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Challenges for introducing risk assessment into land use planning decisions in an Indian context

Anandita Sengupta [a, b, *], Debanjan Bandyopadhyay [a], Sandip Roy [c], Cees J. van Westen [a], Anne van der Veen [a]

[a] University of Twente, Faculty of Geo-information Science and Earth Observation (ITC), P.O. Box 217, 7500AE, Enschede, The Netherlands
[b] Indian Institute of Technology Gandhinagar (IITGN), Ahmedabad, Gujarat, 382355, India
[c] Indian Institute of Technology Bombay (IITB), Mumbai, Maharashtra, 400076, India

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ABSTRACT

The 1984 Bhopal accident in India resulted in severe consequences with more than a thousand people dying in the immediate vicinity of the Union Carbide facility. After this tragedy, the implementation of landuse and zoning restrictions around hazardous installations got accepted worldwide as an important strategy reducing consequences from potential industrial accidents. Many European countries have already formulated specific landuse planning policies taking industrial risks into account. However, till date India is yet to effectively employ risk assessment techniques for landuse planning decisions around industrial clusters, as well as the relevant acceptability or tolerability criteria are yet to be formulated.

In this paper, we have applied the classical quantitative risk assessment method to map cumulative risk levels arising from a number of hazardous installations located in Haldia, a densely populated area where several industrial plants storing and processing dangerous substances are located. The risk maps were prepared using common GIS tools and functions, and their sensitivity to various factors ascertained using uncertainty analysis techniques. Through the analysis of some reference plants, the aim of the paper is to underline the current difficulties an analyst has to face to determine confident risk maps as a basis for planning the uses of land due to deficiencies in the Indian legislation and the lack of guidelines.

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1. Introduction

Over the last few decades, a number of large-scale industrial accidents have occurred in hazardous industries worldwide, resulting in damage and loss of life in the surroundings. Among these events, the accident occurred at the Union Carbide pesticide production plant in Bhopal (India) in 1984, is ranked as the world's worst industrial catastrophe. A leak of 41 metric tons of acutely toxic Methyl Isocyanate (MIC) resulted in the exposure of hundreds of thousands of people living in the neighbouring area of about 50 km^2 (Singh and Ghosh, 1987; Lees, 1996). It was reported that in the neighbourhood colonies of the plant, by the end of the day over 3000 people were killed and in the aftermath several thousands more died as a result of the exposure (Shrivastava, 1995; Eckerman, 2005; Mannan et al., 2005). Among many other reasons including lack of adequate information about the storage and handling of hazardous materials, lack of co-ordination between the factory management and the emergency service providers, inadequate warning systems and plant maintenance practices, limited capacity to cope with the crisis and mitigate the damages, etc., lack of landuse restrictions resulting in the co-existence of densely populated residential areas in close proximity of the plant make the incident worse (Shrivastava, 1995; Bisarya and Puri, 2005). However, even after 30 years of the tragic accident, there has been no significant improvement in this regard in India (NDMA, 2007).

Today the country is one of the emerging economies of the world, and a considerable part of this fast paced GDP can be attributed to the good performance of key industrial sectors mainly the chemical industries. Currently the Indian chemical industry stands as the 3rd largest producer in Asia (after China and Japan) and 8th largest in the world (CeFIC, 2011). Based on its rapid GDP growth, the country is also identified as one of the highly industrialized countries in the world. According to data available with

* Corresponding author. University of Twente, Faculty of Geo-information Science and Earth Observation (ITC), P.O. Box 217, 7500AE, Enschede, The Netherlands.
E-mail addresses: a.sengupta@utwente.nl, ananditasg@iitgn.ac.in (A. Sengupta).

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central agencies, as of 2008, there were 1666 Major Accident Hazard (MAH) industries located in 260 districts in India.[1] And many of these MAH units are often found in clusters to take advantage of common infrastructural facilities and the availability of skilled manpower. An inventory undertaken by the Central Pollution Control Board (CPCB) identified 170 of such industrial clusters housing more than five MAH units across the nation. Furthermore, number of such clusters is anticipated to go up significantly in the form of Petroleum Chemicals and Petrochemicals Investment Regions (PCPIRs) as conceptualized by the Ministry of Chemicals & Fertilizers, Govt. of India and Special Economic Zones (SEZs) thus to provide further impetus to growth of chemical industries.

However, there is a flip side of this growth. In absence of an appropriate regulatory requirement for landuse restrictions, some of these industrial clusters are often located in the vicinity of densely populated areas. Moreover, acting as engines of industrial and economic growth, these areas often witness a steady influx of population resulting from the migration of people from other part of the country to take advantage of jobs and other livelihood opportunities generated by these industries, thus resulting in increasing levels of risk. And in most cases, the concentration of population growth driven by these urban-biased industrial developments evolved without adequate infrastructure, basic civic amenities like housing, transportation, water, sanitation and electricity supply, etc., hence create hazardous living conditions (Shrivastava, 1995). This in-turn led to large number of low-income group people whosoever migrated to this area for job opportunity, do not have any alternative but to settle in adjacent areas to these potentially dangerous chemical plants, thus becoming highly vulnerable to any industrial accidents, of which the Bhopal disaster (1984) is an example (de Souza Porto and de Freitas, 1996).

Nonetheless such a situation is not typical of India alone. Many industrialized western European countries have encountered similar challenges in the past and have evolved objective methods for assessing risk from hazardous industries which then led to the adoption of suitable risk-based landuse planning decision strategies. In order to assess cumulative risk arising from a cluster of hazardous industrial units and evaluate options for area level risk mitigation measures, several studies were carried out in countries like the Netherlands, UK and Italy during the 1970's. Some examples of these risk studies include those undertaken in Rijnmond, the Netherlands (Roodbol, 1984), Canvey Island in the UK and the Ravenna area in Italy (Amendola et al., 1995) during 1970's. But then, it is only after the accidents in Bhopal and Mexico both occurred in 1984, resulting in widespread fatalities to population in the neighbourhood, the importance of restricting the use of land around hazardous installations became widely accepted as a measure for limiting the adverse effects of such accidents (Christou et al., 1999; Christou and Porter, 1999; Christou and Mattarelli, 2000; Christou et al., 2006).

Accordingly, to formalize the adoption of specific landuse planning restrictions for areas surrounding hazardous facilities, European governments amended the first EU Directive 82/501/EEC – so called Seveso Directive of 1982 that focused on the prevention of major accidents and limiting of potential consequences on man and environment. The Article 12, as incorporated in the amended Seveso Directive II (96/82/EC) of 1996, stipulates that appropriate safeguard distances should be implemented through landuse planning decisions (Porter and Wettig, 1999; Wettig et al., 1999). Guided by the Directive II, EU Member States have laid down different approaches for risk assessment and acceptability or tolerability thresholds in accordance with their political, cultural, technical, legal and societal backgrounds (Christou et al., 2006). These methods range from a generic safety distance-based approach as in Germany to a risk-based approach based on results of quantitative risk assessment (QRA) as practiced in the Netherlands and the UK (Papazoglou et al., 1998; Hauptmanns, 2005; Cozzani et al., 2006; Basta et al., 2007). Countries like France and Italy have formulated a hybrid approach as a combination of the consequence and risk-based approaches (Kontic and Kontic, 2009; Sebos et al., 2010; Taveau, 2010).

