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Use of pollutant release and transfer register (PRTR) to assess potential risk associated with chemicals in a drinking water supply facility

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ABSTRACT

Drinking water safety is a serious public health issue. Although the drinking water supply is monitored according to drinking water guidelines, the chemicals released from factories or spills can raise concerns about the quality of drinking water produced at purification facilities. To increase the public trust in drinking water, the reliable control of the source water quality is called for in the framework of catchment management. This paper addresses the problem of the potential risk to a drinking water supply facility from chemical accidents in a basin. The potential risk is defined and assessed as a function of the amount of chemicals transferred, along with their toxicity and distance. Data on the amount of chemical substances transferred to waste treatment facilities are taken from the pollutant release and transfer register, which is an environmental inventory of potentially harmful chemicals. The NFPA-704 health index, which is a standard system from the US National Fire Protection Association, is used for the toxicity. The relative distance between the drinking water supply facility and the location of the transferred chemical is considered. The top-10 chemicals most frequently released in the Nakdong River Basin in South Korea are analyzed using deterministic and stochastic approaches, and cities with high potential risks are identified and prioritized for the efficient monitoring and management of chemicals. Yangsan City, a city located in the southern part of South Korea, is found to have the highest potential risk using these two approaches. This framework can provide decision-makers with useful information for the efficient management of source water in densely populated and highly industrialized catchment areas.

Keywords: Potential risk assessment; Drinking water; Nakdong river; Stochastic; Pollutant release and transfer register (PRTR); Catchment management

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1. Introduction

Existing drinking water supply facilities have been supplying water that meets the drinking water standards based on the end-product testing. However, with the existing management systems, it is difficult to avoid the negative impact on the drinking water supply and public health from contamination by chemical spills and accidents. For example, 30–40 tons of pesticides were released into the Rhine from a Sandoz Ltd. storehouse in Schweizerhalle as a result of the fire in 1986. This chemical was transported to France, West Germany, and the Netherlands, where it caused the deaths of enormous number of fish and benthic organisms [1]. In Camelford, UK, in 1988, a cargo vehicle carrying 20 tons of an aluminum sulfate solution overturned and contaminated a treated water tank. This contaminated water was supplied to 20,000 households and caused a variety of diseases [2]. In 1991, a 30-t phenol leak on the Nakdong River in South Korea caused tap-water contamination [3]. In 2014, 10,000 gallons of chemicals, including 4-methylcyclohexanemethanol (MCHM) and the solvent glycol ether, were released near the Elk River in West Virginia, USA. This area was located 1.5 miles upstream from a drinking water treatment facility that provided water to 15% of West Virginia's citizens, which resulted in 300,000 people not being able to the water [4].

As mentioned above, the pollution of drinking water due to chemical leaks has constantly occurred. However, the existing "end-product" control system has limitations of ensuring the safety of drinking water from pollution such as chemical spills. Once polluted, enormous time and money are required for the remediation. The best way to avoid this loss is to prevent the pollution. For this purpose, the hazard analysis and critical control point (HACCP) system can be applied to drinking water supply facilities.

HACCP is a system that manages and evaluates hazards to protect the water quality from hazardous events by managing, not only the end-product, but also the process of water transporting from the source to consumers [5,6]. The application of HACCP is carried out using the seven principles shown in Fig. 1 [7]. Principle one of HACCP involves analyzing the physical, chemical, microbiological, and radiological hazards in the process of transporting the raw material (water, in this case) to the consumer. Principle two involves determining the critical steps or processes to ensure product safety by preventing, eliminating, or reducing hazards to acceptable levels. Principle three establishes a reference for a hazard to manage the critical control point (CCP), and Principle four establishes a scheme for monitoring the CCP based on the established reference. Principle five establishes corrective actions when a hazard exceeds the reference. Principle six verifies whether this process is effectively carried out, and Principle seven helps continuous improvements of the operation through documentation.

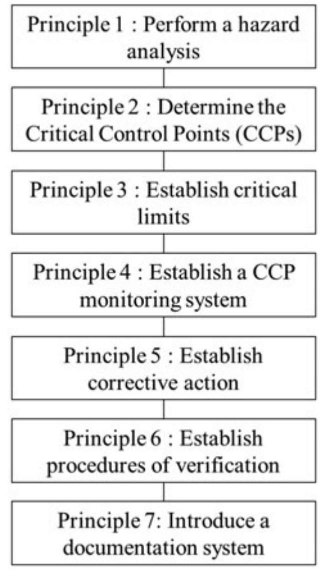

Fig. 1. Seven principles of HACCP [7].

HACCP, which was developed in the food industry for the NASA space program in the 1970s, is currently being applied to manufactured goods worldwide, and its scope has been extended to processed foods, agricultural products, and livestock. If we view drinking water as a food made in a water purification plant, the application of HACCP to drinking water is reasonable. Havelaar [8], who first studied this application, proposed the application not only for a general drinking water supply system but also for bank infiltration. HACCP was applied to a drinking water production process that included an infiltration pond using dune sand along a coastline after a reverse osmosis membrane, ultraviolet irradiation, and membrane filtration were used to purify domestic wastewater [9]. In Iran, HACCP was applied to a general water treatment plant where raw water contaminated by many pollutants from factories, agriculture, and animal husbandry was reclaimed, and a water quality improvement was achieved without additional equipment [10,11]. Studies that applied HACCP to potable water supply systems demonstrated effective quality improvements in Japan [12] and Greece [13]. Drinking water guidelines have been published based on experiences on the application of HACCP to drinking water. Those guidelines are from the World Health Organization [14], USA [15], Australia [16], Canada [17], and New Zealand [18].

