Modeling of a Major Accident in Five Nuclear Power Plants From 365 Meteorological Situations in Western Europe and Analysis of the Potential Impacts on Populations, Soils and Affected Countries

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Abstract

The present study discusses the probability of a major accident in a nuclear power plant and, by simulation of such an accident, it evaluates the harm to people. It aims at characterizing the health effects of ionizing radiation, and it assesses the number of people impacted by a radioactive cloud, and by the deposition of radioactive material on the ground. It further evaluates the number of people in need of a resettlement. It also analyses the size of the area lost for agriculture due to radio-contamination.

More specifically, the Western European nuclear power plants (NPPs) under scrutiny are Beznau, Gösgen, Leibstadt and Mühleberg in Switzerland and Bugey in France. The study models a major nuclear accident using meteorological files, one for each day during the year 2017 with help of the trajectory and dispersion model *Hysplit*. The source terms of the simulated accidents are specific to each of the five NPPs. They represent an amount situated between the Fukushima and Chernobyl releases, according to available literature. Demographic data were treated by a geographical information system GIS software called *QGIS*. Conversion of radiation from Becquerel to Sievert was established according to the literature. Health effects were estimated from the committed collective effective dose (CCED), and used in connection with three risk models for different issues: cancer, cardiovascular and other non-cancer diseases, genetic and other reproductive detriments.

The main results are as follows: Between 16.4 and 24 million European inhabitants on average would be affected by a large radio-contamination. We found between 20,000 and nearly 50,000 radio-induced cancer cases, depending on the specific NPP. Additionally, between 7,500 and 18,500 radio-induced cardiovascular cases (myocardial infarction, cerebrovascular disease) are estimated as late effects of ionizing radiation. Stringent weather dependency of the numbers of victims were demonstrated with 4-fold and 20-fold differences for the highest and lowest deciles, and centiles respectively. The huge number of other radio-induced diseases, such as genetic and other reproductive effects could only be estimated semi-quantitatively due to lack of established risk factors. Furthermore, the number of people who should be evacuated and resettled could, on average, reach 250,000 for the smaller NPP (Beznau) and up to 500,000 for Leibstadt. In addition, the mean size of radio-contaminated crop and grazing land could amount to between 16,000 and 37,000 km^2. The impact of such an accident may heavily affect the population and economic activity of the concerned countries as well as creating a case of transboundary pollution.

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I Context

1.1 Scope of the study

The study models a major nuclear accident in one amongst 5 selected nuclear power plants in Switzerland and neighboring France, in 365 real weather situations, one for each day of the year 2017. The nuclear power plants studied are those of Beznau, Bugey, Gösgen, Leibstadt, and Mühleberg. As far as Switzerland is concerned, the study aims to quantify as comprehensively as possible the health impact, population displacement (migration impact) and the impact on agriculture. In addition, it includes very short questioning on the economic, financial and political impacts that are briefly presented, by contextualizing our results with the literature dedicated to these aspects. For Europe, the study aims to quantify the health, migratory, and political impact of a major accident when Europe as a whole is affected by a radioactive release.

To start, we first remember what is known in terms of the impact from the historic events in Chernobyl and Fukushima. Thereafter, the five selected NPPs are shortly presented.

1.2 Consequences of the Chernobyl and Fukushima accidents

The Chernobyl Nuclear Power plant [NPP] accident took place on 26 April 1986. It followed a nuclear reactor test which went out of control resulting in a nuclear meltdown. According to the International Atomic Energy Administration (IAEA), radioactive clouds were escaping from the ruins for 10 days and the wind was blowing in all directions during this period, dispersing radioactive material (IAEA 2006, 21).

The total area with ^{137}Cs soil deposition of 3,7 kBq/m^2 (1 Ci/km^2) and above covered an area of 192,000 km^2, the surface of soil above 555 kBq/m^2 was 10,300 km^2, while the area of soil above 1,480 kBq/m^2 was 3,100 km^2 (IAEA 2006, 23). Elements other than cesium have contributed to radiological contamination. In particular, a total area of agricultural land of 265,000 hectares received 111 kBq/m^2 of strontium-90 (^{90}Sr) and 3.7 kBq/m^2 of different plutonium isotopes (IAEA 2006, 84). These data as well as the map published by IAEA after the Chernobyl accident strongly show that, in the event of a major nuclear accident, high levels of radio-contamination should be considered up to hundreds of km from the source of the release (IAEA 2006, 25).

Displacement of the population was compulsory in the years 1986-87, for people living in areas with more than 15 Ci/km^2 (555 kBq/m^2) (Yablokov et al. 2009, 25). Consequently, 350,000 to 400,000 persons were forced to leave their homes while many others left the region voluntarily, which amounts to a total of 492,000 persons were to be resettled (United Nations 2002, 32).

Both measurement and modelling data show that the rural populations were exposed to external doses 1.5-times to 2-times higher than the urban populations living in areas with similar levels of radioactive contamination (IAEA 2006, 11). The collective dose to the thyroid was estimated at 2.0E+06 persGy; about half that dose by persons exposed in Ukraine (*ibid.*, 120).

However, information on the extent of the radioactive contamination is still highly controversial. This can be recognized by the divergent collective committed effective doses reported: 1° According to IAEA, the collective committed effective dose (CCED) was 52,000 persSv for approximately five million residents over 20 years (IAEA 2006, 119). 2° According to the World Health Organization, the radio-induced CCED was > 91,000 persSv over 20 years (WHO 2019)[5]. 3° According to Bennet, a collective committed effective dose of 600,000 persSv impacted worldwide populations, 36% of which concerning inhabitants in former USSR, 53% concerning European countries and 11% elsewhere in the northern hemisphere (Bennett 1995, 11; Bennett 1996, 125). 4° Eventually, Yablokov et al. (2009, 24) report that the CCED to be considered was between 600,000 and 900,000 persSv. In short, the spread is more than one order of magnitude.

The accident of 11 March 2011 in Fukushima had a smaller impact on habited areas compared to the Chernobyl accident. This may be explained by a favorable meteorological situation, with winds contributing a major part (about 75 %) of the radioactive emissions towards the Pacific Ocean (Aliyu et al. 2015). Therefore, no evacuation measure for the 50 Million citizens in the Tokyo region had to be considered.

[5] WHO enumerates the number of people having received a dose higher than four levels of individual committed effective dose, which makes: (240,000 * 0.1 Sv) + (116,000 * 0.033 Sv) + (270,000 * 0.05 Sv) + (5,000,000 * 0.01 Sv) = 91,328 persSv.

According to the official committee of the Japanese Parliament, an area of about 1,800 km^2 had a contamination level leading to an effective dose of 5 mSv per year or more (The National Diet of Japan 2012, 19)[6]. People located within a radius of 3 km around the plant were evacuated first, thereafter the evacuation zone was extended to a radius of 10 km and then to a further 20 km (*ibid.*, 38). On 15 March, residents between 20 and 30 km were ordered to remain, even though they faced high radiation levels (*idem*). These residents were finally given the opportunity to leave the 30 km zone one month after 11 March (*idem*). All in all, around 150,000 people were evacuated in response to the accident (*ibid.*, 19). Mismanagement in the evacuation process as well as the absence of implementation of countermeasures to the risk of a major nuclear accident in Japan were "the result of collusion between the government, the regulators" and the operator (*ibid*. 16). "The conceit was reinforced by the mindset of Japanese bureaucracy" dedicated at first to the defense of the interests of their own organization (*ibid.* 9). Operators "strongly influenced" and lobbied the Japanese "energy policy and nuclear regulations", while letting the regulator bear the eventual consequences of the incompleteness of the rules (*ibid*. 43-44). In other words, they "manipulated the cozy relationship with the regulators to take the teeth out of rules and regulations", while abdicating their own responsibilities (*idem*). Finally, the report of the official committee concludes that the Fukushima accident was clearly "manmade" (*ibid.* 9, 16, 21), which will lead us to study the human factor as a cause of risk (*infra* 1.5(iii)).

1.3 Ionizing radiation – health hazards – Importance of epidemiology, linear no threshold model (LNT) and beyond

The health risks of ionizing radiation (IR) were first identified in the late 19th century (Edison 1896) (Doll 1995, 1339-1349). Groundbreaking studies on genetic effects due to IR have been performed by Muller in the early twenties of last century (Muller 1928, 714). Quantitative aspects of health damages in humans due to IR, however, have only been systematically analyzed since around 1950 – especially in the medical radio-diagnostic field (Giles 1956, 447; Stewart 1958, 1495-1508; Pearce 2012, 499-505; Mathews 2013, f2360), in the long-term studies in Japanese nuclear bomb survivors (Ozasa 2012, 229-243), in nuclear workers (Richardson et al. 2015, h5359; Leuraud 2015, e276-e281; Gillies 2017, 276-290), in people exposed to indoor radon gases (Darby 2005, 223) and in children with respect to natural background radiation (Kendall 2013, 3-9; Spycher 2015, 622-628).

The concept of collective dose calculation has been proven useful in IR risk estimations for exposed populations (BEIR VII 2006a; BEIR VII 2006b, 1-4). Recent extensive epidemiological studies on medical effects of IR even in the so-called low dose range (below 100 millisievert, mSv) have led to the presently widely accepted LNT (Linear No Threshold) model (BEIR VII 2006a; BEIR VII 2006b, 1-4; Shore 2018, 1217). According to LNT there is no harmless IR dose: Even very small doses of 1 mSv and below result in a risk for stochastic health effects such as cancer induction, non-cancer diseases and detrimental effects on the reproductive process.

The internationally legally binding limit of radio-contamination by artificial sources is 1 millisievert/year (mSv/a) per person (*infra* 1.5(ii), 2.6(iii)). However, NPP accidents such as the 1986 in Chernobyl /Ukraine and in 2011 in Fukushima/Japan led to IR exposures in the individual dose range mainly below 100 mSv or above this level for many millions of residents (Cardis 1996, 241-271; WHO 2013; IPPNW 2016).

Apart from the above-mentioned basic literature, more in-depth references for assessing the health impact of a major nuclear accident will be given in the section "methodology" (*infra* 2.7).

[6] However, it is difficult to calculate the long-term health impact of such doses, given the prohibition of independent investigations into radioactivity levels around Fukushima (Kim et al. 2013; Fackler 2016). In any case, the contamination of the Pacific Ocean represents the worst and still ongoing ecologic damage due to the Fukushima accident threatening the important Japanese fishery industry as well as the whole pacific food chain.

1.4 Five Swiss and French NPPs under scrutiny

(i) The five NPPs

Together, the five nuclear power plants evaluated in this this study have 9 reactors with a capacity ranging from 1,097 MWth to 3,600 MWth. Three reactors have a power of less than 1,100 MWth (Beznau I & II, Mühleberg). Six reactors have a capacity between 2,785 MWth and 3,600 MWth: Bugey II, III, IV and V, Leibstadt and Gösgen). Of the 9 reactors studied here, the least old is the Leibstadt reactor, which was connected to the grid in 1984. Eight reactors have been operating for 40 years or more, such as Beznau I, which

Table 1.1: The 5 NPPs and 9 nuclear reactors

NPP Name	Reactors No & Type		Construct° Year	& Grid connect° Year	Reactor power MWth	Capacity MWe	Location Country	Close to Country	Decommissioning Date
Beznau	2	PWR	1965-68	1969-71	1130	365	CHE	GER	(…)
Bugey	4	PWR	1972-74	1978-79	2785	880-910	FRA	CHE	(…)
Gösgen	1	PWR	1973	1979	3002	1010	CHE	GER	(…)
Leibstadt	1	BWR	1974	1984	3600	1220	CHE	GER	(…)
Mühleberg	1	BWR	1967	1971	1097	373	CHE	GER, FRA	2019.12

Source: (IAEA 2018a) Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR)

has been in operation for 50 years (it is the oldest operating reactor in the world). Their main characteristics are briefly summarized in Table 1.1.

(ii) The 5 NPPs and conformity to present safety norms

A key problem of the Swiss NPP's and the French Bugey NPP is their technical and physical aging (Majer 2014). Also, whereas physically aging equipment has been regularly upgraded since the beginning of exploitation, the technology of the plants has remained that of the years 1950-1960. Furthermore, defaults in the structure of the reactors and other safety systems have not been corrected.

The best-known among these defaults are the fissures in the reactor core shroud of the Mühleberg reactor, which have been discovered in the 1990ths and interpreted as a consequence of steel corrosion by the coolant (ENSI & TÜV Energie 2009). Despite the presence of these cracks, the core mantle has not been replaced, but only stabilized by a mechanical anchor system, and corrosion has been limited by chemical adds in the cooling water.

Another example of uncorrected defaults has been identified in the reactor of the Beznau-1 NPP: In the reactor pressure vessel about 1,000 cavities due to fabrication errors were detected in 2015 (Bishop 2015). However, after a long period of inspection, the reactor re-started in 2017 without any replacement of the pressure vessel.

All reactors of the 5 NPP's have a record of nuclear events[7]. As an example, we will refer to the record of NPP Leibstadt. The power plant is located in northern Switzerland on the shore of the Rhine-River which also corresponds to the national border with Germany. The power plant is owned by six Swiss electricity companies; ATEL has the maximum share of 27%.

The Planning of the power plant started in 1964 (KKL 2018), but several changes in the initial project resulted in long delays and costs of 4.8 billion CHF. The plant was finally connected to the grid in 1984. Leibstadt has a BWR-6 reactor of General Electric. The plant was initially exploited at a production level of 960 MW. From 1998 to 2003 this level increased in two stages up to 1,165 MW, and in a further stage, in 2012 to 1,275 MW. In 2016, the consequences of dry-out where discovered on nuclear fuel elements, and reactor power had to be reduced by order of the regulator.

NPP Leibstadt has a long history of incidents and management problems. Among these, we mention in particular the following sequence:

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[7] See the reports of the nuclear safety authorities and the compilations on www.wikipedia.com.

- Fuel element damages and problems in staff management were known since the 1990s. Such damages are expressly mentioned in the activity reports of 1995 and 1997. The damages where explained later by fretting (friction induced damages) (ENSI 2019).
- In 1991, the nuclear safety authority HSK discovered falsified inspection reports (HSK 1991).
- An electric generator incident in the spring of 2005 was at the origin of a 6 months shut-down (ENSI 2005).
- In June 2014 a plant inspection discovered that the primary containment had been perforated for the purpose of mounting of a fire extinguisher in the year 2008 (ENSI 2014a).
- This long-lasting incident was followed by another long lasting dry-out event, discovered in 2016, but that had lasted much longer, probably since 2011/2012. Consequently, the power plant had to stop production after several months (SRF 2017; ENSI 2017).
- The most recent incident happened in the spring of 2018, when a water pump of the emergency system was not fully available for 2 months (ENSI 2018).
- In another incident, once more, inspection reports were falsified by a collaborator of the NPP (ENSI 2019).

When considering the entire list of incidents and other problems during the exploitation, one has to consider this NPP as one of the (or as the) most vulnerable nuclear plants in Switzerland.

1.5 Probability of a major nuclear accident in western Europe

This section aims to answer the question of whether the simulations of a major accident are relevant or not. Practically, the question is whether the probability of a large core damage and the massive release of radioactive material is 'very unlikely' and 'remote' (1 major accident for ≥ 1.0E+06 years of reactor operation), as official authorities say (IAEA 2009, 8; 2018b, 45)? Or whether it is 'unlikely' (in the order of 1 accident per 1.0E+05 years)? Or would it actually be 'possible', in the order of 1 accident per 1.0E+04 years? And what would that mean for our understanding of nuclear safety of NPP's in general? The answer to the above-mentioned question will decide as to whether or not, this study is relevant from the perspective of the respective strategies of the countries involved.

We start by a brief presentation of the debate about the scientific validity of the probability numbers published by official bodies and the nuclear industry.

(i) What are deterministic and probabilistic safety analyses?

The question of the probability of a major accident has been discussed by the scientific community, regulatory bodies and above all by the IAEA (IAEA 2009, 2018b). The most widely accepted method for the evaluation of a severe, or a major accident is called "deterministic safety analysis". According to IAEA: "Safety analyses are analytical evaluations of physical phenomena occurring at nuclear power plants, made for the purpose of demonstrating that safety requirements, such as the requirement for ensuring the integrity of barriers against the release of radioactive material and various other acceptance criteria, are met for all postulated initiating events that could occur over a broad range of operational states, including different levels of availability of the safety systems" (IAEA 2009, 7–8). Such analyses are completed by probabilistic safety analyses to identify the sequences that lead to core degradation and also to quantify the more frequent sequences leading to limited damage or no-damage scenarios (IAEA 2009, 7). They aim at identifying and quantifying the many possible accidental sequences, through the use of event tree models that enable the determination of the frequency of each accidental sequence (triggers and event paths) (IAEA 2009, 8; Wheatley et al. 2017, 99; ENSI 2014b, 11). The Swiss Federal Nuclear Safety Inspectorate (hereafter ENSI) enumerates the following initial events that may cause reactor failure: fire, explosion, turbine failure, flood, loss of cooling equipment, failure of various systems, untimely activation of safety systems, accidental aircraft fall, tornadoes, plugging of water intake, and earthquakes.[8] It is admitted that well implemented Probabilistic Safety Analysis (PSA) is a

[8] The appreciation of the probability of earthquakes has been modified since recent studies have shown that the frequency of severe earthquakes is higher than previously assumed. Improvements have since been made to improve resistance to seismic events. Although extreme earthquakes in Switzerland have a low frequency of occurrence, "an earthquake exceeding the dimensioning thresholds cannot be excluded" (ENSI 2014b, 11). Such an earthquake could cause a core meltdown accident and radioactive releases outside the affected nuclear power plant.

useful method to provide methodological support for the safety assessment and for improving the safety of nuclear reactors (Löffler et al. 2017, 29) (*infra* iii).

(ii) Normative requirements

Table 1.2 summarizes the probability of a certain accident level in accident per year, to which NPPs should comply. The IAEA criteria states that events having an expected frequency between 1.0E-04 and 1.0E-02 should not have a radiological impact outside an exclusion area (IAEA 2009). In a more recent publication it is specified that in an "emergency exposure situation" the constraint shall be set between 20 to 100 mSv, and that in a "planned exposure situation" the dose constraint for the exposure of the public should not be greater than 1 mSv per year (IAEA 2018b, 51).

Table 1.3 shows how Article 123(2) of the Radiological Protection Ordinance of the Swiss Federal Council sets the limit of exposure in the range defined by IAEA (Swiss Federal Council 2019, Art. 123(2)(c)(d)). The expected frequency of any event serves as a criterion for setting the limit of different committed effective doses expressed in mSv. If Article 123(5) enjoins the supervisory authority (ENSI) to define the methodology and boundary for the analysis of failure conditions in vague terms, another text specifies its content. The Nuclear Energy Ordinance specifies that *"each risk assessment must incorporate an up-to-date, plant-specific probabilistic safety analysis (PSA)* (Swiss Federal Council 2004, Art. 33(1)(a))*"*, considering internal or external events able to trigger large releases of radioactive substances into the atmosphere, as well as a quantitative evaluation of preventive mitigating measures (Swiss Federal Council 2004, Annex 3(2), Technical documents on PSA).

Table 1.2. Probabilities of an accident and the related normative criteria (IAEA)

Occurrence	Characteristics	Criteria
1.0E-04 – 1.0E-02	Possible	No radiological impact outside the exclusion area
1.0E-06 – 1.0E-04	Unlikely	Radiological impact outside the exclusion area within limits (20-100 mSv)
<1.0E-06	Remote (severe accidents)	Emergency response needed

Simplified from IAEA (2009, 8; 2018b, 45)

Table 1.3. Probabilities of an accident and the related normative criteria (*Swiss Federal Council*)

Expected frequency	Criteria
1.0E-04 – 1.0E-02	The dose resulting from a single such event for members of the public must not be greater than 1 mSv.
1.0E-06 – 1.0E-04	The dose resulting from a single such event for members of the public must not be greater than 100 mSv; the licensing authority may specify a lower dose in individual cases
<1.0E-06	By inference: doses > 100 mSv are allowed by law if the expected frequency is $<10^{-6}$

Ordinance 814.501, From chapter 8: Failures, Article 123(2), letters c, d (Status as of 1 February 2019)

In other terms, PSA is used to show that, (i) the Swiss NPPs won't result in a public exposure > 100 mSv while the 'expected frequency' of the event (determined by PSA) is > 1.0E-06 year per reactor, (ii) they won't result in a public exposure > 1 mSv while the 'expected frequency' of the event is between > 1.0E-04 and < 1.0E-02 year per reactor. In some respects, they would be 'allowed by law', to release doses > 100 mSv in the event of an accident with an expected frequency < 1.0E-06 year per reactor (*infra* 2.6(iii)).

To conclude this point, the PSAs of the five NPPs under scrutiny in this study have to satisfy the above-mentioned limits. However, for newly built plants, plant specific core damage frequencies (CDFs) without notable radioactive releases obtained by PSA have to comply with the limit of 1.0E-06 per reactor-year, rather than the former usual limit of 1.0E-04 per reactor-year (Sornette et al. 2013, 61).

(iii) Structural shortcomings of PSA

A certain arbitrariness lies behind PSA that causes analysts' predictions to be altered by structural shortcomings. As stated in the report subsidized by the European Commission and coordinated by IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*), PSA models – as well as advanced approaches such as dynamic PSA, fuzzy probability approaches, or multi-state Markov-process modelling – do not include certain parts of the risk, either intentionally or due to lack of knowledge (Löffler et al. 2017, 12). PSA models suffer from lack of data, incompleteness, insufficient methods for the assessment of some human actions (Löffler et al. 2017, 29–30). Additionally, as recognized by the Swiss official body ENSI and the study coordinated by the French official body IRSN, industrial sabotage, or terrorist attacks, such as willful plane crashes or acts of war are not taken into accounts by PSA (ENSI 2014b, 11–12; Löffler et al. 2017, 65). These considerations can also be put into perspective with the fact that the conception of none of the 9 reactor pressure vessels under scrutiny have benefited from the lessons drawn by the Three Mile Island, Chernobyl, and Fukushima accidents (*supra* 1.4). Ageing and outdated pressure vessels would therefore worsen the consequences of willful acts due to the so-called human factor that PSA ignore almost systematically. In other terms, since PSAs neither include the wide range of human malignity, nor administrative and political negligence, they are consequently ill-suited to specify the risk related to NPPs.

In addition, empirical evidence seems to confirm the inability of PSA to specify the whole truth about the risk of a major nuclear accident (*infra*).

(iv) Empirical evidence of PSA shortcomings

According to the literature, probabilities calculated in PSA do not fit the experienced frequencies of major reactor failures. The French *Institut de Radioprotection et de sûreté nucléaire* (IRSN) pointed out that severe accidents with core damage have happened more often than predicted by PSA analysts (Löffler et al. 2017, 28). Furthermore, several independent studies have performed statistical analyses of historical data through a "bottom-up" approach and have almost universally found that PSA dramatically underestimates the risk of accidents (Wheatley et al. 2017). On the one hand, several studies have observed four large releases in around 14,500 operating-years (depending on the date of assumption), which makes about 1 large release per 4,000 operating years (2.5E-04) instead of the PSA probability limit of < 1.0E 06) (Lelieveld et al. 2012; Piguet 2015); the discrepancy with PSA is a factor of 250. On the other hand, these historical data do not predict the future occurrence of significant releases, since the safety standards of nuclear power plants have evolved over the seven decades of their history (Rangel & Lévêque 2012, 90).

(v) What could be the probability of a major nuclear accident in the 5 NPPs and the related 9 reactors?

The vast majority of existing reactors in the world pertains to the so-called Generation II and were developed and built between the 1960s to the 1990s. Only Generation III reactors adopted passive safety features instead of active ones (requiring power) (Wheatley et al. 2017, 105). As a matter of consequences, a statistical approach should take into account the historical trend in a wide range of accidents and historical safety improvements (Rangel & Lévêque 2012, 96). Such a historical and complex approach goes beyond the PSA and, although far from being perfect, it is better suited to protect the public interest than the PSA (as well as to protect the insurer's interest). We summarize two important articles among several others below.

According to Rangel & Lévêque (2012, 92), such a purpose requires extending the observations to accidents with levels ≥ level 3 INES and to use a model called Poisson Exponentially Weighted Moving Average (PEWMA) suited for studying time series. This model is more suitable than other statistical models due to the fact that nuclear reactors are in operation for a long lifetime, and the fact that innovations take time to be installed by operators (*ibid.*, 97). As a result, when looking at the core meltdown accidents (with or without large releases), it appears that the expected frequency can be estimated at 1.95E-03 per reactor-year[9], a number considerably higher than 2.00E-05 determined by Gaertner on US reactors through PSA (Gaertner et al. 2008, 3), and twenty times higher than the 1.0E-04 IAEA criterion for a release corresponding to a population dose of < 1mSv. These results are corroborated by another study (*infra*).

Wheatley et al. have analyzed the occurrence of a major accident using a more complete and unique data set containing 216 events; 175 of which have cost values (Wheatley et al. 2017, 102). Estimating cost aims to encompass total economic losses, including environmental remediation, court and insurance claims, and loss of life, estimated at 6 Mio USD per death. This has the advantage of reaching a single metric in USD combining all possible negative effects of accidents (albeit not without imperfection) (*ibid.* 2017, 102). Eventually, the analysis shows that, in terms of costs, there is a 50% chance that (i) a Fukushima accident (or larger) occurs once in 62 years, and (ii) a Three-Mile-Island accident (or larger) occurs once in 15 years (under the assumption of a constant number of NPPs) (*ibid*. 2017, 112). If we consider the 448 operational reactors in the world in year 2017 (IAEA 2018a, 15), the risk of a Fukushima event occurring with large release is roughly 1.8E-05 per reactor-year, a figure 18 times higher than the maximum permissible probability of one large

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[9] (Rangel & Lévêque 2012, 96) The article provides four main results through four methods, (i) MLE Poisson (6.66 10-4), (ii) Bayesian Poisson-Gamma (4.39 10-4), (iii) Poisson with time trend (3.2 10-5), (iv) PEWMA model (1.95 10-3). The authors give precedence to the latter model and result over the three other approaches.

radioactive release per 1,000,000 reactor-years as set by IAEA and other official bodies (IAEA 2009, 8; 2018b, 45).