In India, issues related to the safe siting of hazardous industries although put forward through certain regulatory provisions, but none of the legal provisions provide any specific criteria which can guide landuse planning decisions for an industrial cluster. Section 41A of the Factories (Amendment) Act of 1987 (Ministry of Labour, Govt. of India)[2] requires that the location of hazardous industries has to be evaluated from the safety point of view by a site appraisal committee; but fails to provide a mechanism through which such siting decisions can be linked to landuse planning considerations for an industrial area. The EIA Notification of 2006 (Ministry of Environment & Forest, Govt. of India)[3] does provide scope for the assessment of risk originating from new hazardous industries, but in practice EIA studies seldom evaluate alternative siting based on risk contribution to the neighbourhood communities or provide recommendations for mitigating offsite consequences of the potential accident scenarios. In addition, the CPCB of India has prepared the 'Zoning Atlas for Siting of Industries' taking environmental considerations into account, but risk is yet to be factored into criteria for zoning of an industrial area (Punihani et al., 2002). More importantly, the Zoning Atlas also fails to provide a linkage to the existing landuse zoning regulations as proposed in the UDPFI Guidelines[4] prepared by the Ministry of Urban Affairs & Employment, Govt. of India. Consequently, during discussions at the Second India Disaster Management Congress (2009) organized by the National Institute of Disaster Management (NIDM), a consensus was reached on the need for adoption of landuse planning principles based on scientific rationale as a strategy for risk reduction and mitigation.[5]

However, for the adoption of any systematic approach for risk informed landuse planning in industrial towns, the availability of information on the hazards present in industries and the vulnerability in the surrounding residential areas are vital. In India, an effort to consolidate such information was made through the 'Environmental Risk Reporting and Information System' (ERRIS) which was implemented in selected industrial towns in 2006. The system has subsequently been upgraded to a more versatile platform called the Risk Management Information System (RMIS) and is capable of storing spatial and related attribute data of industries, including their hazardous chemical storage facilities, the nature of the chemicals stored/handled, the nature of the process details, site maps, and detailed information about vulnerabilities in terms of exposed buildings and populations at different time periods (Sengupta, 2007; Bandyopadhyay et al., 2011).

The key objective of this research is to apply a methodology based on Quantitative Risk Assessment (QRA) with necessary adaptation, for estimating and spatially representing cumulative risk originating from a cluster of hazardous industries, based on

[1] http://cpcb.nic.in/upload/NewItems/NewItem_112_nationalchemicalmgmtprofileforindia.pdf.

[2] http://labour.gov.in/upload/uploadfiles/files/ActsandRules/Service_and_Employment/The%20Factories%20Act%2C%201948.pdf.

[3] http://www.envfor.nic.in/legis/env_clr.htm.

[4] http://mhupa.gov.in/w_new/summaryudpfi.pdf.

[5] http://nidm.gov.in/idmc2/PDF/Outcome/Manmade.pdf.

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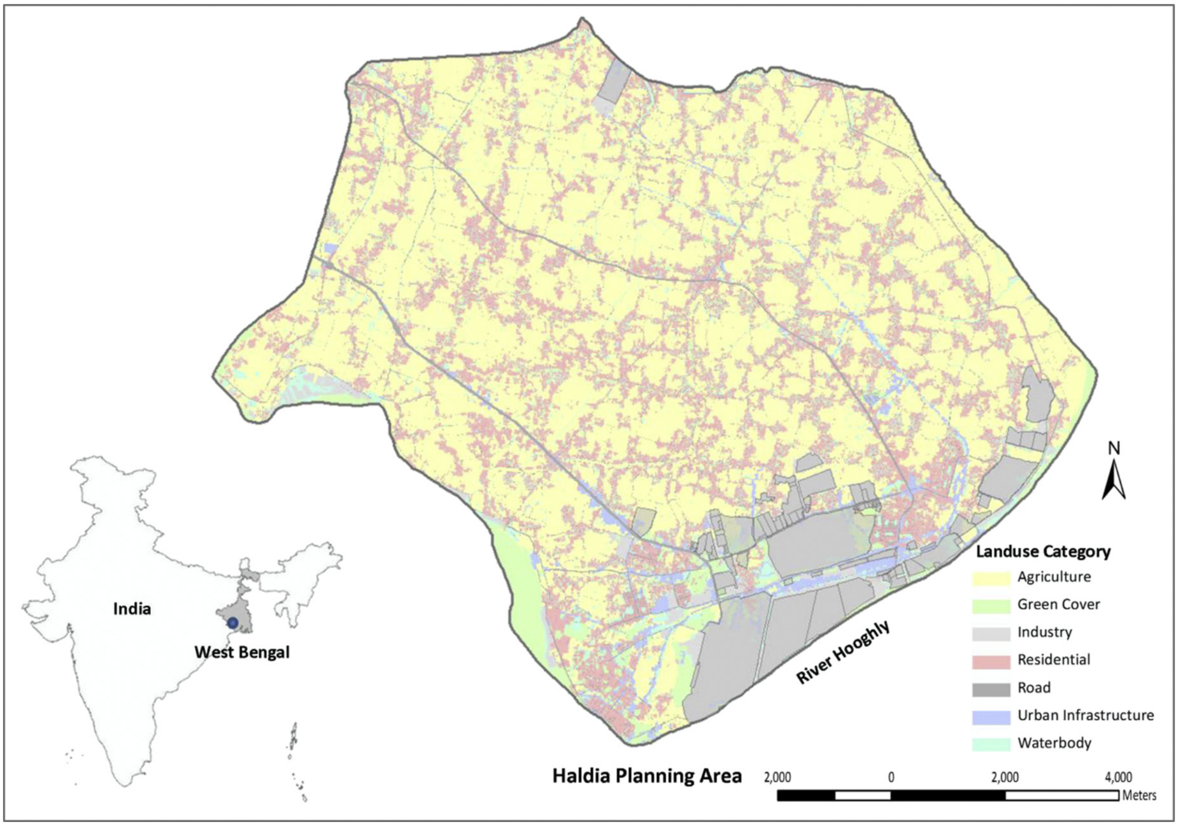

Fig. 1. Location of Haldia in India.

spatial and related attribute information available in the RMIS database. In doing so, we evaluated whether techniques that have been developed and applied in western countries (e.g. the Netherlands or the UK) could suitably be adapted to an Indian context, using GIS tools and techniques. In this study, we have calculated cumulative risk levels, taking into consideration reference accident scenarios from several hazardous units, and spatially overlaying them to arrive at a measure of risk in terms of probable fatalities to resident population. This method can result in the formulation of deterministic risk metrics based on scientific rationale, which can then be used to guide risk informed landuse planning decisions for the area in question.

2. Study area

The study was carried out in Haldia, near the metropolitan city of Kolkata in West Bengal. The Haldia industrial area, one of the largest industrial areas in the eastern part of India, is supported by a large port complex and other infrastructural facilities (Fig. 1). Presently there are 42 industrial units, of which 17 are identified as MAH industries according to the Manufacture Storage and Import of Hazardous Chemicals (MSIHC) Rules 1989 and subsequently amended in 2000. Several new industries are also planned in this area. These industrial units along the River Hooghly are juxtaposed with residential areas with a total population of about 170,000 persons (according to the Census from 2001), including a large area with informal settlements lying in close vicinity of the hazardous industries. In many places it has been observed the industries are already functioning in situations where an increasingly dense mix of residential-commercial population thrives right outside the industries' boundary.

As one of the emerging industrial hubs, the landuse pattern of the Haldia area has undergone rapid changes during the last few decades. The area has recently been declared as the PCPIR of West Bengal, following the PCPIR policy[6] of Govt. of India. The Haldia Development Authority formed as a statutory body under the provision of West Bengal Town and Country (Development and Planning) Act 1979, has the mandate for regulating the land uses of the area under its control. The development authority has prepared a detailed landuse map taking into account cadastral-level landuse information and is presently in the process of updating the existing landuse control and development plan. The information required for undertaking the risk assessment was primarily sourced from the RMIS database of Haldia.

3. Methodology

Industrial risk assessment involves a structured procedure, varying from quantitative to qualitative, and is capable of estimating the levels of risk posed by hazardous industries (Christou et al., 1999). In this research, we have applied a QRA-based approach (Fig. 2) to estimate the risk from hazardous industries to the surrounding communities and to assess the degree of effectiveness of such a risk measure for guiding the landuse planning decisions in the area due to lack of availability of Indian criteria and guidelines. The steps involved in the methodology are discussed in the sections below.

3.1. Scenario selection

An accident scenario is one of many specific situations that

[6] http://cipet.gov.in/pdfs/policy2.pdf.

