

Analysis of Surface Water Pollution Accidents in China: Characteristics and Lessons for Risk Management

Hong Yao¹ · Tongzhu Zhang² · Bo Liu¹ · Feng Lu¹ · Shurong Fang¹ · Zhen You¹

Received: 19 December 2014 / Accepted: 23 December 2015 / Published online: 6 January 2016
© Springer Science+Business Media New York 2016

Abstract Understanding historical accidents is important for accident prevention and risk mitigation; however, there are no public databases of pollution accidents in China, and no detailed information regarding such incidents is readily available. Thus, 653 representative cases of surface water pollution accidents in China were identified and described as a function of time, location, materials involved, origin, and causes. The severity and other features of the accidents, frequency and quantities of chemicals involved, frequency and number of people poisoned, frequency and number of people affected, frequency and time for which pollution lasted, and frequency and length of pollution zone were effectively used to value and estimate the accumulated probabilities. The probabilities of occurrences of various types based on origin and causes were also summarized based on these observations. The following conclusions can be drawn from these analyses: (1) There was a high proportion of accidents involving multi-district boundary regions and drinking water crises, indicating that more attention should be paid to environmental risk prevention and the mitigation of such incidents. (2) A high proportion of accidents originated from small-sized chemical plants, indicating that these types of enterprises should be considered during policy making. (3) The most common cause (49.8 % of the total) was intentional acts

(illegal discharge); accordingly, efforts to increase environmental consciousness in China should be enhanced.

Keywords Surface water pollution accidents · Accumulated probability · Historical analysis · China

Introduction

Many environmental problems have accompanied the recent economic growth in China, the most common being accidents leading to surface water pollution (Huang et al. 2013; Xie et al. 2013; Yao et al. 2015). Xue and Zeng (2011) analyzed the distribution of environmental pollution accidents in China and found that surface water pollution accidents accounted for 46.05–63.03 % of the total from 1990 to 2007 (Xue and Zeng 2011). Many of these accidents have had widespread effects and caused great damage to entire communities, including economic loss, environmental deterioration, and negative social impacts. For example, in 2005 over 100 tons of nitrobenzene was released into the Songhua River, forming an 80 km pollution belt that flowed downstream. This accident disrupted the water supply of all 4,000,000 residents of Harbin for 4 days. Moreover, the pollutants eventually flowed into the Heilongjiang River on the Chinese–Russian border, where they threatened the water quality of the city of Khabarovsk, which has more than 600,000 residents (Wo 2009). In another incident, cadmium pollution entered the Beijiing River in December, 2005 (Protection Wogesae 2011) and an algal bloom led to odorous water in Wuxi in May, 2007 (Wo 2007), both of which seriously affected human health and led to large-scale social panic in China. These accidents have resulted in more attention being paid to pollution to prevent surface water accidents.

Tongzhu Zhang and Hong Yao have contributed equally to this work.

✉ Hong Yao
yaohong80@126.com

¹ School of Geography, Nantong University, Nantong 226019, China

² School of Liberal Arts, Nantong University, Nantong 226019, China

The available analyses of water pollution accidents in China have primarily focused on particular aspects, such as toxicological effects (Lei et al. 2008; Liu et al. 2008), methodologies for risk evaluation (Wang and Zhang 2007; Zhang et al. 2006), treatment technologies, and environmental emergency response (Li et al. 2009; Wu et al. 2006). Although these research projects have improved and enhanced our understanding of the nature of problems caused by water pollution accidents, none have provided a sound portrait of surface water accidents in China. Accordingly, additional work is needed to identify characteristics of surface water accidents to provide decision makers with valid, plausible suggestions regarding water environmental risk evaluation, prevention, and mitigation.

Historical accidents lead to new policies and laws on risk mitigation, and many researchers have conducted historical analyses of pollution accidents (Darbra and Casal 2004; Hohenemser et al. 1977, 1983; Kang 1999; Montiel et al. 1996; Uth 1999; Vilchez et al. 1995; Yang et al. 2010). Uth (1999) evaluated major industrial accidents in Germany from 1993 to 1996, conducted rooted causes analysis based on these cases, and demonstrated the importance of maintenance, detailed knowledge of chemical properties, human factors, and the role of safety organization (Uth 1999). Kang (1999) classified 93 major industrial accidents that occurred from 1988 to 1997 according to the type of accident, equipment involved, circumstances, and causes, concluding that some plants lacked well trained operators, safety inspection, and safety consciousness (Kang 1999). Darbra and Casal (2004) analyzed 471 accidents occurring in seaports between the beginning of the twentieth century and October 2002. The trends showed a significant increase in the frequency of accidents over time, and 51 % of the accidents were found to originate from loss of containment (Darbra and Casal 2004). Montiel et al. (1996) grasped the main features of accidents occurring in the transportation and distribution of natural gas by analyzing 185 accidents from the MHIDAS database (Montiel et al. 1996). Vilchez et al. (1995) investigated the contribution of different situations, activities, and equipment to the risks associated with hazardous materials based on 5325 accidents from the database MHIDAS (Vilchez et al. 1995). Yang et al. (2010) analyzed the characteristics of 322 road accidents that occurred during road transportation of hazardous materials in China from 2000 to 2008 (Yang et al. 2010).

Historical analysis is commonly applied to determine the probability distribution of related types of accidents during environmental risk analysis (Darbra and Casal 2004; Oggero et al. 2006; Yang et al. 2010), and information implied in historical accidents is fairly important to probability prediction during environmental risk evaluation. In contrast to other probability analysis methods such as even-

tree analysis (You and Tonon 2012), mathematical modeling of probability (Thodi et al. 2010), and scenario tree modeling (De Vos et al. 2004), historical analysis is more practical and more easily implemented, especially when there are several types of risk sources.

