Assessment of aircraft accident probability on industrial facilities by means of GIS Risk-Register, the examples of Geneva, "Geneva Risk".

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Keywords

Geneva Risk, Swiss Federal Ordinance on Protection against Major Accidents (Ordinance on Major Accidents OMA), chemical risk assessment, classification and prioritization of chemical hazards (IAEA methodology), major hazard plants, geographic information system (GIS), cartographic representation of environmental safety and risk, land use planning, aircraft accidents, aircraft accident damage, aircraft crash probability, aircraft crash into hazardous facilities, aircraft individual risk contour, accident consequence area.

1. Introduction

Risk assessments currently performed within the frame of the Swiss Federal Ordinance on Major Accidents (OMA) shall also take into account the consequences of highly unlikely events, including the extremely low probabilities of an aircraft crash onto an industrial site. Similar requirements are also tackled in the revised Seveso directive 96/82/EU, whereas until recently, such probability data was so far only determined for Switzerland in a single case, a joint study (EWI 1993) done for the Federal Office on Civil Aviation (BAZL) and the Federal Office of Military Avia-

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tion (BAMF). Hence, only generic aircraft crash probabilities were calculated for the entire area over Switzerland in this study. These values were expressed as the probability per year and square meter for both accidents during the en-route and the approach flight phase. Further, only four aircraft categories were considered for modelling. This is seen as not sufficient with regard to worldwide aviation accident data of the last decades showing different aircraft crash statistics, this mainly caused by the fact that aircraft are not randomly distributed in the airspace but follow standardised procedures especially during taking off and landing. A serious attempt to systematize the data processing of aircraft accident into hazardous facilities was made in 1996 by the US Department of Energy (DOE 1996). When evaluating the adoption of their methodology to the situation around European Airports, it became clear, that various airport conditions and operational modes could not give a sufficiently reliable determination of aircraft crash frequencies. Potential aircraft accident risks in the vicinity of hazardous facilities situated near the Geneva International Airport would consequently not be sufficiently taken into account in the local risk management and land use practices..

In 2004 the Geneva international airport (AIG), together with the federal BAZL and cantonal authorities (OCIRT), decided to compile an electronic map of individual and collective risks around the airport in accordance with the framework of the Sectorial Aviation Infrastructure Plan (SAIP). In 2006 and 2007 a systematic study, entitled "Third party risks posed by aircraft accidents in the vicinity of Geneva airport", was conducted by the German company Gesellschaft für Luftverkehrsforschung (GfL), in close cooperation with OCIRT, AIG and BAZL. This study determined these risks in terms of an Individual Risk and a specific Societal Risk. The individual risk is the probability that someone residing at a specific location around the airport dies due an aircraft accident. The societal risk is the probability of a given number of deaths in particular regions along the aircraft departure or arrival route: these regions are locally referred to as individual segments. These new and more precise probability and risk results were transformed into aircraft accident probabilities per hectare. They were then used in the cantonal risk register (CRR), called Geneva Risk, to calculate and simulate the effect on the global risk profile of the major potentially hazardous installations situated in the vicinity of the different Geneva International Airport (AIG) flight routes in use. This led to a variety of new maps showing the collective and individual risk contours, and hence a new way to study the land use planning practices.

The goals of the project were to evaluate how the risks for different types of industry, in particular those dealing with dangerous chemicals, may increase due to aircraft operations inside the area of the canton of Geneva. This evaluation would then permit the setting up of priorities in monitoring installations and further enhance land-use practices and the preparedness of emergency response planning. Special GIS representations were developed on the basis of these risk calculations values and special procedures will be put in place in order to inform the public.

2. Methods

2.1 Methodological background

The Cantonal ICT infrastructure is made up of different units which interact strongly. The communication infrastructure is managed by the Geneva Technology Information Center (CTI), the Geneva liabilities data are given by the Geneva Companies Competence Centre (REG; http://reg.ge.ch) linked with the Federal Companies Centre (BUR-REE; http://www.admin.bfs.ch/), a wide range of standardized cartographic data are taken from the cantonal geographic database (SITG; http://www.sitg.ch) provided by the Geomatic Competence Centre (GCC). Finally, the information system of the environmental affairs section of the Geneva Labor Inspectorate follows up the technical installations of companies referenced in the Cantonal Risk Register (CRR). This CRR is used to manage the risk calculation data of industrial facilities with chemical and biological risks to allow for cartographic visualization, and also for monitoring and administrative follow-up according to legal compliance of all major hazard facilities situated in the Geneva canton.

