MODELING THE DYNAMICS OF METHYLMERCURY BIOMAGNIFICATION

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Abstract

Methyl mercury (MeHg), which is a heavy metal, accumulates in the body of species through consumption of food including MeHg or through absorption (absorption of MeHg from water by zooplanktons). The concentration of MeHg in the body of the species in the higher level of food chain is higher than the ones in the lower level. This increase in the level of concentration is called biomagnification. In this study, a dynamic simulation model is constructed to study the biomagnification of MeHg in zooplanktons, small fish (Atlantic mackerel), big fish (Bluefin tuna) and Human. The data is taken from studies held in the Mediterranean Sea. The model successfully replicates the real life situation. There are two essential findings. First, the concentration in humans significantly increases by eating higher amount of tuna per week. Second, the concentration in water immediately affects the concentration in the body of each species in the food chain.

Key words: MeHg concentration, biomagnification, dynamics of food chain

1. INTRODUCTION

Relationships between physical-chemical properties of organic chemicals and physiological responses in organisms have been studied since the late 19^{th} century. Especially in nowadays, it is a noteworthy problem that affects health of humanity and the environment.

Environmental toxicology is based on the hypothesis that the amount of chemical reaching an active site in, or on the surface of an organism which creates ecological and health risks. This basic toxicological principle is "the dose that makes the poison" (Gobas & Morrison, 2000). To interpret the toxicological responses of organisms, it is necessary to understand the relationship between the concentration of chemical in environmental media (e.g., water, sediment, or air) and the concentration of chemical in an organism, or in the target part(s) of an organism, in contact with that media. In environmental toxicology literature, environment-organism concentration relationships often are discussed in terms of bioaccumulation and biomagnification.

Biomagnification is the increase in concentration of substance that occurs in a food chain. It is a result of, for instance, heavy metal contamination or in other words persistence of contamination which cannot be decomposed by environmental processes. Besides, the substance's low rate of internal excretion or degradation is another reason for biomagnification. This term is sometimes used interchangeably with "bioaccumulation".

However, there is an essential distinction between these two. While biomagnification occurs across food chain levels, bioaccumulation occurs within an organism in this food chain level. Precisely, bioaccumulation is the increase in concentration of a substance in certain parts of organisms' bodies. It is due to absorption from food and the environment.

Mercury is a global pollutant that knows no environmental boundaries. Its presence and behavior in aquatic systems are interesting and important since it is the only heavy metal that bioaccumulates and biomagnifies through all levels of the aquatic food chain (Lindqvist, Johnasson, Aastrup, Andersson, & Bringmark, 1991). Organic mercury in the form of methylmercury (with the chemical symbol of MeHg), being the most toxic chemical species. It is particularly important for the consequences of human health, as dramatically demonstrated by the Minamata and Niigata disaster in Japan. This disaster is called Minamata disease in the literature.

Fish is widely recognized as the primary source of MeHg intake for humans, resulting in statistical differences between subpopulations with high and low fish consumption (Holsbeek, Das, & Joiris, 1996), (Nakagawa, Yumita, & Hiromoto, 1997). In Minamata region, the seafood was their fundamental consumption. Hair samples of the disease victims and residents of Minamata indicated hazardous results of MeHg level. The maximum mercury level of the patients was 705 ppm (parts per million) which was almost seven times higher than the level of residents' (191 ppm) and also, almost 176 times higher than the level of people (4ppm) living outside the Minamata region (Harada, 1972).

In the literature, there is also a crucial case study which details "A Mercury Model for Mex Bay, Alexandria" with a static model. Mex Bay suffers from serious pollution problems due to the discharge of waste water from many heavy industries, such as cement plant, tanneries, an oil refinery and a chlorine alkali plant. The bay's most serious problem is probably the mercury contamination (which exceeds the limit 1ppm for human food set by WHO) of fish. The model is used to describe the spatial distribution of mercury contamination of the bay. Hall et al.'s paper is a field experiment was conducted to determine the degree to which fish accumulated MeHg via their food or via passive uptake from water through the gills. Their experiment is the first experiment to confirm that food is the dominant pathway of MeHg bioaccumulation in fish at natural levels of MeHg (Hall, Bodaly, Fudge, J.W.M.Rudd, & Rosenberg, 1997). According to this study, it is seen that the concentration levels of mercury are generally much higher in fish and marine mammals than the level of the water. MeHg biomagnifies through the food web, meaning that apical predators, that are carnivorous species feeding at the top of the food chain, tend to have higher levels of MeHg. Also the larger (older) individuals tend to have higher contents.

