THE ASSESSMENT OF THE RADIOLOGICAL IMPACTS OF ROUTINE RELEASES FROM METSAMOR NUCLEAR POWER PLANT (ARMENIA) ON THE PROVINCE OF IĞDIR (TURKEY) BY TWO APPROACHES

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ABSTRACT

THE ASSESSMENT OF THE RADIOLOGICAL IMPACTS OF ROUTINE RELEASES FROM METSAMOR NUCLEAR POWER PLANT (ARMENIA) ON THE PROVINCE OF IĞDIR (TURKEY) BY TWO APPROACHES

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In this study, radiological impacts of atmospheric releases and aquatic discharges due to the routine (normal) operation of Metsamor (Armenia) Nuclear Power Plant (NPP) on the public living in Province of Iğdır (Turkey) were investigated by two approaches, (1) using PC CREAM 08 software and (2) using the method provided in the IAEA SRS 19 safety report (International Atomic Energy Agency). Based on the obtained results, estimated public doses in the region by both approaches comply with 0.1 mSv/year dose constraint (NDK, 2019). The results showed that the main exposure pathways for the public based on maximum public doses in PC CREAM 08 approach are food consumption, external gamma and fish consumption due to atmospheric releases and aquatic discharges whereas food consumption and fish consumption are the main exposure pathways for IAEA SRS 19 approach. In PC CREAM 08 approach, the main dose contributing radionuclides were obtained as ^{14}C, ^{41}Ar, ^{3}H, ^{131}I and ^{137}Cs for atmospheric releases, and ^{137}Cs, ^{134}Cs and ^{3}H for aquatic discharges. On the other hand, the main dose contributing radionuclides were obtained as ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{131}I for atmospheric releases, and ^{137}Cs, ^{134}Cs and ^{90}Sr for aquatic discharges for IAEA SRS 19 approach. As a conclusion, the health risk on the public living in Province of Iğdır due to routine operation of Metsamor NPP was determined as so small (the probability of total cancer risk for an individual is 7.67E-08 in PC CREAM approach and 5.40E-07 in IAEA SRS 19 approach).

Keywords: Radiological Impact Assessment, Dose Assessment, Public Dose, Atmospheric Exposure, Aquatic Exposure, Pc Cream 08, Iaea Srs 19, Metsamor Npp

ÖZ

METSAMOR NÜKLEER GÜÇ SANTRALİNİN (ERMENİSTAN) RUTİN SALIMLARININ IĞDIR İL'İNDEKİ (TÜRKİYE) RADYOLOJİK ETKİLERİNİN İKİ YAKLAŞIM İLE DEĞERLENDİRİLMESİ

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Bu çalışmada, Metsamor (Ermenistan) Nükleer Güç Santralinin (NGS) rutin (normal) işletiminden kaynaklanan atmosferik salımların ve sucul deşarjların Iğdır İlinde yaşayan halk üzerindeki radyolojik etkileri iki yaklaşım ile araştırılmıştır; (1) PC CREAM yazılımının kullanılması ve (2) Uluslararası Atom Enerjisi Ajansı (UAEA) SRS 19 güvenlik raporunda belirtilen metotun kullanılması. Elde edilen sonuçlara göre, her iki yaklaşımla da bölgede tahmin edilen halk dozları 0.1 mSv/yıl doz kısıtına (NDK, 2019) uymaktadır. Sonuçlar, PC CREAM 08 yaklaşımındaki maksimum halk dozlarına dayanarak atmosferik salımlar ve sucul deşarjlar için ana maruziyet yollarının; besin tüketimi, dış gama ve balık tüketimi olduğunu, UAEA yaklaşımı için ise besin tüketimi ve balık tüketiminin ana maruziyet yolları olduğunu göstermiştir. PC CREAM 08 yaklaşımında, atmosferik salım için doza katkı sağlayan ana radyonüklitler ^{14}C, ^{41}Ar, ^{3}H, ^{131}I ve ^{137}Cs, ve sucul deşarjlar için ^{137}Cs, ^{134}Cs ve ^{3}H olarak elde edilmiştir. Öte yandan, UAEA SRS 19 yaklaşımı için atmosferik salımlara ilişkin doza katkı sağlayan ana radyonüklitler ^{137}Cs, ^{134}Cs, ^{90}Sr ve ^{131}I, sucul deşarjlara ilişkin ise ^{137}Cs, ^{134}Cs ve ^{90}Sr olarak elde edilmiştir. Sonuç olarak, Metsamor NGS'nin rutin işletmesi sebebiyle Iğdır İlinde yaşayan halk üzerindeki sağlık riski çok küçük olarak belirlenmiştir (PC CREAM yaklaşımında bir birey için toplam kanser riski olasılığı 7,67E-08 ve UAEA SRS 19 yaklaşımında ise 5,40E-07’dir).

Anahtar Kelimeler: Radyolojik Etki Değerlendirmesi, Doz Değerlendirmesi, Halk Dozu, Atmosferik Maruziyet, Sucul Maruziyet, Pc Cream 08, Iaea Srs 19, Metsamor Ngs

To my beloved and precious parents and grandfather

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LIST OF ABBREVIATIONS

ALARA	: As Low As Reasonably Achievable
ANSI/ANS	: American Nuclear Standards Institute/ American Nuclear Society
Bq	: Becquerel
CJSC	: Closed Joint Stock Company
CNS	: Convention on Nuclear Safety
CREAM	: Consequences of Releases to the Environment Assessment Methodology
CT	: Computed Tomography
EC	: European Commission
EMP	: Environmental (Radiological) Monitoring Program
EPA	: Environmental Protection Agency
ETKB	: Enerji ve Tabii Kaynaklar Bakanlığı *(Ministry of Energy and Natural Resources)*
Gy	: Gray
IAEA	: International Atomic Energy Authority
ICRP	: International Commission on Radiation Protection
LWR	: Light Water Reactor
MGM	: Meteoroloji Genel Müdürlüğü *(Turkish General Directorate of Meteorology)*
MNGS	: Metsamor Nükleer Güç Santrali
MNPP	: Metsamor Nuclear Power Plant

NCRP :National Council on Radiation Protection and Measurements

NDK : Nükleer Düzenleme Kurumu
(Nuclear Regulatory Authority)

NOAA : National Oceanic and Atmospheric Administration

NPP : Nuclear Power Plant

PRIS : Power Reactor Information System

PWR : Pressurized Water Reactor

RESA : Radyasyon Erken Uyarı Sistemi Ağı
(Radiation Early Warning System Network)

ROSATOM : Rosatom State Atomic Energy Corporation

SF : Safety Fundamental

SRS : Safety Report Series

STUK : Säteilyturvakeskuksen

Sv : Sievert

TAEK : Türkiye Atom Enerjisi Kurumu
(Turkish Atomic Energy Authority)

TLD : Thermoluminescence Dosimeter

TOB : Tarım ve Orman Bakanlığı
(Ministry of Agriculture and Forestry)

TÜİK : Türkiye İstatistik Kurumu
(Turkish Statistics Authority)

UAEA : Uluslararası Atom Enerjisi Ajansı
(International Atomc Energy Agency)

UNSCEAR : United Nations Scientific Committee on the Effects of Atomic Radiation

USA : Unites States of America

USNRC : United States Nuclear Regulatory Commission

VVER : Vodo-Vodyanoi Energetichesky Reaktor
(Water Water Energetic Reactor)

WNA : World Nuclear Association

CHAPTER 1

INTRODUCTION

1.1. General

The countries have shifted to nuclear energy due to the clean energy need in the world and to be away from the coal, which caused great air pollution in 1950s. Some countries have reduced the use of nuclear power due to the pre-existing public mistrust whereas some countries reduced it due to the resistance after Fukushima accident (IAEA, 2019a). On the other hand, according to Turkish Ministry of Energy and Natural Resources (ETKB, n.d.), nuclear power plant began to spread in the world in 1970s due to oil crisis. However, independent from the reason, definitely nuclear energy is still one of the important energy resources in the world that currently 449 civil nuclear reactors (reactors generating electricity supplied to customers through electricity grids) are in operation having 397,650 MW_e share of global electricity generation in the world, 54 reactors are under construction having 55,364 MW_e total net installed capacity and 176 reactors have been shutdown permanently (WNA, 2019a ; WNA, 2019b ; IAEA, 2019b ; IAEA, 2019c). The share of nuclear energy in total energy production of the countries is provided in Figure 1.1, where France is the leader with 71.7 % (IAEA, 2019d). However, USA comes first with 99,061 MW_e regarding the total operable net reactor capacity. Total operable net reactor capacity of the countries is given in Figure 1.2 (IAEA, 2019d).

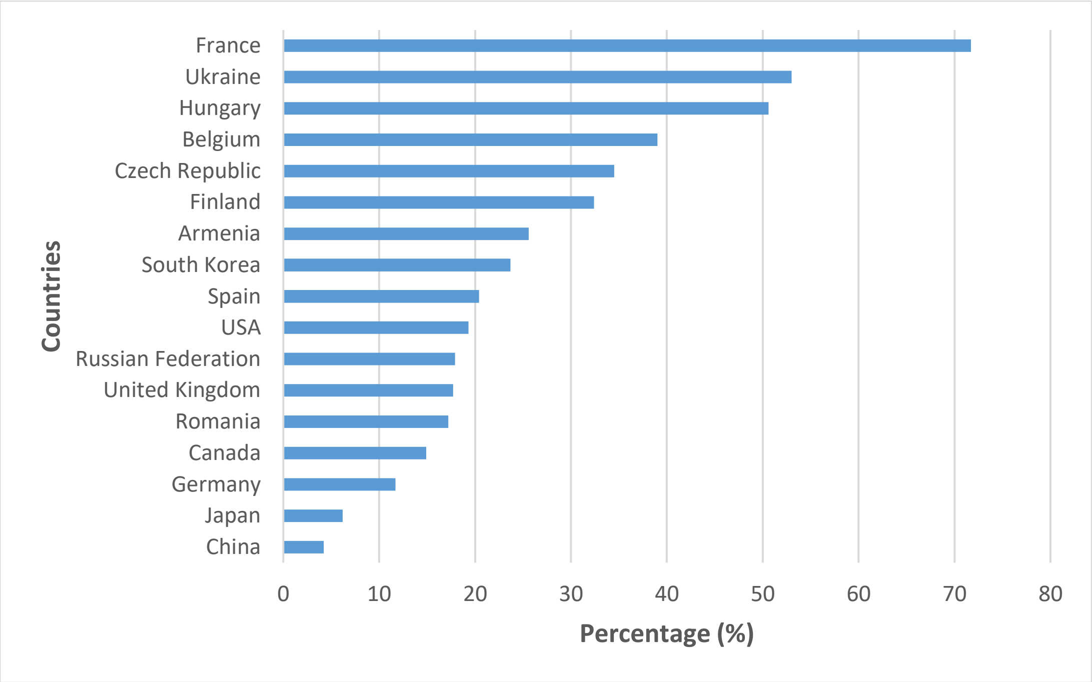

Figure 1.1. The percentage of energy production by nuclear power in different countries (IAEA, 2019d)

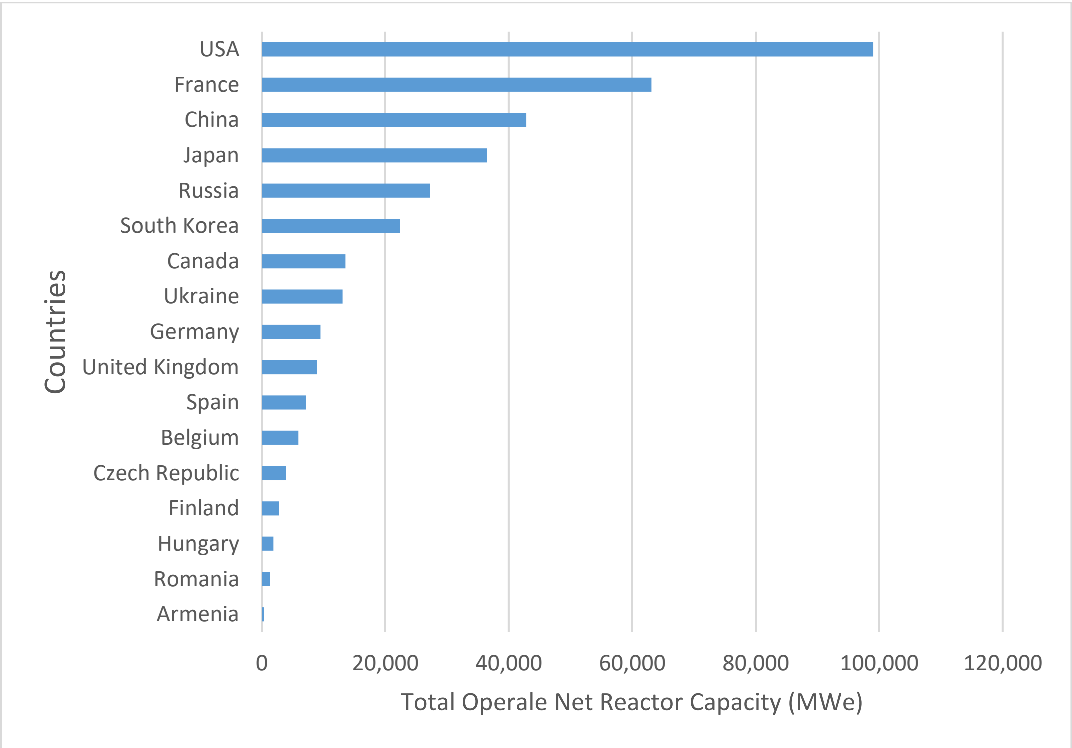

Figure 1.2. Total operable net reactor capacity (MWe) of different countries (IAEA, 2019d)

During normal/routine operation of nuclear power plants, releases and discharges are given to the environment due to nature of the operation of the plant. Releases due to Nuclear Power Plant (NPP) operation include generally volatile gases such as noble gases, iodine, tritium, C^{14}, aerosols and for discharges tritium and activation products (IAEA, 2011). These releases and discharges are allowed at a certain point and related radiological impact on the public, workers and the environment are strictly controlled by regulatory bodies by setting dose limits, dose constraint, release and discharge limits (IAEA, 2014).

Turkey is an embarking country in NPP and there is no NPP in operation now. However, there are several NPPs around the border of Turkey that may cause radiological impacts either due to routine operation or due to accidental conditions. Metsamor NPP in this sense is the closest NPP to the border of Turkey; i.e. ~16 km from Province of Iğdır. Others are Kozloduy NPP in Bulgaria (~330km), Cernavoda NPP in Romania (~300 km), Paks NPP in Hungary (~1015 km), Rostov NPP in Russia (~670 km), South Ukraine NPP in Ukraine (~650 km), Bushehr NPP in Iran (~1160 km) (Ünver, 2014). Therefore, in this study, it is aimed to determine the possible radiological impacts of routine operation of Metsamor NPP on the public of Province of Iğdır.

1.2. The Scope and the Objectives of the Study

The radiological impact of an NPP on public during normal operation depends on the generation of the NPP, type of the NPP, distance of public to the NPP and habits of the public, and the information regarding the radiological impacts of an NPP during routine operation is present in the literature. For example, annual effective public dose due to NPPs in Korea is between 3.14 E−03 mSv/year and 3.55E−02 mSv/year for 2011-2015 (Kong et al, 2017). In USA, maximum total effective dose equivalent for public due to PWRs during the period of 2007-2009 is 1.17E-01 mSv/year (Kong et al, 2018). Due to the operation of Bushehr Nuclear Power Plant Unit-1 (in Iran), maximum individual dose for adults is 14.00E−05 mSv/y in 600 m away from stack of NPP (Sohrabi et al, 2013). In Finland, the maximum annual radiation exposure of public living around Finnish NPPs for the period of 1977-2015 is 3.60E-03 mSv/ year for Loviisa NPP and 1.50E-03 mSv/year for Olkiluoto NPP (STUK,2016). In Bulgaria, the highest effective dose of public within 30 km radius from Kozloduy NPP during the period of 1999-20003 is within the range of 2.68E-04 mSv/year to 3.76E-04 mSv/year (Republic of Bulgaria, 2004). In Hungary, annual public doses are below nSv/year range (Hungary, 2016). In Armenia, public doses living near Metsamor NPP (MNPP) through the food consumption pathway is 0.001 mSv/year due to routine operation of MNPP based on the environmental radiological monitoring program conducted within the territory of Armenia (Armenia, 2007). However, the cross-border radiological impact of MNPP for Turkey is not investigated and presented by Armenia or in literature. In addition, public living in Province of Iğdır is substantially concerned about their health (i.e. cancer risk) due to the operation of MNPP and lots of news and interviews are present in the media for this concern. Therefore, the routine radiological impacts of MNPP on public living in Province of Iğdır in Turkey is aimed to be assessed by using two different approaches available on the literature. The location of Metsamor NPP, Province of Iğdır (center), Aras River and the border between two countries on map are provided in Figure 1.3.

First approach includes using PC CREAM 08 software, which considers atmospheric and aquatic exposure pathways and terrestrial food chain in dose assessments due to routine releases and discharges, which make the software prominent among the other software or models. The second approach applied in this thesis to assess the mentioned doses is using the method numbered as “SRS 19” in the International Atomic Energy Agency (IAEA) safety report which is given as conservative approach in that IAEA report (IAEA, 2001).

Thesis is divided into several individual steps to determine the doses of public living in Province of Iğdır by both approaches, to evaluate and to compare the results obtained by the two approaches mentioned earlier, to determine whether the approach given in IAEA SRS 19 document is really as conservative as provided in that document or not when compared with the result of the first approach, and to provide suggestions for future studies based on the outputs of this thesis.

Figure 1.3. The map showing the location of Metsamor NPP, Province of Iğdır(center), Aras River and the border between Turkey & Armenia by Google Earth

In the first step of the study, information regarding the radionuclide release and discharge of Metsamor NPP (MNPP) during routine operation is collected and the missing information related to release/discharge data for MNPP is completed from Bohunice NPP in Slovakia, having similar reactor type, based on the power of the reactors. Release and discharge data set belonging only to MNPP and the data set completed with Bohunice NPP are used in the assessment of radiological impact due to the routine operation of MNPP to determine the effect of the data set. Then, foods produced in Province of Iğdır, animal and animal products produced in the region, consumption rates of public living there in terms of foodstuffs and animal products, habits of the public; i.e. inhalation rate, occupancy rate, age etc. Moreover, meteorological data representing the long-term meteorological conditions in the region is determined. After this, meteorological statistics for mixing layer height and atmospheric stability classes are determined for PC CREAM 08 software.

In the second step of the study, radionuclide concentrations due to atmospheric releases and aquatic discharges and the related dose analysis are performed by the software with the predetermined inputs (including two data sets) as much as specific to the region.

In the third step of the study, doses for public living in the region for selected locations and the related health risk are estimated for the first approach.

In the fourth step of the study, similar process is performed as a second approach for the methods provided in the safety report series document of IAEA coded as “SRS 19” (IAEA, 2001). For this approach, models given in the related document for aquatic dispersion and atmospheric releases are examined. Firstly, no dilution model and generic environmental model are used for assessment of the radiological impacts of MNPP. Then, detailed environmental model and related equations in the document of IAEA are used to calculate the radionuclide concentration in media and to estimate related public dose. Then, health risk is calculated for doses estimated with the second approach.

In the fifth step, the concentrations estimated with the both approaches are compared with the results of Environmental Radiological Monitoring Program of Turkish Atomic Energy Authority (TAEK) between 2013 and 2016 and the conservativeness of IAEA SRS 19 approach is evaluated. At the end, suggestions based on the result of the thesis are provided for future studies.

1.3. Organization of the Thesis

This thesis consists of 5 main chapters.

In the first chapter, introduction for the study topic, general information, the scope and the objectives of the thesis are provided.

In the second chapter, background information that should be known to understand the topics and the concepts discussed and used in the thesis. Therefore, basic concepts related to the radiation protection and regulatory control in radiation protection are summarized. Moreover, as Metsamor NPP is a pressurized water reactor, introductory information for this type of reactor, specific information for Metsamor NPP are given. Besides, the information and its source where release and discharge data of Metsamor NPP is taken is explained, which is Country Reports for Convention on Nuclear Safety. To be able to model the radionuclides in the atmosphere and the aquatic environment, modelling approaches are presented by comparing the features of the models/software available. Then, reason for selecting PC CREAM 08 software is explained and description of the software and the iterative approach given in IAEA SRS 19 document are provided. In addition, background information regarding health effects of ionizing radiation and the information to estimate the health risk are given.

In the third chapter, methodology applied in the study is explained. For this step, radiation exposure pathways for atmospheric and aquatic dispersion including terrestrial food chain for both approaches are provided as well as the equations to calculate the radionuclide concentrations in the media and the related doses for public. Moreover, the inputs related to meteorology, release and discharge data, food consumption rates, food and animal production data, habits of public and diet of animals required for PC CREAM 08 software and for IAEA approach are given.

In the fourth chapter of the study, results of the two approaches and environmental radiological monitoring program of TAEK are presented and they are compared with each other. Besides, health risks for both approaches are also estimated and compared. Also, the conservativeness of the second approach, which is the method provided in

IAEA SRS 19 (IAEA, 2001), is discussed to determine whether it is as mentioned in IAEA SRS 19 document.

In the fifth chapter, overview and a conclusion for this study are made with the outputs obtained from the thesis. Moreover, suggestions for future studies are provided as a guidance.

CHAPTER 2

BACKGROUND

2.1. Overview

In this chapter, the basic information which makes the ground for this thesis and for the related concepts are provided along with a detailed literature survey. Therefore, information regarding radiation protection, regulatory control over this issue, radiation exposure pathways, PWRs, Metsamor NPP, convention on nuclear safety, routine releases and discharges from NPPs, atmospheric and aquatic modeling approaches and related software/models, and the description of two approaches adopted for this study are presented. Besides, health effects of ionizing radiation are summarized.

2.2. Basic Concepts Regarding Radiation Protection and Regulatory Control in Radiation Protection

Nuclear plants are subject to safety standards due to the radiation risk posed to public and the environment as indicated in safety fundamentals document coded as SF-1 (IAEA, 2006) and general safety requirements document coded as GSR Part 3 of IAEA (IAEA, 2014). The fundamental safety target, which is the protection of public and the environment from the harmful effects of ionizing radiation without limiting the operation of the plant unduly, safety principles and the concepts of IAEA form the basis to the safety standards and to the related safety programs. This safety target is valid for the entire lifetime of the plant including planning, site, design, production, construction, operation and decommissioning. To fulfill and to implement this fundamental safety target IAEA formed 10 safety principles namely; responsibility for safety, role of the government, leadership and management for safety, justification of facilities and activities, optimization of protection, limitation of risks to individuals, protection of present and future generations, prevention of accidents, emergency preparedness and response, and protective actions to reduce existing or unregulated radiation risks documents (IAEA, 2006; IAEA, 2014). These principles are indicated in SF-1 (IAEA, 2006) and GSR Part 3 (IAEA, 2014) document of IAEA and detailed information can be obtained from referred documents.

This thesis is prepared by considering the principles for optimization of the protection, limitation of risks to individuals and protection of present and future generations due to the radiological impacts of routine operation of Metsamor NPP on the public living in Province of Iğdır, Turkey.

To be able to implement and fulfill the related principles mentioned before, basic concepts such as dose, dose limits, dose constraint, critical group, exposure and exposure pathways regarding radiation protection including regulatory control of radiation protection should be very well known. Therefore, definitions and basic information related to the basic concepts for radiation protection and regulatory control of radiation protection are provided below.

Dose is defined in IAEA safety glossary (IAEA, 2018a) as the measure of the energy deposited by radiation in the target, which can be absorbed dose, equivalent dose, effective dose, organ dose, annual dose, committed dose and collective dose. Absorbed dose equals to the total energy imparted in volume element divided by the mass in the element, defined at a point (tissue or organ) and has gray unit (Gy= 1 J/kg). Equivalent dose is the measure of the dose to an organ/ to issue designed to reflect the amount of harm caused and it has the unit of sievert (Sv= 1 J/kg). However, effective dose is the measure of the dose designed to reflect the amount of radiation detriment likely to result from the dose and it has the unit of sievert (Sv= 1 J/kg). Also, summation of the tissue equivalent doses which are multiplied by the related tissue weighting factor is effective dose. Moreover, organ dose is the mean absorbed dose in a tissue/organ of the human body. Besides, committed dose is the lifetime dose expected to result from an intake whereas annual dose is the summation of the dose due to external exposure in a year and internal dose due to the intake of radionuclides in that year and the collective dose is the total radiation dose incurred by the population (IAEA, 2018a).

Dose limit is the limit value of the effective or equivalent dose to individuals due to the controlled practices which shall not be exceeded (IAEA, 2018a). The dose limits of IAEA for public exposure and the limits applied in Turkey for routine operations of NPPs are given in Table 2.1 (TAEK, 2018 ; IAEA, 2014). Dose constraint, however, is the prospective restriction on the dose of individual by a source and determined by regulatory authority. It is used for the planned exposure situations related to the source, in the radiation protection and as an optimization parameter for the safety (IAEA, 2018a). According to the summary table for dose constraint value of countries provided in the expertise thesis of Meltem Nihan Aksoy (Aksoy, 2017), dose constraint varies from the range of 0.05 mSv/year to 0.3 mSv/year based on the source; i.e. NPP, nuclear fuel cycle and research reactors etc. The dose constraint applied in Turkey is 0.1 mSv/year for public (NDK, 2019). The relation of dose limit and dose constraint is provided in Figure 2.1 (IAEA, 2018b).

Table 2.1 *The dose limits for public exposure (IAEA, 2014 ; TAEK, 2018 ; Armenia, 2010)*

Dose type	*Dose level*
Effective Dose	1 mSv in a year; In special circumstances, a higher value of effective dose in a single year could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year
Equivalent dose to the lens of the eye	15 mSv in a year
Equivalent dose to the skin	50 mSv in a year

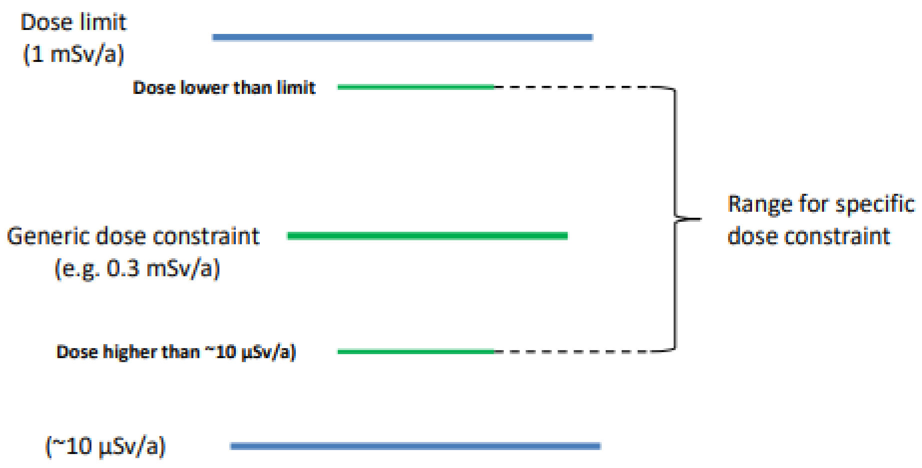

Figure 2.1. The relationship between dose limit and dose constraint (IAEA, 2018b)

Critical group is the members of the public, homogenous in terms of the exposure for a radiation source and it is the typical individuals receiving the highest effective/ equivalent dose from the source. Therefore, in this thesis, critical group will be given in the following parts of the thesis for the public living in Province of Iğdır for the radiological assessment due to the routine releases of Metsamor NPP.

Exposure is the condition of being subjected to irradiation. It can be external, i.e. exposure to radiation from a source from outside of the body or internal, i.e. exposure to radiation from a source within the body due to inhalation and ingestion. The public is exposed to the radiation due to the releases from NPPs by exposure pathways by which the radiation/ radionuclides can reach humans and lead to the exposure (IAEA, 2018a). The exposure pathways during normal operation of NPPs for both atmospheric releases and aquatic discharges are given in Table 2.2 and Table 2.3 (STUK, 2015).

Table 2.2. *Exposure pathways due to atmospheric releases for normal operation and emergency situations (STUK, 2015)*

External Exposure	
Direct and scattered radiation from onsite radiation sources and transportation	N, O, VL, VP
Radioactive substances in a release plume	N, O, VL
Radioactive substances deposited on the ground	N, O, VL, VP
Radioactive substances deposited on bare skin, hair or clothing	O[1], VL[1]
Radioactive substances resuspended into the air	O[1], VP[1]
Internal Exposure	
Inhalation of radioactive substances in a release plume	N, O, VL
Ingestion of plants and products occurring in the wild that contain radioactive substances originating in deposition	N, O, VP
Ingestion of contaminated milk, meat and game	N, O, VP
Radioactive substances directly deposited on surface waters or subsequently filtering from drainage areas in case the water is used for drinking or in case aquatic plants or animals are ingested	O[2], VP[2]
Inhalation of radioactive substances transported into the air through resuspension	VP[1]

N=normal operation, O= operational occurrences and accidents, VL= short term emergencies, VP=long term emergencies, [1]= not normally significant and [2]= may be significant in single doses.

Table 2.3. *Exposure pathways due to aquatic discharges for normal operation and emergency situations (STUK, 2015)*

External Exposure	
Radioactive substances accumulated on shorelines	N, O
Radioactive substances in water during boating or swimming activities	N[1]
Internal Exposure	
Radioactive substances in fish	N, O
Inhalation; via resuspension from substances accumulated on shorelines or via oversplash from a receiving body of water	N[1]

Radioactive substances in drinking water in case water from a receiving body of water is used for drinking	N[1]
Contamination of foodstuffs in consequence of the potential use of water from a receiving body of water for drinking water for cattle and for irrigation	N[1]
Contamination of pastures or arable land as well as their produce through oversplash from a receiving body of water, or through other ways of accumulation	N[1]

N=normal operation, O= operational occurrences and accidents, [1]= not normally significant

2.3. Pressurized Water Reactors

Pressurized Water Reactors (PWRs), one type of Light Water Reactors, are within the scope of this thesis that PWRs are explained in the thesis.

Nuclear power plants produce electricity from the steam generated by the heat arising from the split of atoms. There are two different ways to produce the steam; pressurizing the water and boiling the water (which is out of the scope). The reactors where the water (light water as for both the coolant and moderator (Breeze, 2014)) is kept under pressure in the operation is called Pressurized Water Reactors (USNRC, 2017a). The water is pressurized up to 150 atmospheres and water reached to 325°C without boiling (Breeze, 2014). The schematic diagram of PWRs is provided in Figure 2.2 (USNRC, 2017a). The steam which makes the turbine run is produced in a steam generator in PWRs. There are 3 loops in PWRs. In the first loop, the pressurizer keeps the water flowing through the reactor vessel preventing it to boil by under very high pressure. The heated/hot water passes through steam generator where the steam is generated in the second loop. The generated steam passes through the turbine and the electricity is produced. After the steam passes through the turbine, it is condensed with the condenser. This is achieved with the coolant water in the third loop, which can be from any water body such as lake, river, ocean and sea or from cooling tower (USNRC, 2017b).

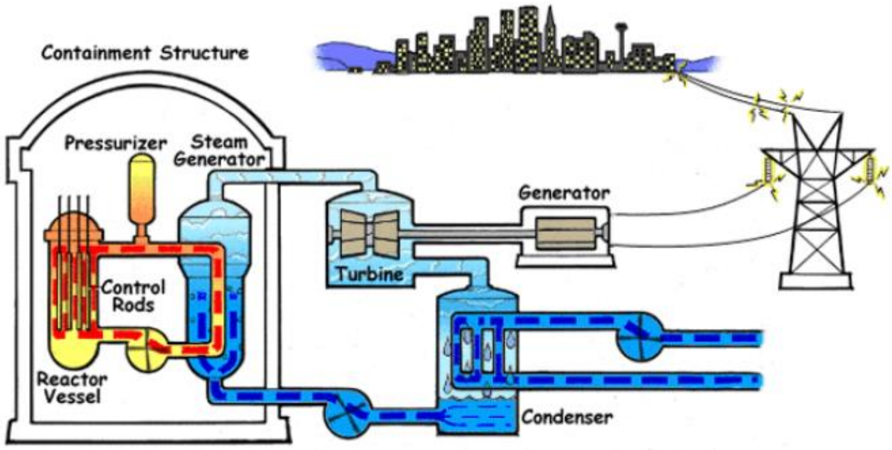

Figure 2.2. Schematic Diagram of Pressurized Water Reactors (USNRC, 2017a)

PWR is the most popular reactor in the world, more than 250 PWRs are in operation (Breeze, 2014). There are several designs of it where VVERs (Water water energetic reactor) is one of them. VVER is a Russian design and 67 VVER reactors have been constructed since 1960s (ROSATOM, n.d.). VVER type reactors are in construction, operation and decommissioning stage in several countries such as China, Czechia, Finland, Hungary, India, Slovakia, Bulgaria, Egypt, Belarus, Turkey (VVER-1200 under construction) and Ukraine in addition to Russian Federation (TAEK, n.d. a ; ROSATOM, 2018). Generations of VVER are provided in Figure 2.3 (ROSATOM, n.d.).

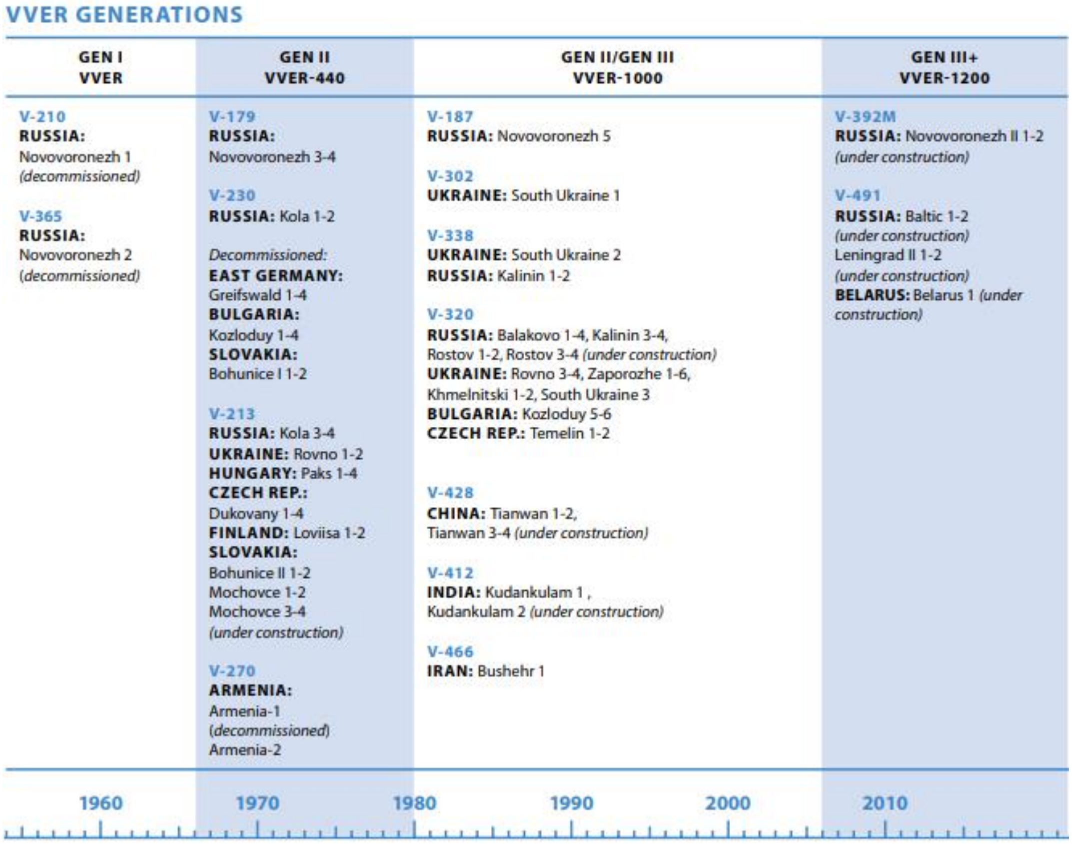

Figure 2.3. Generations of VVERs (ROSATOM, n.d.)

2.4. Metsamor Nuclear Power Plant

Metsamor NPP is approximately 16 km away from the border of Turkey from Province of Iğdır. This NPP has two units of VVER-440 type reactor which were started to operate in 1976 and 1980, respectively. These two units were shut down after the earthquake occurred in 1988 in Armenia although they were not affected by it (Armenia, 2007). 2nd unit of Metsamor NPP (hereinafter referred as Metsamor NPP or MNPP) having 375 MW_e net capacity (VVER-440, V-270 design) was resumed in 1995 with the need of electricity production due to the energy crisis (Armenia, 2007, IAEA, 2019d). The safe operation of Metsamor NPP until 2016 under Energy Development Strategy was approved by the government in 2005 and 10 years of operation license was given to existing NPP following the review and assessment of the submitted documents indicating the safe operation of the NPP; i.e. safety analysis report, emergency response plan, level I probabilistic safety analysis report etc. (Armenia, 2007).

In the report regarding the construction of Armenia new nuclear unit, it is indicated that existing NPP (MNPP) takes cooling water from Sev Jur River, which is also called as Metsamor River. Besides, it is given that water from Zeiva irrigation dam on Sev Jur River and from groundwater collection pond are the other water resources for cooling water for NPP. Also, the annual flow rate of the river near the site is indicated as 11 m^3/s, the flowrate is 6 m^3/s during 2004-2006 as low flow and long-term average flow rate is 20 m^3/s (CJSC, 2010).

Atmospheric releases are made with a stack having height of 150 m during normal operation of NPP. Moreover, liquid discharges from MNPP are specially treated in the purification facility located 5.5 km away from NPP and after the treatment, water is given to the Sev Jur River (Armenia, 2007). Besides, samples are taken from the boreholes (rainwater and sewerage system) located outside of the MNPP to control the discharges in terms of radioactivity level based on legislation (Armenia, 2016).

The annual release and discharge limits applied in Armenia for MNPP is provided in Table 2.4. The dose constraint applied for NPP in operation in Armenia is 0.25 mSv/year (Armenia, 2010).

Table 2.4. *Annual release and discharge limits in Armenia for NPP*

Radionuclide/ Group	**Release Limit**	**Reference**
Radioactive release	203 GBq	(Armenia, 2004)
Long-lived radionuclides (half-life> 24 h)	203 GBq	(Armenia, 2007 ; Armenia, 2010)
Inert radioactive gases	690 TBq	(Armenia, 2010 ; Armenia, 2016)
I-131 (gas and airborne forms)	18 GBq	(Armenia, 2010 ; Armenia, 2016)
Co-60	7.4 GBq	(Armenia, 2010 ; Armenia, 2016)
Cs-134	0.9 GBq	(Armenia, 2010 ; Armenia, 2016)
Cs-137	2 GBq	(Armenia, 2010 ; Armenia, 2016)

Radionuclide/ Group	Release Limit	Reference
Sr+Cs	55 GBq	(Armenia, 2004)
Sr+Cs	55.5 GBq	(Armenia, 2007 ; Armenia 2010)

2.5. Convention on Nuclear Safety

The Convention on Nuclear Safety (CNS) was put into force in 1996 with the objective to accomplish a high level of nuclear safety all over the world by protecting the public and the environment from the potential harmful effects of ionizing radiation and from the radiological consequences of the accidents due to nuclear installations. Turkey signed CNS in 1994 and CNS was ratified by The Grand National Assembly of Turkey in 1995.

Countries signing CNS (contracting parties) are obliged to the implementation of fundamental safety principles regarding legislative, regulatory and technical framework related to siting, design, construction and operation phase of the plants as well as having adequate financial and human sources, the assessment and verification of quality assurance, safety and emergency preparedness (IAEA, n.d.). Contracting parties are also required to submit country (national) reports prepared by the regulatory body for each review meeting showing the national nuclear safety program and the implementation of the abovementioned obligations (IAEA, 2019e ; IAEA, n.d.). Moreover, each contacting party has an opportunity to see the national reports of the other contracting parties and to ask questions for further clarifications. Then, the questions arising from other contracting parties are answered and the country presentations are made. After the process of the national reports are finalized, contracting parties make them publicly available on the internet in terms of the regulatory transparency. In addition to organizational and review meetings, contacting parties are obliged to participate in extraordinary meetings (i.e. after Fukushima accident etc.).

In the national report, the radiation exposure of the workers and the public due to the operation of the nuclear installations shall be ensured based on the As Low As Reasonably Achievable (ALARA) principle and that the exposure of them is not above the national dose limits according to the Article 15 of CNS. Therefore, the information regarding the source term data of the routine operation of concerned nuclear installation (the radioactivity amount and the distribution of the radionuclides that are released into the environment), national dose limits and the dose estimations can be found in the concerned national report under Article 15 Radiation Protection of CNS. In addition to these, further information may be found in the answers of the contracting party for the questions of the other contracting parties, which can be achieved through the CNS secure website that the questions and answers should also be checked (IAEA, n.d.).

2.6. Releases and Discharges from NPPs during Routine Operation

Radioisotopes are released to the environment via both atmospheric and aquatic pathway due to the normal operation of the NPP, which are monitored routinely. The major part of the release is generally formed with gases or volatile elements such as noble gases, tritium (H^3), C^{14}, and iodine whereas the particulate radioisotopes constitute the small portion of the release, which is smaller than 0.0001% of the release. However, nuclear fuel particles are rarely found in the releases due to routine operation of the NPP. In the technical document coded as 1663 of IAEA, it is indicated that the total radioactivity in the release and the effective doses to the public from atmospheric and aquatic pathways are insignificantly small (IAEA, 2011).

Fission products in Light Water Reactors (LWR), i.e. traces of uranium and the activated corrosion products, pass to the primary coolant from the fuel during normal operation if there is a defect or development of a defect on the cladding is available and form the radioactive inventory in the coolant. In consequence of the neutron activation of the primary coolant, activation gases are occurred. The most important volatile radioisotopes and aerosols generated in LWR are noble gases (Ar^{37}, Ar^{41},

Kr^{83m}, Kr^{85m}, Kr^{85}, Kr^{87}, Kr^{88}, Kr^{89}, Xe^{131m}, Xe^{133m},Xe^{133}, Xe^{135m}, Xe^{135}, Xe^{137}, Xe^{138}), halogens (I^{131}, I^{132}, I^{133}, I^{135}), tritium (H^3), Carbon (C^{14}), activation gas formed from water and atmosphere constituents (N^{13}, O^{15}, N^{16}, O^{19}), aerosols (activated corrosion products such as Co^{60}, Co^{58}, Cr^{51}, Mn^{54}, Fe^{59}, Zn^{65} and Zr^{95}, fission products such as Sr^{89}, Sr^{90}, Sb^{124}, Te^{132}, Cs^{134}, Cs^{137}, Be^{140} and Ce^{141}) (IAEA, 1987). These radioisotopes can be given to the atmosphere by three modes; ground-level (ventilation systems), elevated (stack) and mixed release (both stack and ventilation system) (ANSI/ANS, 2013).

In PWR type reactors, most of the radioactive gases leaked from the fuel or generated due to the neutron activation in the coolant stays in the coolant, which are removed from the coolant by chemical and volume control system called letdown line and by simple decompression discharged through the vent of the volume control tanks. Moreover, degassing of the letdown line is useful to remove the radioactive gasses from the primary coolant. Airborne radionuclides coming from the ventilation system of the reactor, auxiliary building, radioactive waste building and turbine building (due to the secondary coolant leakage from turbines, turbine seals and air ejector system) is treated before being discharged into the atmosphere (IAEA, 1987).

Liquid discharge can be given to the environment from NPPs by two ways; from the primary and secondary reactor coolant, and the unpredictable abnormal leakages (abnormal events), which is out of scope. In PWRs, the liquid discharges arise from reactor, reactor coolant systems and related to these systems. However, most of the radionuclides is in the fuel rods and very small portion is available in the coolant. As these liquid radioactive materials are filtered before being given to the environment, the impacts of them to the environment is very small when compared with the impacts due to the natural radiation (Tanrıkul Demir, 2017).

The main radionuclide in liquid releases is tritium in PWRs/ VVERs and is formed due to the reaction of neutron with the chemical materials in the reactor coolant, the reaction of neutron with deuterium and the triple fission mechanism of nuclear fuel.

As the corrosion products accumulates on the fuel surface, corrosion products become activated by capturing neutrons and Fe^{55}, Ni^{63}, Co^{60}, Mn^{54}, Co^{58}, and Fe^{59} are the most activated radionuclides by this mechanism. Therefore, these radionuclides can be observed in the reactor coolant. Co^{60} is the main dose contributing radionuclide from liquid discharge although the activity of tritium is bigger than Co^{60} in the coolant as the dose conversion factor of tritium is very small compared to the factor of Co^{60} (Tanrıkul Demir, 2017). The important radionuclides released and discharged to environment based on the exposure pathways are provided in Table 2.5 (IAEA, 2010).

Table 2.5. *The important radionuclides released and discharged to the environment depending on the exposure pathways (IAEA, 2010)*

Radionuclide	**Important Exposure Pathway**
Discharges to Atmosphere	
H-3	Ingestion of food and inhalation of plume
C-14	Ingestion of foodstuffs
P-32	Ingestion of foodstuffs
Ar-41	External irradiation from plume
Co-57/Co-60	External irradiation from deposited activity and ingestion of food
Kr-89	External irradiation from plume
I-131	Ingestion of foodstuffs (milk)
Cs-137	Ingestion of foodstuffs and external irradiation from deposited activity
U-238	Inhalation of plume
Pu-238/Pu-241	Inhalation of plume
U-238+	Inhalation of plume
U-235+	Inhalation of plume
Th-228+	Inhalation of plume
Ra-228+	Inhalation of plume and ingestion of foodstuffs
Ra-226+	Inhalation of plume and external irradiation
Pb-210+	Ingestion of foodstuffs
Po-210	Inhalation of plume and ingestion of foodstuffs
Discharges to Aquatic Environment	
H-3	Ingestion

Discharges to Aquatic Environment	
C-14	Ingestion
P-32	Ingestion
Co-60	Ingestion and external irradiation from deposited activity
Sr-90	Ingestion
Ru-106	Ingestion and external irradiation from deposited activity
I-131	Ingestion
Cs-137	Ingestion and external irradiation from deposited activity
Pu-239	Ingestion
U-238+	Ingestion of water
U-235+	Ingestion of water
Th-228+	External irradiation
Ra-228+	Ingestion of water and fish
Ra-226+	Ingestion of water and fish
Pb-210+	Ingestion of fish
Po-210	Ingestion of water and fish

2.7. Atmospheric Modelling Approaches and Comparison of the Related Software/Models

Atmospheric dispersion of radioactive gases and aerosols from routine operation of NPPs has two approaches; gradient-transport theory and statistical theory. Gradient transport theory, which is proportional to diffusion with the rate of change of local concentration at a fixed point in the atmosphere, is to determine the flow or the momentum of the material at the fixed points whereas statistical theory (i.e. Gauss) is to determine important statistical features representing the diffusion and the past of the individual particulates. Inputs for the models are wind speed in the region, atmospheric stability classes and flow rate. Models generated with these approaches can be named as variety trajectory model or straight-line Gauss dispersion model depending on the application of the spatial changes of the inputs. Radioactive decay, dry and wet deposition should also be considered in the calculations as well as effective plume height and eddy currents (Aksoy, 2017).

Straight-line Gauss Plume model assumes that the constant average wind speed in the direction of air flow at the release point makes the transport and the diffusion of the release and the simplest atmospheric dispersion model covering Gauss concentration. This model can be used for the assessment of long-term atmospheric releases and it is representative for the continuous releases or long-term intermittent releases several km away from the source. Also, this model assumes that the radionuclides are dispersed equally both against the wind and at the wind direction (Aksoy, 2017).

Gauss-puff model depends on the particulate gradient transport in the cell model and considers that the radionuclides in the air are spatially and temporally changing in three dimensions. Therefore, regional data is required to be used in the model. Also, this model simulates the radionuclides in the air as small puffs which allow to model to take the temporal and spatial changes in the wind into account (Aksoy, 2017).

In addition to these two approaches, Lagrange is another approach which can be used when the site of NPP is complex (hilly, mountainous, valley etc.). For NPPs constructed at complex and hilly site, dispersion of the atmospheric releases can be complex due to the valley circulation, canalized flow, flow through hill in day time and flow through down of the hill in night. Lagrange model can be used in such cases as Gauss plume model is insufficient to model them. The particulates in the air moves in the trajectories determined by the wind, buoyancy and turbulence in Lagrange models and these trajectories are determined with the simple differential equations that are calculated easily. Also, Lagrange model considers some physical processes including radioactive decay and deposition of the radionuclides and the particulates can represent gaseous radionuclides and aerosols (Aksoy, 2017).

Models that can be used for the atmospheric dispersion and/or dose calculation of the routine release are PC CREAM 08, XOQDOQ, ADMS 5, LAPMOD, INPUFF-U, NORMAL, ARTM (Aksoy, 2017). The comparison of these models is given in Table *2.6*.

Table 2.6. *The comparison of the models for the assessment of the routine atmospheric releases from NPPs (Aksoy, 2017)*

Software	Model type	Radioactive Decay	Deposition	Effective plume height	Building effect	Topography	Complex meteorology	Dose calculation	Country where the model is developed
PC CREAM 08	Gauss Plume	✓	✓	✓	*	*	✓	✓	England
XOQDOQ	Gauss Plume	✓	Dry deposition	✓	*	✓	X	X	A.B.D.
ADMS 5	Gauss Plume	✓	✓	✓	✓	✓	*	Gamma dose	England
LAPMOD	Lagrange particulate	✓	✓	✓	*	✓	✓	✓	Italy
INPUFF-U	Gauss Puff	*	✓	X	X	X	*	*	Romania
NORMAL	Gauss Plume	✓	✓	✓	✓	Smooth changes on the terrain	X	✓	Czechia
ARTM	Lagrange particulate	✓	✓	*	✓	✓	✓	✓	Germany

*: cannot be assessed as information regarding the attribute was not found.

Detailed information regarding atmospheric modelling approach for routine atmospheric releases from NPPs can be obtained from the expertise thesis of Meltem Nihan AKSOY prepared for TAEK (Aksoy, 2017).

2.8. Aquatic Modelling Approaches and Comparison of the Related Software/Models

The discharge type (continuous, periodic, anticipated or accidentally), water body in which the discharge is made (river, lake, sea, ocean etc.), source term amount given to the environment during routine operation and sensitive parameters in the modelling should be considered in the selection of the mathematical calculation/model for the dispersion of liquid radioactive discharge in surface water.

The mathematical models can be described in three groups; analytic, compartment and numeric, where each group is separated into two groups as dynamic and steady-state. Dynamic models consider the time-integrated changes whereas steady state models take the system in equilibrium independent from the changes due to time-integration. Analytic models give the approximate or the exact result by basic differential equations modelling the movement of the water and the transport of the radionuclides. Therefore, analytical models can be solved with the calculators. However, compartment models assume homogenous radionuclide dispersion by the complete mixing in each compartment and the average radionuclide concentrations can be calculated by the mathematical patterns considering the transport coefficients connecting the compartments to each other and radionuclide-sediment interaction. On the other hand, numeric models are generally the direct solution of the differential equations describing water movement and radionuclide transport by using finite elements and finite differences methods. Therefore, digital computers, a lot of data and experts in hydrology are necessary for numeric models.

Analytical solution of the diffusion equations is valid only when the continuous-steady state flow rate is available. Moreover, analytic models are divided into steady state and transient types according to the continuous or transient discharge. Steady state analytic model solves diffusion equations by Gaussian-like solution and the solution differs by the dimension of the model and discharge type etc. whereas transient analytic models are used when the discharge is non-continuous, and the diffusion transport in the direction of flow is important. Numeric solutions are used when time-integrated flow or complex receiving media geometry exists.

Two dimensional numeric models accept steady state in vertical direction whereas three dimensional models are preferred during site selection and accidental discharges for license renewal stage of NPPs and are not used for radiological assessment for routine operation of NPPs.

Models that can be used for the aquatic dispersion and/or dose calculation of the routine liquid discharges are PC CREAM 08, LADTAP, OURSON, MARISA, RIAMOM, FETRA, HELCOM, POSEIDON/RODOS, MODFLOW, MT3DMS and ASM (Tanrıkul Demir, 2017). The comparison of these models is given in Table 2.7.

Table 2.7. *The comparison of the models for the assessment of the routine liquid discharges from NPPs (Tanrıkul Demir, 2017)*

Software	**Water body**	**Model type**	**Concentration calculation**	**Dose calculation**	**Exposure pathways considered**	**Sediment interaction**
PC-CREAM 08	River, Sea	Compartment	✓	✓	Ingestion, External exposure	✓
LADTAP	Sea, River, Lake	Analytic	✓	✓	Ingestion, Inhalation, External exposure	✓
OURSON	River, Sea	Dynamic	*	✓	Ingestion, External exposure	✓
MARISA	Sea	Compartment 2-D	✓	✓	Ingestion External exposure	✓
RIAMOM	Ocean	Numeric 3-D	✓	*	*	*
FETRA	Sea, Large lakes	Numeric 2-D	✓	*	*	✓
HELCOM	Sea	Compartment	✓	✓	Ingestion, Inhalation, External exposure	✓

Software	Water body	Model type	Concentration calculation	Dose calculation	Exposure pathways considered	Sediment interaction
POSEIDON/ RODOS	Sea, River, Lake	Compartment	✓	✓	Ingestion External exposure	✓
MODFLOW	Underground water	Numeric 2-D	✓	*	*	*
MT3DMS	Underground water	Numeric 2-D, 3-D	✓	*	*	*
ASM	Underground water	Numeric 2-D	✓	*	*	*

*: The feature is not applicable for the model assessment

Detailed information regarding aquatic dispersion modelling approach for routine liquid discharges from NPPs can be found from the expertise thesis of Ezgi Tanrıkul Demir (2017) prepared for TAEK.

2.9. Description of PC CREAM 08 Software

Features of the models for atmospheric release and aquatic discharges have been already summarized in Chapter 2.7 and 2.8 As it can be seen from Table 2.6 and Table 2.7, PC CREAM is a such a prominent model that it covers both atmospheric releases and aquatic discharges, it also considers the transport of radionuclides in the food chain, it allows users to simulate real cases as much as possible by entering site specific data for meteorology, food production and consumption rates, stack height, receptor points (location of public). Therefore, this software was selected in this thesis to assess the radiological impacts of routine operation of Metsamor NPP on the public living in Province of Iğdır.

PC CREAM 08 software was published by Public Health England which uses Gauss plume model for atmospheric dispersion. Also, this software considers the transport of the radionuclides, released or discharged, from the biosphere to the human (via external exposure, inhalation and ingestion pathways). Moreover, this software can calculate both the individual and critical group doses (Smith et al, 2009; Smith and Simmonds, 2009).

Site specific meteorology data, real release rate and deposition rate to calculate concentrations in the air, radionuclide transport in terrestrial food chain, gamma dose rate due to cloud gamma radiation in the wind direction, doses due to inhalation, ingestion and groundshine, radioactive decay and effective plume height are considered in the software for assessing the radiological impacts due to the atmospheric releases (Tanrıkul Demir, 2017).

PC CREAM uses compartment model to simulate aquatic releases and assumes homogenous mixing in each compartment. The radiological impacts of aquatic discharges due to the radionuclides such as ^{3}H, ^{14}C, ^{51}Cr, ^{89}Sr, ^{90}Sr, ^{131}I, ^{134}Cs and ^{137}Cs can be assessed with the software. Also, sediment-radionuclide interaction is considered in the software and the software make it easy by using dispersion coefficients derived experimentally.

This software consists of several models named as PLUME, RESUS, GRANIS, FARMLAND, DORIS, River Models and ASSESSOR. For assessing the doses arisen from the atmospheric releases, PLUME, RESUS, GRANIS, FARMLAND and ASSESSOR are used whereas screening models and dynamic models (river models) and ASSESSOR are used for dose assessment due to releases discharged to rivers, and DORIS is used for dose assessment due to releases discharged to sea (Smith and Simmonds, 2009).

In this thesis, PLUME, RESUS, GRANIS, FARMLAND, screening model and ASSESSOR are used for the assessment of radiological assessment. PLUME model, which is a Gauss plume model, is the atmospheric model in the software and considers meteorological conditions during release, roughness, land surface and physical characteristics of the radionuclides. This model calculates activity concentration of the radionuclides in the air, deposition rates and cloud gamma dose rates at various distances. These data can be used as input to ASSESSOR of the software. ASSESSOR combines the outputs of PLUME model with site specific meteorological data and actual release rates to calculate concentrations of radionuclides in air, deposition rates and cloud gamma dose rates. RESUS, GRANIS and FARMLAND models are scaled with the deposition rates from PLUME to estimate doses for different exposure pathways due to the atmospheric release.

RESUS model estimates the activity concentrations of resuspended radionuclides in air, which are previously deposited to the ground, by the formula considering the differences in radioactive decay. The activity concentrations are the input to ASSESSOR of the software which combines them with the habit data to estimate doses coming from inhalation of resuspended radionuclides.

GRANIS model estimates the external exposure to gamma radiation due to deposited radionuclides to the ground by modelling the transfer of radionuclides through soil and taking the shielding features of the soil into account in the estimation of doses one meter above the soil surface. This model includes organ doses and effective doses. The effective doses are input to ASSESSOR of the software, which estimates the actual exposure by scaling effective doses with the actual deposition rates at various locations.

FARMLAND model estimates the transfer of radionuclides in the terrestrial foods after radionuclides are deposited onto ground. The most important foods in human diet such as green vegetables, fruit, grain, cow milk, cow milk products, cow meat, root vegetables, sheep meat, cow liver and sheep liver are considered in this model to calculate activity concentrations in each food. Then, these activity concentrations are used in ASSESSOR of the software to estimate ingestion doses by scaling activity concentrations with the actual deposition rates at various locations.

The simple screening model is used to estimate the dispersion of the radionuclides in the rivers. This model is a simple and screening dilution model assuming instantaneous equilibrium between the water and river sediments. If the detailed assessments are required dynamic model can be used which is time dependent model and greater amount of data is required to use it.

ASSESSOR is the dose assessment part of the software, which uses the activity concentrations calculated in environmental media to estimate the effective doses. This model consists of individual and collective doses due to atmospheric release and aquatic discharge to sea and individual doses due to discharges to the rivers. During the run, ASSESSOR considers actual discharge rates, site specific data, habit data and dose coefficients to estimate effective doses for the exposure pathways which are important (Smith et al, 2009).

The detailed information can be obtained from Smith et al (2009) and Smith and Simmonds (2009).

2.10. Description of the Iterative Approach Provided in IAEA SRS 19 Document

In SRS 19 document of IAEA (IAEA, 2001), it is indicated that screening models are used in the iterative approach to determine the impact of the releases and discharges made to the environment with the simplified but conservative assessment and to determine whether the impacts are negligible or not without the need for further analysis or detailed analysis. Also, it was indicated in the document that this approach is only applicable to long term releases made to the environment (IAEA, 2001).

As this approach require simple models to evaluate the radiological impact due to the release and discharge to the environment, this approach is selected to compare its results with the results of more complex model (PC CREAM 08) and its conservativeness will be tested.

The step-wise iterative approach starts with "No-dilution model" stage as provided in Figure 2.4. No-dilution model is a very simple and conservative model assuming that individual of public is at the point of release/discharge (i.e. at the stack for atmospheric release or at the discharge point for aquatic release) and individual is exposed to the radiation there without the dilution/dispersion of the radionuclides in the environment.

Factors for dose calculation are provided in Annex I of SRS 19 document of IAEA. If the critical group doses estimated exceeds the dose constraint by no-dilution model, using more complex model is suggested. The dose constraint for routine operation of NPPs in Turkey is 0.1 mSv/year for public according to Draft Radiation Protection Regulation of Nuclear Regulatory Authority (NDK, 2019).The second stage of this approach is the usage of more complex model than no-dilution model which is called as simple generic environmental model as indicated in Figure 2.4. The generic environmental model considers the dispersion of the radionuclides in the environment on the contrary to no-dilution model. Also, factors for dose calculation, which are based on generic environmental model and standardized assumptions regarding release/discharge conditions, location of food production and critical group, and habits of critical group, are provided in Annex I of SRS 19 document of IAEA. If the estimated doses for critical group by generic environmental group exceeds the reference level, the next stage is to examine generic inputs for the applicability of them to related site. The reference level indicated in this stage refers to the 10% of the dose constraint (0.1 mSv/year as provided in Chapter 2.2), which is 0.01 mSv/year for Turkey. If the data is excessively conservative or inapplicable, a modified generic assessment is suggested as shown in Figure 2.4. If the estimated critical group doses exceed the dose constraint in this case, consulting to a suitable expert for site specific assessment as indicated in Figure 2.4 will be necessary. Examples of factors that are suggested to be considered to check the relevance of the generic assumptions to the related site are presented in Figure 2.5 (IAEA, 2001).

