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Review papers

A review of the effects of tunnel excavation on the hydrology, ecology, and environment in karst areas: Current status, challenges, and perspectives

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ABSTRACT

Due to a lack of awareness of environmental protection at the beginning of tunnel excavation and the unique ecological vulnerability of karst areas, tunnel excavation is beginning to have increasingly serious negative effects on the ecological environments in karst areas, leading to challenges related to regional water resources and ecological security. The groundwater drawdown caused by tunnel drainage has had far-reaching impacts on the hydrology, ecology and environment in karst areas. The most prominent effects of the recent advances in drainage techniques include the destruction of aquifer structures, changes in the distribution patterns of water resources and the groundwater flow field and even the initiation of geological disasters (i.e., collapses) in karst areas. In addition, karst water circulation and hydrogeochemical processes have also been affected. However, due to the complex geological conditions and limited observational data in karst areas, the impacts of tunnel drainage on ecological systems remain poorly understood. With increased understanding, researchers have found that the physical and chemical properties of the soil, the speed of soil erosion, the physiological processes and growth rates of plants, and even the compositions of plant communities are gradually changing in tunnel-affected karst areas, although the understanding of these processes and mechanisms remains far from sufficient. Based on the progress made regarding the understanding of water resource and hydrological process issues resulting from tunnel excavation in karst areas, we expect to experience a worldwide increase in investigations of the eco-hydrogeological effects of tunnel excavation in the future.

1. Introduction

Karst, a special landscape shaped by carbonate dissolution, covers approximately 20% of the Earth's dry ice-free land, and karst aquifers are at least a partial source of drinking water to almost a quarter of the world's population (Ford and Williams, 2007). Carbonates often occupy landscapes where water shortages are common due to significant seasonal variation in rainfall (Ford and Williams, 2007). Furthermore, karst landscapes are generally characterized by thin soil layers, high infiltration capacity and low water holding capacity and are particularly vulnerable to environmental changes and human impacts due to their unique hydrogeological characteristics (Ford and Williams, 2007). Additionally, plateaus and mountains are the dominant landforms in karst areas, especially in Europe and Asia, and act as insurmountable barriers for transportation. As a result, the excavation of tunnels has been a common necessity for efficient transportation in the form of both motorways and railways in karst plateau and mountain areas (Gisbert et al., 2009; Vincenzi et al., 2009; Butscher et al., 2011; Zarei et al., 2011; Liu et al., 2019). Generally, tunnels are excavated below the groundwater table in karst areas, although some tunnels in karst mountains may start in the vadose zone at each end but pass into a transient zone or even a steady-state phreatic zone in their central parts, creating an elongated zone of depression that permits gravity-driven drainage, resulting in a lowered groundwater table (Ford and Williams, 2007; Vincenzi et al., 2009). Karst groundwater drawdown can result in reductions in karst spring discharges (Gisbert et al., 2009; Liu et al., 2019) and the complete loss or drying up of surface water (Vincenzi et al., 2009; Liu et al., 2019). Therefore, any groundwater drawdown could alter the natural hydrogeological flow system and consequently impact groundwater-dependent vegetation, soil and hydrology in surface water systems (springs, wells, streams, lakes, wetlands and associated aquatic ecosystems) and related ecosystems in karst areas. Furthermore, karst water stress is likely to increase dramatically in the future because of an increase in tunnel excavation-induced

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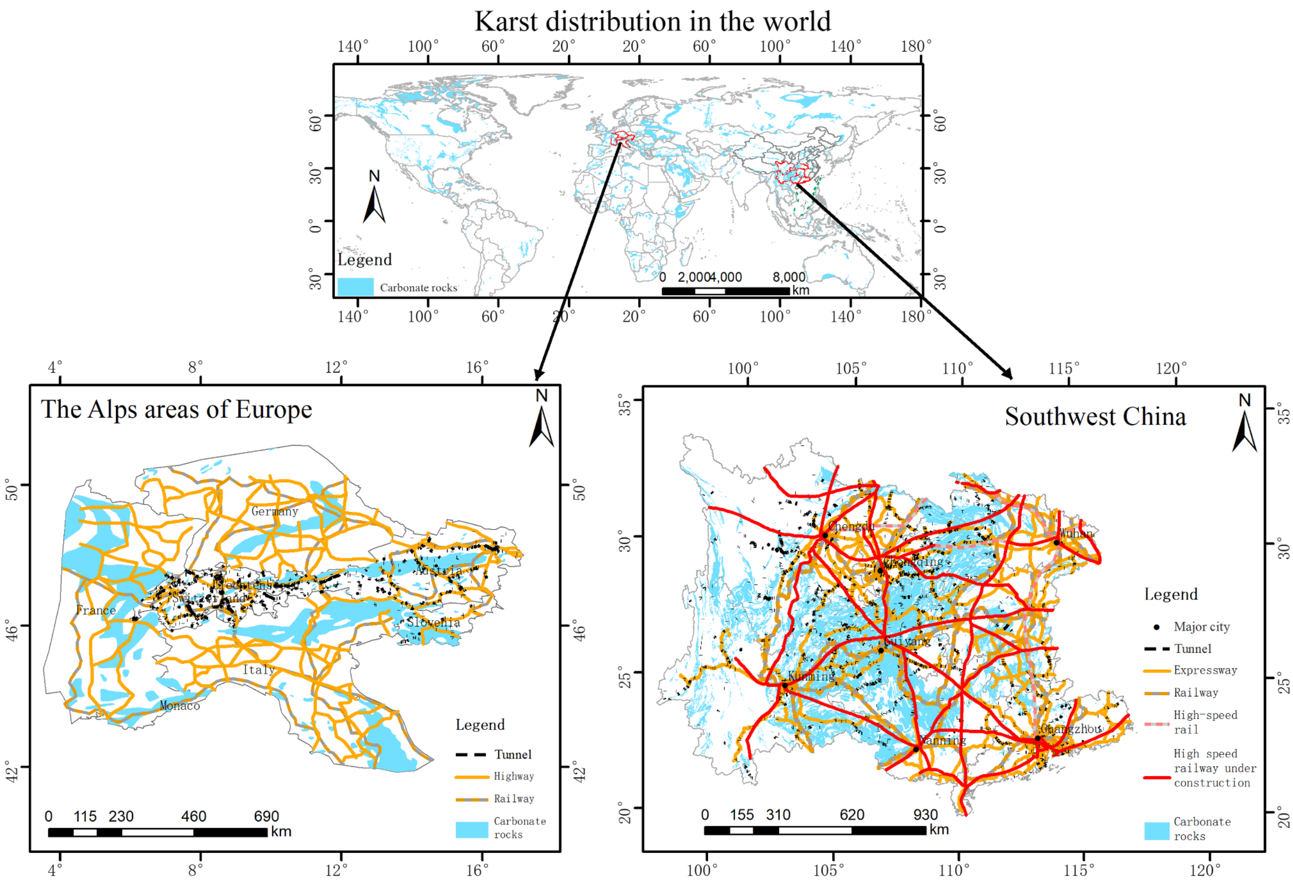

Fig. 1. Distribution of global karst (after Ford and Williams, 2007) and transportation networks and tunnels in the Alps in Europe and Southwest China.

groundwater drawdown with the rapid development of transportation and urbanization in karst areas.

Among these development projects, tunnel construction projects in the Alps in Europe and in Southwest China are particularly notable (Fig. 1). In these areas, the depths of tunnels are generally tens of meters to hundreds of meters, and some are even longer than 1000 m. For example, the depth of the diversion tunnel of the Jinping Hydropower Station in China is 2525 m, the depths of the Gotthard railway tunnel and Lotschberg tunnel in Switzerland are 2438 m and 1300 m, respectively (Masset and Loew, 2013; Vulliet et al., 2003), and the depth of the new Lyon-Turin line tunnel in Italy is close to 2500 m (Bonini and Barla, 2012). Additionally, tunnel lengths are generally hundreds of meters to thousands of meters, and some exceed 10 km. After May 1, 2004, when new countries joined the European Union, the need was felt to link these states through an infrastructure network of motorway and railway links (with high speeds (HS) and high capacities (HC)) easily able to transport all possible goods throughout Europe (Zini et al., 2015). Therefore, many superlong and deep tunnels have been excavated in Alpine karst areas, and inflow into the tunnels has resulted in groundwater drawdown and land settlement (Table 1). Additionally, numerous tunnels have been excavated in the mountainous karst areas of Southwest China. By the end of 2018, 72 railway tunnels with a total length of 1000 km (individual tunnels longer than 10 km) have been built, and 98 railway tunnels with a total length of 1600 km (individual tunnels longer than 10 km) are under construction or planned. Additionally, 10,933 highway tunnels with a total length of 8800 km have been built, including 3896 tunnels with a total length of 4300 km in carbonate areas (Fig. 1). In addition, a large number of tunnels have been built in the karst areas of the United States (Day, 2004), South Korea (Song et al., 2012; Shin et al., 2002, 2005; Shin, 2008; Chae et al., 2008), Iran (Aghda, et al., 2016), Tunisia (Redhaounia, et al., 2015), and so on.