All in all, many other bibliographic sources (Ha-Duong & Journé 2014; Sornette et al. 2013) show that these kinds of statistical methods are widely explored among scholars finding similar results. The gap between the historical approach and PSA can be explained by the numerous limitations of the latter (*supra* 1.5(iii)). Therefore, the probability per reactor and per year of a major accident evaluated at 1.8E-05 by Wheatley et al. likely describes the expected frequency of a major nuclear release by one among the 9 above reactors.

Table 1.4. Probability of a major nuclear release during the operating time of a fleet of 9 reactors designed – and connected to the grid for 8 of them – before or during 1979, year of the Three Mile Island Accident

Source:	Probability of a major accident for 1 reactor over 1 year	Probability of a major accident for 1 reactor over 1 year (%)	Probability of a major accident for 9 reactors over 50 years (%)
1.8E-05 is from Weathley et al. (2017).	1.8E-05	0.0018%	0.810%
The norm ≤ 1.0E-06 is from IAEA*.	≤ 1.0E-06	≤ 0.0001%	≤ 0.045%

* According to the law, IAEA and many regulators, in case of a major nuclear release entailing a committed effective dose ≥100 mSv, the expected frequency of the initiating event should not overpass a probability of 1.0E-06 as calculated by a probabilistic safety analysis (PSA).

If one would consider such a probability at the scale of the fleet of 9 reactors for an operational time of 50 years, one would discover that such ‘catastrophe’ has a probability of 0.8% (Table 1.4)[10]. IAEA itself categorizes such level of risk as “possible” (IAEA 2009, 8), which means it is neither “remote”, nor “very unlikely” as it should be, nor even “unlikely”. It is “possible”. In other words, to know what a major nuclear accident would imply for the Swiss and European people becomes a strategic question, besides an ethical one[11].

1.6. Existing studies on the simulations of the impacts of major accidents in European NPPs

Lelieveld et al. (2012) assessed the exposure to an INES 7 major accident, using particulate ^{137}Cs and ^{131}I as proxies for the fallout. Their results notably indicated that the average surface area in which ≥ 40 kBq of ^{137}Cs would be deposited would be about 165,000 km^2. Using a global model of the atmosphere, they found that more than 90 % of the ^{137}Cs release would be transported beyond 50 km.

A study using the Lagrangian particle model FLEXPART has explored systematically the consequences of a major nuclear accident in NPPs. It was found that substantial consequences (intervention measures) occur frequently for a distance range of up to 100-300 km, and that emergency planning often focuses on too small areas (Seibert et al. 2013).

Two experts from the official and French *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) have issued a study on a core meltdown in a French 900 MWe PWR followed by (i) a severe radioactive release and (ii) a massive radioactive release (Pascucci-Cahen & Patrick 2012, 1–9). On average, a major accident of this size could cost more than € 400 billion, which can be compared with the cost of a large economic crisis, or to the cost of waging a regional war (*ibid.*, 1–9). The cost would be supported by the whole population of France and around 100,000 persons could be in need to be permanently relocated (*ibid*., 1–9).

The Federal Nuclear Safety Inspectorate (ENSI) issued a report in the wake of the Fukushima accident. The report briefly presents the components of simulations of different types of nuclear accidents in Switzerland in order to understand their dangers (ENSI 2014b). The aim is to produce figures illustrating the health pressure on populations in order to prepare emergency planning in the vicinity of nuclear power plants. In concrete terms, level 7 accidents according to the International Nuclear and Radiological Event Scale (INES) are detailed in 3 sub-categories: A4, A5, A6. Category A5 would correspond to an accident of Fukushima's severity level and A6 of Chernobyl's severity level. Accidents are simulated for iodine, cesium and rare gases.

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[10] The question remains open whether the 9 reactors comply with the precautionary measures that are required by law, “in accordance with experience and the state of art in science and technology” (Swiss Federal Assembly 2018) Article 4(3)(a)). It is the third principle of the chapter entitled “Principle of nuclear Safety”.

[11] If one remained totally confident about the completeness of PSA made by ENSI, IAEA or other regulators, he might be amazed by very simple numbers about a potential major accident that the norm aims to avoid. He would discover that a probability per reactor and per year established at 1.0E-06 would rise at 4.5E-04 (0.045% or 0.45 ‰) for a fleet of 9 reactors in operation for 50 years. In other terms, when it comes to envisaging the problem from another scale, the probability of a release entailing a committed expected dose ≥100 mSv would jump from the category ‘very unlikely’ to the category ‘possible’.

- Accident A5: Iodine, 1.0E+17 Bq; Cesium (class Rb-Cs), 1.0E+16 Bq; Rare gases, 100% release.
- Accident A6: Iodine, 1.0E+18 Bq; Cesium (class Rb-Cs), 1.0E+17 Bq; Rare gases, 100% release.

The report illustrates the health pressure with graphs showing the number of millisieverts received for different categories of the population according to their distance from the affected nuclear power plant. In particular, we learn that in the event of an A5 accident, the effective dose is 2,000 mSv for an adult staying unprotected for 48 hours at 2 km from the accident, and 150 mSv at 20 km (ENSI 2014b, 22-23). The report also quantifies the dose to the thyroid as a function of accident level, distance and age. It evaluates the influence of weather on the doses received (ENSI 2014b, 25-26).

It is noticeable that the above reports say nothing about the number of people affected (cases of cancer and cardiovascular disease), and they do not say how many people could be displaced and what can be the overall impact on the country – with the exception of the Pascucci-Cahen & Patrick document. They raise nonetheless many questions that the present article intends to address.

II Methodology

2.1 Outline of the methodology questions

A few methodological points are discussed below: the quantities of Becquerels used in the simulations (source term study) (*infra* 2.2); the physical coefficients of the dispersion of rare gases and aerosols in the atmosphere (deposition velocity, in-and below-cloud removals, the Henry's constant) (2.3); the consideration of meteorological data and their influence on the results (2.4); the assessment of impacted people, soils and countries using a Geographic Information System (2.5); the calculation that allows to use Becquerels to calculate the collective committed effective dose (CCED) received by the populations and the calculation performed to compare individual CED to the legal limits in mSv (2.6); the health impact and the related number of radio-induced diseases (2.7). Only an interdisciplinary approach can carry out such a questioning.

2.2 Source term

(i) The release question

This section aims to define the amounts of nuclides that could possibly be released from the reactor pressure vessel into the containment building and, more specifically, outside the containment building (source term). The list of nuclides and their respective quantities depends on the type of reactor and the kind of accident in question (Table 2.1). If we look at additional data on the respective release profiles of Chernobyl and Fukushima (Table A1 in the Annex), the releases from the lanthanide and cerium groups would be between 1,400 to 9,700 times higher at Chernobyl compared to the Fukushima event (IAEA 2015, 7). By contrast, the aerosols release would be only 9-times higher at Chernobyl compared to Fukushima, if one takes into accounts the relative importance of each nuclide in the source term[12]. Important discrepancies can be found between the two major accidents when looking at the details. The factors range from 1.6 (^{134}Cs), 6.3 (^{137}Cs), 7 (^{131}I), 14 (^{132}Te), 140 (^{90}Sr) to 4.3E+06 and 3.5E+07 for (^{103}Ru) and (^{106}Ru) respectively[13].

Table 2.1. Comparisons of two different assessments of the source term of Chernobyl and Fukushima respectively

Nuclides	Fukushima: Factors inferred from IAEA*. From the lowest to the highest IAEA estimates. *Factor*
Ba-140	18.2
Cs-134	6.0
Cs-137	2.9
I-131	4.0
Ru-103	9.5
Ru-106	1.0
Sr-89	302.3
Sr-90	42.4
Te-132	213.2
Weighted average	5.6

* Data inferred from IAEA (2015) (IAEA 2015, 7)

[12] The comparisons are made through the numbers of the average Fukushima release which we have computed from the low and high IAEA estimations.

[13] We inferred these numbers from: (IAEA 2015, 7)

If we look at Table A2 in the Annex, in relation to the assessment of the Fukushima accident, the factors from the lowest to the highest estimates are the following: 1 for 6 data, ≥ 2 for 17 data, ≥ 4 for 14 data, ≥ 6 for 12 data, ≥ 40 for 6 data, ≥ 100 for 5 data, and ≥ 3,600 on the last line of the list.

(ii) Literature on the source term of the 5 NPPs

The core inventory of the Swiss NPPs, as well as the four French reactors at Bugey, have not been published in a very detailed manner by official bodies. A study with the purpose to shed light on the impact of possible nuclear accidents needs to infer the figure from other bibliographic sources. First, some analogies can be built in order to infer what they can be. For instance, Lelieveld et al. assumed that the potential release of any reactor can be scaled to the Chernobyl accident through its gross capacity (Lelieveld et al. 2012).

Second, we had to find data in the literature and we focused mainly on the figures of the Flexrisk Report (Seibert et al. 2013), of the Oeko-Institut Darmstadt (Ustohalova et al. 2014), and the U.S. Nuclear Regulatory Commission (NRC) (Hanson et al. 1994).

- The Flexrisk project published few data on the source term of 88 European NPPs having between 1 and 4 reactors, with the exception of 4 Russian NPPs having 5 or 6 or – in two cases – 8 reactors (Seibert et al. 2013). The figures of this bibliographic source covers the 9 reactors of our study and the following nuclides: ^{133}Xe, ^{131}I, ^{137}Cs, ^{90}Sr, ^{132}Te et ^{106}Ru (Seibert et al. 2013).
- The second bibliographic source covers three Swiss NPPs and provides data for some of the remaining nuclides: ^{140}Ba, ^{134}Cs, ^{136}Cs, ^{89}Sr, ^{127m}Te, ^{129m}Te (Ustohalova et al. 2014).
- The publication of the NRC documents the possible release of 60 nuclides. It is dedicated to the study of different types of nuclear power plants (Hanson et al. 1994), which allows one to quantify any radioactive release from a nuclear power plant with the same characteristics. Since each of the nine reactors is built on principles similar to at least one of the American reactors, by analogy, it becomes possible to derive the potential release of the nine reactors from the corresponding American reactor.

Analogy between the reactors are perfect for Leibstadt and Mühleberg, quite good for Beznau and Bugey, and acceptable for Gösgen (Table 2.2).

Table 2.2. Analogies between the 5 NPPs and the well-documented U.S. reactors

Country	Type	Name	MWth	Additional characteristics	Constructor
Swiss	PWR	Beznau I & 2	1130	WH 2LP	WH = Westinghouse
US	PWR	Surry 1 & 2	2587	WH 3LP (Dry Subatmospheric)	WH = Westinghouse
Swiss	PWR	Gösgen	3002	PWR 3 Loop (wet type cooling power)	KWU=Kraftwerkunion (D)
US	PWR	Surry 1 & 2	2587	WH 3LP (Dry Subatmospheric)	WH = Westinghouse
France	PWR	Bugey 2,3, 4 & 5	2785	CP0 & PWR 3 Loop	Framatome / Westinghouse licence
US	PWR	Surry 1 & 2	2587	WH 3LP (Dry Subatmospheric)	WH = Westinghouse
Swiss	BWR	Leibstadt	3600	BWR-6 (Mark 3)	GE = General Electric
US	BWR	Grand-Gulf	4408	BWR-6 (Mark 3)	GE = General Electric
Swiss	BWR	Mühleberg	1097	BWR 4 (Mark 1)	GE = General Electric
US	BWR	Peach Bottom 1 & 2	3951	BWR 4 (Mark 1)	GE = General Electric

IAEA, International Atomic Energy Agency. Nuclear Power Reactors in the World (IAEA 2018a) <https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-2-38_web.pdf>.

The release scenario displayed by the NRC is not given with the same accuracy since the scenario compatible with a major accident is not detailed for each reactor. On the one hand, the analogy would lead to underestimated figures for at least 1 out of 5 NPPs (Leibstadt). On the other hand, not drawing an analogy with these data would aggravate the underestimation of the global release (source term). Thus, we decided to integrate the data since it gives an insight on what is missing on the potential sources of underestimation (on the possible underestimation of ^{134}Cs, *infra* 4.3).

(iii) Definition of the source terms for one reactor in each of the 5 NPPs

For each NPP, the amount of the release is estimated for one reactor. Finally, it has been decided to define the list of nuclides to examine from the NRC (Hanson et al. 1994), then to respect systematically the following rule (for each NPP):

1° To select the numbers of the 5 nuclides published by Flexrisk on the 5 NPPs of this study.

When these data do not cover the remaining nuclides on the list:

2° To select the numbers of Ustohalova et al. (2014) on the 6 following nuclides: ^{140}Ba, ^{134}Cs, ^{136}Cs, ^{89}Sr, ^{127m}Te, ^{129m}Te.

If the latter data are not available for the remaining nuclides on the list:

3° To select the numbers we deduced from the NRC.

If the numbers defined in 1° and 2° are not consistent with NRC's framework:

4° To adjust (reduce) the amounts which would exceed the released fraction of each group of isotopes defined by the NRC as high.

We do not integrate the half-life time period in the simulation of the cloud. As many nuclides have a short half-life, which could have resulted in an overestimation of the impact on health, we decided to limit that effect. Therefore, isotopes with a half-life shorter than the simulation duration of the radioactive cloud were excluded from the calculation (i.e. < 72h).

5° Consequently, exclude from the source term nuclides with a half-life below 72h.

As the detailed scenario RGG3 (Gran Gulf) is far from matching a major accident, we increased slightly the figures of a release at Leibstadt with respect to the higher scenario RGG1 whose release fractions are published for each group of nuclides: iodine, cesium, tellurium, strontium, barium, ruthenium, lanthanium and cerium (Hanson et al. 1994, Table A.11).

Table 2.3. Summary of the simulations: Becquerels released and duration

Type	NPP Name	CLOUD Type	Total Amount Released Bq	Duration of the Release h	Per Hour Release Bq
PWR	Beznau	Rare Gas	2.211E+18	0.5	4.4224E+18
PWR	Beznau	Aerosols	5.647E+17	2.0	2.8237E+17
PWR	Beznau	Refractor.	1.148E+16	2.0	5.7399E+15
PWR	Bugey	Rare Gas	5.152E+18	0.5	1.0304E+19
PWR	Bugey	Aerosols	*1.619E+18*	2.0	8.0945E+17
PWR	Bugey	Refractor.	2.829E+16	2.0	1.4147E+16
PWR	Gösgen	Rare Gas	4.704E+18	0.5	9.4076E+18
PWR	Gösgen	Aerosols	1.116E+18	2.0	5.5785E+17
PWR	Gösgen	Refractor.	3.050E+16	2.0	1.5249E+16
BWR	Leibstadt	Rare Gas	7.498E+18	0.5	1.4997E+19
BWR	Leibstadt	Aerosols	1.120E+18	4.0	2.8006E+17
BWR	Leibstadt	Refractor.	4.965E+16	4.0	1.2413E+16
BWR	Mühleb.	Rare Gas	2.282E+18	1.0	2.2824E+18
BWR	Mühleb.	Aerosols	1.187E+18	4.0	2.9681E+17
BWR	Mühleb.	Refractor.	*1.081E+17*	4.0	2.7031E+16

For more details, see Table A3 in the Annex A of this article. See also Table A.7, A.10 and A.11 in Hanson (1994).

We therefore verified that the figures given by the Flexrisk report (Seibert et al. 2013) and Ustohalova (2014) were compatible with the highest release fractions given in an aggregated way by the NRC (Hanson et al. 1994: Tables A.7, A.10, A.11). We thus had to reduce the figures whenever the total of a radionuclide group considerably exceeded the maximal amounts defined by the NRC for each NPP. Consequently, the amount of ^{132}Te defined for Leibstadt by Flexrisk is reduced from 7.54E+17 to 3.47E+17 (about -50%). The objective was to limit the released fraction of the Tellurium group at 4.8% of the core inventory, according to scenario RGG1 (Hanson et al. 1994: Table A11). Similarly, for Mühleberg, the amount of ^{137}Cs is reduced from 8.7E+16 Bq to 6.55E+16 Bq (-25%). The aim was to make the released fraction of the group of alkali metals does not exceed 40% of the related core inventory, as specified for the scenario RPB6 (*ibid.*: Table A.10). Eventually, the duration of the different releases was defined in accordance with Tables A.7, A.10, A.11 (*ibid*.). The final result of this stage of our analysis is summarized in Table 2.3.

For more details on the final selection of the potential release from the five NPPs, see Table A3 in the Annex A. In this Table, the releases of the different NPPs are edited in Becquerels. The bibliographic source is indicated at the right of the Table. The different isotopes are dispatched in three groups according to their respective deposition velocities (*infra* 2.3).

(iv) Comparison with the source terms of Chernobyl and Fukushima

The remaining question is, to what kind of historical nuclear disaster the simulated accident models of this study can be compared?

In order to get some representation of this point, Table 2.4 compares the potential releases of the different NPPs to the Chernobyl accident. The figures express the following ratios: Beznau (Bq) /Chernobyl (Bq); Bugey (Bq) /Chernobyl (Bq); etc. It is shown that the release of aerosols is 6.6-times to 2.3-times less than from the Chernobyl accident. Table 2.5 displays the previous data according to their potential damage. Potential releases of the different NPPs are compared with the Chernobyl accident. The data are expressed as ratios of the *potential* Sieverts. Insofar as the numbers are connected to Sv, they express a *potential* impact on people, which does not take the population density into account. The numbers are almost the same.

Table 2.6 provides a comparison in Becquerel with Fukushima. The releases of aerosols in our accident models are between 1.4-times and 3.9-times the Fukushima release and, on average, 2.7-times. With reference to refractories, the important difference to Fukushima is due to the way Hanson et al. detailed the different scenarios of accidents. Table 2.7 provides a comparison in Sieverts with Fukushima. The releases of aerosols correspond to 1.4-times to 4.3-times the Fukushima release and, on average, 2.8-times.

Table 2.4. Potential release of radioactiviy (Bq): comparison between the 5 NPPs and Chernobyl
(Chernobyl primary source from IAEA 2006 + 2015)

Categories	Bez. to Cherno. *Bq/Bq*	Bug. to Cherno. *Bq/Bq*	Goe. to Cherno. *Bq/Bq*	Lei. to Cherno. *Bq/Bq*	Mue. to Cherno. *Bq/Bq*
Rare gas	0.34	0.79	0.72	1.15	0.35
Aerosols	0.15	0.43	0.29	0.30	0.32
Refractor.	0.05	0.13	0.14	0.22	0.49

Table 2.5. Potential sanitary impact (Sv): comparison between the 5 NPPs and Chernobyl
(Chernobyl primary source from IAEA 2006 + 2015)

Categories	Bez. to Cherno. *Sv/Sv*	Bug. to Cherno. *Sv/Sv*	Goe. to Cherno. *Sv/Sv*	Lei. to Cherno. *Sv/Sv*	Mue. to Cherno. *Sv/Sv*
Rare gas	0.34	0.79	0.72	1.15	0.35
Aerosols	0.15	0.49	0.33	0.30	0.31
Refractor.	0.03	0.08	0.08	0.17	0.54

Table 2.6. Potential release of radioactiviy (Bq): comparison between the 5 NPPs and Fukushima
(Fukushima primary data from IAEA 2015)

Categories	Bez. to Fukush. *Bq/Bq*	Bug. to Fukush. *Bq/Bq*	Goe. to Fukush. *Bq/Bq*	Lei. to Fukush. *Bq/Bq*	Mue. to Fukush. *Bq/Bq*
Rare gas	0.25	0.57	0.52	0.83	0.25
Aerosols	1.36	3.93	2.66	2.79	2.93
Refractor.	246	606	653	1 064	2 317

Table 2.7. Potential sanitary impact (Sv): comparison between the 5 NPPs and Fukushima
(Fukushima primary data from IAEA 2015)

Categories	Bez. to Fukush. *Sv/Sv*	Bug. to Fukush. *Sv/Sv*	Goe. to Fukush. *Sv/Sv*	Lei. to Fukush. *Sv/Sv*	Mue. to Fukush. *Sv/Sv*
Rare gas	0.24	0.57	0.52	0.83	0.25
Aerosols	1.36	4.33	2.95	2.62	2.75
Refractor.	143	353	381	764	2418

To conclude this point, the different comparisons between the five NPPs with Chernobyl and Fukushima show that the simulation of major accidents in the present study is situated between the two historical events.

2.3 Deposition velocity in- and below-cloud wet removal of different nuclides

(i) Framework

The user of *Hysplit* has to specify the deposition velocity of rare gas, aerosols, and particles that are rejected by a source and dispersed by winds. Furthermore, *Hysplit* requires the in- and below-cloud wet removal/scavenging parameters and, for soluble gases only, the Henry's constant (Draxler et al., 2018). As these parameters are partly dependent from weather condition, the numbers to be found are indicative and managed by *Hysplit* accordingly.

(ii) Review of the literature

We give below a short review of the literature on the subject in order to specify below how we aggregated the different isotopes in three clouds.

- Rare gases: The main rare gas with a half-life above 72h is ^{133}Xe. According to Tinker and al., there is no wet or dry removal mechanism for Xe-133 (Tinker et al. 2010). Xenon has no deposition velocity and the related descriptor has to be set-up at '0' (m/s) (Bianchi et al. 2018). The Henry's constant for Xenon can be established at 4.2E-05 (mol/m^3 Pa) (Sander 2015).
- Cesium: The dry deposition velocity of ^{137}cesium is given by the *Hysplit* dispersion program at 0.001 (m/s) (Stein et al. 2015). However, Guglielmelli et al. (2016) set 0.002 (m/s). Direct observation on the Fukushima accident leads to consider the figure of 0.001 (m/s) is robust for ^{137}Cs, ^{136}Cs and ^{134}Cs (Takeyasu & Sumiya 2014). Wet removal/scavenging in- and below-cloud is set at 8.0E-05 (1/s) by *Hysplit* for ^{137}Cs. For this same isotope, wet in- and below-cloud removal is estimated at 3.5E-05 (1/s) (Guglielmelli et al. 2016), or even at 3.36E-04 and 8.4E-05 respectively (Leadbetter et al. 2015).

- Iodine can be released as gas, aerosol, or both. Considering the uncertainty for the fraction of each form, the Flexrisk report subsumed all iodine under the aerosol species (Seibert et al. 2013). We adopt the same approach and look at the deposition velocity and wet removal accordingly. For the aerosol form of iodine, *Hysplit* puts deposition velocity at 0.001 (m/s) and sets wet removal/scavenging in- and below-cloud at 4.0E-05 (1/s) (Stein et al. 2015).

There are few additional figures on the two parameters that we aim to define. No synthetic information is available on the behavior of the radionuclides in the atmosphere (Doi et al. 2013), and data uncertainties of the Fukushima accident do not assist in determining the best physical parameterization of the dispersion of radionuclides (Mathieu et al. 2018). ENSI admits nonetheless, that the deposition velocity can be given for all aerosols (ENSI 2009, 64).

For all aerosols: the deposition velocity is set at 0.0015 (m/s) (ENSI 2009, 64) and the in- and below-cloud removal/scavenging is set at 7.0E-05 (1/s) (ENSI 2009, 65). The latter figures are close to the abovementioned ones on cesium and iodine.

The question is whether the same coefficient for all aerosols can also be used for tellurium and strontium. In order to confirm the point, the ratios Sr/Cs and Te/Cs should be constant in different impacted areas after a nuclear accident (although it may differ for other reasons). Rosenberg et al. found that the ratio $^{90}Sr/^{137}Cs$ was about the same although the small number of samples makes it difficult to ascertain that their dispersion is similar (Rosenberg et al. 2017). Yanaga & Oya (2013) found that the ratio of ^{132}Te to ^{137}Cs was approximately constant in Shinzuoka-city (200 km southwest of Fukushima). However, this finding is not confirmed elsewhere and the opposite might be possible (Doi et al. 2013).

Refractory: the deposition velocity of refractory should have a specific number. Draxler states that the deposition velocity of heavy particles can be set at 0.01 (m/s) in *Hysplit* (Draxler & Rolph 2012). The in- and below cloud removal is more problematic. According to Baklanov & Sørensen (2001, 792), the washout coefficient could be determined by particle size: "the washout coefficient for particles of about 0.4 or 1.2 µm is two orders of magnitude smaller than that of particles equal to 4 µm". If we infer the refractory group from the example of plutonium, which could be about 4 µm, compared to cesium (0.68 µm) and tellurium (0.81 µm) (ibid. 2001, 788), we can assume that, for refractories, the in- and below-cloud wet removal should be set at 7.0E-03 (1/s) (instead of 7.0E-05 (1/s) for aerosols)[14]. Such an assumption is indicative to the extent the size of particles could be modified by several factors.

(iii) Deposition velocities on different types of grounds

The different kinds of land cover have different abilities to capture radioactive particles. For instance, Sehmel quoted by Takeyasu & Sumiya (2014) give the deposition velocity for ^{137}Cs: 0.0003 – 0.0015 m/s for water, 0.0001 – 0.0009 m/s on 'soil', and 0.002 – 0.005 m/s on grass. These figures nonetheless cannot be generalized. Müller & Pröhl quoted by Baklanov & Sørensen (2001, 789) gave – for aerosol bound radionuclides – a deposition velocity at 0.0005 m/s in case of deposition on 'soil', at 0.0105 m/s for deposition on grass and at 0.0005 m/s on trees, knowing that such figures depend on the size of the deposited particles as well as on the size and development of the foliage of trees. Due to the high complexity and the lack of a systematic data collection on this specific issue, we ignore the land cover aspect of the deposition process. Therefore, we will publish all of our detailed results concerning land cover in additional files for further analysis.

(iv) Parameters of deposition velocity and in- and below-cloud wet removal for aerosols and refractories

The selection of the different coefficients affecting the atmospheric dispersion and the deposition of the 32 isotopes of this study is given in Table 2.8. The selected parameters will be used to simulate a major nuclear accident. The selection is made according to the literature, mainly Sander (2015), ENSI (2009), Draxler & Rolph (2012) and Baklanov et al. (2001) (*supra*).

