Uncertainty health risk assessment and regional control of drinking water: a case study of Hanyuan County, southwest mountainous area, China

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Received: 15 December 2021 / Accepted: 3 May 2022 / Published online: 10 May 2022
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Abstract
To evaluate the health risks of drinking water in Hanyuan County, 96 samples of peripheral drinking water were collected from 30 sites in the area. The samples were then analyzed for chemical properties including Fe, Mn, NH₃-N, NO₃⁻, F⁻, Pb, Hg, As, Cr(VI), Cd, and so on. The health risks of ten trace elements in drinking water were probabilistically assessed using the health risk assessment model and Monte Carlo simulation. On this basis, sequential indicator simulations were used to classify the health risk levels of drinking water in the region, to conduct hierarchical management and control. The results showed that except for NO₃⁻, all other indicators met World Health Organization standards and China’s drinking water sanitation standards. Drinking water presents a specific carcinogenic risk to adults, and the cumulative contribution of As and Cr(VI) exceeds 95%, and has a specific non-carcinogenic risk to children if the cumulative contribution of F⁻, NO₃⁻, and As exceeds 90%. Grade I, II, and III non-carcinogenic risk areas accounted for 0.89%, 24.72%, and 74.39% of the total area of Hanyuan County, respectively, while grade I, II, and III carcinogenic risk areas accounted for 27.71%, 45.56%, and 26.73% of the total Hanyuan County area, respectively. Finally, according to the health risk characteristics of each control area, corresponding zoning control suggestions were proposed.

Keywords Drinking water · Uncertainty · Health risk assessment · Monte Carlo simulation · Sequential indicator simulation

Introduction
Safe drinking water is essential to public health, yet a report jointly issued by the United Nations (UN) and the World Health Organization (WHO) in 2019 shows that as of 2017, billions of people still lack access to safe drinking water (WHO 2019). From the water source to the user, drinking water is affected by issues such as water source pollution, outdated water treatment technology, and pipeline network pollution (GUAN et al. 2018). The current focus on drinking water quality is mainly limited to whether it meets, or exceeds, the standard. However, long-term inhalation of, or indirect exposure to, low-dose carcinogens and non-carcinogens in water can also cause significant health risks (Adimalla 2020a).

Water quality health risk assessments can quantitatively describe the health hazards of various indicators in the water to the human body. Existing studies mostly use the risk model recommended by the United States Environmental Protection Agency (USEPA) for certainty health risk assessment. For example, Radfard et al. (2019) investigated the concentration of pollutants in drinking water in Iran’s Sistan and Baluchistan provinces and conducted non-carcinogenic and carcinogenic risk assessments of As in water. Rezaei et al. (2019) conducted a non-carcinogenic risk assessment of F⁻, NO₃⁻, and NO₂⁻ in drinking water in Sanandaj, Iran. Lu et al. (2014) conducted carcinogenic and non-carcinogenic risk assessments of 13 trace elements (Co, Mn, Ni, Cu, Zn, Se, Mo, Cr(VI), As, Cd, Sb, Hg, and Pb) in drinking water in Shenzhen, China. The above studies all used certain values (mean or point values) of pollutant concentrations and exposure parameters to calculate health risk. However, due to the number of
samples, measurement methods, and differences in individual exposure parameters, the entire process of health risk assessment is ambiguous.

The uncertainty assessment in health risk includes the uncertainty analysis of the results and the contribution of each parameter to the assessment results (Yu et al. 2011). Widely used methods to conduct uncertainty analysis are Monte Carlo simulation and triangular fuzzy number. Lindhe et al. (2009) introduced fault tree analysis and Monte Carlo simulation to effectively evaluate the probability of various water supply system incidents and residents’ health risks. Wang et al. (2021) used fuzzy interval number to evaluate uncertainty with fewer data conditions, which better reflected the influence of exposure parameters such as pollutant concentration, average daily water ingestion, and body weight. Wang et al. (2020) used Monte Carlo simulation and sensitivity analysis to fully assess the uncertainty of pollutant concentration, average daily water ingestion, exposure frequency, exposure time, and body weight, as well as obtained As’s probabilistic health risk results and other parameters that significantly influence the health risk of drinking water in Jiangsu Province, China. The above studies (Lindhe et al. 2009; Wang et al. 2021, 2020) only considered the uncertainty of parameters and pollutant concentrations but did not consider the spatial uncertainty of limited sampling points (Zeng et al., 2009).

