In-stack emissions of heavy metals estimated by moss biomonitoring method and snow-pack analysis

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Abstract

Data from the chemical analysis of moss growing close to a thermal power station and snowpack have been used for the estimation of heavy metal deposition close to the point pollution sources. A semi-empirical model was proposed to describe atmospheric trace metal deposition close to the point pollution source. Model parameters were derived from experimental data, and nickel and vanadium quantities, washed out with snow and rain, were calculated. Using long-term meteorological observation data of rain and snow duration and metal uptake efficiencies in moss, the average emission rates of vanadium and nickel from the stack were calculated. The coincidence between data from emission inventory and model results was within 25%. It was estimated that in the vicinity of pollution source (within 30 km) about 15% out of total emitted metals were washed out by rain and snow events. Metal concentrations in the environment become indistinguishable from the background at a distance of about 20 km from the stack. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Heavy metals; Emission; Moss; Deposition

1. Introduction

Mosses are bio-organisms that are sensitive to air pollution and especially to heavy metals. The method of using moss for heavy metal monitoring has been developed in Sweden (Ruhling and Tyler, 1968) and is widely used at present. The moss method is especially well suited to the estimation of heavy metal deposition from the atmosphere on a large time scale (years, decades) or even for reconstruction of historical trends (Ruhling and Tyler, 1969; Steiness et al., 1994; Weiss et al., 1999). The moss biomonitoring method has been employed for many years for the estimation of trace metal deposition and defining geographical patterns (Groet, 1976; Percy, 1983; Markert et al., 1996; Ruhling et al., 1996, 1998; Grodzinska et al., 1999). Mosses receive nutrients needed for vital processes from the atmosphere, while the relationship with the substrate beneath is negligible. Although some recent studies show that this assumption is not correct for some metals in certain environments (Brumelis and Brown, 1997; Wells and Brown, 1996), in general this assumption can be successfully used. For the most part, metals deposited from the atmosphere are received by moss through precipitation, and especially in rain. However, in places with little precipitation and high metal loads, dry deposition may play an important role (Berg et al., 1995).

There are few studies available where biomonitoring methods are applied to estimate real or historical emissions (Bonham-Carter and McMartin, 1997; Bonham-Carter and Kettles, 2001). This is not surprising since there are few biomonitor species that are able to preserve quantitatively atmospheric pollutant fluxes.
In this study, we tried to estimate heavy metal loads around point pollution sources by using a semi-empirical model based on physical processes such as deposition or washout, and applying the available experimental data. Therefore, moss data were used for the estimation of pollutant washout with rain (also partly with snow after subsequent spring snowmelt). Snow analysis, if it is possible to sample snow-pack of the winter period, enables us to distinguish the deposition of pollutants during a cold period. If the experimental data can provide a distinctive spatial concentration pattern close to the point pollution source, then appropriate calculations can be performed to describe the washout of heavy metals from the atmosphere.

2. Materials and methods

There are three major trace metal pollution sources in Lithuania as identified during two international projects on regional trace metal deposition (Rühling, 1994; Rühling et al., 1996, 1998). These are two thermal power stations located in Elektrėnai and Mažeikiai, and a cement factory located in Naujoji Akmenė. Elektrėnai thermal power station is situated in the southern part of Lithuania, in the small city of Elektrėnai. Production of electricity in this station depends on the production rate at the Ignalina nuclear power station. On average 150–200 million tonnes of residual oil and up to 100 million m$^3$ of natural gas are burned every year at the Elektrėnai thermal power station. The other thermal power station, which is situated in a northern, rural part of Lithuania, 10 km from the small city of Mažeikiai, serves as an energy source for an oil refinery station (the largest of its type in the eastern Baltic region). The latter power station burns about half the amount of fuel compared to the first one. The cement factory, which is situated in the outskirts of the small city of Naujoji Akmenė, is the largest factory of its type in the eastern Baltic region. Production rates in all the mentioned industrial enterprises decreased drastically after the split with the Soviet Union and when Lithuania became an independent state due to changes in the economy.

