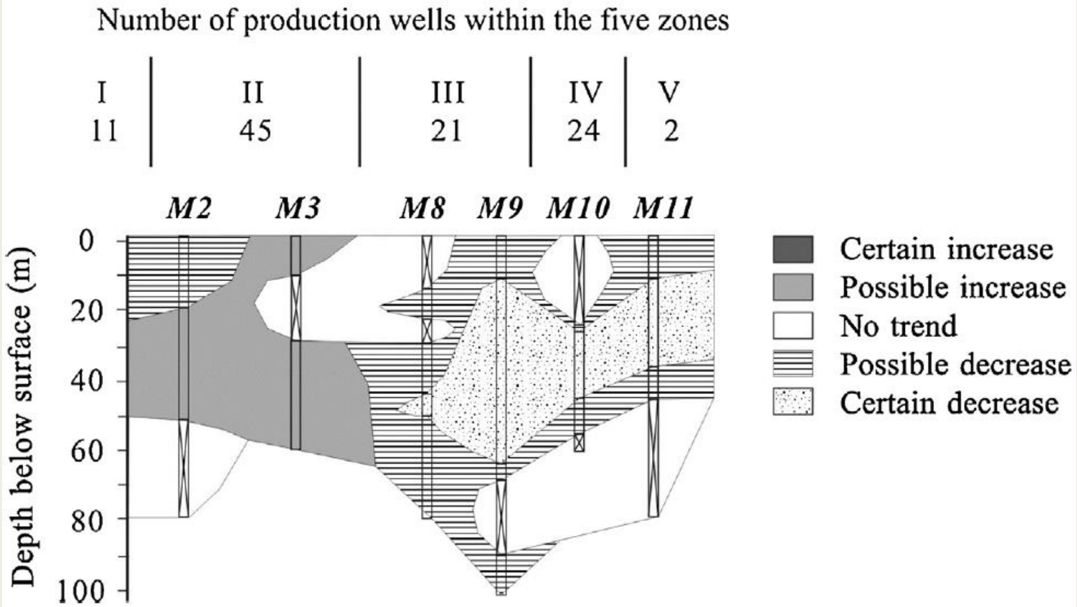
M8-11

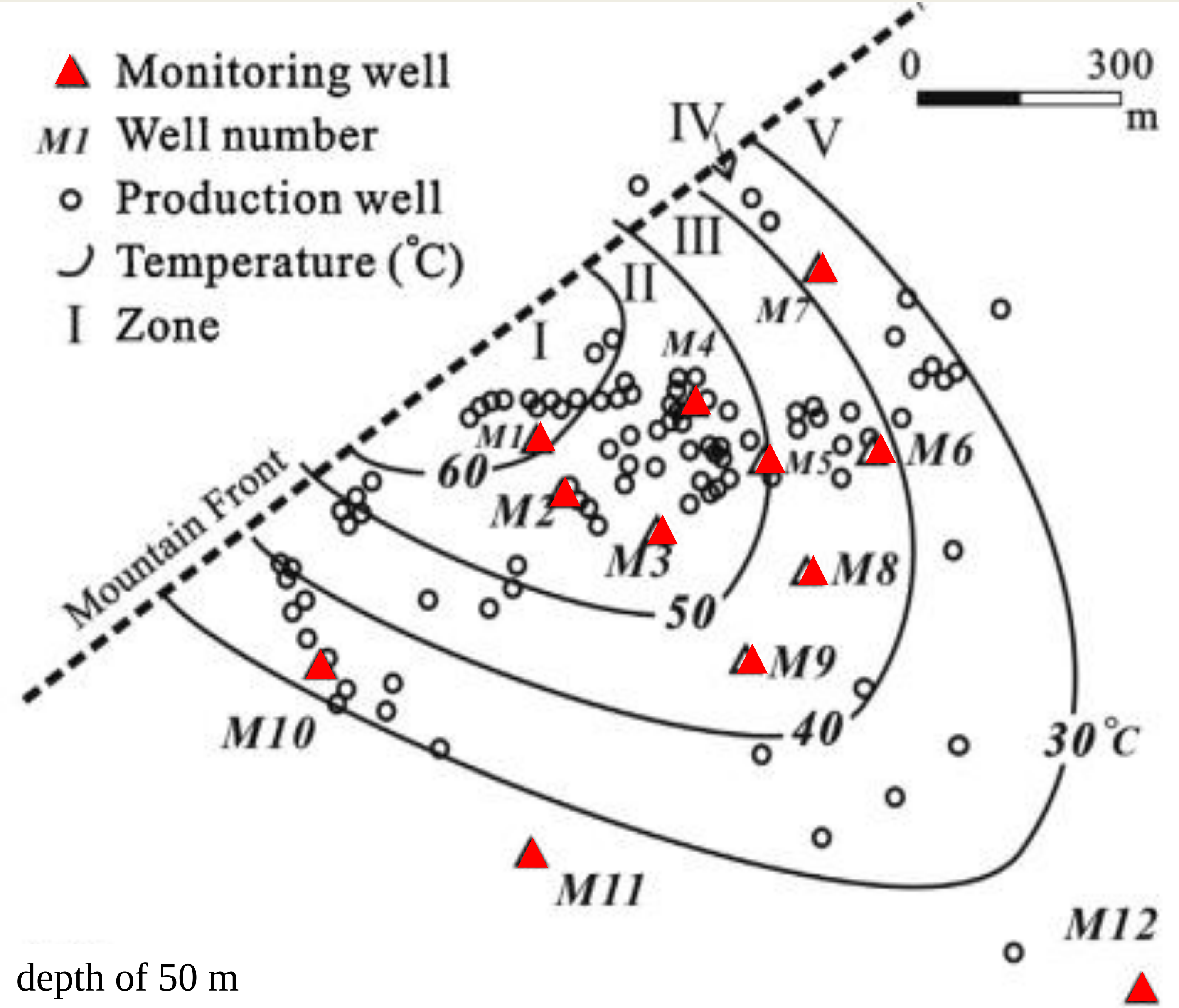
- The certain decreasing trends for monitoring well M8 at a depth of 45 m, for M9 at a depth of 45 m, for M10 at a depth of 35 m, and for M11 at a depth of 19 m from 2011 to 2014.






Production wells
Cold water
Thermal water
boundary in 2014
Source of
thermal water
Thermal water
Flow direction
Thermal water boundary
in 2011
Cold water


Number of production wells within the five zones
I
11
II
45
III
21
IV
24
V
2
M2
M3
M8
M9
M10
M11
Depth below surface (m)
0
20
40
60
80
100
Certain increase
Possible increase
No trend
Possible decrease
Certain decrease


Monitoring well
M1 Well number
Production well
Temperature (℃)
I Zone
0
300
m
I
II
III
IV
V
Mountain Front
60
50
40
30℃
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12

depth of 50 m