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Risk evaluation of groundwater pollution by pesticides in China: a short review

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Abstract

The development of agriculture is closely related to the application of pesticides in China. Excessive use of pesticides has indeed prevented harm by pests and largely improved the product of crops but has also resulted in high groundwater pollution risks. It is increasingly important to recognize groundwater pollution in agricultural areas and evaluate the groundwater pollution risk caused by pesticides. In this research, four major methods of risk evaluation are reviewed. To provide useful advice on the screening of these methods in actual application, the advantages and limitations of each method are stated in detail. Domestic and international research conditions are also reviewed in this paper. Recently, combined use of the existing evaluation methods has become the focus of international research. Some domestic researchers have attempted to use such combined methods to evaluate groundwater pollution risks, but most are based on the DRASTIC index method. Aiming at the deficiencies of the research in this field in China, prospects are considered for the development of risk assessment for groundwater pollution by pesticides. Four aspects were evaluated, including the establishment of a theoretical system, comprehensive consideration of the impact factors, the development of validation methods and combined evaluation methods, and the strengthening of monitoring work and groundwater pollution risk assessment in arid areas. This work enhances the understanding of groundwater pollution risks and provides useful advice on the development of risk evaluation for groundwater pollution by pesticides.

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1. Introduction

Groundwater is one of the most important sources of drinking water. However, the overuse and misuse of pesticides in agriculture puts groundwater at high risk. In China, plentiful research has demonstrated the presence of pesticide residues in agricultural land and in groundwater. Li et al. (2007) detected 13 types of organochlorine pesticides in 56 shallow groundwater samples collected from an agricultural region in Taihu basin [1]. Huang et al. (2008) found that groundwater in area of the Pearl River delta is lightly polluted by organochlorine pesticides [2]. Kong et al. (2004) surveyed the groundwater pollution by pesticides in the Hebei and Shandong sweet-potato planting area, and their results revealed the presence of aldicarb, phorate, and terbufos [3]. Xue et al. (2008) analyzed pesticide the residues in the vadose zone and groundwater in paddy fields and dry farmland in the western portion of Jilin Province. HCH and DDT were detected in almost every sampling layer of soil, and β-HCH was also found in groundwater [4].

Therefore, there is an urgent need to evaluate the groundwater pollution risk by pesticides. Currently, groundwater pollution risk assessment is an indispensable tool for groundwater protection and land use planning and management. Groundwater pollution risk refers to the probability that groundwater will suffer unacceptable contamination due to human activities, and this concept was developed from groundwater vulnerability, which accordingly constitutes the most important part of groundwater pollution risk assessment [5, 6].

Groundwater vulnerability means a groundwater system’s sensitivity to natural and anthropogenic activities (EPA and IAH, 1993), and it includes intrinsic vulnerability and special vulnerability, which respectively take hydro-geological parameters and the impact of human activity into consideration. Unfortunately, there is no consensus with respect to the best method of groundwater pollution risk assessment. In some studies, vulnerability evaluation that takes both intrinsic vulnerability and special vulnerability into account is regarded as the risk assessment. As a whole, there are four major evaluation methods used for the assessment of groundwater pollution risk by pesticides.

2. Major methods used to evaluate groundwater pollution risk by pesticides

2.1. Index methods

Index methods are the most widely used for groundwater contamination risk assessment. Index methods use key parameters that closely relate to the entry of pollutants into groundwater though the vadose and saturated zones to obtain a comprehensive index to characterize pollution risks.

The DRASTIC model (EPA, 1987) is favoured among all of the index evaluation methods, such as GOD (Foster, 1987), AVI (Stempvoort et al., 1993), GLA (Hölting et al, 1995), ISIS (Civita and De Regibus, 1995), SINTACS (Civita and De Maio, 1997), and PI (Goldscheider et al., 2000) [7]. Further, the DRASTIC model is commonly used for intrinsic vulnerability assessment.

There are seven parameters in the DRASTIC model, with each letter of DRASTIC standing for a parameter [8]: D = depth of the groundwater, R = recharge (infiltration), A = aquifer media, S = soil texture, T = topography, I = impact of the vadose zone, and C = conductivity of the aquifer. Each of the parameters is assigned a value and a weight, often according to the opinion of experts, and then one can obtain seven sub-indices by multiplying the value and weight of each parameter. Finally, the comprehensive risk index is obtained by superimposition of the seven parameters.