The present study was conducted to (1) collect representative cases of surface water accidents in China; (2) describe the distribution of these water pollution accidents as a function of time, location, and the materials involved; (3) analyze the accumulated probability of quantities of pollutants in these cases, number of people involved, length of pollution belt, and time for which pollution lasted; (4) summarize the probabilities of occurrences of various types of origin and causes.

Materials and Methods

Accident Collection and Screening

There are no public databases of water pollution accidents in China and no detailed statistical information is available. Accordingly, it is very difficult to gather accident information. For this study, preliminary accident information was obtained from the following sources, which complemented and verified each other:

- (1) Chinese Newspaper Database on the CNKI academic knowledge network service platform (CNKI 2012b). The database contains important academic and archival information from 500 domestic newspapers published after 2000. Searches were conducted individually or together using keywords such as river pollution accident, lake pollution accident, tap-water suspension incident, large area of fish deaths, hazardous material leakage, etc.
- (2) *China Environmental News* This newspaper is the only professional national newspaper pertaining to environmental protection and has been published since 1984. All issues from the first volume to that of December, 2012 were reviewed in their entirety for reports of surface water accidents.
- (3) Journals and magazines in the field of environmental protection (CNKI 2012a). A database of Chinese academic journals was searched using the same keywords as for the Chinese Newspaper Database.
- (4) *Internet* Online data were screened for reliable information using the procedure listed in Fig. 1. Reports were prioritized as follows: official websites (such as that of the local Environmental Protection Bureau, XINHUA.net, Chinanews.net, RENMIN.net), newspaper websites, other dominant and reliable websites (SINA.com, SOHU.com, etc.). For

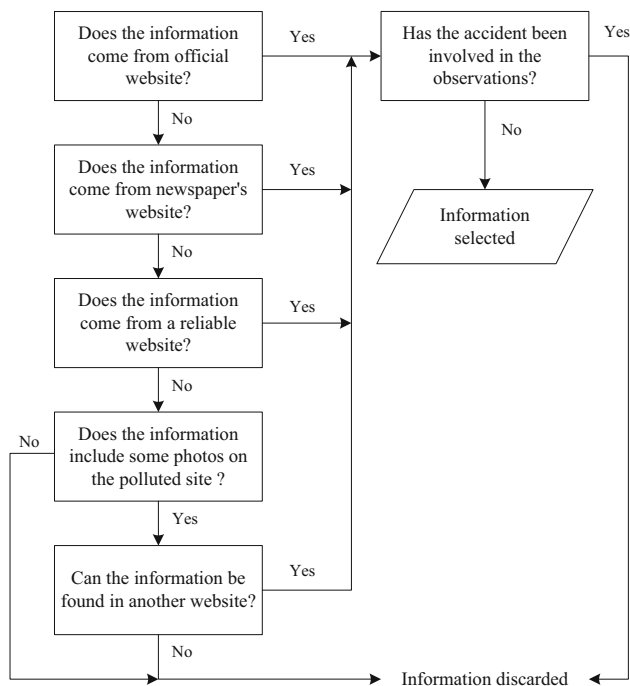


Fig. 1 Flow chart of accident screening from the internet

reports from other sources, credibility was determined based on the presence of photos and multiple reports in other websites.

All accidents selected occurred before December, 2012. For each accident, the time, location, pollutants, length of pollution zone (belt), time for which pollution lasted, cause of the accident, loss of the accident eventually, and information source were provided.

Statistical Analysis

Social risk curves, usually referred to as $F-N$ curves (Haastrup and Brockhoff 1990; Kaspersen 2014), have been used to analyze accident fatality statistics based on accumulated frequency–number of deaths graphs in many studies (Darbra and Casal 2004; Jonkman et al. 2003; Oggero et al. 2006; Yang et al. 2010). This method relates the number of deaths in a particular accident to the relative probability of there being that number of deaths.

This type of plotting was conducted in the present study to describe the distribution and accumulated probability of the characteristics of surface water accidents. The number of deaths in the $F-N$ curve was then expanded to other features. Similar curves can be drawn based on the frequency and quantities of chemicals involved ($F-Q$), frequency and number of people influenced ($F-P$), frequency and number of people affected ($F-A$), frequency and time for which pollution lasted ($F-T$), and frequency and length

of pollution zone ($F-L$). These curves were used to establish whether the probability of occurrence of a type of accident with a given severity is proportional to the probability of occurrence of another accident with a different severity, which is the relative probability. For this analysis, the accumulative probability or frequency was calculated using the equation:

$$P(x \geq j) = \frac{\sum_{i=j}^n N_i}{\sum_{i=1}^n N_i},$$

where j refers to the number of occurrences of one type of accident, such as the number of people poisoned, duration of time for which the pollution lasted (abscissa on the curve), etc., n refers to the overall number of categories or ranges, N_i refers to the number of entries in category i , and $P(x \geq j)$ refers to the probability that the number of occurrences in an accident is $\geq j$ (ordinate on the curve).

The accumulated probabilities of one occurrence can be plotted on a log–log chart. The best fit for a curve of type $P = x^b$ can provide the slope of the curve (the value b) and the probability of occurrence of a type of accident with a given severity (characterized as $x \geq m$) is $(m/n)^b$ times greater than the probability of occurrence of another accident with a different severity (characterized as $x \geq n$). Thus, the severity and features of the occurrence can be analyzed using this slope.

Results and Discussion

Distribution of Accidents According to Information Sources

A total of 653 surface water accidents were screened as research subjects and stored in the database. The sources of the 653 accidents are listed in Table 1. The numbers of accidents collected from the China Environment Newspaper, other national newspapers, and the internet were almost equal and accounted for 83 % of the total. Accidents from local newspapers only accounted for 10 %, while accidents from national channels comprised about 60 % of the total. The source distribution illustrated that information regarding surface water accidents was primarily released by national sectors, while the proportion of accidents reported by public and local media was relatively low.

