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## Hydrogeology of the Pearl River Delta, southern China

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### ABSTRACT

The study describes the hydrogeological setting of the Pearl River Delta, a sub-tropical area of southern China encompassing the metropolises of Guangzhou, Shenzhen, Hong Kong and Macau. In the last 40 years, a booming economy and a population of about 60 million has increased water demand satisfied by a huge system of dams and reservoirs. Aquifers in the studied area are underutilized and only a few recent studies have addressed hydrogeological characterization at a local scale. Understanding groundwater dynamics of the Pearl River Delta is important for developing additional water supplies, understanding and mitigating groundwater pollution, and for implementing 'Sponge City' concepts. Via a collection of data from literature and field surveys, the hydrogeological setting of the area is synthesized and represented through thematic maps, cross sections and a hydro-stratigraphic column. Hydrogeological conceptual models are developed that describe the groundwater dynamics in urban and rural areas within the Pearl River Delta.

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## 1. Introduction

The Pearl River Delta is a sub-tropical area located alongside the South China Sea where a booming economy has developed in the last 40 years. The area encompasses numerous cities and megacities with Guangzhou located at the center of the fluvial delta and Shenzhen, Hong Kong and Macau along the southern edge of the estuary (Figure 1). Urbanization is persistent and continuous throughout the coastal areas and the main valleys. As in other tropical megacities, the area suffers from floods and urban waterlogging during the wet seasons and water shortages during the dry season. Numerous reservoirs and dams on the East River, West River and minor streams collect the abundant rainfall in the area (1650–2250 mm/year) (Main Map).

Despite the economic importance, hydrogeological literature about Pearl River Delta is sparse. GGS (1979, 1981) provided the first overview with two sets of hydrogeological maps scale 1:200,000. GBGP (1980) investigated the subsoil characteristics with a collection of boreholes stratigraphies and pumping tests. Zhong et al. (2009) investigated the Late Quaternary Pearl River Delta stratigraphy and Tang et al. (2011) provided information on Quaternary tectonics.

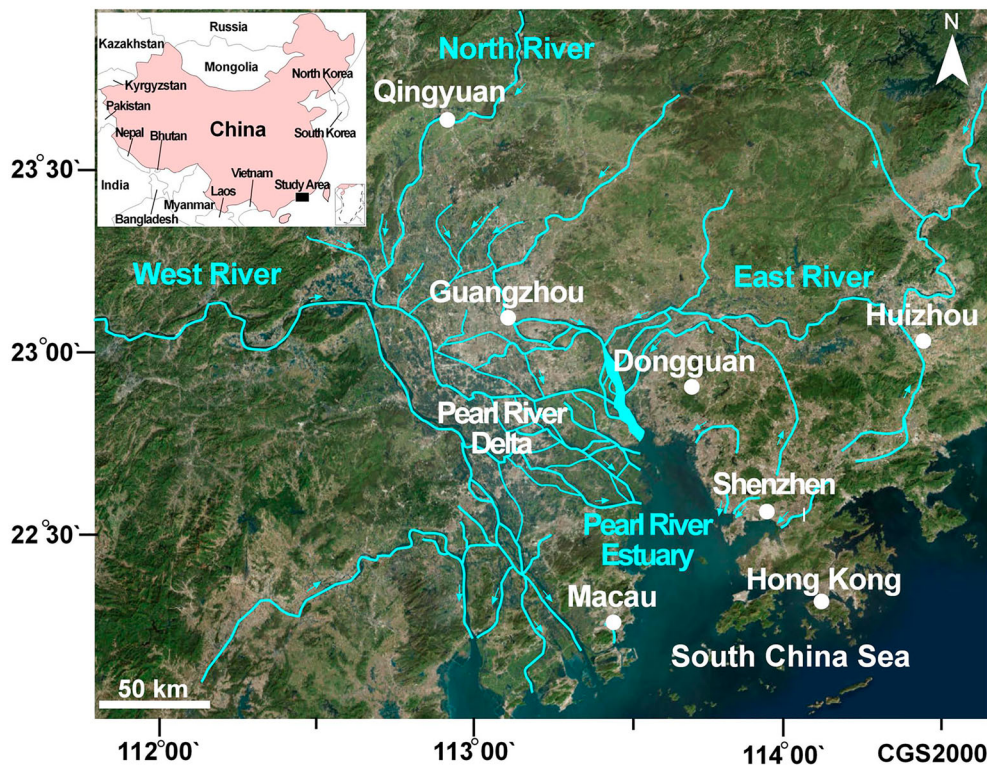
Urbanization and industrialization gave rise to several problems about domestic sewage management (Lu et al., 2008), slope stability (Jiao et al., 2006) and tunneling (Zhang et al. 2018). Huang et al. (2011) studied the distribution of arsenic in surface water and shallow aquifers of Pearl River Delta, observing values twenty to one hundred times higher than the background value. Wang et al. (2017) focus on submarine groundwater discharge via radon isotopes. Huang et al. (2018) and Zhang et al. (2019) analyzed the groundwater chemistry of Pearl River Delta finding groundwater contamination from domestic sewage and industrial wastewater. Lancia et al. (2019a) points out the complex geological setting of Shenzhen and compiled an average groundwater budget.

