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HYDROCHEMICAL INDEXES OF SEAWATER INTRUSION AND COMPREHENSIVE JUDGEMENT ON INTRUSIVE DEGREE

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ABSTRACT: The paper discusses the use of five hydrochemical indexes in evaluating seawater intrusion, and ranking the intrusion degree for Cl^-, M, Br^-, $rHCO_3/rCl$ and SAR. The fuzzy mathematical comprehensive judgement model has been adopted as the method of adjustment. Based on more than 300 water samples obtained from four typical profiles in the coastal region of Laizhou Gulf during the period from June 1993 to June 1995, we made a comprehensive judgement of seawater intrusion degree. The result shows that intrusion degree was becoming heavier from June 1993 to June 1994, but more steady and inactive in the high level of intrusion degree in the perennial severe intrusion zone from December 1994 to June 1995. Since entering the 1990s up to now, the process of seawater intrusion has translated from its peak developmental stage from the 1970s to the 1980s into a stage of equilibrium and slow development mainly because the intruded area expanded inland, precipitation increased at some extent recently and various measures of prevention and harness begin to show the effect.

KEY WORDS: indexes of seawater intrusion, intrusion degree, fuzzy mathematical comprehensive judgement

1 THE HYDROCHEMICAL INDEXES FOR THE JUDGEMENT ON SEAWATER INTRUSION

The hydrochemical characteristic is the direct basis for the judgement on seawater intrusion. In the studies on seawater intrusion so far, it is usually analysed by certain single index. The most commonly used one is the concentration of Cl^-, which is the most important and stable macroelement in seawater and most sensitive to seawater intrusion (Yin, 1992). The degree of mineralization (M) is the next index often used in view of its notable difference in seawater and fresh water. In addition, the conductivity and the resistivity are also used as subsidiary indexes (Liu *et al.*, 1996). However, the level of the Cl^- and M in fresh water are often influenced by other non-seawater factors as well, such as domestic sewage, industrial wastewater or the drainage from mining. As to the conductivity and the resistivity, both they are geophysical indirect indexes and easier to be affected by various geological factors and the nature of underground aquifer. Therefore, it is not all-sided and often brings deviation to make judgement only with single index.

Seawater intrusion will lead to a whole series of hydrochemical changes, so it is necessary and possible to make comprehensive evaluation with multi-indexes. Besides the Cl^- and M, the author chose the following three indexes.

Br^- It is one of the stable macro elements in seawater with the concentration about 65 mg/L (Wu, 1982), but it is a minor element in fresh water with the concentration only about 0.001–0.2 mg/L (He, 1989). Therefore, it is a more sensitive index reflecting the seawater intrusion, too.

$rHCO_3/rCl$ Ratios of the character ions can reflect and magnify the difference between two kinds of waters that have different hydrochemical natures.

The main anion in underground fresh water is HCO_3^- in coastal region of the Laizhou Gulf, but is Cl^- in the seawater. So we chose the ratio of $rHCO_3/rCl$ as one of the indexes. The difference of the ratio values between the two kinds of waters may be several magnitudes. Distinct change of the ratio value will occur with the aggravation of seawater intrusion.

Sodium absorption ratio (SAR) Content of Na^+ in seawater is about 2- 4 magnitudes higher than that in fresh water. In the groundwater and soil contaminated by seawater the concentration of Na^+ rises notably, this is one of the salinization processes in serious contaminated region. SAR is an index for assessing the degree of Na^+ harm in irrigation water, which is shown as follows (Yu *et al*., 1984):

$$SAR = rNa^+ / \sqrt{\frac{1}{2}(rCa^{2+} + rMg^{2+})}$$

Using this index we can evaluate the intrusion degree both from the angle of ratio of the main cations and from the influence of seawater intrusion on soil chemical environment.