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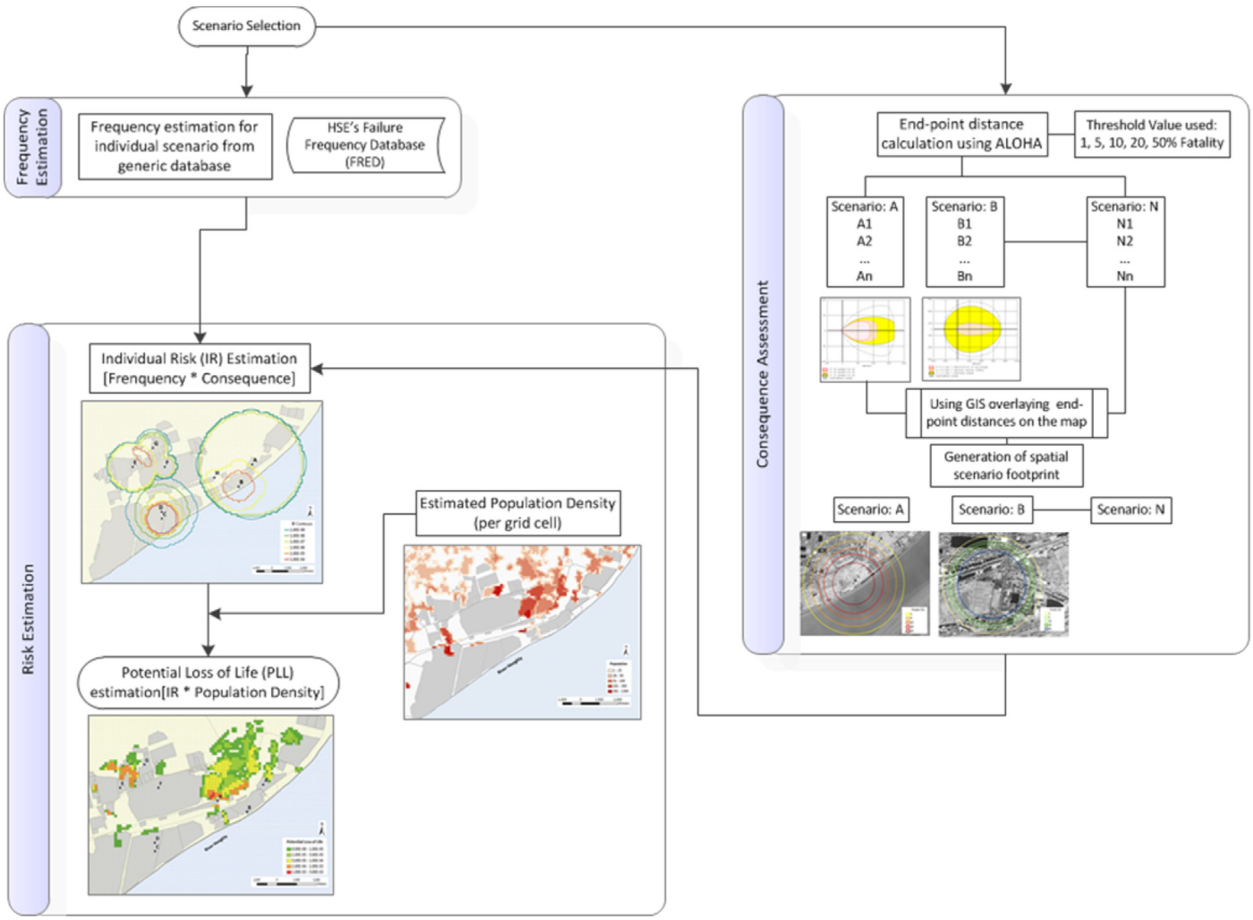

Fig. 2. Methodology applied for the proposed QRA-based approach.

might evolve at the end of an accident sequence, e.g., the development of a toxic cloud in a given direction. To demonstrate the practical applicability of a QRA-based method, we have considered eight number of accident scenarios as ‘reference scenarios’ of Vapour Cloud Explosion (VCE), Boiling Liquid Expanding Vapour Explosion (BLEVE) and toxic release events originating from different hazardous industries located in the study area (Fig. 3). The scenarios were selected with an inherent assumption of having the potential of causing Maximum Credible Loss (MCL) as identified on the basis of facility-level risk assessment study (Table 1). Important to mention here, although it is custom to consider the whole chain of causes, intermediate events and final consequences as a scenario, but for the present study as the causes are not relevant, it is only the hazard potential embodied by quantitate of hazardous substances present considered.

For each scenario, possible release types for example pipe rupture, formation of holes in a pressurized vessels, major or catastrophic failure etc. were identified which can cause in high loss of life in the surroundings. To ensure that the method remains workable, we propose that a number of credible accident scenarios per industry, which may lead to potential offsite consequences, to be considered.

3.2. Assigning frequency and probability

Once the possible scenarios are selected, next step in QRA requires the estimation of their frequencies. However a review of several industry-specific risk assessment reports of MAH units in Haldia point to an absence of any definitive estimate of failures that could result in a major accident with potential offsite consequences. Even at a broader level, no such failure frequency statistics is also known to exist in India.

In order to perform the risk analysis, among many others generic failure-frequency database like the TNO's Purple Book, HSE's Failure Rate and Event Data (FRED), OREDA etc., (Casal, 2008) we have used the HSE's Failure Rate and Event Data for use within Land use Planning Risk Assessments[7] to assign frequency of the above mentioned scenarios as presented in Table 1. However, generic failure frequency data is not proposed as an alternative to estimate scenario-specific failure frequency through the use of system reliability techniques, in particular fault-tree analysis. Nonetheless, due to less frequent failures local failure rate data are often not superior to those of data banks and fault tree analysis often overlooks failure possibilities.

Additionally, in contemporary QRA methodology, the potential incidents for which data is available from failure-frequency databases are further analyzed for conditional probabilities of a range of possible accident sequences which include accident initiation, loss of containment and finally the outcome of the accident. In our research, probability of an accident sequence has been considered equal to the probability of the initiating event i.e. no mitigation measures were considered due to lack of information.

[7] http://www.hse.gov.uk/landuseplanning/failure-rates.pdf.

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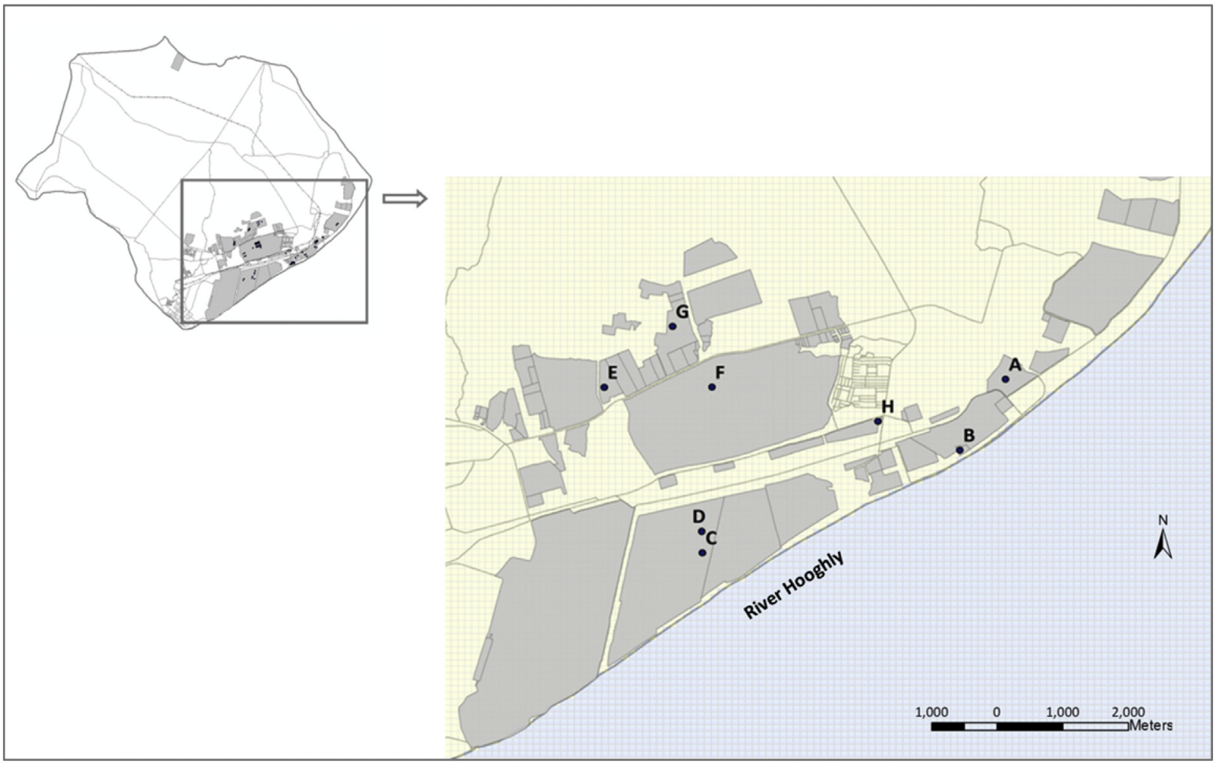

Fig. 3. Location of the storages used for reference scenarios.

