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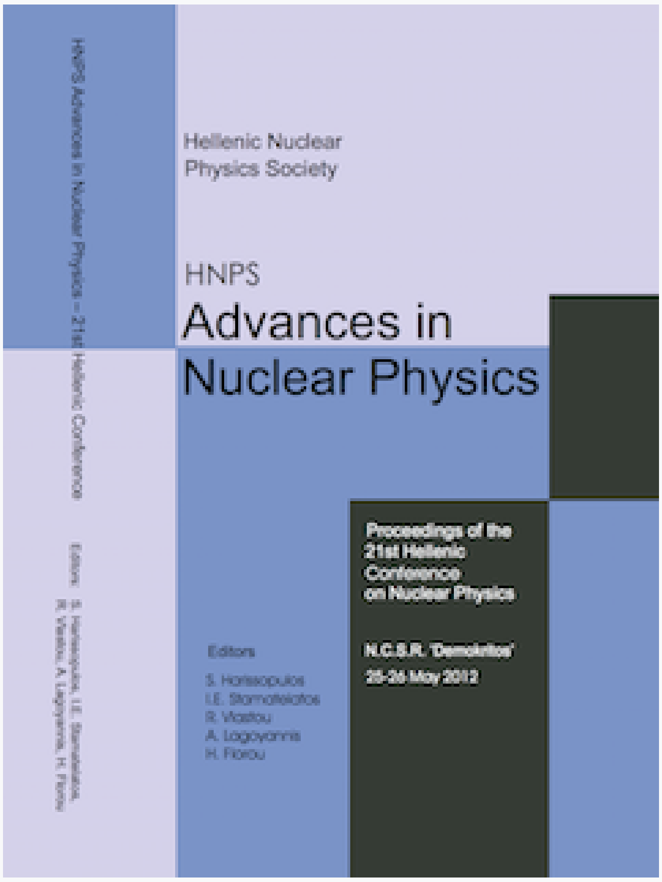

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Abstract

The radiological model of Thermaikos Gulf ecosystem has been designed based on the MOIRA-PLUS Decision Support System properly modified for the marine environment. Radioactive fallout contamination exercises have been performed for ^{90}Sr and ^{137}Cs radioisotopes, within the frame of environmental sensitivity analysis. The model's performance has been calibrated, taking into account the available ^{137}Cs deposition estimations and published experimental concentrations to the sediment, the water and the fish at the Gulf, from the time of the Chernobyl accident up to now. The radiation doses to adults – assuming that their entire food intake from the marine pathway comes from the local environment – after the first year of one instantaneous deposition of 1000 Bq/m^2, were found 0.72 μSv for ^{137}Cs and 8.8 μSv for ^{90}Sr, respectively. The results are consistent with other models estimations in Northern Seas and NE Aegean Sea.

Keyword : radiological modelling; ^{137}Cs; ^{90}Sr; MOIRA-PLUS; marine environment; Thermaikos Gulf

1. Introduction

Approaches to the management of the risk in radioecology have to take into account geographic, climatic, living and dietary habit, as well as ecosystem characteristics. An effective tool that can combine these parameters and give reliable dispersion estimations is radiological modelling. Modelling exercises have given significant information for the vulnerability of different environments [1]. Thus, the environmental sensitivity of each location can be set as a scientific parameter in the environmental management and the policy making [2; 3].

In order to standardize the representation of the radiological state of the environment following accidental pollution and to develop a scale of radioecological sensitivity for use in emergency planning and preparedness, the International Atomic Energy Agency (IAEA) organized the EMRAS II Programme (Environmental Modelling for Radiation Safety), from 2009 to 2011 [4]. Under EMRAS II Working Group 8 on Environmental Sensitivity with aim to investigate which environments, which components of each environment, and which seasons of the year would be most sensitive to a major release of radionuclides, the radiological model of Thermaikos Gulf and radioactive fallout contamination exercises have been realized.