Moss samples were collected at different distances from the pollution source varying from as close as 0.5 km to as far as 20–25 km. Moss species were either Hylocomium splendens or Pleurozium schreberi. The three youngest shoots of Hylocomium splendens and the green part of Pleurozium schreberi were used for analysis as representing deposition over 3 yr. The reason for that is that elder moss segments are already partially decomposed. The sampling scheme followed more or less a wind rose, i.e. more samples were collected in the downwind direction than upwind. This assumption will be discussed later in the paper. The prevailing wind direction was from the west and southwest in all three cases. Snow samples were collected only around the Elektrėnai station during an exceptional winter in 1995–1996 when the collection of snow for the whole winter period was possible (freezing temperatures all winter long are seldom). There were up to 20 moss samples collected around each of the point pollution sources, and 53 snow-pack samples around the Elektrėnai thermal electric power station.

Moss samples were collected in open locations, mainly in pine tree standings, where 3–5 subsamples were gathered with polyethylene gloves. All types of roads, settlements, farms or any other human activities were avoided as much as possible, except when samples were taken as close as possible (500 m) to the pollution sources themselves. In general, sampling procedures were similar to those used in the European projects “Atmospheric trace metal deposition in Northern Europe 1990, 1995, 2000” (Rühling et al., 1996, 1998). Sample preparation and analytical procedures are described in Čeburnis (1997) and Čeburnis et al. (1997).

Snow samples were collected in an open field. At each sampling point, 5 subsamples were taken and the average height of the snow pack was recorded. Samples were collected in nitric acid pre-washed plastic tubes of 15 cm diameter, from which they were transferred into plastic bags, then they were thawed and about 100 ml of water was transferred into acid pre-washed plastic bottles. Samples were acidified to 1–2 pH and analysed within one week of sampling.

Moss and snow samples were analysed using an atomic absorption spectrophotometer Perkin-Elmer Zeeman/3030 according to the methods described in Čeburnis (1997) and Čeburnis et al. (1997). A large set of metals has been analysed, but only data of vanadium, nickel and chromium are discussed in this study. Vanadium and nickel are typical of the metals emitted from oil combustion, whereas all three metals are typical of cement factory emissions. Actual moss concentration data along with coordinate locations of sampling points are presented in Table 1.

QC and QA were ensured using samples from various intercalibrations as during “Atmospheric heavy metal deposition in Northern Europe 1990, 1995” (Frontasyeva et al., 1995) and “EMEP intercomparison of trace metals in precipitation”. Intercalibration results are published in Čeburnis (1997) and Berg et al. (2000).

2.1. Description of the semi-empirical model

A simple model was chosen because of the small number of moss samples (up to 20), and the large uncertainty of the snow-pack analyses (up to 40% for nickel), which is not a good basis for testing of a complex model. The model assumes that the emitted metals are deposited uniformly in every direction (isotropic). In reality, the shape the concentration–distance curve...
The emission from the pollution source in the absence of washout could be expressed as

$$E = 2\pi xvq,$$

where $x$ is the distance from the stack; $v$ is the wind speed; and $q$ is the amount of pollutants in the whole air column, the base of which is the area unit.

As the precipitation fall speed at which pollutants are washed out is $w$, pollutants will reach the ground surface at a distance $r_0 = hv/w$, where $h$ is the effective height of the stack. Effective height means the height at which plume starts to spread. Usually, the plume is lifted some 50 m before spreading starts. The actual height of the stacks at the thermal stations was 250 m; therefore, the effective height was assumed to be about 300 m. The corresponding values for the cement factory were 150 and 200 m, respectively.

At the distance $r_0$ the emission variation can be expressed by equation:

$$dE = -E\mu dr,$$

where $\mu$ is the coefficient of washout, i.e. the part of the pollutants washed out when the air mass has passed the distance of the length unit.

The solution of Eq. (2) is

$$E = E_0 e^{-\mu(x-r_0)} \quad \text{when} \quad x \geq r_0,$$

where $E_0$ is the emission from the stack.

