APPLICATION OF THE ARTIFICIAL INTELLIGENCE TO THE DESIGN OF CONSTRUCTED WETLANDS FOR HEAVY METAL REMOVAL

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ABSTRACT:

Application of the Artificial Intelligence to the Design of Constructed Wetlands for Heavy Metal Removal

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Current design of constructed wetland lacks essential parameters necessary to evaluate the removal of metals contained in water enters the system. Herein, for the first time, the artificial intelligence approach (Fuzzy Logic) is used to assess stochastic implication in the wetland systems. Bioavailable mercury was evaluated, using fuzzy logic approach, for different pH, initial concentration of inorganic mercury, and chloride concentration implied in the constructed wetlands. Fuzzy knowledge base was built based on results obtained from previous data: investigations that were performed in a greenhouse for floating plants, and previous computations for mercury speciation. Fuzzy Decision Support System (FDSS) used the knowledge bases to find out parameters that permit to generate the highest amount of bioavailable mercury for uptake by the floating plant. The fuzzy logic approach provided the required information on the capability of constructed wetland sediments to sorb mercury within the hazy conditions in the system. FDSS used the wetland knowledge bases to provide the final decision. Fuzzy knowledge bases were built manually on one stage and were generated genetically using Genetic Algorithm (GA) on the other stage, where the results in both stages show comprehensive and corresponding results of the soil performance in the system. The obtained information by the fuzzy logic approach supports into providing series of solutions for plant uptake and soil adsorption of mercury that represents the heavy metal removal from

wastewater of the overall system, by which mathematical analyses and modeling were further established to set up constructed wetland design. The criterion of design assumes the removal process in wetlands is similar to a process that combines the treatment process in the attached growth reactor and the adsorption process in the granular activated carbon columns. The hydraulic properties and removal performance were assumed to follow plug flow behavior. The efficiency of constructed wetlands with time was considered to follow the break-through point expression. The approach of this research can be applied in preparing environmental impact assessment, and environmental information systems for natural processes.

I dedicate this work to my mother and my father, I ask god to keep you for me

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NOMENCLATURE

$A', B', ..., C'$:	Represents the inputs (observations)
AOM:	Average of maximums
BOD:	Biological oxygen demand
C_e:	The effluent concentration of mercury
COA:	Center of area
C_o:	The initial mercury concentration
CRI:	Compositional rule of inference
C_w:	The concentration of contaminant in the solution
FDSS:	Fuzzy Decision Support System
GA:	Genetic Algorithm
GGFKB:	Genetically Generated Fuzzy Knowledge Base
k:	The removal rate coefficient
M_c:	Mass of contaminant in the wastewater (g)
MCOA:	The modified center of area
M_s:	Mass of sorbing material (sediments and plants)(g)
$\overline{q}_c$:	Weighted average of the capacity of the wetland system (capacity of sorbing materials to take mercury) (μg/g)
R:	Represents the global relation that aggregates all fuzzy rules (knowledge base)
t:	Detention time in hours

t_r:	Time of residence after which the wetland system components become inefficient to remove mercury (time of regeneration)
U':	Represents the output (conclusion)
Ws:	The weight of contaminant adsorbed on the soil solids
α_1, α_2:	Langmuir empirical constants to be determined from experimental data
α, n:	Freunlich constants to be determined from experimental data
ϕ_1:	Fitness value that is computed as the root mean square error method
ϕ_2:	Denote to the complexity of a knowledge base through its number of fuzzy rules active
o:	Represents the CRI operator
ω_o:	The optimization criteria weight associated to ϕ_1

CHAPTER 1

STATEMENT OF THE PROBLEM - LITERATURE REVIEW

Constructed wetlands have been known as an efficient and low-cost treatment process. They are considered as natural treatment ecosystems that are designed to take advantages of the natural processes to provide wastewater treatment (Metcalf & Eddy, 1991). The removal of metals within wetlands is performed generally by plant uptake or by adsorption onto sediments in the system (El-Agroudy, 1999). Heavy metals including mercury are harmful components associated with many agricultural and industrial wastewaters. Mercury undergoes a variety of physical and chemical transformations, subsequently, various mercury compounds can be found in soils, water, air, and in living species. The hazards of mercury are associated with its toxicity and its impact on the environmental systems.

Constructed wetlands are natural systems for treatment of wastewater. They have been used for the treatment of municipal, industrial, acidic, and agricultural wastewater. The natural treatment system is the one that physical, chemical, and biological processes occur when water, soil, plants, and microorganisms interact. Natural treatment systems are utilized to take advantage of these processes to provide wastewater treatment (Metcalf & Eddy, 1991). Constructed wetlands are man-made complex of saturated substrates, emergent and submergent vegetation, and water that simulate natural wetlands for human benefits (Hammer, 1989). They consist of inundated land areas with water depth typically less than 0.6 m that support the growth of emergent plants such as Cattail, Reeds, and

Water Hyacinth. Both natural and constructed wetlands have been used for the treatment of wastewater, although the use of wetlands is generally limited to the polishing or further treatment of secondary or advanced treated effluent (Metcalf & Eddy, 1991). Constructed wetlands can be designed as free water surface system (FWS) or subsurface flow system (SFS). FWS typically consists of basin with relatively impermeable bottom soil, emergent vegetation, and shallow water depths of 0.1 to 0.6m. SFS consists of basin filled with permeable soil or gravel media where plant growing, and the wastewater is flowing through the permeable media from the inlet toward the outlet with impermeable bed of 1% slope (Metcalf & Eddy, 1991).

Wetland Component Description

1- Wetland Influent Water

The influent wastewater entering the constructed wetlands can be municipal, industrial, mining, agricultural, or stormwater.

- Municipal Wastewater

In many countries, wetlands are being used as a post-treatment facility for domestic wastewater (Denny, 1997). The main components that should be removed from municipal wastewater are organic and inorganic materials, nutrients, pathogens, and suspended solids. Biodegradable components can be removed by bacterial metabolism, whereas some inorganics like phosphorus should be removed by chemical co-precipitation with iron, aluminum, and calcium compounds in the soil (Hammer, 1989). The recommended biological oxygen demand (BOD) loading rate is in the value of 60 kg/ha.d. It must be limited such that the oxygen demand of the applied wastewater does not exceed the oxygen-transfer capacity of wetland vegetation. The oxygen-transfer rate

for emergent plants is in the range 5 to 45 $g/m^2.d$ with average value of 20 $g/m^2.d$, which is considered to be typical. Increased oxygen transfer on a system wide basis can likely be achieved by using alternating vegetated and open-water cells (Metcalf &Eddy, 1991). In Canada, municipal wastewater is being treated by constructed wetlands, including primary and secondary effluent from activated sludge and lagoon systems, landfill leachate, and septic tank effluent (CMHC-SCHL, 2001). The municipality of Stoke (Quebec) completed a constructed wetland in the fall of 1993 to treat the effluent from an existing septic system after carrying out preliminary feasibility study for the wetland system (Pries, 1994). In July 1980, the Ontario Ministry of Environment (MOE) initiated the Listowel Marsh project in Southern Ontario. The community of Cobalt was selected to check the suitability of wetlands for wastewater treatment in Northern Ontario. The results of this project show that the BOD_5 concentration was reduced by 80% (Miller, 1989). Due to the application of wetland systems De Sousa et al. (2001) conducted experiment for utilizing constructed wetlands to treat municipal wastewater including sewage and landfill leachate. The experimental units of wetlands with macrophytes were used successfully for the post-treatment of effluent from a UASB (upflow anaerobic sludge blanket) reactor treating domestic sewage. New York began in the spring of 1988 an investigation of the feasibility of constructed wetlands for landfill leachate treatment (Staubitz et al., 1989). Sewage treatment with emergent aquatic macrophytes was introduced in Denmark in 1983, the results showed the reduction of BOD by 70-90%, total nitrogen by 25-50% and total phosphorus by 20-40% (Brix and Schierup, 1989).

- Industrial Wastewater

Wastewater discarded from industry can be correlated with several activities: the acid mine drainage, oil refining, pulp and paper industry, industrial thermal discharge, and manufacturing processes are some of the activities that release industrial wastewater. CMHC-SCHL (2001) reported that the industrial wastewater treatment by constructed wetlands in Canada could be used for: i) metals removal; ii) pH adjustment; iii) ammonia removal; iv) BOD removal of dairy industry wastewater; v) meat processing and rendering plants; vi) refinery wastewaters.

Industrial wastewater treatment requires that the wetland discharge effluent temperature not to exceed 32.2 °C and pH to be in the range from 6.0 to 8.5 (Ailstock, 1989).

The importance of microorganisms as catalysts of inorganic chemical reactions has been recognized in commercial metal recovery. These reactions are presented with their relevance to generation, prevention, and abatement of acidic drainage in mining processes. Wetlands are enrolling previously mentioned reactions through solubilization and reprecipitation to remove metals such as Fe, Cu, Zn, Mn, and Al (Silver, 1989). The Acid mine drainage is commonly related to coal and metal mining. Several hundreds of wetlands have been constructed in the coal bearing states of Maryland, West Virginia, Pennsylvania, and Ohio to reduce the impacts from acid mine drainage (Kolbash and Romanoski, 1989). In Canada, constructed wetlands are being used to treat fish hatchery wastewater at Rosewall United Fish Farms in Coal Creek (British Columbia) (Pries, 1994).

Separating and recovering oil from other contaminants accomplish primary treatment of wastewater from the refinery process unit, and then the water is discharged to the wetland for secondary series of treatment (Litchfield and Schatz, 1989). Amoco Oil Company used constructed wetlands for wastewater treatment at its refinery in Mandan, North Dakota before to discharge the effluents to the Missouri River (Litchfield and Schatz, 1989).

Natural and artificial wetland systems have been used for treatment of pulp mill effluents. About 60-90% of phenol and m-cresol could be removed by artificial marshes containing Cattail or Reed at a retention time of 24 hours (Wolvercton and McDonald, 1981). Allender (1984) tested the removal effectiveness of a variety of aquatic plants native to Australia on pulp and paper mill effluent. These experiments were conducted under static conditions over a period of weeks. The aquatic plants proved effectiveness in removing several pollutants such as ligo-sulfates, foaming propensity, color, BOD, and total suspended solids (TSS).

- Agricultural Wastewater

In U.S.A in 1984, officials from 49 states reported 29% of lakes and reservoirs evaluated were moderately to severely impact by non-point source of pollution, mainly from agricultural activities (ASIWPCA, 1984).

In Canada, CMHC-SCHL (2001) stated that the agricultural wastewater is a resultant to farm feedlot runoff, milk house wash-water discharge, and runoff subsequent to fertilizer application. In Stratford (Ontario), constructed wetlands are used to treat contaminated barnyard runoff resulted from farms in Fullerton Township-Stratford (Pries, 1994).

Wetlands are used as treatment system in dairy farms; Lough Gara Farms Limited established in Ireland has an intensive dairy farm to produce milk for direct retail sale in 1961. The treatment system in Lough Gara Farms uses natural wetland formed as a result of successive drainage schemes carried out in a lake and its tributaries, and discharging rivers (Costello, 1989). In Maryland the creation of wetlands for the improvement of water quality leaded to have a proposal for incorporation the public lands through joint use of highway- right of way. The proposal identifies a potential highway site for joint use as a constructed wetland to control urban non-point source pollution from highly developed and established urban areas and provides preliminary analysis of the site's control effectiveness and life cost (Linker, 1989).

- Stromwater Runoff

Wetlands are the default recipients of stormwater runoff, due to their position in the landscape. Various wetland types can act as sinks or transformers of nutrients, organic and inorganic materials, and suspended solids of stormwater runoff (Mitsch et al., 1989). Rainfall could affect the component of wetland system by either diluting the pollutant concentration or decreasing the retention time and thus affecting the quality of final effluent (Manios et al., 2000). Runoff from parking lots and roadways in residential areas contains high concentrations of suspended solids, nutrients, trace metals, oil, grease, and deicing salts (Daukas et al., 1989). Runoff at airports may contain leakage from aircraft fueling and de-fueling. In cold weather areas deicing chemicals are also important pollutant (Higgins and Maclean, 2002). Wetlands enhance water quality through a variety of physical, chemical, and biological processes that trap and degrade pollutants. The physical processes of sedimentation, adsorption to soils, filtration, and uptake by plant

are key in capturing pollutants. Pollutants may be degraded biologically by microorganisms and flora, stored, or removed by dredging (Silverman, 1989). Carleton et al (2000) suggested the constructed wetland approach for the treatment of stormwater runoff from residential town home complex in northern Virginia. This approach was to convert dry detention pond facility to be stormwater wetland for the treatment of town runoff. Applying such approach may have a promise for providing a low-cost retrofit to improve water quality at older detention facilities, where water quality improvement was not a primary design issue.

2- Wetland Vegetation

Wetlands have individual and group characteristics related to plant species and to their adaptations to specific hydrological, nutrient, and substrate conditions. Plants utilized in wetlands are either terrestrial or aquatic habitats. Aquatic plants are divided into free floating and rooted forms. The rooted class is subdivided into emergent, floating, and submerged classes. The adaptation of certain plant depends on the design criteria of wetland, morphological, and physiological features of plant. The growth of plant in relation to the water surface should be taken in consideration, as well as the plant foliage, inflorescence, phytosociologic criteria, life growth, and growth form (Guntenspergen et al., 1989).

Vegetation play an integral role in wetland treatment system by transferring oxygen through their roots to the bottom of treatment basins, and by providing a medium beneath the water surface for the attachment of microorganisms that perform the biological treatment. The plants used frequently in constructed wetlands include Cattails, Reeds, Water Hyacinth, Rushes, and Duckweed (Metcalf & Eddy, 1991). Water Hyacinth

(*Eichhornia crassipes*) is an aquatic plant that grows very vigorously and uses highly the nutrients in the environment. The growth rate of Water Hyacinth is affected by the water quality, nutrient content, harvesting interval, and solar radiation. The growth rate of Water Hyacinth is higher in the period from May to June than in other seasons (Aoyama et. al., 1993). Reeds (*Phragmites communis*) grow along the shoreline and in water up to 1.5 m but are poor competitors in shallow waters; they are selected for SFS systems because the depth of rhizome penetration allows for the use of deeper basins (Metcalf & Eddy, 1991). Aquatic plants have ability to uptake trace metals; this phenomenon has brought wetlands to new scale of treatment.

3- Wetland Soils

Mineral composition of the bottom of the wetland has an important impact on the dynamics of pollutant cycle within the wetland. Clay is the most common component of wetland bottom sediments due its low permeability. Clay mineral particles are colloids having high specific surface area that influences soil adsorption properties (Yong et al, 1992). The presence of organic as opposed to mineral soil constituents has an important impact on soil chemical characteristics. The chemical and physical differences between mineral and organic soils play a large role in determining the suitability of particular soil for a specific wastewater treatment (Faulkner and Richardson, 1989). The development of biofilms on contaminated bed sediments can reduce erosion and contaminant transport from the bottom (Ross et al., 2002). Wetlands should have low-permeable soil surfaces (Permeability $<1.41\times10^{-6}$ m/s), because the objective is to treat the wastewater in water layer in wetland; therefore, percolation losses through the soil profile are minimized (Metcalf & Eddy, 1991). The physical and chemical properties of soil affect the design

and the term of treatment. These properties can be summarized as the following: soil matrices of minerals, organic matter, particle size, pore spaces, hydraulic conductivity, specific surface area, ionic charge, cation exchange capacity, pH, and temperature (Faulkner and Richardson, 1989).

The most common sorption models are Langmuir and Freundlich isotherms. The diffuse double layer model (DDL) and Triple-layer model (TLM) describe the sorption process of the charged species into soil particles from the solution. These models can describe the process through which bottom sediments attract the ionic forms of contaminants from wastewaters.

The Freundlich isotherm is a general empirical adsorption isotherm. It has been characterized by sorption that continues as the concentration of sorbate increases in the aqueous phase. It is expressed in the following form:

$$W_s = \alpha C_w^{1/n} \tag{1.1}$$

Where Ws is the weight of contaminant adsorbed on the soil solid; C_w is the concentration of contaminant in the solution; α and n are constants to be determined from experimental data.

The Langmuir isotherm is based on the assumption that a single monolayer of sorbate accumulates at the solid surfaces, it can be derived by assuming that a finite number of sorption sites in the solid phase exists and that the rate of sorption is proportional to the sites remaining. The Langmuir isotherm has the general form:

$$W_s = \alpha_1 \frac{c_w}{1 + \alpha_2 c_w} \tag{1.2}$$

Where α_1 and α_2 are empirical constants to be determined from experimental data (Reible, D., 1999).

In the diffuse double layer (DDL) model, the cations in the wastewater such as heavy metals come to interaction with the negatively charged soil particle surface, which generate an arrangement of negative and positive charges at the interface. The separation distance between positive and negative charges, and the distribution of positive charges are important items considered in the development of what is generally identified as diffuse double layer model (DDL model)(Yong et al, 1992).

The electrical potential drops off exponentially with distance from the particle and reaches a uniform value in the solvent outside the DDL. The zeta potential is the voltage difference between plane a short distance from the particle surface and the bulk liquid beyond the double layer (Tan, 1982).

The thickness of this electric double layer (ion cloud) around colloidal particles determines how close two particles can get to each other before they start experiencing repulsive forces. The thickness depends on some factors such as:

1. The magnitude of the surface charge which depends on the solution concentration of the adsorbing ion;
2. The concentration of electrolyte in solution.

