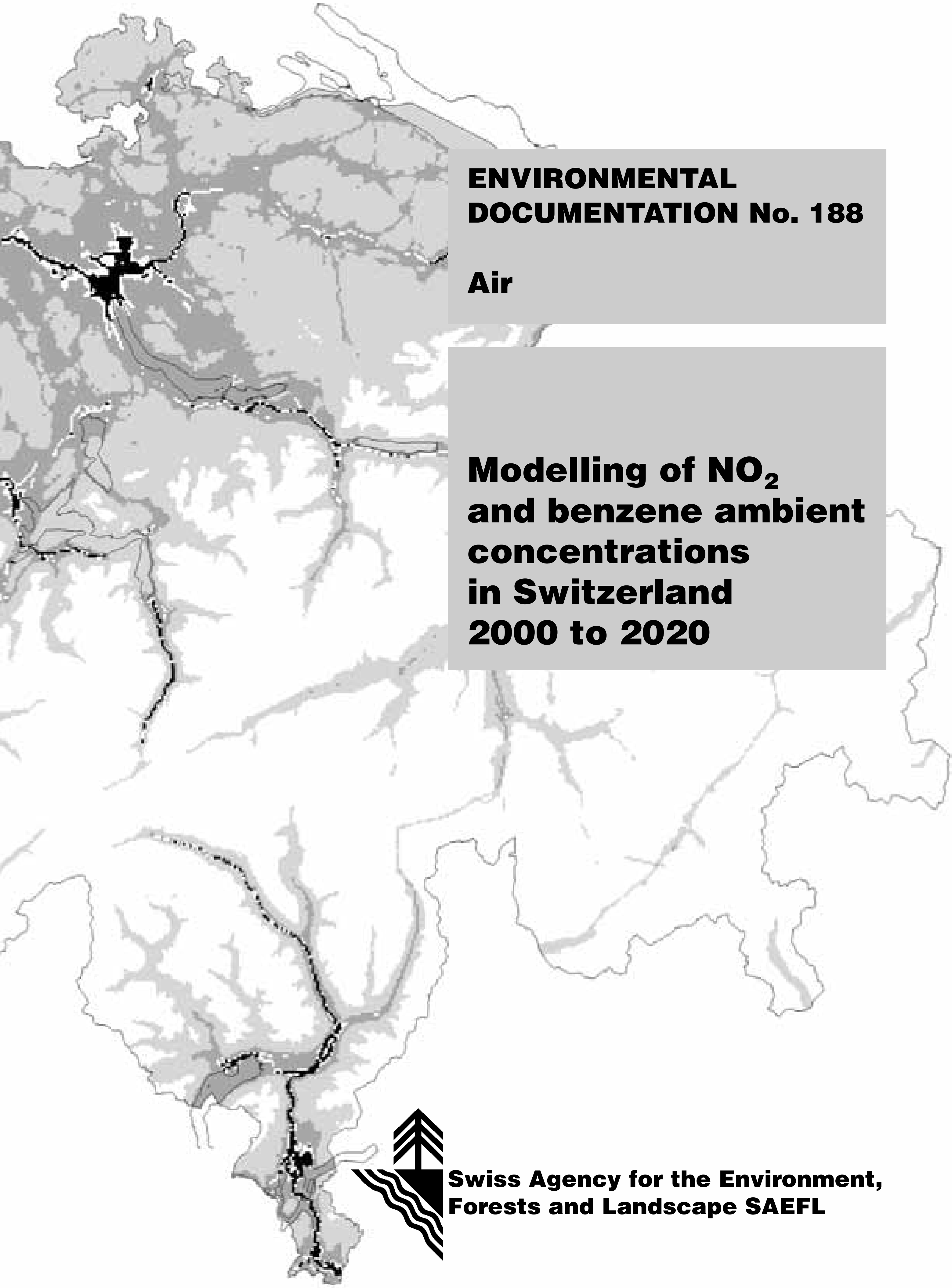

ENVIRONMENTAL DOCUMENTATION No. 188

Air

# Modelling of $NO_2$ and benzene ambient concentrations in Switzerland 2000 to 2020

Swiss Agency for the Environment, Forests and Landscape SAEFL

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# Overview

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# Abstracts

## Simulation of the $NO_2$ and benzene exposure in Switzerland 2000-2020

The present report documents the simulation procedure for $NO_2$ exposure in the whole of Switzerland and presents $NO_2$ concentration maps for the period 2000-2020 at 5-year intervals. Future developments such as the EURO-4 directive for motor vehicles or the mileage-related tax on heavy vehicles are taken into account. Emission inventories with a spatial resolution of 200 m are used for the main source groups (road traffic, off-road traffic, industry, households, agriculture and forestry) covering the whole of Switzerland.

Emissions and their dispersion are simulated based on the sum of all $NO_x$ emitted. From this, the $NO_2$ concentration is determined using an empirical conversion function. The dispersion is modelled by using transfer functions. The transfer functions are calculated using a Gauss function, which was derived from hourly meteorological data for 1998. By using different transfer functions, it was possible to take account of the different characteristics (emission height, time variation of emission intensity) of the source groups, and of the different dispersion conditions (in Alpine valleys, for example, the transfer functions were applied in the direction of the prevailing wind).

The results are displayed in the form of $NO_2$ concentration maps at 400 m resolution for the whole of Switzerland; illustrative examples are also shown at 200 m resolution. The simulation results for 2000 are compared with measured values, and good agreement found. The average $NO_2$ exposure in 2000 was found to exceed the annual average air quality standard (limit value) of 30 $\mu g/m^3$ over 0.8% (344 $km^2$) of the total land area of Switzerland. This area accommodates 16% of the Swiss population (1.16 million inhabitants). In 2010, these values will drop to 0.23% (96 $km^2$) of the land area and 5.3% of the population (0.39 million inhabitants). The values for 2020 are 0.1% (33 $km^2$) of the land area and 1.3% of the population (0.1 million inhabitants).

The benzene exposure for 2000 and 2010 was determined using the same methodology and displayed in charts at 400 m resolution. In addition, four cities are shown at higher resolution (200 m).

**Keywords**: nitrogen dioxide, benzene, air quality, dispersion simulation, scenarios

# Modellierung der $NO_2$- und Benzol-Immissionen in der Schweiz 2000–2020

Der vorliegende Bericht dokumentiert die Methodik der gesamtschweizerischen $NO_2$-Immissionsmodellierung und präsentiert $NO_2$-Belastungkarten für die Periode 2000–2020 in 5-Jahresschritten. Künftige Entwicklungen wie die EURO-4-Richtlinie für Motorfahrzeuge oder die leistungsabhängige Schwerverkehrsabgabe werden berücksichtigt. Für alle grossen Emittentengruppen (Strassenverkehr, Offroadverkehr, Industrie, Haushalte, Land- und Forstwirtschaft) werden landesweite Emissionskataster mit einer räumlichen Auflösung von 200 m verwendet.

Die Modellierung der Emissionen und deren Ausbreitung geschieht für die Summe der Stickoxide ($NO_x$). Daraus wird die $NO_2$-Konzentration mittels einer empirischen Konversionsfunktion bestimmt. Die Ausbreitungsmodellierung erfolgt mit Transferfunktionen. Diese Funktionen sind mit einem Gaussmodell berechnet, das sich auf stündliche meteorologische Daten des Jahres 1998 stützt. Die Verwendung mehrer Transferfunktionen ermöglicht es, die verschiedenen Eigenschaften der Emittentengruppen (Emissionshöhe, Zeitreihen der Emissionsstärke) und die Ausbreitungsbedingungen abzubilden (z.B. werden in Alpentälern die Transferfunktionen in Hauptwindrichtung ausgerichtet).

Die $NO_2$-Immissionskarten für die ganze Schweiz sind in einer 400 m Auflösung dargestellt; illustrative Ausschnitte liegen ausserdem in 200 m Auflösung vor. Im Jahr 2000 ist die mittlere $NO_2$-Immission in 0.8% (344 $km^2$) der gesamten Fläche der Schweiz über dem Jahresmittelgrenzwert von 30 $\mu g/m^3$. In diesem Gebiet leben 16% der schweizerischen Bevölkerung (1.16 Millionen Personen). 2010 reduzieren sich diese Werte auf 0.23% (96 $km^2$) der Fläche und 5.3% der Bevölkerung (0.39 Millionen Personen); 2020 auf 0.1% (33 $km^2$) der Fläche und 1.3% der Bevölkerung (0.1 Millionen Personen).

Mit dem gleichen Ansatz wurden auch die Benzol-Immissionen 2000 und 2010 in der Schweiz berechnet und in einer 400 m Auflösung kartographisch dargestellt. Vier Städte werden zusätzlich in einer feineren Auflösung (200 m) präsentiert.

**Stichworte**: Stickstoffdioxid, Benzol, Luftqualität, Ausbreitungsrechnung, Szenarien

# Modélisation des immissions de $NO_2$ et de benzène en Suisse pour la période 2000 à 2020

Ce rapport présente la méthodologie de modélisation des immissions de $NO_2$ à l'échelle de la Suisse, ainsi que des cartes de l'exposition au $NO_2$ pour la période 2000 à 2020, par tranches de cinq ans. On tient compte pour cela de l'évolution attendue, par exemple suite à l'introduction de la directive EURO 4 sur les véhicules à moteur ou de la redevance poids lourds liée aux prestations. Des cadastres d'émission à l'échelle du pays avec une résolution de 200 m sont utilisés pour tous les grands groupes d'émetteurs (trafic routier, trafic offroad, industrie, ménages, agriculture et sylvieculture).

La modélisation des émissions et de leur diffusion est effectuée pour la somme des oxydes d'azote ($NO_x$). Les concentrations de $NO_2$ sont ensuite calculées grâce à une fonction de conversion empirique. La modélisation de la diffusion se fait en appliquant des fonctions de transfert. Ces fonctions sont calculées avec un modèle gaussien se basant sur des données météorologiques relevées toutes les heures pendant l'année 1998. L'utilisation de plusieurs fonctions de transfert a permis de tenir compte des différentes propriétés des groupes d'émetteurs (niveau des émissions, séries temporelles d'ampleur des émissions, etc.) et des conditions de diffusion (dans les vallées alpines, p. ex., les fonctions de transfert sont orientées selon la direction principale du vent).

Des cartes des immissions de $NO_2$ pour toute la Suisse, avec une résolution de 400 m, sont présentées; certaines zones représentatives sont en outre cartographiées avec une résolution de 200 m. Durant l'année 2000, les immissions moyennes de $NO_2$ ont dépassé la valeur limite fixée à 30 $\mu g/m^3$ sur 0,8% de la surface totale de la Suisse (344 $km^2$). Sur cette surface vivent 16% de la population suisse (1,16 million de personnes). Pour 2010, ces valeurs se réduisent à 0,23% de la surface (96 $km^2$) et à 5,3% de la population (0,39 million de personnes); en 2020, elles devraient être de 0,1% de la surface (33 $km^2$) et de 1,3% de la population (0,1 million de personnes).

La même approche a permis de calculer les immissions de benzène en Suisse pour 2000 et 2010 et de les cartographier à une résolution de 400 m. Quatre villes sont également présentées avec une résolution plus fine (200 m).

**Mots-clés**: dioxyde d'azote, benzène, qualité de l'air, calcul de la diffusion, scénarios

# Modellazione delle immissioni di NO2 e di benzene in Svizzera per il periodo 2000-2020

Il presente rapporto illustra sia il metodo di modellazione delle immissioni di $NO_2$ su scala nazionale che le cartine relative al carico di $NO_2$ per il periodo 2000-2020, suddiviso in fasi quinquennali. Si è tenuto conto dei futuri sviluppi, ad esempio in seguito all'entrata in vigore della direttiva EURO 4 per veicoli a motori o all'introduzione della tassa sul traffico pesante commisurata alle prestazioni. Per tutte le principali fonti di emissioni (traffico stradale, traffico offroad, industria, economie domestiche, ecc.) sono utilizzati catasti delle emissioni con una risoluzione spaziale di 200 metri.

La modellazione delle emissioni e della loro diffusione si basa sulla somma degli ossidi di azoto ($NO_x$). Ciò permette di calcolare le concentrazioni di $NO_2$ mediante una funzione di conversione empirica. La modellazione della diffusione avviene applicando le funzioni di transfer. Tali funzioni sono state calcolate con un modello gaussiano, che poggia sui dati meteorologici del 1998 rilevati su base oraria. L'applicazione di differenti funzioni di transfer ha permesso di riprodurre le diverse caratteristiche delle fonti di emissione (livello delle emissioni, serie temporale della portata delle emissioni) e le condizioni di diffusione (ad es. nelle valli alpine le funzioni di transfer sono orientate in base alla direzione principale del vento).

Delle cartine relative alle immissioni di $NO_2$ su scala nazionale sono stati rappresentati con una risoluzione di 400 m. Alcuni estratti sono inoltre stati rappresentati con una risoluzione di 200 m. I risultati del modello relativo al 2000 sono paragonati con i dati delle misurazioni e la corrispondenza riscontrata è buona. Nel 2000 le immissioni medie di $NO_2$ hanno superato il valore limite di 30 $\mu g/m^3$ sullo 0,8% (344 $km^2$) della superficie totale della Svizzera. In quest'area vive il 16% della popolazione svizzera (1,16 milioni di persone). Nel 2010, tali valori si ridurranno allo 0,23% (96 $km^2$) della superficie e al 5,3% della popolazione (0,39 milioni di persone). Nel 2020 i valori si ridurranno allo 0,1% (33 $km^2$) della superficie e all'1,3% della popolazione (0,1 milioni di persone).

Lo stesso metodo è utilizzato per calcolare le immissioni di benzene in Svizzera per il 2000 e il 2010, le quali sono state cartografate con una risoluzione di 400 m. Inoltre, sono raffigurate quattro città con una risoluzione maggiore (200 m).

**Parole chiave**: biossido di azoto, qualità dell'aria, calcolo della diffusione, scenari.

# Preface

In the past decade, $NO_x$-emissions and ambient concentration levels of $NO_2$ decreased in Switzerland, but the ambient air quality standards for $NO_2$ are still exceeded in densely populated areas and along major highways. In a first report published in 1997, the $NO_2$-concentrations in Switzerland as well as a first guess of the possible future development were illustrated. Meanwhile new vehicle emission standards and the Overland Transport Agreement with the EU came into force or will be introduced in future years according to a fixed time schedule.

As a result of these new emission standards, the $NO_x$ emissions will decrease in the next years. The expected development is documented in the annex of the report "Luftschadstoff-Emissionen des Strassenverkehrs 1950–2020" (SRU 355, SAEFL 2004b). Based on the $NO_x$-emissions of road traffic and of all other sources, the $NO_2$ concentration levels can be calculated using air pollution dispersion models.

The results show a future decrease in $NO_2$-concentrations as well as in population exposure. In the year 2000, 16 % of Swiss population lived in areas with a mean $NO_2$ level above the air quality standard (30 $\mu g/m^3$). For 2010, the corresponding number will be 5.3% and for 2020 1.3%, respectively. In 2020, areas with $NO_2$ levels above the limit value are mainly found around the airports.

The report shows that in future a significant improvement of the air quality with respect to the $NO_2$ load can be expected, but it is also shown that it is still a long way to go. Considerable efforts are still necessary to fasten the process of improvement and to guarantee that the air quality standards for $NO_2$ are met for the whole Swiss population. Furthermore, $NO_x$-emissions must be reduced to lower the acidification and eutrophication of ecosystems. $NO_2$ is one of the most important precursors of tropospheric ozone, and ozone concentrations regularly exceed air quality standards.

Swiss Agency for the Environment,
Forests and Landscape

*Gerhard Leutert*
*Head of the Air Pollution Control*
*and non-ionising Radiation Division*

# 1. Introduction

## 1.1. $NO_2$ air quality standards in Switzerland

The Swiss Ordinance on Air Pollution Control (OAPC) of 16 December 1985, which became effective on 1 March 1986, prescribes that the level and evolution of air pollution have to be monitored. To this end, surveys, measurements and dispersion calculations have to be carried out. The Swiss Agency for the Environment, Forests and Landscape (SAEFL) recommends suitable methods.

OAPC also defines the air quality standards (limit values) of Switzerland. The permitted yearly average for $NO_2$ is 30 $\mu g/m^3$; the short-term standard of 80 $\mu g$ $NO_2/m^3$ may be exceeded only once per year based on a 24-hour average, and the value of 100 $\mu g$ $NO_2/m^3$ must not be exceeded during 95% of all 30-minute averages over the whole year. However, $NO_2$ concentrations in Switzerland frequently exceed these limit values.

## 1.2. Current $NO_2$ air quality

The mean concentrations of $NO_2$ in Switzerland exhibited a clear decrease in the first half of the 1990ies, due to various air pollution control measures initiated by the Federal government, authorities of the Cantons and local communities. In the second half of the 1990ies, however, $NO_2$ concentration levels continued to decrease only modestly (SAEFL 2000a). Between 1991 and 2003, the average $NO_x$ concentration at seven air pollution monitoring stations of the national NABEL network located in urban areas or near major roads decreased by 35%, but the average $NO_2$ concentration decreased by 20% only. $NO_2$ concentrations in the urban agglomerations and along major highways, at present still exceed the Swiss air quality standards. At rural sites, $NO_2$ concentrations are in general lower than the air quality standards, but in the vicinity of major highways, the concentration often exceeds the limit values even in rural areas.

The main problem regarding $NO_2$ still is the mean concentration level, which is generally too high (SAEFL 2000a). In some areas, it is almost twice as high as the annual mean air quality standard value of 30 $\mu g/m^3$. Exceedances of the short-term standard (80 $\mu g/m^3$) and of the 95% percentile (100 $\mu g/m^3$) also occur, but would probably vanish if the annual average concentration complied with the 30 $\mu g/m^3$ standard. According to the Law on the Protection of the Environment (LPE) and the OAPC, therefore, the authorities must initiate further reduction strategies in order to lower the $NO_x$ emissions. In the near future, the introduction of new legislation on motor vehicle emission levels (EURO-3 and EURO-4 limit values), the new mileage-related heavy vehicle tax (MRHVT), and further measures in the industrial, domestic and off-road sector will lead to a further reduction of $NO_x$ emissions. The present report accounts for these future developments in the forecasts of the $NO_2$ concentration up to the year 2020. However, still further reduction measures will be necessary in order to fully comply with the OAPC air quality standards.

## 1.3. Previous modelling studies

$NO_2$ concentration levels for Switzerland for 1990 to 2010 resulting from dispersion modelling were first published in SAEFL (1997). The same modelling approach was also applied in several cantons (AWEL 1996, AfU LU 1998, LHA BS/BL 1998, AfU GR 1999, AfU SO 2000, AUS AG 2001, OSTLUFT, 2003). The results presented in SAEFL (1997) were based on the road transport activity scenarios of GVF (1995). The road traffic emissions were based on SAEFL (2000b), for non-road traffic emissions as well as emissions from stationary sources the results from SAEFL (1995) were used.

## 1.4. Recent developments

Since the publication of SAEFL (1997), several new developments have taken place:

- Introduction of legislation to further reduce the emissions from motor vehicles: EURO-3 (in force since 2001) and EURO-4 (in force in 2006) as well as the so-called 2nd phase of EURO-4 (from 2008 on). The new version 2.1 of the Handbook on Emission Factors for Road Transport (SAEFL 2004a) accounts for this new legislation.

- The bilateral treaty on road transport between Switzerland and the European Community (EC), (i) the so-called Overland Transport Agreement (OTA), includes the increase of maximum allowable lorry weights from 28 tons (until 2000) to 34 tons (as from 2001) and finally to 40 tons (2006), and (ii) the introduction of the mileage-related heavy vehicle tax (MRHVT) for all heavy duty vehicles. Both OTA and MRHVT are in force since January 2001. The traffic activities have been revised accordingly, up to the year 2015 (GS UVEK 1999). Based on these new traffic activities, the estimates on emissions from road transport in Switzerland have been updated as well (SAEFL 2004b).

These new developments have major impacts on the emissions from road transport, also for the period after the year 2010. Therefore, it has become essential to renew the dispersion modelling of SAEFL (1997), taking into account the new emission factors and traffic activities, and to extend the forecasts up to the year 2020.

## 1.5. Model enhancements

For the present study, the fundamentals of the modelling approach are based on SAEFL (1997). The dispersion modelling was enhanced as follows:

- Instead of one set of transfer functions (which represent the impact of a source of unit emission strength to the neighbouring areas) for the whole of Switzerland, the country is divided into three regions with distinct micro-climatological characteristics (alpine region, Central Plateau region, and the remaining part of Switzerland).
- The dispersion model used to calculate the transfer functions complies with the TA-Luft directive (BMJ 1987).
- The new transfer functions are derived from the average of three (alpine region) to five (Plateau region) different transfer functions, each computed using data from a meteorological surface station for a full year in hourly resolution.
- In the alpine region, covering the valley basin of all major alpine valleys in Switzerland, the main valley orientation has manually been derived for all valley segments separately. For each alpine grid cell, the corresponding alpine transfer function is rotated such that it corresponds to the main valley orientation.
- The emission strengths of the emission inventories vary with the season and the hour of the day (stationary sources) or with the hour of the day (traffic sources).
- The parameterization of the $NO_x$ (anthropogenic and biogenic) background concentration has been updated.
- All maps are depicted with a grid cell resolution of 400 m mesh size, instead of 1 km.
- The benzene concentration in Switzerland has been simulated for the years 2000 and 2010 using a model approach in close analogy to the $NO_2$ model.

# 2. Modelling approach

## 2.1. Model concept

The concept basically remains the same as in the SAEFL (1997) study:

- The primary pollutant is $NO_x$ (expressed in $NO_2$ equivalents), being the sum of NO and $NO_2$. $NO_2$ is assumed an inert trace gas.
- All emissions and all dispersion computations take place on a rectangular grid with 200 m mesh size. For road traffic emissions, emissions are computed for all major roads individually, and then projected onto the grid. For all other source categories, first the total emission load is estimated, which then is spatially dis-aggregated by distributing it equally to all grid cells of a certain type (for example, land use category).
- A set of transfer functions (a transfer function represents the impact of a source of unit emission strength to the neighbouring areas) is then used to simulate the dispersion of the emitted pollutants. Each emission inventory is dispersed separately. Different transfer functions for different source characteristics (rural and urban, ground-level and elevated sources, etc.) are used.
- The transformation of the $NO_x$ concentration towards $NO_2$ is performed with an empirical conversion function.
- Area statistics and the population exposure are determined using the annually averaged concentration at the centre of each grid cell. For the population exposure, the residence of the population (population density) is used.

As mentioned in Section 1.5, the dispersion model has been improved in several important parts. These model enhancements are described in further detail in the following sections:

- Three regions with different micro-climatological characteristics are distinguished (Section 2.2.2);
- The new transfer functions are the average of three (alpine region) to five (Central Plateau region) different transfer functions, each computed using data from a meteorological surface station for a full year in hourly resolution (Section 2.2.3);
- A Gaussian plume dispersion model is applied using hourly meteorological data and TA-Luft (BMJ 1987) stability classes (Section 2.2.4);
- The parameterization of the $NO_x$ (anthropogenic and biogenic) background concentration has been updated (Section 2.3).

## 2.2. Dispersion model

### 2.2.1. General approach

When modelling pollutant concentrations for entire countries (Switzerland's land surface area is approx. 41'000 km$^2$), commonly applied dispersion models have to be used. A good example is the empirical dispersion model which has, among other applications, been applied for the present and future situation of the $NO_2$ and $NO_x$ concentrations (SAEFL 1997, Heldstab and Künzle 1997). Such dispersion models assume homogeneous and stationary conditions, and often take into account only one generic climatology, as the main goal is the prediction of the annual mean concentration. This approach worked well in Switzerland for the prediction of annually averaged $NO_x$ concentration throughout the country (SAEFL 1997), but $NO_x$ concentrations from highway emissions in alpine valleys were clearly underestimated.

