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Appraisal of long-term radiation trends in the environs of nuclear power plants – Examples from Switzerland

Annually since 1989, biannually since 1994 the sites of the Swiss nuclear facilities (4 power plant sites, a nuclear research institute and a waste storage facility) are surveyed flying the same survey lines by airborne gamma ray spectrometry. The equipment and the data processing software used for those surveys was built and developed at the Institute of Geophysics, ETH Zurich. For mapping the ground radiation around the nuclear facilities a pixel representation and a modified Spectrum Dose Index (SDI) method is used. In the search for long-term trends the local dose-rates are calculated first and in turn the net dose rates over the time span 1992-2010. So far no significant change in the radiation levels was detected over the last 18 years outside of the fenced sites of the nuclear facilities, except for the operation of an industrial radiation facility in 1995.

Bewertung von Langzeit-Strahlungstrends im Umfeld von Kernkraftwerken – Beispiele aus der Schweiz

Die Umgebung der Schweizer Kernanlagen (vier Kernkraftwerke, ein Kernforschungsinstitut, und ein Lager für radioaktive Abfälle) wird seit 1989 jährlich und seit 1994 im zweijährigen Turnus mittels Aerogammaspektrometrie entlang derselben Fluglinien vermessen. Die Messeinrichtung und die Datenverarbeitung wurden am Institut für Geophysik der ETH Zürich gebaut bzw. entwickelt. Die Kartierung der Bodenstrahlung (Ortsdosisleistung) erfolgt mit einem modifizierten Spektral-Dosis-Index (SDI) und einer Pixeldarstellung. Bei der Suche nach Langzeit-Trends wurden für die Zeitspanne 1992-2010 aus den lokalen Ortsdosisleistungen Nettodosisleistungen bestimmt. Über die untersuchten 18 Jahre konnte konnten ausserhalb der umzäunten Anlagen-Areale -mit Ausnahme einer industriellen Bestrahlungsanlage im Jahr 1995- keine signifikanten Änderungen der Strahlungswerte festgestellt werden.

1 Introduction

Measured radiation levels around nuclear power plants (when well below the limits set by authorities) and their perseverance over the years are important factors in the public acceptance of nuclear energy. Whereas inside of the fenced areas of the power plants special measures are usually taken, the radiation levels in the surroundings are especially in focus of public scrutiny. Unlike permanent, stationary dose-rate monitoring instruments that measure activity at singular points airborne radioactivity surveys provide gapless areal coverage. The temporal behavior of radiation levels in the environs of the power plants can be investigated by repeated airborne surveys.

There are five nuclear power plants in Switzerland, at four sites (Beznau I +II, KKB, PWR; Mühleberg, KKM, BWR; Gösgen, KKG, PWR; Leibstadt, KKL, BWR, see Table 1) with a total generating capacity of 3.24 GWe (production in 2009: 26.1 TWh), supplying nearly 40% of Swiss electricity production. The Paul Scherrer Institute in Würenlingen, a renowned research facility (PSI), belongs also to the Swiss nuclear installations. The Zwischenlager Würenlingen AG (ZWILAG, interim storage facility for all categories of nuclear waste and spent fuel assemblies, in operation since 2001) is a further nuclear installation, subject to regular surveys.

Geographically, the nuclear facilities are all located in northern Switzerland (see Fig. 1); maps of the environs are displayed in Figs. 2 and 5.

The environs of the nuclear facilities are constantly monitored by fixed local networks of ground radiation detectors (MADUK, operated by the Swiss Federal Nuclear Safety Inspectorate (ENSI)) and of thermoluminescence dose detectors (TDL, operated by the operators of the nuclear facilities). A comprehensive surveillance program is carried out in the environs of the nuclear facilities, in close cooperation with the Section Environmental Radioactivity of the Swiss Federal Office of Public Health and various other institutions.

