International Proceedings of Chemical, Biological and Environmental Engineering, Vol. 88 (2015)
DOI: 10.7763/IPCBEE. 2015. V88. 16

A Method for Ecosystem Risk Assessment of Heavy Metal Pollution Due to Intensive Precipitation

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Abstract. Critical load approach aims to identify ecosystems of which the critical loads are exceeded by atmospheric deposition. For more effective air pollution abatement policies it is important to locate areas where adverse impact can be expected to occur as a result of excessive regional deposition. That includes data of emission, meteorology, soil and vegetation characteristics. The impact of climate change has not been well investigated especially under conditions of intensive precipitations. A fuzzy logic method for ecosystem risk assessment of heavy metal pollution caused due to intensive precipitation is proposed. A fuzzy logic model with two inputs and one output is designed in the Matlab software environment using Fuzzy Logic Toolbox and Simulink. The simulation investigations are done. This fuzzy system will be part of the cloud information system for integrated risk assessment of natural disasters.

Keywords: risk assessment, fuzzy logic model, heavy metals, air pollution

1. Introduction

Heavy metal pollution is a big problem almost all over the world. Increasing industrial activity during previous century and poor emission control has resulted in accumulation of toxic elements in soils, water sediments and vegetation. Their direct effect has affected not only human being but all living organisms in hydrosphere, pedosphere and biosphere. The indirect effect is not less important and it has be shown in variation of different levels of trophic chain, changes of dominant species, biodiversity decrease and violation of ecosystem functions. The climate change makes situation worse.

Prevention of acid rain has started by emission control of nitrogen sulfur and acidity given in the Convention of Long Range Transboundary Air Pollution (CLRTAP) from 1979 year. Sites seriously affected by eutrophication has not almost left recently as a result of that international environmental strategy. The main idea was to create an integrated indicator for assessment of the whole ecosystem and its functions because of the complex relationships existing between individuals. Anthropogenic impact on ecosystems has expressed by calculation of critical loads of some air pollutants. It has started by estimation of acidity by calculation of critical loads of main acidifying gaseous such as nitrogen oxides and sulfur dioxide. After successful implementation of that approach to restrict acidity, it has been applied to heavy metal pollution since 90's years of the previous century. By definition, the critical load of metal is "its highest total input rate from anthropogenic sources to an ecosystem, below which harmful effects on human health, or ecosystem structure and function will not occur over the long-term, according to present knowledge" [1]. The critical load is derived with a biogeochemical model, assuming steady-state for the input and output metal fluxes

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from an ecosystem. This chemical equilibrium corresponds to concepts of sustainability [2], [3] and a lack of retention and accumulation of toxicants.

Some metals such as lead, cadmium and mercury are extremely toxic in very low concentrations. In contrast to other metals (Cu, Zn) that are essential at small amount because play role of cofactors of enzymes, Pb, Cd and Hg only cause damage effect. Organisms have not natural biochemical mechanisms for their elimination. That way metals have remained in ecosystems for a long period damaging the most sensitive organisms initially and causing harmful effect of more organisms in the future.

The investigations and knowledge about climate change impact on ecosystem functioning are continuously expanding. A trend of temperature increasing and drought has recently observed at many sites. They are serious stressors for organisms and have affected their vitality. As a result, changes in vegetation growth, mortality increase and shifting species distribution have been detected. On the other hand precipitation has become more intensive and long-lasting although in larger intervals. Some years such as 2005 and 2014 were these with unexpected rain amount and floods. That way atmospheric deposition rate could be substantial and expose organisms and ecosystem functions at large harmful effects. Common practice in an ecosystem risk assessment is to use a lethal concentration of some metals to determine damages that it cause on a specific organism. Biological response of ecosystem on natural disaster impact shows some delay time because of buffering mechanisms that biota has for adaptation. The maintenance of sustainable state of ecosystems to metal pollution requires targeted actions. An important action is risk management. The first step is to assess the risk of metal deposition.

The aim of this paper is to propose a fuzzy logic method for ecosystem risk assessment of heavy metal pollution caused due to intensive precipitation.

2. Definition and Calculation of Critical Load and Limit

The critical load is the acceptable anthropogenic load of heavy metals deposited in an ecosystem. The pathway is mainly through precipitation because the natural metal weathering release is negligible. According to the Steady State Mass Balance Model, critical load relates to the sum of tolerable output fluxes from an ecosystem by harvest and leaching [4], [5]:

$$CL(M) = Mtot + Mle(crit), \qquad (1)$$

where: CL(M) is a critical load for heavy metal, $g.ha^{-1}.yr^{-1}$;

Mtot is the total annual metal net uptake of the harvestable part of plants in the catchment, $g.ha^{-1}.yr^{-1}$;

Mle(crit) is the critical leaching flux of metal, $g.ha^{-1}yr^{-1}$.

