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Health Risk Assessment for Sewer Workers using Bayesian Belief Networks

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***Abstract*—**The sanitary sewerage connection rate becomes an important indicator of advanced cities. Following the construction of sanitary sewerages, the maintenance and management systems are required for keeping pipelines and facilities functioning well. These maintenance tasks often require sewer workers to enter the manholes and the pipelines, which are confined spaces short of natural ventilation and full of hazardous substances. Working in sewers could be easily exposed to a risk of adverse health effects. This paper proposes the use of Bayesian belief networks (BBN) as a higher level of noncarcinogenic health risk assessment of sewer workers. On the basis of the epidemiological studies, the actual hospital attendance records and expert experiences, the BBN is capable of capturing the probabilistic relationships between the hazardous substances in sewers and their adverse health effects, and accordingly inferring the morbidity and mortality of the adverse health effects. The provision of the morbidity and mortality rates of the related diseases is more informative and can alleviate the drawbacks of conventional methods.

***Keywords*—**Bayesian belief networks, sanitary sewerage, health risk assessment, hazard quotient, target organ-specific hazard index.

I. Introduction

A SANITARY sewerage is a separate underground carriage system specifically for transporting sewage from houses and commercial buildings to treatment or disposal. It is widely recognized that the sanitary sewerage connection rate becomes an important indicator of advanced cities. Although the sewerage connection rates of the major cities in Taiwan still lag far behind the cities in other developed countries, they are progressing rapidly. Taipei City, a metropolis in northern Taiwan, reached the sewerage connection rate of 100% in 2010; Kaohsiung City, a metropolis in the south, the sewerage connection rate was enhanced to 60.89% in 2010 from 6.5% of 1989.

Following the construction of sanitary sewerages, the maintenance and management systems are demanded in order to keep pipelines and facilities functioning well. There are three primary tasks in the maintenance and management systems: inspecting pipelines and facilities, investigating the integrity of the sewerage and dredging obstructions in pipelines. These maintenance tasks often require sewer workers to enter the manholes and the pipelines. However, the underground sewers are confined spaces short of natural ventilation and the sewage generates hazardous substances such as toluene, trichloroethylene, trichloromethane, tetrachloroethylene, carbon monoxide, xylene and hydrogen sulfide. Working in sewers could easily lead to a risk of adverse health effects. Therefore some researchers were devoted themselves to health risk assessment of sewer workers [1].

Health risk assessment (HRA) is the process for estimating the nature and probability of adverse health effects in humans who may be exposed to hazardous substances. The risk characterization of noncarcinogenic substances can be evaluated by the hazard quotient (HQ), the ratio of the intake of a hazardous substance to its reference dose. Multiple hazardous substances may affect the same organ (or organ system) causing joint effect; and hence, the target organ-specific hazard index (TOSHI) sums the HQ scores of multiple substances that have joint effect on a specific organ [2]. Several problems arise from using HQ and TOSHI. First, the HQ score for non-critical organs is overestimated because it is derived from the reference dose of the most critical organ with the lowest no-observed-adverse-effect level (NOAEL). Second, reference doses are usually derived from animal studies and it is difficult to precisely manage the uncertainty in animal-to-human extrapolations. Third, summing all HQ scores as a single score, TOSHI may be inappropriate for joint effect on a specific organ because it is valid only if a common toxic mechanism exists. Fourth, it is unlikely for a TOSHI score below 1.0 to result in adverse noncancerous health effects over a lifetime of exposure; whereas a score above 1.0 does not necessarily suggest a likelihood of adverse effects [2]. Compared with the probability, risk characterization of the TOSHI is less clear or precise.

To solve these problems, this paper proposes the use of Bayesian belief networks (BBN) [3] as a higher level of HRA, denoted as the BBN-HRA, for noncarcinogenic HRA of sewer workers. The BBN is a directed acyclic graph with nodes denoting a set of random variables as nodes and arrows indicating their probabilistic cause-effect dependencies. On the basis of the epidemiological studies, the actual hospital attendance records and expert experiences, the BBN is capable of capturing the probabilistic relationships between the hazardous substances in sewers and their (critical and non-critical) adverse health effects, and accordingly inferring the morbidity and mortality of the adverse health effects if pollution concentrations are given. The provision of the morbidity and mortality rates of the related diseases is more informative and can alleviate the uncertainty of the TOSHI.

