DETERMINATION OF THE SURFACE ROUGHNESS LENGTH FOR USE IN MESOSCALE AIR QUALITY MODELLING

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ABSTRACT

The surface roughness length z_0 is an important parameter in air quality modelling. Methods for estimating this parameter for the Eastern Transvaal Highveld, using available data, were investigated. The use of existing geographical maps to determine land cover suffers from certain deficiencies. Tethersonde wind speed profiles were found to be inadequate for the purpose of the determination of z_0, and it would seem that time-averaged wind speed measurements along a mast are required.

OPSOMMING

Die oppervlakgrofheidslengte z_0 *is 'n belangrike parameter in luggehaltemodellering. Metodes om beskikbare data te gebruik om ramings van die parameter vir die Oos-Transvaalse Hoëveld te maak, is ondersoek. Daar is gevind dat die gebruik van bestaande geografiese kaarte om grondgebruik te bepaal, sekere tekortkominge het. Ontledings het getoon dat ankerballonpeilings van vertikale windspoedprofiele ontoereikend is om* z_0 *te bepaal. Tydgemiddelde windspoedmetings langs 'n mas sal waarskynlik nodig wees.*

1. INTRODUCTION

Modern air quality models generally have complex input requirements. The main components of this input are wind and turbulence fields. The wind field can be generated from measurements of wind speed and direction. The required turbulence data can be determined indirectly in terms of Monin-Obukhov lengths and mixing layer heights. Both these parameters are functions of the surface friction velocity, which in turn depends on the surface roughness length z_0. Removal by dry deposition, an important component of air quality modelling, also depends, *inter alia*, on surface properties and as a consequence, on z_0. Thus, the reliable determination of z_0 is a necessary and important component of air quality modelling.

A mesoscale air quality model, MESOPUFF II (Scire, 1984), developed at Environmental Research and Technology, Inc. under contract to the Environmental Protection Agency, USA, is currently being adapted at the Atmospheric Sciences Division to suit local conditions and requirements. This model is a Lagrangian variable trajectory puff superposition model, suitable to modelling the regional advection, the turbulent diffusion and the removal of air pollutants emitted from multiple point and area sources. This model requires representative surface roughness lengths for the area under study, and provides the option to the user either

(a) to assign a predominant land cover category (as listed in Table 1) to each geographical grid element in which case the z_0 given in Table 1 will be assigned to the grid elements on execution of the program, or

(b) to specify z_0 for each grid element.

TABLE 1

LAND USE CATEGORIES AND ASSOCIATED Z_0 IN MESOPUFF II
(Scire, 1984)

Category	Land use type	Summer-time Z_0 (m)
1	Cropland and pasture	0,20
2	Cropland, woodland and grazing land	0,30
3	Irrigation crops	0,05
4	Grazed forest and woodland	0,90
5	Ungrazed forest and woodland	1,00
6	Subhumid grassland and semi-arid grazing land	0,10
7	Open woodland grazed	0,20
8	Desert shrubland	0,30
9	Swamp	0,20
10	Marshland	0,50
11	Metropolitan city	1,00
12	Lake or ocean	10^{-4}

A number of ways of using locally available data to generate the required input, were investigated.

2. DETERMINATION OF SURFACE ROUGHNESS

The effect of surface roughness elements is essentially the slowing down of the near surface flow of air and the transformation of kinetic energy to turbulent energy. As mentioned previously, the surface friction velocity can be expressed as a function of the surface roughness length z_o, which in turn depends on land cover characteristics like the height, shape and density of obstacles, as well as on wind speed (Chamberlain, 1968; Lettau, 1969,Kawatani and Meroney, 1970; Sadeh *et al.*, 1971; Andrè and Blondin, 1986). The recommended procedure to determine z_o for modelling use, is

(a) the classification of land cover according to obstacle type, and

(b) for each category of land cover, the quantification of z_o based on suitable vertical wind profiles or on turbulence measurements.