As an additional measure, the ground radiation in the surrounding regions (approx. 50 km^2) of the nuclear power plants and of the PSI was surveyed annually since 1989 for the ENSI by airborne gamma ray spectrometry ([1], [2], [3]). In 1992, the measurement system has been upgraded (e.g. positioning by GPS; equipment details see below). Since 1994, the surveys are carried out with biannual frequency, within the framework of Swiss National Emergency Operation Center (NAZ) exercises. The objectives are, besides detecting of eventual releases, the establishment of baseline information (undisturbed background for reference in case of accidents), the monitoring of dose rate distribution, and the determination of the variation width of natural radiation. The results are summarized in annual reports to ENSI and NAZ. These reports (reports ‘‘UARM’’) also include descriptions of methodological developments; they can be found and downloaded from http://www.far.ensi.ch/.

Now, after more than 15 years of surveying, it can be investigated, especially around the nuclear plower plants, whether there are some changes in the radiation levels over the time period of measurements. The measured ground radiation is expressed by dose rate ($nSvh^{-1}$), calculated by the modified spectral dose index (SDI) method; details see below.

2 Equipment and calibration

The equipment used for the surveys was assembled in 1993–1994 from commercial components at the Institute of Geophysics ETH Zurich (revised 2002–2005), consisting of a 16.7 l NaI detector, 256 channel energy stabilized spectrometer (EXPLORANIUM 820), PC-based control with recording on memory cards (32 MBytes), and GPS navigation. Detection limit for point sources (at 90 m standard flight altitude, see below) is between 0.4 and 1.9 GBq, depending on radionuclide (emitted gamma energy), vegetation cover, background, and topography. The detection limit for a surface contamination by ^{137}Cs (at 90 m standard flight altitude, see below) is around 0.5–1 $kBqm^{-2}$ depending on vegetation cover, background, and topography. The detector is mounted below a helicopter and the rack with the electronic components is mounted in the passenger cabin (installation time < 4 h). Super Puma helicopters of the Swiss Army are used for the flights.

Since no concrete pads are available in or near Switzerland, calibration was done by point sources (scattering effects in ground and air considered), and at places with known ground activity. Ascending flights above large lakes and above point and volume sources yielded coefficients for data reduction (for details about laboratory and in-flight calibration see [4] and [5]). Close agreement of ground and airborne results indicates reliable calibration (see [6]).

3 Flight parameters

To have uniform coverage of the surveyed sites, the flights are carried out in a regular grid (250 m spacing between flight lines, occasional crossing lines, flight height 90 m above ground). Measurements are taken every second, which corresponds to a distance of 25 m between measurements at a flight speed of 90 kmh^{-1}. To make the repeated surveys comparable, the same line pattern is flown each time. As an example, Fig. 2 shows the flight lines of the 2006 survey at the KKB/KKL/PSI/ZWILAG sites.

4 Data processing and mapping

Data processing first performs quality control of raw data, and then in turn a series of reductions: background removal, spectral stripping, altitude/topographic correction, conversion of the net count rates to ground isotope concentrations, artificial radioactivity indicators, SDI–dose rate at 1 m altitude above ground (nSv h^{-1}, see below). The complete processing including modules for corrections and map output can thus be performed online during flights ([7], [8]). GPS positioning yields the Swiss coordinates within ±10 m.

To keep filtering simple (especially when searching for weak artificial sources), to account for the relatively large measurement errors in AGS and rapidly changing radiation field intensities, the averaging pixel method is used for data representation/color mapping (pixel size 125x125 m, comprises the average of five measurements; recursive nearest neighbor average interpolation). Original values are not changed by this procedure. A variety of maps can be produced: total counts, spectral windows (e.g. ^{60}Co, ^{137}Cs, ^{214}Bi for the ^{238}U series). Three dimensional representations and ternary maps can also be produced ([1], [9]).

5 Ground radiation mapping with the spectral dose index (SDI) method

The gamma radiation of the ground (usually originating from natural and man-made radioisotopes in the top 10–20 cm) manifests itself in the gamma ray spectra measured above ground. For airborne measurements with NaI detectors, the spectra consist of a background (cosmic radiation, activities in the aircraft and the atmosphere) and of various photopeaks with the corresponding Compton continua. Generally speaking, the higher the total number of counts in the spectrum, the higher the dose rate originating from these radiations. The measured spectra include, besides the count rates, also information about the energy distribution of the detected radiation. This information is used to derive and map the ground dose rates by the Spectral Dose Index (SDI) method. The SDI is given by