[14] The impact of this hypothesis on the final result is very small. 1° The different tests we carried on with different coefficients did not lead to significant changes in the cloud map. 2° Compared to aerosols, the importance of the refractories on the total collective committed dose is very limited.

Table 2.8. Parameters of deposition velocity; in- and below-cloud wet removal/scavenging for aerosols and refractories; and the Henry's constant for soluble gas used in this study

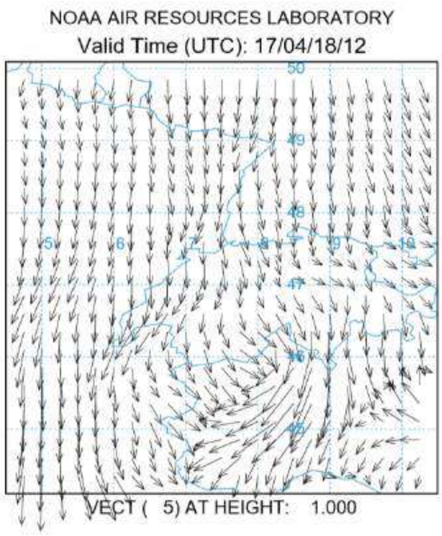
	Deposition velocity (m/s)	in- and below-cloud wet removal (1/s)	Henry's constant (mol/m³ Pa)
gas	(…)	(…)	4.2E-05
aerosols	0.0015	7.0E-05	(…)
refractor.	0.01	7.0E-03	(…)

Together with the release and the duration of the release, the above figures are used by *Hysplit*.

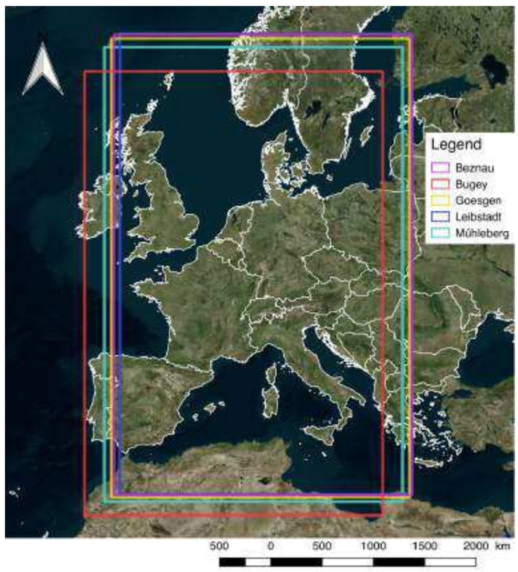
2.4 Meteorological aspects

(i) What are atmospheric dispersion models?

Map 2A. Example of wind field on the 18th April 2017.



Map 2B. Width and height of the dispersion analysis for (15° in each direction from each NPP)



Atmospheric dispersion models have been developed in the 1980s to study the effects of chemical and nuclear incidents. The aim was not only to predict the evolution of the pollutant cloud, but also to trace back the origin of a pollution in the case a signal would have been observed at an observation point. One of the main triggers to develop this kind of models was the Chernobyl accident in 1986. Simple trajectory models existed at the time which allowed qualitative estimates, but it lasted a few years until dispersion models were able to assess the event in a quantitative way (Piedelievre et al. 1990: 1205–1220).

There are many different types of dispersion models; for a review see Leelössy et al. (2014, 257-278). Generally, the dispersion models must be characterized firstly by the content (type and mass of the components) and the emission (rate, duration, height). The transport, diffusion and deposition are then driven by the meteorological fields, mainly winds and precipitation (Map 2.A.).

(ii) Considerations on the resolution of the meteorological fields

Wind fields are rather continuous over flat terrain and water surfaces but can become very complex over mountainous landscape. For Switzerland, a resolution of the order of one kilometer would be needed to represent the winds in the main valleys of the Alps. Even if a 1 km model (COSMO-1) is available at MeteoSwiss, the analyses are not available on a long enough historical basis, which would have been needed for this study. However, the nuclear plants under investigation here are built on the Swiss mainland where the winds are mainly channeled between the Jura and the Alps such that a resolution of the order of 20 km is sufficient to represent correctly the winds.

We have chosen to use the winds provided easily by the NOAA at a resolution of 0.25° latitude and longitude (NOAA 2016). Wind forecasts according time sequences of one hour, are available until +24 hours by a simple FTP request (NOAA 2018a). In order to reach dispersion patterns over 72 hours, we concatenated 3 consecutive 24-hour forecasts. Wind forecasts over 24 hours can be considered accurate and close enough to the observation. Although less accurate, the same can be assumed for precipitation.

(iii) The *Hysplit* dispersion model

Hysplit is a trajectory and dispersion model developed by the US National Oceanic and Atmospheric Administration (NOAA). *Hysplit* has been used in a variety of simulations describing the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. Some examples of the applications include tracking and forecasting the release of radioactive material, wildfire smoke, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash.

The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. A collection of particles can be gathered in so called puffs, which are small clouds emitted by the pollution source. They are transported by the wind field and expand due to the atmospheric diffusion. The mean trajectory of the cloud defined by its centroid is computed and the growth is modelled by a Gaussian distribution. In this puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass (NOAA 2018b). In the particle model, a fixed number of particles are calculated in relation to the model domain "by the mean wind field and spread by a turbulent component. The model's default configuration assumes a 3-dimensional particle distribution (horizontal and vertical)" (NOAA 2018b). A full description of the model is given by Stein et al. (2015) (*infra* iv).

(iv) The *Hysplit* dispersion model evaluated by WMO in the case of Fukushima

The Fukushima accident in 2011 gave an opportunity to assess the various dispersion models. Unlike the Chernobyl case the models have been used in real time in order to protect or evacuate threatened populations. A comparison between dispersion models computed *a posteriori* – using deposition data and meteorological data to calculate atmospheric dispersion back to the source of the release – was carried out for the World Meteorological Organization (WMO) (Draxler et al. 2015). There was not a single ATDM-meteorology combination that provided the best results for both deposition and air concentration predictions. Generally, the *Hysplit* model driven by NOAA meteorological data performed correctly with respect to the other models. It was found that the use of high-resolution mesoscale analyses improved the dispersion model performance; however, high resolution precipitation analyses did not improve the predictions. As stated above (*supra* (ii)), high-resolution analyses were not available for this study, but the Fukushima study showed that the use of meteorological fields with a resolution of 20-50 km is suitable for our purpose.

(v) Production of the immission fields

Technically, we have taken the radionuclide characterization of 5 nuclear plants. Four of them are situated in Switzerland (Gösgen, Mühleberg, Beznau and Leibstadt) and one in France (Bugey). The geographical field of analysis was defined as 15° west longitude and 15° east longitude from each NPP and as 15° south latitude and 15° north latitude from the same NPPs respectively (see Map 2.B.).

For each plant we computed the dispersion for rare gas, aerosols, and refractory material. For each material we computed the amounts of radioactive particles in the bottom 100 m of the atmosphere (Bq/m^3). This layer is representative of the radioactivity to which the population is exposed by inhalation and external exposition. For solid particles (aerosol, and refractory), it is also possible to compute the amount of radioactivity (in Bq/m^2) deposited on the ground and we carried it on for aerosols and refractories.

As a result of *Hysplit* these quantities are stored in so called 'cdump' files. The computations have been carried out for all days of 2017 and 2018 (730 days). Altogether 10,950 cdump files have been stored and can be reused for further analyses.

Hysplit also allows to compute isolines from the cdump files. We adjusted the isolines analyzing one of the clouds in Becquerels to different immission limits expressed in millisieverts, in order to understand whether or not the law would be respected in the event of a major nuclear accident (*infra* 2.6(iv)). All contours are stored in vector form as KML files[15]. Using a Geographic Information System (GIS), we computed the area and population size within isolines. Additional information on the evaluation of the representativeness of the meteorological situations is provided in Annex C.

(vi) Maps related to the simulation of a major nuclear accident

The next pages contain 90 maps, for the 5 NPPs, with the purpose of illustrating the diversity of possible weather situations as well as to give some insight on the distribution of radioactivity. The following 45 maps illustrate the cloud of 17 aerosols (in mSv), then, from the 46th to the 90th, the maps show the deposition of ^{137}Cs as an indicator of the severity of the deposition of the other 16 radioactive aerosols (*infra* 2.6(v)).

Legend 1. Inhalation and external exposure to the cloud of 17 aerosols	Legend 2. Radioactive deposition of the cloud of aerosols
≥ 100 mSv	≥ 1,480 kBq/m^2 of ^{137}Cs
≥ 50 mSv	≥ 555 kBq/m^2 of ^{137}Cs
≥ 20 mSv	≥ 185 kBq/m^2 of ^{137}Cs
≥ 6 mSv	≥ 37 kBq/m^2 of ^{137}Cs
≥ 1 mSv	. . .
≥ 0.2 mSv	
Inhalation and external exposure to the cloud of 17 aerosols	Since each NPP has a different source term, the proportion of the different aerosols varies relatively to the amount of ^{137}Cs.

The next pages contain:

Maps 2C(1–45). Forty-five maps on inhalation and external exposure to the cloud of aerosols released by each NPP (over a 72-hour simulation);

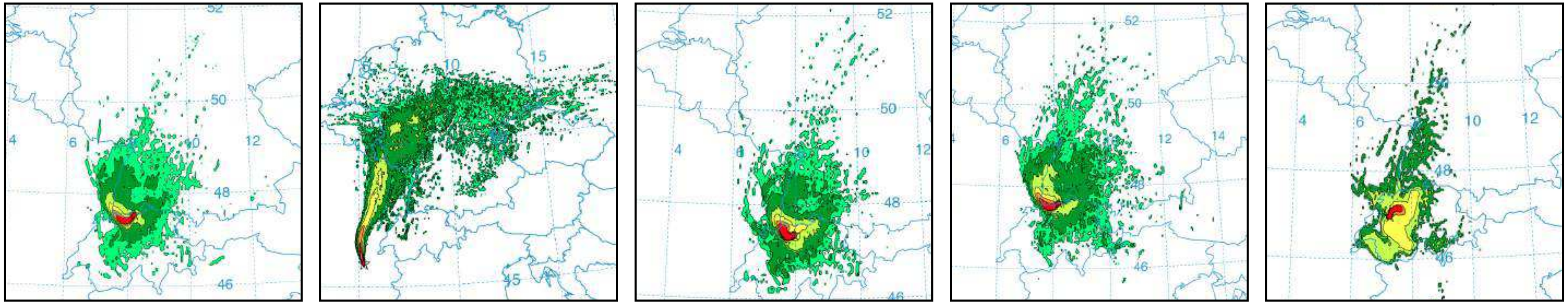
Maps 2D(46–90). Forty-five maps on aerosol depositions after the release of each NPP respectively (over a 72-hour simulation).

All maps are issued from the NOAA HYSPLIT MODEL (*supra* 2.4).

[15] KML means Keyhole Markup Language and the related files are employed for geographic mapping.

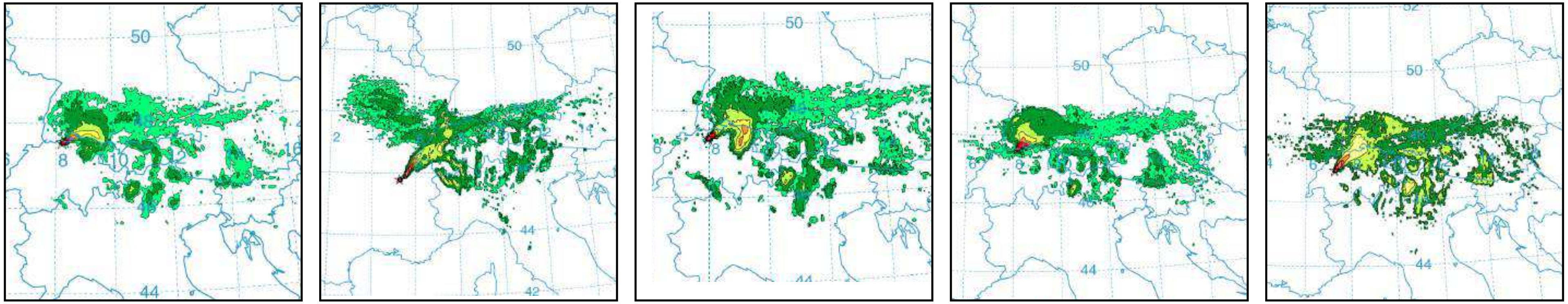
BEZNAU | BUGEY | GOESGEN | LEIBSTADT | MUHLEBERG

27.05.2017



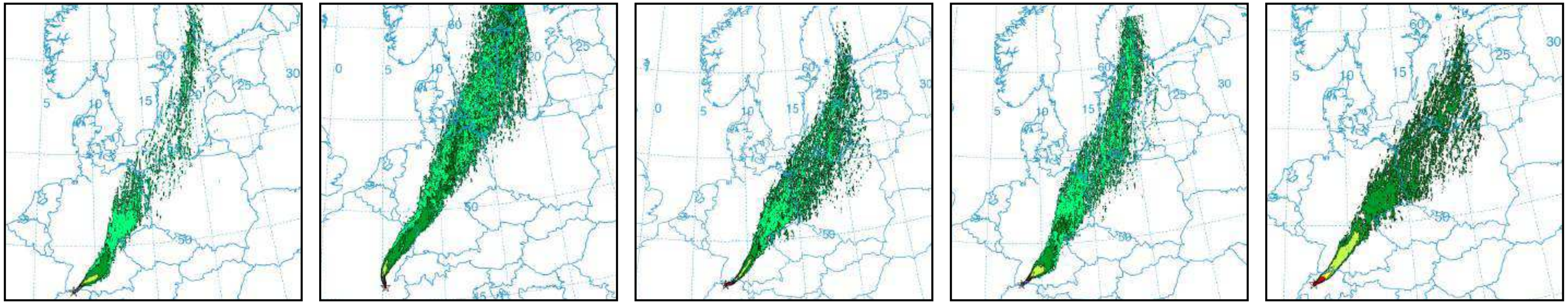
NOAA Hysplit model for cloud dispersion

03.05.2017



NOAA Hysplit model for cloud dispersion

27.02.2017



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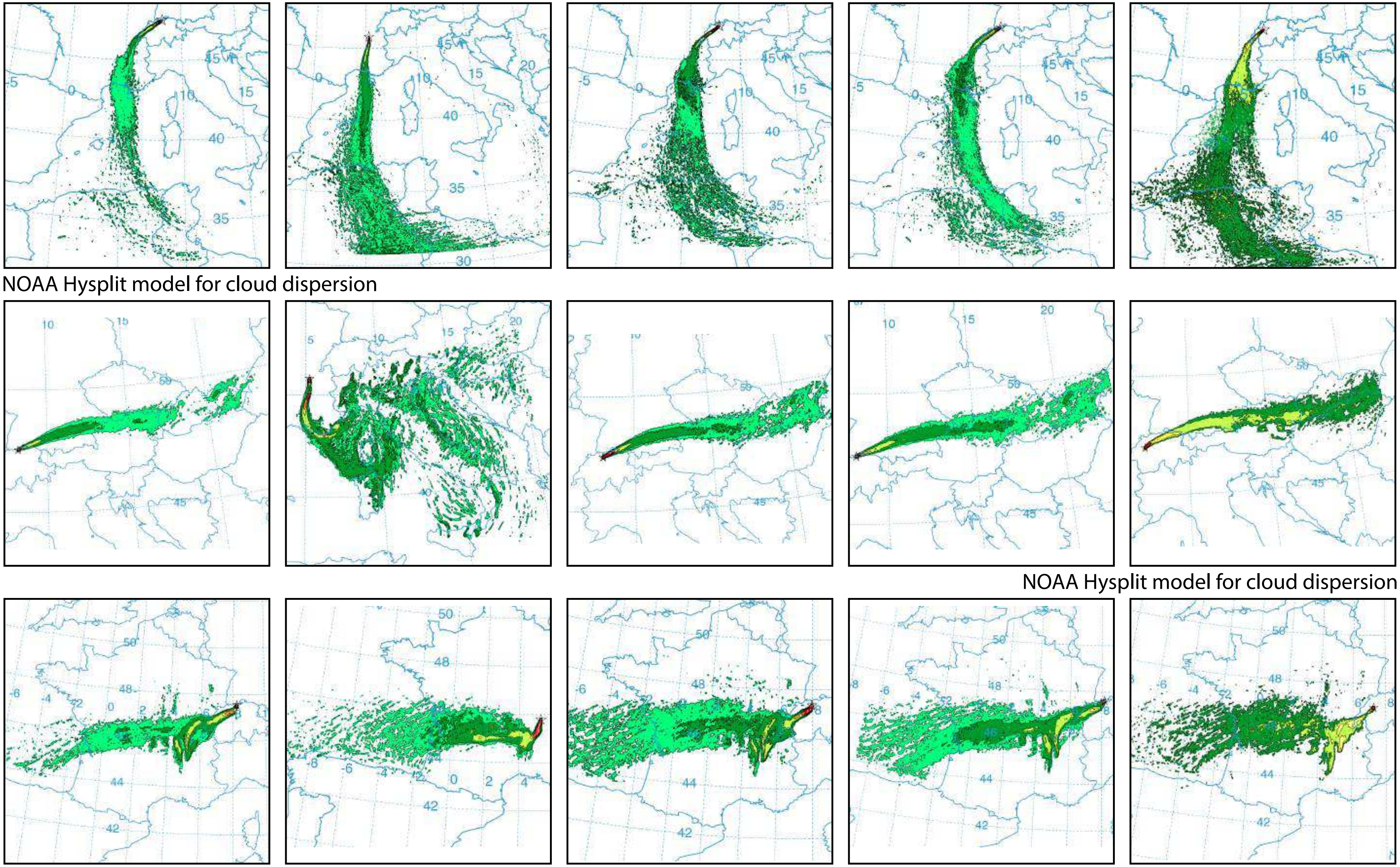
14.11.2017

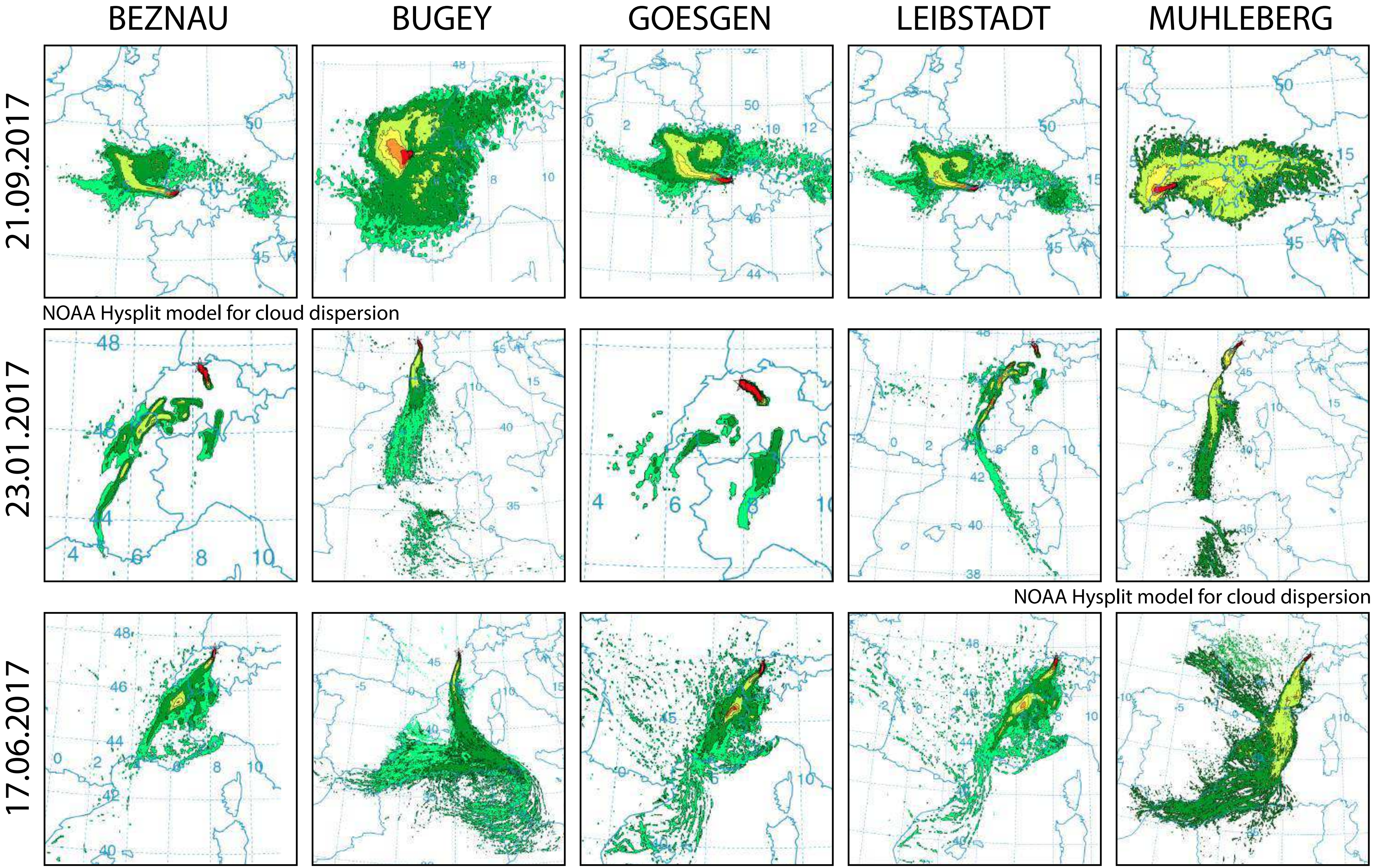
22.02.2017

24.03.2017



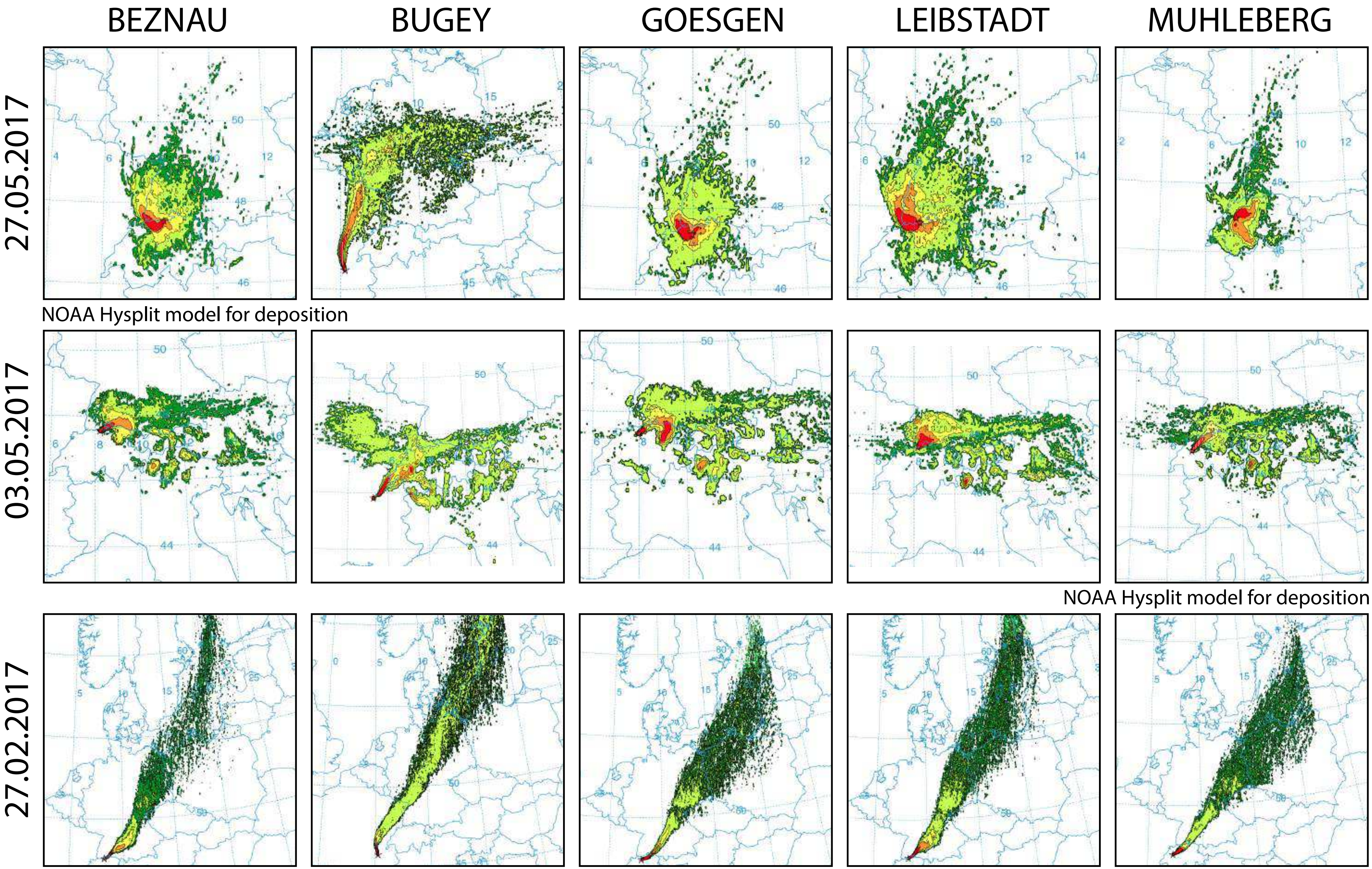
NOAA Hysplit model for cloud dispersion

NOAA Hysplit model for cloud dispersion



NOAA Hysplit model for cloud dispersion

NOAA Hysplit model for cloud dispersion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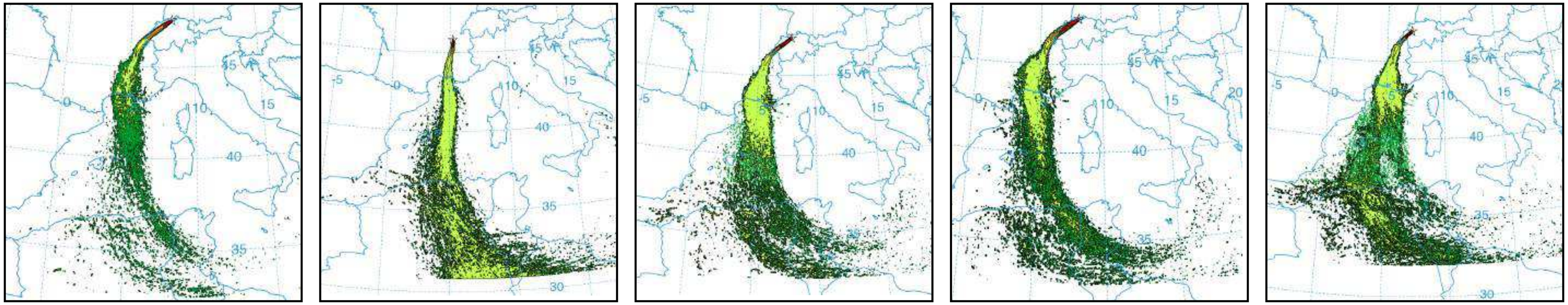
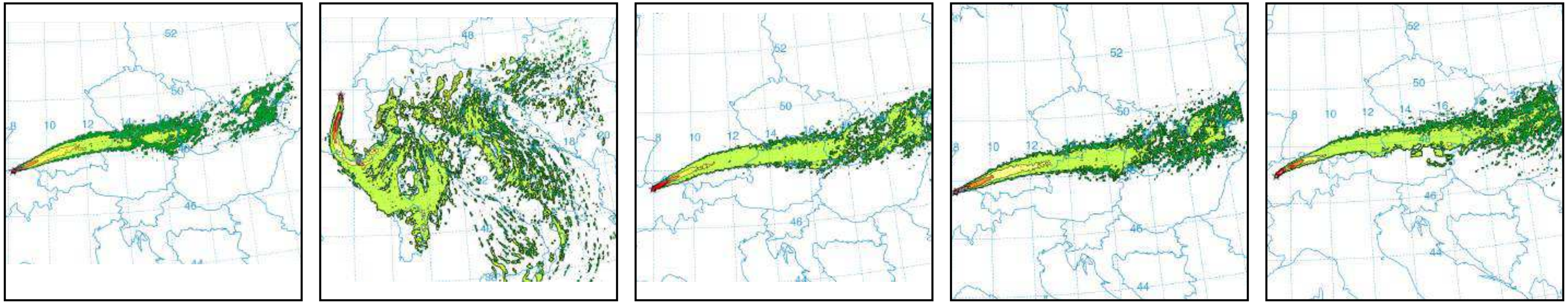
14.11.2017