A shortcoming of the hazard analysis as a core principle of the HACCP system is that it relies on the subjective opinions of analysts [8]. A quantitative analysis of the hazards in the application of HACCP to drinking water supply facilities was attempted in a study [19]. In it, 114 hazardous events were derived from the entire steps to produce drinking water using managed aquifer recharge, and among those hazardous events the chemical, physical and microbiological hazards were identified. Out of 114 nine major hazardous events were particularly screened, including seven events from the catchment area and one event from the storage of the water intake. All these events involved chemical hazards. From the result of the study, authors concluded that, if the hazardous chemical events occurring in the basin are prevented, it is expected that the risk to the drinking water supply facilities can be significantly reduced.

This paper attempts to conduct a quantitative analysis to estimate the potential risks caused by the chemical hazards that occur in the watershed. The potential risk is defined as the value indicating the potential impact on drinking water supply facilities by a chemical accident. A pre-evaluation of the potential risk will contribute to reduce the drinking water accidents.

When we try to assess the potential risk to a drinking water supply facility by chemical spills, the data required can be obtained from a pollutant release and transfer register (PRTR). A PRTR is an inventory of the emissions to the air, water, and soil of potentially harmful chemical substances, as well as chemical substances transferred off site for treatment or disposal which can be referred to as transfers [20,21].

The US Environmental Protection Agency (EPA) utilized the toxic release inventory (TRI), which is similar to the PRTR, and reduced 45% of the total transfers and total emissions of 330 chemicals from 1988 to 1995 [22]. The reduction effect by TRI has been verified, and the EPA concluded that TRI is one of the most valuable tools for protecting the environment and human health concerning water consumption [23]. As PRTR and some other systems similar to TRI have had a positive effect on the many countries, the organization for economic cooperation and development (OECD) strongly encourages the introduction of PRTR to all of its member states [24]. The Ministry of Environment in Korea introduced PRTR and information about emissions and transfers is disclosed to the public as annual data that can be accessed by anyone. There are 39 types of target industries and 415 chemical substances provided by PRTR [25]. The format is shown in Table 1.

PRTR which offers information about sources and quantities of chemical emissions and transfers is valuable for management of chemical substances [26,27], temporal and spatial characterization of heavy metal effluents [28], and evaluation of chemical risk of aquatic system and atmospheric environment [29,30]. This paper introduces PRTR under the premise that the value of PRTR is worked on the assessment of potential risk associated with chemicals in a drinking water supply facility.

2. Mathematical expression of potential risk

The potential risk of chemicals can be expressed as a function of the amount of transfers, distance, and toxicity as shown in Eq. (1).

$$\text{Potential risk} = f(\text{amount of chemical transfers distance, toxicity}) \tag{1}$$

The transfers are the amount of the total transfers from PRTR data. Although there is no direct relation between the transfers and chemical accidents, this paper considers the likelihood of chemical accidents increased by routine emissions. Potential risk in the equation is considered to be made by indirect constituents such as the total transfers. The distance in this equation indicates the spatial distance between a city and the target facility. The concentration of chemicals would decrease as the distance increases due to the effects of evapotranspiration and chemical reaction [31]. The farther the distance is, the smaller the potential becomes. The distance is considered as simple expression of the exposure term. The toxicity is included in the equation since even a small amount of toxic chemical can have a significant impact on the environment and human health. Two approaches, deterministic and stochastic, are employed to express the potential risk as follows.

2.1. Deterministic approach

The deterministic approach makes it relatively easy not only to express the potential risk, but also to integrate the function over time. The relative distance between a city and the target facility is defined as follows:

$$D_c = \frac{\max(d) - d_c}{\max(d) - \min(d)} + 1 \tag{2}$$

Table 1
An example of data provided by PRTR (Y city in South Korea, 2012)

Chemical	Air emissions (kg/yr)	Water emissions (kg/yr)	Soil emissions (kg/yr)	Total emissions (kg/yr)	On-site landfills (kg/yr)	Waste water transfers (kg/yr)	Waste transfers (kr/yr)	Total transfers (kg/yr)
Toluene	145,994	0	0	145,994	0	189	119,920	120,109
Xylene	75,708	0	0	75,708	0	61	82,385	82,446

where d denotes the distance between a city and the target facility. The relative distance (D_c) as a dimensionless number is modified for the potential risk from other research [32]. The operation of the formula gives a value of 1 for the furthest city, and a value of 2 for the closest city from the drinking water supply facility, which means that the potential risk can be increased up to two times, depending on the location of the city.