Further understanding of the groundwater dynamics could efficaciously assist in the development of groundwater resources, in understanding and mitigating groundwater pollution and in the application of the Sponge City concept to urban aquifers (Lancia et al., 2020). Thus, this study provides a comprehensive hydrogeological understanding of the Pearl River Delta at the regional scale via cartographic representation (Main Map); and develops hydrogeological conceptual models that describe groundwater

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**Figure 1.** Satellite image (CNES-AIRBUS 2017) of the Pearl River Delta, Guangdong Province (southern China). White circles indicate megacities, cyan lines main rivers, cyan arrows indicate river flow direction.

dynamics in rural and urban areas in the Pearl River Delta.

## 2. Methods

The map (*Main Map*) was developed via a collection and organization of hydrogeological and environmental data through a GIS database, scale 1:400,000. Elevation is represented with the Guangdong province DEM (Digital Elevation Model) with a resolution of 90 m (ASTER DEM V003), displayed as a shaded relief and grouped in classes to enhance the basin morphology (*Main Map*). Rainfall dataset is a combination of synthetic data from remote sensing and pluviometric stations (Chen et al., 2011). The dataset was interpolated through an ordinary kriging interpolation method (output cell size 0.01 degree; 12 number of points) and contoured with an interval of 50 mm/year (*Main Map*). Geological and hydrogeological data are from maps at various scale (GGS, 1979, 1981; Kirk et al., 2006; Yang et al., 2007), integrated with sketches and drawings from research papers (Huang et al., 2018; Lancia et al., 2019a, 2019b; Zhang et al., 2019; Zhong et al., 2009). Numerous geological formations were merged into nine hydrogeological units, after detailed analysis and interpretation of the available data, based on local hydrogeological features. The hydraulic conductivity dataset was developed from recovery pumping tests covering all the hydrogeological units (GBGP 1980) and estimations from numerical analysis of the groundwater system

in Shenzhen city (Lancia et al., 2019a). Average thickness and stratigraphic relationships among the identified units were represented through a stratigraphic column. Three geological sections illustrate the complex tectonic setting. Quantitative hydrogeological data come from a digitalization of GGS (1979, 1981) maps. Recharge was converted to millimeter per year (originally expressed in  $l/s\cdot km^2$ ) and catchments were manually drawn and associated to each measurement reported in GGS (1979, 1981).

Additional information was extrapolated from satellite image sets from different years, analyzing tone, color and pattern variation among pixels. The photogeological method is fast and efficient for investigating vast areas characterized by dense sub-tropical vegetation, with scarce road accessibility. Method is based on the analysis of color, tone and pattern variation in the satellite image pixels. A Landsat dataset from 1979 was used to describe the area before the massive urbanization of the Pearl River Delta. The geological limit between loose Quaternary deposits and older bedrock was delineated via photogeological detection, at 1:50,000 scale. At the same scale, a detection of tectonic lineaments was also performed. Field surveys were performed to refine the hydrogeological conceptual models and reduce the subsoil uncertainties. With the same technique, urban areas were detected on the CNES-AIRBUS 2017 satellite images at 1:100,000 scale. In addition, a comparison between recent and older satellite datasets was used to map the lands reclaimed after 1979. The Pearl River Delta



channel system was delineated from satellite images; raster files were processed to isolate the shallow water bodies, later converted in shapefiles and manually adjusted at 1:50,000 scale.