The dispersion modelling approach adopted in the present study aims at improving the dispersion modelling in alpine valleys. Several major European transit highways cross the Swiss Alps in the north to south direction, and cause high $NO_x$ concentration levels in these ecologically sensitive areas. Therefore, a method has been developed to model the dispersion of pollutants emitted in the basin of Alpine valleys. Frequency distributions of wind speed and direction, mixing height, and stability class (according to the TA-Luft classification, see BMJ 1987 for further details) are analysed for meteorological stations located in Alpine valley basins, and compared to data from sites on the Swiss Plateau.

Emissions with distinct source characteristics are grouped into different inventories, i.e. urban and extra-urban emissions, and different source heights. For example, urban and extra-urban traffic sources, residential heating sources, and different industrial stack heights are distinguished. The transfer functions are derived from a simple Gaussian plume dispersion model and reflect the annually averaged ground concentration impact of a point source with specific source characteristics onto each of the grid cells in the neighbouring area.

### 2.2.2. Climatologies

65% of the land surface of Switzerland is Alps. The main residential and commercial areas are located in the densely populated so-called Swiss Plateau, between the Jura and the Alpine mountain ridges. Compared to the Alps, the Swiss Plateau might be regarded as being rather „flat“, although it cannot be compared to really flat terrain like the central U.S. However, major transit highways in Alpine valleys cause significant local impacts. As mentioned above, the dispersion matrices used in SAEFL (1997) resulted in an underestimation of concentration levels. In order to improve the concentration calculation in alpine valleys, a set of dispersion matrices representing local climatology in alpine valleys is used.

The total surface of Switzerland is divided into three different regions as shown in Figure 17 (Appendix A3). The Swiss Plateau (Mittelland) is situated between the two Swiss mountain ridges. In the alpine region, covering the valley floors of all major alpine valleys in Switzerland, the main valley orientation has manually been derived for all valley segments separately (color-coded in Figure 17, Appendix A3). For each alpine grid cell, the corresponding alpine transfer function is rotated such that it corresponds to the main valley orientation (i.e., the direction of water flow). The remaining part of Switzerland (i.e., neither Central Plateau nor the floor of a major alpine valley) is treated as a separate climatological region as well, where transfer functions based on isotropic (rotationally symmetric) wind directions are used (details see Section 2.2.4).

### 2.2.3. Meteorological surface station data

The transfer functions are computed using hourly meteorological data of eight surface stations for the year 1998. The five stations representing the Swiss Plateau cover its entire range: Geneva (GVE), Payerne (PAY), Wynigen (WYN), Kloten (KLO), Güttingen (GUT). The three Alpine stations used are situated in those valleys where the major transit routes are: Sion (SIO), Magadino (MAG), Chur (CHU). All stations are operated by MeteoSwiss (the Swiss national meteorological service) on a regular basis. A wide range of parameters can be obtained with an hourly resolution. For this study, wind speed and direction have been used. Additionally, MeteoSwiss kindly provided the TA-Luft stability class and the mixing height based on hourly meteorological data.

Figure 1 displays the distribution of wind directions for each of the meteorological stations. The wind channelling in the Central Plateau is clearly visible. For the Alpine sites, the wind direction is dominated by the local valley orientation. They therefore have been rotated such that they fit on top of each other, corresponding to a valley where water runs from south to north.

Figure 2 shows the distribution of wind speeds. The amount of low wind conditions is roughly the same for Alpine and Swiss Plateau sites. The Alpine sites do experience a somewhat higher amount of high wind episodes caused by Föhn conditions. But the average wind speed of the 5 Plateau and the 3 Alpine sites is very similar.

The distribution of the TA-Luft stability classes, depicted in Figure 3, is very similar as well, a result not expected a priori. As one would expect, very stable conditions are often observed in Alpine regions. However, they are also frequent in Plateau sites. Very unstable conditions are rarely observed in Switzerland at all. This result is mainly due to the model used to predict the mixing heights, which has been developed for applications in the Central Plateau, and is not well suited for Alpine sites.

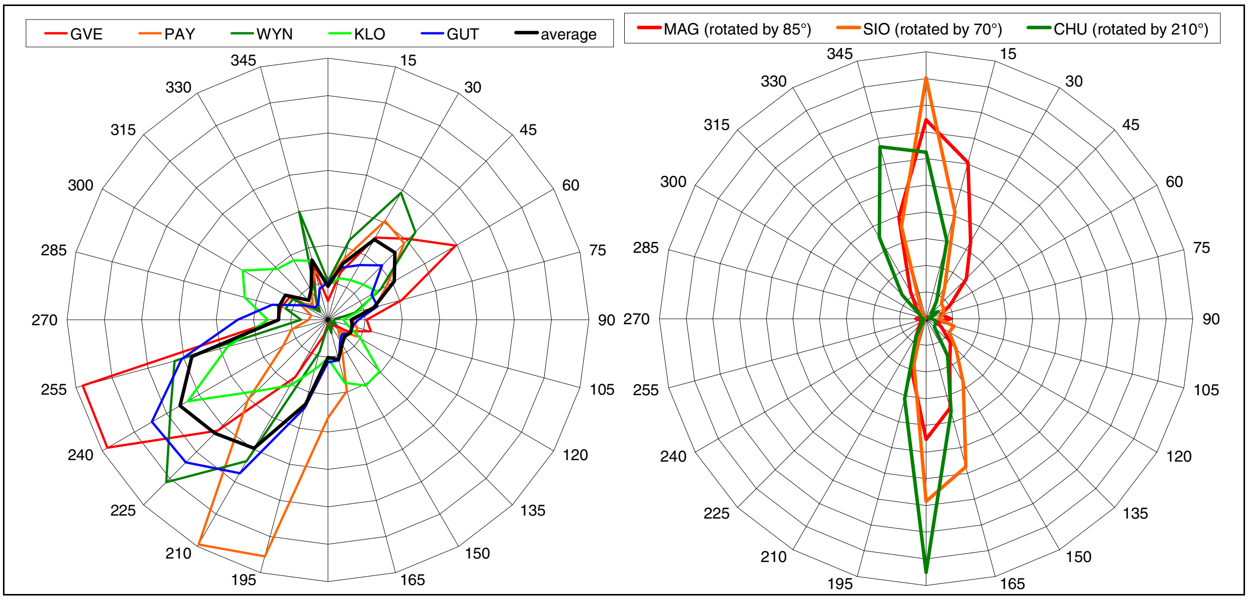


*Figure 1:* *Distribution of wind direction (10-min. average, one measurement per hour) at five Swiss Plateau sites (left) and three Alpine sites (right). Data for 1998, 8760 hours. The wind direction of the Alpine sites has been rotated to a north-south valley orientation.*

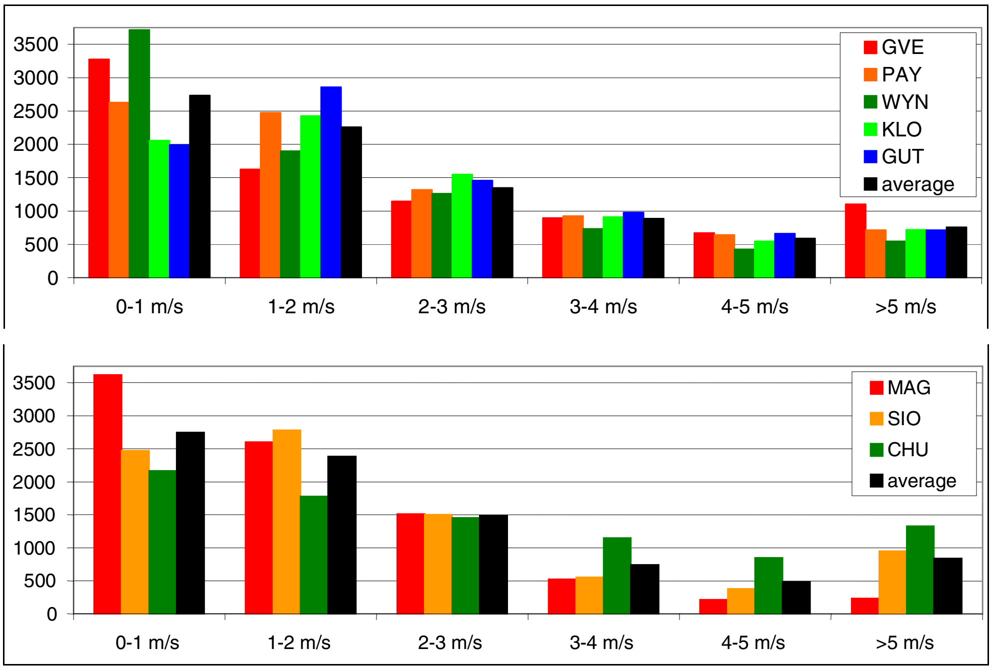


*Figure 2:* *Distribution of hourly wind speed (hourly average) at five Swiss Plateau sites (top) and three Alpine sites (bottom). Data for 1998, 8760 hours.*

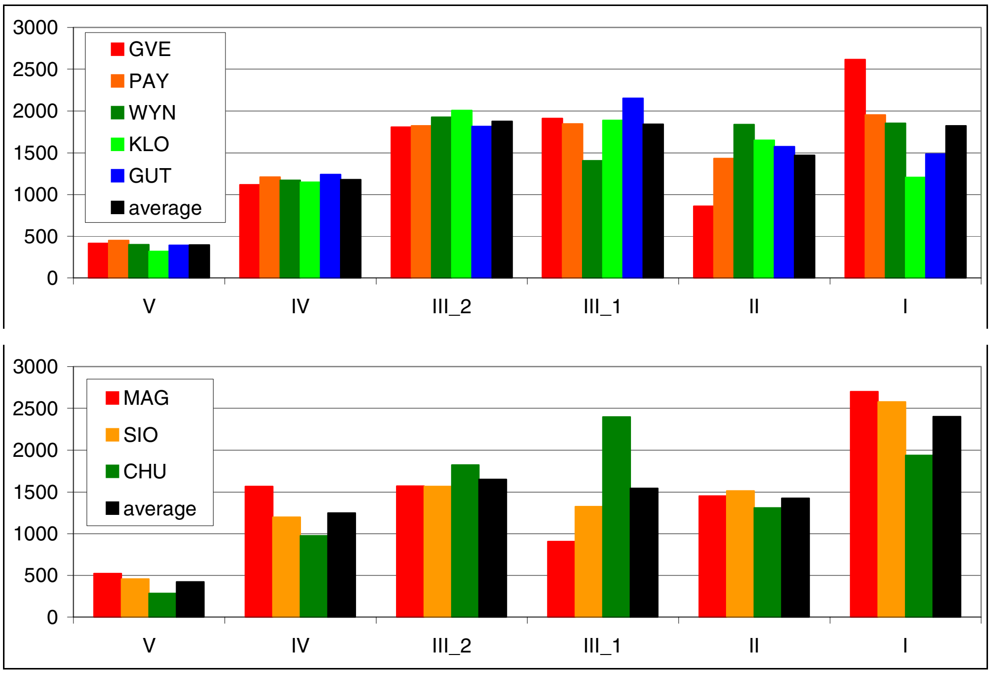


*Figure 3:* *Distribution of TA-Luft stability classes at five Swiss Plateau sites (top) and three Alpine sites (bottom). Data for 1998, 8760 hours. V = very unstable; IV = unstable; III_2 = neutral/unstable; III_1 = neutral/stable; II = stable; I = very stable.*

### 2.2.4. Calculation of transfer functions

A Gaussian plume model is used to produce transfer functions, which give the annually averaged concentration impact per grid cell for a source of unit strength located in the centre of the grid. The averaging process is carried out over 8760 hourly input values. Transfer functions are computed for different source configurations and different local climatology. They actually represent dispersion patterns for the main source types and the most representative Swiss climatologies. They are then used to disperse the inventories of $NO_x$ emissions for the whole of Switzerland.

The Gaussian plume dispersion model applies the stability class definitions from the German regulatory model TA-Luft (BMJ 1987).

In the model used in this study, a total of six mirror sources is placed beneath the ground and above of the mixing height to include the effect of inversion height and to preserve mass conservation. No removal effects (dry and wet deposition, conversion to particulate phase) have been accounted for. To compute the transfer functions, the dispersion model is run for a whole year in hourly resolution; for the Swiss Plateau functions, the average over 5 meteorological stations is used; for the Alpine functions, data from 3 stations are available.

The transfer functions for the remainder part of Switzerland (i.e., neither alpine region nor Swiss Plateau region) are computed using the Swiss Plateau meteorological data, but instead of the observed wind direction, arbitrary wind directions from a random number generator have been used. As a result, the transfer function for this remaining part of Switzerland is fully rotationally symmetrical with respect to the centre of the transfer function (i.e., the source location); it does not anymore show any influence of any predominant wind direction. These transfer functions are therefore used as "neutral" estimate for all those regions where the predominant wind direction is neither similar to the Swiss Plateau conditions, nor is ruled by the complex terrain (valley floors of the Alps). Examples of Swiss regions where these "neutral" transfer functions are used are the Basle region (upper Rhine valley), and all mountainous areas which are not in the basin of a valley. It should be noted, however, that in the Alps, almost all emissions occur on the valley floors, and not on the mountain tops.

Different sampling grids for point, line and area sources ensure a correct estimation of the cell-averaged concentration impact even for grid cells in the vicinity of the source location. To illustrate the resulting transfer functions, Figure 4 shows a transfer function for Plateau (left panel) and Alpine “generic” meteorology (right panel), but with otherwise identical source characteristics. The transfer functions correspond to a source emitting 1 ton per year of $NO_x$. Time series are used to reflect the daily and seasonal cycle of the emission strength (see Section 2.3 for further details).

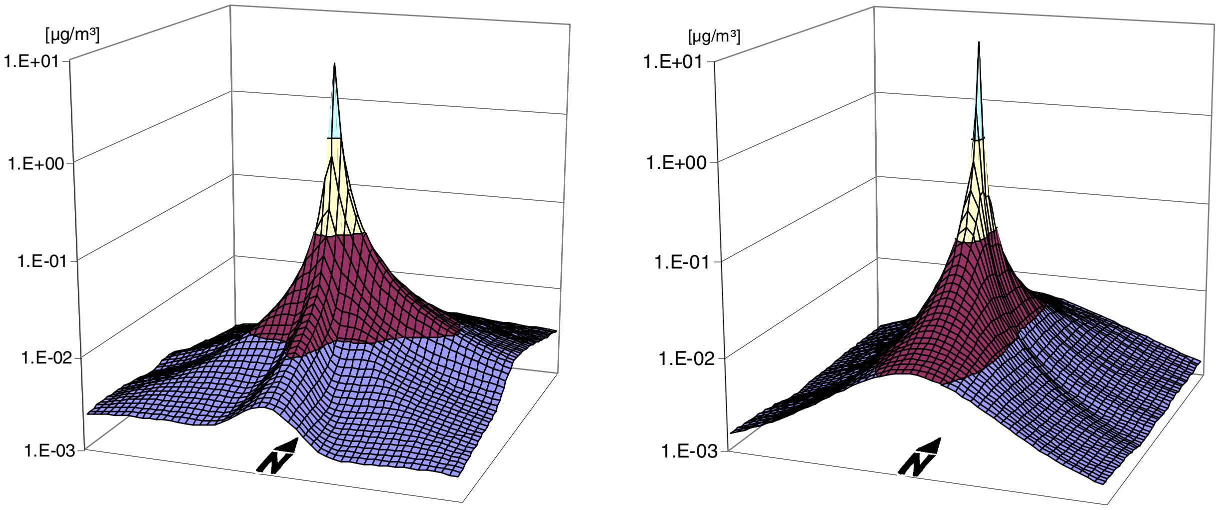


*Figure 4: Dispersion matrix with Plateau (left) and Alpine (right) "generic" meteorology for a source located in the centre, 2-20 m above ground (emission: 1 t/a of $NO_x$). Horizontal axes extend over a square of 10 km by 10 km, each cell is 200 m x 200 m. Vertical axis in µg/m³.*

## 2.2.5. Rural and urban transfer functions

The air pollution level in agglomerations often is dominated by a countless number of small, not well determined emission sources. In Switzerland, roughly one half of $NO_x$ emissions is released inside urban surroundings. The transfer functions used for these urban grid cells should therefore reflect urban dispersion characteristics. In built-up areas, the irregularly spaced tall roughness elements such as buildings induce a so-called roughness sub-layer, which ranges from ground-level to several times the average building height, and where the flow and turbulence fields differ from rural areas. In addition, the energy balance over urban areas is very distinct from the rural surroundings (lower water storage capacity, higher heat storage capacity due to the buildings, anthropogenic heat flux, etc.).

In a first step, all transfer functions have been computed with rural settings (i.e., traditional TA-Luft dispersion coefficients representative for rural dispersion conditions). In a second step, an over-all rural-to-urban correction factor was applied to all cells of the rural transfer functions in order to derive urban transfer functions (de Haan *et al.*, 2001). In the present study, the correction factor described in OSTLUFT (2003) was applied, which is an optimized factor derived from the procedure described in de Haan *et al.* (2001). On average, the sum of all "urban" model enhancements leads to an increase of 20% compared to the rural transfer function (ground-level sources).

## 2.3. Time series of emission strength

The transfer functions used to disperse the emission loads are computed by the dispersion model described in Section 2.2. They are based on the impact of a source with an emission strength of 1 ton per year and computed for a whole year on an hourly basis. Therefore time series are needed for each source category described in this section, such that an hourly emission behaviour can be associated with the annual emission load.

Two different time series of emission strength are used: for elevated sources, the time series depends on the season and the hour of the day; for ground-level sources, they depend on the hour of the day.

The time series for elevated sources (used for emissions from industrial and commercial activities, households, and air traffic) is the weighted average of three different time series: first, a time series representing the average "human activity"; second, a time series for emissions from residential heating; third, a constant time series for those emissions that do not vary during the day (depicted in Figure 5).

It has been assumed that electrical power consumption is well suited to represent "human activity". Because not all consumption of electrical power is related to direct human action, 30.1% of all power consumption is assumed to be constant throughout the year (as a result, the "human activity" shows more pronounced fluctuations than the underlying time series of electrical power consumption). For the winter season (defined as December, January, February), the hourly averaged electrical power consumption of 16 December 1998 is used (BFE 1999). For spring, summer and autumn, the consumption on 18 March, 17 June and 16 September, respectively, is used (BFE 1999). The seasonal dependence of the residential heating emissions is equal to the number of "heating degree days" (German: Heizgradtage) (average for Basle, Berne, Lucerne, St. Gall and Zurich). For the hourly behaviour of heating emissions, a manual estimate has been used.

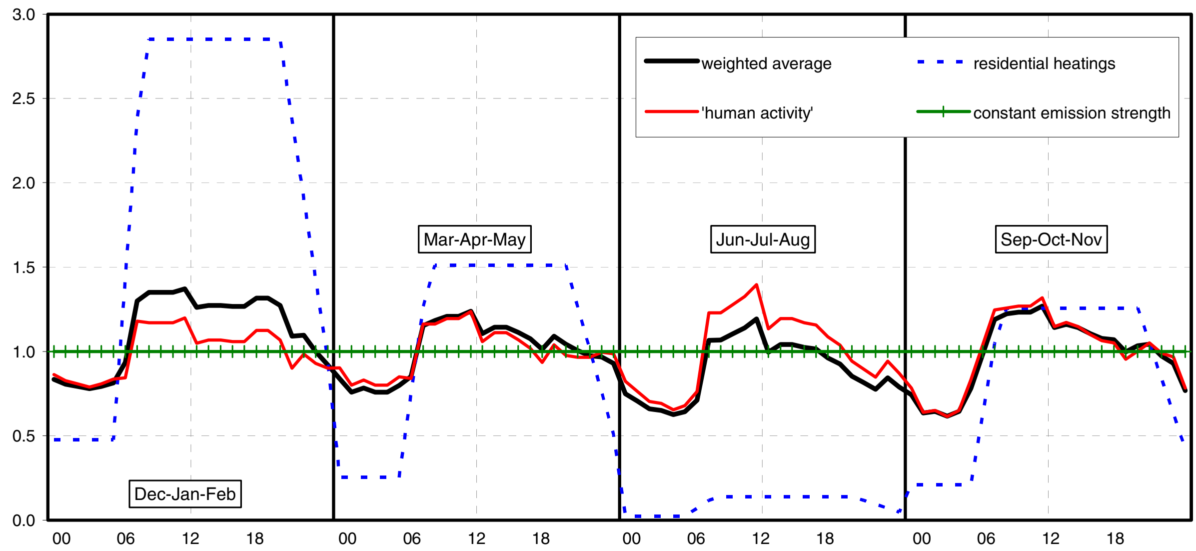


*Figure 5:* *Time series of emissions strength for elevated sources. Average of daily pattern over the four seasons is set to unity for all time series.*

The time series for ground-level sources (i.e., road, rail, water traffic, agriculture, forestry) is the weighted sum of time series for road traffic, rail traffic and agriculture plus forestry, as shown in Figure 6. Road traffic emissions are strictly proportional to the Swiss DTV (average hourly sum of passenger cars, light and heavy duty vehicles), i.e. the fact that lorries have $NO_x$ emission factors much higher than those of passenger cars is ignored. The rail traffic time series is proportional to the hourly total of train kilometres (passenger trains, cargo trains, and service trains). The time series for agriculture and forestry is equal to the hourly "human activity" (see above), where the average over the four seasons has been used.

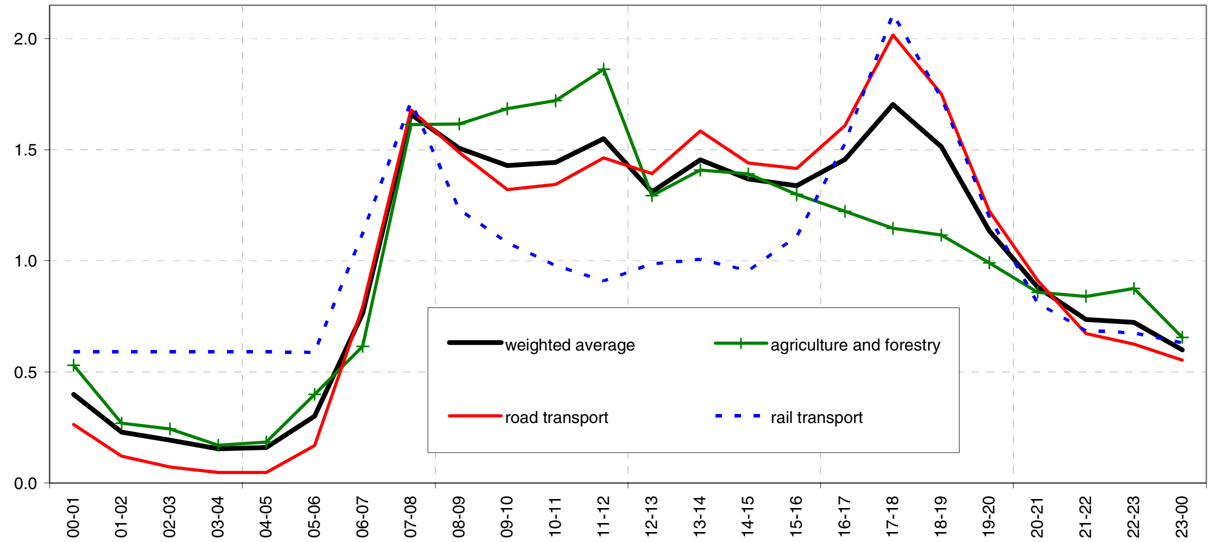


*Figure 6: Time series of emissions strength for ground-level sources. Average over 24 hours is set to unity for all time series.*

## 2.4. $NO_x$ concentration at airports

Information on the $NO_x$ concentration at two major commercial airports of Switzerland, namely Zurich Airport and Geneva International Airports, was kindly provided by the respective airport authorities (Table 1). Their models included emissions from the landing and take-off cycle (LTO) as well as non-LTO emissions (e.g., emissions from infrastructure or road traffic within airport zone). More details on the concentration modelling can be found in AIG (2000) and in Unique (2003).

| $NO_x$ emission [t/a] | 2000 | 2010 | 2020 |
|---|---|---|---|
| Geneva International Airport | 377 | 350 | 430 |
| Zurich Airport | 1803 | 1830 | 1830 |
| Total | 2180 | 2180 | 2260 |

*Table 1: $NO_x$ emission of two major airports of Switzerland for 2000, 2010 and 2020.*

Only Zurich Airport and Geneva International Airport are taken into account. Basle Airport is actually located in France. The regional airports Berne-Belp, Birrfeld, Ecuvillens, Grenchen, La Chaux-de-Fonds Les Eplatures, Lugano-Agno, Samedan, Sion, St.Gallen-Altenrhein are neglected.

