Water Supply

A new method to determine the scale range of environmental damage caused by water pollution accidents

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ABSTRACT

Recently, water pollution accidents have happened frequently and have caused serious environmental damage. The purpose of this study was to propose a new method to determine the scale range of environmental damage in water pollution events. In this study, taking Fen River in Shanxi Province as an example, a computer simulation system was used to simulate the diffusion and migration process of phenol at different concentrations, so as to determine the curve series of the scale range of environmental damage caused by the simulated water pollution event. At the same time, taking the incident of water pollution caused by phenol leakage in Jingle County as an example, the actual scale range of environmental damage was compared with the simulated scale range, so as to determine the error of the scale range of environmental damage. The results showed that the maximum error of the curve series of the scale range of environmental damage was 22.4%, and the minimum error was 7.5%, which indicated that the error of the scale range of environmental damage was small, and proved that this method of quantitatively determining the scale range of environmental damage had certain scientific nature.

Key words: computer simulation, environmental damage, scale range, validation, water pollution accidents

HIGHLIGHTS

- Proposed a new method to determine the scale range of water environmental damage.
- Obtained the curve series of the scale range of water environmental damage.
- The actual scale of environmental damage was compared with the simulated scale.
- The error of the scale range of water environmental damage was small (7.5%–22.4%).
- The method of determining the scale range of environmental damage was scientific.

INTRODUCTION

At present, accidental pollution events such as process leaks, transport accidents, collisions and pipeline leaks occur frequently in many countries (Pulido-Velazquez & Ward 2017) and China (Tang *et al.* 2014). Pollution accidents can cause serious ecological and environmental damage to surrounding areas leading to imbalance of the regional ecological system (Peng *et al.* 2013; Rui *et al.* 2015; Belayutham *et al.* 2016). In various pollution incidents, accidental water pollution incidents have occurred more and more frequently (He *et al.* 2011; Qu *et al.* 2016; Yang *et al.* 2017). Over the past decade, the Ministry of Environmental Protection, China, responded directly to 765 water pollution accidents, corresponding to 58% of the total number of environmental emergencies (Ministry of Environmental Protection 2015–2019). In water pollution events, the effects of water pollutants were mainly manifested in the acute poisoning effect on animals and plants, the chronic poisoning effect and the biological amplification effect in the biological chain (Wang *et al.* 2008; Li *et al.* 2009; Liu *et al.* 2013).

In recent years, determining the scale range of environmental damage caused by water pollution events has attracted worldwide attention (Tao *et al.* 2013; Yang *et al.* 2015). Factors affecting the scale range of environmental damage in water pollution events include the concentration of pollutants, the nature of pollutants, the time of pollution, and the depth, water level, velocity and discharge of the river. Determining the scale range of environmental damage of water pollution events should be based on the actual situation, and should not be generalized. At present, most studies focus on the qualitative

discussion of how to determine the scale range of environmental damage caused by water pollution events. For example, Ding et al. (2017) proved that when the scale range of environmental damage of water pollution events was too large, the large local influence could be ignored. Dong et al. (2017) proposed that the scale range of environmental damage of water pollution events was too small, and some sensitive factors might be missed. Ani et al. (2012) pointed out the influence of the river velocity on the scale range of environmental damage caused by water pollution events. Ren et al. (2017) explained the influence of the concentration and nature of pollutants on the scale range of environmental damage caused by water pollution events. However, these studies still had one major limitation due to the lack of discussion of how to quantitatively determine the scale range of environmental damage in water pollution events. Therefore, the objectives of this study were to develop a new method to quantitatively determine the scale range of environmental damage in water pollution events, and to verify the scientific nature of this method through an actual case.

METHODOLOGY AND MATERIALS

Study area

Fen River is the main river in Shanxi Province of China. It flows from the north to the south of Shanxi Province and finally reaches the Yellow River. The Yellow River is the main source of drinking water in Shanxi Province. The starting point of Fen River in Shanxi Province was taken as the starting point of the study section, and the entrance to the Yellow River was taken as the end point of the study section. Taking the monitoring points of Fen River in Shanxi Province as the research points, there were nine distances from each research point (including the starting point of the research section) to the end point of the research section. These nine distance segments were taken as the research lengths. The research length and research section of Fen River are shown in Table 1.

