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Well Water Level Analysis Based on Barometric Pressure Effects and Earth Tides

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Abstract: Barometric pressure coefficient and tidal factor are used to study the porosity, the solid skeleton volume compressibility coefficient and the water volume compressibility coefficient of the Dahuichang well, Banqiao well, Huanghua well, Dadianzi well, Fengzhen well and Sanhaodi well in the northern region of North China under undrained condition. The results show that there is power function relation between the porosity and the volume compressibility coefficient(the solid skeleton and the water)in the aquifer. In the first quadrant, the solid skeleton volume compressibility coefficient of each well increases with the increase of the porosity, the volume compressibility coefficient of the water decreases with the increase of porosity. Between the volume compressibility coefficient of the solid skeleton and the water exist unary quadratic polynomial relationship, and the volume compressibility coefficient of water is larger than that of solid skeleton, the water is easier to compress. In addition, according to the step barometric pressure response function in the regression deconvolution method, the groundwater type identifying results of the six wells aquifer system are shown that there is an e based exponential function between the lag time and the step barometric pressure response function of each well water level to barometric pressure. The coefficient before the base e is positive or negative to determine the groundwater type of the well aquifer system. For confined wells, the step barometric pressure response function increases with lag time of well water level to barometric pressure, while the unconfined wells and semi-confined wells are opposite.

Keywords: Well Aquifer System, Undrained Condition, Barometric Pressure Coefficient, Tidal Factor, Groundwater Type

1. Introduction

The analysis of the earth tides and the barometric pressure effects, and how they relate to the aquifer parameters. such as, porosity and volume compressibility coefficient of solid skeleton or water and so on, have always been the research focus of the domestic and foreign scholars [2, 4, 6-10, 13, 16, 18, 22-23]. For example, under undrained condition, the quantitative relationship between barometric pressure coefficient (or tidal factor) and porosity, volume compressibility coefficient of solid skeleton (or water) are generally given. But what's the relationship between porosity and volume compressibility coefficient of solid skeleton, and what's the relationship between porosity and volume compressibility coefficient of water. What's the quantitative relationship between the volume compressibility coefficient of the solid skeleton and that of water. In addition, a lot of researches have been carried out on the correction of barometric pressure and earth tide component in water level by using the regression deconvolution method [15, 19-20, 11]. But the quantitative identifying of groundwater type by the step barometric pressure response function, and what's the relationship between the step barometric pressure response function and the lag time of the well water level to the barometric pressure. There are few studies on these aspects.

Based on barometric pressure effects and earth tides of Banqiao well, Dahuichang well, Huanghua well, Fengzhen well, Dadianzi well and Sanhaodi well in the northern region of North China. the porosity, volume compressibility coefficient of solid skeleton and that of water are calculated under undrained condition. By stress variation model in aquifer medium, the change rule between the porosity and volumetric compressibility coefficient of solid skeleton and that of water are analyzed, and the relationship between them are given. In addition, combined with the step barometric pressure response function of water level to barometric pressure in the regression deconvolution method, the groundwater types of well aquifer system in these 6 wells are quantitatively analyzed and identified. The results are compared with the barometric pressure coefficient and the tidal factor results in the corresponding study period. The quantitative identifying of groundwater type is of great significance for the selection of observation points and identifying the quality and reliability of observed datum.

2. Methodology

2.1. Research Area and Parameters Related to Well

In this paper, Banqiao, Dahuichang, Huanghua, Fengzhen, Dadianzi and Sanhaodi 6 wells are mainly located in the northern region of North China(Figure1), and the well depth, aquifer lithology and groundwater type (based on qualitative analysis of storage and burial conditions), water depth and data analysis start time are shown in Table 1.