The individual potential risk for each chemical can be calculated by multiplying Eq. (2) and the total transfer as follows:

$$R_{qc} = \ln\left(\sum_{t=1}^{n} x_{qc}^{t} \times \frac{1}{n}\right) \times D_c \tag{3}$$

where R_{qc} denotes the individual potential risk for each chemical, and t, n, q, c, and x are time (year), number of years, chemical substance, city, and total transfers (kg/yr), respectively. The potential risk for all the chemical substances is defined by incorporating the toxicity into Eq. (3) as follows:

$$R_c = \frac{\sum_{q=1}^{m} (R_{qc} \times h_q)}{\sum_{q=1}^{m} h_q} \tag{4}$$

where R_c, h, and m denote the comprehensive potential risk of a specific city, toxicity, and number of chemicals, respectively. Eq. (4) is based on the method of weighted average [33]. The toxicity of a chemical can be taken from health risk index of the NFPA 704. NFPA 704 is a standard system for the identification of the hazard of chemical substances for emergency response provided by the National Fire Protection Association [34]. NFPA 704 which was established after sufficient numbers of tests of albino rats about oral, dermal, and inhalation toxicity [35] is regarded to be good enough to express toxicity of potential risk to a drinking water supply facility. The values of NFPA 704 are rated on a scale of 0–4 for hazardous substances. This scale is effective because both experts and non-experts can easily recognize degree of hazard.

2.2. Stochastic approach

While the potential risk can be calculated using the historical data, information about the potential risk in the future would be of great concern from the catchment management point of view. Since the PRTR data are not currently sufficient for probabilistic analysis due to the small size of data, synthetic data are generated using the stochastic approach. Once the generated data are fitted to a probability distribution, then the probability of the potential risk which exceeds a certain level can be estimated.

2.2.1. Time-dependent potential risk

Unlike the deterministic approach where the individual and comprehensive potential risks were defined over the entire time period, we now introduce a new potential risk as a function of time:

$$R_c^t = \frac{\sum_{q=1}^{m} (\ln x_{qc}^{t} \times h_q)}{\sum_{q=1}^{m} h_q} \times D_c \tag{5}$$

where R_c^t denotes the time-dependent potential risk.

2.2.2. Synthetic generation of R_c^t

The procedure for generating synthetic R_c^t to overcome the lack of raw data in PRTR is shown in Fig. 2. Step 1 calculates R_c^t using PRTR data and constructs a frequency table of R_c^t. A note of caution is that a city that has data for less than one year should be excluded because the data for more than two years are needed to create a frequency table using the maximum and minimum values. Forming a class that is larger than the maximum class is necessary and it is

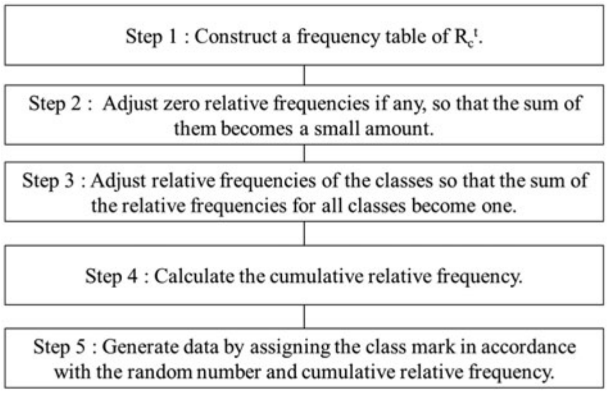

Fig. 2. Procedure of synthetic generation of R_c^t.

intended to create a class that can include the maximum value when each class interval is shifted by a small number (e.g. 0.1). The relative frequency of some classes may turn out to be zero, and in order to avoid such a situation, a small number is assigned to the corresponding relative frequencies in Step 2. The assigned number should be small enough to minimize the disturbance of the distribution of the original data. Except for classes with the relative frequencies of zero value, the relative frequencies of the other classes are slightly reduced until the sum of the relative frequencies for all classes become one (Step 3). After the cumulative relative frequency is calculated (Step 4), synthetic values of time-dependent potential risk ($\tilde{R}_c^t$) are generated based on the random number and cumulative relative frequency (Step 5).

2.2.3. Probability distribution fitting

By assuming that the population of generated data has a certain probability distribution, it is possible to fit the data to the probability distribution. In engineering, the same problem occurs in the rainfall analysis or the estimation of the design wave height [36]. There are various types of probability distributions, and after fitting the data to a distribution, the goodness of the fit must be tested.

Once the optimal probability distribution is selected, the cumulative probability $F(\tilde{R}_c^t)$ can be calculated, which can be converted into the exceedance probability as follows:

$$Q(\tilde{R}_c^t) = 1 - F(\tilde{R}_c^t) \tag{6}$$

where Q denotes the exceedance probability which is the probability of the occurrence of a potential risk over certain level [36]. The return period is the inverse of the exceedance probability:

$$T = \frac{1}{Q(\tilde{R}_c^t)} \tag{7}$$

where T denotes the return period (year) [36].

