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An interval steady-state multimedia aquivalence (ISMA) model of the transport and fate of chloridion in a surface flow constructed wetland system treating oilfield wastewater in China

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ABSTRACT

A surface flow constructed wetland (SFCW) system was built up to treat oilfield wastewater after secondary treatment. Chloridion (Cl^-) in the wastewater was selected as an indicator to investigate the transport and fate of inorganic salts at high levels in the multimedia environments (air, water, soil, flora, and groundwater) by developing an interval steady-state multimedia aquivalence (ISMA) model. The modeled Cl^- profiles were in good agreement with the measured ones, as indicated by the interval average logarithmic residual errors (IALREs) (<0.6 logarithmic units). The modeled results showed that the Cl^- accumulated in the soil (70.80%) and was outputted from the environmental system mainly through periodic collection (34.86%) and advection outflow in groundwater (33.03%). It was also proved from imagery interpretation that the saline soil area was reduced 5.52% after wastewater irrigation, indicating that the tertiary treatment of oilfield wastewater through the constructed wetland was contributed to the local ecological restoration.

1. Introduction

West Jilin Province (WJLP), located in the western Songnen Plain in northern China, is an arid and semi-arid transitional region with special climatic conditions and a unique natural geographical environment. In recent years, due to inner ecological vulnerability, regional ecological and environmental problems such as severe land degradation, soil salinization, and water scarcity have become critical (Wang et al., 2010). The regional wetland loss rate, which is considered the most significant ecological deterioration phenomenon, has reached as high as 82%. Petroleum resources are so abundant in the Jilin oilfield that the total production of crude oil and natural gas in 2011 was more than 7.4 million tons. An abundance of oilfield wastewater is generated by the extracted petroleum due to the high water content (>80%) of Jilin oilfield, and the oilfield wastewater reinjection process may be very expensive. To dispose of the oilfield wastewater and relieve the regional ecological pressure, it has been recommended that after secondary treatment (water–oil separation and filtration), the oilfield wastewater should be reused as a water source to irrigate a reed-bed surface flow constructed wetland (SFCW) (Zhang et al., 2012). However, the mineralization and chloridion (Cl^-) levels in the oilfield wastewater after secondary treatment are still high (12,018 mg/L and 3648 mg/L) compared to the effectiveness of this treatment as measured by chemical oxygen demand (COD), total petroleum hydrocarbon (TPHs), suspended matter (SS). Numerous studies on the constructed wetland treatment of wastewater have reported the degradation effects of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), biochemical oxygen demand (BOD), and hexachlorobenzene (HCB) (Cui et al., 2009; Zhou et al., 2012; Gunes et al., 2012); less research has focused on the transport and fate of Cl^- in the constructed wetland. High levels of inorganic salt ions (such as Cl^-, K^+, Na^+, HCO_3^-) accumulated in the environmental system may become a significant source of secondary salinization in the soil.

The methodology of multimedia fugacity models has proven to be effective in simulating the environmental behaviors of persistent organic pollutants (POPs) in multimedia (Li et al., 2012);

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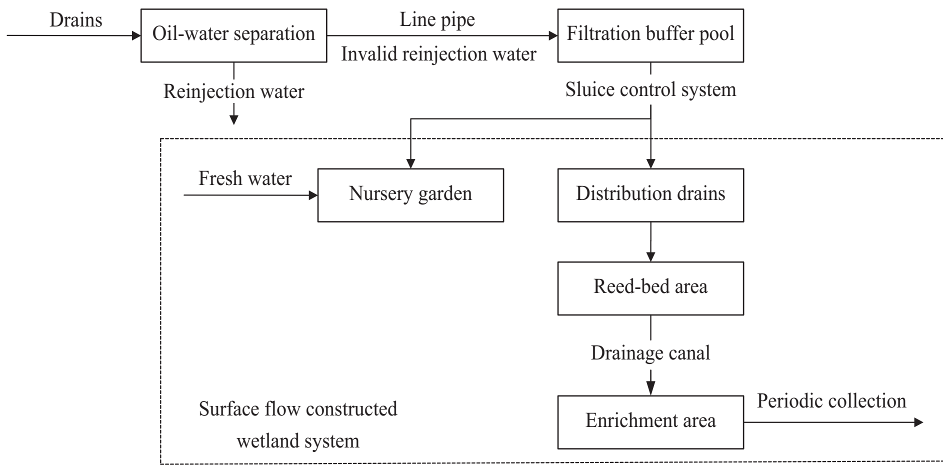