As it is mentioned above, the biomagnification of MeHg causes serious health problems while the environmental pollution such as industrial contamination increase drastically. From this basis, in presented study, a dynamic model is constructed to observe the biomagnification of MeHg concentrations in bodies of different fish species of commercial importance and also, in the body of human. The general aquatic food chain is shown in Figure.1. This study is focused on the food chain which is consisted of zooplankton, small fish, big fish and human.

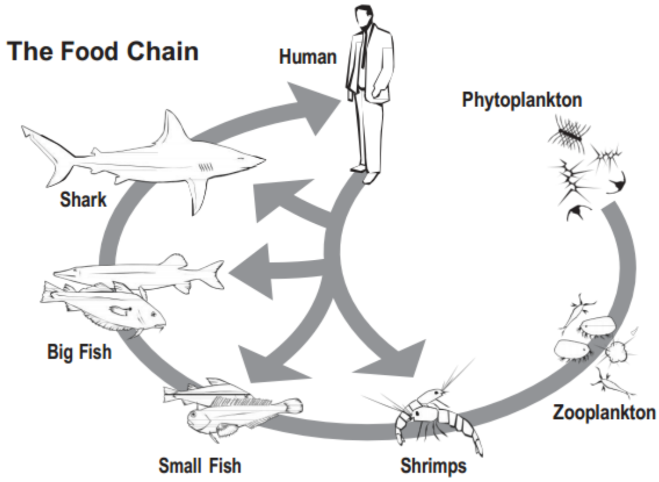

Figure 1: The Food Chain (Food Chain/ Nutrition)

There is no example in system dynamics modeling of MeHg biomagnification in the literature. Therefore, main aim of this study is to build a model that constructs the behavioral structure of MeHg biomagnification through the focused food chain levels. The model suggests showing the increase in MeHg concentration level in all that levels.

2. OVERVIEW OF THE MODEL

The model consists of two sub models:

2.1. The sub-model of biomagnification

In this sub-model, the process of MeHg biomagnification from the water through the food chain levels is shown. There is an assumed initial level of MeHg concentration in water and also, the MeHg contamination to the water is remarked. The food chain levels consist of namely; zooplankton, Atlantic Mackerel (Scomber scombrus), and Bluefin Tuna (Thunnus thynnus). The dietary of the Atlantic mackerel depends only on filtering zooplankton and MeHg in the zooplanktons is transferred to the body of mackerel by filtering.

In marine fish, about 90 % of the mercury exists in the methylated form (methyl mercury). Some of this methylated form of mercury level is excreted from the marine fish. These excretion and mortality rates of the marine fish affect the MeHg concentration level of water. In addition, human consumes fish and its MeHg level is transferred to the body of human. There is certain half-life of MeHg in the body of human. After that time, the elimination of MeHg from the body of human is occurred. Therefore, increase in the level of MeHg concentration from the water through the food chain levels is shown in this sub-model.