Based on the emissions given in the table above, the $NO_x$ concentrations were modelled on different spatial resolutions. The resulting grids (200 m grid-size resolution in the case of

Zurich Airport and 1'000m grid-size resolution in the case of Geneva International Airport) were implemented in the SAEFL model. Note that the transformation from $NO_x$ to $NO_2$ in SAEFL model is different from the respective procedures in the two airport models. These differences might lead to discrepancies if compared to the results in AIG (2001) and Unique (2003).

## 2.5. Background concentration

The transfer functions cover a squared area of 100 km², where the source is situated in the center of the square. Any impact of the source outside of this square is ignored. Instead, these impacts in the far field are accounted for using a background concentration. This background covers the $NO_x$ concentration levels originating from four different "source" categories:

1. The natural (i.e., non-anthropogenic) background concentration;
2. The regional anthropogenic background, defined as the cumulative effect of all emission sources outside of Switzerland;
3. The far field impact of emission sources situated within Switzerland;
4. The total (near field and far field) impact of any $NO_x$ source not covered by the emission inventories (since the emission inventories used are very detailed, this contribution is assumed to be almost negligible, except where mentioned in the text: very tall stacks, Section 3.3.2; missing rail emissions, Section 3.2.1).

For this total $NO_x$ background concentration, $C_{background,NO_x}$, a parameterization of similar form as in SAEFL (1997) is used

$$C_{background,NO_x}\left(h, E_{rel,CH,NO_x}(t)\right) = \left[C_{regional,NO_x} + K_{NO_x} * \exp\left(E_{rel,CH,NO_x}(t)/\gamma\right)\right] * \exp\left(-\frac{h}{h_0}\right) \quad (1)$$

Here, $C_{regional,NO_x}$ denotes the sum of the natural and the regional anthropogenic background concentration. $K_{NO_x}$ and $\gamma$ are constants, determined for the reference year $t_0 = 2000$ and the reference altitude $h_0 = 700\ \mathrm{m}$. $E_{CH,NO_x}$ denotes the sum of all $NO_x$ emissions in Switzerland for a given year and $E_{rel,CH,NO_x} = E_{CH,NO_x}(t)/E_{CH,NO_x}(t_0)$. The values adopted for $C_{regional,NO_x}$ are listed in Table 2, those for $E_{CH,NO_x}$ in Section 3.4 (Table 9).

| | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| $C_{regional,NOx}$ [µg/m³] | 3.1 | 2.7 | 2.3 | 2 | 1.7 |

*Table 2: Assumed sum of the natural and the regional anthropogenic background concentration.*

The closest correspondence of Eq. (1) to measured annually averaged concentration levels at six background stations (NABEL sites Payerne, Tänikon, Lägeren, Rigi, Chaumont, Davos) for 2000 is reached for $K = 11.3\,\mu g/m^3$. The exponential factor $\exp\left(E_{rel,CH,NO_x}(t)/\gamma\right)$ with $\gamma = 1.27$ has been introduced to reflect the assumption that there is a non-linear relationship between the decrease of the total Swiss $NO_x$ emission load (as represented in the emission inventories) on the one hand, and, on the other hand, the background $NO_x$ concentration resulting from both the far field impact of the emission inventories and the total effect of those sources which are missing in the emission inventories (see Figure 7).

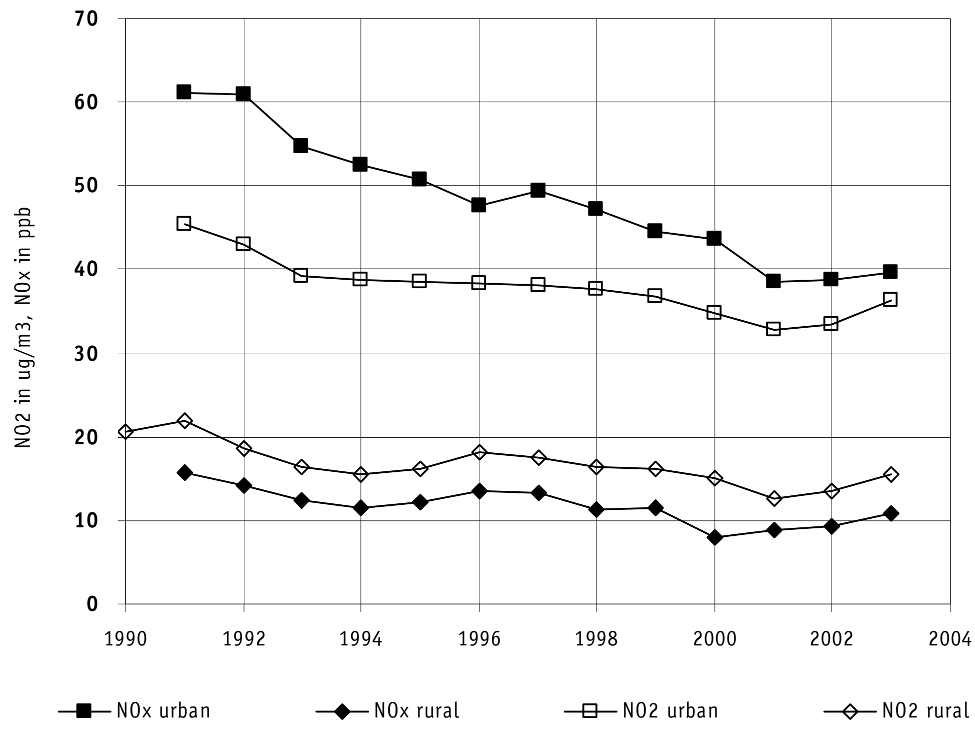


*Figure 7: Averaged $NO_2$ and $NO_x$ concentrations as measured at urban (7 stations) and rural (3 stations) NABEL sites.*

In Eq. (1), the total background concentration is a function of altitude since the population density decreases with increasing height above sea level.

## 2.6. Conversion of $NO_x$ to $NO_2$

Determining the total amount of $NO_2$ at a receptor is challenging since $NO_x$ is emitted mostly as NO. The oxidation to $NO_2$ is controlled by the rate of plume mixing and by gas kinetics. Ozone ($O_3$) is usually responsible for most of this oxidation, but other reactive atmospheric gases can also oxidize NO. This chemical conversion of stack and tail pipe NO emissions to $NO_2$ takes place over distances of some hundred meters. Therefore, in this study, $NO_x$ rather than $NO_2$ is modelled, which is a more robust quantity. For the emission inventory, the $NO_x$ emissions (expressed in $NO_2$ weight equivalents) consist of the sum of the two components NO and $NO_2$. For measurements from the air pollution monitoring stations, again the sum of NO and $NO_2$ is used for $NO_x$. The assumption that $NO_x$ can be assumed as an inert tracer holds to a high degree.

From the total $NO_x$ concentration, the $NO_2$ concentration is then estimated using a so-called first-level technique (Hanrahan 1999)

$$[NO_2] = \frac{A * [NO_x]}{B + [NO_x]} \tag{2}$$

where $[NO_2]$ and $[NO_x]$ denote the concentration of $NO_2$ and $NO_x$, in µg/m$^3$. The values of the constants are $A$ = 75 µg/m$^3$ and $B$ = 79 µg/m$^3$. In Figure 8, results from Eq. (2) are compared with simultaneously measured $NO_x$ and $NO_2$ concentration values (annual averages).

As can been seen in Figure 8, the approach likely over-predicts the $NO_2$ concentration for very high $NO_x$ concentration levels, if these levels originate from major roads in the countryside (station Härkingen). At these stations, the oxidation has not yet taken place to a sufficient extent. This over-prediction is inherent to first-level techniques as applied in the present study. To avoid this problem, it would be necessary to adopt a higher-level modelling technique (see, for example, Hanrahan 1999). On the other hand, street-canyons with a high degree of accumulation are under-estimated (station Berne). Since the model operates on 200 m resolution, is not able to reproduce effects on smaller scales like e.g. street canyons. For the evaluation of the number of inhabitants living on sites with concentrations exceeding the air quality standard, these over- and under-estimations are not very relevant since they typically happen in situations of high $NO_x$ concentration levels exceeding the $NO_2$ quality standard in any way.

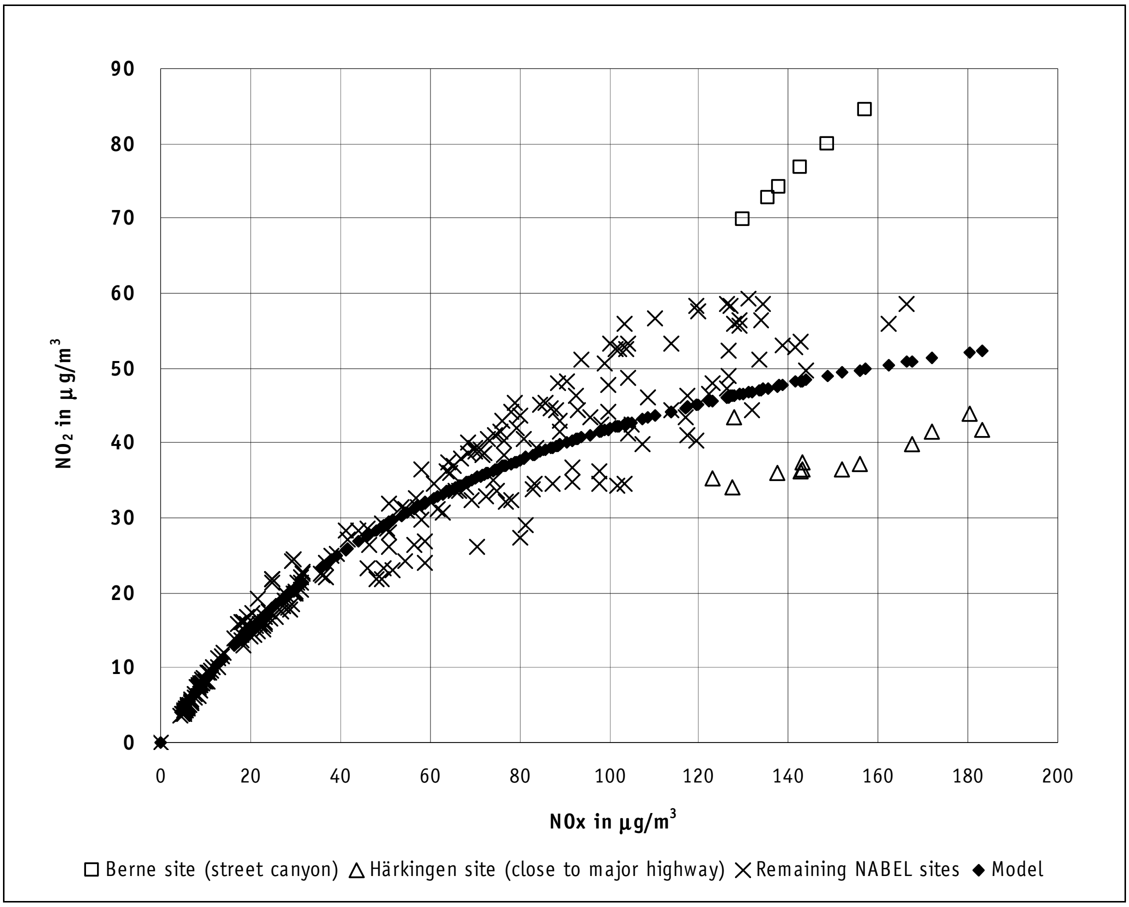


*Figure 8:* *Results from the parameterization of $NO_x$-to-$NO_2$ conversion as in Eq. (2) and simultaneously measured $NO_x$ and $NO_2$ concentration levels (annual averages, 1991 to 2003) from NABEL monitoring stations.*

## 2.7. Model implementation

The dispersion computation consists of the following three steps:

- applying the appropriate transfer function to each cell of each emission inventory separately and summing up the $NO_x$ concentrations of all emissions grids ;
- adding the background $NO_x$ concentration (see Section 2.3);
- computing the total $NO_x$ concentration and the derived $NO_2$ concentration (see Section 2.6).

This approach has been implemented in the software Arc/Info (trade mark of ESRI, Ltd.), a Geographic Information System (GIS). All computations take place on a rectangular grid with 200 m resolution. The accuracy of the available input data does not allow for a higher resolution (due to uncertainties in the land use categorization, and uncertainties in the true location of road links for which only the start and ending points are known). For each of the emission inventories, a transfer function as listed in Table 3 is used.

| Transfer function | Source category |
|---|---|
| Ground-level line sources, rural (Alpine meteorology) | road traffic (if outside of built-up areas) |
| Ground-level area sources, rural (Plateau & "neutral" met.) | road traffic (if outside of built-up areas) |
| | emissions from agriculture and forestry |
| | emissions from rail traffic |
| | emissions from water traffic |
| Ground-level line sources, urban (Alpine meteorology) | road traffic (if in built-up areas) |
| | construction machines |
| | mobile machinery in households (gardening equipment, etc.) |
| Ground-level area sources, urban (Plateau & "neutral" met.) | road traffic (if in built-up areas) |
| Area source at 12m, urban (Alpine, Plateau, "neutral") | Industrial/commercial emissions (emission heights 2m to 20m) |
| | emissions from residential heating + warm water facilities |
| Area source at 25m, urban (Alpine, Plateau, "neutral") | Industrial/commercial emissions (emission heights >20m) |

*Table 3: Link between transfer functions and source category. For each source category in the right-hand column, a separate emission inventory grid is generated. Every emission grid is transformed into a concentration grid using the corresponding transfer function given in the left-hand column. For roads in Alpine valleys, a line source transfer function is assumed, since the main roads are mainly parallel to the valley axis as well as to the most frequent wind directions. For all other emissions, area sources are assumed, since they consist of numerous point sources or the direction of the line source is only by chance parallel to the wind direction.*

# 3. Emissions

## 3.1. Emissions from road transport

### 3.1.1. Road transport modelling in Switzerland

Regarding road transport in Switzerland, several important developments have taken place or have been initiated recently. The bilateral treaty on road transport between Switzerland and the European Community (EC), called Overland Transport Agreement (OTA), includes the increase of maximum allowable lorry weights from 28 tons (until 2000) to 34 tons (as from 2001) and finally to 40 tons (2005), as well as the introduction of the mileage-related heavy vehicle tax (MRHVT) for all heavy duty vehicles. Both OTA and MRHVT became effective in January 2001. These developments only concern heavy-duty vehicles (HDV).

For the needs of the present study, there is not a single road traffic model available which covers both HDV traffic loads and the other vehicle categories on the Swiss road network. Therefore, the relevant data had to be collected from various sources:

- The road network for passenger cars (PC), light-duty (commercial) vehicles (LDV), motor cycles (MC) and buses (both public transport buses and coaches) used is identical to that from SAEFL (1997), including the relative distribution of traffic loads on it.
- For heavy-duty vehicles (HDV), new traffic model results exist which have both an updated road network and a new relative distribution of traffic loads. For the present study, these results have kindly been made available by the Traffic Coordination section of the Federal Office for Spatial Development (FOSD), who in turn used preliminary results from the transfrontier good traffic (for transit and import/export traffic) and the goods transport surveys of 1998 (for estimates on the national traffic) for the years 1998 and 2015.

It proved difficult to merge the traffic which is available for these different road networks. It has therefore been decided to compute the road traffic emissions on the two networks separately. Major differences between the two networks occur in the future; the newer (HDV) network assumes a higher degree of completion of the planned national highway network. As a consequence, on these links only emissions from HDV traffic are available.

The overall sum of the traffic data inputs as described above do not match the overall values as indicated by SAEFL (2004b). Therefore, scaling factors have been applied to all links of both road networks such that the overall traffic activity (vehicle kilometres travelled) and fleet compositions for all relevant years correspond to SAEFL (2004b). The relative distribution of traffic loads on the networks has not been changed. In the case of passenger traffic, a constant correction factor has been applied to the loads on links and zones in order to achieve the overall values. For HDV traffic, the differences between the two sources have been fully attributed to zonal traffic (roughly 11% of national goods traffic is attributed to zonal traffic), whereas the link loads were not altered. For import/export (i.e., international goods transport having either their origin or their destination within Switzerland) transiting goods traffic, it has been assumed that no zonal traffic occurs, and therefore all link loads have been corrected by a constant factor to match the overall values.

For the HDV, the road network and traffic loads only were available for the years 1998 and 2015. For the years 2000 and 2005, a uniform re-scaling factor has been applied to the 1998 data; for 2010 and 2020, the 2015 traffic volume data has been used as the basis of the emission modelling.

### 3.1.2. Emission modelling approach

The emission modelling has been done in exact analogy to SAEFL (2004b), where more details can be found. Since the input data for the concentration modelling have been taken in a provisional state of the emission modelling for SAEFL (2004b), there remains a slight difference between the emissions implemented for the concentration modelling compared to the emission data published in SAEFL (2004b). The differences vary between +0.9% (above SAEFL 2004b) in 2000 to -3.8% in 2020 (below SAEFL 2004b), see Table 5 .The emissions factors are taken from SAEFL (2004a) and take into account the EURO-3 and EURO-4 legislation, as well as the so-called "2nd phase of EURO-4" for HDV from 2008 on, as listed in Table 4. Using scaling factors, it has been assured that the present modelling, which uses detailed road networks, yields exactly the same over-all results (both in vehicle kilometres travelled and in total emissions), as new statistical data based on MRHVT-Data, which only used aggregated traffic statistics.

| Legislation | In force from ... | passenger cars [g/km] diesel | passenger cars [g/km] gasoline | heavy-duty veh. [g/kWh] |
|---|---|---|---|---|
| EURO-2 | type approval: >1 Oct 1996; vehicle registration: >1 Oct 1997 | 0.85* | 0.25* | 7.0 |
| EURO-3 | type approval: >1 Oct 2000; vehicle registration: >1 Oct 2001 | 0.50 | 0.15 | 5.0 |
| EURO-4 | type approval: >1 Oct 2005; vehicle registration: >1 Oct 2006 | 0.25 | 0.08 | 3.5 |
| EURO-4, 2nd phase | 2008 | | | 2.0 |

* approximate limit value, computed from the limit value for the sum of HC and NOx emissions.

*Table 4: $NO_x$-emission factor limits for motor vehicles.*

### 3.1.3. Resulting emissions

The resulting emissions from road transport are listed in Table 5 for 2000 to 2020. These emissions take place on two different road networks, as described in the previous sections.

| Year | Goods transport | Passenger traffic | Total | Difference to |
|---|---|---|---|---|
| | LDV, HDV | PC, MC, buses | implemented | SAEFL (2004b) |
| 2000 | 26'700 | 29'000 | 55'700 | 0.9% |
| 2005 | 20'600 | 22'000 | 42'600 | -0.2% |
| 2010 | 15'700 | 16'600 | 32'300 | -2.1% |
| 2015 | 11'800 | 13'600 | 25'400 | -2.8% |
| 2020 | 9'400 | 12'800 | 22'200 | -3.8% |

*Table 5: $NO_x$ emissions from road transport in Switzerland for 2000 to 2020. Difference to SAEFL (2004b): see text above in 3.1.2*

Emissions from the major road tunnels are removed from the emission inventory (Table 5) by deleting the appropriate amount from the link emission. This procedure is performed for the Gotthard, Seelisberg, Gubrist and Belchen tunnel, and (from 2010 on) for the newly constructed Uetlibergtunnel. The emission load thus deleted is ignored, i.e. the dispersion of the $NO_x$ emissions from the entrances and ventilation stacks of such road tunnels is not modelled. This also means that the effect of these $NO_x$ emissions from road tunnels is part of the background $NO_x$ concentration parameterization (Section 2.5).

### 3.1.4. Spatial dis-aggregation

The spatial localization of emissions from road traffic is performed differently for the link and zonal emissions. The link emissions are known for each link of the road network individually and localized accordingly. Often it is not sufficient to use a straight line between the start and ending node of a road link to localize the emissions. Therefore, the emissions from all road links with a high emission strength are localized at the true road positions, which have been manually derived from maps. This extensive procedure was not yet necessary for the previous study (SAEFL 1997) where concentration maps were depicted with a 1 $km^2$ resolution, but are inevitable for the maps of the present report displaying results with 200 m and 400 m resolution.

The zonal emissions were modelled for each traffic zone, not per road link. Traffic zones often are equal to a single community, or cover the area of several remote communities. The cold start emissions were attributed to the area of each community proportional to the smoothed population density (smoothing on a 400 m scale).

For some cities, the road network is rather coarse. This leads to a disadvantageous relationship between the total link emissions and the total zonal emissions within the city, because the zonal emissions account for all emissions not resolved by the road network. Therefore, as in SAEFL (1997), for the cities of Berne, Zurich, Lausanne, Biel/Bienne and Thun, the positions of those major roads that are not present in the national road network have been manually derived from maps. Then, 80% of all zonal emissions are re-localized onto this additional road network. The remaining 20% are treated as zonal emissions (i.e., uniformly distributed to all areas where the construction of buildings is permitted).

For the city of Zurich, an additional problem is caused by plans to build a tunnel under the city centre to link the major highways entering Zurich from the north and from the south. At present, it is not known how and when this project will be build. In the HDV road network, an assumed version of this project is included, which is not the case for the other networks (PC, LDV, MC, buses). The emissions located on these new highway links have been manually removed and added to the existing links in the city of Zurich. This only concerns HDV emissions for the years 2015 and 2020.

