LUCRARE DE DISERTAȚIE

Coordonatori științifici
Lect. Univ. Dr. Ákos Horváth
Lect. Univ. Dr. Sándor Borbély

Absolvent
Katinka Bakos

2014
THE EFFECT OF WET DEPOSITION ON GROUND-LEVEL GAMMA DOSE RATES

Coordonatori științifici
Lect. Univ. Dr. Ákos Horváth
Lect. Univ. Dr. Sándor Borbély

Absolvent
Katinka Bakos

2014
Abstract

Nuclear environmental monitoring systems around nuclear power plants are good tools for environmental safety and essential tools for the modern technological level. These systems are to trigger signs of artificial pollutions of industrial processes which otherwise make a long term benefit for the population. However the natural radioactivity can also make a signal in these systems and it is important to separate them from the operational emission.

In this study we examine the contribution of the natural radioactivity of the rain to the gamma dose detectors of a nuclear environmental monitoring system that consists of gamma dosimeters at 1 m above the ground around a nuclear power plant. This natural contribution depends on meteorological features. Our aim is to determine the relationship between rainfall with its meteorological circumstances and the dose increase associated with them.

The current study examines a one and a half year period for which the effect of rainwater on the gamma dose rates is shown. The dose increments or extra dose time curves are parametrized using a cloud-rain model provided from former studies in the literature.

The size of the used dataset is so large that only automatized software processing could handle the problem and several steps of software code development is necessary. Besides the numerical processes figures need to be drawn for the reader to be able to overview and check the results, and therefore Python and Latex software environment is coupled on a Linux operating system.

Our main result is the discovery of a seasonal parameter set that describes 80% of the data for a 1.5 year period for 22 dosimetric stations. This new achievement allows the radiation protection system to separate the incidental large extra peaks of the radiation dose from the artificial pollution.
# Table of Contents

Abstract.................................................................................................................................................. 2  
Introduction............................................................................................................................................. 4  
I. Radon progeny in atmospheric processes ......................................................................................... 6  
   II. Model for wet deposition of radon progeny .................................................................................. 9  
      II.1. Equations of the simple rain-out model .............................................................................. 9  
      II.2. Results provided by the model ............................................................................................ 13  
III. Description of the time series dataset ............................................................................................. 14  
      III.1. Dosimetric system of Paks Nuclear Power Plant ............................................................... 14  
      III.2. Measured parameters .......................................................................................................... 15  
      III.3. Description of the general features of the data ................................................................... 16  
IV. Numerical processing of the time series dataset ............................................................................. 19  
V. Results and discussion ....................................................................................................................... 22  
Summary.................................................................................................................................................. 28  
Acknowledgements................................................................................................................................. 29  
References............................................................................................................................................... 30  
Attachments.......................................................................................................................................... 31  
   Attachment 1 ................................................................................................................................... 31  
   Attachment 2 ................................................................................................................................... 40  
   Attachment 3 ................................................................................................................................... 41
Introduction

Radiation monitoring at nuclear power plants deals with significant disturbances from existing natural radiation sources, which have a major contribution on the measured quantities. Variations of \(^{222}\)Rn concentrations in air are influenced by several meteorological conditions, for example, air temperature, atmospheric pressure, humidity, insolation, wind direction and wind speed. The significant increase of measured gamma-dose rate at ground level is due to precipitation, more precisely it is caused by the radiation emission of radon daughters scavenged by precipitation and accumulated on the ground.

The gamma radiation brought by rainwater has been a study of interest since a few decades. Among the numerous studies in this field Paatero and Hatakka [1] studied the washout efficiency of \(^{214}\)Pb by measuring external gamma radiation in Central Finland in 2009. Greenfield et al. [2] determined rain age via relative gamma ray activities from \(^{214}\)Pb and \(^{214}\)Bi condensed from precipitation, their work supporting also the assumption that the accumulation of gamma activity on rain droplets corresponds to the accretion of water during their construction. Yawaza et al. [3] studied wet deposition of short-lived radon decay products in Japan (data from 2004-2006), by measuring their concentration in rainwater and by analyzing radon transport in the atmosphere with a numerical method. They showed the correlation between the radon concentration in air column and the radioactivity concentration in rainwater, which was strongest for continental and convective air masses.

The most relevant for the current study are those which determine gamma radiation dose rate due to atmospheric \(^{222}\)Rn progeny. Nishikawa et al. [4] estimated the gamma radiation dose rate due to atmospheric \(^{222}\)Rn progeny, using the Monte Carlo calculation. Hornga and Jiang [5], determined radon progeny concentration in raindrops as well as in cloud droplets based on a simplified rainout model. A more realistic model was given by Minato [6], presenting a simplified time-independent model which calculates the radioactivities of short-lived radon daughters in rainwater as a function of the rainfall rate for a given unit concentration of radon in cloud.

In this study the semi-empirical model of Minato [6] is applied for a one-year long data series containing information about precipitation, gamma-dose rate and several meteorological parameters. The aim is to prove the correlation between the two quantities and provide a stable prediction method that can be applied in the required fields.
In Chapter I. the behavior of short-lived radon-222 progeny in atmospheric processes is discussed. Chapter II. introduces in more detail the rainout model [6]. In Chapter III. the used time series dataset is presented. Chapter IV. discusses the numerical evaluation of the one year long series using Python, the results being discussed in Chapter V.
I. Radon progeny in atmospheric processes

The major source of atmospheric radon is the direct exhalation from soil gas to the atmosphere. Thus the short-lived radioactive decay products of radon-222, which are emitters of all three radiation types (Fig.I.1.), contribute to the radioactivity of rainwater. The gamma-dose rate measurements deal with $^{218}$Po, $^{214}$Pb and $^{214}$Bi. All three are radon daughters out of which the $^{214}$Pb and $^{214}$Bi emit several gamma-rays with different energies, which is detected with the environmental gamma dose rate monitoring stations.

![Fig. I.1. Main decay diagram of radon and it's decay products [7].](image)

The radon is a noble gas that enters to the soil pores and by diffusion and convection it can be exhaled to the open air. A measurable radon concentration can be obtained at several km altitude since the turbulent mixing of the boundary layer can carry these atoms up. On Fig.I.1 the radon decay chain can be seen which is a subset of the naturally frequently occurring uranium decay chain. The decays demonstrated by vertical lines are the alpha decays like $^{222}$Rn and $^{218}$Po. The line at 45° describes the beta-decays. The half lives are also shown on this figure, which illustrate that $^{210}$Pb stops the decay chain for the processes at the time scale of some years. The isotopes after $^{210}$Pb will be important only after about 100 years. For our purpose the $^{214}$Pb and $^{214}$Bi gamma emitters are the only ones of importance. Their highly abundant gammas have energies above 100 keV which can travel several meters in the open air.
After the decay of $^{222}$Rn present in the atmosphere, the freshly formed nuclides may rapidly attach to ambient aerosol particles, which are mostly very fine particles, their particle diameters ranging between 0.015 and 0.5 μm [8]. These radioactive aerosols in the atmosphere are generated in two steps. After formation from the radon isotope the freshly generated decay product radionuclides react very fast (<1s) with trace gases and air vapors and become small particles with diameters ranging from 0.5 to 5 nm [9], forming small clusters or remaining unattached radionuclides. Besides the cluster formation these radionuclides attach to the existing aerosol particles in the atmosphere within 1-100 s, forming radioactive aerosols, which otherwise serve as cloud condensation nuclei.

