Development of a Decision Support System for Groundwater Pollution Control at Coal-mining Contaminated Sites

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Abstract

Groundwater contamination is one of the major environmental concerns at coal-mining sites. Highly saline or highly acidic water from coal-mining can introduce serious pollution to groundwater and adversely affect its quality. This impact may last a long time even after the mining activity has ceased. Identification of an appropriate remediation technique is critical for effective pollution control. However, due to complexity of considerations involved in the pollution, it is difficult for environmental managers to select optimal techniques. This paper presents a robust decision support system named GCDSS that integrates the functional components of mine characterization, numerical modeling, risk assessment and remediation-technique selection. The results from a case study indicated this system can help improve efficiencies of groundwater pollution control at coal-mining contaminated sites.

Keywords: decision support system, acid mine drainage, groundwater, coal mine

1. Introduction

Groundwater contamination is one of the major environmental concerns at coal mining sites. Acid mine drainage (AMD) is the primary problem associated with pollution from coal mining. AMD is often highly acidic water rich in heavy metals, which can introduce serious pollution to groundwater and adversely affect its quality. A variety of AMD treatment technologies and groundwater remediation methods were developed. Due to the complexities of these technologies, it is often difficult for environmental managers to make optimal decisions in treating specific sites. Decision support systems (DSS) can assist in solving this problem. Many DSSs have been proposed for managing coal mining operations and groundwater remediation. However, there is a lack of study that combines the functions of mine characterization, numerical modeling, risk assessment and remediation-technique selection within a DSS. The objective of this study is to address this gap in previous researches and develop an integrated decision support system (GCDSS) that supports all these functions for groundwater pollution control at coal-mining contaminated sites.

2. Background: AMD and its treatment

AMD from coal mining is a difficult and costly problem. It can seriously affect groundwater quality and cause metals to leach from mine wastes. AMD results from the oxidation of metal sulfides, particularly pyrite (FeS₂). Under the acidic conditions, oxidation of pyrite occurs in the following reaction [1]:
FeS₂ + 14Fe³⁺ + 8H₂O → 15Fe²⁺ + 2SO₄²⁻ + 16H⁺  \[ (1) \]

This reaction demonstrates the polluting capability of the oxidation of pyrite that every mole of pyrite can be converted to 16 moles of hydrogen and 2 moles of sulfate. Much acid is generated through this reaction.

There are two methods for treating AMD: active treatment and passive treatment. Active treatment involves neutralizing acid-polluted water with alkaline chemicals which include limestone, hydrated lime, caustic soda, soda ash, and ammonia [2]. Active treatment is expensive and requires much time and manpower to maintain. Passive treatment employs naturally occurring chemical and biological reactions and requires little or no maintenance. Passive methods include anoxic drains, limestone rock channels, alkaline recharge of groundwater, and diversion of drainage through man-made wetlands or other settling structures.

3. Development of Decision Support System

3.1 Knowledge Acquisition

Knowledge acquisition is a bottleneck in DSS development and involves the processes of knowledge elicitation, analysis and representation. It is crucial because output of the system is only as good as the input. The main sources of knowledge in this study are the domain experts, the statistical data about coal mining, and documents.

3.2 GCDSS

GCDSS consists of the modules for mine characterization, numerical modeling, risk assessment, and remediation technique selection. It also consists of a graphical user interface which allows the user to input and query the site related data, and shows the recommendations and suggestions for the user. Details on the numerical modeling, risk assessment, and remediation technique selection modules are discussed as follows. The architecture of GCDSS is shown in Figure 1.

Fig. 1. Architecture of GCDSS

3.2.1 Mine Characterization Module

Mine characterization is crucial for the following numerical modeling, risk assessment, and the selection of remediation technologies in GCDSS. This module has the function of providing the necessary data and standards input for the other three modules. A number of factors on mine characterization are discussed in this module, for example:

(1) Types of mining

There are two types of coal mines: surface and underground. Surface mining includes open pit mining, highwall or strip mining, which recovers coal at or close to the earth’s surface. Underground mining extracts coal from under the surface.

(2) Mining wastes

The major wastes from coal mining activities are mining water and waste rock, which are serious long-term sources of groundwater deterioration. Mining water, commonly referred to AMD, is highly acid water rich in heavy metals. Mining water can directly pollute groundwater when mining is below the water table, or indirectly through seepage. Waste rock is often disposed in large dumps. When water (such as rainwater, surface water or mining water) infiltrates through waste dumps into subsurface
water, groundwater quality can be also greatly affected [3].