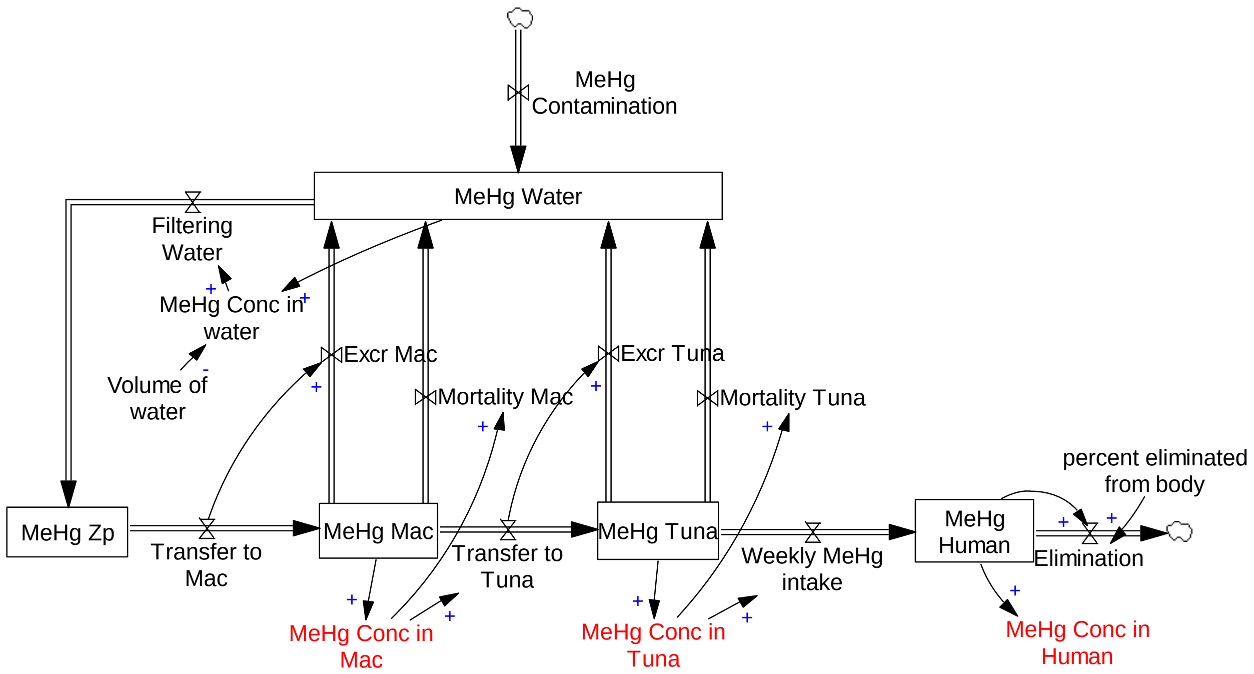

Figure 2: Sub-model consisting of stock-flow structure of the biomagnification of MeHg

2.2. The sub-model of predator – prey relationship

Bluefin tuna and Atlantic mackerel are in a predator – prey relationship. For fishery dynamics, Press' study is a beneficial source. His study models the bio-economic dynamics of a system involving two species consumed by humans: a highly mercury contaminated predator, Bluefin tuna and a tuna prey fish with low levels of contamination, Atlantic mackerel (Michael S. Press, 2000). However, here, the bio-economic dynamics of a system is not considered. Ford's predator – prey model is also consulted to construct the fish dynamics of the model (Ford, 1999).

In presented model, the birth rate of predator depends on how much prey is consumed by the predator's population. If the density of prey is high, the prey consumption is also at a high level, and the birth rate of predator is high where the death rate of predator is low. In time, predator population increases tremendously, and the number of prey becomes insufficient for feeding the whole predator population. This time, predator's birth rate decreases and its death rate increases. The number of predators becomes low, and the number of prey increases. On the other hand, there is a limiting capacity of the water for them. When the prey's density gets higher, because of the crowding effect, which is the result of maximum carrying capacity, the birth fraction decreases and the death fraction increases. The following Figure 3 shows the corresponding stocks and flows.

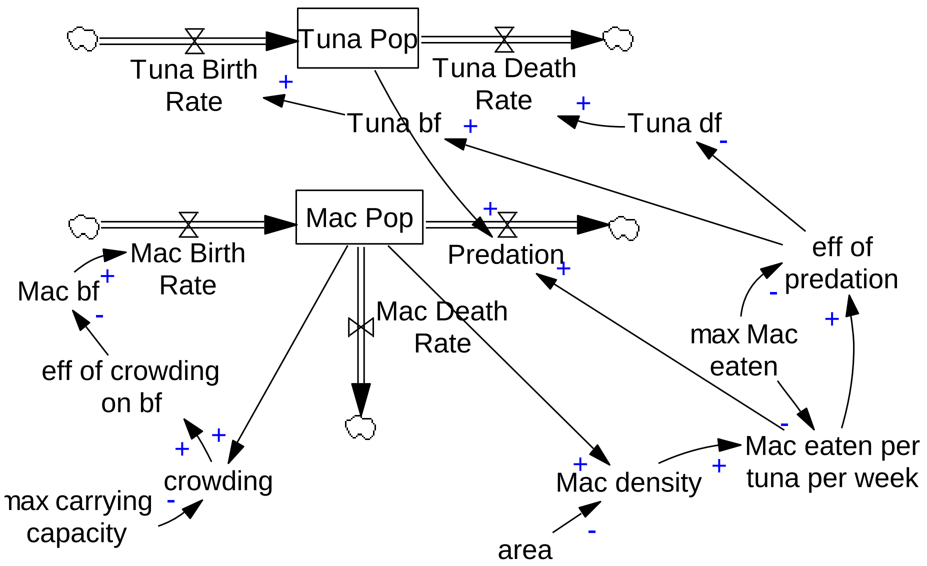

Figure 3: Sub-model consisting of stock-flow structure of Predator – Prey Relationship

3. MODEL DESCRIPTION

The dynamic simulation model consists of five stocks which accumulate MeHg level of water and the food chain organisms. Since weekly fish consumption is considered in the model, time unit is a week and the time horizon is 250 weeks. The assumptions and parameterization are briefly explained below. The complete equations are in Appendix B.

