Seasonal odor impact range of selected wastewater treatment plants – modeling studies using Polish reference model
Izabela Sówka, Yaroslav Bezyk, Agnieszka Grzelka, Urszula Miller and Łukasz Pachurka

ABSTRACT
On-site odor measurements and mathematical modeling are useful for identifying the odor impact at the source and receptors located in areas adjacent to wastewater treatment plants (WWTPs). Impact of open area sources can be significant and may influence air quality both at the WWTP area and downwind in the surrounding areas. In this work, results of the odor measurements carried out in the spring and summer season for sources within three different mechanical-biological WWTPs in Poland are presented. The odor impact assessment was completed using a Polish reference model. The odor emission scenarios considering the contribution of major odor sources within WWTPs and the seasonal variation were determined. Obtained results showed significant differences between spring and summer seasons. The highest and the lowest measured odor concentrations at the WWTP property line were 75 ouE/m³ (July) and 6.4 ouE/m³ (March), respectively.

INTRODUCTION
Emission of odorants from wastewater treatment plants (WWTPs) is a frequent cause of odor nuisance in areas located near WWTPs (Stuetz 2001; Kośmider et al. 2002; Kulig 2005). Odors are created by mixtures of volatile organic compounds present in the waste gas, sewage, and effluents, sewage sludge and waste (Rajbansi et al. 2014). Impurities in WWTPs contain large quantities of organic and inorganic pollutants, among which nitrogen and sulfur compounds are most undesirable, being the main cause of odor nuisance (Ossowska-Cypryk & Kulig 2005). Odorous compounds that cause the odor nuisance of WWTPs may come directly from the influent wastewater or be formed in reactions between the chemical compounds or in other processes. Gaseous pollutants associated with the problem include: sulfur compounds (hydrogen sulfide and other sulfides, thiols), nitrogen compounds (ammonia, amines, ino- doles, skatoles), carboxylic acids (such as acetic, butyric, valeric acid), aldehydes and ketones (Gostelow et al. 2001). Hydrogen sulfide, being the main and the most typical pollution type emitted from WWTPs, is very often used as an indicator of odor nuisance in surrounding areas (Osako 2003; Sobczyński et al. 2014, 2015). Among the objects associated with the most odor nuisance in WWTPs are predes- sedimentation tanks, grit chambers, screen halls, raw sewage tanks, dewatering sludge halls and sludge tanks. Emission of odorants from WWTPs is difficult to investigate due to a large number of potential sources of emission, including different types of wastewater treatment systems and continuity of emission intensity over time (Kulig 2005; Sówka et al. 2009). The main objects that cause odor nuisance, because of the large surface of this kind of source, are passive surfaces (i.e. sludge tanks and primary sedimentation tanks (Sobczyński et al. 2015)). Studies conducted by Frechen (1998) have proved that major odor sources include sludge management, aerated grit chambers and primary sedimentation. The ratio of individual source emission to overall WWTP emission, based on questionnaire surveys conducted among the operators of 100 WWTPs in Germany, is presented in Figure 1.

However, the results of our own research carried out in the area of the selected WWTPs have indicated the highest odor intensity values (the intensity of odors was determined...
using a six-degree intensity scale, where 1 indicates a very weak smell and 6 an extremely strong one) from the following sources and processes: inflow of sewage, grit chamber, sludge management, desulfurization station, primary settling tanks and denitrification chambers (Table 1).

Table 1 | Inventory results of odor sources for selected WWTPs

<table>
<thead>
<tr>
<th>Odor source</th>
<th>Odor character</th>
<th>Odor intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infl ow, unloading and collection of sewage</td>
<td>Industrial sewage fecal</td>
<td>6</td>
</tr>
<tr>
<td>Grit chamber</td>
<td>Sewage</td>
<td>6</td>
</tr>
<tr>
<td>Neutralization node</td>
<td>Sewage</td>
<td>4</td>
</tr>
<tr>
<td>Coagulation node</td>
<td>Sewage</td>
<td>6</td>
</tr>
<tr>
<td>Waste management</td>
<td>Sewage bland/a waste smell</td>
<td>4</td>
</tr>
<tr>
<td>Sludge management</td>
<td>Sewage sludge; bland; biological rancid oil</td>
<td>6</td>
</tr>
<tr>
<td>Desulfurization station</td>
<td>Sewage; sulfur</td>
<td>6</td>
</tr>
<tr>
<td>Primary settling tanks</td>
<td>Sewage; sewage sludge</td>
<td>4; 6</td>
</tr>
<tr>
<td>Secondary settling tanks</td>
<td>Soil/sweetish</td>
<td>3</td>
</tr>
<tr>
<td>Denitrification chambers</td>
<td>Sewage</td>
<td>6</td>
</tr>
<tr>
<td>Sewage basins</td>
<td>Sewage</td>
<td>5</td>
</tr>
</tbody>
</table>

