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ISSN: 0973-4945; CODEN ECJHAO
E-Journal of Chemistry
2010, **7(S1),** S209-S216

Groundwater Quality Assessment Based on Improved Water Quality Index in Pengyang County, Ningxia, Northwest China

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Received 27 March 2010; Accepted 20 May 2010

Abstract: The aim of this work is to assess the groundwater quality in Pengyang County based on an improved water quality index. An information entropy method was introduced to assign weight to each parameter. For calculating WQI and assess the groundwater quality, total 74 groundwater samples were collected and all these samples subjected to comprehensive physicochemical analysis. Each of the groundwater samples was analyzed for 26 parameters and for computing WQI 14 parameters were chosen including chloride, sulphate, pH, chemical oxygen demand (COD), total dissolved solid (TDS), total hardness (TH), nitrate, ammonia nitrogen, fluoride, total iron (Tfe), arsenic, iodine, aluminum, nitrite, metasilicic acid and free carbon dioxide. At last a zoning map of different water quality was drawn. Information entropy weight makes WQI perfect and makes the assessment results more reasonable. The WQI for 74 samples ranges from 12.40 to 205.24 and over 90% of the samples are below 100. The excellent quality water area covers nearly 90% of the whole region. The high value of WQI has been found to be closely related with the high values of TDS, fluoride, sulphate, nitrite and TH. In the medium quality water area and poor quality water area, groundwater needs some degree of pretreated before consumption. From the groundwater conservation view of point, the groundwater still need protection and long term monitoring in case of future rapid industrial development. At the same time, preventive actions on the agricultural non point pollution sources in the plain area are also need to be in consideration.

Keywords: Groundwater, Water quality index, Groundwater quality assessment, Entropy weight, Pengyang County.

Introduction

Groundwater which is used for domestic and industrial water supply and irrigation is vital to local people and industry in semi-arid and arid areas like Pengyang County where groundwater is the main drinking water source. In the last few decades, there has been a tremendous increase in the demand for fresh water due to the rapid growth of population and the accelerated pace of industrialization[1]. Human health is closely related with the groundwater quality and is threatened by the poor quality of groundwater caused by excessive application of fertilizers and unsanitary conditions. Rapid urbanization which caused groundwater pollution has affected the availability and quality of groundwater due to its over exploitation and improper waste disposal. Once groundwater is polluted, it is hard to stop the pollution and restore the water quality. It therefore becomes imperative to regularly monitor the quality of groundwater and to device ways and means to protect it.

At present, there have been lots of methods for water quality evaluation such as fuzzy mathematics method, membership degree method, factor analysis method, gray modeling method and analytic hierarchy process method. However, these methods can not clearly express the water pollutant categories and we can not explain whether the parameters involved in the evaluation meet the requirements of functional areas[2]. Water quality index method (WQI) which attempts to provide a mechanism for presenting a cumulatively derived numerical expression defining a certain level of water quality[3] is widely used in the world due to the capability of fully expression of the water quality information and is one of the most effective tools and important parameters to the evaluation and management of groundwater quality for the concerned citizens and policy makers all over the world. Some studies have been done by several researchers across the world in various fields such as groundwater quality assessment[1,4~5], surface water[2]. However, during the WQI calculating process, the weight of each parameter is usually given by experts according to their practical experience[1, 6], which is much subjective and much useful and valuable information about the water quality get lost. In the paper, improved WQI with entropy weight were applied to the groundwater quality assessment in Pengyang County, Ningxia, Northwest China to provide a theoretical basis and theoretical guarantee for the rational development and utilization of local groundwater resources and groundwater protection.

Study area

Pengyang County is situated in the south of Ningxia Hui Autonomous region, east of Liupan Mountains. It is situated between longitude from 106°32'E to 106°58'E, latitude from 35°41'N to 36°17'N (Figure 1).