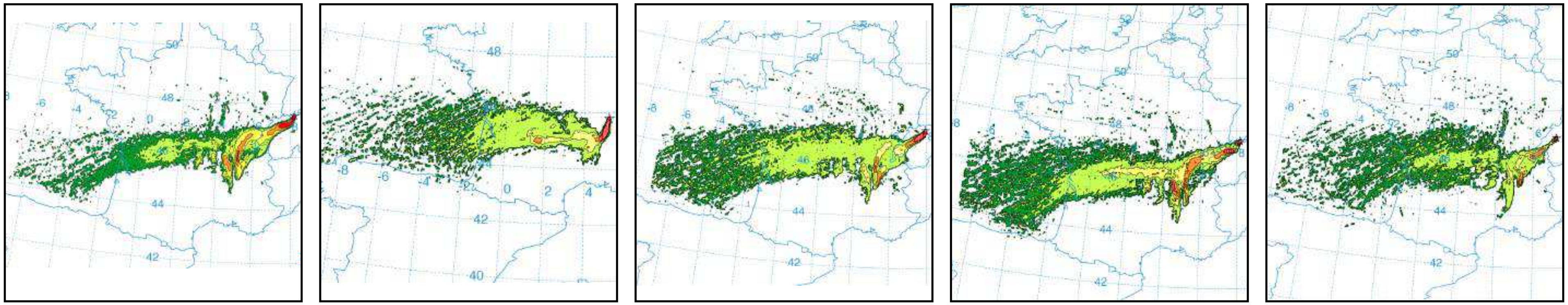
NOAA Hysplit model for deposition

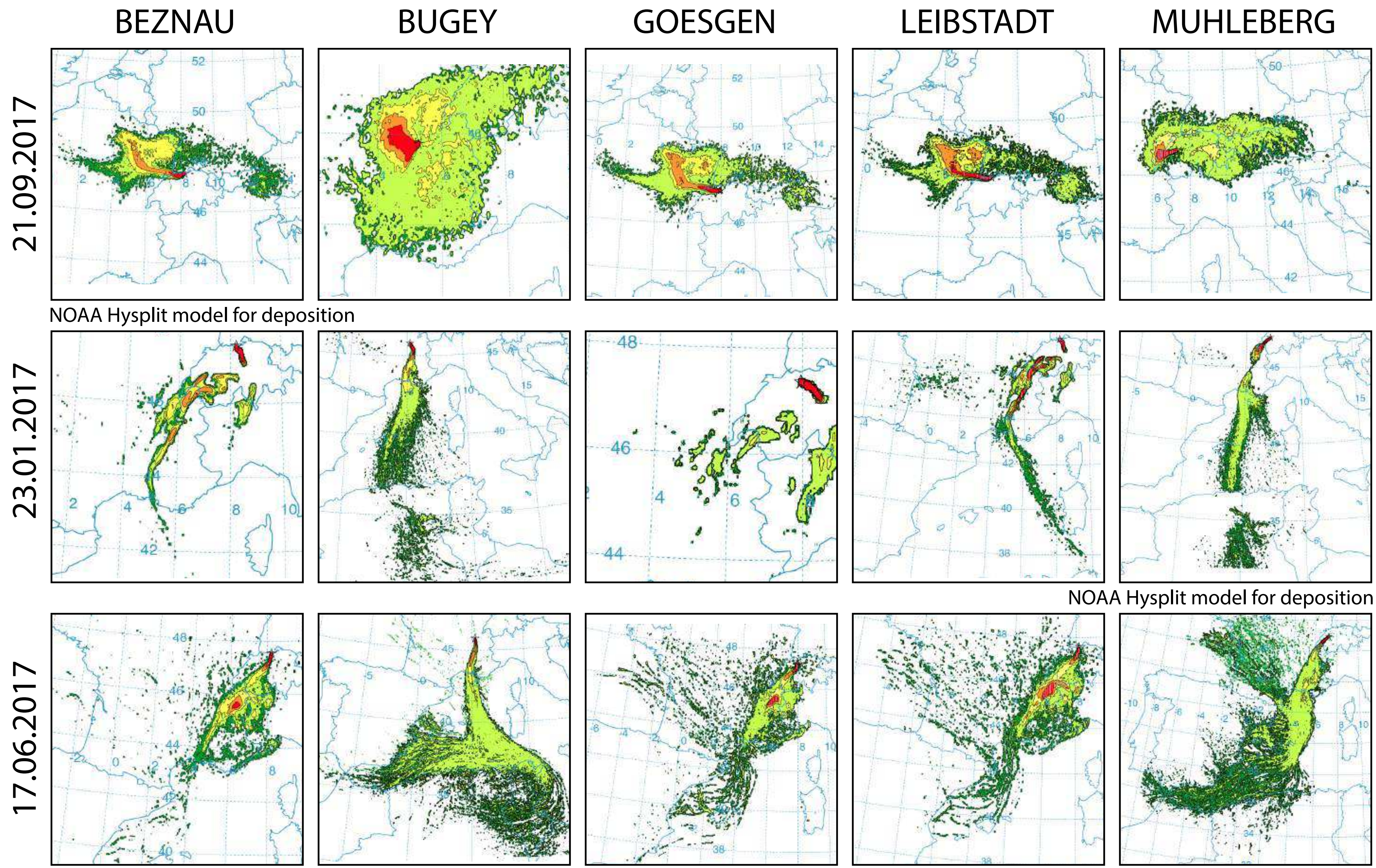
22.02.2017



NOAA Hysplit model for deposition

24.03.2017

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NOAA Hysplit model for deposition
23.01.2017
NOAA Hysplit model for deposition
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2.5 Analysis of the impact through the Geographic Information System (GIS)

The GIS software *QGIS (QGIS Development Team 2018)* was used to perform the statistics on affected terrain and population. The *QGIS* integrated *Python*[16] console allowed the batch processing of the files generated from *Hysplit*. The aforementioned processes regroup *KML* to *ESRI-Shapefile* conversion, topology corrections, data organization, rasterization, and zonal statistics. The population density layer used for the zonal statistics is the *GHS_POP_GPW42015_GLOBE_R2015A_54009_250 (JRC 2015)* , which is a global 250 m resolution layer dating from 2015. The Europe focused 250 m of resolution, 2012 layer *g250_clc12_V18_5 (Corine Land Cover (CLC) 2012, Version 18.5.1)* taken from the *Copernicus Land Monitoring Service (Copernicus 2019)* provided the data for the affected grounds. The CLC layer represents the land cover in 44 different classes but, for the purpose of this study, the original classes of land covers were reduced to 10.

Table 2.9. The 10 selected categories of land-cover
Impermeable urban areas
Urban areas
Non-vegetal exploitations
Recreational areas
Agricultural areas
Grasslands
Forests
Other natural areas
Unproductive areas
Water bodies
See the original categories of CLC in the Annex (Table A4)

The 10 selected classes are listed in Table 2.9, and the full list of the original categories of CLC is found in Annex A, Table A4. More information on this specific stage of the present study has been reported in a separate and online report (Deriaz 2019).

2.6 From Becquerels to the collective dose received by the impacted population

(i) From Becquerels to mSv

The different sources of radioactivity are calculated by *Hysplit* in Becquerels (Bq). To evaluate the health impact of all persons affected implies to estimate the population dose in millisieverts (mSv). The calculation from Bq to mSv is carried out through dose factors given Ordinance 814.501 (Swiss Federal Council 2019), and ENSI (ENSI 2009, Appendice 8). The related equations have to consider the specific unit account of each dose factors, the time integrated concentration expressed in (Bq·s/m^3) or (Bq·s/m^2), (see Table A6 in Annex A).

(ii) First part of the calculation of the health impact

Radioactivity impacting people has been calculated through three clouds (rare gas, aerosols and refractories). The calculation is completed by the integration of the deposition of aerosols and refractories. As a result, it gives the five sources of radioactivity below:

A) External exposition to the cloud of rare gas (with respect to the half-life of ^{133}Xe for 72 hours).

B) Inhalation and external exposition to the cloud of aerosols.

C) Inhalation and external exposition to the cloud of refractories.

D) Exposition to groundshine of deposited aerosols, with respect to the half-life of the nuclides for 1 year.

E) Exposition to groundshine of deposited refractory, with respect to the half-life of the nuclides for 1 year.

Not including the half-life in the calculation of the clouds B and C greatly simplifies the work, without losing much accuracy for the first 24 hours. According to our estimate, the non-integration of the 28 isotopes with a half-life below 72h has reduced the 'potential' committed effective dose during the first 24 hours for an amount that would almost compensate the simplification of the clouds A and B. An additional compensation effect could have worked another way since we selected the most conservative dose factor for iodine (compare column 1 to column 4 in Table A5 – in the Annex).

When calculating committed effective doses from deposition we only considered external exposition. Inhalation of radioactive aerosols from resuspension in the atmosphere is far from negligible. However, we did not calculate it.

[16] Python Software Foundation. Python Language Reference, version 2.7. Available at http://www.python.org

Hysplit ran the five sources of radioactivity in Becquerels (Bq). Besides this, we estimated the committed effective doses (CED) in millisieverts (mSv) via the equation presented in Table A6. The purpose is to prepare the evaluation of the health damages to all affected persons.

The individual committed effective doses (CED) can be used to estimate the collective committed effective dose (CCED) received by the population:

$$CCED = CED * \text{number of affected persons}$$

(iii) Calculation from the perspective of different norms

It was also decided to use data focusing on norms that aim at limiting radioactive contamination of persons. Such kind of data could be of interest for decision-makers and civil servants in charge of the protection of the population. If we look at Ordinance 814.501 (Swiss Federal Council 2019), some of the different thresholds are linked to emergency exposure situations, or former emergency situations and should have a direct impact on how to manage a major nuclear accident (Table 2.10).

Emergency exposure situations

- Under Title 3, ‘Emergency Exposure Situations’, in the event of emergency exposure, it is said that a reference level ≤ 100 mSv in the first year applies to members of the public (Art. 133.1), without any explicit reference to an expected probability (Swiss Federal Council 2019). The Federal Council can set a lower reference level, depending on the specific situation – but not higher than 100 mSv/year (Art. 132.2).
- In case of ‘emergency exposure situations’, deployment-related reference level of 50 mSv per year applies to persons with special responsibilities (art. 134.1).
- However, a reference level of 250 mSv per year is applied for saving human lives, preventing serious damage to health, or for averting a disaster.

Existing exposure situations and, by extension, former emergency exposure situation

- Under Title 4, ‘existing exposure situations’ – which include former ‘emergency exposure situation’[17] – Art. 148.1 states that a reference level of 1 mSv per calendar year applies’. Art. 148.2 specifies that the Federal Council, in individual cases, can set “the reference levels up to 20 mSv per calendar year, in particular if measures are required in accordance with Article 171”.

In other terms, provisions pertaining to Title 3 and Title 4 inform as to how the legislator intends to protect different categories of the population. By contrast, some CED thresholds are linked to ‘planned exposure situations’ and would not have any influence on how to handle a major nuclear accident (*infra*).

Planned Exposure Situations for the Public

- Under Title 2, ‘planned exposure situations’, chapter 8, committed effective dose ≤ 100 mSv is the threshold that should neither be hit nor surpassed in the event of an accident with an expected frequency ≥ 1.0E-06 (Art. 123.2(d)). Accidents with an expected frequency < 1.0E-06 are not concerned by this provision and not even mentioned by Ordinance 814.501.
- For failures with an expected frequency of between 1.0E-02 and 1.0E-04 per year, the dose resulting from a single event for members of the public must not be greater than 1 mSv.
- “Persons aged under 16 years must not be occupationally exposed” (Art. 53.1), which means they pertain to the category ‘member of the public’.

Planned Exposure Situations for Professionals

- Under Title 2, chapter 5, ‘occupational exposures’, for exposed persons in the field, “the effective dose must not exceed the limit of 20 mSv per calendar year” (Art. 56.1). For such persons, “the limit for the effective dose may be up to 50 mSv per calendar year, provided that the cumulative dose over five consecutive years, including the current year, is less than 100 mSv” (Art. 56.2).

[17] According to Art. 141 and 171. Under title 4, Existing Exposure Situations, Art. 141 states the Federal Council is competent to order the transition from an emergency exposure situation to an existing or planned exposure situation (the decision is informed by the Federal Civil Protection Crisis Management Board – CCMB). Art. 171 states that the Federal Office of Public Health (FOPH) “shall prepare the long-term federal and cantonal measures for the management of effects after the transition from an emergency exposure situation to an existing exposure situation in accordance with Article 141”.

- Under chapter 5, ‘occupational exposures’, “for persons aged 16-18 years, the effective dose must not exceed the limit of 6 mSv per calendar year” (Art. 57.1). Similarly, “pregnant women may only be deployed as occupationally exposed persons if it is assured that “the effective dose to the unborn child does not exceed 1 mSv” (Art. 57.2).

Table 2.10. Dose thresholds according to Ordinance 814.501

Threshold (mSv/year)	Emergency exposure situations	Former emergency exposure situation	Planned Exposure Situations for the Public	Planned Exposure Situations for Professionals
≤ 250	Professionals dedicated to saving human life and preventing disasters	(…)	(…)	(…)
≤ 100	Members of the public	(…)	Members of the public if the expected frequency ≥ 1.0E-6	(…)
≤ 50	Professionals with special responsibilities	(…)	(…)	Adults*
≤ 20	(…)	Members of the public (in individual cases)	(…)	Adults
≤ 6	(…)	(…)	(…)	Persons aged 16-18 years
≤ 1	(…)	Members of the public	Members of the public if expected frequency < 1.0E-02 and > 1.0E-04	Unborn child of pregnant women

* ≤ 50 mSv for adult professionals over 1 year if the cumulative dose ≤ 100 mSv over 5 consecutive years.

The different emission limits have different fields of action (Table 2.10). When dedicated to planned exposure situations for the public and professionals, they do not apply to emergency situations nor to former emergency situations. However, we keep them in mind insofar as the emission limits at 1 and 6 mSv provide information on who deserves protection in general.

(iv) Calculation for the alert

In order to save lives, the question of the alerting the population just before the release is crucial. To this purpose, Ordinance 814.501 publishes a set of specific dose factors entitled ‘data for operational radiological protection’ (Swiss Federal Council 2019, 78, Annex 3). Compared to other list of dose factors, Iodine has no specific chemical form in the list provided by annex 3 of 814.501. It is neither an aerosol, nor organic nor elementary. The published dose factor of iodine is a ‘useful’ synthesis to decide a preventive evacuation before getting information on the exact proportion of the 3 forms of iodine. In other words, calculation for the alert is dedicated to quantifying the number of people that the competent authorities may have to evacuate according to the criteria set up by annex 3 of 814.501.

We simulated the data for a preventive alert for the sole cloud of aerosols. Therefore, we adjusted the isolines analyzing this cloud in Becquerels to different immission limits expressed in millisieverts, in order to understand whether or not the law would be respected in the event of a major nuclear accident.

(v) Calculation of deposition thresholds

In addition to the health impact of soil deposition, the study evaluate deposition through the criteria of ^{137}Cs. After Chernobyl, people in area ≥ 555,000 Bq/m^2 were evacuated (Yablokov et al. 2009, 25). The Russian experience drawn from Chernobyl thus lists the different areas according to the following criteria (Urushadze & Manakhov 2017):

- Disaster (zone of compulsory evacuation): >1,480 kBq/m^2 of ^{137}Cs.
- Emergency (zone of compulsory evacuation): 555–1,480 kBq/m^2 of ^{137}Cs.
- Residence permit zone with right of resettlement: 185–555 kBq/m^2 of ^{137}Cs.
- Residence permit zone with privileged socio-economic status: 37–185 kBq/m^2 of ^{137}Cs.

On the one hand, experience from Chernobyl suggests that levels of 555,000 Bq/m^2 of ^{137}Cs would imply yearly committed dose factors of around 5 mSv (UNSCEAR 2000, 475; Kashparov 2006, 156), which is rather ‘low’. On the other hand, IRSN confirms the threshold of ≥ 555,000 Bq/m^2 as an indication for evacuation (IRSN 2007, 40; Pascucci-Cahen & Patrick 2012).

Another threshold seems relevant for two complementary reasons. A ^{137}Cs contamination ≥ 37,000 Bq/m^2 implies a committed effective dose of about 1 mSv for an exposition of one year and can be a critical threshold for agriculture (Lelieveld et al. 2012). A confirmation of this last point is given by putting into perspective cereals growing in soil contaminated by a certain level of ^{137}Cs with the European standard on maximal food contamination ≤ 1,000 Bq per kg of dairy feed (after a nuclear accident) (European Union 2016). If the Bq concentration in cereals is 6.3-times lower than the level of ^{137}Cs deposition on soils as stated by FAO (Winteringham 1989), the standard of 1,000 Bq/kg is reached well below a ^{137}Cs deposition of 37,000 Bq/m^2. In other words, a ^{137}Cs threshold of 37 kBq/m^2 seems to be relevant for a short discussion on the impact of a major nuclear accident on agriculture. The ^{137}Cs thresholds of 555 kBq/m^2 and 1,480 kBq/m^2 are relevant for a discussion on evacuation. Therefore, the assessment of radioactive deposition on soils focuses on the "Russian" thresholds indicated for ^{137}Cs, which should be understood as including the effects of the other nuclides.

We also calculated the number of mSv from deposition over 1 year, according to an indoor factor of 0.4 (ENSI 2009, 67).

2.7 Methodology of the health question

(i) Context

Ionizing Radiation (IR) acts either internally by incorporation of radionuclides (ingestion or inhalation), or externally by skin penetration of beta-, gamma-rays and neutrons (by immersion from cloudshine and groundshine) or direct skin contact with radionuclides. The energy of IR provokes mutations of the genome and other critical cellular processes such as bystander effect leading to genomic instability (Sipyagina et al. 2015, 18-22). In this way radiation induces cancer, congenital malformations, and genetic diseases which are passed from generation to generation.

IR is ubiquitary. IR from natural sources to the world population leads to an annual collective dose of 18,000,000 man-Sievert (2.4 mSv ⁎ (7.6E+09 persons)) (Bennet 1995, 3-12). It has been observed that living organisms for long have developed coping mechanisms for repairing IR-induced cell damages or elimination of hit cells (Little 2003, 6978-6987). However, these mechanisms have limited capacity and frequently fail in case of sudden huge or repetitive IR exposure. In addition, body tissues and repair mechanisms are not prepared to artificial, man-made isotopes; the body handles elements according to their chemical properties and thus is not able to distinguish natural stable isotopes from artificial radioisotopes. Among them, cesium 137, cesium 134, strontium 90, iodine 131, tritium and plutonium 239 are the most typical isotopes spread by nuclear accidents. This leads to highly unbalanced concentrations of specific radionuclides in different tissues, e.g. cesium in the heart muscle, strontium in the bone, and iodine in the thyroid (Bandazhevsky 2003, 488-490). These preconditions explain the broad spectrum of human diseases encountered after IR exposure. Especially developing organisms with high cellular turnover are highly susceptible to IR. Therefore, children are between 3- and 10-times more radiosensitive than adults, and blastulae, embryos, and fetuses much more so (Sumner et al. 1990, 98-100; Alzen & Benz-Bohm, 2011, 407-414). Additionally, differences of the genetic inventory (present in X- and Y-chromosomes) explain the higher IR sensitivity of females in comparison to males. Finally, individuals with distinct mutations show higher radiation sensitivity than the average population (Hall et al. 1990, 1684-1689).

(ii) Estimating the numbers of victims in a major NPP-Accident – retrospectively and prospectively

Several years after 1986 the estimated number of human victims due to the Chernobyl disaster varies between 4,000 cancer deaths (IAEA 2006, 118-120), about 30,000 to 60,000 excess cancer deaths (Fairlie & Sumner 2006, 5) and more than 1,000,000 victims due to cancer and non-cancer pathologies (Yablokov et al. 2009, 58-160). This discrepancy of more than two orders of magnitude is attributable to some degree, to the stochastic nature of health detriments by IR, as well as to long latency periods between exposure and manifestation of radio-induced pathologies. More important, however, are diverging estimates of the source term, populations studied, varying exposure periods and different risk-factors chosen by published scientific studies with diverging commitments (Fairlie & Sumner 2006, Claussen & Rosen 2016, Lenoir 2016). Considering the abovementioned divergence in determining *retrospectively* the number of victims due to the Chernobyl NPP accident, we use the following three calculation models (A, B, C) to estimate *prospectively* the number of victims of a future potential major European NPP accident

(iii) Model A

Model A: Cancer-based model - estimations according to UNSCEAR / WHO

This model places emphasis on victims with radio-induced cancer and is originally based on the ICRP-Document 103 (ICRP 2007). The latter uses an EAR (Excess Absolute Risk) factor of 5.5%/Sv (0.055/Sv) for cancer mortality which is applied to effective collective IR doses. However, calculations by ICRP also include a “reduction factor” (“dose and dose rate effectiveness factor”, DDREF) of 2 which is outdated nowadays according to UNSCEAR/WHO (WHO 2013, 31-32) and also to the German SSK (2014, 5-16). This has indeed been challenged recently in a meta-analysis (Shore et al. 2017, 1064-1078) arguing for a DDREF > 1. However, the authors point to a weakness of this view due to a single outlier study distorting the main outcome of their analysis. Therefore, we still consider a DDREF of 1 appropriate for Model A. It takes into account that incidences (and not only mortality) of radio-induced cancer should be considered for adequate description of the clinical relevance of this severe pathology.

Summary Methodology Model A

Model A contains numeric estimates of radio-induced cancer using a risk factor of 0.2/Sv for incidence and 0.1/Sv for mortality. Results are presented with confidence intervals according to BEIR VII (2006a).

(iv) Model B

Model B: Updated cancer and cardiovascular risk estimates

Model B refers to more recent studies on radio-induced cancer risks. Additionally, cardiovascular risks due to a major nuclear accident are included in Model B.

B1. Cancer risks

With respect to radio-induced cancer risk, there is new epidemiological evidence in favor of higher risk factors (Cardis et al. 2005, 77-80; Körblein & Hoffmann 2006, 109-114; IPPNW 2014, 3; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8) than used in Model A (Table 2.11). These EAR-factors are about 4.5 times higher

Table 2.11. Model B1: Radioinduced cancer: Risk factors for mortality (adults) according to the literature since 2005

Pathology	*Risk factor**	*Reference*	*Remarks*
Cancers other than leukemia	ERR 0.97/Sv	Cardis et al. 2005 (Nuclear workers)	
Cancer	EAR 0.24/Sv	Körblein & Hoffmann 2006 (Background radiation, population Bavaria)	
Cancer	EAR 0.2/Sv	IPPNW 2014 (Review)	
Solid cancer	ERR 0.48/Sv	Richardson et al. 2015 (INWORKS)	
Cancer		Hoffmann 2017 et al. (Population exposed by Mayak nuclear facility according to Krestinina 2005 and Cardis 2007)	EAR 4.4 x higher than ICRP 103**
Cancer		Hoffmann 2017 et al. (Indoor radon exposure)	EAR 4.4 x higher than ICRP 103**
Solid cancer		Hoffmann 2017 et al. (Nuclear workers according to Richardson et al. 2015)	EAR 4.7 x higher than ICRP 103**

* The risk factors used for the collective dose concept describe the likelihood of further cancer cases over and above the spontaneous cancer incidence. Excess absolute risk (EAR) is normally given as a unit of 1/ Sv. Thus, a mortality EAR of 0.2/Sv means that on radiation with 1 Sievert, the added risk of dying of cancer is 20 % – in addition to a 25 % basic risk. This is equivalent to an excess relative risk (ERR) of 0.2/0.25, which is equal to 0.8/Sv (Claussen & Rosen 2016, page 26).