Numerical models were defined and applied to the release and dispersion calculations for a range of sources of risk for the population and the environment, in particular the stationary facilities (storage and production of chemicals and contained use of pathogenic organisms) and the transport infrastructure (motorways, main roads, railways and pipelines). The Geneva Risk project, developed as a joint venture with the ChemRisks project of the canton of Zurich, deals mainly with the risk on industrial installations which fall under the Ordinance on Major Accidents (OMA) (Susini et al 2004, Hansen et al 2005, Susini et al 2006, Susini et all 2007). These first developments were then further enhanced by other Swiss cantons (Aargau, Turgau and Basel-Stadt) joining this partnership and a special geomatic interface called RCat was developed by Basler&Hofmann. The RCat ArcGIS interface makes it possible to import and perform calculations necessary for cartographic risk mapping more efficiently. To integrate the aircraft risk calculations it was necessary to adapt the CRR Oracle data base to be the RCat interface .

According to the individual requirements of OCIRT and AIG, the study conducted by GfL refers to the operational situation at Geneva airport in 2005, during which there were 170.824 air traffic movements. The analyses give a risk assessment posed by the commercial Instrument Flight Rules (IFR) traffic only (151,937), plus a second one including additional flight operations following Visual Flight Rules (VFR).

The study methodology is based on probabilistic aircraft crash rates modelling (Fricke et al. 2004) and Flight procedure analyses (Fricke et al. 2007).

Both risk figures are calculated with GfL's External Risk Model, which has proven its validity in a large set of similar applications, comprising three empirically calibrated sub-models, namely:

- an accident rate sub-model to determine the local accident probability for departing and arriving air traffic only, i.e. explicitly excluding over-flight traffic in the airspace around Geneva,
- an accident location sub-model providing an accident location distribution probability function, referred to the Air Traffic Departure and Arrival Route System and linked to a runway and/or its extension, so as to assess the External Risk at any specific location around Geneva
- an accident consequences sub-model representing crash consequences on ground induced by the aircraft cell and also by secondary domino effects which may be imposed through the hazard potential of industrial plants belonging to the OMA Hazard Category in case of an aircraft accident.

The so formed External Risk Model allows calculations for both Individual and Societal Risk contours for a given investigation area here a 40km square around Geneva Airport at a 100m resolution. The External Risk determination covers the two mentioned types of risks, the Individual (local) risk and a specific Societal (Group) risk.

For achieving these objectives, the following steps were performed in the study :

- Determination of the representative departure routes out of Geneva Airport based on statistical analyses of Air Traffic Control radar data sampled for the reference scenario time frame 2005 kindly provided by Skyguide.
- Calibration of the External Risk model to the infrastructure and traffic situation at Geneva, specifying the local accident rate and specific accident consequence areas.
- Calculation of the Individual Risk at the prescribed resolution of hectares around Geneva for both IFR traffic alone, and total traffic.

By applying the first two sub-models only, the External Risk model can also provide local accident probabilities per hectare. This procedure was especially applied for the Geneva Risk study to allow specific dependency analyses between aircraft operations and OMA plant locations and operational behavior. inside the Geneva canton boundary. With this set of raster probabilities and the area of a chemical plant at a specific location, the probability of an aircraft accident on the plant was calculated. This probability was then compared to the accidental event probability of the plant (stored in the risk register) assuming massive to large-scale or localized release of stored or processed chemical substances. This comparison allowed to valuate whether the accidental risk of the plant is enhanced by air traffic operation at AIG.

As a second and important working hypothesis it was assumed, that, in the case of an aircraft accident on a specific entity containing chemicals stored or processed inside a plant, the full quantity of the substance would be released into the environment. This is clearly a worst-case approach with regard to industrial accidents,

where specific scenarios typically assume that only a part of the chemicals are released . Further details of the calculation model are given in section 2.3.
The overall objective was to automate the inclusion of the additional frequency and damage probabilities due to aircraft accident risks in order test the influence of the input of airport operations onto the total risk profile for nearby industrial sites.