$$SDI = \sum_{i}^{n} (CR_i * i) \qquad (1)$$

where CR_i is the count rate in channel i (i is the channel number). The summation is carried out over n channels, usually above a low-energy threshold. The SDI is then corrected for the contributions of cosmic radiation and the helicopter background; by means of an exponential height dependence the SDI is normalized to a standard flight altitude above ground. Finally the SDI is converted by a factor determined through comparisons with ground measurements to a dose rate at 1 m altitude above ground. The cosmic dose rate part is calculated according to [10] and added. By these means the ambient dose rate equivalent at 1 m above ground $\dot{D}(i,j)$ is obtained. The whole procedure is described in detail in [11].

6 Determination of net dose rates

From the calculated dose rates a grid with cell size of 125 m x 125 m is established for the environs of each nuclear power plant. Since the size of the surveyed areas usually differs from year to year the annual grids are reduced to the area covered each year. Since the emphasis is on the determination of radiation changes in the environs (=outside the fenced power plant sites) the values influenced by activities within the sites are masked.

The next step consists of the determination of the net dose rates by the SDI method, considering each cell of the grid as a measurement station (see [12]). With this approach, the net dose rate NDR is the difference between measured dose rate $\dot{D}(i,j)$ and expected dose rate EDR(i,j),

$$NDR = \dot{D}(i,j) - EDR(i,j) , \qquad (2)$$

To determine the net dose rate the local dose rate is split into locality-dependent (LDP) and time-dependent (TDP) component. The spatially variable component considers the locally varying parameters, the time-variable component the time-dependent influence factors like ground moisture.

The spatially variable part LDP for a given point i is given by the difference of the average dose rate at the point i and the dose rate averaged over all time intervals j over all points i:

$$LDP(i) = \dot{D}_L(i) - \dot{D} \qquad (3)$$

$$\dot{D}_L(i) = \frac{1}{m} \cdot \sum_j \dot{D}(i, j) \qquad (4)$$

$$\dot{D} = \frac{1}{m \cdot n} \cdot \sum_{i,j} \dot{D}(i, j) \qquad (5)$$

where m is the number of time intervals, n the number of measurement points, i the measurement point index, and j the time interval index.

The time-variable part TDP for a given time interval j is given by the measured dose rate Ḋ(i,j) averaged over all points on the given time interval:

$$TDP(j) = \frac{1}{n} \cdot \sum_i \dot{D}(i, j) \qquad (6)$$

where n is the number of measurement points, i the measurement point index, and j the time interval index.

The expected dose rate value EDR is then

$$EDR(i, j) = TDP(j) + LDP(i) \qquad (7)$$

The net dose rate is then given by the difference between the measured and the expected value. The standard uncertainty (variance) of the average dose rate for a given survey is

$$\Delta\dot{D}(j) = \pm\sqrt{\frac{1}{m-1} \sum_i \left(\dot{D}(i, j) - \dot{D}(j)\right)^2} \qquad (8)$$

The standard uncertainty (variance) of the average net dose rate, which is zero for the given data, is

$$\Delta N = \pm\sqrt{\frac{1}{(m-1)\cdot(n-1)} \sum_{i,j} \left(\dot{D}(i, j) - EDR(i, j)\right)^2} \qquad (9)$$

From the variation of the average net dose rate the limit of recognition for the net dose rate NDR(i,j) can be determined. For a confidential interval of 95 % the recognition limit RL is

$$RL = 1.645 \cdot \Delta N \qquad (10)$$

Under the assumption that the uncertainty of a net dose rate at the value of the detection limit is similar to the uncertainty of the average net dose rate and a 5 % probability of wrong evidence the detection limit DL is twice the RL:

$$DL = 2 \cdot RL = 3.29 \cdot \Delta N \qquad (11)$$

7 Results

The temporal variation of the average dose rate value over a given survey area can unveil development trends. In the search of possible (increasing?) radiation trends in the environs of Swiss nuclear power plants the time series of the dose rate averages of the survey areas KKG, KKM and KKB/KKL/PSI/ZWILAG have been plotted (Fig. 3).