2 DETERMINING THE GRADE RANGE OF THE INTRUSION DEGREE FOR THE INDEXES

With the aggravation of seawater intrusion the groundwater will turn from fresh water to slight-salt water and eventually salt water. Within the transitional belt between salt water and fresh water, the changes of hydrochemical indexes in time and space are most sensitive and the gradient of the changes is the greatest. So it is necessary to pay particular attention to the belt in determining the grade of intrusion degree so that the changes in the front of seawater intrusion could be showed projectively. In the sense of water quality, a detailed subdivision in the range of slight-salt water should be made. In view of the above, we divided the intrusion degree into four grades as follows:

Ⅰ. non or light intrusion (the water quality still belongs to fresh water);

Ⅱ. slight intrusion (slight-salt water);

Ⅲ. more serious intrusion (slight-salt water but more salter);

Ⅳ. severe intrusion (the water becomes salt water).

With this frame of the grades, consulting the criterions of water quality concerned and used at home and abroad, referring the precedents in ranking the intrusion degree, and proceeding from the objective reality in the region, we ranked the intrusion degree and determined the limit values and representative criterions of each grade for all indexes.

2.1 The Graduation for the Index Cl^-

The suitable value of Cl^- in the criterions of drinking water quality made by International Health Organization is less than 200- 350 mg/L (Xia *et al*., 1990). In the criterions of irrigation water quality made by our country, the Cl^- content of the first-grade water (good for irrigation) is ≤250 mg/L (GB5084- 92). The limit of Cl^- for judging the interface between the fresh groundwater and intrusive salt water used so far at home and abroad is 250- 300 mg/L generally. Here we adopt 250 mg/L as the limit for grades Ⅰ and Ⅱ.

Both grades Ⅱ and Ⅲ are within the range of the slight-salt water. The limit value between them is 600 mg/L, which is quoted from the greatest allowable concentration of Cl^- for drinking water put forward by the International Health Organization.

The Cl^- in the groundwater of severe intrusion area is more than 1000 mg/L mostly. In the previous studies on seawater intrusion in this region the value of 1000 mg/L had been used as the limit of serious intrusion area. Here we also adopt it as the limit between grades Ⅲ and Ⅳ.

2.2 The Graduation for Index M

Macroscopically speaking, M is in positive relevant to Cl^-. Among the water samples measured, the two extreme values of Cl^- are 28.36 mg/L and 90 175.94 mg/L, while the corresponding M values of the two samples are 345.28 mg/L and 15 900.80 mg/L respectively, which are extreme values too.