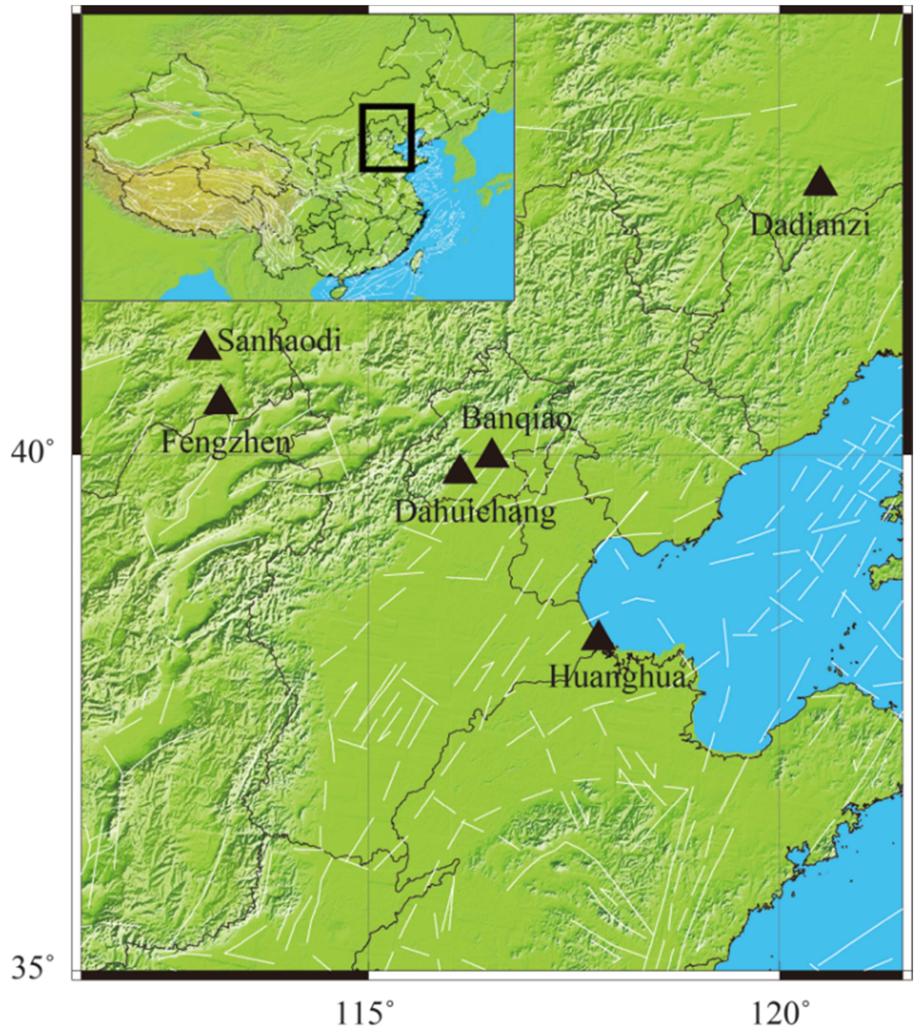

Figure 1. *Distribution of 6 wells studied.*

Table 1. *General information of 6 wells studied.*

Serial number	Well name	Position		Well depth /m	Aquifer lithology	Ground water type*	Water depth/m	Analysis start time
		Longitude/E	Latitude/N					
1	Dadianzi	120.57	42.30	200.76	Sandstone & sand-slate	Fissure confined water	18.8	May 2001
2	Sanhaodi	113.05	41.02	100.0	Basalt	Phreatic water	51.2	January 2011
3	Dahuichang	116.11	39.85	102	Sandy shale	Mixed water	14.5	January 2008
4	Banqiao	116.50	40.00	283.6	Siliceous Limestone	Fissure confined water	39.6	January 2008
5	Fengzhen	113.20	40.50	98.99	Glutenite	Confined water	2.36	January 2011
6	Huanghua	117.80	38.27	1250	Limestone	Fissure confined water	5.2	January 2007

The asterisk indicates that groundwater types is qualitatively determined according to the storage and burial conditions.

2.2. Data Analysis and Processing

To water level and corresponding barometric pressure data of Banqiao, Dahuichang, Huanghua, Fengzhen, Dadianzi, Sanhaodi 6 wells,(1)The hour value data of each well is checked that there must be 24 numbers per day, where the missing number are replaced by cubic spline interpolation and piecewise fitting values of general polynomials.(2) In the 5 main daily wave groups and 5 semidiurnal wave groups of the earth tide, considering the maximum amplitude of the 6 well water M_2 wave in the middle latitudes, it has the largest signal-to-noise ratio, so we choose M_2 wave to do harmonic analysis.(3) In addition, it is necessary to prepare a excel file that includes the date column, water level column, barometric column, theoretical earth tide, and is an equal interval hour value for each well. It needs to be emphasized that the water level must be converted from buried depth to total heads.

2.3. Obtaining Method of Barometric Pressure Coefficient and Tide Factor

(1) Barometric pressure coefficient

Firstly, the water level and barometric pressure data are filtered such as Bill Zerf filter. Secondly, the difference of the filtered data is made such as first-order difference or higher-order difference. Finally, based on the difference results, we use the unary or binary regression model to fit the barometric coefficient [3, 5, 12, 21, 24]. In general, after the data of water level and barometric pressure are processed by filtering and difference. Then the barometric pressure coefficient results can be fitted by using the unary regression model. In this paper, we take the maximum of the water level and the barometric pressure correlation coefficient in 0~3 order difference.