Distribution of Accidents According to Time

The variation in the annual number of the 653 accidents observed in this study is shown in Fig. 2. The annual number of accidents is marked above the columns. Before

Table 1 Date sources of 653 selected accidents

General sources	Specific sources	Number of accidents	Proportion of total (%)
China Environment Newspaper	–	192	29
Other national newspapers	–	172	26
Local newspapers	–	68	10
Internet		185	28
	Official websites	23	3.5
	Newspaper websites	41	6.3
	Dominant websites	94	14.4
	Other websites	27	4.1
Journals and magazines	–	36	6

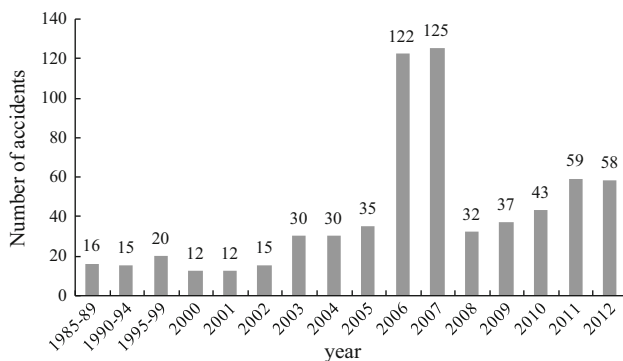
2000, there were relatively fewer accidents; therefore, they were incorporated into the abscissa.

The number of accidents was highest in 2006 and 2007, which is inconsistent with the distribution of water pollution accidents officially registered in China (Xue and Zeng 2011). This difference was likely owing to a lack of concern regarding water pollution accidents before 2006. In December 2005, there was an explosion at the Jilin Petrochemical that led to increased awareness of pollution accidents and a greater demand for safety and environmental risk management (Wo 2009).

Distribution of Accident Location

Provincial Distribution

Guangdong, Jiangsu, Hunan, Zhejiang, Guangxi, and Henan Provinces were the top six locations of the 653 accidents (Fig. 3b), with accidents in these areas accounting for 45 % of the total. The provincial distribution of accidents was generally in accordance with the distribution of the total number of surface water pollution accidents officially reported in 1992–2010 (Committee CEYE 1993–2011) (Fig. 3a). Overall, surface water accidents occurred most frequently in relatively developed areas such as the Yangtze River Delta and the Pearl River Delta, illustrating that the environments of these areas has been overloaded and thus have a high probability of

**Fig. 2** Distribution of accidents as a function of time

accidents. Additionally, the high rate of reporting reflects the stronger environmental awareness of the populations in these regions, likely owing to their higher income and life quality. These conclusions are similar to the perspectives reported (Hou and Zhang 2009; Yang et al. 2010).

Pollution Site Description

Polluted sites were described based on the following four details: regional distribution as a function of population density, type of water carrier, whether more than one administrative region was involved, and whether one drinking water source protection area was involved (Table 2). As pollution belts ran across rural areas as well as suburban and urban areas in some cases, the sum of the proportion of this item is more than 100 %.

Suburban areas constitute the largest percentage of incidents (59 %), which might reflect a lack of effective water environment management in these interlaced regions, as well as the intensive industrial layout in Chinese suburbs (CMLR 2008). Among river accidents, there were many more entries along main streams than in tributaries, possibly owing to media attention to the main streams. It should also be noted that there was a high proportion of accidents affecting multi-administrative regions and involving drinking water source protection areas. The former is likely related to transboundary pollution, which is now difficult to properly dispose of in China (Guo and Yang 2009; Kun 2011; Xie et al. 2013), while the latter directly influences the lives of local residents and is therefore of great concern. Accordingly, more attention should be given to transboundary and drinking water-related risks in water environmental risk prevention and mitigation programs.

Materials Involved

Types of Materials

Two general types and 14 specific types of materials were included in the 653 selected cases. The distribution among