The total metal content in biomass is corresponded to the annual yield and metal content in harvestable plant part:

$$Mtot = Yha . [M]ha, \qquad (2)$$

where: Yha is an yield of harvestable biomass (dry weight), $kg.ha^{-1}.yr^{-1}$;

[M]ha – the metal content in harvestable plant part in a dry wood, $g.kg^{-1}$.

The data for metal concentrations have to be taken from relatively unpolluted areas. The metal content of Pb varies between 0.0005 – 0.010 $g.kg^{-1}$ for Central Europe. The values of Cd for deciduous forest are: 0.00005 – 0.0005 $g.kg^{-1}$ and for coniferous: 0.0001 – 0.0005 $g.kg^{-1}$ respectively [6].

The critical total leaching corresponds to the total vertical leaching rate related to the dissolve metal concentration and that of particulate metal species in drainage water:

$$Mlo(crit) = 10 . Qle . [M]tot(crit) \qquad (3)$$

where: Mtot(crit) is the critical total concentration of heavy metal in drainage water, $mg.m^{-3}$;

Qle – flux of drainage water, $m.yr^{-1}$.

Critical loads of metals can be calculated in dependence on receptors and metals of concern. Indicators of effects on ecosystems are mainly ecotoxicological and receptor – terrestrial and aquatic ecosystem [6], [7]. The different types of critical loads of heavy metals, receptors and indicators are shown in Table 1

Table 1: Different types of critical loads of heavy metals, receptors and indicators

Receptor ecosystem	**Critical loads related to**	**Metals of concern**	**Land cover types**	**Indicator addressed by the critical limit**
Terrestrial	Ecosystem functioning	Cd, Pb	Arable land, grassland	Free ion concentration in view of effects on soil misro-organisms, plants and invertebrates
		Hg	Forests	Total concentration in humus layer in view of effects on soil misro-organisms, plants and invertebrates
	Human health effects	Cd, Pb, Hg	Arable land	Metal content in food
			Grassland	Metal content in grass, animal products
			All ecosystems	Total concentration in soil water below the rooting zone (for ground water protection)
Aquatic	Ecosystem functioning	Cd, Pb, Hg	Fresh water	Total concentration in view of effects on algae, crustacean, worms, fish, top predators
	Human health effects	Hg	Fresh water	Metal concentration in fish

Critical loads are derived from critical limits which related to metal toxicity concentration. The latter are obtained from laboratory toxicity tests of different organisms to some pollutants using an effect-based approach. The most sensitive organisms of all trophic levels of an ecosystem have been tested and the lowest concentration has been selected. Results of sensitivities of soil and water organisms have shown that aquatic organisms are not automatically protected by the same critical limits and vice versa. For example, cadmium critical dissolved concentration for terrestrial ecosystem including ground water protection (3 $mg.m^{-3}$) is ten times higher than one for aquatic ecosystems (0.38 $mg.m^{-3}$). Lead concentrations are almost the same: for terrestrial ecosystem is 10 $mg.m^{-3}$ and for aquatic: 11 $mg.m^{-3}$ [6], [7].

Critical loads based on critical limits express only the sensitivity of ecosystem to some toxic reagent taking into account ecosystem's specific characteristics. The risk of damage can be estimated comparing present loads to critical one. The difference is called exceedance of critical load and calculated by equation:

$$CL(M)ex = Dep(M) - CL(M), \qquad (4)$$

where: CL(M)ex is exceedance of critical load of the metal, $g.ha^{-1}.yr^{-1}$;

Dep(M) is total annual metal deposition rate, $g.ha^{-1}.yr^{-1}$.

Generally in case of negative value of critical load exceedance there is no risk for an ecosystem but in case of positive value of CLex, ecosystem is at risk of damage of heavy metals. The rate of exceedance can be different and this determines a level of risk of damage for the ecosystem.

3. Fuzzy Logic for Ecosystem Risk Assessment

The general idea of this research is to propose on the base of fuzzy logic a method for ecosystem risk assessment of heavy metal pollution due to intensive precipitation. As the qualitative approach, the fuzzy logic method used subjective judgments about the relative importance of the predictive variables and their various states [8].