(2)Tide factor

Firstly, the regression deconvolution method is used to remove the barometric pressure components of the water level. Then, the general polynomial piecewise fitting is used to remove the trend and the periodic components. Finally, the remaining water level is only the tidal response (earth tide effect). By using the Vinnie Dikko J harmonic analysis program, the M_2 wave parameters such as tidal factors can be obtained.

2.4. Porosity and Volume Compressibility Coefficient of Medium

(1) Basic theories

According to the results of previous studies [2, 10, 22-23], under undrained condition, the barometric pressure coefficient and the tide factor can be expressed as:

$$B_P = \frac{nc_w}{c_s + nc_w} \tag{1}$$

$$Bg = -\frac{1-n}{\rho g\left[(1-n)c_s + nc_w\right]} \tag{2}$$

The following formula can be obtained on the basis of the upper two:

$$Bg = -\frac{1-n}{\rho gnc_w\left[\frac{(1-n)(1-Bp)}{Bp}+1\right]} \tag{3}$$

Where Bp is barometric pressure coefficient, Bg is tidal factor, n is Porosity, c_s and c_w are the volume compressibility coefficient between solid skeleton and water in aquifer medium, ρ is density of water in aquifer, g is the acceleration of gravity at the earth's surface.

The porosity and the volume compressibility coefficient of water can also be slid by the formula (3). Finally, the volume compressibility coefficient of the solid skeleton can be obtained by using the formula (1) or formula (2).

(2) Volume change model of aquifer medium

Under natural conditions, the aquifer media are usually solid, liquid and gas three-phase objects which are formed by solid skeleton particles, interconnected pores and fluid materials. The fluid studied is water in this paper (Figure 2).

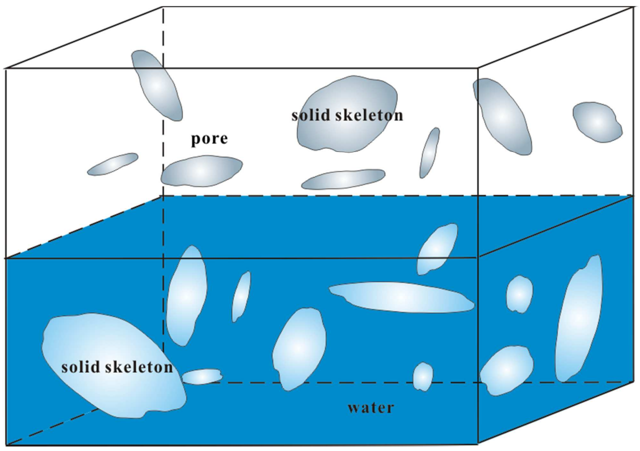

Figure 2. *Schematic of aquifer medium.*

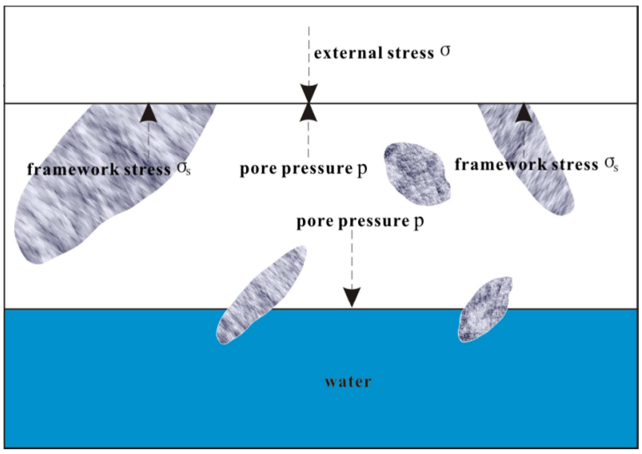

Figure 3. *Aquifer medium stress.*

It is assumed that under the elastic state, the external stress remains unchanged and the total volume of appearance is unchanged, the volume compressibility coefficient of the water and that of solid skeleton can be expressed as [14]:

$$c_w = \frac{\partial V_w}{V_w \cdot \partial p} \tag{4}$$

$$c_s = \frac{\partial V_s}{V_s \cdot \partial \sigma_s} \tag{5}$$

Where c_s and c_w are the volume compressibility coefficient of the solid skeleton and that of water in aquifer. ∂V_w is the volume change of the water. V_w is the volume of the water. ∂p is the change of pore pressure. ∂V_s is the volume change of the solid skeleton. V_s is the volume of the solid skeleton. $\partial \sigma_s$ is the change of the skeleton stress.