## 3.2. Emissions from other transport modes

### 3.2.1. Emissions from rail traffic

In Switzerland, almost the entire rail network is electrified; only very few trains coming from other countries are diesel powered. The only significant use of diesel fuel to power train operations is for diesel locomotives which operate on shunting yards and to deliver freight cars to individual customers, track tractors for track maintenance, and carriages for special operations. The Swiss Federal Railways kindly provided the amount of total diesel fuel consumption resulting from these operations in 1999 (SBB 2001). The emissions were calculated by multiplying the consumption with a global emission factor of 49.7 kg $NO_x$ per ton of diesel fuel (SAEFL 1996). For the years 1999–2020, the emissions are assumed to remain unchanged as a consequence of a slight increase of the transported freight volume on the one hand, and a simultaneous slight decrease of the specific emissions due to new tractor engines on the other hand. The corresponding emissions are listed in Table 6.

| NOx emissions [t/a] | 2000 - 2020 |
|---|---|
| **a) shunting yards** | **100.1** |
| RB Limmattal | 28.0 |
| Basel | 24.7 |
| Chiasso Sm | 20.8 |
| Olten | 6.0 |
| Buchs SG | 3.2 |
| Rorschach | 2.8 |
| Biel | 2.5 |
| Bellinzona | 2.5 |
| Göschenen | 2.1 |
| Winterthur | 2.1 |
| Erstfeld | 1.9 |
| Bern | 1.5 |
| Lausanne | 1.0 |
| Zürich HB | 1.0 |
| **b) other non-localisable operations** (construction etc.) | **226.5** |
| **Rail traffic, total (a+b)** | **326.6** |

*Table 6: Emissions from rail traffic for 2000 to 2020.*

Only the emissions of the shunting yards with annual loads ≥ 1 t/a are implemented in the rail traffic emission inventory (100 t/a) since the non-localizable emissions (226 t/a) are too widely spread and are, therefore, of negligible contribution to the total $NO_x$ concentration. This means that the effect of these $NO_x$ emissions from railway operations are accounted for by the background $NO_x$ concentration parameterization (Section 2.5). It should be noted that the present estimate of rail emissions based on diesel fuel consumption (SBB 2001) differs from the figures in SAEFL (1996).

The rail emissions of the shunting yards are spatially dis-aggregated as follows: the total emissions of all shunting yards as in Table 6 are uniformly distributed to the grid cells covering the actual yard area. This area is manually derived from maps.

### 3.2.2. Emissions from water traffic (navigation)

Emissions from water traffic are obtained from SAEFL (1996) and listed in Table 7.

| NOx emissions [t/a] | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| total ship emissions | 673 | 690 | 707 | 716 | 718 |

*Table 7: Emissions from water traffic for 2000 to 2020.*

For a spatial dis-aggregation of the emissions resulting from water traffic, the emission load is uniformly distributed to all grid cells covering the water surface (manually derived from maps) of all large Swiss lakes where regular passenger transport services per ship are offered: Lakes of Biel/Bienne, Brienz, Morat/Murten, Neuchâtel, Thun, Walen, Zug, Zurich, as well as the Swiss parts of the Bodensee, the Lac Léman, the Lage Maggiore and the Lago di Lugano. No emissions have been attributed to rivers, canals, or small lakes with private boats only.

## 3.3. Emissions from industry, commerce, households, agriculture and forestry

### 3.3.1. Mobile machinery and equipment

Emissions from mobile machinery and equipment are taken into account separately for industry/commerce on the one hand and for households on the other hand. Industrial and commercial machinery includes construction machines (like loaders, compactors, forwarders, front shovels, knuckle-boom loaders, paving equipment, scrapers, etc.) as well as any other industrial mobile machines. Mobile equipment from households includes gardening equipment, do-it-yourself tools, etc. Emission figures have been obtained from SAEFL (1996).

### 3.3.2. Emissions from stationary sources

The emissions resulting from stationary industrial and commercial sources for the years 2000 to 2010 are obtained from SAEFL (1995). Emissions from very tall stacks (like cement and concrete factories) are not included. These emissions are not taken into account in any emission inventory, because their local impact is minor. This means that their impact is covered by the background $NO_x$ concentration function (Section 2.5). The SAEFL (1995) figures do include emissions from mobile machinery, which is treated separately in the present report (see previous section). For mobile machinery emissions, estimates up to the year 2020 are available (SAEFL 1996), but this is not the case for the total sum (SAEFL 1995). Therefore, it has been assumed that the total sum remains unchanged from 2010 on. The remaining emission load is interpreted as the emissions from industrial/commercial stationary sources, and further divided into two emission inventories (one for emission heights up to 20 m, the other for emission higher than 20 m ).

Emissions from households for the years 2000 to 2010 are also obtained from SAEFL (1995). Due to a lack of data, emissions from stationary sources are assumed to remain unchanged from the year 2010 on. Again, this overall figure includes emissions from stationary sources (residential heating and warm water equipment) and emissions from mobile machinery and equipment owned by households (gardening equipment, etc.). Therefore, the emissions from mobile equipment (see previous section) are subtracted from the total in order to obtain the emissions from stationary sources.

### 3.3.3. Emissions from agriculture and forestry

For agriculture and forestry, emission loads are obtained from SAEFL (1995). These figures account for both the $NO_x$ emissions from fertilizers and from mobile machinery and equipment (agricultural tractors and harvesters, forest machines, chain saws, etc.).

### 3.3.4. Summary of emissions from industry, commerce, households, agriculture and forestry

The summary of all emissions from industry, commerce, agriculture, forestry and households is presented in Table 8.

| $NO_x$-emissions [t/a] | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| Industry/commerce (emission height 2-20 m) | 9300 | 8000 | 6700 | 6700 | 6700 |
| Industry/commerce (emission height >20 m) | 12301 | 9565 | 9267 | 8495 | 7721 |
| Mobile machinery (industrial/commercial) | 8299 | 9435 | 10033 | 10805 | 11579 |
| Industry and commerce (total) | 29900 | 27000 | 26000 | 26000 | 26000 |
| Households (heating and warm water) | 6901 | 5364 | 5201 | 5188 | 5178 |
| Households (mobile machinery) | 369 | 369 | 419 | 432 | 442 |
| Households (total) | 7270 | 5760 | 5620 | 5620 | 5620 |
| Agriculture and forestry | 10500 | 11000 | 11400 | 11400 | 11400 |
| Total | 47670 | 43760 | 43020 | 43020 | 43020 |

*Table 8: $NO_x$ emissions from stationary sources and mobile machinery and equipment for 2000 to 2020. Data are taken from SAEFL (1995) and SAEFL (1996).*

The emissions from households and agriculture/forestry are spatially dis-aggregated as follows: All residential emissions (both from station sources and from mobile equipment) are uniformly distributed to the population grid according to BFS (1994). The numbers of inhabitants per community are corrected onto the level of 2000 (BFS 2003). The emissions from agriculture and forestry are uniformly distributed to all land use categories which conform to agriculture areas. Industrial and commercial emissions are distributed to all grid cells within industrial and residential areas (land use categories 16-20 of BFS, 1992/97). The emissions of construction machines are not only distributed to industrial and residential areas, but to grid cells containing roads as well.

## 3.4. Summary

Table 9 presents the $NO_x$ emissions for Switzerland for the years 2000 to 2020 of each major source group. The sharp decrease of road emissions, due to the EURO-3 and EURO-4 legislation, dominates the picture. For the years 2015 and 2020, these figures should be interpreted with care, as due to a lack of data, the emissions from industry/commerce, households and agriculture/forestry had to be assumed to remain at the 2010 level. For the year 2000, the spatially dis-aggregated total $NO_x$ emission per grid cell is shown in Figure 18 (Appendix A3).

| **$NO_x$-emissions [t/a]** | **2000** | **2005** | **2010** | **2015** | **2020** |
|---|---|---|---|---|---|
| Road traffic | 55'700 | 42'600 | 32'300 | 25'400 | 22'200 |
| Rail traffic | 100 | 100 | 100 | 100 | 100 |
| Water traffic | 673 | 690 | 707 | 716 | 718 |
| Air traffic* | 2'180 | | 2'180 | | 2'260 |
| Industry and commerce | 29'900 | 27'000 | 26'000 | 26'000 | 26'000 |
| Households | 7'270 | 5'760 | 5'620 | 5'620 | 5'620 |
| Agriculture and forestry | 10'500 | 11'000 | 11'400 | 11'400 | 11'400 |

*Table 9:* *Summary of $NO_x$ emissions per major source category as implemented in local dispersion modelling for Switzerland for 2000 to 2020. The data is obtained from various publications (SAEFL 1995, 1996, 2004b; AIG 2000, Unique 2003). The sum of the emissions of the table does not correspond to the actual Swiss total $NO_x$ emissions since only the localisable emissions are mentioned. In the concentrations maps, the non-localisable emissions appear as background concentrations.*
**Note that emissions from airports were not transformed into concentrations within the SAEFL modelling scheme, but were implemented as $NO_x$ concentrations grids kindly provided by airport authorities (for details see Section 2.4).*

# 4. Model results: $NO_2$ concentration

## 4.1. $NO_2$ concentration maps

The main result of the present report are annual average $NO_2$ concentration maps for the whole of Switzerland for the years 2000, 2005, 2010, 2015, and 2020. These maps are presented in Appendix A3 in a spatial resolution of 400 m.

For the year 2000, in the alpine mountain area the concentration is below 5 μg/m$^3$. In the Alpine valley basins, the concentrations lie between 5 and 15 μg/m$^3$ , but reach levels up to 45 μg/m$^3$ if there is a main Alpine transit route like St. Gotthard, San Bernardino and Valais. In the Central Plateau, the concentration levels vary from 10 to 25 μg/m$^3$ in the country-side, whereas in the built-up area the levels are higher, 20-45 μg/m$^3$. In several city centres, single values above 45 μg/m$^3$ may occur. Such levels may also be found along the highways. The air quality standard is exceeded in the largest cities and along highways. Due to worse ventilation, the Alpine valley basins show higher concentrations than comparably loaded sites in the Central Plateau. Note that the maximally loaded sites may not be seen because of the coarse spatial resolution of 400 m. Below, some illustrative examples are given on a enlarged scale and depicted in 200 m resolution showing higher concentrations at hot spots. If concentration modelling were carried out on even finer resolutions, of course, even higher concentration would appear.

Between 2000 and 2010, the $NO_x$ emissions are assumed to decrease from 100% to 74%. Until 2020, the emissions should further decrease to 64%. As a consequence, the concentrations will also decrease but less pronounced. The concentration level 2010 ranges from 78%-84% and decreases to 70%-80% in 2020 compared to 2000 (100%).

For the year 2010, the $NO_2$ air quality standard will still be exceeded in the largest Swiss cities and on several sections along highways, i.e. in the Limmattal near Zurich and also in the surroundings of Basle, Geneva, Lausanne and Lugano-Bellinzona. Until 2020, the situation should improve again; the uncertainty of this prediction is, of course, higher than for 2010. Since the emissions from the airports decrease less than those from the road traffic, the airports become prominent hot spots. As only the two international airports of Zurich and Geneva have been included, other airports (like Basle-Mulhouse, Berne-Belp, Birrfeld, Ecuvillens, Grenchen, La Chaux-de-Fonds Les Eplatures, Lugano-Agno, Samedan, Sion, St.Gallen-Altenrhein) do not appear on the concentration maps. It is possible that hey would have become visible on the maps for 2010 and later.

## 4.2. Area statistics and population exposure 2000 to 2020

The percentages of the land and water surface of Switzerland exceeding the air quality standard (30 µg/m$^3$) are computed using the average concentration of each grid cell (200 m x 200 m). Data on special distribution of population is available on a 100 m x 100 m basis (1990 census; BFS 1994). These values have been adjusted to fit the total population as published in 2000 census, BFS (2003). The resulting cumulative density functions are displayed in Figure 9 and Figure 10. It should be noted that using area-averaged concentration values tend to systematically underestimate the true extent of exposure to local ambient $NO_2$ concentration peaks (e.g. in street canyons), since local effects are ignored. In 2000, 0.8% (344 km$^2$) of the total surface of Switzerland have a mean $NO_2$ concentration above 30 µg/m$^3$ (average over grid cells of 200 m). In 2010, approximately on 0.2% (96 km$^2$) and in 2020 on 0.1% (33 km$^2$) of the surface the air quality standard will be exceed.

The total surface of Switzerland consists to a large extent of mountains (roughly 65%) where the population density is very low. Thus, in 2000, 16.0% of the Swiss population (1.16 million persons) have their home location in an area with a mean concentration level above the air quality standard (Figure 10, Table 10). For 2010, the corresponding numbers are 5.3% (0.39 million persons) and in 2020 1.3% (0.094 million persons) of the population which live in the area with too high $NO_2$ concentrations.

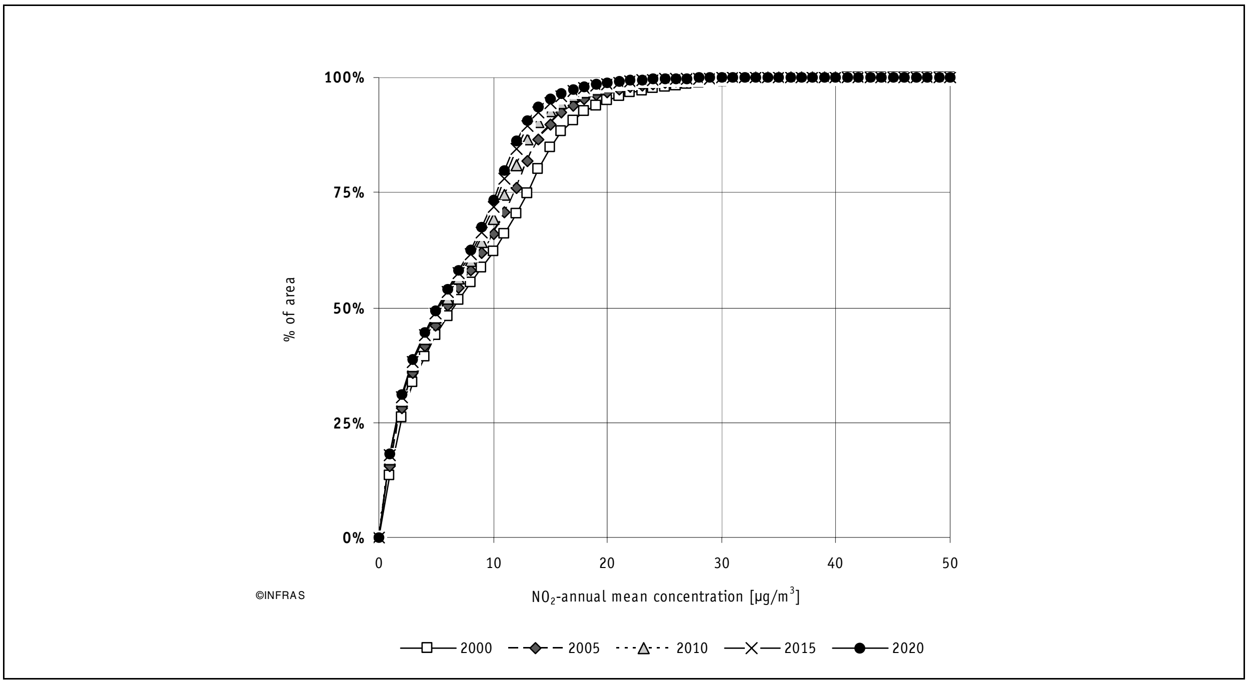


*Figure 9:* *Area statistics (percentage of all 200 m x 200 m grid cells, including water surfaces; concentration is the average over the cell surface) versus annually averaged ambient $NO_2$ concentration level.*

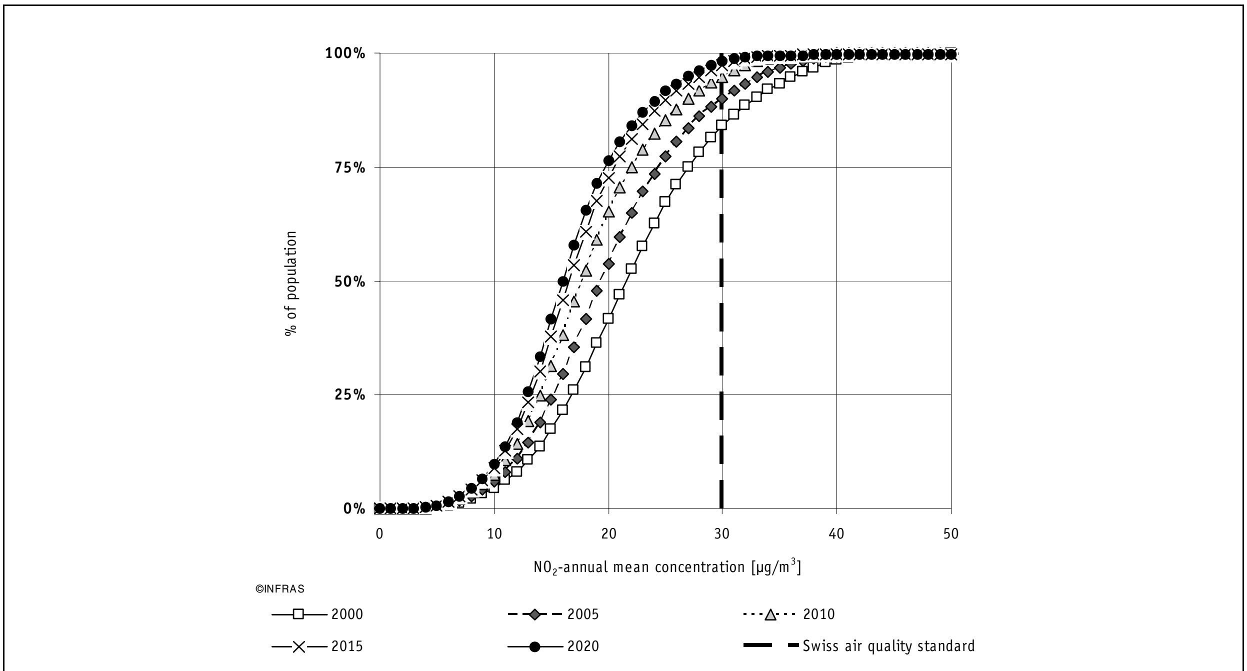


*Figure 10:* *Population exposure (living location) to annually averaged ambient $NO_2$ concentration level.*

| Exposure $NO_2$ [µg/m$^3$] | 2000 | | 2005 | | 2010 | | 2015 | | 2020 | |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 <= 5 | 0.3% | | 0.4% | | 0.5% | | 0.7% | | 0.7% | |
| 5 <= 10 | 4.2% | | 5.5% | | 7.0% | | 8.2% | | 9.0% | |
| 10 <= 15 | 12.8% | 84.0% | 18.1% | 90.1% | 23.7% | 94.8% | 28.8% | 97.3% | 31.8% | 98.3% |
| 15 <= 20 | 24.3% | | 29.6% | | 34.1% | | 34.9% | | 34.9% | |
| 20 <= 25 | 25.6% | | 23.6% | | 20.0% | | 17.0% | | 15.2% | |
| 25 <= 30 | 16.8% | | 12.9% | | 9.5% | | 7.7% | | 6.7% | |
| 30 <= 35 | 9.3% | | 6.7% | | 4.4% | | 2.1% | | 1.2% | |
| 35 <= 40 | 5.1% | | 2.4% | | 0.7% | | 0.4% | | 0.1% | |
| 40 <= 45 | 1.2% | 16.0% | 0.3% | 9.6% | 0.2% | 5.3% | 0.0% | 2.5% | 0.0% | 1.3% |
| 45 <= 50 | 0.3% | | 0.2% | | 0.0% | | 0.0% | | 0.0% | |
| 50 <= 55 | 0.1% | | 0.0% | | 0.0% | | 0.0% | | 0.0% | |

*Table 10: Population exposure to $NO_2$ in Switzerland for 2000 to 2020. All percentages relate to the 2000 population of 7.28 million inhabitants (values do not add up to 100% due to rounding errors). The Swiss air quality standard for $NO_2$ is 30 µg/m$^3$.*

The results from the present study (Figure 10) are also compared to those of the predecessor study, SAEFL (1997) (Figure 11). For the years 2000 and 2010, the new results show a clearly lower population exposure as those of SAEFL (1997) (i.e., a smaller percentage of the population has their home location in areas where the ambient $NO_2$ concentration is above the 30 µg/m$^3$ threshold. This is mainly due to the new emission results from road traffic, that take into account the effect of the EURO-3 and EURO-4 legislation. Also, the background $NO_x$ concentration parameterization functionally depends on the total emission load, and hence further amplifies the trend of decreasing predicted $NO_2$ concentration levels for the future years.

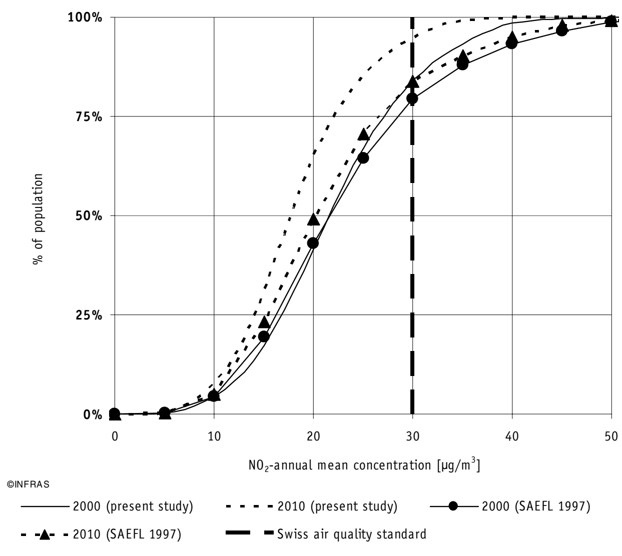


*Figure 11: Comparison of population exposure for the years 2000 and 2010 as from the present study and from its predecessor (SAEFL 1997).*

## 4.3. Illustrative example: $NO_2$ concentration in the Lugano area 2000–2020

In order to illustrate the sharp decrease of $NO_x$ emissions from road traffic between 2000 and 2020, and hence the decrease in $NO_2$ concentrations over the same period of time, the area of the city of Lugano in the southern part of Switzerland is shown at a finer spatial resolution (grid cell mesh size of 200 m) for the years 2000, 2005, 2010 and 2020 (Figure 24 to Figure 27, Appendix A3). The major sources in this area are (i) a major transit highway from Basle to Chiasso, which passes by Lugano. It carries (almost) all lorries that cross the Swiss Alps on their way from northern Europe to Italy. In Figure 24 to Figure 27, it runs from the upper left edge of the area and turns towards the east to cross the Lago di Lugano. (ii) the southern part of Switzerland is exposed to high levels of air pollution that originate from northern Italy (Milan area) and that are transported towards Switzerland depending on the meso-scale weather conditions. Together with the local load, maximal concentrations also arise in the centre of Lugano.

For the year 2000, almost all grid cells covering the immediate area of the highway show $NO_2$ concentrations above 45 µg/m$^3$. The entire area in the vicinity of the highway and the entire area of the city of Lugano have $NO_2$ concentrations above 30 µg/m$^3$. In 2005, when EURO-3 legislation shows its effects, parts of the city of Lugano drop below the 30 µg/m$^3$ threshold. Areas with $NO_2$ concentrations above 45 µg/m$^3$, however, are persistent. In 2010, when large parts of the running fleet already comply with the EURO-4 legislation, the $NO_2$ air pollution in Lugano is at or below the air quality standard. Most (but not all) of the highway area itself still is above this standard. Finally, in 2020, only those grid cells that happen to consists to the larger part of the highway surface itself and some areas in the town centre exceed the air quality standard of 30 µg/m$^3$.

## 4.4. Illustrative example: 200 m resolution maps of $NO_2$ concentration in selected areas of interest

The concentration maps of Figure 28 to Figure 31 (Appendix A3) illustrate the $NO_2$ concentration levels for four selected areas of interest in 2000, at a spatial resolution using a grid size of 200 m (i.e., identical to the computational grid). Two urban agglomerations (Lausanne, Figure 28; Berne, Figure 29) are depicted along with an Alpine valley with a major highway (Monthey area, Figure 30) and a Central Plateau area where the two major highways (Basle–Chiasso and Geneva–St. Gall) are linked to each other (Figure 31).

All maps show large areas where the 30 $\mu g/m^3$ air quality standard is exceeded. In the immediate vicinity of major highways, the annual averaged concentration often exceeds 35 $\mu g/m^3$. These illustrative examples show that for 2000, the traffic on busy highways has to be regarded as one of the main factors which lead to the violation of the air quality standard for large areas.

