AUSBREITUNGSMODELLE FÜR GERUCHSSTOFFE ZUR ABSCHÄTZUNG VON GERUCHSBELÄSTIGUNGEN

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ABSTRACT

Odour emission of livestock buildings is a major burden for ambient residential areas. For modelling the annoying potential of a livestock building dispersion models are used to calculate ambient odour concentrations. The following steps are necessary: (1) assessment of the odour release of the livestock buildings, (2) a dispersion model (e.g. a Gaussian model) to calculate hourly or half-hourly ambient odour concentrations, and (3) a fluctuation module, calculating the instantaneous odour concentration, depending on wind velocity and stability of the atmosphere. Using this assessment of the maximum expected instantaneous odour concentration, (4) the separation distance between livestock buildings and residential areas are defined by odour impact criteria. These criteria are defined by a combination of a pre-selected odour threshold and an exceeding probability of the calculated odour concentration. These four steps of the chain starting with the odour release inside the livestock building up to the nose of the neighbours will be discussed in this paper.

INTRODUCTION

Odour is one of the major nuisances in the environment mainly caused by livestock units and industry. In the USA, about 70% of all complaints on air quality concern odour (Watts and Sweeten, 1995). For the UK, there were 3700 complaints about odour from farms in the years 1989 and 1990. This is about 25% of all complaints received by the Environmental Health Officers. More than half are caused by livestock buildings (building, slurry storage, feeding), the other half by slurry spreading. For Thüringen, Germany, 16% of all complaints in the year 1996 were odour related, 34% of these stem from agricultural sources. The complaints due to farms dominated with 89% over slurry spreading (11%) (cit in Schauberger et al., 2001)

The concentration of odorants can be handled like other volatile pollutants by well-known dispersion models. Therefore the following information has to be available: (1) odour release, describing the odour flow of the source; (2) an appropriate dispersion model to calculate the concentration at a receptor point as a mean value for a defined period (e.g. half-hour, 3-hours mean value, etc.); (3) the calculation of the instantaneous odour concentration; and (4) the validation of the instantaneous odour concentration taking into account the FIDO factors (frequency, intensity, duration and offensiveness) of odour sensation and the reasonableness.

ODOUR RELEASE OF LIVESTOCK

The odour release from livestock buildings originates from the animals, polluted surfaces and the feed. Outdoor odour sources such as slurry tanks or feed storage facilities are not taken into account in this paper. The emission of the livestock building at the outlet air is quantified by the odour flow E in OU/s and the specific odour flow e in OU/s LU normalised by the livestock unit (LU) equivalent to 500 kg live mass. The specific odour flow depends on the kind of animals and how they are kept. Available data are summarised in Table 1 based on a literature review of Martinec et al. (1998).

The odour release depends on several parameters, like other volatile components in the indoor air (e.g. NH_3, dust). (1) As odour production is a biochemical process, the temperature has an important influence. (2) Considering that odour is mainly released by the animals, by polluted surfaces and by feed, a diurnal variation in phase with animal activity seems probable. The temporal fluctuation of the odour release can be taken into account by a sinusoidal function in the same way as it is done for total energy, CO_2 and ammonia release by animals (Schauberger et al., 1999). (3) An important factor modifying the odour release is the air velocity above the relevant surfaces inside the livestock building (surface of the slurry, the floor of animal area, the surface of the animals). This air velocity depends on the volume flow of the ventilation system of the livestock building.

For mechanically ventilated buildings, all these parameters can be assessed by a steady-state balance model for sensible heat, which describes the behaviour of the control unit of the ventilation system (Schauberger et al., 2000a).

Tabel 1. Specific odour flow e (OU/m³ LU) for various species and types of keeping animals according to Martinec at al. (1998). The values can only be used as a first guess due to the small reliability of the measured data.