Table 1
List of selected scenarios.

Scenario ID	Installation	Containment	Frequency (y^{-1})	Total capacity	Scenario description
A	Atmospheric tank single walled	Motor spirit or gasoline (highly flammable liquid)	$5\cdot10^{-6}$ [a]	4200 MT	Catastrophic failure leading to a formation of vapor cloud which is ignited resulting in VCE involving 1200 MT
B	Double walled dome roof tank	Ammonia (liquefied toxic gas)	$4\cdot10^{-4}$ [b]	10,000 MT	Release of toxic vapor involving 50 MT of Ammonia from 20 m height
C	Atmospheric tank single walled	Motor spirit or gasoline (highly flammable liquid)	$2.5\cdot10^{-3}$ [a]	24,150 MT	Minor failure leading to formation of vapor cloud which is ignited resulting in VCE involving 100 MT
D	Tonner	Chlorine (liquefied toxic gas)	$4\cdot10^{-6}$ [c]	1 MT	Cylinder undergoes catastrophic rupture releasing 1 MT Chlorine into atmosphere
E	Atmospheric tank	Motor Spirit or Gasoline (highly flammable liquid)	$1\cdot10^{-4}$ [a]		Major failure involving 400 MT of Motor Sprit
F	LPG bullet	Propane (liquefied flammable gas)	$5\cdot10^{-6}$ [d]	160 MT	A release of 80 MT of Propane as vapor cloud, finds a source of ignition and explodes
G	Horton Sphere	Butane	$9\cdot10^{-7}$ [e]	915 MT	Tank engulfed into fire and resulting in BLEVE or fireball
H	LPG bullet	Butane (LPG)	$1\cdot10^{-5}$ [d]	30 MT	BLEVE involving 25 MT of LPG

[a] Derived from historical data by Glossop (HSE internal report: RAS/01/06); pp. 9.
[b] Documented in a HSE internal report (RAS/00/10) by J. Gould; pp. 14.
[c] Reported in the Major Hazard Assessment Unit Handbook; pp. 23.
[d] Documented in a HSE internal report (RAS/06/04) by Keeley and Prinja; pp. 33.
[e] Proposed by M. Selway, 1988, Failure Rate and Event Data for use within Land Use Planning Risk Assessments, pp. 26.

3.3. Consequence assessment

The consequence assessment involves determining the impact of an event in terms of its physical extent and severity (Lees, 1996). The physical extent of an accident scenario usually involves the calculation of the effect-distance (i.e. maximum distance with certain intensity) from the source within which people might get affected. The severity of an event is expressed as the level of harm to people such as injury or fatality. Existing QRA approaches generally apply two sets of models for estimating the consequences of an accident scenario: a mathematical model to predict the physical effect (i.e. thermal radiation, overpressure and toxic dose) of an accident and a vulnerability model to estimate the impact of an accident on humans (Fabbri and Contini, 2009).

In this research, physical effects of the reference scenarios were analyzed using ALOHA (Areal Locations of Hazardous Atmospheres),[8] one of the standard and widely accepted tools known to calculate conservative effect distances. The choice of ALOHA has been made taking into account the low level of complexity and manageable input requirements of the software. For calculating the

[8] http://www.eh.doe.gov/sqa/central%20registry/ALOHA/Final_ALOHA_Guidance_Report v52404.pdf.

Table 2
Threshold values for each event type.

Probability of fatality (PF)	Radiation (kW/m^2)	Overpressure (psi)	Toxic release (mg/m^3)	
	Butane	Propane, MS	Chlorine	Ammonia
1	65.00	120.00	8000	18,000
0.5	26.50	13.10	870	4000
0.2	20.78	7.15	470	2525
0.1	18.25	5.20	340	2030
0.05	16.42	3.95	260	1680
0.01	13.42	2.40	160	1200

effect distance, we have used real data about the hazardous facilities, e.g., chemical substances, storage condition etc. as obtained from the RMIS database and the most frequent weather conditions of an average wind speed of 3.0 m/s, 35 °C temperature and atmospheric stability class D to model the effects of each scenario.

The severity of the accident scenarios was estimated in terms of fatalities that may be due to effects of thermal radiation, overpressure wave or concentration of toxic substances (Ale, 2002; Fabbri and Contini, 2009). The reference damage assumed was the death of a non-protected person. The applied Probit functions were as follows:[9,10,11]:

$$\text{Thermal Radiation}: P_r = -14.9 + 2.56 \ln\left(Q^{4/3} \cdot t_1\right) \quad (1)$$

$$\text{Overpressure}: P_r = 1.47 + 1.37 \ln(p) \quad (2)$$

$$\text{Toxic release}: P_r = a + b \cdot \ln(C^n \cdot t_2) \quad (3)$$

P_r Probit corresponding to the probability of death
Q heat radiation (kW/m^2)
t_1 exposure time (sec)
p peak overpressure (psig)
a, b, n constants describing the toxicity of a substance[12]
C^n concentration (mg/m^3)
t_2 exposure time (minutes)

The calculated threshold values for each reference scenario for different levels of fatality mentioned above are shown in Table 2. Using a GIS technique, the estimated effect-distances calculated for 1, 5, 10, 20 and 50% fatality as shown in Fig. 4 were then overlaid on the map of the area concerned to visualize the spatial spread of the scenario impact in terms of fatality.

3.4. Risk estimation

Finally, risk was estimated by combining frequency (Section 3.2) with their consequences (Section 3.3). As risk to the people concerned, two indices were used: individual risk and societal risk (Bottelberghs, 2000; Ale, 2002).

3.4.1. Individual risk

Individual Risk (IR) is the probability at which an individual may be expected to sustain a given level of harm from the realization of specified hazards (IChemM, 1985). In simple terms it is the probability of a fatality on a certain grid point, hence measures the distribution of risk over an area in order to adopt measures that reduce risk to an acceptable level. Generally, the IR estimation takes into account the account an annual frequency of occurrence of a reference damage (e.g. fatalities) in any area for a person present 24 h/day and 365 day/year without protection and possibility of being sheltered or evacuated.

Graphically IR can be represented as a set of risk contours around a hazardous installation. In order to generate individual-risk contours, it first requires to estimating the effect of all individual scenarios at each location. Accordingly, risk resulting from each reference scenario was estimated combining frequency of the initiating event (i.e. incident), conditional probability of the scenario (i.e. sequence) and the corresponding probability of fatality (i.e. Probit). In particular, the following expression was used to estimate IR at a given location for a particular accident scenario.

$$IR_{(x,y,i)} = [f_i \cdot PF_i] = \left[\left(f_{incident\ i} \cdot P_{sequence\ i}\right) \cdot PFi\right] \quad (4)$$

- $IR_{(x,y,i)}$ is the individual risk at the geographical location (x, y) for a particular reference scenario *i*.
- f_i is the frequency of occurrence of the accident scenario *i* (y^{-1});
- PF_i is the probability of fatality that the accident scenario *i* will result at location (x, y).

