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Health Impacts of Routine Gaseous Releases from Nuclear Facilities

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Abstract:

This study focuses on the assessment of the environmental impact due to dispersion of gaseous radioactive effluents from nuclear power plants. In this paper the human health regional and local impacts of routine atmospheric releases from a proposed nuclear power plant and also monetary

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unit costs for health impact has been calculated using SIMPACTS model, for different stack heights. The input data include the local and regional population density, human habits, average annual atmosperic radionuclide releases (source term) and metrological data for the selected area. Wind direction and wind speed were analyzed to draw wind rose. While net radiation index and wind speed were prepared as input files in order to calculate the stability class using the Pasquill–Turner Method (PTM). The values of local impacts decreases with increasing the stack height while regional impacts increases with increasing stach height. The total stochastic health effects (cases/y) for both local and regional results are within permissible limits.

Key words: nuclear power plants, gaseous emissions, SIMPACTS, collective dose, monetary cost.

1 INTRODUCTION

Egypt is planning to add nuclear energy to its energy sources (BMI, 2015). Commercial nuclear power plants release small amounts of radiation into the environment under normal operating conditions. Many of the radioactive isotopes that are released are in the form of gaseous or liquid effluents and solid radioactive waste conditioned by the plant. These releases represent one of the by-products of electrical energy generation (Eisenbud and Gesell, 1997). Although it is known that commercial nuclear power plants release small amounts of radioactivity into the environment, there is still the potential for these releases to impact public health (Harris, 2007). So, numerous studies need to be done in order to ensure optimal performance and safety during the operation of a nuclear power plant. Therefore, In a situation where measurements are not available, the assessment could be achieved through modeling using computer codes (Aliyu, et al, 2015). Modeling must be conducted in order to analyze and predict potential paths and patterns of these releases as well as their respective concentrations and consequential doses to the public to ensure that all these parameters are within acceptable standards.

Some assumptions were made in this study. One such assumption was the use of 'generic reactor'; the generic reactor is a reactor that combines the relevant attributes of the two currently proposed reactor designs (i.e., the EPR and the AP1000). The hypotheses of interest are the types of radionuclides that might be discharged, how much might be released each year and the height of stack from which discharges to the air will occur (Aliyu, et al, 2014). For the purpose of assessment, the maximum discharge rates for the EPR and the worst case discharge of the AP1000 reactors have been considered as the normal operation discharge rates of the generic reactor, which could lead to conservative estimates of the health and environmental impacts.

Similar approach, on the use of modeling techniques for environmental risk assessment from energy facilities have been presented in McMahon et al (2013); Nelson et al (2002); Khandakar and Moritomi (2013); Smith et al (2012) ; Aliyu, et al, 2015; Mutshinda et al (2008).

2 METHODOLOGY

2.1. Model description

The Nukpacts Model is built within the Simpacts Model "Simplified Approach for Estimating Environmental Impacts of Electricity Generation" which is consisting of three main models; Airpacts model, Nuckpacts model and Hydopacts, 2003. It implements a method for quantifying and valuing the potential adverse health effects to people arising from routine atmospheric releases of radioactivity from nuclear generating stations based on specified air emission rates. Nukpacts follows an exposure pathways framework which uses atmospheric dispersion, deposition to soil and vegetation, and uptake by various agricultural products to estimate radiological doses to people via inhalation, external radiation from passing cloud or from radioactivity deposited on the ground, and from the ingestion of various agricultural products.

Radiological doses are calculated for local (within 100 km) and regional (100 km to 1000 km) populations. Based on the dose calculations, the model estimates (stochastic) health effects and then carries out a valuation of the predicted health effects. Following the release of a radionuclide to the air, the first step in the impact pathway methodology is to simulate by mathematical means, the movement of that pollutant through the atmosphere. This is known as dispersion modeling, and is used to predict the ambient air concentration of the pollutant at any point of the compass, and at any distance from the source. There are many types of numerical dispersion models available, a full discussion of which models are most appropriate under specific conditions, is given in (EAC, 1996). The most basic form of dispersion model, and the one used most frequently in predicting air pollution, is based on the Gaussian-plume model.
Atmospheric stability (a measure of turbulence), particularly with regard to vertical mixing, also influences the dispersion of pollutants. Atmospheric stability may be estimated using "Pasquill-Gifford Stability Categories", of which there are six. "Category A" represents unstable conditions with convective motions and a high degree of vertical mixing (typical of a warm sunny summer afternoon with light winds). The top of the scale is represented by "Category F", which describes very stable conditions where vertical motion, and consequently mixing, is suppressed. Neutral conditions with mechanically generated wind turbulence, are defined as "Category D", and tend to be associated with overcast skies and moderate to strong winds, occurring day or night.