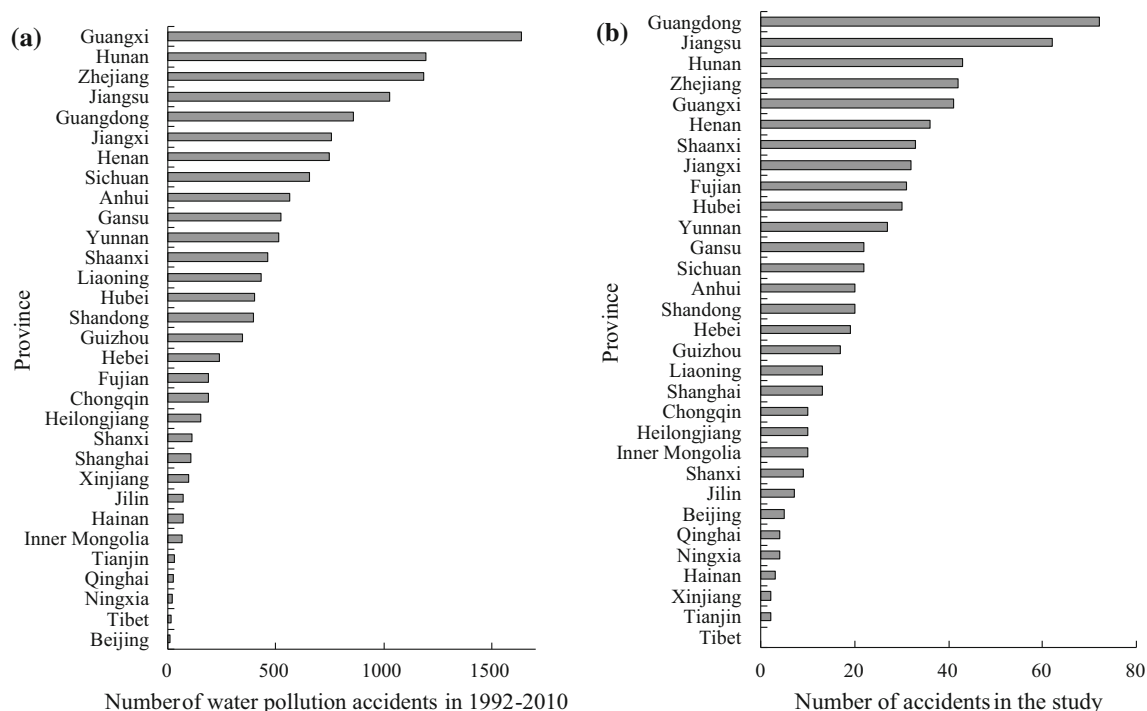


Fig. 3 Comparison of provincial distribution of accidents. **a** Presents the provincial distribution of surface water accidents in 1992–2010 and **b** presents the provincial distribution of cases in this study

Table 2 Distribution of accidents' locations

	General location	Specific location	Number of accidents	Proportion of total (%)
Site as a function of population density	Urban		268	41
	Suburban		385	59
	Rural		152	23
Type of water carrier	Lake		30	5
	Reservoir		56	9
	River	Main stream	567	86
		Tributary	362	55
			205	31
Involvement of more than one administrative region	No		356	55
	Yes		297	45
		Crossing multi-provinces	56	9
		Crossing multi-municipalities	85	13
		Crossing multi-counties	156	24
Involvement of drinking water source protection area	No		260	40
	Yes		393	60

categories is shown in Table 3. The number of accidents involving sewage was approximately equal to that of accidents polluted by chemicals. In sewage pollution accidents, more than one of the considered substances may exist (for example, “high concentration nutrition” and “some other toxic materials” may be present simultaneously); therefore, the sum of the number of the accidents in all specific classifications was higher than that of individual sewage

pollution entries. Only 1 % of the sewage pollution accidents involved unknown materials. Accidents involving high concentrations of nutrients and toxic materials such as phenol and nitrobenzene (but not heavy metals) were both dominant, accounting for 23 and 18 % of the total, respectively, while accidents involving heavy metals accounted for 5 %, which was greater than the proportion for the cases involving high concentration suspensions (3 %).

Table 3 Accidents classified as a function of the substance involved

General classification	Specific classification	Number of accidents	Proportion of total (%)
Sewage		321	49
	Unknown sewage	9	1
	Wastewater with heavy metals	35	5
	Sewage including other toxic materials	120	18
	Wastewater with high concentration nutrients	153	23
	Water with high concentration suspension	18	3
Chemical	Other sewage	13	2
		332	51
	Unknown chemicals	13	2
	Benzene compounds	157	24
	Sulfuric acid compounds	40	6
	Pesticides	30	5
	Heavy metals	64	10
Other chemicals	28	4	

In chemical pollution accidents, benzene compounds accounted for 24 % of the total, followed by heavy metals (10 %). Additionally, 6 and 5 % of the cases involved sulfuric acid compounds and pesticides, respectively.

Quantities of Pollutants

Not all quantities of pollutants were available for all the cases because the information was not reported or the incidents involved sewage, which contains compounds in quantities that are difficult to determine. Indeed, only 14 % of the cases reported quantities, all of which were chemical accidents. Among these, accidents in which 100 to 1000 or 30 to 100 tons accounted for 10 and 18 % of the entries, respectively, while the highest proportions of accidents involved between 10 and 30 tons (34 %) or <10 tons (31 %). Only a few cases involved the release of >1000 tons (Fig. 4a).

Although it is impossible to calculate the quantities in all the accidents owing to there being little available information, it must be assumed that the samples used were representative, which enables a relative frequency to be estimated for accidents in which there were quantities of pollutants above a certain value. Accumulated frequency–quantities of pollutant graphs were plotted to analyze the probability of different amounts of pollutants (Fig. 4b). The best fit for the curve of type $P = Q^b$ gave a b of -0.37 for the discrete points. Based on these findings, the probability of one surface water accident involving 10 tons or

more pollutants is 2.34 times ($10^{(-0.37)}/100^{(-0.37)} = 10^{0.37}$) greater than that of an accident involving 100 tons or more.

Loss Distribution During Accidents

The loss caused by the accidents was analyzed based on three factors: number of people involved by the accidents, length of pollution zone, and the duration of the pollution. The latter two indices primarily reflected the span and severity of the accidents.

Human Involvement in Accidents

Human impact of the accidents has been considered, such as that on human health and well-being. Human involvements were classified using three variables: number of deaths, number of people poisoned, and number of people affected.

(1) Number of deaths

For 83 % (542 cases) of the accidents analyzed, there was no information available regarding fatalities. There were no deaths reported in the majority of the entries, with fatalities occurring in only 16 cases (2.8 %). Of those that did cause fatalities, there were between 1 and 4 deaths. Over half of these cases (9) involved only one death (Fig. 5a).

An accumulated frequency–number of deaths graph was used to analyze accident mortality (Fig. 5b). The graph approximately follows a straight line with a gradient of -1.9 , indicating that the probability of an accident with one or more deaths was 79.4 times greater than that of an accident with 10 or more deaths. The same representation for accidents in process plants and during transport of hazardous substances results in a probability of -0.84 (Vilchez et al. 1995), while for natural accidents (earthquakes, floods, etc.) values ranging from -0.4 to -0.7 have been reported (Darbra and Casal 2004; Fryer and Griffiths 1979; Hohenemser et al. 1977, 1983). For explosions, fires, and marine and mining accidents occurring between 1946 and 1975, the same authors obtained F-N plots that could be approximated to straight lines with slopes ranging from -1.0 to -1.1 (Fryer and Griffiths 1979).