Triple-layer model, as shown in Figure 1.1, is generally more complex than previous models. In the MINTEQA2 (Allison et al, 1991) implementation of the triple-layers model, only protonation and deprotonation of surface sites are assigned to the o-plane. Other specifically adsorbed ions are assigned to the β-plane and determine the charge σ_β and potential ψ_β in that zone. Non-specifically adsorbed ions are envisioned as

residing in the diffuse layer (d) and are influenced by ψ_d potentials. The capacitance between the o-plane and the β-plane is denoted C_{cap1} and between the β-plane and d-plane is denoted C_{cap2}. The potential gradients in the inner and outer zones are linear, but potentials decay exponentially in the diffuse layer zone. The triple-layer model was adopted in MINTEQA2 to investigate mercury behavior within the wetland (El-Agroudy, 1999).

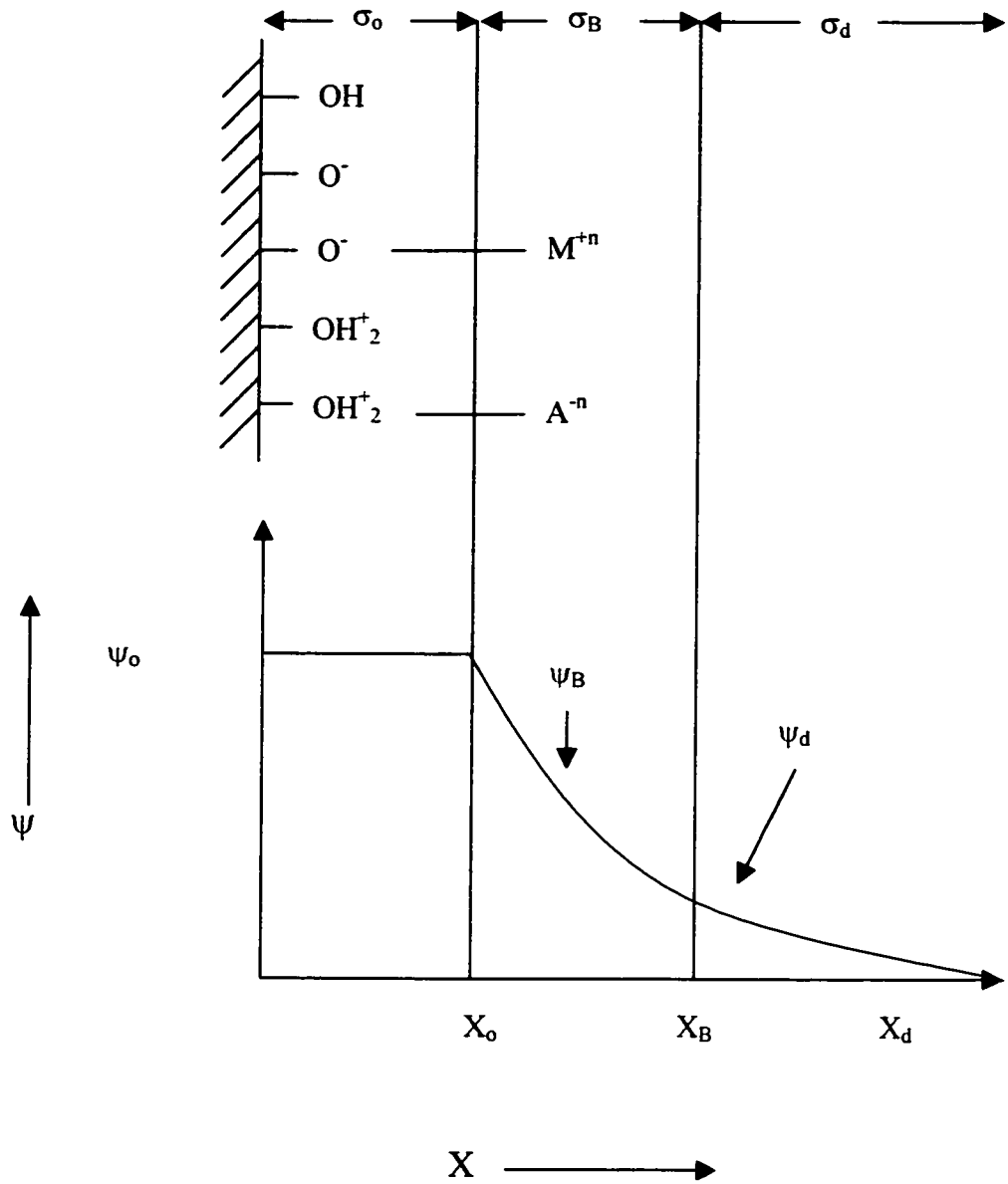

Figure 1.1: Schematic diagram of the triple layer model (after Allison et al., 1991).

Removal of Heavy Metals

Aitchison et al. (2000) obtained results suggested that phytoremediation is a viable alternative to remove dioxane from contaminated soils and should be considered for other hydrophilic contaminants. This is an example for the role of plants to uptake industrial pollutants like those uptake heavy metals in constructed wetlands.

All pollutants found in airport runoff, including heavy metals and glycols, were treated and removed to low levels in well-designed constructed wetland systems (Carleton et al., 2002).

Carleton et al (2000) suggested the constructed wetland approach for the treatment of stormwater runoff from residential townhome complex in northern Virginia. The constituents of the runoff for both townhouse and forested subwatersheds were sinks for metals such as Al, Cu, Pb, and Zn. Most constituents were lower in the outlet of the wetland than in the inlet.

Constructed wetlands are enrolling solubilization and reprecipitation processes to remove metals such as Fe, Cu, Zn, Mn, and Al from wastewaters (Silver, 1989).

El-Agroudy (1999) concluded that Water Hyacinth in constructed wetlands were able to remove up to 95% of the bioavailable mercury discharged within the wetland system during period of 3 days. The bioavailablility of mercury was influenced mainly by initial mercury concentration, chloride concentration, and pH value. These conditions influence the mercury speciation in the solution. Plants are able to uptake the bioavailable ionic form of mercury (Hg_2^{++}) from wastewater.

For the initial mercury concentration in solution of 50 ppb, the average mercury content in the roots of Water Hyacinths were 3.5 times greater than those in Reeds. After

the first three hours, the Water Hyacinth roots accumulate 110.55 μg/g compared to only 28.9 μg/g accumulated in Reeds roots (El-Agroudy, 1999). There is a general tendency for mercury to accumulate in the roots of the plants (Fang, 1978). Gracy and Stewart (1974) showed that mercury concentration in alfalfa roots was 133 times higher than its concentration in alfalfa foliage. Elektorowicz et al. (2002) concluded, using artificial intelligence approach, that the highest bioavailable mercury concentration for Water Hyacinth uptake achieved by maintaining the following conditions: the initial total mercury concentration between 1×10^{-4} and 1×10^{-3} mol/L; the chloride concentration between 1×10^{-8} and 1×10^{-6} mol/L; and pH values between 5.36 and 6.5. Considering the above-mentioned conditions, it is expected to achieve the concentration of bioavailable mercury as 6.7×10^{-6} mol/L. These conditions are recognized as the best removal parameters, as they provide higher bioavailable mercury to be uptaken by plants.

Wetlands Treatment, Specifications and Regulations

With the increased use of constructed wetlands, government agencies are concerned with devising appropriate design criteria, specifications, and regulations. According to the North American Wetlands Conservation Council (Canada), the wetland design requires careful consideration of the wetland system, the configuration, the size, the detention time, the water source, the bottom sediments, and the type of vegetation. Water Pollution Control Federation (1990) recommended a maximum hydraulic loading rate of 0.025 to 0.05 m/d, and a minimum size of 3-4 ha/1000 m^3/d in SFS. The wetland configuration is specified to have (length: width) ratio of at least 2:1, gradual wetland slope on the order of 0.05 %, and deep zones oriented perpendicular to the wetland flow to provide even distribution of the wetland flow. The maximum water depth for surface

flow wetland is confined to 0.5 m. Minimum hydraulic retention time for surface flow and subsurface flow wetlands can be in the range of 5-10 days. Maximum BOD_5 loading rates of 100-110 kg/ha/d are recommended for surface flow wetlands, and 80-120 kg/ha/d for subsurface flow wetlands as regulated by Water Pollution Control Federation (1990) (Pries, 1994). USEPA's Environmental Technology Initiative Program is supporting a team of regulators and affected parties to identify, describe, and provide recommendations to resolve constructed wetlands policy and permitting issues at the federal level (Gelt, 1997). However, no regulation provides information about accepted level of mercury discharge within wastewater.

Good construction practices and specifications should be followed during construction of treatment wetland. Examples include properly evaluating the site, limiting damage to the local landscape by minimizing excavation and surface runoff during construction, and maximizing flexibility of the system to adapt to extreme conditions. Construction specifications and drawings should be utilized that clearly convey the procedures to be used in construction criteria. USEPA stated that general construction storm water CWA Section 402 (NPDES) permit must be obtained for any project 5 acres in size or greater. This permit requires development and implementation of a Stormwater Pollution Prevention Plan including best management practices to minimize pollutant loading during construction. In wetland soils, if possible avoiding soil sources that contain a seed bank of unwanted species. The soil's permeability and the implications for ground water protection should be considered. Vegetation selection criterion is that the species should be chosen for water quality and treatment conducted in the project. The use of weedy, invasive, or non-native species should be avoided. Also designer should

consider the plants' abilities to adapt to various water depths, soils, and light conditions at the constructed wetland site (US EPA, 2000).

Mercury

Among heavy metals, mercury even in small concentrations presents an important problem of the wastewater discharged to the constructed wetlands. Mercury herein will be discussed concerning the following aspects: properties, sources and uses, mercury in environment, mercury toxicity, and regulations and preventive actions.

1- Properties

Mercury as a heavy metal has an atomic number of 80, an atomic mass of 200.6, specific gravity of 13.54, and solubility of 0.03(mg/l) at 25°C. Hg has vapor pressure of 2.63×10^{-6} atm at 25°C, soil partitioning coefficient K_d of 0.05, Henry constant (H) of 0.00114 (atm.m^3/mol), melting point of -38.87°C, and boiling point of 356.9°C (Reible, 1999).

Mercury is a liquid with high toxic effects for human and ecological systems. Metallic mercury has comparatively low acute toxicity when it is not in gaseous form, at the same time its salts as well as organic mercury-compounds like methylmercury are extremely toxic (Magos, 1997). Mercury has many physical and chemical properties that make it highly used in industry. Mercury is able to form alloys with other metals, it has high electrical conductivity, and it has high thermal conductivity of 8.34 W m^{-1} K^{-1} at 27°C that makes it useful to be used as heat transfer agent. Compounds of mercury have proved high potency to be used as catalysts in many industrial processes (Organization for Economic Co-op. & Devlop, 1974).

Mercury is emitted to the atmosphere from natural and anthropogenic sources in the form of elemental vapor and then converted to soluble form Hg^{++} that is returned to the earth surface with rainwater, and may be remitted to the atmosphere. Ocean sediments could be the final sinks where mercury is deposited in the form of HgS (WHO, 1984).

Mercury is distributed to the environment: water, air, soil, and living organisms, it is able to bioconcentrate and biomafnificate in the food chain (Takizawa, 2000). The most important forms of mercury can be classified as: metallic mercury, inorganic ions of mercury, and organic mercury compounds, these classes have different toxicity and different physico-chemical properties.

2- Sources and Uses

Recently, there has been increasing interest in long-range atmospheric transport and deposition of mercury in Europe and North America (Allan, 1996). Before 1970, a major source of Hg pollution to Canada's waters was tailings from gold mines using Hg as an amalgam. After 1970, gold mines stopped to use mercury, and as a result, the mercury release was decreased, however it could not totally eliminate the impact from contaminated tailings near gold mines all over Canada (Trip and Allan, 2000). Mining and metallurgical processes release considerable amount of mercury in many countries (Ferrara et. al., 1991). Regional Hg emissions contribute to global pollution due to the mobility of Hg. A ban on the Hg trade in Europe and North America would significantly diminish global Hg pollution (Hylander, 2001). The most anthropogenic, atmospheric sources of mercury in Northern America, are from coal-fired power stations, waste incinerators, some smelters, and medical incinerators (US EPA, 1996). The total

Canadian atmospheric emissions of Hg in 1990 were 33 ton, but this magnitude reduced to 11 ton by 1995 (Trip and Allan, 2000). Canadian smelters during the year 2000 released about 2.5 ton of mercury.

The most important source of mercury pollution is fuel combustion (54%), which is mainly burning of coal. The industry contributes to 34%, which due to chlor-alkali plants that release about 90% of European anthropogenic mercury to atmosphere (Pacyna, 1994). Pulp and paper industry released large quantities in northern Europe and North America (Rada et al., 1986).

The other categories, which participate in the mercury emission to environmental systems, are paints, fungicides, electrical equipment, instrumentation, amalgamation, and dental use (El-Agroudy, 1999).

Mercury is used in electrical apparatus and control instruments because of its physical properties; hence it is adopted in electrical communication cells, power rectifiers, thermometers, gauges, lamps, and electrical switches. In agricultural processes, mercury is used as fungicides to prevent fungal diseases during germination; many of mercury compounds have been used to treat seed potatoes, flower bulbs, and grain seeds. In some countries, organic mercury compounds have been used as foliage sprays against scab in apple, and disease in rice. For their antiseptic and preservative properties, mercury compounds are used in pharmaceutical materials as soaps, cosmetics, bleach creams, and antiseptic preparations. In pulp and paper industry, mercury compounds have been extensively used for the purpose of prevention of staining and decay of wet vegetable fibers through the fiber processing. Mercury has been used in many other

industries such as paints, plastics, tanning, and dental amalgams (Organization for Economic Co-op. & Devlop., 1974).

3- Mercury in Environment

The major routes by which mercury is distributed into physical environment are air, water, and soil. Mercury can be found as emitted vapor in air, soluble compounds in rivers and lakes, adsorbed materials on sediments and soils, or accumulated substances in living organisms and food chain (Organization for Economic Co-op. & Develop., 1974). In general, mercury is emitted into the atmosphere from natural and anthropogenic sources in the form of vapor. It is converted to a soluble material by which it is returned in the rainwater to the soils and surface waters, and may be converted to vapor and remitted back to the atmosphere (WHO, 1984). Because of its high vapor pressure, metallic mercury evaporates readily to the atmosphere. The solubility of mercury depends on the dissolved oxygen in water. The amount of soluble mercury and that amount to be evaporated into air can be indicated by Henry's constant of 0.00114 ($atm.m^3/mol$), which describes the fate of mercury in each phase. Soluble inorganic mercury can be precipitated from solution by sulfide ions under anaerobic conditions as mercuric sulfide, where it may accumulate in sediments (Organization for Economic Co-op. & Develop., 1974). In rocks and soils, mercury occurs as various combinations of oxides, sulfides, halides, and native metal where the partitioning coefficient (k_d = 0.05), controls the portion of mercury adsorbed onto the soils and sediments (El-Agroudy, 1999).

About 2000 tons of mercury per year is released by industry and this eventually becomes distributed in ground water, rivers, lakes, seawater, and oceans. Over 100 years ago, anthropogenic activities have led to discharge of about 100 million kilograms of

mercury into natural waters, and about five times this amount into land and atmosphere (Mitra, 1986).

The distribution and transport of mercury in environment involves two cycles. The first cycle represent the atmospheric circulation of mercury vapor from land to lakes and oceans. The second cycle depends upon microbial methylation of inorganic mercury from anthropogenic sources. The interchange of mercury between phases represents the transfer of mercury from air phase into aquatic ecosystems, by which it can be brought to the sediments by particle settling and then released by diffusion or resuspension. It could enter the food chain to reach human being, or it can be released back to air by volatilization. The contaminated media of air, water, soil, plant, and living organisms, bring the human being at last to interface with this pollution (El-Agroudy, 1999). Therefore, all approaches, which are able to buffer the dispersion of mercury in environment, are well expected.

4- Mercury Toxicity

The knowledge of mercury toxicity has increased with the increase of anthropogenic emissions caused by the use of mercury in gold and silver mining, and in industrial processes (Clarkson, 1994). Metallic mercury has comparatively low acute toxicity when not in gaseous state; however organic mercury compounds like methylmercury are soluble and toxic (Magos, 1997). At low levels, methyl mercury hampers mental development, whereas large amounts result in severe birth defects (Gearhart et. al., 1995). Methylmercury affects the central nervous system and irreversibly damages areas of the brain, it can bioaccumulate from 10^5 to 10^6 times in fish tissues, by which it represents danger to humans and wild life that consumes the fish

(Cole et al., 1992,). Humans generally uptake mercury in two ways, by ingestion, or by breathing vapors. Elemental mercury can be toxic especially when inhaled, or it could be ingested after methylation, then it biomagnifies in the food chain (El-Agroudy, 1999). Most of mercury present in living tissues is existed in the form of methylmercury (Takizawa, 2000). Inorganic mercury is relatively less toxic to humans than methylmercury or mercury vapor (Organization for Economic Co-op. & Develop. 1974).

Pharyngitis, abdominal pain, nausea, vomiting, bloody diarrhea, and shock can characterize Mercury acute toxicity. In critical cases nephritis, anurea, and hepatitis occur, followed by death from gastrointestinal and kidney lesions (WHO, 1976).

Chronic toxicity of mercury may be well described by Minamata disease, which resulted due to the excessive exposure of methylmercury, which develops central nervous system disturbance. In the period between 1950s and 1960s, thousands of people in Japan, city of Minamata had suffered from nervous disorder 'Minamata disease', as a result of eating fish with high methyl mercury content (Tsuru et al., 1989). The major symptoms of Minamata disease are sensory disturbance, ataxia, hearing impairment, and constriction of visual field. In fetal case of disease, cerebral infantile paralysis-like symptoms are observed, such as mental retardation, speech retardation and swallowing, and disturbances of the body mobility (Takeuchi, 1961).