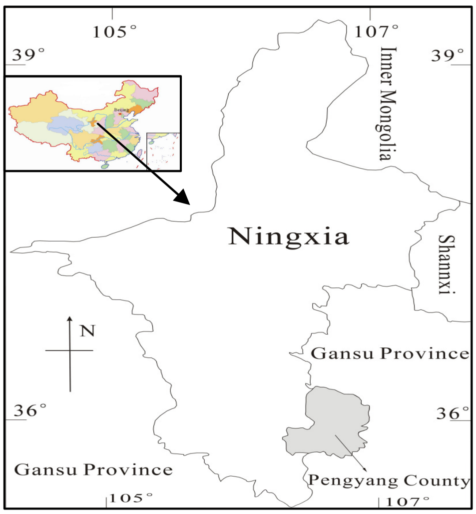

Figure 1. Location of the study area

Typical semi-humid, semi-arid climate with four distinct seasons is dominated here, hot and rain are in the same quarter with little rain and strong evaporation. Average annual rainfall is 450 mm and the rainfall distribution is uneven in space and time, Precipitation in the region mostly concentrated in July, August and September and the total precipitation of the three months accounted for nearly 60% of the total precipitation in the whole year and the precipitation during crop growing season accounted[7] for only 25% of annual precipitation. The average annual evaporation is 1400~1600 mm, which is three times of the rainfall. Rivers in Pengyang County including Ruhe River, Honghe River and Anjiachuan River belong to Jinghe River system. Ruhe River and Honghe River originated from Xiaoguan Mountain while Anjiachuan River originated from "North-South Ancient spine" in northwest Pengyang. Surface water runoff is characterized by small base flow, large flood runoff, obvious seasonality and poor water quality. Landscape types in the region are dominated by medium and low mountains, loess hills and river valley terraces. The exposed rock strata are mainly Cretaceous sandstone, Tertiary sandstone, muddy siltstone and Quaternary alluvial and proluvial deposits. Groundwater in Pengyang can be divided into four different types based on the conditions of groundwater occurrence and water features including pore water in loose rocks, fractured-pore water in clastic rocks, bedrock fissure water and karst fissure water in carbonate rock. Bedrock fissure water and karst fissure water in carbonate rock have no water supply significance due to limited distribution in scope and pore water in loose rocks and fractured-pore water in clastic rocks are important water supply aquifers which are rich in water abundance.

Experimental

Groundwater samples were collected from 74 locations in August 2007. Samples were collected in pre-cleaned plastic polyethylene bottles for physicochemical analysis of sample. Prior to sampling, all the sampling containers were washed and rinsed thoroughly with the groundwater to be taken for analysis. Each of the groundwater samples was analyzed for 26 parameters including carbonate, bicarbonate, chloride, sulphate, phosphate, calcium, magnesium, sodium, kalium, pH, chemical oxygen demand (COD), total dissolved solid (TDS), total hardness (TH), nitrate, ammonia nitrogen, fluoride, total iron (Tfe), total alkalinity, total acidity, chroma, arsenic, iodine, aluminum, nitrite, metasillicio acid and free carbon dioxide by laboratory of Ningxia Monitoring Station for Geological Environment using standard procedures recommended by Chinese Ministry of Water Resources.

Methods

For computing WQI, usually, three steps must be followed[1, 8]. In the first step, a weight must be assigned to each parameter. In the paper, an entropy weight was calculated and assigned to each parameter[9~13].

The concept of information entropy was first proposed by Shannon in 1948 and it was regarded as the uncertainty of a stochastic event or metric of information content[9]. The steps for calculating entropy weight are described as follows:

Suppose there are m water samples taken to evaluate the water quality (i=1,2,…,m). Each sample has ‘n’ evaluated parameters (j=1,2,…,n). According to real data, eigen value matrix X can be constructed:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

In order to eliminate the influence caused by the difference of different units of characteristic indices and different quantity grades, data pretreatment must be put into force[9].