However, tunnel excavation in those areas has resulted in large hydroecological and environmental problems due to the intrinsic vulnerability of karst. Thus, to minimize the impacts on these vulnerable and complex areas, people must learn how to "live with karst" (Anagnostou, 1995; Perrochet, 2005; Park et al., 2008; Pesendorfer and Loew, 2010; Hassani et al., 2016).

Beginning with an analysis of the karst environment vulnerability and the drainage effects of tunnels, early views on the impacts of tunnel excavation on hydrological and ecological environments are reviewed in this paper. Then, the impacts of tunnel excavation on the hydrological system, soil properties, ecosystems and geological disasters in karst areas are summarized. Finally, final considerations and future prospects are presented.

2. The vulnerability of the karst environment and drainage effects of tunnel excavation

2.1. The karst environment and its vulnerability

The karst environment consists of five components: karst weathered residual soil, karst morphology, the karst hydrological system, surface and underground air layers and karst biota (Yuan, 1988a). This system shows a double-layer structure related to the interactions of the atmosphere, hydrosphere and biosphere at the surface and in the subsurface.

Karst environments are characterized by distinctive landforms related to dissolution and dominantly subsurface drainage (Gutiérrez et al., 2014); because of this type of drainage, unique patterns of surface and subsurface runoff occur. On the one hand, this hydrological pattern produces dry surface habitats and can lead to water shortages; on the other hand, the extent of the underground pipeline network varies greatly in different areas, and the network can be easily blocked in low-lying areas in cases of heavy rain, causing local waterlogging. In

Table 1
Maximum inflow, drawdown and ground settlement associated with some tunnels in the Alps (modified from Preisig et al., 2014).

Tunnel	Length, km	Depth, m	Flow rate, L/s	Draw-down, m	Settle-ment, cm	Geology	References
D'Ambin Base Tunnel (new Lyon-Turin Line)	57	2500	–	–	–	Marl, limestone, shale, dolomite, clay and schist	Bonini and Barla (2012)
La Praz Exploratory Adit (a part of D'Ambin Base Tunnel)	0.25	600	40	90	5	Fractured metasedimentary sandy schist	Dzikowski and Villemin (2009)
Modane/Villarodin-Bourget Exploratory Adit (a part of D'Ambin Base Tunnel)	–	–	180	90	> 3	Cargnieules, mylonitic marbles and faults	Sogreah (2007), Lassiaz and Previtali (2007)
Sait Gotthard Highway Tunnel (Switzerland)	16.32	–	300	–	12	Fractured crystalline rocks	Zangerl et al. (2003), Pastorelli et al. (2001)
Gotthard Railway Tunnel (new) (Switzerland)	57	2438	90	–	11	Crystalline rock, limestone and dolomite	Masset and Loew (2013), Loew et al. (2015)
Lotschberg Tunnel (Switzerland-Italy)	34.577	1300	–	60	19	Limestone and unconsolidated sediments	Vulliet et al. (2003)
Rawyl Exploratory Adit (Switzerland)	–	–	1000	230	12	Fractured metasedimentary calcareous schist, Limestone	Schneider (1982), Lombardi (1988)

addition, the direct connection between the surface and the underlying high-permeability aquifers makes karst aquifers extremely vulnerable to natural and anthropogenic hazards (e.g., chemical contamination), and contaminants can be transported rapidly through tunnels in a larger region and are difficult to remediate, reflecting the low threshold elasticity and fragile ecological environment of disaster-prone karst areas (Tuyet, 2001; Gabrovšek et al., 2011; Ilona, 2016; Filipović Marijić et al., 2018).

The soil layer in karst areas is very thin, and the physical erosion rate is higher than the soil formation rate (Yuan, 1988b). Once a soil is lost, it is difficult to regenerate. Additionally, the loss of soil aggravates karst drought, as soil cover is among the largest water reservoirs in karst areas. The above characteristics are one of the fundamental differences between soil vulnerability in carbonate areas and that in areas with other rock types and are also the reasons for the issues associated with land use in karst areas (Jiang et al., 2006; Kiernan, 2010; Smirnova and Gennadiev, 2017).

Due to the low-quality and calcium-rich soil environments, plants in karst areas are mostly lithologically adapted, slender and calcium-loving (Querejeta et al., 2007; Lyu et al., 2019). The growth rate of trees is slow, and vegetation growth is limited by soil and water conditions; consequently, the vegetation in karst areas has a low degree of resilience and is more vulnerable than that in other areas (Nepstad et al., 1994; Baskin et al., 1997; Tenorio and Drezner, 2006; Lawless et al., 2006; Moran et al., 2008).

The high vulnerability of karst environments produces a situation in which it is very easy to damage or destroy natural resources but extremely difficult or impossible to restore conditions back to a pristine situation. Even if remedial measures are taken, the economic costs are usually very high (Parise and Gunn, 2007).

In short, the hydrological systems, soil and ecosystems are the most sensitive factors in karst areas. The impact of tunnel excavation on the atmospheric system is not clear, and the main impact on karst landforms is karst collapse. Therefore, this study mainly focuses on the influence of tunnel excavation on hydrological systems, soil, ecosystems and geological disasters.

2.2. The drainage effect of tunnel excavation

Tunnels in karst areas are generally deeply buried, and large-scale geological disasters, such as rock bursts, collapse and water inrushes, often occur during the construction process. The most significant hydrogeological impacts that can occur during tunnel excavation in an aquifer are the barrier and drain effects (Vázquez-Suñe et al., 2005). The barrier effect is caused by underground impervious structures located below the water table. These structures reduce the effective transmissivity of the aquifer, leading to a rise in the water table upgradient and a drop in the water table downgradient (Shin et al., 2002; Ricci et al., 2007; Shin, 2008; Deveughèle and Zokimila, 2010). The barrier effect may result in geotechnical and/or environmental consequences and may affect pre-existing infrastructure (Custodio and Carrera, 1989; Marinos and Kavvadas, 1997; Tambara et al., 2003; Paris et al., 2010). The drain effect is caused by drainage tunnels, which are designed to extract groundwater to avoid water loads but may have far-reaching environmental and geotechnical consequences (Li and Kagami, 1997; Chae et al., 2008; Vincenzi et al., 2009; Butscher, 2012). The relative position of the tunnel and groundwater level is the key to producing a drainage effect. If the tunnel is located above the regional groundwater level, some epikarst springs may be drained, affecting the shallow groundwater in the aeration zone; if the tunnel is located below the regional groundwater level, large springs or underground rivers may be drained, and the groundwater level will drop significantly.

Tunnel excavation penetrates karst fissures and faults and exposes karst caves. Moreover, existing karst fissures expand under the action of a high-pressure water head and then further develop and split, forming new fissures, increasing water conduction channels, and destroying the

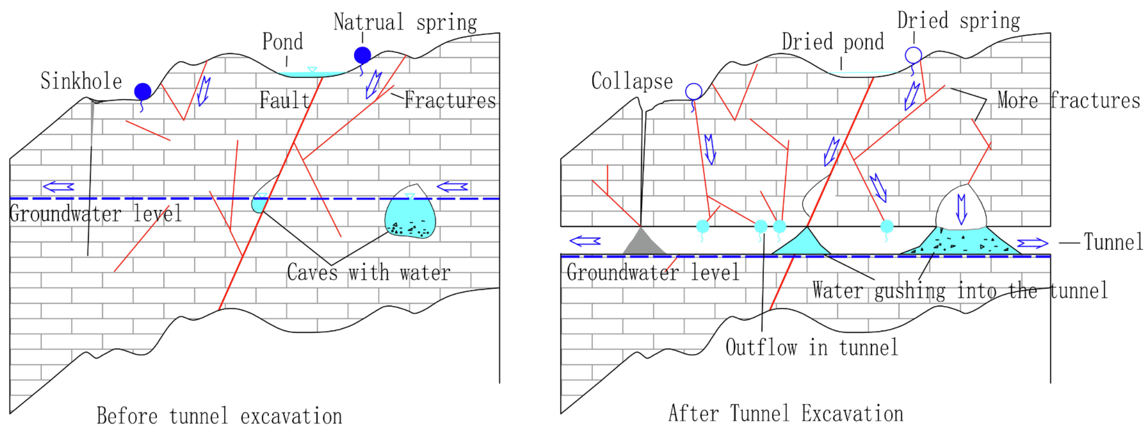

Fig. 2. A sketch of tunnel excavation under the drainage effect.

aquifer structure. As a result, large amounts of surface water and groundwater are discharged into the tunnel through fissures and faults, and the tunnel becomes a new, centralized mean of drainage in the region (Fig. 2).