### 3. Geological and hydrogeological setting

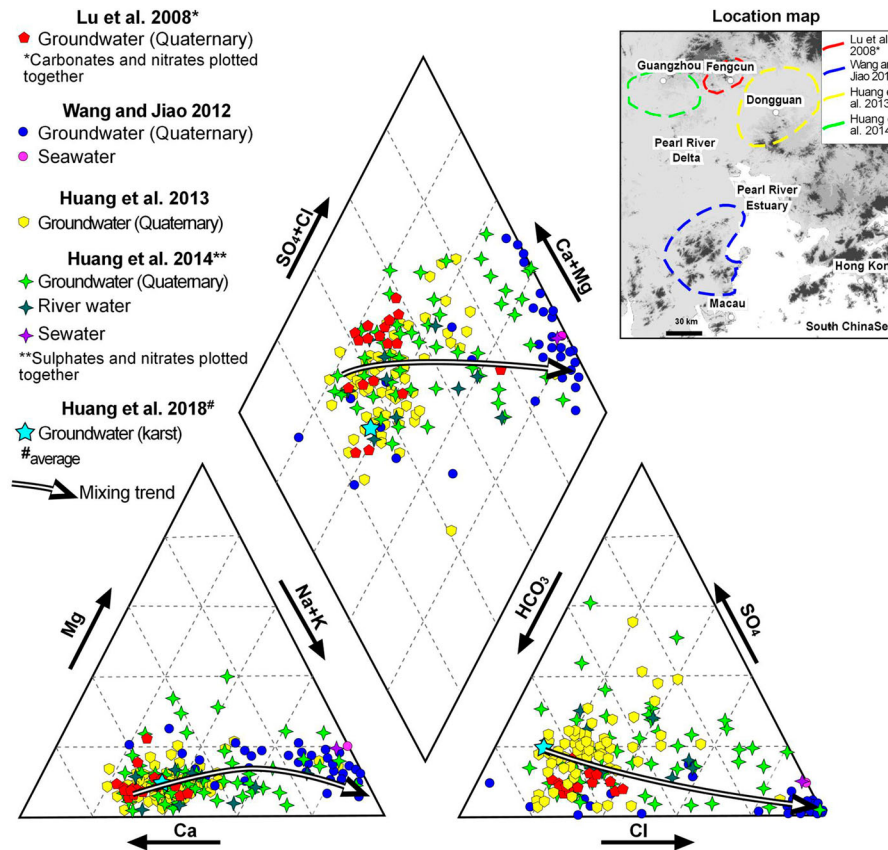
Pearl River Delta is a wide basin of southern China characterized by the confluence of North, East and West Rivers (total average annual discharge  $10,000 \text{ m}^3/\text{s}$ ) via hundreds of natural and anthropic channels with an anastomosed geometry (Figure 1). The study area is located on the southern boundary of the Cathysian block (Zhang et al., 2013). Stratigraphy consists of a metamorphosed Pre-Paleozoic basement overlain by a discontinuous Paleozoic to Mesozoic terrigenous sequence with carbonate units. Upper Mesozoic to Tertiary intrusions and volcanism break up the sedimentary bedrock (Darbyshire & Sewell, 1997). Quaternary marine to continental facies fill the depressions in the studied area. Pre-Paleozoic to Mesozoic bedrock experienced numerous transformations via regional and contact metamorphism, increasing petrographic complexities (Ren et al., 2016). From a structural point of view, the study area is a Neo-Paleozoic depression, superimposed and reworked by Mesozoic to Paleozoic tectonic events. Because of the geological complexity, many authors consider the investigated area a 'geological museum' (Zhang et al., 2018 and references therein). Only Tertiary strike-slip tectonics and more recent normal faulting are easily recognizable, as older structures have been obliterated. Faults are classed into three sets via their trend: NE-SW, NW-SE and W-E. The first set is evident and well-preserved; major tectonic lines shape the morphology of Pearl River Delta Basin and the coast line. Major lineaments in this trend are the Shenzhen fault, the Guangzhou-Conghua fault and the Wugui Mt. fault. Other fault sets are less developed, with a smaller scale and mostly intersecting the NE-SW main tectonic systems. Throughout the basin, shallow seismic exploration and field evidence in nearby Guangzhou reveal that the Quaternary sequence in many localities of the Pearl River Delta is faulted (Tang et al., 2011). Movement of Pearl River Delta faults is likely periodic or paroxysmal, surely not discontinuous or syn-sedimentary. Together with tectonics, climatic variations and subsidence affect the drainage system of the investigated area. Currently, the Pearl River Delta is a wide depression with elevations ranging from 0 to 10 m a.s.l., surrounded by steep reliefs with the highest points reaching 1200 m a.s.l. The Delta has hundreds of channels and streams connected together, increasing their density and connectivity toward the estuary. Groundwater dynamics of the depression is affected by surface water due to the flat morphology and the complicated hydraulic connection among shallow water bodies.