3. Study area

The Study area is the Nakdong River Basin, South Korea ((a) and (b) of Fig. 3). The Nakdong River is one of the major four rivers in South Korea, and its length is about 400.7 km. The upstream region of the Nakdong River is densely populated with numerous factories, while the downstream area has Busan Metropolitan City and industrial complexes along the coastal line. Agriculture is also developed on alluvial plain downstream. Water quality of the Nakdong River as the basis of economic growth was deteriorated and water pollution incidents increased. There were 71 cases of water pollution incidents from 2008 to 2012 [37]. The situation becomes worse. According to the Ministry of the Environment, there were 50% more water pollution incidents during 2010–2012 than the accidents in the period of 2008–2009 [38]. These are evidences which threatened the Nakdong River as a source of water supply.

A drinking water supply facility located in Samrak Park downstream of the Nakdong River ((c) of Fig. 3) is being developed as a means to assist in the drinking water supply for the surrounding cities. In case of Busan as a Metropolitan City including Buk-gu, Gangseo-gu, and Sasang-gu, the population is over 3.6 million. Yangsan city has been industrialized as a satellite city of Busan city after 1970s, and its population has been increased as the city developed. The large population of the surrounding cities demands steady supply of high quality drinking water.

The study area includes 42 cities (Fig. 4). Population and total area of these cities are over 7.7 million–23.7 billion km^2. The chemicals for the analysis are the top-10 chemicals in terms of the total emissions (water, soil, air). They are listed in Table 2 along with the toxicity values.

4. Results and discussion

4.1. Deterministic potential risk

Of the 42 cities, 24 were analyzed using PRTR data from a period of 2001–2012 and the remaining 18 cities had a zero value of the total transfers. Meanwhile, the results of the individual potential risk (R_{qc}) showed that the southern and central cities of the Nakdong River Basin had high values (Fig. 5). In case of the

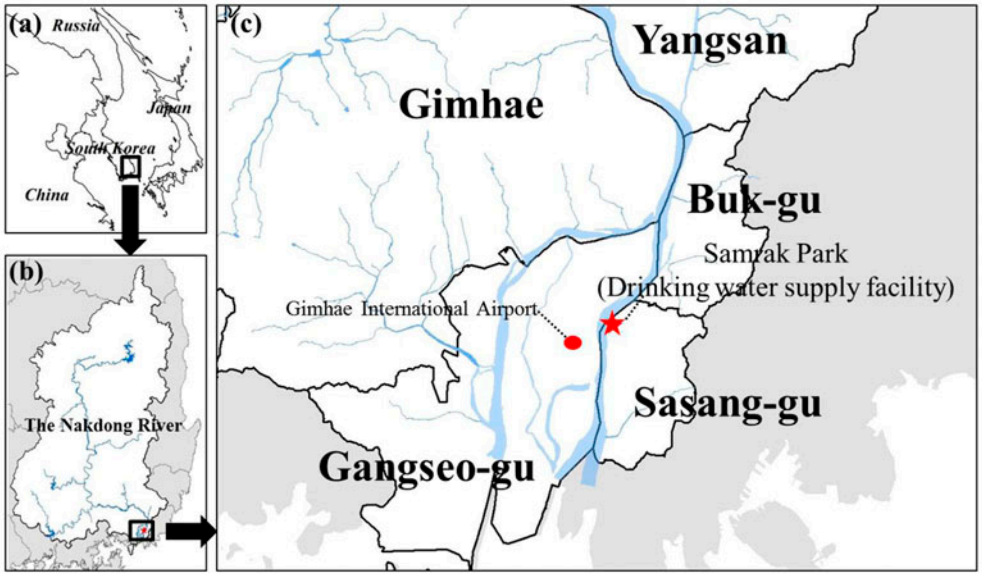

Fig. 3. The location of study area (a, b) and the drinking water supply facility (c).