2.2 IT aspects for cartographic projection of risk calculations

To handle the data forming part of the digital infrastructure of the Geneva canton, the use of relational databases for the data administration (industrial facilities and their associated hazard potentials and risks) is important in order to allow for systematic calculations.
It was decided to use an internationally recognized standard, based upon three hierarchical descriptive levels (Organization, Site and Entity) as defined by the European Union EMAS eco-audit directive (EC No 761/2001), together with a decision form specified by them, on the 7 September 2001, for the implementation of the Regulation (EC No 761/2001). The precise meanings of the descriptive levels is as follows :-

- "Organisation" shall mean a company, corporation, firm, enterprise, authority or institution, or part or combination thereof, whether incorporated or not, public or private, which has its own functions and administrations.
- "Site" shall mean all land at a distinct geographic location under the management control of an Organisation involving activities, products and services. This includes all infrastructure, equipment and materials.
- "Entity" shall mean a part of a site or subdivision seeking to register under one registration number. This includes for example large amounts of chemicals situated in storage and production units located inside an industrial site.

The descriptive level of the site has a key number attribute, initially developed for statistical and fiscal duties that were also used to interface with other available and quality-controlled data, such as the federal building register and the geographic values required to create GIS cartographic representation. The entity descriptive level, , was used for the calculation data. This entity represents, inside an industrial site, a storage or processing part containing significant amounts of chemical substances. In the database this level is geographically referenced by cartesian (x,y) coordinates. Technically speaking, for the Geneva Risk project a Spatial Database Engine (SDE), developed by the Environmental System Research Institute (ESRI), was established to serve the varied needs of different administrative units. The SDE server provides a variety of raster-based information, such as satellite images and maps with different scales, and vector-based data, such as river and highway specifications. Security aspects and personal data protection rules were duly taken into account. There are separate sets of databases accessible to the public, to internal administrative units and to cantonal agencies. The calculations made within the database precisely determine the accidental damage extent of an entity in terms of percentage of affected people with mortality probability indicators (10% and 100%). The calculations and accidental frequencies specific to the entities then form part of several files which are then processed in the RCat interface in order to create visual models in the form of maps. The RCat interface processes the data, together with the Geneva cartographic server (SITG) demographic data in the GIS), in order to calculate the exact extent of the consequences (death,) to people, this result is then multiplied by the accident probability in order to obtain the corresponding risk calculation, In case of an industrial accidental event, according to the specific accident scenario, the probabilities are given by the CRR; in case of an aircraft accident, the probability used is stored inside the RCat interface. The results of these calculations is then exported by RCat in order to be integrated into the the overall data of the CRR. The ArcGIS software interface was used to implement the risk assessment output for visualization purposes. The different file exchanges between the CRR Oracle database and the RCat ArcGIS system are depicted in figure 1.

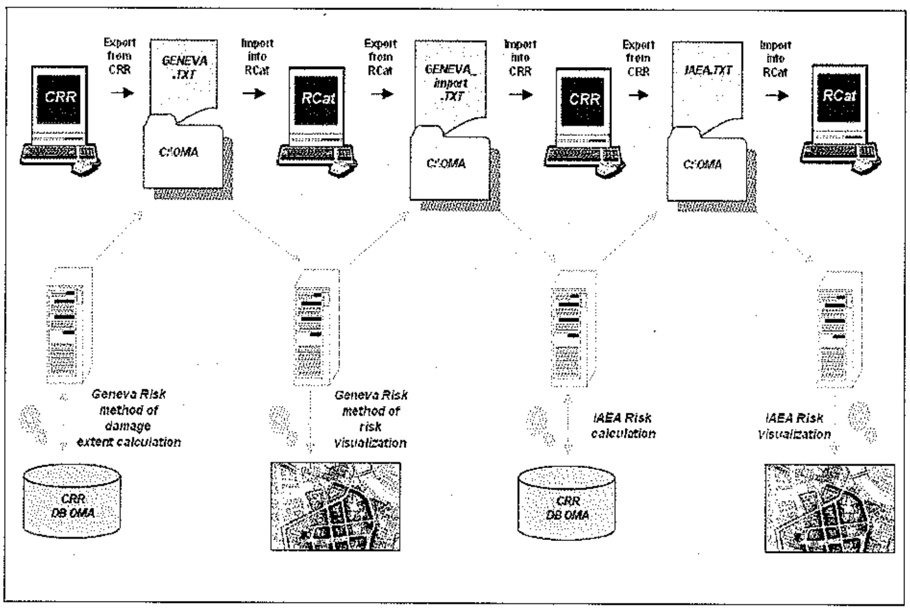

Figure 1: file exchange between the CRR and the RCat for calculations and map visualizations.