The positive correlation is found between the chromosomal aberrations and the concentration of methylmercury in the blood of people eating contaminated fish (Skerfving et al., 1974). At the subcellular level, chemical fractionating has shown that mercury is almost associated with the protein-enzyme fraction and inhibition in

preference to the fat and nucleic acid fraction (Organization for Economic Co-op. & Develop., 1974).

According to the Swedish commission in 1970s, the lowest blood concentration of mercury for the appearance of clinical symptoms of toxicity is 0.2 μg/g; allowing safety factor of 10, the acceptable daily intake is 0.03 mg of mercury as methylmercury. If the fish is contaminated to 1.0 mg/kg, the average man's consumption of fish should not exceed 210 g/week according to the Swedish calculation. The joint of FAO-WHO Expert Committee on Food Additives suggested higher safety factor (Organization for Economic Co-op. & Develop., 1974).

5- Regulations and Preventive Actions

- In North America

Many actions in Canada contribute to reductions in mercury emissions, the principle initiative being a Canada-wide Standard for Mercury being developed jointly by 10 provinces, three territories and the federal government. Internationally, Canada is involved in four activities to promote reductions in global transport and deposition of mercury. These activities include: the Long Range Transboundary Air Pollution (LRTAP) Convention's Heavy Metals Protocol under United Nations Economic Commission for Europe; the North American Regional Action Plan (NARAP) for Hg under the environmental side agreement to the North American Free Trade Agreement (NAFTA); the Circumpolar Nations Arctic Environmental Protection Strategy; and the Binational Toxics Strategy under the Canada-United States Great Lakes Water Quality Agreement (Trip and Allan, 2000).

Canada has established several regulations concerning mercury use and release to the environment. The federal mercury regulations include:

1. Chlor-Alkali Mercury National Emission Standards Regulations;
2. Chlor-Alkali Mercury Liquid Effluent Regulations;
3. Liquid Effluent Discharge from Smelters and base Metal Refineries;
4. Fishing Inspection Act;
5. Food and Drug Act;
6. Ocean Dumping Control Act;
7. Metallurgical Industries Mercury Information Regulations;
8. Hazardous Products Acts;
9. Pest Control Product Act.

For Canadian regulations, the mercury concentration in the groundwater should not exceed 0.1 ppb.

U.S.A developed many acts from the past till now. It started early, in 1938 it had the Food, Drug, and Cosmetic Act. Other acts as Clean Air Act and Federal Water Pollution Control Act were developed later as an extension to previous acts (Organization for Economic Co-op. & Develop., 1974). The sales from the National Defense Stockpile were suspended in 1994 and remain suspended pending completion of an analysis of the potential environmental impact of the sales (Reese, 1997). The limit was set by U.S.A. regulations to have 0.05 mg of mercury vapor per cubic meter of air, in drinking water the limit was set to 50 ppb (Mitra, 1986). U.S. Federal Pollution Prevention Act 1990, involves the concept of integrated waste management in order to prevent pollution when

possible, to recycle and recover the wastes, to treat and transform stream waste, or for the last option to dispose the waste safely.

- WHO Act

The joint FAO/WHO Expert Committee on Food Additives recommended "any use of mercury compounds that increases the level of mercury in food should be strongly discouraged". The permissible tolerable weekly intake of methylmercury in adults should be maintained at 200 μg (3.3 μg/kg body weight) (WHO, 1978; WHO, 1989). However, the committee noted that pregnant women and nursing mothers are likely to be at greater risk, although the data available were not sufficient to recommend a specific mercury intake for these population groups (WHO, 1990).

Regulatory agencies focus on fish as the target organism to protect the health of human. U.S. Food and Drug Administration set the standard of 1 ppm wet weight in fish flesh, and the World Health Organization (WHO) recommends that the dose should not exceed 30 mg/day to protect adult humans. However, the regulations should totally include the mercury fate in the environment, so the presence of mercury in constructed wetlands should be included in the design process.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

Scope of the Problem

The current wetland design approaches lack essential parameters necessary to estimate the wetland response to buffer mercury. Many factors should be evaluated to obtain comprehensive information of the wetland performance, since the conditions of wetland system are uncertain and interrelated; subsequently the decision-makers are often confused to conduct an appropriate design. There are numerous important factors affecting the wetland performance, among of them: wastewater characteristics; wetland dimensions; behavior of aquatic plants; bottom sediment materials, and environmental conditions (temperature, wind). These factors are variable, which influence the speciation of wastewater components (including mercury) in the solution and their sorption onto sediments. Subsequently these factors affect the wetland performance and design. Using the artificial intelligence approach is an outstanding solution to find out the required information on wetland performance when the conditions of wetland are fuzzy and the factors are strongly interrelated.

Research Objectives

The main goal of this research is to develop a methodology for providing supplementary information for the wetland performance in buffering mercury from the discharged waters, which leads to find out the most appropriate conditions and the range of parameters applied for the efficient constructed wetland performance.

The artificial intelligence approach is a suitable facility that can be used to find out the most suitable wetland parameters to achieve efficient performance when all the conditions of the wetland are uncertain.

The particular objectives of this research can be summarized in the following points:

- To use artificial intelligence in order to assess the best conditions required for constructed wetland served as a sink of metal removal;
- To estimate the conditions where mercury is more bioavailable in the solution;
- To generate information on mercury behavior in wastewater and mercury removal by plants;
- To develop a methodology for providing information for mercury removal by adsorption onto wetland sediments within variable conditions implied in the constructed wetland;
- To develop descriptive mathematical analyses and modeling scenarios to represent constructed wetland removal processes, metal removal track, and wetland removal efficiency with the time;
- To provide sufficient information for the wetland design parameters, the dimensions, and the required time for efficient buffering of mercury.

This work is an advanced step to the previous researches in order to enhance the wetland involvement for mercury buffering in wastewaters containing heavy metals (including mercury).

Methodology

The use of artificial intelligence approach in this research was applied to provide more information for the constructed wetland performance. Therefore, the Fuzzy Decision Support system (FDSS) uses the prepared fuzzy knowledge bases to obtain series of solutions on the mercury behavior within the wetland system. In the first step, the artificial intelligent approach is used to specify the bioavailable mercury that can be taken by plant. Bioavailable mercury is susceptible to the environmental conditions comprising the amount of mercury discharged and the characteristics of wastewater. The Fuzzy Decision Support System is a suitable methodology to estimate the bioavailable ionic mercury for any initial mercury concentration within the combination to any concentration of chloride and any pH condition. FDSS depends on manual construction of the knowledge bases of constructed wetland to find out the final decision. The knowledge bases of the wetland system are built depending on the data obtained from previous experimental and computational phases that were conducted in the Department of Building, Civil, and Environmental Engineering at Concordia University. Fuzzy Decision Support System (FDSS) software, called FDSS Fuzzy-Flou, was developed in Ecole Polytechique (Canada) and University of Silesia (Poland). This software is able to obtain series of solutions for bioavailable ionic mercury, by which decision-maker is able to indicate range of parameters that satisfy more bioavailable mercury to be uptaken by

plant. The solution can be applied for any particular situation where natural conditions satisfy the following combination of parameters:

- Initial concentration of total mercury is in the range between 2.5×10^{-8} to 1×10^{-3} mol/L;
- Initial concentration of chloride is in the range between 1×10^{-8} to 1×10^{-4} mol/L;
- The pH value is located in the range from 5.36 to 8.

The experiments and numerical modeling conducted by El-Agroudy (1999) on the plant performance in the system resulted in limitation of parameter manipulation and inability to support into full and optimal design. Experimental investigations were conducted to investigate the ability of wetland floating and rooted plants to uptake mercury from water. Numerical modeling investigations were then carried out to expand the results obtained in the experimental phase by examining the distribution of mercury forms in water within the effects of pH, temperature, and chloride concentrations. An artificial intelligence approach is used to overcome the limitation resulted in previous processes.

In second step, the artificial intelligent approach was used to specify the amount of mercury that can be adsorbed onto soils/sediments in the system. Adsorption of mercury on soils is susceptible to the environmental conditions comprising the concentration of mercury discharged, pH of the solution, soil surface area, and the adsorbent concentration in the solution. The Fuzzy Decision Support System estimates the concentrations of the adsorbed mercury on soil within the combination of the previously mentioned factors. For soil analysis, FDSS depends on manual construction of the knowledge bases of constructed wetland in one stage, and on genetically generated

fuzzy knowledge bases in the other stage. FDSS Fuzzy-Flou software is able to obtain series of solutions for concentration of adsorbed mercury, by which range of parameters that satisfy more adsorbed mercury can be specified. The solution can be applied for any particular situation where natural conditions satisfy the following combination of parameters:

- The initial concentration of total mercury is in the range between 1×10^{-7} to 1×10^{-3} mol/L;
- The pH value is located in the range from 5.36 to 8;
- The specific surface area of the soil is the range up to 1350 m^2/g;
- The adsorbent concentration is in the range between 10 mg/L-10 g/L, where the 10 mg/L represents the suspended colloids in the water column, and 10 g/L represents the bottom sediments.

These conditions were based on the literature review and experimental research results (El-Agroudy, 1999).

FDSS Fuzzy-Flou-GA software, a modification of the previously-mentioned software, uses genetically generated fuzzy knowledge bases (GGFKB) in the fuzzy decision support system, where the genetic algorithm (GA) produces an optimal approximation of a set of sampled data to create knowledge bases from a certain amount of input information.

In the third step, a descriptive scenario is applied to show mercury removal track in constructed wetland within the time. It is applied by mathematical analysis and modeling for parameters such as initial concentration of total mercury, pH value, bottom

soil properties, and chlorine concentration for wetland components (plants and sediments).

This work describes the design criteria that evaluate the heavy metals removal from wastewater of the overall constructed wetland system. These criteria involve setting up all the wetland parameters to achieve best design efficiency; they also provide new approach to describe the constructed wetland processes and metal fate within the system. Heavy metals are being removed from wastewaters by plant uptake and soil adsorption. The series of information for plant uptake and soil adsorption of mercury obtained from the first and second steps are supplied to mathematical analyses and modeling to set up constructed wetland design. In addition, the knowledge of wetland performance in removing mercury and the wetland constituents' behavior provides more details for estimating the time for plant harvesting and break through for adsorbent soils.

Constructed wetlands are designed in many ways according to the research objectives and the designer background. Based on available literature review and experimental research, it is assumed in this work that constructed wetland system neither performs exactly like attached growth reactor nor performs as granular activated column systems. Constructed wetlands have some characteristics from both systems. For this purpose, the hydraulic properties, the pattern of flow, and the removal performance were assumed to follow the plug flow behavior. In addition the removal efficiency of constructed wetlands through the time was considered to follow adsorption column model developed by Thomas (Reynolds, 1982)

Challenges

It should be mentioned that many environmental agencies do not encourage the use of natural wetlands in wastewater treatment, they try to preserve them to protect wild life habitat, and so the investigations are needed to estimate the constructed wetlands powerful treatment.

The major problem within the design of constructed wetlands is the overlapping of environmental parameters and their stochastic appearance. This situation creates confusion and makes the decision difficult. Therefore, the fuzzy logic analysis herein is recommended.

Other challenge is that the Fuzzy Decision Support System (FDSS) needs knowledge bases to make a final decision. As a result, the extensive involvement of an expert to build the knowledge bases is needed. Instead, genetic algorithm (GA) can be used for automatically constructing the knowledge bases. The main advantage of this method is that it can automatically generate the fuzzy knowledge bases without the help of an expert.

Potential Applications

This research introduces the fuzzy logic concept to evaluate indeterminate behavior of natural systems. The application of fuzzy logic as an artificial intelligence approach to constructed wetlands is expected to confirm the validity of this approach in similar environmental cases where decision is difficult. The potential application of the fuzzy approach in the constructed wetland systems can be summarized as the following:

- To optimize the design of constructed wetlands to remove metals from contaminated waters;
- To introduce a program that correlates between design efficiency and its feasibility to the field;
- To apply artificial intelligence for more hazy cases (like all natural systems), where more than one pollutant and plenty of parameters are existed.

The findings of this research could lead to create technical information system that can be installed to overall constructed wetland in order to collect information from the components of the entire system. The data collected could be used as input feed to the FDSS-GA that automatically supports with a decision as long as the conditions are varying.

CHAPTER 3

FUZZY LOGIC

Introduction

Fuzzy logic is a superset of conventional logic that has been extended to handle the concept of partial truth, truth-values between "completely true" and "completely false". It was introduced by Lotfi Zadeh of UC/Berkeley in the 1960's as a mean to model the uncertainty of natural language. Fuzzy Logic is a departure from classical two-valued sets and logic, which uses "soft" linguistic (e.g. large, hot, tall) system variables and a continuous range of truth-values in the interval [0,1], rather than strict binary (True or False) decisions and assignments (Bonde, 2000).

Zadeh says that rather than regarding fuzzy theory as a single theory, we should regard the process of "fuzzification" as a methodology to generalize any specific theory from a crisp (discrete) to a continuous (fuzzy) form. Thus recently researchers have also introduced "fuzzy calculus", "fuzzy differential equations", and so on (Kantrowitz et. al., 1993). Formally, fuzzy logic is a structured, model-free estimator that approximates a function through linguistic input/output associations. Fuzzy rule-based systems apply these methods to solve many types of "real-world" problems, especially where a system is difficult to model, these systems are controlled by a human operator or expert, or where ambiguity or vagueness is common. A typical fuzzy system consists of a rule base, membership functions, and an inference procedure (Bonde, 2000).

How Fuzzy Logic Works

A fuzzy expert system is a system that uses a collection of fuzzy membership functions and rules, instead of Boolean logic, to reason about data. The rules in a fuzzy expert system are usually of a form similar to the following:

if x is low and y is high then z = medium

where x and y are input variables, z is an output variable (a name for a data value to be computed), low is a membership function (fuzzy subset) defined on x, high is a membership function defined on y, and medium is a membership function defined on z. The antecedent (the rule's premise) describes to what degree the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables. Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rule base or knowledge base (Kantrowitz et al., 1993).

In classical set theory, a subset U of a set S can be defined as a mapping from the elements of S to the elements of the set $\{0,1\}$

$$U : S \rightarrow \{0,1\}$$

this mapping may be represented as a set of ordered pairs, with exactly one ordered pair present for each element of S. The first element of the ordered pair is an element of the set S, and the second element is an element of the set $\{0,1\}$. The value zero is used to represent non-membership, and the value one is used to represent membership.

The truth or falsity of the statement

x is in U

is determined by finding the ordered pair whose first element is x. The statement is true if the second element of the ordered pair is 1, and the statement is false if it is 0 (Kantrowitz et al., 1993). As an example, people and "tallness". In this case the set S (the universe of discourse) is the set of people. The fuzzy subset is defined as TALL, which will answer the question "to what degree is person x tall?" Zadeh describes TALL as a *linguistic variable*, which represents the cognitive category of "tallness". To each person in the universe of discourse, the degree of membership should be assigned in the fuzzy subset. The easiest way to do this is with a membership function based on the person's height (Kantrowitz et al., 1993). A typical fuzzy system consists of a rule base, membership functions, and an inference procedure (Bonde, 2000).

The general inference process, as shown in Figure 3.1, proceeds in the following steps:

1. *Fuzzification*

The membership functions defined on the input variables are applied to their actual values, to determine the degree of truth for each rule premise (Gulley and Roger, 1995; Kantrowitz et al., 1993).

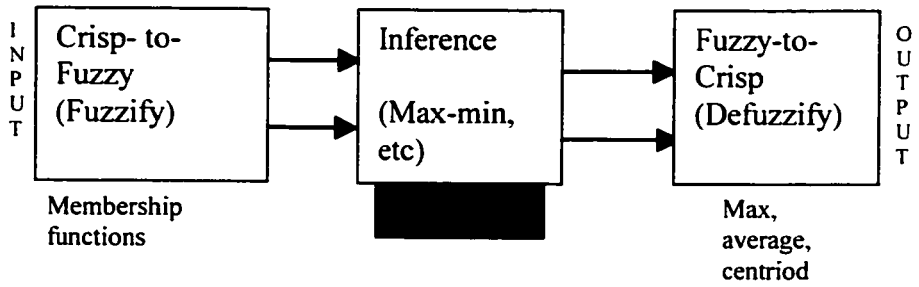

Figure 3.1: Fuzzy inference process (after Bonde, 2000).

2. *Inference*

The truth-value for the premise of each rule is computed, and applied to the conclusion part of each rule. This results in one fuzzy subset to be assigned to each output variable for each rule. Only MIN or PRODUCT is used as inference rules. In MIN inference, the output membership function is clipped off at a height corresponding to the rule premise's computed degree of truth (fuzzy logic AND). In PRODUCT inference, the output membership function is scaled by the rule premise's computed degree of truth (Kantrowitz et al., 1993).

3. *Composition*

All of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. Again, usually MAX or SUM are used. In MAX composition, the combined output fuzzy subset is constructed by taking the point-wise maximum over all of the fuzzy subsets assigned to variable by the inference rule (fuzzy logic OR). In SUM composition, the combined output fuzzy subset is constructed by taking the point-wise sum over all of the fuzzy subsets assigned to the output variable by the inference rule (Kantrowitz et al., 1993).

4. *Defuzzification*

Defuzzification is used when it is useful to convert the fuzzy output set to a crisp number. Two of the more common techniques of defuzzification are the CENTROID and MAXIMUM methods. In the CENTROID method, the crisp value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value. In the MAXIMUM method, one of the variable values at

which the fuzzy subset has its maximum truth-value is chosen as the crisp value for the output variable (Gulley and Roger, 1995; Kantrowitz et al., 1993).