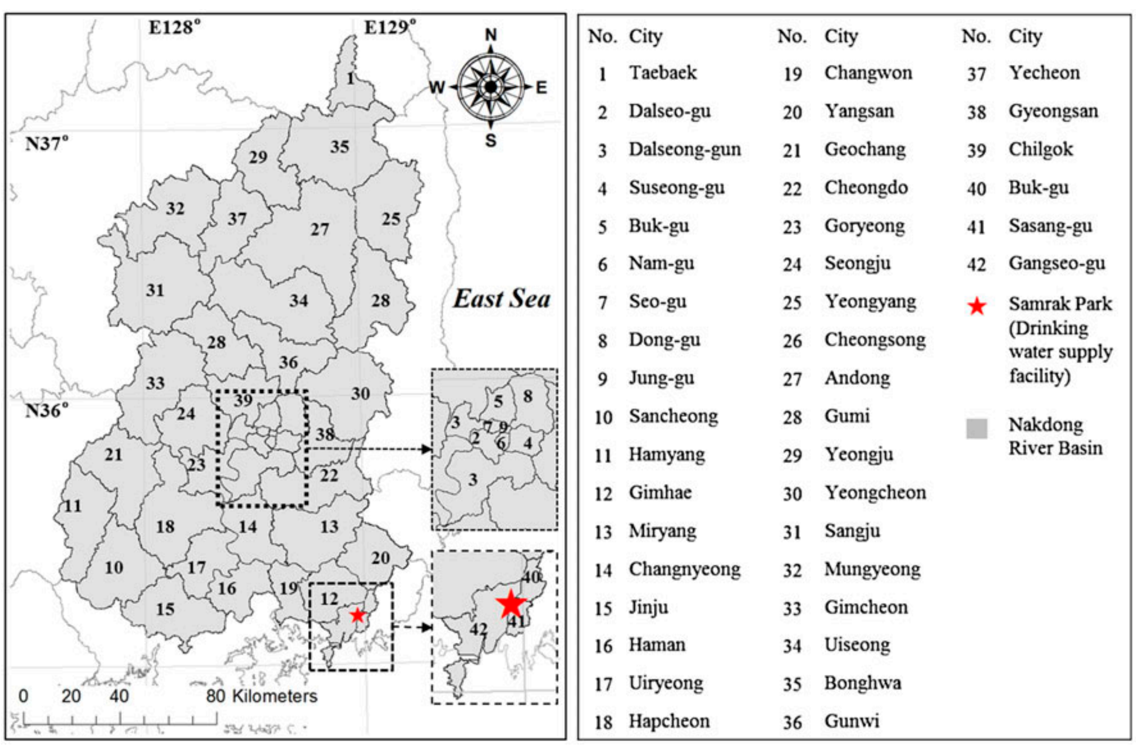

Fig. 4. Numbering for cities within study area.

southern area, both total transfer and D_c were high. The highest values of R_{qc} of methyl alcohol and dichloromethane were recorded in Gimhae (city 12) and Haman (city 16). Xylene and ethylbenzene had the highest R_{qc} in Changwon (city 19). Yangsan (city 20) was the top-ranked city in ethyl acetate, methyl ethyl ketone, and isopropanol. Gangseo-gu (city 42) ranked first in toluene and N,N-Dimethylformamide.

In spite of relatively low values of D_c, cities located in the central region of the Nakdong River Basin had

Table 2
Toxicity of top-10 chemicals [39]

CAS no.	Chemicals	Molecular formula	Toxicity[a]	CAS no.	Chemicals	Molecular formula	Toxicity
1330-20-7	Xylene	C_8H_{10}	2	78-93-3	Methylethylketone	$CH_3COC_2H_5$	1
108-88-3	Toluene	C_7H_8	2	67-63-0	Isopropanol	C_3H_8O	1
75-09-2	Dichloromethane	CH_2Cl_2	2	100-41-4	Ethylbenzene	$C_6H_5C_2H_5$	2
67-56-1	Methyl alcohol	CH_3OH	1	68-12-2	N,N-Dimethylformamide	$HCON(CH_3)_2$	1
141-78-6	Ethyl acetate	$C_4H_8O_2$	1	79-01-6	Trichloroethylene	C_2HCl_3	2

[a]Index about health by National Fire Protection Association. Low (0) < toxicity < high (4).

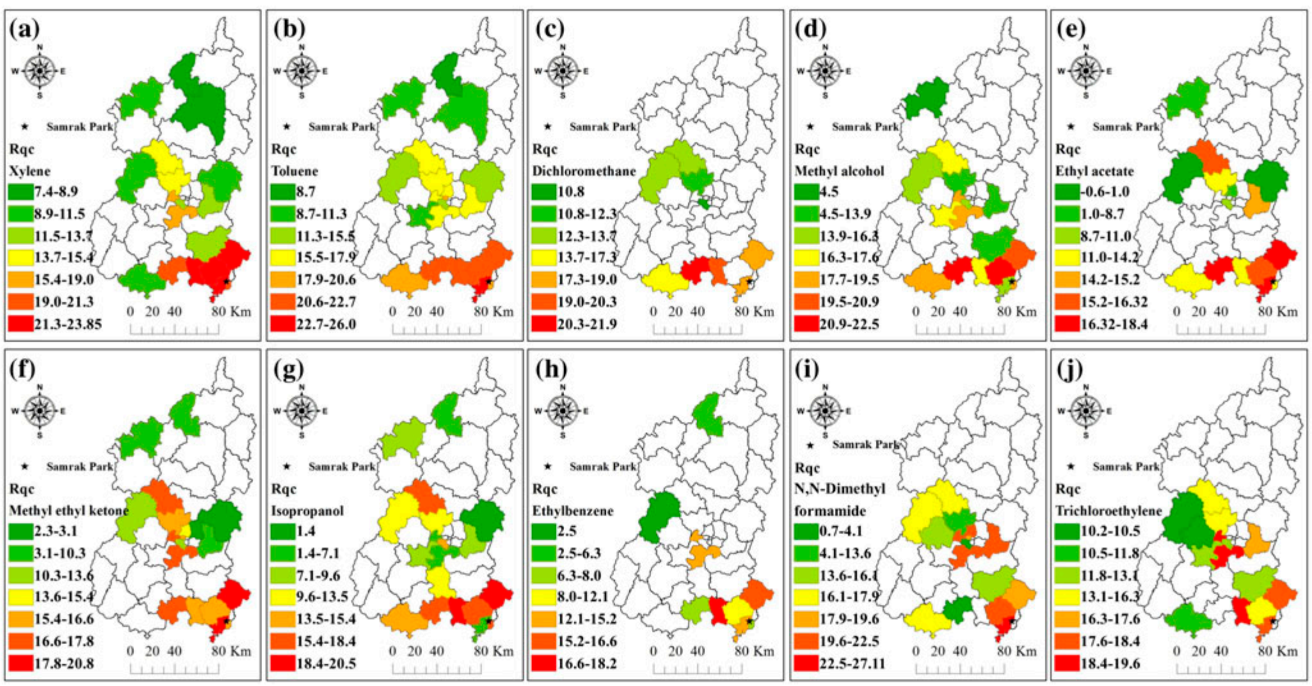

Fig. 5. Individual potential risk (R_{qc}) (deterministic approach).