3.1. Critical Assumptions

The selected fish species, as it is mentioned before, are Atlantic Mackerel and Bluefin tuna which are caught in the Mediterranean Sea. Atlantic mackerel's feeding habitat is zooplankton and small fish (Collette, 1986). Bluefin tuna prey on small schooling fish (anchovies, hakes, mackerel) or on squids and red crabs (Nakamura, 1968). However, feeding habit of mackerel and tuna are assumed only zooplankton and Atlantic mackerel, respectively. Since the assumption that the Atlantic mackerel is only consumed by its predator, MeHg transfer to Bluefin tuna's body is just through its prey.

Additionally, for the case of human, it assumed that the only way MeHg transfer to human is Tuna consumption. Half life of MeHg in human is around 44-80 days (UNEP Chemicals is a part of UNEP's Division of Technology, 2008). This value is assumed as 70 days which is equal to 10 weeks. The weekly tuna intake of human is also assumed constant.

3.2. Parameter Estimation

In this part, estimation of crucial parameters will be explained briefly.

According to Ogrinc's paper, MeHg level in the Mediterranean Sea is $0.5*10^{-3}$ mg/ kg on average (Ogrinc, et al., 2007). The average temperature of the Mediterranean Sea is 19.86 ^{0}C. The mean weight of Atlantic Mackerel is equal to 0,034 kg and its mean MeHg level is 0.045 mg/kg (UNEP Chemicals is a part of UNEP's Division of Technology, 2008). The related table can be found in Appendix A (Table A1).

The parameters which will be explained in the following are going to be used in the discussion after observing the model and obtaining its outcomes.

According to The Codex Alimentarius Commission's recommendation, tolerable MeHg level in non-predatory fish is 0.5 mg methylmercury/kg and in predatory fish is 1 mg methylmercury/kg (UNEP Chemicals is a part of UNEP's Division of Technology, 2008), (Storelli & Marcotrigiano, Fish for human consumption: risk of contamination by mercury, 2000). For the humans, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) has established provisional tolerable weekly intakes (PTWIs) for total mercury at 5 μg/kg body weight and for methyl mercury at 1.6 μg/kg body weight (UNEP Chemicals is a part of UNEP's Division of Technology, 2008).

The average body weight of human is usually country specific and may be derived through national surveys of body mass index. In this study, average body weight is taken into account as 70 kg (Masters, 1991).

According to Ecless & Annau's description of a multiple regression analysis (see chapter 1), excretion rates of MeHg in mackerel and tuna are found. Their analysis show that both inorganic Hg and MeHg elimination rate from fish are both negatively correlated with body size but MeHg elimination rate from fish is positively correlated with water temperature only in long term experiments. Although they do not specifically compare to fish species' half lives, they indicate that MeHg is generally excreted faster in mammals than in fish: the half life of MeHg usually ranges between 5 and 130 days in mammals, while it ranged between 130 and 1030 days in long term experiments on fish (Ecless & Annau, 1987). Their multiple regression analysis is therefore performed using temperature (T; °C), fish weight (W; g), and a dummy variable for chronic (E =1) and acute (E = 0) exposures to find the MeHg excretion in fish with the following formula:

$$\ln K = 0.066(0.019)T - 0.20(0.06)\ln w + 0.73(0.24)E - 6.56(0.45)$$

Applying this equation to the model parameterization, the excretion rates of Atlantic mackerel and Bluefin tuna are 0.061 and 0.056, respectively.

3.3. Model Validation

The formal steps of model validation described in Barlas (1996) are followed. While constructing the model, structural validity is ensured. Dimensional consistency and parameter and variable confirmations are assured in the constructing phase. Besides, some extreme condition tests on some critical variables are done. Real data is used for behavioral validity.

However, there are some misleading parts of calibration so that the numerical accuracy for the Mediterranean Sea could not be validated. The results obtained from the model could be consistent with real data from the Mediterranean Sea in a short while. On the other hand, the analyses of the northwestern seashore of Turkey, namely Tekirdağ and Gulf of İzmit are consistent with the presented model. The fish in these analyses is Horse Mackerel whose values are similar to Atlantic Mackerel that is used in the base scenario.

