学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Sustainable management of a legacy mine considering long-term contaminant transport
(汚染物質の長期的な移行を考慮した休廃止鉱山の持続可能な管理)

Environmental forensics of legacy mine sites and their profound effects on surface and groundwater resources are vital worldwide. In precious and base metal mineral deposits, sulfide minerals are known as accessory ones and are disposed of as mine wastes, which have become one of the main sources of acid mine drainage (AMD). Even after mine closure, these minerals still have the potential to produce acidic pH and toxic metals, for example, Zn, Cu, and Pb. Therefore, appropriate remediation strategies are required in these mine sites. However, unforeseen underground conditions create complicated prediction of contaminant transport in the subsurface environment. Therefore, the evolution of AMD, the delineation of migration paths, and its future environmental risks are essentially required to evaluate groundwater contamination. To solve this issue, the long-term environmental impacts of anthropogenic mining activities on nearby surface and groundwater resources and the site management were evaluated by selecting a 200-year-old legacy mine in northern Japan. These research findings will give insights into decision-making whether immediate remediation is needed or not, and choosing appropriate AMD remediation methods for sustainable mine management.

Chapter 1 provides an overview of AMD, remediation techniques for AMD, and the primary objectives of this study.

Chapter 2 delineates a selected legacy mine site and its effects on nearby water resources by collecting mine water samples, local spring, and river water resources downstream of the mine site. The resultant hydrogeochemical and physicochemical properties showed that all of the mine water exhibited a typical AMD water facies Ca^{2+}-SO_4^{2-}/ Mg^{2+}-SO_4^{2-} type), and the downstream groundwater showed acidic pH, with high concentrations of Al, Cu, Fe, Pb, and Zn. This infers that the contaminant transport occurs downstream of the mine site. Meanwhile, the spring and river water showed Ca^{2+}-HCO_3^-/ Ca^{2+}-SO_4^{2-} types, and Ca^{2+}-HCO_3^- or Na^+-K^+-HCO_3^-, with neutral to alkaline pH, and that the dissolved concentrations of Zn, Cu, and Pb are within the national effluent standard, implying no influence from AMD. The multivariate analysis, PCA, and dendrogram could effectively assist in differentiating the AMD-contaminated areas or not. After delineating the AMD-affected area, the evolution of downstream groundwater contamination from the mine site was evaluated in detail.

Chapter 3 evaluates the primary sources of AMD (tailing dam, sedimentation impoundment, and mine adit) and their influence on the evolution of downstream soil and groundwater contamination by collecting additional surface water and groundwater samples and drilled core samples along groundwater flow. According to the results, a 200-year-old tailing dam was also one of the main sources of AMD. In addition, the percolation of deeper groundwater from the mine adit exhibited more pronounced acidification. Similarly, the core samples in the unsaturated zone also exhibited the presence of sulfide minerals, and the oxidizing conditions have led to additional anthropogenic input to the downstream. However, a gradual decrease in extractable phases and leaching concentrations of toxic metals in the core samples was observed, which implies the retention of the toxic metals and the possibility of natural attenuation.

In Chapter 4, based on the mine's historical hydrochronology, time series plume migration, and its future environmental risks to the downstream river were estimated using conservative groundwater flow tracer (^{3}H),along with the calculated distribution coefficient and retardation factor. The upstream tailing dam and mine adit had younger groundwater ages, and the groundwater downstream became older even if the mixture of younger and older groundwater resources was observed. The frontal plume of Zn approached approximately 500 m downstream (borehole D), while Cu and Pb were relatively slower and reached approximately 313 m downstream (borehole C). The migration of the toxic metals was retarded compared with estimated groundwater flow (16 m/year) by ^{3}H analysis. Based on the calculated migration rates, the time required to reach a nearby river was also evaluated. Then, two types of AMD remediation strategies, such as constructing permeable reactive barrier (PRBs), and natural attenuation in the downstream aquifer were proposed.

Chapter 5 summarizes the main findings of this research and the implications for sustainable long-term AMD management.