Index methods require few field data inputs and involve easy calculations. However, as many researchers have stated, such methods have many faults [6, 9-12]. The index methods results are
subjective because the values and weights are assigned by experts. Moreover, a linear superimposition of key parameters is too simple to reflect their complex relationships. Furthermore, there is no effective way to validate the results. Additionally, index methods are more suitable for assessment of large areas.

2.2. Process-based methods

Pollutants like pesticides must go through a series of physical, chemical, and biologic processes in the vadose zone and saturated zone. Simulation models use numerical models to describe these related migration and transformation processes. By virtue of simulation models, a numerical indicator that characterizes the pollution risk, to a certain extent, can be calculated.

There are several main pesticide transport models that are widely used today [13-17]. For instance, the PRZM (Carsel et al., 1985) can simulate the transport and transformation of pesticides within the crop root zone and vadose zone. Additionally, the ArcPRZM-3 model was recently developed, which combines PRZM-3 with the Geographic Information System (GIS) into a user-friendly model. MACRO (Jarvis, 1994) is a one-dimensional and dual-permeability model and takes macropore flow process into account. Similarly, PEARL (Tiktak et al., 2000) linked with the SWAP model (van Dam et al., 1997) is a one-dimensional model and can mimic many transport processes of pesticides in soil-plant systems, including volatilization in the air, penetration into the plant, degradation using first-order kinetics, and wash-off via rainfall. LEACHM (Hutson and Wagen et al., 1992) can describe the vertical percolation of water and solutes through layered soils under transient conditions, and GLEAMS (Leonard et al., 1987) is applied to simulate pesticide movement on a field scale in soil-climate-management systems. RZWQM (De Coursey et al., 1992) emphasises the impacts of main agricultural management practices on the fate of pesticides. HYDRUS-1D (Šimůnek et al., 1998) considers root water uptake, as well as water flow, solute transport, heat transport, root growth, and CO₂ transport. The Attenuation Factor (AF) model (Rao et al., 1985) reflects the impacts of the degradation and adsorption of pesticides, rainfall, and groundwater depth on pesticide infiltration into groundwater. Additionally, there are many new simulation models, but they are mostly derived models from the models mentioned above.

The application of simulation models for groundwater pollution risk assessment helps to reduce subjectivity and can quantitatively describe the risk [18, 19]. However, such models usually require abundant data about crops, soil geology, hydrology, meteorology, and pesticide characteristics. These parameters are time-consuming to measure and collect, and they are often not available due to a lack of local monitoring. In this case, the uncertainties of the models’ inputs, combined with the assumptions made by the models, result in uncertainties in the results [20]. Therefore, it is crucial to validate simulation models. However, validation requires adequate monitoring data over a long period, and there are few effective ways to do this. Thus, simulation models are mainly used for small study areas.

2.3. Statistical methods [23,24]

Based on the observed contamination information, statistical methods can be used to reveal the relationships between the investigation data and the factors related to the contamination. Then, the evaluation indicators can be ascertained, and each indicator is assigned a value related to its significance as analyzed by the statistical method. Logistic regression (Tesoriero and Voss, 1997), discriminant analysis (Carrara, 1983), likelihood ratio functions (Chung, 2006), and the Weights of Evidence (van Westen et al., 2003) approaches are all statistical methods.

Statistical methods are easy to validate using new groundwater contamination information and can comprehensively analyze contamination-related factors. Further, if new information becomes available, statistical approaches can become real-time evaluation methods. However, practically speaking, the
application of statistical methods for pollution risk assessment is not very common due to the requirement for a large amount of observed contamination information.

2.4. Fuzzy comprehensive evaluation method [25,26]

The fuzzy comprehensive evaluation method first requires one to ascertain the contamination rankings. Additionally, the evaluation indices should be selected, and the standard value of each index under each contamination level must next be collected. Second, the degree to which each sample belongs to every contamination level can be determined by incorporating the data into a relative membership degree formula. In this step, the weight vector of the indices is also needed. Finally, by multiplying the optimal relative membership degree matrix by the ranking matrix, a level characteristic value vector can be achieved, and the pollution risk can be evaluated according to such a vector. Assuming a is an element in this level vector, then the value of a represents the contamination level of a sample, and the risk will become obvious, especially when compared to other elements in the vector.