Tunnel drainage causes changes in the hydrogeological regime, and a progressive stabilization of discharge is observed until a new steady state is reached (Falcone et al., 2008; Celico et al., 2005). However, once the original water resource balance at the tunneling site is broken, a series of ecological and environmental effects is triggered. For instance, water inrushing occurred in a high-speed railway tunnel in southern Spain during excavation, with a peak flow of 800 L/s; after a short period of time, spring discharges dried up (Gisbert et al., 2009). The drawdown produced by tunnel excavation could cause hydrological, hydrogeological and environmental impacts on groundwater-dependent ecosystems (Vincenzi et al., 2009), such as the exhaustion of water resources, changes in water circulation, and karst collapse. In addition, how will tunnel drainage affect soil and ecosystems? This question is also a matter of concern (Fig. 3).

3. Early views on the role of tunnel excavation in hydroecology and the environment in karst areas

In historical research on the ecohydrological and environmental effects caused by tunnel excavation in karst areas, some achievements have been obtained through a large number of scientific observations, data analysis and numerical simulations (Koyama et al., 2012). Traditionally, the influence of tunnel drainage on groundwater has been widely studied in terms of 1) changes in water resource distribution patterns; 2) changes in the groundwater flow field; 3) changes in the water circulation process; and 4) changes in hydrogeochemical processes (Fig. 4, Table 2).

3.1. Impacts of tunnel excavation on the distribution pattern of water resources

First, tunnel drainage destroys the aquifer structure. Then, the surface water and groundwater drain, forming a cone of depression, which expands with the drainage time until the tunnel drainage fully accounts for the recharge from the boundary (Fig. 5). Attanayake and Waterman (2006) argued that the impact of underground engineering construction on the water environment was mainly caused by a decrease in water resources. When there is no reservoir or large body of water near the tunnel, the groundwater recharge above the tunnel may not occur fast enough to avoid a significant excavation-induced water level drawdown (Kim et al., 2001; Moon and Jeong, 2011).

The influential range of tunnel drainage and the amount of water resources to be drained vary greatly. Not only could the radius of influence range from one or two hundred meters to more than ten kilometers, but the water loss also shows anisotropy. Karst aquifers are characterized by highly varied hydraulic properties that are a result of the complex interactions among karst conduits, discrete fractures and the rock matrix (Ford and Williams, 1989). In addition, the

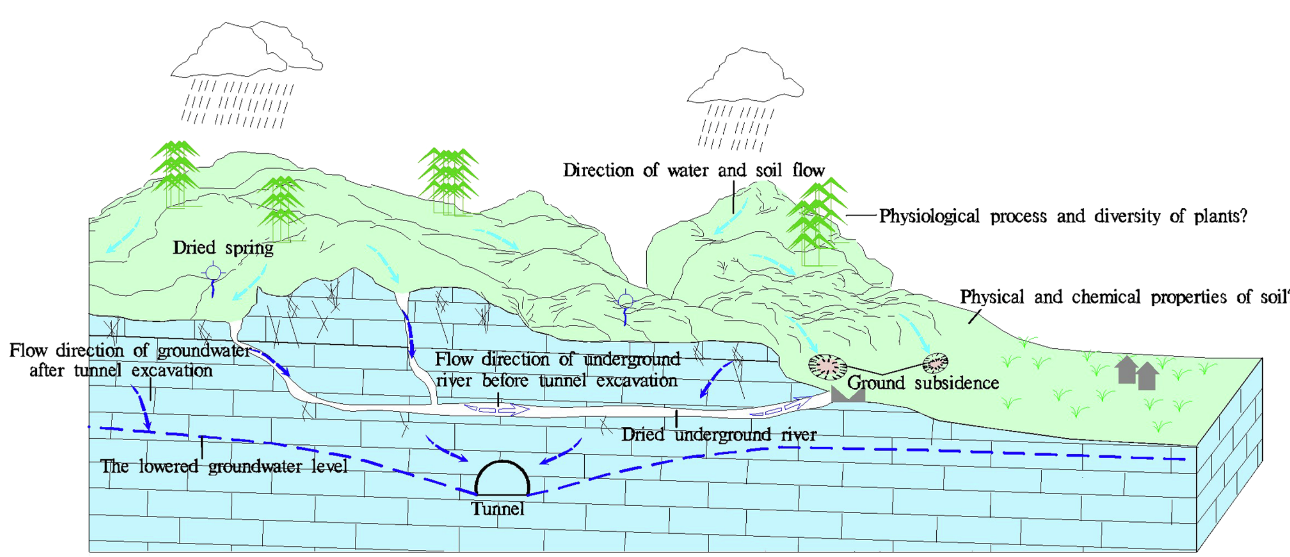

Fig. 3. Ecohydrological and environmental effects caused by tunnel excavation.

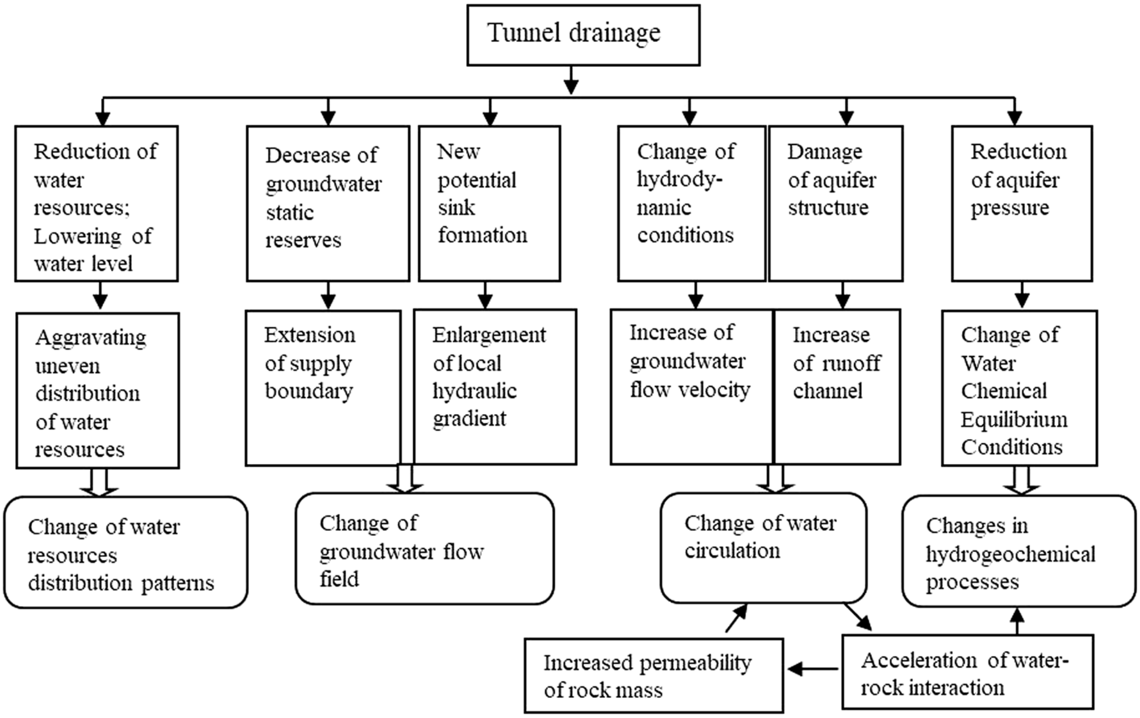

Fig. 4. Effects of tunnel drainage on water resource distribution patterns and hydrological processes.

inhomogeneity of karst development, the difference in the lithological assemblage characteristics of strata, the development degree of faults and fissures in tunnel areas, and the difference in the relative position between the tunnel and regional groundwater levels also play important roles (Zhan and Park, 2003; Sun and Zhan, 2006; Jin et al., 2016; Hadi and Arash, 2018). The existence of large karst caves, thick limestone, water-conducting faults and tunnels located in the lower part of the groundwater table are more conducive to tunnel drainage. Aquifer destruction and differences in tunnel drainage aggravate the uneven distribution of karst water resources, thus changing the spatial

Table 2
Impacts of tunnel excavation on water resources and hydrological processes in karst areas.