Fuzzy Decision Support Systems

Fuzzy decision support systems (FDSS) comprise rule-based approach to decision making using fuzzy logic techniques, based on the compositional rule of inference (CRI). This approach is used to handle uncertain knowledge and was developed in the 60s by Zadeh (1973). Such knowledge can be collected and delivered by a human expert like decision-maker or designer. The CRI may be written in the following form:

$$U' = (C' \times ... \times B' \times A') o\, R \tag{3.1}$$

where: U' represents the output (conclusions); $(A', B', ..., C')$ represents the inputs (observations); the symbol o represents the CRI operator; R represents the global relation that aggregates all rules (knowledge base) (Balazinski and Jemielniak, 1998).

Fuzzy rule-based systems are being applied to solve many types of real-world problems, especially where a system is difficult to model. Human operator or expert controls these systems. A typical fuzzy system consists of a rule base, membership functions, and inference procedures. Three defuzzification methods are usually available, i.e. center of area (COA), average of maximums (AOM), and the modified center of area (MCOA).

The knowledge base consists of two components: the linguistic term base (database) and the fuzzy production rule base. The database is divided in two parts: fuzzy premises and fuzzy conclusions. Knowledge bases can be built up manually based on results from experimental tests and computations, or it can be generated automatically

using genetic algorithm (Baron, 1998; Balazinski et al., 2000). FDSS uses knowledge bases to support the final decision.

In this research, the investigations were performed using FDSS-Fuzzy Flou software developed by University of Silesia (Poland) and Ecole Polytechique (Canada). This software is able to obtain a series of solutions and extensive information for mercury removal by both plant absorption and soil adsorption, by which the designer is able to indicate the range of parameters to implement the best design.

Genetic Algorithm

Genetic Algorithms are stochastic optimization techniques that are based on the analogy of the mechanics of biological genetics and imitate the phenomenon of Darwinian survival-of-the-fittest approach (Baron, 1998). A GA is generally characterized by:

- Coding scheme for each possible solution, using a finite string of bits (called chromosome);
- Fitness value that provides the quality of each solution;
- Initial set of solutions to the problem, called initial population, randomly generated or chosen on a prior knowledge;
- A set of reproduction, mutation and natural selection operators, that allows the evolution of the population.

Each individual of a population is a potential FDSS Fuzzy-Flou knowledge base. They are encoded before applying four operations: reproduction, mutation, evaluation and natural selection, and decoding (Baron, 1998).

Reproduction

The evolution of the population is achieved by reproduction of the best individuals based on their ability to survive natural selection. This reproduction is performed by any of the three-following operators based on different initiating probability (Balazinski et al, 2000).

- Simple crossover

Reproduction is mainly made by crossover of the genotype (chromosome) of two parents to produce the genotype of two children.

- Fuzzy-Sets Displacement

Randomly selecting a fuzzy set on a premise and moving it one step toward the left or right with an equal probability perform the displacement of the fuzzy sets.

- Fuzzy-Rules-Reproduction

Randomly selecting a fuzzy rule, and disabling it perform the reduction of number of fuzzy rules.

Mutation

Mutation is a random inversion of a bit in the genotype of a new member of the population. Mutation allows trying completely different solutions.

Evaluation

The capacity of each individual to survive natural selection is evaluated by two objective functions. The first objective function evaluates the capacity of the knowledge base to approximate the sampled data. This fitness value, denoted ϕ_1, is computed as the root mean square error method (Balazinski et al, 2000).

The second objective function evaluates the complexity of a knowledge base through its number of active fuzzy rules, which are denoted ϕ_2.

The combination of these two contradictory objectives is made through a weighted sum, i.e.:

$$\phi = \omega_o \phi_1 + (1 - \omega_o) \phi_2 \tag{3.2}$$

where the optimization criteria ω_o is the weight associated to ϕ_1.

Natural Selection

Natural selection is performed on a population by keeping the most promising individuals based on their fitness. This is equivalent to using solutions that are the closest to the optimum (Balazinski et al., 2000).

In a steady state GA, a newly created child replaces the worst genotype of the population in the process of creating child solution genotypes using genetic operators such as crossover or mutation. This process of child production is repeated until stopping criteria is met, which normally occurs when thousands of iterations have been conducted. The population has often converged when the stopping criteria have been met. At this level, the genotypes in the population are very similar if not identical to each other. Thus, the population has been homogenized on this solution (Ronald, S., 1994).

In general, constructing the knowledge base manually is much easier than genetically generating it especially when the number of fuzzy rules and premises are not large. However, the GA is an important approach in the cases where expert is not available. In this research both methods were applied.

Applications

Study demonstrated the use of Fuzzy Flou software to design constructed wetlands. This method can be also used in the designing other natural processes, which required an implication of numerous interrelated factors. There are many benefits and applications of the fuzzy logic as an artificial intelligent information system.

The benefits of fuzzy logic approach can be summarized as the following:

* Fuzzy is conceptually easy to understand and implement,

* Fuzzy logic is flexible,

* Fuzzy logic is tolerant for imprecise data,

* Fuzzy logic can model nonlinear functions of arbitrary complexity,

* Fuzzy logic can be built on the top of the experience of experts,

* Fuzzy logic can be blended with conventional control techniques,

* Fuzzy logic is based on natural language, (Gulley and Roger, 1995)

* Fuzzy logic is a simplified & reduced development cycle,

* Fuzzy logic can provide more "user-friendly" and efficient performance (Bonde, 2000).

Some of applications of fuzzy logic criterion can be implemented in the following areas:

- In control systems (Robotics, Automation, Tracking, Consumer Electronics);
- In information systems (DBMS, Info. Retrieval);
- In pattern recognition (Image Processing, Machine Vision);
- In decision support (Adaptive HMI, Sensor Fusion) (Bonde, 2000).

CHAPTER 4

APPLICATION OF THE FUZZY LOGIC TO ESTIMATE THE BEST CONDITIONS FOR BIOAVAILABLE MERCURY SPECIATION IN CONSTRUCTED WETLANDS

INTRODUCTION

Wetlands are considered as natural treatment ecosystems that are designed to take advantage of the natural processes to provide an additional wastewater treatment (Metcalf and Eddy, 1991). Wastewater discharged to constructed wetland often contains heavy metals including mercury. These metals can be partitioned to wetland components in different ways due to variable environmental conditions, which influence the bioavailability of a particular metal. Wetland removal of metals is performed generally by plant uptake or by adsorption onto sediments. Therefore, the ability of constructed wetlands to serve as a sink of mercury before entering larger aquatic systems is an important issue. Study (El-Agroudy, 1999) showed the capability of constructed wetlands (Free Water Surface) to remove mercury from contaminated water/wastewater and reduce the widespread dispersion of this substance to streams, rivers, reservoirs, and oceans.

An accurate design of constructed wetlands requires dealing with different variables. The appearance of environmental events, and compounds behavior and their response to wastewater discharge are not certain. In these circumstances experimental or mathematical approaches to design an accurate constructed wetland show limitations. As a result, current design approaches of constructed wetlands do not take into consideration the uncertainty of variable parameters defining the complex processes within the

wetlands and subsequently to estimate essential parameters necessary to assess the capabilities of the mercury buffering from water. Previous investigations (El-Agroudy and Elektorowicz, 1999) demonstrated limitations on describing bioavailable ionic mercury speciation within a combination of different conditions, hence, plants uptake of mercury and wetland design resulted in a shortage, therefore, artificial intelligence is recommended.

In this chapter, the artificial intelligence is used to achieve the following:

- Generating general information on mercury speciation in wetlands, especially bioavailable mercury and its removal by aquatic plants.
- The use of the artificial intelligence approach to assess the best conditions required for constructed wetland served as a sink of metals (mercury).

The artificial intelligence approach (Fuzzy Logic Knowledge) was applied to analyze uncertain relationships. It is able to estimate, depending on the experimental data previously obtained, the bioavailable ionic mercury concentration for any value of initial total mercury concentration in wastewater within the combination to any concentration of chloride in any pH condition.

METHODOLOGY

This research used the artificial intelligent approach to generate information on bioavailable mercury that can be taken by plants. Bioavailable mercury is susceptible to the environmental conditions comprising the discharged amount of initial total mercury, the variable chlorine (Cl^-) concentration, and variable pH value of the wastewater. The above-mentioned conditions are not certain and mostly overlapping, which makes the decision of the designer difficult. The investigations were performed using FDSS-Fuzzy

Flou software. This software is able to obtain a series of solutions for bioavailable ionic mercury, by which the designer is able to indicate the range of parameters to implement the best design. FDSS uses knowledge bases to support the final decision. Knowledge bases were built manually based on results obtained from experimental setup, and mathematical modeling using MINTEQA2 (El-Agroudy, 1999). FDSS solutions were applied for any particular situation where natural conditions satisfy the following combination of parameters:

- Initial concentration of total mercury is in the range between 2.5×10^{-8} and 1×10^{-3} mol/L;
- Initial concentration of chloride is in the range between 1×10^{-8} and 1×10^{-4} mol/L;
- The pH value is situated between 5.36 and 8.

Three defuzzification methods are usually available, i.e. center of area (COA), average of maximums (AOM), and the modified center of area (MCOA). In this research, the COA was used for defuzzification.

The knowledge base consists of two components: the linguistic term base (database) and the fuzzy production rule base. The database is divided in two parts: fuzzy premises and fuzzy conclusions. Figure 1 in Appendix B shows a screen printout of the fuzzy rules and settings (on the left), and premises and conclusion (on the right) of the FDSS Fuzzy-Flou software.

ANALYSES AND RESULTS

The applied FDSS was able to estimate bioavailable mercury concentration in constructed wetland wastewater; hence FDSS provides information for constructed wetland design, i.e. wetland conditions setting, determination of mercury uptake efficiency, and effluent discharge control.

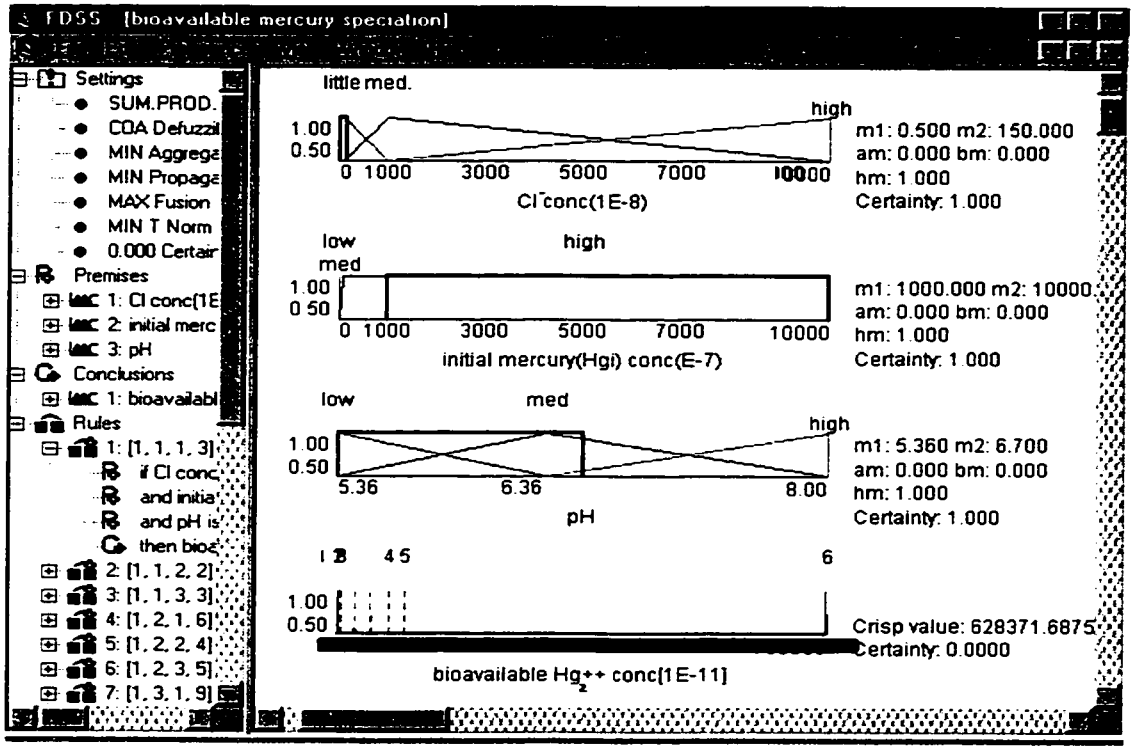

Figure 4.1: Screen shot of FDSS window using the Fuzzy Flou software for mercury speciation within constructed wetland.

Figure 4.1 shows screen shot of FDSS Fuzzy-Flou, in which the knowledge base was built, the input parameters inserted, and in turn the output results were obtained. FDSS was able to predict the speciation of bioavailable mercury for variable combination of the following parameters: initial mercury discharge, pH, and chlorine concentration. Subsequently, comparison is conducted between results obtained from the model using FDSS and experimental results (El-Agroudy, 1999) for Water Hyacinth uptake of bioavailable mercury where different initial total mercury concentrations in water containing Cl^- concentration of 1×10^{-8} mol/L, and pH of 5.36 are examined. The comparison shows an acceptable similarity (Figure 4.2).

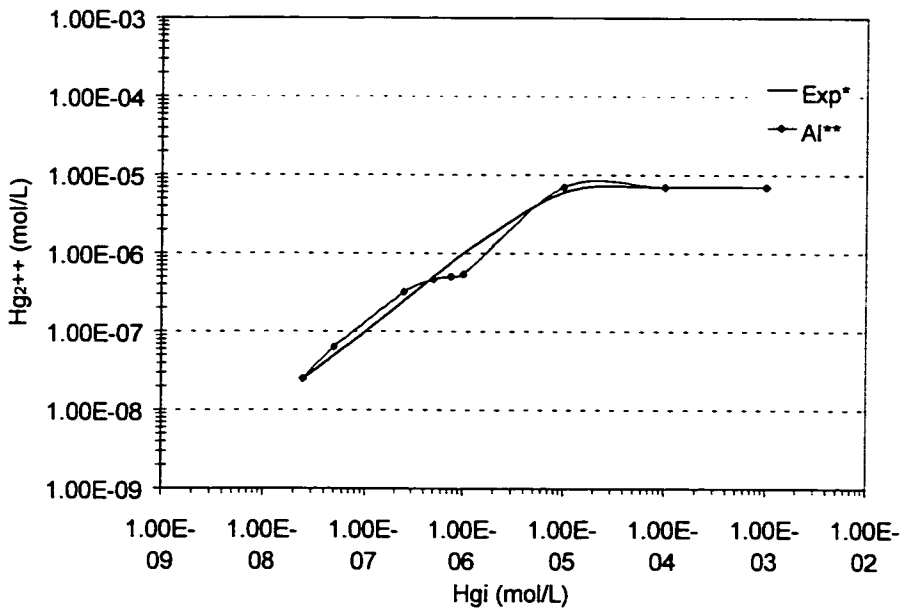

Figure 4.2: Bioavailable ionic mercury (Hg_2^{++}) concentration to be uptaken by plants vs. initial total mercury (Hg*i*) concentration available in wastewater discharge, where Cl^- concentration of 1×10^{-8} mol/L, and pH of 5.36 are maintained.

* Exp. = Results obtained by the experimental setup and its mathematical modeling extension

** AI= Results obtained using artificial intelligence approach.

The great advantage of the use of FDSS is that it is able to predict bioavailable mercury within the combination of various conditions. FDSS provides maneuverability in describing wetland performance under correlated conditions; as a result it is possible to find the values of the most suitable conditions to achieve the best design. Table 4.1 shows best values of ionic mercury in gray rows; these values are correlated with best conditions for bioavailable mercury speciation in wastewater.

The highest bioavailable mercury concentration for Water Hyacinth uptake can be achieved by maintaining the following conditions: (the initial total mercury concentration should be in the range of 1×10^{-4} to 1×10^{-3} mol/L; Cl^- concentration should be in the range of 1×10^{-8} to 1×10^{-6} mol/L; and pH values should be in the range of 5.36 to 6.5). Considering the above-mentioned conditions, it is expected to achieve the concentration of bioavailable mercury as 6.7×10^{-6} mol/L. These conditions are recognized as the best performance parameters, as they provide higher bioavailable mercury to be uptaken by plants, they also provide more flexibility for a designer to set design conditions, but they do not describe the most efficient removal.

Table 4.1: Example of the bioavailable mercury (Hg_2^{++}) concentration in a constructed wetland obtained by mean of FDSS within the combination of some environmental conditions.

Case	*Chloride concentration-(Cl^-) (mol/L)*	*pH*	*Initial total mercury concentration– (Hgi) (mol/L)*	*Bioavailable mercury concentration- (Hg_2^{++}) (mol/L)*
*R1	1×10^{-6}-1×10^{-5}	6.5-7.5	1×10^{-6}-1×10^{-5}	1.33×10^{-6}
R2	1×10^{-5}-1×10^{-4}	7-8	1×10^{-7}-1×10^{-6}	2.72×10^{-8}
R3	1×10^{-8}-1×10^{-5}	5.36-7	1×10^{-4}-1×10^{-3}	3.4×10^{-6}
R4	1×10^{-5}-1×10^{-4}	7.5-8	2.5×10^{-8}-5×10^{-8}	5.13×10^{-9}
R5	1×10^{-8}-1×10^{-6}	5.36-6.5	1×10^{-4}-1×10^{-3}	6.7×10^{-6}
R6	1×10^{-8}-1×10^{-6}	5.36-6	1×10^{-4}-1×10^{-3}	6.99×10^{-6}
**C1	0	5.36	1×10^{-3}	7×10^{-6}
C2	1×10^{-4}	8	2.5×10^{-8}	5×10^{-10}
C3	3×10^{-6}	6.3	1.5×10^{-5}	5.8×10^{-6}
C4	1×10^{-8}	6.4	2.1×10^{-4}	6.8×10^{-6}
C5	7.5×10^{-5}	8	3×10^{-7}	5.3×10^{-9}
C6	6.4×10^{-6}	7.8	4.4×10^{-5}	9.7×10^{-7}

* R = Ranges of values
** C = Crisp value
Shaded rows are correlated with the highest concentration of bioavailable mercury, i.e. the most available for plants.