**Ref. ICRP 103 (2007), Table A 4.1 page 179; full text version: EAR for cancer mortality 5.5% (4.1% for lethal and 1.4% for debilitating nonlethal cases combined)

than the EAR of 0.055 for radio-induced cancer mortality used by ICRP 103 (2007). In Model B this would translate into a doubling of the estimated cancer cases in comparison to Model A (which has already allowed for a DDREF of 1).

B2. Cardiovascular risks

According to ICRP elevated risks for nonmalignant diseases are known after IR exposure (Ozasa 2012, 229-243). However, the suggestion of the ICRP (ICRP 2012, 1-2) for a threshold of 500 mSv for radio-induced diseases other than cancer is outdated (Table 2.12. *Methodology Model B2*). Cardio-vascular excess risks have been described in children and adults due to IR exposure after Chernobyl (Nyagu 1994, Prysyazhnuk et al. 2002, 188-287, Lazyuk et al. 2005, 24-25). Studies on low level exposure to IR found an elevated risk for arterial hypertension in nuclear workers (Azizova et al. 2019) as well as a significant excess mortality from cardiovascular diseases Gillies 2017) at a similar level as excess cancer mortality after IR exposure (Little et al. 2012, 1503-1511). Generally – as for cancer – incidence rates are higher than mortality rates also for cardiovascular diseases. In Europe the ratio of mortality to incidence for cardio-vascular diseases is about 1 to 3 (European Heart Network 2017).

Table 2.12. Model B2: Radio-induced non-cancer diseases: Risk-factors for mortality due to cardio-vascular diagnoses

(In brackets: not statistically significant; x: unknown)

Pathology	*Risk factor*	*Reference*
Cardio-vascular diseases (CVD)	(x)	Nyagu 1994; Prysyazhnuk et al. 2002, 188-287; Lazyuk 2005, 24-25. (Chernobyl: children & adults)
Circulatory diseases	ERR 0.11/Gy	Ozasa et al. 2012, 229-243 (A-bomb-survivors)
Circulatory diseases combined	EAR from 2.5%/Sv [France] to 8.5%/Sv [Russia]	Little et al. 2012, 1503-1511 (Meta-analysis)
Ischemic heart disease (IHD)	ERR 0.10/Sv	
Non-IHD	ERR (0.12/Sv)	
Cerebrovascular diseases (CVA)	ERR 0.20/Sv	
Circulatory diseases apart from heart disease and CVA	ERR 0.10/Sv	
Circulatory diseases	ERR 0.22/Sv	Gillies et al. 2017, 276-290 (Nuclear workers)
Cerebrovascular disease	ERR 0.50/Sv	
Ischemic heart disease	ERR 0.18/Sv	

Summary Methodology Model B

Model B contains numeric estimates of cancer incidence using a risk factor of 0.4/Sv (and 0.2/Sv for cancer mortality) and using a risk factor of 0.15/Sv for cardiovascular disease (CVD) incidence (and 0.05/Sv for mortality).

Severe diseases (cancer and CVD combined) therefore make 0.55/Sv for incidence and 0.25/Sv for mortality. Results are presented both for average and variable meteorological situations without confidence intervals (*infra 3.2*). Taking into account these considerations, the estimates of victims by these two severe radio-induced disease categories combined are numerically 2.75-times higher than in Model A.

(v) Model C

Model C: Broadened Radiation Health Risk Assessment

Acknowledging that cancer and cardiovascular diseases reflect only the "tip of the iceberg" of radio-induced health effects observed after the Chernobyl NPP accident, (Tereshchenko et al. 2003, 283-287) estimates of both Model A and Model B seriously underestimate the true burden of radio-induced pathologies. Model C therefore includes cancer and cardiovascular cases as mentioned in Model B and, in addition, covers the risks for other radio-induced diseases as well as reproductive and developmental hazards by ionizing radiation. For these conditions no EAR-risk factors are established, although for some conditions ERRs (excess relative risks) > 1 are documented (Table 2.13.).

A fundamental difference between the above-mentioned reproductive and developmental hazards, and radio-induced cancer is that the linear no threshold concept (LNT) for risk estimates is not generally applicable (Schmitz-Feuerhake et al. 2016, 10). This is explained by the increasing probability of embryonic or fetal loss with increasing IR dose (which in turn leads to a probability curve similar to the shape of a hogback). The dose response relationship for teratogenic effects however has a sigmoid form, i.e. a positive curvature (Körblein & Küchhoff 1997). Reproductive and developmental hazards through ionizing radiation are underestimated by ICRP. Particularly a risk factor of 0.2%/Sv for genetic damages is orders of magnitude too low (Hoffmann et al. 2017, 10ff).

C1. Non-cancer diseases other than cardiovascular diseases

Apart from cardio-vascular diseases, many other nonmalignant diseases (of the respiratory, gastrointestinal, neurological, central nervous, endocrine, immune- and musculo-skeletal system, infections, skin diseases, non-neoplastic hematological disorders and diseases of the lymphatic system) are associated with exposure to IR (Table 2.13). Many of these diseases, especially of the endocrine, neurologic, and musculo–skeleton system, cause chronic debilitation and eventual death. They are huge burden for individuals, families and society.

Up to 300-folds increments of incidence of these pathologies in contaminated populations of Belarus and the Ukraine as well as in participants in the Chernobyl cleaning process – so called "liquidators" – have been noticed (Nyagu 1994; Prysyazhnuk 2002, 188-287; Pflugbeil et al. 2006, 17, 21, 57, 59; Yablokov et al. 2009, 58-160). The latter received high IR mean doses of 146 mSv (range 50 – 700 mSv) (Tereshchenko et al. 2002, 165-167), but also the general population living in contaminated regions with average lifetime IR doses of 21 mSv (range 15 – 83 mSv) (Cardis 1996, 241-271) showed an increased morbidity. Multi-morbidity was typical (Tereshchenko et al. 2003, 283-287). These non-malignant diseases far exceeded the number of malignant diseases and frequently evolved rapidly during the first decade after the Chernobyl NPP accident (Yablokov 2016, 294). This is clearly different from radio-induced cancer cases which are typically diagnosed in later decades. Thus, increased risks for radio-induced non-cancer diseases were observed shortly after just a few single yearly doses, which correspond to total doses from the low-dose range.

Table 2.13. Model C1: Non-cancer diseases (other than cardiovascular) observed after ionizing radiation
(In brackets: not statistically significant)

Pathology	*Increase of non-cancer diseases in Chernobyl victims: Gomel and Ukrainian populations; Liquidators (Yablokov et al. 2009) comparing pre- and post-Chernobyl era (first decade)*	*Relative risk factor (ERR)*	*Reference*	*Remark*
Respiratory diseases	11 to 109 fold		Nyagu 1994; Prysyazhnuk et al. 2002, 188-287; Pflugbeil et al. 2006, 17, 21, 57,59; Yablokov et al. 2009, 58-160; Yablokov et al. 2016, 294. (Chernobyl)	Morbidity
Gastrointestinal diseases	60 to 213 fold			
Neurological and psychiatric diseases	6 to 53 fold			
Endocrine diseases	26 to 300 fold			
Immunological diseases, infections	18 to 12 fold			
Skin diseases	16 to 51 fold			
Musculo-skeletal diseases	80 to 97 fold			
Hematological and diseases of the lymphatic system	15 to 21 fold			
Respiratory diseases		0.23/Gy	Ozasa et al. 2012, 229-243 (A-bomb survivors)	Mortality
Pneumonia and influenza		0.24/Gy		
Digestive diseases		0.20/Gy		
Genitourinary diseases		0.18/Gy		
Non-neoplastic diseases of the blood		1.7/Gy		
Mental disorders		1.3/Sv	Gillies et al. 2017, 276-290 (Nuclear workers)	Mortality
Non-malignant respiratory disease		0.13/Sv		
Digestive diseases		0.11/Sv		

Of particular concern is the significant excess of many of these conditions in children living in contaminated regions. In the Ukraine this has been observed especially concerning the respiratory, cardiovascular and digestive system, thyroid and other endocrine diseases, and immunodeficiency disorders, with more than 70% of children being chronically ill 10 years after the Chernobyl NPP accident (Prysyazhnuk et al. 2002, 188-276). According to data from the Belarussian Ministry of Public Health, in 1985 – just before the 1986 catastrophe – 90% of children were considered "practically healthy". By 2000, fewer than 20% were considered healthy, and in the most contaminated Gomel Province, fewer than 10% of children were well (Yablokov et al. 2009, 58-160).

Significant excess mortality to respiratory, digestive diseases and nonmalignant diseases of the blood is also documented from Japanese atomic bomb survivors (Ozasa et al. 2012, 229-243). A recent study on nuclear workers' external exposure to low dose of IR demonstrated an elevated mortality associated with mental disorders (significant) and respiratory and digestive diseases (not significant) (Gillies et al. 2017, 276-290) (Table 2.13.).

C2. Reproductive and developmental hazards by ionizing radiation

All along the complex human reproductive process, elevated risks by ionizing radiation at many levels are well known. Their medical and societal relevance is evident considering the extensive radiobiological and epidemiological research over decades on the consequences of the Chernobyl disaster. The hazards are attributable to the high sensitivity to ionizing radiation of the cell division in the developing organism (Brauch & Russell 1952, 369ff). Chronic repetitive exposure typically encountered after radio-contamination by an NPP-accident is more detrimental than a single exposure. IR health effects encompass pre-conceptual aspects such as female endocrine dysfunction leading to infertility as well as preexisting parental irradiation associated with consecutive severe development detriments and diseases in the offspring (Hoffmann et al. 2017, 12). Exposure to IR during pregnancy causes chromosomal aberrations leading – among others – to elevated incidence of Down's syndrome (Sperling 1987, 1991, 1994a, 1994b) and changes of the sex odds ratio (Scherb et al. 2016, 104-111). *In utero* irradiation furthermore leads to adverse effects on the embryo or fetus inducing spontaneous abortions and congenital malformations, radio-induced excess risks for low birth weight, perinatal and infant mortality as well as elevated risks for childhood malignancies (Hoffmann et al. 2017) (Table 2.14).

Table 2.14. Model C2: Reproductive and developmental hazards by ionizing radiation

Precondition	*Pathology*
Female endocrine dysfunction	Infertility
Preexisting parental irradiation	Sterility Spontaneous abortions Chromosomal / Genome alterations Downs Syndrome (trisomy 21) Sex odds changes (loss of female life births) Low birth weight Perinatal mortality Infant mortality Congenital malformations Malignancies Immune deficiency
In utero exposure to radiation	Malignancies: Leukemia, solid cancer Chromosomal aberrations Down's Syndrome (trisomy 21) Spontaneous abortions Congenital malformations Organ dysfunction – e.g. mental retardation, low IQ Excess perinatal mortality
(Hoffmann et al. 2017)	

Contrary to what is stated in ICRP Document 90 (ICRP 2003), there is no scientific reason for establishing a threshold dose of 100 mSv for detriments due to *in utero* exposure (Hoffmann 2017, 10-13). In-depth details about non-cancer health effects are given elsewhere (Claussen & Rosen 2016; Hoffmann et al. 2017, 10-3).

Summary Methodology Model C

To conclude on Model C, quantitative estimates for cancer and cardiovascular diseases are performed according to Model B. In addition, Model C developed semi quantitative estimates of other non-malignant radio-induced health effects according to Yablokov who suggests that these cases outnumber cancer cases by a significant margin (Yablokov et al. 2009, 58-160).

III Results

3.1 Estimated collective committed effective doses

Estimates of health pressure by radioactive releases are based on the Collective committed effective doses (CCED) received by the populations (*supra* 2.6). Collective doses are calculated according to the dose factors and related equations (Tables A5 and A6). The five different sources of radioactivity that were calculated are: the cloud of rare gas, aerosols and refractories, ground deposition of aerosols, and refractories (*supra* 2.6(ii)).

Table 3.1 gives estimates of the average health pressure for the five nuclear power plants (NPPs) related to the source of the release and Europe as geographical impacted area. Collective committed effective doses are calculated (in persSv) as average weather situation. It is obvious that the main source of radiation comes from the cloud of aerosols which constitutes between 55% (Mühleberg) and 72% (Beznau) of the impact in persSv. The second main contributions to CCED, by source, stem from the deposition of aerosols (external exposure calculated for 1 year and according to the half-lives of the 32 isotopes). As a result, a major nuclear accident would result in an average CCED between 50,580 persSv (for Beznau NPP) and 123,439 persSv (for Gösgen) at the scale of Europe. On the last line of Table 3.1, the number of affected persons is calculated for the cloud of aerosols. In this configuration, the number of affected persons is between 16 million (Beznau) and 24 million persons (Bugey).

Table 3.1. Simulation of 365 weather situations in 2017: Average collective committed effective doses (CCED – persSv) by sources in Europe

		Beznau EUR	Bugey EUR	Gösgen EUR	Leibstadt EUR	Mühleberg EUR
A)	rare gas (persSv)	58	48	200	205	38
B)	aerhpress (persSv)	36 164	52 893	88 497	61 416	60 270
C)	refhpress (persSv)	795	903	1 965	2 743	8 661
D)	aerdepo (persSv)	13 409	24 185	32 449	28 287	40 434
E)	refdepo (persSv)	154	170	327	340	569
	Total (persSv)	50 580	78 198	123 439	92 991	109 973
	Numbers of affected persons* (No)	16 396 627	24 033 035	22 927 076	21 303 972	22 962 069
	* Illustrative default case					

Line 1 of Table 3.2 confirms that the affected populations in Europe vary between 16 and 24 million people. These figures are nonetheless determined by the 72 hours of each simulation and by the number of becquerels of the lowest contour of the cloud (which is around 0.1 mSv for the cloud of aerosols and at 0.2 mSv for illustrative images). If the simulation would last for additional days and the number of Bq of the lower contour be lowered, then the number of impacted people would increase. If we consider the 4 Swiss NPPs, the average number of impacted persons is larger in the four countries surrounding Switzerland[18]. However, there is the exception if we look at the potential impact that Mühleberg would have in Austria (1,746,000) and in France (2,716,000), compared to Switzerland (2,867,000). Germany would have far more impacted persons by the five NPPs (including from Bugey, 7,207,000) than any other country. Furthermore, the fractions of populations located outside of the country of the accident, and that would be impacted by the release, would amount to between 78% (for Bugey) and 94% (for Leibstadt).

However, the results have different profiles when looking at the CCED. Switzerland could receive – on average – a larger CCED for three of its four NPPs, except Leibstadt. The CCED fraction impacting a foreign country would be 29%, 32%, 35%, for Bugey, Gösgen and Mühleberg respectively, almost 45 % for Beznau, but more than 60% for Leibstadt according to its peripheral geographic location near the German border.

Table 3.2. Persons and regions impacted on average

Impacted Areas	Country of Location:	Beznau CHE	Bugey FRA	Gösgen CHE	Leibstadt CHE	Mühleberg CHE
EUR	Persons exposed* (No)	16 396 627	24 033 035	22 927 076	21 303 972	22 962 069
	CCED (persSv)	50 580	78 198	123 439	92 991	109 973
CHE	Persons exposed* (No)	1 243 361	1 293 058	1 826 313	1 241 326	2 867 147
	CCED (persSv)	28 331	3 683	84 396	34 444	71 941
GER	Persons exposed* (No)	6 537 424	7 207 004	7 652 514	7 944 493	7 278 122
	CCED (persSv)	15 151	8 968	20 852	41 777	14 840
FRA	Persons exposed* (No)	1 800 470	5 359 260	2 388 067	2 221 993	2 716 167
	CCED (persSv)	3 440	55 363	8 629	8 147	11 184
ITA	Persons exposed* (No)	1 571 500	3 404 078	2 538 760	1 960 409	3 131 200
	CCED (persSv)	1 336	5 564	3 466	2 781	6 608
AUT	Persons exposed* (No)	1 453 017	632 119	1 903 213	1 791 011	1 746 630
	CCED (persSv)	1 166	685	2 814	2 725	2 723
Other EUR	Persons exposed* (No)	3 790 855	6 137 516	6 618 209	6 144 740	5 222 802
	CCED (persSv)	1 155	3 937	3 282	3 117	2 677
EUR minus country of NPP	Persons exposed* (No)	15 153 267	18 673 775	21 100 763	20 062 646	20 094 921
	CCED (persSv)	22 248	22 835	39 043	58 547	38 032
EUR minus country of NPP	Persons exposed (%)	92%	78%	92%	94%	88%
	CCED (%)	44%	29%	32%	63%	35%
	* Illustrative default case					

In the event of a severe accident in a Swiss nuclear power plant, the neighboring states would be affected by radiation in descending average CCED: 1° Germany, 2° France, 3° Italy, 4° Other Europe, 5° Austria (Table 3.2).

[18] Liechtenstein was not included in the mapping of the impact.

In Table 3.3, Collective committed effective doses (CCED) are given for Europe (including Switzerland) according to different meteorological situations. In terms of Europe as an impacted area, comparisons of medians and highest or lowest deciles and centiles illustrate the dependency of CCED on meteorology. Compared to the median CCEDs, the highest centiles are around 2.6-times higher (for Mühleberg) and 4.2-times higher (for Bugey). A comparison of median CCEDs to mean CCEDs – Table 3.3 to Table 3.2 shows lower median CCEDs, 80% to 95% of mean CCED for Leibstadt and Mühleberg respectively, reflecting a slightly skewed distribution because of varying weather situations.

Table 3.3. Simulation of radioactive releases on 365 meteorological situations: Collective committed effective dose endured by all Europeans (including Swiss people) distributed by quantiles (persSv)

Impacted area:	Beznau EUR Total (persSv)	Bugey EUR Total (persSv)	Gösgen EUR Total (persSv)	Leibstadt EUR Total (persSv)	Mühleberg EUR Total (persSv)
Highest centile	154 333	285 638	353 171	264 014	268 455
Highest decile	94 892	127 939	199 233	167 855	176 784
Third quartile	66 717	92 050	149 516	124 525	132 565
Median	43 911	68 452	110 692	75 413	104 978
First quartile	28 166	48 851	79 206	51 800	76 416
Lowest decile	16 907	32 956	59 790	35 101	52 850
Lowest centile	6 429	10 601	20 986	11 364	16 624

Table 3.4 focuses on the impact in Switzerland. It suggests that the highest centile would result in CCEDs about 3.1-times higher than the median (for NPP Mühleberg) and 11.9 times higher for NPP Leibstadt. For Bugey a median of 2 persSv for Switzerland as impacted area, which means Switzerland would be impacted by 1 out of 2 major accidents. In other words, Switzerland would be seriously impacted by NPP Bugey in the event of weather conditions with an occurrence ≤ 25% for a CCED ≥ 1,875 persSv, an occurrence ≤ 10% for a CCED ≥ 13,094 persSv and an occurrence ≤ 1% for a CCED ≥ 51,372 persSv. These figures can be compared with the mean value, which is at 3,683 persSv (table 3.2).

Table 3.4. Simulation of 365 weather situations: Collective committed effective dose (CCED) endured by Swiss people (persSv – distributed by quantiles)

Impacted area	Beznau CHE Total (persSv)	Bugey CHE Total (persSv)	Gösgen CHE Total (persSv)	Leibstadt CHE Total (persSv)	Mühleberg CHE Total (persSv)
Highest centile	122 167	51 372	241 980	187 782	206 884
Highest decile	72 365	13 094	154 037	100 320	115 204
Third quartile	41 440	1 875	109 033	46 922	87 659
Median	16 090	2	69 078	15 759	66 371
First quartile	8 641	0	44 482	5 127	47 110
Lowest decile	4 699	0	28 853	2 475	31 535
Lowest centile	1 523	0	11 911	1 477	8 725

A comparison of median CCEDs (table 3.4) to mean CCEDs (table 3.2) shows a different pattern for median CCED with 45% to 92% of mean values for accidents from a Swiss NPP – for Leibstadt and Mühleberg respectively. This reflects the greater heterogeneity of the distribution of the health impacts, when Switzerland is considered separately from the continental level. This gap is even more pronounced if we consider the impact of Bugey in Switzerland.

Table 3.5. Simulation of 365 weather situations: Collective committed effective dose (CCED) endured by German people (persSv – distributed by quantiles)

Impacted area	Beznau GER Total (persSv)	Bugey GER Total (persSv)	Gösgen GER Total (persSv)	Leibstadt GER Total (persSv)	Mühleberg GER Total (persSv)
Highest centile	73 978	101 247	110 566	148 438	113 407
Highest decile	31 326	26 811	48 427	75 718	36 018
Third quartile	22 892	9 833	30 329	57 022	22 463
Median	12 359	105	14 870	37 139	8 832
First quartile	3 656	0	2 804	18 847	101
Lowest decile	137	0	0	7 751	0
Lowest centile	3	0	0	3 133	0

Table 3.5 shows that Germany could be heavily impacted by a major accident. The ratio of median CCEDs in Germany compared to Switzerland would be 12,300/16,000, if the release comes from Beznau, 105/2 from Bugey, 14,800/69,000 from Gösgen, 37,100/15,700 from Leibstadt, and 8,800/66,300 from Mühleberg. Leibstadt is by far the most dangerous NPP for Germany. In the other respects, Germany is more threatened by Swiss NPPs than France is (Table 3.6), or than Italy and Austria are (see Tables B1 and B2 in the Annex).

Table 3.6 shows France could be heavily impacted by an accident at its Bugey NPP. A severe release from a a Swiss NPP would not hurt France in roughly half of the weather situations. However, it could represent – at the level of the highest decile – between 13% (Beznau), 31% (Leibstadt) and 40% (Mühleberg) of a release from Bugey that would be estimated at the same decile level (12,500; 29,900 and 37,000 respectively to compare to 93,700).

Table 3.6. Simulation of 365 weather situations: Collective committed effective dose (CCED) endured by French people (persSv – distributed by quantiles)

Impacted area	Beznau FRA Total (persSv)	Bugey FRA Total (persSv)	Gösgen FRA Total (persSv)	Leibstadt FRA Total (persSv)	Mühleberg FRA Total (persSv)
Highest centile	33 817	284 086	107 483	85 330	108 198
Highest decile	12 580	93 571	27 785	29 929	37 047
Third quartile	2 281	67 067	7 770	7 436	13 453
Median	0	44 773	13	1	307
First quartile	0	28 576	0	0	0
Lowest decile	0	18 342	0	0	0
Lowest centile	0	5 322	0	0	0

Concerning the possible impact of the five NPPs in Italy and Austria, see Tables B1, B2 in the Annex.

3.2 Results: Health Effects

(i) Victims: Cancer incidence / cancer mortality according to *Model A* (WHO / UNSCEAR)

Table 3.7 proceeds from a simulation of radioactive releases on 365 meteorological situations for 5 NPPs. It estimates (mean and confidence interval) the number of radio-induced cancer cases according to *Model A issued by WHO/UNSCEAR*. For the number of estimated radio-induced cancer deaths divide cancer cases by 2.

Table 3.7. Estimation (mean) for average health impact: Number of radioinduced cancer cases and cancer deaths – Model A (confidence intervals)

		Beznau			Bugey			Gösgen			Leibstadt			Mühleberg		
Country of location:			CHE			FRA			CHE			CHE			CHE	
Imp. areas		Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
EUR	canc.cases	4 552	10 116	17 703	7 038	15 640	27 369	11 109	24 688	43 204	8 369	18 598	32 547	9 898	21 995	38 491
	canc. dths	2 529	5 058	9 610	3 910	7 820	14 858	6 172	12 344	23 453	4 650	9 299	17 668	5 499	10 997	20 895
CHE	canc. ca.	2 550	5 666	9 916	331	737	1 289	7 596	16 879	29 539	3 100	6 889	12 055	6 475	14 388	25 179
	canc. dths	1 417	2 833	5 383	184	368	700	4 220	8 440	16 035	1 722	3 444	6 544	3 597	7 194	13 669
GER	canc. ca.	1 364	3 030	5 303	807	1 794	3 139	1 877	4 170	7 298	3 760	8 355	14 622	1 336	2 968	5 194
	canc. dths	758	1 515	2 879	448	897	1 704	1 043	2 085	3 962	2 089	4 178	7 938	742	1 484	2 820
FRA	canc. ca.	310	688	1 204	4 983	11 073	19 377	777	1 726	3 020	733	1 629	2 851	1 007	2 237	3 914
	canc. dths	172	344	654	2 768	5 536	10 519	431	863	1 640	407	815	1 548	559	1 118	2 125
ITA	canc. ca.	120	267	468	501	1 113	1 947	312	693	1 213	250	556	973	595	1 322	2 313
	canc. dths	67	134	254	278	556	1 057	173	347	659	139	278	528	330	661	1 255
AUT	canc. ca.	105	233	408	62	137	240	253	563	985	245	545	954	245	545	953
	canc. dths	58	117	222	34	68	130	141	281	535	136	273	518	136	272	517
Other EUR	canc. ca.	104	231	404	354	787	1 378	295	656	1 149	281	623	1 091	241	535	937
	canc. dths	58	115	219	197	394	748	164	328	624	156	312	592	134	268	509
EUR – co. of NPP	canc. ca.	2 002	4 450	7 787	6 706	14 903	26 081	3 514	7 809	13 665	5 269	11 709	20 491	3 423	7 606	13 311
	canc. dths	1 112	2 225	4 227	3 726	7 452	14 158	1 952	3 904	7 418	2 927	5 855	11 124	1 902	3 803	7 226
EUR – co. of NPP	canc. ca	44%	44%	44%	95%	95%	95%	32%	32%	32%	63%	63%	63%	35%	35%	35%
	canc. dths	44%	44%	44%	95%	95%	95%	32%	32%	32%	63%	63%	63%	35%	35%	35%

Based on the CCEDs (Table 3.2) and a risk factor (EAR) of 0.2/Sv for cancer incidence (according to UNSCEAR 2013), the numbers of radioinduced cancer cases (and confidence intervals according to BEIR VII (2006a), on average, have been estimated for impacted regions and five NPPs (Table 3.7). Numbers of cancer cases in Europe amount to between around 10,000 (for NPP Beznau, one reactor only) and nearly 25,000 cancer cases (for NPP Gösgen). For cancer deaths, these numbers should be halved. The pattern of incidence among regions impacted reflects the different CCEDs according to the site of the assumed NPP accident. Between one and two thirds of radio-induced cancer cases as a consequence of a Swiss NPP accident would occur in Switzerland. With a Bugey NPP accident (one reactor only), the majority of cancer cases would be expected in France and only 5% in Switzerland. An accident in NPP Leibstadt would result in over 8,300 radio-induced cancer cases in Germany – more than the nearly 6,900 cases in Switzerland.