Fig. I.3. The formation of raindrops containing radioactive nuclei.

In order to condense into a rain droplet, water vapor requires the initial presence of an aerosol particle. Otherwise, a small cluster of pure water molecules will spontaneously evaporate, this being
proved by thermodynamical arguments. So cloud droplets initially form on an aerosol particle and thus capture it, process referred to as in-cloud scavenging. The formed cloud droplets, containing also the radioactive nuclides, then become raindrops due to collision and coalescence processes, until they are large enough to overcome the updraft speed within the cloud and fall as rain [10].

During below-cloud scavenging raindrops falling below-cloud can collide with other aerosol particles, capture them and carry them to the earth's surface. However, these scavenging effects are proved to be less significant than the in-cloud processes [1].

The rain containing the radon daughters will then accumulate on the surface or on plants and buildings. Then it will infiltrate into the soil or will be collected by the sewage pipe system around there.

The gamma dose stations of the radioactivity monitoring system which are at 1 m above the ground can detect the gammas of the water that extend on the surface. The detected gamma dose is proportional to the activity concentration of this rainwater.
II. Model for wet deposition of radon progeny

II.1. Equations of the simple rain-out model

The work of Minato [6] presents a simplified model which calculates radioactivities of short-lived radon daughters in rainwater as a function of rainfall rate for a given unit concentration of radon in the cloud air. The model incorporates processes of impact collection for cloud droplets by raindrops, removal of raindrops from cloud and transport time of raindrops from the cloud base to the ground as forms of semi-empirical formulas.

A rain cloud under a steady state condition is considered, where $^{222}\text{Rn}$ and its daughters are uniformly distributed. It is assumed that in cloud air equilibrium is established between radon and its short-lived progeny. At some specific time point cloud droplets are formed more or less simultaneously when proper atmospheric conditions, such as temperature decrease, suddenly happen. For simplicity it is assumed that after the formation, cloud droplets capture essentially only $^{218}\text{Po}$ in the cloud air rapidly because that $^{218}\text{Po}$ decays by particle emission with a much shorter half-life. Therefore, at the beginning a reasonable assumption of activity ratio of RaA ($^{218}\text{Po}$) : RaB ($^{214}\text{Pb}$) : RaC ($^{214}\text{Bi}$) = 1 : 0 : 0 in cloud droplets is considered. Considering the above described system and the collision of cloud droplets in the formation of raindrops, we can examine the change in the number of the radon daughters in cloud droplets per unit volume:

$$\frac{dn_A}{dt} = -\lambda_A n_A - \Psi_C n_A + a_{\text{Rn}} \quad (1)$$

Here the terms on the right side have the following meanings: the first term is the decay of the A isotope ($^{218}\text{Po}$), the number of radioactive droplet changes because of the isotope disappears, in the same time this term will be an increase of the number of droplet containing the B isotope. Here we assume that the droplets contains only one or zero radon daughters, which is a low activity concentration case. But the radon concentration at the cloud height is quite low, therefore this assumption is well established. The second term on the right side refers to the process when the droplet becomes a raindrop, since many cloud droplets melt to form a raindrop. The probability factor ($\Psi_c$) here is the same for all isotopes (A, B, C) since the raindrop formation is independent from the type of radioactivity. The third term is the radon activity which produces the $^{218}\text{Po}$-s.

We assume an equilibrium and then we can rewrite the equation as follows, and we can apply the
same thinking for the other second isotopes (B, C):

\[
a_{Rn} = \lambda_A n_A + \psi_C n_A \quad (2)
\]
\[
\lambda_A n_A = \lambda_B n_B + \psi_C n_B \quad (3)
\]
\[
\lambda_B n_B = \lambda_C n_C + \psi_C n_C \quad (4)
\]

where \( a_{Rn} \) is the radioactivity of Rn per unit volume in cloud air [Bq/m\(^3\)], \( n_A, n_B, n_C \) are the numbers of cloud droplets containing \(^{218}\)Po (RnA), \(^{214}\)Pb (RnB) and \(^{214}\)Bi (RnC), respectively, \( \lambda_A, \lambda_B, \lambda_C \) are the decay constants for the three elements [1/s] and \( \psi_c \) is the removal rate of cloud droplets by raindrops.

From this the activities of RaA, RaB, and RaC on cloud droplets per unit volume in cloud can be expressed as a function of \( a_{Rn} \):

\[
a_A = \frac{\lambda_A}{\lambda_A + \psi_C} a_{Rn} \quad (5)
\]
\[
a_B = \frac{\lambda_B}{\lambda_B + \psi_C} a_A \quad (6)
\]
\[
a_C = \frac{\lambda_C}{\lambda_C + \psi_C} a_B \quad (7)
\]

\( a_A, a_B, a_C \) being the activities of RaA, RaB, and RaC on cloud droplets per unit volume in cloud [Bq/m\(^3\)].

The raindrops formed by the collision of cloud droplets become larger and larger and sink to the cloud base. During this process the radon daughters in raindrops per unit volume in the cloud are represented by the following equations:

\[
\psi_C n_A = \lambda_A^r N_A + \psi^r N_A \quad (8)
\]
\[
\psi_C n_B + \lambda_A^r N_A = \lambda_B^r N_B + \psi^r N_B \quad (9)
\]
\[
\psi_C n_C + \lambda_B^r N_B = \lambda_C^r N_C + \psi^r N_C \quad (10)
\]

which contain \( N_A, N_B, N_C \) – number of raindrops with RaA, RaB, and RaC and \( \psi^r \) removal rate of raindrops from the cloud.