In combination with the definition of effective porosity, the volume of water increases when the pore pressure decreases. Under the condition that the external stress remains constant, the skeleton stress will increase, the volume of the skeleton decreases, and the pore volume also decreases together. In other words, when the volume of water becomes larger, the volume of the skeleton and the pore are decreasing in the case of effective porosity from 1 to 0. contrarily, when the volume of water is smaller and the volume of the pores and the skeleton become larger, the effective porosity from 0 to 1 (Figure3).

(3) Variation characteristics of porosity and volume compressibility coefficient

(a) There exists power function relationship between the porosity and the volume compressibility coefficient of the solid skeleton for each well in the aquifer medium(Figure 4, Table 2), that is $c_s=b(1\text{-}n)^c$. The range of porosity n is 0~1, and the range of volume compressibility coefficient of solid skeleton c_s is 0~+∞, and power exponent $c<0$. It is shown that in the first quadrant, the volume compressibility coefficient of the solid skeleton increases with the increase of the porosity. It is attributed to the increase of the skeleton volume when the skeleton stress is reduced. Therefore, the volume compressibility coefficient of the solid skeleton increases with the increase of porosity.

(b) In addition, there is obvious power function relationship between the porosity and the volume compressibility coefficient of water for each well, That is $c_w=bn^c(c<0)$. In the first quadrant, the volume compressibility coefficient of water decreases with the increase of porosity (Figure 5, Table 2). In this process, when the pore pressure increases, the water is difficult to compress, and the elastic deformation of water is getting smaller and smaller. This is because the compressibility coefficient of water is getting smaller and smaller, and the volume change is smaller, the water is more difficult to compress. At the same time, the solid skeleton is easy to compress, and its elastic deformation is gradually enhanced.

Table 2. *Fitting results of the porosity and volume compressibility coefficient for 6 wells.*

Serial number	Well name	The relationship between n and c_s			The relationship between n and c_w		
		Fitting equation	R^2	standard deviation	Fitting equation	R^2	standard deviation
1	Sanhaodi	c_s=4.155(1-n)$^{-0.769}$	0.9147	4.785	c_w=0.89061$n^{-1.561}$	0.598	59.86
2	Banqiao	c_s=1.839(1-n)$^{-1.187}$	0.3811	64.05	c_w=0.0403$n^{-2.552}$	0.8204	51.37
3	Huanghua	c_s=0.132(1-n)$^{-2.29}$	0.787	73.22	c_w=1.563×10$^{-9}n^{-6.04}$	0.8911	569.4
4	Dahuichang	c_s=4.93(1-n)$^{-1.345}$	0.7006	370.5	c_w=1.639×10$^{-4}n^{-4.109}$	0.7225	1707
5	Dadianzi	c_s=26.85(1-n)$^{-1.103}$	0.71	360.8	c_w=2.337$n^{-2.54}$	0.87	1881
6	Fengzhen	c_s=59.9(1-n)$^{-0.69}$	0.4651	218.5	c_w=2.563$n^{-1.895}$	0.6702	1203

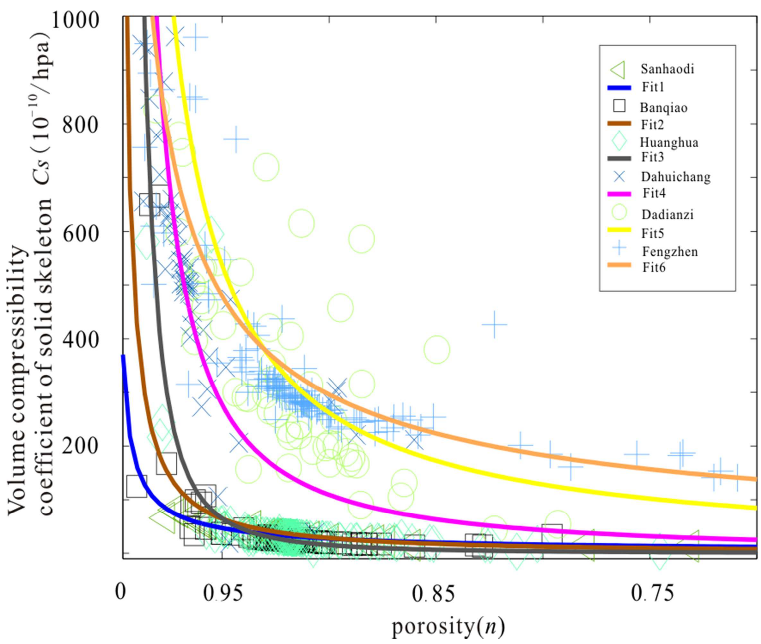

Figure 4. *Relationship of volume compressibility coefficient between the porosity and solid skeleton of 6 wells.*