Gao et al. (2020), Kazemi et al. (2022), and Zuzolo et al. (2020) used kriging interpolation or inverse distance weighted interpolation to study the spatial analysis of water quality health risks. However, kriging interpolation and inverse distance weighted interpolation are certainty interpolation methods, requiring certain data distribution and having smoothing effects, which will lead to incorrect estimation of health risks (Huang et al. 2016; Kong et al. 2021; Yang et al. 2020). Compared to such certainty interpolation methods, sequential indicator simulation (SIS), combining the respective advantages of sequential stochastic simulation algorithm and indicator kriging method, has less limitation of data distribution and can better describe and visualize the spatial uncertainty of data.

Probabilistic assessment based on a Monte Carlo simulation puts ambiguous parameters in a probability distribution into the risk equation. It then calculates a health risk probability density curve, which reduces the variability caused by changes in pollutant concentration and individual residents’ living characteristics in the assessment process (Saha and Rahman, 2020). Compared to fuzzy interval numbers, the probability density curve can better identify the characteristics of undefined parameters. Based on Monte Carlo simulation to describe the influence of exposure parameters and SIS to assign limited water quality sample data spatial heterogeneity, the study conducts probabilistic assessment and divide the health risk hierarchical control zone of the health risk of drinking water in the Hanyuan area; thereby, a graded regional health risk management strategy was proposed.

Materials and method

Description of the study area

Hanyuan County (29°05′–29°43′, 102°16′–103°00′E) belongs to Ya’an City, Sichuan Province, located in a valley bordering the western part of the Panxi River between the Sichuan Basin and the Tibetan Plateau. Hanyuan County is mainly a mountainous terrain, and the mountains and valleys are deep and undulating. It has good mineralization conditions and rich mineral resources within the territory. Hanyuan County belongs to a subtropical monsoonal humid climate with sufficient heat and light, so it is the largest agricultural production county in Ya’an City. Drinking water supply modes in the region include waterworks, centralized rural water supply, and decentralized rural water supply.

Sampling and testing

The study collected 96 peripheral drinking water samples from 30 sites in Hanyuan County from 2012 to 2016. To avoid the influence on evaluation indicators’ concentration caused by the water supply system, all water samples were from end water. Among them, 4 water samples were from water supply plants, 25 water samples were from rural centralized water supply projects, and 1 water sample was a rural decentralized water supply project (shown in Fig. 1).

Different scholars used different indicators to conduct health risk assessment of drinking water, and the used evaluation indicators include Fe, Cr(VI), NO₃⁻, F⁻, As, Cd, Cu, Mn, Se, Pb, Zn, NH₄⁺, N, CN⁻, NO₂⁻, Hg, and phenol (Yu et al. 2012, Zhao 2021, Zheng et al. 2017(Yu et al. 2012, Zhao 2021, Zheng et al. 2017). There are four actual situations in the study area: (1) The concentration of As, Pb, and Cd in soil ranged from 12.2-16ug/g, 60.9-125ug/g, and 0.39-1.18ug/g, respectively, all of which were higher than the corresponding Chinese soil background values of 11.2ug/g, 26.0ug/g, and 0.097ug/g and the Sichuan regional background values of 9.3ug/g, 28.9ug/g, and 0.075ug/g; (2) the average concentration of Cr (VI) and Hg were higher than the Chinese soil background values and Sichuan province regional background values; (3) the research area is rich in minerals, so the mine wastewater features high conductivity and high concentration of Fe and Mn; (4) residents have cases history of dental fluorosis (Hou, 2006; Zhou, 2014). Therefore, 10 parameters (Fe, Mn, NH₄⁺, NO₃⁻, F⁻, Pb, Hg, As, Cr(VI), Cd) were chosen to measure for the analyses of the health risk of drinking water.
Uncertainty analysis and human health risk assessment procedure

Based on the health risk assessment model recommended by USEPA, the study introduces Monte Carlo simulation and SIS to construct a new uncertainty health risk assessment model. The structure of which is shown in Figure 2.

Probabilistic assessment of health risks

Toxic trace elements in drinking water enter the human body mainly through inhalation and skin contact, bringing about carcinogenic and non-carcinogenic risks. Existing research shows that the health risks caused by water ingestion are far more significant than those caused by skin contact (Adimalla 2020b; Chai et al. 2021; Gao et al. 2020). Therefore, this study only considers the threats to health produced by ingesting water. Combining the health risk assessment model proposed by USEPA and actual data from Hanyuan County, the study revised some health risk exposure parameters (Table 1).

According to the International Cancer Institute research on the carcinogenicity of substances, As, Cr(VI), Cd, and their compounds are chemical substances with proven evidence of human carcinogenicity, and thus were selected for the carcinogenic risk assessment. Fe, Mn, NH₃-N, NO₃⁻, F⁻, Pb, Hg, As, Cr(VI), and Cd were selected for the non-carcinogenic risk assessment. The gastrointestinal absorption factors, reference doses of non-carcinogens, and carcinogen intensity coefficients are shown in Table 3. The study considered the impact of toxic trace elements on adults and children, and the risk assessment model is shown in Formulae 1–5 (USEPA 1989, 2004).