2.2. Simplified Gaussian-plume dispersion model

The overall Gaussian-plume dispersal equation is complex and interest is not in how the radionuclides are dispersed 'everywhere', but only on their ground-level concentrations at a given distance from the emission source (Fig. 1), the equation can be simplified as follows:

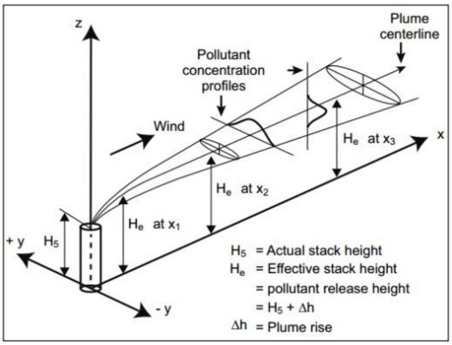

Figure 1. Schematic of Gaussian plume (Schulze and Turner, 1996).

$$C(i, d_j) = \left[\frac{Q(i)}{\pi.\sigma_y.\sigma_z.\mu}\right] \times \left[exp\left[-\frac{H_e^2}{2\sigma_z^2}\right]\right] \qquad (1)$$

Where, $C(i, d_j)$ is the ground-level concentration of radionuclide i at distance d_i from source (Bq per m^3), $Q(i)$ is the emission strength of radionuclide i (Bq per second), H_e is the effective release height (m), μ is the average annual wind speed (m per second), σ_y is the standard deviation (horizontal) and σ_z is the standard deviation (vertical). Eq. (1) does not include a separate term for the distance from the source; the influence of this variable on $C(i, d_j)$ is accounted for in the two standard deviation parameters. These two standard deviation parameters depend on the physical characteristics of the atmosphere as classified by "Pasquill-Gifford Stability Categories". These categories are each represented by different values of the standard deviations. The standard deviations corresponding to "Category D", are given by:

$$\sigma_y = 0.13 \cdot \left(d_j^{0.903}\right) \quad (2)$$

$$\sigma_z = 0.20 \cdot \left(d_j^{0.760}\right) \quad (3)$$

Where d_j is the distance from the emission source in meters (m).

The area around the emission source has been divided into 12 concentric zones, of unequal radius (Fig. 2). The basic data set required to estimate ground-level concentrations of radionuclide i within each of the 12 distance bands (d_j=1, 2, ..., 12) using the above model are: the average annual wind speed; the effective release height; and The emission strength of each radionuclide.

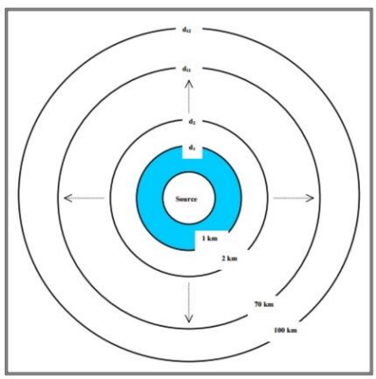

Figure 2. Local spatial distribution of radionuclides and receptors.

The first step of calculation takes into account the source term, i.e., the dispersion of radionuclides in the atmosphere from the normal or abnormal operation of nuclear reactors which are listed in (Tab. 1).

Table 1 Emissions of radionuclides (McMahon et al, 2013).