According to attribution of every index, the feature indexes may be divided into four types: efficiency type, cost type, fixed type and interval type[9]. For the efficiency type, the construction function of normalization is:

$$y_{ij} = \frac{x_{ij} - (x_{ij})_{\min}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \tag{2}$$

While for the cost type, the construction function of normalization is:

$$y_{ij} = \frac{(x_{ij})_{\max} - x_{ij}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \tag{3}$$

After transform, the standard-grade matrix $\boldsymbol{Y}$ can be obtained and shown below:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{4}$$

Then the ratio of index value of the j index and in i sample is:

$$P_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij} \tag{5}$$

The information entropy is expressed by the formula below:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{6}$$

The smaller the value of e_j is, the bigger the effect of j index. Then the entropy weight can be calculated with the below formula:

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{7}$$

In the formula, ω_j is defined as the entropy weight of j parameter. The second step for calculating WQI is to assign a quality rating scale (q_j) for each parameter. The q_j is calculated by the following formula:

$$q_j = \frac{C_j}{S_j} \times 100 \tag{8}$$

Where C_j is the concentration of each chemical parameter in each water sample in mg/L, S_j is the Chinese standard for drinking groundwater of each parameter in mg/L according to Chinese Quality Standard for Groundwater. The WQI can be calculated in the third step by the formula below:

$$WQI = \sum_{j=1}^{n} \omega_j q_j \tag{9}$$

According to WQI, groundwater is classified into five ranks, “excellent water” to “extremely poor water”. The classification standards are listed in Table 1.

Table 1. Classification standards of groundwater quality according to WQI

WQI	Rank	Water Quality
<50	1	Excellent water quality
50~100	2	Good water quality
100~150	3	Medium or average water quality
150~200	4	Poor water quality
>200	5	Extremely poor water quality

Results and Discussion

Before the WQI calculation, statistics of water quality parameters are illustrated in Table 2. From Table 2, some important information can be obtained. Some parameters including Cl^-, SO_4^{2-}, NO_3^-, F^-, TDS and TH exceeded the Chinese Standards for Drinking Groundwater.

Table 2. Statistics of parameters and Chinese Standards for groundwater

Parameters	Chinese Standards	Minimum	Maximum	Mean	Median	SD
Na^+	—	32.00	792.00	151.66	121.00	114.94
K^+	—	1.00	7.00	2.39	2.00	1.18
Mg^{2+}	—	4.75	146.00	41.01	37.98	23.24
Ca^{2+}	—	11.74	195.60	44.30	35.21	29.22
Tfe	≤0.3	0.02	0.30	0.15	0.14	0.07
Cl^-	≤250	13.81	296.87	55.71	35.02	46.99
SO_4^{2-}	≤250	10.61	1437.94	193.08	113.74	240.42
HCO_3^-	—	210.01	739.98	395.93	376.26	94.84
CO_3^{2-}	—	0.00	11.84	0.69	0.00	2.37
NO_3^-	≤20	0.00	22.58	4.23	2.71	4.52
NH_4^+	≤0.2	0.00	0.23	0.00	0.00	0.03
NO_2^-	≤0.02	0.00	0.06	0.01	0.00	0.01
F^-	≤1.0	0.10	2.40	0.87	0.78	0.53
$H_2PO_4^-$	—	0.00	0.30	0.02	0.00	0.05
free CO_2	—	0.00	8.96	4.61	4.33	2.14
COD	≤3.0	0.34	1.89	0.69	0.64	0.26
H_2SiO_3	—	10.80	20.20	16.21	16.25	2.00
TDS	≤1000	252.09	2441.07	706.43	626.77	415.08
TH (as $CaCO_3$)	≤450	91.77	900.18	255.82	212.72	138.76
pH	6.5~8.5	7.74	8.36	8.11	8.11	0.11
As	≤0.05	0.000	0.016	0.004	0.003	0.003
I	≤0.2	0.00	0.12	0.05	0.04	0.02
Al^{3+}	≤0.2	0.000	0.003	0.000	0.000	0.001

All units except pH are in mg/L, SD-Standard deviation, "—" indicate that there's no such standard value for the parameter.

The permissible TDS for drinking groundwater is 1000 mg/L. It's found from the analysis results that TDS varies from 252.09~ 2441.07 mg/L and 16.22% of the 74 samples exceeded the standards. Generally speaking, high values of TDS in groundwater are generally not harmful to human beings but high concentration of these may affect persons who are suffering from kidney and heart diseases. Water containing high solids may cause laxative or constipation effects[1].