4. Scenario Analysis

4.1. Base Scenario

When the model is run with the specified parameters in section 3.2, the long term values of the stocks are as provided in Figure 4. The crucial dynamics can be recognized by examining the concentration values of each agent in the model as presented in Figure 4. Tuna having more MeHg concentration than Mackerel is the evidence for biomagnification of MeHg. We analyze a human eating 300 g Tuna per week in order to investigate whether or not he is taking too much MeHg into his body. Recalling that the weekly tolerable intake for a human of 70 kg is stated as 0.11 mg by WHO, the weekly intake value for human which is found to be 0.19 mg is an indication of a potential problem. The weekly intake can be seen in Figure 5.

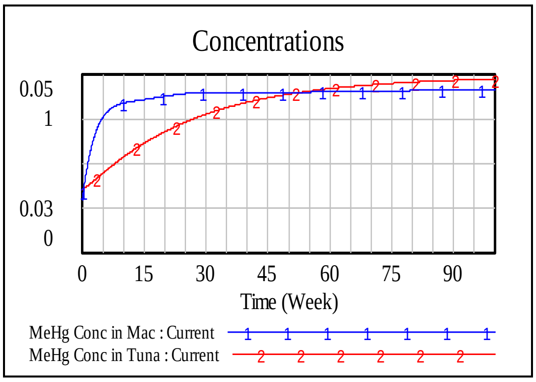

Figure 4: MeHg concentration level in Mackerel and Tuna

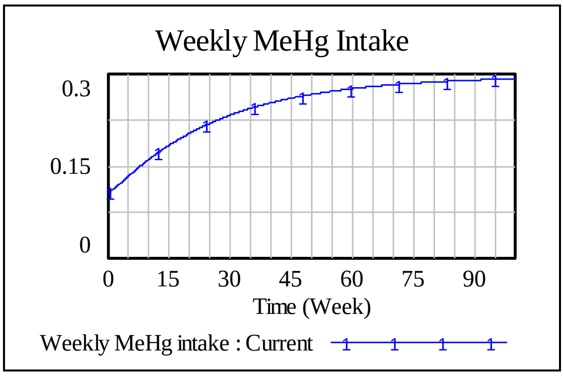

Figure 5: Weekly intake of MeHg by human

As it is mentioned before, there is a prey-predator relationship between Atlantic mackerel and Bluefin tuna. Figure 6 shows the dynamics of Mackerel and Tuna populations for 250 weeks, corresponding to 5 years.

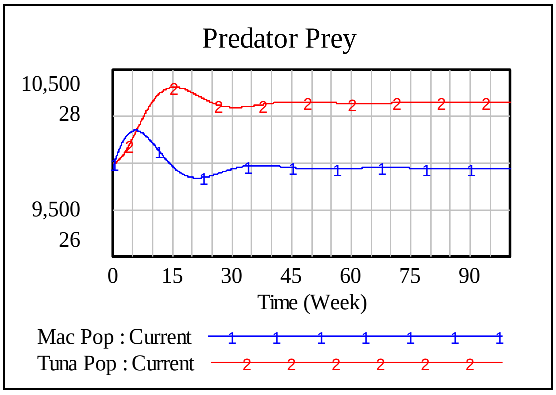

Figure 6: Population Stocks in the base scenario

4.2. Scenario 1: Human only consumes a high amount of Tuna

Assume that the amount of contamination is constant at a low level. A human who usually eats 300 gr Tuna per week increases his diet to 2 kg per week. The weekly intake of MeHg is too high compared to the tolerable level (0.11 mg per week).

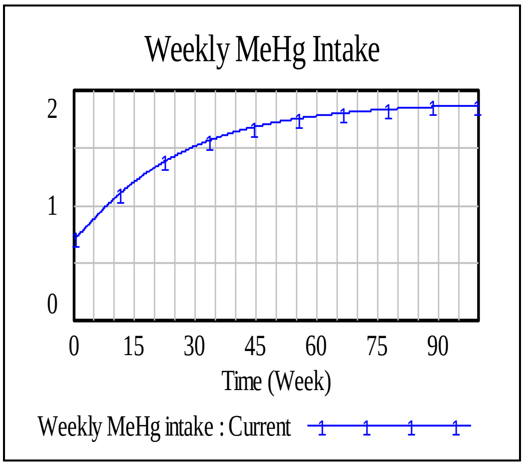

Figure 7: Human weekly MeHg intake in Scenario 1

4.3. Scenario 2: Human consumes only Mackerel

Assume that a human is aware of the threat regarding the biomagnification of MeHg and he avoids consuming big fish. He consumes Mackerel instead of Tuna. In the model, the human eats 300 g Mackerel per week. Weekly MeHg intake reduces and the new concentration level in the human's body is lower. Therefore, eating 300 g Mackerel per week is better than eating 300 g Tuna per week with the current parameter setting.