Human exposure to contaminants in drinking water can be assessed by average daily dose (ADD, mg/kg/day) of contaminants. ADD was calculated as follows:

$$\text{ADD}_{\text{ingestion}} = \frac{C \times IR \times EF \times ED \times ABS \times BW \times AT}{BW \times AT}$$  \hspace{1cm} (1)

where $\text{ADD}_{\text{ingestion}}$ is the average daily dose of the drinking water pathway, mg/kg per day; $C$ is the contaminant concentration in drinking water, mg/L; IR is the daily water intake, L/d; EF is the exposure frequency, d/a; ED is the exposure duration, a; BW is the body weight, kg; AT is the average time, days (shown in Table 1); and ABS is the gastrointestinal absorption factor, unitless (shown in Table 2).

The hazard quotient (HQ, unitless) represents the potential non-carcinogenic risk caused by a single pollutant. The
Fig. 2 Uncertainty health risk assessment steps

Table 1 Distribution of probabilistic health risk evaluation parameters

| Parameters                              | Symbol | Units       | Probabilistic distribution types | Values                      |
|-----------------------------------------|--------|-------------|----------------------------------|-----------------------------|
| Ingestion rate of water (adult)         | IR(A)  | L/day       | Triangular                       | 1.95 (0.5 ~ 3.66)          |
| Ingestion rate of water (children)      | IR(C)  | L/day       | Triangular                       | 1.25 (0.3 ~ 3)             |
| Body weight (adult)                     | BW(A)  | kg          | Normal                           | 59.5 ± 9.2                 |
| Body weight (children)                  | BW(C)  | kg          | Triangular                       | 30 (10, 70)                |
| Exposure frequency                      | EF     | day/year    | Constant                         | Constant                   |
| Exposure duration (adult)               | ED(A)  | year        | Constant                         | 365b                       |
| Exposure duration (children)            | ED(C)  | year        | Constant                         | 30b                        |
| Averaging time (non-carcinogen, adult)  | AT(nc,A)| day        | Constant                         | Constant                   |
| Averaging time (non-carcinogen, children)| AT(nc,C)| day        | Constant                         | Constant                   |
| Averaging time (carcinogen)             | AT(c)  | day         | Constant                         | 71.2 × 365                 |
| Gastrointestinal absorption coefficient  | ABS    |             | Constant                         | See Table 2                |
| Carcinogenic slope factor (ingestion)   | SF     | (mg/(kg · day))⁻¹ | Constant                         | See Table 2                |
| Reference dose (ingestion)              | Rfd    | mg/(kg-day) | Constant                         | See Table 2                |

*Deng (2013); *USEPA (1996); *MEPC (2013)
HQ value > 1.0 indicates that exposure levels are likely to cause non-carcinogenic effects in a person’s lifetime (USEPA 2004). HQ was calculated as follows:

\[
HQ_{\text{ingestion}} = \frac{ADD_{\text{ingestion}}}{Rfd_{\text{ingestion}}}
\]

where HQ\text{ingestion} is the non-carcinogenic hazard quotient of the drinking water pathway, unitless; ADD\text{ingestion} is the average daily dose of the drinking water pathway, mg/kg per day; and Rfd\text{ingestion} is the reference dose of the dermal contact pathway, mg/kg day (shown in Table 2).

The hazard index (HI, unitless) represents the potential non-carcinogenic risk caused by all the ten pollutants, which is the sum of HQ and calculated as follows:

\[
HI = \sum_{i=1}^{10} HQ
\]

The carcinogenic risk (CR) denotes the carcinogenic risks via the oral exposure pathway. In this study, the International Commission on Radiological Protection (ICRP)—recommended value \(5 \times 10^{-5} \text{a}^{-1}\) (Valentin 2002) is used as the acceptable level of risk. The CR value > \(5 \times 10^{-5} \text{a}^{-1}\) indicates that the risk is obvious.

\[
CR_{\text{ingestion}} = ADD_{\text{ingestion}} \times SF_{\text{ingestion}}
\]

where CR\text{ingestion} is the carcinogenic risks of the drinking water pathway, unitless and SF\text{ingestion} is the slope factor that converted the ADD over a lifetime of exposure directly to the cancer risk (mg/(kg ⋅ day))\(^{-1}\) (shown in Table 2).