From these equations, the activities of RaA, RaB, and RaC in raindrops per unit volume (\( A_A, A_B, A_C \)) can be expressed as:
Finally, raindrops from the cloud base fall down to the ground with a certain t falling time, which is the time required for the raindrop to get from the cloud base to ground-level. The radon daughters under the cloud base are calculated from the following equations:

\[
\frac{dA_A}{dt} = -\lambda_A A_A \\
\frac{dA_B}{dt} = \lambda_B (A_A - A_B) \\
\frac{dA_C}{dt} = \lambda_C (A_B - A_C)
\]

In the gamma dosimeters that are in the monitoring system the gamma radiation will give signals. The \(^{218}\)Po produce only \(\alpha\)-radiation, so only B and C isotopes contribute to the dose of interest. We assume that the 2 isotopes make signals in the detectors with the same efficiency. Therefore in a final form the radioactivity observed on ground level will be given by the sum of \(A_B\) and \(A_C\) as it can be written with the following formula:

\[
A_B + A_C = A_{B0} e^{-\lambda_A t} + A_{A0} \frac{\lambda_B}{\lambda_B - \lambda_A} \left( e^{-\lambda_A t} - e^{-\lambda_B t} \right) + A_{C0} e^{-\lambda_C t} + A_{B0} \frac{\lambda_C}{\lambda_C - \lambda_B} \left( e^{-\lambda_B t} - e^{-\lambda_C t} \right) \\
+ A_{A0} \frac{\lambda_C \lambda_B (\lambda_C - \lambda_B) e^{-\lambda_A t} - (\lambda_C - \lambda_A) e^{-\lambda_B t} - (\lambda_B - \lambda_A) e^{-\lambda_C t}}{|\lambda_B - \lambda_A||\lambda_C - \lambda_A||\lambda_C - \lambda_B|}
\]

(17)

This still needs to be converted from the radioactivities of raindrops per unit volume in cloud air to the activities of rainwater, \(\alpha A\), \(\alpha B\) and \(\alpha C\), in units of Bq/mL using the following relation:

\[
\alpha_B + \alpha_C = \frac{\rho}{L_r} (A_B + A_C)
\]

(18)

where \(L_r\) gives the water content of raindrops in the volume of the cloud \([\text{g/m}^3]\).

The water content of raindrops can be expressed as a function of the rainfall rate \(P\), derived from the
Marshall-Palmer formula [11]:

\[
L_r = 0.089 P^{0.84}
\]  \hspace{1cm} (19)

The \( \psi_c \) the removal rate of cloud droplets by raindrops gives the probability of the removal of one cloud droplet by a raindrop per unit time \([1/s]\). This quantity was defined in a former study [12] and the empirical formula was given by numerical calculations:

\[
\psi_c = \left[ 0.028 - 0.036 e^{-0.19 <R>} \right] P^{0.83}
\]  \hspace{1cm} (20)

where \(<R>\) is the mean radius of cloud droplet in \(\mu m\).

The \( \psi_r \) removal rate of raindrops from the cloud gives the probability for a raindrop to fall out from the cloud per minute. This is derived from the definition of the rainfall rate, \( P \) in \(mm/h\):

\[
P = \psi_r L_r D \]  \hspace{1cm} (21)

\[
\psi_r = 0.187 \frac{P^{0.16}}{D}
\]  \hspace{1cm} (22)

where \( D \) is the cloud depth in \(km\) – the difference between cloud top and cloud base.

Finally an average velocity of raindrops under the cloud \(<v>\) is needed to calculate the transport time from the cloud base to the ground. This can be derived from the following relation:

\[
P = <v> L_r \]  \hspace{1cm} (23)

\[
<v> = 0.187 P^{0.16}
\]  \hspace{1cm} (24)

\(<v>\) being given in units of \(km/min\).

In this manner the radioactivity of ground-level rainwater can be concluded, more specifically the model gives the rainfall rate dependence of specific activity of rainwater at ground level given unit concentration of radon in cloud air. Other necessary parameters are the average cloud droplet radius, cloud base height and cloud depth, which differ depending on the season and cloud type.
II.2. Results provided by the model

By solving equation (17) for different rainfall rates and Rn concentration in the cloud air, in Fig.II.2.1. we can see that the increase of rainfall rate doesn't cause an increase in the radioactivity at ground level. This can be explained by the fact that even the smallest amount of precipitation is capable of depositing most of the airborne progeny, further precipitation merely dilutes the activity in a larger water volume. This is also in agreement with previous studies [1] which show that the below-cloud processes are less important than the in-cloud ones. The increase in precipitation intensity, which would result in an increased number of collisions between falling hydrometeors and aerosol particles, doesn't yield higher values. However an increase of Rn radioactivity in unit volume of cloud air produces a higher activity concentration observed in ground level rain water.

Fig.II.2.1. The dependence of the ground-level radioactivity as a function of rainfall rate for a given concentration of radon in cloud – other parameters: $R = 11 \mu m$, $D = 8 km$, $h = 2 km$. 
III. Description of the time series dataset

III.1. Dosimetric system of Paks Nuclear Power Plant

The accurate monitoring of radiation exposure is a key element in practical radiation protection. For this purpose in Hungary the National Directorate General for Disaster Management operates more than 130 dosimetric stations to monitor the dose rate of background radiation. The used autonomous gamma detectors are designed for measuring radioactivity of gamma radiation in open areas, with a measuring range from 10 nSv/h up to 10 Sv/h.

![Daily background dose rate](image)

**Fig.III.1.1. Background dose rate available for one of Paks's dosimetric systems [1].**

In Hungary the normal dose rate values range between 50-180 nSv/h, and values that exceeds 250 nSv/h are considered a potential threat and the involved area is subject to increased attention. The warning level is reached if the dose rate increases above 500 nSv/h [14.]. The background dose rate for every dosimetric station is available for the current day, and as shown in Fig.III.1.1. it displays the daily average and the two warning levels.

The current study deals with the data provided by the 20 dosimetric systems surrounding Paks Nuclear Power Plant, as seen in Fig.III.1.2. The measurements were taken in the years 2010 and 2011 with 10 minute intervals, providing thus a fine resolution of the radiation conditions.
III.2. Measured parameters

The natural background radiation varies with respect to the different geographic parameters, such as altitude, soil type but is also largely influenced by natural effects, like atmospheric pressure, precipitation etc.

In order to analyze the correlation between the dose rate and the meteorological parameters, a fine resolution in the acquired data was necessary. The data series provided by the Paks Nuclear Power Plant contains 10 minute averages for the years 2010 and 2011, a sufficiently large data set to study.

The data series contains information for each station regarding the gamma dose rate, which is converted to nSv/h units and meteorological parameters for the corresponding area, as follows: precipitation summed over 10 minutes (mm/10 min), solar irradiance (W/m²), velocity (m/s) and direction of wind, temperature (°C) and atmospheric pressure (hPa).

Fig.III.1.2. Dosimetric system of Paks Nuclear Power Plant [15].
III.3. Description of the general features of the data

The most relevant feature for the current study is the increase in the dose rate due to precipitation. The short, prominent increases of around 15-20% are observed after rainfall events up to 1.5 hours. On Fig.III.3.1. an example of this case can be observed: during the time period in which a rainfall event occurs, marked with light blue streak, a sudden increase in the measured dose rate can be observed, which returns to the normal value after the rainfall event has stopped.

![Dose rate vs Day](image)

**Fig.III.3.1.** The rainfall event marked with a light blue streak triggers an increase in the measured dose rate.

In order to determine the precipitation dependence of the measured dose rates, the model described in Chapter II.2. is implemented. The aim is to find the appropriate values of the parameters for different precipitation types and for the different seasons. The ultimate goal is to create a reliable tool that can predict the increase in ground-level radioactivity due to precipitation.