2.3 Risk calculations

The specific risk linked to an aircraft accident on a particular entity inside an industrial site is defined as the product of the maximized damage multiplied by the probability per square hectometre of that accident. Where, inside an entity, there are different substances that undergo risk calculations, the risk to the entity as a whole is the sum of all of these differentl risks. To show if the risk due to aircraft operations has any impact, we have to compare the effects of a maximized site damage due to an aircraft accident per hectare with the latent site risk independent of air traffic operations (e.g. that due to human error scenario, design failure, corrosion, etc.)..The comparison will so allow to figure out whether there is an influence linked to air traffic. The following paragraphs give more details on the specifics of the calculation process.

Calculation of the aircraft accident probability P_{AC}

P_{AC} is obtained by applying two sub-models :

- the accident ratio model deriving the total probability of an aircraft accident inside an investigation area (the area around the Geneva international Airport AIG), and
- the accident location model distributing that total probability over the investigation area according to empirical findings. The distribution follows analytically a combination of two probability density functions (PDF), a specifically shaped Laplace PDF (across the aircraft trajectory) and a Weibull PDF (along the aircraft trajectory)

Calculation of the total probability of the release of substance $P_{TOT\_SUBSTANCE}$

$P_{TOT\_SUBSTANCE} = P_{Sc} + P_{AC}$

P_{Sc}: Probability of the accidental scenario specific to the entity, inclusive of generic probabilities (e.g. of fires, human error, ruptures due to corrosion), and of factors specific to each entity

P_{AC}: Probability of aircraft accident on the entity, calculated in ArcGIS by superposition of the exact geographic location of the entity (X/Y-coordinates given by the risk register) and its area with the hectare raster of aircraft accident probability provided by GfL's External Risk calculation.

Quantity of liberated substances in case of an aircraft accident M_{Ac}

It is assumed that, as a consequence of the accident, the total quantity of chemical substances stored or processed in the entity is liberated into the environment:

$M_{AC} = M_{MAX}$

Calculation of the lethality radius of an aircraft accident

$LR100_{MAX} = LR100_{RSc} * (M_{MAX} / M_{RSc})^a$	AC:	scenario Air Crash
	MAX:	maximal quantity of substance
$LR10_{MAX} = LR10_{RSc} * (M_{MAX} / M_{RSc})^a$	RSc:	reference scenario
	LR100:	lethality radius (100% mortality)
	LR10:	lethality radius (10% mortality)
	M:	mass of substance (kg)
	a:	substance correction factor

The same calculations were used to determine the lethality radius in the case of a normal accident scenario, albeit with the proviso that a smaller quantity of substances would be released.

Calculation of the potential damage in case of an aircraft accident

Potential damage to the population is calculated by a superposition of the extent of the propagation, in terms of lethality radius, onto the grid containing geographical information of the effective population density given in number of residents and of working people per hectare and the aircraft accident probability per hectare. The following calculation references the two lethality radii of 10% and 100% of probability of death :

$Deaths = 0.1 * \cdot (w_{10} - w_{100}) + w_{100}$	w_{10} : Population inside the radius R_{L10} w_{100} : Population inside the radius R_{L100}

The outcome corresponds to the maximum damage caused by the most representative accidental release of the stored or processed chemical substance, with the worst consequences in terms of damage to the population expressed in death of exposed people. The same calculations are made for the estimation of the damages of normal accident scenarios.

Calculation of the risk in the case of an aircraft accident

The total risk for an industrial site, comprising a significant number of entities present in the site , is considered to be the sum of all risks of the substance scenarios (leakage of vessel release) of all the entities associated to this site added to all the aircraft accident risks of all the substances of all the entities. Calculations of this risk for all the hazardous industrial facilities present in the CRR allow us to identify the cases where the risks due to an aircraft accident are predominant over the classical industrial risks. All the detailed formulas are listed below.