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II. MATERIAL AND METHODS

A. Study Area

Kaohsiung City is a coastal city with a population of about 150 million and becomes the transportation and commercial center in southern Taiwan. Besides, five industrial zones, two export processing zones, and other several important factories such as Taiwan Steel Corporation, Taiwan International Shipbuilding Corporation and Chinese Petroleum Corporation etc. turn Kaohsiung City into an industrial center as well. However, accompanying with the rapid development of Kaohsiung City, environmental pollution seriously affects the life quality of the residents. Before 1989, the domestic sewage and industrial wastewater directly or indirectly discharged into the river and threaten human and environmental health because the sewage connection rate in this city was only 6.5%. Therefore, at that time the Kaohsiung City Government launched the Kaohsiung City sewage system, which is shown in Fig. 1. The sewage connection rate in this city was upgraded to 60.89% in the end of 2010.

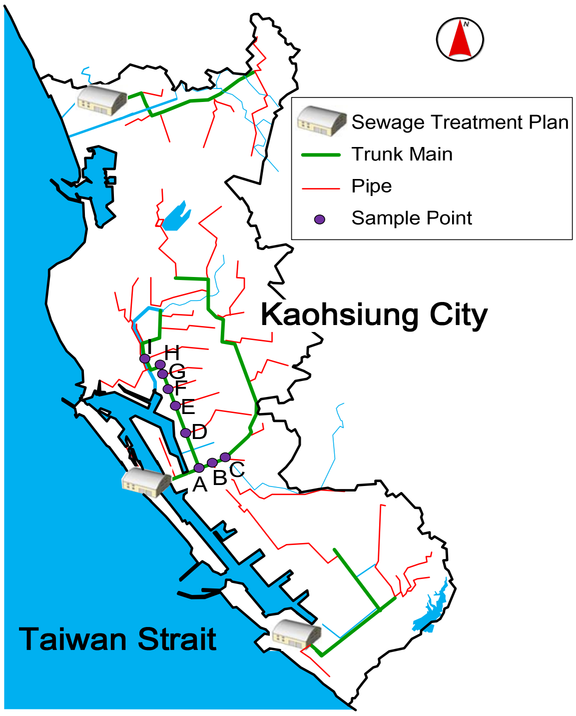

Fig. 1 Kaohsiung City sanitary sewerage and nine sample points [4]

Lin [4] analyzed the hazardous substances in the Kaohsiung City sanitary sewerage and took nine sampling points (from A to I, see Fig. 1) spreading over industrial, commercial and residential districts. He considered two situations for each sample point: before ventilation and ventilation for 15 minutes. To illustrate our approach, this paper only adopts three sampling points (A, B and C) where the concentrations of the hazardous substances are listed in TABLE I. Sampling point A lies in an interception station, in which the concentration of tetrachloroethylene is relatively high but still lower than the standard value. Sampling points B and C are situated in a residential district but close to an export processing zone; therefore, the concentrations in trichloromethane and tetrachloroethylene are extraordinary high. After 15-minute ventilation, the concentrations of hazardous substances in the three sample points are dropped dramatically, as shown in table I.