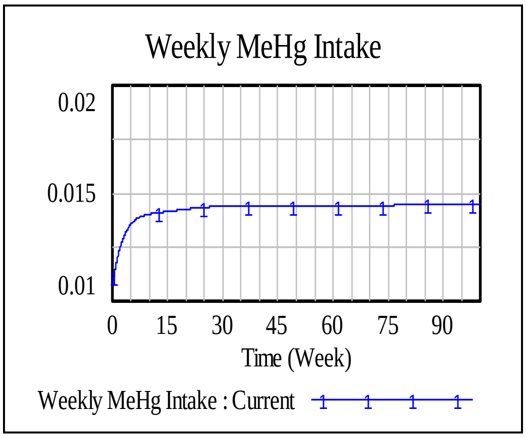

Figure 8: Human weekly intake of MeHg in Scenario 2

4.4. Scenario 3: Human only consumes high amount of Mackerel

Compare to the first scenario; a human is aware of the threat regarding the biomagnification of MeHg and he avoids consuming big fish. Again the assumption is that he consumes Mackerel instead of Tuna. In the model, the human eats 2 kg Mackerel per week. Weekly MeHg intake increases and the new concentration level in the human's body is higher. However, consuming 2 kg Mackerel per week is better than eating 2 kg Tuna per week with the current parameter setting. The crucial part of this scenario is consuming small fish even in high amount is more healthy than the big one because of the biomagnifications process.

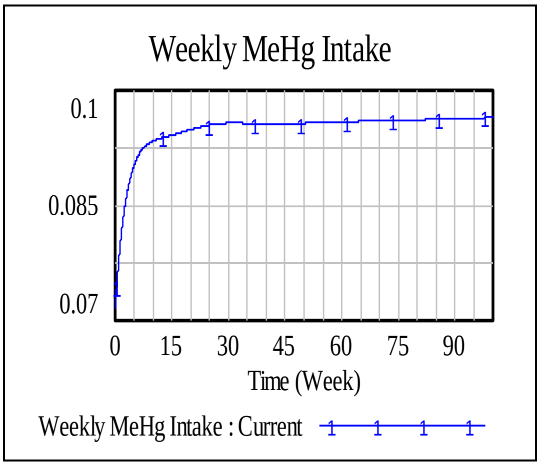

Figure 9: Human weekly intake of MeHg in Scenario 3

4.5. Scenario 4: Changing contamination level

Assume that in the beginning there is no contamination through the water but there is a huge contamination through the water two times, discretely. Human consumes 300 g Mackerel per week and avoids eating Tuna. In this case the weekly MeHg concentration in Mackerel and Tuna are still higher than tolerable level indicating that, if the water is not clean, one should avoid eating any kind of fish.