high values of R_{qc} for some chemicals. City 3 was the top ranked in trichloroethylene, and R_{qc} of cities 5, 28, and 38 were relatively high in N,N-Dimethylformamide and isopropanol.

A map of the comprehensive potential risk (R_c) based on Eq. (4) is shown in Fig. 6. R_c was high mostly near the south coast. City 20, 42, and 19 had the highest values of R_c, while city 12, 16, and 28 were in the high rank. Note that city 28 (Gumi) is located only in the middle of the Nakdong River Basin, and other cities are near the coastline. This implies that these cities can seriously affect the drinking water supply facility in terms of the distance, the total transfer and the toxicity.

4.2. Stochastic potential risk

The time-dependent potential risk (R_c^t) of 12 years can be obtained using Eq. (5). As an example, the values of R_c^t for city 33 are listed in Table 3. Even though R_c^t is generally on an uptrend, drinking water supply of city 33 is less risky than other cities. When taking into consideration that all values of R_c^t in the Nakdong River Basin are between 0.419 and 20.3, R_c^t values of city 33 are small.

Since data for 12 years may not be insufficient for probabilistic analysis, the synthetic data generation of R_c^t was implemented according to Fig. 2. Consequently, synthetic data ($\tilde{R}_c^t$) over 30-year period are

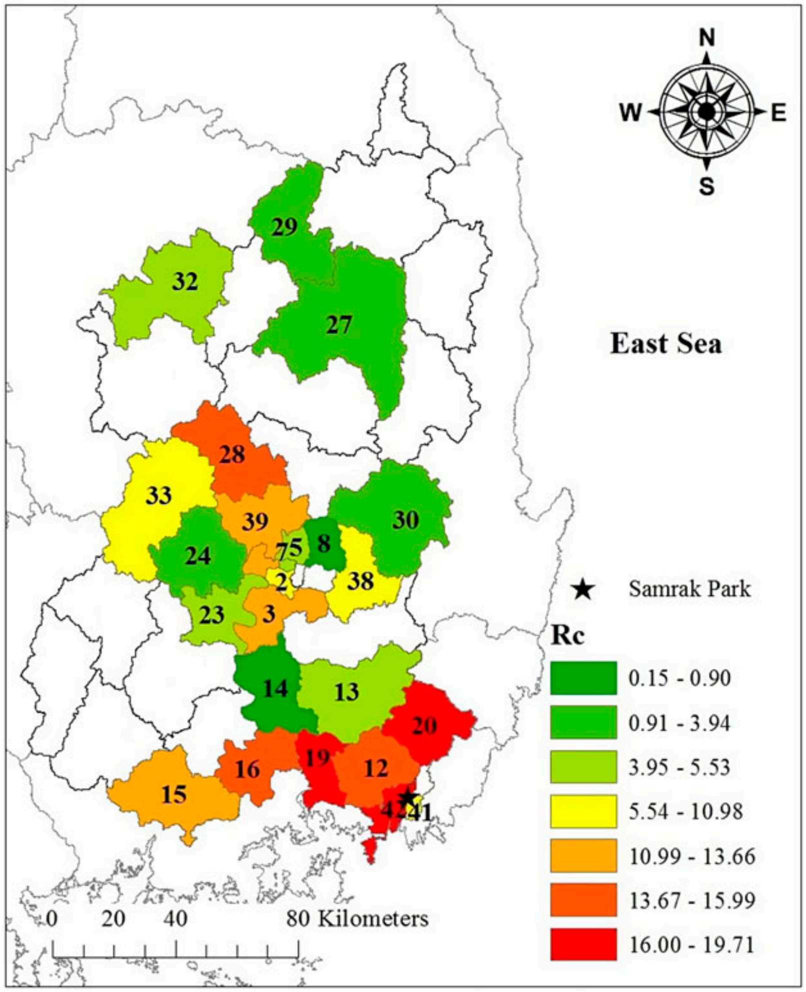

Fig. 6. Ranges of comprehensive potential risk (R_c) and cities numbered (deterministic approach).

Table 3
Time-dependent potential risk (R_c^t) in city no. 33

Year	2001	2002	2003	2004	2005	2006
R_c^t	5.28	4.35	4.90	7.23	7.22	9.73
Year	2007	2008	2009	2010	2011	2012
R_c^t	7.96	7.65	8.04	6.93	8.03	8.35

generated (Table 4). The range of $\tilde{R}_c^t$ from 5.05 to 9.90 is slightly larger than the range of R_c^t since class intervals in the frequency table were made sufficiently large to contain all of R_c^t.