The total carcinogenic risk (TCR) represents the carcinogenic risk caused by all the three pollutants, which is the sum of CR and calculated as follows:

\[
TCR = \sum_{i=1}^{3} CR
\]

### Spatial uncertainty analysis of health risks

The study regards the expected HI and TCR values at the sampling points as variables that change with space, uses SIS to simulate their spatial distribution, and obtains the non-carcinogenic health risk and carcinogenic risk exceedance probability map and standard deviation map. The specific algorithm steps are as follows (Goovaerts 2001):

1. **0–1 discrete coding**

   The expected values of HI and TCR of 30 sampling points are converted into indicator values I(z, x).

   \[
   I(z, x) = \begin{cases} 
   1, & x \leq z \\
   0, & x > z 
   \end{cases}
   \]

   where z is the desired cut-off value of x (HI and TCR). Take HI as 1. For TCR, take the ICRP-recommended value \(5 \times 10^{-5} \text{a}^{-1}\). When I(z, x) is 0, HI or TCR exceeds the standard value. That is, a health risk is identified. When I(z, x) is 1, the situation is reversed.

### Table 2: Toxicity parameters and chemical parameters of evaluation indicator

| Trace elements | ABS (unitless) | Rfd\text{ingestion} (mg/(kg d)) | SF\text{ingestion} (mg/(kg d))\(^{-1}\) |
|----------------|---------------|----------------------------------|--------------------------------------|
| Fe             | 0.15\(a\)     | 0.3\(a\)                         |                                     |
| Mn             | 0.04\(a\)     | 0.046\(a\)                      |                                     |
| NH3-N          | 0.2\(c\)      | 0.97\(c\)                       |                                     |
| NO\(_3^-\)     | 0.5\(a\)      | 1.6\(a\)                        |                                     |
| F\(^-\)        | 1\(b\)        | 0.06\(a\)                       |                                     |
| Pb             | 1\(b\)        | 0.0014\(a\)                     |                                     |
| Hg             | 0.07\(a\)     | 0.0003\(a\)                     | 15\(b\)                             |
| As             | 0.41\(a\)     | 0.0003\(a\)                     | 15\(b\)                             |
| Cr(VI)         | 0.02\(a\)     | 0.003\(a\)                      | 41\(a\)                             |
| Cd             | 0.05\(a\)     | 0.0005\(a\)                     | 6.1\(a\)                            |

\(a\)USEPA (2010); \(b\)There is no relevant data at present. Use “1” instead; \(c\)ORNL (2018)

### Table 3: Descriptive statistics of water quality indicators included in the health risk assessment

| Trace elements (mg/L) | Detection limit | Mean | Min | Max | Standard value (WHO) | Standard value (China) |
|-----------------------|-----------------|------|-----|-----|-----------------------|------------------------|
| Fe                    | 0.05            | 0.025| 0.025| 0.025| 0.3                   | 0.3                    |
| Mn                    | 0.05            | 0.025| 0.025| 0.025| 0.4                   | 0.1                    |
| NH3-N                 | 0.02            | 0.025| 0.01 | 0.01 | 0.01                  | -                      |
| NO\(_3^-\)           | 0.15            | 2.76 | 0.075| 28.26| 11                    | 20                     |
| F\(^-\)               | 0.1             | 0.22 | 0.03 | 0.835| 1.5                   | 1                      |
| Pb                    | 0.0025          | 0.00125| 0.00125| 0.00125| 0.01                  | 0.01                  |
| Hg                    | 0.0001          | 0.00005| 0.00005| 0.00005| 0.006                 | 0.001                 |
| As                    | 0.0002          | 0.000421| 0.00005| 0.006| 0.01                  | 0.01                  |
| Cr(VI)                | 0.004           | 0.002| 0.002| 0.002| 0.05                  | 0.05                  |
| Cd                    | 0.0005          | 0.00025| 0.00025| 0.00025| 0.003                 | 0.005                 |

\(\ldots\) there is no standard value
(2) Obtain several indicator variograms corresponding to the given cut-off values \( z_k \) according to Eq. (7):

\[
\gamma_i(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [I(x_i, z_k) - I(x_i + h, z_k)]^2
\]

where \( h \) is the distance between locations \( x_i \) and \( x_i + h \), and \( N(h) \) is the number of data pairs for \( x_i \) and \( x_i + h \).

(3) Grid the study area and perform sequential simulation

Divide the study area into a 70×70 grid and outline a random path through all unknown points. The first unknown point is selected according to a random path, and the probability \( \hat{I}(x, z) = \text{Prob}\{x \leq z\} \) that HI and TCR exceed the corresponding threshold is estimated by the kriging method. Randomly select a random number \( p \) uniformly distributed in the interval [0,1], compare \( p \) with \( \hat{I}(x, z) \), and determine the HI and TCR indication values at that position. Add the new simulation value to the known data and repeat the simulation process until all points are simulated. If needed, this process can be repeated numerous times.