Animal	Kind of keeping animals	Specific odour flow e OU/s LU
Laying hen		
	cage / dry manure	17 to 23
	cage / liquid manure	89 to 153
	cage / partly dried manure	36 to 55
	ground / breeding	13 to 122
Turkey	Fattening	13 to 138
	Breeding	19 to 112
Duck	Fattening / cage / liquid manure	68 to 190
	Breeding / cage / liquid manure	75 to 379
Broiler	ground	8[1] to 318[2]
Pig	fattening / fully slatted floor	38 to 78 (495[s])
	fattening / partly slatted floor	52
	breeding sows	4 to 77
	pigglets / flatdeck	7 to 195
	young sows	32 to 419[s]
Cattle		2 to 56

[1] *start of the fattening period;* [2] *end of the fattening period;* [s] *for summer conditions only*

The approach presented here describes only mechanically ventilated livestock buildings. Naturally ventilated livestock buildings cannot be handled in this way because there is a lack of information about the specific odour flow for such systems. Furthermore, appropriate models are not available to calculate the volume flow caused by buoyancy and wind pressure. A simple assessment of the odour release of naturally ventilated buildings can be found by Jiang and Sands (1998).

DISPERSION MODELS

The concentration of odorants can be handled like other volatile pollutants by well-known dispersion models. Most of the regulatory dispersion models are based on the Gaussian concept. This means that the models calculate a mean ambient odour concentration for an integration time of a defined period (e.g. half-hour, 3-hours mean value, etc.).

The use of one of the Gaussian models to calculate odour concentration imposes some restrictions to the generalisation of the results achieved. The model is applicable only in flat terrain. Building influence on the dispersion as well as the influence of low-level capping inversions on the concentrations are not considered. The model is reliable only for wind velocities equal to or above 1 m/s and is advised to be applied for distances equal to or larger than 100 m. The restrictions are, however, not very severe because a lot of large livestock farms are situated in general in rather flat terrain.

Table 2: Overview of dispersion models used for odour emissions. Besides the type of the model also the assessment of the instantaneous odour concentration (peak-to-mean) is mentioned.

Name	Model type	Peak-to-Mean	Author
AODM	Austrian odour dispersion model; Gaussian model	stability and distance depending	Schauberger et al. (2000b and 2001)
AUSPLUME	Gaussian model	$(t_p/t_m)^{0.2}$; t_p=1s	Jiang and Sands (1998)
BAGEG	Gaussian model	fluctuation parameter is used for calibration	Krause and Lund (1993)
CALLPUFF	multi-layer, multi-species non-steady-state puff Gaussian model	not included	EPA http://www.epa.gov/ scram001
CARNEY	Gaussian model	factor 5 for 180 s to 5s	Carney and Dodd (1989)
CHEN	Gaussian model; adaptation of the variation parameters for odour	not included	Chen et al. (1998)
IBJXOdor	hybride Euler-Gaussian modell	?	Janicke (www.janicke.de)
LASAT	Lagrangian model	not included	Janicke (www.janicke.de)
MISKAM	3D non-hydrostatical model; only valid for neutral stability	not included	Eichorn (www.sfi-software.de)
ODIF 2.0	Gaussian model	TA Luft Faktor 10 ?	Medrow (1991) cit in Juergens and Promnitz 1998

ON M 9440	Gaussian model, regulatory model for Austria	not included	ÖNorm M 9440 (1992/96)
TA Luft	Gaussian model; regulatory model for Germany	peak-to-mean ratio = 10	TA Luft (1998)

Treating more complex meteorological or topographic conditions, more elaborate dispersion models have to be used. Such models (e.g. Lagrangian model) extend the statistical principle of the Gaussian idea to a more sophisticated incorporation of the atmospheric physics.

THE PEAK TO MEAN PROBLEM - ASSESSMENT OF THE EXPECTED MAXIMUM CONCENTRATION IN AN INTERVAL OF A BREATH -

The odour sensation is triggered by the odour stimulus and characterised by intensity and frequency. To predict these parameters it is necessary to consider short-term fluctuations of odorant concentrations at the receptor point. Odour sensation can only be observed if the odorant concentration is higher than the odour threshold of the substances. Due to fluctuations an odour sensation can take place even if the mean odorant concentration is lower than the odour threshold.

The Austrian regulatory model calculates half hour mean concentrations. The sensation of odour, however, depends on the momentary odour concentration and not on a mean value over a long time of integration. In the following, the approach of the Austrian odour dispersion model (AODM) to calculate peak concentrations is presented (Schauberger et al., 2000b and 2001) which depends on the wind velocity and on the stability of the atmosphere (stability classes SC, Reuter, 1970).