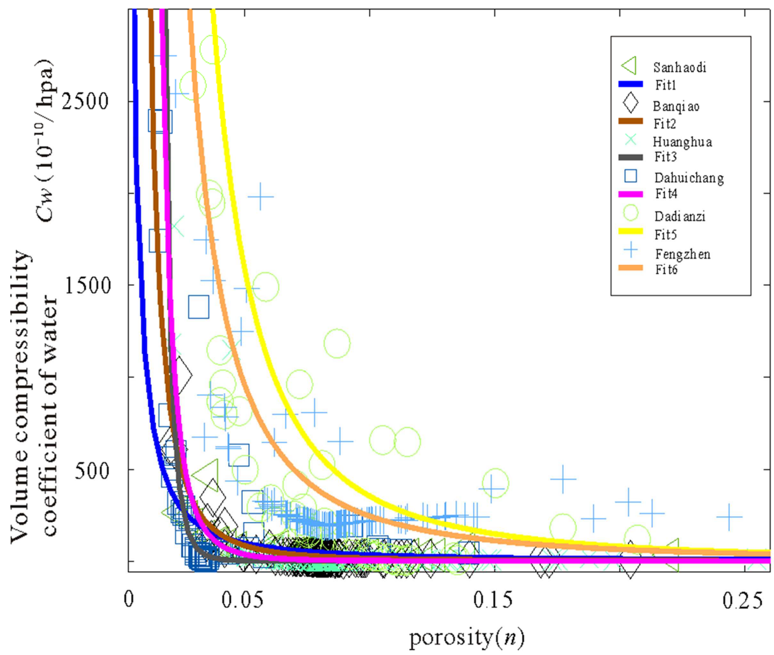

Figure 5. *Relationship of volume compressibility coefficient between the porosity and water of 6 wells.*

(c) There is unary quadratic polynomial relationship between the volume compressibility coefficient of the solid skeleton and the water in the aquifer, and the volume compressibility coefficient of water is larger than that of the solid skeleton (Figure6, Table 3). When the volume compressibility coefficient of water is constant, the volume compressibility coefficient of the solid skeleton from small to large is Sanhaodi well, Banqiao well, Huanghua well, Dadianzi well, Fengzhen well, Dahuichang well. The volume compressibility coefficient of the solid skeleton is small, which indicates that the volume change of the skeleton is small, the harder the skeleton is, the harder it is to compress. By the lithology of each well in Table 1, Sanhaodi well, Banqiao well and Huanghua well are mainly hard and difficult to compress basalt or limestone, so the compressibility coefficient of its solid skeleton are relatively small. Dadianzi well, Fengzhen well and Dahuichang well are mainly composed of relatively loose and easily compressible sandstone, so the compressibility coefficient of its solid skeleton are relatively large. That is, the compressibility coefficient of the sandstone skeleton is higher than that of the limestone and the basalt.

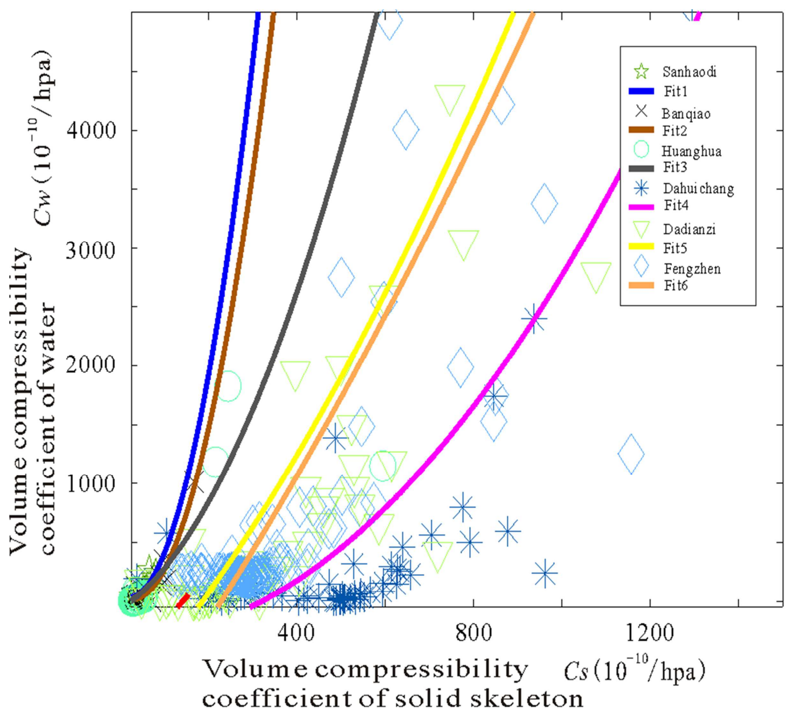

Figure 6. *Relationship curve of volume compressibility coefficient (cs and cw) of 6 wells.*