Evaluation of odor nuisance around an object belonging to a WWTP can be performed on the basis of odor concentration measurements, odor emission determination and dispersion modeling using an appropriate mathematical model. Field studies on odor concentrations (field olfactometry), intensity, odor character (performed in a grid or in a plume) and spatial distribution using geostatistical tools have been used as well (Sówka et al. 2015; Barczak & Kulig 2016). These methods provide reliable information on the range of odor impact of the analysed WWTPs. For economic reasons, using simulated patterns is acceptable. Correct estimation of amounts of odorant emitted from individual sources makes performing correct model calculations possible. Awareness of the connection between odor emission amounts and factors such as pH, wastewater temperature, atmospheric pressure, or air turbulence over the source is very important because the above-mentioned parameters affect the high variability of passive emissions from passive surface sources.

The variability of odor emissions influences the extent of the olfactory impact of municipal sewage treatment plants. (Schwarzenbach et al. 2003; Nagaraj & Sattler 2005; Hudson & Ayoko 2008). Therefore, assessing the impact of odor emissions – especially from surface sources – on the range of olfactory influence of WWTPs, which is the purpose of this work, is very important.
CHARACTERISTICS OF WWTPS

The investigation of odor nuisance was carried out in three different WWTPs located in Poland (Figure 2). The sampling sessions on these sites took place between 2011 and 2015. The field measurement data were collected over relatively long sampling times (a whole day for every sampling session). The observations were made considering fluctuations in emissions from temperature changes and operational changes within the site.

The measurements in the first WWTP (WWTP#1) were conducted using the dynamic olfactometry method in two sessions: first sampling in March 2015 and the second sampling in July 2015. For the first object, located in the northern part of Poland, which clears water for an agglomeration of about 470,000 people, the spring odor concentration measurements were carried out for four sources, and the summer measurement campaign for nine area sources. WWTP#1 is located in a residential zone, 750 m west and 450 m north-east of the nearest districts.

In the case of the second object (WWTP#2), sited in the south-west part of Poland and which purifies wastewater produced by the population of about 1,000,000, both in the spring (May 2014) and summer (July 2014) sessions, measurements were carried out for one source – primary settling tank (considered to be the greatest contributor to the formation of odor nuisance). WWTP#2 is located in a non-residential area 1800 m north-west and 1200 m north of the nearest residential areas. For the third object (WWTP#3), situated in the middle-west part of Poland (a population of 1,200,000), measurements were conducted in a summer (June–July 2011) session within 5 days. The plant facilities are near the surrounding residential area, 450 m west and 750 m south-east of massive districts. During the measurement sessions, areas of odor monitoring in WWTPs were split into two major groups, the first one being the wastewater stream treatment processing objects, including primary settling tank, inlet channel, distribution chamber, bio-reactors tanks, and biofilters (Table 2). Another group of the most relevant sources of odor pollution from WWTPs was identified along the sludge treatment process, including the primary sludge tank and the sludge drying building. Key characteristics of major sources of odors from WWTPs are presented in Table 2.

MATERIALS AND METHODS

In order to determine odor emission from selected sources, the odor concentration in gaseous samples collected from selected sources in the WWTP in spring and summer were measured according to the method described in PN-EN 13725: 2007 (PKN 13725: 2007). Samplers and polytetrafluoroethylene (PTFE) bags with no absorption or odor separation were used for sampling. The remaining components of the sampling kit were also made of odorless materials (PTFE, Hornik Ltd). Samples were taken during an average time of 30 min (VDI 3880 2011). Having been collected, samples were immediately transported to the Olfactometric Laboratory to determine odor concentrations. Odor concentration measurement was performed using the dynamic olfactometry method, according to the procedures described in PN-EN-13725: 2007 (PKN 2007). The measuring device was a four-station TO8 olfactometer with all the necessary instrumentation. Based on calculations, emission values from individual sources (identified as major emitters of odors) and the concentration at receptor points were estimated using OPERAT FB according to the methodology from the Regulation of the Minister of Environment (2010). The odor modeling calculations were performed based on the Pasquill formula:

\[
S_{xy} = \frac{E_i}{2\pi \sigma_y \sigma_z \Delta t} \cdot \exp\left(\frac{y^2}{2 \sigma_y^2}\right) \cdot \left\{ \exp\left[ -\frac{(z - H)^2}{2 \sigma_z^2} \right] + \exp\left[ -\frac{(z + H)^2}{2 \sigma_z^2} \right] \right\} \cdot 1000
\]
where $S_{xyz}$ – concentration of the substance in the air averaged over 1 h [$\mu g/m^3$], $E_g$ – maximum emission of gaseous substance [mg/s], $\sigma_x$ – horizontal atmospheric diffusion coefficient [m], $\sigma_z$ – vertical atmospheric diffusion coefficient [m], $\bar{u}$ – average wind velocity in the layer from the geometric height of the emitter $h$ to the effective height of the emitter $H$ [m/s], $y$ – component of the emitter distance from the point at which the calculation is made perpendicular to the direction of the wind [m], $z$ – the height for which the concentration of the substance in the air is calculated [m].

Modeling criteria used in the OPERAT FB software included the emission sources’ basic parameter values (presented in Table 2) as well as the physicochemical parameters of emitters and dispersion conditions (meteorological conditions and topographical features, shown in Table 3). The measurements were taken with wind speed varying from 3 up to 6 m/s during field

### Table 2: Characteristic of the emitters and odor emission rate of municipal wastewater treatment plants (WWTPs)

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Emitter name</th>
<th>Emitter height [m]</th>
<th>Emitter diameter [m]</th>
<th>Emitter size [m x m]</th>
<th>Emitter area [m²]</th>
<th>Odor concentrations [ouE/m³]</th>
<th>SOER [ouE/m² s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Primary settling tank</td>
<td>3</td>
<td>37</td>
<td>1,080</td>
<td>5,296</td>
<td>69.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inlet channel</td>
<td>0.5</td>
<td>43 x 7</td>
<td>300</td>
<td>73,301</td>
<td>961.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distribution chamber</td>
<td>3</td>
<td>6.5 x 6.5</td>
<td>42</td>
<td>108,213</td>
<td>1,415.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settling chamber</td>
<td>3</td>
<td>10 x 10</td>
<td>100</td>
<td>38,431</td>
<td>502.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Primary sludge tank</td>
<td>3</td>
<td>20</td>
<td>300</td>
<td>89</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge drying building</td>
<td>8</td>
<td>37.5 x 38.7</td>
<td>1,450</td>
<td>160</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bio-reactor</td>
<td>2</td>
<td>72 x 71</td>
<td>5,100</td>
<td>216</td>
<td>2.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biofilter 1</td>
<td>2.8</td>
<td>7 x 5</td>
<td>35</td>
<td>331</td>
<td>4.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biofilter 2</td>
<td>2.8</td>
<td>7 x 5</td>
<td>35</td>
<td>2,872</td>
<td>37.57</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>Primary settling tank</td>
<td>3</td>
<td>42</td>
<td>1,385</td>
<td>927</td>
<td>12.12</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>Primary settling tank</td>
<td>3</td>
<td>39</td>
<td>1,200</td>
<td>11,130</td>
<td>145.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Secondary settling tank</td>
<td>3</td>
<td>39</td>
<td>1,200</td>
<td>119</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattices between primary settling</td>
<td>2.0</td>
<td>21.5 x 21.5</td>
<td>462</td>
<td>1,410</td>
<td>18.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tanks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickener</td>
<td>2.2</td>
<td>22</td>
<td>380</td>
<td>37,991</td>
<td>496.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biofilter 1</td>
<td>2.5</td>
<td>6 x 8</td>
<td>48</td>
<td>8,138</td>
<td>106.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biofilter 2</td>
<td>2.5</td>
<td>6 x 8</td>
<td>48</td>
<td>2,017</td>
<td>26.38</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>Primary settling tank</td>
<td>3</td>
<td>37</td>
<td>1,080</td>
<td>534</td>
<td>6.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inlet channel</td>
<td>0.5</td>
<td>43 x 7</td>
<td>300</td>
<td>2,439</td>
<td>31.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distribution chamber</td>
<td>3.0</td>
<td>6.8 x 6.6</td>
<td>45</td>
<td>7,912</td>
<td>103.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settling chamber</td>
<td>3.0</td>
<td>10 x 10</td>
<td>100</td>
<td>1,011</td>
<td>13.22</td>
<td></td>
</tr>
</tbody>
</table>