A previous analysis of the given data showed that, apart from a few randomly appearing sharp maximums, which were probably due to maintenances, the A and G type stations are highly correlated. The values obtained from the cross-correlation matrix range between 0.5 and 0.9. This establishes our assumptions that a common cause for the increase in the dose rate prevails, which for the high values is due to the radioactivity of radon daughters brought by precipitation.
Fig.III.3.2. The dependence of temperature and Rn concentration in time, night hours marked with gray, data from 2003 [16].

Another relevant feature of the data was the slight systematic increase of dose rate during nights, which is due to the inversion of the atmospheric boundary layer, having to do mainly with the temperature gradient of the air. During the day the boundary layer above the ground surface is heated by the ground, and thus the air current moves upward, reaching an altitude up to 1500 - 2000 m. During the night however, due to the lack of rising convective vortices, a stable layer is formed with only a few thousand meters altitude or less. Here the Rn concentration increases, because the Rn exhaled during the day is captured in this layer, and furthermore atoms exhaled from the soil are added to this. Fig.III.3.2. presents the increase of Rn concentration (colored in red) in air due to this inversion phenomena [16]. Fig.III.3.3. illustrates the phenomena on the measured gamma dose rates from our data.

It is also known that there is a seasonal dependence of the measured radioactive concentration. In winter relatively high concentrations are specific due to the short mixing height caused by the short daylight duration. The lowest values are obtained in early spring, when the mixing of the boundary layers is much more efficient, and furthermore the exhalation of $^{222}\text{Rn}$ is reduced due to the snow cover
and frozen ground. The high diurnal variations are observed especially in late summer and autumn because of the strong radon exhalation and simultaneously of the frequent nocturnal surface inversions [1].

*Fig.III.3.3. Diurnal variations in the dose rate observed in our data from 2010.*
IV. Numerical processing of the time series dataset

The dataset due to its large size and complexity required computational processing. This was achieved using Python, an open source general-purpose language. The program, shown in Attachment 1, processed the acquired measurements from the dataset and implemented the already discussed rain-out model, which calculates a theoretically estimated activity or dose rate for a given precipitation.

The time series dataset contains information for the year 2010 and 5 months for 2011, from June to October. In order to analyze the effect of precipitation on the measured dose rate, as a first step the rainfall events had to be determined. A time period with precipitation was considered a rainfall event, in which the measured precipitations weren't apart for more than 40 minutes. The program identified for the year 2010 a number of 369 such events on 143 days, while in 2011 there were 71 rainfall events on 36 days.

![Graph showing dose rate over time](image)

*Fig.IV.1. Determination of the extra dose rate by subtracting daily averages.*

In order to identify the extra dose rate attributed to rainfall events, an average daily value was determined and subtracted from the data, as shown in Fig.IV.1. This diurnal average value was a simple average of those data points of one day which weren't preceded by a rainfall event for at least 3
hours (daily dry average). This eliminates the inclusion of extra radioactivity due to precipitation, as the time for the short-lived radon progeny to decay requires 2.5 hours. Furthermore the diurnal variations of the daily dry dose rate weren’t taken into account because the radioactivity brought by rainfall is of a much larger scale. In the program this was done for all 20 dosimetric stations.

Furthermore for each time step of 10 minutes the program calculated a theoretical dose rate having as input the precipitation rate for the given period, and as parameters the radioactive concentration of Rn in unit volume of cloud air and the cloud height and cloud depth. Thus the dose rates brought by rainfall were determined, considering also the decay of the formerly present radioactive nuclei at ground level.

In order to measure the difference between the values given by the model and the values actually observed, the normalized root-mean-square deviation (NRMSD) was used, further referred to as NR. This was calculated by dividing the average of the square of the differences between the extra dose rates \( x_{1,t} \) and theoretical dose rates \( x_{2,t} \) by the range of observed dose rates. For measuring the normalized average difference between the two time series the formula becomes:

\[
NR = \frac{1}{x_{\text{max}} - x_{\text{min}}} \sqrt{\frac{\sum_{t=1}^{n} (x_{1,t} - x_{2,t})^2}{n}}
\]

The value expresses a percentage, where lower values indicate less residual variance, and a better prediction strength of the model.

In order to process the results, for each rainy day the extra dose rates for all the 20 stations, the theoretical dose rate and the precipitation intensity was plotted. The extra dose rates, named AA, were plotted with shifted values in order to have a more compact form, showing also the resulting NRMSD value calculated for the given extra dose rate and the theoretical value. A sample plot can is shown in Fig.IV.2.

After doing all the necessary analysis, in order to document all the rainfall events Latex script was embedded into Python to create a pdf file with all the possible plots. For each rainy day the measured dose rates for all the 20 stations, the theoretical dose rate and the precipitation intensity was plotted, marking also the data points which where taken into consideration for the daily averages. An extra plot also documented information about concentration in the rainwater that was collected in sewage pipes for further analysis. A sample page of the pdf documentation can be seen in Attachment 2.
**Fig.IV.2.** Displaying the processed data of a rainy day: the AA represents the extra dose rates, the number identifying the station from which the measurements were provided. For a more concise representation the AA values are shifted with the values indicated in the legend, showing also the NR calculated from the comparison of the given extra dose rate and the theoretically calculated value.
V. Results and discussion

The main results of this study were given by the comparison of the measured and theoretical dose rate values. In order to have a good correlation between the two data series optimal parameter sets had to be found for each season, that would also cover the different precipitation types.

The most important parameter was the radioactivity of Rn in cloud air per unit volume \(a_{Rn}\), its value being considered in the range of 0.2 – 2 Bq/m\(^3\), based on former studies [1,3,6]. In Hungary the clouds that yield precipitation have heights in the range between 1 – 3 km, often under 2 km, thus an average value of 1.8 km was taken for the cloud height (h) for all seasons. An average cloud drop radius of \(R = 10 \mu m\) was also considered regardless of the season. The cloud depth D was considered in a range of 3 – 8 km.

For winter the best results were given by choosing a relatively small radioactivity value, and considering smaller clouds. For the values \(a_{Rn}= 0.4\) Bq/m\(^3\), \(D = 3\) km, \(h = 1.8\) km and \(R = 10\) \(\mu m\) the normalized root-mean-square deviation ranged between 0.15 – 0.46 in 75% of the cases - all the values being displayed in Table 1 from Attachment 3. This gave a good agreement between measured and theoretical values for January - February (Fig.V.1.) and November – December 2010 (Fig.V.2.).