Name	Release rate of radionuclide (Bq/s)
^{3}H	9.70E+05
^{14}C	3.30E+04

^{58}Co	8.50E+00
^{60}Co	3.30E+00
^{85}Kr	2.10E+05
^{131}I	1.08E+01
^{133}I	2.03E+01
^{133}Xe	7.70E-01
^{134}Cs	2.50E+00
^{137}Cs	2.20E+00

The second stage of calculation considers the transport and dispersion of radionuclides. The calculation of the annual average concentration of radiation per unit volume (Bq/m^3) is performed using the model of Gaussian plume dispersion (Seinfeld et al, 1998). The data needed for this calculation are: the released power of each radionuclide, the annual average wind speed, the effective time of the release of the radionuclide and the corresponding category of stability according to the model of "Gifford-Pasquil" **(**Athar, 2003). The atmospheric stability is calculated using The Pasquill–Turner Method (PTM) (AERB, 2008; Nassar, 2012) is listed in (Tab. 2).

Table 2 Pasquill–Turner stability classes.

Name	Occurrence of Stability Classes (%)
A - very unstable	2.37
B - moderately unstable	12.01
C - slightly unstable	23.47
D – neutral	43.10
E – stable	16.06
F - very stable	2.99

The third step calculates the deposition of radionuclides according to Eq. (4).

$$W_i = C_i \times V_d \quad (4)$$

Where: W_i is the average flow of the radionuclide ($Bq/m^2.s$); C_i is the annual average concentration of radionuclide in the air per unit volume (Bq/m^3); and V_d is the average speed of deposition (m/s).

The fourth step treats of the exposure of the general public to radionuclides, and considers the following pathways: (1) The inhalation of radionuclides in the air; (2) The external irradiation from radionuclides immersed in clouds; (3) The external irradiation from deposited radionuclides; and (4) The ingestion of radionuclides in agricultural products. The methodology used to estimate the total collective dose occurring in the 'local' public population (i.e. Inhabitants residing within 100 km of the emission source) via each of these pathways is outlined in (Markandya, 1999). For Kr-85 and Xe-133, only impact pathway 2 is applicable, because these noble gases do not deposit or remain in the body's organs (ExternE,1995). For atmospheric releases of H-3, C-14 and Kr-85; global dose assessment is also carried out using special models developed by the IAEA (IAEA, 1985).

The fifth step, corresponding to the expected impacts on human health, consider the fatal cancer caused by radiation that can occur in the population, cases of non-fatal cancer and the cases of severe effects of the radiation on future generations of exposed populations.

The occurrence of each of the main stochastic health effects (i.e. fatal and non-fatal cancers and severe hereditary effects) arising as a result of routine atmospheric emission from a nuclear facility are calculated as:

$$N_h(i,g) = \sum_{Pathways} H_P^{TCD}(i,g) \times R_h \qquad (5)$$

Where: $N_h(i,g)$ is the total occurrence of heath effect h on the 'local' or 'global scale (number of cases per year of releases), $H_P^{TCD}(i,g)$ is the total 'global' or 'local' collective dose occurring via pathway and R_h is The risk factor for health effect h (cases per man Sv) p (man Sv per year of releases).The risk factors used to calculate the expected number of health effects, as recommended by the ICRP 60 (ICRP, 1991).

The sixth and final stage performs the conversion of the impacts identified in monetary terms (monetary valuation). The model has the economic values data of the impact of radiation on the health of the population of many countries; however, the program user can enter their own values previously calculated. This information should be provided in monetary units ($, €, etc.) and standard units of currency for energy ($ / kWh, € / kWh, etc.). Two approaches are used to assess the value of fatal cancers; the first is based on the Value of a Statistical Life (VOSL) and the second is based on the Value of a Life Year Lost (VLYL). The latter differs from the former in that it takes into account the latency period of different types of cancers. A component related to the cost of illness has also been included. Full details of both approaches are given in (Markandya, 1997).

$$D_h(l, r, g; VOSL, VLYL) = N_h(l, r, g) \times V_h(VOSL, VLYL) \quad (6)$$

Where: $D_h(l, r, g; VOSL, VLYL)$ is the total damage in terms of health effect h on the 'local', 'regional' and 'global' scale, valued using the VOSL or VLYL approach (US $1995 per year of release), $N_h(l, r, g)$ is the total occurrence of heath effect h on the 'local','regional' and 'global' scale (number of cases per one year of releases) and $V_h(VOSL, VLYL)$ is the adjusted economic unit value of health effect h based on the VOSL or VLYL approach (US $1995 per case).