The Quaternary sequence is characterized by an anisotropic and heterogeneous groundwater flow (Huang et al., 2011). Zhong et al. (2009) describes two continental units and two marine units interbedded, with a total thickness varying from 20 to 90 m (GGS, 1979, 1981; Yang et al., 2007). Marine silt and clay deposits impede the groundwater dynamics and limit groundwater exchange between Quaternary and bedrock aquifers. At the base of the Quaternary sequence, bedrock aquifers are confined. In fact, Tertiary reworked sequence, karst layers and cataclastic rocks constitute subsoil zones rich in groundwater (Cui et al., 2015; Liu et al., 2017).

### 4. Hydrogeochemistry setting

Hydrogeochemistry of Pearl River Delta is complex due to the sea level variations at the geological time scale, accumulation of organic matter under tropical conditions as well as recent urbanization and industrialization. Water chemistry from Lu et al. (2008), Wang and Jiao (2012) and Huang et al. (2013, 2014, 2018) is synthetized in the Piper diagram of Figure 2. Groundwater sampled from Quaternary aquifers shows a mixing trend. From the estuary to the delta, an increment of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{HCO}_3^-$  ions is observed to the detriment of the  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$  and  $\text{Na}^+$ . In the coastal sector, groundwater shows high salinity, elevated concentrations of As,  $\text{NH}_4^+$ , dissolved organic carbon and low concentrations of  $\text{NO}_3^-$  and  $\text{NO}_2^-$ . High salinity (total dissolved solids [TDS] up to  $25,000 \text{ mg/L}$ ) derive from an initial marine transgression that flooded the Pearl River Delta and a subsequent migration of the shoreline towards the current condition during the late Holocene (Wang & Jiao, 2012). Reductive dissolution of iron oxyhydroxide is one of the important processes that mobilizes solid arsenic in groundwater, with concentrations up to  $0.16 \text{ mg/L}$  (Wang & Jiao, 2012). Abnormally high concentrations of  $\text{NH}_4^+$  (up to  $600 \text{ mg/L}$ ) are linked to the decomposition of organic material in the aquitard layers (Wang et al., 2013). Toward the north, groundwater has characteristics similar to the shallow water (Figure 2) with a low salinity (mean TDS  $450 \text{ mg/L}$ ) (Huang et al., 2014). Higher concentrations of  $\text{K}^+$  and  $\text{NO}_3^-$  are directly link with discharge of domestic sewage and septic tanks (Huang et al., 2018; Lu et al., 2008). However, Zhang et al. (2019) state that almost 22% of the porous aquifers of Pearl River Delta have a poor-quality, due to natural or anthropogenic conditions.

Karst sequences are confined and located beneath the Quaternary sequence. Water has high concentrations of  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  ions (Figure 2) and excellent quality (Huang et al., 2018). Similarly, fractured aquifers are also confined and located beneath the Quaternary aquifers. Water chemistry is variable depending on the water-rock interaction. The infiltration of



**Figure 2.** Piper diagram of Pearl River Delta representing groundwater and surface water, data from Lu et al. (2008), Wang and Jiao (2012), Huang et al. (2013, 2014, 2018).

agricultural fertilizer, and domestic sewage into groundwater is responsible for the increment of TDS,  $K^+$ ,  $Na^+$ ,  $Cl^-$ ,  $SO_4^{2-}$  and  $NO_3^-$  in fissured aquifers. However, only 9% of the fractured aquifers have a poor water quality (Huang et al., 2018).

## 5. Results and discussions

The **Main Map** describes the hydrogeological setting of Pearl River Delta. Collected information synthesizes the complex geological setting which are represented with four conceptual models. Presented models describe groundwater dynamics of rural and urban areas throughout the Pearl River Delta. The distribution of the identified conceptual models is illustrated in **Figure 3**.