The resulting overall IR at that particular location (x, y) was then calculated as the sum of the individual IR's corresponding to each reference scenario.

$$IR_{(x,\ y)} = \sum IR_{(x,\ y,\ i)} \quad (5)$$

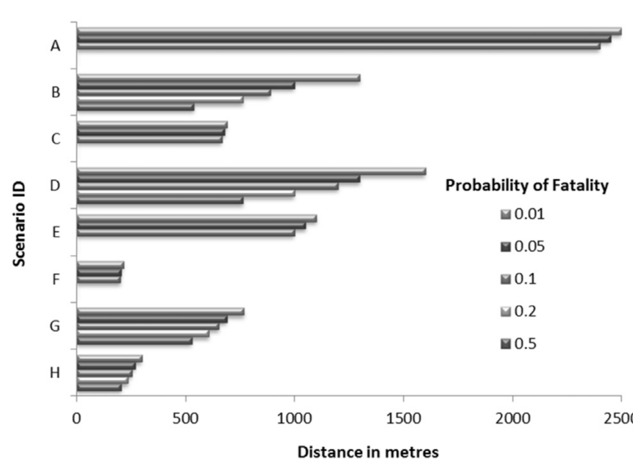

Fig. 4. Effect-distances of the reference scenarios.

[9] Lees 1996; AIChE 2000.
[10] HSE Guidebook.
[11] Lees 1996; AIChE 2000.
[12] For ammonia: a = −15.6; b = 1; n = 2; and chlorine: a = −6.35; b = 0.5; n = 2.75 were considered.

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- $IR_{(x,y)}$ is the overall IR at the geographical location (x, y) for all reference scenarios

It is important to mention here that all events were considered to have radial effects, except for the scenarios involving toxic release which were considered as a directional footprint with its spread distributed in a sector of 22.5°, using a wind direction probability of 0.125 taking any of 8 principal wind directions.

3.4.2. Societal risk

Societal Risk (SR), another risk measure of the QRA approach, is the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards (IChem, 1985). Therefore, if no people are present around the hazardous activity, SR is zero whereas IR may be quite high (Bottelberghs, 2000).

A number of measures can be found in the literature to estimate or express the societal risk (Laheji et al., 2000; Jonkman et al., 2003). Among them, we have chosen the PLL measure as it allows spatial display of the risk to society by combining the damage potential with population density estimates. It is expected that the result would be helpful for the planners and other decision makers to understand the severity of existing risk level and accordingly identify the areas where risk stabilization measures should be adopted, or where to focus for adopting risk reduction strategies either in the form of rehabilitation or restrictions for no further residential area development. It is important to mention here that the societal risk estimation is conservative since it considers all people to be unsheltered and always present at their residences. Here, we have estimated SR in terms of Potential Loss of Life (PLL) using the following expression as adapted from the literature (Jonkman et al., 2003).

$$PLL_{(x,\,y)} = \left[IR_{(x,\,y)} \cdot NP_{(x,\,y)}\right] \tag{6}$$

- $PLL_{(x,\,y)}$ is the Potential Loss of Life at a geographical location (x, y);
- $IR_{(x,\,y)}$ is the individual risk at location (x, y); and
- $NP_{(x,\,y)}$ is the number of people at a geographical location (x, y).

To be able to estimate PLL across a spatial grid, it is necessary to have a high-resolution spatial population database for the area. This is not readily available for the Haldia area. In order to do so, the area was divided into a series of grid cells measuring 100 × 100 m's. The number of people per grid cell was estimated by interpolating the census population data (available per administrative unit) to the spatial spread of residential areas using a dasymetric approach (Bhaduri et al., 2007) (Figs. 5 and 6).

4. Results

4.1. Cumulative risk maps of Haldia

The methodology presented in Section 3, was applied in a subset comprising of about 100 sq. km of the larger Haldia Planning Area to estimate the existing cumulative risk to the people in the vicinity of the hazardous industries. Fig. 7 shows iso-risk contours depicting the probability of an unprotected individual being killed in the vicinity of such industries per year. Finally, the societal risk in terms of the number of probable fatalities that may be caused in an area has been estimated using a PLL function by combining the IR with the number of persons residing in each cell of the grid. The societal risk (unit being no. of people in each grid who can suffer fatalities/year) is presented in Fig. 8.

4.2. Uncertainty analysis

The methodology was designed based on a traditional QRA approach. However, for applying this method in an Indian situation, several assumptions had to be made due to lack of guidelines and data available. These included the frequency of initiation events, the probability of sequence leading to the accident scenario, the selection of a limited number of scenarios, the use of MCL criterion etc. Therefore, the reliability of the results presented in the above section, are dependent on these assumptions. To evaluate the validity of these assumptions, an uncertainty analysis was carried out for the key variables on which the sensitivity of the results may vary (Amendola et al., 1992). As a part of the study, these variables were analyzed to stimulate discussion between risk assessment professionals, local planners and/or the National Authorities who are responsible for risk issues.

4.2.1. Scenario frequency

For the performance of a consistent QRA, it is essential to determine event frequencies as realistic as possible. Alternatively, over or under-estimation of these values can lead to an error of more than one order of magnitude in the calculation of risk. Generally, the estimation of failure frequency for QRA is done based on data obtained either from different research projects, historical analysis of accidents or by the expert's judgment, which are documented in the generic failure-frequency databases. Likewise, frequency of each scenario was estimated based on an international generic failure database. However, whether these levels of failure frequency will be viable for Indian MAH installations has to be discussed and agreed upon, since frequency of accident in India might be different from those in the Western European countries because of factors like enforcement of the regulations on maintenance, replacement, safety management etc. Hence, the alteration of risk contribution from different scenarios has been studied, based on the variation of scenario frequencies. A comparison between estimated frequency based on HSE's database as compared to considering a common frequency, indicative of tolerable risk and assumed to be 1×10^{-4} in this case, for all scenarios is presented in Table 3.

From Table 3, it is evident that further research needs to be carried out to establish frequencies of the initiating events and probabilities of possible sequences which may result in different accident outcomes and consequently spatial distribution of risk levels.

4.2.2. Weather condition

The results of consequence predictions can vary to a significant extent based on input weather factors like wind speed, direction, stability class etc (Marx and Cornwell, 2009). The variability in individual risk levels, when using actual wind direction data recorded at a weather station compared to an assumed equal probability wind direction averaged across eight wind directions, is shown in Fig. 9.

4.2.3. Resolution

The societal risk results are also sensitive to the defined grid size and the level of detail, at which landuse is captured for population interpolation. Given these facts, the methodology was also tested at a smaller grid size of 50 × 50 m, and a comparison of the societal risk levels between the 100 × 100 m and the 50 × 50 m grids is shown in Fig. 10.

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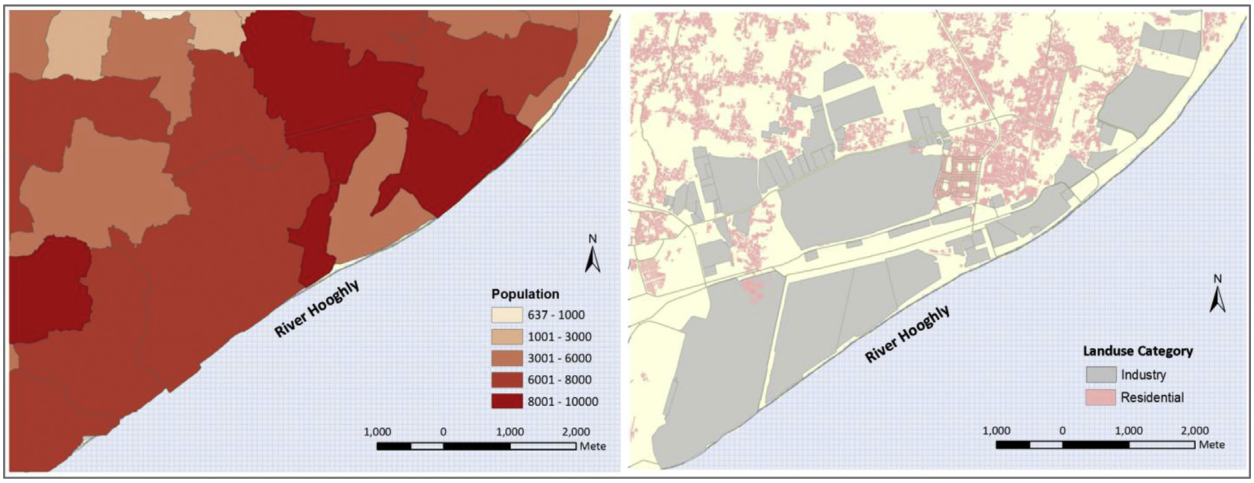

Fig. 5. Population per administrative unit (left); Residential areas from landuse map (right).