2.3. Study area and meteorology

The proposed site is located in the north coast of Egypt it is a coastal area with low population consists mainly of bed wins, local inhabitants and transient tourists. The weather in the area is dry with precipitation occurs only in winter months (December, January and February). Hourly metrological data of the year 2014 was obtained from (http://www.noaa.gov/) which are temperature, shown in (Fig. 3), wind speed, shown in (Fig. 4, 5), wind direction and net radiation index. These data are prepared as input files in order to draw the wind rose of the area using WRPLOT code (Jessel et al, 2011) as shown in (Fig. 6) and to calculate the stability classes which are calculated using the Pasquill–Turner Method (PTM) as seen in (Fig. 8).

Analysis of the met data shows that the wind blows most frequently from the NW (North West direction) with the maximum wind speed reaching 15.2 m s^{-1} as shown in (Fig. 4).

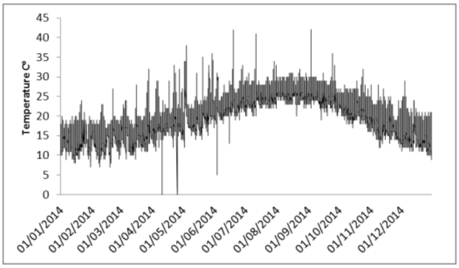

Figure 3 Temperature distribution of the year 2014 for the area.

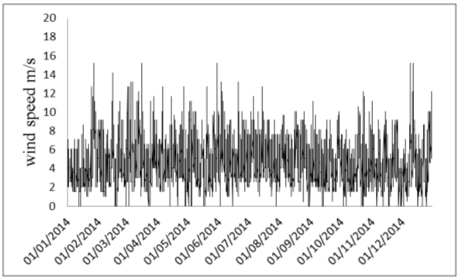

Figure 4 Wind speed distribution of the year 2014 for the area.

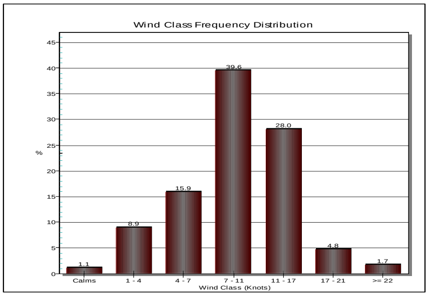

Figure 5 Wind class frequency distribution of the year 2014 for the area.

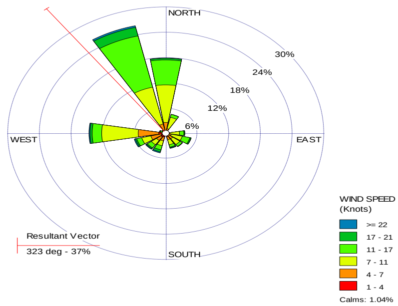

Figure 6 Wind rose for all year of selected area.

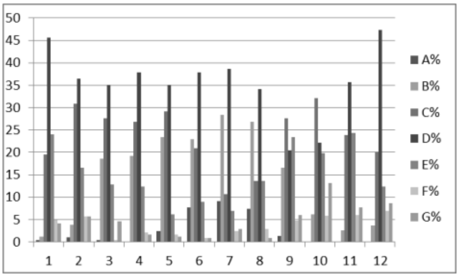

Figure 7 Monthly atmospheric stability classes of the selected area.

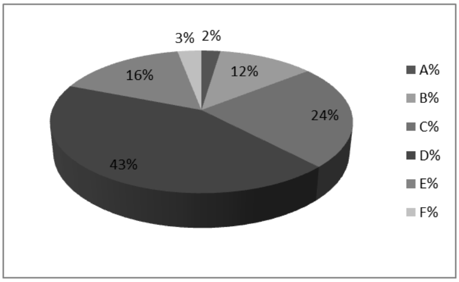

Figure 8 Full year atmospheric stability classes of the proposed area.