**SOER** – specific odor emission rate.

### Table 3: Input data used in model simulations

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>22.2</td>
<td>66.9</td>
<td>1,028.2</td>
<td>223</td>
<td>1.13</td>
<td>6 x 6</td>
<td>100</td>
</tr>
<tr>
<td>#2</td>
<td>20.4</td>
<td>63.8</td>
<td>1,019.1</td>
<td>300</td>
<td>0.73</td>
<td>6 x 6</td>
<td>100</td>
</tr>
<tr>
<td>#3</td>
<td>23.7</td>
<td>66.3</td>
<td>1,021.8</td>
<td>275</td>
<td>1.0</td>
<td>6 x 6</td>
<td>100</td>
</tr>
<tr>
<td>#4</td>
<td>9.3</td>
<td>62.5</td>
<td>1,025.5</td>
<td>234</td>
<td>1.13</td>
<td>6 x 6</td>
<td>100</td>
</tr>
<tr>
<td>#5</td>
<td>10.1</td>
<td>61.3</td>
<td>1,018.2</td>
<td>300</td>
<td>0.73</td>
<td>6 x 6</td>
<td>100</td>
</tr>
</tbody>
</table>
sessions at the fixed anemometer height of 14 m. Calculations were conducted in grid format receptors with matched size and step of adjacent grid cells and aerodynamic roughness coefficient for each study area. The analysis determining the odor nuisance for residential areas under Polish conditions was established

Figure 3  
(a) Calculation results of highest odor concentrations (ouE/m³) obtained for the first WWTP (four area sources included, for measurement data from spring 2015) at the level of buildings simulated within the assumed odor threshold of 1 ouE/m³, and wind rose. Base map of plant area – OpenStreetMap. (b) Calculation results of highest odor concentrations (ouE/m³) obtained for the first WWTP (four area sources included, for measurement data from summer 2015) at the level of buildings simulated within the assumed odor threshold of 1 ouE/m³. Base map of plant area – OpenStreetMap. (c) Calculation results of highest odor concentrations (ouE/m³) obtained for the first WWTP (nine area sources included, for measurement data from spring 2015) at the level of buildings simulated within the assumed odor threshold of 1 ouE/m³. Base map of plant area – OpenStreetMap. (d) Calculation results of odor concentrations (ouE/m³) obtained for the first WWTP (source: primary settling tank, for measurement data from spring 2015) at the level of buildings simulated within the assumed odor threshold of 1 ouE/m³. Base map of plant area – OpenStreetMap. (e) Calculation results of highest odor concentrations (ouE/m³) obtained for the first WWTP (source: primary settling tank, for measurement data from summer 2015) at the level of buildings simulated within the assumed odor threshold of 1 ouE/m³. Base map of plant area – OpenStreetMap.
within the range of values 1 and 5 ouE/m$^3$ and frequency of exceedances 3% and 2%, respectively. The permissible frequency of exceedances of 1 ouE/m$^3$ equal to 3% was adopted on the basis of the Polish draft act on preventing odor nuisance (Polish Ministry of Environment 2009). The permissible frequency of exceedances of 5 ouE/m$^3$ of 2% has been established on the basis of the Dutch guidelines (Piringer & Schauberger 2013), according to which the value of 5 ouE/m$^3$ is generally acceptable to humans, with a maximum admissible amount of exceedance of 2% during the year.

**RESULTS AND DISCUSSION**

The mapping of the concentration of odors from selected WWTPs (Figure 2) was conducted to predict the range of odor influence in different stages of wastewater treatment.
Some odor sources, including primary settling tank, inlet channel, distribution chamber, and bio-reactors (marked on the map as E1–E4, in Figures 3–5), were grouped being parts of the wastewater stream treatment process, the others being grouped as part of the sludge treatment process: primary sludge tank, sludge drying building (marked on the map as E5–E9, in Figures 3–5). The first group of sources showed the highest level of odor influence.

Three main scenarios of odor influence were modeled via OPERAT FB for selected WWTPs considering seasonal and operating (amount of sources included) variables. The comparison of different odor concentration scenarios at selected locations around the studied WWTPs is shown in Table 4. The highest odor concentration values in the case of WWTP#1, including primary settling tank, inlet channel, distribution chamber, and bio-reactors (marked on the map as E1–E4, in Figures 3–5), are shown in Figure 3. The odor activity values contained within the fence line of WWTP#1 were higher than 6 ouE/m³ in spring (Figure 3(a)) and amounted to more than 73 ouE/m³ in summer. The highest odor concentrations at the level of buildings simulated for WWTP#2 were higher than 11 ouE/m³ in spring and 27 ouE/m³ in summer (Figure 4(a) and 4(b)). For the WWTP#3 the highest concentration value was estimated at 62 ouE/m³ in the summer sampling session (Figure 5(a)). Hence, the simulation at the level of buildings shows that the surrounding residential area (external buildings near the plants were marked on the maps as B1–B6) was strongly influenced by odor concentrations during the spring and summer sampling periods.