TABLE I
MEASUREMENTS OF HAZARDOUS SUBSTANCES OF CASE STUDY

Pollutants (ppm)	Standard (8-hour mean)	Before ventilation			Ventilation for 15 minutes		
		A	B	C	A	B	C
Toluene	100	5.4	28.8	ND	0.0026	0.0138	ND
Trichloroethylene	50	5.2	ND	ND	0.0025	ND	ND
Trichloromethane	10	4.5	327.3	131.3	0.0022	0.1572	0.0630
Tetrachloroethylene	50	21.0	223.9	103.3	0.0101	0.1755	0.0496
Carbon monoxide	35	0.5	85.4	84.4	0.0002	0.0410	0.0405
Xylene	100	10.7	12.3	7.5	0.0051	0.0059	0.0036
Hydrogen sulfide	10	ND	4.1	ND	ND	0.0020	ND

A. *Identification of Key Factors and Their Causal Relationships*

The primary hazardous substances which can cause non-carcinogenic effects in sanitary sewerage are toluene, trichloroethylene, trichloromethane, tetrachloroethylene, carbon monoxide, xylene and hydrogen sulfide. According to related research [4], the non-carcinogenic effects of the seven hazardous substances are summarized below. Toluene can lead to central nervous system diseases, dermatitis, kidney diseases and cardiovascular diseases; trichloroethylene induces dermatitis, liver complaint and cardiovascular diseases; trichloromethane can cause central nervous system diseases, kidney diseases and liver complaint; tetrachloroethylene induces kidney diseases and liver complaint; carbon monoxide can lead to cardiovascular diseases; xylene can cause cardiovascular diseases and respiratory system diseases; and exposure to hydrogen sulfide can result in respiratory system diseases. These hazardous substances and the induced diseases are the nodes in the BBN, as shown in Fig. 2.

B. *Development of Cpts*

Discretization of continuous variables. The seven hazardous substances are essentially continuous variables. However, most BBN software cannot deal with continuous variables so that the solution is to discretize variables and build models over discrete domains. That is, the values for each node in the BBN should be categorized into the finite number of levels. How to discretize the variables is more difficult a question because the number and division points of the levels can make a notable difference in the complexity and precision of the resulting model. The bigger the number of levels, the more complex and precise the model is but more data are needed for it to construct probabilistic dependencies. In practice, 2-10 levels are reported in ecological studies [5]. In this research, the concentrations of the seven hazardous substances are divided into five levels.

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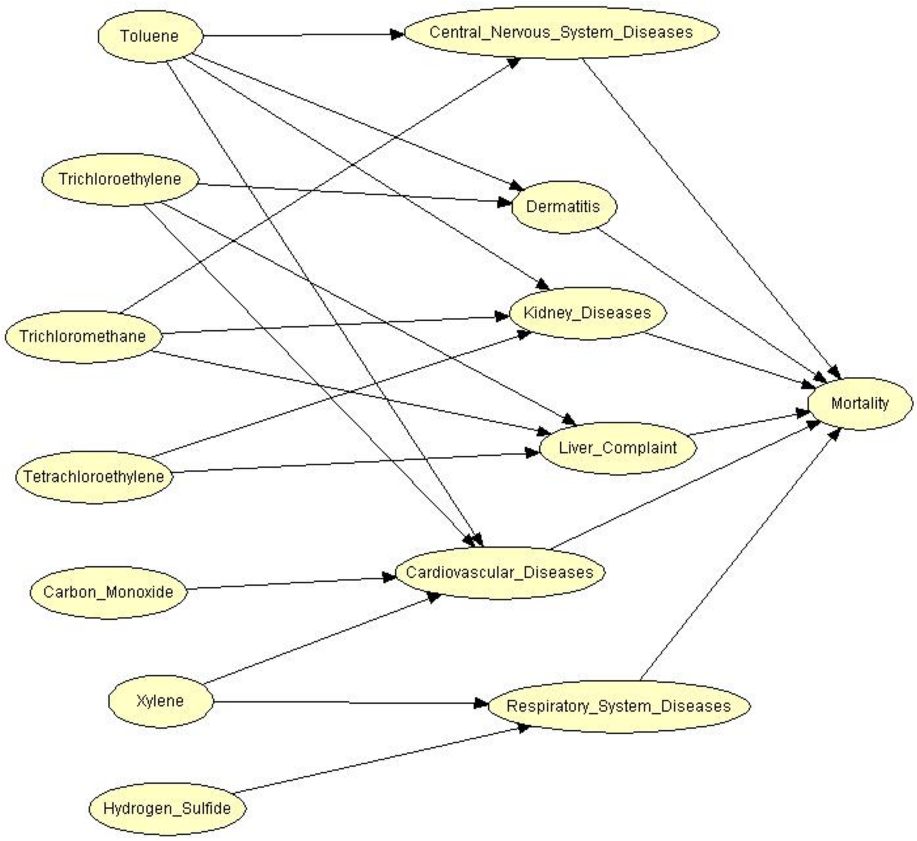