Here, a fuzzy logic model is designed to demonstrate the essence of the fuzzy logic method for ecosystem risk assessment. In particular, the fuzzy logic model is presented as a fuzzy logic system with two inputs and one output. The inputs correspond to the linguistic variables (indicators), which described *Critical load exceedance* and *Critical limit exceedance*. These variables are informative enough as well as simple and easy to estimate. The output represents *Ecosystem risk assessment* of heavy metal pollution due to intensive precipitation.

The variety values of the input variables (*Critical load exceedance* and *Critical limit exceedance*) required normalization to be the first step of the model development. After normalization, the input variables are varied in the selected interval [-1, 1]. The following formulas are used for normalization of the input data:

$$XL = \frac{PL - CL}{CL} \quad \text{and} \quad XC = \frac{PC - C\lim}{C\lim}, \tag{5}$$

where: the XL and XC are normalized values of the Critical load exceedance and Critical limit exceedance, respectively; PL is present load; CL – critical load; PC – present concentration; Clim – critical limit (toxic concentration).

The normalized values XL and XC are regarded as main information for performing assessment and taking decisions about the level of ecosystem risk from heavy metal pollution due to intensive precipitation.

The expert knowledge and experimental data are used to define the number, type and shape of the membership functions of the presented fuzzy model. The formation of fuzzy sets' membership functions was carried out according to fuzzy logic theory [9], [10].

The input linguistic variable *XL* - *Critical load exceedance* is represented by five trapezoid membership functions: "*XLnegBig*" – negative big *XL*; "*XLnegLow*" – negative low *XL*; "*XLzero*" - zero *XL*; "*XLposLow*" – positive low *XL*; "*XLposBig*" – positive big *XL* (Fig. 1).

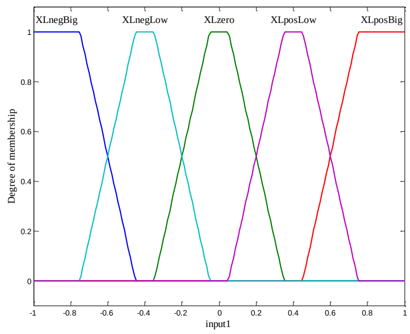

Fig. 1: Membership functions of the input 1: *XL* - *Critical load exceedance*.

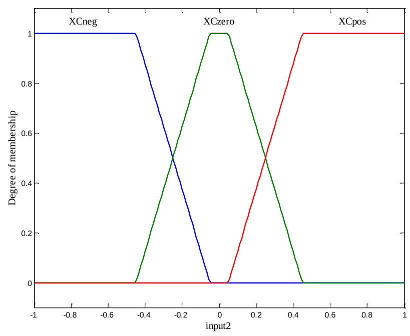

Fig. 2: Membership functions of the input 2: *XC - Critical limit exceedance.*

The input linguistic variable *XC - Critical limit exceedance* is represented by three trapezoid membership functions: "*XCneg"* - negative *XC*; "*XCzero"* - zero *XC*; "*XCpos"* - positive *XC* (Fig. 2).

The fuzzy logic system output - the linguistic variable *Ecosystem risk assessment* is described by seven trapezoid membership functions, corresponding of the seven ecosystem risk levels: *Y1* – lowest level; *Y2* – lower level; *Y3* – low level; *Y4* – middle level; *Y5* - high level; *Y6* – higher level; *Y7* - highest. The output variable is assessed in the interval [0, 10] (Fig. 3).

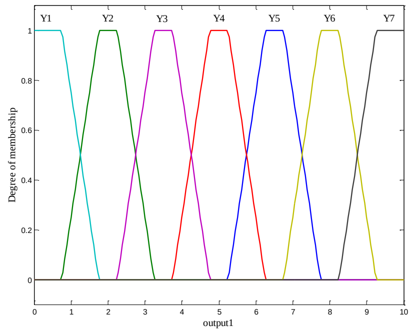

Fig. 3: Membership functions of the fuzzy system output: *Ecosystem risk assessment*.

The inference rules in the fuzzy logic system are defined through "IF - THEN"-clause. Here, the special logic matrix for *Ecosystem risk assessment* is designed using expert knowledge about heavy metal pollution due to intensive precipitation. The rule number of the knowledge base is 15.

The inference rules of fuzzy logic system with two input variable can be expressed also in the form of matrix table. The logic matrix is shown as Table 2.