(2) Number of people poisoned

Only 9.0 % (59 cases) of the 653 accidents analyzed in this study contained information regarding the number of people poisoned. Overall, 8738 individuals were poisoned, with 60 % of the accidents that reported poisoning involving between 1 and 100 people. Only two cases involved poisoning of more than 1000 people (Fig. 6a).

The accumulated frequency–number of people poisoned is plotted in Fig. 6b. The graph approximately follows a

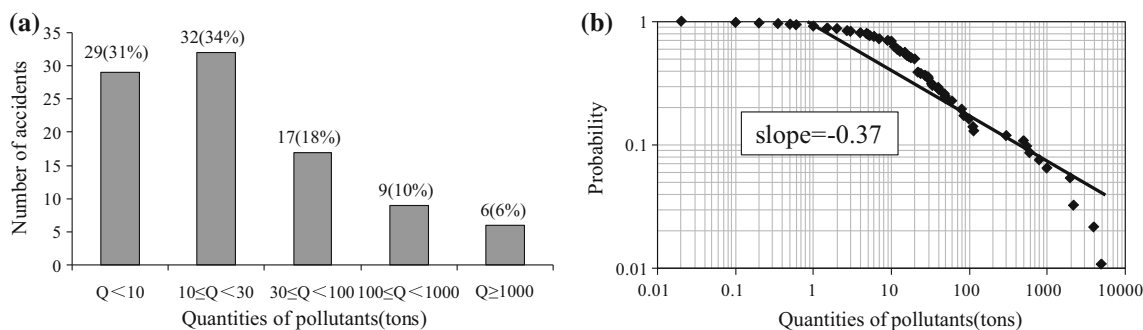


Fig. 4 Proportion (a) and accumulated probability (b) of accidents with Q amount of pollutants

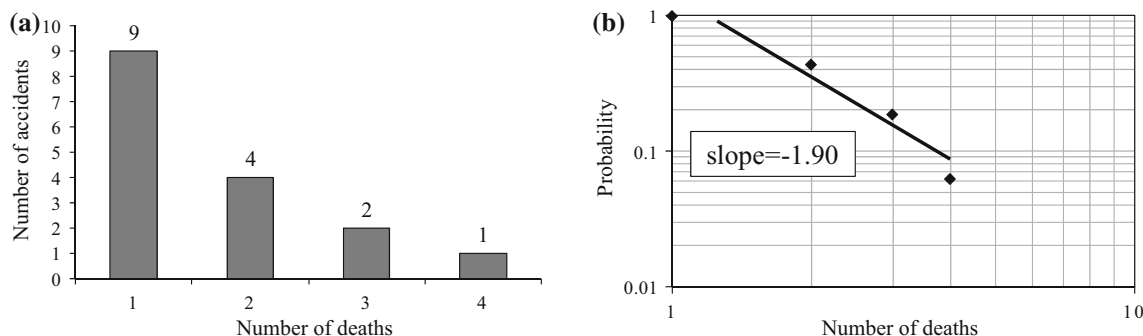


Fig. 5 Proportion (a) and accumulated probability (b) of accidents with N deaths

straight line with a gradient of -0.51 , indicating that the probability of an accident with 10 or more poisoned people is 3.24-times greater than that of an accident involving poisoning of 100 or more people.

(3) Number of people affected

The selected reports were also evaluated for the number of people affected by the adverse consequences of the accidents, including drinking water suspension, panic associated with the incidents, and decreased recreational activities. About 21.1 % (138 cases) of the 653 accidents included information regarding the number of people affected, with the highest amount being 10,000,000. In eight of these 138 accidents, between 1 and 1000 people were affected, while between 1000 and 5000 were affected in 15, between 5000 and 100,000 in 38 cases, and between 100,000 and 500,000 in 55 cases. Twelve cases involved between 500,000 and 1,000,000 people, while 10 cases involved more than 1,000,000 people (Fig. 7a).

The accumulated frequency–number of people affected is plotted in Fig. 7b. In the figure, the units on the horizontal axis are thousands of people. The graph approximately follows a straight line with a gradient of -0.38 , indicating that the probability of an accident involving 10,000 or more people is 2.4-times greater than that of an accident influencing 100,000 or more people.

Length of Pollution Zone

It was only possible to obtain data describing the length of pollution zones for 13.6 % (89 cases) of the total cases investigated. Of these 89 accidents, 38 involved < 1 km in rivers, while 21 involved between 1 and 5 km, 14 between 5 and 10 km, and 14 between 10 and 100 km. Only two involved > 100 km (Fig. 8a).

The accumulated frequency–length of pollution zones is plotted in Fig. 8b. The graph approximately follows a straight line with a gradient of -0.46 , indicating that the probability of an accident involving 1 km or more in a river is 2.88-times greater than that of an accident involving 10 km or more.

Duration of Pollution

Overall, 13.0 % (85 cases) of the cases contained details regarding the duration of pollution. Of these, 24 involved pollution lasting less than 12 h, 18 between 12 and 24 h, 14 between 24 and 48 h, and 13 between 48 and 96 h, while 16 cases involved pollution lasting for more than 96 h (Fig. 9a).