The gulf of Thermaikos, located in the North Aegean Sea, was selected for the modeling exercise of radiological sensitivity since it is a typical coastal Mediterranean environment. The selected region is characteristic while it is the coastal zone of Thessaloniki, the second more populated urban centre in Greece, with intensive fishing and significant mussel cultivation and production. The scenario is enhanced by the fact that it is realistic, as two operating nuclear plants in Cernavoda (Romania) and Kozloduy (Bulgaria) are located 360 km and 580 km respectively, far from the studied area, and two more are planned to be constricted in Scutari (Albania) and Akkuyu (Turkey). Indicative is the fact that the impact of the Chernobyl nuclear accident in the region was significant [5], even though that the nuclear reactor was located further away (~ 1200 km).

2. Study area

Thermaikos Gulf is a semi-enclosed bay located in northeastern Mediterranean (40.20N, 23.00E) covering approximately a 3,630 km^2 surface. The gulf is a rather shallow coastal region with depth varying from 10 to 150 m, bordered on three sides by land and widely open (~ 45 Km) towards the south to the Aegean Sea. The hydrology of the region is strongly affected by the Black Sea water incomes and the big rivers inflows associated with wide catchments, while two of the largest rivers in Greece (Axios and Aliakmonas) discharge into the northern part of the gulf (see Fig. 1A). The topographical features of the North Aegean contribute to the formation of specific coastal currents and permanent eddies with sifting direction through time, resulting to high homogenization of the water masses throughout the gulf [6].

Despite the fact that the North Aegean Sea ecosystem is an oligotrophic region, it is among the most productive areas in the Eastern Mediterranean mainly due to the influence of nutrient rich, low saline, Black Sea waters and the local river flows. Small pelagic fish (mainly anchovy, *Engraulis encrasicolus*, and sardine, *Sardina pilchardus*) dominate landing, while significant is the productivity of the European hake (*Merluccius merluccius*), red mullets (*Mullus barbatus*), commercial shrimps (*Parapenaeus longirostris*), and cephalopods (such as *Octopus vulgaris* and *Eledone spp.*) [7]. Moreover, according to the data of the Greek Ministry of Agriculture in 2002, Thermaikos Gulf hosts the 70 % of the whole Greek production of the bivalve mollusc species, mainly mussels and oysters, aquaculture. The annual fish catch and mussel production inside the gulf is of the order of 23 and 10 tones y^{-1}, respectively, considering that the fishing period lasts almost all the year (January - October).

Five municipalities are sharing Thermaikos Gulf coastline. The total number of habitants, according the census of 2001, living in this area is 1,589,327, with age distribution: 0-5 years: 131,096; 6-15 years: 90,281 and >15 years: 1,367,950 persons. The diet and the recreational habits of the population are considered to be typical Mediterranean characterized by high fish consumption (16 kg y^{-1}), boating, shoring and swimming time (0.3 man-days $month^{-1}$).

3. Model description

In order to perform the risk scenario exercise the computerized decision support system MOIRA-PLUS (MOdel-based computerized system for Management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic Ecosystems and drainage areas) was selected [8]. MOIRA-PLUS is specifically designed for assisting managers, as well as experts in assessing the appropriateness of suitable strategies for the management of aquatic ecosystems contaminated by radionuclides.

MOIRA-PLUS is a box-parameterization model based on quantitative evaluations and balance of radionuclide contents in the water system components (surface water, deep water, surface sediment, bottom sediment) accounting for the radionuclides' transfer among them. It includes predictive user-friendly and intentionally not very complex models, driven by small number of readily accessible environmental parameters, which simulate:

- the time behavior of the hydrological, morphologic and environmental quantities and of the migration parameters of contaminants through the water ecosystems;

- the migration of pollutants from the catchment to the aquatic system;
- the migration of pollutants through the abiotic components of the aquatic system;
- the migration of pollutants from the abiotic components to fishes species;
- the effect of selected countermeasures to reduce the contamination levels of the water bodies and the radiological doses to man.
- Further sub-models are used to evaluate some significant environmental processes that influence the migration of contaminant (water thermal stratification, dynamic of chemical sand nutrients in water, dynamics of biomass).