After the data generation process was applied to all cities, suitable probability density functions were sought. FARD 2006 software [40] was used for parameter estimation and the goodness-of-fit. Table 5 lists the results of the parameter estimation and goodness-of-fit tests. Cities 2, 5, 7, 12, 13, 23, 29, 32, 38, and 42 passed all four goodness-of-fit tests. Other cities passed at least one test. Only one city (No. 20) did not pass any of the goodness of fit tests. The validity check, however, showed that some of the probability distributions could be fitted for this city, even though the accuracy was insufficient. Overall, the Weibull distribution (2-parameter) was the most frequently chosen probability density function, while the normal distribution and Gumbel distribution followed.

Once the probability distribution is determined, the exceedance probability can be calculated using Eq. (6). The $\tilde{R}_c^t - Q(\tilde{R}_c^t)$ curves for the top-10 cities are shown in Fig. 7. At a certain Q, the more a curve is drawn to the right the higher probability of $\tilde{R}_c^t$ is obtained. In other words, a curve on the right is riskier than the one on the left. For the top-ranked city 20 (Yangsan), for instance, when the potential risk $\tilde{R}_c^t = 10$, the exceedance probability corresponds to one. It means an event with a potential risk greater

Table 4
Synthetically generated data ($\tilde{R}_c^t$) for city no. 33 by stochastic approach

Year	1	2	3	4	5	6	7	8	9	10
$\tilde{R}_c^t$	7.75	8.29	9.90	8.29	7.21	7.21	5.05	8.29	8.29	7.21
Year	11	12	13	14	15	16	17	18	19	20
$\tilde{R}_c^t$	5.05	9.90	7.21	5.05	7.75	7.75	8.29	8.29	8.29	7.21
Year	21	22	23	24	25	26	27	28	29	30
$\tilde{R}_c^t$	7.21	7.21	5.05	8.29	7.21	7.75	8.29	7.75	6.67	7.21

Table 5
Determination of probability distribution

		Parameter			Goodness-of-fit[a]			
City no.	Probability distribution[b]	Location	Scale	Shape	χ^2	K–S	CVM	PPCC
2	WBU2	–	8.17	4.082	o	o	o	o
3	NOR	10.946	3.157	–	x	x	o	x
5	GUM	4.44	0.249	–	o	o	o	o
7	GUM	4.198	0.561	–	o	o	o	o
12	WBU2	–	12.647	5.109	o	o	o	o
13	WBU2	–	1.876	1.002	o	o	o	o
15	WBU2	–	7.1	2.776	x	o	o	o
16	NOR	13.564	2.304	–	x	x	o	x
19	WBU2	–	16.919	7.425	x	o	o	o
20	NOR	18.083	2.155	–	x	x	x	x
23	NOR	2.526	0.729	–	o	o	o	o
24	NOR	0.464	0.606	–	x	x	o	x
27	NOR	1.116	1.184	–	x	o	o	x
28	WBU2	–	13.875	11.636	o	x	x	x
29	WBU2	–	2.976	1.53	o	o	o	o
30	NOR	2.155	1.552	–	o	o	o	x
32	GUM	1.523	1.367	–	o	o	o	o
33	WBU2	–	7.986	7.264	x	o	o	o
38	WBU2	–	8.769	4.078	o	o	o	o
39	NOR	7.67	4.149	–	x	x	o	x
41	WBU2	–	10.103	17.633	x	o	o	o
42	WBU2	–	16.62	4.364	o	o	o	o

[a]Pass (o) or not (x). χ^2: Chi-square Test, K–S, Kolmogrov–Smirnov Test, CVM, Cramer von Mises Test, PPCC, Probability Plot Correlation Coefficient Test.
[b]GUM: Gumbel distribution, NOR, normal distribution, WBU2, Weibull distribution by two variables.

than 10 occurs with a probability of 100%. If a potential risk $\tilde{R}_c^t$ is 24, the exceedance probability becomes 0.0113, indicating that an event with a potential risk greater than 24 happens with a probability of 1.13%.

Table 6 lists the comparison of the top-10 riskiest cities evaluated by two different approaches. There are slight differences in the rank while some cities do not even appear on the list of the other approach.

The return period of $\tilde{R}_c^t$ can be determined by Eq. (7). To illustrate the idea, city no. 20 is selected because it turned out to pose the highest risk to the drinking water supply facility of our interest. 10-, 50-, and 100-year return periods were considered as in many engineering applications. The return period of 10-, 50-, and 100-years corresponds to 0.1, 0.02, and 0.01 of $Q(\tilde{R}_c^t)$, and $\tilde{R}_c^t$ can be read from Fig. 7. Alternatively, values of $F(\tilde{R}_c^t)$ from Eq. (6) can be used to find the $\tilde{R}_c^t$ values using the normal distribution with a location parameter (mean) 18.083, and a scale parameter (standard deviation) 2.155. Table 7 lists some $\tilde{R}_c^t$ values for representative return periods for City 20.

