Quantifying Groundwater Exchange Mechanisms and Tunnel Drainage Impacts in a Regional Karst Aquifer : A Coupled GemPy and MODFLOW-CFPv2 Approach

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1. Introduction

To systematically study how tunnel drainage affects water exchange in karst aquifers, this research uses a typical karst tunnel in Guizhou Province as a case study. The main goals are: (1) to build a MODFLOW-CFPv2 model dynamically coupling tunnel excavation and drainage; (2) to quantitatively reveal the spatiotemporal evolution of the groundwater flow field and matrix-conduit water exchange under tunnel dewatering; and (3) to quantitatively predict water inflow and groundwater level dynamics during construction, providing a scientific basis for tunnel water hazard prevention and regional water environment management.

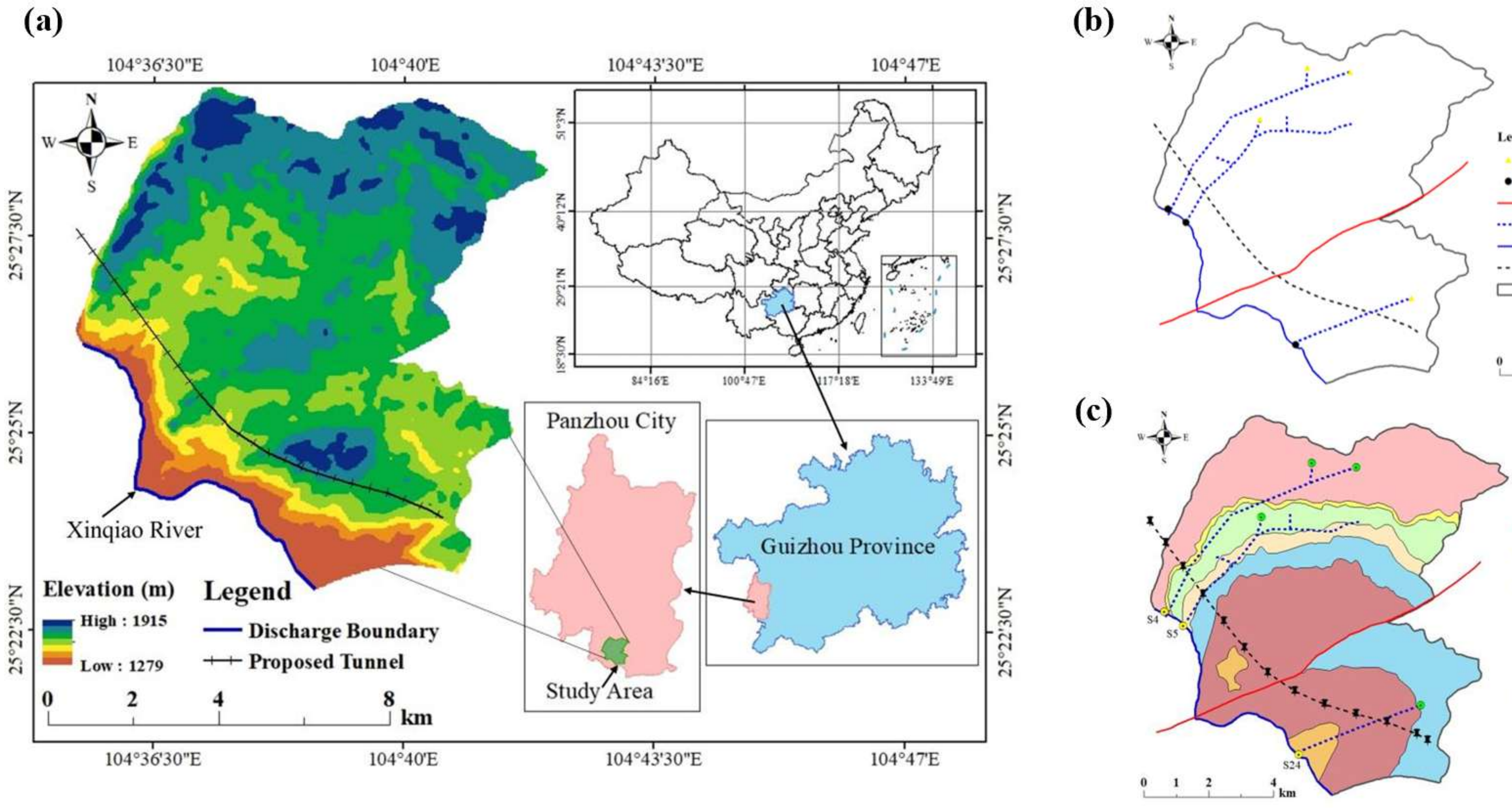

Fig. 1 Overview of the study area: (a) Location and digital elevation model of the study area; (b) Boundary conditions of the study area; (c) Hydrogeological map.