(4) Probability spatial distribution of health risks

Through Formula (8) and Formula (9), the probability and standard deviation of each simulated HI and TCR point exceeding the standard value can be calculated (Shi et al. 2007).

\[
P_{\text{SIS}}\{x > z\} = \frac{n(x > z)}{N_{\text{SIS}}} \tag{8}
\]

\[
S_{P_{\text{SIS}}\{x > z\}}^2 = \frac{P(1 - P)}{N_{\text{SIS}}} \tag{9}
\]

where \( P_{\text{SIS}}\{x > z\} \) is the health risk probability; \( S_{P_{\text{SIS}}\{x > z\}}^2 \) is the standard deviation of the health risk; \( x \) is the HI and TCR at the simulated point; \( z \) is the threshold of HI and TCR; \( N_{\text{SIS}} \) is the total number of SIS, the number of
simulations in this study is 100; and n is the number of times the result at the simulation point exceeds the threshold in all \( N_{\text{SIS}} \) simulations.

The research used Matlab software to implement SIS, Oracle Crystal Ball 11 to implement Monte Carlo simulation, and ArcGIS 10.2 to draw the SIS results of health risk.

Results and discussion

Monitoring data statistics

Monitoring data showed that all indicators met the standards except for the maximum \( \text{NO}_3^- \) concentration which exceeded WHO’s and Chinese standards for drinking water quality (MHC 2006; WHO 2011). Among 10 indicators, only \( \text{NH}_3\text{-N}, \text{F}^- \), and \( \text{As} \) were detected (Table 3), while the rest were below the detection limit. However, not being detected or below the standard value does not mean that there is no negative impact on the human body. Long-term exposure to low-dose pollutants (especially those with high toxic effects) can still cause certain health risks. According to the “Technical Guidelines for Statistical Analysis of Environmental and Health Cross-sectional Survey Data” (MEPC 2017), when analyzing the relationship between environmental pollution and human health, the non-detected value is replaced by one-half of the method detection limit. Therefore, health risks should be calculated using half of the 7 undetected indicators (Fe, Mn, \( \text{NO}_3^- \), Pb, Hg, Cr(VI), Cd) corresponding detection limits.

Probabilistic health risk assessment

Non-carcinogenic and carcinogenic risks

When conducting probabilistic health risk assessment, the maximum result value may be higher than the actual value; therefore, the 95% quantile of the probabilistic assessment result is determined as the maximum estimated value of the health risk assessment result (Kavcar et al. 2009).

The results of the non-carcinogenic risk assessment show that the maximum estimates of HI for adults and children are 0.89 and 1.41, respectively, and the probability of exceeding safety level is 2.58% and 14.58%, respectively (Fig. 3), which agreed with the results obtained by Radfard et al. (2019) in southeastern Iran, with values of 1 in adults and 1.09 in children, and were higher than the results of Fang et al. (2021), with mean values of 0.38 in adults and 0.69 in children.

The contribution of each indicator to HI is \( \text{Fe}^- > \text{NO}_3^- > \text{As} > \text{Pb} > \text{Cd} > \text{Mn} > \text{Cr}(	ext{VI}) > \text{Fe} > \text{Hg} > \text{NH}_3\text{-N} \) (Fig. 5). The non-carcinogenic risk assessment results show that children have a specific non-carcinogenic risk. Among them, \( \text{F}^- \), \( \text{NO}_3^- \), and \( \text{As} \) represent 45.14%, 25.05%, and 22.33%, respectively. Combined with residents suffering from dental fluorosis, it can be seen that \( \text{F}^- \) has caused certain non-carcinogenic hazards.

The results of the carcinogenic risk assessment show that the probabilities of the total carcinogenic risk of adults and children exceeding \( 5 \times 10^{-5} \text{ a}^{-1} \) are 93.84% and 4.12%, respectively, and the maximum estimated TCR values are \( 5.24 \times 10^{-4} \text{ a}^{-1} \) and \( 4.82 \times 10^{-5} \text{ a}^{-1} \) (Fig. 4), which were
lower than the results obtained by Yin et al. (2019) with a level of $1.06 \times 10^{-4}$ in drinking water of Shaoxing, Zhejiang, China. The carcinogenic risk level of this study agreed with the results obtained by Mohammed et al. (2021) with values of $1.13 \times 10^{-4}$ and $6.63 \times 10^{-5}$ in adults and children during the dry season, and less than the values of $7.39 \times 10^{-6}$ and $4.27 \times 10^{-6}$ in adults and children during the wet season; though there are differences with the wet season results, it is consistent that adults are at greater carcinogenic risk than children.