The high concentration of SO_4^{2-} may be attributed to little rain, high temperature and strong evaporation as well as aquifer medium abundant in sulphate in the area. Enrichment induced by evaporation and strong water-rock interaction both affect the concentration of SO_4^{2-}. The concentration of SO_4^{2-} varies from 10.61~1437.94 mg/L, among which the highest value is over 5 times of the standard.

According to the classification standards of TH (as $CaCO_3$) in Chinese Standards for Drinking Water Quality, groundwater can be divided into soft water (TH<150 mg/L), moderately hard water (150<TH<300 mg/L), hard water (300<TH<450 mg/L), extremely hard water (TH>450 mg/L). Of the total 74 samples, 13 samples fall under the soft water class, 41 samples fall under the moderately hard water class, 15 samples fall under the hard water class and only 5 samples fall under the extremely hard water class which exceed the chinese standard for drinking water quality.

Fluoride is a widely distributed element in rocks. It is a necessary element for human being. However, too much absorption of fluoride may be harmful to human health. Too much fluoride may cause people to suffer from dental fluorosis and crippling fluorosis. According to the research, the fluoride content in the study area was found to be slightly over the permissible levels. Of all the 74 samples, 23 samples exceeded the standard. The highest concentration of fluoride is 2.4 mg/L which is over 2 times of the standard value. The WQI was calculated according to the steps mentioned above and the calculated results of entropy weight and WQI values were shown in Table 3 and Table 4.

Table 3. Information entropy and entropy weight of parameters

Item	Tfe	Cl^-	SO_4^{2-}	NO_3^-	NO_2^-	NH_4^+	F^-
e_j	0.967	0.994	0.994	0.990	0.990	0.997	0.983
ω_j	0.183	0.034	0.035	0.056	0.058	0.018	0.097
item	COD	TDS	TH	pH	As	I	Al^{3+}
e_j	0.993	0.990	0.993	0.974	0.987	0.983	0.987
ω_j	0.041	0.055	0.041	0.143	0.073	0.097	0.070

Table 4. Assessment results according to computed WQI

Sample ID	WQI	Rank	Sample ID	WQI	Rank	Sample ID	WQI	Rank
P001	12.40	1	P036	51.37	2	P069	42.55	1
P002	30.88	1	P037	19.29	1	P070	42.87	1
P003	23.80	1	P038	82.30	2	P071	144.95	3
P004	20.62	1	P039	28.29	1	P072	69.97	2
P005	26.81	1	P040	20.20	1	P073	75.96	2
P007	27.83	1	P041	29.12	1	P074	107.58	3
P009	29.77	1	P043	33.23	1	P075	60.13	2
P010	29.38	1	P045	24.05	1	P076	33.39	1
P011	48.96	1	P046	27.26	1	P077	21.52	1
P012	34.80	1	P049	23.32	1	P079	30.64	1
P013	24.13	1	P050	193.49	4	P079	30.64	1
P014	30.62	1	P051	26.59	1	P081	96.56	2
P016	17.78	1	P052	21.46	1	P083	117.94	3
P018	14.35	1	P053	26.73	1	P085	33.64	1
P019	55.70	2	P055	75.12	2	P086	185.10	4
P020	15.54	1	P056	43.27	1	P087	54.48	2
P021	19.35	1	P058	26.07	1	P088	24.76	1
P022	57.75	2	P059	87.31	2	P089	32.96	1
P024	47.82	1	P060	184.18	4	P090	27.57	1
P027	55.37	2	P061	21.70	1	P091	34.89	1
P031	34.37	1	P062	43.37	1	P092	31.67	1
P032	205.24	5	P063	16.44	1	P093	76.38	2
P033	29.71	1	P064	18.05	1	P095	16.93	1
P034	26.07	1	P066	76.91	2	P097	29.86	1
P035	26.44	1	P068	28.41	1			

In the study, WQI values ranges from 12.40 to 205.24. Table 4 shows the calculated WQI values and groundwater quality assessment results. The assessment results indicate that the groundwater qualities in the study area are relatively good and most of the samples are excellent quality water or good quality water. These excellent quality and good quality water samples account for 90.54% of the total samples, medium water quality samples account for 4.05% and poor quality water and extremely poor quality water account for 4.05% and 1.35% respectively in the study area. The high value of WQI has been found to be closely related with the high values of TDS, fluoride, sulphate, nitrite and TH.