Fig. 2 BBN-HRA structure for hazardous substances in sanitary sewerage

C. Development of conditional probabilities

The difficulty of defining conditional probabilities arises when the relevant literature on probabilistic relationships between causes and effects is insufficient. In such situation, experienced experts are usually able to use subjective judgment to assist in this task. In this paper, the determination of conditional probabilities suffers this difficulty due to the lack of sufficient information and therefore subjective judgment is exploited. In Taiwan, the morbidities of central nervous system diseases, dermatitis, kidney diseases, liver complaint, cardiovascular diseases, respiratory system diseases and mortality for 20-59 year old males are 11.36%, 23.27%, 1.11%, 2.36%, 3.57%, 4.67% and 1.07% respectively, which are baseline situations. Subsequently, experts use their expertise to determine the morbidities and mortality for the worst situations. Therefore, morbidities of central nervous system diseases, dermatitis, kidney diseases, liver complaint, cardiovascular diseases, respiratory system diseases and mortality for the worst situations are 70.8%, 66.4%, 27.8%, 42.4%, 35.7%, 46.7% and between baseline and worst situations are calculated assigned on an interpolative basis.

III. Results and Discussion

A. HRA through BBN

The information of the three sample points is inputted into the BBN-HRA model. For example, the results of sampling point B before ventilation are estimated as follows: central nervous system diseases of 41.10%, dermatitis of 23.27%, kidney diseases of 14.47%, liver complaint of 22.39%, cardiovascular diseases of 5.58%, respiratory system diseases of 4.67% and mortality of 1.90%, as demonstrated in Fig. 3. After 15-minute ventilation, the morbidity and mortality rates in this sample point will decrease to the baseline conditions; that is, central nervous system diseases of 11.36%, dermatitis of 23.27%, kidney diseases of 1.11%, liver complaint of 2.36%, cardiovascular diseases of 3.57%, respiratory system diseases of 4.67% and mortality of 1.07%. The entire outcomes of the morbidity and mortality rates for the three sample points are listed from the 10th to 16th rows of TABLE II. In these rows, the results higher than the standard values are denoted by single-underlines; obviously, they occur only in sample points B and C before ventilation, including central nervous system diseases, kidney diseases, liver complaint and cardiovascular diseases.