The phenol leakage event

At 16:56 pm on May 22, 2016, on provincial highway S313, a tanker carrying 24.35 tons of phenol from Kelan to Shijiazhuang, Hebei Province, overturned in a traffic accident on the west road of Yaohui Village in Jingle County in Shanxi. As a result, the phenol leaked and about five tons of it flowed into Fen River along the drainage channel on the north side of the road. The phenol leakage event was located in Jingle County, Shanxi Province, China. The study area is located at the accident site in the Liudu Bridge section.

Environmental damage model of water pollution accidents

In order to study the influence of the phenol leakage event on the downstream and banks of Fen River, the Environmental Damage Model of Water Pollution Accidents was used to simulate the pollutant concentration. This model perfectly combines the most advanced calculation engine of hydrodynamic–water-quality numerical simulation Delft3D-FLOW in the world with the standard 'Map World' of the China Bureau of Surveying and Mapping, and it can analyze and predict accidental water pollution events by drawing grids, setting parameters, calculating results and rendering.

Table 1 | The research length and research section of Fen River

Name of research section	The starting point of the research section	The end point of the research section	Research length R (km)
I	1-the starting point of Fen River	10	710
II	2-Hexi Village	10	608
III	3-Thunder Temple	10	512
IV	4-Fen River Reservoir outlet	10	409
V	5-Shanglan	10	368
VI	6-Wenna club	10	249
VII	7-Xiaodian Bridge	10	187
VIII	8-South of Wangzhuang Bridge	10	109
IX	9-Shangpingwang	10	52

Mesh generation

Mesh generation is a key step in realizing the information attributes of all elements in the watershed to be illustrated by the mathematical model (Yang *et al.* 2015). The grid generalization model employs a 2D model for the large-scale complex boundary conditions of rivers, and a suitable grid density is reached by repeating computations until a satisfactory independent grid is found.

Natural rivers have irregular three-dimensional shapes, which make the geometric and boundary conditions difficult to characterize. The system can transform irregular geometries of a physical domain into simple and regular geometries of a computational domain, which is automatically generated with the help of GIS spatial analysis modules.

Parameter set

The names and values of parameters are shown in Table 2. A flowchart of the study is shown in Figure 1.

RESULTS AND DISCUSSION

Simulation results

The computer simulation system Environmental Damage Model of Water Pollution Accidents was used to simulate the migration process of phenol with different concentrations in each research length of Fen River, in order to determine the simulated concentration of phenol (C_1) at the starting point of each research length when the simulated concentration of phenol (C_2) at the end point of the research section reached about the safe concentration C_s (0.20 mg/L). Then, if the simulated concentration of phenol at the starting point of each research length was C_1, the corresponding research length was the scale range of environmental damage. The simulated concentration of phenol at the starting point of the research section and the corresponding simulated concentration at the end of the research section are shown in Table 3.

According to Table 3, in study section I, when the simulated concentration of phenol at the beginning of the study section was 390 mg/L, the simulated concentration of phenol at the end of the study section was 0.19 mg/L ($\approx$0.20 mg/L). In study section II, when the simulated concentration of phenol at the beginning of the study section was 330 mg/L, the simulated concentration of phenol at the end of the study section was 0.22 mg/L ($\approx$0.20 mg/L). In study section III, when the simulated concentration of phenol at the beginning of the study section was 260 mg/L, the simulated concentration of phenol at the end of the study section was 0.21 mg/L ($\approx$0.20 mg/L). In study section IV, when the simulated concentration of phenol at the beginning of the study section was 210 mg/L, the simulated concentration of phenol at the end of the study section was 0.19 mg/L ($\approx$0.20 mg/L). In study section V, when the simulated concentration of phenol at the beginning of the study section was 180 mg/L, the simulated concentration of phenol at the end of the study section was 0.23 mg/L ($\approx$0.20 mg/L). In study section VI, when the simulated concentration of phenol at the beginning of the study section was 150 mg/L, the simulated concentration of phenol at the end of the study section was 0.17 mg/L ($\approx$0.20 mg/L). In study section VII, when the simulated concentration of phenol at the beginning of the study section was 120 mg/L, the simulated concentration of phenol at the end of the study section was 0.24 mg/L ($\approx$0.20 mg/L). In study section VIII, when the simulated concentration of phenol at the beginning of the study section was 80 mg/L, the simulated concentration of phenol at the end of the study section was 0.18 mg/L ($\approx$0.20 mg/L). In study section IX, when the simulated concentration of phenol at the beginning of the study section was 60 mg/L, the simulated concentration of phenol at the end of the study section was 0.15 mg/L ($\approx$0.20 mg/L).