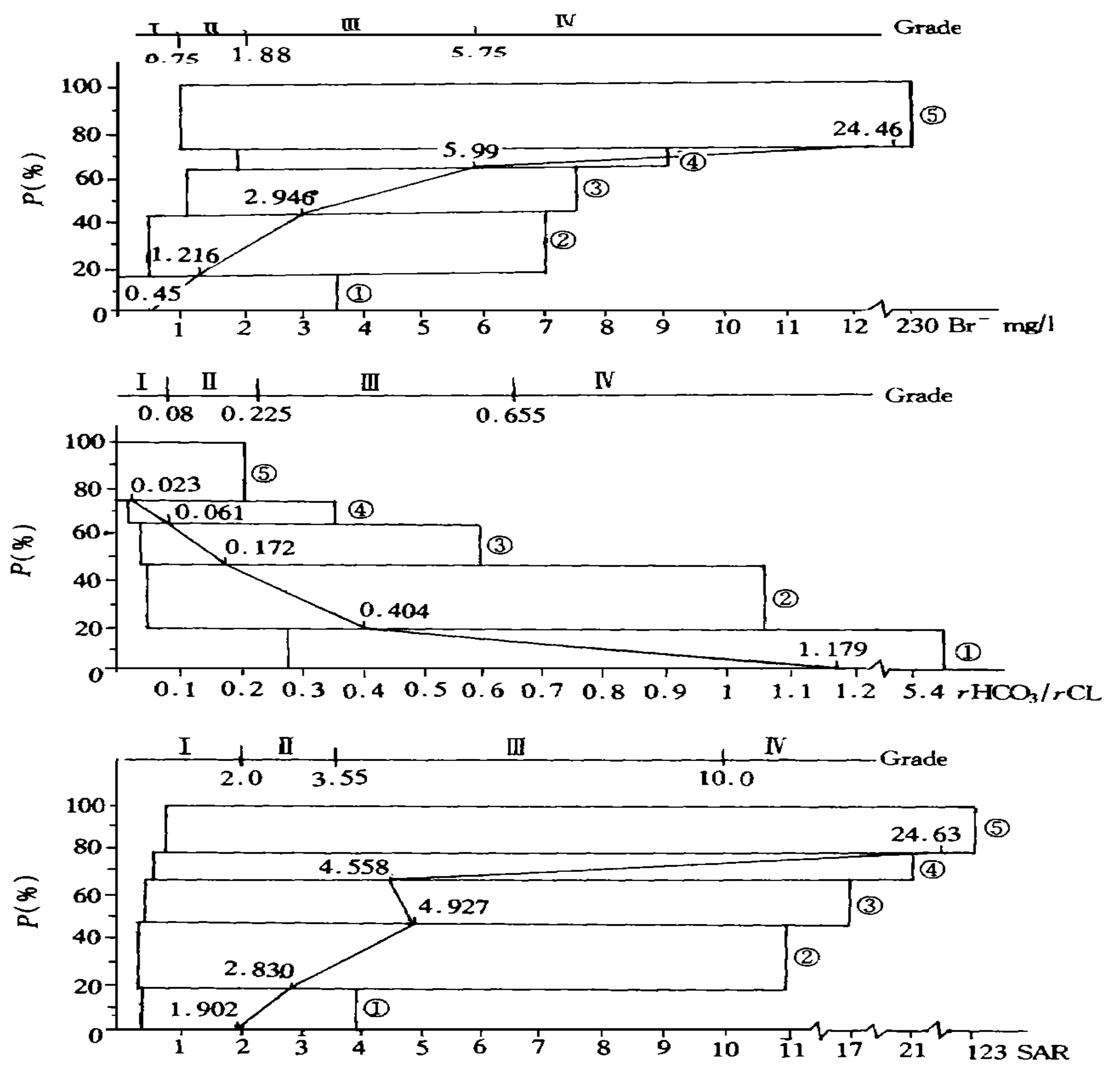
But, the relationship between the two indexes is not linear. In this study, I take the criterions of M for fresh water to salt water used commonly and currently as the limits of the grades of index M, but divided the range of the slight-salt water into two grades.

2.3 The Graduation for Indexes Br^-, SAR and $rHCO_3/rCl$

The grading for the three indexes is according to the analysis of more than 300 water samples obtained from more than 70 observation wells at different times. Firstly, all samples were divided into five groups according to their levels of Cl^-. Then the statistical analysis of the ranges of numerical value and the average values of each index in each group were made. The analytical results are shown in Fig. 1:

It can be seen from Fig. 1 that:

1) The distribution of the data is more dispersive. The discreteness of Br^- and SAR are very



① Cl^- < 250 mg/L ② Cl^- 250– 600 mg/L ③ Cl^- 600– 1500 mg/L ④ Cl^- 1500– 2200 mg/L ⑤ Cl^- > 2200 mg/L

P(%): The percentage of the samples of each group in the total specimens

Fig. 1 The chart of statistics in groups of Br^-, $rHCO_3/rCl$ and SAR marked in the groups of high level of Cl^-, while the discreteness of $rHCO_3/rCl$ is very notable in lower Cl^- level groups.