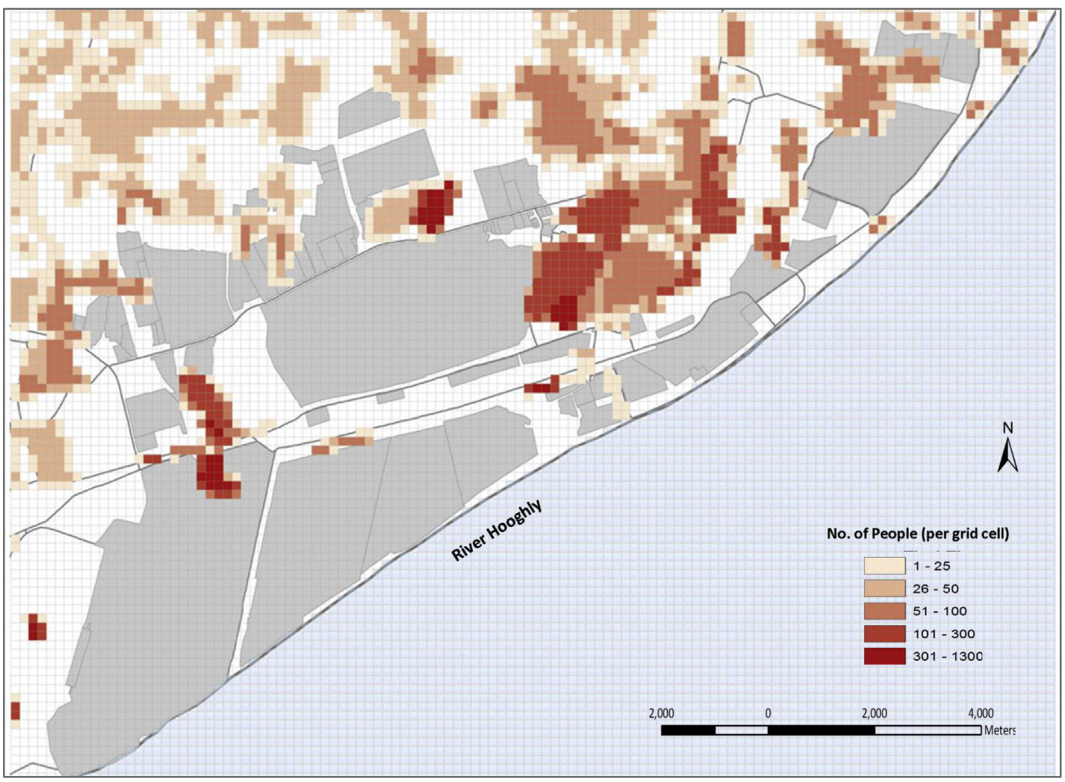

Fig. 6. Estimated number of people at 100 × 100 m grid.

5. Conclusion & recommendation

This work was generated by the recognition that the current practice and legislation in India is far from being effective for a national risk reduction policy. Results can lead to backward linkage with harmonization of industrial risk assessment method based on standards and criteria as acceptable to the risk management actors. Moreover there is a scope for using the outcomes in the exploration of forward linkage with the adoption of risk-informed landuse planning strategies based on agreed levels of acceptable risk at the societal level. However, testing the classical QRA methodology in an Indian context revealed several important concerns requiring further research and discussion.

The implication of the accident scenario in risk-informed land-use planning decisions is two-fold. First is the selection of the scenario with an offsite-impact. The experts of the European Working Group on Land-use Planning (EWGLUP) have indicated that for the purpose of risk-based landuse planning, accident scenarios have to be selected based on their frequency of occurrence and the severity of their consequences (Christou et al., 2006). On contrary, in India risk analysis presently undertaken by the MAH industries are mostly based on the MCL scenarios representing the probable scenario that can cause maximum offsite consequences only. However, no clear criteria is yet formulated for identifying such scenarios (NDMA, 2007). Moreover, the choice of MCL scenario is dependent on the methodology adopted for facility-level

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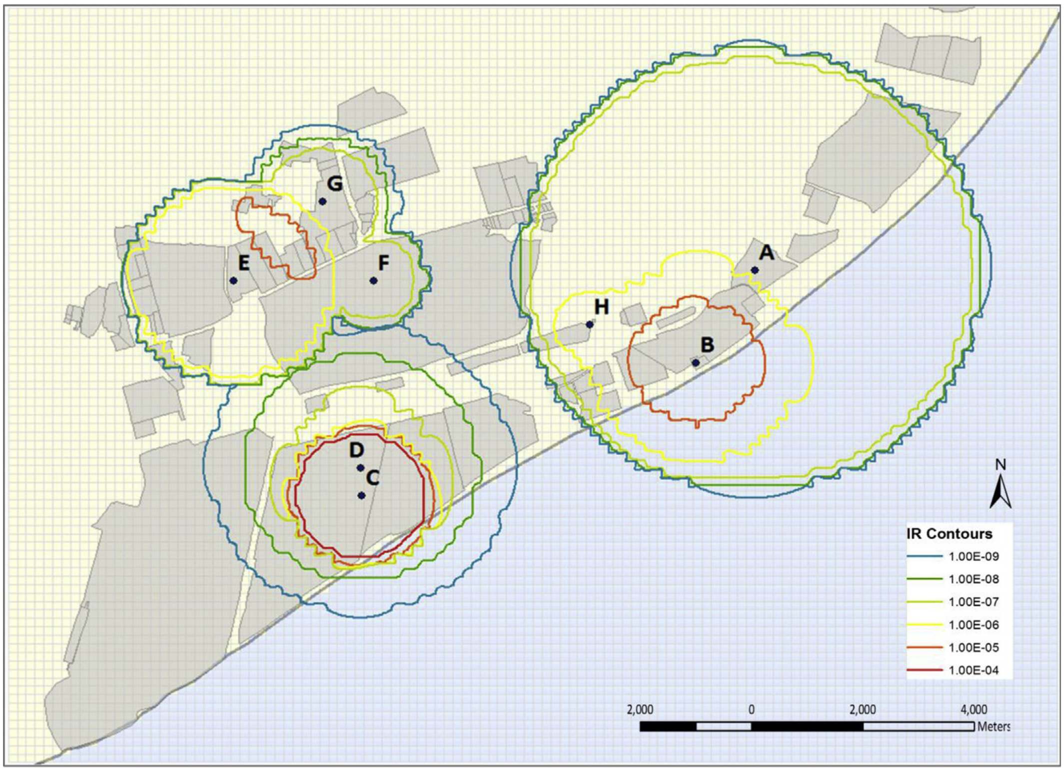

Fig. 7. Individual risk. Iso-risk contours of all reference scenarios.