CONCLUSION

The investigations showed an efficient ability of fuzzy logic analysis to be used for estimating the bioavailable mercury concentration under a changing of various parameters within the constructed wetlands. The FDSS is a suitable methodology to estimate the bioavailable ionic mercury for initial total mercury concentration discharged to the wetland within the combination to any concentration of chloride in any pH condition in the wastewater.

The Fuzzy Decision Support System assessed variable conditions potentially found in constructed wetlands, and permitted to an excellent prediction of mercury speciation in wetland water within the combination of different parameters. Herein, the optimal wetland conditions have been established for the highest mercury removal by floating plants. The approach of this research can be applied to wetlands and all natural processes where correlation between them is uncertain. The findings of this research could also be applied in preparing environmental information systems.

CHAPTER 5

APPLICATION OF THE FUZZY LOGIC APPROACH TO ESTIMATE MERCURY SORPTION ONTO SEDIMENTS IN CONSTRUCTED WETLANDS

INTRODUCTION

Mineral composition at the bottom of a constructed wetland has a significant impact on the dynamics of the pollutant cycle. Clay is the most common component of wetland sediments due its low permeability. Clay mineral particles are colloids having high specific surface area that influences soil adsorption properties (Yong et al 1992). Wetlands should have low-permeable soil surfaces ($<1.41\times10^{-6}$ m/s), in order to avoid percolation losses through the soil profile (Metcalf and Eddy, 1991). Several environmental conditions, implied in constructed wetland ecosystem, influence the sorption on soils. Among these conditions, the initial total concentration of mercury discharged in the wastewater, the pH value of the wastewater, the specific surface area of the soil medium, and the adsorbent concentration in the wetland are the most important. The conditions are mostly interlocked; as a result the soil performance within these conditions is unclear. Fuzzy logic analysis as an artificial intelligence approach provides with information for the soil sorption capability for all interrelated and uncertain conditions.

METHODOLOGY

This chapter describes the approach carried out to generate information on mercury adsorbed onto soil sediments in the constructed wetland within some parameters such as: 1) the initial total concentration of mercury in the wastewater; 2) the pH value; 3) the specific surface area of the soil; 4) the adsorbent concentration in the system.

The objectives of this research are:

- To develop a methodology for providing information for mercury sorption onto wetland sediments;
- To develop a methodology for providing information for mercury sorption onto suspended matter in the water column;
- To provide more details of the soil sorption capability within varying the above mentioned parameters in the constructed wetland;
- To provide sufficient information on wetland parameters to conduct efficient design.

The sorption capacity of soil is variable due to the influencing parameters associated within the wetland system; as a result mercury compounds respond to the sorption as a function of sediment characteristics. Combination of numerous possible values of environmental parameters with variable characteristics of bottom sediments requires new approach, which overcomes limitations associated with experimental tests and computations.

The Fuzzy Logic approach was used to overcome limitations. This chapter shows the implementation of the artificial intelligent approach to generate information for mercury adsorption on soil medium within different conditions. Soil adsorption capability

is susceptible to the environmental conditions that are variable and mostly interrelated. Fuzzy-Flou software, which involves Fuzzy Decision Support System (FDSS), was able to obtain series of solutions for mercury adsorption on soils. Subsequently, it generates a range of parameters that satisfies the designer's assumptions. If the sediments express a function of buffer, the highest mercury removal from the water column via sorption will present a sufficient criterion for the best design for sediments. As discussed in Chapter 2, FDSS uses knowledge bases that can be built manually or they can be genetically generated to find out the final decision. In this chapter, knowledge bases are established in two ways. In the first way, the knowledge bases are established manually depending on results that were obtained from computations conducted by El-Agroudy (1999) using MINTEQA2 software within certain range of parameters. In the second way, the knowledge bases are genetically generated using FDSS Fuzzy-Flou-GA software. This software uses Genetically Generated Fuzzy Knowledge Bases (GGFKB) in the fuzzy decision support system (FDSS), where the Genetic Algorithm (GA) produces an optimal approximation of a set of sampled data in order to create knowledge bases from a certain amount of input information.

Fuzzy decision support system implies rule-based approach to take final decision using fuzzy logic techniques (Balazinski and Jemielniak, 1998). In this research, the center of area (COA) is the defuzzification method.

In general, the type of sets obtained by genetic algorithm makes it much easier to construct the knowledge base when an expert is not able to conduct a manual construction of knowledge bases.

This first approach of GA to wetland design was based on data collected from different resources: literature review, previously generated experimental and computation data by the Department of Building, Civil, and Environmental Engineering at Concordia University, and experience within the development of GA system in the Department of Mechanical Engineering at Ecole Polytechnique (Montreal). An accurate application of collected data into FDSS provides a decision related to soil behavior, particularly mercury sorption to clayey soils.

Sorption onto Wetland Soils

Heavy metals have received considerable attention with regard to accumulation onto sediments. The physical-chemical properties of soil affect the design and the term of treatment. Principal properties such as: soil matrices of minerals, particle size, particle distribution, pore spaces, reactive specific surface area, ionic charge, cation exchange capacity, pH, and temperature, influence the sorption of metals (Faulkner and Richardson, 1989). The inorganic components of soil can take the form of minerals (silica and alumina) crystalline and non-crystalline material. Clayey soil consists of mineral groups with high specific surface area and cation exchange capacity. For example, chlorite is a clay mineral group composed of silica and alumina sheets. It has specific surface area ranges from 70-150 m^2/g and cation exchange capacity ranges from 10-40 cmol/kg, whereas the specific surface area of montmorillonite ranges from 600-800 m^2/g and its cation exchange capacity is 80-120 cmol/kg (Yong et al., 1992).

Sediments counted as clay colloids adsorb charged species. The particle charge is balanced by an equal and opposite charge carried by ions in the surrounding liquid.

Helmholtz assumed that the electric charge on metal surface was balanced with equal charge, which sets in the surrounding layer a little away from the surface (Hunter, 1993).

Triple-layer concept was applied to mercury sorption onto bottom sediments. Allison et al. (1991) suggested the triple-layers model as discussed in Chapter 1, where only protonation and deprotonation of surface sites are assigned to the o-plane. Other specifically adsorbed ions are assigned to the β-plane and determine the charge σ_β and potential ψ_β in that zone. Non-specifically adsorbed ions are envisioned as residing in the diffuse layer (d) and are influenced by ψ_d potentials. The capacitance between the o-plane and the β-plane is denoted C_{cap1} and between the β-plane and d-plane is denoted C_{cap2}. The potential gradients in the inner and outer zones are linear, but potentials decay exponentially in the diffuse layer zone. The triple-layer model was adopted in the computation software MINTEQA2 to investigate mercury speciation in the bottom sediments in the wetland (El-Agroudy, 1999).

FDSS solution were applied for any particular situation where natural conditions satisfy the following combination of parameters:

- The initial concentration of total mercury is in the range between 1×10^{-7} to 1×10^{-3} mol/L;
- The specific surface area up to 1350 m^2/g ;
- The pH value is located between 5.36 to 8;
- The adsorbent concentration is in the range between 10 mg/L (suspended solids) to 10 g/L (bottom sediments).

FDSS-GA solution depends on genetically generated fuzzy knowledge bases that satisfy the following combination of parameters:

- The initial concentration of total mercury is in the range between 1×10^{-7} to 1×10^{-3} mol/L;
- The specific surface area equals to 129 m^2/g;
- The pH value is located between 5.36 to 8;
- The adsorbent concentration in the solution equals to 10 g/L.

Fuzzy decision support system does not have any limitation. The previous ranges are being taken into consideration because the history of the constructed wetland performance was available within the above-mentioned ranges.

ANALYSES AND RESULTS

In the first stage of work, FDSS Fuzzy-Flou software provided several series of solution for mercury adsorption onto soil for different conditions. Fuzzy decision support system used manually built fuzzy knowledge bases to provide an accurate estimation of the amount of adsorbed mercury within the combination of different parameters that affect the capability of soil adsorption. Figure 5.1 shows a printout of FDSS Fuzzy-Flou window, which includes the premises that describe the conditions that influence soil performance, the settings of the operation executed by FDSS, the rules of decision, and the conclusion set that brings to final end-user results. In Figure 5.1, the input variables and output results represent suitable ranges for better soil adsorption capability and subsequently, better buffering capacity of the constructed wetland.

FDSS is able to estimate the amount of sorbed mercury onto soil media for any value of the parameters in the system.

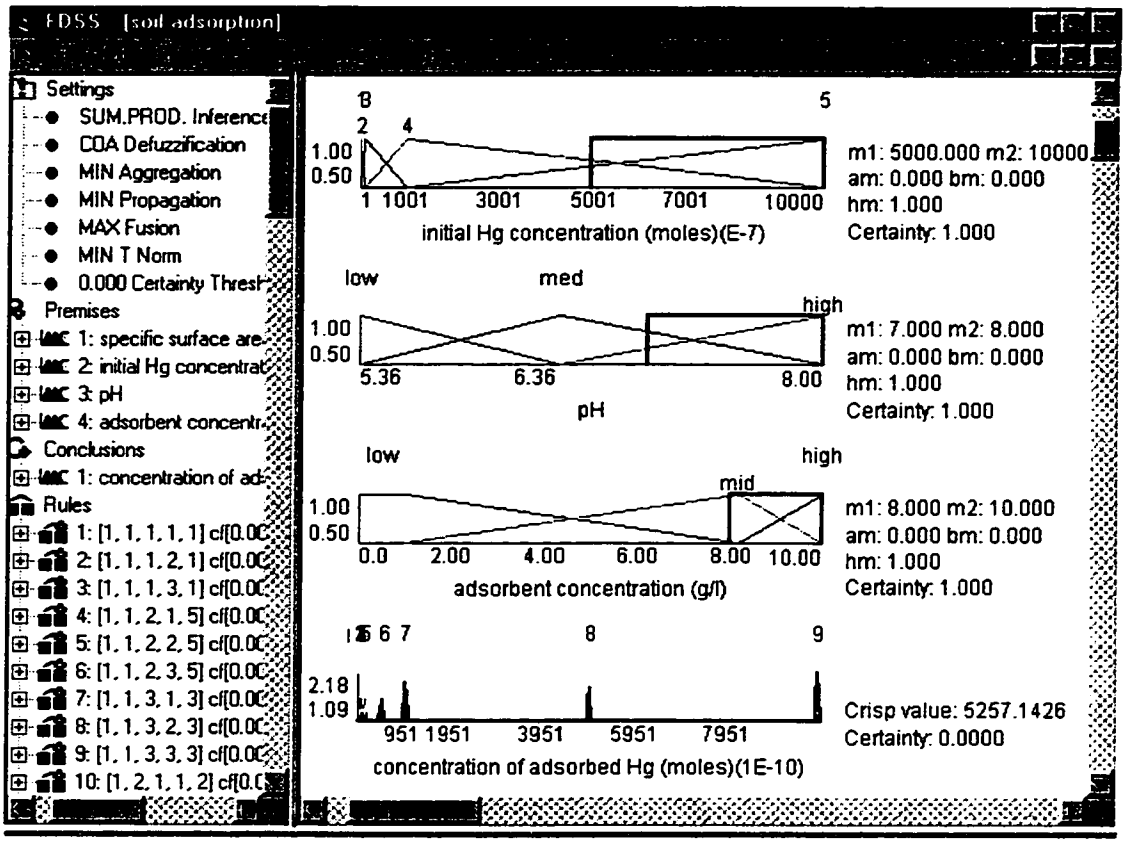

Figure 5.1: Screen-shot of FDSS window using the Fuzzy Flou software for adsorbed mercury onto soils within constructed wetland system.

Figure 5.2 describes the FDSS results of adsorbed mercury for different initial total mercury discharged in the wastewater, where the pH equals 8, specific surface area equals 1350 m^2/g, and sediments concentration in the wetlands equals 10 g/L. The results obtained by FDSS show that the fuzzy approach well describes wetland soil performance. FDSS estimations showed that the most optimal mercury removal could be achieved within the combination of the following parameter ranges: initial mercury concentration ranges from 5×10^{-4}-1×10^{-3} mol/L; specific surface area ranges from 1000-1350 m^2/g; pH value ranges from 7.5-8; and the sediment concentration of 8-10 g/L.

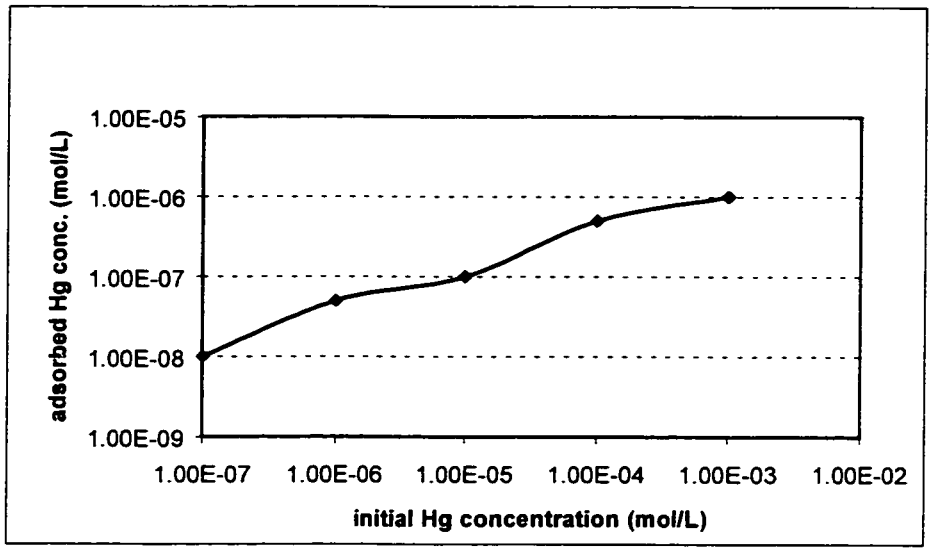

Figure 5.2: The concentrations of mercury adsorbed onto soil as an obtained results by artificial intelligence (AI)-FDSS, in wetland system for different mercury concentration when pH equals to 8, specific surface area equals to 1350 m^2/g, and adsorbent concentration equals to 10 g/L.

Table 5.1 shows the mercury adsorption onto soil for different conditions, where the shaded rows represent the best removal. However, these results do not represent the highest removal efficiency of the system (see discussion in Chapter 6). Some cases cannot be fit to the field because they are not feasible and difficult to set by designer; therefore parameters of constructed wetlands are preferable to set up in the field based on a flexible range of values.

Table 5.1: Concentrations of adsorbed mercury obtained by FDSS within the combination of variable parameters.

Case	*Specific surface area (m^2/g)*	*pH*	*Sediment concentration (g/L)*	*Initial total mercury-Hg (molL)*	*Sorbed Hg concentration (mol/L)*
*R1	340-509	6.5-7.5	5-7	1×10^{-6}-1×10^{-5}	3.52×10^{-8}
R2	100-245	6-7	8-10	7×10^{-7}-1×10^{-6}	9.9×10^{-9}
R3	812-1000	7.5-8	7.5-9	1×10^{-6}-1×10^{-5}	5.8×10^{-7}
R4	100-135	5.36-6	0.1-1.8	2.5×10^{-7}-5×10^{-6}	1.3×10^{-9}
R5	1200-1350	7.8-8	9-10	7×10^{-6}-1×10^{-5}	7.8×10^{-7}
R6	1000-1350	7.5-8	8-10	5×10^{-6}-1×10^{-5}	6.4×10^{-7}
**C1	80	5.36	0.001	1×10^{-7}	1×10^{-10}
C2	800	6	1	2.5×10^{-5}	1×10^{-8}
C3	129	6.5	10	7×10^{-7}	3.7×10^{-9}
C4	1000	7	7	2.1×10^{-4}	2.17×10^{-7}
C5	1350	8	10	1×10^{-5}	1×10^{-8}

* R = Ranges of values
** C = Crisp value
Shaded rows are correlated with highest soil adsorption of mercury i.e. best removal condition

In the second stage of this work, the fuzzy knowledge bases are genetically generated. The modified Fuzzy-Flou software used genetically generated fuzzy knowledge bases (GGFKB) in the fuzzy decision support system, where the genetic algorithm (GA) produces an optimal approximation of a set of sampled data to create knowledge bases from a certain amount of input information. Figure 5.3 shows

comparison between results obtained by FDSS-manual knowledge bases and FDSS

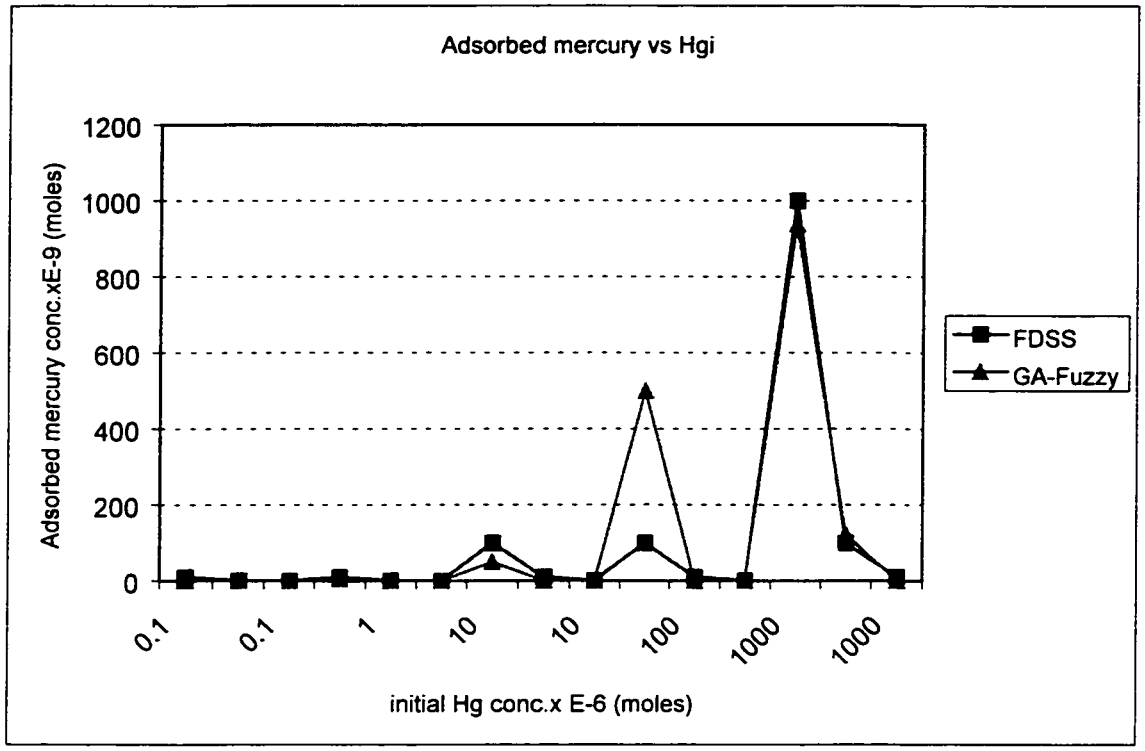

Figure 5.3: Comparison between FDSS and FDSS-GA results for different initial mercury concentration, when pH varies between 5.36-8, for natural soil, where specific surface area equals to 129 m^2/g, and the adsorbent concentration equals to 10 g/L.