2) In the samples of the lower Cl^- level group, the concentrations of Br^- are less than 3.5 mg/L, the average value is 0.45 mg/L; the values of SAR are lower than 3.91, the average is 1.942; while the ratios of $rHCO_3/rCl$ are lower than 0.28, the average value is 1.179. Contrastively, we can see the great disparity of numerical value of the data between the samples in the groups of high Cl^- level and that in the groups of lower Cl^- level.

3) On the whole, there is a positive correlation between the average values of most indexes in each group and the concentrations of Cl^-, in the other words, with the increase of Cl^- the averages of Br^- as well as that of SAR increase rapidly too, but that of $rHCO_3/rCl$ ratios decrease quickly. While it can be seen that the increasing of SAR tend to be gentle in the area of the more serious intrusion, that is because of the ion exchange and absorption of the Na^+.

The correlativity between the indexes and Cl^- is the theoretical basis for the grading. The concrete method for the determination of the limit values of grades for each index is: evaluating the medians between the average values of the data in adjacent groups firstly (giving up the extreme values), then making a revision to them according to the cases of the deviation of the centralization range of the data from the medians, and finally, determining the limits of adjacent grades and the representative criterions of the grades according to the revised values and average values. The ranges and the representative criterions of the grades for all indexes are listed in Table 1.

Table 1 The rank and representative criteria of the indexes for judging seawater intrusion

Indexes	I		II		III		IV	
	R*	C*	R	C	R	C	R	C
Cl^- (mg/L)	< 250	100	250– 600	400	600– 1500	800	> 1500	2200
M (mg/L)	< 100	500	1000– 2000	1500	2000– 3000	2500	> 3000	3500
Br^- (mg/L)	< 0.75	0.25	0.75– 1.875	1.25	1.875– 5.75	2.50	> 5.75	9.00
$rHCO_3/rCl$	> 0.655	1.00	0.655– 0.225	0.31	0.225– 0.08	0.14	< 0.08	0.02
SAR	< 2.00	1.40	2.00– 3.55	2.60	3.35– 10.00	4.50	> 10.00	15.50

* R: Range of grade; C: Representative criteria

3 THE FUZZY MATHEMATICAL COMPREHENSIVE JUDGEMENT ON THE DEGREE OF SEAWATER INTRUSION

The mixing and contamination of fresh groundwater by seawater is a gradual change process. The limit between the two kinds of waters is indistinct in fact, and it is hard to determine a clear boundary. The method looked accurate that ranking the intrusion degree with single index and dividing it into a series of sudden change or platform-like grades, but it neglects the objective fact of the transitionness in the intrusive area and often gives rise deviation. The fuzzy mathematical comprehensive judgement is a better method to deal with the problems that have a dim extensive limit (Yang, 1993). With the method we made a judgement of intrusion degree to water samples collected from the four profiles in the coastal region of the Laizhou Gulf during several years.

3.1 To Give the Indexes, Grades and the Criterions for Judgement

The indexes used for judgement are five hydrochemical indexes, the grades are four grades of seawater intrusion degree mentioned above, and the criteria for judgement are the representative criterions of the indexes in each grade.

3.2 To Conduct the Evaluation for Singular Index

The second step is to make evaluation of intrusion degree to each measured datum of each index of all samples, directing to the representative critera of the index in every grades, in order to calculate the membership values of this index belonging to each grade. Here, the linear membership function was used, to be more exact, the ascendant and descendant half-trapezoid membership functions were used to calculate the membership values of the both end grades respectively, and the symmetrical hill-shape membership function was used to count the membership values of the middle grades. The calculated membership values of every indexes to every grades (r_{ij}) form the fuzzy judgement matrix R:

$$R = (r_{ij})_{mn}$$

where $m = 5$ (five indexes), $n = 4$ (four grades of seawater intrusion degree).