The processes of sedimentation, radioactive decay, radionuclide migration from water to sediment (diffusion/adsorption) and from sediment to water (re-suspension/re-mobilization), radionuclide burial to passive sediment, radionuclide migration from catchment and radionuclide transport through the compartments chain are considered in the elementary compartment activity concentration calculations. The fish contamination in water bodies with spatial and time-dependent pollution levels is based on the principles of first-order dynamics and the correlation of bioconcentration factors to the concentration of K and Ca, derived from the water salinity. The doses to fish and to the critical individuals, as well as the collective dose are calculated based on the standard assessment equations, taking into account the dietary and costal recreational habits of the population.

For the model implementation in the present scenario, appropriate modifications of the migration models had to be made, so that can be described water bodies characterized by two-way water fluxes between different portions of the aquatic system and by current circulations, typical of the marine environment. These modifications practically allow the simulation of the movement of water masses through all adjoining segments, included in the latest version of MOIRA-PLUS (release 4.1.2) [9].

4. Model implementation

The implemented model consists of the main morphological, hydrological and essential environmental-sociological characteristics of the area, which were retrieved from the literature, unpublished scientific data or directly calculated from site specific models. Standard values for the radionuclides' parameters referring to their behavior towards the abiotic and biotic elements of the environment were also selected, while mean or slightly modified values were partially used for reducing the model's complexity and maximizing the modeling prediction efficiency.

The study area was parameterized using 5 box segments representing the main rivers that exit into the gulf and another 5 marine compartments (see Fig. 1B). Mean annual river fluxes, calculated catchments' run off, precipitation and evaporation values from the last decade have been used for the modelling of the hydrology, while mean monthly values of fluxes between the marine segments were calculated in order to simulate the Black Sea water income, the circulation and mixing processes in the gulf. The default model's values for reservoir-type segments were used for the migration constants, while all other parameters where extracted either from site specific data or estimated taking into consideration the relative literature [10; 11].

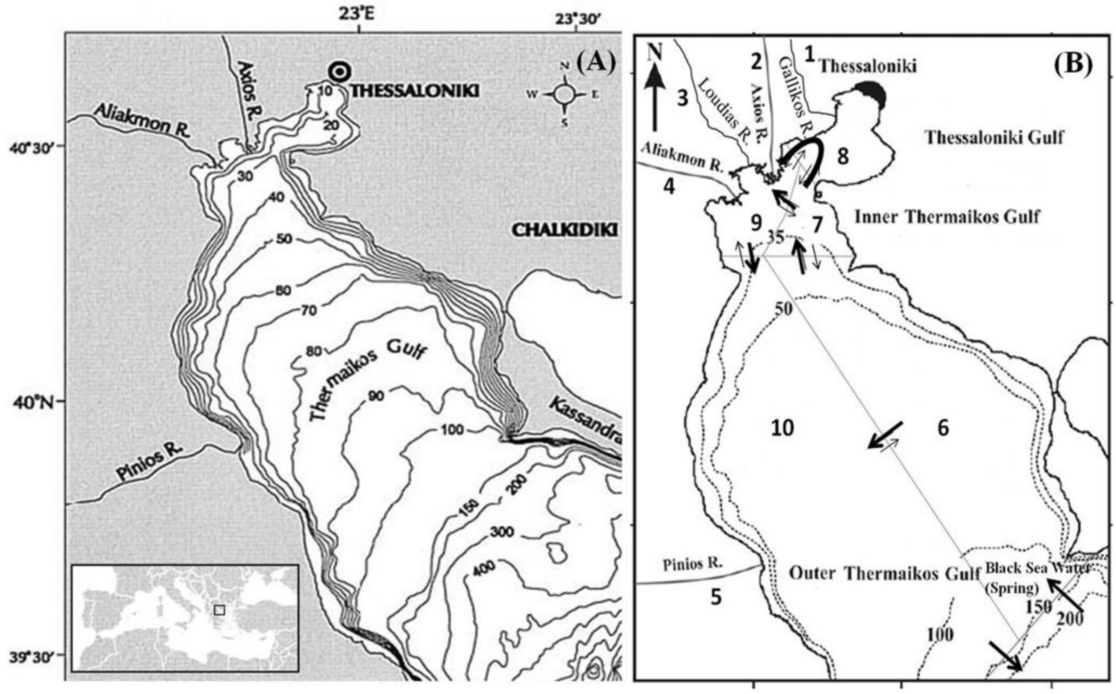

Fig. 1. (A) The Gulf of Thermaikos located at the North Aegean Sea (NE Mediterranean); (B) Box-model of the five river and five marine segments of Thermaikos Gulf, up to 150 m isobaths line, included in the simulation with the main water flux structures considered in the model.