GGFKB for certain conditions. For certain initial mercury concentration the adsorbed mercury is decreasing from its upper value when pH equals 8 to its lower value when pH equals 5.36. This comparison shows vital agreement between the two methods. More demonstration is found in Figure 5.4 and Figure 5.5. The manual construction of the fuzzy knowledge bases is not always simple; especially when there are many fuzzy rules and no experience to the system behavior; therefore the GGFKB is a suitable criterion for such cases.

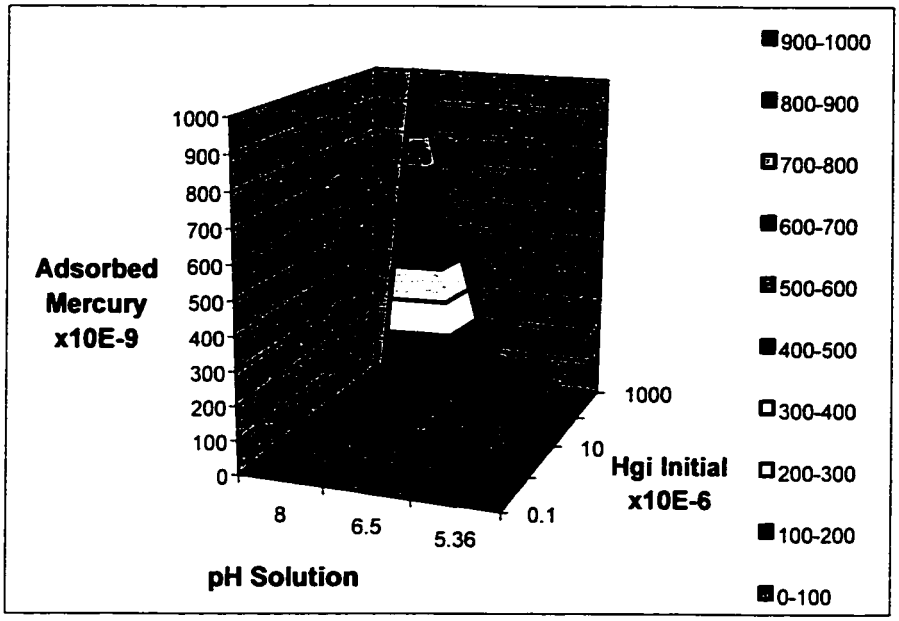

Figure 5.4 : Adsorbed Hg conc.vs (Hgi Initial- pH in Solution) obtained by FDSS for manually built-fuzzy knowledge bases, where the sediment concentration equals 10 g/L, and soil specific surface area equals 129 m^2/g.

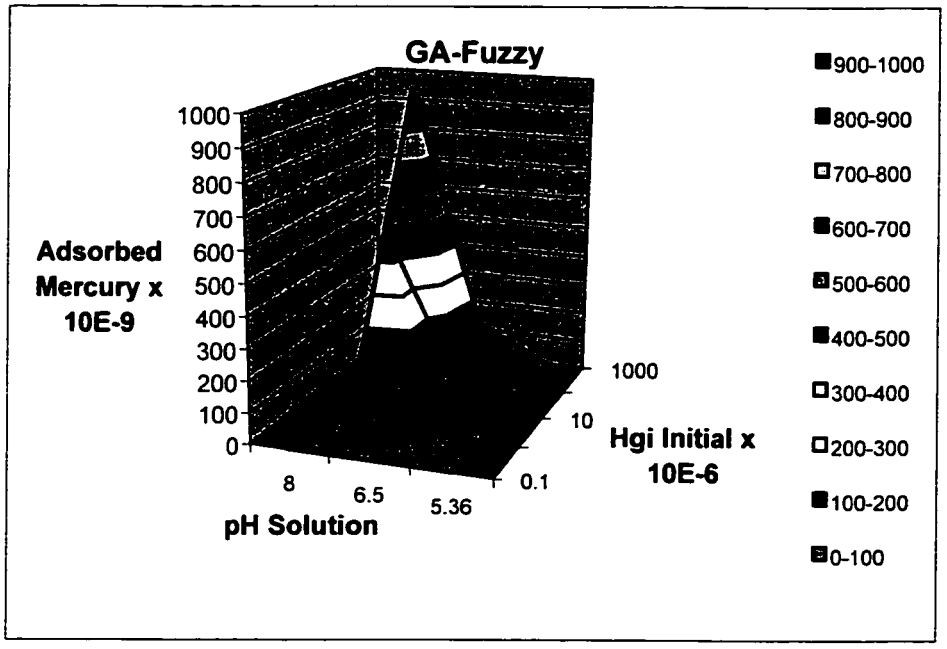

Figure 5.5 : Adsorbed Hg conc.vs (Hgi Initial- pH in Solution) obtained by FDSS for GGFKB of the soil, where the sediment concentration equals 10 g/L, and soil specific surface area equals 129 m^2/g.

CONCLUSION

Results obtained in this chapter show the ability of fuzzy logic analysis to efficiently provide information for mercury adsorption onto wetland sediments. The constructed wetland parameters are stochastic and highly interrelated that brings the application of fuzzy logic into vital role. Fuzzy decision support system uses both manual constructed fuzzy knowledge bases and genetically generated fuzzy knowledge bases to assess variable combination of initial mercury concentration, specific surface area, pH value, and adsorbent concentration. It was able, by both corresponding criteria, to find out the optimal wetland conditions that satisfy more adsorption of mercury onto soil. As a result it provides sufficient information on wetland parameters to conduct the efficient design. The approach of this research can be applied to any other wetland component and all natural processes where their correlation is uncertain.

CHAPTER 6

INTEGRATED CONSTRUCTED WETLAND DESIGN: APPLICATION FOR MERCURY REMOVAL

INTRODUCTION

Constructed wetland consists of different components, which behave in a way that is difficult to describe due to the component sensitivity to the wetland variable conditions. However, an accurate design of constructed wetlands should take into consideration every component and its overall effect on the system. The response of the entire system to wastewater discharge should be considered. The behavior of wetland constituents is complex within variable conditions. The following main variable parameters govern the efficiency of constructed wetland as a buffer of metals: the initial mercury content in the wastewater, the pH value of wastewater, the chloride concentration, and the properties of sediments and suspended materials. These conditions influence the efficiency of each constituent to remove mercury. Consequently, it is difficult to model the constructed wetland and set up an efficient design. The principal design parameters for constructed wetland systems include hydraulic detention time, basin depth, basin geometry (width and length), and hydraulic loading rate (Metcalf and Eddy, 1991). Some methods of design use regression analyses of performance data from operating systems to make design criteria (Knight et al., 1993). Other methods suggest the areal loading approach, in which the treatment performance is related to the volume of water or mass of pollutant divided by the area of the wetland (Smith, 1980). A third

approach assumes that the biological reactions, which occur in the wetland system, are similar to reactions happening in attached growth wastewater treatment process (Knight et. al., 1993). Each of the above-mentioned approaches does not reflect all complexities of the wetland systems. In this research fuzzy logic analysis is applied to give extended possibility to assess the constructed wetland performance in removing mercury form contaminated waters. The fuzzy logic approach gives necessary information to cover the combination of variable wetland conditions. It will also provide the required parameters to achieve best design of constructed wetlands, for example: dimensions and geometry, detention time, and removal efficiency. The application of the results and analyses obtained in Chapter 4 and Chapter 5 enables to set up the requirements for building up constructed wetland to serve as a buffer for mercury discharge to the environmental systems and protect the quality of surface waters.

METHODOLOGY

This research describes the manipulation of results obtained by fuzzy logic approach that was conducted on the wetland components in previous chapters. These results provide more information on wetland behavior for mercury removal within the time, by which mathematical analysis and modeling can be conducted within maintaining the required parameters (initial total mercury, pH value, soil medium properties, and chloride concentration) in the system.

The objectives of this chapter are:

- To develop descriptive analyses of the obtained results of the fuzzy logic approach to show constructed wetland performance.

- To develop a mathematical modeling for providing an accurate scenario for wetland removal process;
- To provide more details to the metal removal track versus the time within the constructed wetland system;
- To provide sufficient information of wetland design parameters, dimensions, and required time for efficient removal.

This chapter describes the methodology of constructed wetland design for purpose of heavy metals removal from wastewater. It uses certain criteria for setting up wetland parameters to achieve the best design efficiency. It was assumed that heavy metals are being removed from wastewaters by plant uptake and by sediment sorption. Information obtained in Chapter 4 and Chapter 5, supply into series of solutions for plant uptake and soil sorption of mercury, by which mathematical analyses and modeling can further be established to set up constructed wetland design. In addition, the knowledge of wetland constituents' performance in removing mercury provides the required information for undisturbed operation activities (e.g. longevity of wetland constituents, time of service, etc).

Constructed wetlands may be designed in many ways according to the objectives and the designer background. In this research, it was assumed that the removal process in wetlands is similar to a process that combines between the treatment process in the attached growth reactor (AGR) and the adsorption process in the granular activated carbon (GAC) columns. The hydraulic properties, pattern of flow, and removal performance are assumed to follow the plug flow behavior. Plug flow conditions are approached as the number of tanks in series approaches infinity (Horan, 1990).

PRILEMENARY DESIGN REQUIREMENTS

The principal design parameters for constructed wetland systems include hydraulic detention time, basin depth, basin geometry (width and length), and hydraulic loading rate. Other preliminary applications should be taken in consideration, include site evaluation and selection, topography, and climate. Pre-application procedures for wetlands systems, for example to get rid of algae and phosphorus, should be implemented to polish the influents to achieve more stringent regulatory effluent requirements (Metcalf and Eddy, 1991). Flood hazard is one of items that should be controlled in wet seasons, rainfall for example could affect the component of wetland system by either diluting the pollutant concentration, or decreasing the retention time and thus affecting the quality of final effluent (Manios et al., 2000). Wetland bottom should be impermeable with sufficient slope to ensure complete drainage when necessary and to provide an outlet, which permits adjustment of water level at the end of the wetlands. This adjustment can be used to set the required water surface slope and to drain the wetland (Reed et. al., 1995).

Periodic maintenance and operational processes are significant to the overall wetland components to keep efficient performance.

DESIGN SCENARIO AND ANALYSES

The results obtained in Chapter 4 and Chapter 5, are being used in this chapter to support with representative design scenario to the constructed wetland systems. It can be concluded from Chapter 4 through the information obtained by fuzzy analyses that the best removal efficiency of mercury is achieved when the initial concentration is in the

range (1×10^{-7}-1×10^{-6} mol/L), the pH is low, and the Chloride concentration is low. The previous mentioned conditions satisfy posing most of mercury content as bioavailable mercury (that will be taken by plant) and the remaining non-bioavailable mercury will be sorbed onto sediments. Consequently, they satisfy high removal efficiency. In this chapter, the conditions used for design are the following: the initial mercury concentration equals to 7×10^{-7} mol/L, Cl^- concentration of 1×10^{-8} mol/L, pH of 6.5, specific surface area of soil of 129 m^2/g (natural soil), and sediment concentration of 10 g/L. These values were applied to the FDSS for four stage-steps (cells) as trial and error iteration. The results obtained by FDSS show that the removal efficiency of mercury by overall wetland system equals 97.57% as shown in Table 6.1. This removal efficiency coincides with results were obtained by experimental test conducted by El-Agroudy (1999) for Water Hyacinth during 72 hours. Within this period the removal rate coefficient (k) for the overall system is calculated, for the 97.57% removal efficiency, to be 0.05 h^{-1}.

Table 6.1 shows the results obtained using FDSS-Fuzzy Flou software for mercury removal by plants and soils in constructed wetland system. The initial mercury concentration was 7×10^{-7} mol/L. This value was applied into FDSS-Fuzzy Flou upon previously mentioned conditions in order to obtain the amount of mercury uptaken by plants and amount of mercury sorbed onto sediments. The net remaining mercury in the water can then be calculated for the first stage-step (cell) in the plug flow system. The net mercury calculated will be the initial mercury concentration in the second stage-step in the plug flow. This process continues in this trend till the efficiency of the system reaches the value of recommended level.

Table 6.1: Mercury removal by plants and soil in constructed wetland system during 72 hours (Application of FDSS-Fuzzy Flou software)

Stage -Step	*Mercury removed by plants (mol/L)*	*Mercury removed by soils (mol/L)*	*Net mercury remaining in solution (mol/L)*
1	2.38×10^{-7}	3.7×10^{-9}	4.6×10^{-7}
2	2.1×10^{-7}	2.6×10^{-9}	2.47×10^{-7}
3	1.56×10^{-7}	1.65×10^{-9}	8.93×10^{-8}
4	7.19×10^{-8}	1×10^{-10}	1.7×10^{-8}

The results in Figure 6.1 shows plug flow-like behavior; as a result the following model determines the required detention time to remove mercury in the system:

$$C_e = C_o\, e^{-kt} \tag{6.1}$$

where (C_e) is the effluent concentration of mercury, (C_o) is the initial mercury concentration, (k) is the removal rate coefficient (calculated as 0.05 $h^{-1}$from Table 6.1), and (t) is detention time in hours.

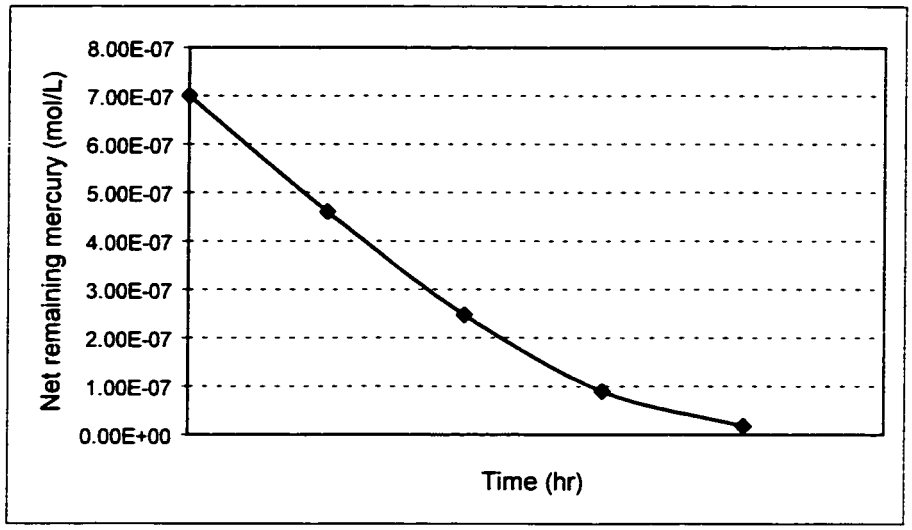

Figure 6.1: The net of mercury remaining in solution during the time for first 72 hours of wetland system (plot of the data shown in Table 6.1)

In this work, the most efficient mercury removal is correlated with the initial mercury discharge of 7×10^{-7} mol/L, consequently, the detention time to achieve certain level of mercury removal can be calculated using equation (6.1). For certain wastewater flow rate, herein the wetland geometry can be estimated (Q = V/t). Table 6.2 shows an example of the suggested design of the constructed wetland for the following conditions: i) the initial mercury concentration (C_o) equals 7×10^{-7} mol/L; ii) the Cl^- concentration equals 1×10^{-8} mol/L; iii) the pH equals 6.5; iv) surface area of soil equals 129 m^2/g; v) the sediment concentration equals 10 g/L, where the removal rate coefficient k = 0.05 h^{-1} and the effluent concentration (C_e) was chosen as 5×10^{-10} mol/L according to Canadian standards for mercury in ground water. The results shown in Table 6.2 satisfy 99% removal efficiency.

Table 6.2: Design application of constructed wetland parameter according to the scenario suggested in this chapter (see the text for details).

Design parameter	Unit	Value
Cl^- concentration	mol/L	1×10^{-8}
pH value		6.5
Initial mercury concentration	mol/L	7×10^{-7}
Effluent mercury concentration	mol/L	5×10^{-10}
Rate coeff.	h^{-1}	0.05
Removal efficiency	%	99
Soil surface area	m^2/g	129
Sediment concentration	g/L	10
Detention time	day	6
Discharge flow rate	m^3/d	957 *
Water depth	m	0.5 *
Wetland area	m^2	11484

* The value of the parameter is set as in general wetland systems.