3.3 To Determine the Weight Set of Indexes

The weights of the indexes were evaluated by formulary method. The formula used to calculate the weight values W_i of indexes Cl^-, M, Br^- and SAR is as follows:

$$W_i = \frac{u_i}{S_i} \qquad S_i = \frac{1}{n}\sum_{j=1}^{n} V_j$$

Whereas the formula for the weight of $rHCO_3/rCl$ is:

$$W_i = \frac{1}{u_i} \cdot \frac{1}{S_i} \qquad S_i = \frac{1}{n}\sum_{j=1}^{n} \frac{1}{V_j}$$

where u_i denotes the measured values of indexes, S_i is the mean of the representative criterions (V_j) of each index in each grade, and n is the number of grades.

The weight set (A) is formed finally by the terms (a_i) which are obtained through the normalization of the calculated weight values:

$$A = (a_i)_m = (a_1, a_2, \ldots, a_m) \ (m = 5)$$

3.4 To Conduct the Comprehensive Judgement

After getting the R and A, the next step is to conduct the composition operation of R with A using the operator (•>). The result obtained is the set of comprehensive judgement (B):

$$B = A \cdot R = (b_j)_n = (b_1, b_2, \ldots, b_n) \ (n = 4)$$

$$B_j = \mathop{>}\limits_{i=1}^{m} (a_i \cdot r_{ij}) \ (i = 1, 2, \ldots m; \ j = 1, 2, \ldots, n)$$

The final judgement set is got by the normalization of the B set, and in which the comprehensive membership values (b_j) of water samples to every grades are listed in order. Among the membership values in the final B set, the largest one is taken as the judgement grade of the sample, and which also denotes the extent of the water sample belonging to that grade of intrusion degree.

4 THE FUZZY COMPREHENSIVE JUDGEMENT ON THE TYPICAL PROFILES IN THE COASTAL REGION OF LAIZHOU GULF

From June 1993 to June 1995 we made observations to the more than 70 observation wells of four typical monitoring profiles in Shouguang, Changyi, Laizhou and Longkou regions two times a year (Fig. 2), and collected more than 300 water samples.

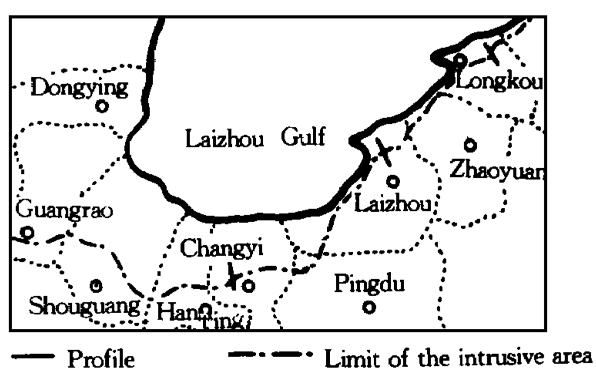


Fig. 2 The location of the profiles for monitoring sea water intrusion

We made the fuzzy comprehensive judgement on to all samples. The result can reflect the state of change in seawater intrusion in the region in recent years objectively and accurately. The statistics of judgement results are listed in Table 2. From Table 2 we can see that the situation of four profiles are different obviously. Contrasting the percentages of the samples of grade Ⅰ and that of grade Ⅱ– Ⅳ in every times of the observations, we can see that the intrusion degree is more stable recently in the profiles of Shouguang and Changyi, and even lightened slightly, but in the profiles of Laizhou and Longkou the intrusion is getting heavier. The situations of the four profiles are consistent with the change tendencies of seawater intrusive degree in different parts of the coast region of Laizhou Gulf. In the southern coastal region of Laizhou Gulf including the Shouguang and Changyi cities, the mean linear velocity of the intrusion was 292 m/a in the period of 1980– 1993, whereas had reduced to 166 m/a in 1993– 1995, and now in part of the area the limit of the intrusion even retreated slightly. While in the southeast coast region of Laizhou Gulf where the Laizhou and Longkou cities are located the mean linear velocity was 124 m/a during the period of 1980– 1993, but it rose up to 153 m/a in 1993– 1995.