A single, instantaneous deposition of 1000 Bq m^{-2} of ^{137}Cs and ^{90}Sr radionuclides, have been assumed as the start-point radiological stress on the study area. Different initial seasonal conditions were not taken into account, because of their negligible effect to the doses as only the marine aquatic pathway has been included in the analysis. The initial fall out was simulated as a constant rate deposition for a period of 1 month though out the region's elements (catchment areas, marine and river compartments), due to model input limitation.

Radionuclide concentrations in time were simulated to sea water, seabed sediment, fish and mussels. Consequently, radiation doses have been calculated for three different age groups of the population (0-5 years; 6-15 years and >16 years) during the 1st year, 2nd year and 10th year after the releases of the radionuclides, assuming that their entire food intake from the marine pathway comes from the local environment.

4. Results

In order to verify the functionality and maximize the reliability of the model, calibration was performed by simulating the ^{137}Cs dispersion, following the Chernobyl accident, in the biotic and abiotic components of the costal marine environment. The initial radiocesium fallout was set as a homogenous deposition of 30 kBq m^{-2} [12]. Additional monthly, exponentially decreasing, contamination burden from the open sea towards the gulf has been also considered, due to the Black Sea water influence in the hydrology of the region. The initial generic values of cesium migration parameters for reservoir-type segments of MOIRA-PLUS model are reported in Table 1, while the model's input values of the main morphological and hydrological features are illustrated in Table 2. The calibration was performed by comparing the results of model with the available empirical data and, consequently, modifying the values of the appropriate parameters, within established limits from the relative literature [13-24].

Table 1. Default radionuclides' migration values for the reservoir-type segments of MOIRA-PLUS model.

Parameter	Unit	^{137}Cs	^{40}Sr
Radionuclide migration velocity to sediment (v)	$m\ s^{-1}$	1.0E-06	3.5E-07
Migration rate to deep sediment (K_{ds})	s^{-1}	1.2E-08	-
Migration rate from bottom sediment (K_{sw})	s^{-1}	1.5E-08	1.5E-08
Quick radionuclide interaction of water-sediment upper layer (h_{Δ})	m	6	0
Transfer coefficient from catchment (ε)	m^{-1}	0.2	0.2

Table 2. Main morphological characteristics of the hydrological features included in the model.

Compartment number	Description	Average depth (m)	Average length (km)	Average width (km)	Average flux (m^2 $month^{-1}$)	Catchment area (km^2)
1	Gallikos River	0.49	65	0.03	3.09E+07	9.30E+02
2	Axios River	1.29	388	0.08	2.64E+08	2.37E+04
3	Loudias River	0.67	130	0.04	6.10E+07	1.00E+03
4	Aliakmon River	0.71	322	0.05	6.97E+07	9.25E+03
5	Pinios River	1.04	216	0.07	1.64E+08	1.08E+04
m.1	East. Outer Thermaikos Gulf	72.5	67.3	22.7		7.50E+02
m.2	East. Inner Thermaikos Gulf	16.32	17.4	7.8		3.00E+01
m.3	Thessaloniki Gulf	40.37	14.5	19.3		
m.4	Weast. Inner Thermaikos Gulf	31.23	16.4	9.4		
m.5	Weast. Outer Thermaikos Gulf	81.2	67.3	25.6		

Table 3 contains the calibrated values of mixing ratio between marine segments, sedimentation rate and transfer parameters for ^{137}Cs, while for ^{90}Sr, where empirical data were not available, default model's values for reservoir-type compartments were assumed.