Table 3. *Statistics of the 6 wells volume compressibility coefficient (c_s and c_w).*

Serial number	Well name	Fitting equation	R^2	Standard deviation
1	Sanhaodi	c_w=0.058c_s^2-2.24c_s+58.67	0.8659	23.95
2	Banqiao	c_w=0.04888c_s^2-2.746c_s+53.62	0.9374	24.5
3	Huanghua	c_w=0.0119c_s^2+2.63c_s-66.88	0.9435	490
4	Dahuichang	c_w=0.003094c_s^2-0.01124c_s-316.2	0.7337	1686
5	Dadianzi	c_w=0.00263c_s^2+4.27c_s-898	0.623	3101
6	Fengzhen	c_w=0.00155c_s^2+5.26c_s-1290	0.4641	1309

2.5. Quantitative Analysis and Diagnosis of Groundwater Type

(1) Theory and method

[15] describe how barometric pressure response changes cause a range of ground water responses. Regression deconvolution method was used to estimate the barometric pressure response function using paired water level-barometric pressure observations. The residual-or corrected-head can be calculated once the response function is known [19]. A linear set of equations is established to estimate the unknown barometric pressure response function [1]:

$$\Delta W(t) = \sum_{i=0}^{m}\alpha(i)\Delta B(t-i) + \sum_{i=0}^{m}\beta(i)\Delta ET(t-i) \tag{6}$$

where i is lag time, m is the maximum time lag, $\Delta W(t)$ is the changes in water level at time t, $a(i)$ is the unit response function at lag i, $\Delta B(t-i)$ and $\Delta ET(t-i)$ are the changes in barometric pressure and earth tide i time steps before t, $\beta(i)$ is the response coefficient of earth tide.

The response function is found using ordinary least squares linear regression. Once the values of $a(i)$ are found, then the step barometric pressure response function $A(j)$ is calculated by summing the impulse responses:

$$A(i) = \sum_{j=1}^{i}\alpha(j) \tag{7}$$

The step barometric pressure response function is useful for diagnosing the aquifer type (confined or unconfined), borehole storage effects, well skin effects, and even estimating aquifer hydraulic properties. [15, 17] document the regression deconvolution method and its use as a diagnostic tool.

Using the response function, a correction variable for each observation is calculated using:

$$\begin{bmatrix} W_m^* \\ W_{m+1}^* \\ W_{m+2}^* \\ \vdots \\ W_n^* \end{bmatrix} = \begin{bmatrix} \Delta B_1 & \Delta B_2 & \Delta B_3 & \cdots & \Delta B_m \\ \Delta B_2 & \Delta B_3 & \Delta B_4 & \cdots & \Delta B_{m+1} \\ \Delta B_3 & \Delta B_4 & \Delta B_5 & \cdots & \Delta B_{m+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \Delta B_{n-m+1} & \Delta B_{n-m+2} & \Delta B_{n-m+3} & \cdots & \Delta B_n \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \vdots \\ \alpha_m \end{bmatrix} \tag{8}$$

where W^*_t is the correction variable for each observation within t from m to n, m is the maximum lag selected by the user, and n is the total number of observations in the data set.

(2) Relationship between step barometric pressure response function and lag time

Because BETCO program uses the input file and a maximum lag time of m=12 to estimate the initial response function, so the data time step is set at 1 h for all observations, and a maximum time a lag of 12 h is used when both barometric and earth tide effects are removed [19].

(a) Between the step barometric pressure response function and lag time of well water level to barometric pressure for 6 wells studied fit the e exponential function forms:

$$A(i)=ae^{bi}+c \tag{9}$$

Where $A(i)$ is the step barometric pressure response function. i is the lag between the barometric pressure change and the total head response. a, b and c are the coefficient of equations, incorporate the well shape and size and aquifer hydraulic properties.

(b) With the increase of the lag time for water level to barometric pressure, the step barometric pressure response function of Banqiao well, Fengzhen well and Huanghua well is decreased, Here they are all the unconfined well or the semi-confined well. On the contrary, for confined well (For example, Dadianzi well, Sanhaodi well and Dahuichang well), the step barometric pressure response function of the water level to the barometric pressure is increased with the increase of lag time. The coefficient a before e that is positive or negative to determine the groundwater types.