Table 2 The statistics of the fuzzy comprehensive judgement of seawater intrusion in the coastal region of Laizhou Gulf

Profiles	Grade of intrusion degree	1993– 06		1993– 12		1994– 06		1994– 12		1995– 06	
		Number of samples	%	Number of samples	%	Number of samples	%	Number of samples	%	Number of samples	%
Shouguang	Ⅰ	2	22.22	1	9.09	3	30.00	1	10.00	3	30.00
	Ⅱ	6	66.67	7	63.64	3	30.00	6	60.00	4	40.00
	Ⅲ	1	11.11	1	9.09	3	30.00	3	30.00	3	30.00
	Ⅳ	0	0.00	2	18.18	1	10.00	0	0.00	0	0.00
Changyi	Ⅰ	1	11.11	1	11.11	1	12.50	1	14.29	1	16.67
	Ⅱ	4	44.44	3	33.33	1	12.50	2	28.57	2	33.33
	Ⅲ	0	0.00	5	55.56	2	25.00	4	57.14	3	50.00
	Ⅳ	4	44.44	0	0.00	4	50.00	0	0.00	0	0.00
Longkou	Ⅰ	9	37.50	8	33.33	6	23.08	9	29.03	5	23.81
	Ⅱ	5	20.83	5	20.83	7	26.92	10	32.26	6	28.57
	Ⅲ	4	16.67	4	16.67	6	23.08	6	19.35	5	23.81
	Ⅳ	6	25.00	7	29.17	7	26.92	6	19.35	5	23.81
Laizhou	Ⅰ	1	4.76	0	0.00	0	0.00	0	0.00	0	0.00
	Ⅱ	5	23.81	2	8.69	2	11.11	1	5.00	1	4.75
	Ⅲ	6	28.57	1	4.35	3	16.67	2	10.00	6	28.57
	Ⅳ	9	42.86	20	86.96	13	72.22	17	85.00	14	66.67
Total	Ⅰ	13	20.63	10	14.93	10	16.13	13	16.18	9	15.52
	Ⅱ	20	31.75	17	25.37	13	20.97	19	27.94	13	22.41
	Ⅲ	11	17.46	11	16.42	14	22.58	15	22.06	17	29.31
	Ⅳ	19	30.16	29	43.28	25	40.32	23	33.82	19	32.76

This regional difference in seawater intrusion is closely related to the regional hydrogeological and geomorphological features as well as the way of seawater intrusion. In southeast region of Laizhou Gulf, the Quaternary aquifer is relative thinner with thickness of about 20– 60 m, and has simpler structure with one or two layers. In the surface of underground bedrock the weathering is more intensive and the fractures quite develop. Therefore the whole loose layer and the upper layer of bedrock are good medium for the intrusion. In landforms, this region is the more narrow diluvial and littoral plains 2– 5 km in width generally. The intrusive zone is more concentrative and close to the sea coast. The way of intrusion is facial intrusion along the coastal aquifer that has direct hydraulic relation with the seawater, and the gradient of the front interface is often more steeper. All these make the limit of intrusion zone susceptible to the influence of various factors, and more easier to move towards inland. On the other hand, once the groundwater is contaminated by the intrusive seawater, it is hard to restore.

The southern coast region is broad alluvial and marine deposition plain. The Quaternary sediments are up to 100– 200 m in thickness, and contain several layers of aquifers with complex structures. The ways of seawater intrusion are various, besides by the tide action along the rivers, coastal seawater breeding action and the cause of salt fields, which all could lead to the contamination of the groundwater bordering the sea through drawing the seawater into inland, the more important way is the intrusion of underground ancient seawater (salt water). The intrusive area expanded fast in the initial stage, but it has been contained to some extent in recent years mainly because the intrusive area has expanded towards inland about 20 km, the relief of the region is smooth and broad, and slope of ground surface is only about 1‰– 5‰. Consequently the provoking effect of the gradient changes of various factors (such as topography, water head pressure, density and concentration of salt water and fresh water) is more weaker in the region than in the southeast coastal region. In addition, the benefits of some prevention and harness measures and agricultural measures carried out in recent years are more distinct. These measures include diversion water from the Huanghe (Yellow) River, the Mihe River and Xiashan reservoir, making full use of the deep underground fresh water and reducing the extraction of the shallow groundwater, carrying out the economical irrigation and building several tide barrages in the northern parts of Changyi City and Hanting district.