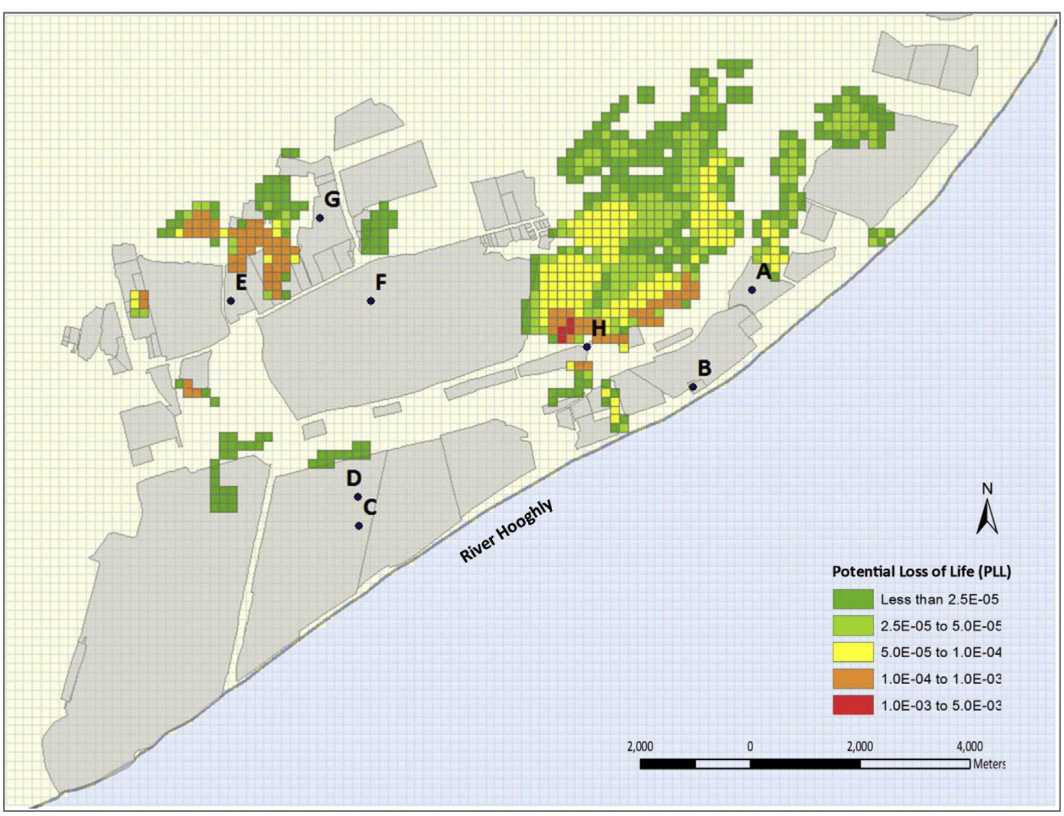

Fig. 8. Societal Risk. Expected PLL of each grid from all reference scenarios.

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Table 3
Contributions of the reference scenarios to the PLL estimation (%).

Scenario ID	Estimated frequency/year (as per HSE)	Assumed common frequency/year (1×10^{-4})
A	39.72	75.08
B	9.17	0.22
C	0.00	0.00
D	0.25	0.59
E	28.52	2.70
F	0.00	0.00
G	0.43	4.58
H	21.90	16.83

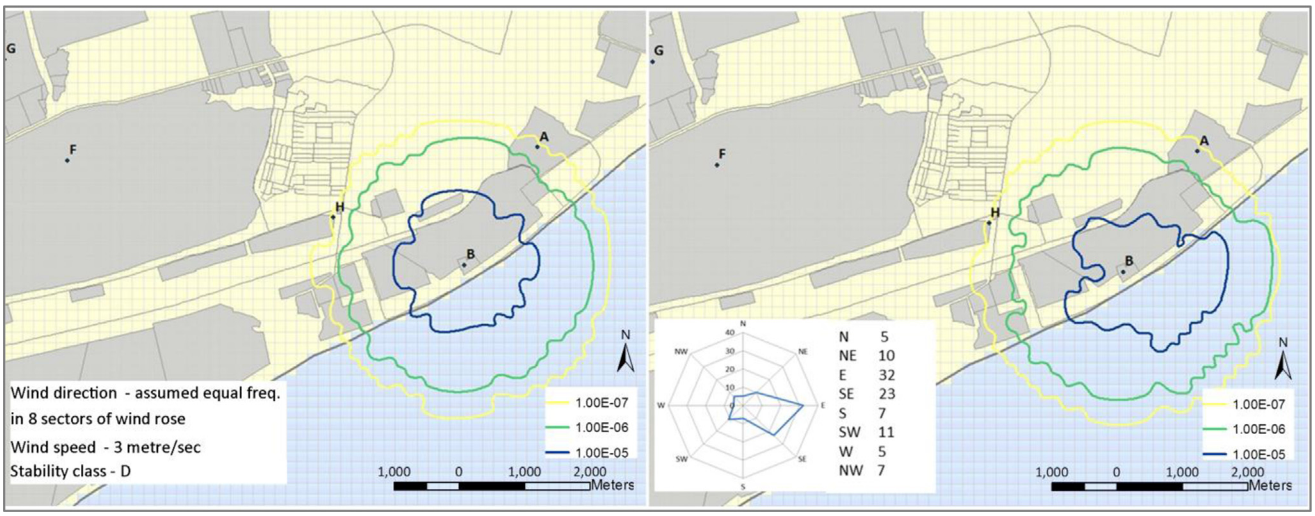

Fig. 9. Variation in IR levels accounting for wind direction probability – based on assumed weather data (left); and from wind rose (right).

risk assessment based on a number of assumptions made during the exercise and then presented through a safety report, which will bring in inherent uncertainties in QRA studies involving multiple facilities. Hence, it is strongly recommended to arrive at a commonly acceptable method for risk assessment which would enable a cumulative risk assessment study otherwise the results

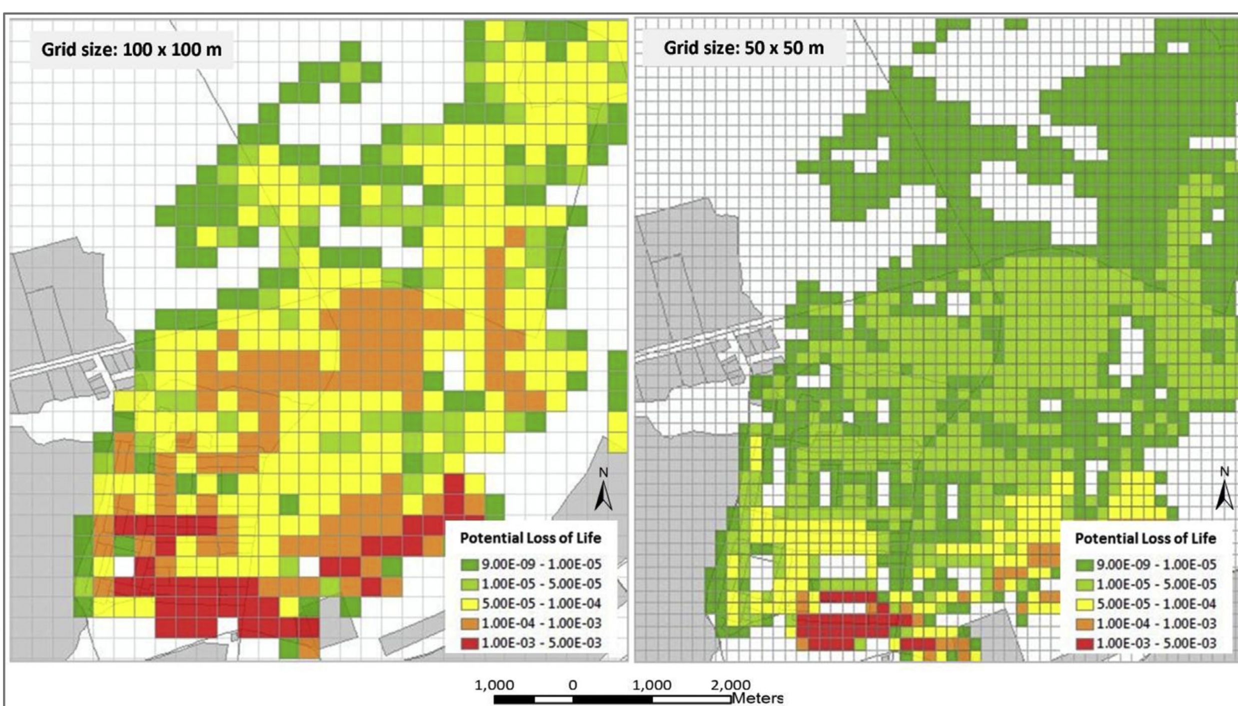

Fig. 10. Changes in the level of societal risk at different resolution.