Table 2: The special logic matrix for *Ecosystem risk assessment*

	XCneg	*XCzero*	*XCpos*
XLnegBig	*Y1*	*Y2*	*Y3*
XLnegLow	*Y2*	*Y3*	*Y4*
XLzero	*Y4*	*Y5*	*Y5*
XLposLow	*Y5*	*Y6*	*Y6*
XLposBig	*Y6*	*Y7*	*Y7*

Analyzing the fuzzy logic rules in the Table 2 it can be concluded that the safest situation for an ecosystem is this with the lowest exceedances of critical load and critical limit simultaneously (*Y*1). That means no damage at present or future because input rate and dissolve metal concentration are far from critical values. Lower level of risk (*Y*2) can be realized in situation of a present load value close to critical load or metal concentration equals to critical one. No damages at present or future still can be seen. When the present load is close to the critical load and metal concentration is equal to the critical limit or the metal concentration is higher than critical limit and deposition is very low, the risk level is *Y*3. Some sensitive organisms can be injured by high metal concentration but. A middle risk is realized in situation of increase of the critical limit and a lack of the critical load or when the present load is equal to the critical load (*Y*4). In situation of the reached critical load and an equal or a higher metal concentration than the critical limit or low excess of the critical load (*Y*5), present damage can be observed but recovery will be in process by reducing the metal concentration to the critical limit. Higher level of risk (*Y*6) and future damages are realized in low critical load exceedance. When not only critical load are exceeded but the critical level is reached or higher, a measures for reducing of the metal concentration and emissions are needed for recovery of the ecosystem. The highest level of risk is occur in situation of a big difference between the present load and the critical one and the exceedance of critical metal limit. Then a present damages can be seen and no recovery of the ecosystem foresees in the future [11].

In order to assess the utility of the proposed fuzzy model, a number of experiments are performed in *MATLAB—Fuzzy toolbox* computer environments. The output of the fuzzy model is calculated as an average weighted of all the inference rules, including in the fuzzy logic matrix. The fuzzy system is based on Mamdani's inference machines, max/min operations and center of gravity defuzzification. The inference surfaces in 3D for the proposed fuzzy logic system with two input variable and one output fuzzy model are given on Fig. 4.

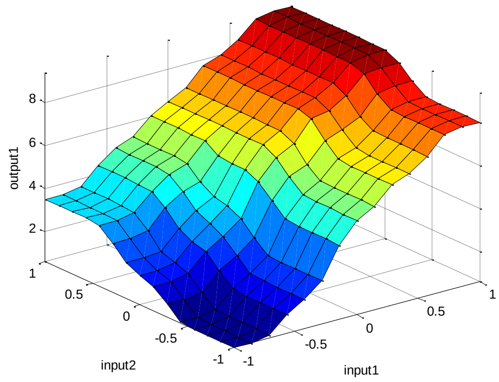

Fig. 4: Surface of the designed fuzzy logic system with two input variable and one output.

The interval [0, 10] of the output variable *Ecosystem risk assessment* is divided into seven parts to determine the risk level for the given ecosystem about heavy metal pollution due to intensive precipitation:

IF *Ecosystem risk assessment* $\in$ [0, 1.5) THEN *Ecosystem risk* has a lowest level.

IF *Ecosystem risk assessment* $\in$ [1.5, 2.9) THEN *Ecosystem risk* has a lower level.

IF *Ecosystem risk assessment* $\in$ [2.9, 4.3) THEN *Ecosystem risk* has a low level.

IF *Ecosystem risk assessment* $\in$ [4.3, 5.7) THEN *Ecosystem risk* has a middle level.

IF *Ecosystem risk assessment* $\in$ [5.7, 7.1) THEN *Ecosystem risk* has high level.

IF *Ecosystem risk assessment* $\in$ [7.1, 8.5) THEN *Ecosystem risk* has higher level.

IF *Ecosystem risk assessment* $\in$ [8.5, 10] THEN *Ecosystem risk* has a highest level.

Here, two applications of the proposed fuzzy logic model for ecosystem risk assessment of heavy metal pollution due to intensive precipitation are given:

Example 1: Let *CL*=20 and *PL*=35, and

$$XL = \frac{PL - CL}{CL} = \frac{35 - 20}{20} = \frac{15}{20} = \frac{3}{4} = 0.75 \quad \text{and} \quad XC = \frac{PC - C\lim}{C\lim} = \frac{1 - 3}{3} = \frac{-2}{3} = -0.67$$

Thus, if *XL*=0.75 and *XC*=-0.67 then the system output variable (*Ecosystem risk assessment*) calculated by fuzzy logic model is *Y*=8. Therefore, *Ecosystem risk* has higher level.