Effects		Methods	Main literature and conclusions
Distribution pattern of water resources	Destruction of aquifer structure	Migration & GPR	Increased channels for runoff of karst fracture water (Zhang et al., 2012)
	Resource	Monitoring & water resource assessment	Aquifer dewatering (Gisbert et al., 2009)
		Numerical modeling	The average percentage loss of inflow to the Feitsui reservoir from 2006 to 2010 is estimated to be 1.74% (Chiu and Chia, 2012)
Groundwater flow field	Decrease in groundwater level	Monitoring	Significant decline in groundwater level in local or regional areas (Kim et al., 2001).
	Expansion of the groundwater system boundary	Multitracer tests	Groundwater runoff channels increased, flow rate accelerated, and watershed expanded (Vincenzi et al., 2009)
Water circulation	Slowdown of water circulation	Multitracer tests	Seepage lags precipitation by 3 months (Rademacher, et al., 2003)
		Numerical analysis	Tunnel excavation-induced hydraulic conductivity reduction (Fernandez and Moon, 2010)
	Acceleration of water circulation	Monitoring & tracer tests	The impact radius is 2.3–4.0 km in calcareous regions. Linear flow velocity is 39 m/day in the calcareous rocks. Discrete fault zones were identified between impacted streams and draining tunnels as main hydraulic pathways (Vincenzi et al., 2014)
		Numerical modeling	Tunneling may broaden and shift capture zones, leading to changes in origin and the age of groundwater and the access of groundwater from preferential flow paths (Butscher et al., 2011)
Hydrogeochemistry and water environment	Changes in the chemical composition of groundwater	Monitoring	The change in the chemical composition of well water was more obvious than that of groundwater level (Li and Kagami, 1997)
		Monitoring	The leakage of water into the tunnel caused changes in the hydrogeology with increased groundwater flow and a lowering of the groundwater level in the bedrock and in the overburden, resulting in a change in the hydrochemistry (Mossmark et al., 2015)
	Decline in water quality	Monitoring	The content of acrylamide in tunnel drainage can reach 95500 g/L (Weideborg et al., 2001)
		Hydrochemical analysis	The toxic components of grouting can pollute karst aquifers and cause long-lasting hazardous consequences on subsurface karst species (Bonacci et al., 2009)
		Hydrochemical analysis; geochemical modeling	Increase in iron and manganese concentration in groundwater and change in chemical properties (Chae et al., 2008)

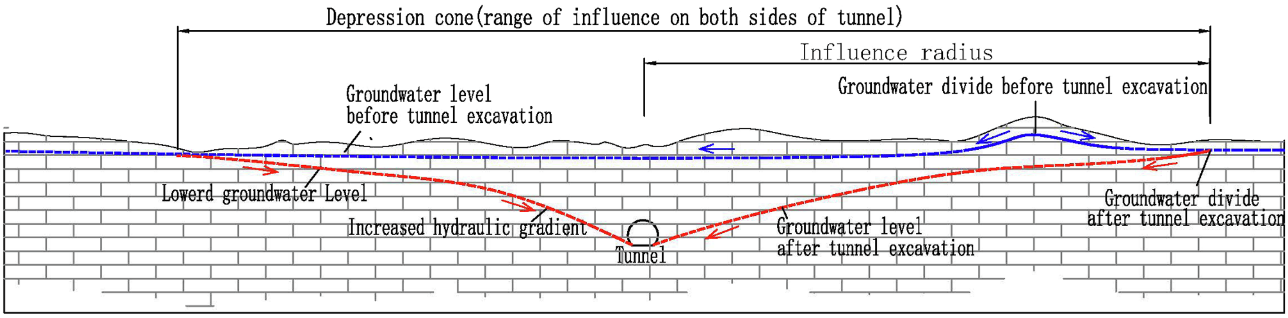

Fig. 5. Water resources and hydrological processes affected by tunnel drainage.

distribution pattern of water resources (Table 2).

Abundant monitoring data on draining water resources and lowering groundwater levels during tunnel excavation have been accumulated; consequently, there is widespread agreement about changes in the distribution pattern of water resources. However, in karst areas with different hydrogeological structures, the influence of tunnels on the distribution pattern of water resources also varies. Therefore, it is necessary to effectively summarize and establish a hydrogeological model for karst tunnels affecting the distribution pattern of water resources and hydrological processes. In addition, previous studies have focused on the impact of tunnel excavation on the spatial distribution of water resources, while only a few studies have focused on the impact on the annual distribution and multiyear changes in surface water, soil water, and groundwater.

3.2. Impacts of tunnel excavation on the groundwater flow field

Under natural conditions, karst groundwater runs along corroded channels from high to low elevations. During tunnel excavation, however, karst groundwater is continuously discharged into the tunnel due to the drainage effect, and the flow velocity and direction of groundwater change accordingly. As a result, tunnel drainage changes the hydrodynamic conditions of the tunnel site area and forms a new potential sink center (Fig. 5); then, the local hydraulic gradient is significantly enhanced, and the groundwater runoff pattern changes significantly. Groundwater level decline is the most prominent manifestation of this flow field change. The construction of subway tunnels may cause a significant local or regional drop in groundwater levels due to the seepage (and removal) of the surrounding groundwater into the tunnel (Kim et al., 2001).

At the same time, tunnel excavation drainage may use static groundwater reserves to increase the recharge and expand the recharge boundary of groundwater, thus changing the regional groundwater flow field. Two multitracer tests proved the connection between losing streams and numerous water inlets in a tunnel, and these connections had a maximum linear distance of 1.4 km and velocities of up to 135 m/d. Several of the demonstrated flow paths passed under previous groundwater divides (mountain ridges), proving that the tunnel had completely modified the regional flow system (Vincenzi et al., 2009). In addition, regional and local flow systems may also change as the groundwater level and velocity change.

Because of the inadequate number of boreholes and natural springs near the tunnel site, the groundwater flow field must be qualitatively studied to some extent by groundwater simulation software. However, due to the heterogeneity in karst aquifers and the uncertainty in the model itself, its applicability in simulating karst aquifers is limited, and the simulation results are often unsatisfactory. Shoemaker et al. (2008) added a pipeline flow program based on the MODFLOW-2005 open source program. The Hagen Poiseuille equation and Darcy Weisbach equation were used to describe laminar and turbulent flow in a karst pipeline medium. Compared with an equivalent porous medium, the pipeline flow program is more accurate in terms of water level and flow measurements. MODFLOW-CFP has been tested (Hill et al., 2010), applied (Gallegos et al., 2013; Giese et al., 2018) and improved (Zargham, et al., 2018). However, although MODFLOW-CFP can calculate the flow process of different nodes, it does not consider the hydrodynamic process inside the pipeline, the description of the flow characteristics in the pipeline is relatively fuzzy, and the flow exchange between the pipeline medium and the fracture medium is represented by a linear equation, assuming that the flow exchange is directly proportional to the head difference between the two, which does not conform to actual flow exchange behavior. Therefore, long-term efforts are needed to improve existing models. In addition, in some karst valley areas, there are several parallel tunnels in the same hydrogeological unit, forming a tunnel group. The influence of the tunnel group on the groundwater flow field is more complex, and this complexity should be a focus in future research.

3.3. Impacts of tunnel excavation on water circulation

Tunnel excavation may accelerate or slow water circulation. Spectral analysis of precipitation and groundwater seepage records showed that seepage lagged precipitation by 3 months. This delay was related to the advancement of the wetting front and an increase in the number of active flow paths (Rademacher et al., 2003). Additionally, tunnel excavation penetrates cracks and fractures, exposes karst caves, changes the aquifer structure, and increases the groundwater flow paths. The unique fissure and network structure of a karst aquifer causes the tunnel water inflow to respond rapidly to rainfall and can have a larger range of impacts (Gisbert et al., 2009).

Tunneling may broaden and shift capture zones, leading to changes in the origin and age of groundwater and the migration of groundwater along preferential flow paths (e.g., faults) due to the drainage effect of the tunnel (Butscher et al., 2011). Moreover, the influence of tunnel excavation on karst areas is more serious than in nonkarst areas. A comprehensive hydrological monitoring program was implemented with four multitracer tests, focusing on four sections of seven railway tunnels in a high-speed railway line between Bologna and Florence (Italy). The impact radius was 200 m in the thin-bedded sequences but reached 2.3–4.0 km in calcareous and thick-bedded arenitic turbidites. Linear flow velocities, as determined from the peaks of the tracer breakthrough curves, ranged from 3.6 m/day in the thin-bedded turbidites to 39 m/day in the calcareous rocks (average values from the four test sites) (Vincenzi et al., 2014). There are two main reasons for these differences: the change in hydrodynamic conditions in the area caused the acceleration of groundwater movement; in addition, tunnel excavation strengthened the hydraulic links between adjacent aquifers. The tunnel drainage formed a cone of depression, which gave the aquifer enough space to receive external recharge water and strengthened the infiltration transformation of surface water to groundwater. In addition, the long-term drainage of some tunnels also accelerates the dissolution of carbonate rock, resulting in an increase in the permeability of the rock mass, which in turn accelerates the water circulation (Fig. 4).

At present, there are few quantitative descriptions of soil water in water circulation studies in karst tunnel areas. The conversion process comprising precipitation, surface water, soil water, groundwater and tunnel water may be a research hotspot in the future. In addition, due to the unique geological structure of karst areas, the ability of karst areas to absorb rainfall is very strong. It is only in the case of heavy or regular rainstorms that slope flow can occur, while other forms of rainfall are absorbed by the surface zone. Whether tunnel drainage has an impact on the runoff generation mechanism in tunnel site areas has not yet been studied. Additionally, whether the process of rainfall runoff generation is affected by tunnel drainage conditions is also a matter of concern.