The contribution of each indicator to the total carcinogenic risk is $\text{As} > \text{Cr(VI)} > \text{Cd}$ (Fig. 5). According to the carcinogenic risk assessment results, adults have a greater risk of carcinogenesis, among which As and Cr(VI) contribute significantly at 88.52% and 10.97%, respectively.

**Sensitivity analysis**

Sensitivity analysis results reflect the relationship between each evaluation parameter variable and health risk. The absolute value of the sensitivity reflects the correlation between the evaluation parameter variable and the health risk, and the positive or negative sensitivity indicates whether the evaluation parameter variable is positively or negatively correlated with that health risk.

The results of non-carcinogenic risk sensitivity analysis are shown in Fig. 6. IR has the most significant impact on the non-carcinogenic risk of adults and children, with correlation coefficients of 48.8% and 40.6%, respectively. In addition, as far as adults are concerned, changes in
F\(^{-}\), As, and NO\(_3\)\(^{-}\) concentration have a more significant impact on non-carcinogenic risk than BW. This conclusion is contrary to the results of the sensitivity analysis of children. That is, changes in F\(^{-}\), As, and NO\(_3\)\(^{-}\) concentration will increase the likelihood of non-carcinogenic risks in adults, which is consistent with Rezvani Ghalhari et al. (2021) that pollutant concentrations have a greater impact on adults than children. This is consistent with the views of Mohammed et al. (2021), Saha and Rahman (2020), and Tarafdar and Sinha (2019), which concluded that the key reason why adults had greater health risk than children is that ED in adults is greater than in children.

The carcinogenic risk sensitivity analysis results are shown in Figure 7. The concentration of arsenic has the most significant impact on the carcinogenic risk of adults, and IR has the most significant effect on the carcinogenic risk of children, with correlation coefficients of 74.1\% and 40.8\%, respectively. Body weight is also a significant factor in cancer risk in both adults and children, which is consistent with Wang et al. (2020).

Due to the lack of informative data that can reflect the situation in the study area, uncertainties will remain despite using survey studies from Deng (2013) and MEPC (2013) to improve and Monte Carlo simulations to reduce uncertainties. Therefore, to get further exposure parameters (ED, EF) of the residents is needed for a more accurate human health risk assessment and sensitivity analysis.

**Spatial uncertainty health risk analysis**

**Semivariogram of indicator variables**

In the SIS, “1” and “5e-5” were selected as the indicator variable thresholds for HI and TCR, respectively. In this

| Simulation index | Model type  | RMSE  | Model parameters | Simulation index | Model type  | RMSE  | Model parameters |
|------------------|-------------|-------|------------------|------------------|-------------|-------|------------------|
|                  |             |       | \(C_0\)          |                  |             |       | \(C + C_0\)      | Range (m) |
| Adult HI         | Spherical   | 0.0188|                  |                  | Exponential | 0.0187| 0.023 0.021       | 35,000 |
|                  | Exponential | 0.0271|                  |                  | Gaussian    | 0.0186|                   |        |
|                  | Gaussian    | 0.0189|                  |                  |             |       |                  |        |
| Adult TCR        | Spherical   | 0.0333| 0.164 0.098      | 2867             | Exponential | 0.0331|                   |        |
|                  | Gaussian    | 0.0331|                   |                   |             |       |                  |        |
| Child HI         | Spherical   | 0.0188|                  |                  | Exponential | 0.0187| 0.023 0.019       | 33,824 |
|                  | Gaussian    | 0.0186|                   |                   |             |       |                  |        |
| Child TCR        | Spherical   | 0.0306| 0.202 0.050      | 2348             | Exponential | 0.0339|                   |        |
|                  | Gaussian    | 0.0333|                   |                   |             |       |                  |        |

**Fig. 8** Results of the 1st, 50th, and 100th SIS simulations of non-carcinogenic risk of drinking water to adults in Hanyuan County
research, we used a particle swarm optimization algorithm and least-squares method to fit three theoretical variation models (spherical, exponential, and Gaussian) of indicator variables including adult HI, adult TCR, child HI, and child TCR. The theoretical semivariogram with the least error was selected as the experimental semivariogram, and the parameter values are shown in Table 4.

**Probability spatial distribution of health risks**

According to the probabilistic health risk assessment results, the drinking water in Hanyuan County contains various health risks to both adults and children. To study the distribution and uncertainty of the health risks, to both adults and children, of drinking water in this area, SIS was used to conduct random modelling. Taking adult non-carcinogenic risks as an example, the random model generated by the SIS method better describes the spatial distribution of health risks in the study area and reflects its spatial uncertainty (Fig. 8).