The previous analyses show removal performance of wetland; however, this performance may be depreciated with time due to the capacity of the wetland system. Figure 6.2 shows the performance efficiency of constructed wetland during time.

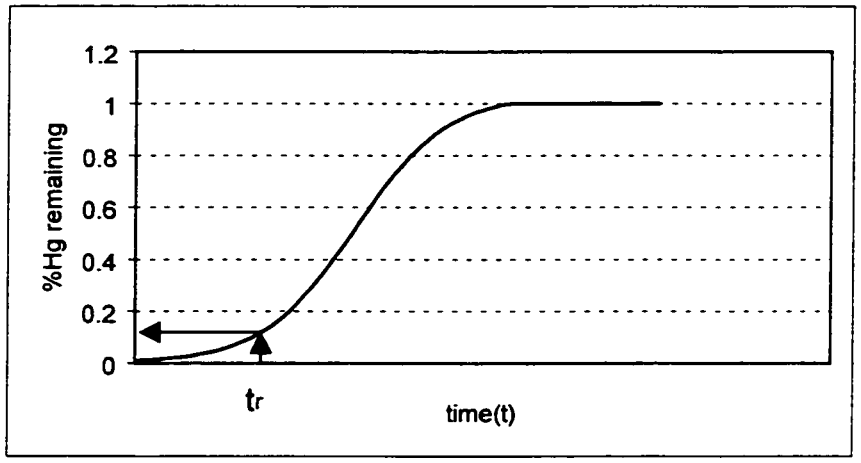

Figure 6.2: The removal efficiency in constructed wetland system during the time, and the idea of break through point after which regeneration is needed.

As shown in Figure 6.2, after certain time (t_r) the wetland system components become inefficient to remove mercury, because both plants and sediments in the wetland system have limited capacity to take mercury. The following model, a modification for Thomas expression for adsorption column (Reynolds, 1982), is modified to best represent the track behavior and the system capacity shown in Figure 6.2:

$$\frac{C_o}{C} = e^{-kt\left(\frac{M_c}{M_s} - \bar{q}_c\right)} \qquad (6.2)$$

where:

C_o: influent mercury concentration (mol/L);

C: effluent mercury concentration (mol/L);

k: rate constant of the overall wetland system (h^{-1});

t: time of service (hour);

$\bar{q}_c$: weighted average of the capacity of the wetland system (capacity of sorbing materials to take mercury) (μg/g);

M_c: mass of contaminant in the wastewater (g);

M_s: mass of sorbing material (sediments and plants)(g).

This model performs as a monitoring tool to the effluent concentration and its compliance to the standards. After the time that the efficiency declined below the demanded levels (e.g. removal efficiency < 80%) the regeneration of wetland constituents is needed, so the harvesting of Water Hyacinth and the replacement of bottom sediments should be installed.

CONCLUSION

The analyses conducted in this chapter show comprehensive design for the wetland parameters. The results obtained show compliance to the regulatory levels; as well the efficient removal of mercury to satisfy the required standards is achieved. The mathematical analyses conducted are well describing the constructed wetland performance and behavior in different stages with time. The mathematical modeling provides the required scenario for wetland performance and capacity. The results in this chapter provide more details to the mercury removal track within the constructed wetland system and provide sufficient information for wetland design parameters, dimensions, and the required time for efficient removal.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

This research shows that the application of artificial intelligence approach is an efficient method for estimating wetland parameters. This approach serves as an information system that estimates the behavior of constructed wetlands in removing mercury. The decision support system involved in this approach gives the required results for wetland performance in different conditions, by which the decision-maker is able to manipulate wetland parameters, and he is able to perform an efficient design. The results obtained in this research show that this approach fulfills the requirement of constructed wetland design as this approach overcomes the problems associated with the hazy behavior of constructed wetlands.

The conclusion of this research can be summarized in the following points:

1- This research is the first work that conducts the artificial intelligence approach (Fuzzy Logic approach) to natural environmental ecosystems;

2- The artificial intelligence approach was used to assess the best conditions required for constructed wetland served as a sink of metal removal;

3- Fuzzy logic analysis showed efficient ability for estimating bioavailable mercury concentration under various parameters within the constructed wetlands;

4- The Fuzzy Decision Support System assessed variable conditions that can be found in the wetland system, and resulted in an excellent prediction of mercury speciation in

wetland water within the combination of different values of the initial mercury concentration, the Cl^- concentration, and the pH value;

5- The optimal wetland conditions have been estimated for the most efficient mercury removal by plants, i.e., The highest bioavailable mercury concentration for Water Hyacinth uptake can be achieved by maintaining the following conditions: the initial total mercury concentration should be in the range of 1×10^{-4} to 1×10^{-3} mol/L; Cl^- concentration should be in the range of 1×10^{-8} to 1×10^{-6} mol/L; and pH values should be in the range of 5.36 to 6.5;

6- Fuzzy logic analysis showed comprehensive information for the mercury adsorbed onto sediments under overlapping and uncertain conditions of constructed wetlands;

7- Fuzzy decision support system assessed variable combination of initial mercury concentration, specific surface area, pH value, and adsorbent concentration, and was able to find out the optimal wetland conditions that satisfy more adsorption of mercury onto soil/sediments;

8- Fuzzy decision support system used both manual constructed fuzzy knowledge bases and genetically generated fuzzy knowledge bases to assess variable combination of soil parameters in the wetland system;

9- Both FDSS and FDSS-GA provide corresponding and sufficient information on wetland parameters to conduct efficient design;

10- The results obtained by the artificial intelligence approach on soil and plant were used to conduct comprehensive wetland design;

11- The wetland design obtained by the artificial intelligence approach showed efficient buffering of mercury and compliance to the regulatory levels;

12- The pH of the wetland system is the problem of its performance; since at high pH, the soil adsorption process represents best function, on the other hand at low pH, the plant uptake process represents best function, so the pH arrangement to both cases in the wetland system is needed;

13- The mathematical analyses conducted on wetland design are well describing the constructed wetland performance in different stages with time;

14- The mathematical modeling describes the wetland removal efficiency and capacity during the time;

15- The work done on wetland design provides more flexibility to the mercury removal within the constructed wetland system and supports with sufficient information of the wetland design parameters, dimensions, and time required for efficient removal;

The success of the artificial intelligence approach in this research will lead to expanded involvement of the approach concept for the future research. The recommendations to the further work can be summarized in the following points:

- Further experimental tests can be conducted to the overall wetland system for several conditions to support the results and conclusion obtained in this work;
- The artificial intelligence approach can be directly conducted to the overall wetland system to find out the optimal design configuration;
- Technical information system (similar to one conducted in Inland Water Institute, NRC, Winnipeg, Manitoba) can be installed overall the constructed wetland in order to collect information for the conditions of the wetland components. As a link between design and natural conditions, the data collected could be used as an input

feed to the FDSS-GA that automatically provides design decision whenever the conditions vary;

- Due to the problem mentioned in conclusion No. 12, varying pH into two stages could satisfy the contradictory impact of pH for both cases, where each stage satisfies one of the wetland components;
- In the more hazy cases where more than one pollutant and plenty of parameters are existed, such complicated systems can be managed by the application of the artificial intelligence approach;

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APPENDIX A : Knowledge Bases

A.1 Bioavailable Mercury Speciation: Settings, Premises, Conclusions, and Rules

[Settings]

inference_type=SUM.PROD.

defuzz_mode=COA

Aggregation=MIN

Propagation=MIN

Fusion=MAX

TNorm=MIN

Cert_Treshold=0.00

[ScreenLayout]

TitleFont=Arial,10,0,0

AxisFont=Arial,10,0,0

SubTitleFont=Arial,10,0,0

LegendFont=Arial,10,0,0

[Premise 1]

name=Cl conc(1E-8)

1=0.000000;100.000000;0.000000;900.000000;1.000000;little

2=10000.000000;10000.000000;9000.000000;0.000000;1.000000;high

3=1000.000000;1000.000000;900.000000;9000.000000;1.000000;med.

[Premise 2]

name=Hgi(E-7)

1=0.250000;0.500000;0.000000;5.000000;1.000000;low

2=2.500000;10.000000;2.200000;10.000000;1.000000;med

3=100.000000;10000.000000;90.000000;0.000000;1.000000;high

[Premise 3]

name=pH

1=5.360000;5.360000;0.000000;1.140000;1.000000;low

2=8.000000;8.000000;1.50000;0.000000;1.000000;high

3=6.500000;6.500000;1.140000;1.500000;1.000000;med

[Conclusion 1]

name=bioavailable Hg++[1E-11]

1=50.000000;50.000000;500.000000;500.000000;1.000000;1

2=100.000000;100.000000;500.000000;500.000000;1.000000;2

3=2500.000000;2500.000000;500.000000;500.000000;1.000000;

4=5000.000000;5000.000000;500.000000;500.000000;1.000000;3

5=25000.000000;25000.000000;500.000000;500.000000;1.000000;

6=50000.000000;50000.000000;500.000000;500.000000;1.000000;

7=75000.000000;75000.000000;500.000000;500.000000;1.000000;4

8=100000.000000;100000.000000;500.000000;500.000000;1.000000;5

9=700000.000000;700000.000000;500.000000;500.000000;1.000000;6

[Rules]

1=1;1;1;3;0.00

2=1;1;2;2;0.00

3=1;1;3;3;0.00

4=1;2;1;6;0.00

5=1;2;2;4;0.00

6=1;2;3;5;0.00

7=1;3;1;9;0.00

8=1;3;2;5;0.00

9=1;3;3;9;0.00

10=2;1;1;2;0.00

11=2;1;2;1;0.00

12=2;1;3;2;0.00

13=2;2;1;3;0.00

14=2;2;2;2;0.00

15=2;2;3;4;0.00

16=2;3;1;6;0.00

17=2;3;2;6;0.00

18=2;3;3;6;0.00

19=3;1;1;3;0.00

20=3;1;2;2;0.00

21=3;1;3;2;0.00

22=3;2;1;5;0.00

23=3;2;2;3;0.00

24=3;2;3;4;0.00

25=3;3;1;8;0.00

26=3;3;2;7;0.00

27=3;3;3;8;0.00

A.2 Mercury Sorption to Wetland Sediments: Settings, Premises, Conclusions, and Rules

[Settings]

inference_type=SUM.PROD.

defuzz_mode=COA

Aggregation=MIN

Propagation=MIN

Fusion=MAX

TNorm=MIN

Cert_Treshold=0.00

[ScreenLayout]

TitleFont=Arial,10,0,0

AxisFont=Arial,10,0,0

SubTitleFont=Arial,10,0,0

LegendFont=Arial,10,0,0

[Premise 1]

name=specific surface area (m2/g)

1=0.000000;80.000000;0.000000;60.000000;1.000000;low.

2=129.000000;400.000000;49.000000;600.000000;1.000000;med

3=1000.000000;1350.000000;600.000000;0.000000;1.000000;high

[Premise 2]

name=Hg concentration (moles)(E-7)

1=1.000000;1.000000;0.000000;9.000000;1.000000;1

2=10.000000;10.000000;9.000000;90.000000;1.000000;2

3=100.000000;100.000000;90.000000;900.000000;1.000000;3

4=1000.000000;1000.000000;900.000000;9000.000000;1.000000;4

5=10000.000000;10000.000000;9000.000000;0.000000;1.000000;5

[Premise 3]

name=pH

1=5.360000;5.360000;0.000000;1.140000;1.000000;low

2=8.000000;8.000000;1.500000;0.000000;1.000000;high

3=6.500000;6.500000;1.140000;1.500000;1.000000;med

[Premise 4]

name=adsorbent concentration (g/l)

1=0.001000;1.000000;0.000000;7.174000;1.000000;low

2=8.174000;8.174000;7.174000;1.826000;1.000000;mid

3=10.000000;10.000000;1.826000;0.000000;1.000000;high

[Conclusion 1]

name=concentration of adsorption sites (moles)(1E-10)

1=1.000000;1.000000;50.000000;50.000000;1.000000;1

2=5.000000;5.000000;50.000000;50.000000;1.000000;2

3=10.000000;10.000000;50.000000;50.000000;1.000000;3

4=50.000000;50.000000;50.000000;50.000000;1.000000;4

5=100.000000;100.000000;50.000000;50.000000;1.000000;5

6=500.000000;500.000000;50.000000;50.000000;1.000000;6

7=1000.000000;1000.000000;50.000000;50.000000;1.000000;7

8=5000.000000;5000.000000;50.000000;50.000000;1.000000;8

9=10000.000000;10000.000000;50.000000;50.000000;1.000000;9

[Rules]