Ten-year return period 20.8447 in Table 7 is much higher than the potential risk values of other cities. Only three cities (city no. 19, 20, and 42) have effective

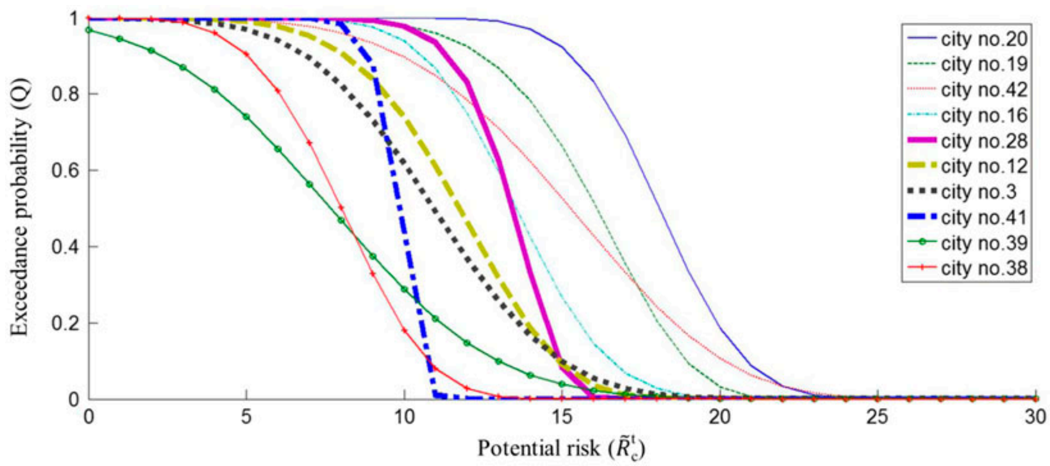

Fig. 7. Exceedance probability of top-10 cities.

Table 6
Comparison of ranks: Stochastic vs. deterministic approach

Rank	Deterministic	Stochastic
1	Yangsan (20)	Yangsan (20)
2	Gangseo-gu (42)	Changwon (19)
3	Changwon (19)	Gangseo-gu (42)
4	Gimhae (12)	Haman (16)
5	Haman (16)	Gumi (28)
6	Gumi (28)	Gimhae (12)
7	Dalseong-gun (3)	Dalseong-gun (3)
8	Chilgok (39)	Chilgok (41)
9	Jinju (15)	Sasangi-gu (39)
10	Dalseo-gu (2)	Gyeongsan (38)

Table 7
The prediction of potential risk of city no. 20 for some return periods

T_R (yr)	10	50	100
$\tilde{R}_c^t$	20.8447	22.5088	23.0963

exceedance probability at this value. These three cities need appropriate actions to reduce potential risk on the target facility. The appropriate actions do not mean quantitative decrease of the transfers. The improvement of subjective factors such as proficiency and fatigue on work is more important. The application of HACCP enables this improvement. HACCP includes physical and systematic improvement of facility, and this capacity of workers and managers [7]. This paper is in the first step of HACCP seven principles. The constant research of HACCP will increase safety of drinking water.

5. Conclusion

The existing production facilities for drinking water have relied on end-product testing. As a result, response to a sudden water incident will be late or insufficient. There is a global trend of introducing risk analysis and management systems such as HACCP to overcome this problem. Here, we investigated the potential risk to a drinking water supply facility posed by chemicals using PRTR data to effectively manage and consequently prevent water-related accidents. The potential risk was defined as a function of the total transfers of chemicals, distance between a facility and city, and toxicity of the chemicals. Deterministic and stochastic approaches were proposed to assess the potential risk for a drinking water supply facility where aquifer storage transfer and recovery is implemented in the downstream of a highly industrialized basin.

The deterministic approach made it possible to find the riskiest city to the drinking water supply facility by calculating the comprehensive potential risk (R_c) from chemicals. For probabilistic analysis, synthetic potential risk ($\tilde{R}_c^t$) was computed using a stochastic method and the riskiest city was found using the exceedance probability curve for $\tilde{R}_c^t$. When two approaches were compared, the riskiest city to the facility was the same. However, the two approaches had a little difference. It is concluded that PRTR data are useful in assessing the potential risk due to the chemicals transferred in a watershed, and the developed method could be useful to identify the source of the risk and to reduce it through the preventive management of potentially dangerous chemicals in a basin.

Even though the factors of the potential risk function are insufficient to express chemical accidents, the potential risk function is valuable because the result gives a solution to determine effects of chemicals on a drinking water supply facility and decide priority over management to reduce potential risk. Potential risk is not an absolute value but a relative value between cities. The relative comparison of these values gives us valuable information in terms of potential.

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Symbols and abbreviations

c — city
d — distance between a city and the target facility
d_c — distance between the specific city and the location of interest
h_q — toxicity of a chemical
m — the number of chemicals
n — the number of years
q — chemical substance
t — time (year)
x_{qc}^t — total transfers (kg/yr)
D_c — relative distance
R_c — comprehensive potential risk of a specific city
R_{qc} — individual potential risk for each chemical
R_c^t — time-dependent potential risk
$\tilde{R}_c^t$ — synthetic values of time-dependent potential risk

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