By the well clusters we can analyse the changes of the intrusion at different depths. Fig. 3 shows the curves of the judgement results of the observation data at two well clusters in Longkou profile. Both well clusters are near the interface between the fresh water and salt water, and composed of three observation wells in depths of 10– 12 m, 12.5– 14 m, and 15.5 – 17 m, and their aquifers are coarse sand gravel. We can see in the figure, the change of intrusion

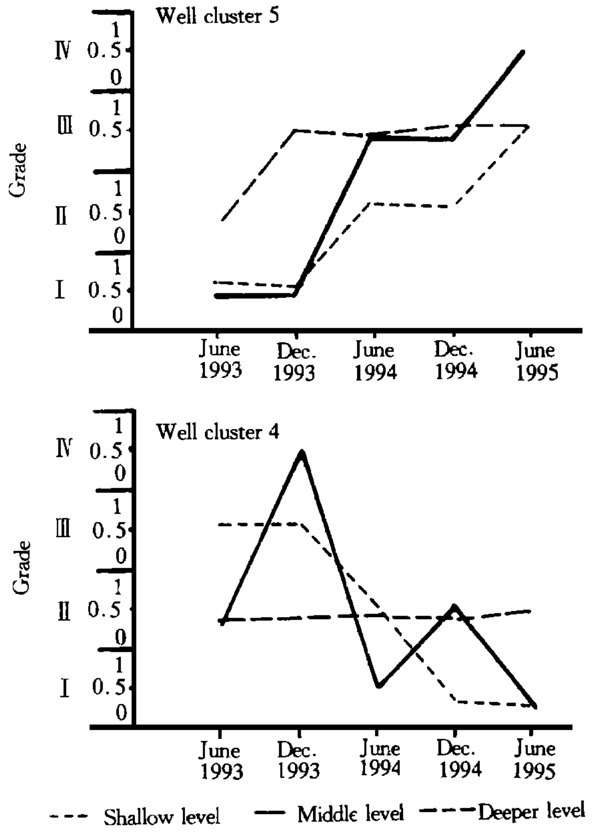


Fig. 3 The change of the seawater intrusion degree in different depths at monitoring site 4, 5 in Longkou City

degree is more sensitive in the shallow and deeper levels, but more tardy in the middle level, and particularly in the shallow level the scope of the change is the largest. The shallow level is better than deeper level when the intrusion degree is reducing, but is worse than deeper level during the intrusion degree is aggravating.

Overall statistically, during June 1993 to June 1994, the samples of grade Ⅳ increased, those of the grade Ⅰ and Ⅱ decreased, which shows that intrusion degree was becoming heavier in that period. But in the period of December 1994 to June 1995 the samples of both grade Ⅰ and Ⅳ decreased, those of the grade Ⅱ and Ⅲ increased. This fact reflects that the change of intrusion degree was more steady and inactive in the high level of the intrusion degree in the perennial severe intrusion zone, while it tended to be aggravating in the front of the intrusion and the transitional zone despite the advance of front limit of the intrusion had been somewhat contained. All the above show that since entering the 1990s up to now, the process of seawater intrusion has translated from its peak development stage during the 1970s to the 1980s into a stage of equilibrium and slow development mainly because the intruded area expanded inland quite far from the sea, precipitation increased at some extent recently, and various measures of prevention and harness begin to show the effect.

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