Table 2 | The names and values of parameters

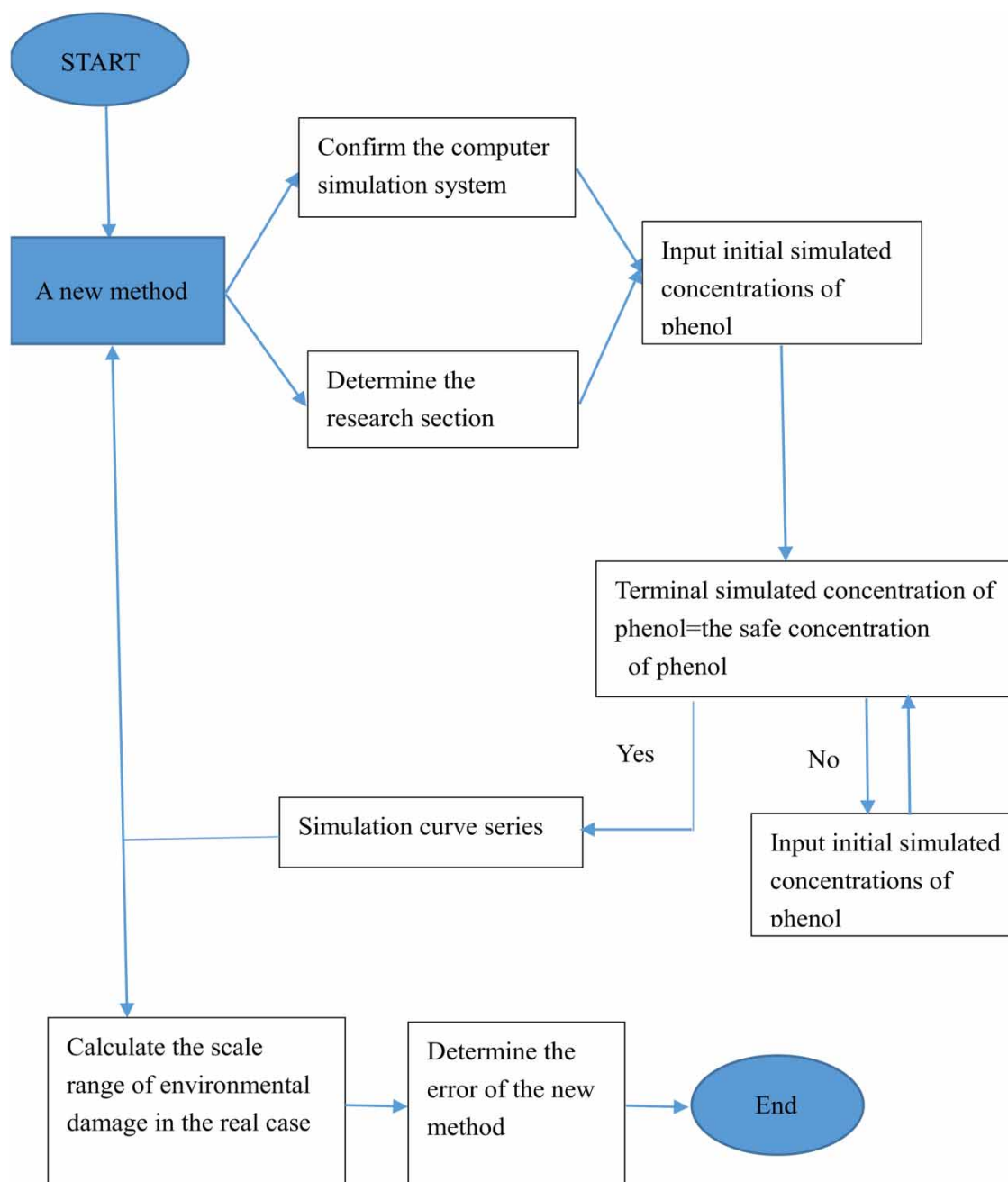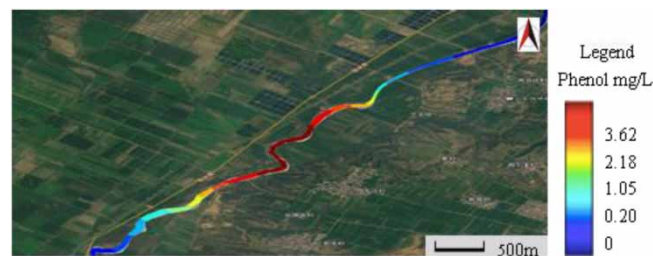| Name	Value
River flow	7.7 m^3
Pollutant leakage time	2 h
Diffusion simulation time	62 h
Pollutant attenuation coefficient	0.0006 day^{-1}
Safe concentration of pollutant	0.20 mg/L