![Fig.V.1. Displaying results for winter 2010: the AA values show the extra dose rates from the different stations. For a concise representation the values are shifted with the displayed values. The used parameters are as follows: \(a_{Rn}= 0.4\) Bq/m\(^3\), \(D = 3\) km, \(h = 1.8\) km and \(R = 10\) \(\mu m\).]
Fig.V.2. Using the same representation as in Fig.V.1., the parameters for November-December 2010 are: $a_{Rn} = 0.4 \text{ Bq/m}^3$, $D = 3 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \text{ μm}$.

For summer and autumn a larger value was chosen for $a_{Rn}$, considering also higher cloud depth due to the frequent occurrences of cumulonimbuses. The parameters were set for $a_{Rn} = 0.75 \text{ Bq/m}^3$, $D = 8 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \text{ μm}$. The normalized root-mean-square deviation ranged between 0.15 – 0.46 in 73% of the cases (see Table 3. in Attachment 3). In 2010 these parameters provided good agreement between measured and theoretical values for June-October (Fig.V.3. and Fig.V.4).

Fig.V.3. Parameters for summer of 2010: $a_{Rn} = 0.75 \text{ Bq/m}^3$, $D = 8 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \text{ μm}$. 
Fig. V.4. Parameters for autumn of 2010: $a_{Rn} = 0.75 \text{ Bq/m}^3$, $D = 8 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \mu\text{m}$.

It is interesting to note that for these parameters systematical and large differences occurred for the station AA3, like in the case of Fig. V.4. October. Even if the other stations data gave an NR number between 0.15 and 0.3, for this station the value was in the most cases above 0.5. This could be related to the location of the station, which in Fig. III.1.2. corresponds to the station A3 being positioned between the Danube and a fish pond, where other physical processes could have noticeable effects.

Fig. V.5. Parameters for summer of 2011: $a_{Rn} = 0.75 \text{ Bq/m}^3$, $D = 8 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \mu\text{m}$. 
For the same parameter set the NR value showed good agreement between July and October 2011 (Fig.V.5. and Fig.V.6., for Nr values see Table 3. in Attachment 3). Even in this year did the values from the station A3 show a significantly different behavior.

**Fig.V.6.** Parameters for autumn 2011: \( a_{Rn} = 0.75 \text{ Bq/m}^3 \), \( D = 8 \text{ km} \), \( h = 1.8 \text{ km} \) and \( R = 10 \mu\text{m} \).

**Fig.V.7.** Parameters for spring of 2010: \( a_{Rn} = 0.25 \text{ Bq/m}^3 \), \( D = 5 \text{ km} \), \( h = 1.8 \text{ km} \) and \( R = 10 \mu\text{m} \).
For spring season the smallest radioactivity value of $a_{\text{Rn}} = 0.25 \text{ Bq/m}^3$ was chosen based on the observations of former studies [1] (according to smaller radon flux from soil) and also the value of $D$ was an intermediate one between those considered for summer and winter. Thus for the following parameter set of $a_{\text{Rn}} = 0.25 \text{ Bq/m}^3$, $D = 5 \text{ km}$, $h = 1.8 \text{ km}$ and $R = 10 \mu\text{m}$ gave good results for 75% of the cases studied (see Table 2. in Attachment 3) between March and May 2010 (Fig.V.7.).

The parametrization of the model covered also a wide range of different precipitation types. For short, barely significant rainfall events with small precipitation the predicted dose rate behaved in the same manner as the measured ones, barely noticeable from the average fluctuation, as seen in Fig.V.8.

**Fig.V.8.** *Short rainfall events with low intensity, producing non-prominent dose rate values, data from spring 2010, with the parameters used for this period.*

The same was valid for short, but intense rainfall events. These produced also barely noticeable increases in the dose rates, predicted also by the model, as seen in Fig.V.9.

For rainfall events, which took place for a longer time and with an increased precipitation intensity, the correspondence between the data was also favorable, the theoretical value giving a good approximation for the measured increases in the dose rates for most of the cases. Examples are shown in Fig.V.10.
**Bakos Katinka**

**The effect of wet deposition on ground-level gamma dose rates**

**Fig. V.9.** Short, but intense rainfall events, producing only increases in the dose rate values, data from summer and autumn 2010, with the parameters used for this period.

**Fig. V.10.** For long and significant rainfall events the correspondence between the two values was also favorable, data from autumn 2010 and 2011, with the parameters used for this period.
Summary

In our study the effect of rainwater on the ground-level gamma-dose rate was successfully studied by applying a semi-empirical rain-out model for radon progeny already present in the literature [6].

In order to have good correlation between the measured and theoretical dose rate values throughout the year, different parameter sets were defined, taking into consideration the location of the dosimetric stations. For winter low activity concentration of Rn in cloud air was considered, taking also low values for cloud depth. The highest radioactivity was used for summer and autumn together with high values for cloud depth. The lowest radioactive concentrations were taken for spring, the cloud depth being an intermediate value between those used for winter and summer. This parametrization of the model gave good results for the majority of the rainfall cases.

Naturally, as it was expected, a full coverage cannot be achieved due to the variety and complexity of atmospheric processes. However, with the provided parametrization a good estimation of radioactive dose rate increase provided by rainfall events can be achieved and can be useful in determining the presence of other unregarded radioactive sources.

The results are currently being prepared for publication.
Acknowledgements

First of all I would like to thank my foreign supervisor Dr. Horváth Ákos for accepting my application to pursue this research at Eötvös Loránd University during the first semester, and for providing his professional guidance in the development of this scientific work.

I would like to thank my home supervisor Dr. Borbély Sándor for his encouragement, creative suggestions and insightful comments.

I would also thank Prof. Dr. Néda Zoltán for his support and efforts in my application for this scientific work.

Special thanks to C. Szabó István for providing the one and a half year long data series from Paks Nuclear Power Plant.
References


Attachments

Attachment 1

# -*- coding: utf-8 -*-
from matplotlib import pylab
from pylab import *
import time
import os
from datetime import date
bkod='utf-8'
#========================================================================
# monthly average
#==========================================================================
def hatter1(E,A):
    s = 0
    nr = 0.0001
    n = len(E)
    for i in range (12,n):
        if (sum(E[i-12:i+2])==0):
            s += A[i]
        nr += 1
    d = s/nr
    return d
#==========================================================================
# daily average
#==========================================================================
def hatter2(Tt,E,A):
    s = 0
    nr = 0.001
    n = len(Tt)
    D = zeros(n)
    j = 0
    for i in range (12,n):
        if ( int(Tt[i]) == int(Tt[i-1]) ) :
            j+=1
if (sum(E[i-18:i+1]) == 0):
    s += A[i]
    nr += 1
else:
    d = s/nr
    D[i-j:n] = d
    nr = 0.001
    s = 0
    j = 0

return D

# def periodus(n, Tt, E, E2, A2, Abc, k, v):
#    e = E[k[n]-2:v[n]+18]
#    ef = E2[k[n]-2:v[n]+18]
#    Tt = Tt[k[n]-2:v[n]+18]
#    a = A2[k[n]-2:v[n]+18]
#    abc = Abc[k[n]-2:v[n]+18]
#    return 0