(ii) Victims: Cancer and cardio-vascular disease-incidence according to *Model B*

Model B is more recent and seems preferable to Model A due to new epidemiological data (Cardis 2005, 77-80; Körblein & Küchenhoff 2006, 109-114; IPPNW 2014; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8). With respect to cancer cases, in comparison to the previous model, Model B implies a doubling of the risk factor (EAR) from 0.2/Sv to 0.4/Sv and, consequently, leads to doubling the estimated numbers of radio-induced cancer cases (*supra* 2.7(iv)).

In Table 3.8, the highest estimates are obtained for an accident at NPP Gösgen with nearly 50,000 and more than 33,700 radio-induced cancer cases in Europe and Switzerland respectively. Moreover, major accidents in the NPPs of Beznau, Bugey, Leibstadt and Mühleberg would result in 20,000 to nearly almost 44,000 radio-induced cancer cases in Europe and in more than 11,300 to more than 28,700 cancer cases in Switzerland. For cancer mortality, the numbers have to be halved.

Based on recent scientific evidence for elevated risks for radio-induced non-cancer diseases, Model B – unlike Model A – also takes radio-induced cardiovascular diseases such as heart attacks or strokes into account (Little et al. 2012, 1503-1511; Gillies et al. 2017, 276-290; European Heart Network 2017). In Table 3.8, the estimated figures are from around 7,600 cases (for NPP Beznau) to 18,500 cases (for Gösgen NPP) in Europe and – with respect to Swiss NPP origin – more than 4,200 cases (for Beznau NPP) to more than 12,600 cases (for Gösgen NPP) in Switzerland. For an accident in NPP Leibstadt radio-induced cardiovascular cases would be more frequent in Germany than in Switzerland (with more than 6,200 and 5,100 estimated cases, respectively). For mortality by radio-induced cardiovascular diseases, incidence figures have to be divided by three.

Table 3.8. Estimation (mean) for average health impact over 365 simulations: Number of radioinduced cancer cases, cardiovascular cases, cancer mortality and cardiovascular mortality – Model B

	NPP:	Beznau		Bugey		Gösgen		Leibstadt		Mühleberg	
	Country of Location:	CHE		FRA		CHE		CHE		CHE	
Impacted Areas		(cases)	(deaths)	(cases)	(deaths)	(cases)	(deaths)	cases	(deaths)	(cases)	(deaths)
EUR	Rad. cancer cases and deaths	20 232	10 116	31 279	15 640	49 376	24 688	37 196	18 598	43 989	21 995
	Rad. cardio. cases and deaths	7 587	2 529	11 730	3 910	18 516	6 172	13 949	4 650	16 496	5 499
CHE	Rad. cancer cases and deaths	11 333	5 666	1 473	737	33 758	16 879	13 778	6 889	28 776	14 388
	Rad. cardio. cases and deaths	4 250	1 417	552	184	12 659	4 220	5 167	1 722	10 791	3 597
GER	Rad. cancer cases and deaths	6 061	3 030	3 587	1 794	8 341	4 170	16 711	8 355	5 936	2 968
	Rad. cardio. cases and deaths	2 273	758	1 345	448	3 128	1 043	6 266	2 089	2 226	742
FRA	Rad. cancer cases and deaths	1 376	688	22 145	11 073	3 452	1 726	3 259	1 629	4 474	2 237
	Rad. cardio. cases and deaths	516	172	8 304	2 768	1 294	431	1 222	407	1 678	559
ITA	Rad. cancer cases and deaths	535	267	2 226	1 113	1 386	693	1 113	556	2 643	1 322
	Rad. cardio. cases and deaths	200	67	835	278	520	173	417	139	991	330
AUT	Rad. cancer cases and deaths	466	233	274	137	1 126	563	1 090	545	1 089	545
	Rad. cardio. cases and deaths	175	58	103	34	422	141	409	136	408	136
Other EUR	Rad. cancer cases and deaths	462	231	1 575	787	1 313	656	1 247	623	1 071	535
	Rad. cardio. cases and deaths	173	58	590	197	492	164	468	156	402	134
EUR – co. of NPP	Rad. cancer cases and deaths	8 899	4 450	9 134	4 567	15 617	7 809	23 419	11 709	15 213	7 606
	Rad. cardio. cases and deaths	3 337	1 112	3 425	1 142	5 856	1 952	8 782	2 927	5 705	1 902
EUR – co. of NPP	R. canc. cases & deaths (%)	44%	44%	29%	29%	32%	32%	63%	63%	35%	35%
	R. cardio. cases & deaths (%)	44%	44%	29%	29%	32%	32%	63%	63%	35%	35%

For Model B, estimates of the numbers of severe radio-induced diseases (i.e. cancer and cardiovascular diseases added), according to varying meteorological conditions, have been performed. Table 3.9. presents the estimates according to 365 different weather situations (year 2017). It specifies the regions impacted and the estimated number of cases with severe radio-induced diseases distributed in quantiles (median, highest, and lowest decile). For the estimates of the number of deaths, the number of cases is to be divided by 2.2. In the interest of clarity, Table 3.9. only shows median and both highest and lowest decile of the distribution of cases. For full content of calculations including centiles and mortality data, refer to Table B3 in Annex B.

Table 3.9. Model B: Simulation of 365 weather situations: Estimated severe radio-induced diseases (cancer cases and cardiovascular cases combined)

Impacted Areas		Beznau (No)	Bugey (No)	Gösgen (No)	Leibstadt (No)	Mühleb. (No)
EUR	Highest decile	52 191	70 366	109 578	92 320	97 231
	Median	24 151	37 649	60 881	41 477	57 738
	Lowest decile	9 299	18 126	32 884	19 305	29 067
CHE	Highest decile	39 801	7 202	84 720	55 176	63 362
	Median	8 850	1	37 993	8 668	36 504
	Lowest decile	2 584	0	15 869	1 361	17 344
GER	Highest decile	17 229	14 746	26 635	41 645	19 810
	Median	6 798	58	8 178	20 427	4 858
	Lowest decile	75	0	0	4 263	0
FRA	Highest decile	6 919	51 464	15 282	16 461	20 376
	Median	0	24 625	7	1	169
	Lowest decile	0	10 088	0	0	0
ITA	Highest decile	1 782	7 771	5 337	4 485	9 199
	Median	0	144	6	1	73
	Lowest decile	0	0	0	0	0
AUT	Highest decile	2 027	1 068	4 816	4 525	4 466
	Median	96	0	365	286	326
	Lowest decile	0	0	0	0	0

As discussed earlier, CCED – alongside the NPP source terms – depend on weather conditions and, to a higher degree, on the 'boundary effect', as to whether a specific country is considered, or whether it is the continental level that is taken into account. Similarly, for the highest decile as well as the highest centile respectively, the distances to the median can be very different. Thus, more than 109,000 cases of severe radio-induced diseases in Europe, that would result from a major accident in the Gösgen NPP are estimated (highest decile). In some weather situations, also France, Italy, and Austria would be affected seriously by radioactive fallout. In Table 3.9, at the level of the highest decile, the estimates for severe radio-induced disease cases by a Swiss NPP accident would amount to between 17,229 to 41,645 in Germany, 6,919 to 20,376 in France, 1,782 to 9,199 in Italy, and 2,027 to 4,816 in Austria[19]. By contrast, the lowest decile is 0 for France, Italy and Austria. However, Germany would be only affected by Leibstadt and, in a lesser proportion, by Beznau. Similarly, an accident in one of the reactors of the NPP Bugey would lead to more than 70,000 European victims (highest decile). At the scale of countries, the highest decile could exceed 51,400 in France, 14'700 in Germany, 7,700 in Italy, 7,200 in Switzerland or 1,000 in Austria, while the median does not exceed 144 for the most impacted country (except France). For data on quartiles and centiles, see Table B3 in the Annex B.

(iii) Victims: according to *Model C*

There is ample scientific evidence of the huge numbers of non-cancer health effects after the Chernobyl NPP accident (Pflugbeil et al. 2006, Yablokov et al. 2009, Yablokov et al. 2016, Claussen & Rosen 2016). However, there are no established EARs for radio-induced health effects in humans other than considered in Model A and Model B in this study. Therefore, instead of numerical calculations, only qualitative (*supra* Table 2.13) or semi-quantitative estimates (Table 3.10.) can be provided.

For all radio-induced pathologies it should be kept in mind that - due to the substantially higher population density - the number of potential victims from an accident in a Western European NPP could be greater than the number of victims of Chernoby.

Radio-induced diseases (other than cancer and CVD diseases)

Millions of victims with radio-induced non-cancer diseases must be expected from an eventual major NPP accident in one of the five Western European NPPs studied - far more than the number of cancer cases estimated according to Models A or B (Yablokov et al. 2009).

Malformations:

Extrapolating available data on congenital malformations and the total number of children born in the territories contaminated by Chernobyl (Yablokov et al. 2009), we must assume that each year several

[19] An addition of these figures would be senseless since they come from diametrically opposite weather conditions.

thousand newborns in Europe will also bear larger and smaller hereditary anomalies that would be caused by the radioactive fallout of an eventual major nuclear accident in a European NPP.

Genetic changes

Although severe genetic risks such as the significantly increased incidence of trisomy 21 (Down's syndrome) were observed early after the Chernobyl NPP accident (Sperling 1991, 1994a, 1994b, 2012), the overwhelming majority of Chernobyl-induced genetic changes are predicted to become visible after several generations only (Yablokov et al. 2009) and the genetic consequences of the Chernobyl catastrophe will impact hundreds of millions of people. This could be worse in a major western European NPP accident due to the substantially greater population densities surrounding NPPs in comparison to Chernobyl.

Table 3.10. Victims: Non-cancer health effects estimated in an eventual major NPP-accident in Western Europe (For instance in NPPs Beznau, Bugey, Gösgen, Mühleberg, Leibstadt)

Region impacted	*Non-cancer health effects*	*Semi quantitative estimate*	Ref.
Europe	Non-malignant diseases	Millions of people	Yablokov et al. 2009, 58-160
	Malformations	Thousands per year	
	Genetic changes	Hundreds of millions of people	

3.3 *Estimate of the number of persons to be evacuated before a major radioactive release (preventive action)*

We number people possibly receiving different levels of committed effective doses, according to the simulation of the passage of the cloud. As stated in Section 2.6(iii), the levels 1, 6, 20, 50, and 100 mSv have different normative implications. A preventive evacuation for people to be potentially reached at a level ≥ 100 mSv is confirmed by the Swiss Federal Council's Ordinance 814.501 (Art. 133.1).

Table 3.11. Simulation of radioactive releases on 365 meteorological situations. Population protection in the event of a preventive evacuation: potential and average number of persons impacted – in Europe – by different levels of committed effective doses (per person CED)

2017	Beznau EUR	Bugey EUR	Goesgen EUR	Leibstadt EUR	Mühleb. EUR	Average EUR
Persons > 1mSv	3 917 490	6 289 074	6 568 596	6 380 034	6 756 608	5 982 360
Persons > 6 mSv	929 329	1 447 333	1 936 164	1 515 456	2 024 604	1 570 577
Persons > 20 mSv	362 885	464 709	777 673	528 281	673 676	561 445
Persons > 50 mSv	190 624	207 804	427 323	272 832	265 130	272 743
Persons > 100 mSv	110 919	116 925	268 061	161 644	136 971	158 904

Committed effective doses are calculated from the dose factors used for the protection of the population in the event of an alert (according to annex 3 of Ordinance 814.501)

Table 3.12. Simulation of radioactive releases on 365 meteorological situations. Population protection in the event of a preventive evacuation: potential and average number of persons impacted – in Switzerland – by different levels of committed effective doses (per person CED)

2017	Beznau CHE	Bugey CHE	Goesgen CHE	Leibstadt CHE	Mühleb. CHE	Average CHE
Persons > 1mSv	776 843	613 978	1 312 597	788 596	2 095 162	1 117 435
Persons > 6 mSv	410 560	143 764	867 281	433 543	1 225 745	616 178
Persons > 20 mSv	226 912	23 500	544 397	229 751	532 668	311 446
Persons > 50 mSv	137 608	5 176	345 723	137 602	234 070	172 036
Persons > 100 mSv	86 779	1 078	227 558	87 339	127 624	106 076

Committed effective doses are calculated from the dose factors used for the protection of the population in the event of an alert (according to annex 3 of Ordinance 814.501)

Table 3.11 gives the number of people on average that would receive different CEDs. With regards to the impact at the European scale, Bugey would impact less persons than Goesgen, Leibstadt, and Mühleberg (for each six levels in mSv) despite the fact that it has the higher release of aerosols (*supra* 2.2(iv)). Swiss nuclear power plants are located in more populated areas, while specific simulations show that the clouds from the Bugey would not often reach Lyon.

In the Annex C, Table C1 shows, concerning the impact on EUR for the years 2017-2018, that the number of severely impacted persons with a CED ≥ 100 mSv varies greatly from the lowest to the highest decile: Beznau (5,900 to > 217,000 persons), Bugey (0 to > 203,000), Goesgen (19,000 to > 518,000), Leibstadt (14,800 to > 391,000), Mühleberg (22,800 to > 253,000). The number of severely impacted persons can be 'very low' in 5% to 10% of the situations and, at the opposite end, it can surpass 1 Mio persons (for all NPPs but Beznau). In other words, Table C1 could constitute a basis to question whether members of the population could be preserved from a CED of ≥ 100 mSv by civil protection bodies. Depending on weather conditions, inhabitants of Germany and its civil protection authority[20], or inhabitants from different countries such as France, or Italy could be in very difficult situations.

If we look at the alert question with a CED ≥ 100 mSv, at the Swiss level (Table 3.12), Goesgen presents the most danger for people and is the most challenging for the Swiss Federal Office for Civil Protection[21] with more than 227,000 persons – on average – potentially receiving a CED ≥ 100mSv. Mühleberg would potentially hurt more than 127,000 persons, and Beznau exhibits almost the same level as Leibstadt (86,000).

If we compare table 3.12 to table 3.11, it appears that the Swiss NPPs, on average, could impact less people in Switzerland in comparison to the rest of Europe – at a CED level ≥ 1 mSv and ≥ 6 mSv (below 20 mSv), except Mühleberg that would have a more significant impact in Switzerland in comparison with the rest of Europe for a CED level ≥ 6 mSv and < 20 mSv. However, Leibstadt would have – on average – a lesser impact in Switzerland compared to the rest of Europe with a CED level ≥ 20 mSv and < 50 mSv, and an almost equivalent impact between these two areas for a CED level ≥ 50 mSv and < 100 mSv.

3.4 Estimate of the number of displaced persons due to long-term radioactive deposition

According to Ordinance 814.501, in the year following a major nuclear accident, the limit to the population should not exceed 20 mSv (*supra* 2.6(iii)). Unfortunately, the isolines that we defined to analyze radioactive deposition and its consequences on health, do not focus on the legal threshold of 20 mSv.

Table 3.13. Exposition to Cs-137 deposition given in Becquerels and CED in milliSievert related to the deposition of all aerosols during the first year after the simulated accident (Europe).
The factor of 0.4 for indoor shelter is included in the calculation (ENSI 2009, 67).

Cs-137 critical levels (Bq)	Beznau all aero. (mSv/yr)	Bugey all aero. (mSv/yr)	Goesgen all aero. (mSv/yr)	Leibstadt all aero. (mSv/yr)	Mühleb. all aero. (mSv/yr)
≥ 1.48E+06	12.0	20.3	16.4	11.5	28.1
≥ 5.55E+05	4.5	7.6	6.2	4.3	10.5
≥ 1.85E+05	1.5	2.5	2.1	1.4	3.5
≥ 3.70E+04	0.3	0.5	0.4	0.3	0.7

For Beznau, Goesgen and Leibstadt data on Cs-134 comes from Ustohalova (2014) while they are inferred from NRC (1994) for Bugey and Mühleberg. This could explain the above discrepancies.

Table 3.14: Cumulated number of impacted persons on average in Europe where Cs-137 is above different critical thresholds (Average on 365 weather simulations over year 2017)

Depo. of Cs-137 (Bq)	Beznau EU persons	Bugey EU persons	Goesgen EU persons	Leibstadt EU persons	Muhleb. EU persons
≥ 1.48E+06	252 251	217 879	426 871	502 596	309 555
≥ 5.55E+05	541 840	543 523	971 388	1 238 520	825 666
≥ 1.85E+05	1 456 640	1 798 173	2 478 633	3 521 534	2 336 411
≥ 3.70E+04	6 129 401	9 300 832	9 303 511	12 585 790	8 446 406

On Table 3.13, discrepancies between the NPPs could be explained by the heterogeneity of the bibliographic sources on Cs-134. For Beznau, Goesgen, and Leibstadt, data on Cs-134 come from Ustohalova et al. (2014), whilst they are inferred from Hanson et al. (1994), for Bugey and Mühleberg. In other terms, when looking carefully at Table A3 (Annex) and Table 3.13, one could assume deposition would be more consistent if we had not included the data from Ustohalova et al. (2014). If this assumption is correct, the figures for Beznau, Goesgen, and Leibstadt in Table 3.13 would be underestimated. It would mean that a level of ^{137}Cs ≥ 1.48E+06 Bq/m^2 could imply a yearly CED for all aerosols ≈ 20 mSv/year (during the first year). The above assumption is indirectly confirmed by IRSN, where the Russian experience is drawn from Chernobyl and the related thresholds (*supra* 2.6(v)): ≥ 1,480 kBq/m^2 for compulsory evacuation.

Table 3.14 gives the cumulated number of impacted persons for the year 2017. On average, from both a medical perspective and a normative perspective (*supra* 2.6(iii)), between 250,000 persons up to 500,000 persons would be forced to leave their homes. Furthermore, they would need to be housed outside the evacuation zone for at least one year and, for the majority of them, for several years (*infra* 4.3 (ii)).

[20] The Federal Office of Civil Protection and Disaster Assistance (BBK). https://www.bmi.bund.de/EN/topics/civil-protection/bbk/bbk-node.html

[21] Swiss Federal Office for Civil Protection. https://www.babs.admin.ch/en/home.html

3.5 *Estimate of the different categories of soils that would become unsuitable for their specific purpose*

The question of the deposition of radionuclides on soils and water is critical for several activities and agriculture. In this edition of the present study we give global results and a few numbers on agriculture at the European scale.

Table 3.15 shows that, for a deposition level of $^{137}Cs \geq 37{,}000$ Bq/m^2 in Europe as a geographical entity, the surface of impacted land cover is nearly 32,000 km^2 in the event of a major accident at Beznau, and could rise to 70,000 km^2 if the disaster came from Leibstadt. Deposition ≥ 1,480 kBq/m^2 would imply, on average, an exclusion zone between 800 km^2 (Beznau) and 1,900 km^2 (Leibstadt). By contrast, if we were to consider additional examples of quantiles for the latter deposition level in the event of a major accident in Leibstadt, the multiplier between the lowest and highest deciles would equate to 7-times (545 to 3,892 km^2, whilst between the two most extreme centiles, it would be as high as 54-times (131 to 7,090 km^2).

Table 3.16 considers ^{137}Cs deposition on agricultural + grazing areas. For a deposition level of $^{137}Cs \geq 37{,}000$ Bq/m^2, the average impacted area would reach 16,000 km^2 after an accident at Beznau, 20,000 km^2 if it occurred at Mühleberg, above 25,000 km^2 whilst considering Bugey or Goesgen, it could even surpass 37,000 km^2 after a major radioactive release from Leibstadt. In other terms, the surface of productive soils that would be unavailable in the geographical area of Europe – pertaining to at least one harvest or to be expected for several years – would represent between 40% and 90% of Switzerland's whole territory (41,285 km^2).

Table 3.15. Total all land cover impacted above four critical levels of Cs-137. Average number of impacted km^2 for year 2017 in Europe

	EUR Area ≥ 37 kBq/m2 of Cs-137 km2	EUR Area ≥ 185 kBq/m2 of Cs-137 km2	EUR Area ≥ 555 kBq/m2 of Cs-137 km2	EUR Area ≥ 1,480 kBq/m2 of Cs-137 km2
Beznau	32 149	6 432	2 041	824
Bugey	52 191	11 951	3 738	1 384
Goesgen	49 876	11 063	3 455	1 163
Leibstadt	71 577	17 709	5 588	1 950
Mühleberg	42 947	9 598	3 060	1 169

Table 3.16. Total all agriculture + grazing areas impacted above four critical levels of Cs-137. Average number of impacted km^2 for year 2017 in Europe

	EUR Area ≥ 37 kBq of Cs-137 km2	EUR Area ≥ 185 kBq of Cs-137 km2	EUR Area ≥ 555 kBq of Cs-137 km2	EUR Area ≥ 1,480 kBq of Cs-137 km2
Beznau	16 368	3 172	973	384
Bugey	26 865	6 128	2 079	837
Goesgen	25 139	5 314	1 622	522
Leibstadt	37 460	8 877	2 735	923
Muhleberg	20 452	4 444	1 487	615

Table 3.17. Total agricultural areas impacted above four critical levels of Cs-137. Average number of impacted km^2 for year 2017 in Europe

	EUR Area ≥ 37 kBq of Cs-137 km2	EUR Area ≥ 185 kBq of Cs-137 km2	EUR Area ≥ 555 kBq of Cs-137 km2	EUR Area ≥ 1,480 kBq of Cs-137 km2
Beznau	10 939	2 082	694	301
Bugey	19 202	4 365	1 562	671
Goesgen	17 049	3 352	1 119	406
Leibstadt	26 545	5 651	1 761	618
Mühleberg	13 158	2 937	1 126	525

Table 3.17 only considers agricultural areas – without grazing areas – that would be impacted by radioactive nuclides. For a deposition level of $^{137}Cs \geq 37{,}000$ Bq/m^2, impacted agricultural areas would be almost 11,000km^2 after a Beznau accident, not far from 18,000 km^2 yet considering Bugey and Goesgen, it could reach 26,000 km^2 if Leibstadt was the source of a major release. In other terms, the surface area dedicated to agriculture, where production would be unavailable for mankind and livestock, would represent between 1.4-times and 3.3-times the Swiss agricultural area (8,000 km^2). On average, the area of production that would become too radioactive would represent 2.2-times of Switzerland's agricultural surface area.

Table 3.18 aims at illustrating the interactions of the borders between Switzerland, Germany, and the rest of Europe for agricultural areas. Among other aspects, it shows how much agricultural areas in Europe, Switzerland, Germany and the rest of Europe would be impacted – on average – by a major accident, for a deposition level ≥ 37,000 Bq/m^2. With regard to column 'Leibstadt' for instance, the results are 26'500 km^2, 1,100 km^2, 8,200 km^2 and 17,200 km^2 respectively. The 'border effect' is more effective for Leibstadt than for

Mühleberg, Beznau, Bugey, and Goesgen. The NPPs would impact Swiss agricultural areas from 767 km^2 (Bugey) to 2,278 km^2 (Mühleberg). On average, the French NPP Bugey would be 'only' 23% less 'destructive' for Switzerland than the NPP Beznau.

Table 3.18. Agricultural surfaces above 37 kBq/m^2 of Cs-137 in 4 different territories. Average number of impacted km^2 for year 2017 in Europe, Switzerland, Germany and the rest of Europe

Impacted areas	Beznau Area ≥ 37 kBq of Cs-137 km2	Bugey Area ≥ 37 kBq of Cs-137 km2	Goesgen Area ≥ 37 kBq of Cs-137 km2	Leibstadt Area ≥ 37 kBq of Cs-137 km2	Muhleberg Area ≥ 37 kBq of Cs-137 km2
All EUR	10 939	19 202	17 049	26 545	13 158
CHE	1 000	767	1 348	1 140	2 278
GER	4 225	4 144	5 352	8 202	3 648
Rest of EUR	5 714	14 292	10 348	17 203	7 232

IV. Discussion

4.1 From five different releases to collective committed effective doses

(i) Release

The selection of the main important figures was drawn cautiously from the available literature. The number of possibilities was limited to three main bibliographic sources (Seibert et al. 2013; Ustohalova et al. 2014; Hanson et al. 1994). Three clouds were identified and the whole methodology in use was presented, from the question of the source-term to the question of the half-life (*supra* 2.2). The five releases issued from our research were between 1.4 to 3.9 times higher than the releases from Fukushima and between 2.3 and 6 times less than the releases from Chernobyl.

(ii) Cloud meteorological behavior

We identified the deposition velocity and complementary parameters from the literature, in relation to the behavior of the 3 clouds in the atmosphere. The objective was to investigate as many different patterns of dispersion and deposition as possible. It has been questioned as to why we decided not to take into account the characteristics of the land-cover which influences the deposition (*supra* 2.3(iii)).

(iii) From Bq to mSv

We used different lists of dose factors in order to cope with different situations, inhalation, external exposition, and the dose factors defined by the Swiss Federal Ordinance 814.501 for taking preventive measures of civil protection.

For calculating the health impact, during the passage of the cloud, we followed the recommendation of ENSI, that does not use an in-door factor, and assumes that adults are breathing in a stressed mood (see Table A6 in the Annex). Concerning the first-year of exposition to groundshine, the estimate of the committed effective doses from deposition was based on external exposition only. We followed the recommendation of ENSI, that recommends an indoor factor of 0.4 (*supra* 2.6(v)). The calculation related to deposition was restricted to the first year, an option which limits the CCED (*supra* 2.6(ii)).