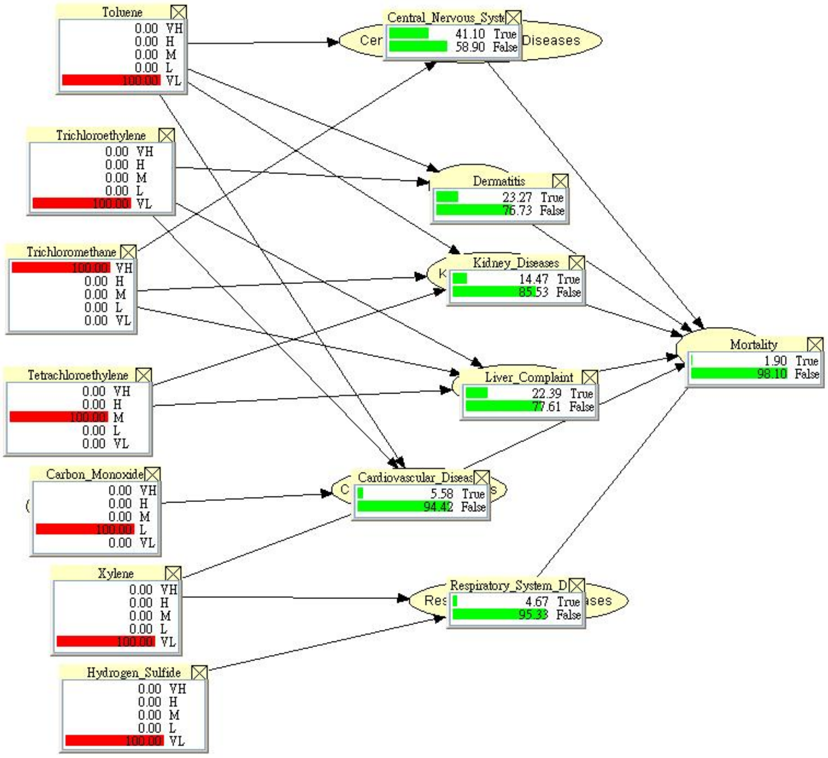

Fig. 3 BBN-HRA results for sampling point B

TABLE II
HRA analysis of case study

		Standard (8-hour mean)	Before ventilation			Ventilation for 15 minutes		
			A	B	C	A	B	C
BBN-HRA	Central nervous system diseases	11.36%	11.36%	41.10%	18.80%	11.36%	11.36%	11.36%
	Dermatitis	23.27%	23.27%	23.27%	23.27%	23.27%	23.27%	23.27%
	Kidney diseases	1.11%	1.11%	14.47%	5.56%	1.11%	1.11%	1.11%
	Liver complaint	2.36%	2.36%	22.39%	9.04%	2.36%	2.36%	2.36%
	Cardiovascular diseases	3.57%	3.57%	5.58%	5.58%	3.57%	3.57%	3.57%
	Respiratory system diseases	4.67%	4.67%	4.67%	4.67%	4.67%	4.67%	4.67%
	Mortality	1.07%	1.07%	1.90%	1.42%	1.07%	1.07%	1.07%
HQ	Toluene	1.00	0.05	0.29	0.00	0.00	0.00	0.00
	Trichloroethylene	1.00	0.10	0.00	0.00	0.00	0.00	0.00
	Trichloromethane	1.00	0.45	32.73	13.13	0.00	0.02	0.01
	Tetrachloroethylene	1.00	0.42	4.48	2.07	0.00	0.00	0.00
	Carbon monoxide	1.00	0.01	2.44	2.41	0.00	0.00	0.00
	Xylene	1.00	0.01	0.01	0.01	0.00	0.00	0.00
	Hydrogen sulfide	1.00	0.00	0.41	0.00	0.00	0.00	0.00
TOSHI	Central nervous system diseases	1.00	0.50	33.02	13.13	0.00	0.02	0.01
	Dermatitis	1.00	0.16	0.29	0.00	0.00	0.00	0.00
	Kidney diseases	1.00	0.92	37.50	15.20	0.00	0.02	0.01
	Liver complaint	1.00	0.97	37.21	15.20	0.00	0.02	0.01
	Cardiovascular diseases	1.00	0.18	2.74	2.42	0.00	0.00	0.00
	Respiratory system diseases	1.00	0.01	0.42	0.01	0.00	0.00	0.00

In risk characterization of noncarcinogenic substances, the HRA can be evaluated by the hazard quotient (HQ), the ratio of the intake of a hazardous substance to its reference dose. Multiple hazardous substances may affect the same organ (or organ system) causing joint effect; and hence, the target organ-specific hazard index (TOSHI) sums the HQ scores of multiple substances that have joint effect on a specific organ [2]. In this case study, Fig. 3 shows that the target organ systems of toluene are cardiovascular and respiratory systems; trichloroethylene: dermatitis, liver complaint and cardiovascular system; trichloromethane: central nervous system, kidney and liver; tetrachloroethylene: kidney and liver; carbon monoxide: cardiovascular system; xylene; cardiovascular system and respiratory system; hydrogen sulfide: respiratory system. On the basis of the toluene, trichloroethylene, trichloromethane, tetrachloroethylene, carbon monoxide, xylene and hydrogen sulfide concentrations described in Section 3.1, their HQ and TOSHI scores can be computed, as shown from the 17th to the 29st rows of TABLE II. The HQ and TOSHI scores reveal that trichloromethane, tetrachloroethylene and carbon monoxide in sample points B and C before ventilation are possible to cause central nervous system diseases, kidney diseases, liver complaint and cardiovascular diseases adverse noncancerous effects, the rest hazardous substances will not induce any adverse noncancerous effect. The comparisons between the TOSHI and the BBN-HRA are discussed in the following.