#==========================================================================
# NRMSD of vectors a and b:
#==========================================================================

def RMS(a, b):
    rmsdiff = 0.
    for (x, y) in zip(a, b):
        rmsdiff += (x - y) ** 2
    rmsdiff = math.sqrt(rmsdiff / (len(a)))
    rmsdiff = rmsdiff / min(max(a), max(b))
    return rmsdiff

# def periodus(n, Tt, E, E2, A2, Abc, k, v):

# Reading the data:
#    Tt - time
#    A - measured dose rate
#    AA - extra dose rate
#    mA - data for calculating background dose rate
#    Abc - theoretical activity
Bakos Katinka

The effect of wet deposition on ground-level gamma dose rates

# E - rain intensity
# DD - background dose rate
# KV - sewage & Co
#

m = loadtxt('2010paks.txt', skiprows=2)
Tt = m[:,0]
E = m[:,1]
n = len(m)
nea='2010paks.txt'
f=open(nea,'r')
sz=f.readline().rstrip('
')
pm=sz.split('	')
sz=f.readline().rstrip('
')
mtke=sz.split('	')
npk=len(mtke)

# print npm, pm, mtke

A = [[0 for x in xrange(n)] for x in xrange(21)]
for i in range (1,21):
    A[i] = m[:,i+1]

KV = [[0 for x in xrange(n)] for x in xrange(5)]
KV[1]=m[:,22]
KV[2]=m[:,23]
KV[3]=m[:,26]
KV[4]=m[:,27]

# The rainout model for radon daughters - Parameters
# a - Rn activity concentration [Bq/m3] default value: 1
# R - average radius of cloud droplets [micrometer] default value: 11
# P - rainfall rate [mm/h]
# D - cloud thickness [km] default value: 8
# h - height of cloud bottom [km] default value: 2
# Ro - density of water [g/ml]
#

33
The effect of wet deposition on ground-level gamma dose rates

\[ a = 0.5 \]
\[ R = 11 \]
\[ D = 10 \]
\[ h = 2 \]
\[ c = 0.693 \]
\[ n = \text{len}(E) \]
\[ AA = \text{zeros}(n) \]
\[ AB = \text{zeros}(n) \]
\[ AC = \text{zeros}(n) \]
\[ Abc=\text{ones}(n) \]
\[ \lambda_A = \frac{c}{3.1} \]
\[ \lambda_B = \frac{c}{26.8} \]
\[ \lambda_C = \frac{c}{19.9} \]

for i in range (1,n-3):
    Aa = 0
    Ab = 0
    Ac = 0
    if (E[i]!=0):
        Lr = 0.089*\text{pow}(E[i]/10,0.84)
        v = 0.187*\text{pow}(E[i]/10,0.16)
        t = \frac{h}{v}
        PsziR = v / D
        PsziC = (0.028-0.036*\text{exp}(-0.19*R))*\text{pow}(E[i]/10,0.83)
        konst = PsziC * lambdaA * a / (lambdaA + PsziC)
        eA = \text{exp}(-\lambda_A * t)
        eB = \text{exp}(-\lambda_B * t)
        eC = \text{exp}(-\lambda_C * t)
        a0 = \frac{\lambda_A}{\lambda_A + PsziC} * a
        b0 = \frac{\lambda_B}{\lambda_B + PsziC} * a0
        c0 = \frac{\lambda_C}{\lambda_C + PsziC} * b0
        Aa0 = \frac{PsziC}{\lambda_A + PsziR} * a0
        Ab0 = \frac{PsziC}{\lambda_B + PsziR} * b0 + \frac{\lambda_B}{\lambda_B + PsziR} * Aa0
        Ac0 = \frac{PsziC}{\lambda_C + PsziR} * c0 + \frac{\lambda_C}{\lambda_C + PsziR} * Ab0
        B = \text{lambdaA*lambdaB*(((lambdaC-lambdaB)*eA - (lambdaC-lambdaA)*eB + (lambdaB-lambdaA)*eC)/((lambdaB-lambdaA)*(lambdaC-lambdaA))} \text{lambdaC-lambdaB))}
        Aa = Aa0 * \frac{eA}{Lr}

34
The effect of wet deposition on ground-level gamma dose rates

\[ Ab = \left( A_{b0} \times e^{B} + A_{a0} \times \frac{\lambda_{b}}{\lambda_{b} - \lambda_{a}} \times (e^{C} - e^{B}) \right) / L_r \]

\[ Ac = \left( A_{c0} \times e^{C} + A_{b0} \times \frac{\lambda_{c}}{\lambda_{c} - \lambda_{b}} \times (e^{B} - e^{C}) + \frac{\lambda_{c}}{\lambda_{a}} \times A_{a0} \right) / L_r \]

#the activity from 10 min before is added

\[ b_{1} = \lambda_{a} \times \lambda_{b} \left( \frac{(\lambda_{c} - \lambda_{b}) \times e^{-\lambda_{a} \times 10} - (\lambda_{c} - \lambda_{a}) \times e^{-\lambda_{b} \times 10} + (\lambda_{b} - \lambda_{a}) \times e^{-\lambda_{c} \times 10}}{(\lambda_{b} - \lambda_{a}) \times (\lambda_{c} - \lambda_{a}) \times (\lambda_{c} - \lambda_{b})} \right) \]

\[ AA[i] += A_{a} + AA[i-1] \times e^{-\lambda_{a} \times 10} \]

\[ AB[i] += A_{b} + AB[i-1] \times e^{-\lambda_{b} \times 10} + AA[i-1] \times \lambda_{a} \times \lambda_{b} / (\lambda_{b} - \lambda_{a}) \times (e^{-\lambda_{a} \times 10} - e^{-\lambda_{b} \times 10}) \]

\[ AC[i] += A_{c} + AC[i-1] \times e^{-\lambda_{c} \times 10} + AB[i-1] \times \lambda_{b} \times \lambda_{c} / (\lambda_{c} - \lambda_{b}) \times (e^{-\lambda_{b} \times 10} - e^{-\lambda_{c} \times 10}) + AA[i-1] \times \lambda_{c} \times b_{1} \]

\[ Abc[i] *= (AB[i] + AC[i]) \]

# Calculation of background dose rate

\[ aa = zeros(n) \]
\[ D = zeros(n) \]
\[ DD = [[0 for x in xrange(n)] for x in xrange(21)] \]
\[ AA = [[0 for x in xrange(n)] for x in xrange(21)] #! a 0-ik az atlag \]
\[ mA = [[-20 for x in xrange(n)] for x in xrange(21)] \]

for i in range(n):
    for j in range (1,21):
        A[0][i]+=A[i][j]/20

hatter = hatter2(Tt,E,A[0])

hatter[0:12]=hatter1(E,A[0])