After performing 100 SIS on the health risks to adults and children in the study area, we used Formulae (8)–(9) to perform statistical analysis to obtain the diagram of the probability of health risk and the diagram of variance of health risk (Figs. 9 and 10). The regional risk probability value and standard deviation respectively represent the possibility and uncertainty of health risks to humans caused by various pollutants in drinking water. When the risk probability value is high, risks to health are more likely in that area. When the risk probability value is low, the health risk is low, but its standard deviation is large, which leads to increased uncertainty. To provide environmental risk managers with extensive, intuitive, and accurate information, we referred to the classification of groundwater and soil health risk assessments and hierarchical risk control areas by Zeng Guangming and Huang Jinhui (Huang et al. 2016; Zeng et al. 2009). This study uses 5%, 25%, 50%, 75%, and 95% probability of exceeding the standard as the benchmark, and the health risks of the study area are separated.
As shown in Figure 9, the spatial distribution of non-carcinogenic risks exceeding the probability is the same in adults and children. The area with a standard exceeding probability value greater than 0.75 is mainly located around the S30 point. The areas where the risk of adult carcinogenesis is more significant than 0.75 are mainly located around S5, S8, S12, S13, S19, and S21. The areas where the risk of children’s carcinogenesis is more significant than 0.75 are mainly located around S10, S12, S13, S18, S19, and S21.

The contribution analysis results of the non-carcinogenic risk (Fig. 5) showed that the key cause of high non-carcinogenic risk in the point S30 is $F^-$. The concentration of $F^-$ in drinking water is 0.835 mg/L, which is close to the Chinese standard values.

The contribution analysis results of the carcinogenic risk (Fig. 5) showed that the key cause of high carcinogenic risk is As. The high carcinogenic risk areas S5, S8, S10, S13, S19, and S21, located in Fuchun Township, Dayan Township, Fuxiang Township, Sunjing Township, and Katama Township, respectively, belong to the dry and hot valley area of Dadu River with a hot climate, average temperature of 17.9 °C, and frost-free period of about 300 days. These areas have developed agriculture and are the main fruit and vegetable growing areas. The use of pesticides and chemical fertilizers will cause heavy metals such as As and Cd to enter water bodies, which is the main reason that the regions are at high carcinogenic risk.

The types of water supply in these points except point S12 from waterworks are all centralized water supply projects or decentralized water supply in rural areas, which are with simple purification process and limited decontamination capacity, and this is the reason why these points are in high non-carcinogenic or carcinogenic risk.

It can be seen from Figures 9 and 10 that the areas with a health risk probability significant standard deviation within the study area are mainly concentrated in the locations where the health risk exceeds the standard
The probability of 25 to 75%. This signifies significant uncertainty, indicating that the health risk level of the region is unstable, and could possibly change to high risk.

**Grading of control areas according to health risk levels**

Combining Figures 9 and 10, the areas with carcinogenic risk and non-carcinogenic risk with over-standard probability greater than 75% are classified as class I areas, and areas with a 25–75% probability, that is, areas with large standard deviations, are classified as class II areas. The remaining areas are described as level III areas (Fig. 11).

The grade I non-carcinogenic and carcinogenic risk covered 19.67 km² and 612.58 km², accounting for 0.89% and 27.71% of the total Hanyuan County area, respectively. For drinking water in grade I areas, due to the high probability of non-carcinogenic and carcinogenic risk exceeding the standard, various pollutants in the drinking water pose a more significant threat to health; thus, this area should be regarded as a priority control area for environmental risks. For pollutants containing F⁻, NO₃⁻, As, and Cr(VI) contributing to health risks, the water processing plants within those study areas need to undertake corresponding purification processes.

In addition, all risk information should be made public, to prompt widespread awareness among local residents and encourage them to monitor their drinking water quality.

Grade II non-carcinogenic and carcinogenic risk areas constituted 546.48 km² and 1007.19 km², accounting for 24.72% and 45.56% of the total Hanyuan County area, respectively. For drinking water in grade II areas, since the non-carcinogenic risk and probability of carcinogenic risk exceeding the standard are relatively small, the standard deviation is large, and the drinking water health risk could increase from low to high. Therefore, these areas should be considered as environmental risk key control areas. Relevant departments need to strengthen the monitoring and early warning system of water sources and drinking water quality in high-risk areas within the study area and take measures to reduce pollution when necessary to avoid deterioration of drinking water quality.

Grade II non-carcinogenic and carcinogenic risk areas covered 1644.53 km² and 590.92 km², accounting for 24.72% and 45.56% of the total area of Hanyuan County, respectively. For drinking water in grade III areas, since various pollutants in this area constitute low non-carcinogenic and carcinogenic risk to adults and children, the sites should be determined as general environmental risk control areas. It
is recommended that relevant departments conduct regular sampling and inspections of the drinking water quality in these areas.