It is visible from Figure 3 that from 1994 on the nuclear sites are surveyed in a two-year turn. The gap is due to the fact that in 2002 only a small part of the KKB environs could be surveyed, for logistic reasons.

The net dose rates averaged over the survey areas are at all nuclear sites and over all years practically zero. As an example, the net dose rates averaged over the survey area of KKG is given in Figure 4, along with the 95 % confidence intervals.

8 Discussion

The calculated net dose rates and their variation enable to determine the detection limit, see Eqs. (10) and (11). The numerical values found are 13 $nSvh^{-1}$ for the KKG area, 17 $nSvh^{-1}$ for the KKM area and 18 $nSvh^{-1}$ for the KKB/KKL/PSI/ZWILAG area. Consequently, an additional annual dose of 0.2 mSv could be detected for the KKB/KKL/PSI/ZWILAG area.

The variance (standard deviation) of the net dose rates in the individual pixels is given, as an example, for the KKG area in Figure 5. There is one location visible with significantly higher variance in Figure 5. It is located right at a building in Däniken/SO in which an industrial irradiation facility is operated. During the 1995 survey, a net dose rate of 39 nSv h^{-1} was detected at that point. This is about three times the detection limit of 13 $nSvh^{-1}$. Due to improved shielding, no elevated values have been found in subsequent years.

With the determined sensitivity limits an annual increase by 0.2 mSv could be detected at any grid cell in any of the surveyed areas. Nevertheless, no increase whatsoever is apparent in the environs of all Swiss nuclear installations; the variations are all well within the uncertainty limits.

A comparison of the average values determined from aeroradiometric surveys with the values measured by the automatic stationary network MADUK is plotted in Figure 6. MADUK measures at 57 locations around the Swiss nuclear installations the dose rate in 10 minutes intervals using Geiger-Müller probes. The measuring range starts from 10 $nSvh^{-1}$ (low dose rate detector) and goes up to 10 Svh^{-1} (high dose rate detector). It is evident from Figure 6 that both results show a similar course. The MADUK measurements reflect seasonal variations, due to changing ground moisture and vegetation, which can manifest themselves also in aeroradiometric survey results. The reason of generally lower aeroradiometric values is that all MADUK measurement stations are on solid ground whereas the aeroradiometric surveys cover water surfaces like rivers too.

9 Conclusions

Repeated airborne surveys of the environs of the Swiss nuclear facilities over 18 years enable to search for changes of the radiation levels and/or to depict possible trends. Neither the time series of local dose rates nor those of the net dose rates exhibit any such features: the annually repeated measurements show that the radioactivity level in the environs remained constant within measurement uncertainties, i.e. no change in the radiation levels was detected over the last 18 years outside of the fenced sites of the nuclear facilities so far. Especially, no artificial radioactivity was present that could not be explained by nuclear weapon tests or by the Chernobyl event. Comparison of the aeroradiometric results with fixed ground instrumentation in the nuclear facility environs show excellent agreement. The determined aeroradiometric detection limits for the net dose rate are within the range of 12 to 20 $nSvh^{-1}$.

The absence of any radiation level increase around the Swiss nuclear facilities demonstrates their highly reliable operation.

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Figure 1: The locations of the Swiss nuclear facilities.

Figure 2: The flight lines of the 2006 survey at the KKB/KKL/PSI/ZWILAG sites. Swiss coordinates (km). Digital maps PK100©2003 swisstopo (reproduced by permission of swisstopo (BA110219))