AA[0] = A[0] - hatter

for i in range(21):
    for j in range(12,n):
        if (sum(E[j-18:j+2])==0):
            mA[i][j]=A[i][j]

for i in range(1,21):
    aa = A[i]
    D = hatter2(Tt,E,aa)
    D[0:12]=hatter1(E,aa)
    DD[i]=D
    AA[i] = A[i] - D

#===========================================

# Periods with rain
Bakos Katinka

The effect of wet deposition on ground-level gamma dose rates

# k - start of rain (sorszam)
# v - end of rain (sorszam)
# nn - nr. of rainy days

# ================
k = zeros(n/100)
v = zeros(n/100)

for i in range (4,n-4):
    if (E[i-4] == 0) & (E[i-3] == 0) & (E[i-2] == 0) & (E[i-1] == 0) & (E[i] != 0):
        k[ik] = i
        ik +=1
        #print E[i], AA[1][i+2]
    if (E[i-1] != 0) & (E[i] == 0) & (E[i+1] == 0) & (E[i+2] == 0) & (E[i+3] == 0) & (E[i+4] == 0):
        v[iv] = i
        iv += 1

nn = zeros(ik)
d=0
for i in range(ik):
    nn[i-d] = int(Tt[k[i]])
    if (nn[i-d] == nn[i-d-1]):
        nn[i-d] = 0
        d+=1
n1=zeros(ik-d)
i=0
for j in range (n):
    if ( int(Tt[j]) == nn[i]):
        n1[i] = j
        i+=1

# Plotting of rainy days, writing data for Latex, saving data to pdf file
# ==============================================================
texf = open('sspaks.tex', 'w')
texf.write("\documentclass{article}\n\usepackage{graphicx}\n'.encode(bkod))
texf.write("\usepackage[utf8]{inputenc}\n")
texf.write("\usepackage{float}\n")
eltolodas = zeros(ik-d)
eltolodas[ik-d-2] = 4
eltolodas[ik-d-1] = 4
datfr=datf
figon=0
npic = 0
c1 = [0,-20,-40,-60]
ks=-40 #0
elt = ones(n)
romai = ['VI','I','II','III','IV','V']
for j in range (ik-d):
    for i in range (1,21,4):
        fig = figure()
        ax1 = fig.add_subplot(111)
        ax1.set_xlabel('Elapsed time [days]
ax1.set_ylabel('Dose rate [nSv/h]
ax1.set_ylim((0,180))
ax2 = ax1.twinx()
ax2.set_ylabel('Precipitation rate [mm/10 min]
ax2.set_ylim((0,9))
st=int(n1[j])
sp=int(st+170)
ks+=20 #15
aline1 = ax1.plot(Tt[st:sp],AA[i][st:sp]+20*elt[st:sp],label='AA'+str(i)+' + 20; NR: %.2f' %RMS(AA[i][st:sp],Abc[st:sp]))
aline2 = ax1.plot(Tt[st:sp],AA[i+1][st:sp]+40*elt[st:sp],label='AA'+str(i+1)+' + 40; NR: %.2f' %RMS(AA[i+1][st:sp],Abc[st:sp]))
aline3 = ax1.plot(Tt[st:sp],AA[i+2][st:sp]+60*elt[st:sp],label='AA'+str(i+2)+' + 60; NR: %.2f' %RMS(AA[i+2][st:sp],Abc[st:sp]))
aline4 = ax1.plot(Tt[st:sp],AA[i+3][st:sp]+80*elt[st:sp],label='AA'+str(i+3)+' + 80; NR: %.2f' %RMS(AA[i+3][st:sp],Abc[st:sp]))
linem4 = ax1.plot(Tt[st:sp],mA[i+3][st:sp]-40*elt[st:sp],'*')
lineelm = ax1.plot(Tt[st:sp],Abc[st:sp]+DD[i+3][st:sp]-40*elt[st:sp],label='Theoretical dose rate - 40')
eline = ax2.plot(Tt[st:sp],E[st:sp],label='Precipitation'.decode(bkod))
setp(eline, color = 'b', linewidth=1.5)
setp(aline1, color = 'r', linewidth=1.5)
setp(linem1, color = 'r', linewidth=2.0)
setp(aline2, color = 'y', linewidth=1.5)
setp(linem2, color = 'y', linewidth=2.0)
setp(aline3, color = 'm', linewidth=1.5)
setp(linem3, color = 'm', linewidth=2.0)
setp(aline4, color = '#8B0000', linewidth=1.5)
setp(linem4, color = '#8B0000', linewidth=2.0)

setp(lineelm, color = 'g', linewidth = 1.5)
ax1.legend(loc=2)
ax2.legend(loc=0)

npic += 1
print npic

mnap = int(T[n1[j]])

datf = str(date.fromordinal(date(2010, 1, 1).toordinal() + mnap ))+ ' ' + romai[npic%6]
suptitle(datf)
fig.savefig(datf,bbox_inches=0)
fig.clf()

if (npic%2 == 1):
    texf.write(chr(92)+'begin{figure}[H]
')
    figon=1
    texf.write(chr(92)+'mbox{\includegraphics[width=0.5\textwidth]{'+datf+'}}
')
if (npic%2 == 0):
    datfr = str(date.fromordinal(date(2010, 1, 1).toordinal() + mnap ))+ ' ' + romai[npic%6-1]
textf.write(' \caption{Left: '+datfr+', Right:'+datf+'} \n')
    textf.write('end{figure}\n')
    textf.write('vskip -0.2in
')
figon=0

if (npic%6 == 5):
    fig2 = figure()
    ax3 = fig2.add_subplot(111)
    ax3.set_xlabel('Elapsed time [day].decode(bkod)')
    ax3.set_ylabel('Activity concentration [Bq/m3].decode(bkod)')
    ax3.set_ylim((0,700))
    ax4 = ax3.twinx()
The effect of wet deposition on ground-level gamma dose rates

```python
ax4.set_ylabel('Precipitation rate [mm/10 perc]'.decode(bkod))
ax4.set_yscale((0,9))

# line1 = ax3.plot(Tt[st:sp+107],KV[0][st:sp+107],label='Sewage – measured concentration [kBq/m3]')
line2 = ax3.plot(Tt[st:sp+254],KV[1][st:sp+254],label=pm[22]+' [nSv/h]')
line3 = ax3.plot(Tt[st:sp+254],KV[2][st:sp+254],label=pm[23]+' [kBq/m3]')
line4 = ax3.plot(Tt[st:sp+254],KV[3][st:sp+254],label=pm[26]+' [kBq/m3]')
line5 = ax3.plot(Tt[st:sp+254],KV[4][st:sp+254]/10,label=pm[27]+' [10 Bq/m3]')
eline2 = ax4.plot(Tt[st:sp+254],E[st:sp+254],label='Rainfall rate')

setp(eline2, color = 'b', linewidth=1.5)
#setp(line1, color = 'r', linewidth=1.5)
setp(line2, color = 'y', linewidth=1.5)
setp(line3, color = 'm', linewidth=1.5)
setp(line4, color = '#8B0000', linewidth=1.5)
setp(line5, color = 'g',linewidth=1.5)

ax3.legend(loc=2)
ax4.legend(loc=0)
npic += 1
print npic
datf = str(date.fromordinal(date(2010, 1, 1).toordinal() + mnap ))+ ' - ' + roman[0]
suptitle(datf)
fig2.savefig(datf,bbox_inches=0)
fig2.clf()
txf.write(chr(92)+'mbox{includegraphics[width=0.5'+chr(92)+'textwidth]{'+datf+'}}
')

datfr = str(date.fromordinal(date(2010, 1, 1).toordinal() + mnap ))+ ' - ' + roman[5]
txf.write(': \caption{Left: '+datfr+', Right: '+datfr+'.}')
figon=0
txf.write('\\end{figure}
')
txf.write(chr(92)+vskip -0.2in\n')
txf.close()
```
Attachment 2

Figure 1: Left: 2010-01-03-I, right: 2010-01-03-II.