1=1;1;1;1;1;0.00

2=1;1;1;2;1;0.00

3=1;1;1;3;1;0.00

4=1;1;2;1;5;0.00

5=1;1;2;2;5;0.00

6=1;1;2;3;5;0.00

7=1;1;3;1;3;0.00

8=1;1;3;2;3;0.00

9=1;1;3;3;3;0.00

10=1;2;1;1;2;0.00

11=1;2;1;2;2;0.00

12=1;2;1;3;2;0.00

13=1;2;2;1;6;0.00

14=1;2;2;2;6;0.00

15=1;2;2;3;6;0.00

16=1;2;3;1;4;0.00

17=1;2;3;2;4;0.00

18=1;2;3;3;4;0.00

19=1;3;1;1;3;0.00

20=1;3;1;2;3;0.00

21=1;3;1;3;3;0.00

22=1;3;2;1;7;0.00

23=1;3;2;2;7;0.00

24=1;3;2;3;7;0.00

25=1;3;3;1;5;0.00

26=1;3;3;2;5;0.00

27=1;3;3;3;5;0.00

28=1;4;1;1;4;0.00

29=1;4;1;2;4;0.00

30=1;4;1;3;4;0.00

31=1;4;2;1;8;0.00

32=1;4;2;2;8;0.00

33=1;4;2;3;8;0.00

34=1;4;3;1;6;0.00

35=1;4;3;2;6;0.00

36=1;4;3;3;6;0.00

37=1;5;1;1;5;0.00

38=1;5;1;2;5;0.00

39=1;5;1;3;5;0.00

40=1;5;2;1;9;0.00

41=1;5;2;2;9;0.00

42=1;5;2;3;9;0.00

43=1;5;3;1;7;0.00

44=1;5;3;2;7;0.00

45=1;5;3;3;7;0.00

46=2;1;1;1;1;0.00

47=2;1;1;2;1;0.00

48=2;1;1;3;1;0.00

49=2;1;2;1;5;0.00

50=2;1;2;2;5;0.00

51=2;1;2;3;5;0.00

52=2;1;3;1;3;0.00

53=2;1;3;2;3;0.00

54=2;1;3;3;3;0.00

55=2;2;1;1;2;0.00

56=2;2;1;2;2;0.00

57=2;2;1;3;2;0.00

58=2;2;2;1;6;0.00

59=2;2;2;2;6;0.00

60=2;2;2;3;6;0.00

61=2;2;3;1;4;0.00

62=2;2;3;2;4;0.00

63=2;2;3;3;4;0.00

64=2;3;1;1;3;0.00

65=2;3;1;2;3;0.00

66=2;3;1;3;3;0.00

67=2;3;2;1;7;0.00

68=2;3;2;2;7;0.00

69=2;3;2;3;7;0.00

70=2;3;3;1;5;0.00

71=2;3;3;2;5;0.00

72=2;3;3;3;5;0.00

73=2;4;1;1;4;0.00

74=2;4;1;2;4;0.00

75=2;4;1;3;4;0.00

76=2;4;2;1;8;0.00

77=2;4;2;2;8;0.00

78=2;4;2;3;8;0.00

79=2;4;3;1;6;0.00

80=2;4;3;2;6;0.00

81=2;4;3;3;6;0.00

82=2;5;1;1;5;0.00

83=2;5;1;2;5;0.00

84=2;5;1;3;5;0.00

85=2;5;2;1;9;0.00

86=2;5;2;2;9;0.00

87=2;5;2;3;9;0.00

88=2;5;3;1;7;0.00

89=2;5;3;2;7;0.00

90=2;5;3;3;7;0.00

91=3;1;1;1;1;0.00

92=3;1;1;2;1;0.00

93=3;1;1;3;1;0.00

94=3;1;2;1;5;0.00

95=3;1;2;2;5;0.00

96=3;1;2;3;5;0.00

97=3;1;3;1;3;0.00

98=3;1;3;2;3;0.00

99=3;1;3;3;3;0.00

100=3;2;1;1;2;0.00

101=3;2;1;2;2;0.00

102=3;2;1;3;2;0.00

103=3;2;2;1;6;0.00

104=3;2;2;2;6;0.00

105=3;2;2;3;6;0.00

106=3;2;3;1;4;0.00

107=3;2;3;2;4;0.00

108=3;2;3;3;4;0.00

109=3;3;1;1;3;0.00

110=3;3;1;2;3;0.00

111=3;3;1;3;3;0.00

112=3;3;2;1;7;0.00

113=3;3;2;2;7;0.00

114=3;3;2;3;7;0.00

115=3;3;3;1;5;0.00

116=3;3;3;2;5;0.00

117=3;3;3;3;5;0.00

118=3;4;1;1;4;0.00

119=3;4;1;2;4;0.00

120=3;4;1;3;4;0.00

121=3;4;2;1;8;0.00

122=3;4;2;2;8;0.00

123=3;4;2;3;8;0.00

124=3;4;3;1;6;0.00

125=3;4;3;2;6;0.00

126=3;4;3;3;6;0.00

127=3;5;1;1;5;0.00

128=3;5;1;2;5;0.00

129=3;5;1;3;5;0.00

130=3;5;2;1;9;0.00

131=3;5;2;2;9;0.00

132=3;5;2;3;9;0.00

133=3;5;3;1;7;0.00

134=3;5;3;2;7;0.00

135=3;5;3;3;7;0.00

APPENDIX B: Illustrative Forms

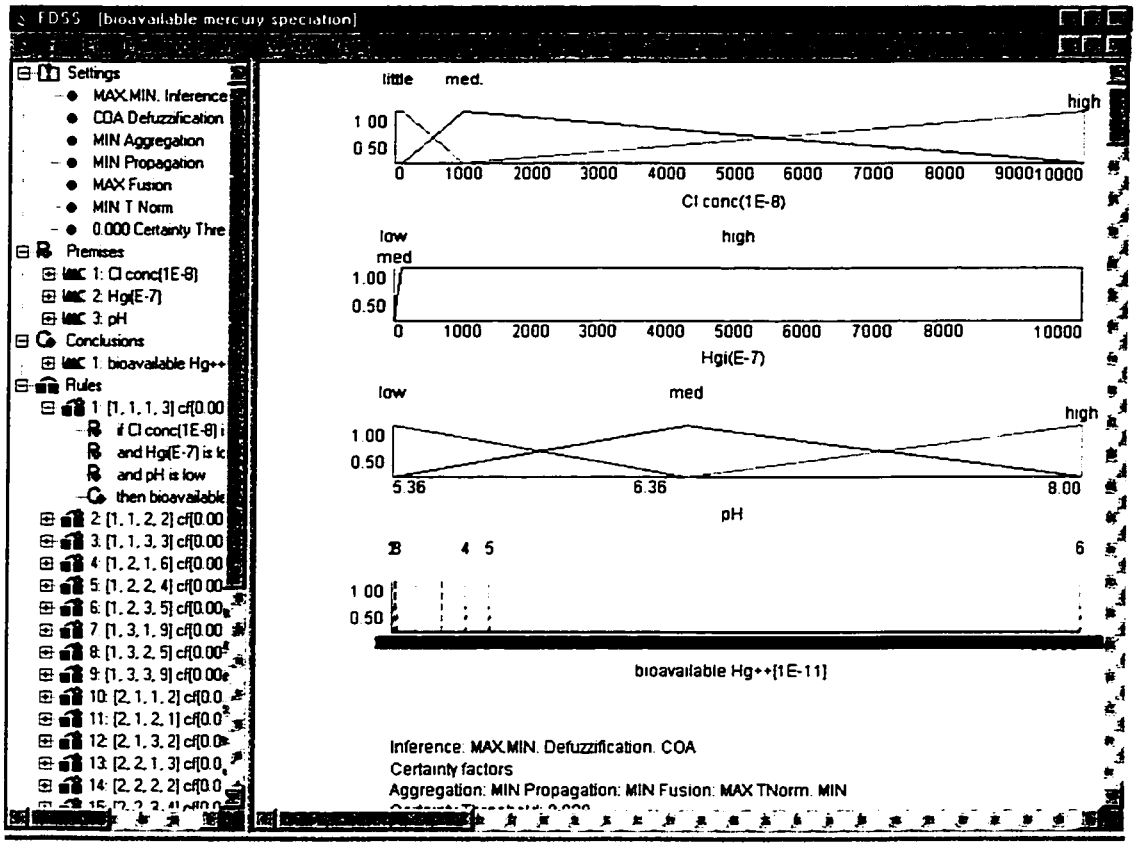

Figure 1: Screen printout of the FDSS Fuzzy-Flou Software window to estimate bioavailable mercury speciation where the settings, premises, conclusions, and rules are appearing in the window.

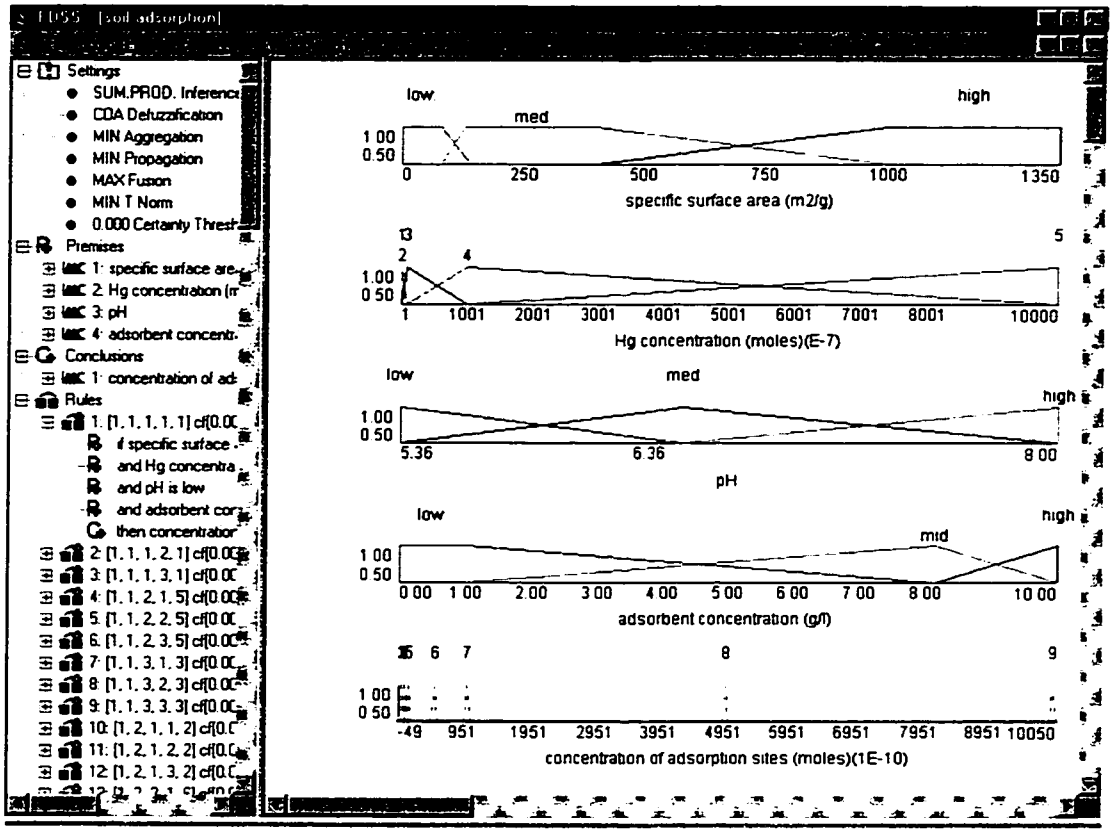

Figure 2: Screen printout of the FDSS Fuzzy-Flou Software window to estimate mercury sorbed onto wetland sediments where the settings, premises, conclusions, and rules are appearing in the window.

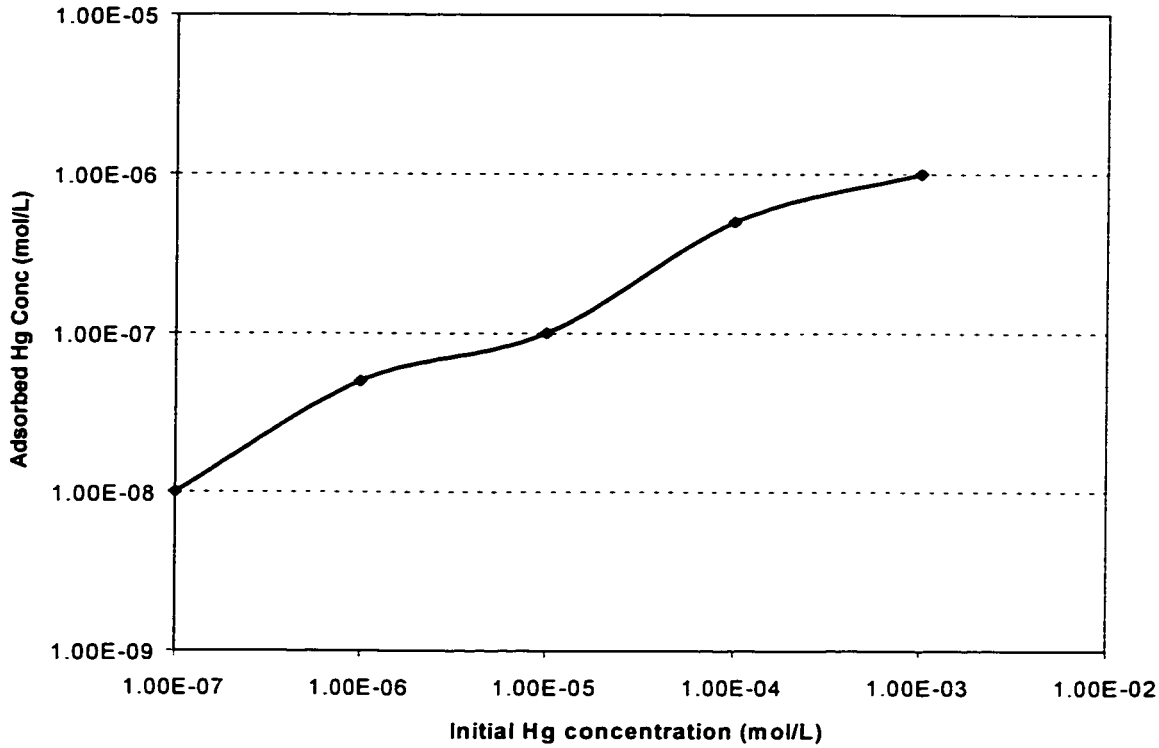

Figure3: Relation between the adsorbed mercury on soils versus the initial mercury concentration in the solution, where pH equals to 8, adsorbent concentration 10 g/l, and specific surface area 129 m^2/g

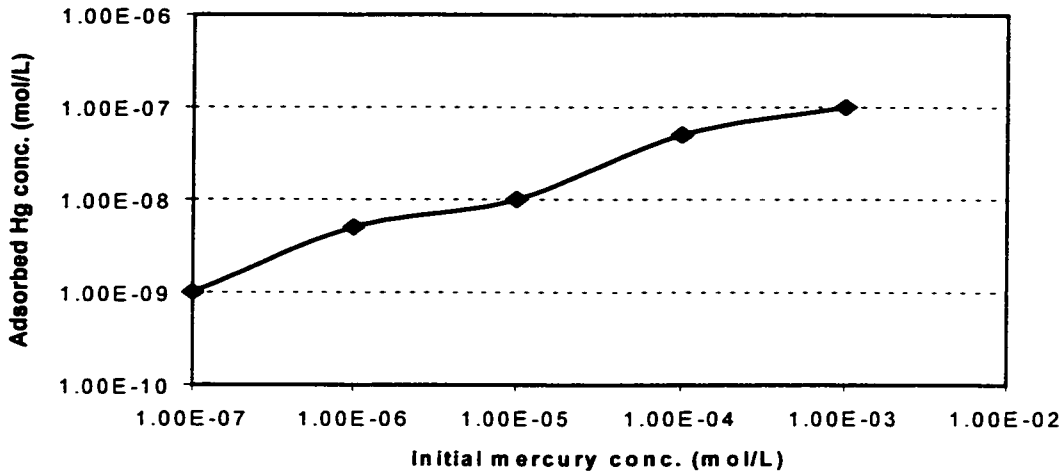

Figure 4: Relation between mercury sorbed on soils versus the initial mercury concentration in solution, where pH = 6.5, the adsorbent concentration = 10 g/l, and the specific surface area = 129 m^2/g

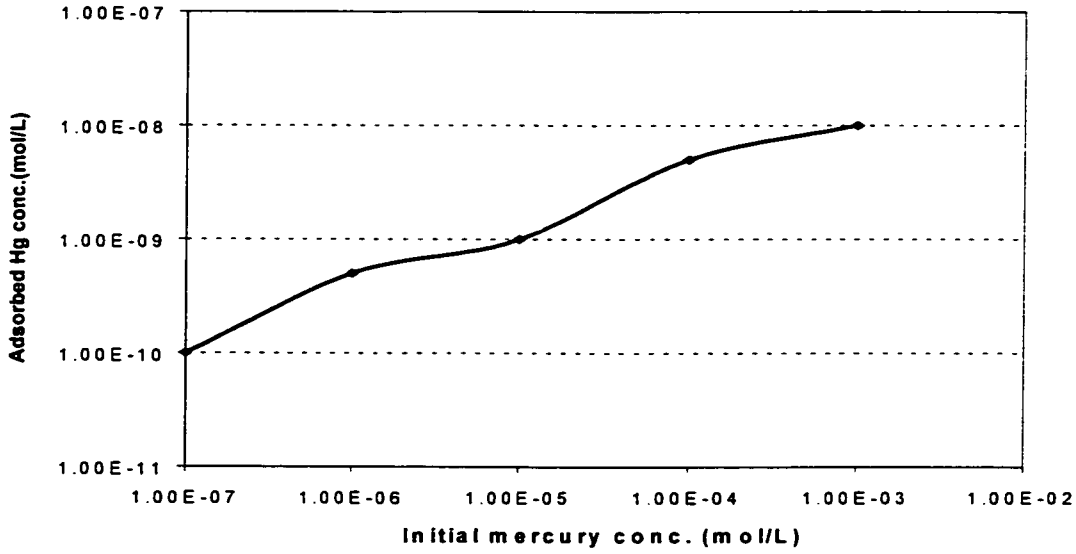

Figure 5: Relation between mercury sorbed on soils versus the initial mercury concentration in solution, where pH = 5.36, the adsorbent concentration = 10 g/l, and the specific surface area = 129 m^2/g

Table1: Premises and conclusions for fuzzy soil performance in constructed wetlands where the adsorbent concentration equals 10 g/l, and soil specific surface area equals 129 m^2/g.

Premise 1 (pH of solution)	Premise 2 (initial mercury concentration- mol/L)	Conclusion (Adsorbed mercury concentration- mol/L)
8	1×10^{-7}	1×10^{-8}
6.5	1×10^{-7}	1×10^{-9}
5.36	1×10^{-7}	1×10^{-10}
8	1×10^{-6}	5×10^{-8}
6.5	1×10^{-6}	5×10^{-9}
5.36	1×10^{-6}	5×10^{-10}
8	1×10^{-5}	1×10^{-7}
6.5	1×10^{-5}	1×10^{-8}
5.36	1×10^{-5}	1×10^{-9}
8	1×10^{-4}	5×10^{-7}
6.5	1×10^{-4}	5×10^{-8}
5.36	1×10^{-4}	5×10^{-9}
8	1×10^{-3}	1×10^{-6}
6.5	1×10^{-3}	1×10^{-7}
5.36	1×10^{-3}	1×10^{-8}

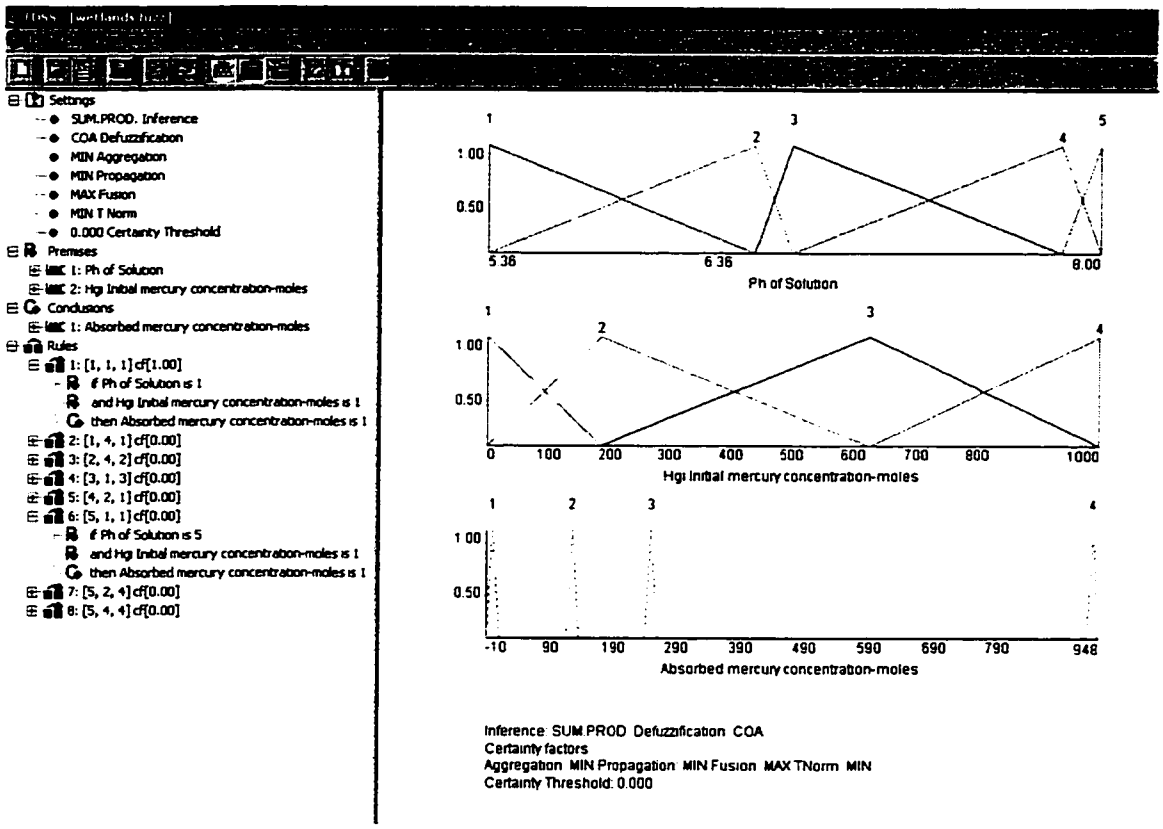

Figure 6: Genetically Generated Fuzzy Knowledge Bases (GGFKB) for soil conditions described in Table 1. These GGFKB are directly being used in FDSS-Fuzzy Flou Software.