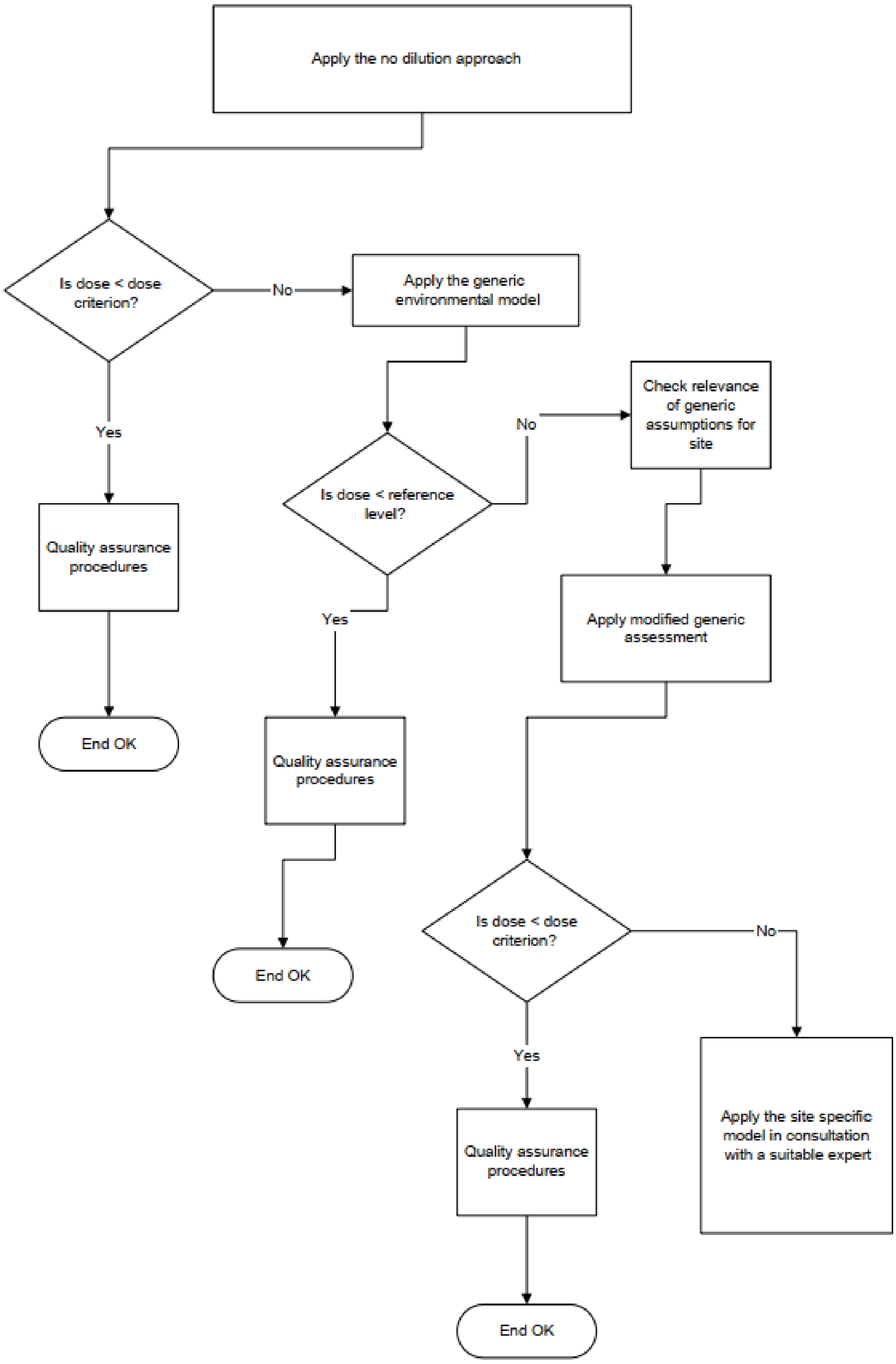

Figure 2.4. The iterative approach provided in SRS 19 document of IAEA (IAEA, 2001)

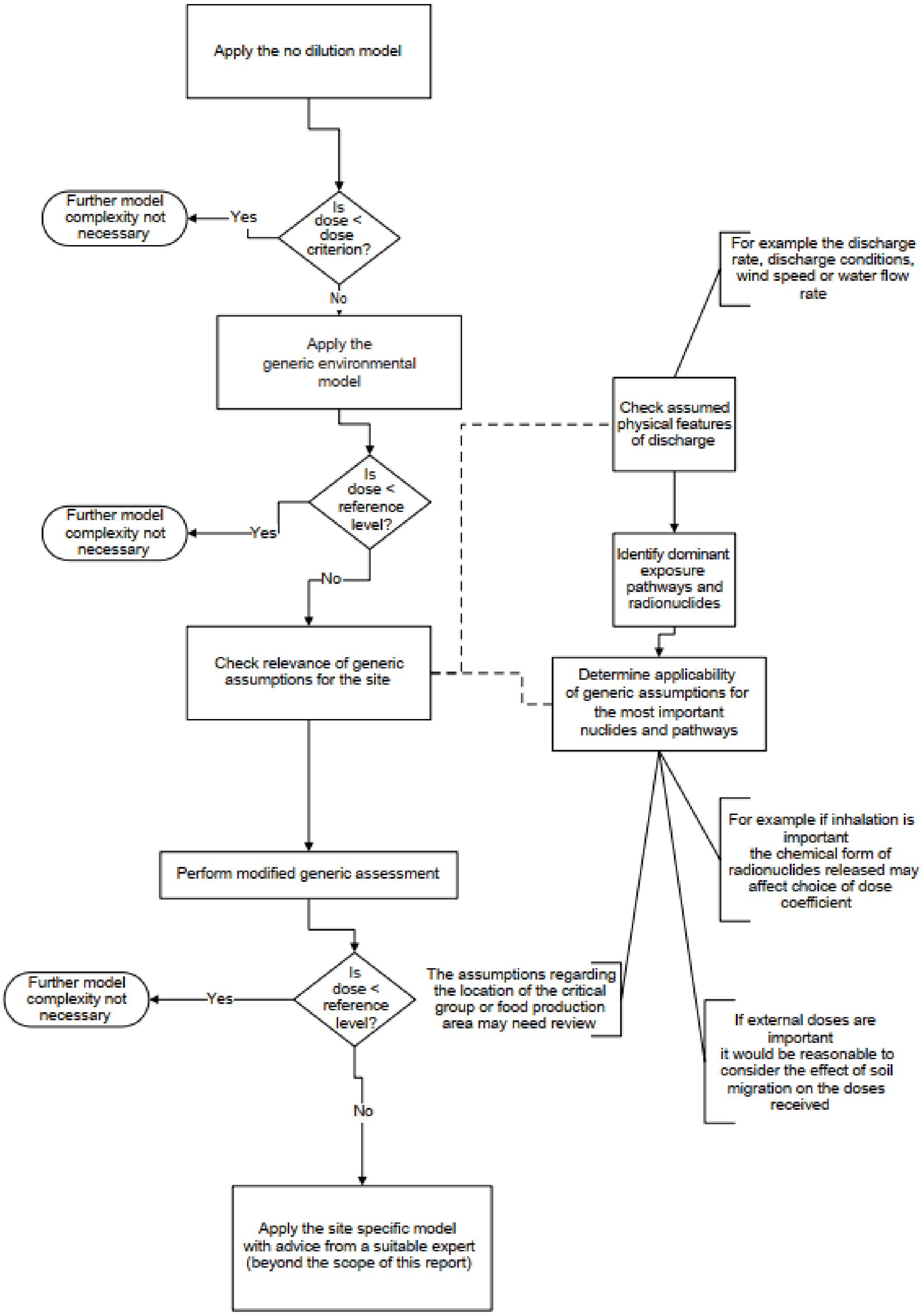

Figure 2.5. Example factors to control the assumptions related to site (IAEA, 2001)

2.11. Health Effects of Ionizing Radiation

Ionizing radiation can affect the atoms which may affect cells, tissues, organs and the whole body, ultimately. Cellular damage can occur by the mechanism of direct and indirect effects. When ionizing radiation interacts with DNA or cell components crucial to cell to survive or reproduce itself, chromosomes do not replicate itself or cells may be destroyed if enough atoms are affected by the radiation. This mechanism is named as the direct effect of ionizing radiation. In the indirect effect mechanism, cells can be destructed by the toxic substances (such as H_2O_2) formed by radicals (H and OH) of water in the cell (H_2O) of which bonds are broken by radiation, which is called as radiolytic decomposition of water in the cell (USNRC, n.d.).

Biological effects of radiation can be classified into two categories which are for high doses (acute) and low doses (chronic). Effects for high doses is the exposure to high doses of radiation over short period of time and this causes short term/ acute effects tending to kill so many cells which damage the tissues and organs. This damage causes whole body to respond so rapidly to the radiation, which is called as acute radiation syndrome including effects such as changes of blood count, vomiting, death, skin burns, hair loss etc. based on received dose. Effects of low doses is the exposure to low level radiation over an extended period of time resulting in chronic/ long term effects which do not result in an immediate effect to any organ. Therefore, this chronic effect occurs at the cell level and its effect may not be observed for decades (USNRC, n.d.).

The effects of exposure to low level doses are categorized as genetic, somatic and in-utero. Genetic effects are the mutation of the reproductive cells (sperm or egg cells) inherited to the next generations of the individual exposed to ionizing radiation whereas somatic effect (carcinogenic) is the effect principally suffers the exposed individual and primary consequence of it is cancer. However, in-utero effect is the effect of radiation on fetus/embryo resulting in malformations in developing embryos which causes intrauterine death, growth retardation, developmental abnormalities and childhood cancers depending on the stage of fetal development at the time of exposure to radiation (USNRC, n.d.).

There are several hypotheses for dose-response curve indicating the relation of exposure to radiation and cancer which are linear-no threshold model, exponential model, hormesis model and stochastic (dots) model. Linear no threshold model assumes that the risk of cancer is proportional to the dose received whereas risk of cancer rises exponentially with the increasing exposure to radiation. In the hormesis model, it is assumed that low-level doses have protective effects (positive effects) and high-level doses result in harm. In the dots model, cancer risk and the dose relation are not correlated (Gori and Münzel, 2011). These hypotheses are presented in Figure 2.6.

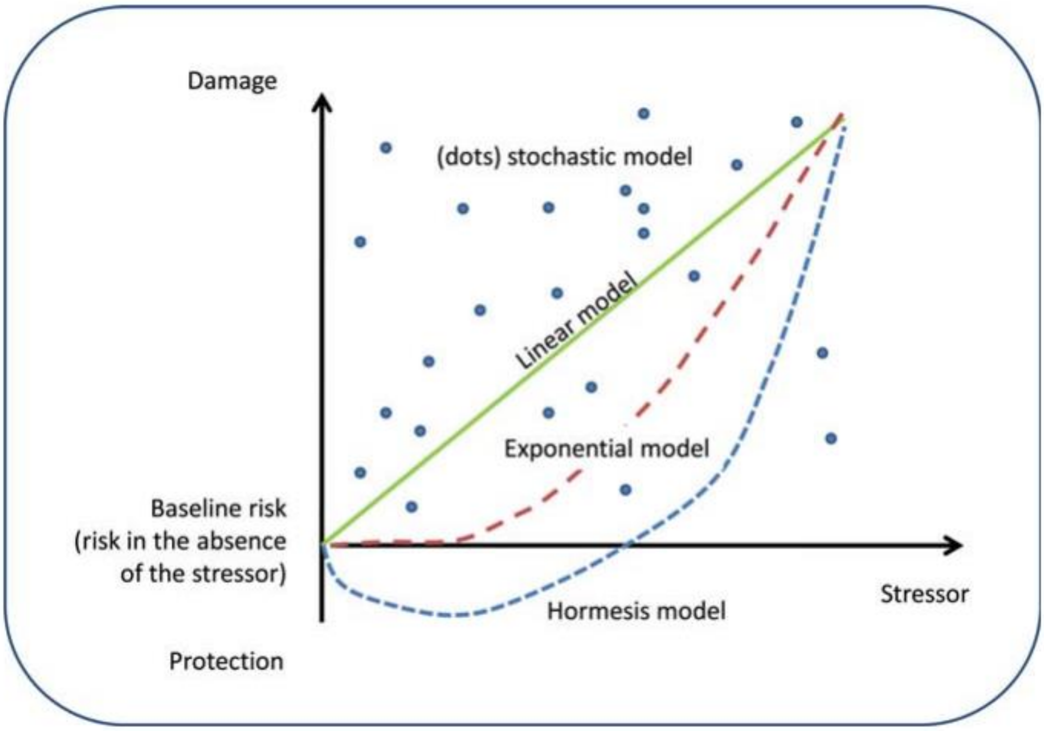

Figure 2.6 Hypotheses on the dose-response curve for the relationship of radiation exposure and cancer risk (Gori and Münzel, 2011)

Turner (2007) mentions about the studies performed by International Commission on Radiation Protection (ICRP), National Council on Radiation Protection and

Measurements (NCRP), Radiation Effects Research Foundation, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the National Radiological Protection Board of the United Kingdom, and the National Academy of Sciences–National Research Council in the United States to estimate health risk of radiation. Besides, Turner (2007) indicates the probability coefficients per Sv effective dose of public to estimate stochastic effects due to radiation exposure. These coefficients are determined based on the abovementioned studies and they are provided in Table 2.8.

The health risk of a person from public is found by multiplying the received dose (in Sv unit) with the appropriate probability coefficient provided in Table 2.8. For example, if a person (from public) is exposed to 1 Sv dose, the probability of a person (Rahm-Crites, 1994) to have fatal cancer is 5%, to have nonfatal cancer is 1% and to have severe genetic effects is 1.3.

Table 2.8 *Probability coefficients per Sv effective dose (for stochastic effects) (Turner, 2007)*

Detriment	**Whole population (10^{-2} Sv^{-1})**
Fatal cancer	5.0
Nonfatal cancer	1.0
Severe genetic effects	1.3
Total	7.3

CHAPTER 3

METHODOLOGY

3.1. Overview

In this chapter, the methodology of the study for two approaches and the necessary input data are presented. Radiation exposure pathways and dose assessment considered in PC CREAM 08 software and the iterative approach in IAEA SRS 19 are explained. Moreover, related equations to estimate concentrations in related environmental media and animal regarding exposure pathways and equations to estimate related public doses are provided.

3.2. Radiation Exposure Pathways in PC CREAM 08

The exposure pathways including terrestrial food chain considered in the software for both atmospheric releases and aquatic discharges to rivers are provided in Table 3.1.

Table 3.1. *The exposure pathways in PC CREAM 08 software (Smith et al, 2009)*

Atmospheric Exposure Pathways	***Exposure Pathways for Rivers***
Inhalation of radionuclides in the plume	External gamma dose from radionuclides in sediment
External gamma dose from radionuclides in the plume	External beta dose from radionuclides in sediment
External beta dose from radionuclides in the plume	Consumption of radionuclides in freshwater fish
External gamma dose from deposited radionuclides	Consumption of radionuclides in drinking water
External beta dose from deposited radionuclides	-
Inhalation of resuspended radionuclides	-

Atmospheric Exposure Pathways	***Exposure Pathways for Rivers***
Consumption of radionuclides in cow meat, cow liver, cow milk, sheep meat, sheep liver, green vegetables, root vegetables, fruit* and grain.	-

*: not available for collective dose assessments.

3.2.1. The Transfer of Radionuclides in Terrestrial Food Chain

The transfer of the radioisotopes from terrestrial environment to food chain is a complex process due to the properties of the radionuclides and the environment. PC CREAM 08 software uses FARMLAND dynamic food chain model, which uses compartment model and is flexible, and its mechanism is presented in Figure 3.1. It considers the transfer of radionuclides in food chain after the radioisotopes are deposited onto the ground as a result of the atmospheric routine releases from NPPs. Besides, the variations in agricultural activity or the season of it are not important in the software as it takes continuous releases into consideration.

Transfer of radionuclides in foods, which are important in the diet of human, are grouped into green vegetables, grain products, root vegetables including potatoes, fruit, meat, liver, milk and milk products in the software. Also, cattle and sheep are considered as animals in the software with the transfer of radionuclides through pasture and animal metabolism. As pigs and chickens are reared permanently indoors, they are not considered in the software. Goats are also not included in the software.

The three important process in the transfer of the radionuclides in food chain are transfer of radioisotopes in soil, transfer of radionuclides to plants and transfer of radioisotopes to animals (Smith and Simmonds, 2009). Details of these processes are given in latter sub-chapters.

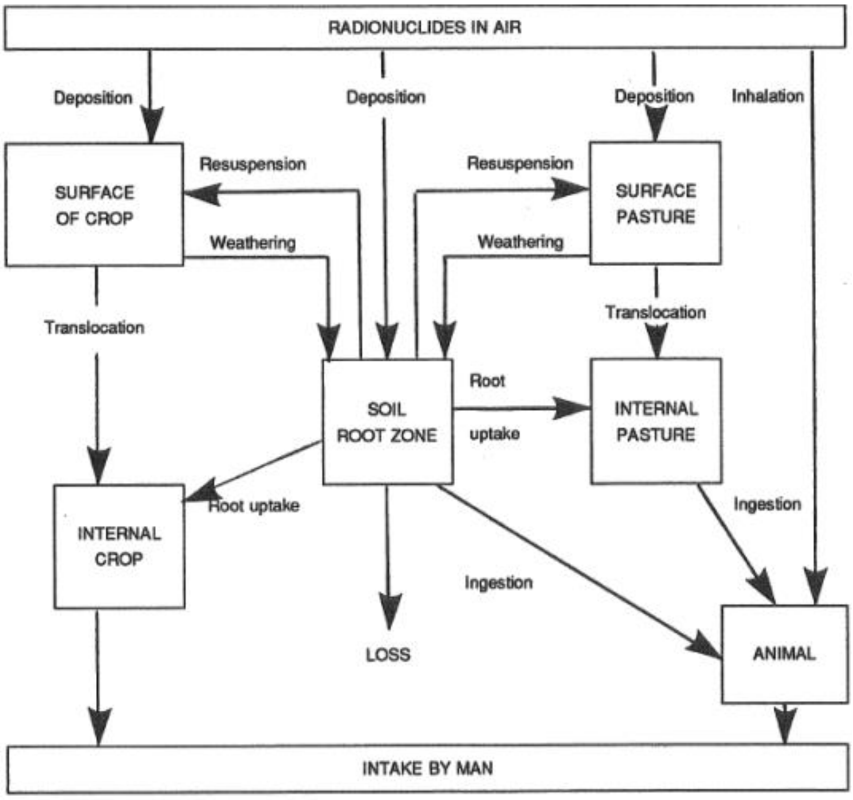

Figure 3.1. Radionuclide transfer in terrestrial food chain (Smith and Simmonds, 2009)

3.2.1.1. Transfer of Radioisotopes to Plants

The schema for the transfer of radionuclides to plants is provided in Figure 3.2Figure 3.2. In this figure, the soil compartment is appropriate for well-mixed soil where all the plants consumed by people comes from the frequently cultivated lands. Also, internal and external compartments are available for plants as given in the figure. Radionuclides can be transferred onto the surface of plants by interception of depositing radionuclides or by resuspension of radionuclides from soil whereas internal transfer of radionuclides can occur by the root uptake and by translocation of radionuclides from surfaces of the plant. During interception process, dry and wet deposition is considered in total in routine releases of radioisotopes in the atmosphere. The process where the radionuclides are absorbed and transferred to the other parts of the plant is called translocation and important for cesium. The radionuclide concentration can be reduced when green vegetables are washed and outer leaves of them are separated (non-edible parts). Same is valid for grain as the outer part of it is removed when the flour is produced (Smith and Simmonds, 2009).

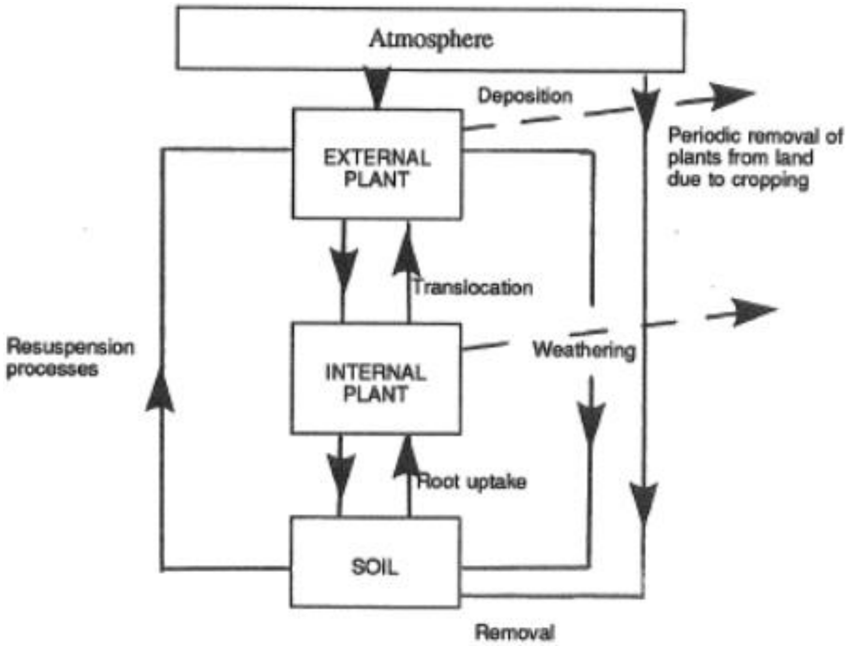

Figure 3.2. Radionuclide transfer mechanism in plants (Smith and Simmonds, 2009)

3.2.1.2. Transport of Radionuclides in Soil

Soil is important in the transport of radionuclides to human foodstuffs. There are two models in the transfer of radioisotopes in soil; model for undisturbed land and model for well-mixed soil. Model for well-mixed soil is valid for the soil ploughed or cultivated frequently/annually whereas model for undisturbed soil is used for undisturbed agricultural areas such as permanent pasture (Smith and Simmonds, 2009). In well-mixed soil model, radioisotopes are assumed to be mixed evenly through the first 30 cm of the soil from the top, which covers the various depth of roots of the plants. On the other hand, in undisturbed soil model, series of transfers among the compartments based on different depths by assuming uniform radionuclide concentration mixing in each compartment are considered. As distribution of terrain is 41% for pasture, which is greater than agricultural areas (33%) in the region of Province of Iğdır (TOB, 2019), undisturbed soil model is used in the analysis. The schema for radionuclide transport in soil for undisturbed soil in PC CREAM is provided in Figure 3.3.

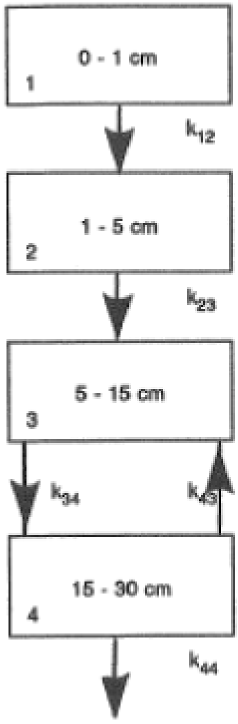

Figure 3.3. Radionuclide transport in undisturbed land (Smith and Simmonds, 2009)

3.2.1.3. Transfer of Radioisotopes to Animals

The radionuclides are transferred to the animals by two pathways; ingestion and inhalation. As a subsequent metabolism due to these pathways, the radionuclides are transferred to animal tissues which are consumed by human. Therefore, the exposure of animals to radiation is important in the exposure pathway of human due to ingestion of animal products that are affected by the radionuclide transfer. The process considered in PC CREAM software is provided in Figure 3.4 (Smith and Simmonds, 2009).

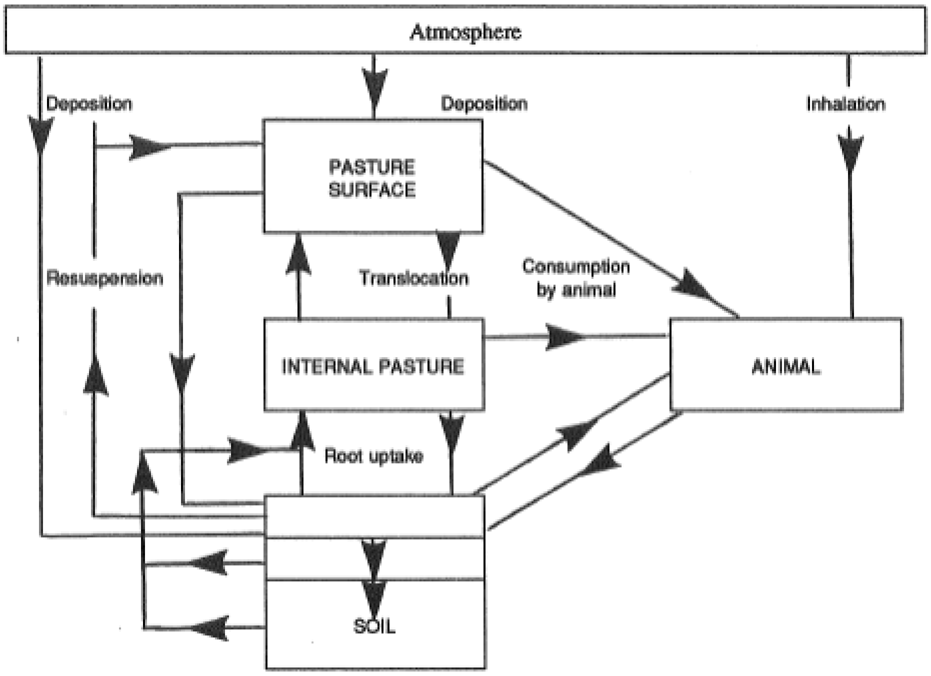

Figure 3.4. Schema of the transfer mechanism of radionuclides in grazing animals (Smith and Simmonds, 2009)

3.2.2. External Exposure from Surface Deposition and Resuspension of Deposited Radionuclides

External exposure due to surface deposition onto top 30 cm soil are considered for both photons and electrons. Beyond this depth, the external exposure due to surface deposit is neglected in the software as it is almost zero. Migration of Sr^{90} in soil from the top is considered as rapid downward migration in the software.

Deposited radionuclides onto the soil can be resuspended as a result of man-made activities such as traffic, farming and digging activities or wind driven factor. Therefore, inhalation of resuspended radionuclides forms an exposure pathway for human. Moreover, re-deposition of radionuclides onto the crops and foods which cause the contamination of them and further exposure for animals and human when they consumed them. Man-made activities cause localized resuspension and hence localized exposure. However, wind-driven resuspension is more important than man-made resuspension for collective dose assessment. It is indicated that PC CREAM 08 considers only wind-driven resuspension in the dose analysis, which varies according to the meteorological conditions in the region in consideration. Resuspension due to undisturbed land, ploughed land and urban surfaces are considered in the software.

Resuspension is considered in the software with factor k (m^{-1}) where it is the ratio of concentration of radionuclides in the air due to resuspension (Bq/m^3) to surface deposition of radionuclides (Bq/m^2) (Smith and Simmonds, 2009).

The equation to estimate the resuspension factor is provided as below (Smith and Simmonds, 2009):

$$k(t) = 1.2\ 10^{-6} t^{-1} + 10^{-9} \qquad (1)$$

During the first day of resuspension, 1.2 10^{-6} is assumed for k. Then, modified formula is presented as follows (Smith and Simmonds, 2009):

$$k(t) = (1.2\ 10^{-6} t^{-1} + 10^{-9}) e^{-\lambda t} \qquad (2)$$

where,

λ: Radioactive decay constant (day^{-1}),
t: Time after deposition (days).

The integrated activity concentration in air for resuspension is also provided in Smith and Simmonds (2009) in detail.

3.2.3. Transport of Aquatic Discharges in River

Transport of radionuclides in river includes the contamination of water and sediment and then the contamination of foods such as fish, drinking water and by irrigation from river due to the transfer of radionuclides from the river to foods. (Smith and Simmonds, 2009). The biological, chemical and physical transformation and transport mechanism of radionuclides are provided for rivers in Figure 3.5. When a discharge is made into the river, advection and the dispersion can be dominant, however, biological and chemical processes can be crucial in the long term (Smith and Simmonds, 2009).

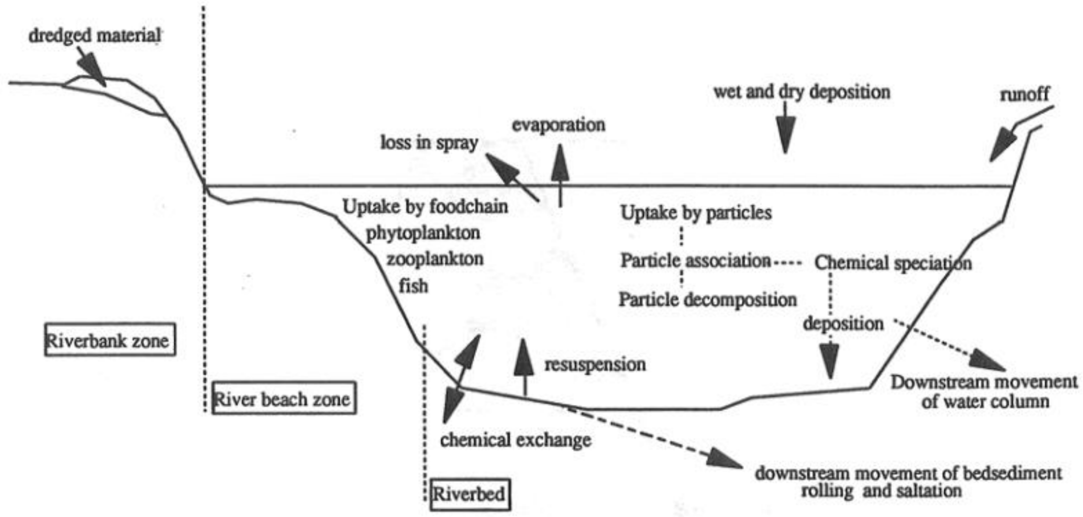

Figure 3.5. The transport and transformation process of radionuclides in rivers (Smith and Simmonds, 2009)

Activity concentration in unfiltered water (C_{uw} (Bq/m^3)) can be calculated according to the equation given below (Smith and Simmonds, 2009):

$$C_{uw} = C_{fw} + C_{ssl}\alpha \qquad (3)$$

where,

α: Suspended sediment load (t/m^3).

Activity concentration of solute or in filtered water (C_{fw}) can be calculated according to the equation provided below (Smith and Simmonds, 2009):

$$C_{fw} = \frac{C_{uw}}{1 + K_d\alpha} \qquad (4)$$

where,

C_{uw}: Concentration of radionuclide activity n unfiltered water at the outfall assuming dilution of it instantaneously (Bq/m^3),

K_d: Sediment-water distribution factor (m^3/t).

Activity concentration in sediment (C_{ssl} (Bq/t)) can be calculated according to the equation given as (Smith and Simmonds, 2009):

$$C_{ssl} = \frac{C_{uw}K_d}{1 + K_d\alpha} \qquad (5)$$

When K_d values get lower, radionuclides stay in the solute more and disperse by the current of the river, such as for technetium. However, it is reverse when the K_d becomes higher and the radionuclides adhere to the sediment near the discharge point and do not disperse widely. Moreover, decay rate of the radionuclide, properties of the aquatic environment like flow rate and suspended sediment load are other important factors affecting the dispersion of the radionuclides in the water body.

There are three approaches in the software to model dispersion radionuclides in the river namely; simple dilution, hydraulic and semi-empirical models (Smith and Simmonds, 2009).

The effluent is assumed to be diluted in the river volume whenever it is discharged into the river in simple dilution models. However, the sediment effect is generally ignored although it can be important in the transport and removal of radionuclides from river. There are three types of simple dilution models as screening models which are simple screening model, extended screening model for complete mixing and extended screening model for incomplete mixing.

In simple screening model, concentration of radionuclide activity in the river water can be estimated with the equation given below Smith and Simmonds, 2009):

$$C_{uw} = \frac{Q}{F} \qquad (6)$$

where,

C_{uw}: Concentration of radionuclide activity in unfiltered water at the outfall assuming dilution of it instantaneously (Bq/m^3),
Q: Annual radionuclide discharge rate (Bq/s),
F: Volumetric flowrate of the river at the outfall (m^3/s).

The assumptions regarding this model are constant discharge rate over the related period, constant flow rate of the river over the related period, no dilution of radionuclide activity in the effluent itself, instantaneous and complete dilution of effluent in total flow of the river and ignoring radioactive decay. Therefore, this model is suggested to be more applicable to situations in which the radionuclides do not interact strongly with the sediment of river, i.e., tritium or distances immediately downstream of the aquatic discharge point and it may be used for screening purpose to estimate exposures cautiously due to radionuclides in water body.

Extending screening models consider the dilution of the radionuclides by the river flow, radioactive decay and downstream transit times. Also, these models are more appropriate to radionuclides having short half-life (i.e. less than 1 year). In these models continuous and constant discharge rate over the related period, constant river flow rate for the related period, dilution of the discharge in the river with a dilution factor of 1000 and dilution of discharge at the point downstream through the degree of dilution, transit time and radioactive decay are assumed.

As mentioned before, there are 2 types of extending screening models; complete mixing and incomplete mixing. Complete mixing occurs according to the Smith and Simmonds (2009) for locations some tens of kilometers away from the discharge point as the flowrate of discharge is generally smaller than the flow rate of the river.

If the complete mixing is used, radionuclide concentration in the river (C_{uw}) can be estimated with the following equation (Smith and Simmonds, 2009):

$$C_{uw} = \frac{Q}{F} e^{-\lambda t} \qquad (7)$$

where,

λ: Decay constant (1/s or 1/y)

t: Transit time at the point

$$t = \frac{x}{V_w} \qquad (8)$$

where,

x: Downstream distance from the discharge point (m),
V_w: Velocity of the water (m/s)

$$V_w = \frac{F}{wd} \qquad (9)$$

where,

w: Width of the river (m),
d: Depth of the river (m).

If incomplete mixing is assumed, radionuclide concentration in river can be estimated with the equation given below:

$$C_{uw} = \frac{Q}{ED} e^{-\lambda t} \qquad (10)$$

where,

E: Effluent flow rate (m^3/s),
D: Dilution factor.

It is indicated in document of Smith and Simmonds (2009), hydraulic models are not included in the software, which are developed for describing water quality and sediment transport in the rivers. It is recommended to use it by USNRC for nuclear installations near river sites.

Semi-empirical models represent the process in the water and sediment transport, however, they are difficult and expensive for validation and application for radiological situations. Therefore, at least some parameters are required to be derived. The software retains spatial and temporal properties of the hydraulic models however it simplifies radionuclide-sediment interaction by the empirically derived K_d. This model assumes that radionuclide concentration in solution decreases exponentially downstream from the discharge point because of the dilution, absorption of radionuclides onto the sediments. Also, this model assumes that the discharge is constant and continuous and effluent is diluted instantaneously in the total flow of the river at the discharge point. This model is called dynamic model in the software. k' is the Schaeffer parameter representing the removal of radionuclides to bedsediments, which should be determined empirically for each radionuclide. Detailed information for Schaeffer model can be found in the document of Smith and Simmonds (2009).

3.3. Radiation Exposure Pathways in IAEA SRS 19 Approach

The exposure pathways considered in SRS 19 document of IAEA is provided in Figure 3.6 for both atmospheric releases and aquatic discharges. Also, doses coming from the indicated pathways are also shown in that figure. These pathways are external exposures from immersion in the plume and from radionuclides deposited on ground, internal exposure due to the inhalation of radionuclides in the air and the ingestion of radionuclides in food and water. The same situation is valid for the river water usage and dose estimation as indicated in previous chapter of this thesis.

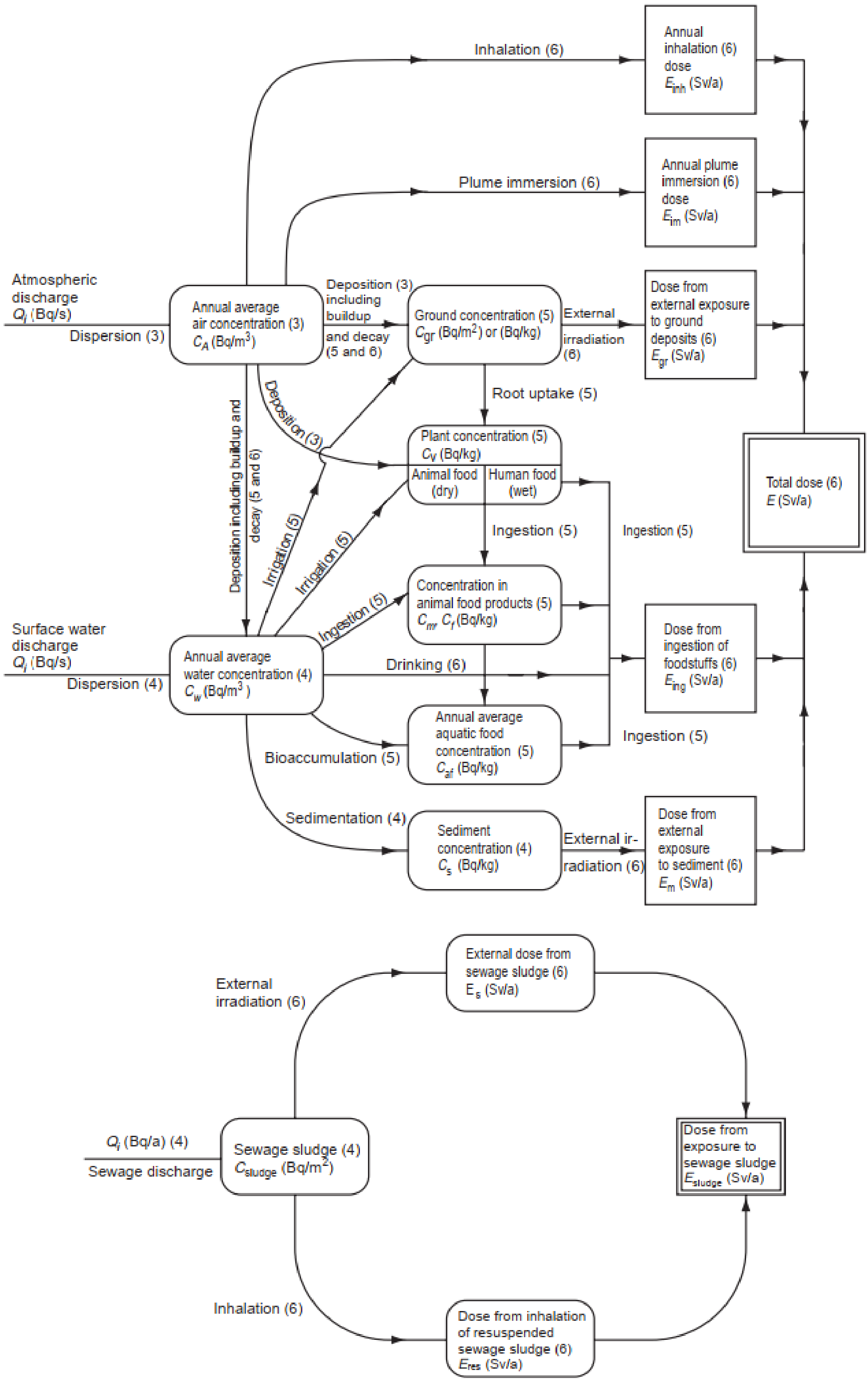

Figure 3.6. The exposure pathways considered in SRS 19 document of IAEA (IAEA, 2001)

3.4. Dose Assessment in PC CREAM 08 Software

3.4.1. Doses due to Atmospheric Exposure Pathway

Concentrations of radionuclides in the air can be estimated from the Gauss Plume equation provided in the software and simplified as given below by assuming that the equation is equally applicable to aerosols, meteorological conditions remain constant and wind-rose is uniform for continuous release, the reflection of the plume from both ground and from the top of the mixing layer are taken into account (Smith and Simmonds, 2009):

$$\bar{X}\,(x,z) = \frac{Q_0}{x 2\pi u_s A} \qquad (11)$$

where,

$\bar{X}$: Mean activity concentration of radionuclides in air at (x, z) (Bq/m^3)
x: Downwind distance from NPP (m),
z: Height above ground where the radionuclide concentration is estimated (m),
Q_0: Release rate of the radionuclides (Bq/s),
u_s: Wind speed at the height of the plume or at the effective release height (m/s),
A: Mixing layer height (m).

Radioactive decay is considered with the equation given below in the software where the decay of parent radionuclide is considered (Smith and Simmonds, 2009):

$$R_d = \frac{\lambda_d}{\lambda_p - \lambda_d}\left[exp\left(-\lambda_d \frac{x}{u_s}\right) - exp\left(\lambda_p \frac{x}{u_s}\right)\right] \quad (12)$$

where,

R_d: Radioactive decay rate,
λ_d: Radioactive decay constant for daughter radionuclide (s^{-1}),
λ_p: Radioactive decay constant for parent radionuclide (s^{-1}).

Wet deposition is taken into account in the software with the equation given below (Smith and Simmonds, 2009):

$$D_w = \frac{\Lambda Q'(t)}{x\alpha u_s} \qquad (13)$$

where,

D_w: Wet deposition rate per unit area,
x: Distance from release point of NPP,
α: Angular width of the sector (i.e. radians),
Λ: Washout coefficient,
t: Time from the beginning of the rain in seconds,
Q': Total amount of radionuclide remaining in the plume.

Dry deposition is considered in the software with the below equation (Smith and Simmonds, 2009):

$$D_d = V_g C \qquad (14)$$

where,

C: Radioactivity concentration in the air at ground level/ its time integral,
V_g: Deposition velocity,
D_d: Dry deposition rate or time integral of it.

10^{-3} m/s value is used in the software for the deposition velocity of all radionuclides, which are representative of 1 µm particles. However, this value is not assumed for noble gases as they are not deposited onto the ground and it is different for organic iodine, which is 10^{-5} m/s, and for inorganic iodine which is 10^{-2} m/s.

Doses to individuals are estimated according to the habit data. Models previously mentioned in Chapter 3.2 are used to estimate the radionuclide concentration in the air and the deposition rates. Doses due to inhalation of the radionuclides and external exposure are proportional to radionuclide distribution in air. Doses due to deposition are also dependent to the concentration in the relevant media.

Dose rate due to inhalation, and for resuspension as well, can be estimated with the equation provided below:

$$\dot{H}(d_{n,}\theta_{n,}t) = x(d_{n,}\theta_{n,}t)H_{inh}I_{inh} \quad (15)$$

where,

$x(d_{n,}\theta_{n,}t)$: Concentration of radionuclide in the air in annular segment n at time t (Bq/m^3),
d: Distance from the source,
H_{inh}: Effective dose per unit intake of radionuclide by inhalation (Sv/Bq),
I_{inh}: Inhalation rate of air (m^3/y).

Doses due to ingestion can be calculated with the equation provided below:

$$C_f(t)I_fH_{ing} \quad (16)$$

where,

$C_f(t)$: Radionuclide concentration in edible parts of the food f at time t (Bq/kg),
I_f: Ingestion rate regarding food f (kg/y),
H_{ing}: Organ dose equivalent or effective dose per unit intake due to ingestion (Sv/Bq).

3.4.2. Doses due to Aquatic Exposure Pathway

The models explained in Chapter 2.9 of this thesis are used to estimate the doses due to aquatic discharge to the river, such as ingestion of drinking water, fish and agricultural products which are irrigated with the contaminated water of river, and may be the river sediment.

The radionuclide concentration in the drinking water, which is extracted from the river water, is normally less than the radionuclide concentration in the river water with a factor which differs according to the treatment method of the drinking water.

Radionuclides on the suspended sediment can be easily removed from drinking water by treatment processes such as filtration, coagulation and sedimentation whereas treatment efficiency of the soluble radionuclides is less and depends on the chemical process applied at the potable water treatment plant. In the software, doses for adults, children (10 years old) and infants (1-year-old) due to ingestion of drinking water containing radionuclides can be estimated for simple dilution model with the equation provided below (Smith and Simmonds, 2009):

$$E = C_{fw} I_w H_{ing} \qquad (17)$$

where,

E: Individual effective dose due to drinking water consumption (Sv/y),
C_{fw}: Radionuclide activity concentration in filtered river water (Bq/L),
I_w: Intake rate for drinking water (L/y),
H_{ing}: Effective dose per unit intake by digestion (Sv/Bq).

Doses due to ingestion of drinking water for dynamic model can be calculated with the equation provided below (Smith and Simmonds, 2009):

$$E_i = C_{fwi} I_w H_{ing} Treat \quad (18)$$

where,

E_i: Individual effective dose for river section i (Sv/y),
C_{fwi}: Radionuclide concentration in filtered water in river section I (Bq/L),
I_w: Intake rate for drinking water (L/y),
H_{ing}: Effective dose per unit intake due to ingestion (Sv/Bq),

Treat: Treat= 1- Removal Efficiency/100, values for removal efficiency are provided in Table 4.4 of the document of Smith and Simmonds (2009).

Transfer of radionuclide activity to the fish is estimated with the element dependent concentration factor which relates the activity concentration in the edible parts of the fish to the activity concentration in filtered water. The factors for elements are provided in Table 4.3 of the document of Smith and Simmonds (2009). The software estimates the doses arising from the ingestion of fish with the equation given below:

$$E = Cfood I_f H_{ing} \quad (19)$$

where,

E: Individual effective dose due to ingestion of fish (Sv/y),
C_{food}: Radionuclide activity concentration in fish (Bq/L),
I_f: Intake rate for fish (t/y),
H_{ing}: Effective dose per unit intake due to ingestion (Sv/Bq),

where,

$$Cfood = C_{fw} CF \quad (20)$$

C_{fw}: Radionuclide activity concentration in filtered water (Bq/m^3),
CF: Element dependent concentration factor for fish (Bq/t per Bq/m^3).

External exposure is possible through immersion in the river water by bathing or fishing or occupancy of the river bank or boats. In the software, external exposure due to contaminated river bank is modelled and it is assumed that the activity concentration n river bank sediment is equal to the activity concentration in the bed sediment. The software uses the following equation to estimate doses due to external exposure from river bank sediments for gamma:

$$E = C_{bedsed} GAMM\ DF\ Conv\ 0.87\ DTW\ Occ \quad (21)$$

where,

E: Effective dose in µSv/y,
C_{bedsed}: Radionuclide activity concentration in sediments, dry (Bq/kg),
GAMM: Gamma energy (MeV),
DF: Dose rate in the sediment, wet = 0.288 (µGy/h per Bq/g per MeV),
Conv: Conversion from Bq/kg to Bq/g (1 10^{-3}),

0.87: Sv per Gy,
DTW: Dry to wet radionuclide concentration conversion= 0.9,
Occ: Occupancy time on sediment (h/y).

The software uses the following equation to estimate doses due to external exposure from river bank sediments for beta:

$$E = C_{bsed} Dens\ t\ DF\ wt\ Occ\ Conv \qquad (22)$$

where,

E: Effective dose in μSv/y,
C_{bsed}: Radionuclide activity concentration in sediments, dry (Bq/kg)
Dens: 1500 kg/m^3,
t: Deposition thickness 0.01 m,
DF: Beta skin dose factor at 1 m (Sv/y per Bq/m^2),
wt: Skin weight factor 0.01,
Occ: Occupancy time on sediment (h/y)/8760 h/y,
Conv: Conversion from Sv/y to μSv/y (1 10^6).

The software does not consider the exposure pathway due to consumption of crops which are irrigated with the contaminated river water or treated with dredged river bed sediments which are used as soil conditioner or fertilizer.

Doses due to spray irrigation is considered by transfer of radionuclide to the external surface of the plants, root uptake and translocation in the plant, which is similar to the process given for deposition of radionuclides onto plants from atmosphere. This pathway is considered as negligible when compared to the doses due to inhalation, external radiation and resuspension for collective doses.

When the river sediment is used as fertilizer, radionuclides can be transferred into food chain, which will result in accumulation of radionuclides in agricultural soil in next years. The rate of radionuclide deposition for this case can be estimated by multiplying the radionuclide concentration in river sediment (Bq/m^3) with the application rate in $m^3/(y\ m^2)$ concentration.

Consumption of river water by animals can cause accumulation of the radionuclides in meat and milk products. For example, annual intake of radionuclide for cattle can be estimated by multiplying the radionuclide concentration in unfiltered river water (Bq/m^3) with the annual consumption of water for cattle (m^3/y) and by using uptake factors, radionuclide concentration in meat can be derived in Bq/kg (Smith and Simmonds, 2009).

3.5. Dose Assessment in the Approach of IAEA SRS 19 Document

3.5.1. No Dilution Method

3.5.1.1. Atmospheric Releases

The most conservative method in screening model is no-dilution method as indicated before, which assumes the receptor point; i.e. public/individual, at the release point that radionuclide concentration at the receptor point is equal to radionuclide concentration of the atmosphere. This situation is explained with the equation below as provided in SRS 19 document of IAEA (2001):

$$C_A = \frac{P_p Q_i}{V} \qquad (23)$$

where

C_A: Ground level air concentration of radionuclide at the downwind distance x (Bq/m^3)

Q_i: Average release rate of radionuclide i (Bq/s)

V: Volumetric flow rate of air at the vent/stack of NPP where release is made (m^3/s)

P_p: Wind blow time fraction towards the receptor

For the screening purposes P_p is suggested to be used as 0.25. Also, it is indicated that calculated C_A can be used to estimate ground level concentration and subsequent dose estimation for the public. If the estimated doses by screening method exceed the reference level, generic environmental model should be used as explained before.

Screening dose calculation factors for atmospheric releases regarding no dilution method are presented in Table I-I of SRS 19 document of IAEA (2001). Doses due to atmospheric release are estimated by multiplying the screening factor with the undiluted annual average concentration of the radionuclide by using Equation (23).

Volumetric flowrate of the stack is assumed as 72 m^3/s from the data of joint ventilation stack of 2 units of Mochovce NPP based on capacity of the NPPs (EC, 2014).

3.5.1.2. Aquatic Discharges

Based on the most conservative method, i.e. no dilution method, for aquatic releases, the concentration of radionuclide in the water body (for example; river) independent from its type is estimated according to below equation (IAEA, 2001):

$$C_{w,tot} = C_0 = \frac{Q_i}{F} \qquad (24)$$

where,

$C_{w,tot}$: Total radionuclide concentration (Bq/m^3)
C_0: Radionuclide concentration in the discharge outfall (Bq/m^3)
Q_i: Annual average discharge rate of radionuclide i (Bq/s)
F: Flow rate of the liquid discharge (m^3/s)

It is indicated also that this equation can be used to estimate sedimentation concentrations and concentrations in aquatic foods and subsequent critical group doses. If the estimated doses by screening method exceed the dose criterion, generic environmental model taking the dilution into account based on the type of the water body should be used as explained before.

Screening dose calculation factors for aquatic discharges regarding no dilution method are presented in Table I-II of SRS 19 document of IAEA (2001). Doses due to aquatic releases are estimated by multiplying the screening factor with the undiluted annual average concentration of the radionuclide (C_0) by using Equation (24).

Flow rate of liquid discharge is assumed as 0.05 m^3/s from the liquid discharge rate of Bohunice V2 NPP (Unit 3 & Unit 4) based on the capacity of the NPPs (Slovenské Elektrárne, 2016).

3.5.2. General Environmental Screening Methodology

3.5.2.1. Atmospheric Dispersion

The receptor (public) is assumed to be where the release height is greater than 2.5 times of the building height; i.e. there is no building effect on the release, as indicated in SRS 19 document of IAEA (2001). Single wind direction to estimate each air concentration, single long-term average speed of wind and neutral atmospheric stability class of D are assumed in this method. Therefore, the equation given below is suggested by the document to be used for concentration estimation for atmospheric releases where there is no building effect:

$$C_A = \frac{P_p F Q_i}{u_a} \qquad (25)$$

where,

C_A: Ground level air concentration of radionuclide at the downwind distance x in sector p (Bq/m^3),

P_p: Wind blow time fraction towards the receptor during the year in sector p,

u_a: Geometric mean of wind speed representative of one year at the release height (m/s)

F: Gaussian diffusion factor for release height and downwind distance x (m^{-2})

Q_i: Annual average discharge rate of radionuclide i (Bq/s)

Also, it is explained in the document that F is a function of downwind distance x based on different values of H, which is provided in Table I of the document (IAEA, 2001).

F is derived by the equation below using 30° sector averaged for gauss plume model where σ_z is diffusion parameter in vertical (m):

$$F = \frac{12}{\sqrt{2}\pi^3} \times \frac{\exp[-(H^2/2\sigma_z^2)]}{x\sigma_z} \qquad (26)$$

These are valid for terrain covered with pasture, forest and small villages; i.e. relatively flat terrain. The dispersion factor F in Equation (26) is provided in Table 3.2 based on height and distance of the receptor (IAEA, 2001).

Table 3.2. *The dispersion factor F (m-2) for atmospheric releases in generic environmental model (IAEA, 2001)*

Downwind Distance x (m)	**Release Height, H (m)**						
	0-5	**6-15**	**16-25**	**26-35**	**36-45**	**46-80**	**>80**
100	$3*10^{-3}$	$2*10^{-3}$	$2*10^{-4}$	$8*10^{-5}$	$3*10^{-5}$	$2*10^{-5}$	$1*10^{-5}$
200	$7*10^{-4}$	$6*10^{-4}$	$2*10^{-4}$	$8*10^{-5}$	$3*10^{-5}$	$2*10^{-5}$	$1*10^{-5}$
400	$2*10^{-4}$	$2*10^{-4}$	$1*10^{-4}$	$8*10^{-5}$	$3*10^{-5}$	$2*10^{-5}$	$1*10^{-5}$
800	$6*10^{-5}$	$6*10^{-5}$	$5*10^{-5}$	$4*10^{-5}$	$3*10^{-5}$	$2*10^{-5}$	$1*10^{-5}$
1,000	$4*10^{-5}$	$4*10^{-5}$	$4*10^{-5}$	$3*10^{-5}$	$3*10^{-5}$	$1*10^{-5}$	$1*10^{-5}$
2,000	$1*10^{-5}$	$1*10^{-5}$	$1*10^{-5}$	$1*10^{-5}$	$1*10^{-5}$	$4*10^{-6}$	$5*10^{-6}$
4,000	$4*10^{-6}$	$4*10^{-6}$	$4*10^{-6}$	$4*10^{-6}$	$4*10^{-6}$	$1*10^{-6}$	$2*10^{-6}$
8,000	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$3*10^{-7}$	$5*10^{-7}$
10,000	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$1*10^{-6}$	$2*10^{-7}$	$3*10^{-7}$
15,000	$5*10^{-7}$	$5*10^{-7}$	$5*10^{-7}$	$5*10^{-7}$	$5*10^{-7}$	$1*10^{-7}$	$1*10^{-7}$
20,000	$4*10^{-7}$	$4*10^{-7}$	$4*10^{-7}$	$4*10^{-7}$	$3*10^{-7}$	$6*10^{-8}$	$9*10^{-8}$

Dose calculation factors for atmospheric releases in generic environmental model is provided in the document (IAEA, 2001) in Table I-III. After calculating the concentrations by Equation (25), concentrations are multiplied with the related dose calculation factors to estimate doses for atmospheric releases (IAEA, 2001).

Plume is under removal process once it is released into the air which are radioactive decay, dry deposition and wet deposition. According to the document (IAEA), activity correction of plume for very short distance is neglected except for radionuclides having very short half-life. The calculated air concentration can be corrected for the distances where plume correction is necessary by multiplying the concentration with the reduction factor f, of which the equation is provided below:

$$f = \exp\left(-\lambda_i \frac{x}{u_a}\right) \qquad (27)$$

λ_i represents the constant for radioactive decay of radionuclide i (s^{-1}) and the values for this constant are presented in the Annex II of the document (IAEA, 2001).

In generic environmental model, ground deposition rate is suggested to be calculated by the document with the equation provided below (IAEA, 2001):

$$d_i = (V_d + V_w)C_A \qquad (28)$$

where,

d_i: Total daily average ground deposition rate for radionuclide i due to both dry and wet deposition including either on to impervious surface or on to vegetation and soil (Bq m^{-2} d^{-1})
V_d: Dry deposition coefficient for radionuclide i (m/d),
V_w: Wet deposition coefficient for radionuclide i (m/d).

In the document, it is suggested for generic model that 1000 m/d total deposition coefficient, summation of the dry and wet deposition coefficients, can be used and 0 m/d values for ^{3}H and ^{14}C and non-reactive gases like Krypton (IAEA, 2001).

It is indicated in the document that resuspension of deposited radionuclides due to man-made activities is localized and affects a few person and resuspension due to wind driven is found to be minor exposure pathway for routine releases of radionuclides to the atmosphere. Wind driven resuspension is only important for non-continuous releases. Therefore, resuspension of deposited radionuclides is not taken into account in generic model (IAEA, 2001).

Annual effective dose due to immersion to atmospheric release E_{im} (Sv/a) can be estimated by using the equation provided below (IAEA, 2001):

$$E_{im} = C_A DF_{im} Q_f \qquad (29)$$

where,

C_A: Annual average concentration of radionuclide i in the air, as calculated with Equation (25) in this thesis (Bq/m^3),
DF_{im}: Effective dose coefficient for immersion (Sv/a per Bq/m), values for selected radionuclides are given in Table XV of the document of IAEA (2001),
Q_f: Fraction of the year for which critical group member is exposed to radiation due to this exposure pathway, values for screening purposes are provided in Table XIV of the document of IAEA (2001).

The annual skin dose can be estimated with using dose coefficients given for skin in Table XV of the document of IAEA (2001):

$$E_{im,s} = C_A DF_s Q_f \qquad (30)$$

where,

$E_{im,s}$: Annual skin dose due to β irradiation (Sv/a),
DF_s: Skin dose due to β irradiation per unit air concentration (Sv/a per Bq/m^3), values for coefficients are given in Table XV of the document of IAEA (2001).

Annual effective dose due to ground deposition E_{gr} (Sv/a) can be estimated with the equation given below (IAEA, 2001):

$$E_{gr} = C_{gr} DF_{gr} Q_f \qquad (31)$$

where,

DF_{gr}: Dose coefficient for exposure to ground deposition (Sv/a per Bq/m^2), values for selected radionuclides are given in Table XV of the document of IAEA (2001),
C_{gr}: Deposition density for radionuclide i (Bq/m^2), which is calculated from the equation below (IAEA, 2001):

$$C_{gr} = \frac{d_i\left[1 - \exp(-\lambda_{E_i^s} t_b)\right]}{\lambda_{E_i^s}} \quad (32)$$

where,

d_i: Rate for total ground deposition ($Bqm^{-2}d^{-1}$),
$\lambda_{E_i^s}$: Effective rate constant to reduce the activity of the soil from top 10-20 cm of it (d^{-1}), where $\lambda_{E_i^s}=\lambda_i+\lambda_s$, values for λ_i are given in Annex II of the document of IAEA (2001),
λ_s: Rate constant for reduction of soil activity due to processes other than radioactive decay, default values for it are provided in Table X of the document of IAEA (2001),
t_b: Duration of release of the radionuclide (d), default values for it are provided in Table VIII of the document of IAEA (2001).

Dose coefficients to estimate effective dose due to unit deposition onto the ground for several radionuclides are provided in Table XV of the document of IAEA (2001).

Annual effective dose due to inhalation E_{inh} (Sv/a) can be estimated from the equation provided below (IAEA, 2001):

$$E_{inh} = C_A R_{inh} DF_{inh} \qquad (33)$$

where,

C_A: Radionuclide concentration in the air (Bq/m^3),
R_{inh}: Inhalation rate, default values for adults and 1-2 years old infants, given in Table XIV of the document of IAEA (2001), (m^3/a),
DF_{inh}: Inhalation dose coefficient, given in Table XVI of the document of IAEA (2001), (Sv/Bq).