The accumulated frequency–time of pollution lasting graph is shown in Fig. 9b. The graph approximately follows a straight line with a gradient of -0.65 , indicating that

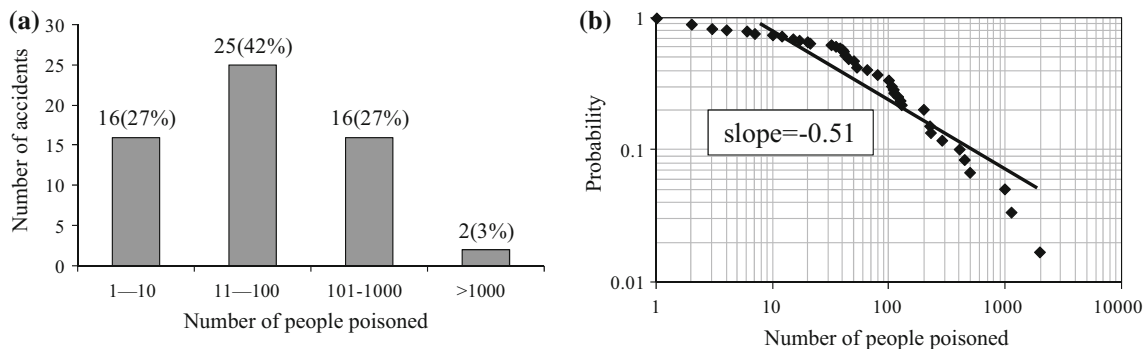


Fig. 6 Proportion (a) and accumulated probability (b) of accidents with N people poisoned

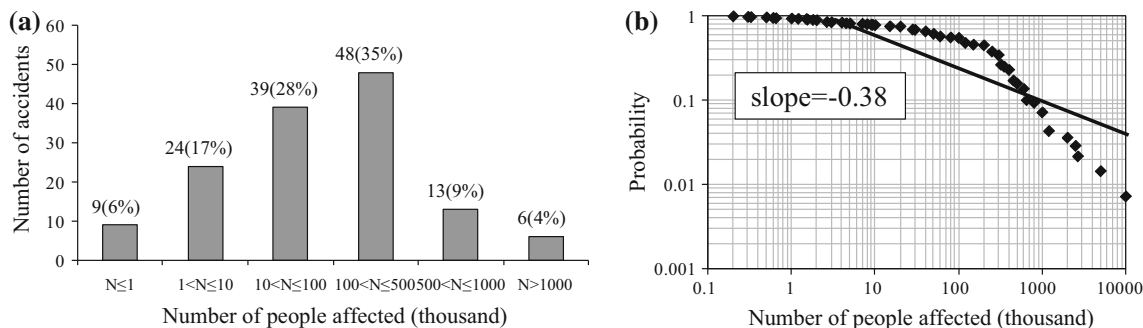


Fig. 7 Proportion (a) and accumulated probability (b) of accidents with N people affected

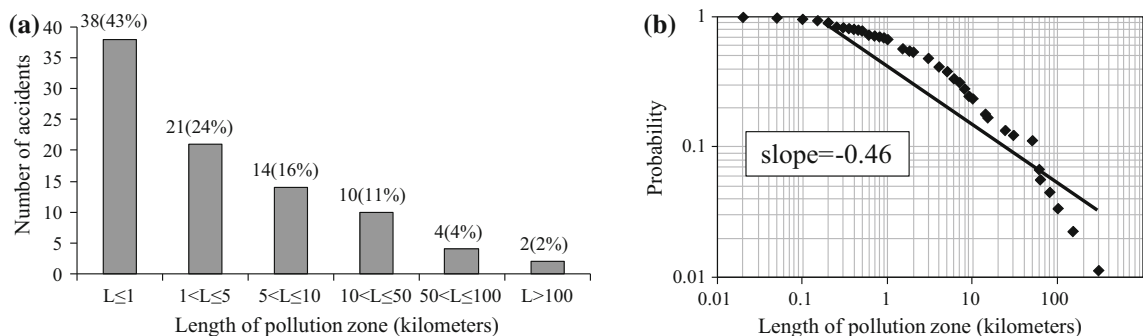


Fig. 8 Proportion (a) and accumulated probability (b) of accidents with L length of pollution zone

the probability of an accident lasting for 1 h or longer is 4.47-times greater than that of an accident lasting 10 h or more.

Origin of Accidents

Six different classifications of the process or activity were considered as the general origin of the accidents, process plants, storage plants, transportation, agricultural activity, residential activity, and others. Of the 653 surface water accidents, only 1.4 % (9 cases) was of unknown origin. The accidents of the remaining cases

classified as a function of origin are provided in Table 4. The sum of the accidents in this table was more than 644 because some accidents had more than one type of origin.

The most important contribution to surface water accidents was process plants (49.0 %), followed by transportation (25.0 %). When combined with storage plants (10.4 %) and agricultural activity (10.4 %), these four types of accidents accounted for more than 90 % of the total. Overall, these findings indicate the importance of process plants and transportation to mitigation of surface water accidents.

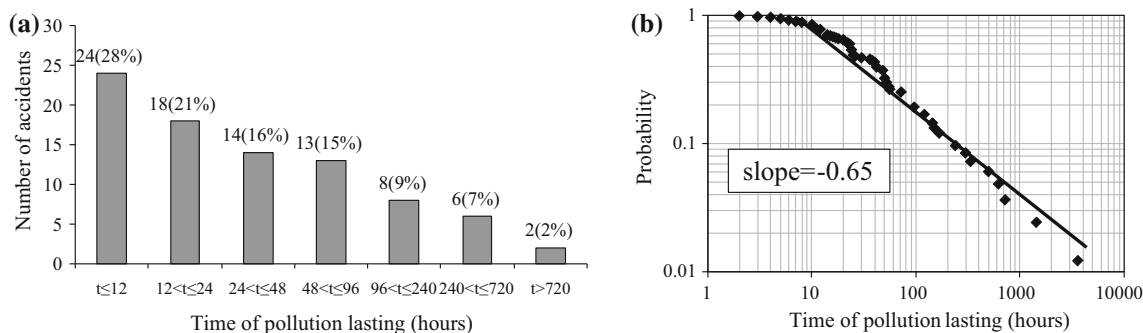


Fig. 9 Proportion (a) and accumulated probability (b) of accidents with T duration of pollution