2.1 Determination of land cover

In some countries land cover data can be supplied by centralised information centres, e.g. in the USA by the MAP3S data bank (Sheih, *et al.* 1979) and in Japan by the Digital National Information data bank (Kondo and Yamazawa, 1986). Where such data are not readily available, the land cover characteristics of the area of interest must be established by *in situ* surveys, map analyses, remote sensing techniques or a combination of these methods.

2.2 Quantification of Z_o

Although there have been some attempts to determine z_o from turbulence measurements, e.g. gust measurements (Wieringa, 1973, Wieringa, 1981), the determination of z_o from vertical wind profiles remains, for various reasons, the preferred method (Businger, *et al.*, 1971; Fiedler and Panofsky, 1972; Tennekes, 1973; Munro and Oke, 1973; Nieuwstadt, 1977; Brutsaert, 1982; Ming, *et al.*, 1983).

This method is based on the similarity theory of Monin and Obukhov (1954):

$$\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{kz} \Phi_m(\xi) \qquad (1)$$

where

z	is height (m),
u	is wind velocity (m.s.$^{-1}$),
u_*	is surface friction velocity (m.s.$^{-1}$),
k	is the von Karman constant,
$\Phi m(\xi)$	is dimensionless wind shear.

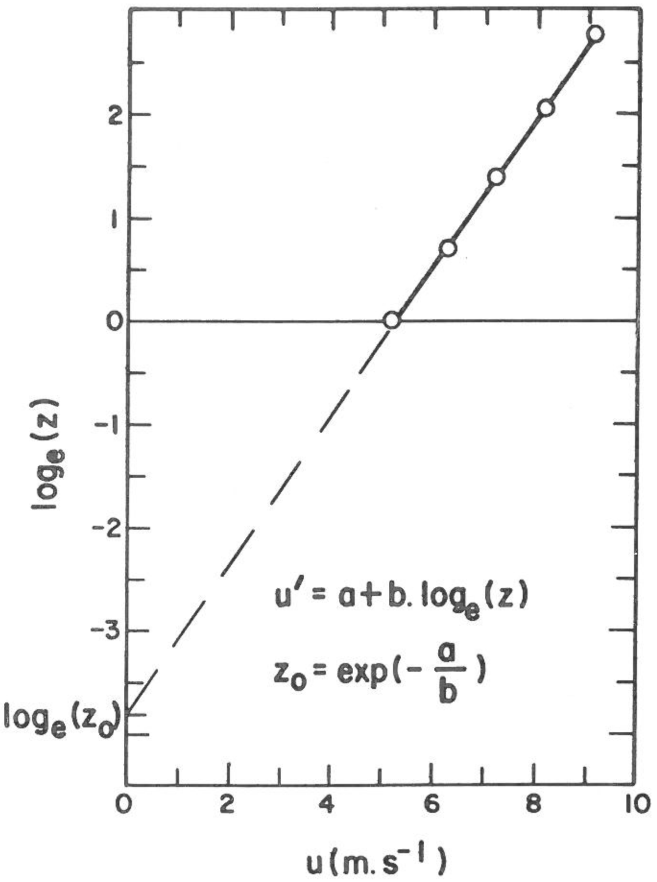

Figure 1 *Illustration of the use of regression analysis to determine z_o from wind profiles measured under neutral conditions.*

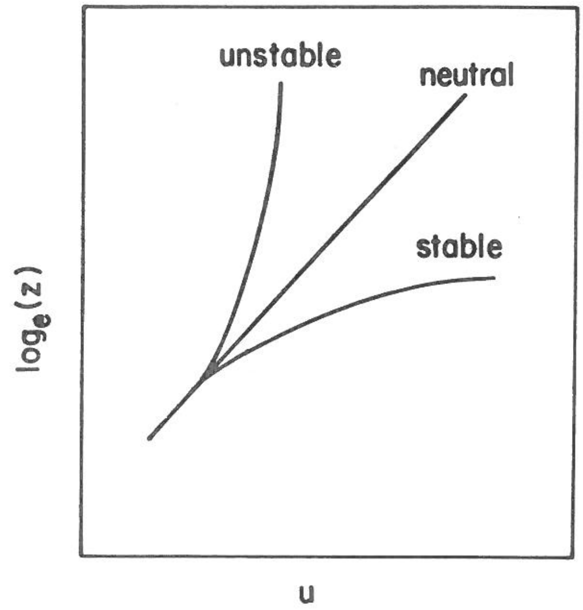

Figure 2. *Vertical wind speed profiles measured under unstable, neutral and stable conditions. From: Randerson, 1984.*