Fig. 1. Major processing craft for oilfield wastewater treatment.

however, this method is not suitable when simulating nonvolatile chemicals. Consequently, the concept of "aquivalence" has been developed as a new equilibrium criterion and applied to the investigation of the multimedia environmental behaviors of heavy metals (Mackay and Diamond, 1989). The multimedia environmental model has not been available to the simulation of the transport and fate of inorganic ions. Also, the large-scale multimedia environmental model has a number of uncertainties that must be analyzed in order to determine the level of variation in the model solution. The traditional method of analyzing model uncertainty is the Monte Carlo simulation, which is limited by the assumption of a distribution function and the generation of a pseudo random number (Fan et al., 2010). In contrast to the Monte Carlo simulation, interval analysis arithmetic can express the range of parameters regardless of the distribution function and contains the possible value without requiring a generated pseudo random number. The chemical concentration always varies in a wide range due to the heterogeneity of the environmental system. Validation with an interval solution can therefore better reflect the consistency between the modeled values and the measured ones.

In this paper, an interval steady-state multimedia aquivalence (ISMA) model is first described and then applied to explore the multimedia environmental behaviors of Cl^- in a SFCW system treating oilfield wastewater. The results enable quantitative evaluation of the adverse impact of high levels of Cl^- in the oilfield wastewater, and should facilitate environmental management practices.

2. Materials and methods

2.1. Surface flow constructed wetland system

The SFCW system and its surrounding area in Jilin oilfield, which is located in the WJLP of China, were selected as the study area. The study area is under the influence of a temperate continental monsoon climate, and the seasonal mean temperatures range from −4.2 °C in winter to 22.1 °C in summer, with a mean annual temperature of 4.9 °C. The annual precipitation (402 mm) is much lower than the evaporation (1220 mm) in the study area, and the average wind speed is 3.0 m/s.

The oilfield wastewater after water–oil separation in combined-station was transferred to a filter system through a waterline; the oilfield wastewater after primary treatment was divided into two parts: reinjection and irrigation. Part of the wastewater was transferred to a desalting filtration buffer pool, and the wastewater after secondary treatment was discharged into the SFCW system for biological treatment. The SFCW system covered 2.00 km^2 and was located in the north of the filtration buffer pool. The SFCW system contained sluice control system, distribution drains (main distribution drains, vice distribution drains, and branched distribution drains), reed-bed area, drainage channels, enrichment area, and nursery garden. The major processing craft is shown in Fig. 1.

2.2. Development of the ISMA model

The fugacity approach has proven to be effective at describing the multimedia environmental behaviors of organic chemicals in a variety of environments; however, it is not applicable for nonvolatile chemicals due to their immeasurable characteristics, such as the partition coefficients of metals, polymers, and ionic compounds. Therefore, the new equilibrium criterion of aquivalence (mol/m^3) has been developed and applied to modify the QWASI model (Mackay and Diamond, 1989; Diamond et al., 1990). As described by Diamond et al. (1990), the linear relationship between fugacity (f) or aquivalence (Q) and concentration (C) is described as

$$C = fZ = QZ \tag{1}$$

The fugacity capacity (Z) for the water compartment (Z_W) is defined as 1.00, and Q for the water compartment (Q_W) is the dissolved concentration (mol/m^3) of the chemical. For a nonvolatile chemical, the fugacity capacity for the air compartment (Z_A) is negligible because the air–water partition coefficient (K_{AW}) is essentially zero. In the aquivalence approach, chemical transfer rates (N) for different environmental processes could also be represented by the multiplication of the transfer rate coefficient (D) and Q with identical units, which could be added and compared when they are applied to processes originating in one compartment.

The traditional steady-state mass balance equation of the fugacity approach in multimedia environments is described as follows:

$$E_i + G_{Ai}c_{Bi} + D_{ji}f_j - (D_{ij} + D_{Ri} + D_{Ai})f_i = 0 \tag{2}$$

in which E_i is the emission rate into compartment i (mol/h), G_{Ai} is the advection inflow rate of compartment i (m^3/h), c_{Bi} is the background inflow concentration of the adjacent region in compartment i (mol/m^3), D_{ij} is the transfer rate coefficient from compartment i to j (mol Pa^{-1} h^{-1}), D_{Ai} and D_{Ri} represent the advection flow rate coefficient and the degradation rate coefficient of compartment i (mol Pa^{-1} h^{-1}), respectively, and f_i is the fugacity of compartment i (Pa).