# 5. Model validation

## 5.1. Comparison of model results and measurements

In this section, the predicted annually averaged $NO_2$ concentrations for 2000 are compared to measurements obtained throughout Switzerland. The measured data was kindly provided by air quality authorities and is used without any exclusion of data. It should be noted that contrary to SAEFL (1997), the transfer functions of the present modelling approach have not been calibrated towards measurements. For calibration purposes, the over-all rural-to-urban correction factor (see Sect. 2.2.5) has been reduced to minimise the differences between modelled and measured values. Also, the parameters of the background function (Sect. 2.5) allow some variations in order to reduce the differences to the measurements.

Figure 12 depicts a scatter plot of predicted vs. observed $NO_2$ concentrations for 38 monitoring sites for 2000. 25 of the 38 predicted concentrations (66%) are within a factor of 1.23 of the measured values (dashed lines). The correlation coefficient is high $\left(R^2 = 0.8\right)$; the mean of all predicted values is 24.6 µg $NO_2/m^3$, the average of all measurements is 25.5 µg $NO_2/m^3$.

The points lying above the +123% line are urban sites with heavy local traffic (Berne, Lausanne, Zurich) and closed building situations (street canyons). For such situations, the model is under-estimating the real concentrations.

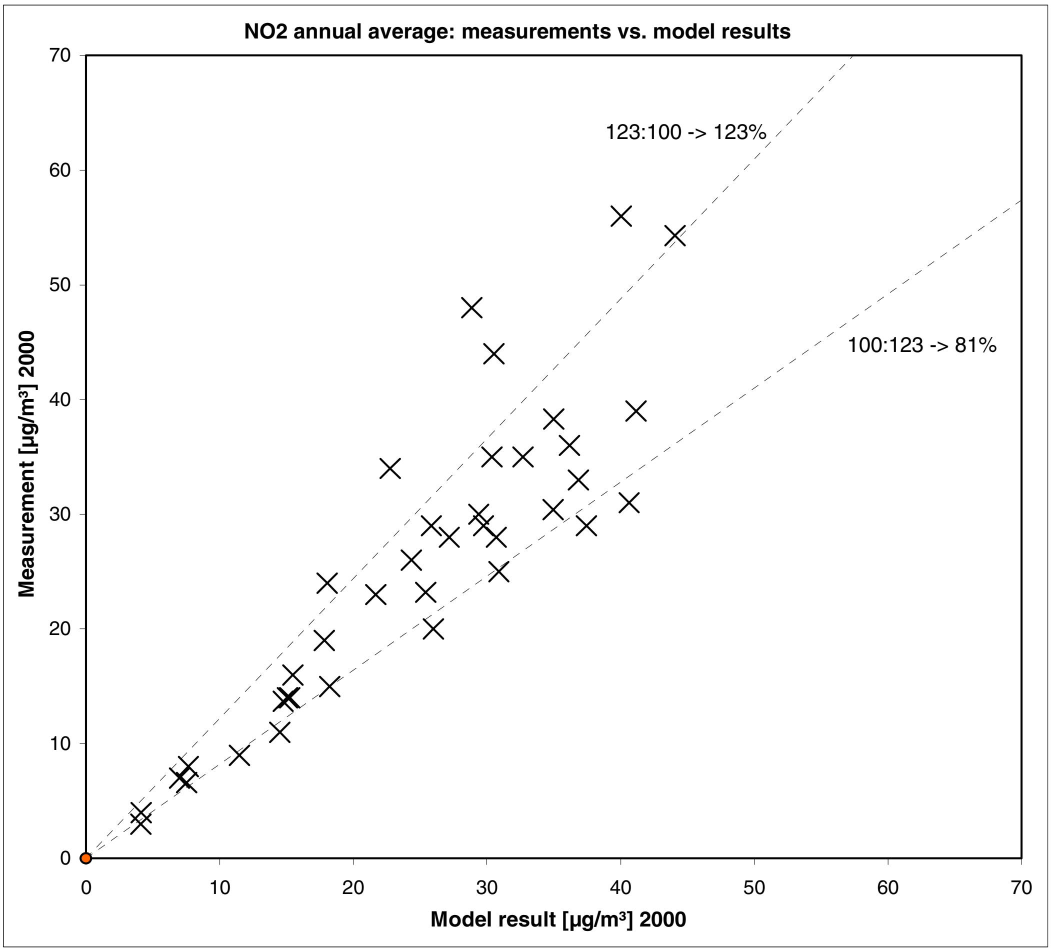


*Figure 12: Scatter plot of observed and modelled annual average $NO_2$ concentration. 25 of 38 data points (66%) lie within the lines 81% and 123%. See text for further explanations.*

## 5.2. Residual analyses

The differences between the predicted and measured values, i.e. the model errors (residuals), are depicted as a function of other modelled components in order to analyse any systematic model errors. Figure 13 shows the residuals as a function of the height above sea level of the individual air pollution monitoring stations. Hardly any systematic deviance can be detected, illustrating that the altitude dependence of the $NO_x$ background concentration function seems to be good. Figure 14 depicts the residuals against the $NO_x$ concentration originating from road traffic. Again, no systematic deviance was found. When comparing the observed and predicted $NO_2$ concentrations for the sites (monitoring and sampler tube sites) that are located in a grid cell to which the Alpine transfer functions have been applied, it can be shown that 66% of the predicted values are within 74-126% of the measured concentrations. This suggests that the special approach developed for the basins of Alpine valleys has improved (less under-prediction) compared to the previous study (SAEFL 1997).

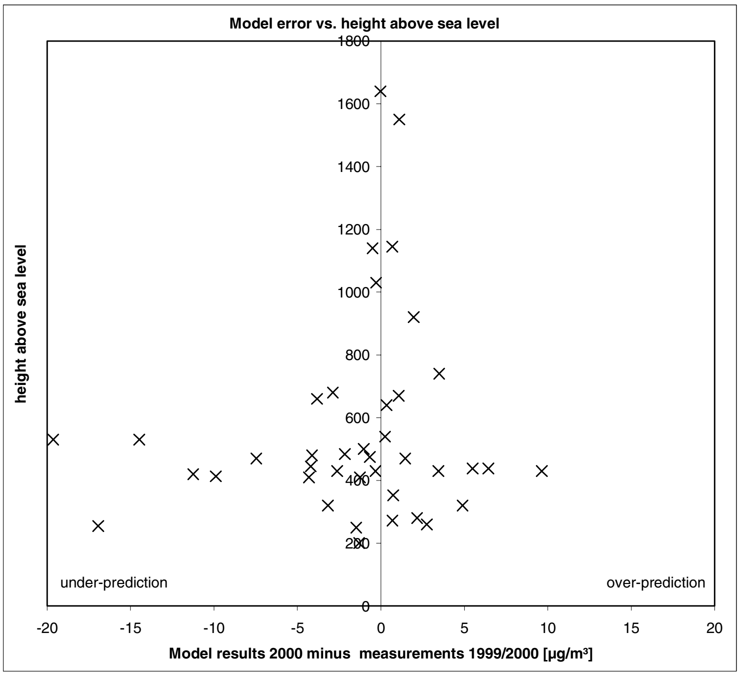


*Figure 13: Model prediction error as a function of the elevation above sea level.*

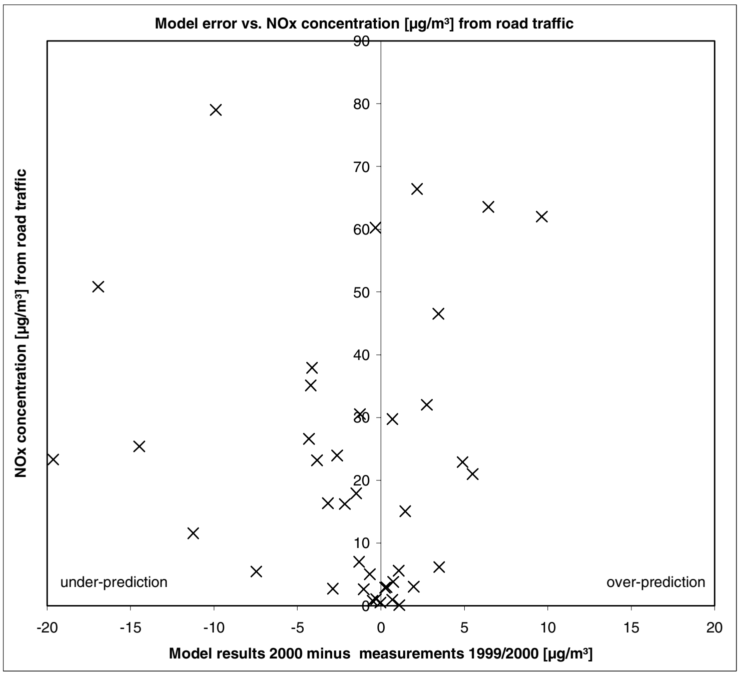


*Figure 14: Model prediction error as a function of the modelled $NO_x$ concentration originating from road traffic sources.*

# 6. Modelling benzene concentration

## 6.1. General remarks

Benzene is a carcinogenic air pollutant. Additionally, benzene plays a minor role in the formation of tropospheric ozone and secondary aerosols. In the Swiss Ordinance on Air Pollution Control (OAPC), benzene is classified as a carcinogenic substance, and therefore limits apply to its various emission levels, but there is no actual ambient air quality standard. As a carcinogenic substance, the concentrations should be reduced as much as possible.

The only available dispersion modelling study for benzene accomplished so far in Switzerland focused on the city of Zurich (AGU 1997). The modelling approach used for the dispersion modelling of $NO_x$, as presented in the previous sections, can easily be adopted for the dispersion modelling of benzene, since both pollutants may be treated as inert trace gases.

At present, approximately 75% of benzene emissions in Switzerland originate from the production, distribution and burning of gasoline (in refineries, at gasoline stations, and during the combustion processes of the traffic), and about 10% are emitted during wood burning processes. Various measures, especially the ban on the use of benzene as a solvent, already have reduced ambient benzene concentration levels since the 1980ies. A further decrease can be found after January 2000, as a direct consequence of new regulations on fuel quality in the European Union: Directive 98/70/EC of the European Commission introduced significantly lower maximum amounts of benzene (1% by volume), aromatics (42% by volume), and sulphur (0.015% by mass for gasoline, and 0.035% for diesel fuel). The OAPC adopted these limit values.

## 6.2. Emission loads and localization

### 6.2.1. Road transport

Benzene emissions from road transport have been computed in exact analogy to the $NO_x$ emissions (see Section 3.1 for details), using version 2.1 of the Handbook on Emission Factors (SAEFL 2004a) to estimate the emissions from all major roads in Switzerland separately. The content of benzene has been assumed to be 1%, in line with the new limit value on the benzene content of 1% (by volume) as of January 2000. On average in 1999, the estimated content of benzene in fuel was 2.2%.

The resulting emissions are listed in Table 11. The major part of the emissions result from passenger traffic. For 2010, it is expected that benzene emissions from road traffic reduce to less than a half of 2000. Roughly one half of all benzene emissions from road transport occur during the engine cold start phase and another 16% result from diurnal evaporation and hot soak emissions. These emissions are not attributed to the road network, but are instead distributed proportionally to the smoothed population grid (see section 3.1.4). ). This also holds for 85 tons that are emitted from gasoline stations and other fuel storage and handling activities.

In contrast to the procedure adopted for $NO_x$, the emissions of benzene in the cities of Berne, Biel/Bienne, Lausanne, Thun and Zurich were not manually re-located.

| **Benzene-emissions [t/a]** | **2000** | **[%]** | **2010** | **[%]** |
|---|---|---|---|---|
| Goods Transport (LDV, HDV) | 100 | 9% | 50 | 11% |
| Passenger Traffic (PC, MC, buses) | 938 | 84% | 345 | 78% |
| Road Traffic (Fuel Storage and Handling) | 85 | 8% | 50 | 11% |
| Total | 1123 | 100% | 445 | 100% |

*Table 11: Benzene emissions from road transport in Switzerland for the years 2000 and 2010.*

### 6.2.2. Emissions from industry/commerce, households, agriculture, forestry and off-road

For the emission loads from industry/commerce and households, the figures from EKL/SAEFL (2003) have been used. Benzene emissions from agriculture and forestry are assumed to be zero. Estimates on the benzene emissions from off-road traffic have been estimated by SAEFL. The spatial dis-aggregation of the emissions from industry/commerce and households is performed in the same manner as for $NO_x$ (see Section 3.3). Emissions from off-road traffic are distributed to all grid cells within industrial and residential areas (land use categories 16-20 of BFS, 1992/97).

### 6.2.3. Emissions from fuel production and storage

Benzene emissions also occur during the production, storage and distribution of fuel. In Switzerland, two refineries exist; additionally, large fuel storage tank locations exist near the border of the country, and a series of smaller in-land fuel storage tanks is also present. Additional emissions occur at the gasoline stations which are spread throughout the country.

VOC emission loads from fuel production, storage and distribution were kindly provided by Schürmann (2001). In 2000, approximately 196 t/a of VOC are emitted from refineries. Assuming a benzene content (by volume) of 1%, approximately 2 t/a of benzene are emitted from refineries (Cressier refinery: 60%; Colombay-Aigle refinery: 40%). The corresponding VOC emissions from fuel storage tank facilities at the border are estimated to be 487 t/a, which results in some 4.9 t/a of emitted benzene. It is assumed that the Basle (Birsfelderhafen) storage facility has a share of 50% of these emissions, the Geneva Vernier facility approximately 40%, and the remaining 10% originate from the Stabio/Mendrisio site in southern Switzerland. The emission loads from the two refineries are spatially allocated as follows: the emissions are uniformly distributed to the immediate area covered by the refineries, as manually derived from maps. The emissions from the three fuel storage facilities in Basle, Geneva and Stabio are uniformly distributed to the areas of these facilities, as manually derived from maps. Emissions from inland fuel storage tanks (304 t/a of VOC, and 3.0 t/a of benzene) are neglected since their impact would be negligible (background concentration).

### 6.2.4. Summary

The resulting total benzene emissions for 2000 and for 2010 are listed in Table 12. The main source of benzene emissions for 2000 clearly is road traffic, even though the content of benzene in fuel has been reduced recently. For 2010, emissions of road traffic will be reduced to almost the same level as the emissions from industry/commerce, and households. It should be kept in mind, however, that the emissions from various source categories have not been taken into account due to a lack of data. These emissions were accounted for by means of the benzene background concentration parameterization.

| **Benzene-emissions [t/a]** | **2000** | **[%]** | **2010** | **[%]** |
|---|---|---|---|---|
| Road Traffic (Exhaust, Evaporation, Cold Start) | 1038 | 74% | 395 | 56% |
| Road Traffic (Fuel Storage and Handling) | 85 | 6% | 50 | 7% |
| Off-road Traffic | 75 | 5% | 45 | 6% |
| Refineries | 2 | 0% | 3 | 0% |
| Industry/commerce, and households | 200 | 14% | 217 | 31% |
| Total | 1400 | 100% | 710 | 100% |

*Table 12: Total benzene emissions in Switzerland for the years 2000 and 2010.*

# 6.3. Concentration modelling

## 6.3.1. Dispersion modelling

The dispersion modelling is conducted in exact analogy to the approach for $NO_x$ (see Section 2.2). The same transfer functions as for $NO_x$ are used, since both $NO_x$ and benzene can be regarded as an inert, non-depositing tracer. Using the same transfer functions means that the same time series as for $NO_x$ emissions are used (Section 2.3).

## 6.3.2. Background concentration

In analogy to the $NO_2$ dispersion modelling approach, the background concentration is the sum of (i) the natural background (i.e., not of anthropogenic origin); (ii) the impact of benzene emissions released in Switzerland's neighbouring countries; (iii) the far field impact of emission sources situated within Switzerland; and (iv) any impact from benzene emissions within Switzerland not explicitly resolved within the emission inventories.

The analytical form of the benzene background derivation is adopted from Eq. 1

$$C_{background,benzene}(h) = \left[C_{regional,benzene} + K_{benzene} * \exp\left(E_{rel,CH,benzene}(t)/\gamma\right)\right] * \exp\left(-\frac{h}{h_0}\right) \quad (3)$$

The value of $C_{regional,benzene}$ has been assumed to be in the order of 10% of the total background in 2000, decreasing to 9% in 2010. Again, $K_{benzene}$ and $\gamma$ are constants, determined for the reference year $t_0 = 2000$ and the reference height $h_0 = 1000$ m. $\gamma$ was set to the same value as used for $NO_2$ dispersion modelling and $K_{benzene}$ was set to 1.5 in order that the measurements from background sites fit best with model values. Figure 15 shows the model values in comparison with background measurements from three sites.

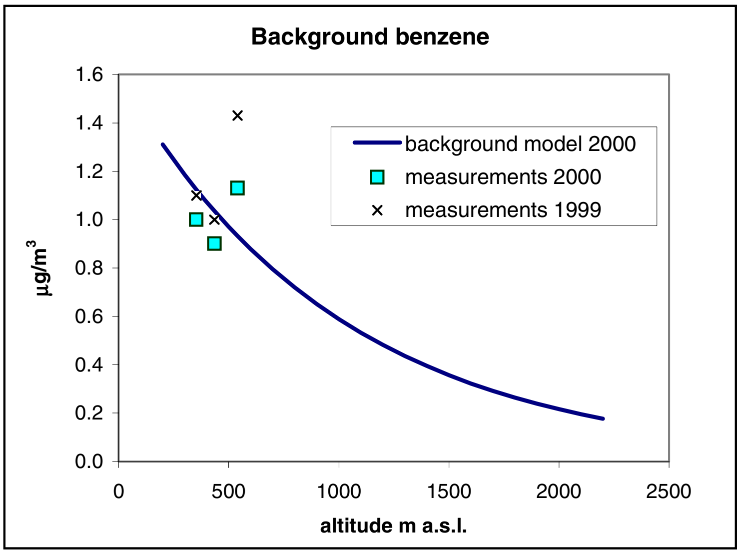


*Figure 15: Modelled benzene background concentration for 2000 (solid line: Eq. 2), and background measurements for 2000 and 1999 (Grenchen Witi 0.9 µg/m³, Aesch Schlatthof 1.0 µg/m³, Tänikon 1.1 µg/m³).*

## 6.4. Model results: benzene concentration

### 6.4.1. Benzene concentration in Switzerland

The resulting maps with the benzene concentration in Switzerland for the years 2000 and 2010 are shown in the Appendix A3 (Figure 32 and Figure 33).

In contrast to the $NO_2$, the concentration of benzene is primarily found in the built-up area and not along the roads in the country-side. This is a direct consequence of the fact that two thirds of the traffic emissions (cold start emissions, diurnal evaporation and hot soak emissions) occur in the living location area of the inhabitants.

A detailed description of the concentration levels in Switzerland and of the population exposure is given in EKL/SAEFL (2003). Based on epidemiological arguments, a reduction of the benzene emissions down to 100 t/a is recommended. According to the perspective 2010 shown in Table 12, the emissions should therefore be reduced by a factor of 7, which can only be reached if further reducing measure will be realised.

### 6.4.2. Benzene concentration in selected Swiss agglomerations

The benzene concentration as modelled for four major Swiss agglomerations in 2000 is shown in Figure 34 to Figure 37 (Appendix A3). Unlike for $NO_2$, the highest emission levels of benzene occur in the agglomeration as mentioned above (cf. Section 6.2.1). This approach naturally leads to high concentration levels, >4.5 µg/m³, in the large agglomerations.

## 6.5. Comparison with measurements

Benzene is monitored by the National Air Pollution Monitoring Network (NABEL) at the Dübendorf and the Tänikon site. Some values for the annual averages of benzene concentration exist in the cantons of Zurich, Schaffhausen and Lucerne (SAEFL 2000c), and in the cantons Uri, St. Gall, Zug, and both Basle cantons. However, due to the sharp decrease in the benzene content of gasoline, any concentration measured before January 2000 cannot be compared to the present results (cf. measurements from 1999 and 2000 in Table 13).

In general, the annually averaged benzene concentration varies between approximately 1 µg/m³ at rural background stations in higher altitudes and about 5 µg/m³ if measured near major roads in the city centres. The pronounced decrease from 1999 to 2000 in the range of 25% is easily visible. Benzene is measured using gas chromatography (GC) and passive sampling tubes (PS). For the PS measurements, 3M tubes are used, for which extended cross checks with GC measurements were performed with excellent correspondence between the two methods: The difference in the annually averaged values amount to only 3% (LHA BS/BL 2001). Figure 16 shows a scatter plot of measured and modelled annual benzene concentration levels for 2000. Modelled and measured benzene concentrations agree within a factor 1.3

| Station name (institution) | altitude<br>m a.s.l. | method | 1999<br>[µg/m³] | 2000<br>[µg/m³] | 2000/1999<br>% |
|---|---|---|---|---|---|
| Dübendorf (NABEL) | 430 | GC | 2.8 | 1.9 | 68 |
| Basel, St. Johannplatz (LHA BS/BL) | 260 | PS | 2.5 | 1.9 | 76 |
| Basel, Feldbergstrasse (LHA BS/BL) | 255 | PS | 8.4 | 5.5 | 65 |
| Aesch, Schlatthof (LHA BS/BL) | 353 | PS | 1.1 | 1 | 91 |
| Breitenbach SO, Gässliacker (AfU SO) | 392 | PS | 1.4 | 1.3 | 93 |
| Grenchen, Witi (Afu SO) | 435 | PS | 1 | 0.9 | 90 |
| Solothurn, Werkhofstrase (AfU SO) | 450 | PS | 4.5 | 3.1 | 69 |
| Zug, Neugasse 2 (in-LUFT) | 420 | GC | - | 5.2 | - |
| Tänikon (NABEL) | 540 | GC | 1.4 | 1.1 | 79 |
| Average | | | 2.9 | 2.4 | 79 |

*Table 13: Benzene measurements in Switzerland for 1999 and 2000. The decrease from 1999 to 2000 is due to the new regulations on fuel quality as of Jan 1st 2000. "PS" measurement device denotes passive benzene collector systems; "GC" denotes gas chromatograph measurements.*