Figure 1 | A flowchart of the study.

Taking the study section as IX, when the simulated concentration of phenol at the starting point of the study section was 60 mg/L, Figures 2–5 show the simulation diagram of phenol diffusion at 6, 10, 14 and 18 h respectively. As can be seen from Figures 2–5, the pollutant moved in the form of a 'pollutant band' from upstream to downstream. The darker the color is, the higher the concentration of phenol is, and vice versa. Red represents the most polluted area, and the concentration of phenol represented by orange, yellow and green decreases in turn. Blue indicates that the concentration of phenol has fallen below the surface water quality standard.

As seen in Figures 2–5, the color of the 'pollutant band' gradually changes from red to blue, which indicates that the pollutant moved from upstream to downstream with an increasing pollution area but a decreasing phenol concentration. The expansion of the pollution area was mainly caused by transverse and longitudinal diffusions and was affected by their

Table 3 | Simulated concentration of phenol in each research section

Name of research section	Simulated concentration of phenol at the starting point of the research section C_1 (mg/L)	Simulated concentration of phenol at the end point of the research section C_2 (mg/L)	Safe concentration of phenol C_s (mg/L)
I	500	3.67	0.20
	450	1.42	0.20
	400	0.35	0.20
	350	0.04	0.20
	360	0.07	0.20
	380	0.15	0.20
	390	0.19	0.20
II	380	1.96	0.20
	360	1.04	0.20
	350	0.70	0.20
	340	0.51	0.20
	330	0.22	0.20
III	320	1.73	0.20
	300	0.78	0.20
	280	0.46	0.20
	270	0.32	0.20
	260	0.21	0.20
IV	250	2.26	0.20
	230	1.29	0.20
	220	0.54	0.20
	210	0.19	0.20
V	200	1.65	0.20
	190	0.67	0.20
	180	0.23	0.20
VI	170	1.80	0.20
	160	0.79	0.20
	150	0.17	0.20
VII	140	1.91	0.20
	130	0.88	0.20
	120	0.24	0.20
VIII	100	1.49	0.20
	90	0.63	0.20
	80	0.18	0.20
IX	70	1.84	0.20
	65	0.77	0.20
	60	0.15	0.20

Figure 2 | Diffusion status 6 h after the phenol leakage event.

speeds. Furthermore, the reasons for the decrease of phenol concentration were the transportation and degradation of the pollutant and the self-purification of the river. In addition, the color of the 'pollutant band' gradually reddens from the outside to the inside, indicating that the area with the highest concentration of phenol was near the center of the 'pollutant band'. The

Figure 3 | Diffusion status 10 h after the phenol leakage event.

Figure 4 | Diffusion status 14 h after the phenol leakage event.