Table 4 Accidents classified as a function of origin

General origin	Specific origin	Number of accidents	Proportion of total (%)
Process plant		320	49.0
	<i>Industry</i>		
	Machinery manufacturing	45	6.9
	Chemical production	207	31.7
	Waste treatment	29	4.4
	Mineral exploitation	13	2.0
	Electric power production	9	1.4
	Building site	7	1.1
	Others	4	0.6
	Unknown	6	0.9
	<i>Enterprise scale</i>		
	Large	23	3.5
	Medium	57	8.7
	Small	101	15.5
	Mini	139	21.3
Storage plant	–	68	10.4
Transportation		163	25.0
	Shipping	43	6.6
	Road tanker	93	14.2
	Rail tanker	0	0.0
	Pipeline	27	4.1
Agricultural activity	–	68	10.4
Residential activity	–	49	7.5
Others	–	7	1.1

The specific origin was also analyzed in the second column of Table 4. About 66 % of the accidents in process plants involved chemical production. Considering the scales of plants (Statistics 2011), the largest contribution to accidents is mini enterprise (21.3 % of the total), followed by small-sized enterprises (15.5 %), which together represent more than 36 % of all cases. When compared with other origins, these proportions indicate that more attention should be paid to mini-sized and small-sized chemical production plants to prevent surface water accidents.

Among accidents associated with transportation, the main contributor was road tankers (14.2 %). However, there was little difference among the number of accidents that originated during shipping and those associated with pipelines, while no cases involved rail tankers.

Causes of Accidents

Causes of the accidents were analyzed based on the origin (transportation and others [plant, agriculture, residents]) in

Table 5 Accidents classified as a function of the cause

General origin	General cause	Specific cause	Number of accidents	Proportion of total (%)
Transportation	Leak		143	22.0
		Equipment failure	50	7.7
		Operation error	16	2.5
		Traffic accident	77	11.8
Others	Intentional		18	2.8
	Production accidents		187	28.7
		Equipment failure	129	19.8
		Operation error	58	8.9
	Intentional		307	47.0
	Natural		57	8.7
	Others		36	5.5

Table 5. Five possible causes were considered, leakage during transportation, intentional illegal release, production accidents, natural factors and others (e.g., intensive layout of enterprises). Overall, 636 (97.4 %) accidents had a reported cause. However, some causes were associated with more than one item; thus, the sum of the entries was >100 %.

The most frequent cause was intentional illegal release (49.8 %), followed by production accidents (28.7 %) and leakage during transportation (22 %). The high frequency of illegal releases with intent might be explained by the lagging environmental awareness and environmental risk perception among the population (Ge et al. 2011; Huang et al. 2010; Schmidt and Wei 2006). Such actions might be mostly driven by the greed of the owners and/or top management of the culprit industrial facilities seeking to save money for technology improvement and waste treatment.

Specific causes of leakage during transportation and production accidents were also determined. The biggest factor associated with leakage during transportation was traffic accidents, accounting for approximately 12 % of the total, followed by equipment failure and operation error. Equipment failures were responsible for almost 69 % of the production accidents, and were more common than operation errors.

Conclusions

653 cases of environmental accidents were screened from publically available data. The severity and other features of the accidents, frequency and quantities of chemicals involved, frequency and number of people poisoned, frequency and number of people affected, frequency and time of pollution lasting, and frequency and length of pollution zone were plotted using historical data to relate the

occurrence of a type of accident with a given severity in a particular accident to the relative probability of there being that occurrence in surface water accidents. Additionally, the probabilities of occurrences of various origin and causes were summarized based on the 653 observations.

Some general conclusions can be drawn: (1) The high proportion of accidents involving transboundary and drinking water crises indicates that more attention should be paid to environmental risk prevention and mitigation; (2) The proportion of accidents originating from mini and small-sized chemical plants indicates the need for increased consideration of these two types of enterprises during risk management; (3) As the most frequent cause of pollution was intentional illegal discharge, environmental awareness in China should be improved. These understanding on aquatic environmental accidents might be helpful in risk prevention and mitigation decisions.

Acknowledgments This work was sponsored by the National Natural Science Foundation of China (41501601, 41301646, 21177067), QingLan Academic Leaders' Project of Jiangsu and Natural Science Research Project of Nantong University (14Z001).

References

- CMLR (2008) Distribution of new investment and development zones in China. http://www.mlrgovcn/zt/direction/200801/t20080103_97861htm
- CNKI (2012a) China academic journal network publishing database. <http://www.acadcnkinet/Kns55/brief/result.aspx?dbPrefix=CJFQ>
- CNKI (2012b) Chinese newspaper database. <http://www.acadcnkinet/kns55/brief/result.aspx?dbPrefix=CCND>
- Committee CEYE (1993–2011) China environment yearbook (1993–2011). China Environment Yearbook Press
- Darbra RM, Casal J (2004) Historical analysis of accidents in seaports. *Saf Sci* 42:85–98. doi:10.1016/s0925-7535(03)00002-x
- De Vos CJ, Saatkamp HW, Nielen M, Huirne RBM (2004) Scenario tree modeling to analyze the probability of classical swine fever