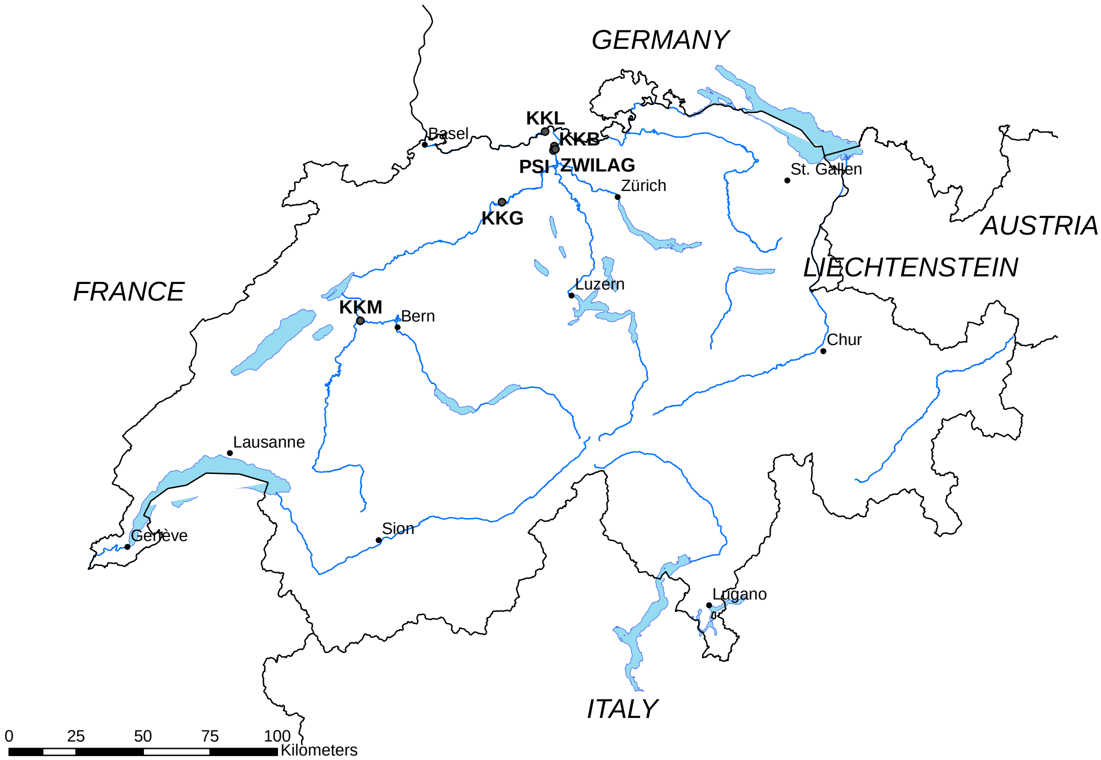
Figure 3: Temporal variation of the dose rates averaged over the aeroradiometric (ARM) survey areas around the Swiss nuclear power plants Beznau (KKB), Gösgen (KKG), Mühleberg (KKM), Leibstadt (KKL; along with KKB, the Paul Scherrer Institute PSI and the ZWILAG). The 95 % confidence interval bars are also plotted.

Figure 4: Temporal variation of the net dose rates averaged over the survey area of KKG, along with the 95 % confidence intervals.

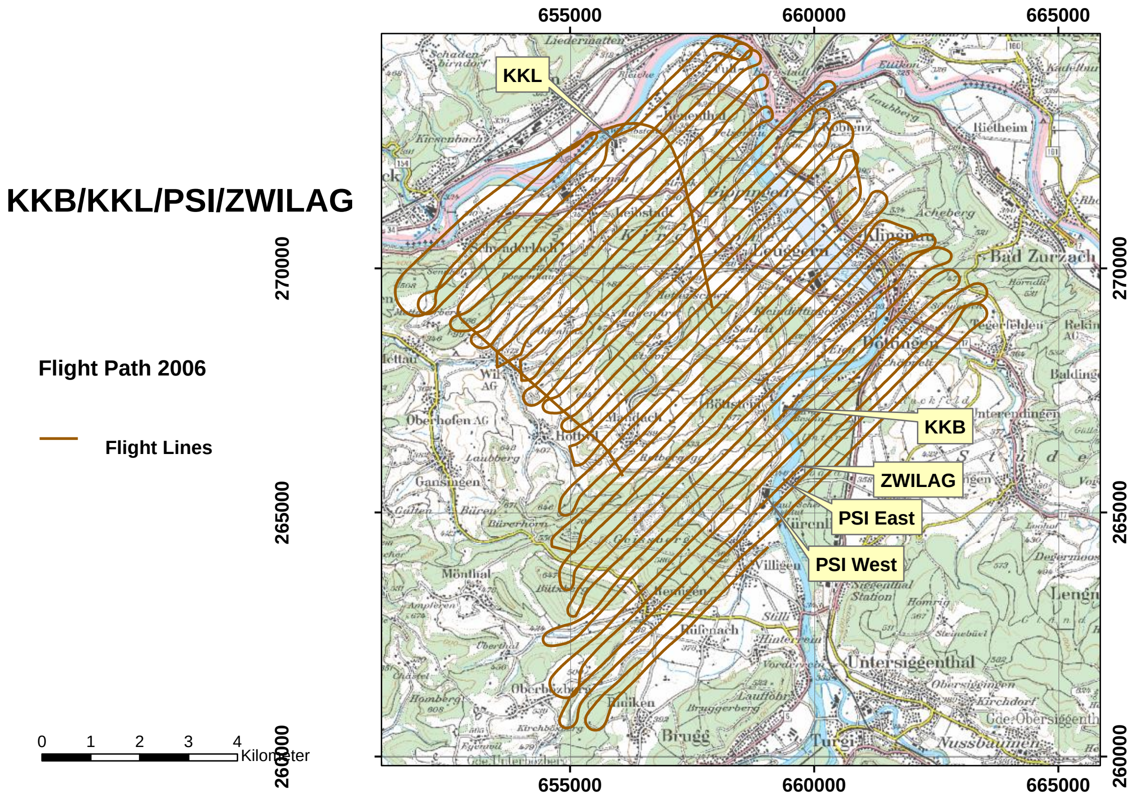
Figure 5: Standard deviation of the net dose rates over the years 1992 to 2010 in the survey area KKG. Digital maps PK100©2003 swisstopo (reproduced by permission of swisstopo (BA110219))