Figure 5 | Diffusion status 18 h after the phenol leakage event.

pollutant ultimately remained in the river so that the water quality of the relevant area needed to be monitored until the river water quality returned to normal. Additionally, the pollutant had a certain degree of impact on the river ecosystem and the health of the residents.

Determination of the scale range of environmental damage

A series of different phenol concentrations were taken, which were required to be less than the corresponding simulated concentration of phenol at the beginning of each study section (C_a) when the simulated concentration of phenol at the end of the study section (C_b) was about the safe concentration (when the concentration of phenol at the beginning of each study section was greater than C_a, the scale range of environmental damage was larger than the corresponding study length L), and the diffusion and migration process of the phenol was simulated in the corresponding study length in order to determine the corresponding migration length when the phenol concentration (C_b) was reduced to about the safe concentration, and this migration length was the scale range (Table 4).

According to the data in Table 4, the curve series of the scale range of environmental damage can be obtained and there are nine curves (Figure 6). In Figure 6, the coordinate x of the curve series is the initial simulated concentration of phenol C_a (mg/L) at the starting point of each study section. The coordinate y is the scale range of environmental damage L (km) corresponding to C_a at the starting point of each study section. The coordinate z represents the distance between the starting point of each study section and the end point of the study section, namely the study length R (km).
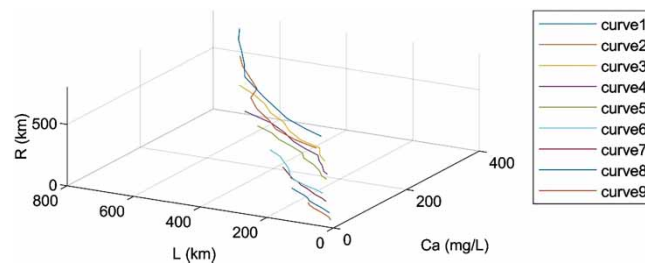
Table 4 | Simulated concentration of phenol and the corresponding scale range

The starting point of the study section	The initial simulated concentration of phenol C_a (mg/L)	Phenol concentration (about the safe concentration) C_b (mg/L)	The corresponding scale range L (km)
1-the starting point of Fen River	390	0.19	710
	345	0.17	664
	300	0.21	605
	250	0.23	542
	200	0.21	486
	170	0.18	428
	130	0.22	351
	100	0.24	288
	60	0.23	205
	30	0.18	116
	10	0.25	47
2-Hexi Village	330	0.22	643
	290	0.22	591
	250	0.24	525
	210	0.25	460
	170	0.21	435
	130	0.20	373
	90	0.18	291
	60	0.17	239
	30	0.22	148
	10	0.23	62
	260	0.21	568
	230	0.17	489
	200	0.22	425
	170	0.16	376
3-Thunder Temple	140	0.19	303
	110	0.23	254
	80	0.21	186
	60	0.22	107
	30	0.18	73
	10	0.17	36
	210	0.19	497
	180	0.22	385
	150	0.24	311
	120	0.16	252
4-Fen River Reservoir outlet	100	0.19	197
	80	0.21	134
	60	0.25	109
	40	0.17	77
	20	0.16	51
	10	0.22	29
	180	0.23	426
	160	0.16	360
	140	0.19	319
	120	0.24	258
5-Shanglan	100	0.22	203
	80	0.20	177
	60	0.17	125
	40	0.19	86
	20	0.16	57
	10	0.19	31
	150	0.17	355
	130	0.17	302
	110	0.19	269
	90	0.21	234

(*Continued.*)

Table 4 | Continued

The starting point of the study section	The initial simulated concentration of phenol C_a (mg/L)	Phenol concentration (about the safe concentration) C_b (mg/L)	The corresponding scale range L (km)
6-Wenna club	70	0.24	208
	50	0.18	183
	30	0.16	116
	20	0.23	74
	10	0.18	43
	120	0.24	284
	100	0.22	247
	80	0.25	211
	70	0.21	183
7-Xiaodian Bridge	60	0.20	164
	50	0.24	135
	40	0.18	111
	30	0.18	87
	20	0.16	56
	10	0.19	33
	80	0.18	213
	70	0.21	186
	60	0.21	155
	50	0.24	132
8-South of Wangzhuang Bridge	40	0.22	116
	30	0.18	88
	20	0.19	57
	10	0.22	31
	5	0.22	17
	60	0.15	142
	50	0.18	126
	40	0.16	101
	35	0.20	85
9-Shangpingwang	30	0.22	69
	25	0.19	56
	20	0.21	42
	15	0.23	30
	10	0.22	22
	5	0.24	13

Figure 6 | The curve series of the scale range of environmental damage.