Smith (1973) gives the following relationship:

$$\frac{C_p}{C_m} = \left(\frac{t_m}{t_p}\right)^a \qquad (1)$$

with the mean concentration, C_m, calculated for an integration time of t_m and the peak concentration, C_p, for an integration time of t_p. Smith (1973) suggests the following values of the exponent a depending on the stability of the atmosphere: 0.35 (SC=4, neutral), 0.52 (SC=3, unstable) and 0.65 (SC=2, very unstable). Using t_m = 1800 s (calculated half-hour mean value) and t_p = 5 s (duration of a single breath), the following peak-to-mean factors, depending on atmospheric stability, are derived by a quadratic function based on the values of Smith (1973): 43.25 (SC=2), 20.12 (SC=3), 9.36 (SC=4), 4.36 (SC=5, slightly stable), 1.00 (SC=6, stable) and 1.00 (SC=7, very stable). The use of Eqn. 1 for periods that are as short as the period of a single breath are based on measurements of Mylne (1990).

These values are only valid close to the odour source. Due to turbulent mixing, the peak-to-mean ratio is reduced with increasing distance from the source. Mylne and Mason (1991) analysed the fluctuation of the plume concentration and developed the following relationship: The peak-to-mean ratio in equation (1) is modified by an exponential attenuation function of T/t_L, where $T=x/u$ is the time of travel with the distance, x, and the mean wind velocity, u, and t_L is a measure of the Lagrangian time scale (Mylne, 1992):

$$\Psi = 1 + (\Psi_o - 1)\exp\left(-0.7317\frac{T}{t_L}\right) \quad (2)$$

where Ψ_0 is the peak-to-mean factor calculated in equation 1.

The time scale, t_L, is taken to be equal to σ/ε where σ is the variance of the wind velocity as the mean of the three wind components *u, v*, and *w*, respectively, and ε is the rate of dissipation of turbulent energy using the following approximation:

$$\varepsilon = \frac{1}{k\,z}\left(\frac{\sigma_w}{1.3}\right)^3 \quad (3)$$

where k=0.4 is the von Karman constant and z=2m is the height of the receptor, the human nose. The ratio of the variances of the three components *u, v* and *w* to the horizontal wind velocity u depending on the stability of the atmosphere. For stability classes 6 and 7 no change of the peak-to-mean ratio is assumed. For σ_u / u and σ_v / u, values are taken from Robins (1979), and no change with stability is assumed. σ_w / u is taken to be stability-dependant, using our long-term Sodar experience which suggests an increasing importance of σ_w compared to *u* in unstable conditions.

The peak concentration, C_p, is calculated by the following equation:

$$C_p = C_m \cdot \Psi \quad (4)$$

The approach assures a gradual decrease of the peak to mean – ratio with increasing distance, wind velocity and stability, as can be seen from Fig. 1. For classes 2 and 3, Ψ, starting at rather high values near the source and at low wind velocities, rapidly approaches 1 with increasing wind velocity and distance. This is in agreement with the premise that vertical turbulent mixing in weak winds can lead to short periods of local high-ground level concentrations, whereas the ambient mean concentrations are low. For class 4, the decrease of the peak to mean – ratio is more gradual with increasing wind velocity and distance, because vertical mixing is reduced and horizontal diffusion is dominating the dispersion process. This is even more the case for class 5, when the peak to mean – ratio never exceeds 2. Compared to uncorrected peak to mean the damping is most effective for class 2 and decreases with increasing class number.

The peak-to-mean problem is discussed in detail by a Katestone Scientific report (1998). The approach presented in this paper is a major improvement compared to a constant peak-to-mean ratio e.g. a factor of 10, according to the German regulatory TA Luft (1986) or a pure dispersion models for odour using no correction for the instantaneous concentration. In Germany, the BAGEG model (Begehungskalibrierte Ausbreitungssimulation für Geruchsstoffe), developed by Krause and Lung (1993), uses a Gaussian model and a fluctuation module which is used for a calibration against field measurements according to VDI 3940 (1993). Nevertheless this approach has no meteorological background.