3.4. Impacts of tunnel excavation on groundwater hydrogeochemistry and water environment

Tunnel excavation can cause changes in groundwater hydrogeochemistry in several ways: tunnel drainage leads to a decrease in aquifer water pressure and changes in the geochemical equilibrium conditions; the process of groundwater circulation accelerates the interaction between water and rock, thus changing the chemical composition of the groundwater (Mossmark et al., 2015) (Fig. 4); and tunnel drainage destroys the aquifer's structure and promotes the mixing of groundwater from different aquifers, thus changing the chemical characteristics of groundwater. Li and Kagami (1997) studied the variations in groundwater level and chemical compositions during the construction of the Songben Tunnel Project in Japan. When the tunnel passed through unfavorable strata, such as coal-bearing strata, geochemical reactions would oxidize the sulfides in the strata, produce sulfate and hydrogen ions, and cause groundwater chemical anomalies. These chemical anomalies caused the hydrolysis or dissolution of calcium-bearing minerals and released calcium ions, which lead to a change in the hydrochemical type and an increase in mineralization. It was found that the changes in the groundwater chemical compositions were more obvious than the changes in groundwater levels. The change in hydrochemical characteristics caused by tunnel drainage has also been noted in many other studies, including studies on the subway system in Seoul (Chae et al., 2008) and the new Colle Di Tenda road tunnel between France and Italy (Banzato et al., 2011). Moreover, hydrochemical changes are difficult to predict since they are dependent on geological and hydrological conditions and tunnel design. These changes may have an adverse effect on the environment and could affect the lifespan of construction materials, such as rock support, drainage systems and sealing systems (Mossmark et al., 2015).

Tunnel excavation very easily causes water pollution. The wastewater from construction easily enters the groundwater system. It is difficult to estimate the amount of contaminants that leak into the tunnel, and these chemicals can be difficult to measure. A study on the hydrochemistry of groundwater seeping into subway tunnels in Seoul showed that tunnel excavation may affect redox conditions, thus influencing the chemical properties of urban groundwater and leading to a significant increase in dissolved manganese and iron concentrations in urban groundwater (Chae et al., 2008). It is believed that the blasting products (such as nitrate and nitrite) and the components of heavy metal-rich minerals in the rock walls and waste residues, which can be released by chemical reactions, enter the water body during tunnel construction. Dust from tunnel excavation, oil leakage from construction machinery, waterproof grouting material and shotcrete-anchor support material can also pollute the surrounding surface water. In particular, the liquid leaking from reinforcements containing harmful ingredients has some of the most significant impacts on the water environment. Some studies have shown that the content of acrylamide in tunnel drainage can reach 95500 g/L when using a reinforcing agent containing acrylamide (Weideborg et al., 2001). Acrylamide is completely soluble in water and may cause acute lethal effects on fish or other aquatic organisms. Some ingredients and chemicals used in the preparation of mortars and grouting suspensions may be toxic, neurotoxic or carcinogenic and may be irritants or corrosives. Their use is dangerous to both humans and the environment. These toxic components can pollute karst aquifers and can have long-lasting hazardous consequences for underground karst species. Both physically and chemically, these materials rapidly destroy underground habitats and have killed an enormous number of rare, endangered and endemic species (Bonacci et al., 2009).

Previous studies have shown that karst tunnel construction accelerates the interaction between water and rock, but whether it further changes the spatial and temporal evolution characteristics of regional hydrogeochemical fields needs to be confirmed by observation data. In addition, whether tunnel drainage further promotes karstification has yet to be studied systematically.

In summary, the distribution of karst water resources becomes more uneven due to tunnel drainage. More importantly, tunnel drainage directly causes groundwater drawdown and destroys karst aquifers and the flow field and geochemical characteristics of groundwater change accordingly. In addition, unreasonable construction practices also lead to groundwater pollution. However, due to the complex geological conditions and limited observational data in karst areas, the impacts of tunnel drainage on soil and vegetation have been neglected. In the research that does exist, researchers have found that the physical and chemical properties of soil, plant physiological processes, growth rate and coverage in tunnel-affected karst areas are gradually changing. Geological hazards, especially subsidence or collapse, are widespread in karst tunnel areas and have seriously affected the local ecological environment. Therefore, it is necessary to sort the existing research, summarize its patterns, analyze its mechanisms, and identify problems and directions for future research.

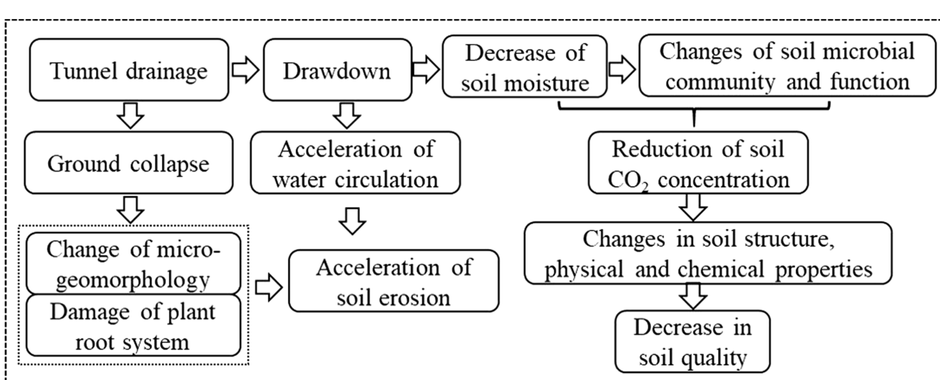

Fig. 6. Impacts of tunnel excavation on soil properties.

Table 3
Impacts of tunnel excavation on soil properties.

Effects	Methods	Main literature and conclusions
Increase in soil temperature	Calculation	The heat load of surrounding rock increases, and the temperature of soil rises (Glehn and Bluhm, 2000)
Decline in soil quality	Sampling and analysis	Changes of soil microbial community and function. Significant reduction in soil CO_2 concentration. Changes in soil structure and physical and chemical properties (Jiang, 2019)
		Changes in soil types and chemical properties (Miller and Chanasyk, 2010)
Acceleration of soil erosion	Estimates & numerical simulation	Increased modulus and amount of soil erosion (Meng et al., 2012)

4. Impacts of tunnel excavation on soil properties

As shown in Fig. 6 and Table 3, the physical and chemical properties of soil can be modified, and soil erosion can be accelerated by tunnel excavation in karst areas. Tunnel drainage can result in the drying up of surface water and the drawdown of groundwater, cutting off the connections among surface water, groundwater and soil water, leading to a decrease in soil moisture and consequently impacting soil microbial communities and functions. With the decrease in soil moisture, microbial abundance and diversity, the concentration of CO_2 in the soil will decrease significantly, which may change the soil structure and physical and chemical properties, potentially resulting in an increase in the soil bulk density and clay content and a decrease in organic matter and nutrient contents. Eventually, the quality of the soil will decrease (Jiang, 2019). At the same time, the groundwater drawdown and surface collapse caused by tunnel drainage will further accelerate water circulation, destroy the micromorphology of the soil, disrupt plant root systems, and finally accelerate soil erosion.

4.1. Changes in soil physical properties

The influence of tunnel excavation and operation on soil physical characteristics is mainly manifested in the decrease in soil moisture and the increase in soil temperature (Table 3). Tunnel drainage dries surface water and lowers the groundwater level, resulting in reduced soil moisture (Liu et al., 2019). Due to the lack of monitoring data, there are few studies on the temporal and spatial variation characteristics of soil moisture during the tunnel construction period.

The influence of subway tunnels on the increase in soil temperature has been a research hotspot in recent years, with the main research methods being field measurements, scale model simulations of the experimental platform, theoretical analyses and numerical simulations (Cavagnaro and Brulard, 1997; Glehn and Bluhm, 2000). Subway operations result in an increase in air temperature and the temperature of the surrounding rock in the tunnel, which in turn leads to an increase in soil temperature. In such a system, the trains are the heat source, and the air, surrounding rock and groundwater are the main heat conduction media (Ampofo et al., 2004). Moreover, the changes in soil temperature show great temporal and spatial differences. Soil texture, geological conditions (stratum and structure) and engineering conditions (lining layer and impervious layer) are the main factors influencing the spatiotemporal variation in soil temperature (Lee et al., 2004). It is presumed that the driving factor is the increase in soil evaporation.

4.2. Changes in soil chemical properties

In addition to the soil water contents, the soil organic matter and pH values may also be reduced by tunnel excavation. The decrease in groundwater level and the acceleration of water circulation both promote the transport of soil nutrients to deeper levels or into groundwater. In one study, the soil morphology, the physical and chemical properties of soil horizons, water fluxes in the saturated zone, and tritium content in groundwater were determined at nine sites (Miller and Chanasyk, 2010). The results showed that the soil types were different between the recharge area with a shallow groundwater level (≥ 1.81 m) and the discharge area with a deep groundwater level (≥ 2.60 m). The leaching of carbonates from the B horizons was consistent with the downward groundwater flow, and the high water-soluble Na levels in the three Orthic soils suggested an influence from a shallower water table at some point. Moreover, the unreasonable disposal of construction waste residue and liquid will lead to soil pollution.