As can be seen from Figure 6, the longer the study section was, the larger the initial simulated concentration of phenol at the starting point of the study section was, and the longer the scale range of environmental damage was. According to the curve series, the scale range of environmental damage corresponding to the diffusion and migration of phenol with any concentration in this coordinate system could be obtained. However, the scale of the environmental damage in Figure 6 was

obtained under the simulated condition. Next, the actual case would be used to verify the scientificity of this quantitative method to determine the scale range of environmental damage.

The phenol pollution event

Taking the phenol pollution event in Jingle County as an example, the scale range of phenol migration was obtained according to the monitoring data of phenol concentration in the event. The maximum concentration of phenol at each monitoring point was the location of the pollution cluster. When the concentration of phenol at the monitoring point was reduced from the maximum concentration to about the safe concentration (0.20 mg/L), the corresponding migration length of phenol was the scale range of environmental damage.

The monitoring data of phenol concentration in the event are shown in Table 5. The monitoring data were provided by Xinzhou Municipal Environmental Protection Bureau.

Verification of the scale range of environmental damage

According to the monitoring data of phenol concentration in the event in Jingle County, point A_x ($x = 1, 2, 3, 4, 5$) was obtained by taking the initial concentration of phenol (the maximum concentration of phenol at each monitoring point) as the x-coordinate and the actual scale range of environmental damage as the y-coordinate. At the same time, in the curve series of the scale range of environmental damage, the corresponding point B_x ($x = 1, 2, 3, 4, 5$) could be found where the x-coordinate was the initial concentration of phenol in the monitoring data. The y-coordinates of point A_x and point B_x were compared to compare the actual scale range of environmental damage with the simulated scale range of environmental damage, and the error of the curve series of the scale range of environmental damage was determined, so as to judge the scientificity of this quantitative method to confirm the scale range of environmental damage.

In the phenol pollution event in Jingle County, the calculation equation of the actual scale range (L_a) of environmental damage is shown in Equation (1):

$$L_a = v \times t \tag{1}$$

In Equation (1), v is the average flow velocity of Fen River from the leakage point to each monitoring point, and t is the migration time of the phenol, which is the time required for the decrease of the concentration of phenol at the monitoring point from the maximum concentration (C_{max}) to the safe concentration (C_s) when the phenol migrates to a monitoring point. The calculation results of L_a at each monitoring point are shown in Table 6.

According to L_a, a series of points (A_x) could be obtained. By comparing a series of corresponding points (B_x) in the curve series of the scale range of environmental damage with A_x, the error (E) of the curve series of the scale range of environmental damage could be calculated. The calculation equation of E is shown in Equation (2), and the calculation results of E are shown in Table 7.

$$E = \frac{|L - L_a|}{L_a} \times 100\% \tag{2}$$

As can be seen from Table 7, the maximum value of E was 22.4% and the minimum value was 7.5%. The calculation results of E showed that the error of the curve series of the scale range of environmental damage was small and the curve was practical, which proved the quantitative method to determine the scale range of environmental damage had certain scientificity. In conclusion, the results of this study can lay the certain foundation for determining the scale range of environmental damage caused by sudden water pollution events and provide favorable technical support and practical experience, and may offer the basis for the related work of identifying the scale range of environmental damage.