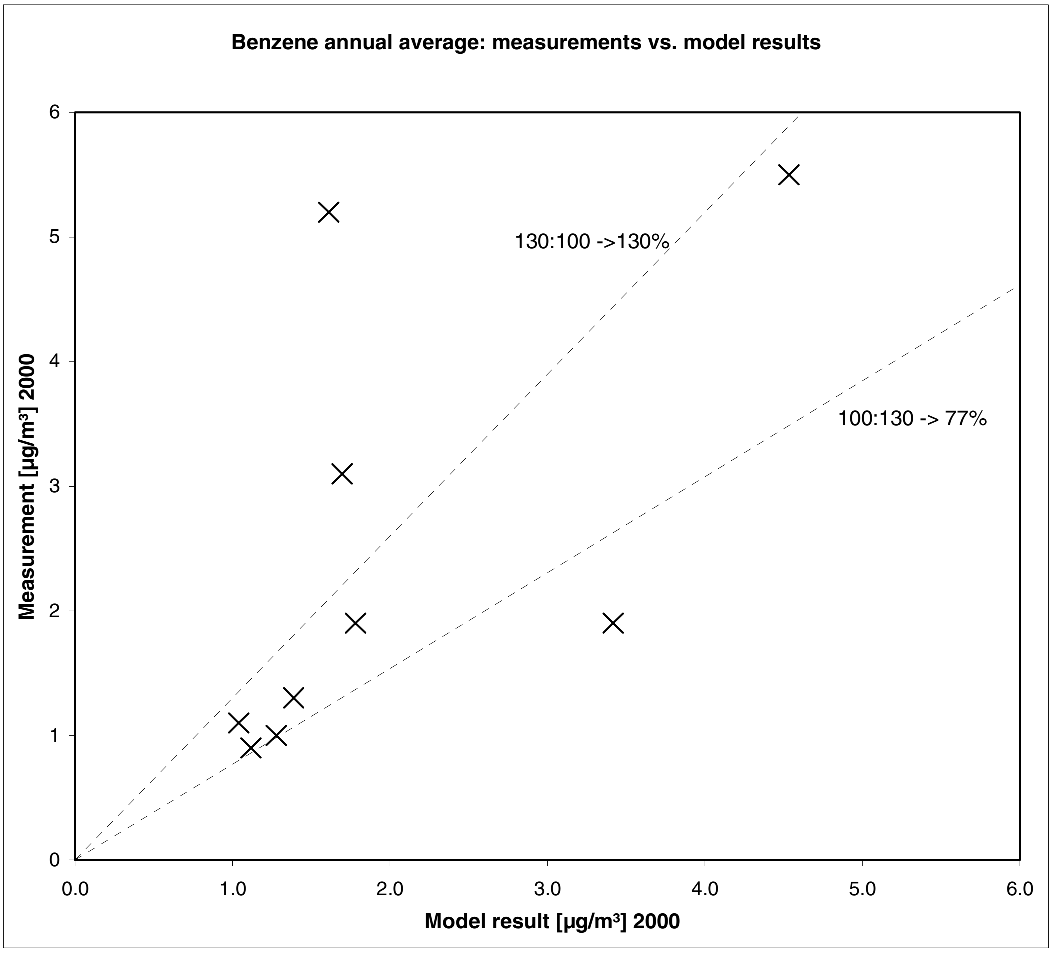


*Figure 16:* *Scatter plot of measured and modelled annual mean benzene concentrations for the year 2000. 6 of 9 data points lie within 77% and 130% lines.*

# Appendix

# A1. Abbreviations

| | |
|---|---|
| DTV | Daily Traffic Volume (number of vehicles per day, averaged over 1 year) |
| FOSD | Federal Office for Spatial Development (German: Bundesamt für Raumentwicklung, ARE) |
| GIS | Geographical Information System |
| HDV | Heavy-Duty Vehicles |
| LDV | Light-Duty (commercial) Vehicle |
| LPE | Law on the Protection of the Environment (German: Umweltschutzgesetz, USG) |
| MRHVT | Mileage-Related Heavy Vehicle Tax (German: Leistungsabhängige Schwerverkehrs-Abgabe, LSVA) |
| MC | Motorcycle |
| NABEL | Swiss National Air Pollution Monitoring Network (German: Nationales Beobachtungsnetz für Luftfremdstoffe, NABEL) |
| NO | nitrogen monoxide |
| $NO_2$ | nitrogen dioxide |
| $NO_x$ | nitrogen oxide (sum of NO and $NO_2$) |
| OAPC | Swiss Ordinance on Air Pollution Control (German: Luftreinhalte-Verordnung, LRV) |
| OTA | Overland Transport Agreement (German: Landverkehrsabkommen) |
| PC | Passenger Car |
| SAEFL | Swiss Agency for the Environment, Forests and Landscape (German: Bundesamt für Umwelt, Wald und Landschaft, BUWAL) |

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# A3. Maps with $NO_2$ and benzene concentrations for Switzerland

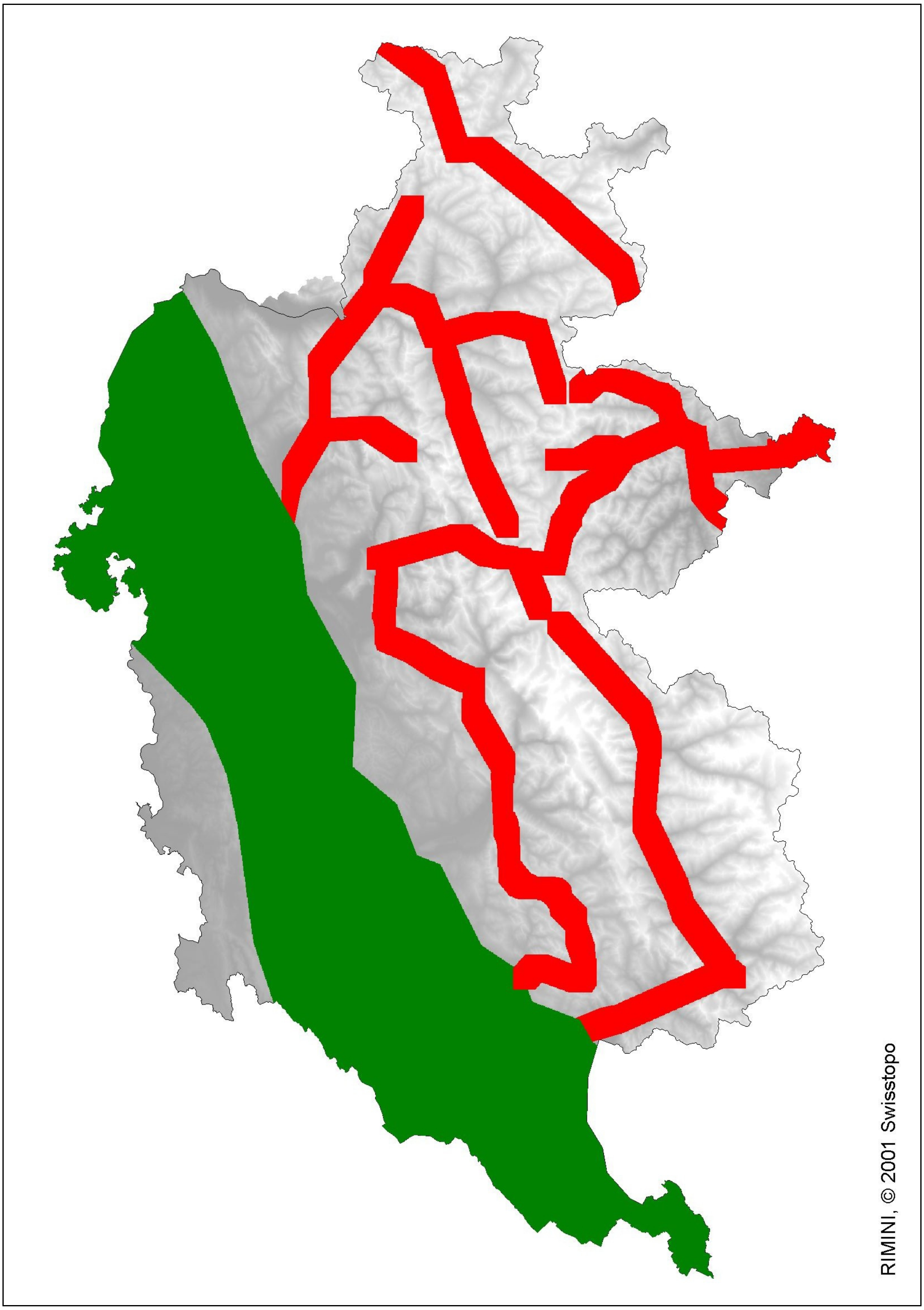


*Figure 17:* *Definition of the regions where the transfer functions apply: Central Plateau (green), Alpine valley (red), and remaining part (transparent).*

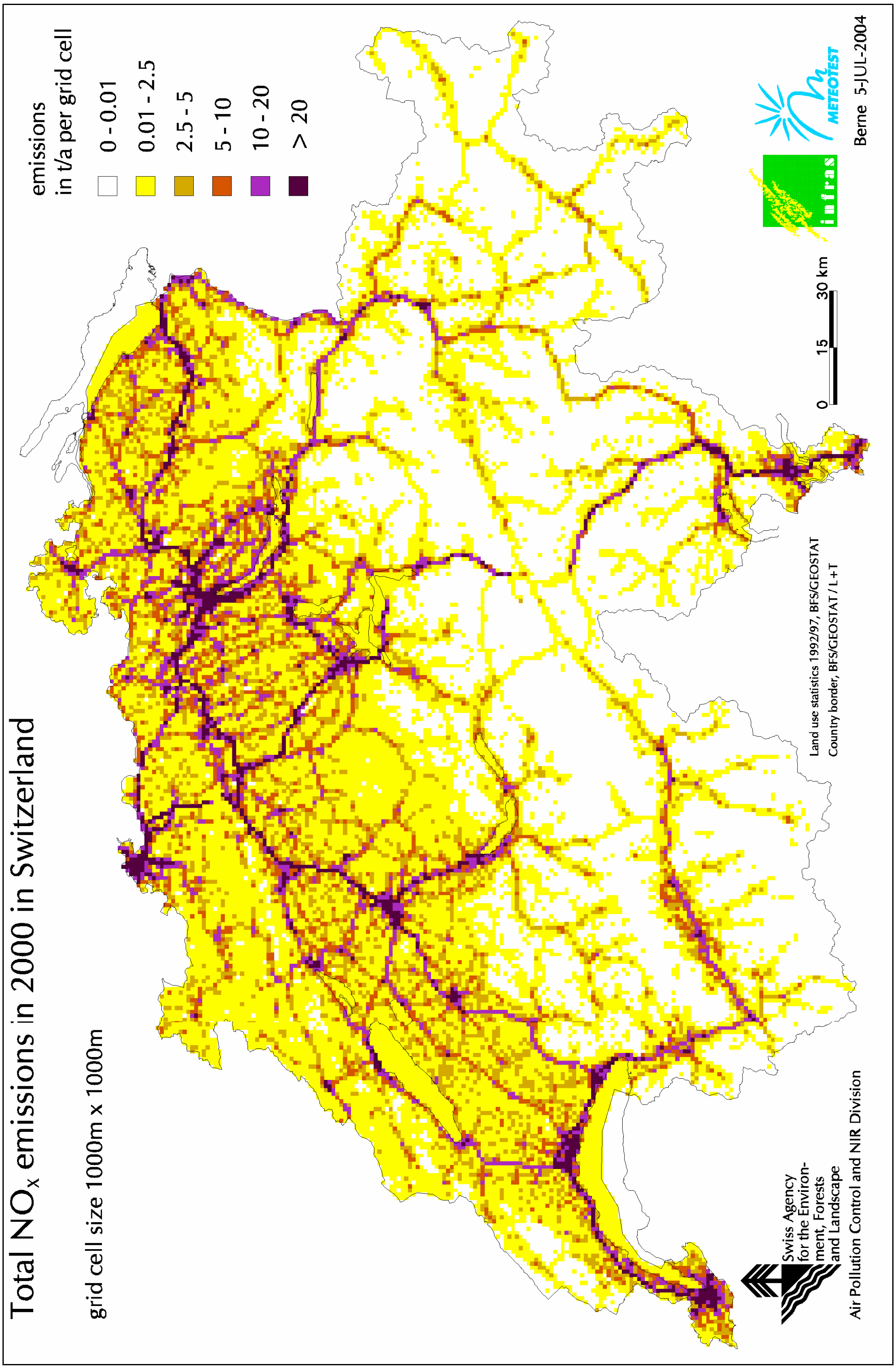


*Figure 18: Total $NO_x$ emissions (without airports Zurich, Geneva) in Switzerland for 2000.*