4.3. Acceleration of soil erosion

The groundwater drawdown caused by tunnel excavation may aggravate soil erosion. Until now, little research has been conducted on the mechanism by which tunnel excavation induces soil erosion, but many observations have demonstrated a correlation between coal mining subsidence and soil erosion (Sinha et al., 2016). Therefore, we hypothesize that the ground subsidence caused by drainage may be a direct cause of accelerated soil erosion. Subsidence reshapes the surface structure and morphology, steepens the slope and destabilizes the soil body in some areas, thus accelerating gravitational erosion and hydraulic erosion. Simulation results have shown that the maximum modulus of erosion and the erosion volume of the subsidence basin without water logging would increase by 78% and 23%, respectively, compared with those of the original situation and that the edge of the subsidence basin is subject to the greatest acceleration in soil erosion (Meng et al., 2012). In addition, deposition of sediment can destroy plant roots and affect the uptake of water by plants.

The decrease in vegetation caused by a drop in water level and ground subsidence may be an indirect cause of the acceleration in soil erosion (Daniels, 2010; Sinha et al., 2016). As the vegetation root system is destroyed or dies, the water holding capacity of the surface weakens, and rainfall-induced soil erosion becomes more likely to occur.

5. Impacts of tunnel excavation on karst ecosystems

Because of the calcium-rich rock, the circulation of water and air and its unique double-layer structure, karst ecosystems have poor soil fertility, poor water retention ability, low vegetation coverage and low degrees of resilience. Due to the lack of a systematic surface water hydrological network in karst areas, natural vegetation is mainly dependent on the consumption of groundwater resources for survival, so vegetation is very sensitive to groundwater changes.

The decrease in groundwater level and soil water content caused by tunnel drainage has negative impacts on the ecological environment and ecological processes, with specific results such as a reduced plant growth rate, changes in plant physiological processes, and changes in plant communities (Table 4**).**

5.1. Changes in plant physiological processes

Plants adapt to water stress by changing water absorption strategies and efficiency, especially plants with dimorphic root systems in karst areas. The surface roots of dimorphic root systems potentially take up water from the upper soil layers, while deeper roots extract water stored in epikarst and even underground rivers (Williams and Ehleringer, 2000; Kulmatiski et al., 2006; Heilman et al., 2009; Hasselquist et al., 2010). When the groundwater level declines due to drought, mining or tunnel excavation, plants adjust their water

Table 4
Impacts of tunnel excavation on ecological systems.

Effects	Methods	Main literature and conclusions
Changes in plant physiological process	δ^2H & $\delta^{18}O$	Change in the plant uptake water pattern (Liu et al., 2019)
Decrease in plant growth rate	Tree rings	The lowered groundwater table significantly reduced the growth rate of pine trees, and the low growth rate remained for 15 years (Zheng et al., 2017)
Changes in plant communities	Investigation & observation	Soil contamination leads to the death of animals and plants (Sjolander-Lindqvist, 2005)
	Spatial autocorrelation analysis	Approximately 32.3% of the plant seeds in a highway tunnel do not live near the tunnel entrance (Dark, 2004)
	Geospatial and statistical analyses	Tunnels and vehicles can be used as carriers of plant seed migration (Rutkovska et al., 2013)

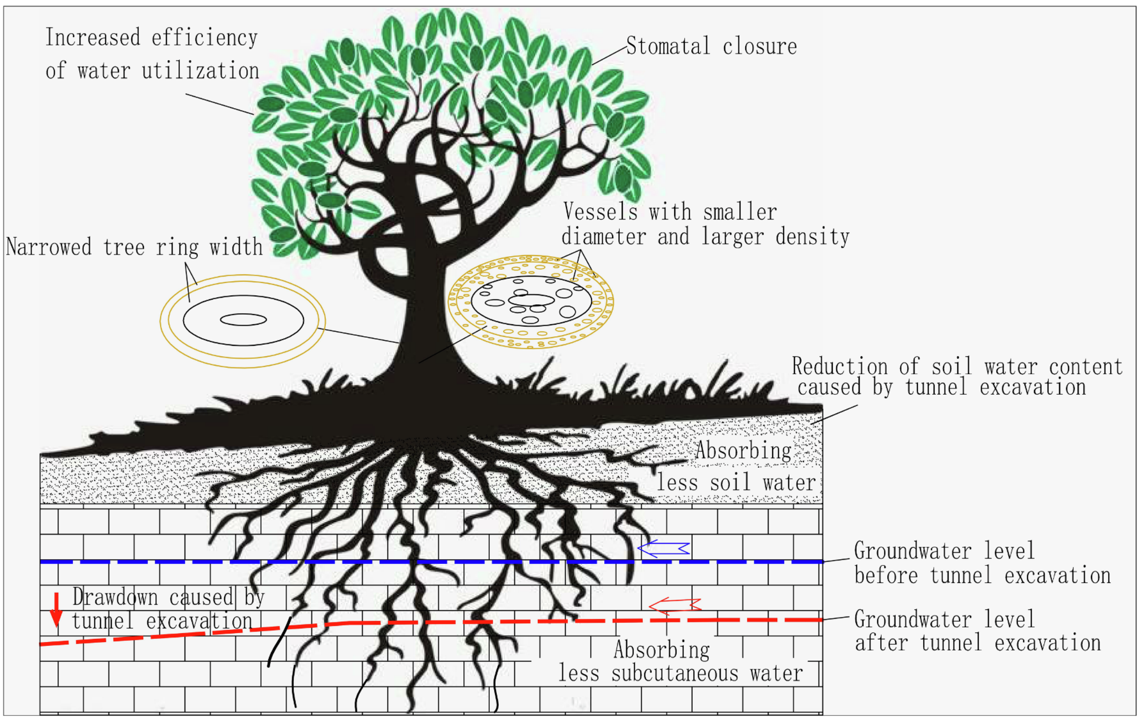

Fig. 7. Changes in plant growth rate and physiological processes: the decrease in groundwater level leads to an increase in groundwater utilization and water use efficiency through closure of the stomata, eventually slowing the growth rates of plants.

utilization strategies and absorb deep groundwater (Fig. 7). An analysis of the results of δ^2H and $\delta^{18}O$ analyses indicated that the drawdown caused by tunnel excavation in a karst valley induced a decrease in the soil water content, which led to the transformation of the plant water absorption pattern from dominantly exploiting soil water sources in the rainy season to dominantly exploiting subsurface water sources in the dry season (Liu et al., 2019). Plants can also change their strategies and efficiency of water absorption by adjusting the size and density of vessels to adapt to changes in the groundwater level (Fig. 7). The lumen areas of vessels were separately measured in 26 tree rings from six trees, and the results suggested that vessel size and density were correlated with circumferential stem growth, which is in turn governed by the local water supply (Schume et al., 2004). Different tree species also show different physiological characteristics. Oak showed a stress avoidance strategy involving a decrease in conduit size under drought, leading to a reduction in water-conducting capacity and a lower risk of cavitation; in contrast, pine reduced the carbon costs of the water-conducting system during drought by decreasing the number and cell-wall thickness of conduits, while the lumen diameter and efficiency of water conduction may increase (Eilmann et al., 2009).

In addition, stomatal control is also a strategy for plants to cope with water deficits, and the main response is a reduction in stomatal conductance or stomatal closure. Due to variations in the water content and canopy water potential of different tree species, the sensitivity of stomatal behavior also varies (Sparks and Black, 1999; Zweifel et al., 2007).

5.2. Decrease in plant growth rate

The narrowing of tree ring width is an index for decreases in the tree growth rate. The study of tree rings in woody species can provide information on past and present ecological controls on tree establishment, growth and death, including those related to climate and water availability (Bogino and Villalba, 2008; Dussart et al., 1998; Esper et al., 2002; Máguas et al., 2011; Martin and Germain, 2016; Witt et al., 2017).

The tree ring widths widen and narrow due to the rise and fall in the groundwater levels, respectively (Stockton and Fritts, 1973; Yanosky, 1982, 1983, 1984; Sloan et al., 2001; Lageard and Drew, 2008). The groundwater table has been shown to be the dominant factor influencing oak growth at one site, especially during times of intensive drainage (Scharnweber et al., 2014). Some studies have attempted to use tree rings as an indicator of groundwater level decline caused by tunnel excavation (Zheng et al., 2017). Growth reduction caused by tunnel drainage can be easily identified by a dramatic decline in tree ring width (Fig. 7). Lowering of the groundwater table significantly reduces the growth rate of pine trees (for 15 years), and the effect can extend up to 1 km away from the tunnel axis (Zheng et al., 2017).

Groundwater is the most important limiting resource for plant distribution and growth. Soil moisture and salinity affect natural vegetation growth and are closely related to the groundwater level. A decrease in the groundwater level may lead to plant wilting and death. Therefore, the concepts of the ecological water level of groundwater, ecological balance of groundwater and threshold of groundwater level depth were proposed (Boutaleb et al., 2000; Horton et al., 2001), and the maximum allowable water discharged from tunnels was determined based on the ecological water requirement of vegetation.

In addition, land subsidence destroys plant roots, leading to a decline in the growth rate and even death of plants (Daniels, 2010).