Precipitation fallout speed and wind speed vary and subsequently $r_0$ varies, so only averaged $r_0$ with the standard deviation $\sigma$ could be determined i.e. the element $E dr$ will obey the Gaussian distribution law:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-r_0)^2}{2\sigma^2}}.$$

Consequently,

$$E = E_0 \int_{r_0}^{\infty} e^{-\mu(x-r_0)} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-r_0)^2}{2\sigma^2}} dr.$$

or putting together Eqs. (1) and (5)

$$q = \frac{E_0}{2\pi \sigma \sqrt{2\pi}} \int_{r_0}^{\infty} e^{-\mu(x-r_0)} e^{-\frac{(x-r_0)^2}{2\sigma^2}} dr.$$

Pollutants will pass the distance $r = vt$, and after marking $\mu v = x$ (the washout rate)(s$^{-1}$),

$$q = \frac{E_0}{2\pi \sigma \sqrt{2\pi}} \int_{r_0/v}^{\infty} e^{-\mu(x-vt)} e^{-\frac{(x-vt)^2}{2\sigma^2}} dt \quad \text{(g/m}^2\text{)}.$$

Rate of the pollutant fallout to the Earth’s surface will be equal $q\alpha$, thus:

$$d = \frac{E_0\alpha}{2\pi \sigma \sqrt{2\pi}} \int_{r_0/v}^{\infty} e^{-\mu(x-vt)} e^{-\frac{(x-vt)^2}{2\sigma^2}} dt$$

and owing $x = \mu v$:

$$d = \frac{E_0\mu}{2\pi \sigma \sqrt{2\pi}} \int_{r_0}^{\infty} e^{-\mu(x-r_0)} e^{-\frac{(x-r_0)^2}{2\sigma^2}} dr \quad \text{(g/m}^2\text{s)}.$$
Multiplying \( d \) by the time \( T \), pollutant surface concentration could be expressed as

\[
e = \frac{E_0 \mu T}{2\pi^{3/2} x \sigma} \int_{r_0}^{\infty} e^{-\mu(r-r_0)} e^{-\frac{(x-r)^2}{2\sigma^2}} dr \quad (g/m^2).
\]

(10)

Note that although dimensions of Eqs. (7) and (10) are the same, the meaning is different, i.e. \( q \) is a column concentration (amount of pollutant in the air column of unit area), while \( c \) is surface concentration (amount of pollutant deposited on unit area). Eq. (10) is a general equation. It is the same for rain and snow events. The only difference is that the fall speed of snowflakes is usually much lower than the wind speed and according to \( r_0 = \frac{h \nu}{w} \) pollutants will reach the Earth’s surface at a farther distance from the stack, e.g. 1–2 km from the stack. Speed of rain droplets on the average is several times higher than the wind speed (15 and 5 m/s, respectively), so \( r_0 \) during rain events will be equal to 50–100 m, i.e. pollutants will reach the Earth’s surface at 50–100 m distance from the stack. This distance in comparison with the investigated area (about 20 km radius) is extremely small, so in the case of rain we can assume that \( r_0 \) and \( \sigma \) are equal to zero: \( r_0 = 0, \sigma = 0 \).

As the integral in Eq. (10) is the probability integral, when \( r_0 \to 0 \) and \( \sigma \to 0 \), Eq. (10) becomes simple, as the probability integral converts into a step function:

\[
e = \frac{E_0 \mu T}{2\pi x} e^{-\mu x}.
\]

(11)

We could also mark \( A \) as a constant:

\[
A = \frac{E_0 \mu T}{2\pi}.
\]

(12)

A special attempt was made to estimate dry deposition close to the point pollution source. For this purpose, meteorological data from the Vilnius air quality station was used. As Vilnius and Elektrėnai are not far apart (50 km distance), meteorology does not differ much (Kaušysla and Šver, 1983). Pollutant flux to the Earth surface can be calculated according to Zanetti (1990) using the recurrence of atmospheric stability classes and wind speed data assuming 100% aerosol capture by surface. The maximum flux is therefore at a distance of 4–5 km from the stack and within this distance, about 6% of all emitted pollutants can be deposited. Unfortunately, due to limited data it was impossible to calculate a capture value, but it is obvious that 100% capture is not appropriate, so dry deposition value of 6% is highly overestimated. Therefore, we conclude that dry deposition in the close vicinity of the stack (up to 6 km) does not play an important role especially in eastern Baltic region with regular precipitation. Spatial concentration patterns presented in Figs. 1–3 are good evidence of this. After this estimation, it should be stressed that the main mechanism of uptake of metal ions from precipitation in moss is ion exchange. Direct capture of aerosol particles is not as efficient. Moreover, moss bags exposed in the polluted city environment with apparently high dry deposition loads did not exhibit quantitative response.
However, during dry periods, pollutants can be carried far from the sources, but in that case they are spread in a large volume (area is proportional to the square of distance) and therefore the influence is even smaller. Considering long-range transport it is obvious that long-range transport is a superposition of many sources and an individual source does not considerably affect the already existing background.