3.2.2 Numerical Modeling Module

Numerical modeling of groundwater flow and transport requires a number of data inputs on soil hydraulic properties, time integration parameters, initial and boundary conditions, porous media dispersivities, species solubility, and other many parameters. This module implements the general multicomponent transport equation which can be expressed as follows [4].

$$\frac{\partial}{\partial t}(\theta_m C_{wm}) + \frac{\partial}{\partial x}(\theta_m C_{wm} v_m) + \frac{\partial}{\partial t}(\rho P_{wm}) + \frac{\partial}{\partial t}[(1-f)\rho P_{wm}] = \frac{\partial}{\partial x}\left(\theta_m D_{ij} C_{wm,ij} - \frac{\partial}{\partial x}(q_i C_{wm}) - q_i C_{wm}\right)$$

where $\theta_m$ and $\theta_{im}$ are the fractions of the soil filled with mobile and immobile water respectively; $C_{wm}$ and $C_{wim}$ are the concentrations of contaminant w in the mobile and immobile water respectively [ML$^{-3}$]; $q_i$ is the Darcy velocity [LT$^{-1}$]; $P_{wm}$ and $P_{wim}$ are adsorbed phase concentrations of contaminant w in the mobile and immobile phase respectively [MM$^{-1}$]; $f$ is the fraction of sorption sites which is in direct contact with mobile liquid; $\rho$ is soil bulk density [ML$^{-3}$]; $q_s$ is the volumetric flow rate of fluid injection (or withdrawal) per unit volume of the porous medium [L$^3$T$^{-1}$]; $C_{ws}$ is the concentration of contaminant w in the injected fluid [ML$^{-3}$]; and $D_{ij}$ is the hydrodynamic dispersion tensor [L$^2$T$^{-1}$].

3.2.3 Risk Assessment Module

Environmental risk is the probability of injury, disease or death under carcinogen and noncarcinogen circumstances [5]. Assessment of the risk of pollution of groundwater includes: simulation for the fate and transport of contaminants in groundwater, assessment of leaching from waste products or polluted soil, analysis of toxicological effects on health and environment, and exposure assessment. Two methods for risk assessment were recommended by USEPA (1992) [6]: excess lifetime cancer risk (ELCR) for cancer-driven pollutants, and hazard quotient (HQ) for noncancer-driven pollutants.

(1) Excess Lifetime Cancer Risk (ELCR)

ELCR is estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. It may be expressed as follows:

$$\text{ELCR} = \text{CDI} \times \text{SF}$$

where CDI is chronic daily intake (mg/kg·day), SF is the slope factor which is a maximum estimate of the probability of an individual developing cancer over a lifetime of exposure to a particular level of a potential carcinogen. In this study, CDI may be obtained from the equation (4), based on the concentration of contaminant w in groundwater [7].

$$\text{CDI} = \text{CW} \times \text{IR} \times \text{EF} \times \text{ED} / (\text{A.T} \times \text{BW})$$

where CW is the concentration of contaminant w in groundwater (mg/L), IR is human ingestion rate (L/day), EF is exposure frequency (days/year), ED is average exposure duration (year), AT is average time (AT = 365 × days/year × ED), and BW is body weight (kg). In this study, the values for these parameters for an adult may be: IR = 2 L/day, EF = 350 days/year, ED = 70 years (lifetime), AT = 365 × days/year × 70 years, BW = 70 kg.

(2) Hazard Quotient (HQ)

HQ is used to describe the potential for noncarcinogenic toxicity, and may be expressed as follows:

$$\text{HQ} = \text{CDI} / \text{RfD}$$

where RfD is reference dose (mg/kg • day). The greater the value of HQ, the greater the level of concern. For example, the value 0.05 of HQ indicates that the probability of getting a health injury is 5%. However, the level of concern does not increase linearly as the RfD is approached or exceeded because RfD does not have the same accuracy or precision as the level of concern and is not based on the same severity of toxic effects [7].

3.2.4 Remediation-Technique Selection Module

A number of technologies are available to remediate groundwater contaminated by coal-mining activities. Groundwater remediation methods can be classified into
two classes: in situ and ex situ methods. In situ methods treat polluted groundwater in place, while ex situ methods excavate contaminants and transport them off-site for treatment. The methods for treating AMD may be active and passive. Since it is difficult for the user to select a suitable remediation technique for the specific sites, the decision support system can support the decision making process. The user can input the required data such as site characteristics and the parameters for numerical simulation through the friendly user interface. GCDSS can evaluate various combinations of remediation techniques and AMD treatment methods and identify an optimal strategy for groundwater pollution control at a specific coal-mining site.

4. Conclusions

In this study, an integrated decision support system (GCDSS) is proposed for groundwater pollution control at coal-mining contaminated sites. Through the developed GCDSS, the functions of mine characterization, numerical modeling, risk assessment and remediation-technique selection are effectively integrated. The user can access various resources within this system and obtain support on selection of different remediation technologies.

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