4.2 Health Effects

(i) Estimated number of nuclear victims from a nuclear accident

Estimations of the numbers of victims are open to controversy, in already established major NPP accidents such as in Chernobyl (Claussen & Rosen 2016). Furthermore, this might hold true in hypothetical situations as described in the present study. Apart from the difficulties of characterizing the source term, varying meteorological and complex geographical conditions, large uncertainties come from diametrically opposed perceptions of radiation induced non-cancer health effects. Politicians and economists have different views on health issues than physicians do. However, population safety aspects should primarily rely on scientifically based medical knowledge. In the thirty three years since the Chernobyl NPP accident – for more than one human generation – the WHO has failed to conduct an adequate broad systematic evaluation of the health of the millions of inhabitants of radio-contaminated regions. Therefore, the several thousands of reports given on community, district, or country levels and their comprehensive reviews (Yablokov et al. 2009: 58-160) are all the more important. If the WHO then takes a retrospective position on the countless non-cancer health effects after the Chernobyl catastrophe, this cannot satisfy scientific criteria (WHO 2006). Purported, improved reporting, cited as the reason for the obvious, in explicit terms, massively increasing health problems is not a sufficiently valid explanation, especially as many studies compare populations in regions with different radio-contamination levels.

A similar position is taken by UNSCEAR for radio-induced health effects in general and even for radio-induced cancers (where EARs are established), arguing that future excess cancers, due to radiation after the Fukushima NPP accident would not be statistically discernible (UNSCEAR 2013, 77-79)[22].

In contrast, our estimations predicated on the latest scientific evidence, reveal that there may be up to 100,000 cancer victims from a hypothetic major accident at one of the Swiss NPPs or the Bugey NPP (depending on meteorology). According to the perspective of the physicians' ethics code, it is unjust to discount a large number of victims based on the argument that their occurrence seems to be diluted at the large scale (when comparing the number of affected persons to the millions of radio-contaminated persons). Furthermore, 'dilution' is not an argument since persons close to the source of a major nuclear accident will have between a 10%, 20%, or even a higher risk percentage of contracting a malignant or cardiovascular disease.

It is well known that an individual cancer case cannot be linked to ionizing radiation as causative factor. However, this does not invalidate the statistical relevance at the scale of a radio-contaminated population. This is certainly the case for individual cancer patients in the cohort of nuclear bomb survivors (Ozasa et al. 2012, 229-243) in Japan, which represents the backbone of the actual radiation risk calculation concepts – according to recent observations even in the low dose range (Grant 2017, 515-537).

(ii) Strengths of the health impact assessment

- Presenting three different risk models on radio-induced health effects may achieve more understanding for differing views. However, estimates according to WHO/UNSCEAR focusing only on radio-induced cancer already show the devastating health effects for tens of thousands of affected people by a possible major accident in a Western Europe NPP. This could alert responsible authorities for a rapid revision of the highly insufficient radioprotection measures as presently planned by the Swiss Federal Office for Civil Protection.
- The integration of cardiovascular diseases into risk assessment for the first time in a published study enables a somewhat broader assessment of the incidence of life-threatening radio-induced non-malignant health effects.
- Considering not only cancer, but also other non-cancer health effects such as reproductive hazards into risk estimations is mandatory from the medical view point even if only a semi-quantitative approach seems feasible. This is justified by the huge numbers of human body systems and functions affected by ionizing radiation. It seems rewarding to warn non-medical authorities and the general population about these radiation hazards that are well known to physicians since more than 60 years (Stewart et al. 1956, 447).

(iii) Shortcomings of the health impact assessment

- As the aim of this study was giving an estimate on the orders of magnitude of radio-induced victims due to a major nuclear accident, distinct entities like thyroid cancer or leukemia have not been dealt with.
- This study does not pay attention to gender aspects, nor does it specifically calculate risks for children who are much more radiosensitive than adults.
- Ingestion by nutrition and water intake as well as resuspension with inhalation and external irradiation has not been considered. These important aspects however have been described extensively in an earlier study on an eventual Mühleberg NPP accident (Sailer et al. 1990).
- This study didn't take into account an eventual "optimal" emergency management scenario which clearly would have an individual dose-reducing effect. However, a meaningful estimate of the number of victims with evacuation taken into account corresponds likely to a "chaotic" scenario in the event of a major

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[22] *"A general radiation-related increase in the incidence of health effects among the exposed population would not be expected to be discernible over the baseline level"* UNSCEAR 2013, 77-79.

nuclear accident in Switzerland as radioprotection concepts presently underestimate population exposure to radiation by a factor 30. A French study on a possible accident at NPP Dampierre described “negligible” numbers of lethal cancer cases in an “optimal” scenario in contrast to 10,000 lethal cancer cases in a “realistic” scenario (IRSN 2007, 21).

- Furthermore, the health effects covered by the study are explained by direct ionizing radiation effects. Additional important health aspects such as radio-phobia, social effects, induced abortions, psychological adaptive difficulties to the huge economic and societal changes provoked by a major nuclear accident could not be assessed in this study since they are all an indirect consequence of the specific property of a nuclear accident: The extremely intrusive, temporally and spatially illimitable radio-contamination.

4.3 Preventive evacuation and long-term evacuation

(i) Preventive evacuation

Preventive evacuation aims at preventing people from receiving a CED ≥ 100 mSv. It is not a systematic measure. It should protect the most fragile people that would be unable to remain below that threshold by remaining in their home for instance. In other terms, it has to be selective. The problem is that a situation of alert for a potentially forthcoming major nuclear accident could degenerate in a vast traffic jam since different panic behaviors, for instance parents that will rush to their children's school to keep them safe, have the potential to create an indescribable chaos. According to our calculations, the number of people in areas with more than 100 mSv ranges from 110,000 to 268,000 on average, depending on the NPP causing the alert. These figures suggest that the situation could become unmanageable for civil protection as a result of the phenomena just described.

(ii) Long-term evacuation

To evaluate the number of people to be evacuated was based on the criterion of a deposition ≥ 1,480 kBq/m^2 of ^{137}Cs. We found that, on average, between 250,000 persons to 500,000 persons would need to be housed outside the evacuation zone for at least one year and, for the majority of them, for additional several years. Such a displacement could likely extend over a few decades with all the ingredients of a highly problematic migratory movement against a new class of relocated inhabitants that would face contempt and hatred in the very country they lived in for years and even, for a majority of them, the duration of their entire lives, before a major radioactive release swept them out of their households.

However, if the case occurred in reality, the effective result would depend on the intent of civil authorities regarding the current norm of ≥ 20 mSv/year for long-term evacuation (*supra* 2.6 (iii)), and the operational ability to handle such migratory movements. The question as to whether the norm would be upheld, or whether it would be relaxed by the Swiss Federal Council for such a number of persons, has no answer at this stage.

(iii) Strengths and shortcomings

Concerning alert situations, the dose factors used and their relevance according to Swiss norms may not be relevant outside that country.

With regards to the possible criterion for long-term evacuation (^{137}Cs ≥ 1,480,000 Bq/m^2), a question remains open. On the one hand, this criterion could be estimated too high when considering two studies from IRSN (*supra* 2.6). On the other hand, our estimate of the CED over one year could be used to plead that, with regards to certain NPPs, the ^{137}Cs criterion could be too low. To conclude this point, since we have identified a possible cause for the underestimation of external exposure to the groundshine in mSv, the level ≥ 1,480,000 kBq of ^{137}Cs seems relevant for the evaluation of the number of people requiring a long-term evacuation policy.

4.4 Radioactive deposition on land cover and more specifically crop and grazing lands

(i) Strengths and shortcomings

We found that ^{137}Cs deposition ≥ 37 kBq/m^2 is – on average for the 5 NPPs – almost 50,000 km^2. By comparison, the average number for the deposition of ^{137}Cs from European NPPs is 165,000 km^2 in the study of Lelieveld et al. (2012, p. 4251). Understanding this gap requires further research.

V Conclusion

The study simulated the release of 32 radioactive nuclides, their atmospheric transportation and the deposition process on the ground, after a major, simulated nuclear accident in one of the four Swiss NPPs and the NPP Bugey in France. It aimed to evaluate the impacts on health issues, population displacement (migration) and agriculture.

We showed that the probabilistic safety analysis employed by the nuclear industry, neither evaluates the human factor as a cause of a major nuclear accident, nor assess statistically the cost and occurrence of past accidents from an historical perspective. We reported a more accurate evaluation of the risk based on a complex and historical approach. It suggests that a major nuclear accident in western Europe is 'possible', and is neither 'unlikely', nor 'very unlikely' according to the terminology of the IAEA. With regards to the 9 reactors of the study, considered over a period of 50 years, the probability of such an event is estimated at 0.8%. Such a probabilistic level, compared to the considerable number of potential victims and the related harm that it would cause, seems very high. Let us return to the other results.

Firstly, at the onset of the accident, the civil protection would be totally unable to respond preventively to the most severe impacts during the passage of the cloud (in violation of different legal norms).

Secondly, the 5 NPPs would release, on average, an estimated committed collective effective dose (CCED) of more than 91,000 Sievert. Using the WHO/UNSCEAR standards leads to anticipate that this CCED (91,000 Sv) would imply more than 18,200 radio-induced cancer cases.

Thirdly, according to the same estimated CCED, in accordance with more recent medico-scientific evidence, between 20,000 to nearly 50,000 radio-induced cancers were found for the smaller and larger NPPs respectively, as well as 7,500 to 18,500 radio-induced cardiovascular cases (myocardial infarction, cerebrovascular disease) are most likely to develop, as late effects of ionizing radiation (on average). Furthermore, taking other non-cancer diseases, genetic and reproductive disorders in consequence from the experience gained in the aftermath of the Chernobyl disaster, the above-mentioned estimates may be far more than doubled, resulting in at least 100,000 victims by radio-induced health effects. From an ethical viewpoint, these high numbers of victims are not negligible even if individual cases cannot be retrospectively identified as radio-induced.

Fourthly, all of these above-mentioned estimates must once more be nearly doubled in 10% of cases due to meteorological variability. In view of the location of the Swiss NPPs, more than 40% of all victims would occur in the surrounding European countries. In the case of a major accident in the Leibstadt NPP, the number of German radiation victims could be considerably higher than the number of victims in Switzerland.

Fifthly, during the first year after the deposition of radioelements on the ground, a major nuclear accident would have a profound health impact on the populations. The average number of people to be resettled in Europe would range between 250,000 and 500,000 (from the least impacting NPP to the most impacting one). Such a situation could be unmanageable by governmental bodies.

Sixthly, the surface of grazing and crop lands that would be unavailable in Europe – depending on the NPP – would represent between 16,000 to 37,000 km^2 – in comparison with Switzerland's surface area (41,285 km^2).

To summarize, a major nuclear accident in Western Europe is 'possible', even if that evidence is blurred by the ill-adapted probabilistic tool used by the regulators and the nuclear industry. Since a major nuclear accident could hit so many people with regards to their health, their belongings and households, and even more so the confidence in their country, it should be underlined that the probability of such an event is far from 'unlikely'.

From a strategic perspective and in accordance with the literature, the whole set of impacts combined could trigger serious, economic, institutional and political consequences for the most affected country, whether it be Switzerland[23], Germany, France, Italy or Austria. In the case of significant transboundary pollution, the question remains open as to whether the victim country would take legal action against the country responsible for having underestimated the ageing process of the reactor vessel of its nuclear power plants, as well as neglecting the human factor as a possible cause of a major nuclear accident.

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[23] If the small Swiss territory received the bulk of the radioactive elements from a major nuclear accident, a relatively large proportion of its inhabitants would have to deal with significant radio-induced health problems while being compelled to leave their households (despite legitimate interrogation on the means of a credible resettlement policy). Insofar as the probability of such a disaster is deemed 'possible' (and not 'unlikely'), the question arises as to whether Switzerland could overcome a crisis of such magnitude or if it would eventually disappear from the European and International political scenes as an independent and free country.

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Annex A. Methodology

Table A1. Comparison of the mean releases at Chernobyl with the mean releases at Fukushima

Aerosols	Chernobyl mean releases Bq	Fukushima mean releases Bq	Chernobyl to Fukushima releases Factor
Ba-140	2.40E+17	1.06E+16	22.7
Cs-134	4.70E+16	2.92E+16	1.6
Cs-137	8.50E+16	1.35E+16	6.3
I-131	1.76E+18	2.50E+17	7.0
Ru-103	1.68E+17	3.93E+10	4 274 809
Ru-106	7.30E+16	2.10E+09	34 761 905
Sr-89	1.15E+17	6.52E+15	17.6
Sr-90	1.00E+16	7.17E+13	139.5
Te-132	1.15E+18	8.14E+16	14.1
Refractories			
Ce-141	8.40E+16	1.80E+13	4 667
Ce-144	5.00E+16	1.10E+13	4 545
Cm-242	4.00E+14	5.49E+10	7 286
Pu-238	1.50E+13	1.07E+10	1 402
Pu-239	1.30E+13	1.81E+09	7 202
Pu-240	1.80E+13	1.86E+09	9 704
Pu-241	2.60E+15	6.00E+11	4 332
Zr-95	8.40E+16	1.70E+13	4 941

Source: IAEA (2015)

Table A2. Comparison between the low and high estimates of the Fukushima releases

	Fukushima (low) *Bq*	Fukushima (high) *Bq*	Low to high estimation *Factor*
Ru-106	2.10E+09	2.10E+09	1.0
Ce-141	1.80E+13	1.80E+13	1.0
Ce-144	1.10E+13	1.10E+13	1.0
Zr-95	1.70E+13	1.70E+13	1.0
Mo-99	8.80E+07	8.80E+07	1.0
Np-239	7.60E+13	7.60E+13	1.0
Xe-133	6.00E+18	1.20E+19	2.0
Cs-137	7.00E+15	2.00E+16	2.9
Te-129m	3.30E+15	1.22E+16	3.7
I-131	1.00E+17	4.00E+17	4.0
Kr-85	6.40E+15	3.26E+16	5.1
Cs-134	8.30E+15	5.00E+16	6.0
Pu-240	5.10E+08	3.20E+09	6.3
Pu-239	4.10E+08	3.20E+09	7.8
Pu-238	2.40E+09	1.90E+10	7.9
Ru-103	7.50E+09	7.10E+10	9.5
Cm-242	9.80E+09	1.00E+11	10.2
Ba-140	1.10E+15	2.00E+16	18.2
Sr-90	3.30E+12	1.40E+14	42.4
Te-132	7.60E+14	1.62E+17	213.2
Sr-89	4.30E+13	1.30E+16	302.3
I-133	6.80E+14	3.00E+17	441.2
Pu-241	3.30E+08	1.20E+12	3 636.4

Source: IAEA (2015)

Table A3. Final selection of the potential release from the five NPPs

Isotope(s) Name	Group	Beznau Potential release Bq	Bugey Potential release Bq	Gösgen Potential release Bq	Leibstadt Potential release Bq	Mühleberg Potential release Bq	Bibliographic sources Hanson et al. 1994 (Nureg_6094—NRC) U. = Ustohalova et al. (2014) S. = Seibert et al. (2013) Flexrisk
Rare Gases							
Kr-85	1	8.20E+15	2.02E+16	2.18E+16	3.33E+16	7.37E+15	inferred from nureg_6094
Xe-133	1	2.20E+18	5.13E+18	4.68E+18	7.47E+18	2.28E+18	Flexrisk
		2.21E+18	**5.15E+18**	**4.70E+18**	**7.50E+18**	**2.28E+18**	
Aerosols							
Ba-140	5	9.00E+15	4.07E+16	2.40E+16	2.90E+16	1.82E+17	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Co-58	6	2.86E+13	7.05E+13	7.60E+13	5.80E+13	3.31E+13	inferred from nureg_6094
Co-60	6	2.20E+13	5.42E+13	5.85E+13	7.02E+13	3.95E+13	inferred from nureg_6094
Cs-134	3	3.35E+15	2.98E+16	9.00E+15	1.10E+16	5.02E+16	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Cs-136	3	7.00E+14	8.41E+15	1.80E+15	2.20E+15	1.28E+16	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Cs-137	3	4.40E+16	9.60E+16	7.80E+16	1.17E+17	6.55E+16	Flexrisk
I-131	2	2.75E+17	7.53E+17	4.86E+17	5.38E+17	3.98E+17	Flexrisk
Rb-86	3	4.95E+13	1.22E+14	1.32E+14	6.43E+13	1.60E+14	inferred from nureg_6094
Ru-103	6	3.96E+15	9.76E+15	1.05E+16	1.40E+16	7.90E+15	inferred from nureg_6094
Ru-106	6	6.90E+15	1.09E+17	9.10E+16	3.97E+15	2.40E+16	Flexrisk
Sb-127	4	2.09E+16	5.15E+16	5.55E+16	5.57E+15	1.82E+16	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Sr-89	5	5.50E+15	2.36E+16	1.50E+16	1.80E+16	1.28E+17	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Sr-90	5	5.00E+15	1.40E+16	7.00E+15	3.00E+15	2.00E+15	Flexrisk
Te-127m	4	3.30E+14	7.05E+15	8.80E+14	1.10E+15	2.56E+15	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Te-129m	4	1.00E+15	4.88E+16	2.70E+15	3.20E+15	1.71E+16	U. (Bez, Goe, Lei); Nureg (Bug, Mue)
Te-132	4	1.89E+17	4.27E+17	3.34E+17	3.74E+17	2.79E+17	Flexrisk
		5.65E+17	**1.62E+18**	**1.12E+18**	**1.12E+18**	**1.19E+18**	
Refractory							
Am-241	7	4.18E+10	1.03E+11	1.11E+11	4.54E+11	7.26E+11	inferred from nureg_6094
Ce-141	8	1.98E+15	4.88E+15	5.26E+15	6.30E+15	2.78E+16	inferred from nureg_6094
Ce-144	8	1.21E+15	2.98E+15	3.22E+15	4.05E+15	1.82E+16	inferred from nureg_6094
Cm-242	7	1.54E+13	3.80E+13	4.09E+13	1.21E+14	1.92E+14	inferred from nureg_6094
Cm-244	7	9.24E+11	2.28E+12	2.46E+12	6.56E+12	1.04E+13	inferred from nureg_6094
Nb-95	7	1.87E+15	4.61E+15	4.97E+15	8.83E+15	1.39E+16	inferred from nureg_6094
Nd-147	7	8.36E+14	2.06E+15	2.22E+15	4.04E+15	6.09E+15	inferred from nureg_6094
Pr-143	7	1.87E+15	4.61E+15	4.97E+15	9.08E+15	1.39E+16	inferred from nureg_6094
Pu-238	8	1.32E+12	3.25E+12	3.51E+12	5.63E+12	2.46E+13	inferred from nureg_6094
Pu-239	8	2.97E+11	7.32E+11	7.89E+11	1.46E+12	6.20E+12	inferred from nureg_6094
Pu-240	8	3.74E+11	9.22E+11	9.94E+11	1.80E+12	7.80E+12	inferred from nureg_6094
Pu-241	8	6.27E+13	1.55E+14	1.67E+14	3.04E+14	1.39E+15	inferred from nureg_6094
Y-91	7	1.65E+15	4.07E+15	4.38E+15	7.57E+15	1.17E+16	inferred from nureg_6094
Zr-95	7	1.98E+15	4.88E+15	5.26E+15	9.34E+15	1.50E+16	inferred from nureg_6094
		1.15E+16	**2.83E+16**	**3.05E+16**	**4.97E+16**	**1.08E+17**	

Table A4. Land cover categories used in this study and the correspondent original CLC categories

This study categories	CLC categories
Impermeable urban areas	Continuous urban fabric
Urban areas	Discontinuous urban fabric
Urban areas	Industrial or commercial units
Urban areas	Road and rail networks and associated land
Urban areas	Port areas
Urban areas	Airports
Non-vegetal exploitations	Mineral extraction sites
Non-vegetal exploitations	Dump sites
Non-vegetal exploitations	Construction sites
Recreational areas	Green urban areas
Recreational areas	Sport and leisure facilities
Agricultural areas	Non-irrigated arable land
Agricultural areas	Permanently irrigated land
Agricultural areas	Rice fields
Agricultural areas	Vineyards
Agricultural areas	Fruit trees and berry plantations
Agricultural areas	Olive groves
Grasslands	Pastures
Agricultural areas	Annual crops associated with permanent crops
Agricultural areas	Complex cultivation patterns
Agricultural areas	Land principally occupied by agriculture with significant areas of natural vegetation
Forests	Agro-forestry areas
Forests	Broad-leaved forest
Forests	Coniferous forest
Forests	Mixed forest
Grasslands	Natural grasslands
Other natural areas	Moors and heathland
Other natural areas	Sclerophyllous vegetation
Other natural areas	Transitional woodland-shrub
Unproductive areas	Beaches - dunes - sands
Unproductive areas	Bare rocks
Unproductive areas	Sparsely vegetated areas
Unproductive areas	Burnt areas
Water bodies	Glaciers and perpetual snow
Other natural areas	Inland marshes
Other natural areas	Peat bogs
Other natural areas	Salt marshes
Non-vegetal exploitations	Salines
Water bodies	Water courses
Water bodies	Water bodies
Water bodies	Coastal lagoons
Not used in this study:	Intertidal flats
Not used in this study:	Estuaries
Not used in this study:	Sea and ocean

Table A5. Dose factors in use

Mains source: IFSN/ENSI (2009), G14/f Appendice 8 ENSI: Dose factor for different age groups (Amad for aerosols = 1 µm) * For cloushine, dose factors come from Ordinance 814.501.	Dose Factors (1) for Members of the Population (Inhalation) Inhalation (adult) Sv/Bq	Dose Factors (2) Related to External Exposition to Cloudshine External exposit° Sv·m^3/Bq·s	Dose Factors (3) Related to External Exposition to Groundshine External exposit° Sv·m^2/Bq·s	Alert Main source Ordinance 814.501 Annex 3 Nuclide	Dose factors (4) in the event of an alert (Ordinance 814.501) Inhalat° (adult) (Sv Bq-1)
1rst cloud: Rare Gases				1rst cloud: Rare Gases	
Kr-85 *	(…)	2.556E-16	9.874E-18	Kr-85	(…)
Xe-133 *	(…)	1.389E-15	3.245E-17	Xe-133	(…)
2nd cloud: Aerosols				2nd cloud: Aerosols	
Ba-140/La-140	5.10E-09	1.032E-13	1.879E-15	Ba-140	1.60E-09
Co-58	1.60E-09	3.920E-14	7.646E-16	Co-58	1.70E-09
Co-60	1.00E-08	1.012E-13	1.772E-15	Co-60	1.70E-08
Cs-134	6.60E-09	6.205E-14	1.223E-15	Cs-134	9.60E-09
Cs-136	1.20E-09	8.724E-14	1.659E-15	Cs-136	1.90E-09
Cs-137/Ba-137m	4.60E-09	2.247E-14	4.573E-16	Cs-137/Ba-137m	6.70E-09
I-131 (aerosols)	7.40E-09	1.456E-14	3.078E-16	I-131[24]	1.10E-08
Rb-86	9.30E-10	4.287E-15	1.471E-16	Rb-86	1.30E-09
Ru-103	2.40E-09	1.855E-14	3.828E-16	Ru-103	2.20E-09
Ru-106/Rh106	1.80E-08	9.079E-15	3.009E-16	Ru-106/Rh-106	3.50E-08
Sb-127	1.70E-09	2.620E-14	5.428E-16	Sb-127	1.70E-09
Sr-89	6.10E-09	3.765E-16	6.759E-17	Sr-89	5.60E-09
Sr-90/Y-90	3.60E-08	7.190E-16	1.079E-16	Sr-90	7.70E-08
Te-127m	7.40E-09	8.445E-17	3.635E-18	Te-127m	6.20E-09
Te-129m	6.60E-09	1.448E-15	5.146E-17	Te-129m	5.40E-09
Te-132/I-132	5.10E-09	1.004E-13	2.000E-15	Te-132	3.00E-09
3 rd cloud: Refractory				3 rd cloud: Refractory	
Am-241	4.20E-05	6.094E-16	1.852E-17	Am-241	2.70E-05
Ce-141	3.20E-09	2.805E-15	6.262E-17	Ce-141	3.10E-09
Ce-144/Pr-144	3.60E-08	2.834E-15	1.627E-16	Ce-144	2.90E-08
Cm-242	5.20E-06	2.216E-18	3.806E-19	Cm-242	3.70E-06
Cm-244	2.70E-05	1.842E-18	3.359E-19	Cm-244	1.70E-05
Nb-95	1.50E-09	3.083E-14	6.021E-16	Nb-95	1.30E-09
Nd-147	2.40E-09	5.023E-15	1.172E-16	Nd-147	2.40E-09
Pr-143	2.20E-09	1.730E-16	1.993E-17	Pr-143	2.20E-09
Pu-238	4.60E-05	2.025E-18	3.502E-19	Pu-238	3.00E-05
Pu-239	5.00E-05	2.501E-18	1.710E-19	Pu-239	3.20E-05
Pu-240	5.00E-05	2.005E-18	3.359E-19	Pu-240	3.20E-05
Pu-241	9.00E-07	0.000E+00	0.000E+00	Pu-241	5.80E-07
Y-91	7.10E-09	5.324E-16	7.291E-17	Y-91	6.10E-09
Zr-95	4.80E-09	2.957E-14	5.799E-16	Zr-95	4.20E-09

Assessment of the impact of 5 main sources:

A) External exposure to the cloud of rare gas using the dose factors (2)

B) Inhalation and external exposition to the cloud of aerosols using the dose factors (1) and (2) respectively

C) Inhalation and external exposition to the cloud of refractory using dose factors (1) and (2) respectively

D) Exposition to groudshine of deposited aerosols using dose factors (3), with respect to the half-life of the nuclides for 1 year

E) Exposition to groudshine of deposited refractory using dose factors (3), with respect to the half-life of the nuclides for 1 year

F) Alert on a possible situation of inhalation of aerosols evaluated preventively using the dose factors (4) and (2) respectively

[24] Iodine has no specific chemical form in the list provided by Annex 3 of 814.501. It is neither an aerosol, nor organic nor elementar. The dose factor is a 'useful' synthesis to decide a preventive evacuation before getting information on the exact proportion of the 3 forms of iodine. By comparison, the iodine dose factor from list (1), which is employed for the health impact assessment, is considerably lower.

Table A6. Calculations of committed effective doses (CED)

(i) Inhalation of aerosols and refractory

We calculated the Committed Effective Dose through the dose factors of Ensi (2009), G14, Appendix 8. The dose factor e is expressed in Sv/Bq.

