Investigation of sustainable resource management of Jiaoxi hot spring by using hydro-thermal numerical simulation in a heterogeneous hydrogeological model

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Abstract

Jiaoxi, with its unique flatland sodium bicarbonate hot springs, attracts visitors from all over Taiwan during the holidays. This study aims to evaluate the suitable usage of hot spring by integrating the hydro-thermal numerical simulation in a heterogeneous hydrogeological model (HHM). We used the Groundwater Modeling System (GMS) and employed geological statistical methods to analyze the spatial distribution of materials. The outcomes were fed into the TPROGS to generate dozens of HHMs using the Markov chain, combined with two homogeneous bedrocks to form 3D geological models. Under the proper hydrological conditions, groundwater level simulation results for various geological models were statistically analyzed to identify a typical one. Then, the geological model was converted into a numerical groundwater flow model (MODFLOW) and combined with a solute transport model (MT3DMS) for hydro-thermal simulations to obtain the distribution of groundwater head and temperature.

Model 21, chosen from 30 3D geological models, was deemed representative based on the highest coefficient of determination and smallest mean absolute error. Calibration of the steady-state groundwater flow model revealed a strong agreement (R^2=0.9) between simulated and observed data in the sedimentary layer, confirming the model's representativeness. Thermal transport simulation showed that the temperature distribution of groundwater in bedrock is similar to that of observation. Subsequent evaluations, considering water quantity and temperature, will determine the suitable pumping rates for guiding sustainable management of hot spring resources in study area.

Keywords: Jiaoxi Hot Spring, Groundwater management, Markov chain, Heterogeneous hydrogeological model, Groundwater flow simulation, Heat transport simulation.

以水-熱模式結合異質性地質模型探討礁溪溫泉水資源管理

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摘要

礁溪，有著台灣少見的平地碳酸氫鈉溫泉，一到假日總是吸引各地的遊客爭相到訪。隨著遊客人數的成長，溫泉使用量亦隨之提升。本研究透過建立礁溪地區三維異質性地質模型，並結合地下水流模式和熱傳輸模擬，以評估適當的溫泉使用量使其達到永續利用。本研究首先蒐集不同來源的地質鑽探資料，以及 2020 年間監測井水位及水溫資料等水文觀測數據。接著，運用地下水模擬系統(Groundwater Modeling System, GMS)，先以地質統計方法分析水文地質材料的空間分布，再將結果輸入 TPROGS 套件，以馬可夫鏈法(Markov chain)產製數十個異質性水文地質模型，並結合底部均質性基盤成為三維地質模型。在假設水文條件下，針對不同地質模型模擬的地下水位，利用統計方法選定一礁溪地區代表水文地質模型。隨後，再將其轉換為 MODFLOW 地下水流數值模型，並結合 MT3DMS 套件進行水-熱模擬，以獲取地下水流場和溫度場的分布情況。

研究結果顯示，水文地質材料在東北-西南方向上有最大連續性，與沉積粒徑分布一致。本研究於 30 個三維地質模型中，以決定係數(R-squared)最高及平均絕對誤差(Mean absolute error)最小的統計特性，挑選模型 21 為代表地質模型。將抽水量及降雨量等水文觀測數據輸入代表模型中，並將其轉換為地下水流與溫度傳輸數值模式。穩態地下水流模式率定顯示，沉積層模擬水位與實際觀測水位相當一致(R^2=0.9)，顯示地下水流模式具有一定的代表性。熱傳輸模擬結果顯示，礁溪溫泉區內基盤溫度場的空間分布與目前溫度觀測相似。後續將考量水量與水溫情況下，評估研究區合適抽水量，以提供研究區未來的溫泉水資源管理參考，達到溫泉資源的永續發展。

關鍵字： 礁溪溫泉、水資源管理、馬可夫鏈法、異質性水文地質模型、地下水流模擬、溫度傳輸模擬。