2. Methods

This study develops a MODFLOW-CFPv2 model for karst groundwater simulation. The domain (~138.38 km²) uses a 121×113×20 grid (100 m cells) with 117,778 active cells. Parameters from pumping tests, lithology, and tracer tests were optimized via PEST (calibration r=0.98; validation r=0.89). Tunnel construction (Jan 2024–Apr 2025) spans 16 stress periods with dynamically activated cells. Two drainage modes are simulated: primary (short-term, high-flow upon excavation exposure) and secondary (long-term, reduced permeability by one order of magnitude post-support). The Flopy interface dynamically updates drainage parameters for coupled spatiotemporal simulation.

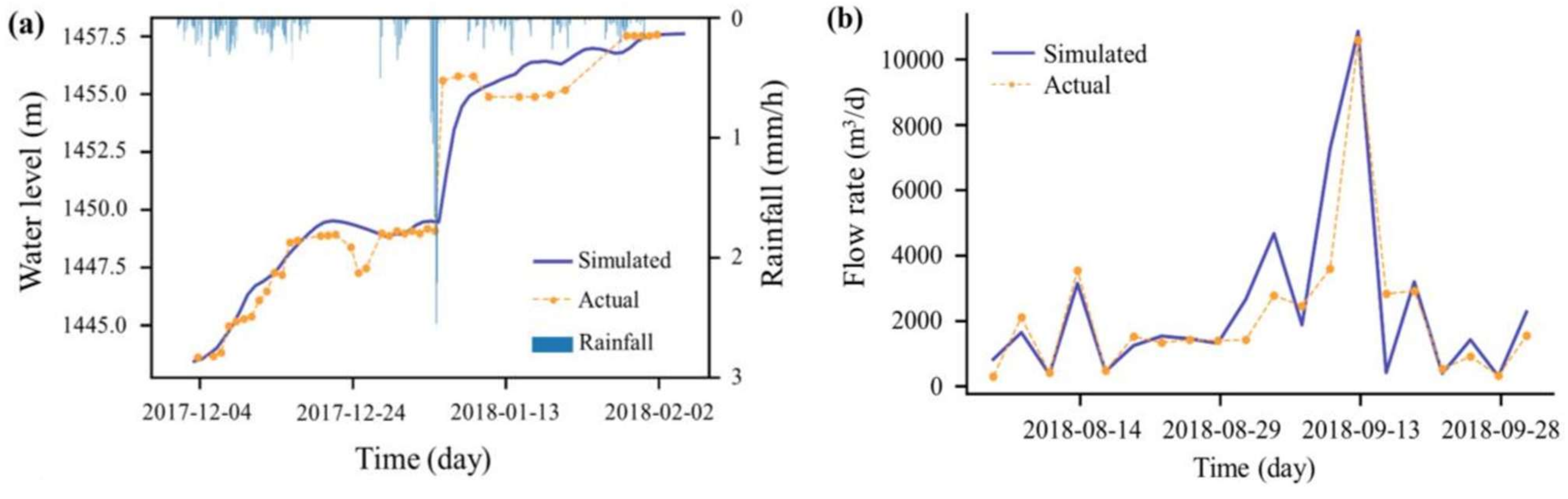

Fig. 2 Calibration and validation results: (a) Borehole water level fit; (b) Spring discharge validation