Conclusion

The study evaluated the hazards to human health posed by Fe, Mn, NH₃-N, NO₃⁻, F⁻, Pb, Hg, As, Cr(VI), and Cd in the peripheral drinking water of Hanyuan County; analyzed the uncertainty of risk; and classified health risk control areas. The conclusions are as follows:

(1) Except for NO₃⁻, all other indicators met World Health Organization standards and China's water sanitation standards.

(2) The maximum estimated value of the children’s HI is 1.41, with a 14.58% probability of exceeding safety level 1, and the contribution of F⁻, NO₃⁻, and As is relatively large. The maximum estimate of the total carcinogenic risk for adults exceeding 5.24 × 10⁻⁴ a⁻¹ is 93.84%, and the contribution of As and Cr(VI) is relatively significant.

(3) Sensitivity analysis results showed that IR, BW, F⁻, NO₃⁻, and As concentration significantly affect the health risks of both adults and children.

(4) The non-carcinogenic risks of grade I, grade II, and grade III areas account for roughly 0.89%, 24.72%, and 74.39% of the total area of Hanyuan County. The carcinogenic risks of grade I, grade II, and grade III areas accounted for about 27.71%, 45.56%, and 26.73% of the total area of Hanyuan County.

(5) The drinking water quality meets relevant standards, which does not denote that there is no health risk. Combining Monte Carlo simulation uncertainty analysis and sequential indicator simulation can effectively determine different risk control areas. In view of the risk characteristics of various regions, suggestions are made to assist relevant departments in formulating more scientific, economic, and flexible drinking water safety management strategies.

Acknowledgements We sincerely appreciate the editors’ and anonymous reviewers’ significant comments and suggestions for adding to the quality of the study.

Author contribution All authors contributed to the study conception and design. Material preparation and analysis were performed by Zhengjiang Lin, Ying Liu, and Zhihui Cheng. Data collection was performed by Ying Liu. The first draft of the manuscript was written by Zhengjiang Lin and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was supported by the National Natural Science Foundation of China (Grant No. 51779211, Grant No. 51209178) and the Sichuan Science and Technology Program (Grant No. 2019YJ0233).

Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

References

Adimalla N (2020a) Controlling factors and mechanism of groundwater quality variation in semiarid region of South India: an approach of water quality index (WQI) and health risk assessment (HRA). Environ Geochim Health 42:1725–1752
Adimalla N (2020b) Spatial distribution, exposure, and potential health risk assessment from nitrate in drinking water from semi-arid region of South India. Hum Ecol Risk Assess Int J 26:310–334
Chai N, Yi X, Xiao J, Liu T, Liu Y, Deng L, Jin Z (2021) Spatiotemporal variations, sources, water quality and health risk assessment of trace elements in the Fen River. Sci Total Environ 757:143882
Deng Y (2013) Health risk assessment associated with water quality of rural drinking water sources: a case of Mingshan Distract. Master Degree Thesis, Sichuan Agricultural University, Yanan, China, 43–48 pp
Fang H, Lin Z, Fu X (2021) Spatial variation, water quality, and health risk assessment of trace elements in groundwater in Beijing and Shijiazhuang, North China Plain. Environ Sci Pollut Res 28:57046–57059
Gao S, Li C, Jia C, Zhang H, Guan Q, Wu X, Wang J, Lv M (2020) Health risk assessment of groundwater nitrate contamination: a case study of a typical karst hydrogeological unit in East China. Environ Sci Pollut Res 27:9274–9287
Goovaerts P (2001) Geostatistical modelling of uncertainty in soil science. Geoderma 103:3–26
Guan Y, Kong H-n, Zhang S-d, Li X-d, Liu H, Lin Y (2018) Progess in drinking water safety for residents. Environ Eng 36:18–22
Hou J (2006) Environment geochemistry research and environment assessment of heavy metal in paddy soil around Tangjiia Zink-Pb mine ,Hanyuan Sichuan. Master Degree Thesis, Chengdu University of Technology (In Chinese)
Huang J-h, Liu W-c, Zeng G-m, Li F, Huang X-l, Gu Y-l, Shi L-x, Shi Y-h, Wan J (2016) An exploration of spatial human health risk assessment of soil toxic metals under different land uses using sequential indicator simulation. Ecotoxicol Environ Saf 129:199–209
Kavcar P, Sofuoglu A, Sofuoglu SC (2009) A health risk assessment for exposure to trace metals via drinking water ingestion pathway. Int J Hyg Environ Health 212:216–227
Kazemi A, Esmaeilbeigi M, Sahebi Z, Ansari A (2022) Health risk assessment of total chromium in the qanat as historical drinking water supplying system. Sci Total Environ 807:150795

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