Under neutral atmospheric conditions, provided the boundary layer is characterised by small variations in stress, the terrain is horizontally uniform and the pressure and Coriolis force are negligibly small, the above relationship reduces to

$$u = \frac{u_*}{k} \log_e \left(\frac{z}{z_o} \right) \qquad (2)$$

where z_o is surface roughness length (m).

Thus, when vertical wind profiles measured under neutral conditions are subjected to linear regression analysis the constants of the regression of u on $\log_e$ (z) can be used to determine z_o, as illustrated in Figure 1. Typical profiles for stable, neutral and unstable conditions are shown in Figure 2 to demonstrate the non-linear relationships which apply under stable and unstable conditions.

3. LAND COVER CLASSIFICATION OF EASTERN TRANSVAAL HIGHVELD

In the coal-rich Eastern Transvaal Highveld (ETH), SO_2 is emitted from a large number of coal-fired power stations. Being an area of known poor dispersion characteristics during winter, the ETH presents a unique opportunity of applying MESOPUFF II. As no numeric land cover data were available for the ETH, it was decided to analyse maps of the area. Although 1:10 000 orthophotomaps would yield more recent data of high resolution, the acquisition and analysis of the 1 400 maps required to cover the area (200 km x 140 km) argued against this approach. It was consequently decided to analyse 1 : 50 000 maps and to support the analysis with orthophotomaps and *in situ* area surveys where necessary.

TABLE 2

REVISED LAND USE CATEGORIES AND SUGGESTED Z_o

Land use type	Winter-time Z_o (m)	Summer-time Z_o (m)
* Buildings	–	–
* Huts	–	–
* City	–	–
High level urban	2,0	2,0
Low level urban	0,5	0,5
* Dry pans	0,01	0,01
* Cultivated land	0,02	0,5
* Trees and bushes	0,2	0,2
* Marshes, vleis	–	–
Vleis	0,12	0,12
* Non-perennial water	0,01	10^{-4}
* Water	10^{-4}	10^{-4}
* Grassland	0,02	0,15

* Indicated on 1:50 000 maps.

The choice of suitable land cover categories was based on the type of information given on the maps, on area surveys and on a literature study of conditions for which z_o had been established (see Table 2).

In view of the size of the area of interest and certain limitations imposed by the model, the grid element size was set to 10 km x 10 km. Due to the variability of land cover and the size of the grid elements, it was not possible to allocate a single land cover category to each element, and a modified procedure of establishing the effective surface roughness length for each grid element as required by MESOPUFF II was followed.

For each grid element in the study area, the percentage of the area which could be allocated to each land cover category was evaluated visually. The effective surface roughness length Z_o^{eff} for each element was calculated as follows (Mulholland, 1977):

$$z_o^{eff} = \exp \frac{\sum_{j=1}^{n} A_j \,.\, \log_e (z_{oj})}{\sum_{j=1}^{n} A_j} \qquad (3)$$

where A_j is percentage of area of grid element allocated to land cover category j,
z_oj is z_o chosen for land cover category j,
n is number of land cover categories.

4. DETERMINATION OF Z_o FROM TETHERSONDE DATA

The possibility of the determination of z_o by regression analysis of actual vertical wind profiles was also investigated. The only potentially suitable data were instantaneous tethersonde data collected during winter for the period 1982–1985 at selected sites in the ETH (Held, 1985).