Calculation of the accident scenario risk of the substance $R_{Sc\_SUBSTANCE}$ and the aircraft accident induced risk of the substance $R_{AC\_SUBSTANCE}$

$R_{Sc\_SUBSTANCE} = C_{Sc\_SUBSTANCE} \times P_{Sc}$ $R_{AC\_SUBSTANCE} = C_{Sc\_SUBSTANCE} \times P_{AC}$	$C_{Sc\_SUBSTANCE}$: Damage linked to the substance P_{Sc} : Probability of the scenario accident P_{AC} : Probability of the aircraft accident on the entity

Calculation of the total risk of the substance (accident scenario and air crash) $R_{TOT\_SUBSTANCE}$

$R_{TOT\_SUBSTANCE} = R_{Sc\_SUBSTANCE} + R_{AC\_SUBSTANCE}$	$R_{Sc\_SUBSTANCE}$: Risk scenario of the substance $R_{AC\_SUBSTANCE}$: Risk aircraft accident of the substance

Calculation of the risk of an accident scenario and of an aircraft accident on the entity

$R_{Sc\_entity} = \Sigma\ [R_{Sc\_substance}]$
$R_{AC\_entity} = \Sigma\ [R_{AC\_substance}]$

Calculation of the total risk of an entity (scenario and air crash) R_{TOT_Enity}

$R_{Tot\_entity} = [R_{Sc\_entity}] + [R_{AC\_entity}]$

Calculation of the risk linked to the site

$R_{Sc\_SITE} = \Sigma\ [R_{Sc\_entity}]$
$R_{AC\_SITE} = \Sigma\ [R_{AC\_entity}]$

Calculation of the total risk of the industrial site

$\mathbf{R_{Tot\_SITE} = [R_{Sc\_SITE}] + [R_{AC\_SITE}]}$

The same calculations were performed using the IAEA method, originally developed in 1996 for a quick assessment of risks in industrial zones (estimation of probability and damage of an accident scenario based on tables given in the manual), already existing inside the CRR. The objective was also to prioritize groups of sites through automatic calculations of industrial site risks stored inside the CRR. The interesting aspect of the IAEA method is that it can integrate correction factors linked to technical and organisational safety measures. The calculated results can also be used in order to generate interactive FN-curves (Frequency of N or more fatalities, as a function of N) for industrial facilities.

The accident damage was also similarly maximized by an automatic choice of an IAEA parameter which is related to the maximized released quantity, so that the final formula, with the same use of hectare aircraft accident probability retrieved from the RCat interface, is then

$R_{AC\_subst\_IAEA} = \text{Potential damage(entity)}_{max\_IAEA} \times P_{AC}$

The procedure to automate as much as possible the operational steps was the following :-

- The oracle database calculated new damage extent and generated a results file .
- This results file was imported into the ArcGIS RCat platform, where an accurate damage assessment was made using the detailed demographic data available in SITG.
- Risk calculations were performed based on the imported parameters. The new risk and probability values were again put back into the database.
- These new values were also used for the IAEA calculations to calculate a global plant risk by the summation of the risks of the different units.

The sequence of the various file exchanges between the Oracle database and the RCat ArcGIS part of the system is shown in figure 1.

3. Results and Visualization

The basic hypothesis is that in the case of an aircraft accident on a specific entity containing chemicals stored or processed inside that site, the full quantity of the substance is released into the environment. This is clearly a worst-case approach with regard to typical industrial accidents in which specific scenarios envisage only parts of the chemicals being released. These calculations were automatically performed for a large number of plants referenced inside the cantonal risk register. The results made it possible to identify those sites collections for which air traffic operations .do have a negative impact on the accidental risk.
If produced only as tables of numerical values, the results of this project would be hard to use, communicate or explain. A graphical presentation was thus one of the key goals. The following two figures show how risk assessment results may be clearly presented. Figure 2 shows the potential risks to plants induced by aircraft accident based on their location.. Figure 3 shows the specific risk contributions of air traffic operation hazard related to Geneva Airport and those due to normal accident scenarios.

As might be expected, the results show several cases where there is a significant increase in risks for plants situated located closely a given departure or arrival flight route from or to Geneva Airport.