Ingestion doses for adults and infants can be estimated from the equation below (IAEA, 2001):

$$E_{ing,p} = C_{p,i} H_p DF_{ing} \qquad (34)$$

where,

$E_{ing,p}$: Annual effective dose due to consumption of radionuclide i in food p (Sv/a),

$C_{p,i}$: Concentration in food for radionuclide i at the time of consumption (Bq/kg),

H_p: Consumption rate of food p (kg/a),

DF_{ing}: Dose coefficient for ingestion of radionuclide i (Sv/ Bq).

Default intake rates and dosimetric data are provided in Table XIV, Table XVII and XVIII of the document of IAEA (2001).

Doses due to drinking water can be estimated with the equation given for ingestion, however, H_p will be drinking water intake rate and C_p will be the radionuclide concentration in drinking water (IAEA, 2001).

For detailed environmental model, example calculations provided in Annex IV of SRS 19 document of IAEA are used to estimate concentrations and doses due to atmospheric releases including the transport in terrestrial food chain. Besides, doses due to tritium and C-14 are estimated from the equations given in Annex III of IAEA SRS 19 document (IAEA, 2001).

3.5.2.2. Aquatic Dispersion

River width B (m), longitudinal distances from release point to the receptor point x (m) and radioactive decay constant for radionuclide i λ_i (s^{-1}) are the basic river characteristics required for general environmental model for aquatic discharges as indicated in the document. Moreover, 30-year low annual flow rate q_r (m^3/s), flow depth D (m) corresponding to 30-year low annual flow rate, river velocity U (m/s) corresponding to flow depth are desirable site-specific values. If these values are not available, they can be estimated as provided in the document. q_r corresponding to river width can be obtained from Table III of the document and it can be assumed that 30-year low annual flow rate of river is 1/3 of the mean annual flow rate of the river for default calculation. Then, river width and the river depth corresponding to 30-year low annual flow rate of the river can be obtained from Table III of the document. (IAEA, 2001).

If the water usage from the river is opposite side of the river from radionuclide discharge point, the recommended equation given below is used for total concentration of radionuclide in river water (IAEA, 2001):

$$C_{w,tot} = \frac{Q_i}{q_r} \exp\left(-\frac{\lambda_i x}{U}\right) = C_t \qquad (35)$$

where,

$C_{w,tot}$: Total radionuclide concentration in river water (Bq/m^3),
Q_i: Average discharge rate of radionuclide I (Bq/s),
Q_r: Mean flow rate of river (m^3/s),
λ_i: Radioactive decay constant (s^{-1}),
x: Distance between discharge point and the individual/receptor (m),
U: Net freshwater velocity (m/s).

U can be calculated by the equation given below:

$$U = \frac{q_r}{BD} \qquad (36)$$

λ_i values are given in Annex II of SRS 19 document of IAEA as mentioned previously. For this case, radionuclide traverses at least half of the width of the river to reach the opposite bank to the discharge point. Moreover, maximum concentration of radionuclide is the cross-sectional averaged concentration.

It is recommended in the document to calculate sediment effects only the exposure to sediment is available (IAEA, 2001). Moreover, it is mentioned in the document that the suspended sediment is removed from surface water in the water treatment facility when the surface water is used for drinking purpose. Therefore, sediment effect is not considered in this thesis.

If the radionuclides are discharged to sewerage system, it is assumed that no radionuclide is retained in the sludge of the sewage, all discharged in liquid form to the river/water body and all radionuclide is retained in the sludge of sewage at the wastewater treatment plant. For the first assumption, radionuclide concentration can be calculated as in surface water. For second assumption, it can be assumed that complete transfer of discharged activity to the sludge occurs (IAEA, 2001). The sludge of sewage and related concentration for radionuclides in the sewage sludge is out of the scope of this thesis as it retains in the border of Armenia whether it is discharged to the sewage from NPP.

For detailed environmental model, example calculations provided in Annex IV of SRS 19 document of IAEA are used for the estimation of concentrations and doses due to aquatic releases including the transport in terrestrial food chain. Moreover, doses due to tritium and C-14 are estimated from the equations given in Annex III of IAEA SRS 19 document (IAEA, 2001).

3.5.2.3. Terrestrial Food Chain

In general environmental model methodology, dose contribution due to ingestion can be important from terrestrial food chain in total received doses and so concentrations in human foods need to be calculated. In this methodology, radionuclide concentration in food crops C_v (Bq/kg), in milk C_m (Bq/L) and in meat C_f (Bq/kg) due to either air concentration C_A (Bq/m^3) or ground deposition rate d_i (Bq m^{-2} d^{-1}) or water concentration C_w (Bq/m^3) are considered for calculations. Therefore, dry or wet deposition, interception and retention by vegetation from surface of it, translocation of radionuclides to edible parts of the vegetation, post-deposition retention by vegetation and soil, uptake of radionuclides from the root of vegetation, adhesion of soil onto vegetation, inadvertent ingestion of soil by human/ grazing animals, transfer of radioisotopes to air, soil, water, vegetation, milk and meat of animals are the processes included in this methodology (IAEA, 2001).

Concentration due to direct contamination in and on the vegetation due to radionuclide i can be calculated by equation provided below (IAEA, 2001):

$$C_{v,i,1} = \frac{d_i \alpha \left[1 - \exp(-\lambda_{E_i^v} t_e)\right]}{\lambda_{E_i^v}} \qquad (37)$$

where,

$C_{v,i,1}$: Measured in Bq/kg dry matter vegetation that is consumed by grazing animals and in Bq/kg fresh matter vegetation that is consumed by humans,

d_i: Deposition rate of radionuclide i on the ground due to wet and dry deposition ($Bqm^{-2}d^{-1}$),

α: Fraction of deposited radionuclide activity intercepted by edible portion of vegetation per unit mass due to wet and dry deposition; for pasture the unit of mass is in dry weight and for fresh vegetables the unit is in wet weight,

$\lambda_{E_i^v}$: Effective rate constant for reduction of radionuclide i activity concentration to crops (d^{-1}), where $\lambda_{E_i^v} = \lambda_i + \lambda_w$,

λ_i: Radioactive decay rate constant for radionuclide i (d^{-1}),

λ_w: Rate constant for reduction of radionuclide concentration deposited onto plant surfaces due to processes other than radioactive decay (d^{-1}),

t_e: Time period for crops exposure to contamination during growth period (d).

Vegetation radionuclide activity concentration due to indirect processes such as uptake from soil and adhesion of radionuclides to the vegetation from soil can be calculated from the equation given below (IAEA, 2001):

$$C_{v,i,2} = F_v \times C_{s,i} \qquad (38)$$

where,

$C_{v,i,2}$: Measured in Bq/kg dry matter vegetation that is consumed by grazing animals and in Bq/kg fresh matter vegetation that is consumed by humans,

F_v: Radionuclide concentration factor for uptake of it from soil through edible parts of crops (Bq/kg plant tissue per Bq/kg dry soil),

$C_{s,i}$: Radionuclide i concentration in dry soil (Bq/kg) and defined by the below equation (IAEA, 2001):

$$C_{s,i} = \frac{d_i \left[1 - \exp(-\lambda_{E_i^s} t_b)\right]}{\rho \lambda_{E_i^s}} \qquad (39)$$

where,

$\lambda_{E_i^s}$: Effective rate reduction constant for radionuclide activity concentration in the root area of soils (d) where $\lambda_{E_i^s} = \lambda_i + \lambda_s$,

λ_s: Rate constant for reduction of radionuclide concentration deposited in the root area of soils due to processes other than radioactive decay (d^{-1}),

t_b: Duration of discharge of radionuclide (d),

ρ: Standardized surface density for effective root area in soil (kg/m^2, dry soil).

Equation (38) represents total deposit and does not consider the amount absorbed to the vegetation. Total radionuclide concentration on the vegetation during consumption can be calculated from the equation provided below (IAEA, 2001):

$$C_{v,i} = \left(C_{v,i,1} + C_{v,i,2}\right) \exp(-\lambda_i t_h) \qquad (40)$$

where,

$C_{v,i}$: Measured in Bq/kg dry matter vegetation that is consumed by grazing animals and in Bq/kg fresh matter vegetation that is consumed by humans,

λ_i: Radioactive decay rate constant for radionuclide i (d^{-1}),

t_h: Delay time representing time interval between harvest and the consumption for food (d).

Default mass interception fractions for plants and food crops are provided in Table VI of the document of IAEA (2001) which include the translocation effect of radionuclides from foliage to edible part of the vegetation. Moreover, default values to estimate the radionuclide removal from vegetation based on a half-life of 14 days are given in Table VII of the document of IAEA. Besides, default values for crop exposure period, time period between harvest and consumption of crop and the period for soil exposure during operation of NPP are provided in Table VIII of SRS 19 document of IAEA (2001).

In general environmental model, it is assumed in the SRS 19 document of IAEA that total deposition of radionuclides reaches to the soil surface irrespective of the canopy cover and subsequent vegetation harvesting. Besides, t_b is assumed as 30 years for deposition onto soil. Moreover, default values for surface soil densities ρ (kg/m^2) are provided in Table IX of the document of IAEA (2001). Incorporation of radionuclides especially cesium and strontium into soil is important due to root uptake of vegetation and removal of them by harvesting/ consumption. These processes are considered in generic environmental model with loss rate constant λ_s (d^{-1}). For anions like Cl^{-1}, I^{-1} and TcO_4^{-1} default value for loss rate constant is 0.5 a^{-1} which is 0.0014 d^{-1} whereas default value for strontium and cesium is 0.05 a^{-1} which is 0.00014 d^{-1}. Default values for other radionuclides regarding loss rate constant is zero as indicated in Table X of the document (IAEA, 2001).

Soil adhesion is considered with uptake in generic environmental model by the concentration ratio F_v (Bq/kg vegetation per Bq/kg dry weight of soil). Values for it are provided in Table XI of the document for forage as $F_{v,1}$ (dry weight), crops as $F_{v,2}$ (fresh weight), milk as F_m (d/L), and meat as F_f (d/kg).

In generic environmental model, concentration in animal feed due to radionuclide i can be calculated with the below equation (IAEA, 2001):

$$C_{a,i} = f_p C_{v,i} + (1 - f_p) C_{p,i} \qquad (41)$$

where,

$C_{a,i}$: Concentration of radionuclide i in animal feed (Bq/kg dry weight),

$C_{v,i}$: Concentration of radionuclide i for pasture (Bq/kg dry weight), calculated using Equations (9) – (12) with t_h=0,

$C_{p,i}$: Concentration of radionuclide i in feeds which are stored (Bq/kg dry weight) , calculated using Equations (36) – (39) and t_h=90 d,

f_p: Fraction of the year for fresh pasture vegetation consumption of animals (dimensionless).

Radionuclide intake by animals depends on the specie of the animal, mass of animal, age of animal, growth rate of animal, feed digestibility and milk yield. In generic environmental model, grazing animals are assumed as cattle which is on a diet of only fresh pasture. Radionuclide sources regarding intake by animals are fresh or stored feed and drinking water. Default values F_v (soil-plant uptake factor) regarding pasture and water consumption for generic milk and meat producing animals are provided in Table XII of the document of IAEA (2001). Uptake factors from feed to animal milk (F_m) and meat (F_f) are given in Table XI of the document of IAEA (2001).

Radionuclide concentration in milk is directly related with the radioactivity concentration in the feed consumed by animal. The concentration of radionuclide i in milk can be estimated with the below equation (IAEA, 2001):

$$C_{m,i} = F_m \left(C_{a,i}Q_m + C_{w,i}Q_w\right) exp\,(-\lambda_i t_m) \quad (42)$$

where,

$C_{m,i}$: Concentration of radionuclide i in milk (Bq/L),

F_m: Fraction of daily intake of radionuclide i of the animal in each liter of milk at equilibrium (d/L) as given in Table XI of the document of IAEA (2001),

$C_{a,i}$: Concentration in animal feed of radionuclide i (Bq/kg dry weight),

$C_{w,i}$: Concentration in water of radionuclide i (Bq/m^3),

Q_m: Daily feed consumption amount of animal (kg/day) as given in Table XII of the document of IAEA (2001),

Q_w: Daily water consumption amount of animal (m^3/day) as given in Table XII of the document of IAEA (2001),
λ_i: Radioactive decay rate constant for radionuclide i (d^{-1}),
t_m: Average time between milk collection and consumption of it by human, assumed to be 1 day for fresh milk as given in Table VIII of the document of IAEA (2001).

The radionuclide concentration in meat can be calculated with the equation given below (IAEA, 2001):

$$C_{f,i} = F_m \left(C_{a,i}Q_f + C_{w,i}Q_w\right) exp\left(-\lambda_i t_f\right) \quad (43)$$

where,

$C_{f,i}$: Concentration of radionuclide i in flesh of animal (Bq/kg),
F_f: Fraction of daily intake of radionuclide i of the animal in each kg of flesh at equilibrium or at the slaughter time (d/kg) as given in Table XI of the document of IAEA (2001),
$C_{a,i}$: Concentration in animal feed of radionuclide i (Bq/kg dry weight),
$C_{w,i}$: Concentration in water of radionuclide i (Bq/m^3),
Q_f: Daily feed consumption amount of animal (kg/day) as given in Table XII of the document of IAEA (2001),
Q_w: Daily water consumption amount of animal (m^3/day) as given in Table XII of the document of IAEA (2001),
λ_i: Radioactive decay rate constant for radionuclide i (d^{-1}),
t_f: Average time between slaughter of meat and consumption of it by human, default value is 20 days as given in Table VIII of the document of IAEA (2001).

Transport of radionuclides to aquatic foods due to liquid charges can be calculated with the equation given below (IAEA, 2001):

$$C_{af,i} = C_{w,i}B_p/1000 \quad (44)$$

where,

$C_{af,i}$: Concentration in aquatic food p for radionuclide I (Bq/kg),

$C_{w,i}$: Concentration in water for dissolved radionuclide I (Bq/m^3),

B_p: Equilibrium ratio of concentration in aquatic food for radionuclide i to its dissolved concentration in water, which is known as bioaccumulation factor (Bqkg^{-1}/BqL^{-1}, or L/kg), default values for generic calculations are provided in Table XIII of the document of IAEA,

1000: Conversion factor of m^3 to L (IAEA, 2001).

3.6. Release & Discharge Data of MNPP

It is important to indicate that direct discharge to Aras River from Metsamor NPP and usage of this water for any purpose from public of Province of Iğdır are not present. As can be seen from Google Maps as given Figure 3.7, there is no direct discharge of radionuclides to River of Aras, which passes between the borders of Turkey and Armenia. It should be taken into account that passage of public to the river is restricted with the fence controlled by Turkish Armies. Besides, the water of Aras River is shared between Turkey and Armenia by joint Serdarabat Regulator equally for irrigation purposes based on “Protocol on the Beneficial Uses of Boundary Waters” (Punsmann, 2010). As provided in Chapter 2.4, liquid discharges from MNPP are given to Sev Jur River after being treated in the purification facility located 5.5 km away from NPP. However, the treatment level of direct discharge of contaminated water from the plant (treatment in terms of radioactivity like storage, sedimentation and waiting for decay of radionuclides etc.) and the exact location of discharge of the treated water to Sev Jur River and the branches of this river whether it connects to Aras River or not are not known. Therefore, the contribution due to aquatic pathway will be examined in this thesis both for PC CREAM and IAEA SRS 19 approach assuming that the discharged radionuclides reach to Aras River and affect the public living in Mürşitali and Aşağıalican, from where Aras River passes. For this process, simple screening river model will be used for PC CREAM 08 software as explained in Chapter 3.2.3 because of having limited information for Sev Jur River (including its location, connection point to Aras River, depth and width of it etc.).

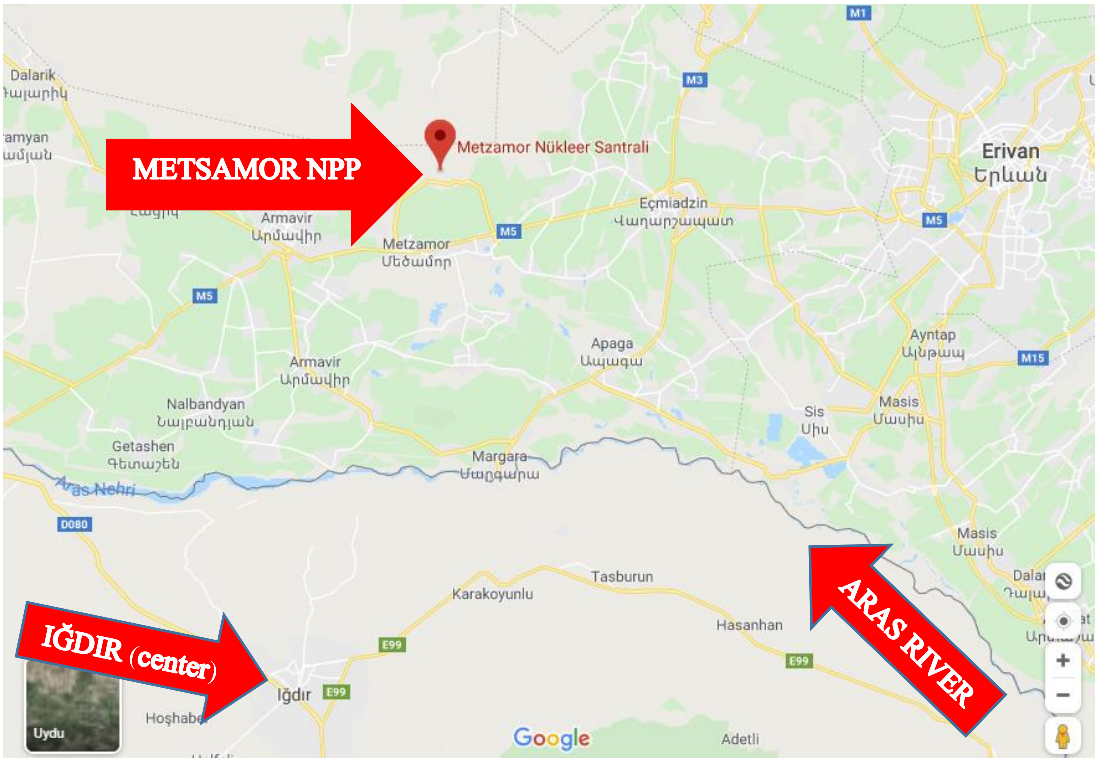

Figure 3.7. Location of Metsamor NPP, Province of Iğdır(center) and the water bodies around it and its connection to Aras River on Google Maps

In the national report of Armenia under CNS for 2007, percentile distribution of radionuclides for atmospheric releases, total radioactivity rate for atmospheric releases (including inert gases) in 2006 and total radioactivity rate for aquatic discharge as "Cs+Sr" are given. Both atmospheric release and aquatic discharge rate data for 2006 are calculated and are summarized in Table 3.3 (Armenia, 2007).

Table 3.3. *Release and Discharge data in National Report of Armenia under CNS (Armenia, 2007)*

Radionuclide in Atmospheric Release	**Release Rate (Bq/y)**	**Radionuclide in Aquatic Discharge**	**Discharge Rate (Bq/y)**
Co-60	8.57E+07	Cs+Sr	1.184E+9
Cs-134	2.28E+06		
Cs-137	4.64E+07		
Fe-59	6.27E+06		
Sr-90	2.85E+05		
Ag-110m	1.62E+07		

Radionuclide in Atmospheric Release	Release Rate (Bq/y)	Radionuclide in Aquatic Discharge	Discharge Rate (Bq/y)
I-131	3.31E+07		
Inert Gas	27.00E+12		

The distribution of the inert gases in the release and radioisotopes of Cs and Sr in the aquatic discharge, as given in Table 3.3, was not indicated in the CNS report of the Armenia. Therefore, other radionuclides and the percentile distribution of inert gases and Cs+Sr data for aquatic discharge were aimed to be completed from similar VVER-440 type NPP. For this aim, VVER-440 NPPs were examined. It was found that MNPP was a VVER-440 V230 design before having some modifications to upgrade seismic resistance. After these modifications, it has become V270 design. Thus, Bohunice NPP, VVER-440 V230design, was selected to complete the remaining data of MNPP. The release and discharge rate data of Bohunice NPP (2004-2008) can be found in EC Radiation Protection 164 (Van der Stricht and Janssens, 2010).

During data completion process, the capacity of both NPPs and the closeness of the Bohunice NPP data to the available data (MNPP) were taken into account. When the data of Bohunice (2004-2008) was examined, the data belonging to year of 2004 was found as the representative data to complete the data of MNPP. During 2004, 4 units of Bohunice was in operation and the capacity of the 4 units was 408 MW whereas the capacity was 376 MW for MNPP in 2006 (IAEA, 2019b).

To observe the effect of the radionuclides in the release and the discharge on the public doses, two data sets as Scenario 1 (CNS data completed with EC Radiation Protection 164 report data (Van der Stricht and Janssens, 2010)) and Scenario 2 (Only CNS data with percentile distribution of Bohunice NPP for inert gases and Cs+Sr aquatic discharge) were formed. The data sets to be used to model radiological impacts of Metsamor NPP in both PC CREAM software and SRS approach provided in IAEA document are presented in Table 3.4.

Table 3.4. *Release and discharge data for Scenario 1 (CNS data completed with data of EC Radiation Protection 164 (Van der Stricht and Janssens, 2010)) and Scenario 2 (Only CNS data) (Armenia, 2007)*

Group	Radionuclide	Half-life	Scenario 1 Activity rate (Bq/yr)	Scenario 2 Activity rate (Bq/yr)
Atmospheric Releases				
Beta/Gamma Emitters	C-14	5730 a	5.14E+10	-
	H-3	4500 d	3.43E+11	-
	I-131	8.04 d	3.31E+07	3.31E+07
	Co-58	70.8 d	2.56E+06	-
	Co-60	5.3 a	8.57E+07	8.57E+07
	Cr-51	27.7 d	3.76E+06	-
	Fe-59	44.5 d	6.27E+06	6.27E+06
	Mn-54	312 d	9.40E+05	-
	Nb-95	35.1 d	1.73E+06	-
	Sr-89	50.5 d	5.09E+04	-
	Sr-90	29.1 a	2.85E+05	2.85E+05
	Zn-65	244 d	2.56E+05	-
	Zr-95	64.0 d	9.88E+05	-
	Ag-110m	250 d	1.62E+07	1.62E+07
	Ce-141	32.5 d	2.33E+05	-
	Ce-144	284 d	5.00E+05	-
	Cs-134	2.1 a	2.28E+06	2.28E+06
	Cs-137	30.0 a	4.64E+07	4.64E+07
	Sb-124	60.2 d	3.53E+05	-
	Co-57	272.1 d	5.35E+04	-
	Rh-106	30.1 s	1.66E+05	-
	Ru-103	39.3 d	5.69E+05	-
Noble Gases	Ar-41	1.8 h	5.85E+12	5.85E+12
	Kr-85	10.7 a	2.28E+11	2.28E+11
	Kr-85m	4.5 h	1.62E+11	1.62E+11
	Kr-87	1.27 h	9.74E+10	9.74E+10
	Kr-88	2.8 h	2.60E+11	2.60E+11

Group	Radionuclide	Half-life	Scenario 1 Activity rate (Bq/yr)	Scenario 2 Activity rate (Bq/yr)
	Xe-131m	11.8 d	4.76E+11	4.76E+11
	Xe-133	5.24 d	1.85E+13	1.85E+13
	Xe-133m	2.2 d	1.71E+11	1.71E+11
	Xe-135	9.14 h	1.13E+12	1.13E+12
	Xe-135m	15.3 m	5.01E+10	5.01E+10
	Xe-138	14.1 m	2.53E+10	2.53E+10
Alpha Emitters	Pu-238	87.7 a	2.44E+03	-
	Am-241	4.32E+2a	3.39E+03	-

Aquatic Discharges

Group	Radionuclide	Half-life	Scenario 1 Activity rate (Bq/yr)	Scenario 2 Activity rate (Bq/yr)
Beta/Gamma Emitters	H-3	4500 d	2.97E+12	-
	Cr-51	27.7 d	1.08E+06	-
	Mn-54	312 d	1.17E+06	-
	Fe-59	44.5 d	2.02E+05	-
	Co-58	70.8 d	1.09E+06	-
	Co-60	5.27 a	2.01E+06	-
	Zn-65	244 d	2.11E+05	-
	Sr-89	50.5 d	4.47E+07*	4.47E+07*
	Sr-90	29.1 a	3.05E+07*	3.05E+07*
	Zr-95	64.0 d	2.33E+05	-
	Nb-95	35.1 d	2.79E+05	-
	Ru-103	39.3 d	1.33E+05	-
	Ag-110m	250 d	2.53E+06	-
	Sb-124	60.2 d	3.78E+05	-
	I-131	8.04 d	4.31E+05	-
	Ce-141	32.5 d	1.28E+05	-
	Ce-144	284 d	4.03E+05	-
	Cs-134	2.06 a	1.81E+08*	1.81E+08*
	Cs-137	2.30E+6a	9.28E+08*	9.28E+08*

Group	Radionuclide	Half-life	Scenario 1 Activity rate (Bq/yr)	Scenario 2 Activity rate (Bq/yr)
	Co-57	272.1 d	4.70E+04	-
	Rh-106	30.1 s	1.18E+05	-
Alpha Emitters	Pu-238	87.7 a	1.06E+04	-
	Am-241	4.32E+2a	1.00E+04	-

*: "Cs+Sr" data of CNS (1.184 GBq/year) is partitioned based on the percentile distribution of EC Radiation Protection 164 data within the total activity of Cs-134, Cs-137, Sr-89 and Sr-90.

3.7. Meteorology and Terrain Data

The topography of Province of Iğdır and the region between MPP are relatively flat. Therefore, the meteorological data collected in Province of Iğdır was used in the analysis as it is the closest station in Province of Iğdır to Armenia and represents the meteorological conditions near the region.

The meteorological data of Province of Iğdır (2006-2007, 2016-2018) including long-term statistics taken from General Directorate of Meteorology (MGM) was processed and the related statistics are calculated using Microsoft Excel® with macro. The long-term meteorological statistics belonging to the period of 1941-2018 are compared with the calculated statistics of 5 years data of MGM (2006, 2007, 2016, 2017 and 2018). The year that best represents the long-term statistics was selected as meteorological year, which is 2018 (in terms of precipitation, humidity, air pressure, temperature, solar radiation, cloudiness and wind speed and direction).

PC CREAM 08 software requires the frequency of stability classes in wind sectors (A, B, C, D, E, F, C_{rain}, D_{rain}) and the mixing layer height as meteorological data. The criteria for Pasquill Stability Class is provided in Table 3.5. A class represents extremely unstable, B class represents moderately unstable, C class represents slight, D class represents neutral, E class represents slightly stable and F class represents moderately stable conditions in Pasquill Stability Classes (NOAA, 2018). For daytime insolation, Strong is >700 W/m^2, Moderate is 350-700 W/m^2 and slight is <350 W/m^2

(Seinfeld and Pandis, 2012). The required frequencies for Pasquill Stability classes were calculated from the wind speed, solar radiation and cloudiness data of 2018 by using the criteria given in Table 3.5. As PC CREAM 08 requires stability classes for C_{rain} and D_{rain}, these classes were calculated as well (Smith and Simmonds, 2009 ; Smith et al, 2009) and presented in Table 3.6. IAEA SRS 19 approach only requires wind blowing frequency to estimate air concentrations of radionuclides (IAEA, 2001).

Table 3.5. *Criteria for Pasquill Stability Classes (NOAA, 2018)*

Surface wind speed (m/s)	***Daytime insolation***			***Night-time conditions***	
	Strong	***Moderate***	***Slight***	***Thin overcast or >4/8 low cloud***	***<= 4/8 cloudiness***
<2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Table 3.6. *Calculated frequency of Pasquill Stability Classes for Province of Iğdır*

Stability Classes	***Frequency***
A	6.93E-02
B	4.08E-01
C	1.70E-02
D	8.78E-03
E	2.66E-01
F	2.27E-01
C_{rain}	3.01E-03
D_{rain}	5.78E-05

Data of upper atmosphere was taken from Province of Erzurum rawinsonde station as there is not any rawinsonde station of MGM in Province of Iğdır. According to the phone call made with Prof. Dr. Selahattin İncecik who is a meteorology engineer and give consultancies for the meteorological issues related to NPPs in Turkey, the upper atmospheric meteorology data measured in Province of Erzurum, which is the closest place that the related measurement is done by MGM, can be used for Province of Iğdır to derive statistics for mixing layer height. Also, with this phone call, usage of meteorological data for Metsamor NPP was verified that meteorology data belonging to Province of Iğdır can be used in the analysis as the topography of the region is relatively flat and there is not any closer meteorology station to MNPP other than Province of Iğdır (İncecik, 2019).

Besides, PC CREAM 08 software requires the selection of terrain property to estimate wind speed at source height, which is presented in Table 3.7 (Smith and Simmonds, 2009). Agricultural area was selected in the analysis as agricultural activity is very common in Province of Iğdır.

Table 3.7. *Terrain feature to estimate wind speed at source height (Smith and Simmonds, 2009)*

Terrain	**Roughness Length z_0 (m)**	**n**
Sea, very short grass	0.01	0.14
Open grassland	0.04	0.17
Low lying crops (i.e. root crops)	0.1	0.20
Agricultural areas	0.3	0.26
Parks, open suburbia	0.4	0.28
Cities, wood lands	1 o 4	0.39-1.1

3.8. Soil Input Data

PC CREAM 08 software considers the deposition of radionuclides released from NPP with GRANIS model as mentioned earlier. It requires the selection of soil model either undisturbed or well mixed. For each soil model, generic dry or wet soil property is required to be selected for pre-determined soil depth. Moreover, elemental percentage data of the generic wet or dry soil can be entered if available. Besides, new material data present in the soil can be added to the model (Smith et al, 2009).

The property of soil in Province of Iğdır is given as azonal soil by Provincial Directorate of Agriculture and Forestry (TOB, 2019). However, the property of soil according to depth could not be obtained. Therefore, default data of PC CREAM software was used in the analysis.

3.9. Production of Agricultural and Animal Products Data

The agricultural products produced in Province of Iğdır was taken from Turkish Statistics Authority (TÜİK) (TÜİK, 2019). The agricultural products produced in greenhouses were not considered as they are closed places to plat a plant, the air circulation is very low, and they are less affected by the air flow when it is compared to the open agricultural areas.

According to the data of TÜİK, green beans, cabbage, cauliflower, broccoli, curly lettuce, lettuce, iceberg lettuce, spinach, parsley, rucola, pepperwort, mint, dill, bel pepper, green pepper, cucumber, gherkin, marrow, pumpkin, shallot and leek are produced as green vegetables in Province of Iğdır. Moreover, grain except durum grain, corn, barley and paddy are produced as grain. Besides, grapes, apple golden, apple starking, apple Amasya, apple granny smith, pear, apricot, cherry, sour cherry, peach, nectarine, plum, oleastro, mulberry, walnut, watermelon, melon and tomatoes are cultivated as fruit. In addition to these, carrot, garlic, onion, radish, peanut, potatoes and sugar beet are produced as root vegetables.

PC CREAM 08 software requires production rate (kg/km^2) for green vegetables, grain, pasture, potatoes, fruit, root vegetables. The data (both the production and the cultivated area) of 2006 (as release data belongs to 2006 according to CNS report of Armenia (Armenia, 2007)) and the long-term data (2004-2017) were processed and compared. The production data of 2006 represents the long-term data that it was used to calculate the production rate required by the software (Table 3.8). Moreover, the pasture data was taken from the review study of Topçu and Özkan (2017) for Eastern Anatolia Region of Turkey. It was assumed that the pasture data of province of Iğdır is similar with the data of Eastern Anatolia Region of Turkey, which is provided in Table 3.8 with the previously mentioned agricultural production rate kg/km^2.

Table 3.8. *Agricultural production and pasture yield data of Province of Iğdır (kg/km^2)*

Green Vegetables	Grain	Potatoes	Fruit	Root Vegetables	Pasture
2,489,890	222,315	2,571,429	2,125,718	3,970,994	345,000*

*: dry fodder

PC CREAM requires data regarding animal products (milk and carcass meat) produced in province of Iğdır, which was taken from TÜİK website (2018) and processed for analysis. The average carcass data belonging to 2018 is presented in Table 3.9 as carcass data is available only for the period of 2010-2018 in TÜİK website. However, milk data for 2006 is available and it is presented in Table 3.9.

PC CREAM software also requires data for cattle and sheep. However, the software doesn't consider the barndoor fowl (chicken etc. as these animals are kept in generally closed/semi closed places). Moreover, weight of the liver for cattle for simple model and complex model in PC CREAM 08 software is 6 kg and for sheep is 0.8 kg and 1.0 kg respectively (Smith and Simmonds, 2009).

Table 3.9. *Milk and carcass production data for Province of Iğdır*

Milk of Cattle (Lt/day)	Milk of Sheep (Lt/day)	Cattle Carcass (kg/year)	Sheep Carcass (kg/year)
120,816	44,030	9,100,646.2	30,469,121.26

3.10. Habits of the Public

Daily food consumption of public in Turkey that can be used in modelling for adult is provided in Table 3.10 according to different references (Ünver, 2014; UNSCEAR, 2000). The data marked as bold in Table 3.10 were used to calculate the food consumption rate (kg/year) as required by PC CREAM software for the analysis.

Table 3.10. *Daily Food Consumption Data of Turkey (kg/day/capita)*

Data	Grain	Milk	Green Vegetables	Potato	Root Vegetables	Meat
TÜİK (Ünver, 2014) Turkey	1.040	0.269	0.054	**0.200***	0.127	0.065
UNSCEAR (2000) Turkey	0.547	**0.343**	**0.274**	-	-	0.110
Survey (Ünver, 2014) Turkey	0.324	0.274	0.137	0.100	0.135	0.103
Survey (Ünver, 2014) Eastern Anatolia Region	**0.685**	0.107	0.135	0.132	**0.180**	**0.119**
Data	**Fruit**	**Fish**	**Butter**	**Cheese**	**Yogurt-Ayran**	
TÜİK (Ünver, 2014) Turkey	0.999	0.025	0.008	0.063	0.148	
UNSCEAR (2000) Turkey	0.411	-	-	-	-	
Survey (Ünver, 2014) Turkey	0.638	**0.036**	**0.025**	0.069	**0.154**	
Survey (Ünver, 2014) Eastern Anatolia Region	**1.085**	0.035	0.005	**0.071**	0.066	

*: data given in bold is the selected values as input to the modeling study for Province of Iğdır

PC CREAM software also requires inhalation rates and consumption rate of drinking water to estimate the doses of individuals. The default inhalation rates for average individuals and critical groups in the software, which are taken from ICRP, are provided in Table 3.11.

Table 3.11. *Inhalation rates for individuals and critical group (m^3/year) (Smith and Simmonds, 2009)*

Age	Inhalation rate (m^3/year)
Infant	1900
Child	5600
Adult	8100

The default drinking water consumption rates in the software are presented in Table 3.12. Besides, the default average and critical food consumption rates in the software are provided in Table 3.13 and in Table 3.14. Fish consumption ratios of child and infant are taken from Table 3.15 and calculated based on the adult fish consumption data given in Table 3.10.

Table 3.12. *Water consumption rates (m3/year) (Smith and Simmonds, 2009)*

Age	Water intake rate (m^3/year)
Infant	0.26
Child	0.35
Adult	0.60

Table 3.13. *The default average food ingestion rates (kg/year) (Smith and Simmonds, 2009)*

Food type	Adult	10 years old	1 year old
Cow liver	2.75	1.5	0.5
Cow meat	15	15	3
Cow milk	95	110	130
Cow milk products	20	15	15
Fruit	20	15	9
Grain	50	45	15
Green vegetables	35	15	5
Root vegetables	60	50	15
Sheep liver	2.75	1.5	0.5
Sheep meat	8	4	0.8

Table 3.14. *The default critical food ingestion rates (kg/year) (Smith and Simmonds, 2009)*

Food type	Adult	Child	Infant
Cow liver	10	5	2.75
Cow meat	45	30	10
Cow milk	240	240	320
Cow milk products	60	45	45
Fruit	75	50	35
Grain	100	75	30
Green vegetables	80	35	15
Root vegetables	130	95	45
Sheep liver	10	5	2.75
Sheep meat	25	10	3

Table 3.15. *Average and critical group aquatic food intake rates (kg/year) (Smith and Simmonds, 2009)*

	Average intake rate (kg/y)			Critical intake rate (kg/y)		
	Adult	**Child**	**Infant**	**Adult**	**Child**	**Infant**
Marine fish	15	6	3.5	100	20	5
Freshwater fish	1	0.7	0.3	20	5	1
Crustacea	1.75	1.25	-	20	5	-
Mollusca	1.75	1.25	-	20	5	-
Seaweed	-	-	-	-	-	-

Data of cow liver and sheep liver are directly taken from default critical data of PC CREAM software for adult, child and infant (Table 3.14). All data except cow liver and sheep liver for adult is available as provided in *Table 3.10*. The consumption rate data for infant and child are derived separately from default consumption rate data of the software based on the available data of adult consumption rate.

The default age groups in the software are 1-year old infant, 10 years old child, and 20 years old adult and the committed doses from intake of radionuclides into the body are estimated to age 70 (Smith and Simmonds, 2009). It is indicated in Smith and

Simmonds (2009) that there are no significant differences in dose estimations between other age groups; i.e. 5 years old child and 15 years old child and therefore it is sufficient to consider previously mentioned age groups in the dose estimation (Smith and Simmonds, 2009).

In IAEA SRS 19 approach, the default data regarding external exposure, inhalation and ingestion of adult and infant are provided in SRS 19 document of IAEA and presented in Table 3.16 (IAEA, 2001).

Table 3.16. *Default habit and consumption data for adult and infant in SRS 19 document of IAEA (IAEA, 2001)*

Type of exposure	Adult		Infant (1 year old)	
	Occupancy (h/year)	**Fraction O_f**	**Occupancy (h/year)**	**Fraction O_f**
External exposure				
Surface contaminated owing to air deposition	8760	1	8760	1
Working/playing over contaminated sediments	1600	0.18	1000	0.12
Submersion in air	8760	1	8760	1
Garden and ground exposure from irrigation	500	0.06	500	0.06
Inhalation	**Intake per person**			
Breathing rate (m^3/year)	8400		1400	
Ingestion				
Freshwater fish (kg/year)	30		15	
Marine fish (kg/year)	50		25	
Marine shellfish (kg/year)	15		0	
Water and beverages (m^3/year)	0.600		0.260	
Fruit, vegetables and grain, including potatoes (kg/year)	410		150	
Milk (L/year)	250		300	

Type of exposure	Adult		Infant (1 year old)	
	Occupancy (h/year)	Fraction O_f	Occupancy (h/year)	Fraction O_f
Meat (kg/year)	100		40	

3.11. Locations of the Public

The locations of the public (population centers) in the region of Province of Iğdır which is present within 30 km zone from MNPP are presented in Figure 3.8. Degree of the locations from MNPP was determined from North direction, which is taken as 0°, to clockwise direction and presented in Table 3.17 along with the distance to MNPP.

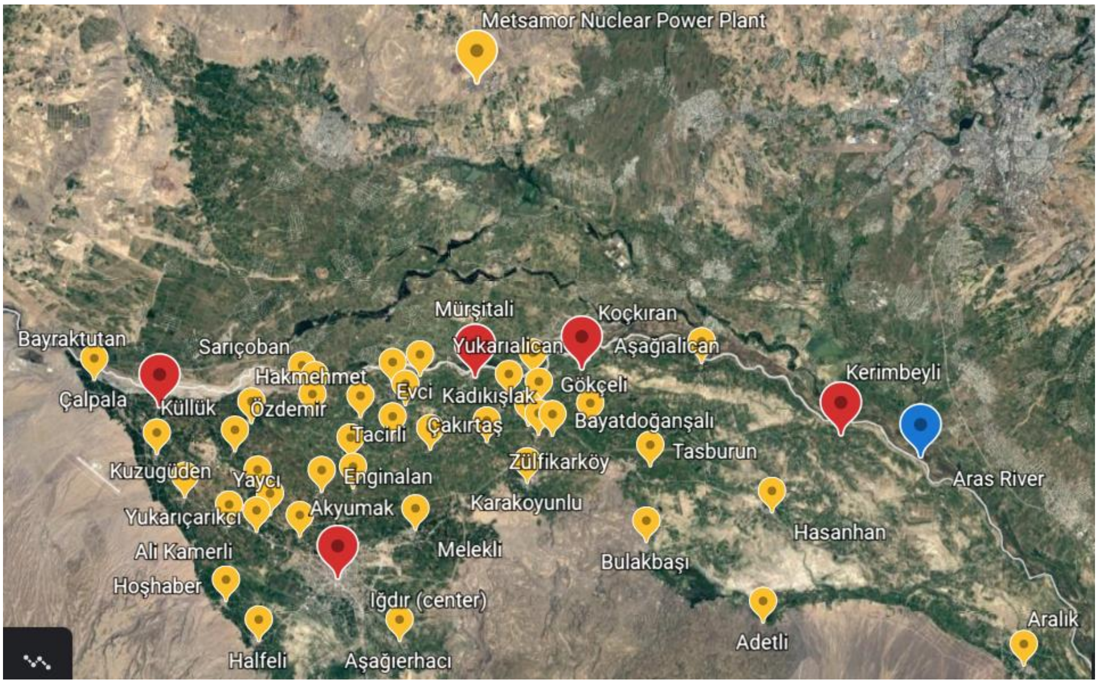

Figure 3.8: Population centers according to MNPP in Province of Iğdır with Google Earth

Table 3.17. *Distance and degree of population centers in Province of Iğdır within 30 km zone from MNPP*

Location Name	**Distance (km)**	**Degree of the location (°)**	**Location Name**	**Distance (km)**	**Degree of the location (°)**
Mürşitali	17.20	180	Karakoyunlu	23.70	175
Alican Border Gate	17.40	171	Hakmehmet	23.90	212
Kadıkışlak	17.50	189	Taşburun	24.20	153
Aşağıalican	17.90	157	Akyumak	24.80	195
Necefali	18.40	193	Enginalan	25.50	198
Yukarıalican	18.40	175	Kuzugüden	25.80	211
Çakırtaş	19.00	190	Melekli	26.40	187
Ortaalican	19.00	171	Bayraktutan	26.60	224
Şiracı	20.40	173	Kasımcan	27.20	204
Yüzbaşılar	20.70	197	Obaköy	28.00	203
Sarıçoban	20.70	206	Çalpala	28.40	231
Koçkıran	21.00	139	Hakveyiş	28.50	200
Zülfikarköy	21.00	179	Küllük	28.70	220
Gökçeli	21.00	172	Bulakbaşı	28.70	157
Kacerdoğanşalı	21.10	160	Alikamerli	29.30	204
Bayatdoğanşalı	21.20	170	Kerimbeyli	29.70	133
Evci	21.30	191	Yaycı	29.70	206
Tacirli	21.70	186	Yukarıçarıkçı	29.70	214
Kazancı	21.70	205	Iğdır center	30.00	194
Özdemir	23.20	196			

Among all the locations in that figure, 39 population locations which are within 30 km distance from MNPP are selected and presented in Figure 3.8 with red bullets. The selection criteria of the locations for dose analysis includes prevailing wind direction towards the region, population density, distance from MNPP, calculation range of the approach in SRS 19 (the approach is limited with 20 km distance as indicated in IAEA report (IAEA, 2001)) and locations in Environmental Radiological Monitoring

Program of Iğdır (30 km) (the details of this monitoring program are given in Chapter 3.13 of this study). The prevailing wind direction is mostly northern winds according to meteorological data of Iğdır. In the dispersion analysis, wind bringing radionuclides to the region of Province of Iğdır is important to estimate doses of the public living there, due to the scope of this thesis. Therefore, population locations present near the direction of WSW and W, having the higher wind blowing frequency other than northern directions, were considered. Moreover, locations within 20 km from MNPP were also determined to make analysis for the approach of SRS 19 and to compare its result with PC CREAM results. As most of the locations are close to each other, locations having high population were selected. Moreover, locations present in Environmental Radiological Monitoring Program of Iğdır was taken into account to allow to make comparison with the results of PC CREAM and IAEA SRS 19 approach. When all the criteria are intersected, Mürşitali, Aşağıalican, Bayraktutan, Kerimbeyli and center of Province of Iğdır (Iğdır center) are selected as locations for dose analysis as indicated with red bullets in Figure 3.8.

3.12. Diet of Animals

Feeding diet of animals (kg/day) in Eastern Anatolian Region of Turkey, where Province of Iğdır is located, is provided in Table 3.18 (Ünver, 2014). Also, parameters for animals in PC CREAM software are provided in Table 3.19 (Smith and Simmonds, 2009).

Table 3.18. *Feeding Diet of Animals in Eastern Anatolia Region of Turkey (kg/day) (Ünver, 2014)*

Feedstuff	**Silage**	**Pasture**	**Hay**	**Cons. Feeds**	**Maize silage**	**Pasture**	**Hay**	**Cons. Feeds**
Animal	**Winter**				**Summer**			
Lamb	-	5	-	0.5	-	5	-	0.5
Goat	-	5	-	0.5	-	5	-	0.5

Feedstuff	Silage	Pasture	Hay	Cons. Feeds	Maize silage	Pasture	Hay	Cons. Feeds
Animal	**Winter**				**Summer**			
Cow (400 kg))	-	25	-	7	-	15	10	7
Beef Cattle	-	17	-	5	-	10	6.7	5

Table 3.19. *Parameters for animals in PC CREAM software (Smith and Simmonds, 2009)*

Parameters	Cattle	Sheep
Amount eaten per day (kg dry wet/d)		
Pasture	13	1.5
Grain	-	-
Mean life (y)	6	1
Soil consumption as % of dry matter intake	4	20
Weight of muscle (kg)		
Simple model	230	18
Complex model	360	30
Weight of liver (kg)		
Simple model	6	0.8
Complex model	6	1.0
Milk production rate (Liters per day)	10	-
Number of animals per km^2	400	500
Inhalation rate m^3s^{-1}	1.5E-3	1.0E-4

3.13. Environmental Radiological Monitoring Program of TAEK

The environmental radiological monitoring program (EMP) is performed by TAEK in Province of Iğdır due to Metsamor NPP for several aims:

- To monitor whether the atmospheric release and aquatic discharge given to the environment from MNPP is under control,
- To make a comparison in order to determine how much the environment is affected incase a possible accident occurs in MNPP,
- To detect long-term radiological changes in environmental media in the region of Province of Iğdır,
- To estimate doses due to ingestion of drinking water under the scope of the Regulation on Waters for Humanitarian Consumption,
- To assess the investigation and alarm levels by controlling the results of the program (TAEK, 2017).

The monitoring radius for EMP is 30 km centered region from MNPP and several villages from Turkey are present in this region. In this program, sampling from agricultural products, milk, air, surface water, soil, terrestrial plants, feedstuff, sediment, aquatic plant are performed, and their related analysis are made in the accredited laboratories of TAEK. Besides, gamma dose rate is monitored by Thermoluminescence Dosimeter (TLD) within the scope of the program (TAEK, 2017).

The results belonging to 2013-2016 period of EMP are used in thesis. The median gamma dose rate values, which are measured continuously with RESA stations (Radiation Early Warning System Network) are given in Table 3.20 (TAEK, 2017). The maximum median value for gamma dose rate is 90 nSv/h in the region.

Table 3.20. *Median gamma dose rate in air*

RESA station	**Dose Rate (nSv/h)**
Alican	80
Iğdır	60
Karakale	90
Karakoyunlu	70

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, radiological impact of routine operation of MNPP is assessed by two approaches namely PC CREAM 08 software and IAEA SRS 19 approach provided in IAEA document, with two input data scenarios. Moreover, the results obtained by two approaches and with two input datasets are compared with each other and with the results of environmental radiological monitoring program of TAEK performed for region of province of Iğdır. In addition, related health risks for public are estimated for the results for MNPP and compared with each other.

4.1. Results of Scenario 1 with PC CREAM 08 software

Scenario 1 includes the CNS release and discharge data of MNPP completed with the data of EC Radiation Protection 164 report. This data set was run with other input data in PC CREAM 08 software to estimate annual public doses in the region of province of Iğdır. The results are provided below.

4.1.1. Atmospheric Releases

PC CREAM software was run with the inputs provided for Scenario 1 and for the locations given in Table 3.4 in Chapter 3 and the results regarding atmospheric releases are summarized below. The resultant annual doses and doses integrated for 30 years for adult, child and infant are provided in Table 4.1. The outputs of PC CREAM software for Scenario 1 due to atmospheric releases are provided in Appendix A (Figure A.1- Figure A.30).

Table 4.1. *Results of Scenario 1 for atmospheric releases*

Location	Distance to MNPP (km)	Age Group	Integration Time	Dose (µSv/ year)
Mürşitali	17.2	Adult		4.34E-03
		Child	1 year	4.32E-03
		Infant		5.06E-03
Mürşitali	17.2	Adult		4.37E-03
		Child	30 year	4.34E-03
		Infant		5.09E-03
Aşağıalican	17.9	Adult		4.19E-03
		Child	1 year	4.12E-03
		Infant		4.89E-03
Aşağıalican	17.9	Adult		4.22E-03
		Child	30 year	4.19E-03
		Infant		4.92E-03
Bayraktutan	26.6	Adult		2.97E-03
		Child	1 year	2.95E-03
		Infant		3.46E-03
Bayraktutan	26.6	Adult		2.99E-03
		Child	30 year	2.97E-03
		Infant		3.48E-03
Kerimbeyli	29.7	Adult		2.69E-03
		Child	1 year	2.67E-03
		Infant		3.14E-03
Kerimbeyli	29.7	Adult		2.71E-03
		Child	30 year	2.69E-03
		Infant		3.16E-03
Iğdır center	30.0	Adult		2.67E-03
		Child	1 year	2.65E-03
		Infant		3.11E-03
Iğdır center	30.0	Adult		2.69E-03
		Child	30 year	2.66E-03
		Infant		3.13E-03

All the annual doses (1 year time integration) are in the order of nSv/year and smaller than 1 mSv/year dose limit (Table 2.1) and dose constraint (0.1 mSv/year as provided in Chapter 2.2) for public according to Table 4.1. Besides, doses integrated for 30 years (based on 1 single year release) also comply with the dose constraint and dose limit.

The highest annual doses (4.34E-03 µSv/year for adult, 4.32E-03 µSv/year for child and 5.06E-03 µSv/year for infant) estimated with PC CREAM 08 software for Scenario 1 are for Mürşitali, which is the closest population center among the 5 selected locations to MNPP. Similarly, the lowest annual doses (2.67E-03µSv/year for adult, 2.65E-03 µSv/year for child and 3.11E-03 µSv/year for infant) are for Iğdır (center) which is the furthest population center from MNPP. Besides, Aşağıalican has similar doses in terms of magnitude and its values are a little bit smaller than Mürşitali, which is compatible with the distance.

Bayraktutan presents on west side of the region whereas Kerimbeyli presents on the east side of the region. Also, no significant difference was observed between the annual doses in the order of the magnitude of the results although the results of Bayraktutan is slightly higher than Kerimbeyli. This can be due that Bayraktutan is closer to the MNPP than Kerimbeyli. Similarly, Mürşitali and Aşağıalican have higher dose rates than Iğdır (center) because of being closer to the MNPP. Also, it can be summarized that public doses decrease with the increase in distance from the release point based on the obtained results.

In each location, the annual doses for adult are greater than the annual doses for child whereas the annual doses for adult are smaller than the doses for infant as can be seen from Table 4.1 and Appendix A (Figure A.1- Figure A.30). The reason of this can be the higher consumption rate of the infant for milk used in the software as given in Table 3.14.

When the results for pathway breakdown in doses for Scenario 1 provided in Appendix-A are assessed, the main exposure pathways are the food consumption (grain, fruit, cow milk products, cow milk) and external gamma in the total dose for Scenario 1 regarding atmospheric discharges for public at 5 locations as given in Appendix A.

In terms of radionuclide breakdown in doses for Scenario 1 provided in Appendix A, the main dose contributor radionuclides to the annual doses due to the atmospheric releases for public at 5 locations are C-14, Ar-41, H-3, I-131 and Cs-137, respectively.

4.1.2. Aquatic Discharges

Doses due to the aquatic discharge from MNPP to Aras River as mentioned in Chapter 3.6 for aquatic scenario were estimated for adult, child and infant by simple screening river model of the software for the data of Scenario 1. This model calculates the doses independently from the distance between the discharge point and the location of public, and assumes constant discharge rate over the related period, constant flow rate of the river over the related period, no dilution of radionuclide in the effluent itself, instantaneous and complete dilution of effluent in total flow of the river and ignoring radioactive decay as mentioned in Chapter 3.2.3, which make the results conservative. Therefore, these doses can be used for the contribution to total dose from aquatic discharges for public residing in Mürşitali and Aşağıalican, which are very close to Aras River along the border between Turkey and Armenia. These doses are presented in Table 4.2 and the results of the software are provided in Appendix C (Figure C.1-Figure C.6).

Table 4.2. *Results of scenario 1 for aquatic discharges*

Group	**Total Dose (μSv/year)**
Adult	1.05E+00
Child	4.81E-01
Infant	9.38E-02

As seen from the Table 4.2, doses for adult, child and infant are all quite below the dose constraint for public which is 0.1 mSv/year. The main radionuclides in total dose distribution for adult, child and infant is ^{137}Cs, ^{134}Cs and ^{3}H for Scenario 1 for aquatic discharges as provided in Appendix C. External gamma, fish consumption and drinking water the main exposure pathways in the total dose for Scenario 1 regarding aquatic discharges for public as given in Appendix C.

4.1.3. Total Annual Dose

Dose contribution from aquatic discharge are considered for Mürşitali and Aşağıalican as they are close to Aras River and the public of them is assumed to be affected by aquatic exposure pathway; i.e. standing near the river, eating the fish caught from the river. Total annual dose for public for selected locations are summarized in Table 4.3 considering both the aquatic discharges and atmospheric releases of MNPP.

Table 4.3 *Total annual dose of public based on Scenario 1 with PC CREAM*

Location	**Distance to MNPP (km)**	**Age Group**	**Dose (µSv/ year)**
Mürşitali	17.2	Adult	1.05E+00
		Child	4.85E-01
		Infant	9.89E-02
Aşağıalican	17.9	Adult	1.05E+00
		Child	4.85E-01
		Infant	9.87E-02
Bayraktutan	26.6	Adult	2.97E-03
		Child	2.95E-03
		Infant	3.46E-03
Kerimbeyli	29.7	Adult	2.69E-03
		Child	2.67E-03
		Infant	3.14E-03
Iğdır (center)	30.0	Adult	2.67E-03
		Child	2.65E-03
		Infant	3.11E-03

Total annual doses for adult living in Mürşitali and Aşağıalican are the maximum annual doses (1.05E+00 µSv/ year) among 5 locations. This is due to the contribution from aquatic exposure pathway scenario, which is very conservative as mentioned in Chapter 3.6. Still, all the total annual doses for public are quite below 0.1 mSv/year dose constraint.

4.2. Results of Scenario 2 with PC CREAM 08 Software

Scenario 2, which includes only CNS release and discharge data, was run with PC CREAM for the same locations and public and the doses are estimated. The results are provided below both for atmospheric releases and aquatic discharges.

4.2.1. Atmospheric Releases

PC CREAM software was run with the inputs provided for Scenario 2 regarding atmospheric releases in Chapter 3. The results are summarized in Table 4.4 and the outputs of PC CREAM software for Scenario 2 for atmospheric releases are provided in Appendix B (Figure B.1- Figure B.30).

Table 4.4. *Results of scenario 2 for atmospheric releases*

Location	Distance to MNPP (km)	Age Group	Integration Time	Dose (μSv/ year)
Mürşitali	17.2	Adult		4.45E-04
		Child	1 year	4.70E-04
		Infant		7.05E-04
Mürşitali	17.2	Adult		4.72E-04
		Child	30 year	4.93E-04
		Infant		7.33E-04
Aşağıalican	17.9	Adult		4.24E-04
		Child	1 year	4.47E-04
		Infant		6.74E-04
Aşağıalican	17.9	Adult		4.50E-04
		Child	30 year	4.70E-04
		Infant		7.01E-04
Bayraktutan	26.6	Adult		2.55E-04
		Child	1 year	2.70E-04
		Infant		4.29E-04
Bayraktutan	26.6	Adult		2.73E-04
		Child	30 year	2.87E-04
		Infant		4.48E-04

Location	Distance to MNPP (km)	Age Group	Integration Time	Dose (µSv/ year)
Kerimbeyli	29.7	Adult		2.20E-04
		Child	1 year	2.34E-04
		Infant		3.76E-04
Kerimbeyli	29.7	Adult		2.36E-04
		Child	30 year	2.48E-04
		Infant		3.94E-04
Iğdır center	30.0	Adult		2.17E-04
		Child	1 year	2.31E-04
		Infant		3.72E-04
Iğdır center	30.0	Adult		2.33E-04
		Child	30 year	2.45E-04
		Infant		3.89E-04

All the annual doses (1 year time integration) are even below the order of nSv/year and quite smaller than 1 mSv/year dose limit (Table 2.1) and dose constraint (0.1 mSv/year as provided in Chapter 2.2) for public in accordance with Table 4.4. Doses integrated for 30 years (based on 1 single year release) also comply with the dose constraint and dose limit.

The highest annual doses (4.45E-04 µSv/year for adult, 4.70E-04 µSv/year for child and 7.05E-04 µSv/year for infant) estimated with PC CREAM 08 software for Scenario 2 are for Mürşitali, the closest population center among the 5 selected locations to MNPP. Similarly, the lowest annual doses (2.17E-04 µSv/year for adult, 2.31E-04 µSv/year for child and 3.72E-04 µSv/year for infant) are for Iğdır (center), the furthest population center from MNPP among the selected locations. Besides, Aşağıalican has similar doses in terms of magnitude and its values are a little bit smaller than Mürşitali, which is compatible with the distance difference of two locations.

As in Scenario 1, there is no significant difference observed between the annual doses in the order of the magnitude of the results although the results of Bayraktutan (on west side of the region) is slightly higher than Kerimbeyli (on east side of the region).

Similar to Scenario 2, Mürşitali and Aşağıalican have higher dose rates than Iğdır (center) due to being closer to the MNPP. In addition, the estimated annual doses are decreasing with the increase in the distance of locations from MNPP according to the obtained results similar to Scenario 1.

In each location, the annual doses for infant are greater than the annual doses for child and doses for child are greater than adult as can be seen from Table 4.4 and Appendix B (Figure B.1- Figure B.30). The reason of this can be the higher consumption rate of the infant for milk used in the software as given in Table 3.14 and the effect of the release and discharge data used for Scenario 2 as provided in Table 3.4.

In terms of pathway breakdown in doses provided in Appendix B for Scenario 2, the main exposure pathways are the external gamma and food consumption (grain, fruit, cow milk products, cow milk) in the total dose for Scenario 2 regarding atmospheric discharges for public at 5 locations as given in Appendix B.

According to the radionuclide breakdown results for Scenario 2 of the software provided in Appendix B, the main dose contributor radionuclides to the annual doses due to the atmospheric releases for public at 5 locations are ^{41}Ar, ^{131}I, ^{137}Cs and ^{133}Xe respectively.

4.2.2. Aquatic Discharges

The same procedure applied in Chapter 4.1.2 was used to estimate public doses due to aquatic discharges of Scenario 2. The calculated doses that can be used for the public living in Mürşitali and Aşağıalican, similar to Scenario 1 of aquatic discharge, are given in Table 4.5 and the outputs of the software are presented in Appendix D (Figure D.1-Figure D.6).

All the estimated doses for public are even below µSv/year order, which have already complied 0.1 mSv/year dose constraint for public. ^{137}Cs and ^{137}Cs are the main dose contributor radionuclides for adult, child and infant as provided in Appendix D. Besides, external gamma and fish consumption are the main exposure pathways in the total dose for Scenario 2 regarding aquatic discharges for public as given in Appendix D.