5.3. Changes in plant communities

Tunnels and vehicles can inadvertently transport plant seeds, which increases the likelihood of species invasion (Rutkovska et al., 2013) and changes in plant community diversity. One study found that approximately 32.3% of the plant seeds in a highway tunnel did not live near the tunnel entrance (Dark, 2004). Both the magnitude of seed deposition and the species richness in the seed samples from two motorway tunnels were higher in the lanes leading out of the city than in the lanes leading into the city, indicating an export of urban biodiversity via traffic. As proportions of seeds of nonnative species were also higher in the outbound lanes, traffic may foster invasion processes in cities and may transport nonnative species to the surrounding landscapes (Lipper and Kowarik, 2010). At present, it has been assumed that the increase in plant seed species in tunnels will cause species invasion and changes in plant diversity, but more concrete conclusions will required additional observational data.

Furthermore, the destruction of the plant root system caused by ground subsidence and the decrease in plant growth rate or even death due to groundwater drawdown may also lead to a reduction in plant species or promote the gradual vegetation succession to xerophytes. However, whether the long-term drainage of tunnels will lead to vegetation succession has seldom been studied, and this hypothesis needs to be confirmed by observational data.

6. Impacts of tunnel excavations on karst environments (geological hazards)

6.1. The process of ground collapse caused by tunnel drainage

Collapse is often a side effect of tunnel excavation and is one of the most common geological hazards (Casagrande et al., 2005). The development process of ground collapse caused by tunnel drainage can be divided into three stages (Fig. 8).

In the first phase, groundwater maintains the natural water level and is relatively stable in the natural state. In the bedrock, a hole or funnel forms through dissolution. At this time, the soil is also affected by the buoyancy of the karst water and the resistance to sliding of the soil itself, which allows the overlying soil to exist in a basically stable state.

In the second phase, the groundwater level drops rapidly after a large amount of the tunnel is drained (Fig. 8). The water flow process can cause erosion and movement of the soil in the surface overburden and karst conduit and gradually forms caves in the soil. The surface soil shows signs of tension cracks and subsidence because of gravity. The vibrations, pressure and hydraulic pressure caused by gunstocks during construction are destructive and enhance the connectivity of deep and shallow karst fissures and conduits.

In the third phase, with the further development of the soil cave, the roof soil layer becomes increasingly thin. When the negative vacuum pressure and the weight of the soil exceed the collapse resistance, a collapse occurs.

6.2. Impacts of ground collapse

Tunnel excavation, in addition to drainage, may cause dramatic changes in the local hydrogeology, leading to enhanced internal erosion, the development of sinkholes and the subsequent formation of karst collapse (Milanovic, 2000; Bonetto et al., 2008; Vigna et al., 2010; Gutiérrez et al., 2014). Ground subsidence, settlement and karst collapse are the most common changes (Table 5).

According to incomplete statistics, nearly all long railway tunnels built in karst areas in Southwest China have experienced karst collapse to varying degrees. In the Pinglin tunnels of the Taipei-Ilan Expressway Project (Taiwan), the sudden groundwater inflow was up to 750 L/s, which led to a collapse at the tunnel face, and a tunnel boring machine (TBM) in the pilot tunnel was trapped and damaged (Tseng et al., 2001). Although stiff lining segments were used and grouting mortar was utilized to fill any gap between the linings and surrounding soil, investigations have demonstrated that surface collapses appear to be unavoidable (Fargnoli et al., 2015) and have caused some damage to residential areas and buildings above the tunnels (Farrell et al., 2014; Lavasan et al., 2016).

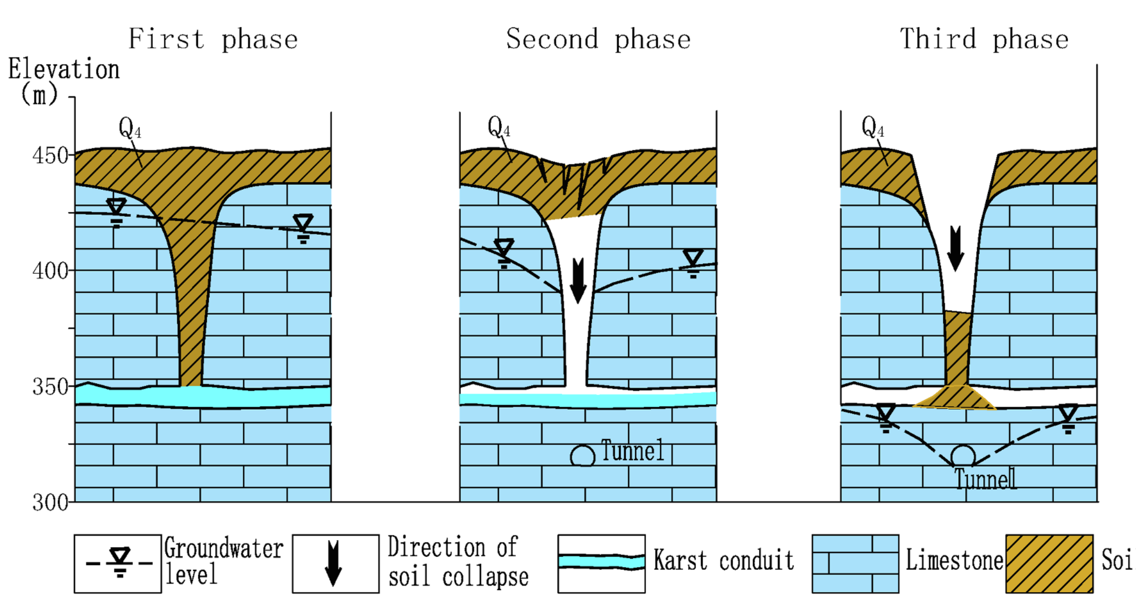

Fig. 8. Schematic diagram of ground collapse caused by tunnel drainage.

Table 5
Impact of tunnel excavation on geological hazards.

Effects	Methods	Main literature and conclusions
Ground subsidence/settlement	Analytical solutions	Improvement to the ground subsidence prediction method (Loganathan and Poulos, 1998)
	Numerical modeling	The highest soil settlement is obtained for vertically oriented tunnels, while horizontally oriented tunnels cause the lowest settlement (Chehade and Shahrour, 2008).
	Numerical modeling	Agreement between the modification to the greenfield settlement profile, displayed by the buildings, and estimates made from existing predictive tools is observed. The horizontal strains, which are induced in the buildings, are typically at least an order of magnitude smaller than the greenfield values (Farrell et al., 2014).
	Numerical modeling	Effective grouting can reduce settlement (Masini et al., 2014)
	Analytical solutions	A displacement-controlled technique is adopted to simulate tunnel excavation, which produces settlement troughs in agreement with the empirical Gaussian predictions at different volume losses under free-field conditions (Amorosi et al., 2014)
	3D FE analysis & modeling	A building is found to modify the deformative pattern at the ground surface in relation to its stiffness and weight, reducing the differential settlements compared to those calculated under free-field conditions (Fargnoli et al., 2015)
Collapse	Investigation	The sudden groundwater inflow (up to 750 L/s) led to a collapse at the tunnel face (Tseng et al., 2001)
	Data collection; Statistical analysis	Due to partial or total excavation of the tunnel section, landslides and emptying of karst cavities filled with soil began to develop. The reduced cohesion and unsuitable geomechanical characteristics of the soils filling the karst cavities generated serious instability problems (Alija et al., 2013)
	Data collection; Statistical analysis	The excavation of tunnels may cause karst collapse (Gutiérrez et al., 2014)
Rock collapse & subsidence	Data collection; Statistical analysis	Rock collapse, subsidence and groundwater intrusion necessitated remedial grouting and lining of approximately 45% of the tunnels, costing approximately $50 million above estimates and delaying completion by 9 months (Day, 2004)
	Data collection; Statistical analysis	The potential geo-hazards include groundwater ingress, ground surface settlement, and strata collapse (Chen et al., 2017)

6.3. Interfering factors and preventive measures

The change in effective stress and the increase in hydrodynamic pressure caused by tunnel drainage in the overlying loose soil layer are the most fundamental causes of ground subsidence. Areas with fluctuating groundwater levels and strong runoff zones are often prone to collapse, and the change in hydrodynamic conditions is the main factor driving karst collapse (Fig. 8), as has been confirmed by an abundance of observational data.

The most perceptible impact when tunneling with the earth pressure balance (EPB) method is soil movement during tunnel excavation. Soil movements can be divided into short- and long-term movements. Short-term movements are mainly caused by 1) ground loss during excavation, which redistributes the stress in the soil and results in stress relief (Ercelebi et al., 2011); 2) injection of grout; and 3) advancement of the TBM and consequent pushing of the soil (Pujades et al., 2015). Long-term movements are observed after the excavation process and are associated with creep, stress redistribution, consolidation of the soil after drainage, and perhaps soil consolidation resulting from groundwater changes due to the interaction between the tunnel and the aquifer (Ercelebi et al., 2011; barrier effect or drain effect).