Another test was performed to estimate the background concentration. The value of background concentration is important for modelling data at larger distances. However, model parameter $m$ does not change much regarding different background concentrations, since $m$ value is generally determined by high metal concentrations at closer points. The test was performed according to the following considerations. Pollutant concentration around the stack is proportional to $c \sim \exp(-\mu x)/x$ (Eq. 11). If we plot the $\ln(2\pi xc)$ versus $x$, we get a linear relationship. Therefore, data points should follow a decreasing pattern and exhibit as little scatter as possible. This estimation is more precise when more data points are available. Consequently, this modelled concentration should match the apparent regional (e.g. for Lithuania) background concentration obtained from European scale studies (Rühling et al., 1996). Background concentrations in rural areas in Lithuania, far from any prominent sources, were the following: V, 2.5–5.0 μg/g; Ni, 1.2–2.0 μg/g; Cr, 1.0–1.5 μg/g (Čeburnis, 1997; Rühling et al., 1996, 1998). Note that these concentration ranges apply because of apparent differences in surrounding vegetation, secondary (non-atmospheric) sources, which affect “local background” concentration. These aspects were discussed in Čeburnis et al. (1998). The calculated background concentrations were as follows: V—2.5, 4.5, 2.7 μg/g for Elektrėnai, Mažeikių and N.Akmenė, respectively; Ni—1.0, 2.2, 1.2 μg/g for Elektrėnai, Mažeikių and N.Akmenė, respectively; Cr—1.4 μg/g (N.Akmenė). Consequently, the calculated concentrations agree well with the measured ones. We believe that background concentration estimated in this way is the most appropriate and uses the simplest possible approach. On the other hand, background concentration could be included as a parameter into the model. However, we believe that this could only be done if a large number of data points are available (e.g. >50). As this was not the case in our study, we believe the latter approach would introduce more errors rather than being beneficial.

3. Results and discussion

With respect to the distribution of metal concentrations in moss around the stack, two distinctive features are illustrated in Figs. 1–3. Generally, patterns are very similar to a “bullseye”—with highest concentration in the centre of anomaly, decreasing outwards. The other important point is that the patterns are almost radial, but somewhat elongated downwind. This is due to the prevailing wind direction at the particular site. It is
obvious that upwind concentrations reach background values at a shorter distance than downwind ones do. Therefore, samples were collected (or only those used in calculations) up to the distance when they approached background values. The most important data points are located close to the stack, as they determine the shape of the model curve and therefore quantitative parameters. It must be stressed again that the main purpose of all calculations was an estimation of in-stack emissions, not a modelling and representation of an existing deposition pattern.

Using the method of least squares, parameters $\mu$ and $A$ (Eq. (12)) were calculated for the case of moss, and $\mu$, $\sigma$, $A$ and $r_0$ for the case of snow. The main parameters $\mu$, $\sigma$, $A$ and $r_0$ are presented in Table 2 for different metals at different thermal electric power stations and the cement factory. It must be stressed that model parameters could be correctly derived only for metals with concentrations at the very closest points exceeding the background values by at least three times. The larger the difference, the more reliable are the parameter values that were obtained.

Fig. 4 shows measured concentrations and a model curve for vanadium around the Elektrėnai thermal electric power station. Eq. (11) was fitted to experimental data by the method of least squares. The agreement between real concentrations in moss and calculated ones is reasonable. It must be noted that a model curve is below experimental points at a distance of 10 km. This disagreement is due to the uncertainty of $x$ which was tested to be about 11%. One could also notice a disagreement of calculated and measured values close to the stack. This was due to a non-uniform pattern of real concentrations, as our model used an approach of uniform deposition as discussed previously. It is believed that this is not a large disadvantage of the model since it includes all data points and therefore a non-uniformity of the real deposition pattern is accounted for indirectly. The only limitation of the model is that generally we cannot predict the real concentration at a particular point, i.e. calculated values are underestimated or overestimated. However, there will certainly be points where calculated and measured values correspond well. Note that this limitation was not important regarding our ultimate goal.