A zoning map of different water quality was drawn by surfer 8.0 software with Kriging interpolation method (Figure 2). The Figure 2 tells us in most part of the study area, water quality is excellent and the excellent quality water area covers nearly 90% of the whole region which indicates that the groundwater in most part of the area has not been severely polluted due to small population and laggard economy and industrial manufacture. Poor quality water area mainly locates in the northwestern part because of strong water-rock interaction and stratum formation.

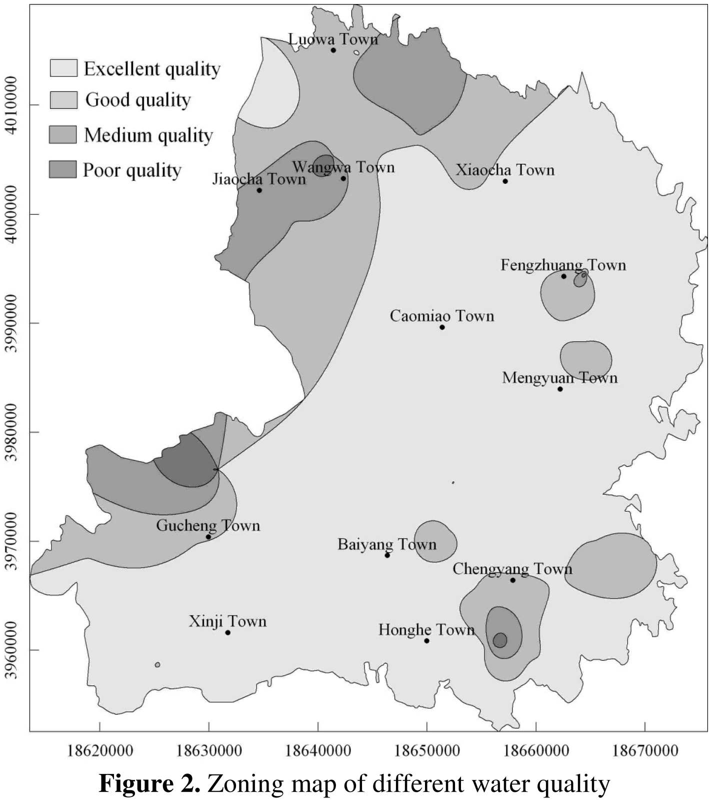

Figure 2. Zoning map of different water quality

Conclusion

Water quality index method is an effective tool to assess the status of the drinking groundwater. Entropy weight makes WQI perfect and makes the assessment results more reasonable. The WQI for 74 samples ranges from 12.40 to 205.24 and over 90% of the samples are below 100. The excellent quality water area covers nearly 90% of the whole region. The high value of WQI has been found to be closely related with the high values of

TDS, fluoride, sulphate, nitrite and TH. Although in most part the groundwater has not been severely polluted, from the groundwater conservation view of point, the groundwater still need protection and long term monitoring in case of future rapid industrial development. At the same time, preventive actions on the agricultural non point pollution sources in the plain area are also need to be in consideration. In the medium quality water area and poor quality water area, groundwater needs some degree of pretreated before consumption.

Acknowledgments

This research project was supported by the National Natural Science Foundation of China (Grant No. 40772160). The Research on Drinking Water Environment and Endemic in Villages and Small Towns in New Socialist Countryside Project (Grant No. 010) supported by the Ningxia Land and Resources Department, Program for Changjiang Scholars and Innovative Research Team in University of Ministry of Education of China (Grant No. IRT0811) and the Program of Introducing Talents of Discipline to Universities (111 Project) (Grant No. B08039). Authors also want to express their sincere appreciation to the anonymous reviewers whose comments have led to the generation of a greatly improved version of this article.