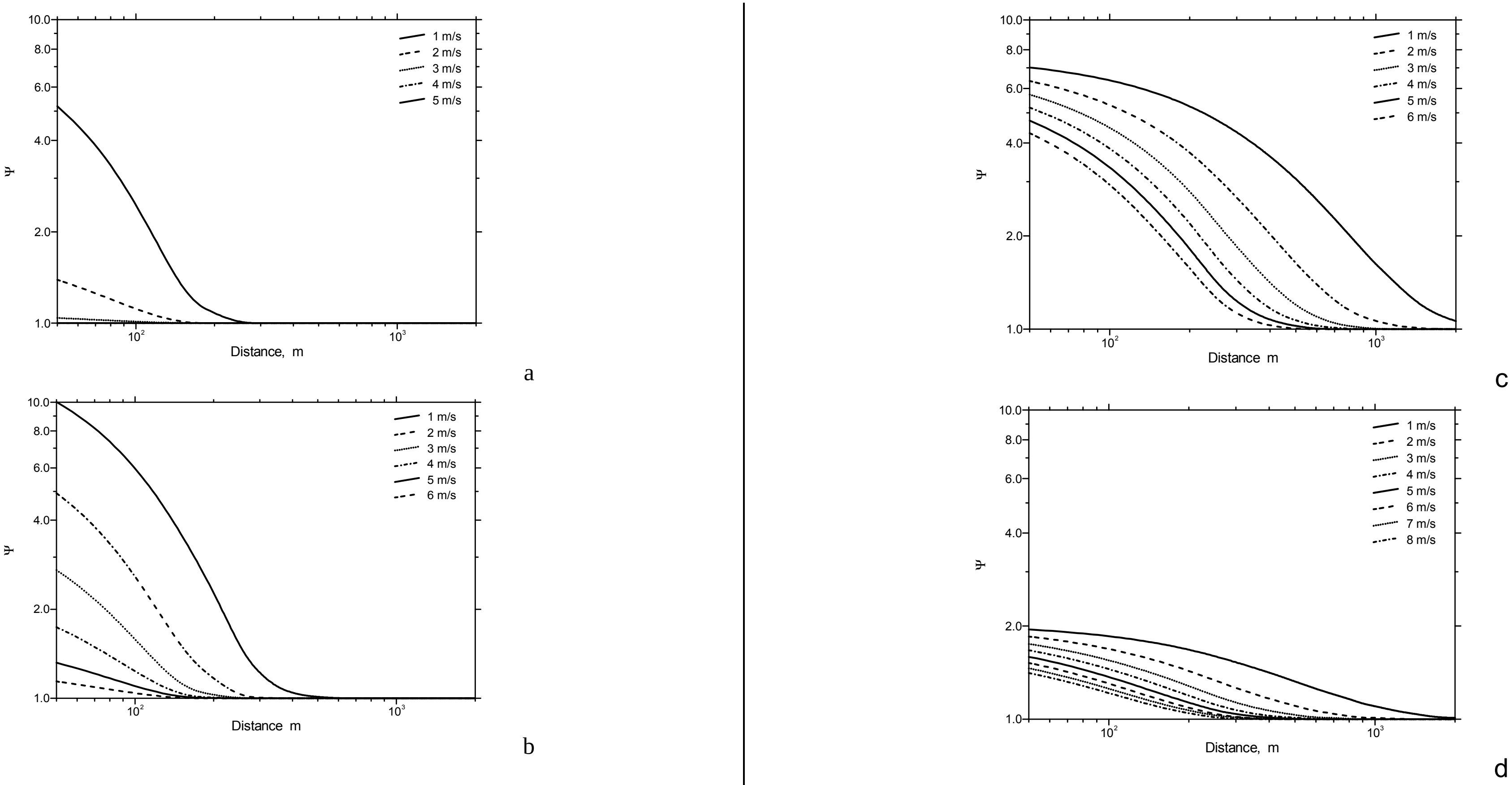

Figure 1: Dependence of the attenuation function Ψ of the peak to mean ratio with distance for stability class 2 (a), 3 (b), 4 (c) and 5 (d)

ODOUR IMPACT CRITERIA

With the selected dispersion model, the separation distance is calculated by using a threshold of the odour concentration and its exceeding probability. The odour impact criteria are based on these two parameters and are summarised in Table 3 for Austria (Stangl *et al.*, 1993), Germany (Knauer, 1994; Kypke, 1994), Thüringen, Germany (Lotze and Schwinkowski, 1998), UK (Hobson, 1997, personal communication), Australia (Jiang and Sands, 1999), The Netherlands (Hagen and van Belois, 1998, Denmark, New Zealand and Massachusetts (USA) (after Jiang and Sands, 1998).