3. Resullts and discussion

3.1 The effect of tunnel engineering drainage on water exchange direction

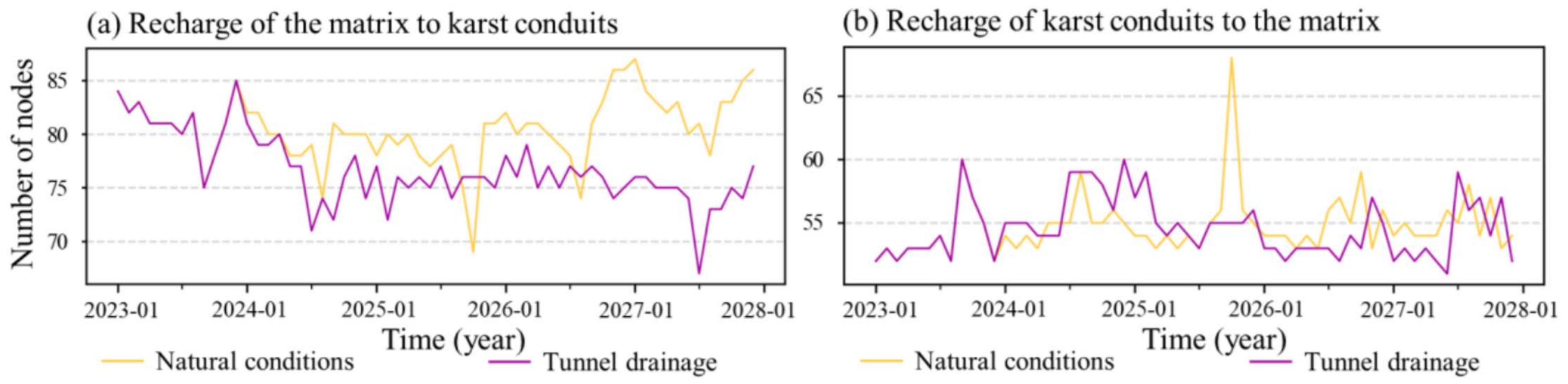

Fig. 3 Comparison of active water exchange nodes under natural and tunnel drainage conditions: (a) Matrix-to-conduit recharge; (b) Conduit-to-matrix recharge

3.2 The impact of tunnel engineering drainage on water exchange volume

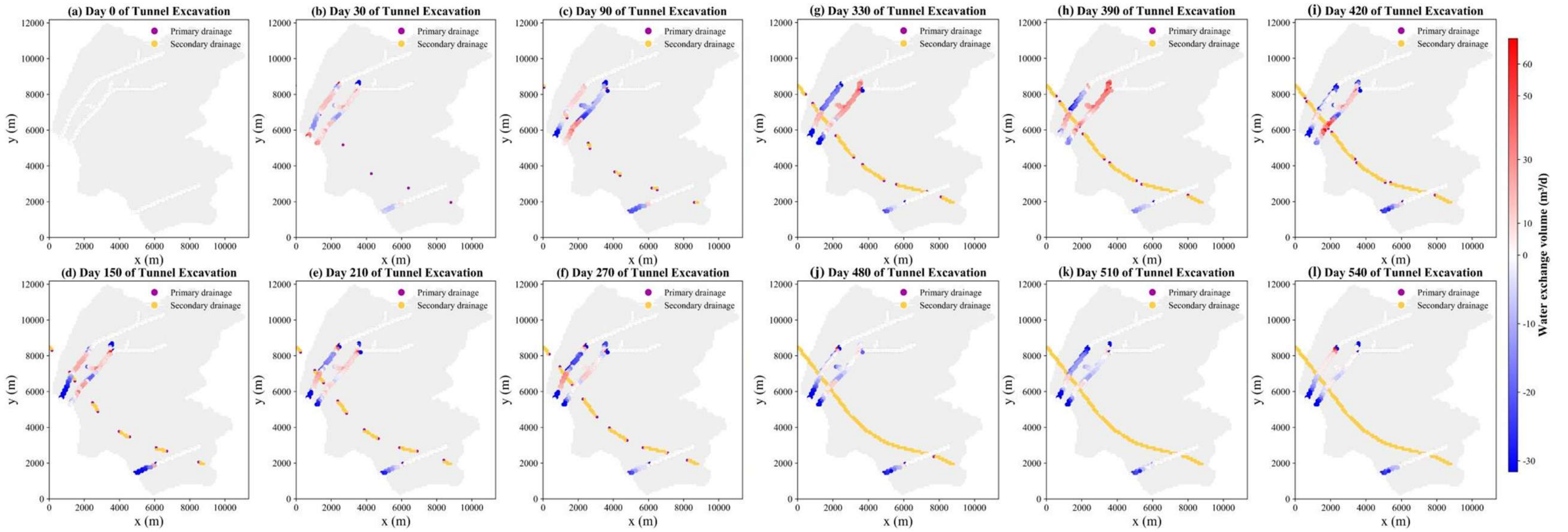

Fig. 4 Temporal evolution of water exchange volume during tunnel drainage (0–540 days).