Example 2: Let Let *CL*=20 and *PL*=15, and

$$XL = \frac{PL - CL}{CL} = \frac{15 - 20}{20} = \frac{-5}{20} = \frac{-1}{4} = -0.25 \quad XC = \frac{PC - C\lim}{C\lim} = \frac{3.5 - 3}{3} = \frac{0.5}{3} = 0.16$$

Thus, if *XL*=-0.25 and *XC*=0.16 then the system output variable (*Ecosystem risk assessment*) calculated by fuzzy logic model is Y=4.57. Therefore, *Ecosystem risk* has a middle level.

The designed fuzzy logic model is not complex but the results obtained are quite reliable. This saves much time and the process of Ecosystem risk assessment is more cost-effective.

4. Conclusions

A method for ecosystem risk assessment of heavy metal pollution is proposed. Uncertainties in exceedances depend on variables from emissions to depositions and biological response. In particular, a fuzzy logic system with two inputs and one output is designed. This fuzzy logic method allows a more comprehensive arranging of the ecosystem risk of heavy metal pollution due to intensive precipitation.

The designed fuzzy logic systems on based of proposed method will be a part of the cloud information system for integrated risk management of natural disasters which will be developed. This cloud information system will combine different methods and tools. Also, the system will be implement in a web-based GIS environment. Thus it might serve as a unified platform for interdisciplinary research of the impact of natural disasters. Major goal of this system is to support the effective management of the decision making process regarding risk prevention and risk mitigation for given areas. Stakeholders on different administrative level could use this cloud information system for an efficient risk management.

5. Acknowledgements

The authors express their gratitude to the Bulgarian National Science Fund for the considerable opportunity for Bulgarian – Chinese scientific cooperation under the Grant № DNTS/ China 01/6 from 2014 and for the partial financial support of this publication under the Grant № DFNI - I02/15 from 2014.

6. References

[1] J. Nilsson, and P. Grennfelt. *Nordic Council of Ministers*, Copenhagen, Denmark, 1988.

[2] J. Slootweg, J.-P. Hettelingh, M. Posch, G. Schütze, T. Sprander, W. De Vries, G. J. Reinds, M. Van't Zelfde, S. Dutchak, I. Ilyin. European critical loads of cadmium, lead and mercury and their exceedances. *Water Air Soil Pollution.* 2007, **7**: 371-377.

[3] J. Slootweg, J. P. Hettelingh, M. Posch, G. Schütze, T. Spranger, W. De Vries, G. J. Reinds, M. Van't Zelfde, S. Dutchak, I. Ilyin. Integrated Assessment of Air pollution effects on biodiversity. www. mnpnl/cce, 2008.

[4] W. De Vries, D. J. Bakker, H. U. Sverdrup. *Manual for calculating critical loads of heavy metals for aquatic ecosystems. Guidelines for critical limits, calculation methods and input data.* DLO Winand Staring Centre, Report 165, Wageningen, The Netherlands, p. 91, 1998.

[5] J. P. Hettelingh, M. Posch, J. Slootweg. *Critical load, dynamic modelling and impact assessment in Europe: CCE Status Report 2008*, Coordination Centre for Effects, 2008.

[6] UBA. *Modelling and Mapping Manual: Manual on methodologies and criteria for modelling and mapping critical loads &levels and air pollution effects, risks and trends*, Fed. Environm. Agency, Berlin,UBA-Texte, **52**(04), 2004

[7] World Health Organization. *Guidelines for drinking water quality*. 3rd ed., **1**, Recommendations, Geneva, 2004.

[8] K. Shang, and Z. *Hossen, Applying Fuzzy Logic to Risk Assessment and Decision Making*, Casualty Actuarial Society, Canadian Institute of Actuaries, Society of Actuaries, p. 59, 2013

[9] S.Sivanandam, S.Sumathi, S.Deepa. *Introduction to Fuzzy Logic using MATLAB*. Berlin, Springer, 2007: 277–320

[10] G. Kirov. Fuzzy approach for FDDI network performance improvement. *First international IEEE symposium Intelligent Systems*, Varna, Bulgaria, September 10-12, 2002, vol. III, pp. 17-23.

[11] S. Damyanova, I. Ivanova, N. Ignatova Water quality assessment of aquatic ecosystems using ecological criteria - case study in Bulgaria, *Biotechnology & Biotechnological Equipment*. 2014, **28**(6):1050-1056.