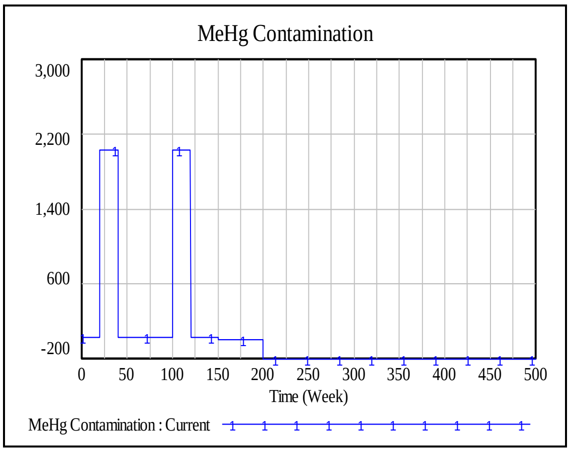

Figure 10: Change in MeHg contamination in Scenario 4

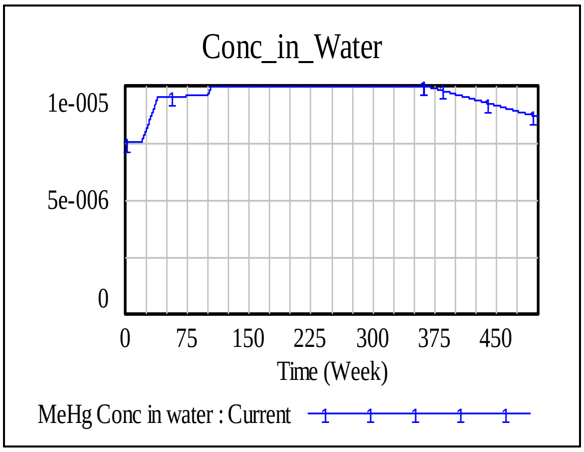

Figure 11: MeHg concentration in water in Scenario 4

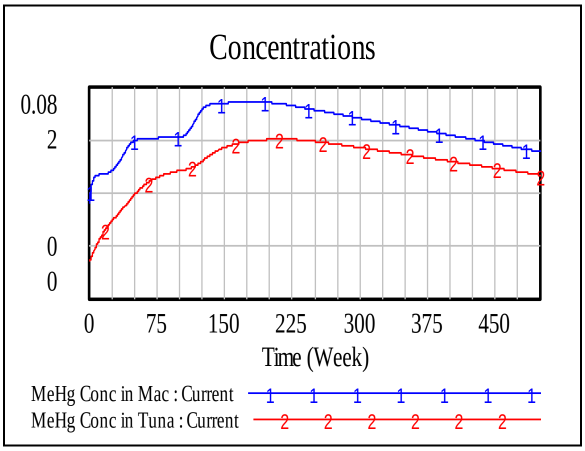

Figure 12: MeHg concentration in fish in Scenario 4

5. CONCLUSION & FUTURE RESEARCH

Methyl mercury (MeHg), which is the most common mercury-containing chemical pollutant and toxin, accumulates in the body of species through consumption of MeHg-including food or through absorption (absorption of MeHg from water by zooplanktons). The concentration of MeHg in the body of the species in the higher level of food chain is higher than the ones in the lower level. This increase in the level of concentration is called biomagnification. In recent years, "biomagnification" increasingly calls researcher's attention. In this study, a dynamic simulation model is constructed to study the biomagnification of MeHg through the food chain from zooplanktons, small fish (Mackerel), big fish (Bluefin tuna) to Human. The data is taken from studies held in the Mediterranean Sea. Tuna is the predator and Mackerel is the prey.

The base scenario successfully creates the real life situation where the concentration of MeHg is higher in Tuna than in Mackerel. The concentration in a human is not as much as in the fish species where the reason is low consumption of fish by humans. In the scenario analysis, it is found that the effect of water contamination is immediately perceived by fish and the humans who consume the fish. In a contaminated area, it is better to consume the type of fish which is small in size. In every scenario, the weekly MeHg intake of a human being is compared with the tolerable weekly intake of MeHg which is specified by WHO.

The presented study can be used for an educative need. MeHg biomagnification is not a well known environmental fact for some departments so this SD model of biomagnification can be helpful to understand its dynamics.

For the future research, delayed effect of contamination perception can be put into account. Like in Minemata Disease, people did not realize immediately factory's harmful contamination effect on humanity and nature. Besides, since the model is built basically, there can be a study on validation with parameters. The literature is highly confusing and hard to find out field work for the model realization. Therefore, there may be a co-work with Environmental Department to work on a field such as Istanbul Bosporus as a future research.