CONCLUSIONS

The purpose of this study was to propose a new method to determine the scale range of environmental damage in water pollution events, and verify the scientific nature of this method through an actual case. This has not been mentioned in previous studies. In this study, taking Fen River in Shanxi Province as an example, a computer simulation system was used to simulate the diffusion and migration process of phenol at different concentrations, so as to determine the curve series of the scale range of environmental damage caused by the simulated water pollution event. At the same time, taking the incident of water pollution

Table 5 | The monitoring concentration of phenol in the event

Name of monitoring station	Leakage time (h)	Monitoring concentration (mg/L)
The leakage point	2	95.59
	4	81.37
	6	74.22
	8	62.59
	10	51.66
	12	43.83
	14	30.12
	16	14.70
	18	10.19
	20	7.84
	22	4.55
	24	0.98
	26–38	0.00
Hexi Village	2	0.00
	4	49.68
	6	71.19
	8	62.56
	10	50.11
	12	39.37
	14	30.90
	16	27.46
	18	21.82
	20	16.33
	22	12.69
	24	9.07
	26	5.51
	28	2.57
	30–42	0.00
Thunder Temple	2–4	0.00
	6	15.88
	8	28.45
	10	37.09
	12	32.66
	14	26.31
	16	20.18
	18	14.05
	20	10.26
	22	6.13
	24	3.58
	26	1.14
	28–40	0.00
Fen River Reservoir outlet	2–10	0.00
	12	13.68
	14	25.79
	16	32.14
	18	25.80
	20	18.54
	22	12.91
	24	7.33
	26	2.24
	28–40	0.00
Shanglan	2–12	0.00
	14	6.83
	16	17.76
	18	23.15

(*Continued.*)

Table 5 | Continued

Name of monitoring station	Leakage time (h)	Monitoring concentration (mg/L)
	20	18.69
	22	12.26
	24	8.48
	26	3.52
	28	1.06
	30–42	0.00
Wenna club	2–16	0.00
	18	3.96
	20	8.33
	22	11.09
	24	8.23
	26	5.77
	28	2.61
	30	0.58
	32–44	0.00

Table 6 | The calculation table of L_a at each monitoring point

Name of monitoring station	v (m/s)	C_{max} (mg/L)	C_s (mg/L)	$t = t_s - t_{max}$ (h)	L_a (km)
1-Hexi Village	2.9	71.19	0.00	$24 = 30 - 6$	250.56
2-Thunder Temple	1.7	37.09	0.00	$18 = 28 - 10$	110.16
3-Fen River Reservoir outlet	1.6	32.14	0.00	$12 = 28 - 16$	69.12
4-Shanglan	1.1	23.15	0.00	$12 = 30 - 18$	47.52
5-Wenna club	0.8	11.09	0.00	$10 = 32 - 22$	28.80

Table 7 | The calculation table of E

Name of monitoring station	C_{max} (mg/L)	L_a (km)	L (km)	E (%)
1-Hexi Village	71.19	250.56	231.79	7.5
2-Thunder Temple	37.09	110.16	85.63	22.3
3-Fen River Reservoir outlet	32.14	69.12	57.22	17.2
4-Shanglan	23.15	47.52	36.86	22.4
5-Wenna club	11.09	28.80	23.09	19.8

caused by phenol leakage in Jingle County as an example, the actual scale range of environmental damage of the incident was obtained according to the monitoring data of phenol concentration, and the actual scale range of environmental damage was compared with the simulated scale range, so as to determine the error of the scale range of environmental damage. The results showed that the maximum error of the curve series of the scale range of environmental damage was 22.4%, and the minimum error was 7.5%, which indicated that the error of the scale range of environmental damage was small, and proved that this method of quantitatively determining the scale range of environmental damage had certain scientific nature.

The advantage of this study was to propose a new method using computer simulation software to determine the scale range of environmental damage in water pollution events, and this proposed method was proved to be scientific by a practical case. Meanwhile, the disadvantage of the study was that the simulation results were not accurate enough due to only one value being able to be assigned to each parameter in the simulation process, and the impact of the changes of those parameters on simulation results could not be reflected. Therefore, the simulation system in this study should be further optimized and improved in following studies. For example, an ensemble empirical mode decomposition (EEMD) is used to realize the diversification of parameter values (Alizadeh et al. 2019; Roushangar & Alizadeh 2019).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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