2.4. Data collection

Collecting data for the selected area is the first step in calculation, these data are divided into four input tabs, the first input tab is dispersion and receptor parameters, listed in (Tab. 3) which contain: local and regional population density (persons per km^2), rural and urban population distribution which are available at (http://www.matrouh.gov.eg/) website. Knowledge of deposition rates of radionuclides from the air to soil and vegetation is required to evaluate impact pathways 3 and 4. The average wet and dry deposition velocity is taken as

5.00E-3 m/s (ExternE, 1995). The average annual breathing rate of an adult of 7500 m^3/y is used in NukPacts according to (ExternE, 1995). The effective release height is taken to be 30, 60, 80 and 100 m in order to compare the results of the effective doses for each case.

The second input tab [Annual Food Consumption Rate (kg per person per year) and Edible Fraction (%)] which contain the average annual consumption rates of the population around the site which are listed in (Tab. 4). The third input tab entitled (Emissions and Meteorology) which contains the release rate of radionuclides in Bq/s, listed in (Tab. 1) and Atmospheric stability class of selected area, listed in (Tab. 2). The forth input tab is entitled Health effects and valuation, which contain the Risk Factors for Main Stochastic Health Effects (cases per man Sv), listed in (Tab. 5) and the Egyptian Economic Unit Values of Radiological Health Impacts (US$ of year 2000) which are listed in (Tab. 6).

Table 3. Dispersion and receptor parameters.

Parameter	Input
Local population density (persons per km^2)[a]	9
Regional population density (persons per km^2)[a]	4.4
Urban distribution (%)[a]	73.5
Rural distribution (%)[a]	26.5
Average annual wind speed (m/s)	5.0
Effective release height (m)	30,60,80 and 100
Average wet and dry deposition speed (m/s)	0.005
Deposition velocity (m/s)	0.005
Mean adult annual breathing rate (m^3/year)	7500

[a]: http://www.matrouh.gov.eg/

Table 4 Annual food consumption rate (kg/person/yr) and Edible fraction (Selim, 2008).

Name	Average food consumption rate	Edible fraction (%)
Beef	13	90
Pig	0	100
Chicken	5	80
Sheep	10	80
Cereals	70	100
Green veg	20	100
Root veg	30	90
Fresh Milk	50	100
Other Milk	13	100

Table 5 Risk factors for main stochastic health effects (cases/man Sv), (ICRP, 1991).

Fatal cancer	0.05
Non-fatal cancer	0.12
Severe hereditary effects	0.01

Table 6 Economic unit values of radiological health impacts (US$ of year 2000).

Country	Egypt
Fatal cancer (VOSL)	2.34E+05
Fatal cancer (VLYL)	1.04E+05
Non-fatal cancer	7.79E+04
Severe hereditary effects	2.34E+05

3 RESULTS AND DISCUSSION

The nukpacts tool in Simpact model calculates the total collective doses to the inhabitants by multiplying the average dose to a person within a given radial ring by the number of people assumed to live in the same radical ring. The calculation was made for different stack heights 30, 60, 80 and 100 m, The estimated collective doses have been calculated by selecting appropriate habit and food consumption data as well as using the calculated activity concentrations in the environmental media near the site, (Fig. 9). The habit and food consumption data used in this study may be conservative, leading to some overestimation of doses. However this will not affect the conclusions drawn from the dose trends. It was also assumed that the individuals obtained 100% of their annual food intake from their region inside 100 km radial around. In accordance with (Fig. 9). the doses decreases with increasing the distance from the stack. With assuming constant release rate from the stack and taking into account the prevailing wind in NW direction with an angle of 323, the SW area from the stack is the mostly probable area for high doses. Nevertheless, the doses don’t not exceed the permissible limits.

The total local collective doses for different stack height are plotted (Fig. 10), the highest doses obtained in this study are that for 30 m stack height with total dose of 1.13E-03 man Sv/year, the highest pathway dose is the exposure from ingestion of C-14 with 1.08E-03 man Sv per year, the lowest pathway dose is from the external irradiation from the cloud of 1.97E-07 man Sv/year.