3.3 Tunnel drainage volume prediction and groundwater level response

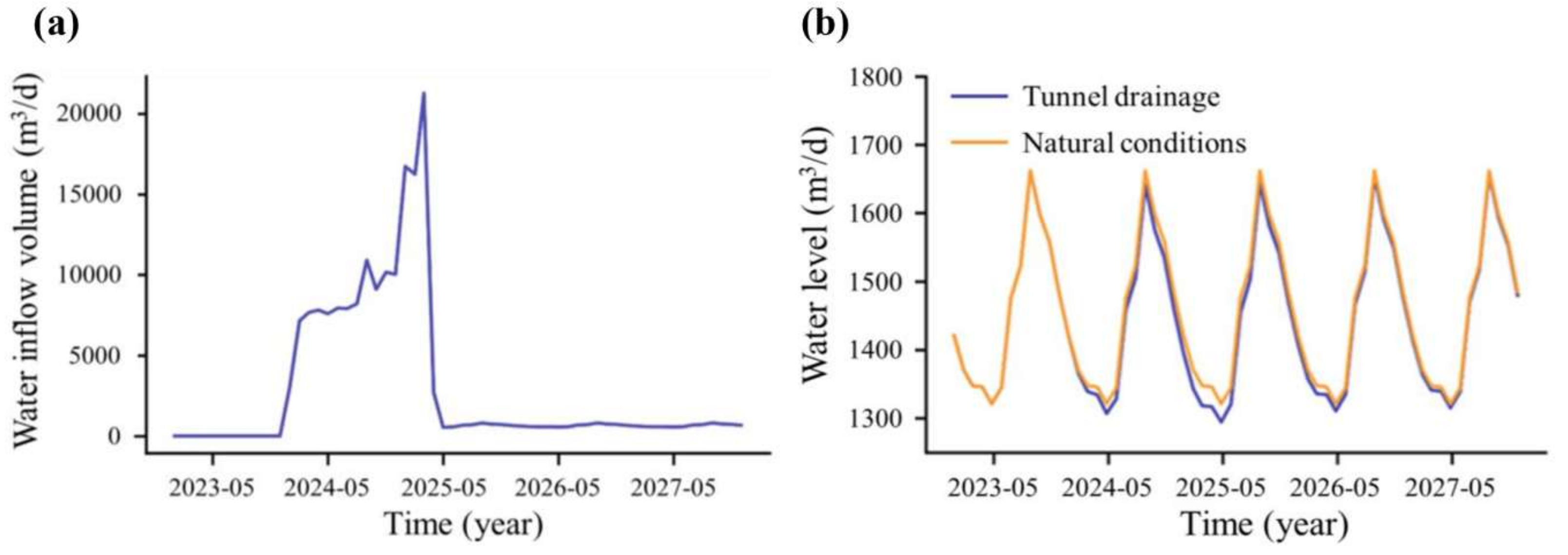

Fig. 5 (a) Predicted tunnel inflow volumes during and after construction; (b) Groundwater level variations under natural and tunnel drainage conditions.

4. Conclusions

(1) Flow field reorganization: Tunnel drainage reversed water exchange within 30 days, reaching new equilibrium ~390 days later, with total exchange reduced by ~2,987 m³/d—an irreversible shift leaving water levels 1.5–2.0 m below baseline.

(2) Spatial heterogeneity: Peak inflows exceed 20,000 m³/d at the tunnel-conduit intersection, while the southern aquifer exhibits wider but slower drawdown due to secondary drainage.

(3) Management strategy: High-risk zones require enhanced pre-drainage and grouting; a region-wide long-term monitoring and adaptive management framework is recommended.