On the one hand, the usual equation is as follows:

Dose [Sv] =
dose factor [Sv/Bq] · concentration [Bq/m^3] · inhalation rate (VISA) [m^3/s] · duration of exposure [s]

On the other hand, the dispersion model *Hysplit* is issuing the ''Time Integrated Concentration'' in (Bq-s m-3), a unit that we can change in an "equivalent" unit (Bq·s m-3). The two account units are the same.

Thus, we calculated the committed effective dose (CED) through the following equation:

CED = TIC · DCF · VISA · 1000

CED = Committed Effective Dose → mSv

TIC = Time Integrated Concentration → Bq·s m-3

DCF = Dose Conversion Factor → Sv/Bq

VISA = Volume Inhaled by Stressed Adult remaining outdoor → 3.50E-04 m3/s (ENSI 2009, 66)

1000 = Conversion factor from Sv to mSv

ii) External exposure

About aerosols and refractory, we calculated the Committed Effective Dose through the Dose Conversion Factor (DCF1) of Ensi (2009), G14, Appendix 8. The dose factor e is expressed in (Sv·m^3/Bq·s).

About rare gas, we calculated the effective dose through Annex 6 of Ordonnance 814.501. The Dose Conversion Factor *e*imm is expressed in [(mSv/h)/(Bq/m3)]. Additionally, the dispersion model *Hysplit* is issuing the ''Time Integrated Concentration'' in (Bq·s m-3).

In order to calculate the Committed Effective Dose (CED) of external exposure through the same unit, we converted the published Dose Conversion Factor (DCF2) from [(mSv/h)/(Bq/m3)] into (Sv·m^3/Bq·s) through the following equation:

DCF1 = DCF2 / 1000 / 3600

Where

DCF1 = Dose Conversion Factor 1 → (Sv·m^3/Bq·s)

DCF2 = Dose Conversion Factor 2 → (mSv/h)/(Bq/m3)

3,600 = Time conversion factor → 3,600 s = 1h

1,000 = Unit conversion factor from mSv to Sv

Second stage, we calculated the Committed Effective Dose (CED) of rare gas, aerosols and refractory, through the following equation:

CED = TIC · DCF1 · 1000

CED = Committed Effective Dose → mSv

TIC = Time Integrated Concentration → Bq·s m-3

DCF1 = Dose Conversion Factor → Sv·m^3/Bq·s

1,000 = Unit conversion factor from Sv to mSv

Annex B. Additional results

Table B1. Simulation of 365 weather situations: Collective committed effective dose (CCED) endured by Italian people (persSv – distributed by quantiles)

Impacted area	Beznau IT Total (persSv)	Bugey IT Total (persSv)	Gösgen IT Total (persSv)	Leibstadt IT Total (persSv)	Mühleberg IT Total (persSv)
Highest centile	24 964	87 225	52 464	43 469	99 311
Highest decile	3 240	14 128	9 704	8 155	16 725
Third quartile	194	3 752	1 612	646	2 826
Median	0	263	11	1	133
First quartile	0	0	0	0	0
Lowest decile	0	0	0	0	0
Lowest centile	0	0	0	0	0

See also Tables 3.4, 3.5, 3.6 (*supra*)

Table B2. Simulation of 365 weather situations: Collective committed effective dose (CCED) endured by Austrian people (persSv – distributed by quantiles)

Impacted area	Beznau AU Total (persSv)	Bugey AU Total (persSv)	Gösgen AU Total (persSv)	Leibstadt AU Total (persSv)	Mühleberg AU Total (persSv)
Highest centile	11 258	11 277	22 038	21 527	18 469
Highest decile	3 685	1 942	8 756	8 227	8 119
Third quartile	1 623	182	3 916	3 972	4 175
Median	175	0	663	519	593
First quartile	0	0	0	0	0
Lowest decile	0	0	0	0	0
Lowest centile	0	0	0	0	0

See also Tables 3.4, 3.5, 3.6 (*supra*)

Table B3. Model B: Estimated severe radio-induced diseases (cancer cases + cardiovascular cases) distributed by quantiles according to the simulation of 365 weather situations (year 2017) *Estimated radioinduced cancer mortality (factor 0.2) + radioinduced cardiovascular mortality (factor 0.05)*						
Impact. areas		Beznau (No)	Bugey (No)	Gösgen (No)	Leibstadt (No)	Mühleberg (No)
EUR	Highest centile	84 883	157 101	194 244	145 208	147 650
	Highest decile	52 191	70 366	109 578	92 320	97 231
	Third quartile	36 694	50 627	82 234	68 489	72 911
	Median	24 151	37 649	60 881	41 477	57 738
	First quartile	15 491	26 868	43 563	28 490	42 029
	Lowest decile	9 299	18 126	32 884	19 305	29 067
	Lowest centile	3 536	5 831	11 542	6 250	9 143
CHE	Highest centile	67 192	28 254	133 089	103 280	113 786
	Highest decile	39 801	7 202	84 720	55 176	63 362
	Third quartile	22 792	1 031	59 968	25 807	48 213
	Median	8 850	1	37 993	8 668	36 504
	First quartile	4 752	0	24 465	2 820	25 911
	Lowest decile	2 584	0	15 869	1 361	17 344
	Lowest centile	838	0	6 551	813	4 799
GER	Highest centile	40 688	55 686	60 811	81 641	62 374
	Highest decile	17 229	14 746	26 635	41 645	19 810
	Third quartile	12 591	5 408	16 681	31 362	12 355
	Median	6 798	58	8 178	20 427	4 858
	First quartile	2 011	0	1 542	10 366	55
	Lowest decile	75	0	0	4 263	0
	Lowest centile	2	0	0	1 723	0
FRA	Highest centile	18 600	156 247	59 115	46 931	59 509
	Highest decile	6 919	51 464	15 282	16 461	20 376
	Third quartile	1 254	36 887	4 274	4 090	7 399
	Median	0	24 625	7	1	169
	First quartile	0	15 717	0	0	0
	Lowest decile	0	10 088	0	0	0
	Lowest centile	0	2 927	0	0	0
ITA	Highest centile	13 730	47 974	28 855	23 908	54 621
	Highest decile	1 782	7 771	5 337	4 485	9 199
	Third quartile	107	2 063	887	356	1 554
	Median	0	144	6	1	73
	First quartile	0	0	0	0	0
	Lowest decile	0	0	0	0	0
	Lowest centile	0	0	0	0	0
AUT	Highest centile	6 192	6 202	12 121	11 840	10 158
	Highest decile	2 027	1 068	4 816	4 525	4 466
	Third quartile	893	100	2 154	2 185	2 296
	Median	96	0	365	286	326
	First quartile	0	0	0	0	0
	Lowest decile	0	0	0	0	0
	Lowest centile	0	0	0	0	0

Annex C. Evaluation of the representativity of weather situations over years 2017-2018

Table C1. Distribution by quantiles of the number of persons in possible need to be evacuated before the arrival of the radioactive cloud (over years 2017-2018)

Beznau pop EUR exposed ≥ 20 mSv		Beznau pop CHE exposed ≥ 20 mSv		Beznau pop EUR exposed ≥ 100 mSv		Beznau pop CHE exposed ≥ 100 mSv	
Max	1 968 998	Max	1 424 727	Max	711 424	Max	707 807
Q99	1 643 556	Q99	1 035 052	Q99	612 066	Q99	425 073
Q95	996 089	Q95	746 807	Q95	260 272	Q95	255 012
Q90	835 803	Q90	617 010	Q90	217 777	Q90	198 868
Q75	503 520	Q75	382 783	Q75	142 400	Q75	123 390
Q50	277 697	Q50	158 464	Q50	89 992	Q50	52 581
Q25	170 952	Q25	72 034	Q25	48 951	Q25	28 786
Q10	82 814	Q10	41 317	Q10	5 944	Q10	5 944
Q5	54 691	Q5	34 831	Q5	311	Q5	311
Q1	27 047	Q1	24 467	Q1	0	Q1	0
Min	16 488	Min	16 488	Min	0	Min	0

Bugey pop EUR exposed ≥ 20 mSv		Bugey pop CHE exposed ≥ 20 mSv		Bugey pop EUR exposed ≥ 100 mSv		Bugey pop CHE exposed ≥ 100 mSv	
Max	6 619 809	Max	1 384 281	Max	1 776 074	Max	196 610
Q99	2 811 976	Q99	844 624	Q99	1 282 260	Q99	19 225
Q95	1 514 050	Q95	75 632	Q95	342 035	Q95	0
Q90	1 108 739	Q90	0	Q90	203 527	Q90	0
Q75	520 033	Q75	0	Q75	142 705	Q75	0
Q50	272 440	Q50	0	Q50	90 553	Q50	0
Q25	162 989	Q25	0	Q25	41 928	Q25	0
Q10	97 475	Q10	0	Q10	0	Q10	0
Q5	71 765	Q5	0	Q5	0	Q5	0
Q1	28 243	Q1	0	Q1	0	Q1	0
Min	22 238	Min	0	Min	0	Min	0

Goesgen pop EUR exposed ≥ 20 mSv		Goesgen pop CHE exposed ≥ 20 mSv		Goesgen pop EUR exposed ≥ 100 mSv		Goesgen pop CHE exposed ≥ 100 mSv	
Max	3 745 081	Max	2 476 049	Max	1 895 031	Max	1 882 431
Q99	2 878 668	Q99	2 307 413	Q99	1 189 378	Q99	1 189 378
Q95	1 955 816	Q95	1 636 678	Q95	742 856	Q95	527 996
Q90	1 605 064	Q90	1 249 738	Q90	518 483	Q90	453 332
Q75	1 002 441	Q75	718 647	Q75	330 619	Q75	306 078
Q50	620 740	Q50	449 177	Q50	224 494	Q50	200 506
Q25	395 522	Q25	265 425	Q25	157 019	Q25	122 626
Q10	263 855	Q10	168 655	Q10	19 200	Q10	19 200
Q5	200 647	Q5	145 349	Q5	0	Q5	0
Q1	111 182	Q1	109 216	Q1	0	Q1	0
Min	92 717	Min	92 717	Min	0	Min	0

Leibstadt pop EUR exposed ≥ 20 mSv		Leibstadt pop CHE exposed ≥ 20 mSv		Leibstadt pop EUR exposed ≥ 100 mSv		Leibstadt pop CHE exposed ≥ 100 mSv	
Max	2 238 291	Max	1 744 153	Max	1 001 268	Max	842 439
Q99	2 145 303	Q99	1 572 191	Q99	858 875	Q99	511 730
Q95	1 328 418	Q95	950 024	Q95	576 203	Q95	376 464
Q90	1 160 353	Q90	609 815	Q90	391 495	Q90	252 395
Q75	778 192	Q75	429 790	Q75	192 223	Q75	107 877
Q50	381 276	Q50	133 509	Q50	109 512	Q50	39 710
Q25	216 036	Q25	40 056	Q25	58 512	Q25	11 028
Q10	133 388	Q10	15 019	Q10	14 807	Q10	5 313
Q5	90 986	Q5	11 557	Q5	0	Q5	0
Q1	36 686	Q1	10 265	Q1	0	Q1	0
Min	30 796	Min	8 068	Min	0	Min	0

Mühleberg pop EUR exposed ≥ 20 mSv		Mühleberg pop CHE exposed ≥ 20 mSv		Mühleberg pop EUR exposed ≥ 100 mSv		Mühleberg pop CHE exposed ≥ 100 mSv	
Max	3 687 345	Max	3 246 604	Max	1 002 146	Max	911 500
Q99	2 803 105	Q99	2 362 719	Q99	709 366	Q99	626 683
Q95	1 657 754	Q95	1 232 602	Q95	326 581	Q95	313 883
Q90	1 277 812	Q90	1 009 133	Q90	253 563	Q90	231 619
Q75	841 710	Q75	704 403	Q75	172 162	Q75	167 778
Q50	528 617	Q50	445 252	Q50	116 817	Q50	115 726
Q25	323 075	Q25	285 311	Q25	76 690	Q25	74 959
Q10	208 897	Q10	193 209	Q10	22 840	Q10	22 389
Q5	133 553	Q5	126 354	Q5	6 915	Q5	5 888
Q1	29 044	Q1	19 668	Q1	0	Q1	0
Min	16 488	Min	8 316	Min	0	Min	0

Table C2. Meteorological classification

The impact of an eventual nuclear accident can also be stratified according to the type of weather situation. This way it is possible to evaluate the situations which are riskier with respect of touched population or agricultural surface for instance.

Many types of weather type classification over Switzerland have been used in the past. They were all subjective and dependent on the individual carrying out the attribution to a specific class. Recently a project for an automated classification under the framework of COST 733 has been conducted and implemented [25]. The classification GWT26 using surface pressure has been chosen in order to distinguish the situations with a degree of details. Since most of the transport happens in the lower troposphere the classification based on the surface field has been chosen.

Computation of dispersion patterns has been carried out on the years 2017 and 2018. One can use the classification to assess how typical these two years have been with respect to the long time series 1957 – today.

The following table gives an evaluation of this characteristics.

It is visible that some classes are underrepresented, the extreme being the class "South, indifferent" where the 2017-2018 frequency is 0.41% when the long-term frequency 1957-2018 is 1.98%. The worst overrepresentation can be seen in the class "NorthEast, anticyclonic", the 2017-2018 frequency being 11.10% with a long-term frequency of 6.90%. It is obviously not possible to rescale the impact on population and landscape by frequency biases given in the table, but qualitatively it is possible to reevaluate the occurrence of all the classes.

The 26-class classification is possibly too detailed and regrouping of the classes can be operated. The following mapping in 6 classes is proposed: East and Northeast → East, North and Northwest → North, West and Southwest → West, South and Southeast → South. The distinction between cyclonic, indifferent and anticyclonic which has in influence on rainfall is skipped. The low and high situations are left as they are.

The same statistics as above can be computed with the following results.

Varying between 85% and 135%, the frequency bias is not very strong so that the period 2017-2018 can be considered as close to the long-term frequency. Both classifications will however be used for the following impact estimations.

Low pressure situations with weak winds produce most impact with a mean of over 400,000 people receiving more than the critical value of 100 mSv, most of them in Switzerland itself. In contrast the situations with southerly winds affect for one third regions situated outside Switzerland, mostly in Germany for this case.

In the next pages, tables on the stratification of the results by weather classes are presented in the following order: Beznau, Gosgen, Leibstadt, Mühleberg and Bugey.

[25] Weusthoff, T: 2011, Weather Type Classification at MeteoSwiss – Introduction of new automatic classifications schemes, Arbeitsberichte der MeteoSchweiz, 235, 46 pp. https://www.meteoschweiz.admin.ch/content/dam/meteoswiss/en/Ungebundene-Seiten/Publikationen/Fachberichte/doc/ab235.pdf

Table C3. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP BEZNAU (2017-2018)

26 classes	Occur.	Switzerland	Europe
West, cyclonic	11	16 312	19 749
Southwest, cyclonic	14	54 582	91 170
Northwest, cyclonic	13	40 294	57 559
North, cyclonic	18	41 523	59 666
NorthEast, cyclonic	35	123 790	130 589
East, cyclonic	39	79 477	86 236
SouthEast, cyclonic	21	143 053	158 596
South, cyclonic	8	59 784	101 076
West, anticyclonic	62	31 360	55 477
Southwest, anticyclonic	54	61 756	116 024
Northwest, anticyclonic	46	50 154	66 003
North, anticyclonic	43	96 192	111 409
NorthEast, anticyclonic	81	121 125	129 609
East, anticyclonic	57	121 013	138 804
SouthEast, anticyclonic	42	103 042	135 006
South, anticyclonic	42	96 323	144 319
West, indifferent	7	34 966	43 178
Southwest, indifferent	9	85 075	107 822
Northwest, indifferent	9	60 739	91 222
North, indifferent	9	53 233	72 638
NorthEast, indifferent	28	119 455	123 668
East, indifferent	25	99 662	113 409
SouthEast, indifferent	10	92 834	102 574
South, indifferent	3	113 615	126 415
Low Pressure	11	77 765	92 802
High Pressure	33	93 260	133 998

Table C4. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP BEZNAU (2017-2018)

6 classes	Occur.	Switzerland	Europe
West	157	46 071	86 849
North	138	63 336	78 133
East	265	113 122	146 323
South	126	104 166	125 520
Low	11	77 765	111 483
High	33	93 260	137 230

Table C5. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP BUGEY (2017-2018)

26 classes	Occur.	Switzerland	Europe
West, cyclonic	11	115	45 135
Southwest, cyclonic	14	0	43 408
Northwest, cyclonic	13	0	68 569
North, cyclonic	18	0	131 343
NorthEast, cyclonic	35	0	96 393
East, cyclonic	39	143	144 911
SouthEast, cyclonic	21	0	158 069
South, cyclonic	8	0	197 641
West, anticyclonic	62	1 092	74 996
Southwest, anticyclonic	54	0	43 109
Northwest, anticyclonic	46	2 358	153 518
North, anticyclonic	43	0	117 375
NorthEast, anticyclonic	81	0	109 220
East, anticyclonic	57	0	181 771
SouthEast, anticyclonic	42	0	236 866
South, anticyclonic	42	0	105 085
West, indifferent	7	0	54 811
Southwest, indifferent	9	21 846	42 464
Northwest, indifferent	9	0	93 060
North, indifferent	9	0	195 837
NorthEast, indifferent	28	0	102 539
East, indifferent	25	0	136 779
SouthEast, indifferent	10	0	236 779
South, indifferent	3	0	30 905
Low Pressure	11	1 751	85 171
High Pressure	33	0	190 498

Table C6. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP BUGEY (2017-2018)

6 classes	Occur.	Switzerland	Europe
West	157	1 692	56 354
North	138	786	130 178
East	265	21	130 278
South	126	0	172 405
Low	11	1 751	85 171
High	33	0	190 498

Table C7. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP GOESGEN (2017-2018)

26 classes	Occur.	Switzerland	Europe
West, cyclonic	11	145 629	149 601
Southwest, cyclonic	14	227 560	265 543
Northwest, cyclonic	13	151 887	170 064
North, cyclonic	18	198 120	211 489
NorthEast, cyclonic	35	280 402	286 936
East, cyclonic	39	257 466	267 659
SouthEast, cyclonic	21	216 076	259 195
South, cyclonic	8	287 766	374 618
West, anticyclonic	62	161 601	184 180
Southwest, anticyclonic	54	170 664	246 260
Northwest, anticyclonic	46	218 950	233 234
North, anticyclonic	43	280 824	302 865
NorthEast, anticyclonic	81	225 487	234 574
East, anticyclonic	57	232 863	273 964
SouthEast, anticyclonic	42	270 812	356 545
South, anticyclonic	42	238 524	363 200
West, indifferent	7	172 509	178 691
Southwest, indifferent	9	228 841	267 476
Northwest, indifferent	9	310 909	355 370
North, indifferent	9	210 989	219 189
NorthEast, indifferent	28	183 823	185 587
East, indifferent	25	345 893	359 653
SouthEast, indifferent	10	291 841	409 147
South, indifferent	3	379 224	516 263
Low Pressure	11	340 732	353 238
High Pressure	33	243 882	355 722

Table C8. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP GOESGEN (2017-2018)

6 classes	Occur.	Switzerland	Europe
West	157	173 822	214 895
North	138	234 673	253 193
East	265	245 989	261 455
South	126	256 253	351 663
Low	11	340 732	353 238
High	33	243 882	355 722

Table C9. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP LEIBSTADT (2017-2018)

26 classes	Occur.	Switzerland	Europe
West, cyclonic	11	7 068	18 980
Southwest, cyclonic	14	38 449	149 066
Northwest, cyclonic	13	29 919	69 218
North, cyclonic	18	24 070	59 653
NorthEast, cyclonic	35	124 596	159 612
East, cyclonic	39	89 248	135 148
SouthEast, cyclonic	21	216 577	349 328
South, cyclonic	8	27 888	125 187
West, anticyclonic	62	17 274	59 842
Southwest, anticyclonic	54	31 774	108 110
Northwest, anticyclonic	46	36 280	82 510
North, anticyclonic	43	87 631	152 265
NorthEast, anticyclonic	81	132 964	184 985
East, anticyclonic	57	143 102	233 259
SouthEast, anticyclonic	42	144 965	293 689
South, anticyclonic	42	79 308	241 539
West, indifferent	7	17 789	41 641
Southwest, indifferent	9	120 691	215 606
Northwest, indifferent	9	43 995	112 537
North, indifferent	9	47 895	87 303
NorthEast, indifferent	28	128 366	161 313
East, indifferent	25	112 575	166 757
SouthEast, indifferent	10	115 996	235 906
South, indifferent	3	186 913	366 286
Low Pressure	11	78 889	149 991
High Pressure	33	76 903	181 012

Table C10. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release
NPP LEIBSTADT (2017-2018)

6 classes	Occur.	Switzerland	Europe
West	157	29 386	89 655
North	138	51 350	102 283
East	265	125 196	180 462
South	126	126 281	272 023
Low	11	78 889	149 991
High	33	76 903	181 012

Table C11. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP MÜHLEBERG (2017-2018)

26 classes	Occur.	Switzerland	Europe
West, cyclonic	11	71 072	71 072
Southwest, cyclonic	14	120 946	122 896
Northwest, cyclonic	13	65 513	65 513
North, cyclonic	18	120 676	124 137
NorthEast, cyclonic	35	122 899	122 899
East, cyclonic	39	121 378	149 794
SouthEast, cyclonic	21	122 215	123 399
South, cyclonic	8	173 434	173 462
West, anticyclonic	62	112 179	112 517
Southwest, anticyclonic	54	153 378	159 293
Northwest, anticyclonic	46	105 050	106 351
North, anticyclonic	43	130 711	133 421
NorthEast, anticyclonic	81	136 829	137 354
East, anticyclonic	57	125 765	141 527
SouthEast, anticyclonic	42	141 388	152 882
South, anticyclonic	42	154 509	158 836
West, indifferent	7	49 680	49 680
Southwest, indifferent	9	145 036	151 360
Northwest, indifferent	9	151 498	151 520
North, indifferent	9	134 739	134 739
NorthEast, indifferent	28	162 081	168 568
East, indifferent	25	126 381	127 094
SouthEast, indifferent	10	120 291	153 984
South, indifferent	3	169 660	169 660
Low Pressure	11	139 620	140 378
High Pressure	33	146 598	146 626

Table C12. Stratification of the results by weather classes through the following criterion: average population exposed to more than 100 mSv from a major release

NPP MÜHLEBERG (2017-2018)

6 classes	Occur.	Switzerland	Europe
West	157	123 348	126 053
North	138	116 325	118 056
East	265	132 018	140 503
South	126	143 600	151 746
Low	11	139 620	140 378
High	33	146 598	146 626

Table C13. Stratification of the results by weather classes through the following criterion: average radioactive ground-surfaces in km2 with a 137Cs deposition ≥ 1,480,000 Bq/m2 after a major release
NPP BEZNAU (2017-2018)

	Switzerland			Europe		
6 classes	Urban areas	Agricultural areas	Forests	Urban areas	Agricultural areas	Forests
West	33	119	109	61	220	268
North	42	146	128	61	218	210
East	83	246	232	97	292	297
South	90	251	246	149	443	476
Low	59	219	231	76	294	315
High	65	200	195	99	296	335

Table C14. Stratification of the results by weather classes through the following criterion: average radioactive ground-surfaces in km2 with a 137Cs deposition ≥ 1,480,000 Bq/m2 after a major release
NPP BUGEY (2017-2018)

	Switzerland			Europe		
6 classes	Urban areas	Agricultural areas	Forests	Urban areas	Agricultural areas	Forests
West	2	6	3	70	490	207
North	1	5	3	107	683	461
East	0	1	1	102	672	439
South	0	0	0	137	785	306
Low	6	12	27	94	539	366
High	0	0	0	159	947	353

Table C15. Stratification of the results by weather classes through the following criterion: average radioactive ground-surfaces in km2 with a 137Cs deposition ≥ 1,480,000 Bq/m2 after a major release
NPP GOESGEN (2017-2018)

	Switzerland			Europe		
6 classes	Urban areas	Agricultural areas	Forests	Urban areas	Agricultural areas	Forests
West	87	199	192	116	295	366
North	122	265	238	137	311	329
East	136	375	315	153	431	406
South	117	287	311	183	531	596
Low	162	377	347	172	402	408
High	100	214	230	157	373	467

Table C16. Stratification of the results by weather classes through the following criterion: average radioactive ground-surfaces in km^2 with a ^{137}Cs deposition ≥ 1,480,000 Bq/m^2 after a major release
NPP LEIBSTADT (2017-2018)

	Switzerland			Europe		
6 classes	Urban areas	Agricultural areas	Forests	Urban areas	Agricultural areas	Forests
West	26	104	85	112	379	603
North	47	190	158	117	461	547
East	133	444	417	198	645	743
South	94	263	249	270	841	1055
Low	60	240	199	133	459	513
High	53	180	160	173	600	840

Table C17. Stratification of the results by weather classes through the following criterion: average radioactive ground-surfaces in km2 with a 137Cs deposition ≥ 1,480,000 Bq/m2 after a major release
NPP MÜHLEBERG (2017-2018)

	Switzerland			Europe		
6 classes	Urban areas	Agricultural areas	Forests	Urban areas	Agricultural areas	Forests
West	93	378	292	105	416	333
North	76	387	217	80	402	262
East	87	534	261	101	581	328
South	102	552	336	127	684	499
Low	82	437	329	85	439	354
High	111	535	358	118	554	400

Annex D. Glossary

Bq – Becquerel	Activity of radioactive material, number of nuclei decaying per second
CED	Committed Effective Dose
CCED	Collective Committed Effective Dose
CVD	Cardiovascular disease
ENSI	Swiss Federal Nuclear Safety Inspectorate
EAR	Excess Absolute Risk
ERR	Excess Relative Risk
Gy – Gray	Energy dose emitted by radiation, 1 Gy = 1 J/kg
IR	Ionising radiation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
persSv	Collective dose = number of people (persons) x average dose (Sv)
NPP	Nuclear Power Plant
Sv – Sievert	Unit of measurement for the radiation dose. The limit officially considered safe: 0.001 Sv (1 mSv) per annum
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization.

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