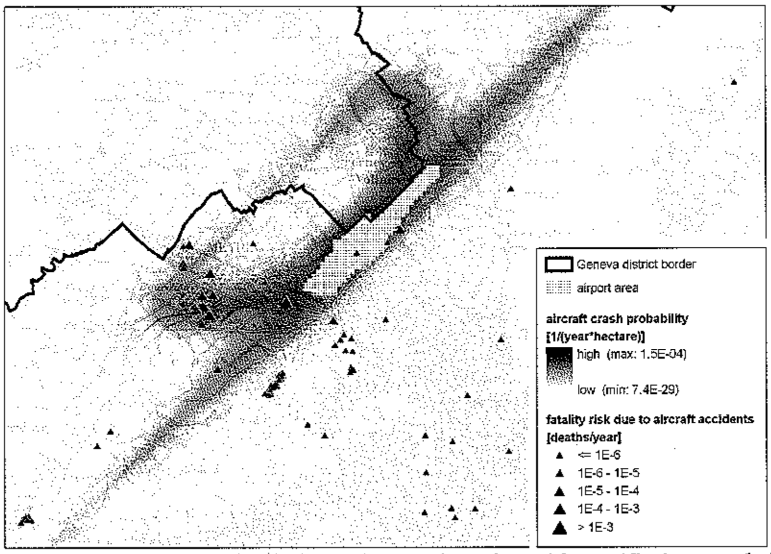

Figure 2: Potential risk of plants due to aircraft accidents (fictive results)

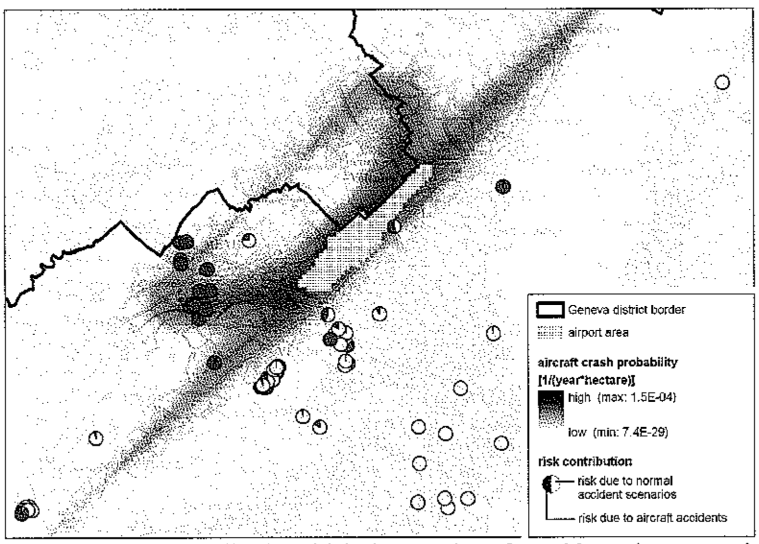

Figure 3: Risk contribution (risk due to aircraft accidents in comparison to risk due to normal accident scenarios) (fictive results)

4. Conclusion

The cartographic representation of hazards due to aircraft supplements the wide range of tools and projects forming part of Geneva Risk, a project initially dealing only with potential risks and damages caused by dangerous chemical substances (Susini and al. 2004; Hansen and al. 2005) and later completed with biological risks (Susini and all. 2006 and 2007). GIS methods make it possible to combine and sum up the risks derived from individual storage or process events into a cumulative risk for the plant. GIS also allows to visualize the risk levels and to partition them to specific areas. Furthermore, GIS facilitates the interpretation of data and presentation of the final numerical results. The accumulated risk layers of aircraft accident with major hazard plants lead to a prioritization of plants susceptible to involve significant risks to the population in the case of aircraft accidents. All of this was made possible by automating the interaction between an Oracle database, and various different GIS - layers.

Risk visualization using GIS is used to identify risk clusters and to facilitate control and law enforcement, as well as for the prevention and mitigation of the effects of possible future accidents .

The main beneficial results of the project can be summarized as :-

- The projections could be shared with other governmental units in the Canton of Geneva, in particular land management involving permits regarding storage of toxic gas inside sensible major hazard plants.
- Inspections of industrial facilities were prioritized based on the Geneva Risk decision-support tools.
- Safety improvement measurements were evaluated.
- A map for information of the public is now available.

The results calculated and visualized by means of GIS are judged to be an important instrument of risk communication between stakeholders, authorities, public and the airport.

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