Table 4.5. *Results of Scenario 2 for aquatic discharges*

Group	**Total Dose (µSv/year)**
Adult	9.86E-01
Child	4.39E-01
Infant	3.46E-02

4.2.3. Total Annual Dose

Dose contribution from aquatic discharge are considered for Mürşitali and Aşağıalican as in Chapter 4.1.2 because they are close to Aras River and the public of them is assumed to be affected by aquatic exposure pathway; i.e. standing near the river and eating the fish caught from the river etc.. Total annual dose for public for 5 locations are summarized in Table 4.6 for both the aquatic discharges and atmospheric releases of MNPP.

Table 4.6. *Total annual dose for public based on Scenario 2 with PC CREAM*

Location	**Distance to MNPP (km)**	**Age Group**	**Dose (µSv/ year)**
Mürşitali	17.2	Adult	9.86E-01
		Child	4.39E-01
		Infant	3.53E-02
Aşağıalican	17.9	Adult	9.86E-01
		Child	4.39E-01
		Infant	3.53E-02
Bayraktutan	26.6	Adult	2.55E-04
		Child	2.70E-04
		Infant	4.29E-04
Kerimbeyli	29.7	Adult	2.20E-04
		Child	2.34E-04
		Infant	3.76E-04

Location	Distance to MNPP (km)	Age Group	Dose (µSv/ year)
Iğdır center	30.0	Adult	2.17E-04
		Child	2.31E-04
		Infant	3.72E-04

According to Table 4.6, total annual doses for adult living in Mürşitali and Aşağıalican are the maximum annual doses (9.86E-01 µSv/ year) among 5 locations. This is due to the contribution from aquatic exposure pathway scenario, which is very conservative as mentioned in Chapter 3.6. Nonetheless, all the total annual doses for public are quite below 0.1 mSv/year dose constraint.

4.3. Results of IAEA SRS 19 Approach

The iterative approach provided in SRS 19 document of IAEA (2001) and in Chapter 2.10 was performed for Mürşitali and Aşağıalican among the 5 selected locations as the modeling range of the approach provided in SRS 19 is limited with 20 km. The doses calculated with this approach are provided below for each step and scenario.

4.3.1. Results for Scenario 1

Release and discharge data of Scenario 1 provided in Table 3.4 in Chapter 3 was used in the analysis. The methodology presented in Figure 2.4 was applied. First of all, no dilution method was applied to the release and discharge data for Scenario 1 and the calculated doses have exceeded 0.1 mSv/year dose constraint as can be seen from Table 4.7. Therefore, second step in the iterative approach was applied to the data of Scenario 1. With generic environmental model, the resultant doses have exceeded the reference level of 0.01 mSv/year as provided in Table 4.7. So, detailed environmental model was performed as third step in the iterative approach which covers the equations provided for both concentration calculations and dose estimations regarding both atmospheric releases and aquatic discharges in SRS 19 document. In this step, calculated total doses due to all available pathways in SRS 19 document (IAEA, 2001) for public (adult and infant) in Mürşitali and in Aşağıalican are all below 0.1

mSv/year, as provided in Table 4.8 and all doses comply with the public dose constraint.

Table 4.7. *The calculated doses for Scenario 1 for no-dilution model and generic environmental model provided in SRS 19 document of IAEA (2001)*

Step of Iterative Approach	**Dose due to Atmospheric Release (mSv/year)**	**Dose due to Aquatic Release (mSv/year)**	**Total Dose (mSv/year)**
No Dilution	1.45E+00	2.96E+00	4.41E+00
Generic Environmental Model			
<u>Locations</u>			
Mürşitali	4.66E-07	8.13E-01	0.81E+00
Aşağıalican	4.54E-07	8.13E-01	0.81E+00

Table 4.8. *The calculated doses for Scenario 1 for detailed environmental model provided in SRS 19 document of IAEA (2001)*

Locations / Groups / Doses (mSv/year)	**Mürşitali Adult**	**Mürşitali Infant**	**Aşağıalican Adult**	**Aşağıalican Infant**
Dose due to H-3	1.20E-04	1.20E-04	1.14E-04	1.14E-04
Dose due to C-14	3.70E-04	3.70E-04	2.31E-04	2.31E-04
Dose due to Immersion in the Plume	5.23E-09	5.23E-09	3.26E-09	3.26E-09
Dose due to Inhalation	3.59E-07	1.77E-07	2.24E-07	1.10E-07
Dose due to Ground Deposition	2.67E-09	2.67E-09	1.67E-09	1.67E-09
Dose due to Sediment	4.13E-05	2.75E-05	4.13E-05	2.75E-05
Dose due to Food Crops				
Atmospheric Release	1.75E-03	1.27E-03	1.75E-03	1.27E-03
Aquatic Discharge	1.39E-04	7.66E-05	1.39E-04	7.66E-05

Doses (mSv/year) \ Locations Groups	Mürşitali Adult	Mürşitali Infant	Aşağıalican Adult	Aşağıalican Infant
Dose due to Milk				
Atmospheric Release	1.38E-04	4.59E-04	1.38E-04	4.59E-04
Aquatic Discharge	3.81E-06	4.61E-06	3.81E-06	4.61E-06
Dose due to Meat				
Atmospheric Release	2.26E-04	2.45E-04	2.26E-04	2.45E-04
Aquatic Discharge	2.93E-04	1.55E-04	2.93E-04	1.55E-04
Dose due to Fish	4.32E-03	1.96E-03	4.32E-03	1.96E-03
Total Dose	7.40E-03 (0.007)	4.69E-03 (0.005)	7.26E-03 (0.007)	4.54E-03 (0.005)

4.3.2. Results for Scenario 2

The same calculation process was applied to the release and discharge data of Scenario 2 provided in Table 3.4 in Chapter 3 to estimate public doses with IAEA SRS 19 approach. The results obtained for no dilution method, generic environmental model and detailed environmental model are presented in Table 4.9 and Table 4.10.

As can be seen from Table 4.9, dose constraint is not satisfied with no dilution method. Besides, reference level of 0.01 mSv/year is not satisfied with generic environmental model. However, the doses estimated with detailed environmental model for public (adult and infant) in Mürşitali and in Aşağıalican are all below 0.1 mSv/year, as provided in Table 4.10.

Table 4.9. *The calculated doses for Scenario 2 for no-dilution model and generic environmental model provided in SRS 19 document of IAEA (2001)*

Step of Iterative Approach	**Dose due to Atmospheric Release (mSv/year)**	**Dose due to Aquatic Release (mSv/year)**	**Total Dose (mSv/year)**
No Dilution	1.45E+00	2.96E+00	4.41E+00
Generic Environmental Model			
Locations			
Mürşitali	2.90E-07	8.13E-01	0.81E+00
Aşağıalican	2.83E-07	8.13E-01	0.81E+00

Table 4.10. *The calculated doses for Scenario 2 for detailed environmental model provided in SRS 19 document of IAEA (2001)*

Locations / Groups / Doses (mSv/year)	**Mürşitali Adult**	**Mürşitali Infant**	**Aşağıalican Adult**	**Aşağıalican Infant**
Dose due to H-3*	-	-	-	-
Dose due to C-14*	-	-	-	-
Dose due to Immersion in the Plume	4.44E-09	4.44E-09	2.77E-09	2.77E-09
Dose due to Inhalation	2.84E-07	1.51E-07	1.75E-07	9.32E-08
Dose due to Ground Deposition	2.61E-09	2.61E-09	1.63E-09	1.63E-09
Dose due to Sediment	2.47E-12	1.65E-12	2.47E-12	1.65E-12
Dose due to Food Crops				
Atmospheric Release	2.18E-04	1.95E-04	2.18E-04	1.95E-04
Aquatic Discharge	1.39E-04	7.63E-05	1.39E-04	7.63E-05
Dose due to Milk				
Atmospheric Release	1.25E-04	3.89E-04	1.25E-04	3.89E-04
Aquatic Discharge	3.81E-06	4.58E-06	3.81E-06	4.58E-06

Doses (mSv/year) \ Locations Groups	Mürşitali Adult	Mürşitali Infant	Aşağıalican Adult	Aşağıalican Infant
Dose due to Meat				
Atmospheric Release	1.67E-04	1.47E-04	1.67E-04	1.47E-04
Aquatic Discharge	2.93E-04	1.54E-04	2.93E-04	1.54E-04
Dose due to Fish	4.32E-03	1.96E-03	4.32E-03	1.96E-03
Total Dose	5.27E-03 (0.005)	2.93E-03 (0.003)	5.27E-03 (0.005)	2.93E-03 (0.003)

*: CNS data does not include C-14 and H-3 rate data that related dose calculations are not performed for Scenario 2.

4.4. Results of EMP for Province of Iğdır

The maximum radioactivity concentration observed in environmental media in the region are presented with the results of the software and IAEA SRS 19 approach in Table 4.11.

Table 4.11. *Maximum radioactivity concentration observed in environmental media in Iğdır (TAEK, 2017) and obtained results for PC CREAM software and IAEA SRS 19 approach*

Media & Radionuclide	EMP of Iğdır	SRS 19*
Milk (Bq/kg)	Kerimbeyli	
I-131	<22	2.23
Cs-134	<1.0	7.31
Cs-137	<3.7	7.98
Sr-90	0.08	2.39
Meat (Bq/kg)	Karakoyunlu	
I-131	<2.7	1.62
Cs-134	<0.1	26.9
Cs-137	<2.7	29.9
Sr-90	<0.84	5.9
Fruit (Bq/kg)	Apple (Kerimbeyli)	Food crops
I-131	<11.7	0.66
Cs-137	<11.7	6.03
Sr-90	<0.12	6.03

Media & Radionuclide	EMP of Iğdır	SRS 19*
Wheat (Bq/kg)	(Kerimbeyli)	Food crops
I-131	<4.8	0.66
Cs-137	<5.4	6.03
Sr-90	<0.08	6.03
Surface water (Bq/L)	Aras River (Kadıkışlak)	
Cs-137	<4.44	1.39
Sr-90	<0.27	0.17
H-3	1.11	0.59
Feedstuff (Bq/kg)	Kerimbeyli	Pasture
I-131	<12	15.2
Cs-134	<0.4	45.7
Cs-137	<16.2	49.9
Sr-90	2.18	49.8
Soil (Bq/kg)	Kerimbeyli	-
I-131	<2.8	
Cs-137	<3.6	
Sr-90	<3.85	
Fish (Bq/kg)	-	
Cs-137		8.36
Sr-90		8.67E-03
H-3		-

*: Contribution from aquatic discharge is ignored as it is so small when compared with the concentration due to atmospheric release in SRS 19

4.5. Comparison of the Results and Discussion

4.5.1. PC CREAM Software

The estimated maximum annual public doses with Scenario 1 is 1.05E+00 µSv/ year for Mürşitali and Aşağıalican whereas maximum annual public dose is 9.86E-01 µSv/ year for Mürşitali and Aşağıalican for Scenario 2. These results are very close to each other (approximately 1 µSv/ year). Results for Bayraktutan, Kerimbeyli and Iğdır center are 1 order of magnitude smaller for Scenario 2 run with PC CREAM software and the doses are actually in the order of nSv/year, i.e. 2.97E-03 µSv/ year for

Bayraktutan in Scenario 1 and 2.55E-04 µSv/ year for Bayraktutan in Scenario 2 for adult. Therefore, it can be concluded that all the annual public doses estimated by the software for both data sets comply with the dose constraint and filling CNS data set of MNPP as provided in Table 3.4 and running the software for Scenario 1 didn't change the annual public doses enormously.

4.5.2. IAEA SRS 19 Approach

The estimated maximum public dose by detailed environmental model in IAEA SRS 19 approach for Scenario 1 in Mürşitali and in Aşağıalican is 0.007 mSv/year and for Scenario 2 in Mürşitali and in Aşağıalican is 0.005 mSv/year. The obtained doses are in the order of µSv which quite comply with the dose constraint (0.1 mSv/year). The main exposure pathways for IAEA SRS 19 approach for maximum observed doses are food consumption and fish consumption. The main dose contributing radionuclides regarding maximum observed doses for IAEA SRS 19 approach are ^{137}Cs, ^{134}Cs, ^{90}Sr and ^{131}I for atmospheric releases and ^{137}Cs, ^{134}Cs and ^{90}Sr for aquatic discharges. There is no significant change in the doses by calculating the doses with the filled data set (Scenario 1) and CNS data set (Scenario 2).

4.5.3. PC CREAM Software and IAEA SRS 19 Approach

Atmospheric release and aquatic discharge of the radionuclides and the dispersion of the radionuclides in food chain were considered by both approaches, but by their own way.

The public doses estimated by PC CREAM 08 software are for 1 year (annual) and 30 years of integration of 1 single year release (user defined time integration period) as provided in Appendices whereas public doses estimated with IAEA SRS 19 approach are for the 30th year of discharge. The contribution of radionuclides to total doses for public, through the dispersion in environmental media, estimated by IAEA SRS 19 approach includes the effect of previous 29 years of released and discharged radionuclides to the environment (IAEA, 2001). Therefore, direct comparison of the results of both approaches are not reasonable as the resultant doses represent different meanings in terms of duration of the release and discharge time. Yet, it can be emphasized that all the estimated doses by two approaches are pretty below from the dose constraint.

Besides, data of the public used in PC CREAM 08 software is mostly specific to region of interest. However, IAEA SRS 19 approach uses generic data to represent the critical group (public) to estimate public doses and does not consider stack height where atmospheric releases are made. Also, food consumption rates, occupancy factors based on exposure scenario; i.e. working/ playing over contaminated soils, members of the critical group, and dose conversion factors are different for two approaches. In addition to these, child and its related data are not present in IAEA SRS 19 approach.

Estimated doses by IAEA SRS 19 approach is quite smaller than dose constraint as mentioned before. Therefore, it can be concluded that IAEA SRS 19 approach is very conservative. As the release and discharge of radionuclides to the environment would be inevitable and be more for NPPs having multiple units and capacity more than MNPP (1 Unit in operation with 376 MW_e capacity), although the treatment technology used at the stack vent is developed, IAEA SRS 19 approach to determine radiological impacts of routine operation of such NPPs on public can be applicable, especially for environmental impact assessment reports and for licensing process. Yet, more detailed and site specific modeling study, such as with PC CREAM 08 software or any other applicable model to the related site as mentioned in Table 2.6 and Table 2.7, may be requested by regulatory authorities for NPPs on flat terrain having multiple units at one site and having total capacity over 4000 MW during site license and construction license process to evaluate the radiological impacts of NPPs on public. In addition, IAEA SRS 19 approach is free of charge that it can be used by students and researchers for scientific studies when any software is not available or software is expensive to buy and to perform the related analysis. In this way, IAEA SRS 19 approach helps to have an idea about the radiological impact of an NPP on the public with the limited information regarding the site and the habits of the public. Moreover, IAEA SRS 19 approach can be used in estimating the radiological impacts of the facilities in nuclear fuel cycle; i.e. research reactors, and mining activities of rare earth elements. It should be noted that both approaches (the software and IAEA SRS 19 approach) use Gauss plume dispersion in the atmosphere and therefore they are not applicable to the sites having complex terrain; i.e. terrain which are not flat.

4.5.4. IAEA SRS 19 Approach, EMP of Iğdır and PC CREAM Software

The results obtained with SRS 19 approach and the available results in EMP report of Iğdır are provided in Table 4.11.

In PC CREAM 08 software, FARMLAND model calculates activity concentrations in foods based on user defined deposition rate and these activity concentrations are used as input to ASSESSOR where they are scaled by the actual deposition rate at the desired locations downwind of the discharge point and by the habit data to obtain ingestion doses (Smith et al, 2009). Therefore, concentrations presented in Table 4.11 for PC CREAM 08 are preliminary values obtained with FARMLAND model; they are not the concentrations calculated based on the input meteorology, habit data and for selected locations. As location specific concentrations could not be obtained with the software, it may not be meaningful to compare FARMLAND concentration values with the results of EMP and IAEA SRS 19 Approach.

The analysis result for fish samples are not available in EMP of Iğdır due to not being able to take samples from Aras River because of security reasons (TAEK, 2017) that comparison could not be made for EMP of Iğdır. Radionuclide concentration in river estimated with IAEA SRS 19 approach are compatible with the results of EMP of Iğdır.

Besides, the results obtained with IAEA SRS 19 approach are similar in the order of magnitude to the results of EMP of Iğdır as provided in Table 4.11. However, cesium activities estimated for meat, strontium and cesium activities for pasture as feedstuff are slightly higher than the results of EMP of Iğdır. This situation is very natural as generic information are used in IAEA SRS 19 approach instead of site-specific information to estimate concentrations in environmental media and related doses to public. Therefore, it can be concluded that the results of EMP of Iğdır and the results obtained in this thesis for IAEA SRS 19 approach are compatible with each other.

4.5.5. Health Effects of Routine Operation of MNPP on Public Living in Province of Iğdır (in Turkey)

The background information for the health effects of ionizing radiation is provided in Chapter 2.11 of this thesis. As doses obtained for two approaches and with two scenarios as a result of the routine operation of MNPP are considerably smaller than dose constraint (0.1 mSv/year), resultant doses can be classified as low-doses and biological effects of chronic exposure to radiation.

The health risk of public living in Province of Iğdır due to routine operation of MNPP was estimated by using the coefficients provided in Chapter 2.11 in Table 2.8 (Turner, 2007). The results are provided in Table 4.12. The maximum doses obtained from Scenario 1 and Scenario 2 for both approaches were used in the health risk estimation study.

Table 4.12 *Estimated health risks for public living in Province of Iğdır due to routine operation of Metsamor NPP*

Dose Calculation Method	**Maximum Dose Obtained from Approaches**	**Detriment**	**Coefficient (10^{-2} Sv^{-1})**	**Health Risk (Probability)**
PC CREAM	1.05 µSv/ year (1.05E-06 Sv)	Fatal cancer	5.0	5.25E-08
		Nonfatal cancer	1.0	1.05E-08
		Severe genetic effects	1.3	1.37E-08
		Total	7.3	7.67E-08
SRS 19	7.4 µSv/year (7.4E-06 Sv)	Fatal cancer	5.0	3.70E-07
		Nonfatal cancer	1.0	7.40E-08
		Severe genetic effects	1.3	9.62E-08
		Total	7.3	5.40E-07

According to the results provided in Table 4.12, total health risk posed to public living in Province of Iğdır due to routine operation of MNPP is 7.67E-08 for PC CREAM approach whereas it is 5.40E-07 for IAEA SRS 19 approach. In other words, the probability of a person to experience stochastic effect (total) due to MNPP is 7.67 in 100,000,000 based on PC CREAM approach and 5.4 in 10,000,000 according to IAEA SRS 19 approach.

The estimated doses for two approaches are 1.05 µSv/ year (software, based on 1-year discharge) and 7.4 µSv/ year (IAEA SRS 19 approach, based on 30 year discharge) due to radiological impact of routine operation of MNPP. Actually, public is exposed to average 2.5 mSv annual dose in the world based on the geographical conditions and the physical properties of the place where s/he lives (TAEK, n.d. b). 87% of this dose comes from natural sources (including cosmic ray, radon, K-40 in foods, natural background radiation), 12% of it is due to medical applications (including whole body CT, head CT, mammogram, chest X-ray, upper gastrointestinal X-ray etc.) and the rest of it is because of occupational exposure (including working with radiation sources, radiation workers in NPPs etc.) and other man-made sources (including living near an NPP, nuclear fallouts due to nuclear weapon tests, nuclear accidents etc.). Dose contribution of NPP operation for radiation sources takes part in part of 1 % where doses due to nuclear weapon tests and nuclear accidents take part in as well.

Table 4.13. *Radiation sources in daily life and the related radiation exposures (TAEK, n.d. c ; EPA, n.d.)*

Radiation Source	**Dose**
Each 10,000 m. flight	0.04 mSv
Each breast X-ray	0.1 mSv
Radon gases (due to living in basement)	0.8 mSv/year
Smoking cigarette (annual average over 25 years)	80 mSv/year
Each mammogram	0.42 mSv
Each whole-body CT	10 mSv
Each head CT	2 mSv
Each upper gastrointestinal X-ray	6 mSv

Radiation Source	Dose
Radiation in the body (natural)	0.29 mSv/year

All the dose values given in Table 4.13 are significantly higher than the estimated public doses due to the normal operation of MNPP. Therefore, it should be noted that the cancer risk for the public due to the routine operation of MNPP will not be higher than the cancer risks for person smoking cigarettes, travelling with flights, living in basement or taking medical applications such as breast X-ray, mammogram or CT.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The countries were forced to produce clean energy due to atmospheric pollution in 1950s when the coal was main energy source. Therefore, nuclear energy was considered as an option for clean energy production starting from that era and began to spread in 1970s because of the oil crisis that the countries faced with (ETKB, n.d.). However, some countries have been decreasing the nuclear energy in their countries as a result of public mistrust and Fukushima accident (IAEA, 2019a). Nevertheless, nuclear energy is still one of the important energy resources in the world. Currently, 449 nuclear reactors are in operation whereas 54 reactors are under construction and 176 reactors have been shutdown permanently (WNA, 2019a ; WNA, 2019b ; IAEA, 2019b ; IAEA, 2019c). Turkey is an embarking country in energy production from nuclear power and up to now Akkuyu Nuclear JSC has granted the construction license of 1st and 2nd units of Akkuyu NPP. Also, there is another NPP project in Turkey in Sinop which is in the environmental impact assessment stage. Although there is no NPP in operation in Turkey, there are commissioned ones around the border of Turkey such as Metsamor NPP in Armenia (~16 km), Kozloduy NPP in Bulgaria (~330km), Cernavoda NPP in Romania (~300 km), Paks NPP in Hungary (~1015 km), Rostov NPP in Russia (~670 km), South Ukraine NPP in Ukraine (~650 km), Bushehr NPP in Iran (~1160 km). Among these, Metsamor NPP (Unit 2) is the most risky NPP in operation due to being commissioned on a highly seismic location and the closest one to the border of Turkey from Province of Iğdır.

Releases and discharges to the environment occur in normal operation of NPP to some extent, which are under strict control of nuclear regulatory body in every country by means of dose limits, dose constraint, release and discharge limits (IAEA, 2014). The releases generally consist of volatile radioactive gases (noble gases, iodine, tritium, ^{14}C etc.) and aerosols whereas discharges consist of tritium and activation products

(IAEA, 2011). Therefore, in this thesis, it is aimed to determine the radiological impact of the routine operation of Metsamor NPP on the public living in Province of Iğdır. To achieve this aim, two different approaches are adopted; (1) using PC CREAM 08 software and (2) using the methods provided in safety report of IAEA coded as "SRS 19" for radiological assessment. Moreover, the conservativeness of the approach suggested by IAEA is discussed as an output of the study. Besides, the health risk is estimated for the results of both approaches.

In the first approach, routine radiological impact assessment software of Public Health England, PC CREAM 08, was used as it is a prominent model that considers the almost all exposure pathways for routine releases and discharges to the environment and allows users to put the specific inputs into the analysis including meteorology, release/discharge data, river properties, habits of public, location of public, agricultural and animal products' production rates etc. The radionuclide concentrations in each environmental media and related doses with this software were calculated and health risks were estimated for public living in Province of Iğdır to determine the radiological impacts during normal operation phase of Metsamor NPP (MNPP), which is located very close to the border of Turkey.

In the second approach, iterative approach, which is given as conservative and simple approach in SRS 19 coded safety report of IAEA was adopted to estimate public doses living in Province of Iğdır. This approach is suggested to be used before applying any detailed/complex analysis or using software/model which requires too much information in the dispersion analysis and dose assessment process. Moreover, this approach provides a starting point in the dose assessment with limited information or site-specific information to perform the related analysis. Therefore, radionuclide concentrations in environmental media including both atmospheric and aquatic exposure pathways and related doses were estimated. After this, related health risk was estimated for the public.

In the thesis, lacking parts of data set of MNPP (Armenia, 2007) were filled with a similar NPP to it (Bohunice NPP, VVER-440), used as Scenario 1 in the analysis, to assess the effect of the completed dataset on the public doses as the dataset (Scenario 2) provided in Convention on Nuclear Safety Report of Armenia (Armenia, 2007) does not include the distribution and the radioactivity rate of all the possible radionuclides released and discharged to the environment from the MNPP. Therefore, two data sets for the release and discharge from Metsamor NPP were used as inputs to estimate public doses by two approaches. The maximum estimated public doses for Province of Iğdır due to the routine releases and discharges of Metsamor NPP for Scenario 1 are 1.05 μSv/ year with PC CREAM 08 software and 7.40 μSv/ year with IAEA SRS 19 approach. For Scenario 2, the maximum estimated public doses are 0.99 μSv/ year with PC CREAM 08 software and 5.30 μSv/ year with IAEA SRS 19 approach. The public doses estimated by PC CREAM 08 software are for 1 year (annual) whereas public doses estimated with IAEA SRS 19 approach are for the 30th year of discharge; i.e. including the effect of previous 29 years of released and discharged radionuclides to the environment. Thus, direct comparison of the results of both approaches are not reasonable because of the different duration interval of the release and discharge in the dose estimation. Still, all the estimated public doses quite comply with the public annual dose constraint of 0.1 mSv/year (NDK, 2019). Therefore, it can be concluded that there is no enormous difference observed regarding the public doses for both input scenarios used in both approaches. Moreover, it can be concluded that IAEA SRS 19 approach is conservative for MNPP as well as the small-scale facilities as mentioned in IAEA SRS 19 safety series report.

The main exposure pathways for the public are food consumption, external gamma, fish consumption due to atmospheric release and aquatic discharge according to the results of PC CREAM for both scenarios whereas food consumption and fish consumption are for IAEA SRS 19 approach. In addition, the main radionuclides that contribute the doses mostly are ^{41}Ar, ^{131}I and ^{137}Cs for atmospheric releases, and ^{137}Cs and ^{134}Cs for aquatic discharges with PC CREAM approach for both input scenarios.

On the other hand, ^{134}Cs and ^{90}Sr for atmospheric releases and ^{137}Cs, ^{134}Cs and ^{90}Sr for aquatic discharges are the main dose contributing radionuclides for IAEA SRS 19 approach.

The radionuclide concentrations obtained by IAEA SRS 19 approach are quite compatible with the concentrations measured in EMP of Iğdır. However, comparison of the location specific concentrations for the software with the concentrations measured in EMP of Iğdır is not possible as FARMLAND gives the concentrations independent from the location and habits of public, and location specific concentrations are determined and processed in ASSESSOR to estimate doses.

The maximum public doses estimated by both approaches are quite lower than the doses exposed due to natural sources, medical applications and other man-made sources. Therefore, it can be concluded that the health risk of public living in Province of Iğdır due to the routine and safe operation of MNPP will not be higher than the health risk of the public due to chest X-ray, mammogram, CT, smoking cigarettes, travelling with flights and living in basement (radon gas exposure).

^{14}C release rate data in the thesis was completed from Bohunice NPP, in Slovakia, and it was determined that ^{14}C is one of the main dose contributing radionuclide in the radiological impact assessment analysis of MNPP. Therefore, the release rate of ^{14}C is necessary data for future dose estimation in a realistic modeling of a VVER.

Performing a detailed survey regarding the habit of the public living near NPP (at least within 30 km zone) can be suggested for future studies. The survey study should cover the residing location of the person (city center, village etc.), income of the person, daily food and drinking water consumption rate of the person based on age groups and gender. In addition to these, the ratio of the locally produced and consumed agricultural and animal products in the region should be investigated for ingestion doses.

This thesis can be used to determine the sampling locations and sampling media in Environmental Radiological Monitoring Program of TAEK in its future activities.

Uncertainty analysis is also suggested as a future study when assessing the public doses due to radiological impacts of a NPP in normal operation. However, it should be noted that uncertainty comes from 3 main parts of the radiological impact assessment analysis namely; atmospheric and aquatic dispersion part, terrestrial and aquatic transport part, and dose estimation part. Meteorological data, parameters of deposition rates, resuspension, surface roughness, air dispersion parameters and Gauss-plume dispersion model are the uncertainty sources for dispersion part of the analysis, which should be considered in the future study. Besides, transport properties of the soil, transfer of radionuclides to terrestrial and surface water biota, locally produced and consumed agricultural products in the region, properties of the aquatic environment (suspended sediment load of the river, flow rate, width, depth and length of the river based on the sections of the river, if the receiving aquatic media is the river) are the uncertainty sources to be taken into account for terrestrial and aquatic transport part. Moreover, daily habits of the person (location where s/he lives, where s/he works, how much s/he works in a day, food consumption habits), properties of the person (age, weight, length, gender, inhalation rate), the properties of the houses where s/he lives (construction material and type of the houses) are the other uncertainty sources that should be considered. Therefore, covering all the abovementioned uncertainty sources in the radiological impact assessment analysis would be necessary in the future study.

Finally, the doses estimated with this thesis for public living in Province of Iğdır due to routine operation of MNPP is so small that studying the radiological impacts of MNPP for the same region due to possible accidental conditions is suggested as future study.

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APPENDICES

A. The Results of Scenario 1 for PC CREAM 08 Software due to Atmospheric Releases for Public in Province of Iğdır

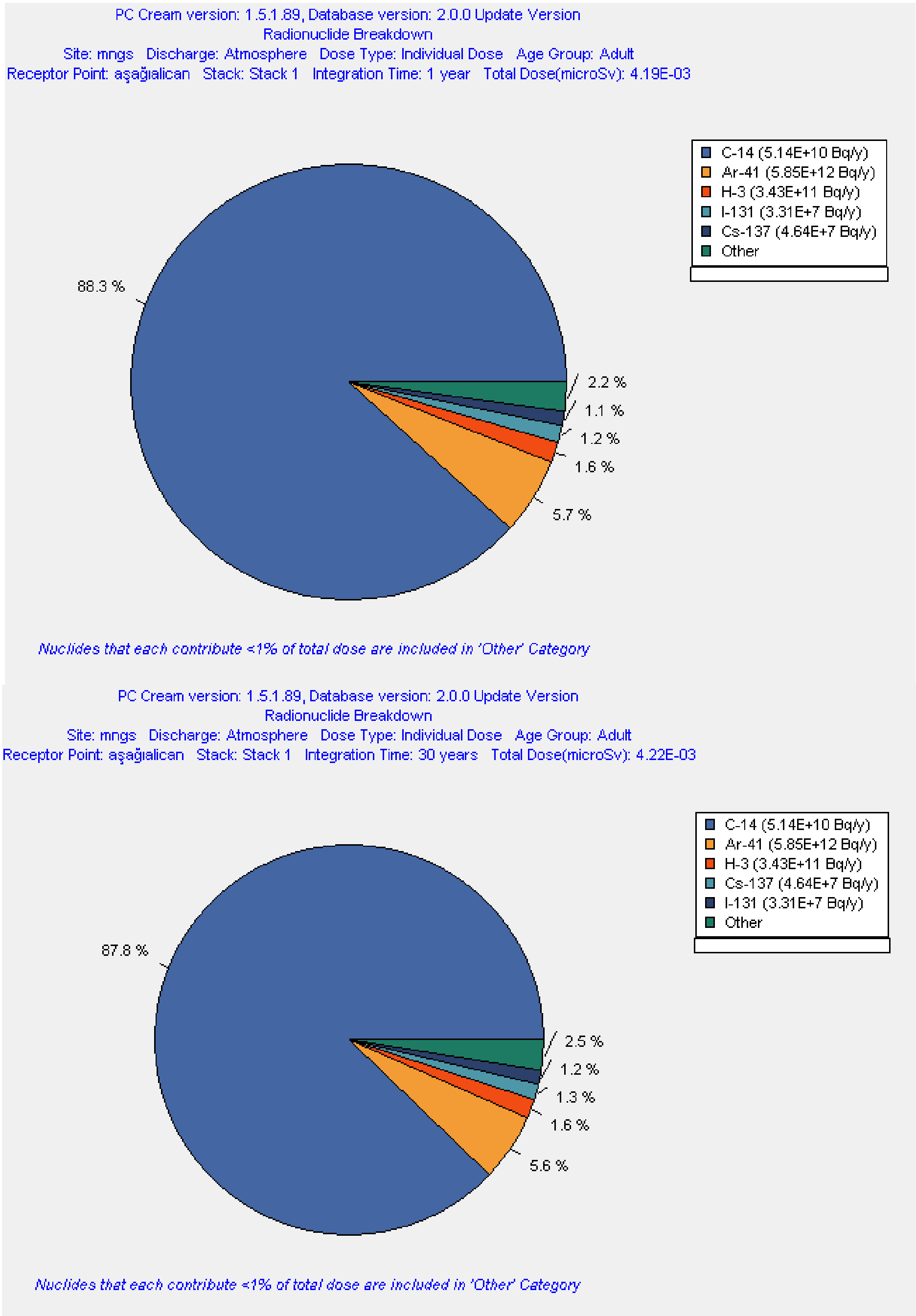


Figure A. 1 Radionuclide distribution in total atmospheric dose for adult in Aşağıalican for 1 year and 30 years integration time

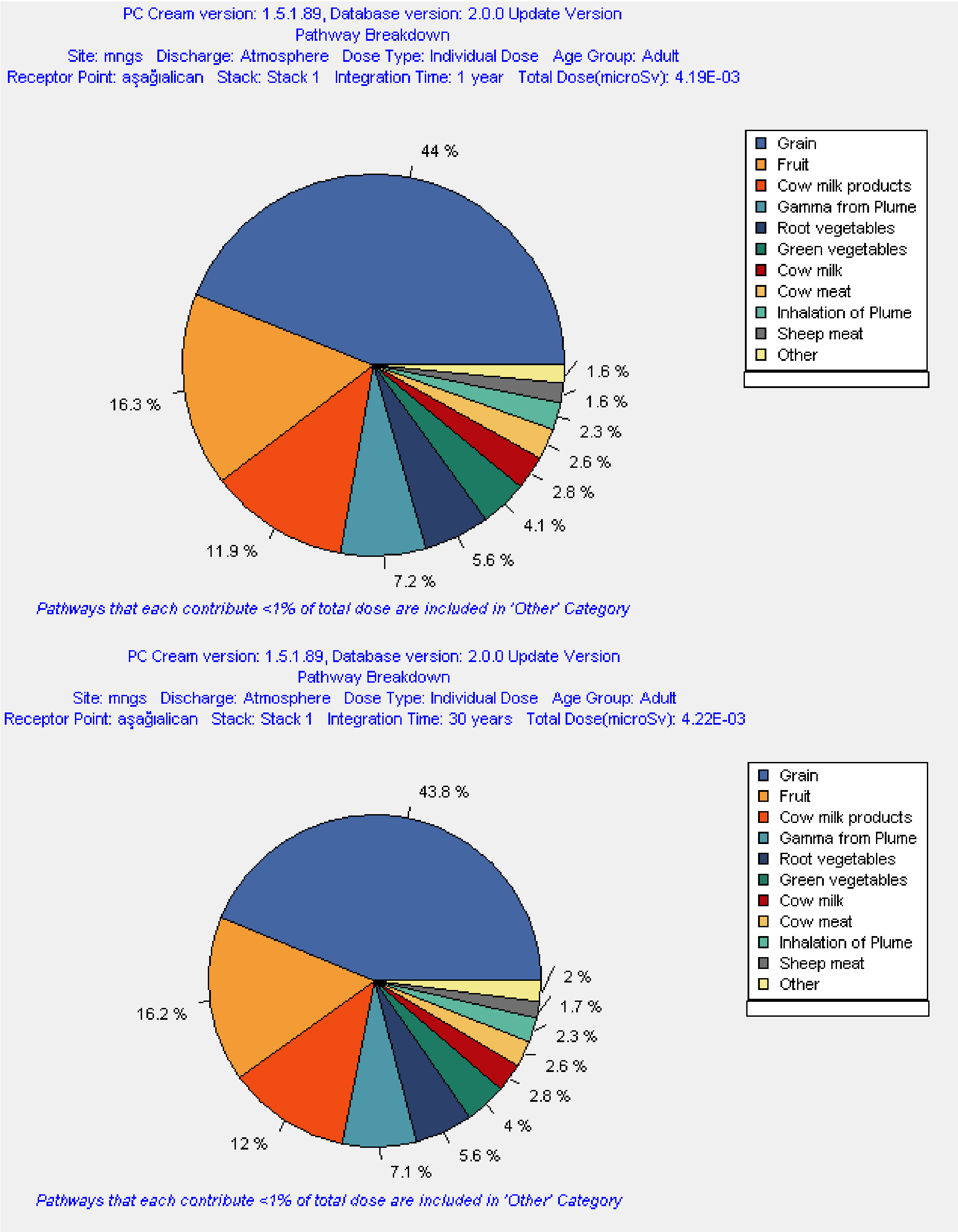


Figure A. 2 Pathway distribution in total atmospheric dose for adult in Aşağıalican for 1 year and 30 years integration time

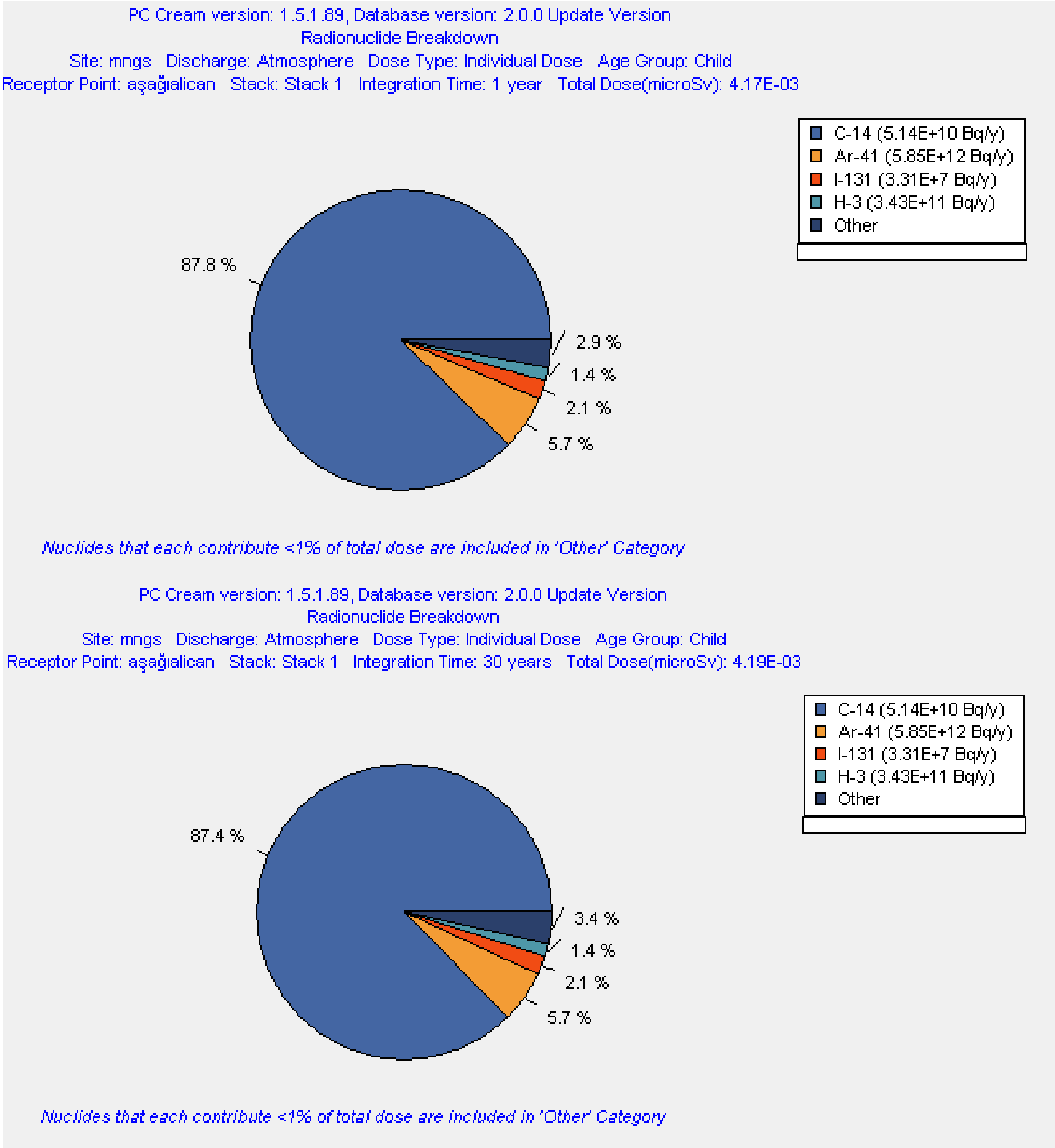


Figure A. 3 Radionuclide distribution in total atmospheric dose for child in Aşağıalican for 1 year and 30 years integration time

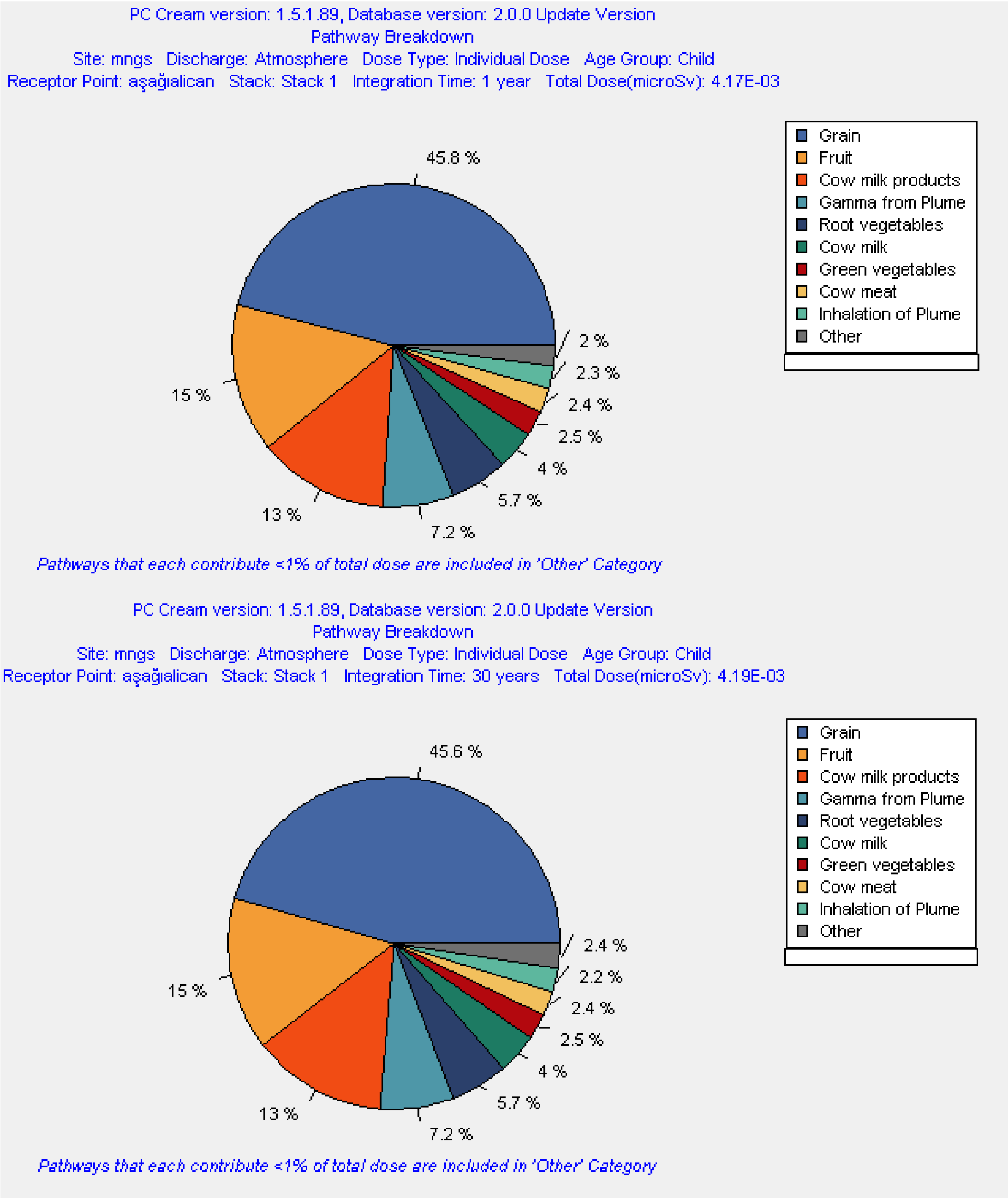


Figure A. 4 Pathway distribution in total atmospheric dose for child in Aşağıalican for 1 year and 30 years integration time

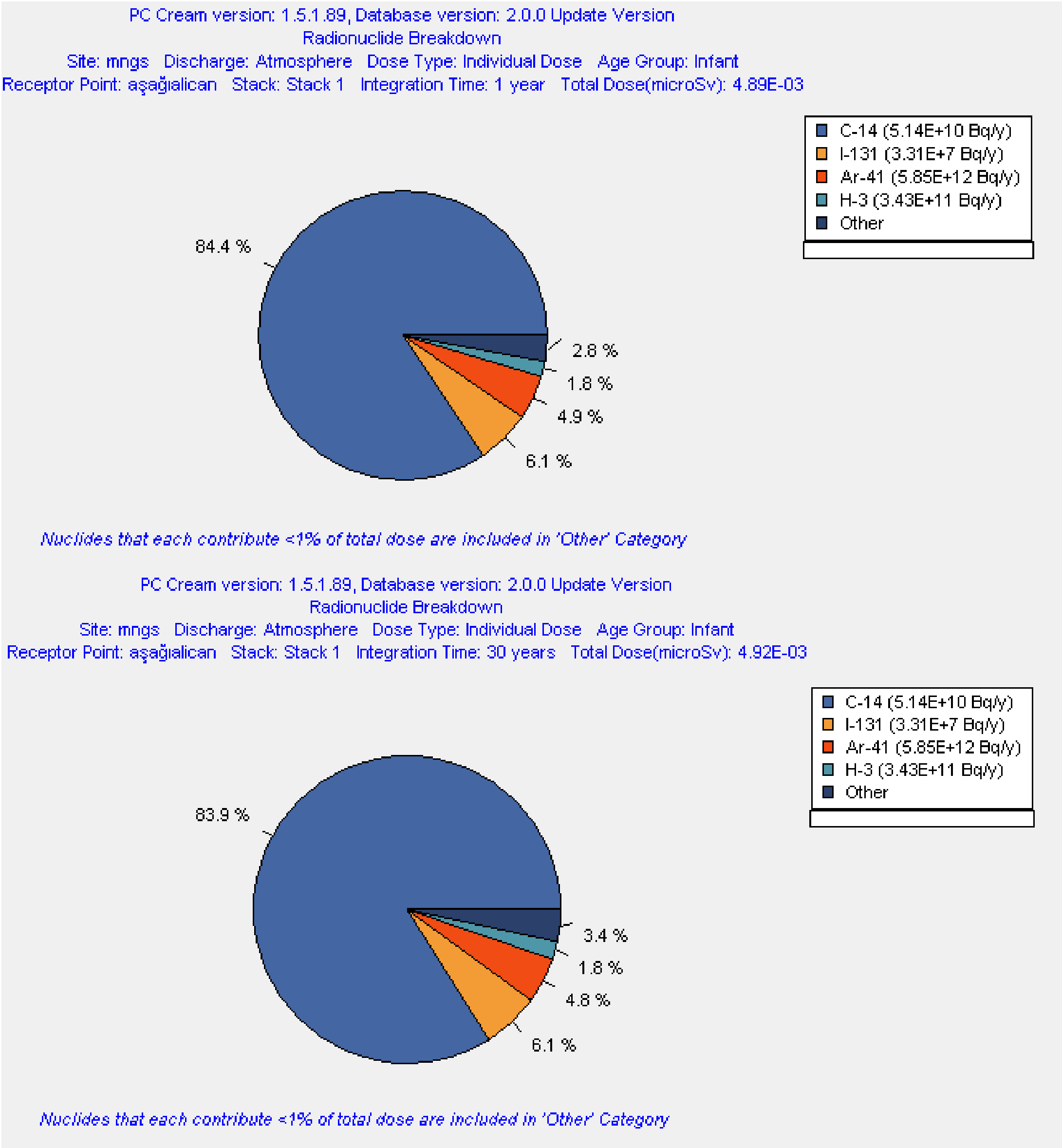


Figure A. 5 Radionuclide distribution in total atmospheric dose for infant in Aşağıalican for 1 year and 30 years integration time

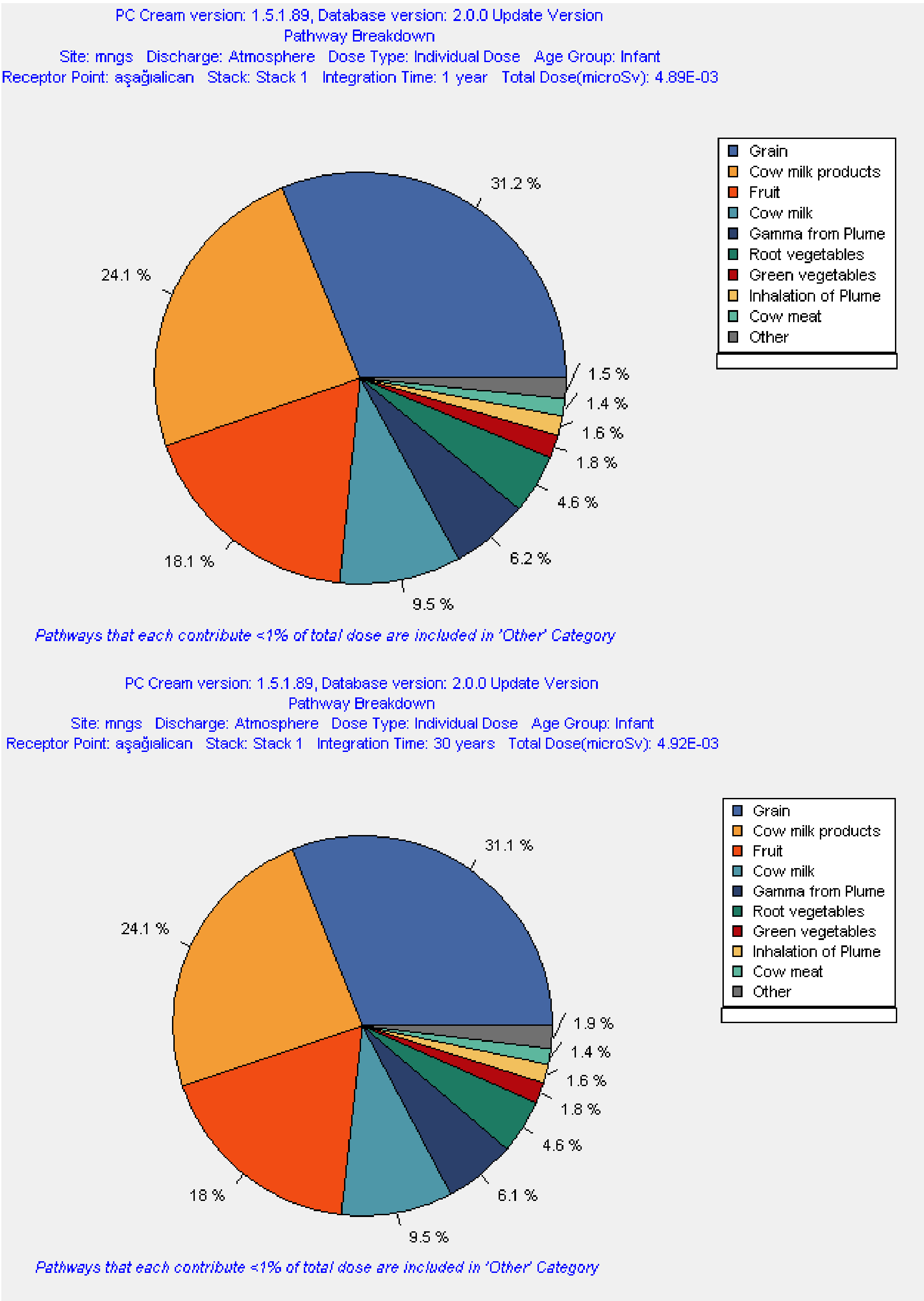


Figure A. 6 Pathway distribution in total atmospheric dose for infant in Aşağıalican for 1 year and 30 years integration time

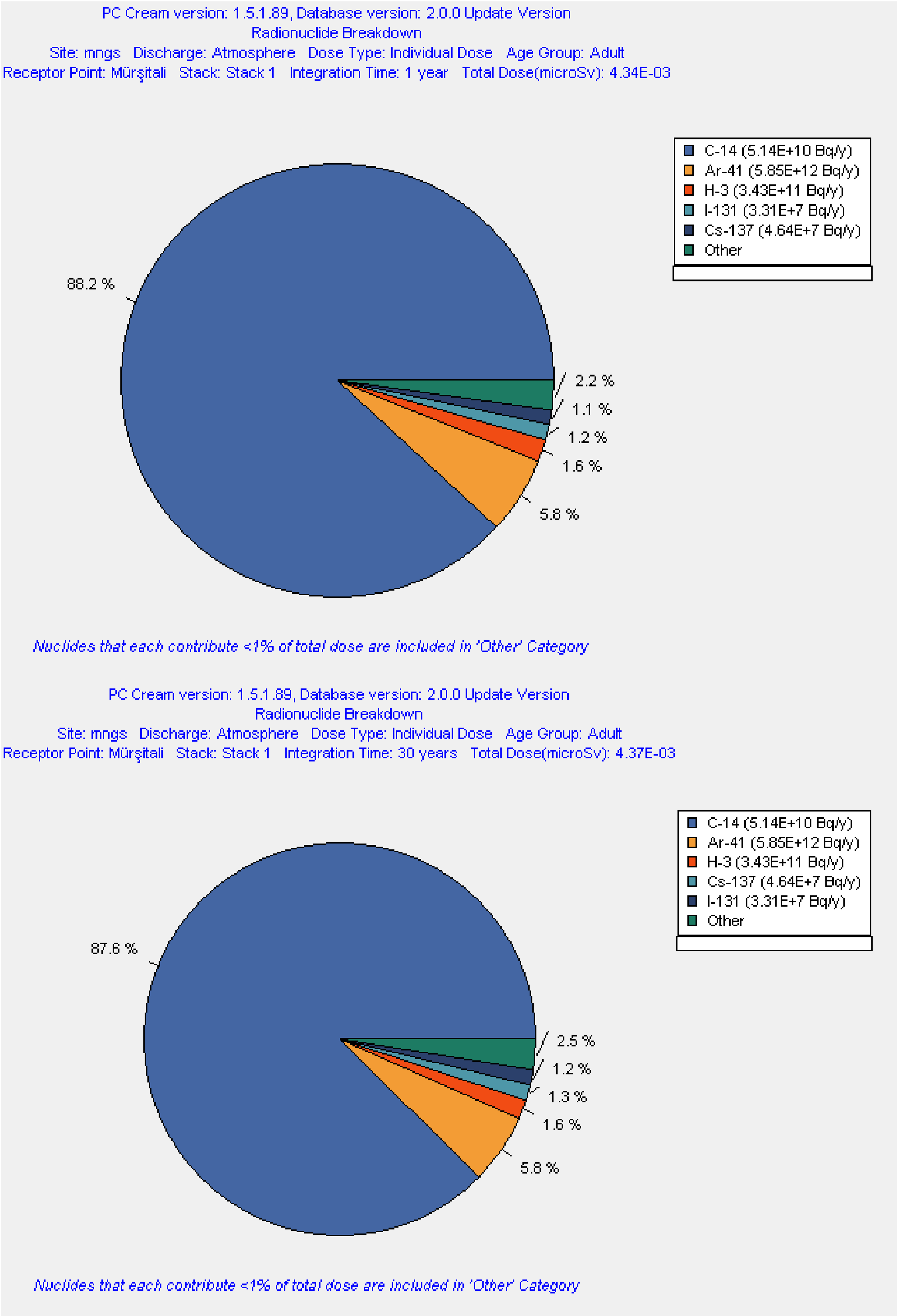


Figure A. 7 Radionuclide distribution in total atmospheric dose for adult in Mürşitali for 1 year and 30 years integration time

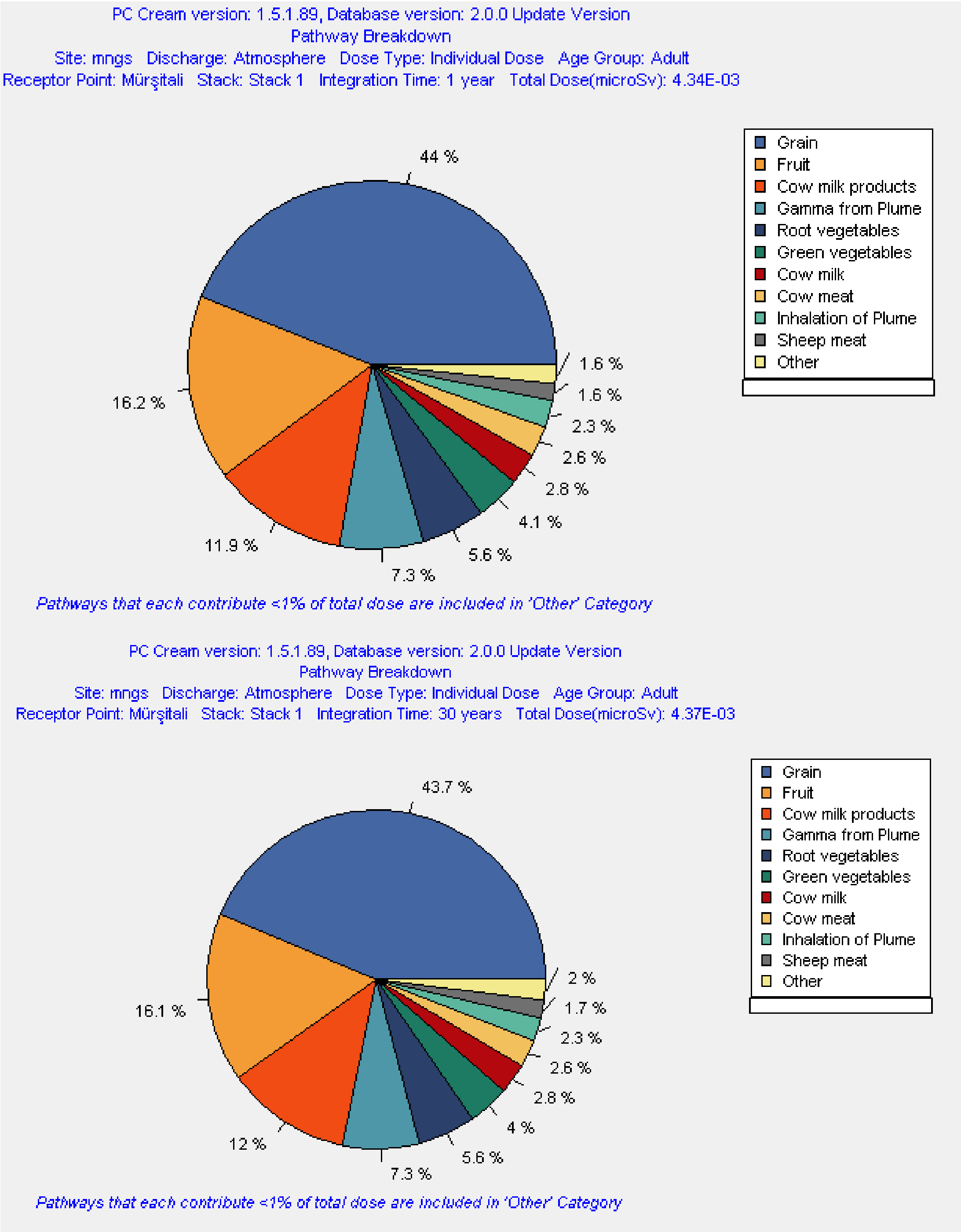
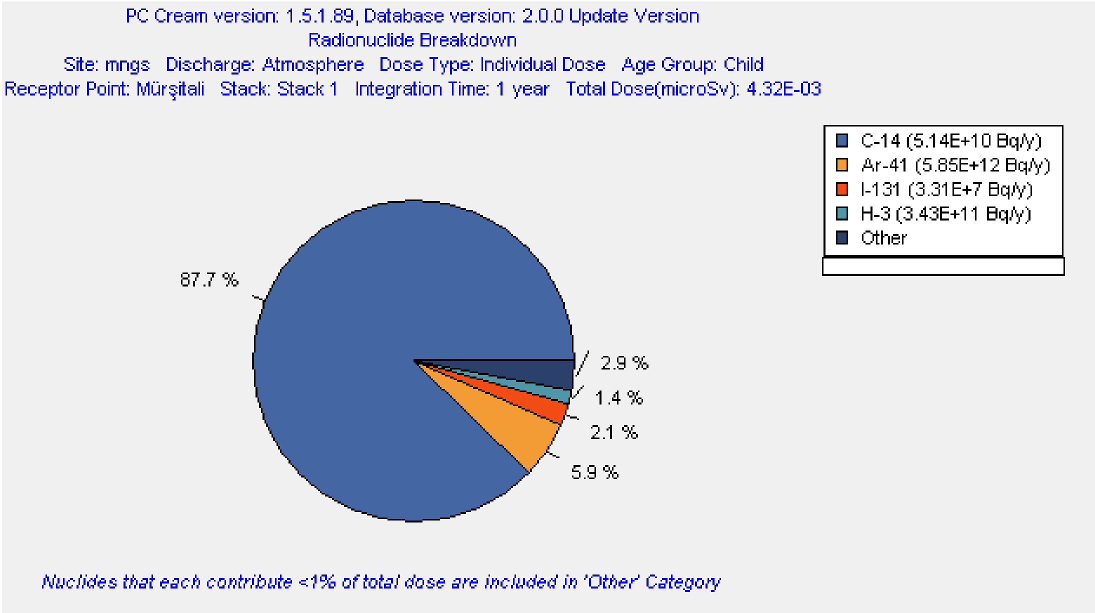