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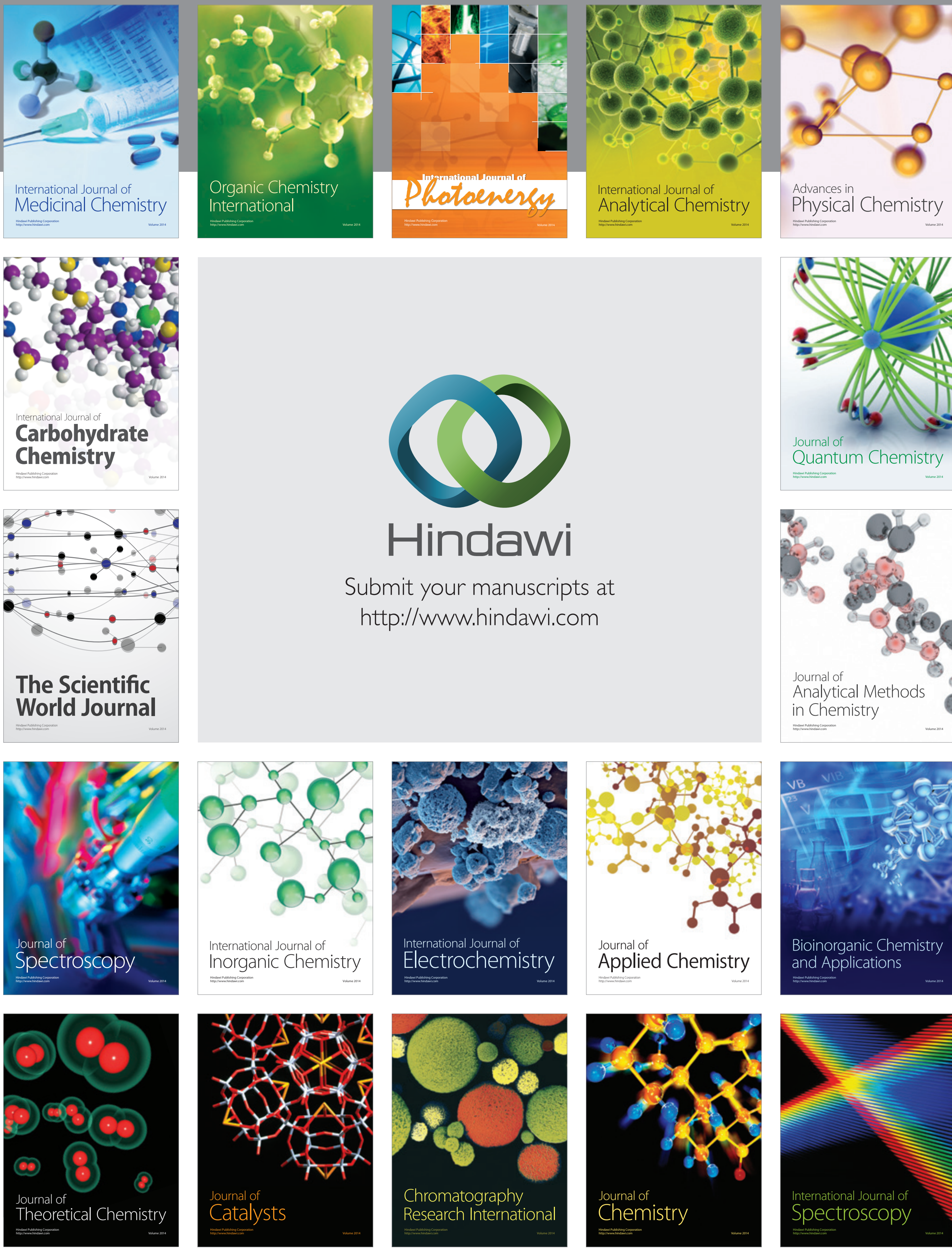
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