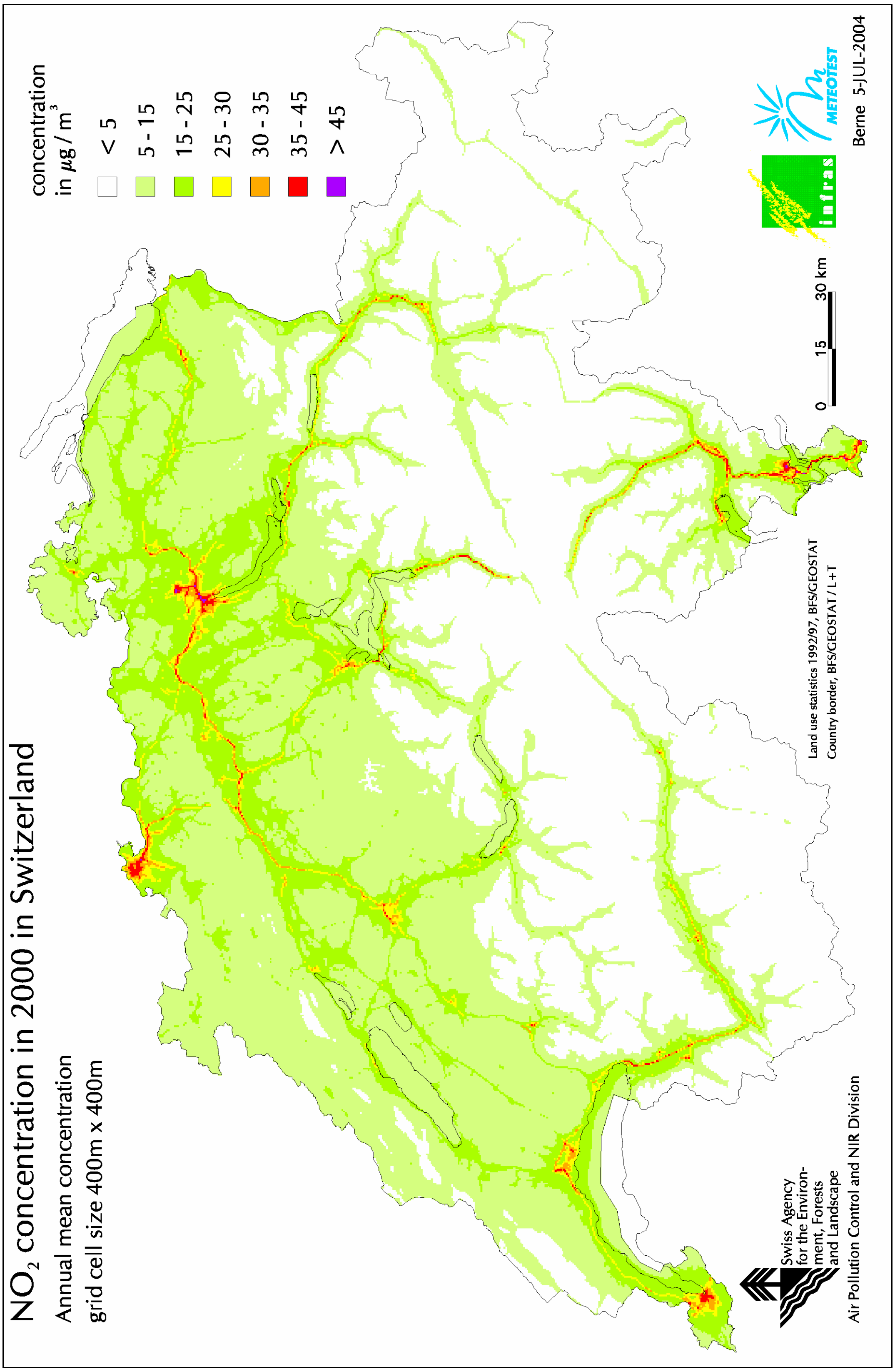


*Figure 19: $NO_2$ concentration in Switzerland for 2000.*

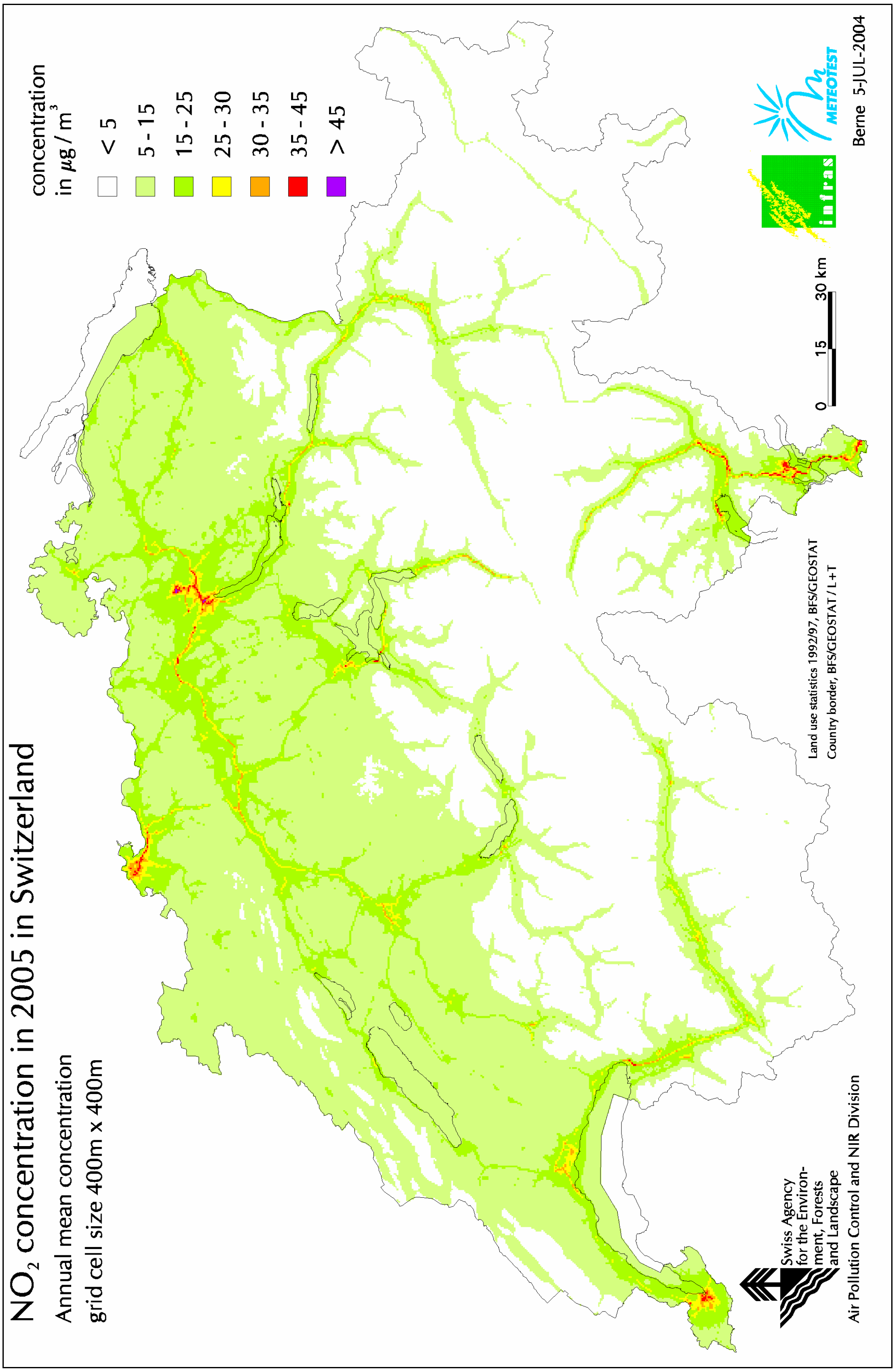


*Figure 20:* *$NO_2$ concentration in Switzerland for 2005.*

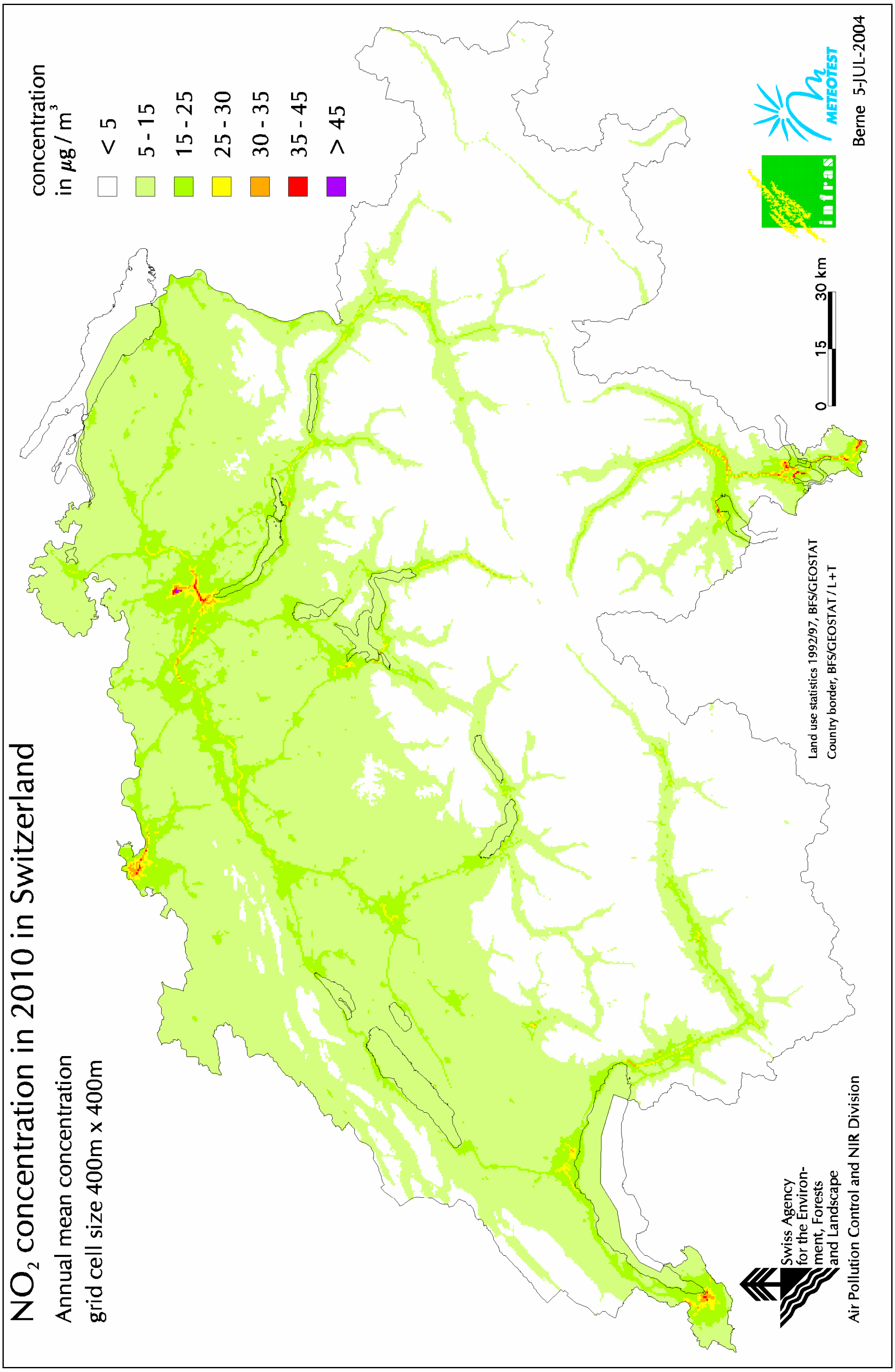


*Figure 21:* *$NO_2$ concentration in Switzerland for 2010.*

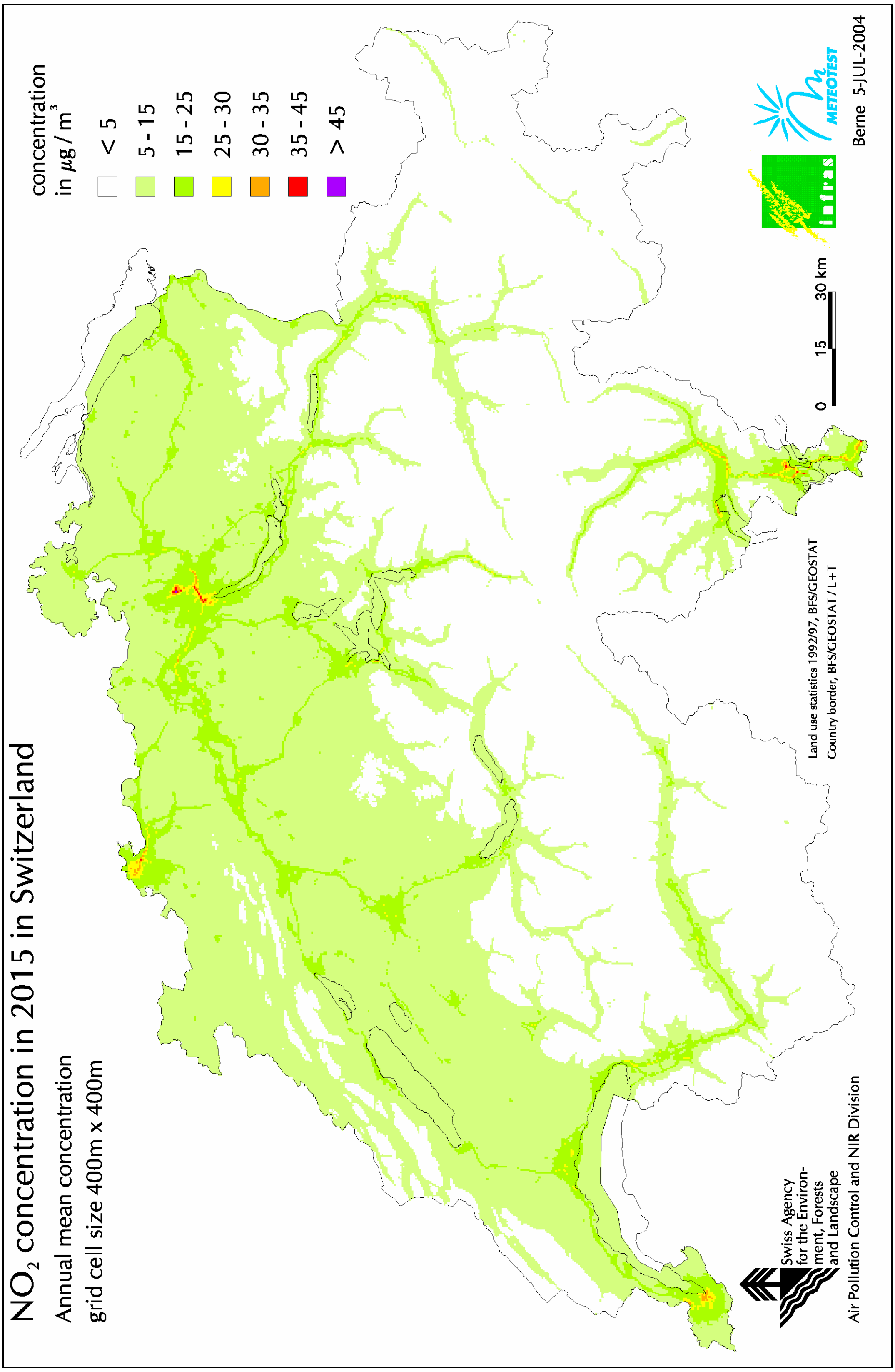


*Figure 22: $NO_2$ concentration in Switzerland for 2015.*

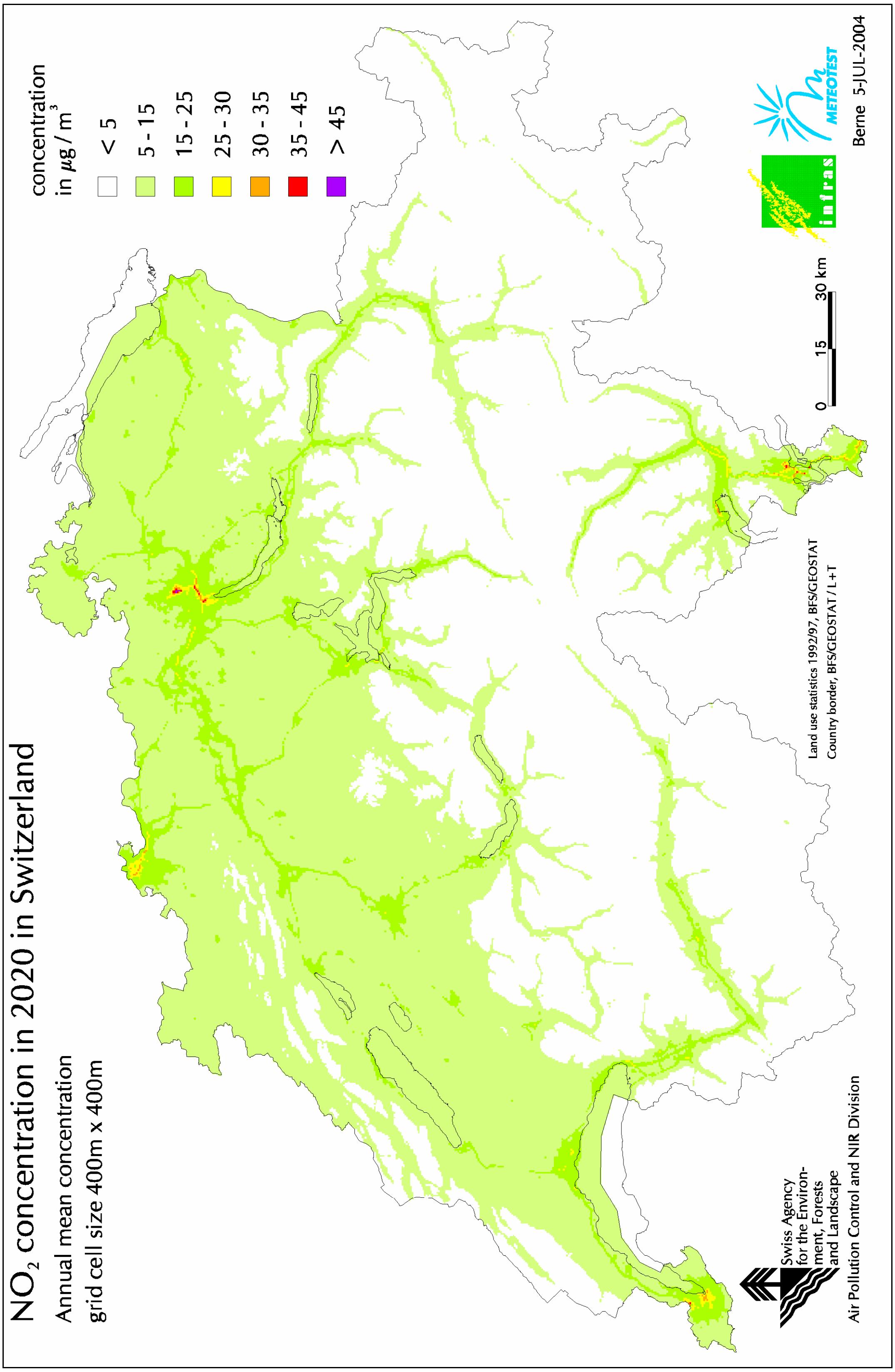


*Figure 23: NO$_2$ concentration in Switzerland for 2020.*

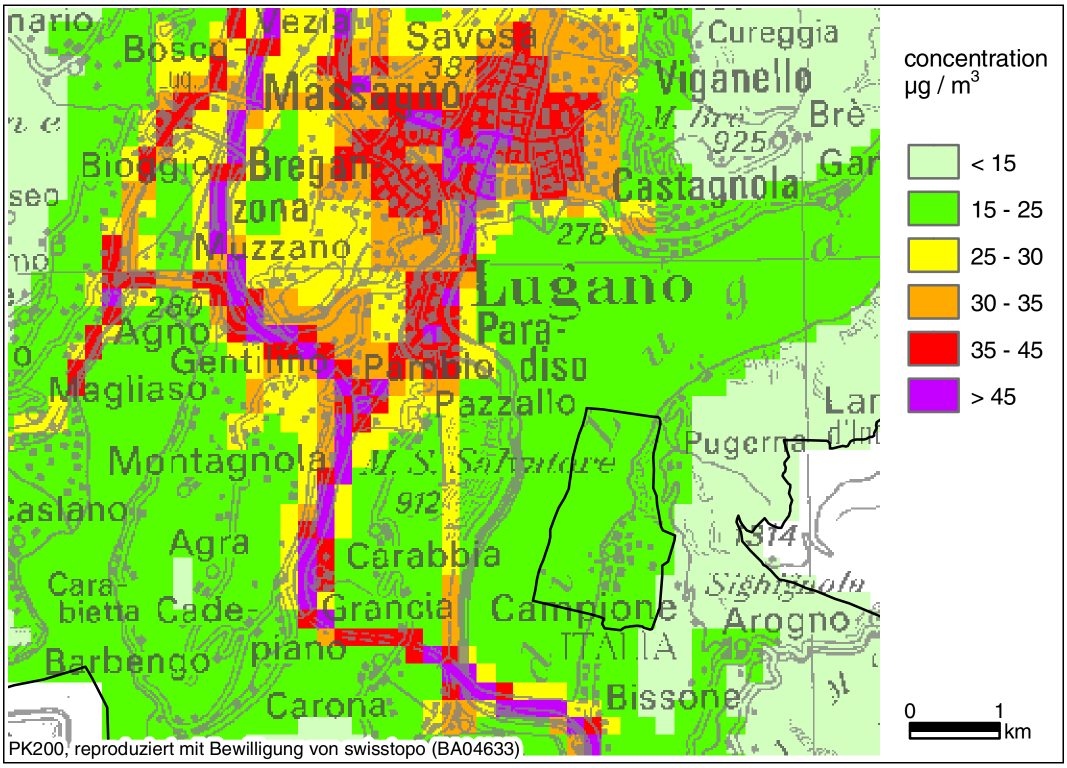


*Figure 24: $NO_2$ concentration in the Lugano area for 2000.*

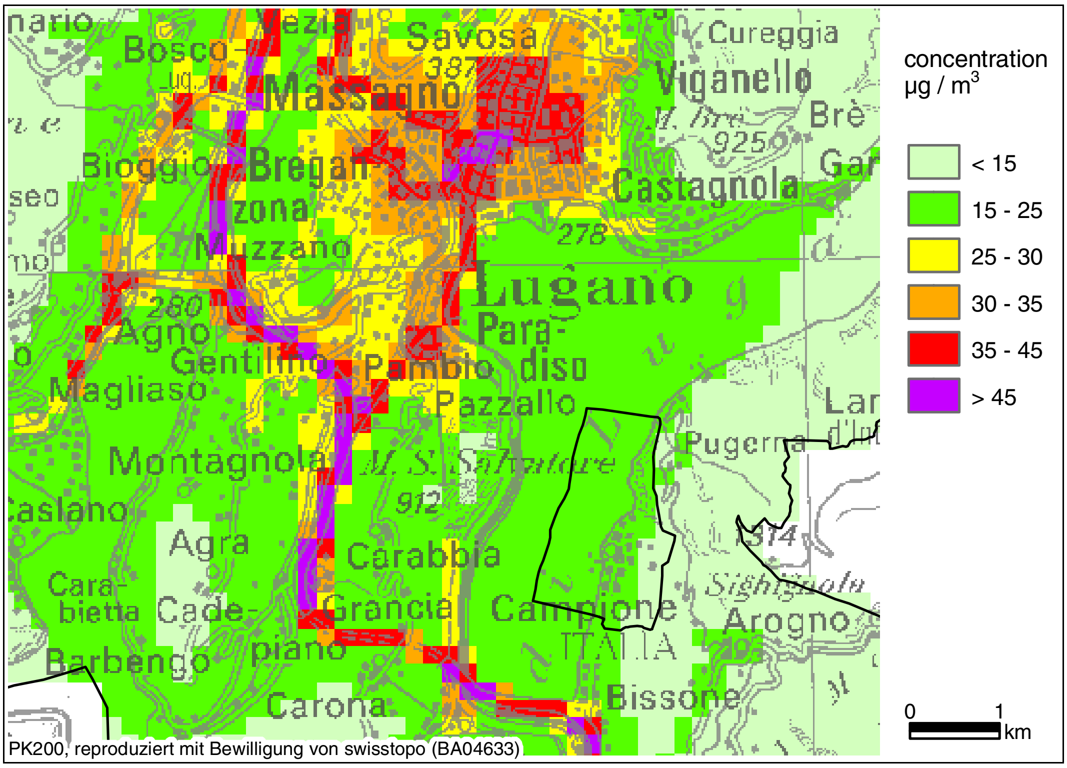


*Figure 25: $NO_2$ concentration in the Lugano area for 2005.*

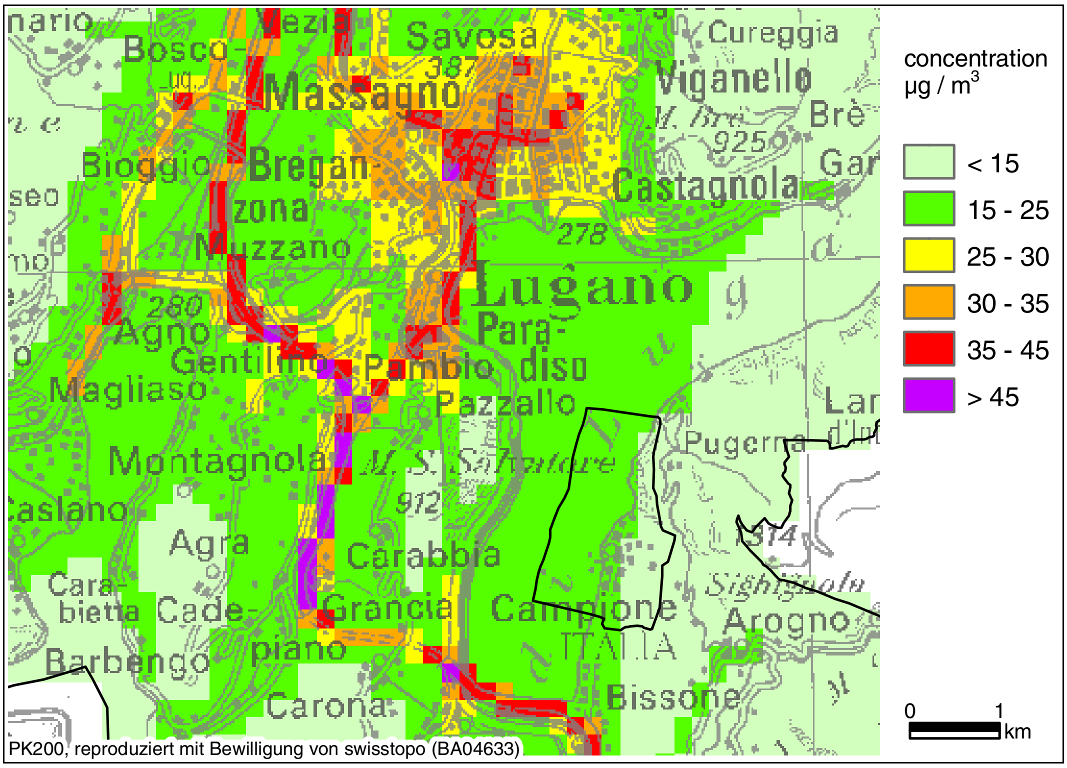


*Figure 26:* *$NO_2$ concentration in the Lugano area for 2010.*

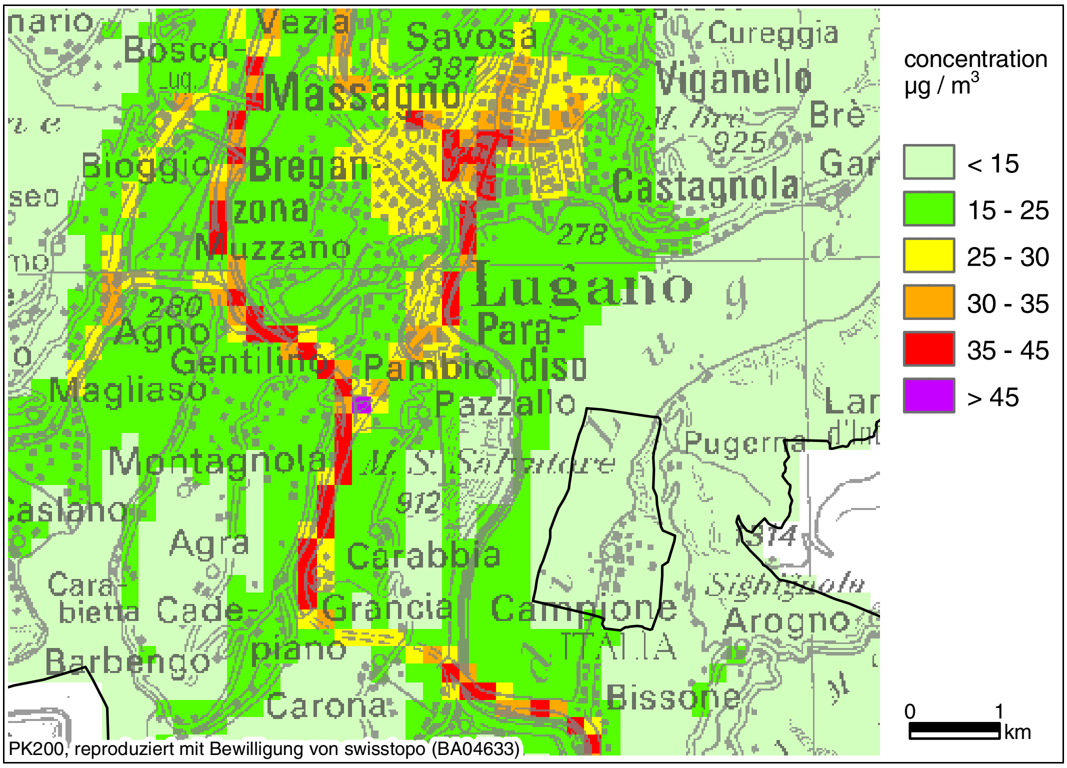


*Figure 27:* *$NO_2$ concentration in the Lugano area for 2020.*

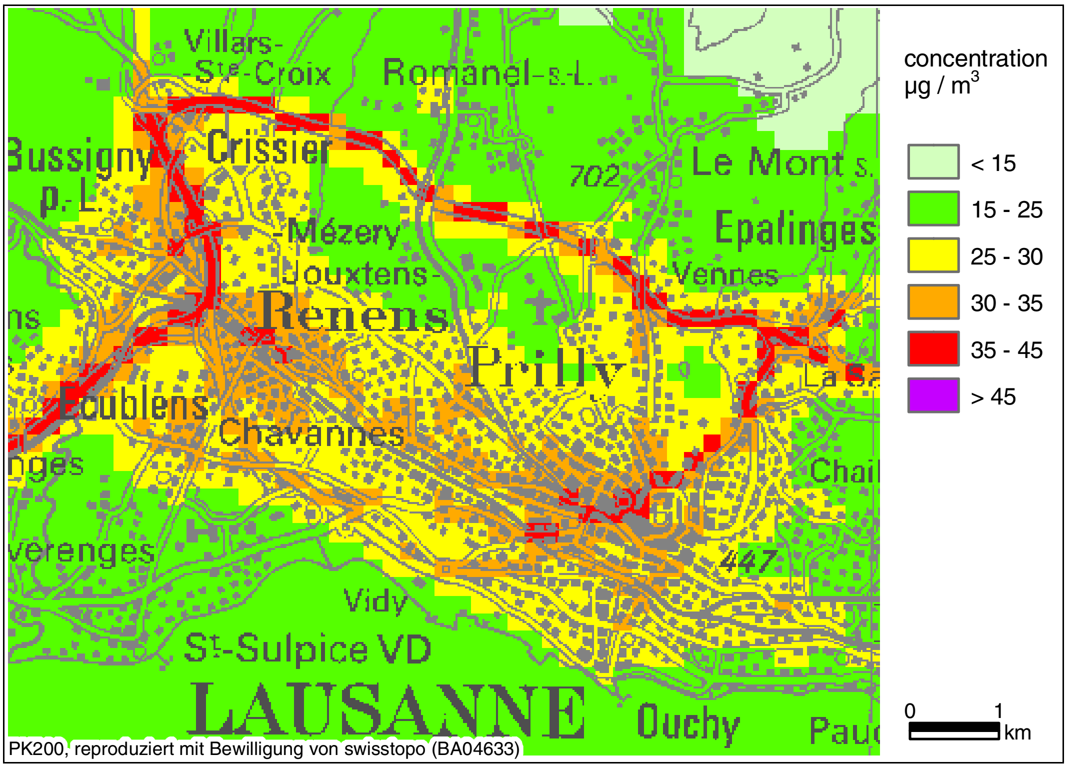