(c) No matter what the groundwater type of the well aquifer system is in 6 wells, the coefficient b is less than zero. and b is related to the well shape and size(structure) and aquifer hydraulic properties [15, 20].

(d) In the early stage, due to obvious borehole storage effects and well skin effects [15, 19-20] with the increase of the lag time for water level to barometric pressure, the step barometric pressure response function of Dadianzi well, Sanhaodi well and Dahuichang well is increased. The step barometric pressure response function at the later stage (also known as the optimal step barometric pressure response function) is relatively stable and transformed into the corresponding aquifer model. Therefore, considering the strength or weakness of confined well aquifer system, Dadianzi well's the strongest, Sanhaodi well next, Dahuichang well is the weakest. The results of the step barometric pressure response function of the water level to the barometric pressure show that Banqiao well, Fengzhen well and Huanghua well are all the unconfined well or the semi-confined well.

(3) Proof of barometric pressure effects and earth tides

For the confined well aquifer system, the greater the confined capacity is, the greater the response of the water level to the earth tide and barometric pressure. The barometric efficiency (or barometric pressure coefficient) of well water level varies from well to well, which is restricted by many factors. It is mainly related to rock properties and aquifer hydraulic properties [22]. Besides, the main factors that affect the response of the earth tide are the hydraulic properties of aquifer, the borehole structure and the frequency of earth tidal waves [10, 16].

By calculation of the barometric pressure coefficient, the tidal factor and the step barometric pressure response function in 6 wells based on their respective research periods, The consistency and difference between the earth tide effect, the barometric pressure effect and the groundwater type are analyzed and compared. The results show that (a)There is an obvious consistency between the step barometric pressure response function, barometric pressure coefficient and M_2 wave tide factor of Dadianzi well, Sanhaodi well and Dahuichang well. In the 3 confined wells, the step barometric pressure response function of well water level to barometric pressure is bigger, and the corresponding barometric pressure coefficient and M_2 wave tide factor are also bigger (Figure7, Table 4). (b) The relationship is not obvious between the barometric pressure coefficient, the tidal factor and the step barometric pressure response function in Banqiao well, Fengzhen well and Huanghua well.

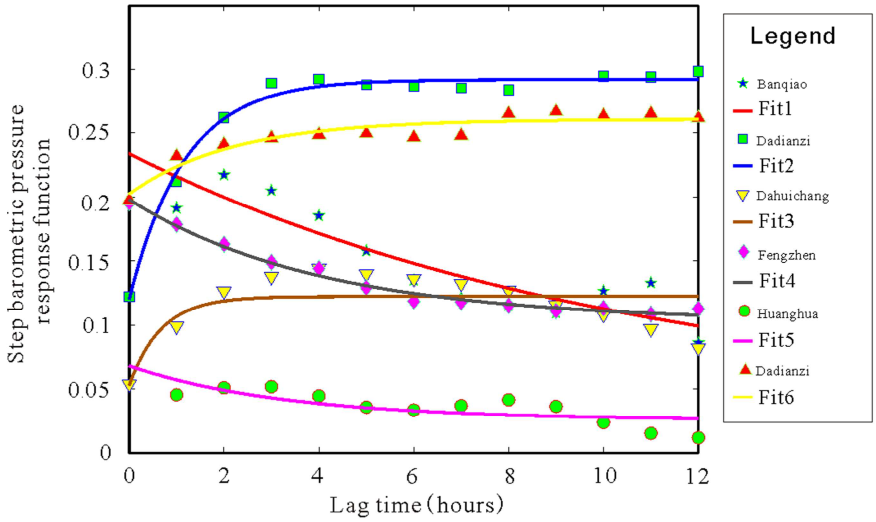

Figure 7. *Relationship between step barometric pressure response function and lag time of 6 wells.*

Table 4. *Information between step barometric pressure response function and lag time in 6 wells.*

Serial number	Well name	Fitting equation	R^2	Standard deviation	Type of groundwater*	Barometric pressure coefficient(mm/hpa)	M_2 wave tide factor(mm/10^{-9})
1	Dadianzi	$A(i)$=-0.1718$e^{-0.86i}$+0.292	0.987	0.0063	confined	3.2	0.979
2	Sanhaodi	$A(i)$=-0.05837$e^{-0.4529i}$+0.27	0.890	0.0069	confined	2.1	0.337
3	Dahuichang	$A(i)$=-0.06935$e^{-1.487i}$+0.122	0.525	0.0201	confined	1.8	0.157
4	Banqiao	$A(i)$=0.1994$e^{-0.09361i}$+0.035	0.827	0.0193	unconfined	4.0	2.150
5	Fengzhen	$A(i)$=0.09519$e^{-0.2452i}$+0.103	0.988	0.0035	unconfined	2.0	0.235
6	Huanghua	$A(i)$=0.2644$e^{-0.01281i}$-0.2078	0.775	0.0068	unconfined	1.95	1.258

Asterisk represents the groundwater type determined by step barometric pressure response function method.