Figure 6: Course of areal dose rate averages from aeroradiometric surveys (ARM) in the environs of the Swiss nuclear installations KKB, KKL, PSI and ZWILAG, compared to the results of the MADUK network around KKL and KKB in the same time window. Also plotted are the 95 % confidence intervals of the aeroradiometric results of the area KKB/KKL/PSI/ZWILAG.

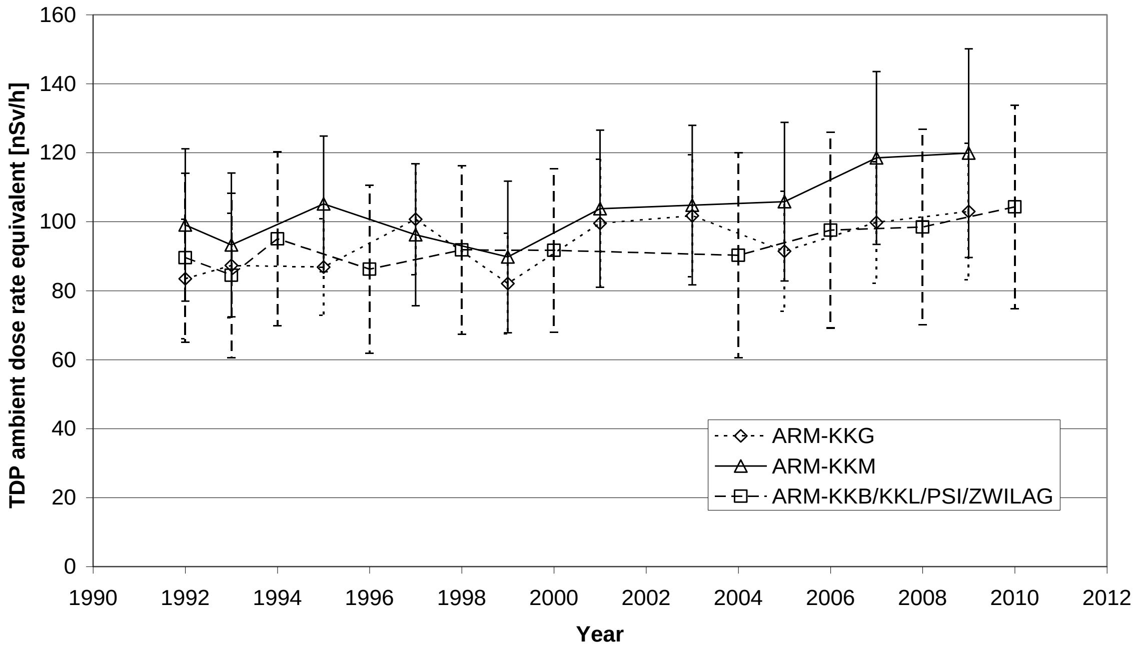
Bucher et al.   Figure 1



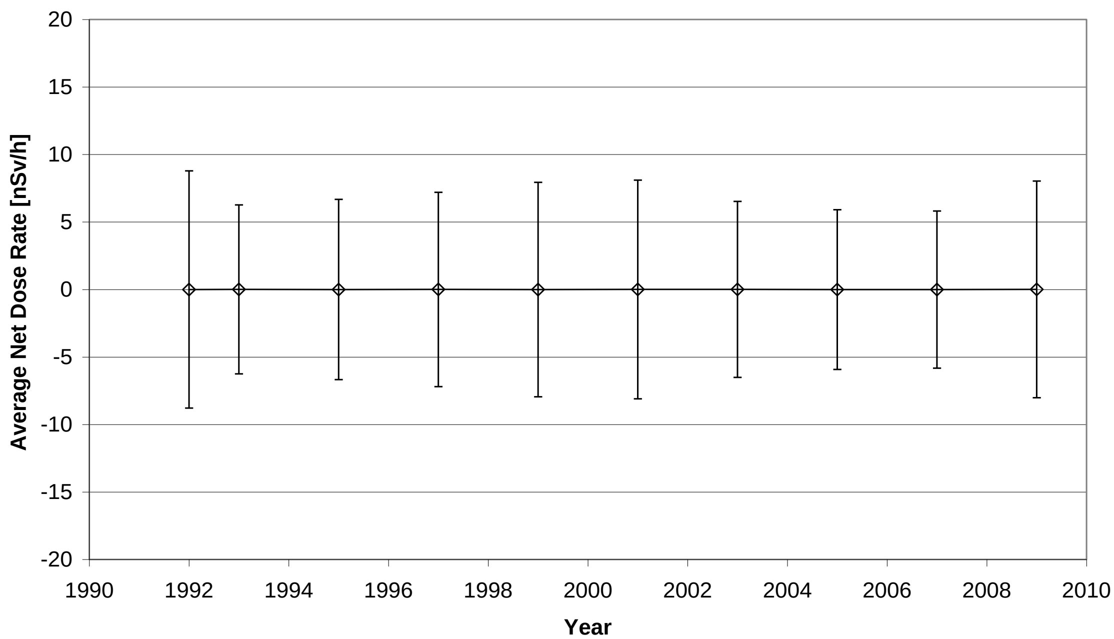
Bucher et al.   Figure 2



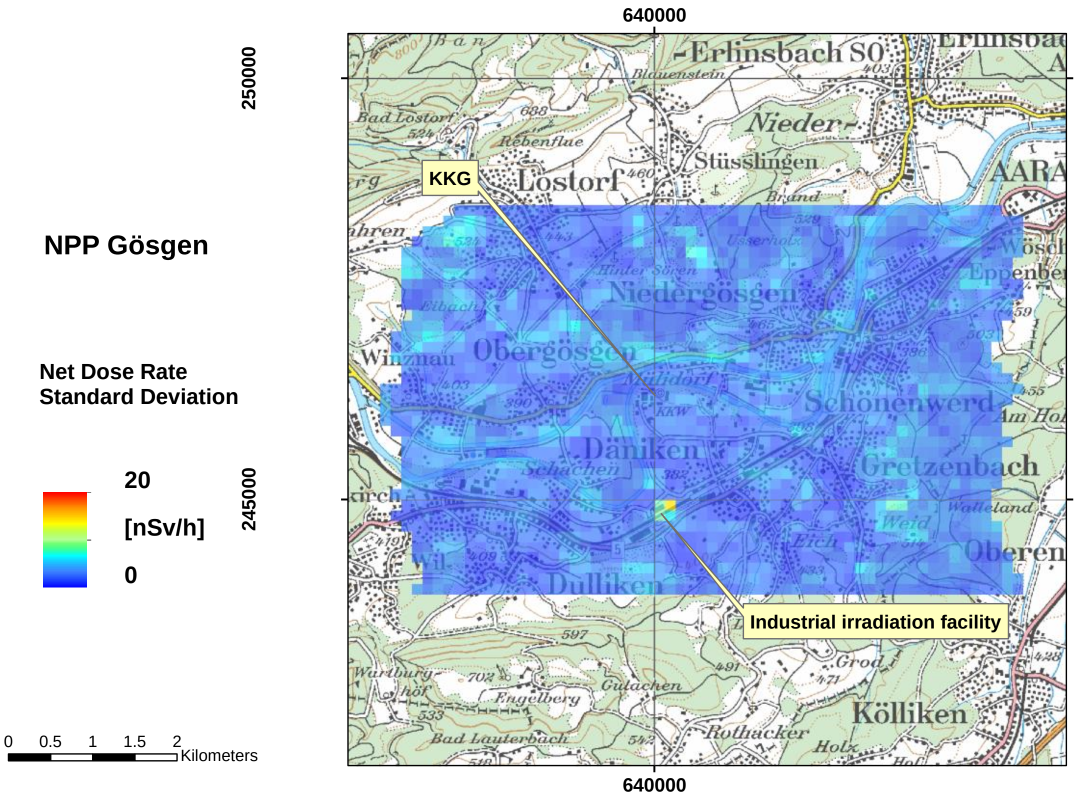
Bucher et al.   Figure 3



Bucher et al.   Figure 4



Bucher et al.   Figure 5



Bucher et al. Figure 6