Additionally, groundwater ingress is another factor triggering ground subsidence. During construction, due to the instability of the cutting face, large amounts of groundwater from leaking fractures and fissures can flow into the completed tunnel, and this loss of groundwater produces an effective stress that leads to ground consolidation and ground surface settlement (Chen et al., 2017).

Ground subsidence is obviously affected by rainfall, which increases the groundwater level and the hydraulic gradient. Rapidly flowing water can carry large amounts of sediment, which accelerates the development of ground subsidence. Ground subsidence always occurs or expands during the rainy season. Since the compressibility and thickness of the overlying strata vary from place to place, it is postulated that differential ground surface settlement will also occur (Amorosi et al., 2014; Loganathan and Poulos, 1998). For double-line or multiline tunnels, tunnel spacing and construction sequences have a great influence on the amount, shape and scope of ground collapse. The ground collapse resulting from parallel tunnels is larger and wider than that resulting from a single-track tunnel. With the decrease in tunnel spacing, a grouped caving effect will occur, and the amount of collapse will increase (Chehade and Shahrour, 2008).

Several techniques, including grout injection (Masini et al., 2014), can be employed to avoid issues such as cracking, tilting, or settling. To accurately predict settlement by analytical or numerical methods, it is important to know the soil parameters. Furthermore, steering parameters such as the face pressure or grout pressure in the annular gap can be adapted to the surrounding soil to ensure an unimpaired construction workflow.

7. Final considerations and future prospects

In recent years, in response to rapid economic development, tunnel excavation in karst areas has continued to accelerate. Due to the lack of environmental protection awareness at the beginning of tunnel excavation and the unique ecological vulnerability of karst areas, the negative effects of tunnel excavation on the ecological environments in karst areas are becoming more significant and are producing challenges for regional water resources and ecological security, even potentially causing strong social repercussions, in China, South Korea and the Alps. To analyze the impact of tunnel excavation on hydrology, ecology and the environment, a series of studies have been conducted, and some advances have been achieved. Most of the existing studies focus on the specific manifestations and ecological environment effects caused by tunnel excavation. It is agreed upon that the decline in the groundwater level caused by tunnel excavation is the basic reason for the observed ecological environmental effects. However, there are still some deficiencies in the explanations of the mechanisms by which tunnel excavation impacts hydrological processes, vegetation, and soil; the evolutionary trends of hydroecological environmental effects; and related research methods and means. Overall, research on the ecological environmental effects of tunnel excavation is still relatively lacking. The following aspects need to be addressed in the future:

7.1. Impacts of tunnel excavation on karst water resources and hydrological processes

Tunnel excavation often passes through karst aquifers, forming a large artificial pipeline. Due to the uneven development of the water-bearing medium and the complex hydraulic characteristics of karst aquifers, the groundwater immediately flows into the tunnel after tunnel excavation, resulting in varying degrees of surface water leakage and groundwater drawdown, which further aggravates the uneven distribution of water resources and challenges the reliability of regional water resources. The tunnel drainage forms a cone of depression with the tunnel as the center, the local hydraulic gradient increases instantly, the flow system is disturbed, and the groundwater supply boundary expands, all of which significantly alter the groundwater flow field. Many tunnels are located below the groundwater level. In the process of excavation, the formation of artificial pipelines and the release of high water pressures destroy the karst aquifer, change the runoff path of groundwater, strengthen the relationships between different aquifers, enhance the interaction between water and rock, and consequently change the water circulation process and the hydrogeochemical characteristics of the groundwater. In addition, unreasonable tunnel excavation practices can also produce water quality problems.

Previous studies have focused little on soil water. To improve the observations of soil water and carry out quantitative analysis of the transformation of precipitation, surface water, soil water, groundwater and tunnel water, long-term monitoring, experiments and numerical simulations should be conducted.

The ecohydrological effect of a single tunnel and the influence of a new tunnel on an existing tunnel have been abundantly researched. The interaction and superposition effect among multiple tunnels have seldom been studied but will be a hot topic in future research. Establishing a monitoring network for a tunnel group is suggested to optimize the numerical simulation model and quantitatively depict the superposition effect of the tunnel group.

In addition, the ecological environmental impact of extralong and deeply buried tunnels cannot be ignored. Whether such tunnels affect the ecological functions in mountain areas (e.g., the Alps) is also worth studying. To establish a monitoring network, relevant research should be carried out, and timely measurements should be obtained.

7.2. Impacts of tunnel excavation on soil properties

The groundwater drawdown caused by tunnel drainage results in a decrease in the soil water content, which leads to changes in the soil microbial community, function and CO_2 concentrations and to changes in the structural, physical and chemical properties of the soil, thus reducing the soil quality. Furthermore, tunnel excavation not only accelerates water circulation but also causes ground collapse, which destroys the soil microtopography and plant roots, thereby promoting soil erosion. However, there are few studies in this area, and no large observational dataset exists. What are the mechanisms and processes behind this impact? Does tunnel drainage result in changes in the soil microbial community and functions and, consequently, changes in soil quality? Does tunnel drainage reduce soil quality by reducing soil moisture and enhancing leaching? No related studies were found. It is suggested that the systematic monitoring of soil physical, chemical, biological, microbial, CO_2 and erosion characteristics should be strengthened to explore the processes and mechanisms of the responses of soil characteristics to tunnel excavation at different spatial and temporal scales.

7.3. Impacts of tunnel excavation on ecological karst systems

Plants adapt to water stress by changing water absorption strategies and efficiency, including through changes in conduit size and density, stomatal closure, and deeper root development. A sharp decline in tree ring width indicates that the growth speed of some trees around a tunnel decreases, and some trees even die, which further affects the ecosystem in this area. Additionally, tunnels also provide a pathway for the migration of plant seeds, which can cause changes in biodiversity. This is an interesting topic. Do these effects exist in other areas, and if so, what is the mechanism? Does this process affect other physiological processes of plants or even cause changes in plant communities around the tunnel? These questions have yet to be answered.

By using ^{18}O, ^{2}H, ^{3}H, and ^{13}C to analyze the changes in water absorption strategies and the efficiency of plants in tunnel-affected areas and by observing the widths of tree rings, vessels and stomata, the changes in plant growth rate and physiological characteristics can be analyzed and used to explore the mechanisms of vegetation growth rate and physiological process affected by tunnel excavation.

By means of sampling, remote sensing technology, and modeling, we can explore changes in vegetation coverage and plant diversity under tunnel disturbance conditions, verify the possibility of species invasion in the tunnel site area, and reveal the process of vegetation succession from aquatic or arbor vegetation to terrestrial, xerophytic or shrub and herbaceous vegetation.

7.4. Impacts of tunnel excavation on karst environments (geological hazards)

The groundwater drawdown caused by tunnel excavation results in a decrease in groundwater buoyancy; the movement of water flow accelerates potential soil erosion and forms soil caves. With the development of soil caves and the action of gravity, surface cracks, subsidence and collapse appear gradually. The rapid change in groundwater dynamic conditions is the main cause of collapse. Analysis and numerical methods can be effectively used to predict collapses and then carry out scientific grouting. However, at present, collapses still occur frequently in the process of tunnel construction. It is still necessary to carry out long-term monitoring to better understand the mechanisms and patterns of collapses and to optimize the design concept and calculation parameters to improve the prediction accuracy. Moreover, optimizing the construction scheme and avoiding a large amount of drainage may be the most favorable means to reduce collapse.

7.5. Prevention of hydrological, ecological and environmental problems

In the past, workers have gradually reduced the negative impacts of tunnel excavation through geological hazard risk assessments, advanced geological predictions, improvements to lining materials, and improvements to construction technologies. However, significant challenges remain. The following work is still necessary.

Before tunnel excavation, it is necessary to carry out systematic surveys and monitoring of karst landforms and the hydrogeology, establish a real hydrogeological conceptual model, and accurately simulate and predict tunnel-related geological disasters in order to make accurate and scientifically founded decisions during tunnel excavations. To adapt to heterogeneous karst aquifers, the existing analytical solution should be modified in the prediction of tunnel water inflow. Different methods for early warning index systems and engineering verifications should be proposed for tunnel projects with different geological structures in karst areas. Additionally, the design scheme should be optimized such that the tunnel does not intersect areas with strong karstification or water saturation zones as much as possible.

For a tunnel under excavation, the principles of dynamic investigation, dynamic evaluation and dynamic construction should be adhered to. During construction, hydrogeological monitoring and investigation should be carried out, emergency conditions should be dealt with in a timely manner, prediction and evaluation should be upgraded, the scientificity and reliability of previous evaluation methods should be revised and verified, and construction strategies should be adjusted in a timely manner.

After tunnel excavation, it is necessary to carry out hydrological and ecological environmental investigations and monitoring, enhance the study of the classification and evaluation methods of ecological environmental impacts, optimize the quantitative evaluation index system of the ecological environmental impact, and propose evaluation criteria to improve the decision-making and management of tunnel construction and operation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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