3. Results AND Discussion

(1) The porosity and volume compressibility coefficient (solid skeleton and water) exists power function relationship. The domain(refers to the porosity)range is 0~1. The codomain(refers to the volume compressibility coefficient of solid skeleton or water) range is 0~+∞, and power exponent c < 0. In the first quadrant, the volume compressibility coefficient of the solid skeleton increases with the increase of the porosity, the volume compressibility coefficient of water decreases with the increase of the porosity.

(2) The volume compressibility coefficient of solid skeleton and water exist unary quadratic polynomial relationship, and the volume compressibility coefficient of water is larger than the volume compressibility coefficient of solid skeleton, and the water is more easily compressed.

(3) It is assumed that the aquifer medium is elastic, but the solid matter can only be elastic within a certain range of stress, beyond this range (or the elastic limit) of the material, and the solid material will have an unrecoverable plastic deformation.

(4) The results of this paper show that it is simple and easy to obtain the porosity of the aquifer medium, the volume compressibility coefficient of the solid skeleton or the volume compressibility coefficient of water by using the datum of earth tides and barometric pressure, and is different from traditional pumping test and lab experiment. Of course, the above studies are based on the assumption that the aquifer medium is linear, homogeneous and isotropic, with the water in the well as an ideal fluid, and while the external stress and the total volume of the surface remain unchanged.

(5) In addition, there is e exponential function form between the step barometric pressure response function and lag time of well water level to barometric pressure for 6 wells studied. for

confined well(for example, Dadianzi well, Sanhaodi well and Dahuichang well), the step barometric pressure response function of the water level to the barometric pressure is increased with the increase of lag time. On the contrary, Banqiao well, Fengzhen well and Huanghua well are the unconfined well or the semi-confined well, this is due to with the increase of the lag time, the step barometric pressure response function is decreased. The coefficient a before e that is positive or negative to determine the groundwater types.

(6) In the 3 confined wells(for example, Dadianzi well, Sanhaodi well and Dahuichang well), the step barometric pressure response function of well water level to barometric pressure is bigger, and the corresponding barometric pressure coefficient and M_2 wave tide factor are also bigger. On the contrary, the relationship is not obvious between the barometric pressure coefficient, the tidal factor and the step barometric pressure response function in Banqiao well, Fengzhen well and Huanghua well. This is probably related to the hydraulic characteristics, borehole structure and the frequency(or cycle) of earth tidal waves. In the future, in the process of identifying the groundwater type by using this method, the barometric pressure coefficient and M_2 wave tide factor can be used for comprehensive determination and inspection, especially for the confined wells.

(7) Diagnosis of groundwater type by the step barometric pressure response function is based on the close relationship between the well water level, the barometric pressure and the tidal stress. It does not need to consider the factors such as structure, lithology, geomorphology and cause of formation. The method is simple. It can be used for reference in the selection of measuring points and the quality and reliability of observation data.

4. Conclusion

There is power function relation between the porosity and the volume compressibility coefficient(the solid skeleton and the water)in the aquifer. In the first quadrant, the solid skeleton volume compressibility coefficient of each well increases with the increase of the porosity, the volume compressibility coefficient of the water decreases with the increase of porosity. Between the volume compressibility coefficient of the solid skeleton and the water exist unary quadratic polynomial relationship, and the volume compressibility coefficient of water is larger than that of solid skeleton, the water is easier to compress.

In addition, according to the step barometric pressure response function in the regression deconvolution method, the groundwater type identifying results of the six wells aquifer system are shown that there is an e based exponential function between the lag time and the step barometric pressure response function of each well water level to barometric pressure. The coefficient before the base e is positive or negative to determine the groundwater type of the well aquifer system. For confined wells, the step barometric pressure response function increases with lag time of well water level to barometric pressure, while the unconfined wells and semi-confined wells are opposite.

Three Key Points

i. The porosity and the volume compressibility coefficient.
ii. The lag time and the step barometric pressure response function.
iii. The groundwater type identified by the regression deconvolution method.

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