From Table 3 it is apparent that odour thresholds in combination with their exceeding probabilities are explicitly related to land-use categories in Germany, the Netherlands, and Australia only. In all these countries, residential areas, in which, apart from existing installations, animal farming usually is not allowed, are best protected. However, the threshold systems are different. In Germany (including Thüringen) and the Netherlands, only the exceeding probability varies according to the land-use category. In Australia, the odour threshold varies, whereas the exceeding probability is fixed. In the UK, the odour thresholds are related to different levels of annoyance. Depending on the kind of odour threshold fulfilled for the investigated farm, the level of annoyance can be determined. Property domains are relevant for the validity of odour thresholds in Denmark, New Zealand, and Massachusetts, USA. Medical aspects led to the definition of the Austrian odour threshold.

Table 3: Odour impact criteria: Limits of odour concentration and exceeding probability used in Austria (Stangl et al.*, 1993), Germany (Knauer, 1994; Kypke, 1994), Thüringen, Germany (Lotze and Schwinkowski, 1998), UK (Hobson, 1997, personal communication), Australia (Jiang and Sands, 1998), The Netherlands (Hagen and van Belois, 1998, Denmark, New Zealand and Massachusetts (USA) (after Jiang and Sands, 1998)*

Odour impact criteria[1]	Land use category[2]	Label[3]
Australia		
5 OU/m³ / 0.5%	rural and urban area; New South Wales	AUS1
2 OU/m³ / 0.5%	residential area; Victoria	AUS2
10 OU/m³ / 0.5%	residential areas	AUS3
Austria		
1 OU/m³ / 8% and 3 OU/m³ / 3%	threshold for reasonable odour sensation for medical purpose	AUT
Denmark		
5 - 10 OU/m³ /.1%	plants	DEN1
0.6 – 20 OU/m³ / 1%	surrounding	DEN2
Germany		
1 OU/m³ / 3%	pure residential areas and residential areas	G-PURE
1 OU/m³ / 5%	residential and structured areas	G-MIX1
1 OU/m³ / 8% and 3 OU/m³ / 3%	restricted business-areas and village-area with mixed utilisation	G-MIX2
1 OU/m³ / 10% and 3 OU/m³ / 5%	village-areas with predominantly agricultural utilisation	G-AGR
Germany, Thüringen		
1 OU/m³ / 7%	pure residential areas and residential areas (WR)	GT-PURE
1 OU/m³ / 10%	general residential areas and mixed utilisation (WS, WA; WB, MI, MK)	GT-MIX1
1 OU/m³ / 12%	villages (MD)	GT-VIL1
1 OU/m³ / 15%	villages with existing livestock units above a certain limit (MD)	GT-VIL2
1 OU/m³ / 15%	business areas (GE)	GT-BUS
1 OU/m³ / 15%	Industry (GI)	GT-IND
Massachusetts, USA		
5 OU/m³ / 0.5%	plant boundary	USA
The Netherlands		

1 OU/m³ / 2%	residential areas; existing units	NL
1 OU/m³ / 0.5%	residential areas; new installations	NL
1 OU/m³ / 5%	residential areas outside of villages and business areas	NL
New Zealand		
2 OU/m³ /.0.5%	property boundary	NZ
UK		
10 OU/m³ / 2%	Serious annoyance expected with near certainty	UK1
5 OU/m³ / 2%	Generally acceptable for existing installations. Emissions from stacks or large area sources may be acceptable at the relaxed end of the range	UK2
1 OU/m³ / 2%	No serious annoyance expected in the large majority of cases	UK3
1 OU/m³ / .5%	Safe target value for new sources	UK4
10 OU/m³ / 0.01%	Safe target value for new sources applicable to highly intermittent sources	UK5

[1] *Odour concentration threshold (OU/m^3) / Percentile compliance: Exceeding probability for the odour concentration threshold p (%);* [2] *The lend use category varies the accepted protection level;* [3] *The labels are used in the following tables and figures*

Odour concentrations calculated by dispersion models at a certain point have to be evaluated against the odour impact criteria. Watts and Sweeten (1995) suggest the four factors frequency, intensity, duration and offensiveness (FIDO) of odour to assess the nuisance capacity. Besides these FIDO factors the concept of reasonableness has to be taken into account (e.g., land use category). Based on this concept, a definition is suggested based on the exceeding probability of a certain threshold and reasonableness for rural and urban sites. The odour threshold T (OU/m³) as a function of the exceeding probability p (h/a) is calculated by $T_{rural} = 800/p$ and $T_{urban} = 400/p$. According to Miner (1995), the reasonableness of odour sensation is causing fewer objections within a community where odour is traditionally part of the environment. Lohr (1996) found that personal knowledge of the operator of the livestock unit, long term residence, economic dependence on farming, familiarity with livestock farming and awareness of agricultural-residential context are related with fewer reports of annoyance.