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7. APPENDIX

7.1. Appendix A

Seafood sample	Species	Region	n	Mean length (cm)	Mean weight (kg)	Range Hg concentration (mg/kg)	Mean Hg + SD (mg/kg)	Reference
Albacore tuna	*Thunus alalunga*	Fiji Islands	31	72.7	21.3	0.03 - 1.01	0.34 ± 0.22	Kumar et al. (*in press*[a])
Yellowfin tuna	*Thunus albacore*	Fiji Islands	24	71.3	15.2	< 0.02 - 0.40	0.11 ± 0.11	Kumar et al. (*in press*[a])
Skipjack tuna	*Katsuwanas pelamis*	Fiji Islands	12	45.7	2.4	< 0.02 - 0.16	0.06 ± 0.04	Kumar et al. (*in press*[a])
Marlin	*Tetrapturus audax/ Mokaira mazara*	Fiji Islands	5	167.6	67.4	0.45 - 5.60	1.76 ± 1.94	Kumar et al. (*in press*[a])
Reef fish		Fiji Islands	5	17.2	0.1	< 0.02 - 0.04	0.04 ± 0.01	Kumar et al. (*in press*[a])
Barracuda	*Sphyraena sp*	Fiji Islands	4	61.3	1.3	0.18 - 0.38	0.26 ± 0.07	Kumar et al. (*in press*[a])
Bokkem	*Trachurus trachurus*	Adriatic sea	100	32.7	0.36	ND - 1.87	0.23 ± 0.47	Storelli et al. 2003
Gilt sardine	*Sardinella aurita*	Adriatic sea	150	18.8	0.03	ND - 0.30	0.09 ± 0.07	Storelli et al. 2003
Pilchard	*Sardina pilchardus*	Adriatic sea	300	15.9	0.03	ND - 0.40	0.13 ± 0.14	Storelli et al. 2003
Sprat	*Sprattus sprattus*	Adriatic sea	70	12.9	0.03	ND - 0.14	0.06 ± 0.05	Storelli et al. 2003
Pandora	*Pagellus erythinus*	Adriatic sea	170	14.9	0.06	ND - 0.70	0.22 ± 0.19	Storelli et al. 2003
Four spotted megrim	*Lepidorhombus bosci*	Adriatic sea	180	24.9	0.11	0.14 - 0.69	0.35 ± 0.19	Storelli et al. 2003
Megrim	*L. whiffiagonis*	Adriatic sea	150	29.6	0.12	0.09 - 1.17	0.39 ± 0.45	Storelli et al. 2003
Red fish	*Helicolenus dactylopterus*	Adriatic sea	220	21.8	0.10	0.11 - 0.84	0.42 ± 0.20	Storelli et al. 2003
Striped mullet	*Mullus barbatus*	Adriatic sea	270	16.5	0.07	ND - 1.74	0.39 ± 0.47	Storelli et al. 2003
Skate	*Starry ray*	Adriatic sea	120	44.0	0.41	0.09 - 1.78	0.73 ± 0.54	Storelli et al. 2003
Forkbeard	*Phycis blennoides*	Adriatic sea	330	18.9	0.05	0.16 - 0.57	0.36 ± 0.14	Storelli et al. 2003
Goldline	*Sarpa salpa*	Adriatic sea	140	26.7	0.31	0.06 - 0.16	0.08 ± 0.05	Storelli et al. 2003
Frost fish	*Lepidopus caudatus*	Adriatic sea	300	70.2	0.37	0.09 - 1.61	0.61 ± 0.38	Storelli et al. 2003
Angler fish	*Lophius budegassa*	Adriatic sea	200	57.0	0.87	0.19 - 1.77	0.76 ± 0.46	Storelli et al. 2003
Picarel	*Spicara flexuosa*	Adriatic sea	180	15.9	0.02	0.09 - 0.60	0.20 ± 0.13	Storelli et al. 2003
Tuna	*Thunnus thynnus*	Japanese markets	58			0.36 - 5.25	1.11	Nakagawa et al. 1997
Bonito	*katsuwonus pelamis*	Japanese markets	18	NA	NA	0.12 - 0.41	0.25	Nakagawa et al. 1997
Yellow tail	*Seriola dorsalis*	Japanese markets	8	NA	NA	0.06 - 0.76	0.26	Nakagawa et al. 1997
Seabass	*Seriola purpuraseens*	Japanese markets	6	NA	NA	0.04 - 0.37	0.20	Nakagawa et al. 1997
Anchovies		USA markets	40	NA	NA	ND - 0.34	0.04	US FDA 2006
Butterfish	*Pampus argenteus*	USA markets	89	NA	NA	ND - 0.36	0.06	US FDA 2006
Catfish	*Ictalurus sp*	USA markets	23	NA	NA	ND - 0.31	0.05 ± 0.08	US FDA 2006
Cod	*Gadus morhua*	USA markets	39	NA	NA	ND - 0.42	0.10 ± 0.09	US FDA 2006
Croaker Atlantic	*Micropogonias undulates*	USA markets	35	NA	NA	0.01 - 0.15	0.07 ± 0.04	US FDA 2006
Herring	*Alosa sapidissima*	USA markets	38	NA	NA	ND - 0.14	0.04	US FDA 2006
Mackerel Atlantic	*Scomber scombrus*	USA markets	80	NA	NA	0.02 - 0.16	0.05	US FDA 2006

Table A1: (UNEP Chemicals is a part of UNEP's Division of Technology, 2008)