The fuzzy comprehensive evaluation method can reduce the subjectivity caused by the artificial assignment of assessment indicators, and the weights can be determined by the tone operator comparison method without introducing experts’ opinions. Subjectivity cannot be avoided though because the evaluation indices must be selected based on our knowledge of the important impact factors. Indeed, even in the tone operator comparison method [23], the judgment of the significance between two indices is subjective. The complex steps and calculation involved in the fuzzy comprehensive evaluation method also constrain its use for groundwater pollution assessment.

3. Domestic and international research conditions

3.1. International research

Currently, for groundwater pollution risk assessment, the focus of the international research has shifted from the application of a single evaluation method to the combined use of existing methods, mostly based on GIS. Moreover, researchers attempt to consider more impact factors during the risk assessment of groundwater pollution by pesticides.

Early in 1998, M. Soutter and A. Musy respectively applied three leaching models (AF, LEACHM, and LEACHA), coupling 1D Monte-Carlo simulations and geostatistics to assess groundwater contamination risks by pesticides in a part of the upper Rhone river valley in Western Switzerland [27]. Posen et al. (2008) incorporated pesticide catabolic activity and the AF numerical model into a GIS-based groundwater risk assessment and produced a map displaying the groundwater contamination risk by isoproturon [28]. Based on GIS, Nobre et al. (2007) produced three maps by using numerical modelling (i.e., MODFLOW, MODPATH, and the DRASTIC model) and a fuzzy hierarchy model [29]. The integration results of these three maps can be used to assess the groundwater pollution risk. To take both the micropore and macropore flow paths into account, Holman et al. (2004) combined the preferential flow pesticide leaching model MACRO and the substrate attenuation factor model AQUAT to assess the spatially distributed risk of pesticides [30]. Dixon (2005) used the DRASTIC model to select parameters for the fuzzy rule-based model and then produced a groundwater sensitivity maps coupled with GIS [31]. Two other risk maps were also generated by further incorporating land use/pesticide application and soil structure information, respectively, into the first map. The contamination potential map containing the soil structure information was more in accordance with the field monitoring data in Woodruff County in the Mississippi delta region of Arkansas.
3.2. Domestic research

Compared to international research on groundwater pollution risk assessment, Chinese work in this field began relatively late. Currently, researchers in China are attempting to use newly developed methods, mostly based on DRASTIC index method and GIS. However, most research in this field is still limited to that concerning intrinsic groundwater vulnerability.

Li and Zhang (2003) investigated the groundwater vulnerability in the Tangshan Plain [32]. They selected six indices by consulting the DRASTIC model, as well as the specific conditions and available data for the Tangshan Plain. Then, these six indices were used as evaluation factors, and the numerical model HYDRUS was used to establish an evaluation factor scoring system. The relative weight system for the six evaluation factors was constructed by two statistical analysis methods, i.e., the principal component analysis and factor analysis methods. Finally, GIS was used to generate a vulnerability map. Bian et al. (2008) incorporated DRASTIC with GIS and a fuzzy optimum model to develop the MEQU-DRASTIC method [33]. They then used MEQU-DRASTIC to evaluate the vulnerability of shallow groundwater in Tongyu County in west Jilin. Cheng et al. (2010) assessed groundwater vulnerability in the Huangshuihe catchment in Shandong Province by using transport simulations (including Hydrus1D and Monte-Carlo), the DRASTIC index system, and a new tentative index system, respectively [12].

There is also some research that evaluates the groundwater pollution risk from pesticide without using DRASTIC. Xiong et al. (2004) used the PEARL simulation model to evaluate the groundwater pollution risk from pesticide penetration in Pengzhou City, Sichuan Province [16]. Via the K-t50 figure, one of the outputs of the simulation, the risk of application of pesticides on groundwater was established. Guo and Du (2010) analyzed the groundwater pollution risk in Qiqihar City [34]; three modules (MODFLOW, MODPATH, and MT3DMS) were introduced to simulate the migration of pollutants in this study. According to the results produced by the simulation models, figures demonstrating that the pollution plume changed with spatial and time variation could be plotted, and such figures may provide accurate information on groundwater pollution. Sun et al. (2007) applied the fuzzy synthetic evaluation model to groundwater pollution risk by pesticides [35]. Alternatively, Cheng et al. (2007) selected the SCI-GROW model (USEPA) to predict risks to groundwater caused by five types of pesticides commonly used in sugarcane fields in Fujian Province [36]. Their results demonstrate that the SCI-GROW model is able to quickly forecast the groundwater pollution risk by pesticides but only for regions where groundwater is susceptible to pollution.