Figure A. 8 Pathway distribution in total atmospheric dose for adult in Mürşitali for 1 year and 30 years integration time



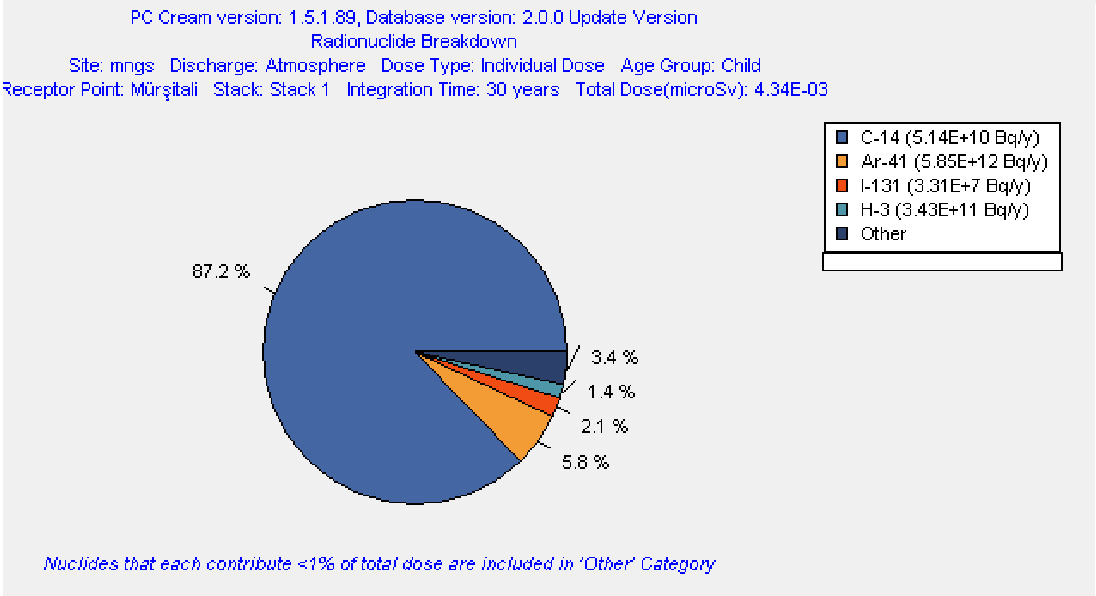


Figure A. 9 Radionuclide distribution in total atmospheric dose for child in Mürşitali for 1 year and 30 years integration time

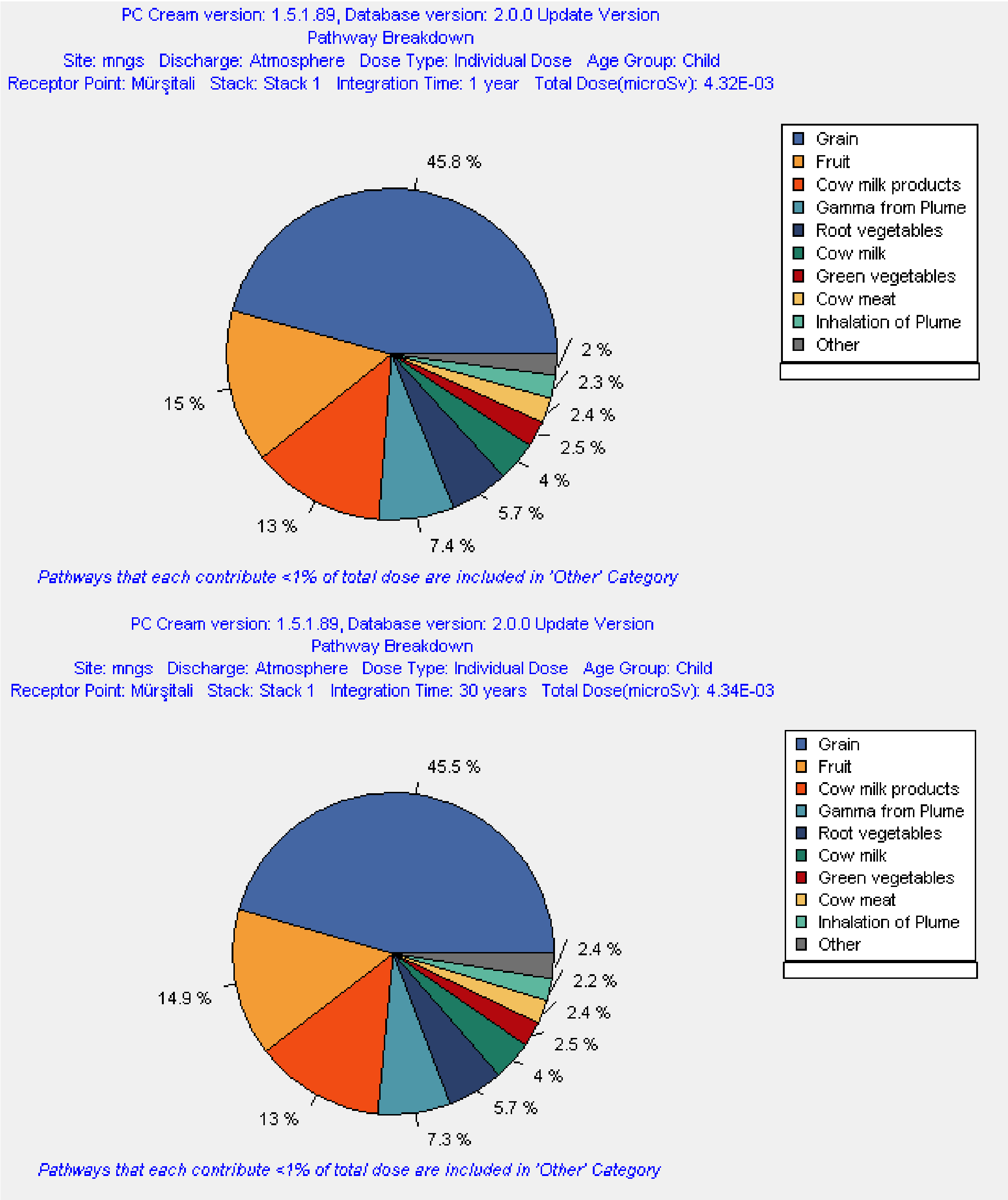


Figure A. 10 Pathway distribution in total atmospheric dose for child in Mürşitali for 1 year and 30 years integration time

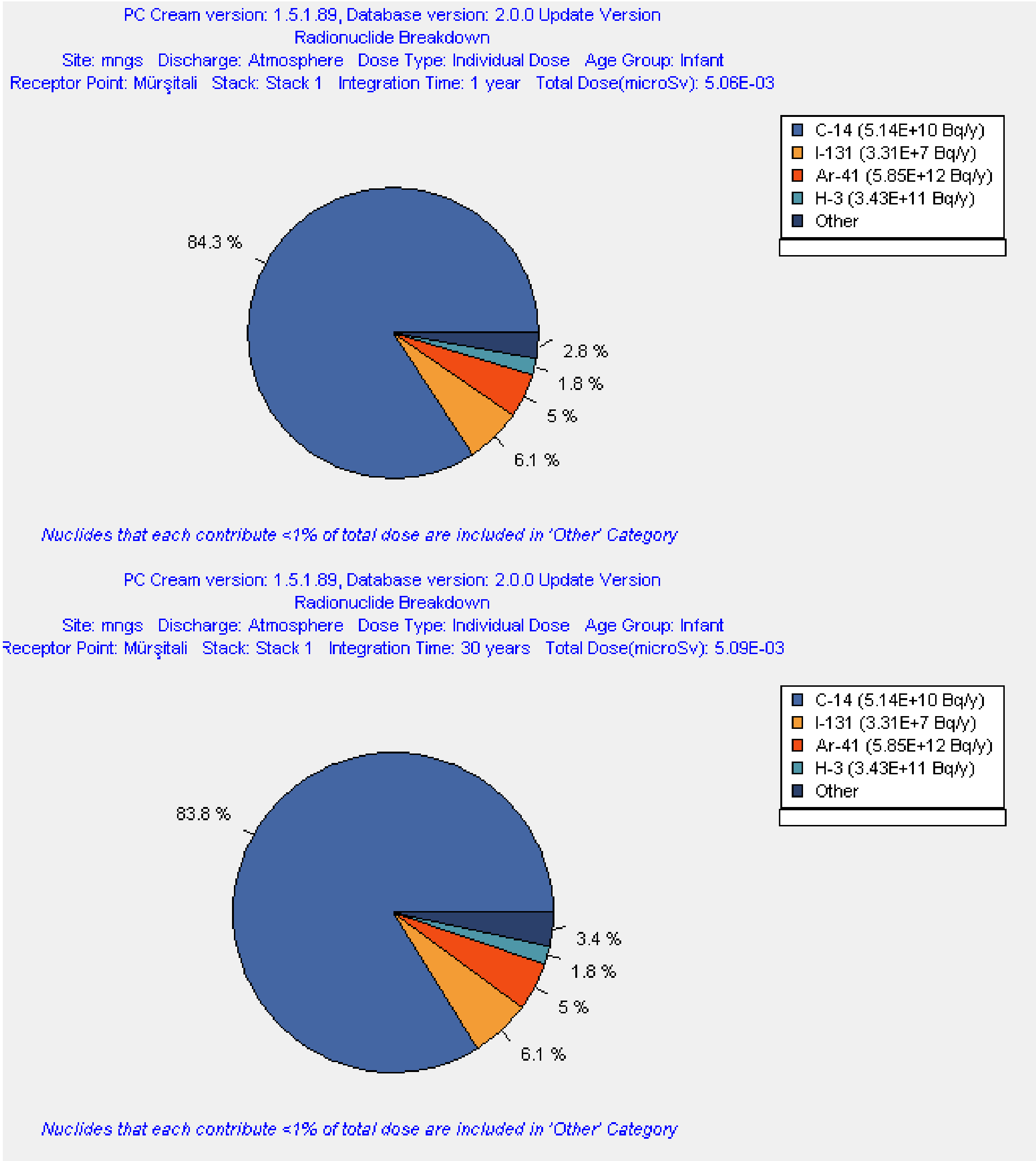


Figure A. 11 Radionuclide distribution in total atmospheric dose for infant in Mürşitali for 1 year and 30 years integration time

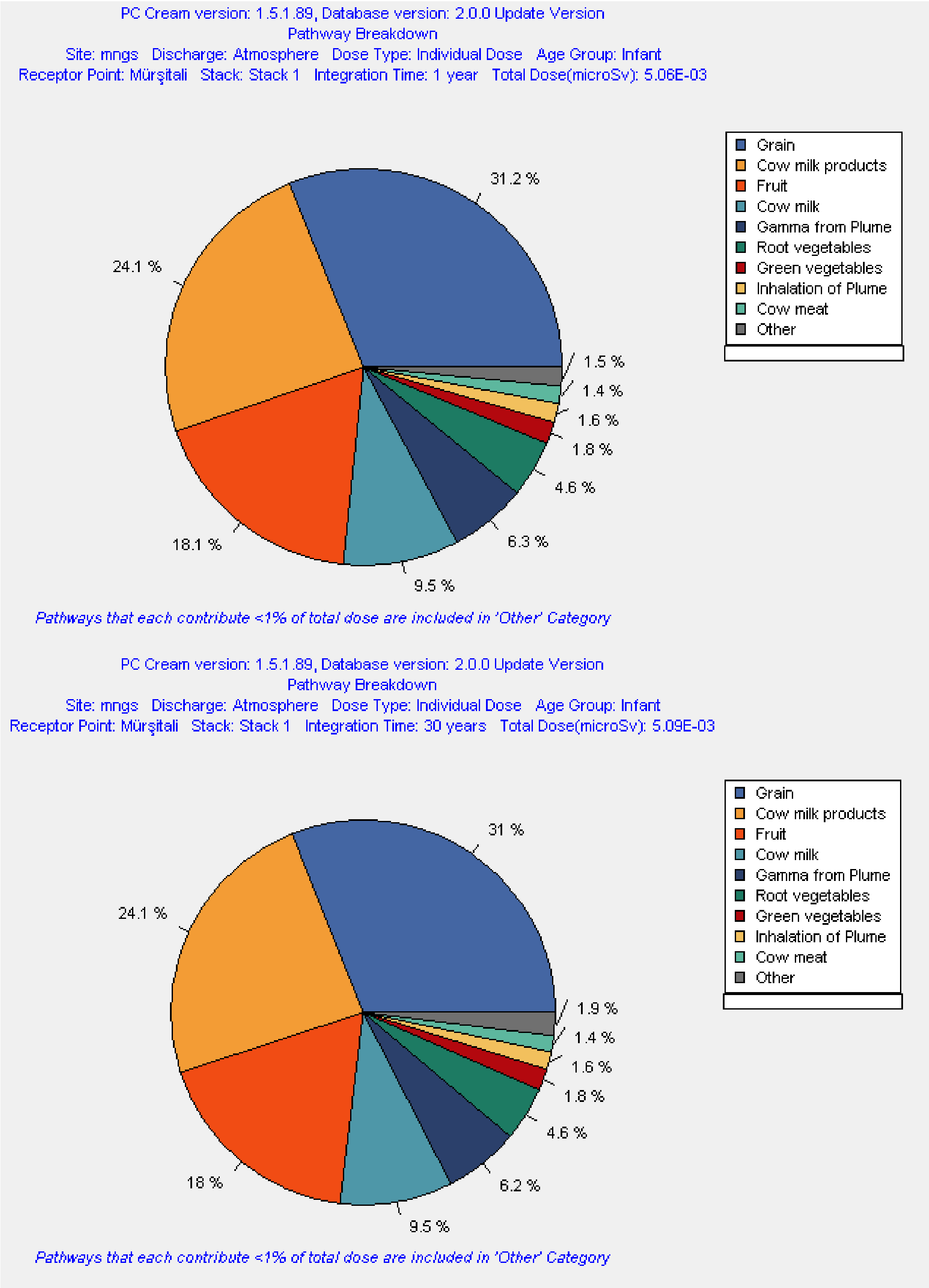
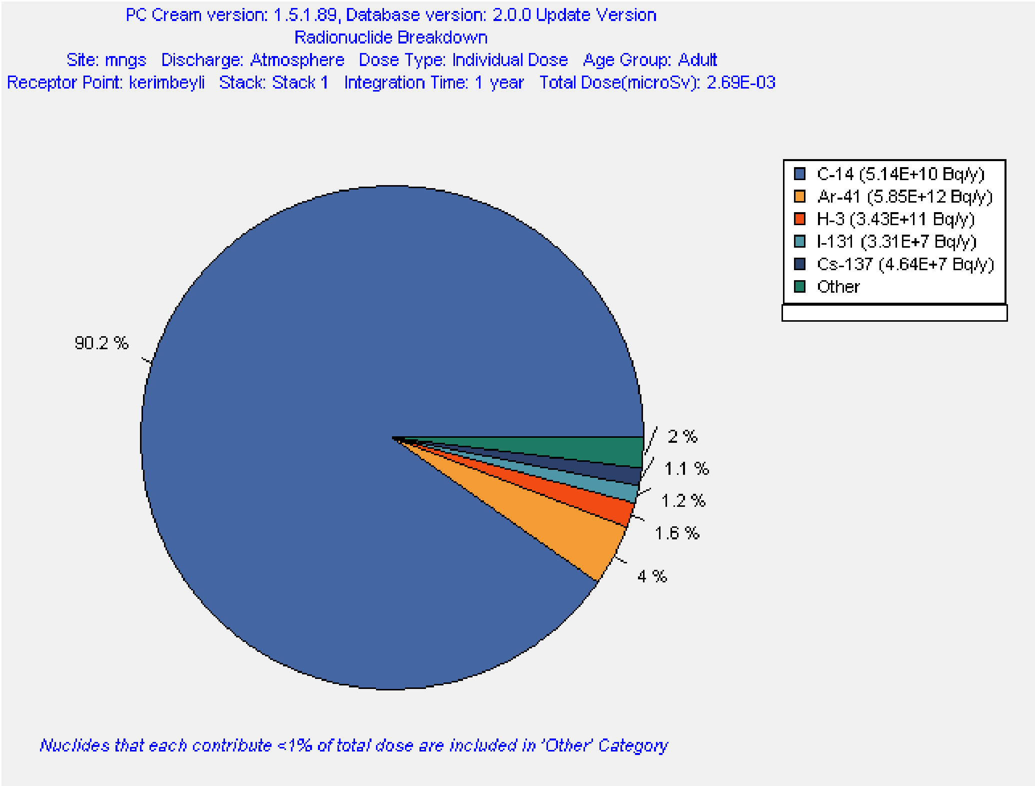


Figure A. 12 Pathway distribution in total atmospheric dose for infant in Mürşitali for 1 year and 30 years integration time



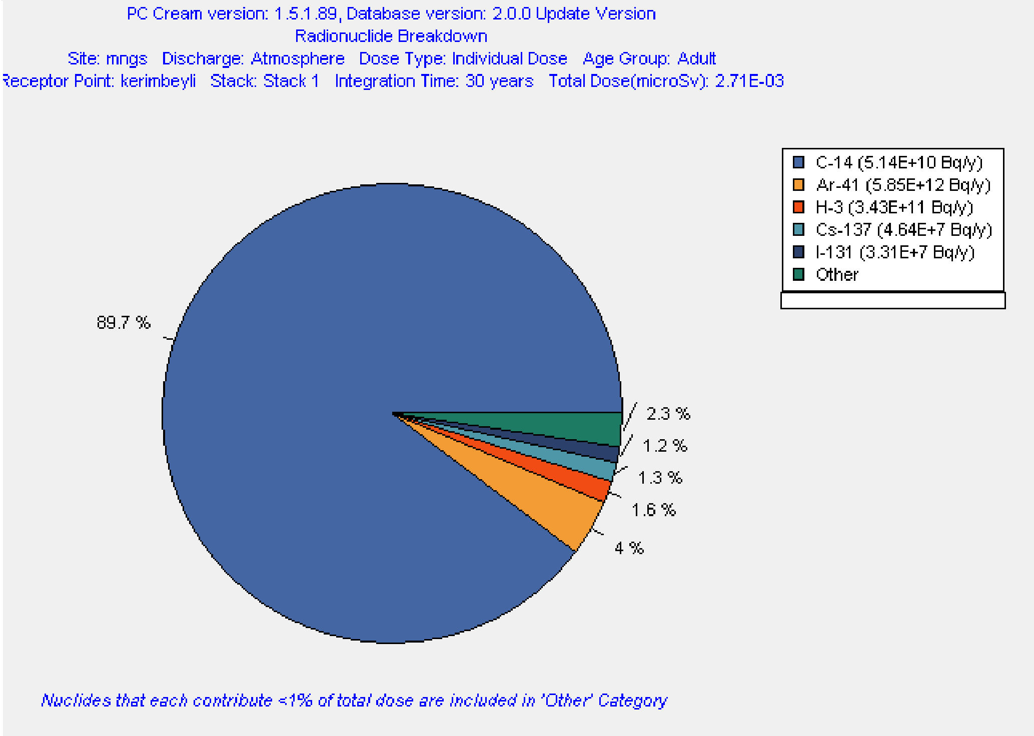


Figure A. 13 Radionuclide distribution in total atmospheric dose for adult in Kerimbeyli for 1 year and 30 years integration time

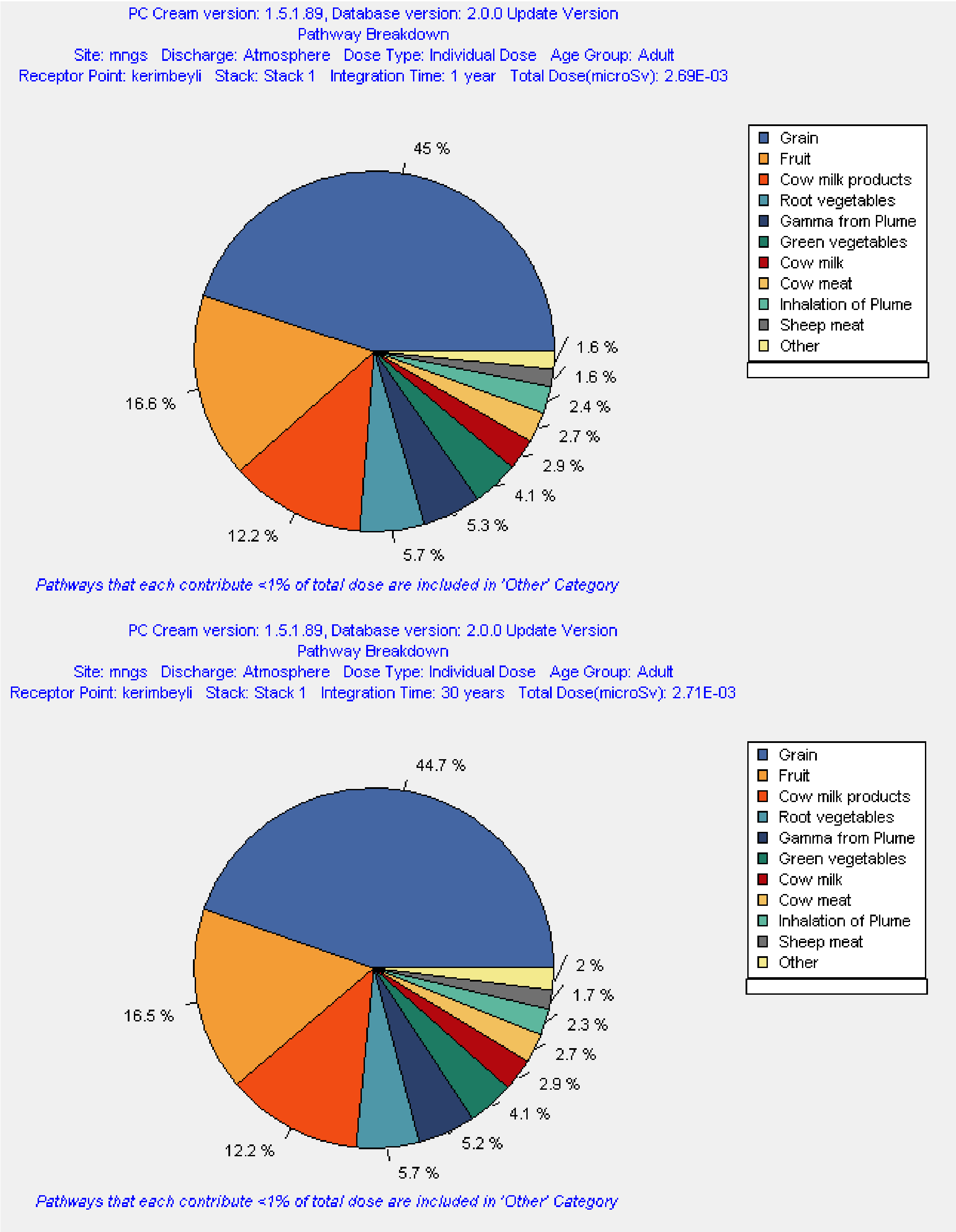


Figure A. 14 Pathway distribution in total atmospheric dose for adult in Kerimbeyli for 1 year and 30 years integration time

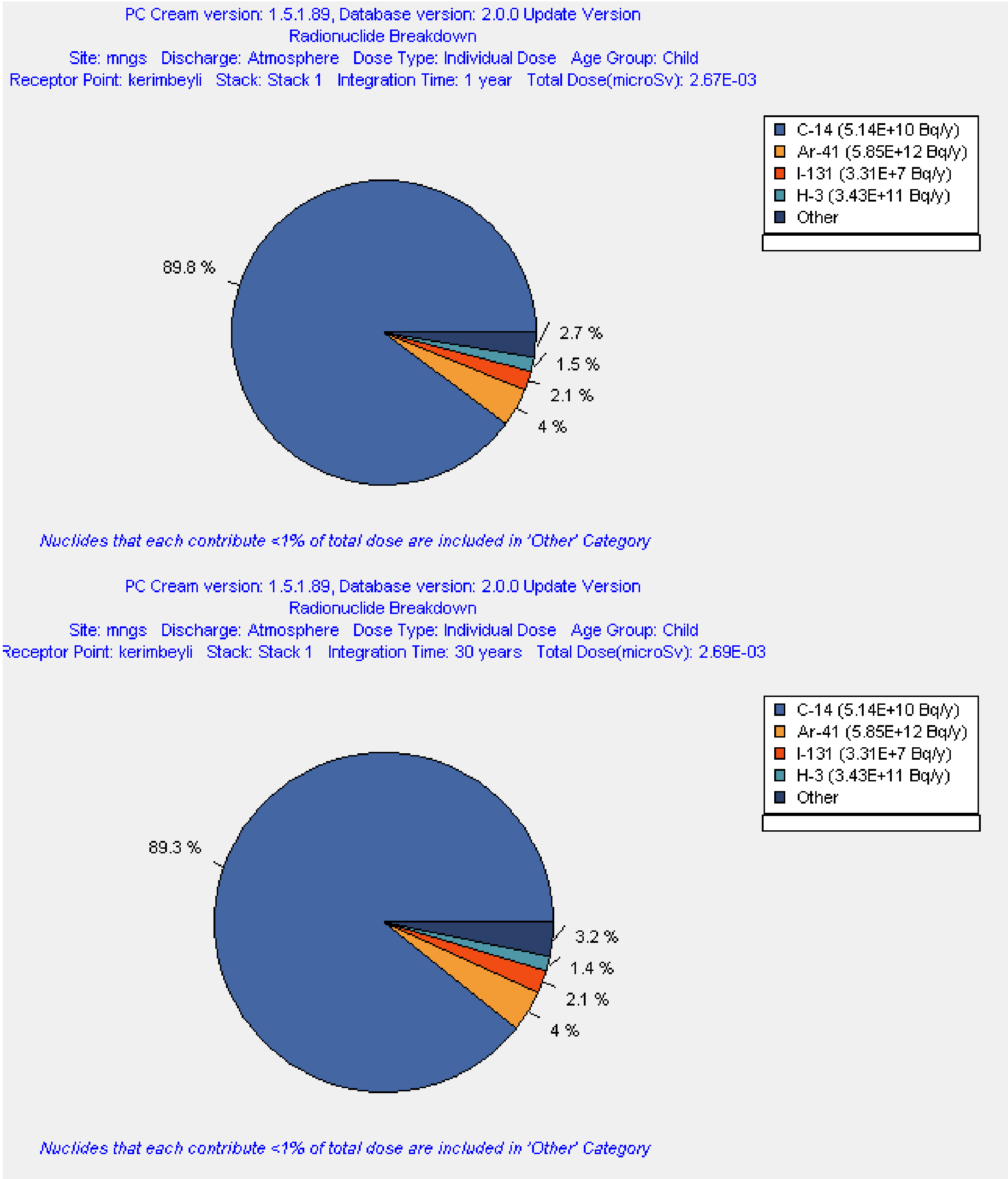


Figure A. 15 Radionuclide distribution in total atmospheric dose for child in Kerimbeyli for 1 year and 30 years integration time

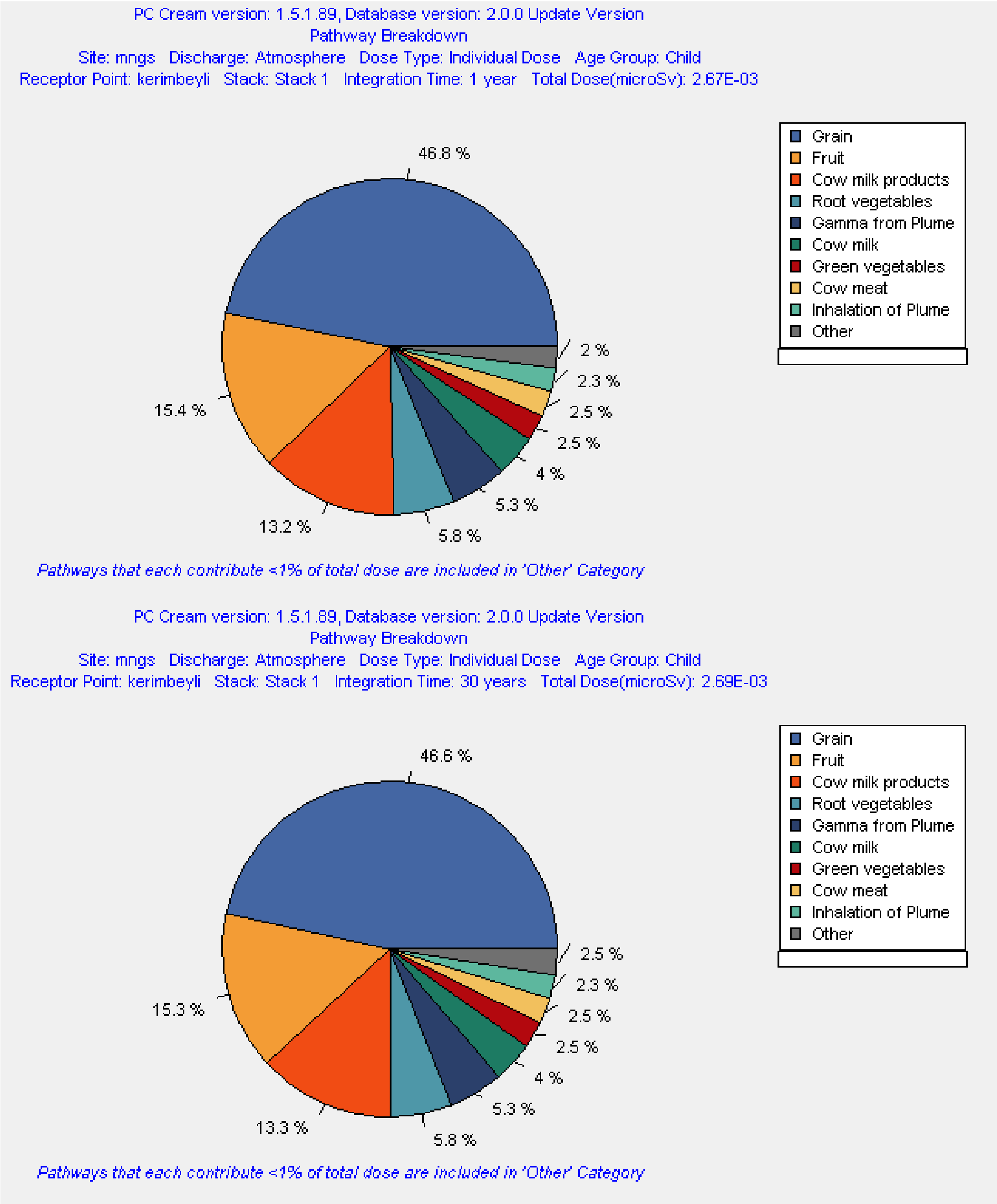


Figure A. 16 Pathway distribution in total atmospheric dose for child in Kerimbeyli for 1 year and 30 years integration time

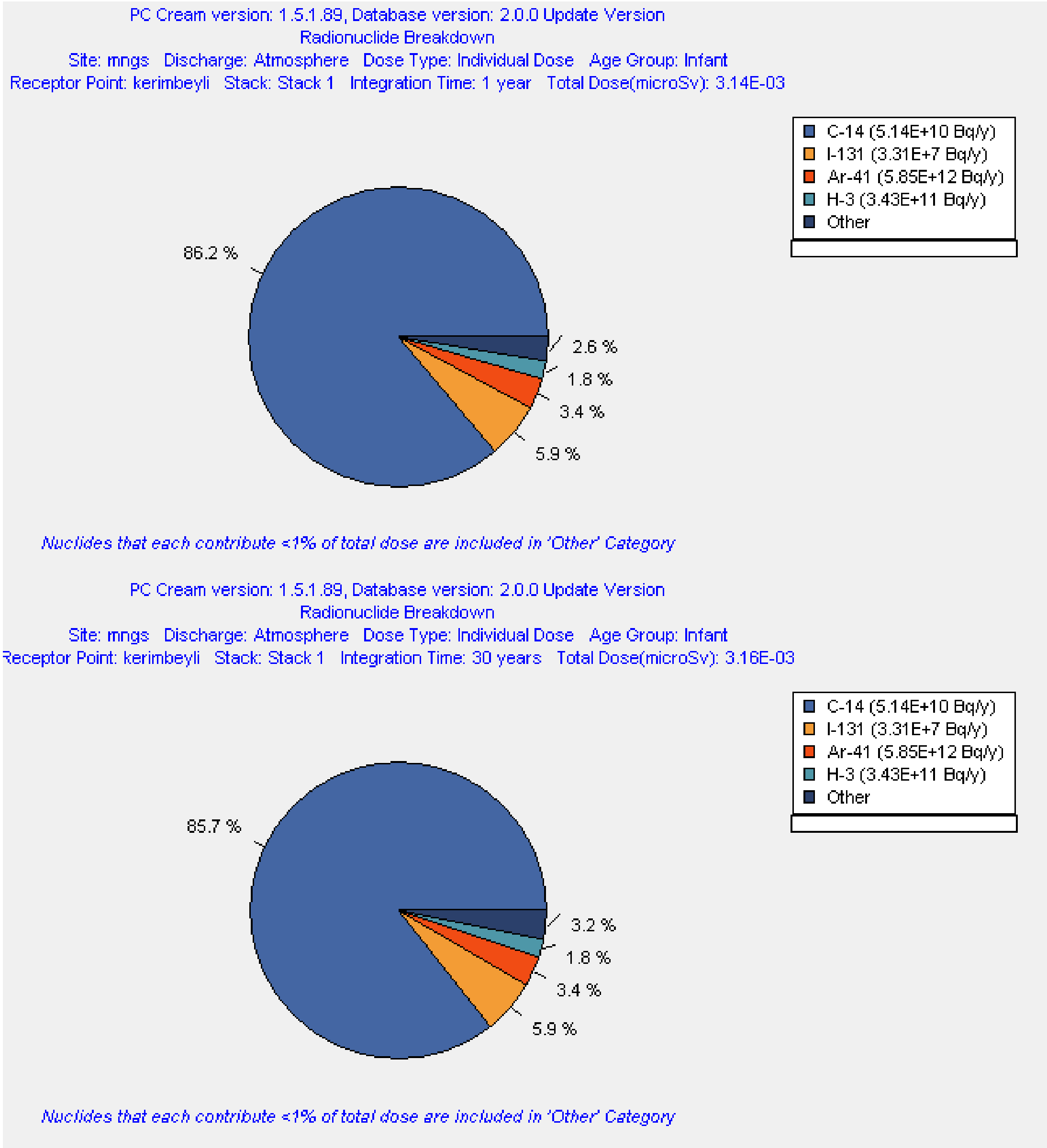


Figure A. 17 Radionuclide distribution in total atmospheric dose for infant in Kerimbeyli for 1 year and 30 years integration time

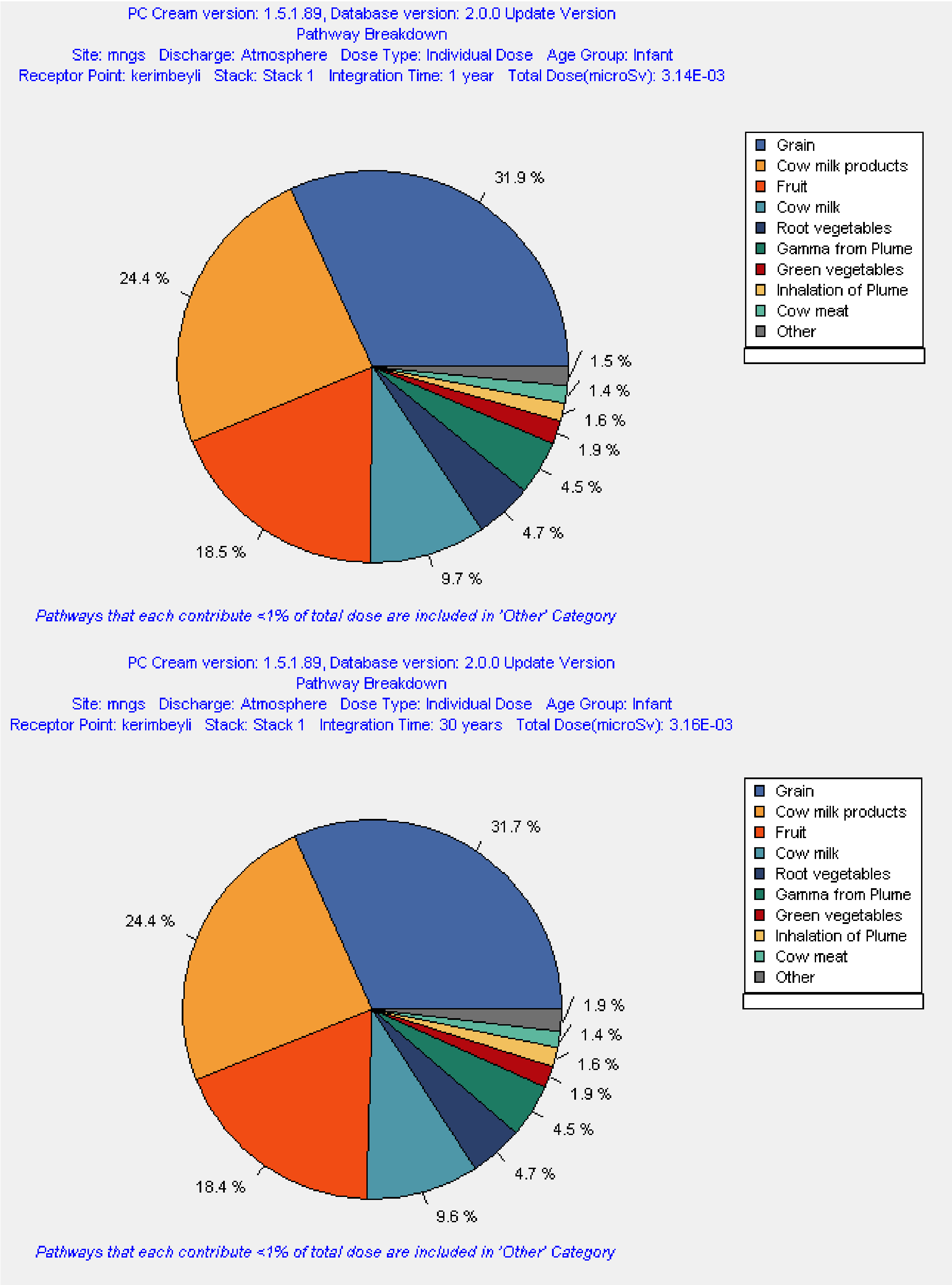


Figure A. 18 Pathway distribution in total atmospheric dose for infant in Kerimbeyli for 1 year and 30 years integration time

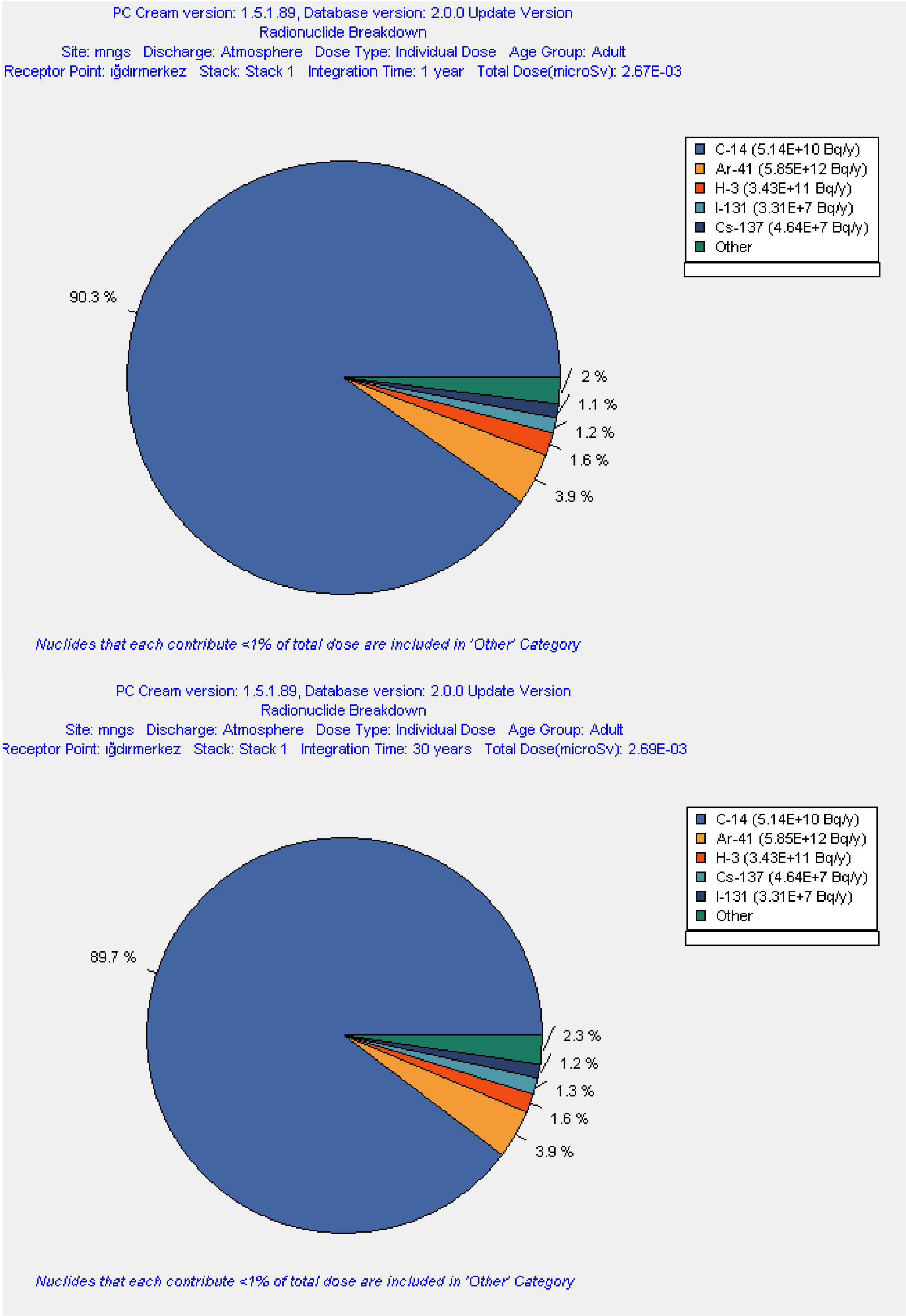


Figure A. 19 Radionuclide distribution in total atmospheric dose for adult in Iğdır center for 1 year and 30 years integration time

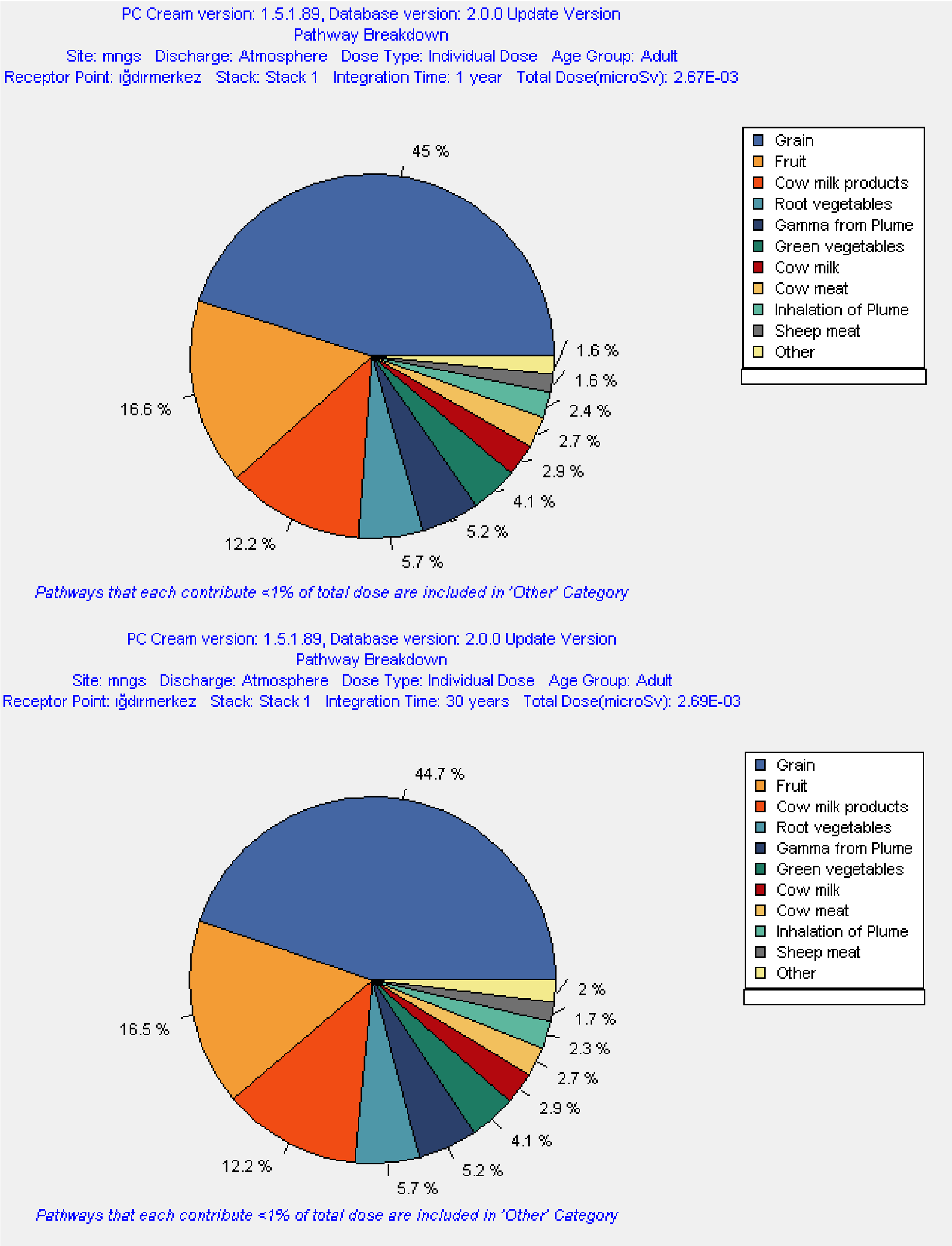


Figure A. 20 Pathway distribution in total atmospheric dose for adult in Iğdır center for 1 year and 30 years integration time

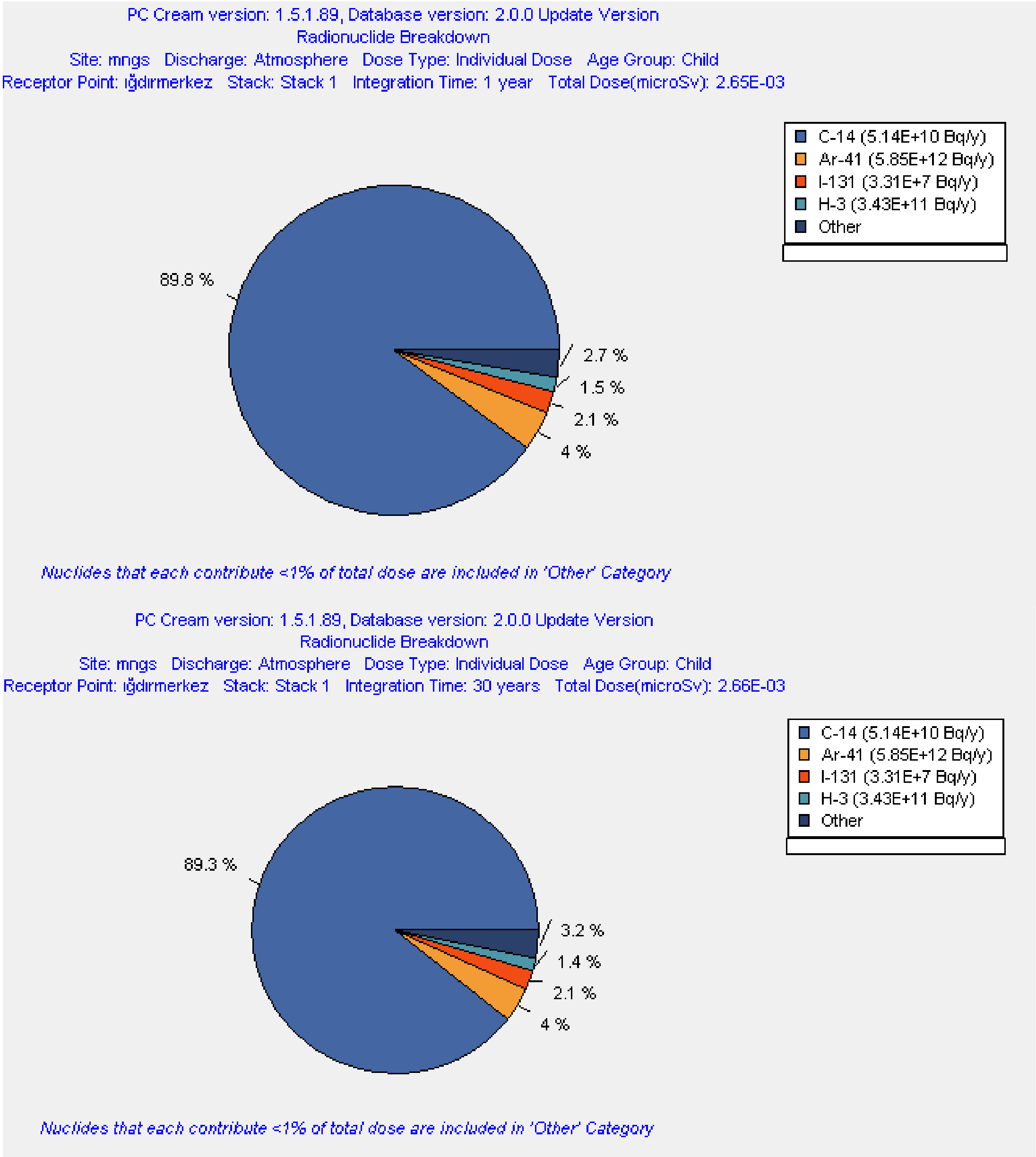


Figure A. 21 Radionuclide distribution in total atmospheric dose for child in Iğdır center for 1 year and 30 years integration time

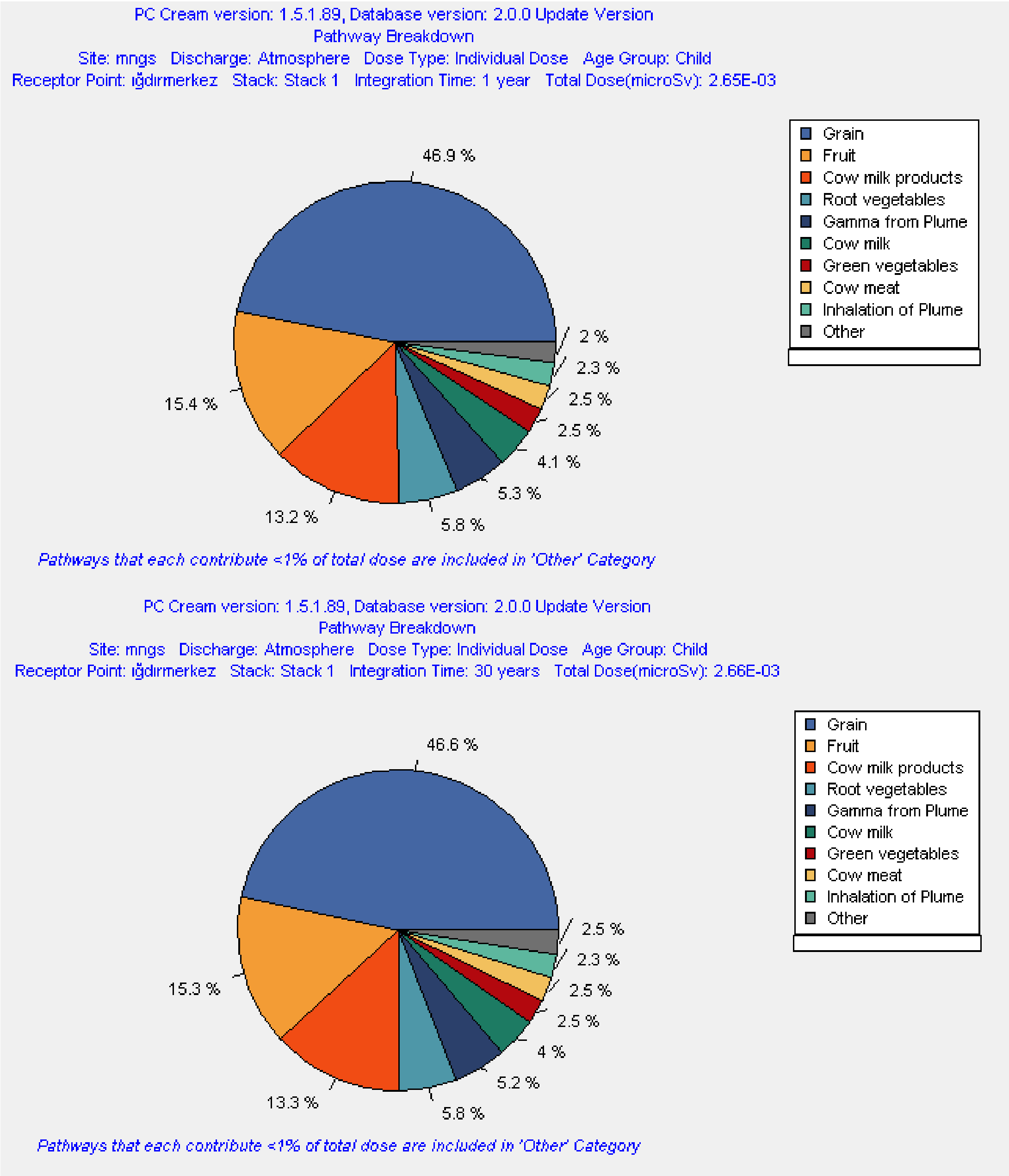


Figure A. 22 Pathway distribution in total atmospheric dose for child in Iğdır center for 1 year and 30 years integration time

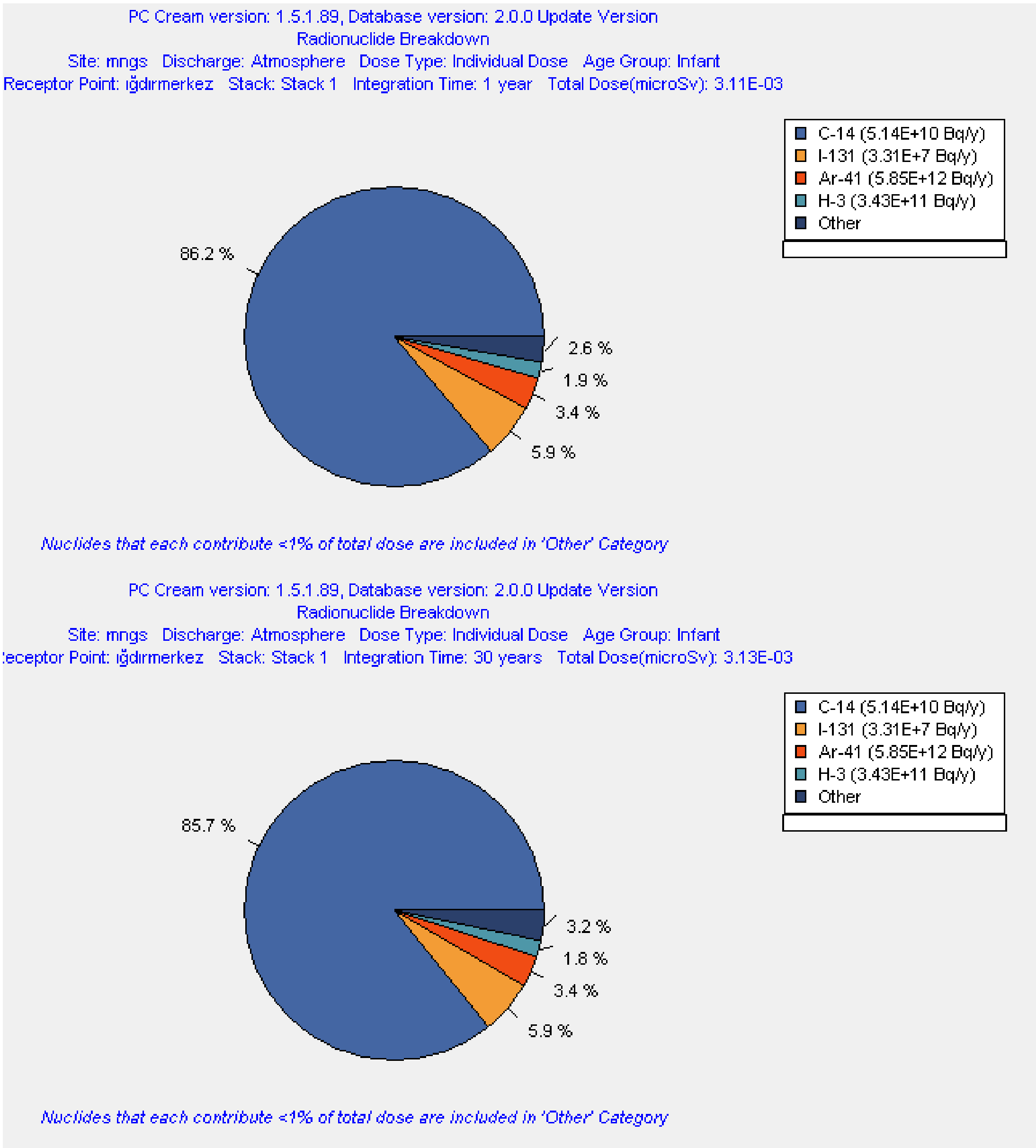


Figure A. 23 Radionuclide distribution in total atmospheric dose for infant in Iğdır center for 1 year and 30 years integration time