During the spring measurement session, the odor concentration was 1 ouE/m³ at distances from the plant between 1,800 and 1,900 m (Figure 3(a)). The odor contribution observed during the summer measurement session had a much higher influence on local communities in three different cases. It varied from 27 up to 74 ouE/m³ at a distance of more than 3.4 km from the border of the tested plants (Table 4). The odor concentration at the plant border was equal to 73 and 74 ouE/m³ for spring (Figure 3(b)) and summer (Figure 3(c)) seasons and 62 ouE/m³ for summer (Figure 5(a)) for WWTP#1 and WWTP#3, respectively. The permissible odor frequency of 1 ouE/m³ (exceedances equal to 3%) was exceeded by up to 5.8% in the study site #2 (Table 4) as well as for the concentration of about 27 ouE/m³ during the summer sampling period. The highest odor concentrations in WWTP#2 were observed for the primary settling tank source (Figure 4(a)). Moreover, the plume distribution from the primary settling tank chamber was identified as a source with the highest odor impact in each of studied areas (Table 4).

Table 4 | Comparisons among the odor plume range for different scenarios based on seasonal variability and operating conditions (numbers of odor emission sources included)

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Scenarios</th>
<th>Max odor concentration outside plant border [ouE/m³]</th>
<th>Distance of odor nuisance in frequency of 1 ouE/m³ [m]</th>
<th>Distance of odor nuisance in frequency of 5 ouE/m³ [m]</th>
<th>Frequency of exceedances of 1 ouE/m³ per year [%]</th>
<th>Frequency of exceedances of 5 ouE/m³ per year [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Spring: Four area sources</td>
<td>6.4</td>
<td>1,850</td>
<td>250</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Summer: Four area sources</td>
<td>73.2</td>
<td>5,300</td>
<td>4,780</td>
<td>15.7</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>Summer: Nine area sources</td>
<td>74.5</td>
<td>5,500</td>
<td>4,840</td>
<td>15.8</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>Spring: primary settling tank</td>
<td>1.1</td>
<td>750</td>
<td>50</td>
<td>1.2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Summer: primary settling tank</td>
<td>24.2</td>
<td>3,400</td>
<td>1,300</td>
<td>5.3</td>
<td>3.1</td>
</tr>
<tr>
<td>#2</td>
<td>Spring: primary settling tank</td>
<td>11.7</td>
<td>3,100</td>
<td>1,100</td>
<td>4.2</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Summer: primary settling tank</td>
<td>27.6</td>
<td>3,700</td>
<td>1,480</td>
<td>5.8</td>
<td>3.4</td>
</tr>
<tr>
<td>#3</td>
<td>Summer: Six area sources</td>
<td>62.1</td>
<td>5,700</td>
<td>5,100</td>
<td>16.9</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>Summer: primary settling tank</td>
<td>57.2</td>
<td>4,300</td>
<td>3,400</td>
<td>7.4</td>
<td>4.8</td>
</tr>
</tbody>
</table>

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CONCLUSION

In this study, the results of odor measurements and calculations were determined for spring and summer seasons. The amounts of odors measured during spring and summer 2015 sessions showed strong variation, being higher in summer.

The seasonal scenarios and operation scenarios were modeled separately via OPERAT FB for the selected three WWTPs, which have significant impact on the odour quality of the air on account of their being located close to residential areas. The highest level of odor concentration in the surrounding residential area was detected in July, while the lowest was detected in March. The most affected area in the summer scenario including nine emission sources was near the first WWTP as well as for six emission sources tested in WWTP#2.

The highest concentration of odors at the plant border in summer was always higher than 74 ouE/m³ with the frequency of exceedances of 1 ouE/m³ higher than 15.8% per year (WWTP#1). The highest odor level in spring was close to 6 ouE/m³, measured 3.6 km from plant border. The highest concentration values from the second site were 27.6 ouE/m³ (summer) and 11.7 ouE/m³ (spring), more than 3 km from the WWTP. In the case of the second site during the summer sampling, the highest values of odor concentration were at the WWTP. In the case of the second site during the summer scenario including nine emission sources was near the first WWTP as well as for six emission sources tested in WWTP#2.

These data are evidence that odorous pollutant quantities are positively related to meteorological conditions and with the type of odor sources.

REFERENCES


Regulation of the Minister of Environment dated 26 January 2010 on reference values for some substances in the air. Journal of Laws 2010, no. 16, item 87.


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