The odour thresholds for urban and rural impact as well as some odour impact criteria used in various countries for regulatory purposes are shown in Figure 2. The review of Watts and Sweeten (1995) shows that the presently used limits to assess odour nuisance are based on very little data. Only one paper was found which presents the result of a dispersion model and a sociological survey assessing the percentage of “annoyed” and “very annoyed” people in the vicinity of an odour source (Miedema and Ham, 1988). Winneke *et al.* (1990) give an exceeding probability of 3% to 5% of the year for an average sensitive person. The limits of odour impact criteria suggested by Watts and Sweeten show a similar behaviour. Especially if a pair of limit values is used for the definition (G-AGR, AUT and G-MIX2) of the impact criteria, the slope of these lines are almost the same, as shown in Figure 2.

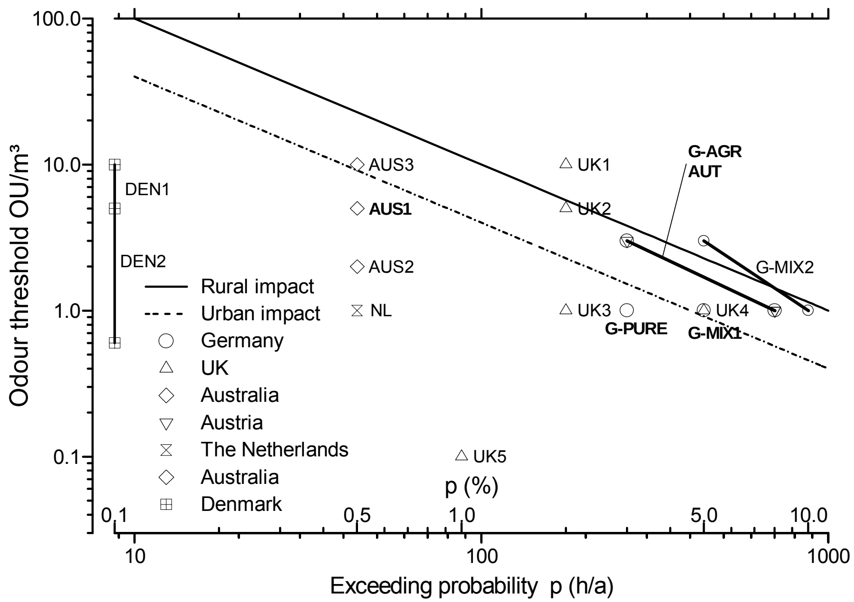

Figure 2: Impact criteria of various countries defined by an odour threshold and its exceeding probability (Tab.3) and the criteria for rural and urban impact, suggested by Watts and Sweeten (1995).

CONCLUSIONS

The model calculation of odour dispersion and the subsequent evaluation of the ambient odour concentration by the odour impact criteria describes the chain of the odour release inside the livestock building to the nose of the neighbours and the prospective annoyance by odour sensation with varying levels of quality and uncertainties.

- The assessment of odour emission of livestock buildings is based on few data. Up till now no long-term measurements are available to evaluate and to improve the model.
- Dispersion models which are in use for odour emissions are well validated. This chain-link needs no further improvement compared to the other model steps.
- The model to calculate the instantaneous odour concentration is based on few experiments, most of them were done for a neutrally stratified atmosphere. For an improvement, additional measurements for the stable and unstable atmosphere seems necessary.
- The odour impact criteria which are used to evaluate the calculated odour concentrations in the vicinity of a livestock building are based on very simple statistical criteria (exceeding probability and odour concentration threshold). Additionally, a weighting of odour sensation by the time of the day and time of the year, in a similar way as it is done for noise, seems to be appropriate to improve the assessment.

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