Table 3. Calibrated values of model parameters for ^{137}Cs in the Thermaikos Gulf.

Parameter	Unit	Value
Mixing coefficient between marine segments	$m^3\ s^{-1}$	10
Sedimentation rate	$m\ month^{-1}$	0.0003
Bioaccumulation factor (fish)	$kg\ m^{-3}$	0.1
Bioaccumulation factor (mussels)	$kg\ m^{-3}$	0.03
Biological transfer rate (fish)	$month^{-1}$	0.35
Biological transfer rate (mussels)	$month^{-1}$	0.058

In Fig. 2 are illustrated the predicted concentrations of the calibrated model in comparison with the empirical concentrations of ^{137}Cs in water, sediment, fish and mussels for a period of 25 years since the initial deposition. Considering the complexity of the environment, the model limitations and simplifications, the measurements' uncertainties, spatial dispersion and sampling conditions, the results are satisfactory with the divergence for the expected values less than one order of magnitude. Exception is the predicted concentration in sediment, where the greater disagreement is attributed to the fact that completely different costal and deep sediments characteristics (sedimentation ratios, composition, radionuclides' deposition etc.) that cannot be integrated in a single compartment. Nevertheless, actual sediment concentrations are indifferent, concerning the exercise goals.

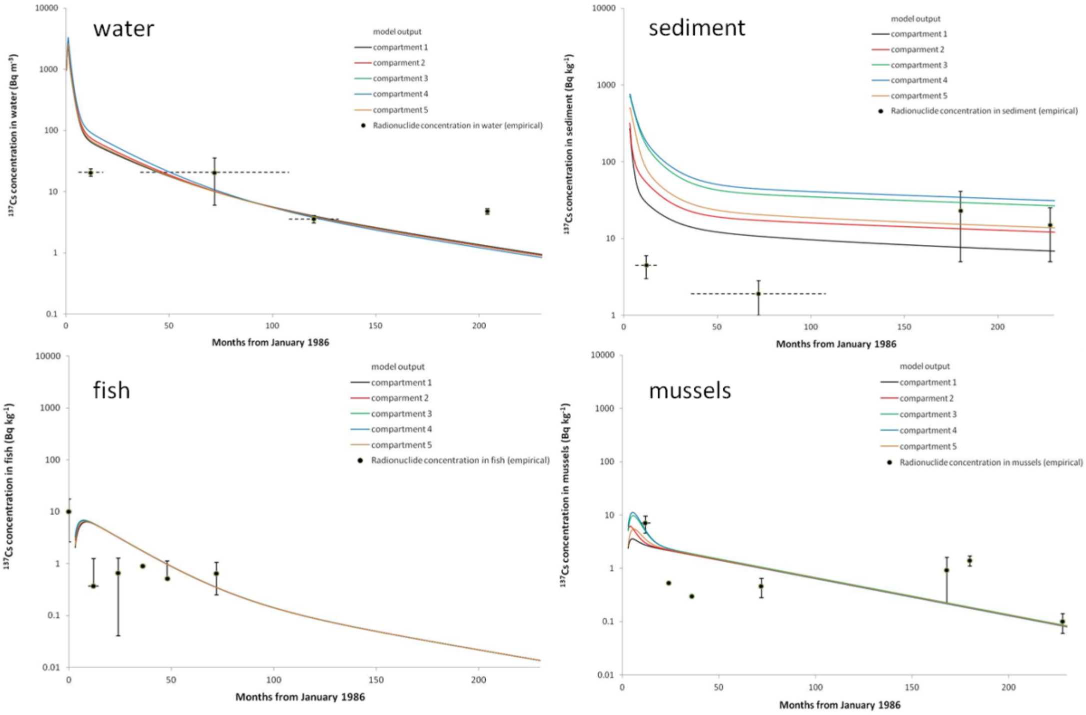

Fig. 2. Model estimations for ^{137}Cs concentrations at the water, the sediment, the fish and the mussels in the Gulf, after the Chernobyl accident fallout.