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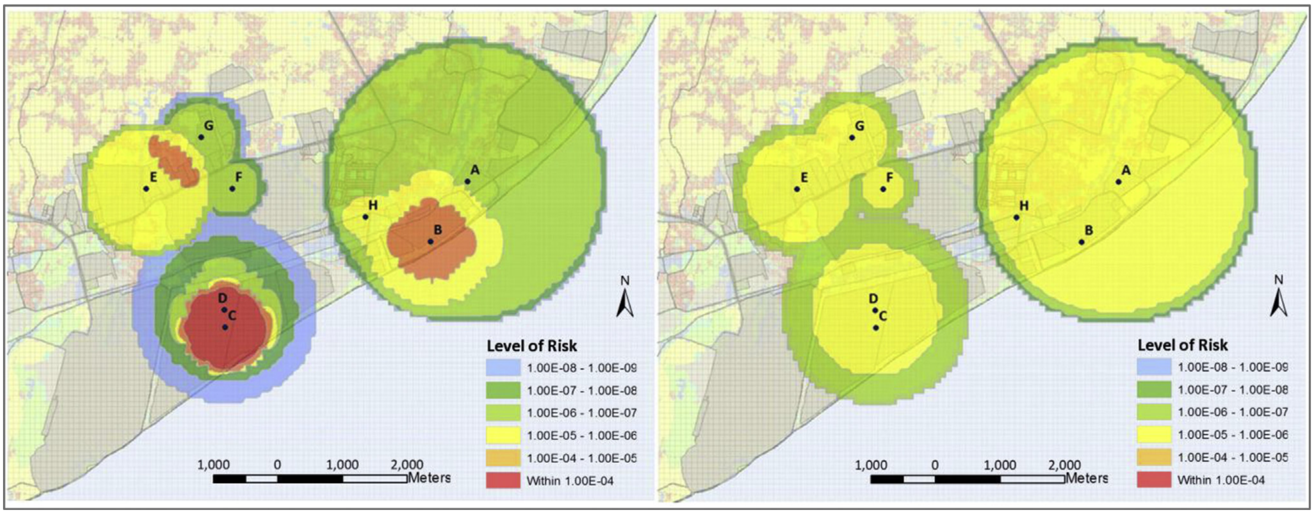

Fig. 11. Application of risk-based approach (left); consequence-based approach (right) to study area.

may be faulty and thus convey a wrong picture.

Second is the accuracy or trustworthiness of the scenario and the resulting risk estimation. It has been noted that alteration of any modeling assumptions or variables may exhibit substantial variations in the size of the impact area and thereby the consequences from similar scenarios. Therefore to arrive at a harmonized result, recommended parameters and other input variable (like threshold values for effect-distance calculation, Probit equations etc.) to estimate the consequence of an accident scenario, need to be done in order to generate consistent risk scenarios prevailing in an industrial area.

The next important issue is the number of scenarios that have to be accounted for in order to arrive at a decision. In this paper we have only used eight 'reference scenarios'. However, in reality there could be an N-number of such scenarios in an industrial area like Haldia which could have major consequences for the residential areas located in between. In such cases, criteria need to be formulated for selection of the reference scenarios to assess the existing level of risk. The selection of the number of scenarios is also critical as the total individual risk is calculated by adding up the values of the individual scenarios. Ideally all possible scenarios should be taken to arrive at a correct IR value; but that may mean considering more than 1000 scenarios. And as risks of different scenarios differ easily orders of magnitude, the small ones contribute little and can be neglected; only the large risks count. So for practical purposes, the scenarios to be considered have to be restricted using certain limiting criteria.

In India, a specific risk acceptability criterion is not yet defined; hence we made an attempt to compare the results with the Dutch and UK criteria used for landuse planning decision. It has been observed that the application of these criteria might be difficult in India as it would result in too much unacceptable area for landuse planning decisions. Hence further research is required for establishing risk acceptability criteria for India in accordance with its societal background and existing regulatory framework.

Regarding risk-informed landuse planning, many European countries have formulated different risk assessment approaches. From a methodological point of view two main approaches can be distinguished. The first one based only on consequences of the reference scenarios, is known as a 'consequence-based' approach and which intrinsically takes the probability of the accident; while the second one considers both probabilities and consequences, and is known as the 'risk-based' approach. Therefore, for a given hazardous installation, the 'consequence-based' approach shows the consequence area for lethal effects and serious injuries resulting from the reference scenarios assessed, whereas the 'risk-based' approach shows an area within which there is a given probability of a specified level of harm resulting from the large number of possible accident scenarios (Christou and Mattarelli, 2000). Therefore in proposing a risk-based approach, in comparison to a consequence-based approach, the proposed methodology assigns due weight to the issue of optimal use of scarce land resources for planning purposes in India. For this purpose, both approaches were tested in the study area (Fig. 11) and percentages of total area affected as well percentage of affected area under different landuse category were compared in Tables 4 and 5 respectively. It is evident that a risk-based approach results in more strict landuse planning, therefore would be suitable to adopt only for new industrial area.

Table 4
Comparison of area-affected in consequence and risk-based approaches.

Iso-risk contour value	Risk-based approach		Consequence-based approach	
	Area (sq. km)	(%)	Area (sq. km)	(%)
Within 10^{-4}	1.67	5.92	0	0
10^{-4} to 10^{-5}	1.84	6.53	0	0
10^{-5} to 10^{-6}	5.48	19.44	20.60	72.51
10^{-6} to 10^{-7}	12.70	45.05	5.66	19.92
10^{-7} to 10^{-8}	3.58	12.70	1.83	6.44
10^{-8} to 10^{-9}	2.92	10.36	0.32	1.13

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Table 5
Percentage of affected area in different landuse category in both approaches.

Iso-risk contour	Risk-based approach				Consequence-based approach			
value	Agri.[1]	Green[2]	Indus.[3]	Resi.[4]	Agri	Green	Indus.	Resi.
Within 10^{-4}	0	0	5.93	0	0	0	0	0
10^{-4} to 10^{-5}	0.25	0.50	4.18	0.46	0	0	0	0
10^{-5} to 10^{-6}	3.00	2.11	7.29	2.32	10.07	4.29	30.21	12.96
10^{-6} to 10^{-7}	8.46	1.82	13.43	11.39	0.25	1.50	10.75	1.93
10^{-7} to 10^{-8}	5.75	0.93	2.07	0.93	1.36	0.43	2.79	1.00
10^{-8} to 10-9	0.82	0.86	6.07	0.93	0.21	0.07	0.46	0.21

[1] Agriculture
[2] Green cover
[3] Industry
[4] Residential

A host of analytical approaches have been formulated and used by risk analysts to predict potential damage, in terms of injury or fatality, from an accident involving a toxic release, fire or explosion in a hazardous installation. Regulatory authorities have varying opinions on the outcome of consequence modeling. Some agencies like Environment Protection Agency in the US, stress the use of simple consequence modeling equations for prediction of worst case damage distances to specific end-points whereas other agencies, like RIVM in the Netherlands or the HSE in the UK, prescribe the use of specific tools like SAFETI and RISKAT respectively (implementing full QRA), to be applied based on certain requirements and boundary conditions (Ale, 2005; Pasman, 2011). Several independent evaluations undertaken in this regard, however, point to the need for adhering to agree upon benchmarks and prescribed calculation methods for undertaking such risk analysis. Therefore adapting such methods would lead to a reliable and standardized estimate of risk or for judging the severity of consequences which could subsequently be summed up to arriving at a measure of cumulative risk.

Another key aspect of the methodology presented for estimation of risk measures in a spatial context is that no complex or proprietary software tool has been used in realizing the method. The proposed approach takes advantage of using simple GIS functions and the ALOHA model, one of the known and accepted effect models by the regulatory and industrial communities. Therefore, the methodology aligns with the accepted framework set by many countries, like the Netherlands and the UK that risk analysis should not be a preserve of risk analysts, but a decision maker or planner should be able to apply the same after receiving a basic training. For fast growing industrial areas, landuse planners can thus easily consider various risk scenarios and spatially overlay them on the present landuse in order to allocate future land for future industrial and residential development.

In addition, the present approach also applies a novel method to estimate the potential loss of life based on a grid-basis population estimate derived from Census data using dasymetric interpolation technique. Generally for risk representation, ward-level population detail as extracted from census data is used, without considering the exact location of population. That's why we tried to estimate the exact location of people by interpolating the census data thus to estimate the number of people who might be affected.

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