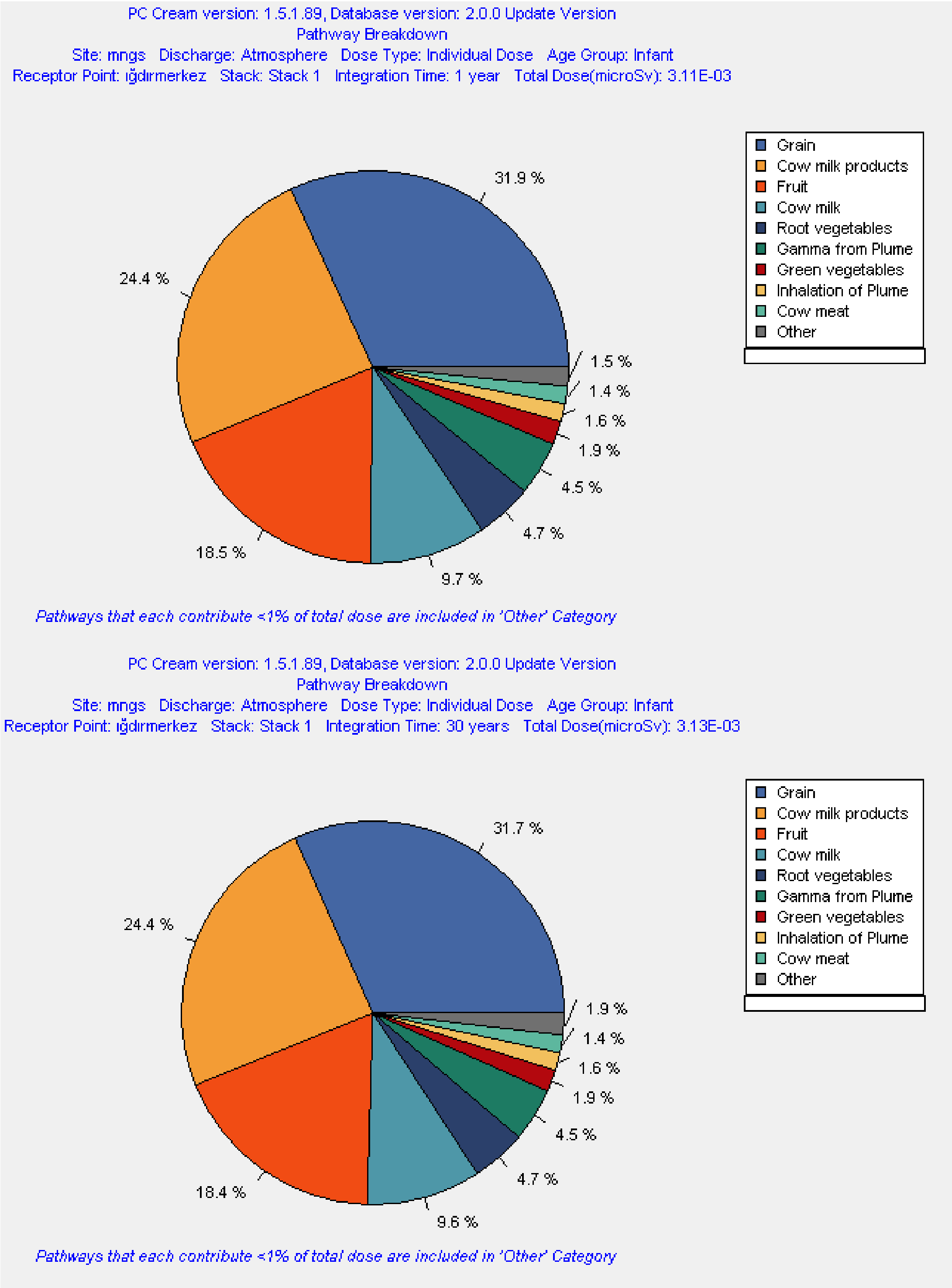
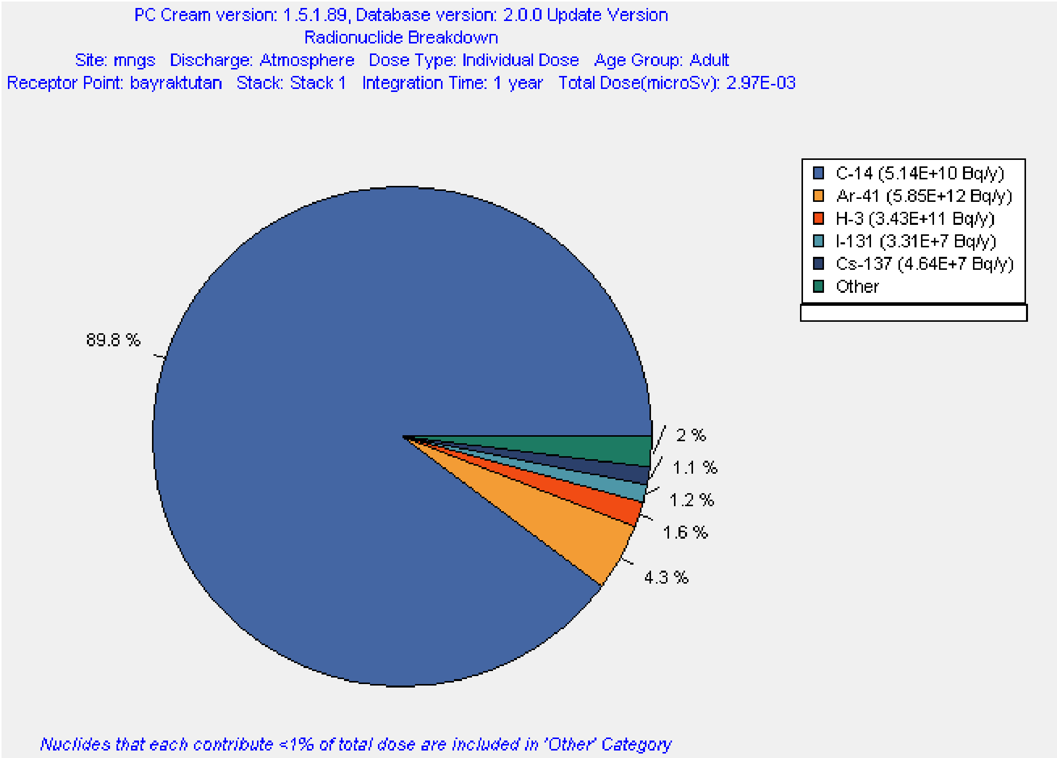


Figure A. 24 Pathway distribution in total atmospheric dose for infant in Iğdır center for 1 year and 30 years integration time



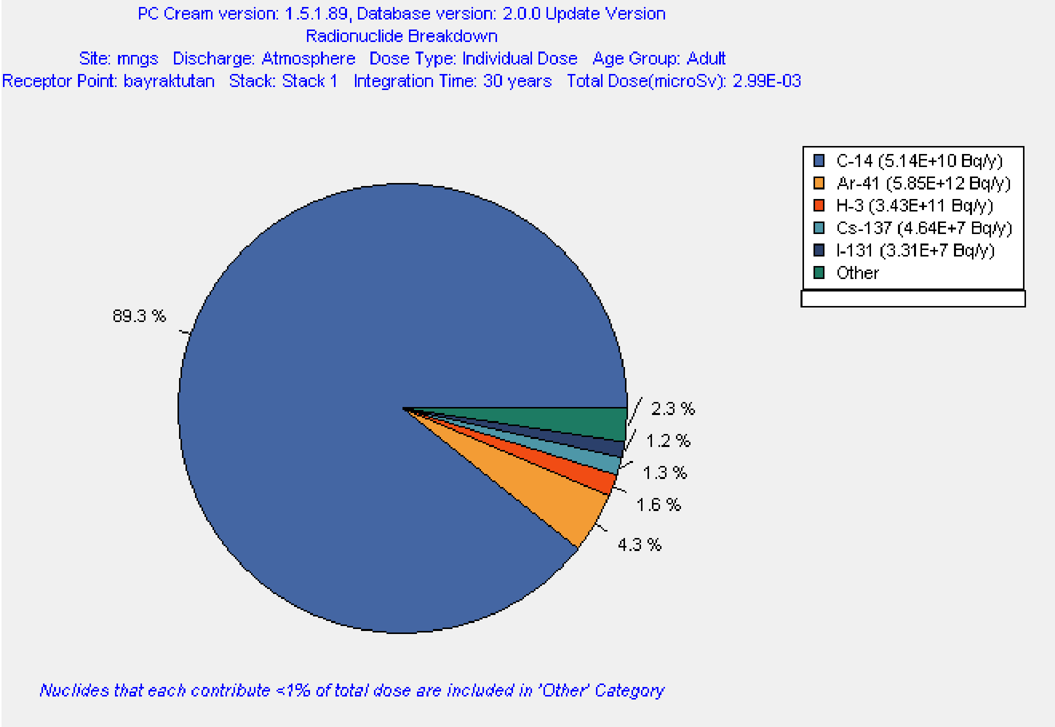


Figure A. 25 Radionuclide distribution in total atmospheric dose for adult in Bayraktutan for 1 year and 30 years integration time

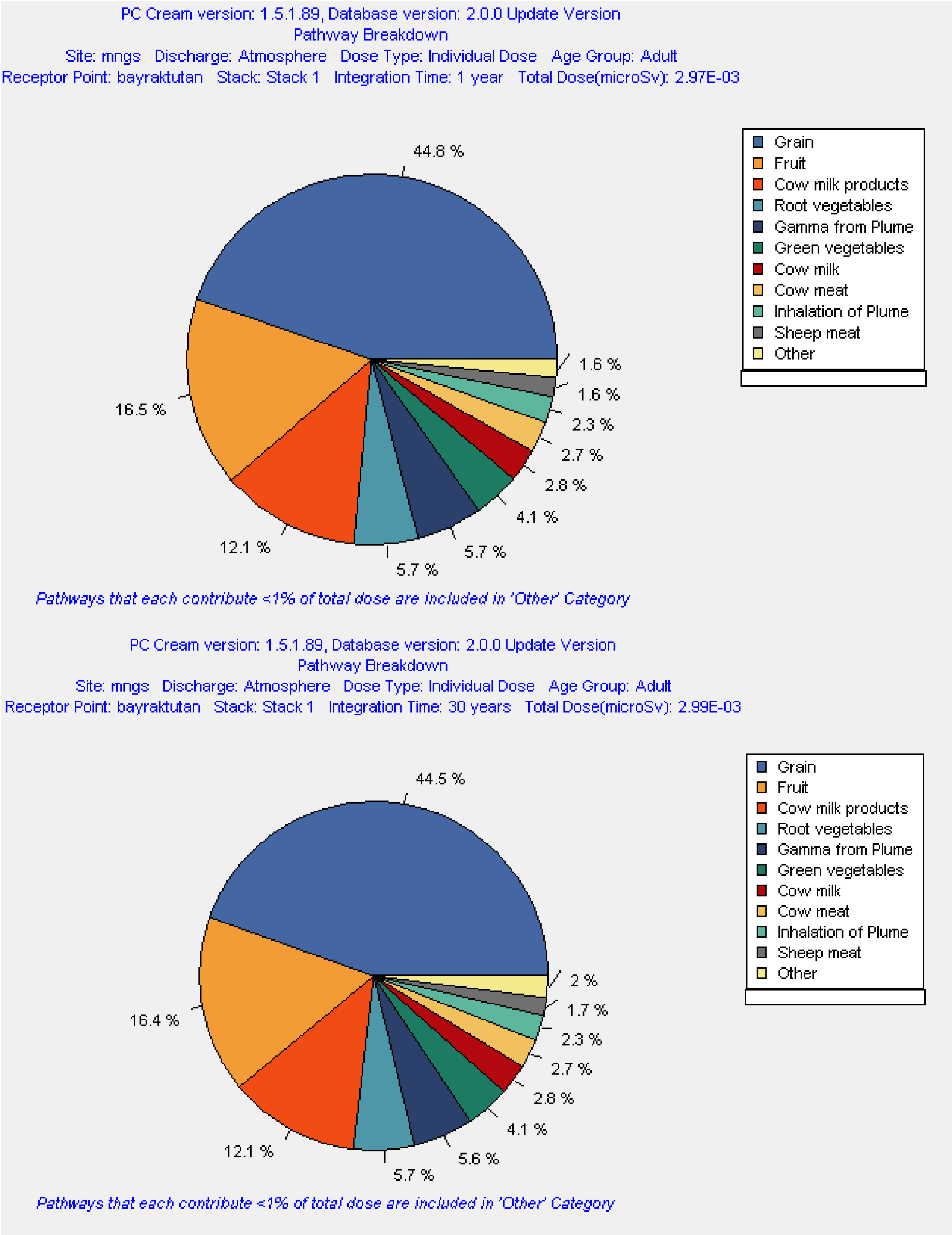


Figure A. 26 Pathway distribution in total atmospheric dose for adult in Bayraktutan for 1 year and 30 years integration time

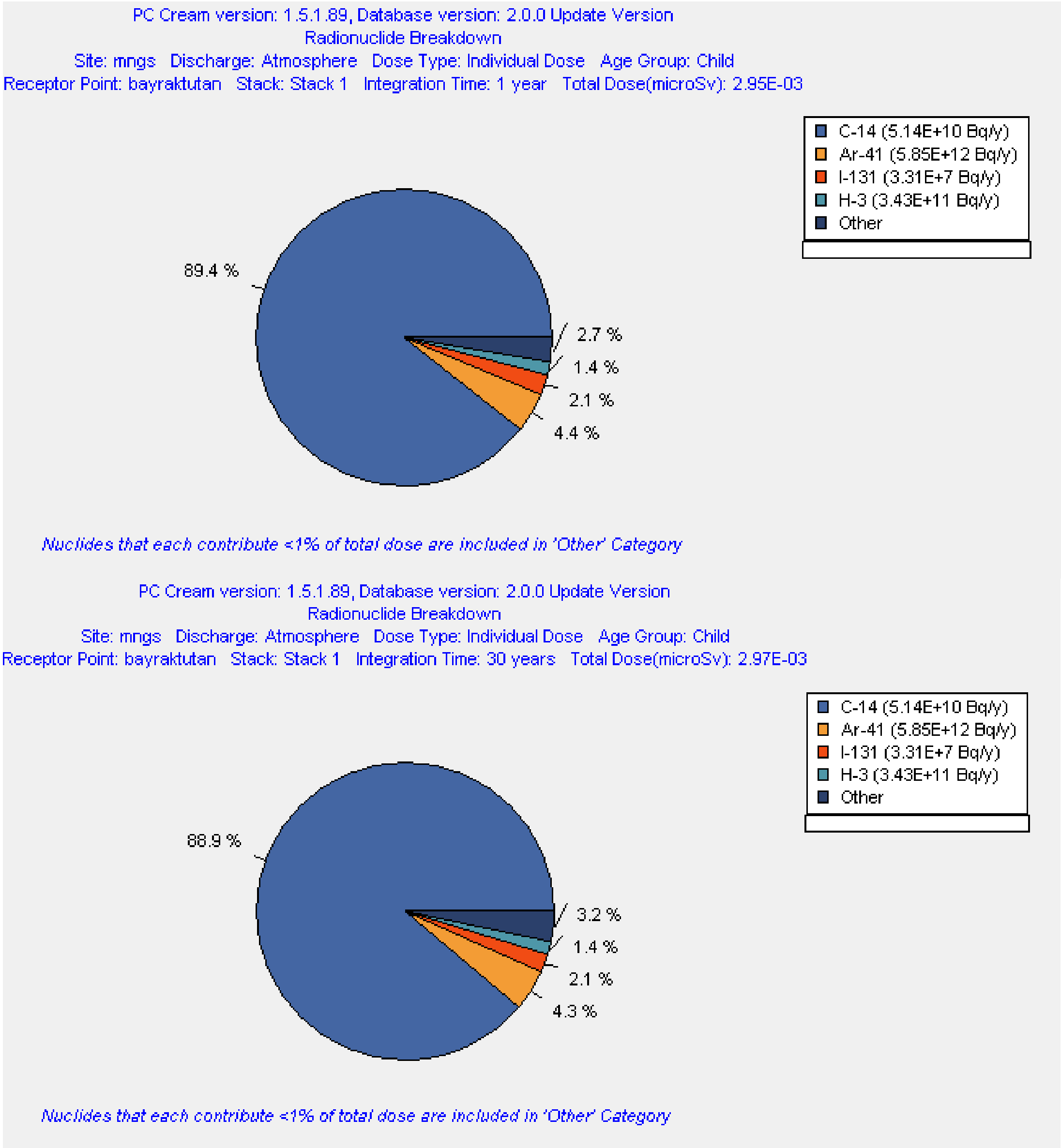
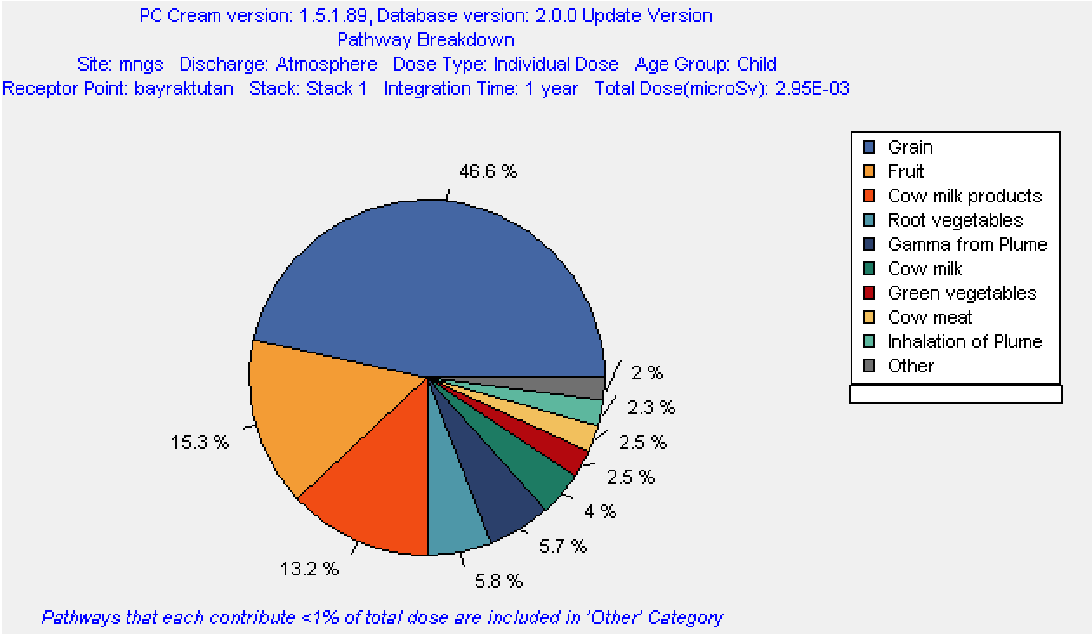


Figure A. 27 Radionuclide distribution in total atmospheric dose for child in Bayraktutan for 1 year and 30 years integration time



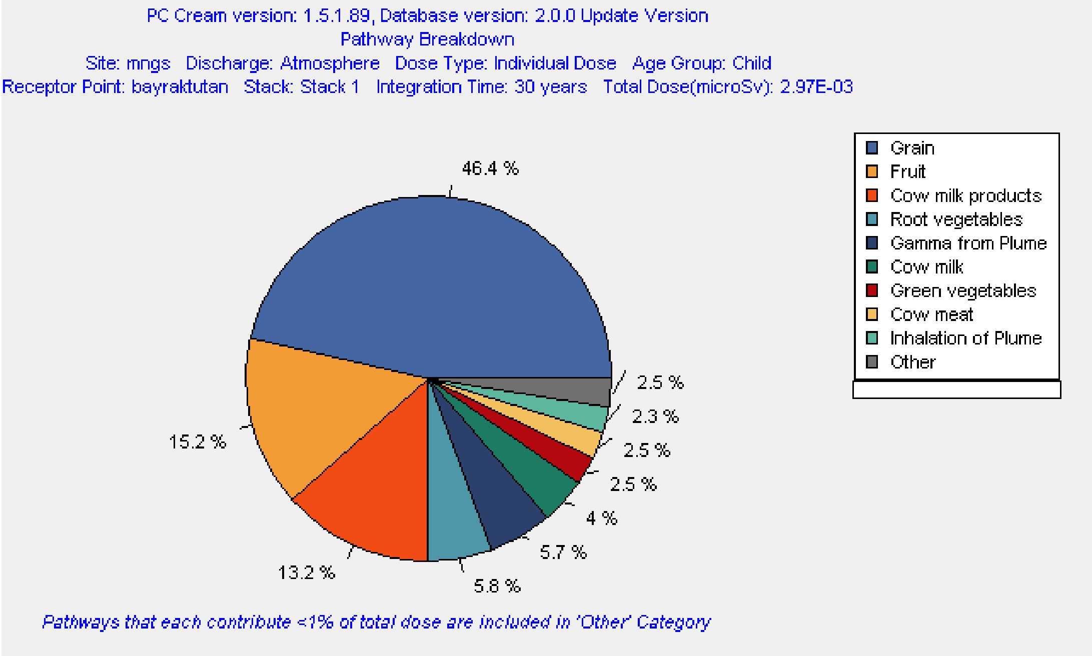


Figure A. 28 Pathway distribution in total atmospheric dose for child in Bayraktutan for 1 year and 30 years integration time

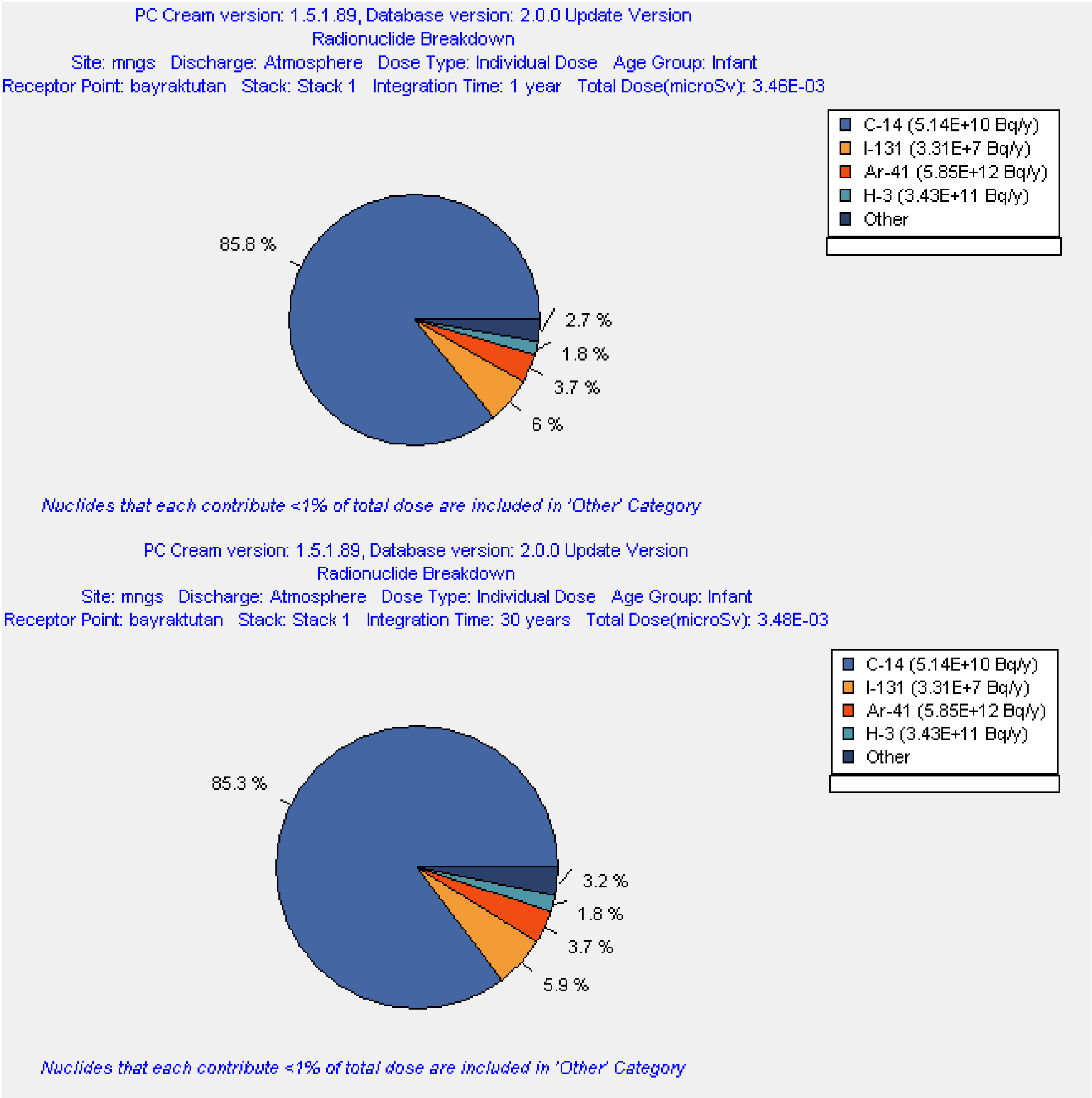


Figure A. 29 Radionuclide distribution in total atmospheric dose for infant in Bayraktutan for 1 year and 30 years integration time

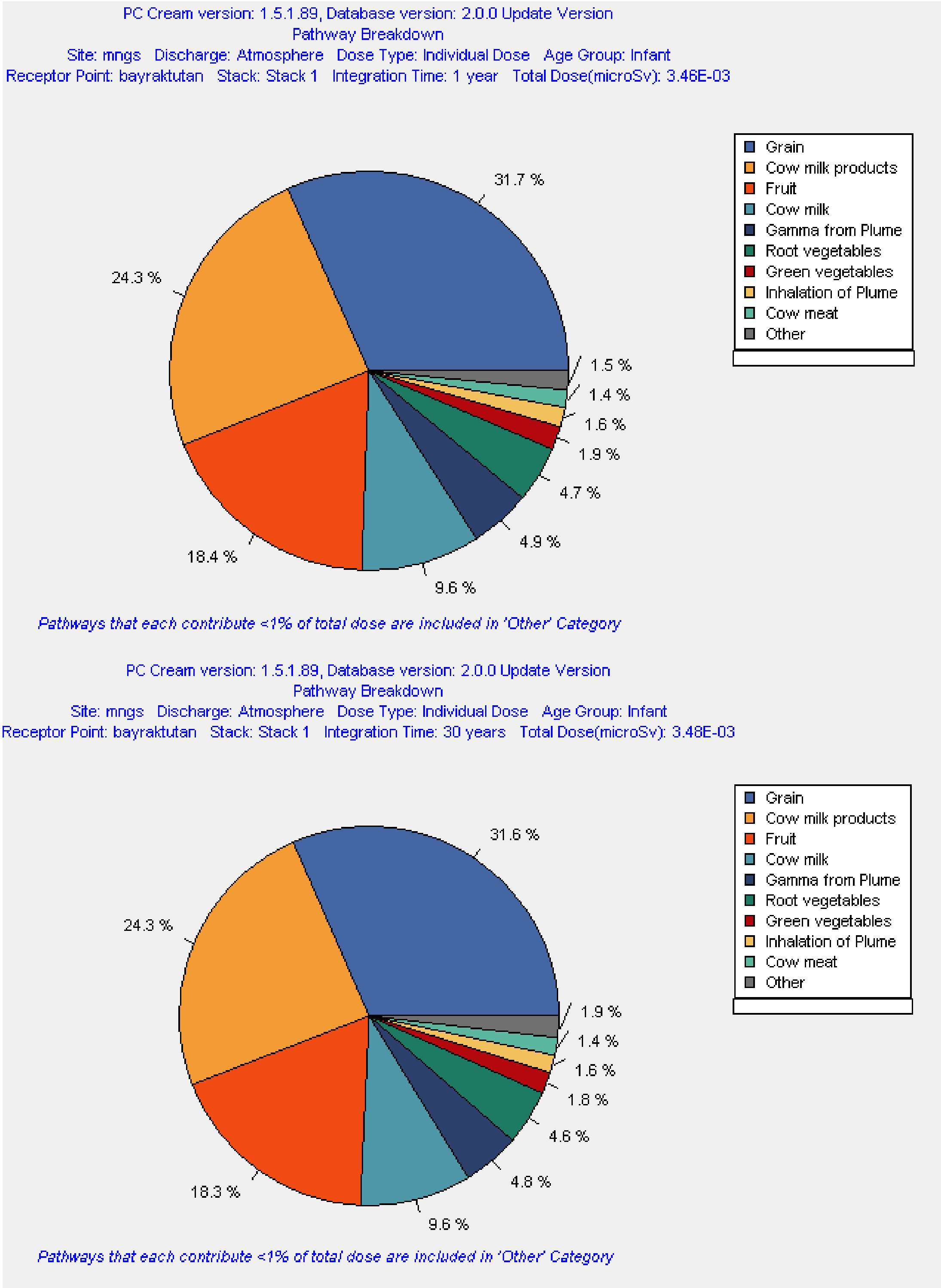


Figure A. 30 Pathway distribution in total atmospheric dose for infant in Bayraktutan for 1 year and 30 years integration time

B. The Results of Scenario 2 for PC CREAM 08 Software due to Atmospheric Releases for Public in Province of Iğdır

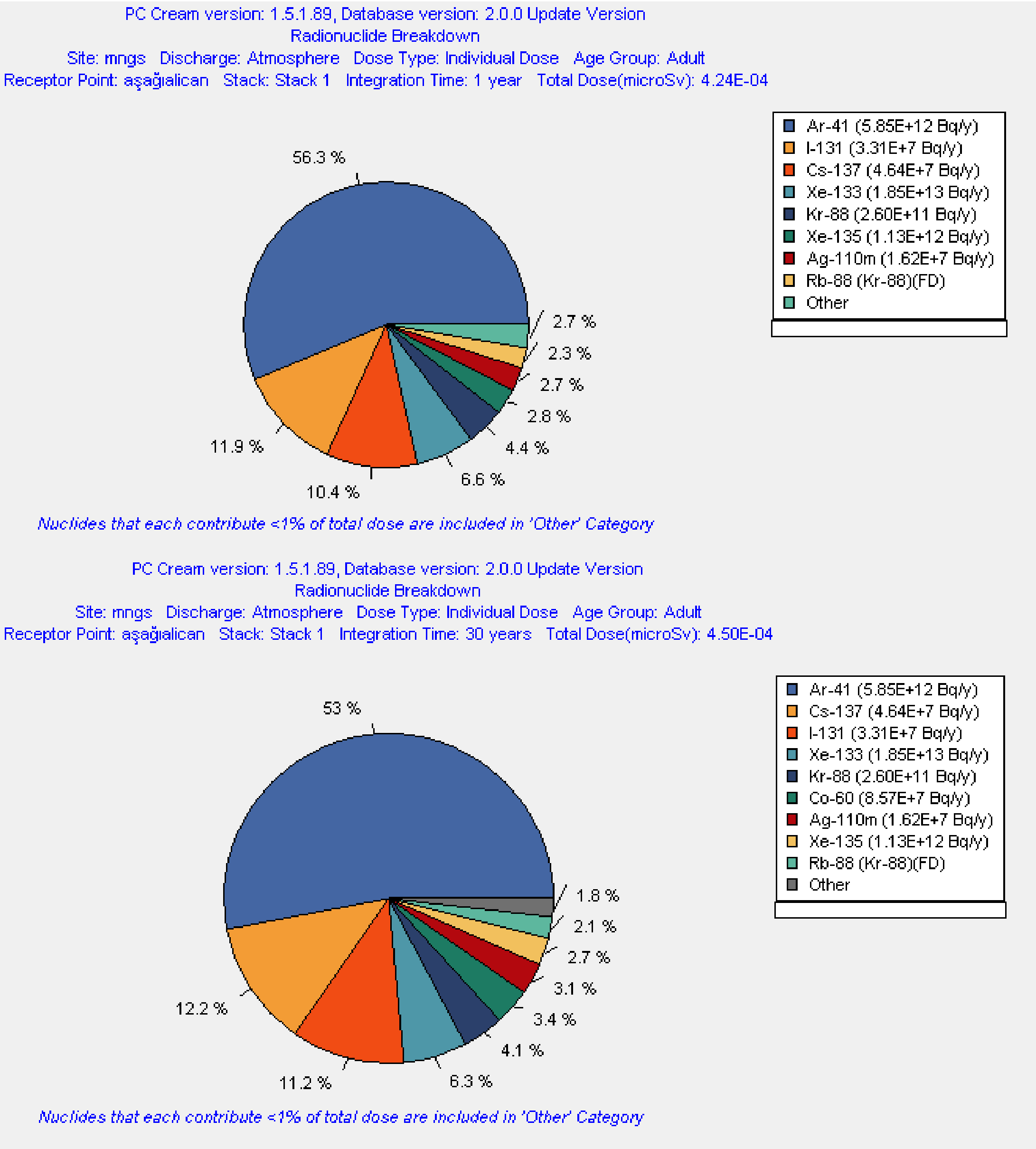


Figure B. 1 Radionuclide distribution in total atmospheric dose for adult in Aşağıalican for 1 year and 30 years integration time

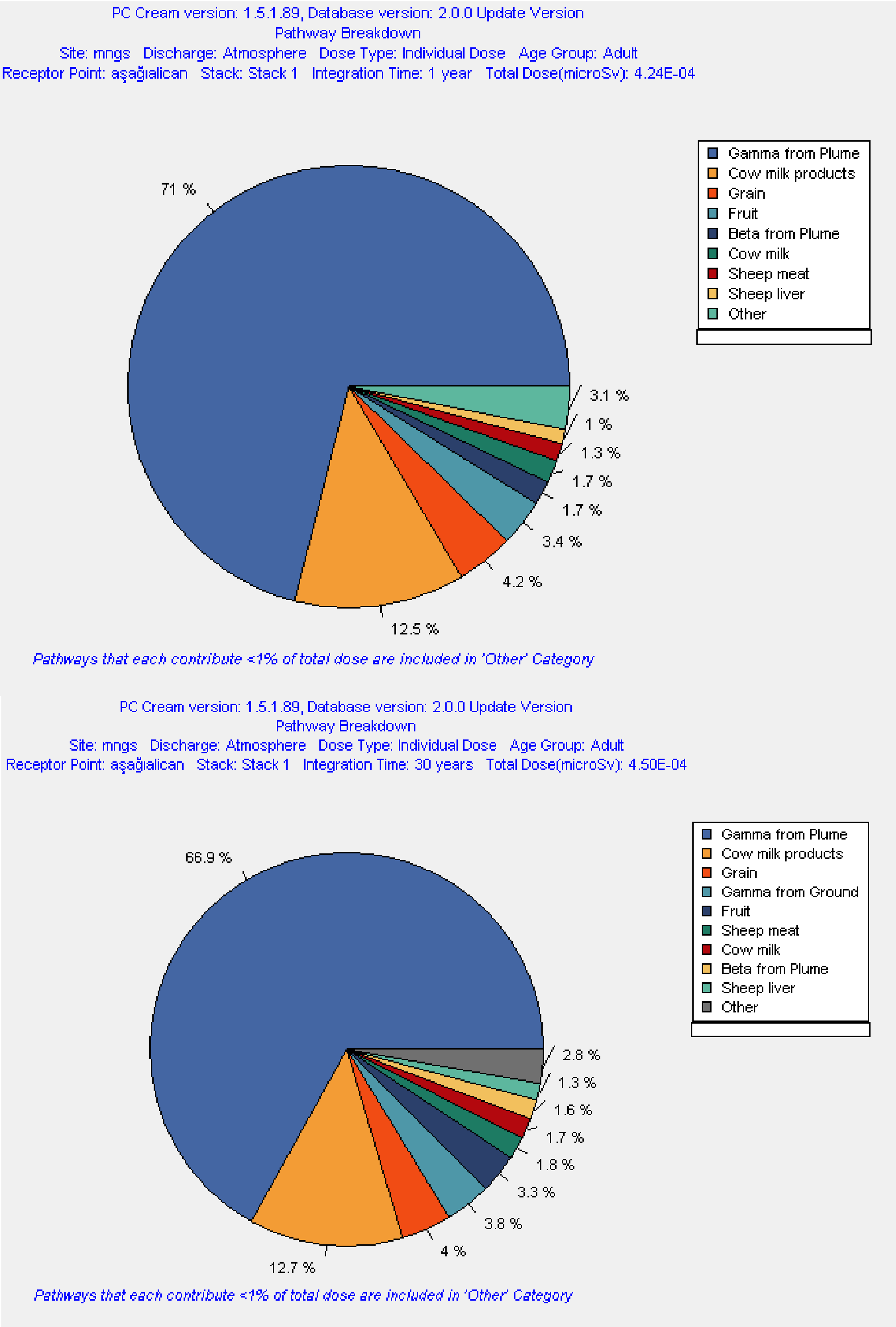
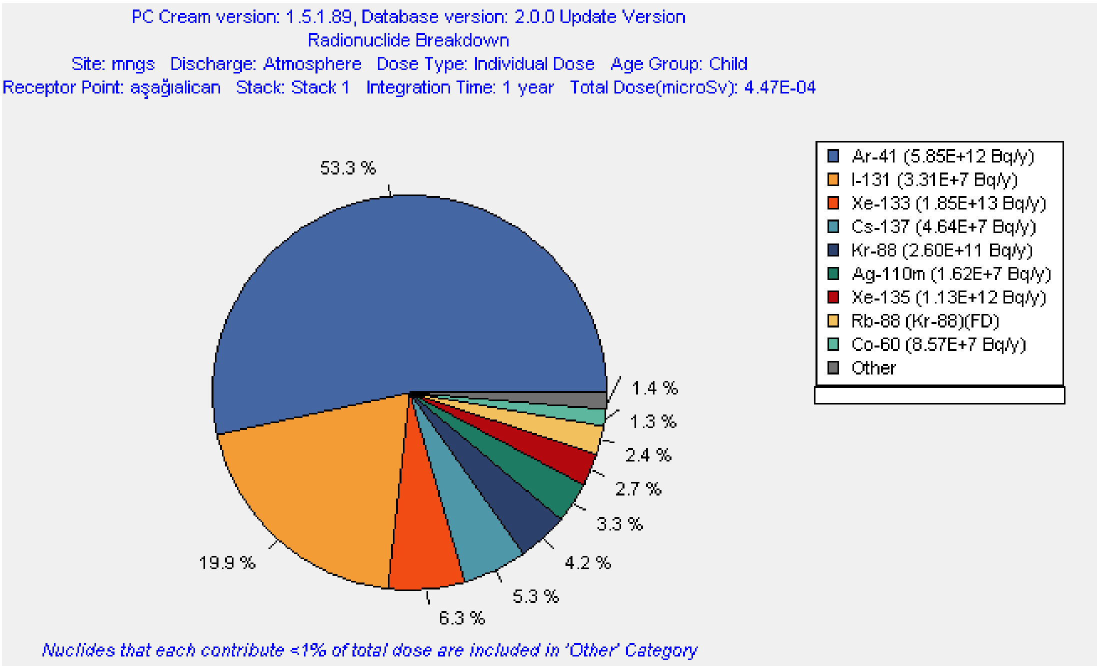


Figure B. 2 Pathway distribution in total atmospheric dose for adult in Aşağıalican for 1 year and 30 years integration time



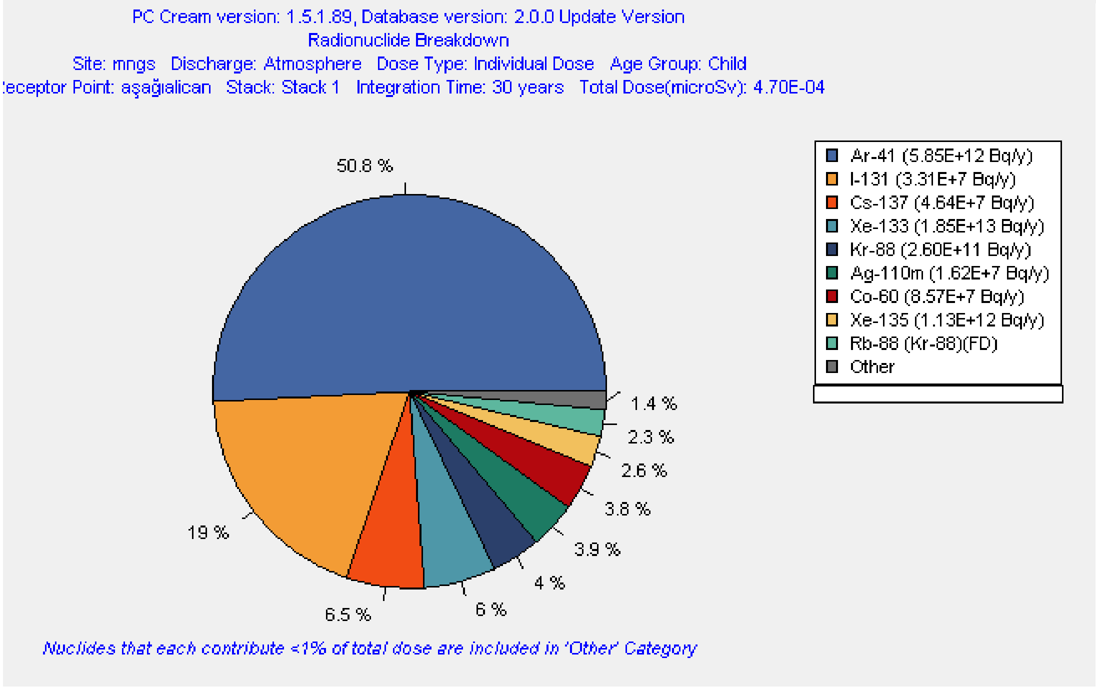
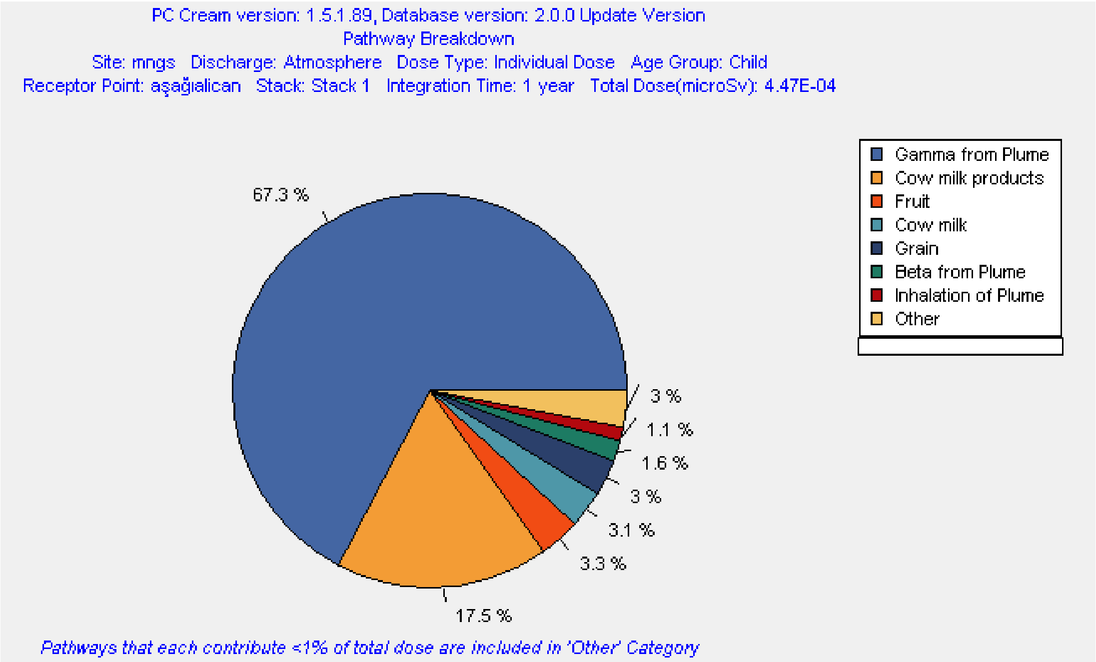


Figure B. 3 Radionuclide distribution in total atmospheric dose for child in Aşağıalican for 1 year and 30 years integration time



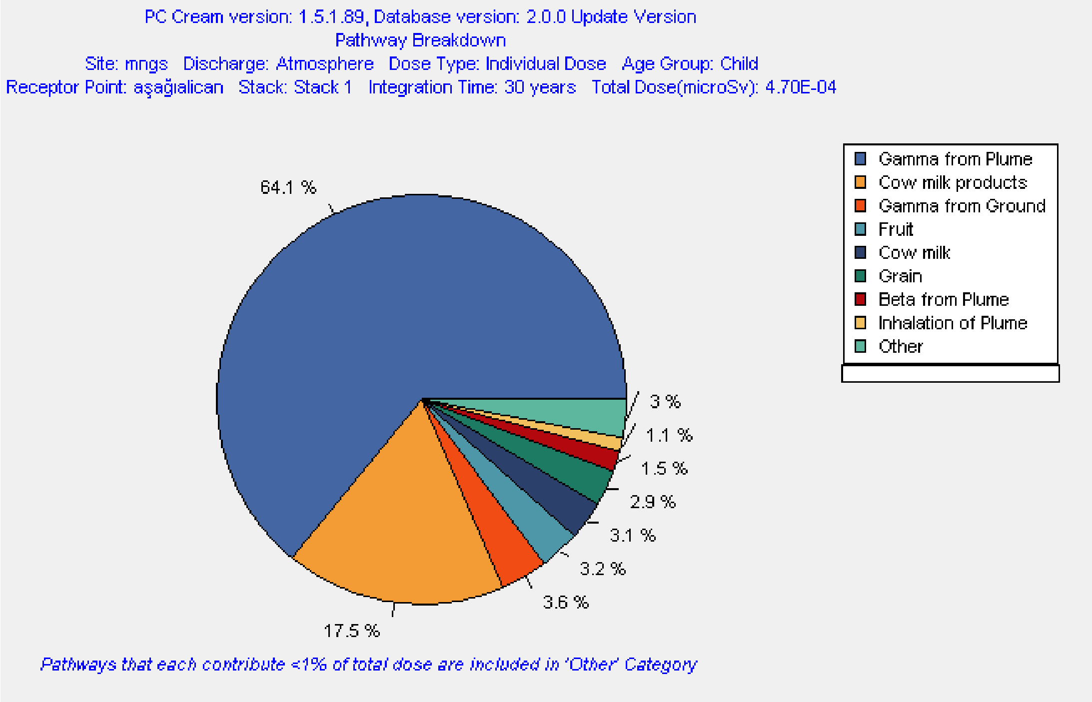


Figure B. 4 Pathway distribution in total atmospheric dose for child in Aşağıalican for 1 year and 30 years integration time

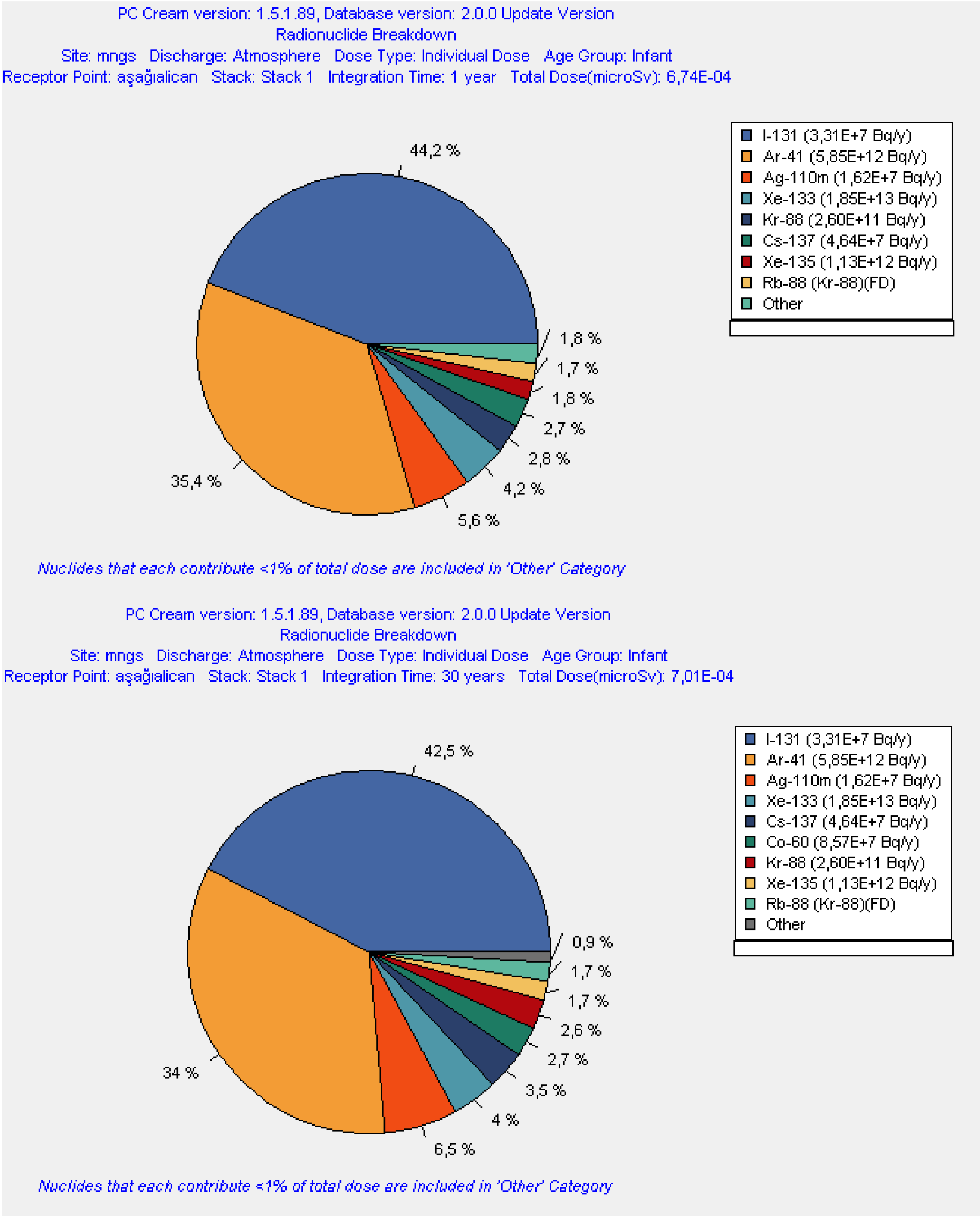


Figure B. 5 Radionuclide distribution in total atmospheric dose for infant in Aşağıalican for 1 year and 30 years integration time

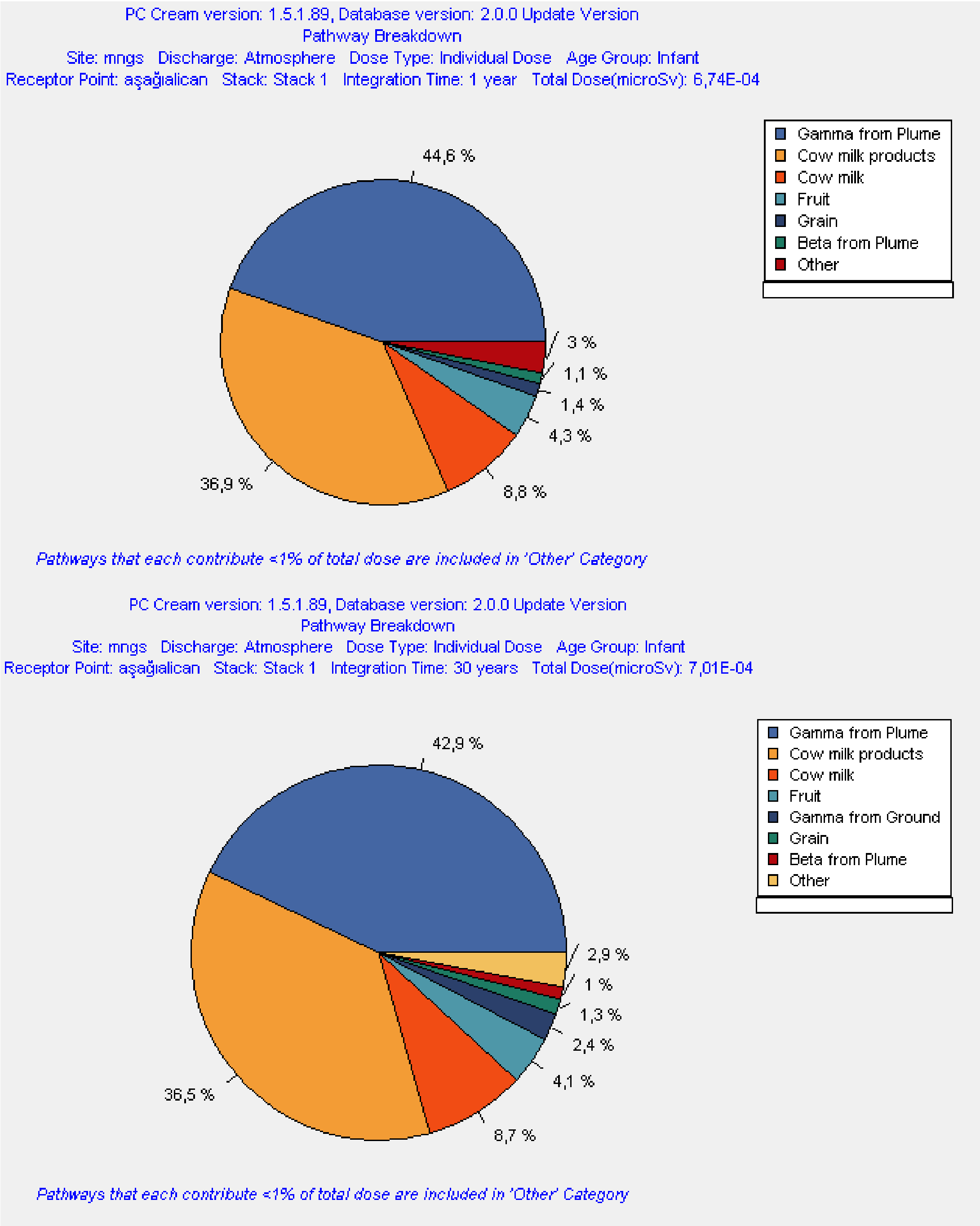


Figure B. 6 Pathway distribution in total atmospheric dose for infant in Aşağıalican for 1 year and 30 years integration time

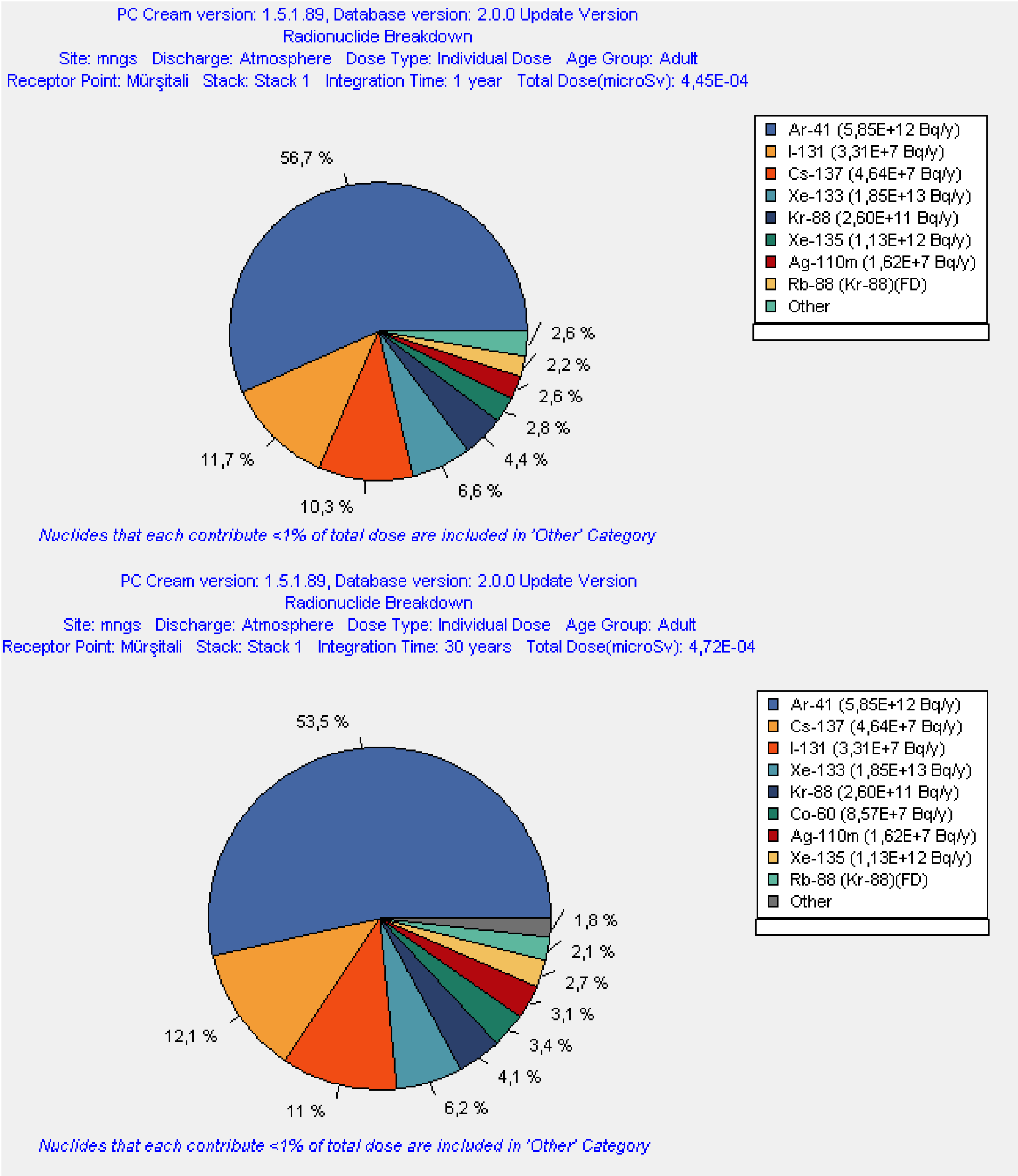
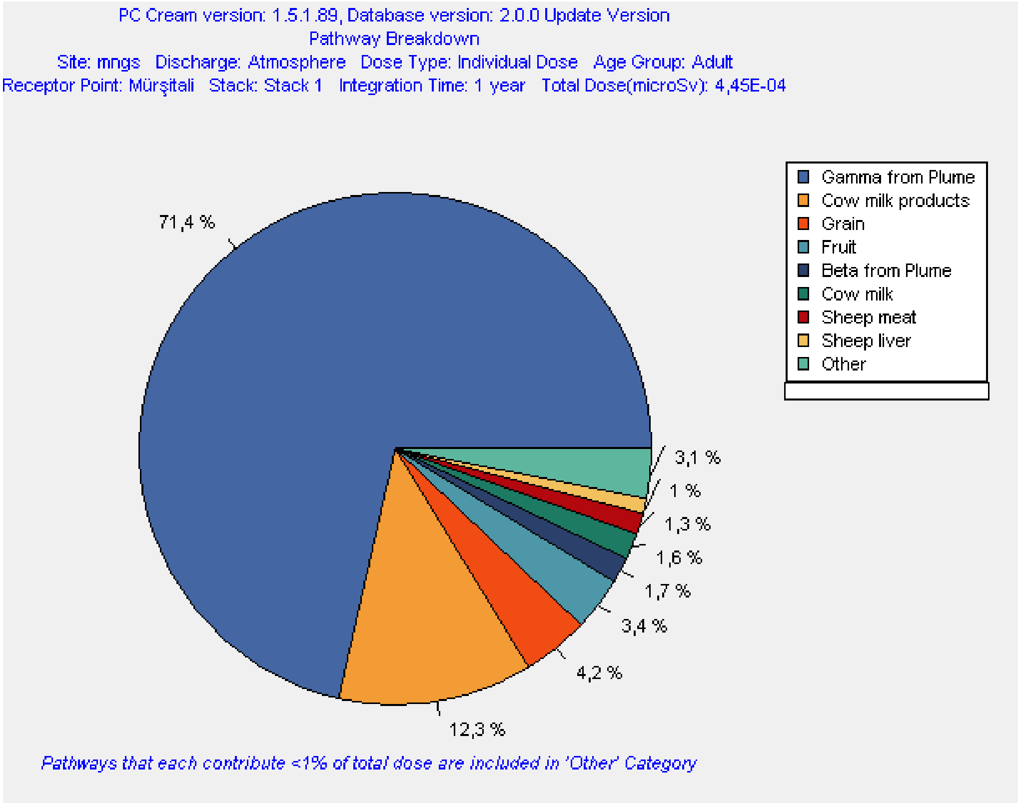


Figure B. 7 Radionuclide distribution in total atmospheric dose for adult in Mürşitali for 1 year and 30 years integration time