Figure 2: Left: 2010-01-03-III, right: 2010-01-03-IV.

Figure 3: Left: 2010-01-03-V, right: 2010-01-03-VI.
Table 1. Average values of NR calculated from the 20 stations for observed rainy days in winter 2010, accepted values in bold.
## The effect of wet deposition on ground-level gamma dose rates

**Table 2.** Average values of NR for observed rainy days in spring 2010, accepted values in bold.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Date</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>2010-03-01</td>
<td>0.20</td>
</tr>
<tr>
<td>$a_{\text{Rn}} = 0.25 \text{ Bq/m}^3$</td>
<td>2010-03-03</td>
<td>0.28</td>
</tr>
<tr>
<td>$D = 5 \text{ km}$</td>
<td>2010-03-10</td>
<td>0.35</td>
</tr>
<tr>
<td>$h = 1.8 \text{ km}$</td>
<td>2010-03-11</td>
<td>0.39</td>
</tr>
<tr>
<td>$R = 10 \text{ \mu m}$</td>
<td>2010-03-22</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2010-03-27</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>2010-03-31</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>2010-04-01</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>2010-04-05</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>2010-04-06</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>2010-04-09</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>2010-04-11</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>2010-04-12</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2010-04-13</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2010-04-14</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>2010-04-16</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>2010-04-19</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2010-04-21</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>2010-04-23</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>2010-04-27</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>2010-04-28</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>2010-05-03</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>2010-05-04</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>2010-05-06</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>2010-05-09</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>2010-05-12</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>2010-05-13</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>2010-05-14</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>2010-05-15</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td>2010-05-16</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>2010-05-17</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>2010-05-18</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2010-05-20</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>2010-05-21</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>2010-05-22</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2010-05-23</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>2010-05-25</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>2010-05-29</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>2010-05-30</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>2010-05-31</td>
<td>0.21</td>
</tr>
</tbody>
</table>
The effect of wet deposition on ground-level gamma dose rates

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Date</th>
<th>NR</th>
<th>Date</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer and Autumn</td>
<td>2010-06-01</td>
<td>0.50</td>
<td>2010-10-20</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>2010-06-02</td>
<td>0.28</td>
<td>2010-10-22</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>2010-06-03</td>
<td>0.50</td>
<td>2010-10-25</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2010-06-04</td>
<td>0.65</td>
<td>2010-10-26</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2010-06-16</td>
<td>0.18</td>
<td>2010-10-28</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>2010-06-18</td>
<td>0.13</td>
<td>2010-10-25</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2010-06-19</td>
<td>0.52</td>
<td>2010-10-26</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2010-06-20</td>
<td>0.22</td>
<td>2010-10-28</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>2010-06-22</td>
<td>0.97</td>
<td>2011-07-01</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>2010-06-25</td>
<td>0.52</td>
<td>2011-07-02</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>2010-06-26</td>
<td>1.52</td>
<td>2011-07-03</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2010-06-28</td>
<td>0.37</td>
<td>2011-07-05</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>2010-06-29</td>
<td>0.28</td>
<td>2011-07-18</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>2010-07-06</td>
<td>0.15</td>
<td>2011-07-20</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2010-07-12</td>
<td>0.38</td>
<td>2011-07-21</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>2010-07-25</td>
<td>0.27</td>
<td>2011-07-23</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>2010-07-26</td>
<td>0.46</td>
<td>2011-07-24</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2010-07-30</td>
<td>0.10</td>
<td>2011-07-25</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>2010-07-31</td>
<td>0.11</td>
<td>2011-07-27</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>2010-08-03</td>
<td>0.25</td>
<td>2011-07-28</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>2010-08-04</td>
<td>0.41</td>
<td>2011-08-04</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>2010-08-06</td>
<td>0.10</td>
<td>2011-08-08</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>2010-08-30</td>
<td>0.80</td>
<td>2011-08-09</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>2010-08-31</td>
<td>0.56</td>
<td>2011-08-19</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>2010-09-04</td>
<td>0.13</td>
<td>2011-08-29</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>2010-09-06</td>
<td>0.61</td>
<td>2011-09-01</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>2010-09-07</td>
<td>0.25</td>
<td>2011-09-08</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>2010-09-08</td>
<td>0.27</td>
<td>2011-09-09</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>2010-09-09</td>
<td>0.31</td>
<td>2011-09-12</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>2010-09-10</td>
<td>0.42</td>
<td>2011-09-15</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2010-09-11</td>
<td>0.28</td>
<td>2011-09-17</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>2010-09-12</td>
<td>0.43</td>
<td>2011-10-08</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>2010-09-17</td>
<td>0.32</td>
<td>2011-10-10</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>2010-09-18</td>
<td>0.39</td>
<td>2011-10-11</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>2010-09-19</td>
<td>0.62</td>
<td>2011-10-13</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>2010-09-25</td>
<td>0.66</td>
<td>2011-10-17</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>2010-09-26</td>
<td>0.27</td>
<td>2011-10-20</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2010-09-27</td>
<td>0.30</td>
<td>2011-10-21</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>2010-10-05</td>
<td>0.30</td>
<td>2011-10-22</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>2010-10-18</td>
<td>0.25</td>
<td>2011-10-23</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>2010-10-19</td>
<td>0.93</td>
<td>2011-10-24</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 3. Average values of NR for observed rainy days in summer and autumn of 2010 and 2011.
Declarație

Prin prezenta declar că Lucrarea de disertație cu titlul “The effect of wet deposition on ground-level gamma dose rate” este scrisă de mine și nu a mai fost prezentată niciodată la o altă facultate sau instituție de învățământ superior din țară sau străinătate. De asemenea, declar că toate sursele utilizate, inclusive cele de pe Internet, sunt indicate în lucrare, cu respectarea regulilor de evitare a plagiatului.

Cluj-Napoca, 26.06.2014. Absolvent:
Bakos Katinka