Table 2

<table>
<thead>
<tr>
<th>Metal</th>
<th>Rain</th>
<th>Snow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Elektrėnai thermal electric power station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.061</td>
<td>0.046</td>
</tr>
<tr>
<td>Ni</td>
<td>0.059</td>
<td>0.023</td>
</tr>
<tr>
<td>Mažeikių thermal electric power station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.053</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td>Naujoji Akmenė cement factory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>0.21</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Plot of measured chromium concentration in moss (μg/g) around Naujoji Akmenė cement factory.
Figs. 6–8 represent measured and model values for other pollution sources. One may notice that the agreement between values of parameter $m$ for two different thermal power stations is excellent. This is not surprising since the height of the stacks and operational parameters of both thermal power stations are the same (with the exception of the amount of burned fuel). At the same time, good agreement between values validates the proposed semi-empirical model. Different washout values of $m$ in the case of the cement factory are caused by the fact that the height of the stack, as well as composition and size of aerosol particles, emitted from the stack of the cement factory, are different. The size of emitted aerosol particles is certainly larger, the effective height of the stack is almost half of that of the thermal power stations and therefore washout efficiency must be higher. Consequently, these features must definitely lead to higher $m$ values.

Metal concentration distribution in snow was calculated and fitted to experimental data according to Eq. (10). The results are presented in Fig. 5. The non-uniformity of the deposition pattern and the larger analytical uncertainty of snow samples play a more important role than the moss data, as can be seen in Fig. 5. However, the general results for the moss data apply also for snow data. Fig. 5 is a good evidence of why the moss biomonitoring method is so widely used and recognised. Mosses are able to integrate deposition efficiently and suppress small-scale variations, whereas snow-pack or precipitation analysis provides information on short-term deposition, but suffers from
the stability of the output parameter within uncertainty limits in order to establish the pollution source simply by integrating Eqs. (10) or (11): the total mass of pollutants deposited around the point pollution source. The concentrations around the point pollution source. The concentrations decreased by twice their initial values. It is worthwhile to discuss and compare differences between our study and that of Bonham-Carter and McMartin (1997). This study is likely to be the only study where a similar approach and a similar modelling approach were used. Unfortunately, there is no place to consider specific details of this study. Generally speaking, both studies assumed exponential decay of metal concentrations around the point pollution source. The major difference is that Bonham-Carter and McMartin (1997) used simple mathematical fitting of experimental data while our approach is based on the particular physical processes. For example, Bonham-Carter and McMartin (1997) used the decay parameter in their model, which was the “half distance” at which metal concentrations decreased by twice their initial values. It is not clear as to the physical meaning of this parameter considering the on-going processes in the atmosphere. However, it must be pointed out that the model, used by Bonham-Carter and McMartin (1997) and Bonham-Carter and Kettles (2001) is mathematically correct. Especially valuable is the part where model errors were estimated by Monte-Carlo simulation.

Further on, it is rather straightforward to calculate the total mass of pollutants deposited around the pollution source simply by integrating Eqs. (10) or (11):

$$m = \int_{r_0}^{\infty} 2\pi cx \, dx.$$  \hspace{1cm} (13)

For the case of rain (integrating from moss data), the moss uptake efficiency of metal ions from precipitation and the net production of moss (total amount of moss biomass produced in 3 yr) were taken into account. The uptake efficiency value of 60% was applied for both vanadium and nickel (Ceburnis and Valiulis, 1999). Net production of moss was selected to be 350 g of moss per 1 m$^2$ in 3 yr (Rühling et al., 1987; Milukaitė, 1996). In the case of snow, additional parameters were used such as the depth of the snow-pack and the amount of water in snow. The depth of snow-pack was measured during the sampling campaign and was found to be 41 cm on average. The amount of water in a snow-pack, as derived from long-term meteorological observations, was 0.29 g/cm$^3$ (Hydromet, 1996). The reason why average values were used instead of individual ones at every sampling point is that averaged values were only needed for the comparison of modelled values with measured ones, i.e. model gives surface concentration, while measured values are volumetric or mass concentrations. It must be also stressed that sampling area was generally small 20 × 20 km, so the moss biomass production as well as the depth of snow cover did not differ much. The data for the Elektrėnai thermal electric power station is presented in Table 3.