Ones the model calibrated, the additional social and environmental data were included in the model. The population age classification and the spatial distribution along the coast, as well as the fish and mussels productivity are shown in Table 4.

Table 4. Calibrated values of model parameters for ^{137}Cs in the Thermaikos Gulf.

Marine compartment	Population (persons)			Fish production (kg y^{-1})	
	0-5yr	6-15yr	>16yr	Fish	Mussels
1	5224	3527	55860	10116901	
2	3083	2062	31141	247713	
3	76043	53391	812982	217342	
4	14429	9594	147443	422918	6551750
5	32317	21707	320524	12243426	3527865

The evolution of the collective dose rates to the population for ^{137}Cs and ^{90}Sr as derived from the model implementation are depicted in Fig. 3, while the environmental sensitivity results for various parameters are presented in Table 5.

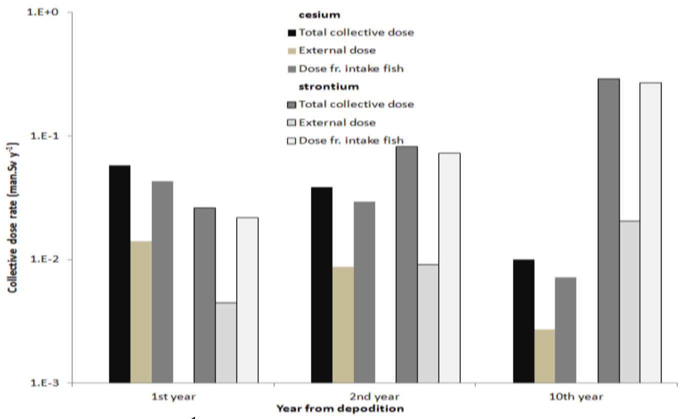

Fig. 3. Collective dose rates (manSv y^{-1}) for the years after the fallout deposition due to the aquatic pathway.

Table 5. Environmental sensitivity analysis for ^{137}Cs and ^{90}Sr.

Measure of the effect	Unit	Age (yr)	Sensitivity=Measure of the effect/1000 Bq m^{-2}					
			^{137}Cs			^{90}Sr		
			1st year	2nd year	10th year	1st year	2nd year	10th year
Max. dose to critical individual	mSv y^{-1}		7.23E-07	2.02E-07	8.84E-09	8.76E-06	4.62E-06	1.85E-06
Total collective dose			5.76E-05	1.92E-05	9.96E-07	2.62E-05	4.08E-05	2.91E-05
External dose			1.42E-05	4.38E-06	2.74E-07	4.49E-06	4.54E-06	2.06E-06
Dose from intake fish			4.33E-05	1.48E-05	7.22E-07	2.17E-05	3.64E-05	2.71E-05
Max. dose to fish	mGy y^{-1}		3.83E-06	2.41E-06	7.49E-07	1.72E-06	2.45E-06	1.69E-06
Total dose	Sv y^{-1}	0-5	7.39E-11	5.10E-11	1.36E-11	5.98E-11	1.15E-10	1.08E-10
		6-15	1.85E-10	1.25E-10	3.41E-11	1.26E-10	2.43E-10	2.15E-10
		> 16	3.32E-10	2.29E-10	5.88E-11	1.56E-10	2.54E-10	1.87E-10

In order to validate the consistence of the model's estimations, the results were compared with the analogue estimations of other two models implemented in different costal marine regions in the framework of the EMRAS II Programme: the NRPA box model [25] applied in various regions in Northern Seas and the NTUA 3D model [26] applied at the NE Aegean Sea. As presented in Fig. 4, the results of the dose rates from ^{137}Cs and ^{90}Sr to a representative individual after the 1st year of the instantaneous deposition are in the same order of magnitude for ^{137}Cs suggesting satisfactory agreement between the models. In case of ^{90}Sr, where the dose is an order of magnitude higher in Thermaikos Gulf compared with the Northern Seas, the discrepancy can be attributed to the large amount of water from rivers that Thermaikos Gulf receives and the MOIRA-PLUS approach used here that allows ^{90}Sr input from the river catchment areas.