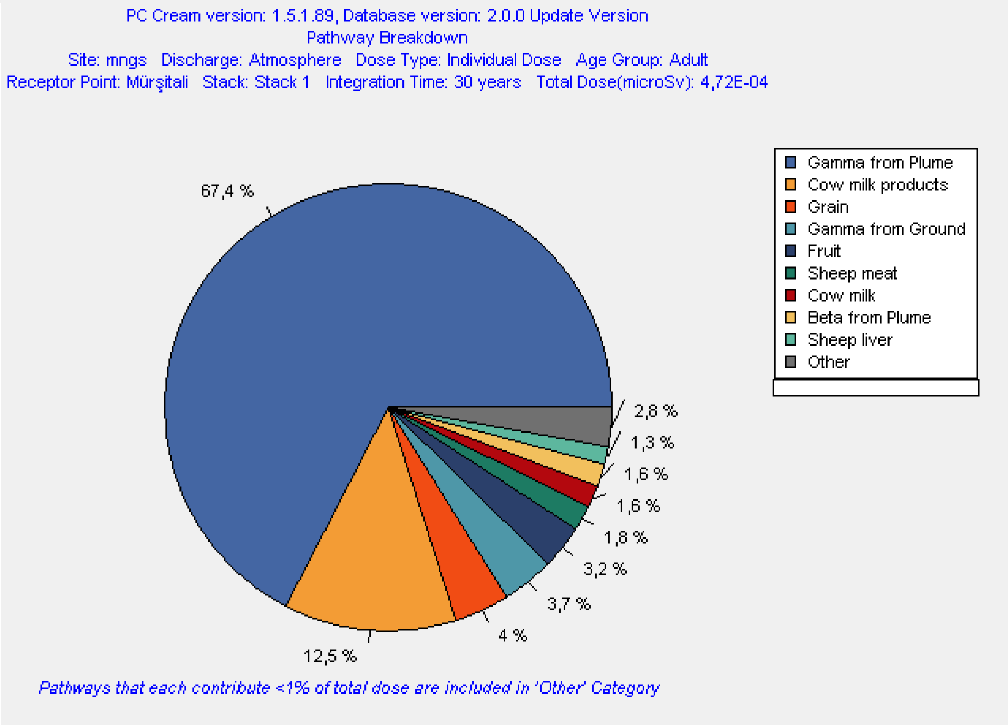


Figure B. 8 Pathway distribution in total atmospheric dose for adult in Mürşitali for 1 year and 30 years integration time

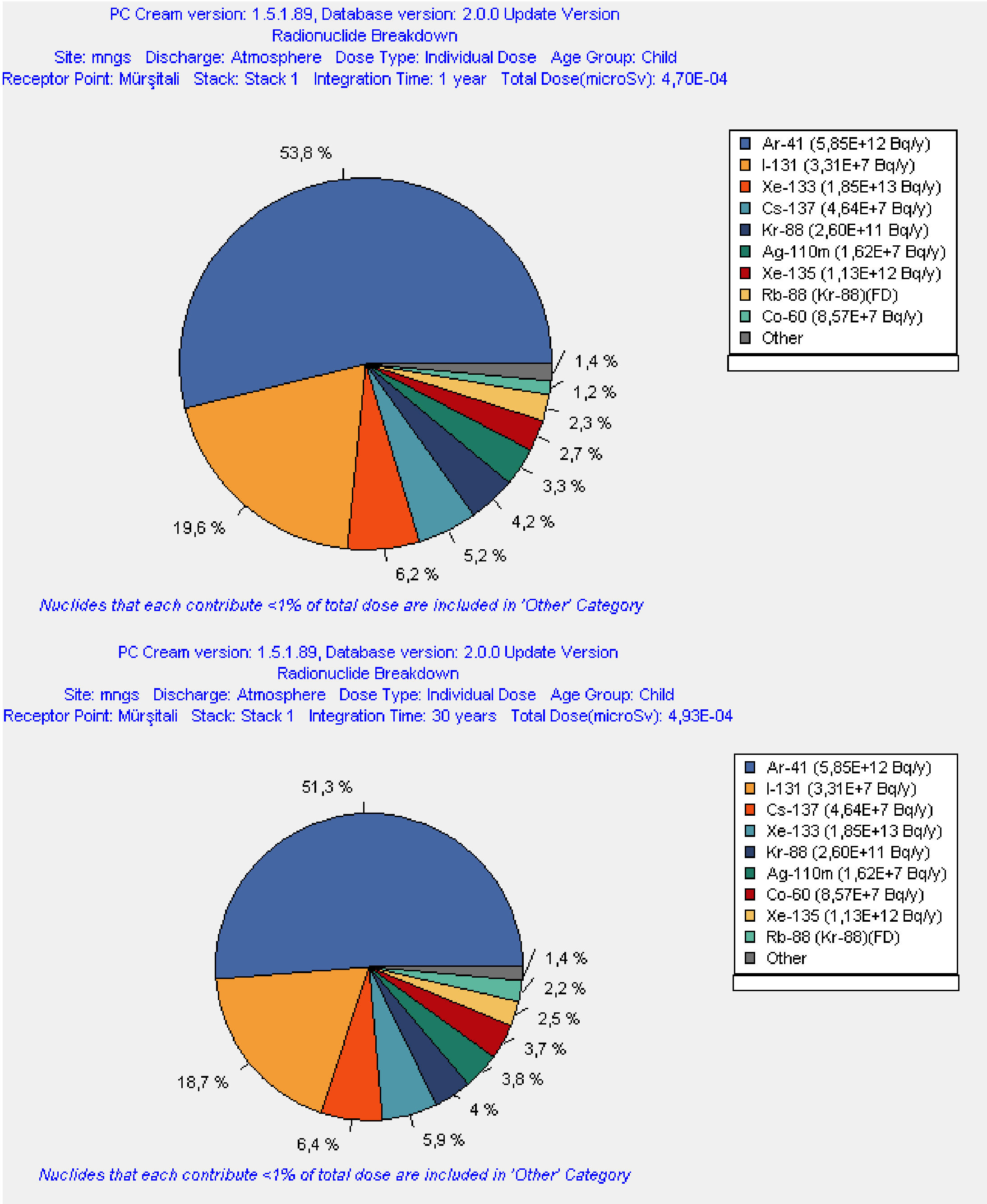


Figure B. 9 Radionuclide distribution in total atmospheric dose for child in Mürşitali for 1 year and 30 years integration time

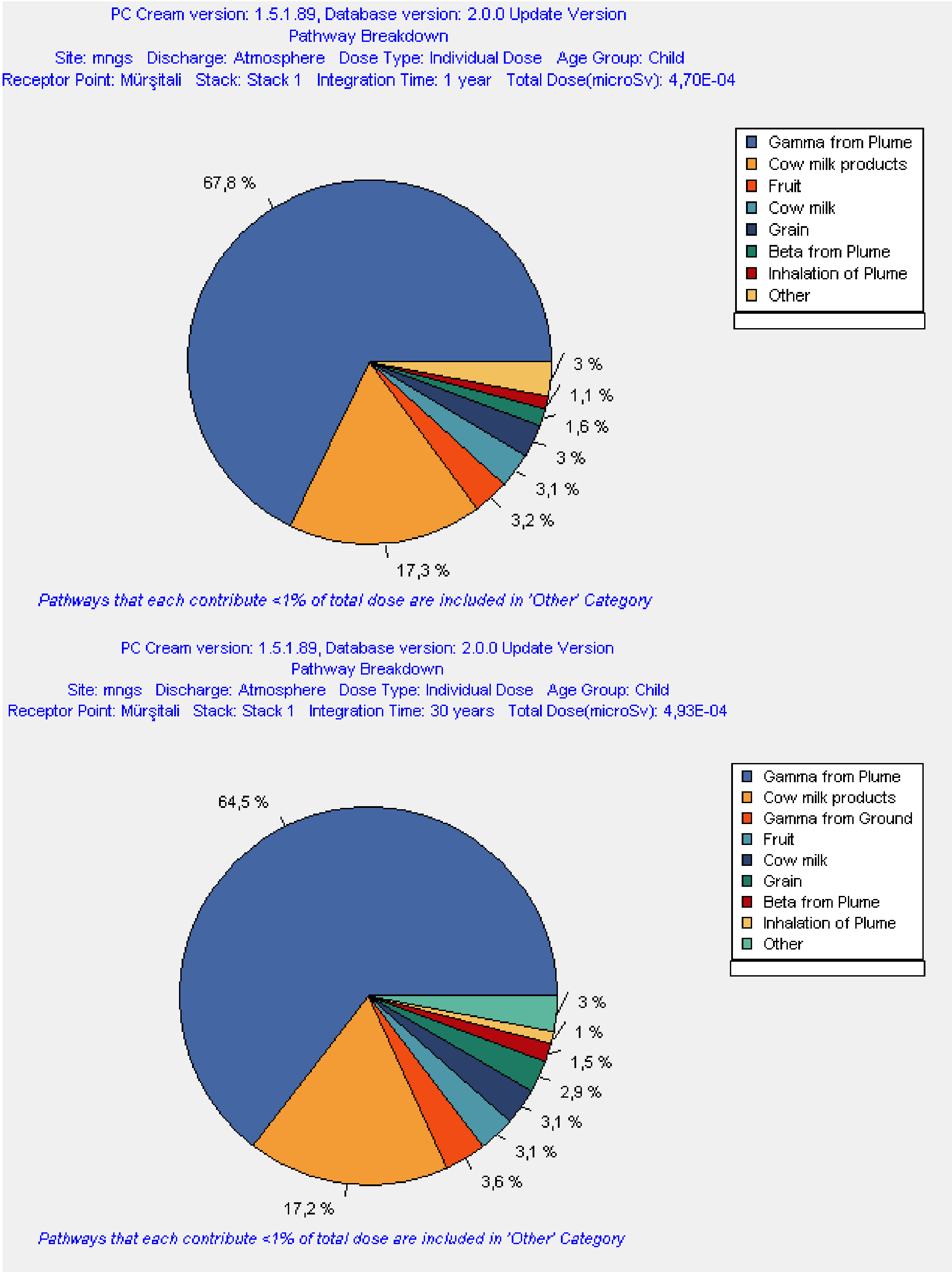


Figure B. 10 Pathway distribution in total atmospheric dose for child in Mürşitali for 1 year and 30 years integration time

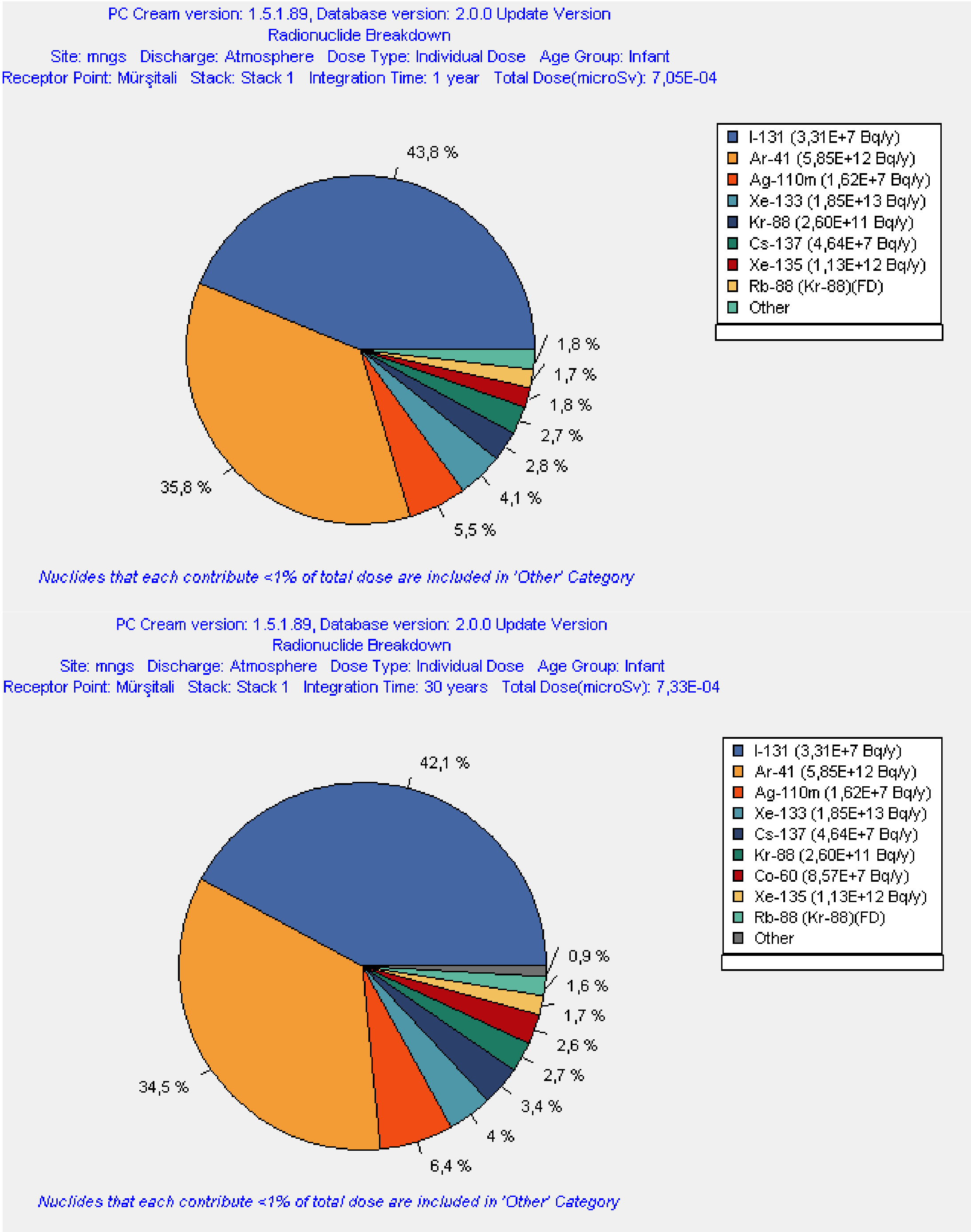


Figure B. 11 Radionuclide distribution in total atmospheric dose for infant in Mürşitali for 1 year and 30 years integration time

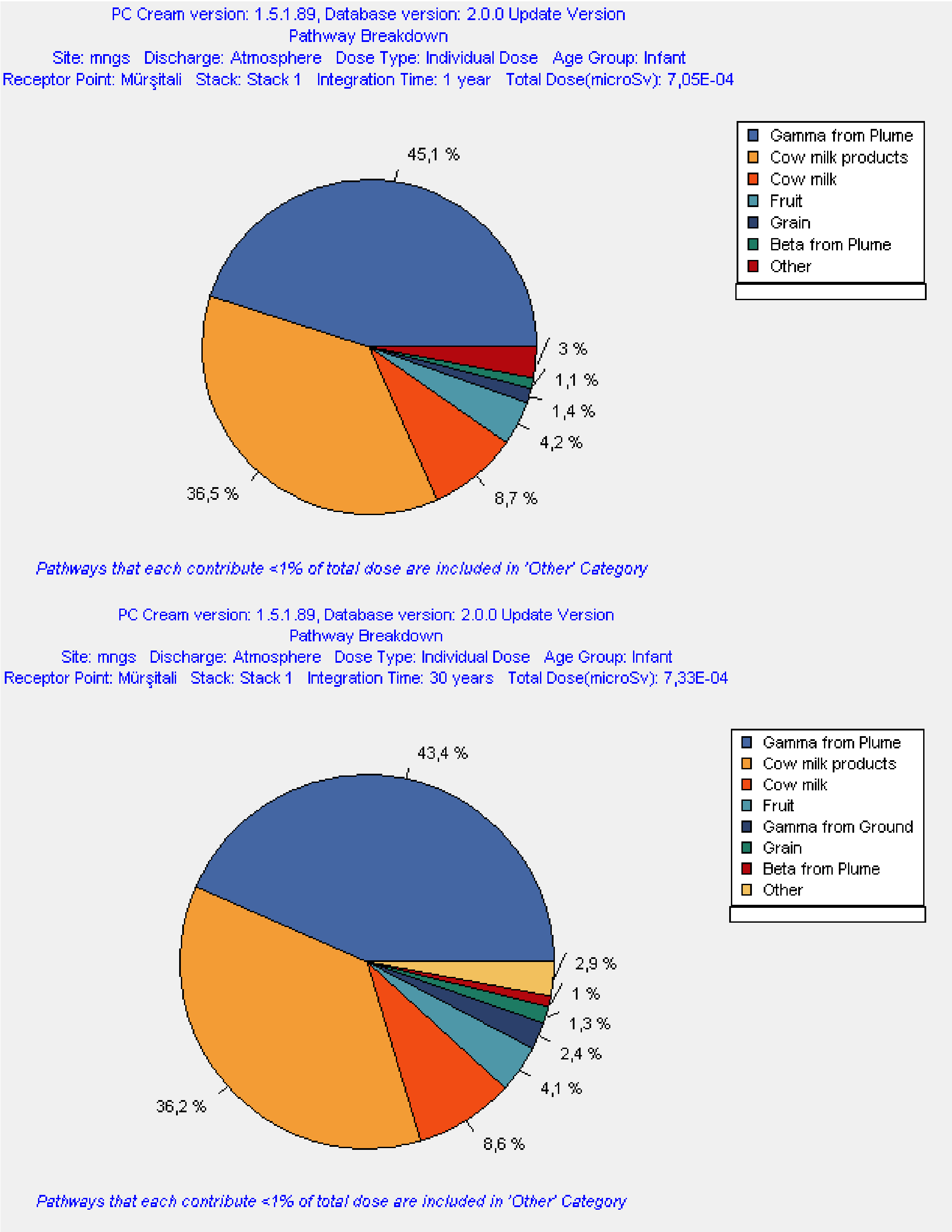


Figure B. 12 Pathway distribution in total atmospheric dose for infant in Mürşitali for 1 year and 30 years integration time

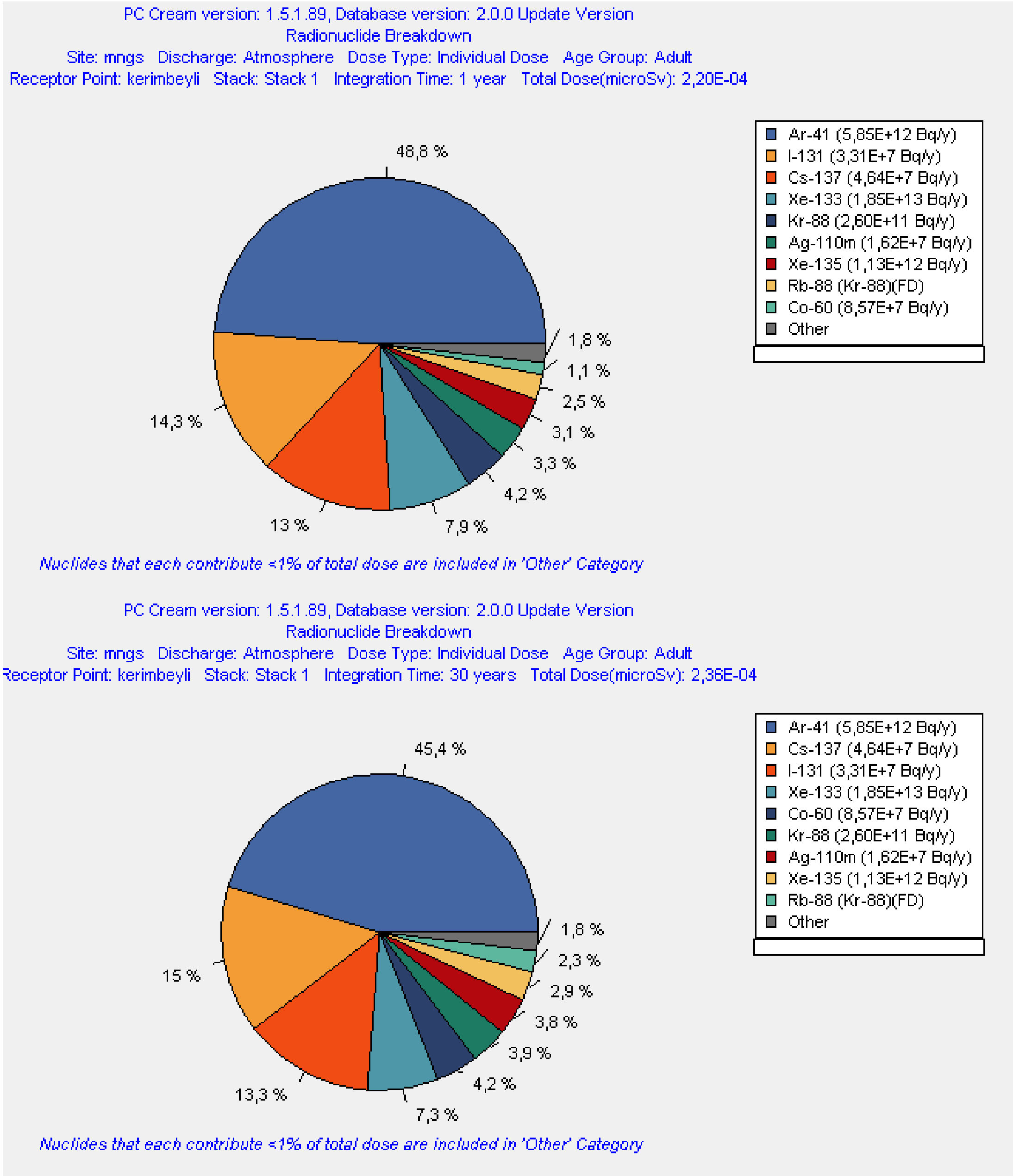


Figure B. 13 Radionuclide distribution in total atmospheric dose for adult in Kerimbeyli for 1 year and 30 years integration time

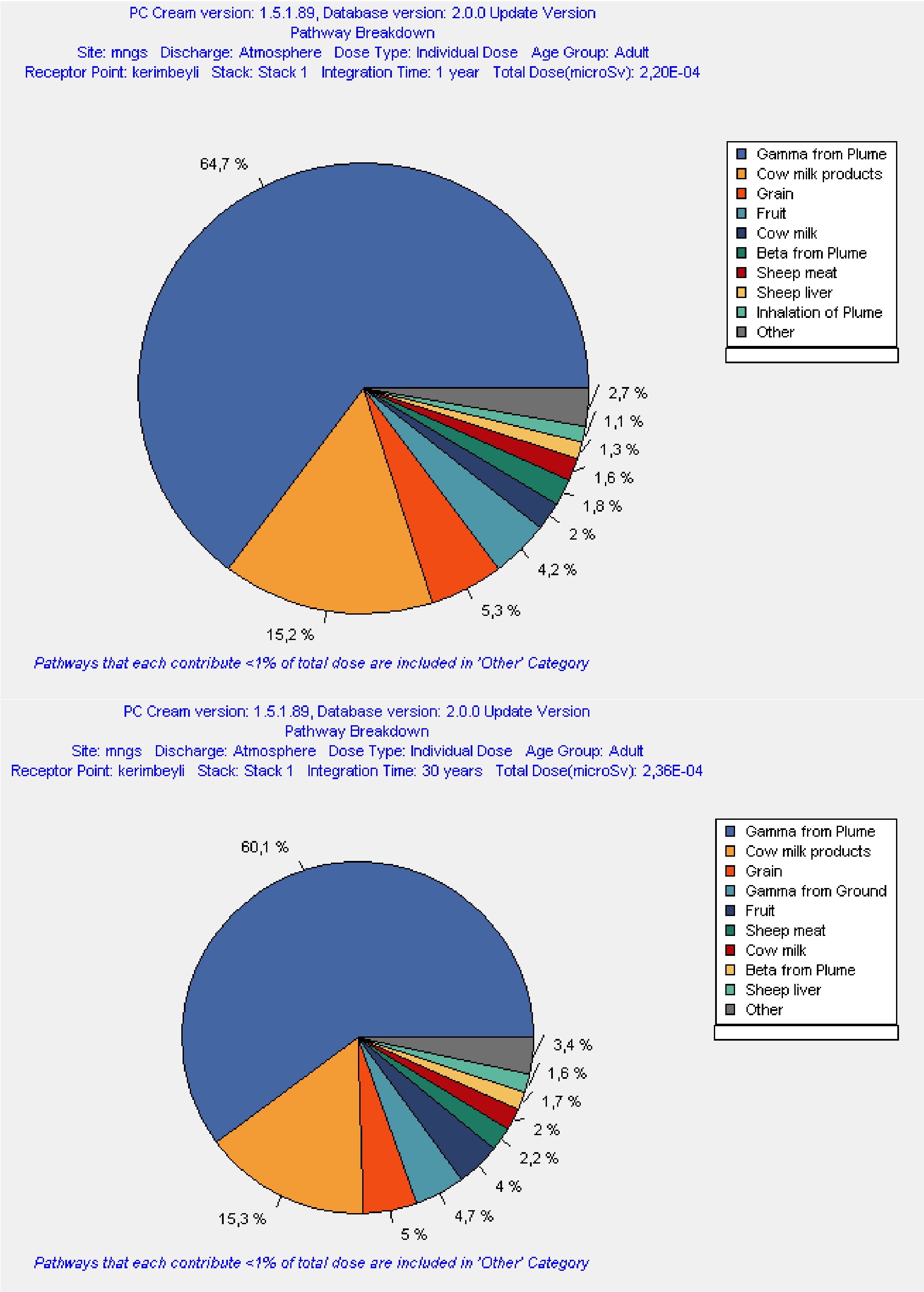


Figure B. 14 Pathway distribution in total atmospheric dose for adult in Kerimbeyli for 1 year and 30 years integration time

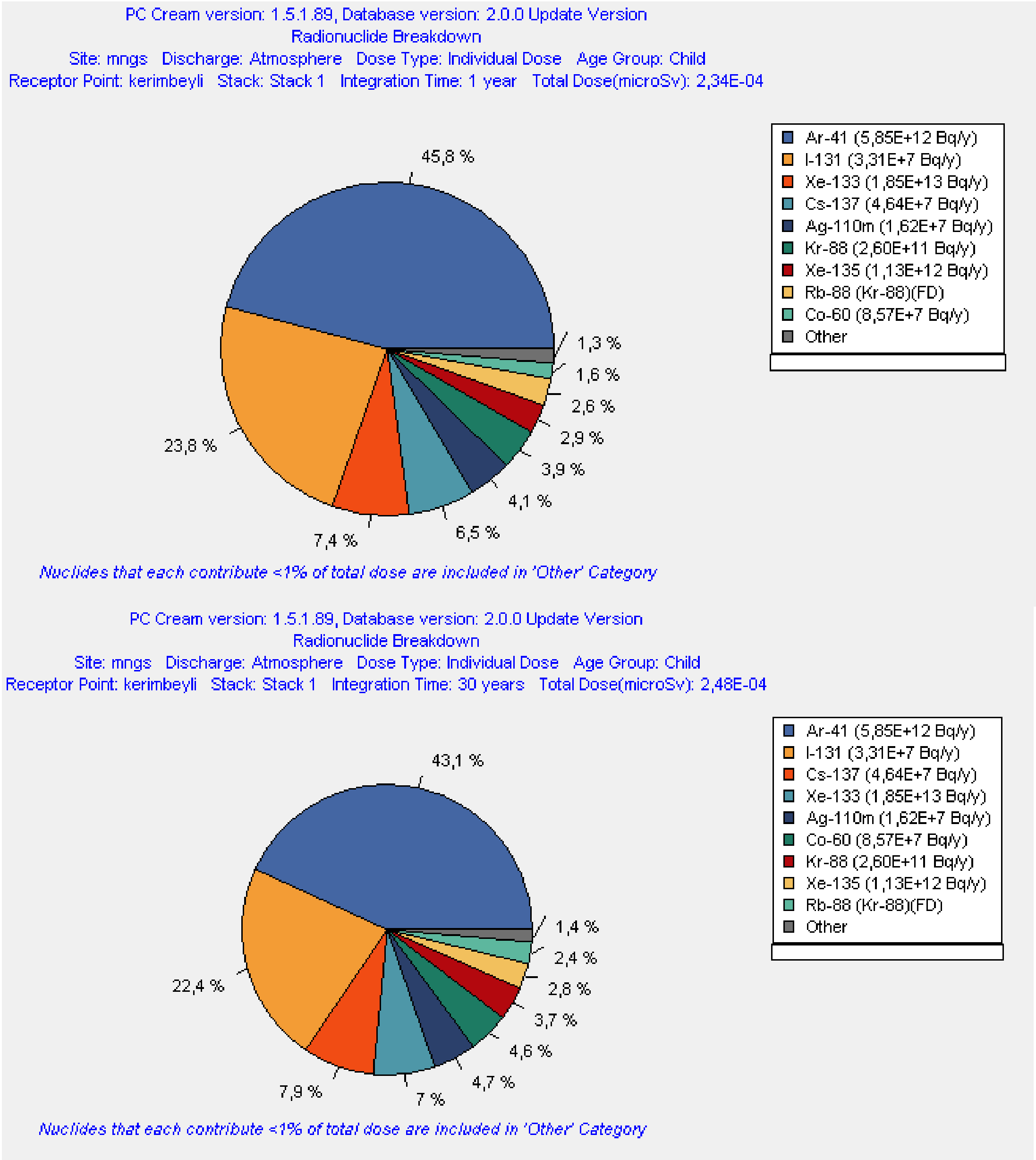
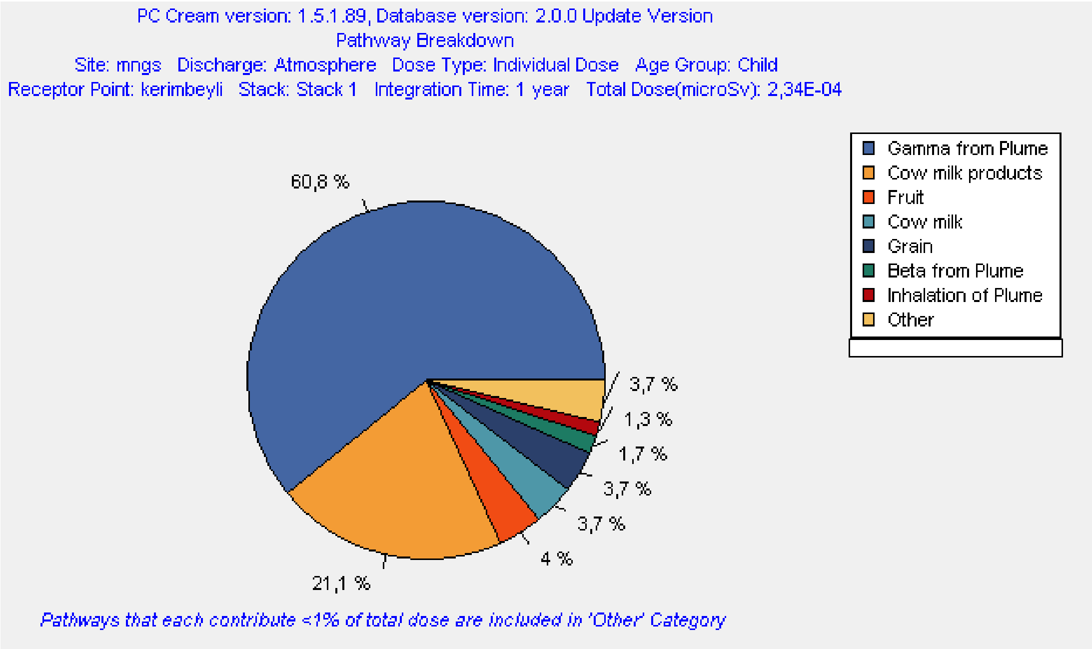


Figure B. 15 Radionuclide distribution in total atmospheric dose for child in Kerimbeyli for 1 year and 30 years integration time



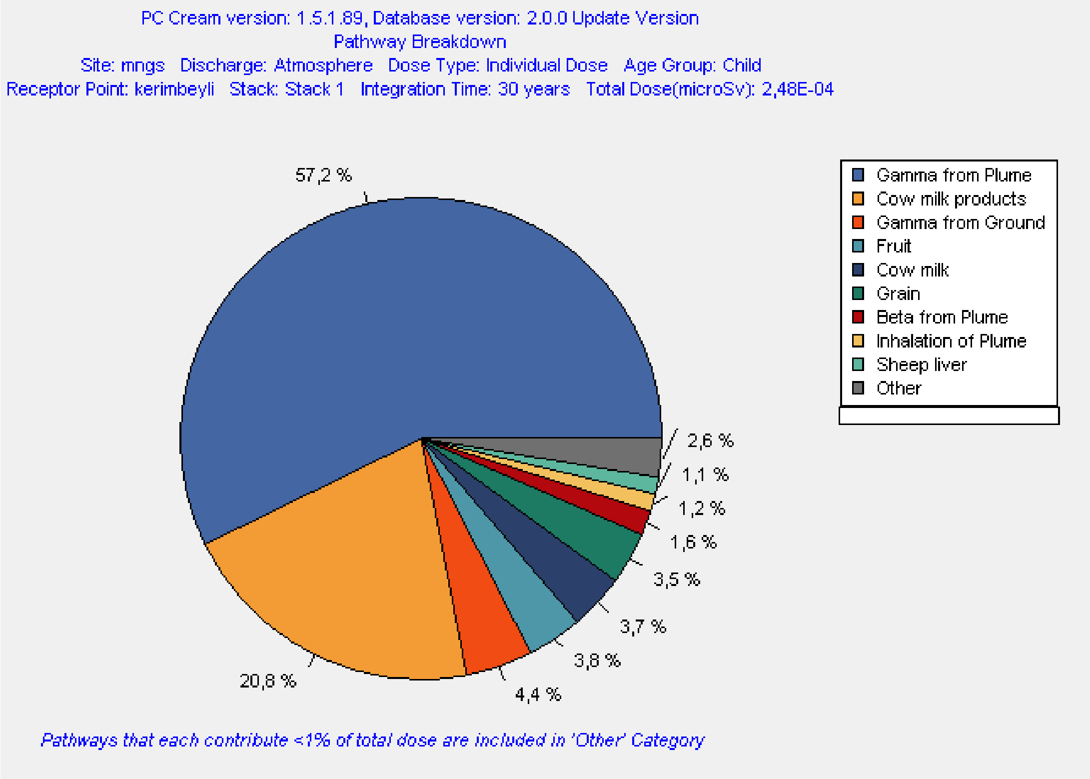
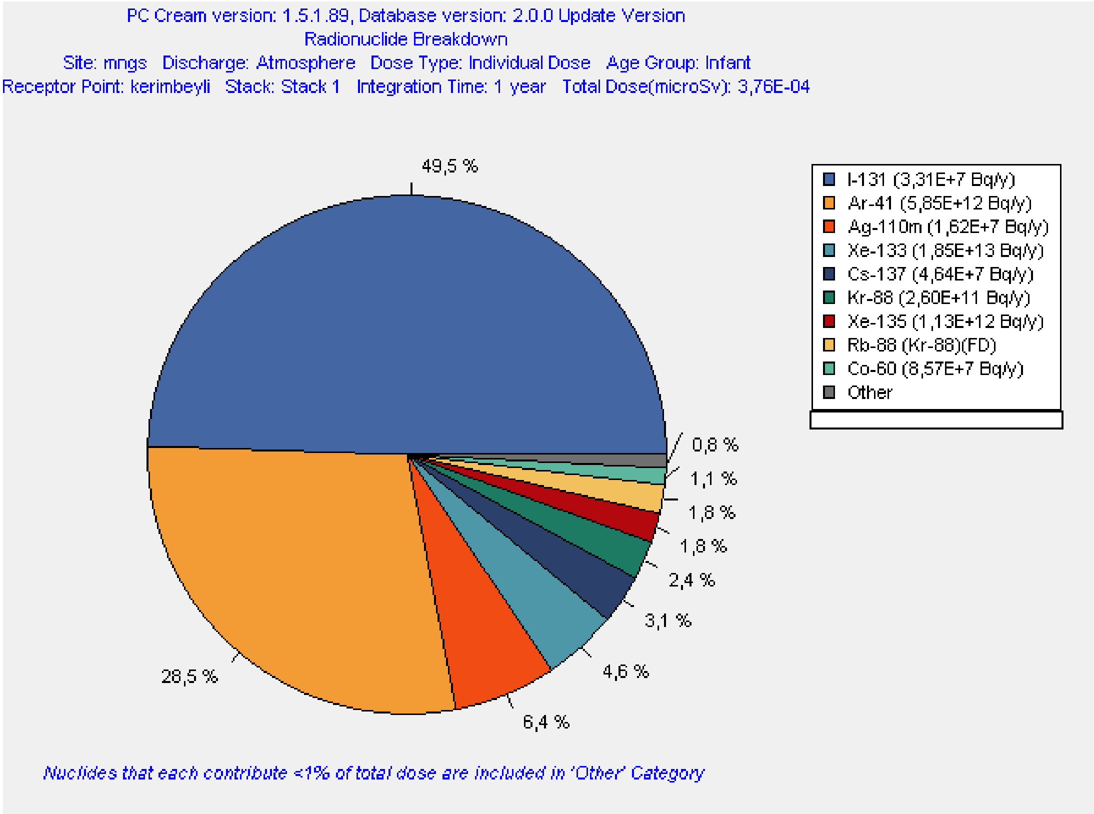


Figure B. 16 Pathway distribution in total atmospheric dose for child in Kerimbeyli for 1 year and 30 years integration time



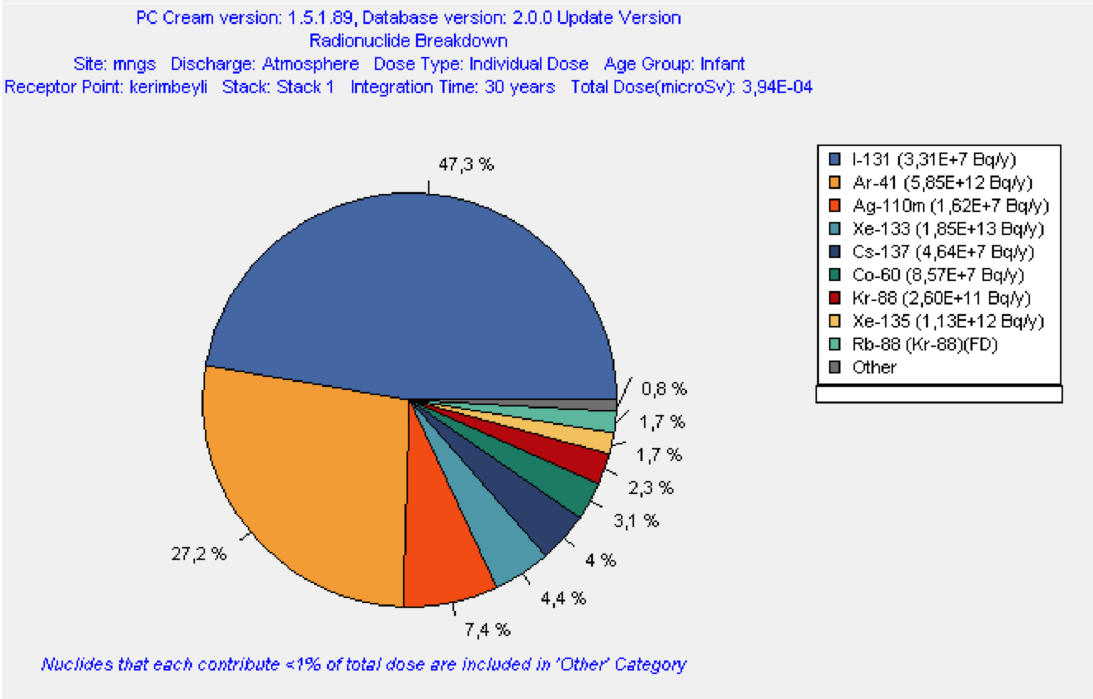


Figure B. 17 Radionuclide distribution in total atmospheric dose for infant in Kerimbeyli for 1 year and 30 years integration time

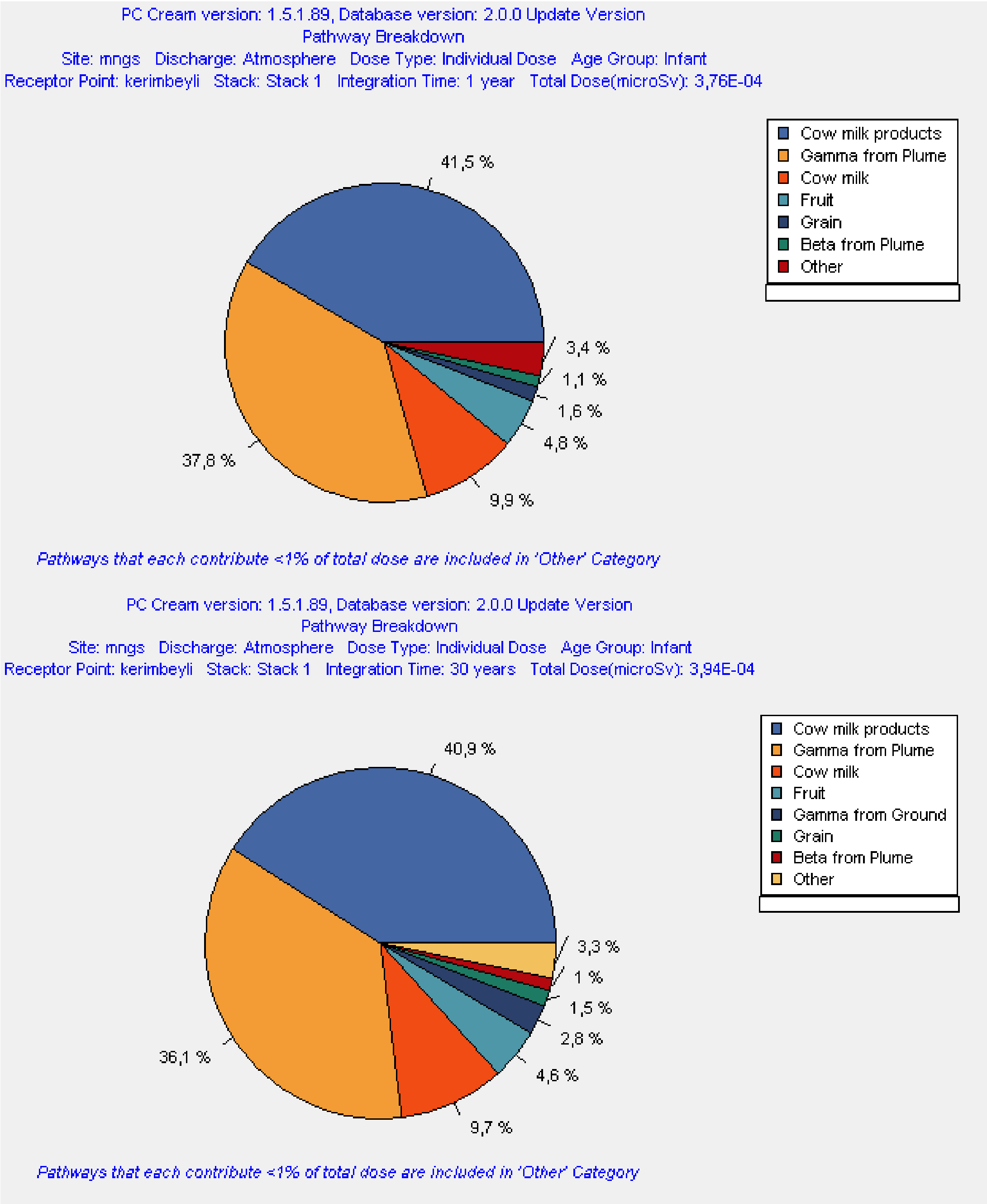
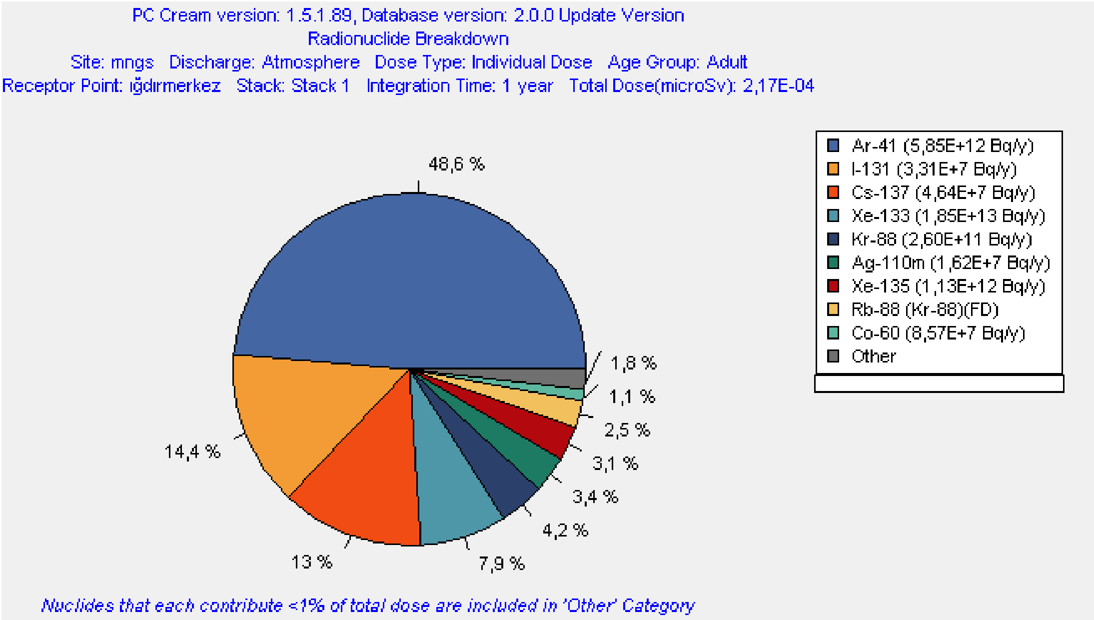


Figure B. 18 Pathway distribution in total atmospheric dose for infant in Kerimbeyli for 1 year and 30 years integration time



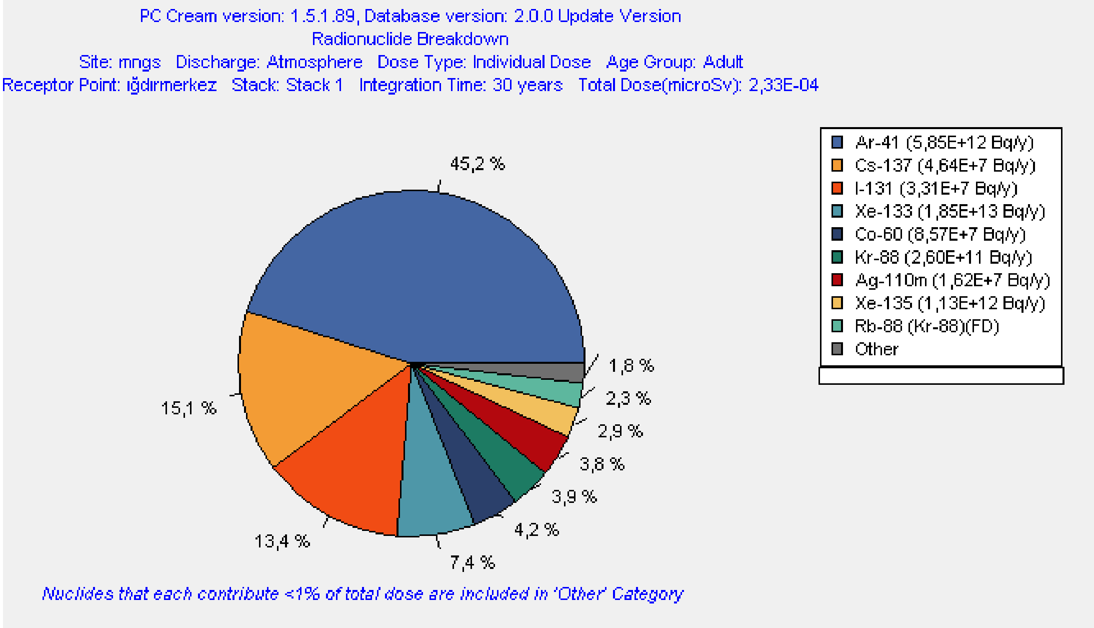
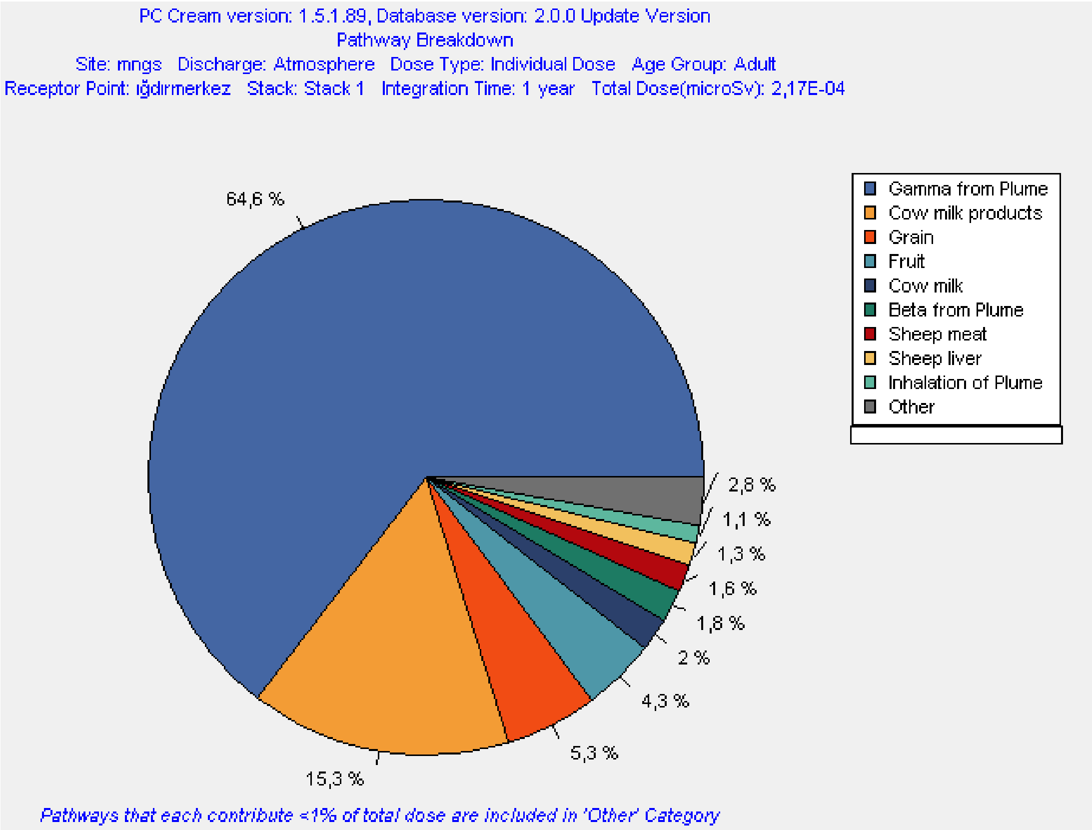


Figure B. 19 Radionuclide distribution in total atmospheric dose for adult in Iğdır center for 1 year and 30 years integration time



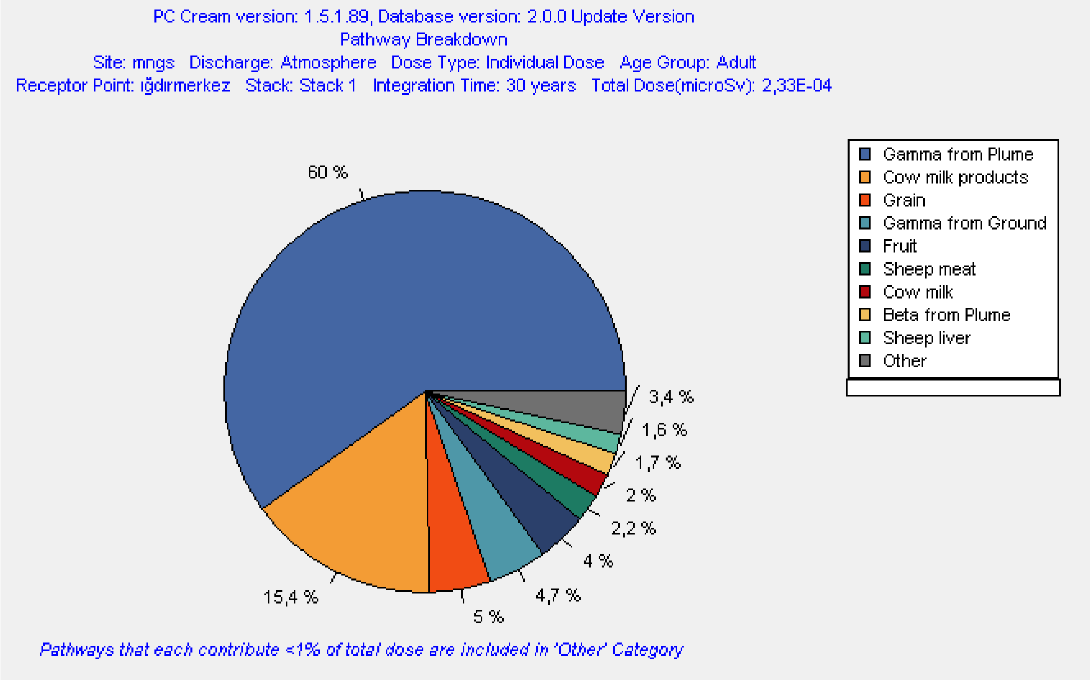
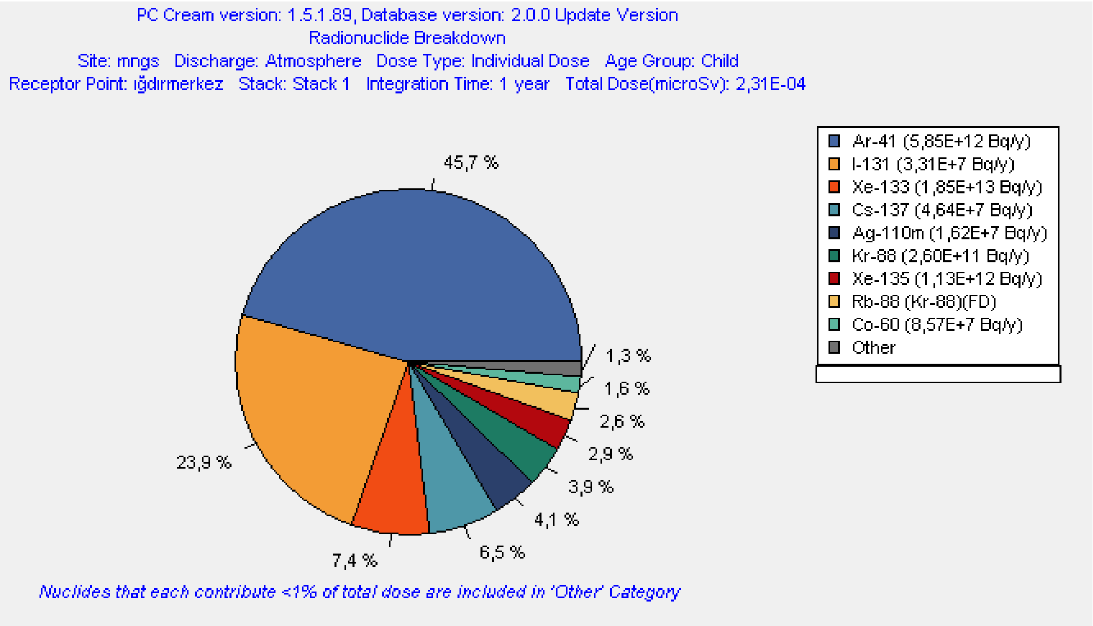


Figure B. 20 Pathway distribution in total atmospheric dose for adult in Iğdır center for 1 year and 30 years integration time



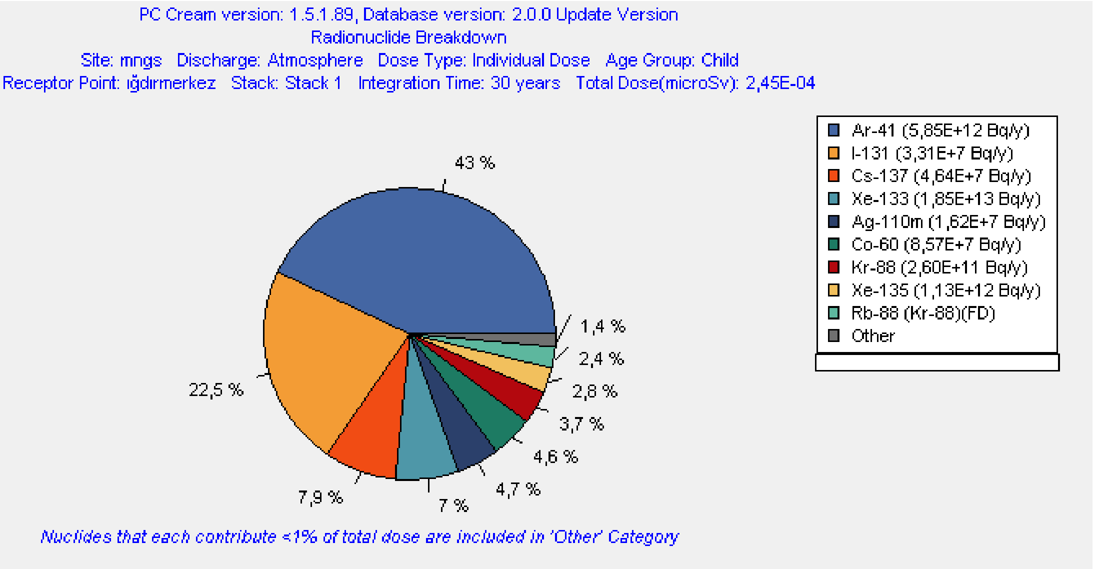
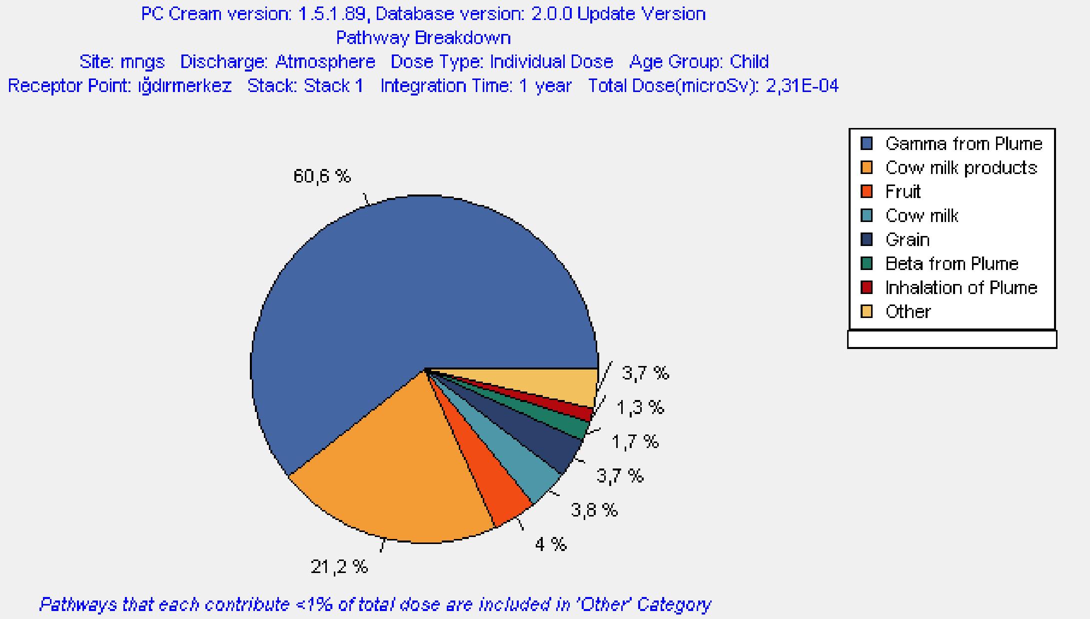


Figure B. 21 Radionuclide distribution in total atmospheric dose for child in Iğdır center for 1 year and 30 years integration time