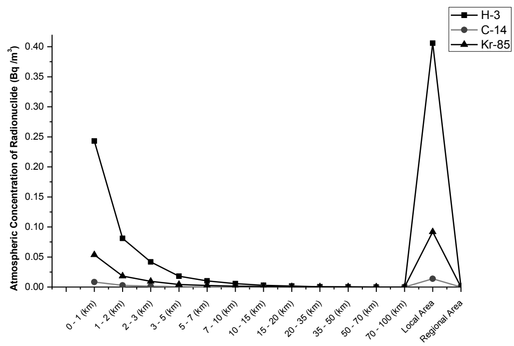

Figure 9.a Atmosheric concentration of radionuclides H-3, C-14 and Kr-85.

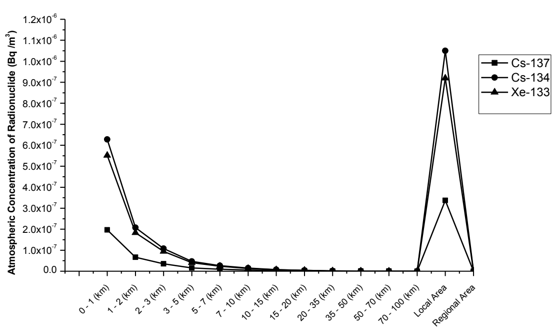

Figure 9.b Atmosheric concentration of radionuclides Cs-137, Cs-134 and Xe-133.

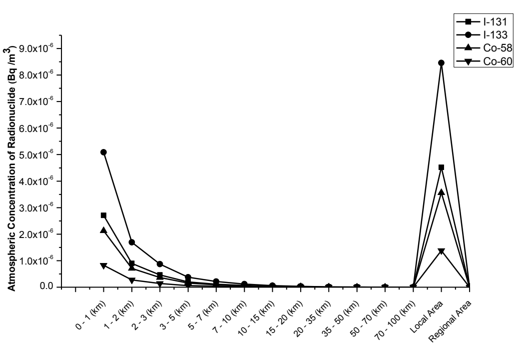

Figure 9.c Atmosheric concentration of radionuclides I-131, I-133,Co-58 and Co-60

For the case of regional impact the total regional collective doses (Fig. 11) for stack height 100 m are slightly higher than those from other stack heights. The values of total regional collective doses are 9.40E-03, 9.40E-03, 9.45E-03, and 9.49E-03 man Sv/y for stack heights 30,60,80 and 100 m respectively.

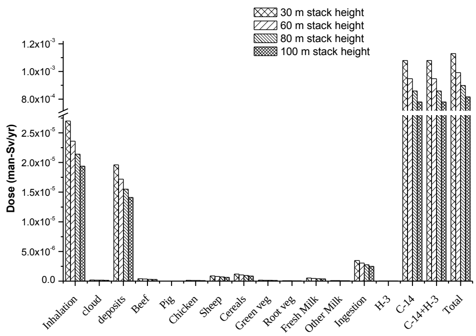

Figure 10 The total local collective doses (man Sv/y).

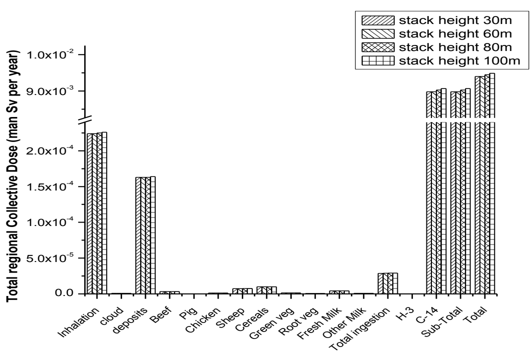

Figure 11 Total regional collective doses (man Sv/y).