Three sites, at which the largest number of profiles were measured, were selected for analysis. Due to the diverse conditions under which the soundings were done, a screening procedure was introduced to identify profiles or portions of profiles suitable for regression analysis:

(a) profiles measured under calm conditions, i.e. with more than 25% of the observed wind speeds lower than 1 m.s^{-1}, were disqualified;

(b) in the remaining profiles, outlying observations (i.e. with speed increments of less than $-0,3$ m.s.$^{-1}$) were eliminated;

(c) the upper limit of the smoothly increasing portion of each remaining profile was established at observation j when

$$u_{j+1} - u_j > 0,5 \text{ m.s.}^{-1} \text{ and } u_{j+2} - u_j > 1,0 \text{ m.s.}^{-1}.$$

Acceptable profiles or portions of profiles were analysed as described in Section 2.2 and z_o and the correlation coefficient r were calculated for each case. Results of analyses with $r > 0,9$ were classified according to the time of measurement, i.e. daytime, night-time or transitional, and the mean z_o for each group calculated. These results are presented in Table 3. It is fair to assume that over the ETH during winter, stable conditions prevail during most of the night, and conversely, unstable conditions during the day. Fitting a straight line to a transformed profile measured under stable conditions will yield a lower slope and higher intercept on the log(z)-axis (see Figure 2). Conversely, under unstable conditions, a higher slope and lower intercept will be obtained. Because z is transformed logarithmically, relatively small variations in slope can lead to drastic changes in the z_o derived from the regression analysis.

TABLE 3

MEAN SURFACE ROUGHNESS LENGTH Z_o FOR DAYTIME; NIGHT–TIME AND TRANSITIONAL PERIOD

Measuring site	Z_o (m)		
	Day	Night	Transitional
Witbank Central	0,3	4,8	3,1
Grootvlei Single Quarters	0,01	1,2	0,3
Kriel Base	0,4	2,1	0,7

The study was extended to evaluate the effect of the size of upwind terrain fetch on the value of z_o. It has been suggested that the lower part of the vertical wind profile will be determined by roughness elements in the immediate vicinity of the measuring point, and the upper part by roughness elements farther away (Wieringa, 1981; Ming, *et al.*, 1983). The lower and upper parts of the profiles measured at Kriel Base were analysed and significant differences in z_o were observed (see Table 4). These differences could, however, not be ascribed to terrain effects. Most of the profiles were measured under stable conditions, thus, as mentioned previously, decreased slopes and increased intercepts on the log(z)-axis will be displayed, and this effect will be enhanced when only the upper parts of such profiles are used.

TABLE 4

SURFACE ROUGHNESS LENGTH Z_o DETERMINED FOR THE LOWER AND UPPER PARTS OF WIND PROFILES MEASURED AT KRIEL BASE

Height range (m)	Number of profiles	Z_o (m)
1 – 60	10	0,5 ± 0,7
5 – 100	17	4,0 ± 3,7
60–200	41	25,9 ± 13,3

5. CONCLUSIONS

5.1 Land cover

The validity of the use of map-derived land cover data in air quality modelling is subject to uncertainty because

(a) the standard 1:50 000 maps are generally not updated with sufficient frequency to accommodate case studies,

(b) these maps do not contain information about seasonal variations in, for example, vegetation cover and growth stages of crops, and

(c) the land cover types indicated on these maps and the land cover categories for which z_o has been documented, are not the same.

A centralised facility from which land cover data could be withdrawn would be of immense value in air quality modelling.

5.2 Surface roughness length Z_o

5.2.1 The results of this study again emphasise that only when it can be established that vertical wind speed profiles were recorded under neutral conditions, can linear regression analysis based on equation (2) be used to determine surface roughness lengths z_o.

5.2.2 Generally, the values of z_o, calculated from the lower part of tethersonde profiles recorded during neutral conditions, appeared to be physically reasonable, but displayed a fairly high degree of variability with standard deviations of approximately the same magnitude as the means. This variability can probably be ascribed to differences in the land cover of the upwind terrain fetch around the measuring site, or to the instantaneous nature of the wind speed measurements. When the results were grouped according to upwind terrain fetch, the number of individual z_o values in each group (sometimes none) was insufficient to obtain statistically significant means. Had the basic tethersonde data set been much bigger, the variability introduced by the instantaneous observations might have been minimised by statistical manipulation, but establishing and processing such a large data set would not be feasible. Thus, for the present, time-averaged continuous measurements of wind speed at selected heights along a fixed mast remains the most accurate way to obtain surface roughness lengths z_o.

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