- virus introduction into member states of the European Union. *Risk Anal* 24:237–253. doi:10.1111/j.0272-4332.2004.00426.x
- Fryer LS, Griffiths RF (1979) Worldwide data on the incidence of multiple fatalities accidents. *Safety Reliability Directorate* 149
- Ge Y, Xu W, Gu ZH, Zhang YC, Chen L (2011) Risk perception and hazard mitigation in the Yangtze River Delta region. *Chin Nat Hazards* 56:633–648. doi:10.1007/s11069-010-9579-5
- Guo Y, Yang L (2009) Analysis on the barrier of transboundary water pollution governance cooperation mechanisms. *Environ Prot* 416:185–187
- Hastrup P, Brockhoff L (1990) Severity of accidents with hazardous materials—a comparison between transportation and fixed installations. *J Loss Prevent Proc* 3:395–405. doi:10.1016/0950-4230(90)80010-8
- Hohenemser C, Kasperson R, Kates R (1977) The distrust of nuclear power. *Science* (New York, NY) 196:25–34. doi:10.1126/science.841337
- Hohenemser C, Kates RW, Slovic P (1983) The nature of technological hazard. *Science* (New York, NY) 220:378–384. doi:10.1126/science.6836279
- Hou Y, Zhang TZ (2009) Evaluation of major polluting accidents in China—results and perspectives. *J Hazard Mater* 168:670–673. doi:10.1016/j.jhazmat.2009.02.094
- Huang L, Sun K, Ban J, Bi J (2010) Public perception of blue-algae bloom risk in Hongze Lake of China. *Environ Manag* 45:1065–1075. doi:10.1007/s00267-010-9480-8
- Huang L, Ban J, Han YT, Yang J, Bi J (2013) Multi-angle indicators system of non-point pollution source assessment in rural areas: a case study near Taihu Lake. *Environ Manag* 51:939–950. doi:10.1007/s00267-013-0024-x
- Jonkman SN, van Gelder P, Vrijling JK (2003) An overview of quantitative risk measures for loss of life and economic damage. *J Hazard Mater* 99:1–30. doi:10.1016/s0304-3894(02)00283-2
- Kang SJ (1999) Trends in major industrial accidents in Korea. *J Loss Prevent Proc* 12:75–77. doi:10.1016/s0950-4230(98)00040-0
- Kasperson R (2014) The risk society revisited: social theory and governance. *Risk Anal* 34:2188. doi:10.1111/risa.12340
- Kun C (2011) Discussion on the construction of negotiation mechanism of cross-boundary water pollution treatment in Changjiang River. *Meteorol Environ Res* 12:91–95
- Lei BL, Huang SB, Qiao ML, Wang TY (2008) Prediction of the environmental fate and aquatic ecological impact of nitrobenzene in the Songhua River using the modified AQUATOX model. *J Environ Sci China* 20:769–777
- Li JF, Zhang B, Liu M, Wang Y (2009) Numerical simulation of the large-scale malignant environmental pollution incident. *Process Saf Environ* 87:232–244. doi:10.1016/j.psep.2009.03.001
- Liu RP, Liu HJ, Wan DJ, Yang M (2008) Characterization of the Songhua River sediments and evaluation of their adsorption behavior for nitrobenzene. *J Environ Sci China* 20:796–802
- Montiel H, Vilchez JA, Arnaldos J, Casal J (1996) Historical analysis of accidents in the transportation of natural gas. *J Hazard Mater* 51:77–92. doi:10.1016/s0304-3894(96)01819-5
- Oggero A, Darbra RM, Munoz M, Planas E, Casal J (2006) A survey of accidents occurring during the transport of hazardous substances by road and rail. *J Hazard Mater* 133:1–7. doi:10.1016/j.jhazmat.2005.05.053
- Protection Wogesae (2011) Cadmium pollution incident in Beijing River. http://www.gesepcom/news/show_178_316956.html
- Schmidt MR, Wei W (2006) Loss of agro-biodiversity, uncertainty, and perceived control: a comparative risk perception study in Austria and China. *Risk Anal* 26:455–470. doi:10.1111/j.1539-6924.2006.00744
- Statistics NBo (2011) The enterprise-scale division method statistically. http://www.statsgovcn/tjbz/t20110909_402753122.htm
- Thodi PN, Khan FI, Haddara MR (2010) The development of posterior probability models in risk-based integrity modeling. *Risk Anal* 30:400–420. doi:10.1111/j.1539-6924.2009.01352.x
- Uth HJ (1999) Trends in major industrial accidents in Germany. *J Loss Prevent Proc* 12:69–73. doi:10.1016/s0950-4230(98)00039-4
- Vilchez JA, Sevilla S, Montiel H, Casal J (1995) Historical-analysis accidents in chemical-plants and in the transportation of hazardous materials. *J Loss Prevent Proc* 8:87–96. doi:10.1016/0950-4230(95)00006-m
- Wang DY, Zhang Y (2007) Statistical analysis on drinking water source and supply system contamination threats and incidents for urban areas in China during 2006. *J Saf Environ* 7:150–155 (in Chinese)
- Wo X (2007) The water crisis with odorous tap water in Wuxi. <http://www.newsqqcom/zt/2007/wxzlszw/>
- Wo X (2009) The Songhua River accident in China in 2005. <http://www.newsqqcom/a/20090729/001188.htm>
- Wu XG, Yin DX, Song JR, Huang YD (2006) Study on the emergency mechanism for sudden pollution of water resources. *Water Resour Prot* 22:76–79
- Xie RR, Pang Y, Li Z, Zhang NH, Hu FJ (2013) Eco-compensation in multi-district river networks in North Jiangsu, China. *Environ Manag* 51:874–881. doi:10.1007/s00267-012-9992-5
- Xue PL, Zeng WH (2011) Trends of environmental accidents and impact factors in China. *Front Environ Sci Eng China* 5:266–276. doi:10.1007/s11783-010-0267-1
- Yang J, Li FY, Zhou JB, Zhang L, Huang L, Bi J (2010) A survey on hazardous materials accidents during road transport in China from 2000 to 2008. *J Hazard Mater* 184:647–653. doi:10.1016/j.jhazmat.2010.08.085
- Yao H, Qian X, Yin H, Gao H, Wang Y (2015) Regional risk assessment for point source pollution based on a water quality model of the Taipu River, China. *Risk Anal* 35:265–277. doi:10.1111/risa.12259
- You XM, Tonon F (2012) Event-tree analysis with imprecise probabilities. *Risk Anal* 32:330–344. doi:10.1111/j.1539-6924.2011.01721.x
- Zhang Y, Wang DY, Yang K (2006) Statistical analysis on water pollution incident in urban water supply area in China during the year 1985 to 2005. *J Saf Environ* 4:79–84 (in Chinese)