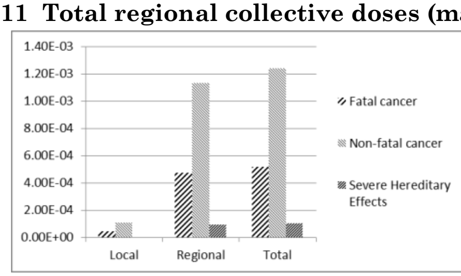

Figure 12 Stochastic health effects for stach height 30 m

In this study the stochastic health effects (cases/y) for both local and regional case are presented in (Tab. 7). Obviously that the highest local health effects are for 30 m stack height and the lowest are that for 100 m stack height. The regional stochastic health effects increases with increasing stack height which the opposite of the local health effects which decreases with stack height. Also noticed from (fig. 12) that the regional stochastic health effects are much higher than highest local health effects and the probability of occurrence of non-fatal cancer is higher than fatal cancer and the lowest is the sever hereditary effects.

Table 7 The total stochastic health effects (cases/y).

Stack height	30 m			60 m			80 m			100 m		
Parameter	Local	Regional	Total	Local	Regional	Total	Local	Regional	Total	Local	Regional	Total
Fatal cancer	5.67E-05	4.67E-04	5.23E-04	4.96E-05	4.70E-04	5.20E-04	4.50E-05	4.72E-04	5.17E-04	4.08E-05	4.74E-04	5.15E-04
Non-fatal cancer	1.36E-04	1.12E-03	1.26E-03	1.19E-04	1.13E-03	1.25E-03	1.08E-04	1.13E-03	1.24E-03	9.79E-05	1.14E-03	1.24E-03
Severe hereditary effects	1.13E-05	9.33E-05	1.05E-04	9.92E-06	9.40E-05	1.04E-04	8.99E-06	9.45E-05	1.04E-04	8.16E-06	9.49E-05	1.03E-04

Table 8 Damage cost per year of health effects in local.

Stack height	30 m			60 m			80 m			100 m		
Parameter	Local	Regional	Total	Local	Regional	Total	Local	Regional	Total	Local	Regional	Total
Fatal cancer - VOSL approach	1.33E+01	1.09E+02	1.22E+02	1.16E+01	1.10E+02	1.22E+02	1.05E+01	1.11E+02	1.21E+02	9.55E+00	1.11E+02	1.21E+02
Fatal cancer - VLYL approach	5.89E+00	4.85E+01	5.44E+01	5.16E+00	4.89E+01	5.41E+01	4.68E+00	4.91E+01	5.38E+01	4.24E+00	4.93E+01	5.36E+01
Non-fatal cancer	1.06E+01	8.72E+01	9.78E+01	9.27E+00	8.79E+01	9.72E+01	8.41E+00	8.83E+01	9.67E+01	7.63E+00	8.87E+01	9.63E+01
Severe hereditary effects	2.65E+00	2.18E+01	2.45E+01	2.32E+00	2.20E+01	2.43E+01	2.10E+00	2.21E+01	2.42E+01	1.91E+00	2.22E+01	2.41E+01

Monetary unit costs for health Impact is calculated using the two approaches addressed in Eq. (7) and listed in (Tab. 8). It can be noticed that the values of VLYL approach are less than values of VOSL approach as it takes into account the latency period of different types of cancers. A component related to the cost of illness has also been included. and as aconcequent result from the total collective doses the values of monetary unit costs for health impacts for stack height 30 m are heigher than other stack heights. the results also indicated that the damage cost per year for fatal cancer (VLYL approach) is smaller than that of non-fatal cancer and This is because the probability of occurrence of fatal cancer (case /y) is much less than the probability of occurrence of non-fatal cancer.

4 CONCLUSION

In this study the analysis of meteorological data showed that the main wind direction is north north west direction and the stability class D has the highest percent and class A has the lowest percent, so it should be taken into account when constructing the power plant that the offsite people are away from the prevailing wind. Also the total collective doses were calculated using nuckpakts model for the radioactive emissions from the routine operation. The local health effects decreases with increasing stack height and while the regional health effects increases with increasing stack height. The total collective doses will not exceed the permissible limits. Monetary unit costs for health impacts has been calculated using VLYL and VOSL approach; The values of VLYL approach are less than values of VOSL approach. As a consequent result from the total collective doses the values of monetary unit costs for health impacts for stack height 30 m are higher than other stack heights.

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