Using data from Table 3 the metal emission rate from the Elektrėnai thermal power station stack can be estimated. On average, in the southeastern part of Lithuania, including Elektrėnai, the total precipitation during 3 yr was found to be 188 days (Kaušysla and Sver, 1983). Total precipitation duration means the non-stop continuous precipitation event. During the rest of the time only dry deposition occurred. Thus, the emission of vanadium from the stack was calculated to be 0.49 g/s. The duration of snow events during winter time was 32.3 days, hence, the emission rate of vanadium from the stack during winter time was calculated to be 0.80 g/s.

An external validation of the model was carried out according to the fuel consumption at the Elektrėnai thermal power station and the data of vanadium concentrations in the exhaust gas of that station, derived from the Report of the Lithuanian Environmental Protection Ministry (1995). The calculated 3 yr-average emission rate was 0.58 g/s and the value during an apparent cold period was 0.66 g/s. As the Environmental Protection Ministry has not presented data for nickel, the comparison for this metal is not given. The errors of calculated emission values using our model were

Table 3

<table>
<thead>
<tr>
<th>Metal</th>
<th>Rain (3 yr)</th>
<th>Snow (3 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>7.9 ± 1.2</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>Ni</td>
<td>2.1 ± 0.3</td>
<td>1.1 ± 0.4</td>
</tr>
</tbody>
</table>

Fig. 8. Chromium concentration in moss (μg/g) versus distance from the stack of Naujoji Akmenė cement factory as plotted from measured and calculated values.
estimated as not to exceed 20%, due to the analytical uncertainties, as well as other errors associated with model fitting as stated above. Data from the Environmental Protection Ministry was based on single measurements; therefore, error in the latter values may exceed 25%. However, it may be asserted that the agreement between the values is reasonable. We agree that the absence of error analysis, e.g. using Monte-Carlo simulation, makes our error estimation somewhat approximate. However, it must be stressed again that the small number of samples prevents an adequate application of Monte-Carlo simulation.

Referring to these data, calculations show that snow and rain close to the thermal electric power station (up to 30–50 km) washes out up to 15% of the total amount of nickel and vanadium emitted from the stack, while further transfer of these pollutants makes up 85%. It must be pointed out that measured values (not model) accounted for both dry and wet deposition of pollutants. However, after comparison of calculated and measured values it becomes obvious that close to the point pollution source, wet deposition plays a more significant role than the dry deposition. This is particularly true for the areas of regular precipitation pattern. The proposed model could become a powerful tool in the estimation of heavy metal deposition, as well as an indicator of the emission rate from the point pollution source. In one sense, the model was tested twice. Firstly, when comparing real emission values with the calculated ones, and secondly, when independently comparing two different thermal power stations.

4. Conclusions

The proposed semi-empirical model describes deposition close to a point pollution source. Using experimental data of metal concentrations in moss (or snow), the model revealed agreement between calculated and measured emission rates of vanadium from the stack. The accuracy of 20–25% could be regarded as satisfactory. Calculations showed that precipitation washes out up to 15% of the total amount of nickel and vanadium emitted from the stack of the thermal power station within the distance of 30 km from the stack. It must also be pointed out that data required for the model can be obtained rather easily, since only about 20 good data points (in the case of moss) are needed to run the model and to obtain reasonable results.

The deposition profiles and the apparent calculations showed that values of key parameters were in agreement within 15%, in the case of the two thermal power stations. Therefore, it proves that the approach and the model are validated reasonably.

In the case of the thermal power station, about 6% of combustion metals are trapped from the air column in one kilometre distance during precipitation events. The value for the cement factory was about 25%. The difference is attributed to a larger aerosol size and lower stack height.

The presented results show that, using a rather simple model and measurement data of pollutant concentration distribution in moss and snow, close to the pollution source, the amount of pollutants emitted from the stack and/or washout with precipitation can be estimated reliably.

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