The HQ score for non-critical organs is overestimated because it is derived from the reference dose of the most critical organ with the lowest no-observed-adverse-effect level (NOAEL). The same HQ score is assigned to all (critical or non-critical) organs due to the general absence of organ-specific reference doses. In TABLE II, the HQ score of trichoromethane in sample point B before ventilation is transferred to central nervous system, kidney and liver simultaneously although it is known that the critical effects occur in central nervous system. On the other hand, the BBN-HRA is developed according to epidemiological studies, the actual hospital attendance records and expert experiences in order to elaborate the respective morbidity and mortality rates of all the related diseases under certain pollution concentrations. The results of BBN-HRA in sample point B before ventilation in TABLE II reveal that the critical effect of trichoromethane is central nervous system diseases while its non-critical effects are kidney and liver diseases.

The above additive assumption in TOSHI enables that it is unlikely for a TOSHI score below 1.0 to result in adverse noncancerous health effects over a lifetime of exposure; whereas a score above 1.0 does not necessarily suggest a likelihood of adverse effects [2]. In TABLE II, the TOSHI score of cardiovascular system in sample point B before ventilation is 2.74, which is difficult to decide whether it will cause illness or not. However, through BBN-HRA calculation an increase of cardiovascular disease from 3.57% to 5.58% is more informative.

IV. Conclusions

This study proposed a BBN-HRA model for sewer workers with features including the representation of probabilistic relationships between hazardous substances and adverse human effects through the graph structures of the BBN, the construction of dose-response relationships by CPTs of the BBN, and the capability of predicting morbidity and mortality rates of the related diseases with the inference mechanism of the BBN. This BBN-HRA model can address the some problems of applying the TOSHI to HRA. Its graph structure can pinpoint the relationships between hazardous substances and the induced diseases. Moreover, on the basis of epidemiological studies, actual hospital attendance records and expert experiences, the BBN-HRA can specifically identify the probability of each induced disease under certain concentration of a hazardous substance, which can overcome the problem of overestimation of HQ for non-critical organs. The BBN-HRA model provides more concrete information on the morbidity and mortality rates of all the related diseases, thus reducing the uncertainty in the TOSHI.

The BBN-HRA model was demonstrated by a practical case study, which shows that with no ventilation in sewers, the probabilities for the workers in the worst situation (sample point B) to contract central nervous system diseases, dermatitis, kidney diseases, liver complaint, cardiovascular diseases, respiratory system diseases and mortality were be 41.10%, 23.27%, 14.47%, 22.39%, 5.58%, 4.67% and 1.90%, respectively. However, a 15-minute ventilation reduced the abovementioned probabilities to the baseline condition; that is, 11.36%, 23.27%, 1.11%, 2.36%, 3.57%, 4.67% and 1.07%, respectively.

We suffered several difficulties in applying the BBN to HRA and they still need further endeavor to solve. The first one was to discretize appropriately the variables because the bigger the number of discretization, the more complex and precise the CPTs are but more data are needed. In this paper, five concentration levels of hazardous substances were adopted but they required more solid study in future research. The second difficulty was to gather sufficient epidemiological studies to avoid subjective judgments. The third difficulty came from insufficient studies on the joint effects of multiple pollutants, which compelled us to use expert experiences in aggregating conditional probabilities. Indeed, the last two difficulties are not due to the model itself, but for the lack of relevant epidemiological studies to support this model. If these difficulties can be overcome, the BBN will be very beneficial in HRA.

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