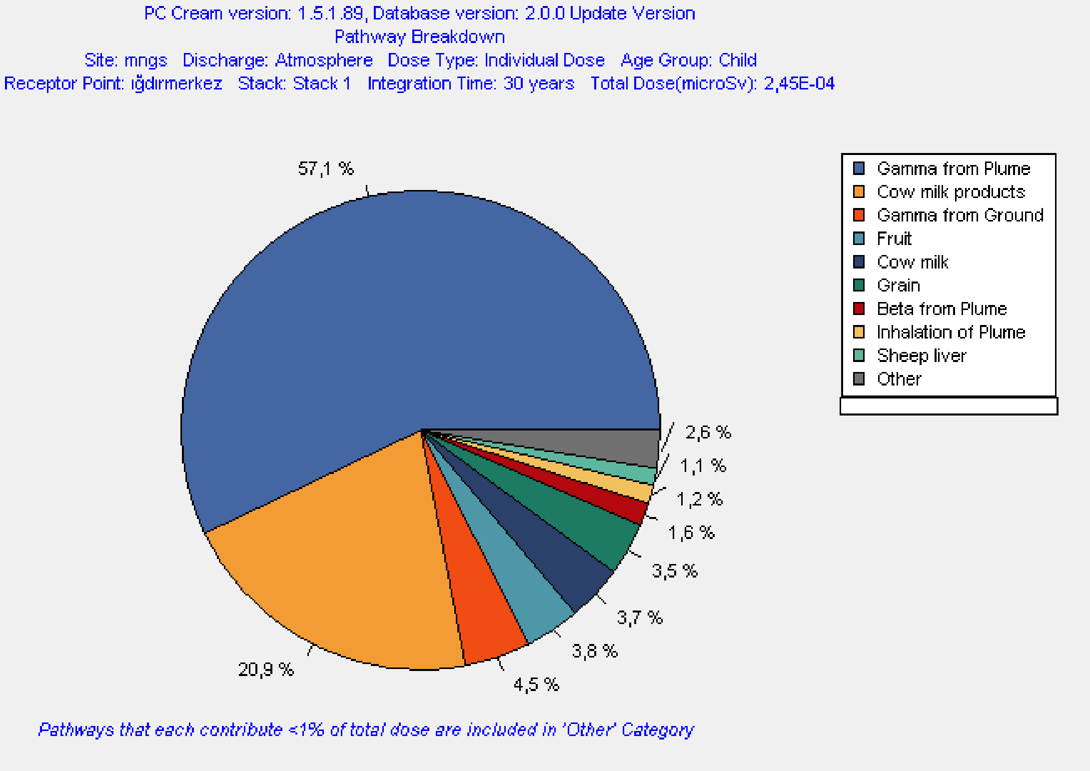


Figure B. 22 Pathway distribution in total atmospheric dose for child in Iğdır center for 1 year and 30 years integration time

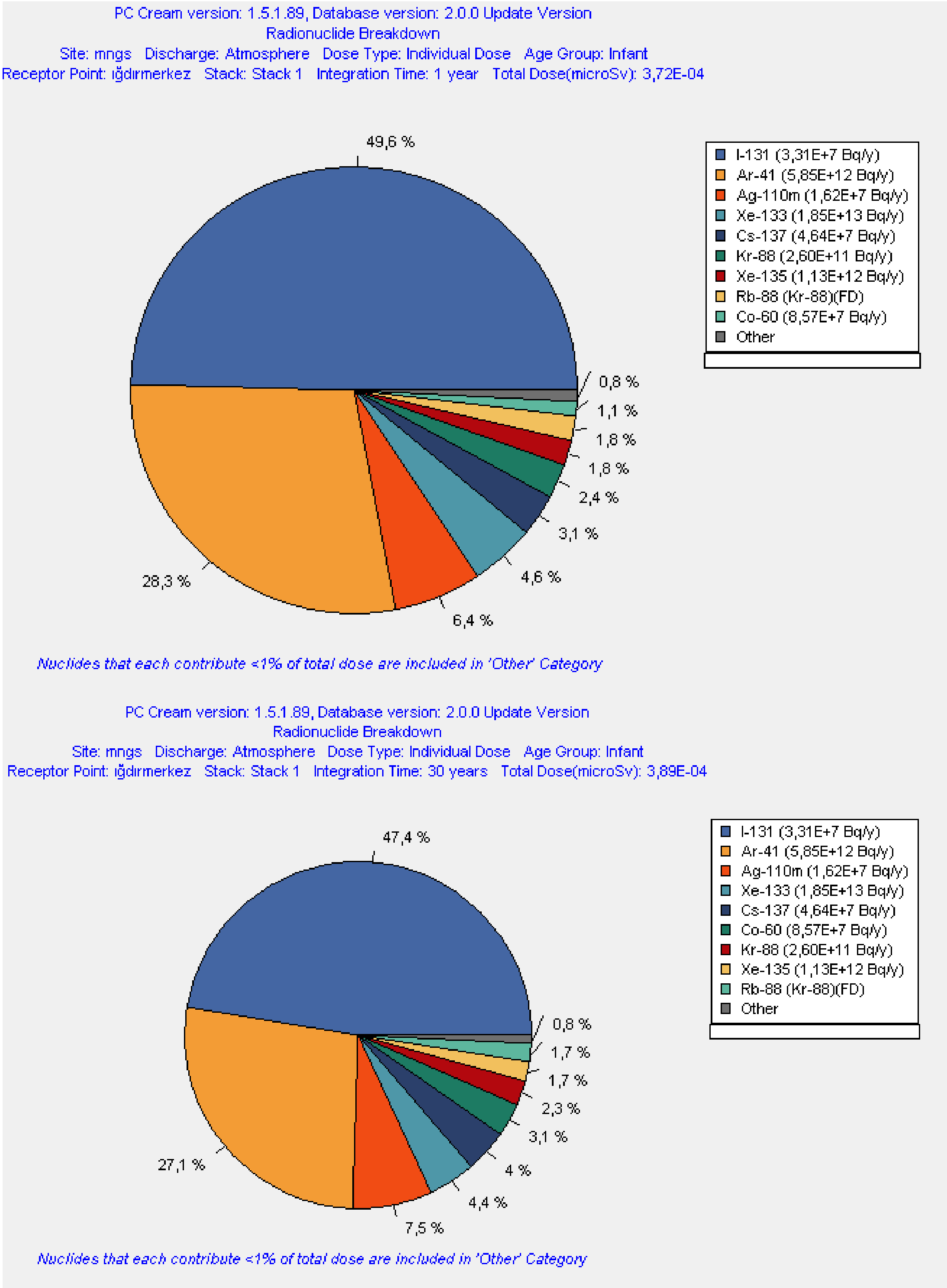


Figure B. 23 Radionuclide distribution in total atmospheric dose for infant in Iğdır center for 1 year and 30 years integration time

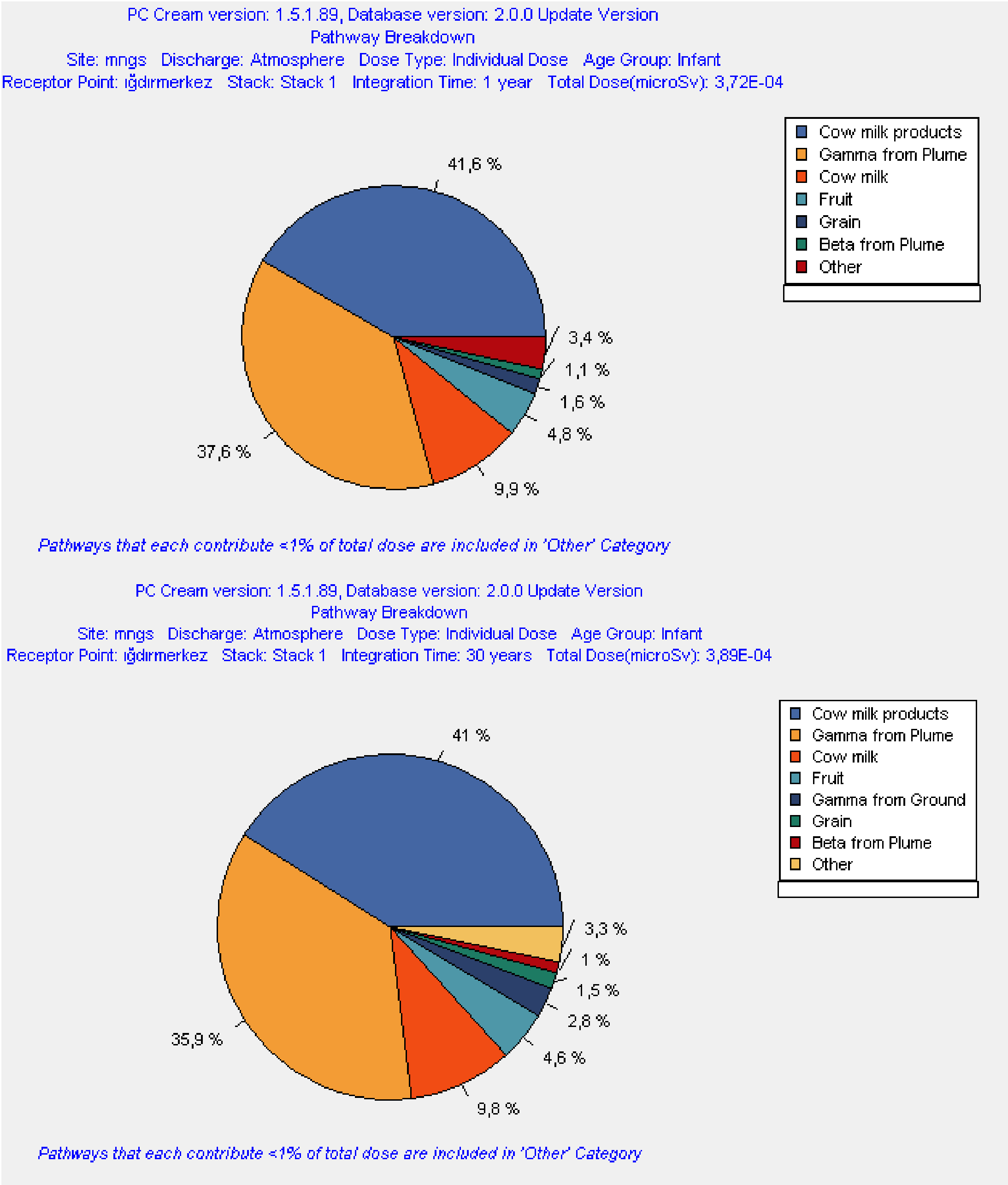


Figure B. 24 Pathway distribution in total atmospheric dose for infant in Iğdır center for 1 year and 30 years integration time

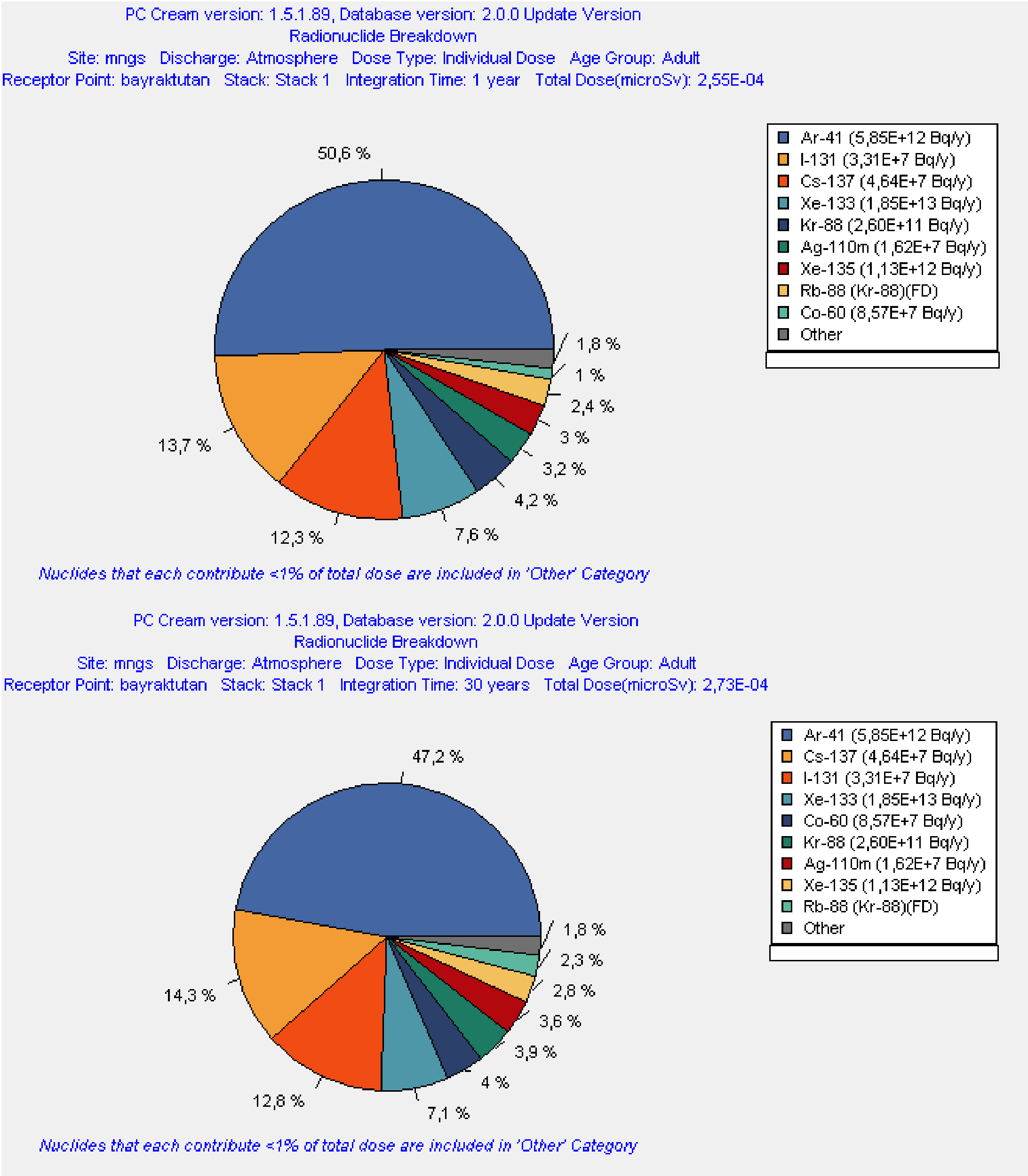
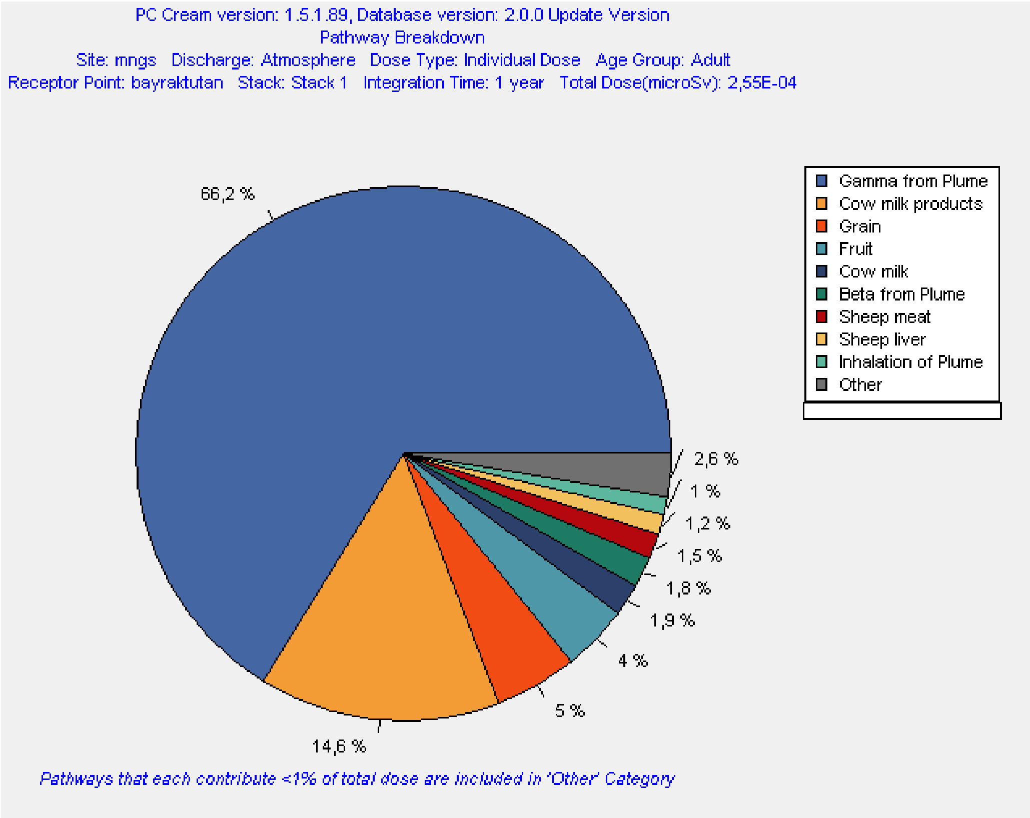


Figure B. 25 Radionuclide distribution in total atmospheric dose for adult in Bayraktutan for 1 year and 30 years integration time



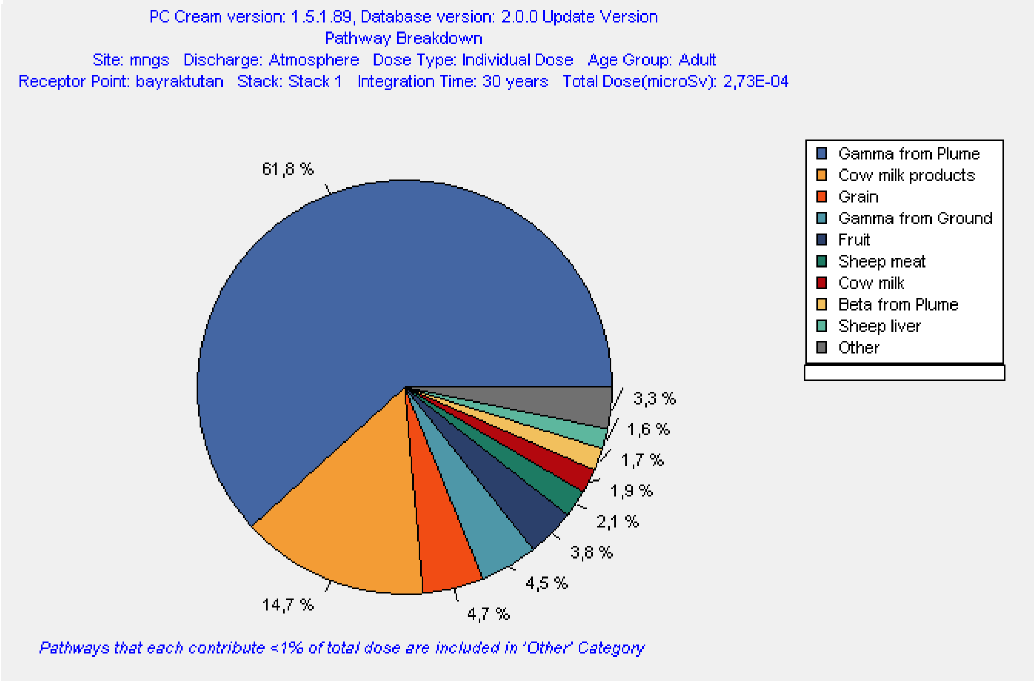


Figure B. 26 Pathway distribution in total atmospheric dose for adult in Bayraktutan for 1 year and 30 years integration time

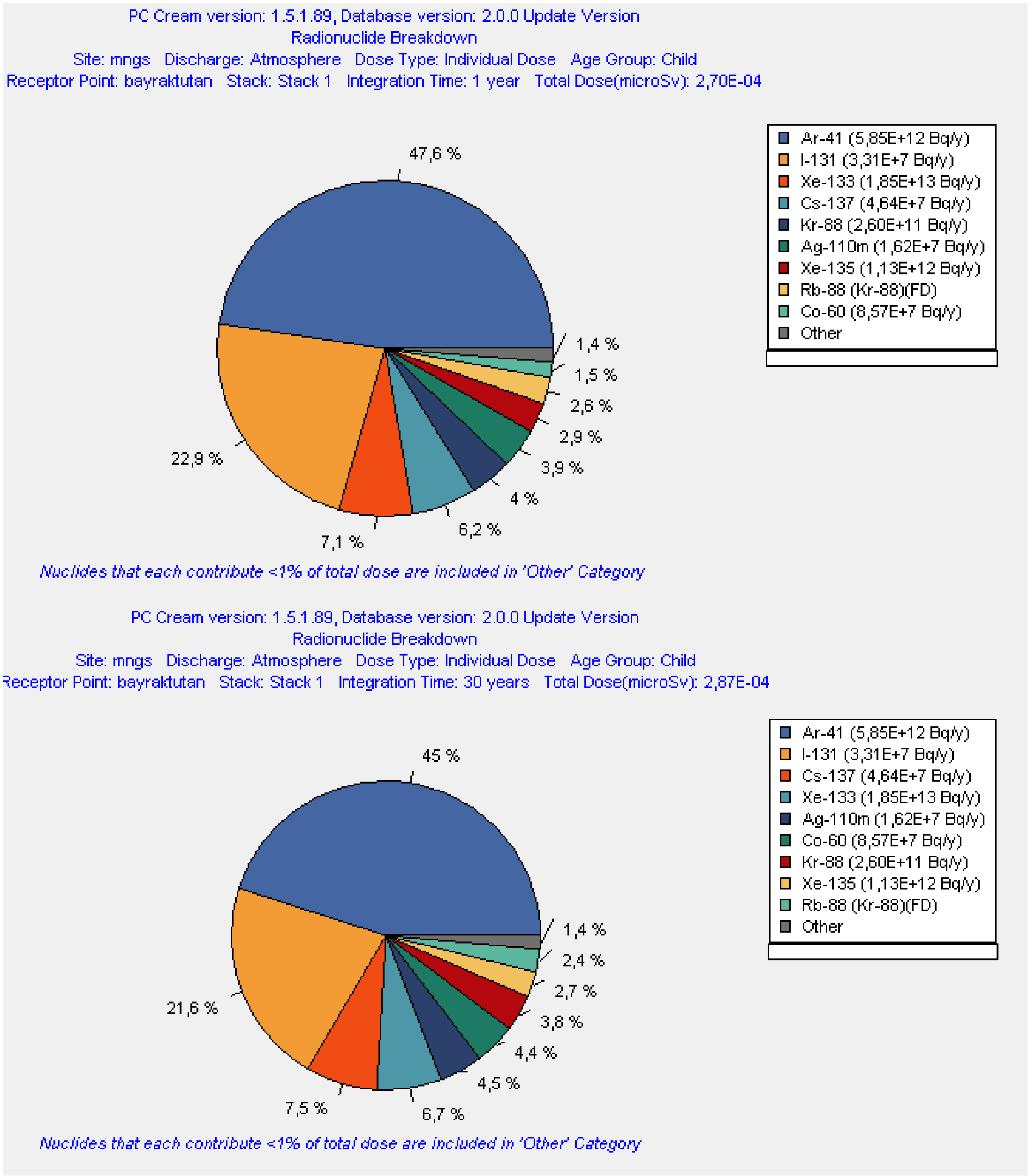


Figure B. 27 Radionuclide distribution in total atmospheric dose for child in Bayraktutan for 1 year and 30 years integration time

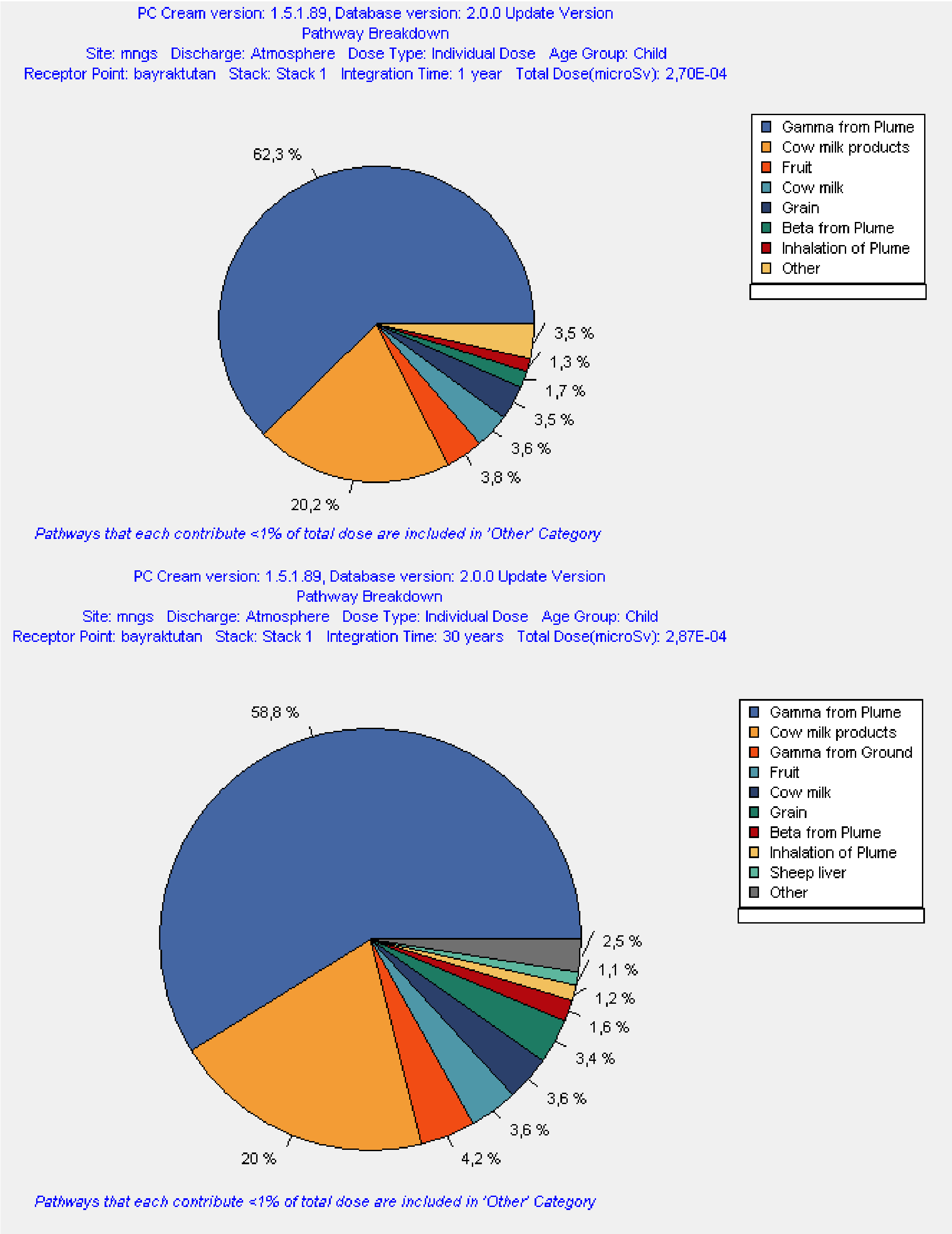


Figure B. 28 Pathway distribution in total atmospheric dose for child in Bayraktutan for 1 year and 30 years integration time

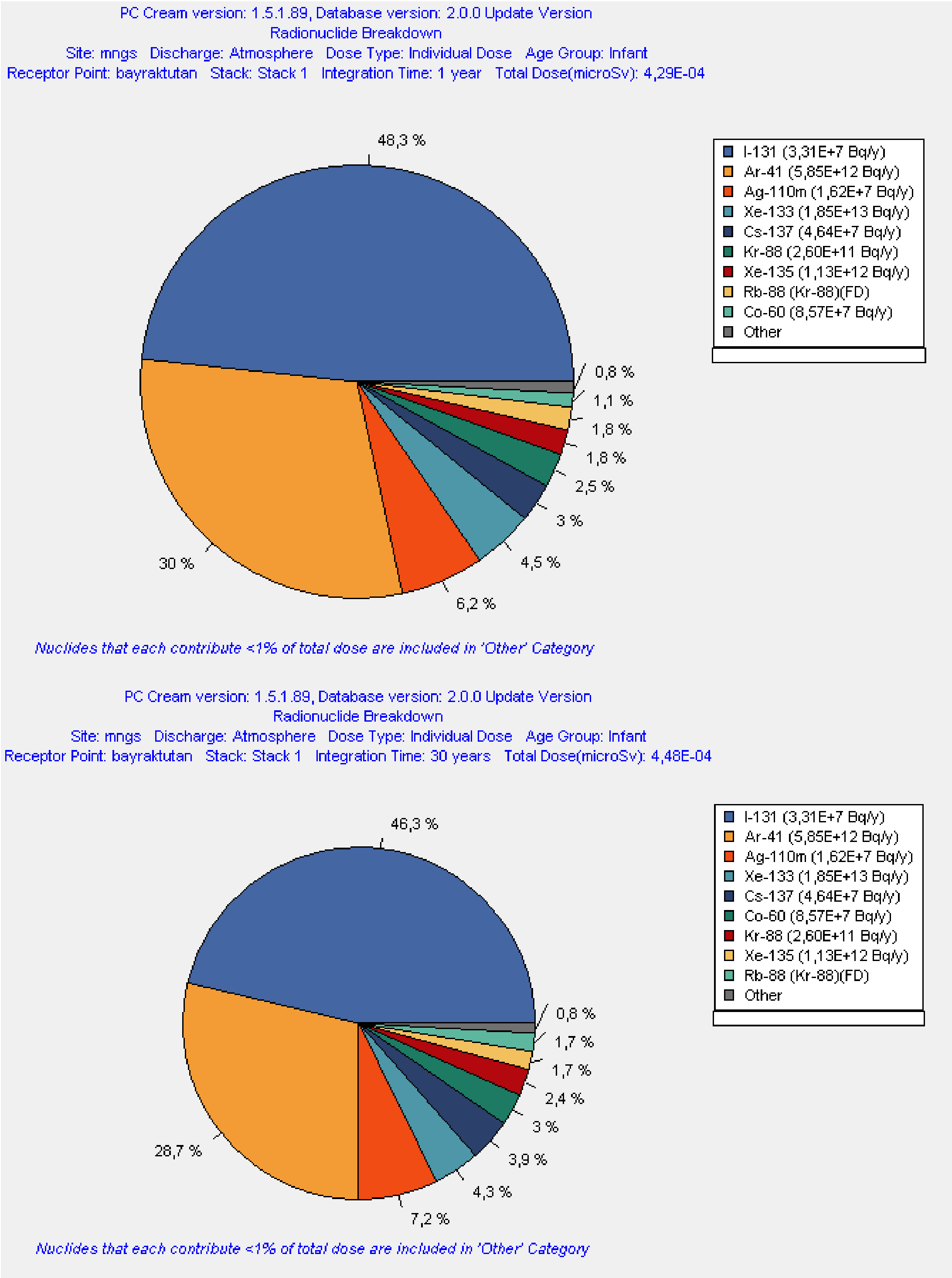


Figure B. 29 Radionuclide distribution in total atmospheric dose for infant in Bayraktutan for 1 year and 30 years integration time

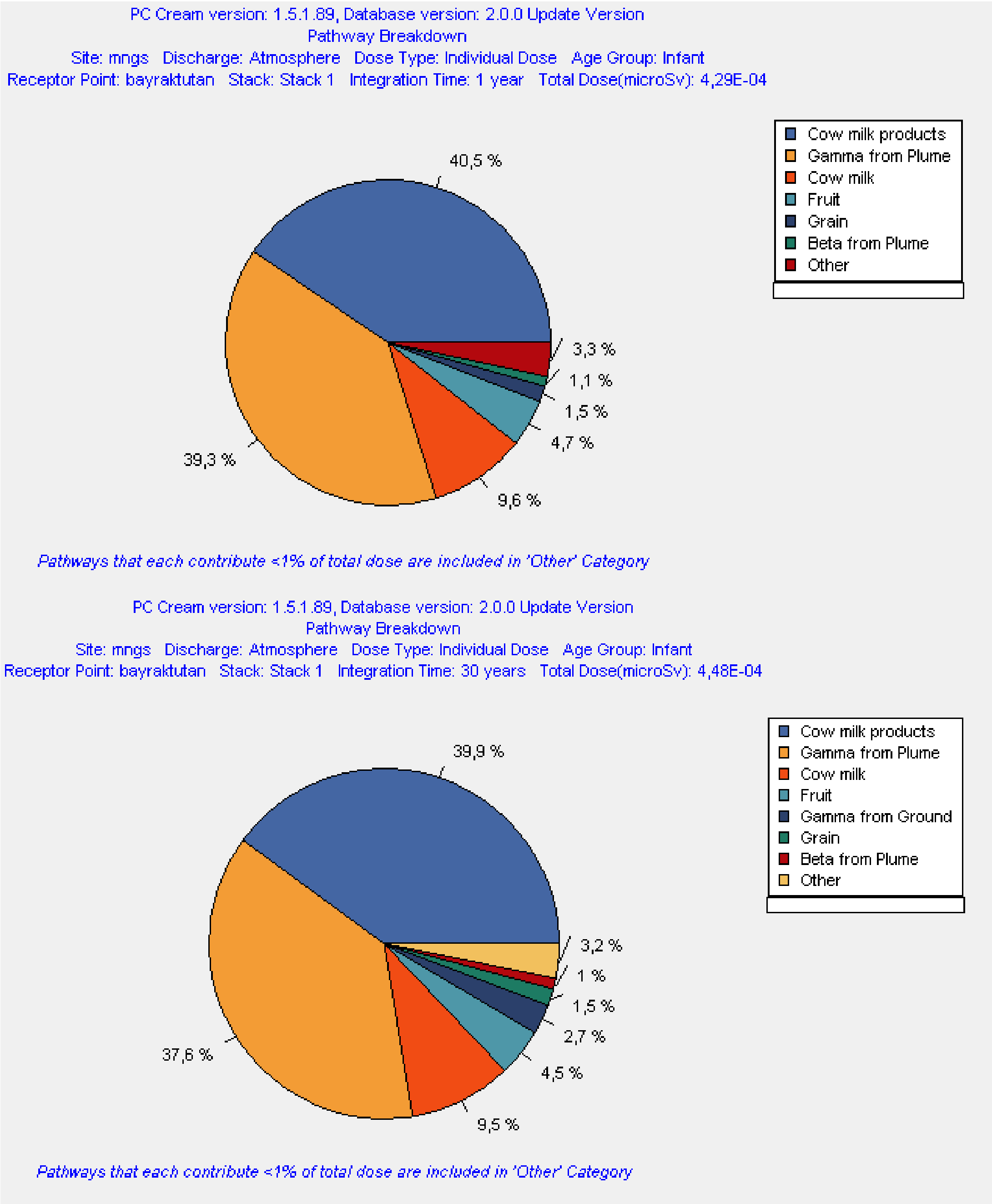


Figure B. 30 Pathway distribution in total atmospheric dose for infant in Bayraktutan for 1 year and 30 years integration time

C. The Results of Scenario 1 for PC CREAM 08 Software due to Aquatic Discharges for Public in Province of Iğdır

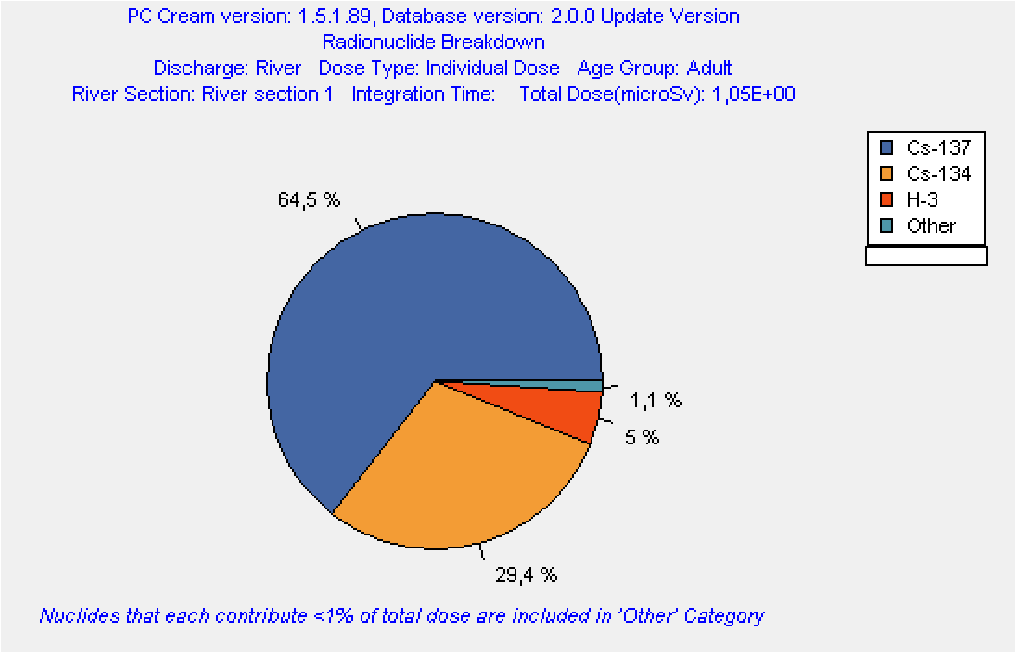


Figure C. 1 Radionuclide distribution in total dose for adult due to aquatic discharge

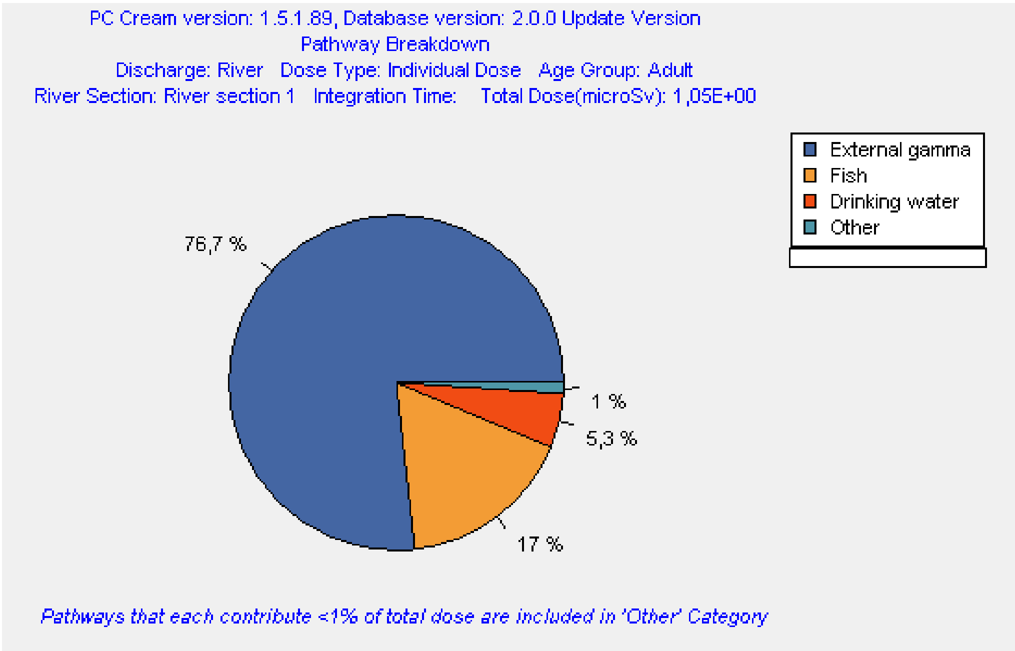


Figure C. 2 Pathway distribution in total dose for adult due to aquatic discharge

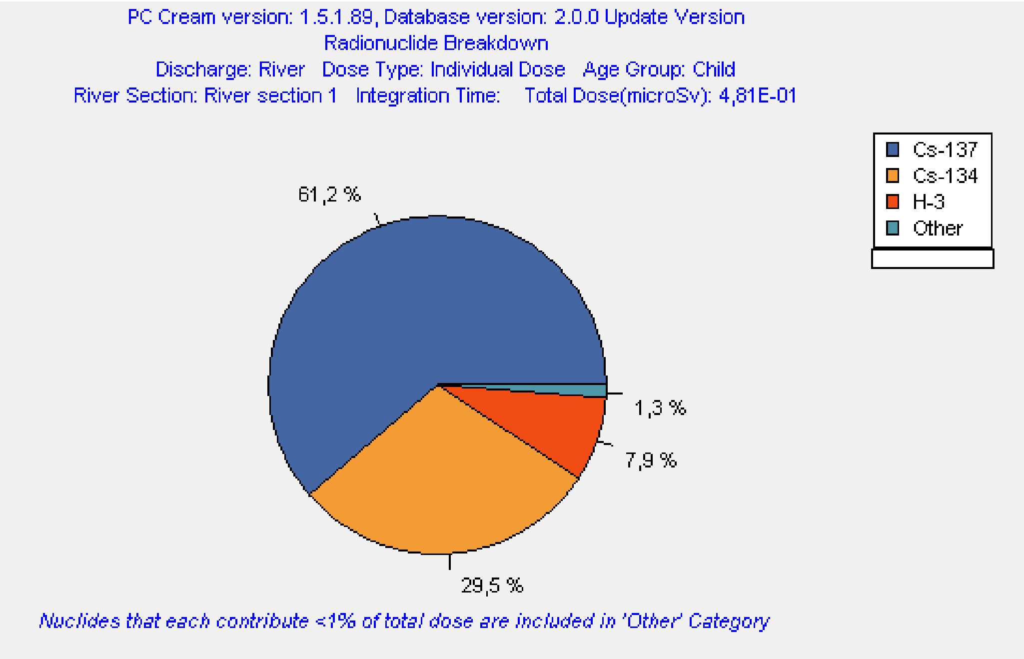


Figure C. 3 Radionuclide distribution in total dose for child due to aquatic discharge

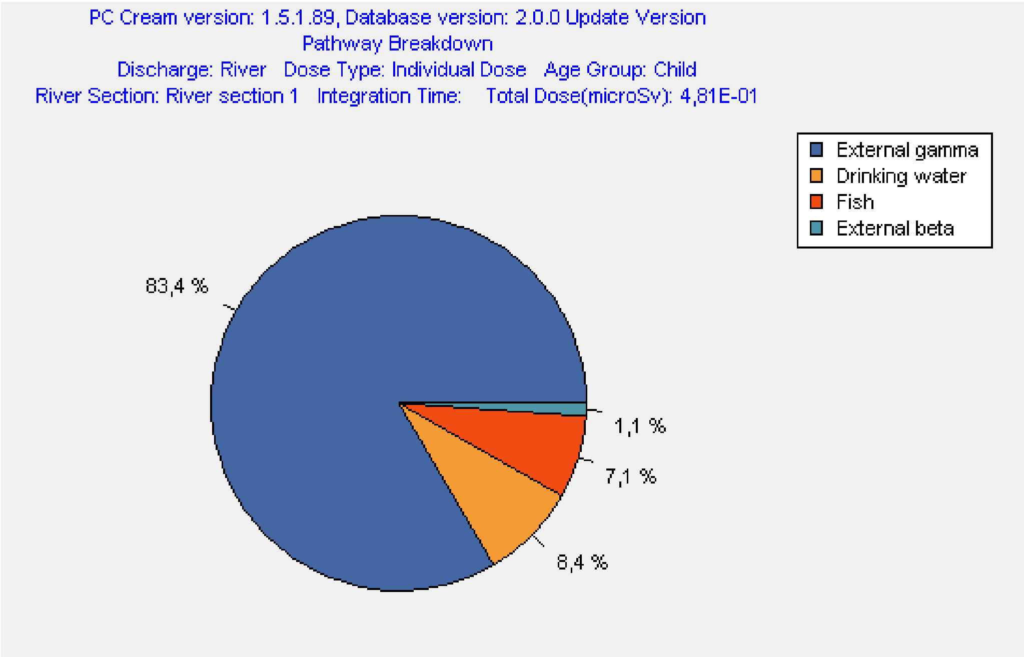


Figure C. 4 Pathway distribution in total dose for child due to aquatic discharge

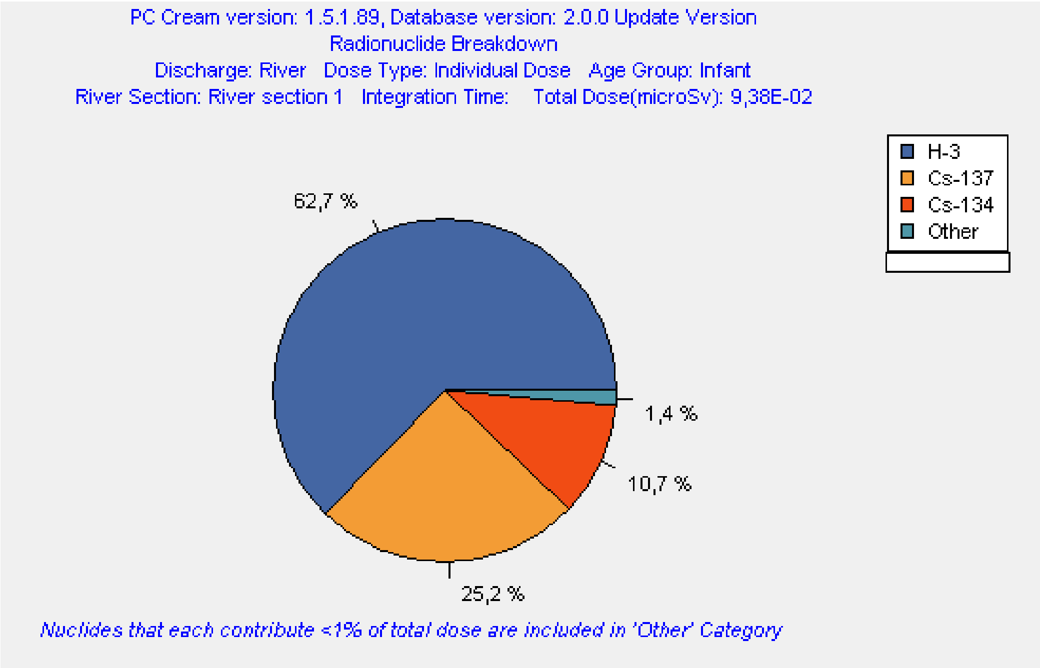


Figure C. 5 Radionuclide distribution in total dose for infant due to aquatic discharge

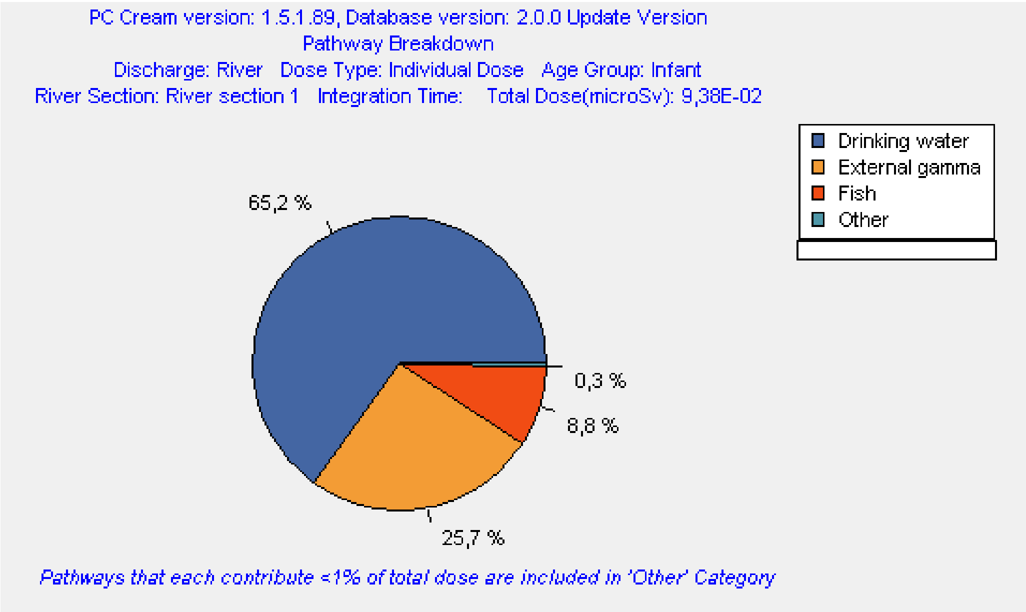


Figure C. 6 Pathway distribution in total dose for infant due to aquatic discharge

D. The Results of Scenario 2 for PC CREAM 08 Software due to Aquatic Discharges for Public in Province of Iğdır

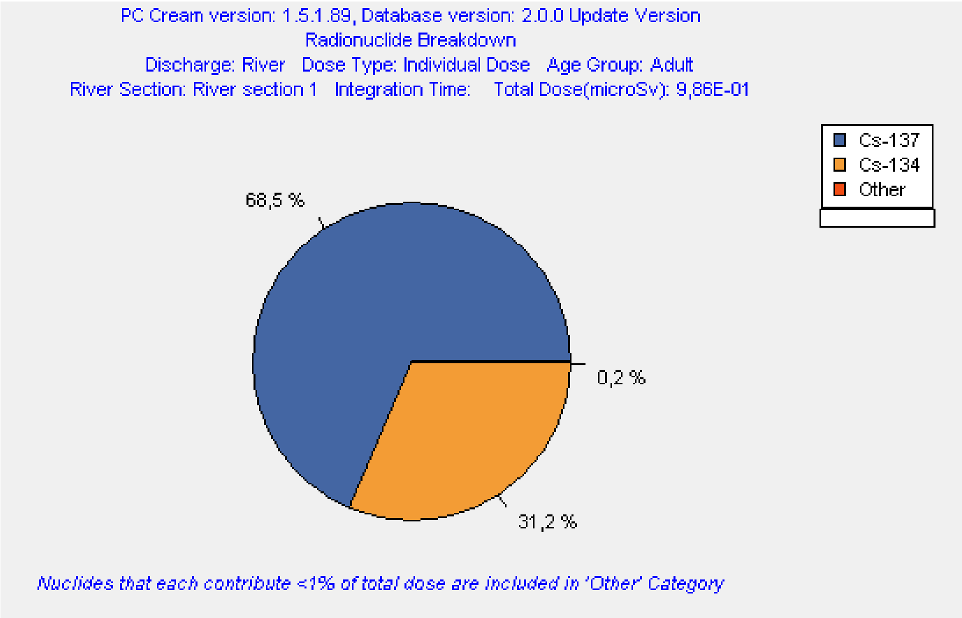


Figure D. 1 Radionuclide distribution in total dose for adult due to aquatic discharge

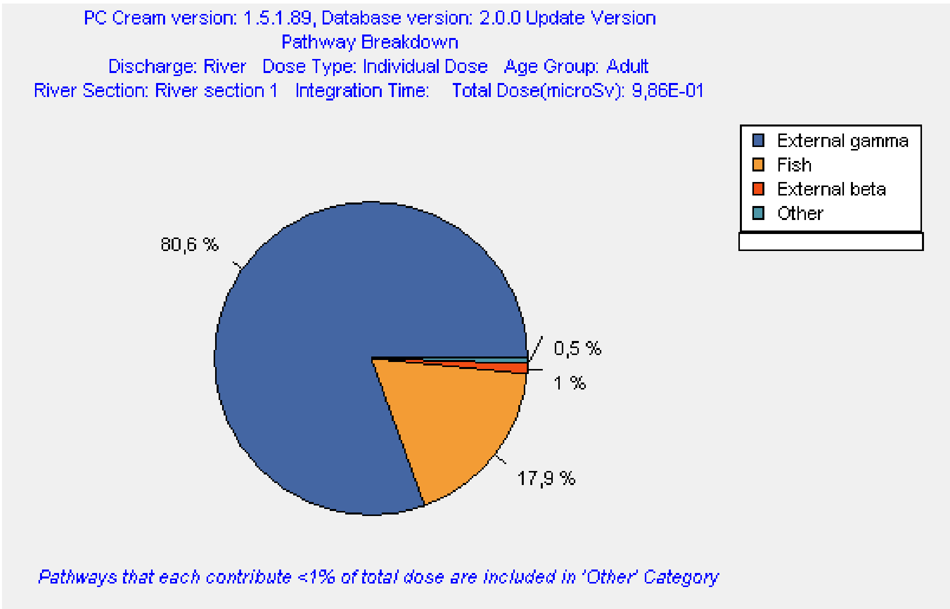


Figure D. 2 Pathway distribution in total dose for adult due to aquatic discharge

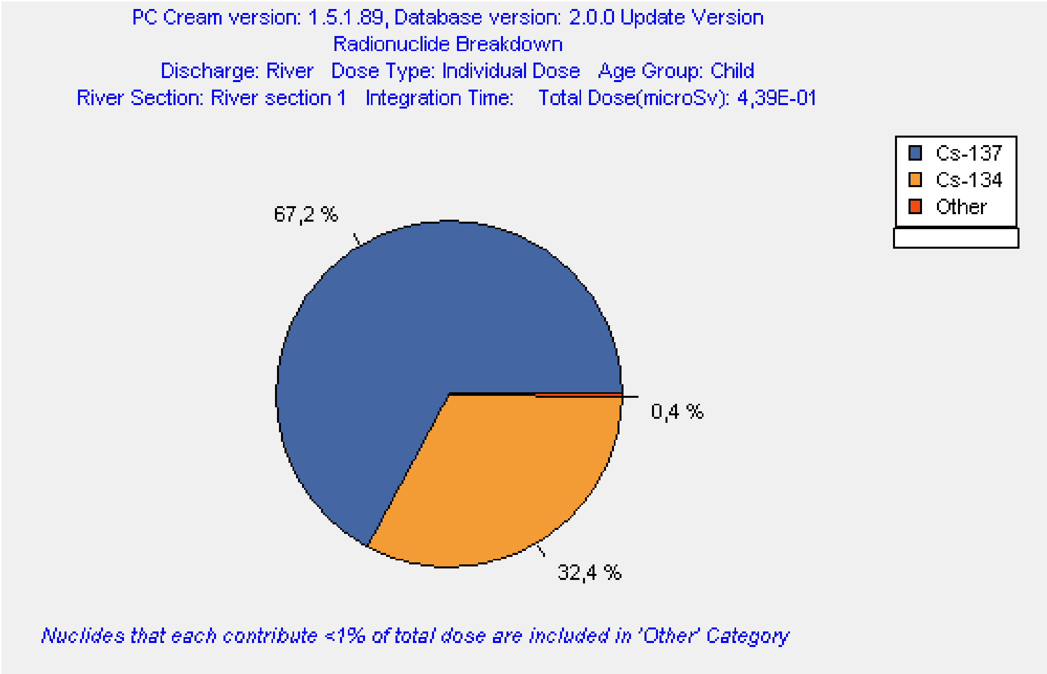


Figure D. 3 Radionuclide distribution in total dose for child due to aquatic discharge

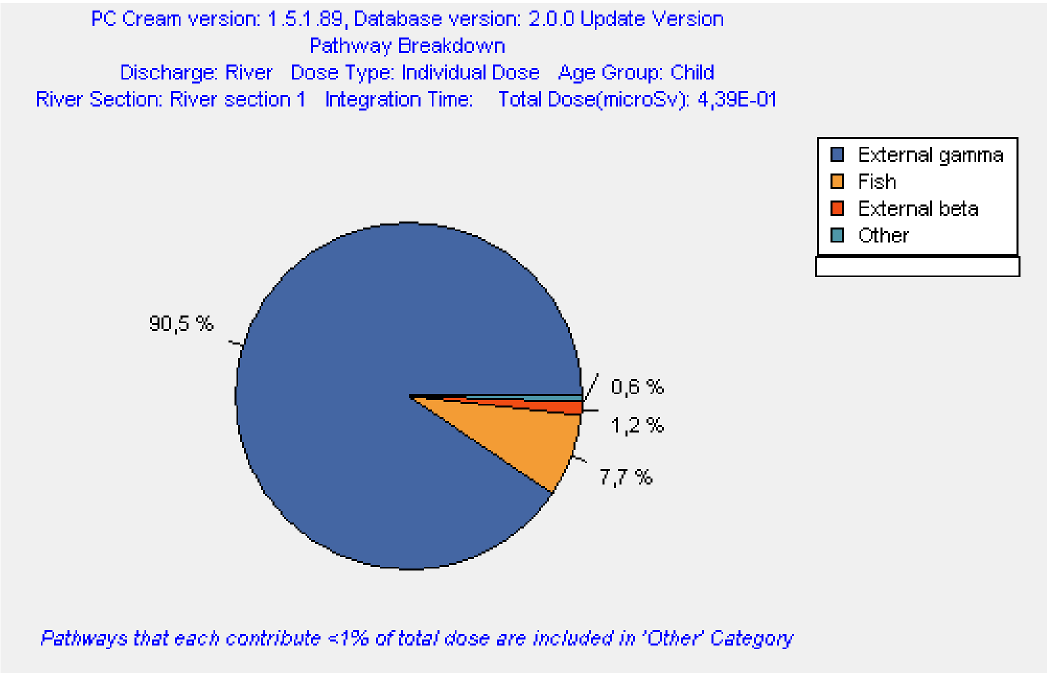


Figure D. 4 Pathway distribution in total dose for child due to aquatic discharge

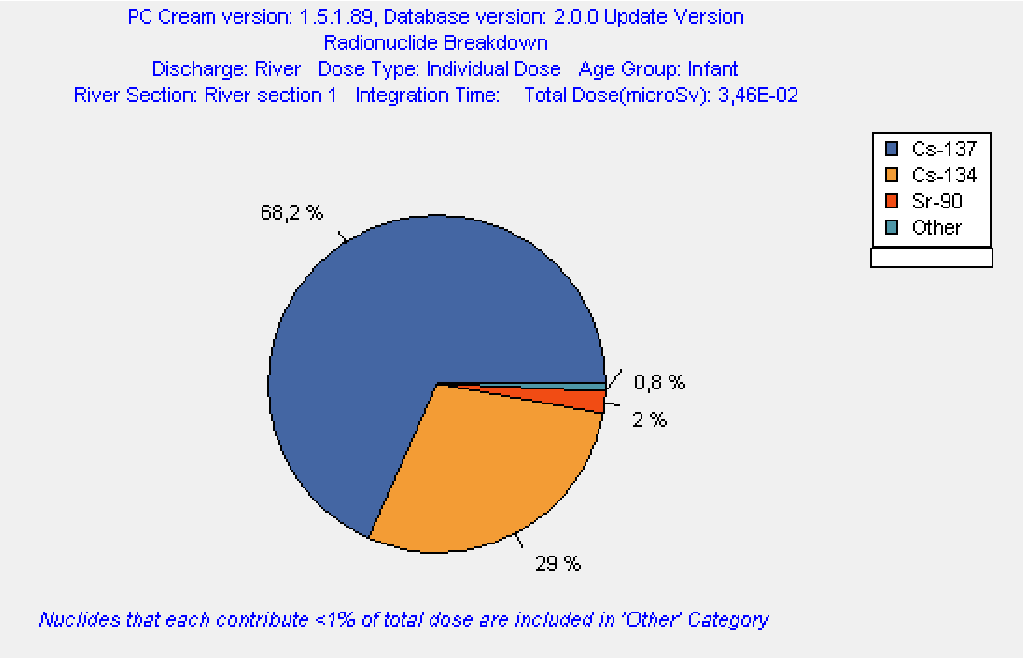


Figure D. 5 Radionuclide distribution in total dose for infant due to aquatic discharge

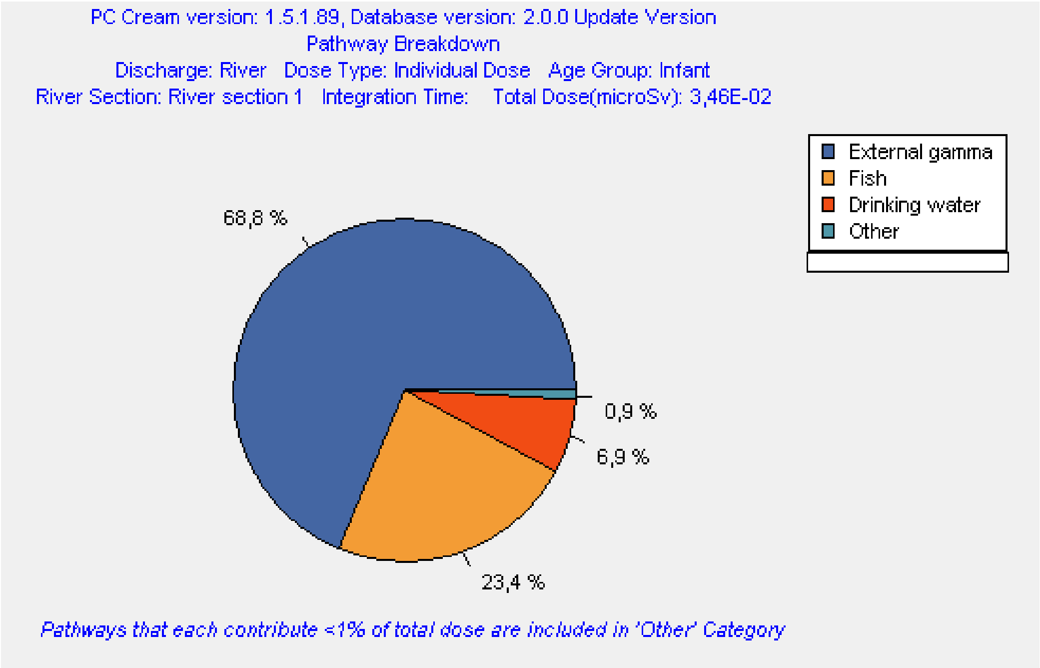


Figure D. 6 Pathway distribution in total dose for infant due to aquatic discharge