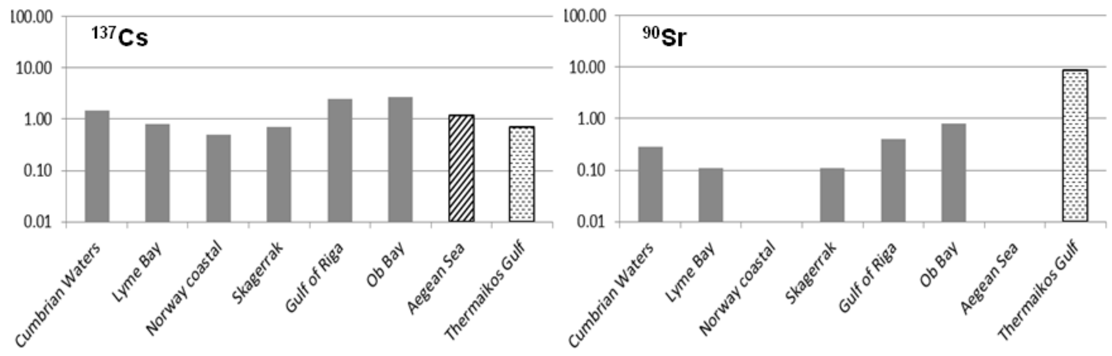

Fig. 4. Comparison of the dose rates (μSv) to an individual after the first year of the same fallout radionuclide deposition as estimated from three different models at Northern Seas (NRPA box model), NE Aegean Sea (NTUA 3D model) and Thermaikos Gulf (MOIRA-PLUS model).

5. Discussion and conclusions

The analysis of the deposition exercise results showed that the main contribution in the total collective dose to the population is the fish intake for adults. ^{90}Sr and ^{137}Cs environmental sensitivity factors are of the same order of magnitude (Table 5). In the first year the value for cesium is slightly enhanced, compared the one for strontium. However, over time the contamination effect from strontium becomes more important, while the dose rate increases significantly in contrast with dose rate for caesium which decreases slowly with the time. The dominant ^{90}Sr effect, from an environmental sensitivity point of view, is also shown in the maximum dose to critical individuals, where the values for the two radionuclides are of the same order of magnitude in the 1st year, but after one decade the difference is significantly greater.

The external dose, corresponding to the concentration radionuclides in water and in shore sediments, slowly decreases for ^{137}Cs, while it is almost constant for ^{90}Sr. This trend can be explained by the fact that the contribution of ^{90}Sr from the catchments of rivers flowing into the Gulf is higher than for ^{137}Cs. The dose from fish intake, corresponding to the concentration of radionuclides in fish, can be explained by accounting for the long term accumulation of ^{90}Sr in fish bones compared to the fast turnover of ^{137}Cs in fish flesh. The high content of potassium and the consequent low value of the bioaccumulation factor lead to low levels of ^{137}Cs concentrations in fish, while persistent levels of contamination for ^{90}Sr indicate higher sensitivity in long term.

Different meteorological condition have negligible effect on the model predictions; thus seasonality was absent from the analysis. The seasonal behavior of the radionuclides is mainly due to thermal stratification of the water column. Due to the shallow water depth and the high mixing rate throughout the year, the thermocline of the water column in the Gulf is almost stationary and fixed. Thus, the predators (pelagic fish) of the region essentially move through the entire water column and seasonal differences in radionuclide activity concentrations are not noticeable in fish contamination.

It is important to note that in the implemented exercise pathways other than the marine one have been excluded. Effects from other pathways are expected to be much more significant, not only because of the direct terrestrial pathways (food consumption, external irradiation from the soil), but also from the long term influence of the freshwater aquatic pathways (drinking water consumption, irrigation), due to the agricultural production in the wide catchments of the region.

In conclusion, ones the results are also consistence compared with other radiological models, the developed model can be consider robust and reliable for dispersion predictions (for ^{137}Cs and ^{90}Sr) in the marine environment and is a useful tools for realistic estimations of radionuclides fate and doses to the habitants after radioactive fallouts or relishes (river, catchments or currents).

Acknowledgments

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