4. Prospects

The risk of groundwater pollution by pesticides has recently received increasing attention in China. As described above, much research into this problem has been performed, but compared to international research, there is still room for improvement in groundwater pollution risk assessment in China.

4.1. Establishment of a theoretical system and more attention to pesticides

The concepts involved in determining groundwater risk assessment must be perfected, and a risk evaluation system suitable for China should be constructed. Indeed, in China, there is no complete system for groundwater pollution risk assessment, and thus understanding groundwater pollution risks is vitally important. As many scholars say, the value of groundwater, both in water quality and quantity, should be the main concern of assessments [5, 37-38].

According to the results of our literature review, the assessment of groundwater pollution risks from pesticides is in progress, and abundant research focuses on nitrate pollution instead of pesticides. In our
opinion, groundwater pollution risks from pesticides deserve much more attention due to the relatively high mobility and low biological degradation activity of these compounds.

4.2. Comprehensive consideration of the impact factors

The impacts of soil pH, preferential flow, vegetation, and climate change have been considered by many researchers using both index and process-based methods [39-41]. However, few reports consider the impacts of fertilizers and intense rainfall, as well as interactions between surface water and groundwater. Furthermore, factors involved in evaluation methods are simply superimposed. The combined effect is often ignored, and instead, all of the impacts are simply combined.

The application of fertilizers largely increases the organic matter in surface soil and changes the adsorption abilities of pesticides on soil. Microbial degradation is also affected. Therefore, impacts caused by the use of fertilizer must be considered, i.e., the frequency and amounts of fertilizer applied should be investigated.

Different pesticides possibly have different or even opposite characteristics, and the ways and strength by which they interact with air, soil, and microorganisms may be totally different. Additionally, in actual application, pesticides are mixed with one another to enhance their insecticidal effects, and by doing this, the inherent features of each pesticide involved may change due to the presence of other pesticides. Thus, characteristics of specific pollutants and combined pollution should be fully considered in groundwater risk assessment.

Surface water can become groundwater by passing through the vadose zone, while groundwater can also merge with surface water, usually because of a rise in the water table and the impact of topography. Thus, pesticides in groundwater may also affect surface water, and such interactions should be included in simulation models to fully describe the transport of pesticides.

In our opinion, performing laboratory simulation tests is a direct and effective way to investigate the impact of each factor and combined impacts between these factors. Indeed, some laboratory simulation tests have previously been performed [42]. From the results of these analyses, evaluation models can be greatly improved.

4.3. The development of validation methods and combined evaluation methods

An evaluation method without validation cannot improve the reliability of the results it has obtained. Thus, the development of an effective validation method should also be given equal attention.

Groundwater systems are so complicated that a single evaluation method cannot take all of the impact factors into account. No evaluation model can simultaneously describe behaviour including volatilization, leaching, runoff, and the degradation of pesticides. The results of existing research demonstrate that the combined use of evaluation methods can compensate for the defects inherent in single models. For example, the index-simulation method can both reduce the subjectivity caused by index methods and characterize the risk via a comprehensive evaluation index. To comprehensively and precisely assess the groundwater pollution risk, the use of combined evaluation methods cannot be avoided.

4.4. Strengthening monitoring work and groundwater pollution risk assessment in arid areas

Sufficient data concerning local meteorology, hydrogeology, and groundwater largely reduces the difficulties in groundwater pollution risk assessment. For example, Worrall and Besien (2005) used a Bayesian methodology, one of statistical methods, to directly calculate the vulnerability of groundwater to pesticide contamination from monitoring data [43]. Unfortunately, the lack of monitoring data in China
limits the use of the evaluation methods, especially statistical methods and the fuzzy comprehensive evaluation method. Both of these approaches require sufficient data or field information to establish the scoring and weight systems. Process-based methods also need enough accurate input data to ensure the correctness of the simulation results. Moreover, the invalidation of evaluation methods is performed by comparing the risk prediction results with the measured data.

As for the risk assessment of groundwater pollution by pesticides, there has been limited investigation in arid areas of China [6, 38]. It is well known that the soil texture in arid areas is different from that in humid areas. Further, the half-lives of pesticides can be very long in arid areas, and the degradation rates of pesticides in soil usually decrease with temperature and soil water content. Even worse, soil cracks in arid areas make preferential flow much more common. Therefore, risk assessment of groundwater pollution in arid areas should be given greater attention.

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