*Figure 28:* *$NO_2$ concentration in the Lausanne area for 2000.*

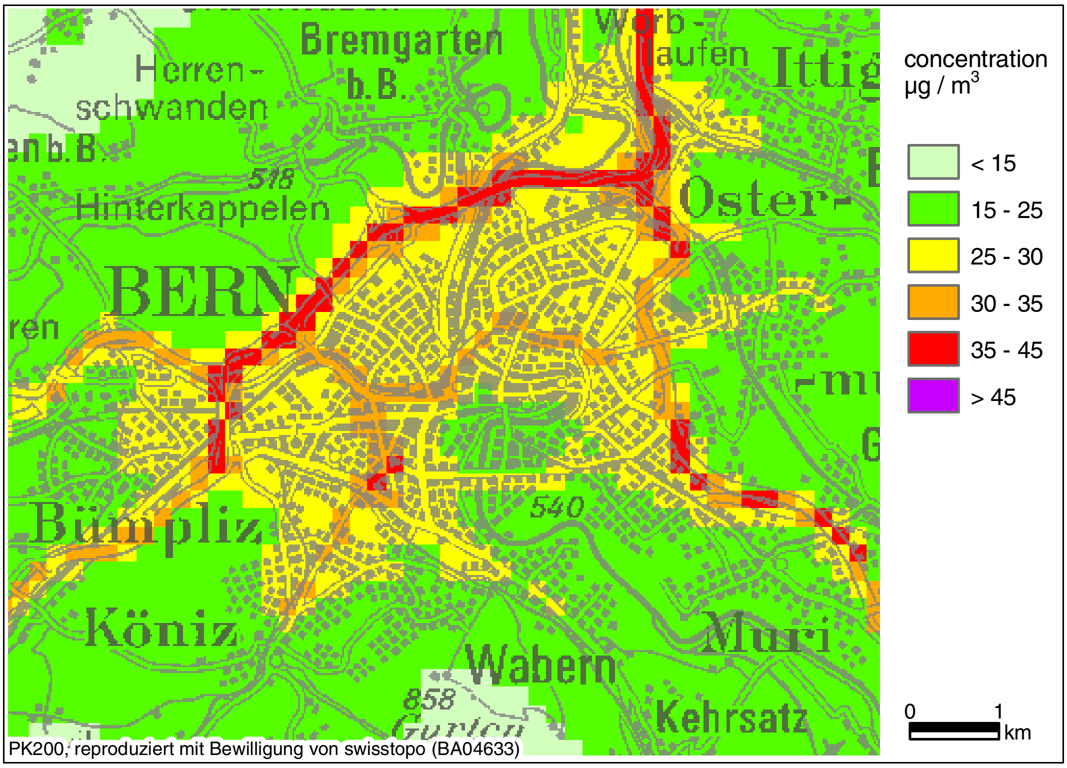


*Figure 29:* *NO2 concentration in the Berne area for 2000.*

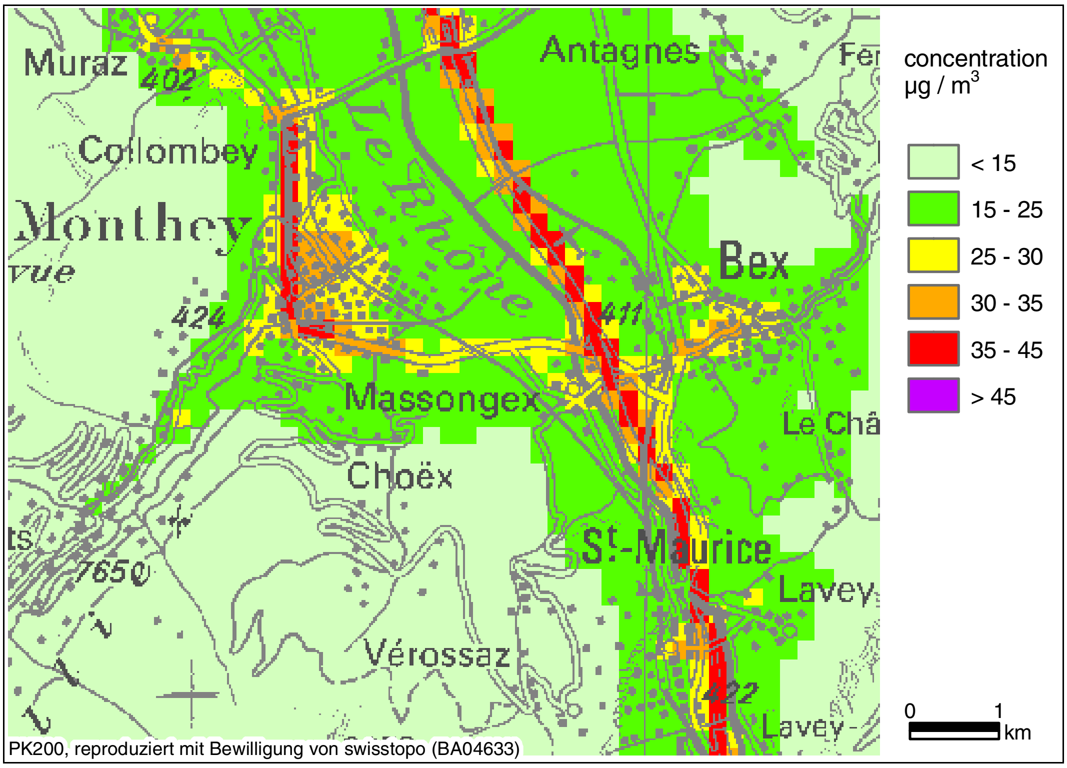


*Figure 30:* *$NO_2$ concentration in the Monthey area for 2000.*

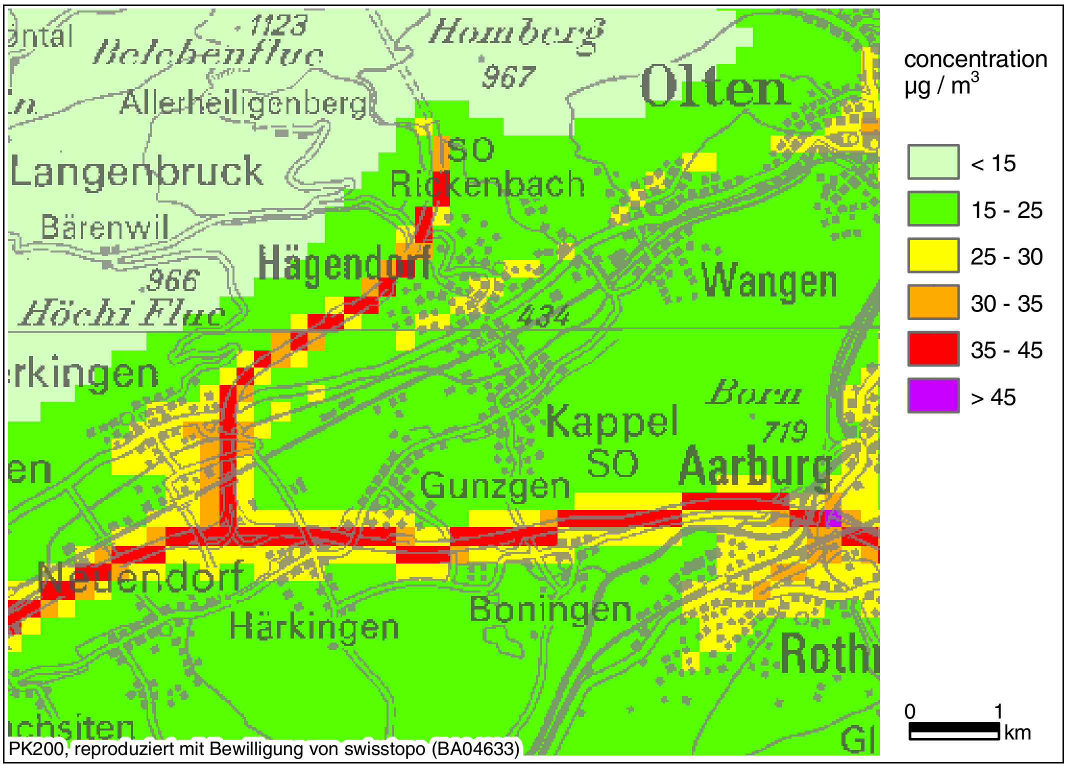


*Figure 31:* *$NO_2$ concentration in the Härkingen area for 2000.*

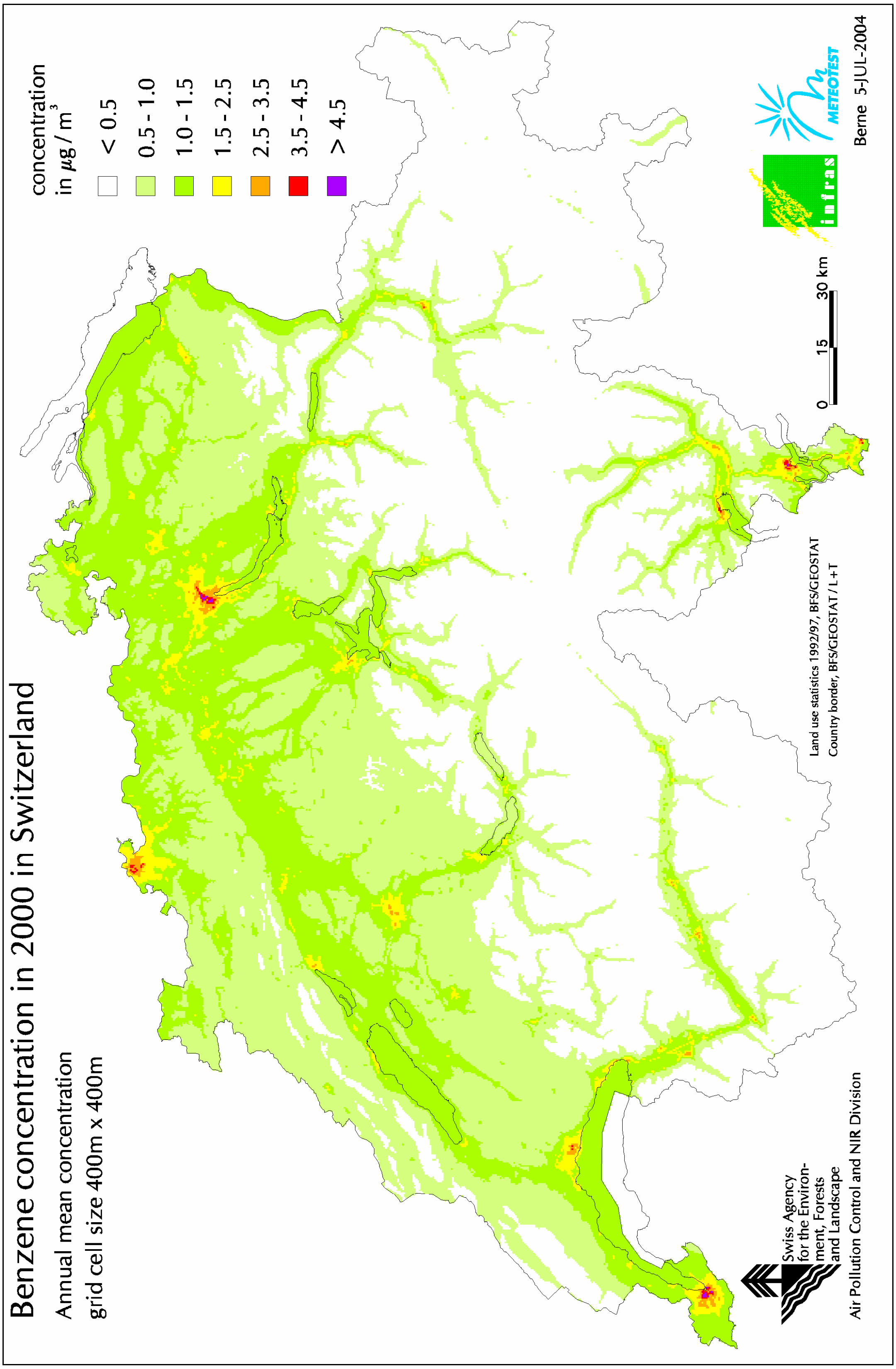


*Figure 32: Benzene concentration in Switzerland for 2000.*

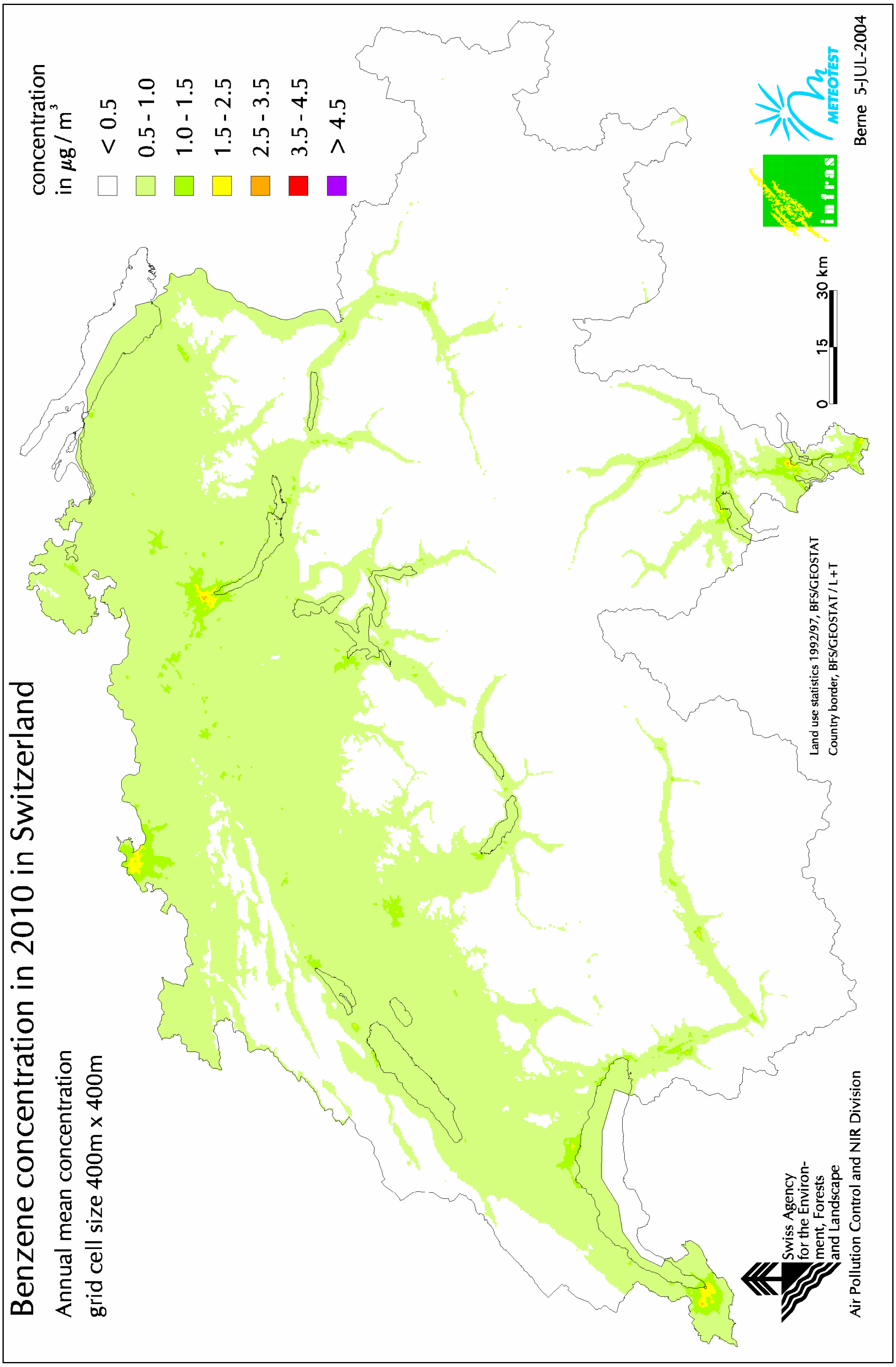


*Figure 33: Benzene concentration in Switzerland for 2010.*

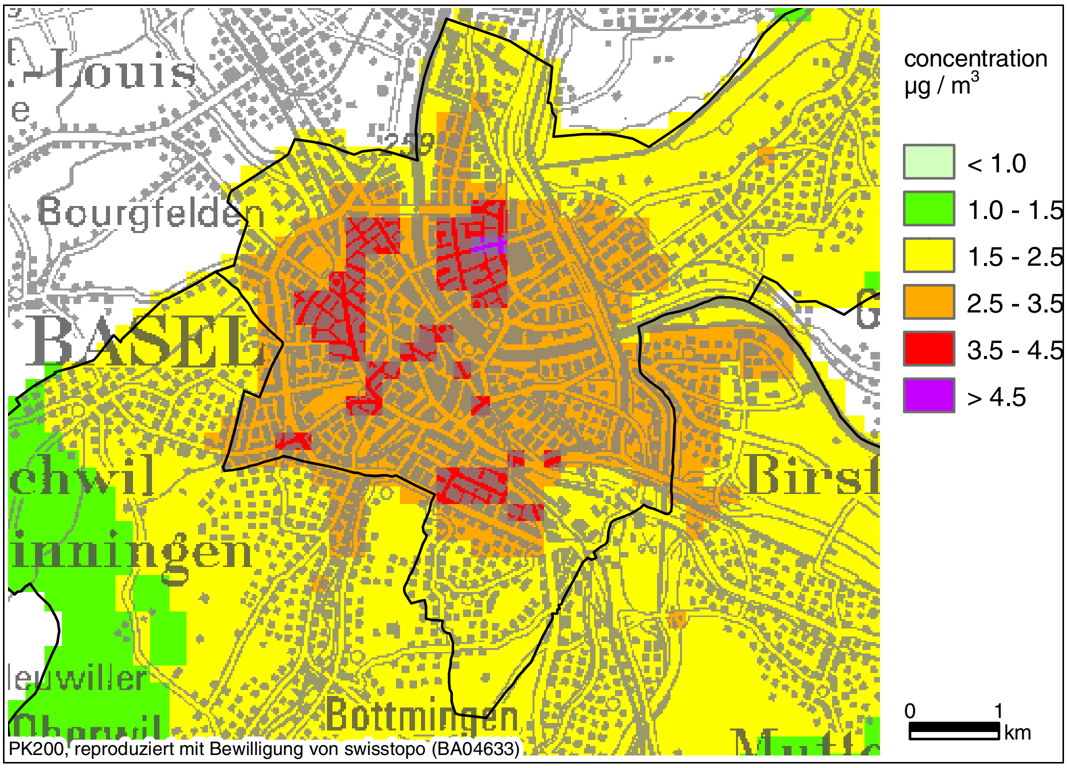


*Figure 34: Benzene concentration in the Basle area for 2000.*

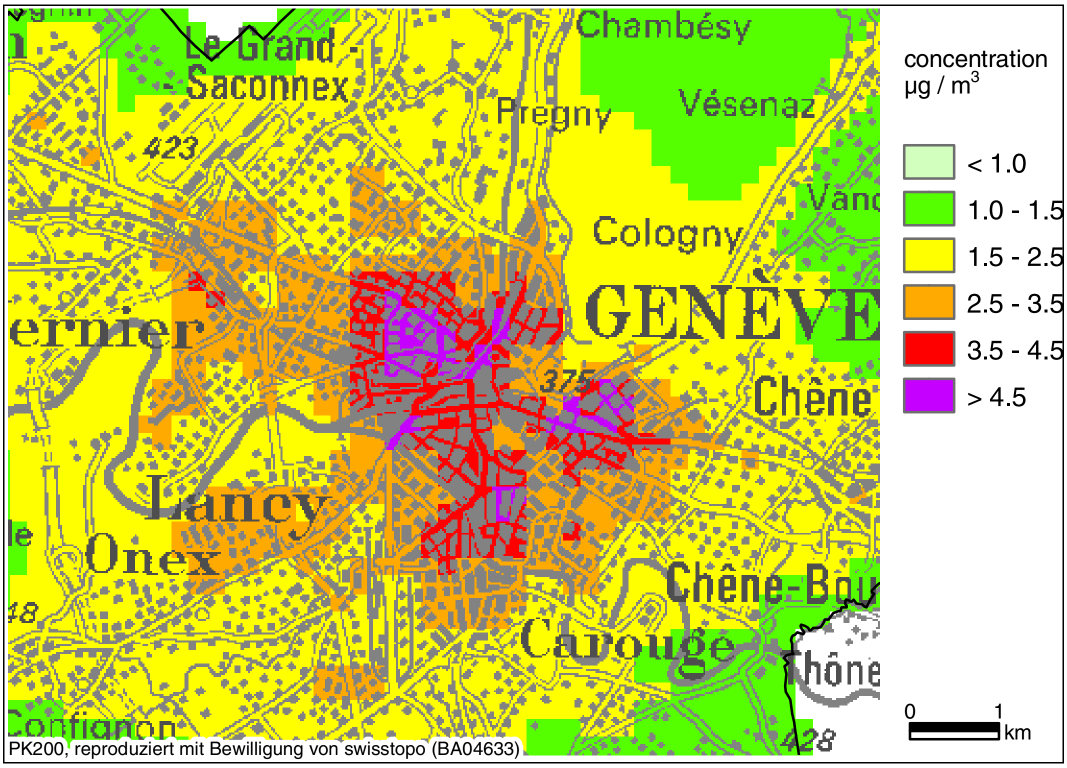


*Figure 35: Benzene concentration in the Geneva area for 2000.*

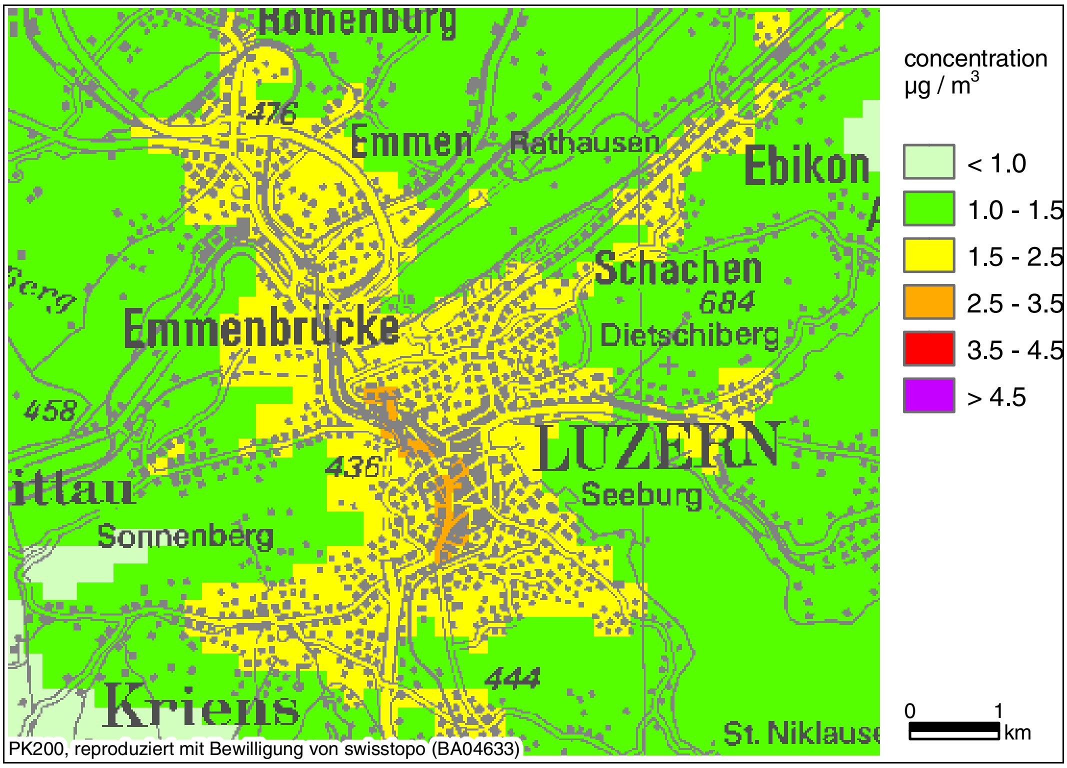


*Figure 36: Benzene concentration in the Lucerne area for 2000.*

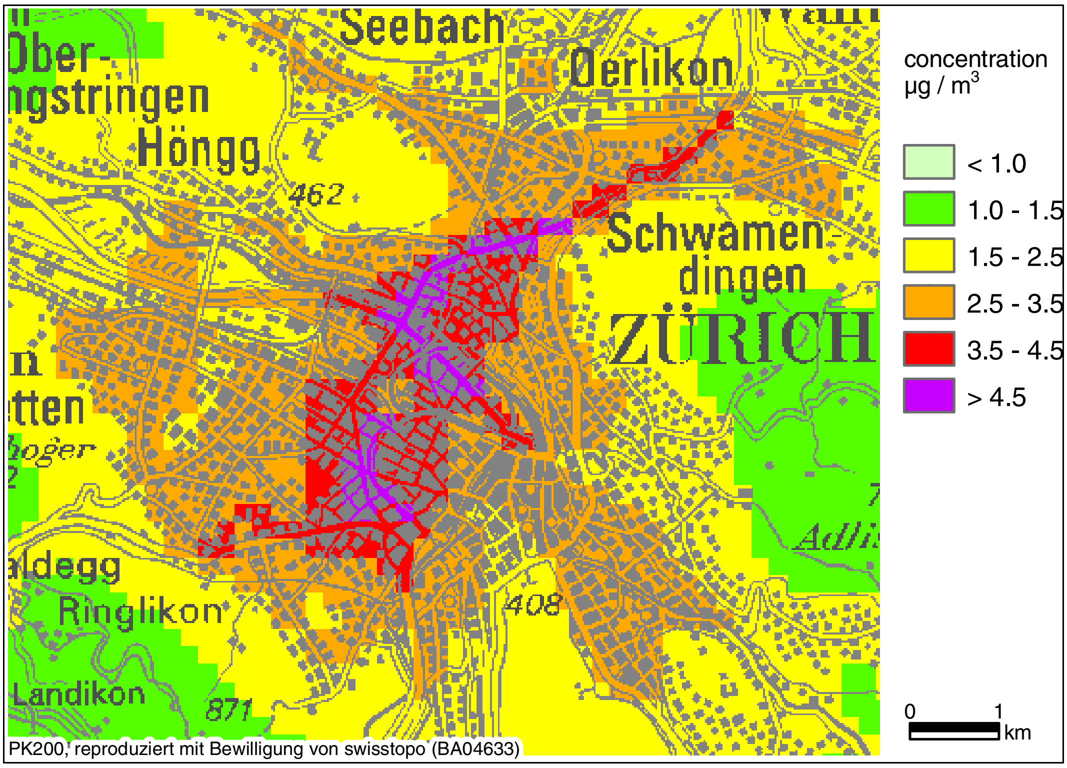


*Figure 37: Benzene concentration in the Zurich area for 2000.*