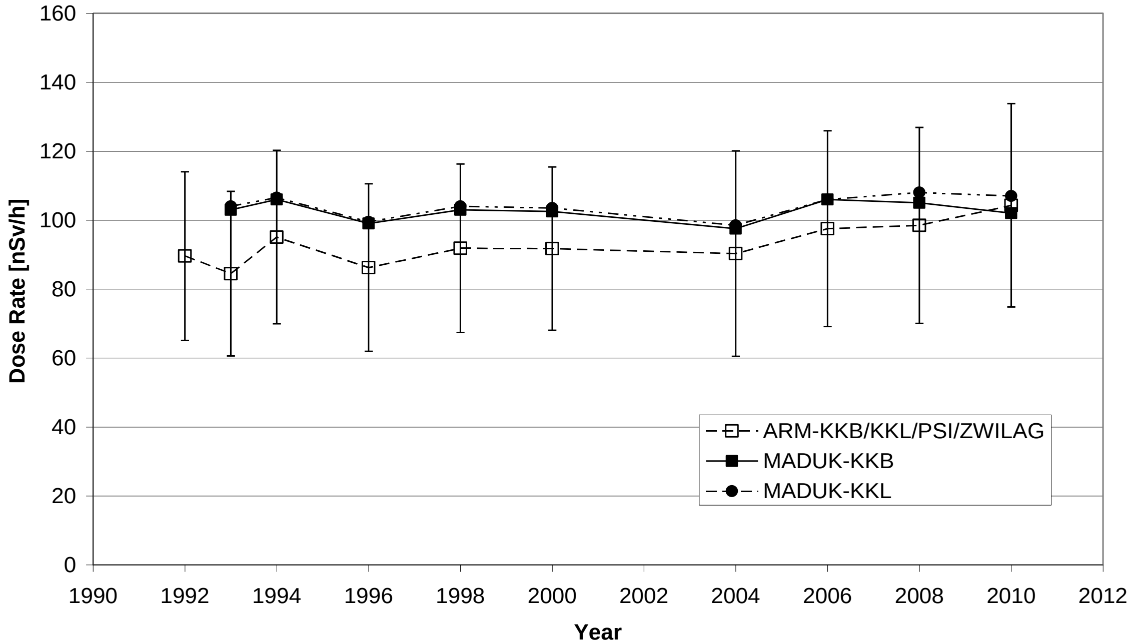


Table 1: The Swiss nuclear power plants

Plant	Symbol	Type	MWe	Cooling	Since
Beznau	KKB I KKB II	PWR PWR	365 365	River River	1969 1971
Mühleberg	KKM	BWR	373	River	1972
Gösgen	KKG	PWR	970	Cooling tower	1979
Leibstadt	KKL	BWR	1165	Cooling tower	1984

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