## 6. Hydrogeological conceptual models

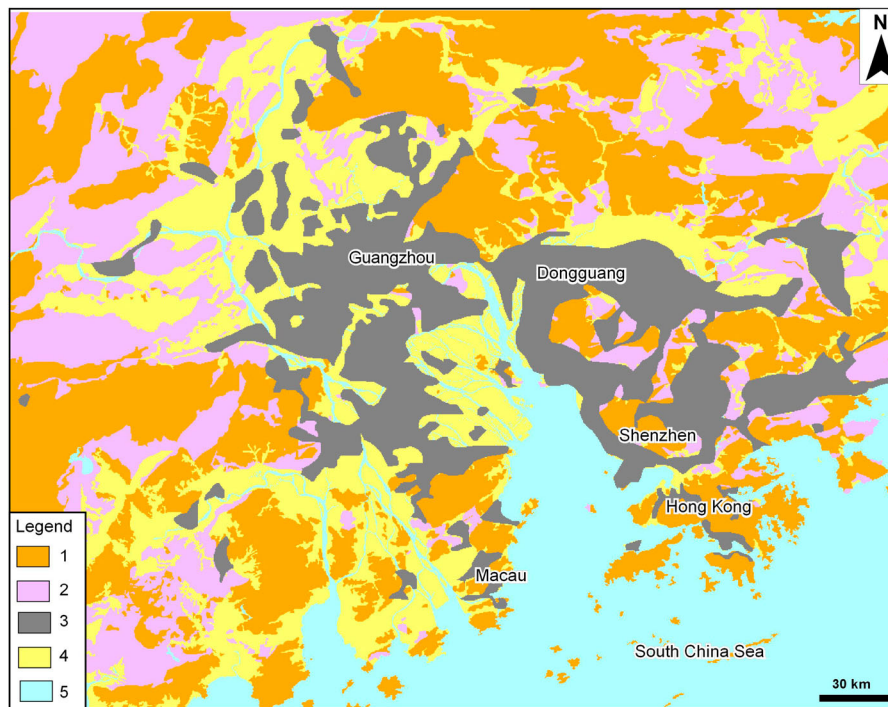
### 6.1. Intrusion bedrock model (rural areas)

Intrusive rocks (4, upper Mesozoic intrusion unit, in **Main Map**) characterize the main relief of the Pearl River Delta with large intrusions of several square kilometers. Bedrock has negligible porosity and open fractures are generally sparse and do not constitute a continuous net. The unit is an extended aquitard but fracturing locally increases in the cataclastic bands. The bands constitute local fissured aquifers with groundwater flow direction parallel to the fault trend. The fissured aquifer can extend below the Quaternary,

becoming confined. Mylonitic fault cores and metamorphism limit fissured aquifer extension. Towards the ground surface, subtropical conditions have created a continuous weathered blanket (Chen et al., 2017; Lancia et al., 2019b) comprising sand and silty sand (saprolite) and fractured to laminated bedrock. The weathered blanket constitutes a shallow aquifer distributed along the slope with an average thickness of 30 m. Groundwater flows parallel to the slope towards streams but anthropogenic elements such as roads or building foundations can interrupt the flow (**Figure 4** (a)). Recharge depends on many factors including the slope acclivity and exposure, occurrence of flow landslide as well as vegetation density (**Figure 4**(b)). Groundwater is collected along the valley incisions and contributes to the base flow of streams. Along the piedmont, farmers exploit this water for irrigation with rudimentary pipe systems. This conceptual model is also applicable to the fissured lava flows and pyroclastic flows (3, upper Mesozoic volcanic unit, in **Main Map**), when characterized by low porosity and hydraulic conductivity. The conceptual model is schematized in the **Main Map**.

### 6.2. Sedimentary bedrock model (rural areas)

The terrigenous bedrock (5 Mesozoic terrigenous unit, 6 Paleozoic terrigenous unit, 8 Paleozoic terrigenous clastic unit, 9 Basement unit in **Main Map**) is characterized



**Figure 3.** Distribution of the identified conceptual models throughout the study area. Key to the Legend: upper Mesozoic intrusive unit (1); sedimentary unit (2); urban areas (3); Quaternary unit in rural areas (4); water bodies (5).

by low hydraulic conductivity. Metamorphic processes confer stiffness to the rock masses reducing fracture aperture and length (Figure 4(c)). Due to the tropical conditions, a continuous weathered blanket covers the bedrock. The blanket is generally thinner when compared to the intrusive rocks. Recharge depends on many factors including the slope acclivity and exposure, occurrence of flow landslide as well as vegetation density (Figure 4(d)) (Lancia et al., 2019b). Along the surface, cataclastic bands (Figure 4(e)) or fracture zones are less developed than in the granite intrusions and the fissured aquifers have a lower transmissivity. The carbonate sequences have a different hydrogeological behavior. Limestone and dolostone (Paleozoic carbonate unit 7 in Main Map) are fissured aquifers with modest transmissivity. If exposed, aquifers are strongly karstified due to the sub-tropical conditions. Karst basins are mostly preserved at the bottom of the basins and fluvial valleys as carbonate media are resistant to weathering processes if metamorphosed. Current drainage is also mature in marble layers with open fractures, also mineralized (Figure 4(f)). When located below the Quaternary sequence, these aquifers are confined and can exchange groundwater flow with the coarser Quaternary sequence. The conceptual model of the sedimentary bedrock units is schematized in the Main Map.

### 6.3. Quaternary plain models (urban and rural areas)

The groundwater table is flat and water exchange between groundwater and shallow water occurs

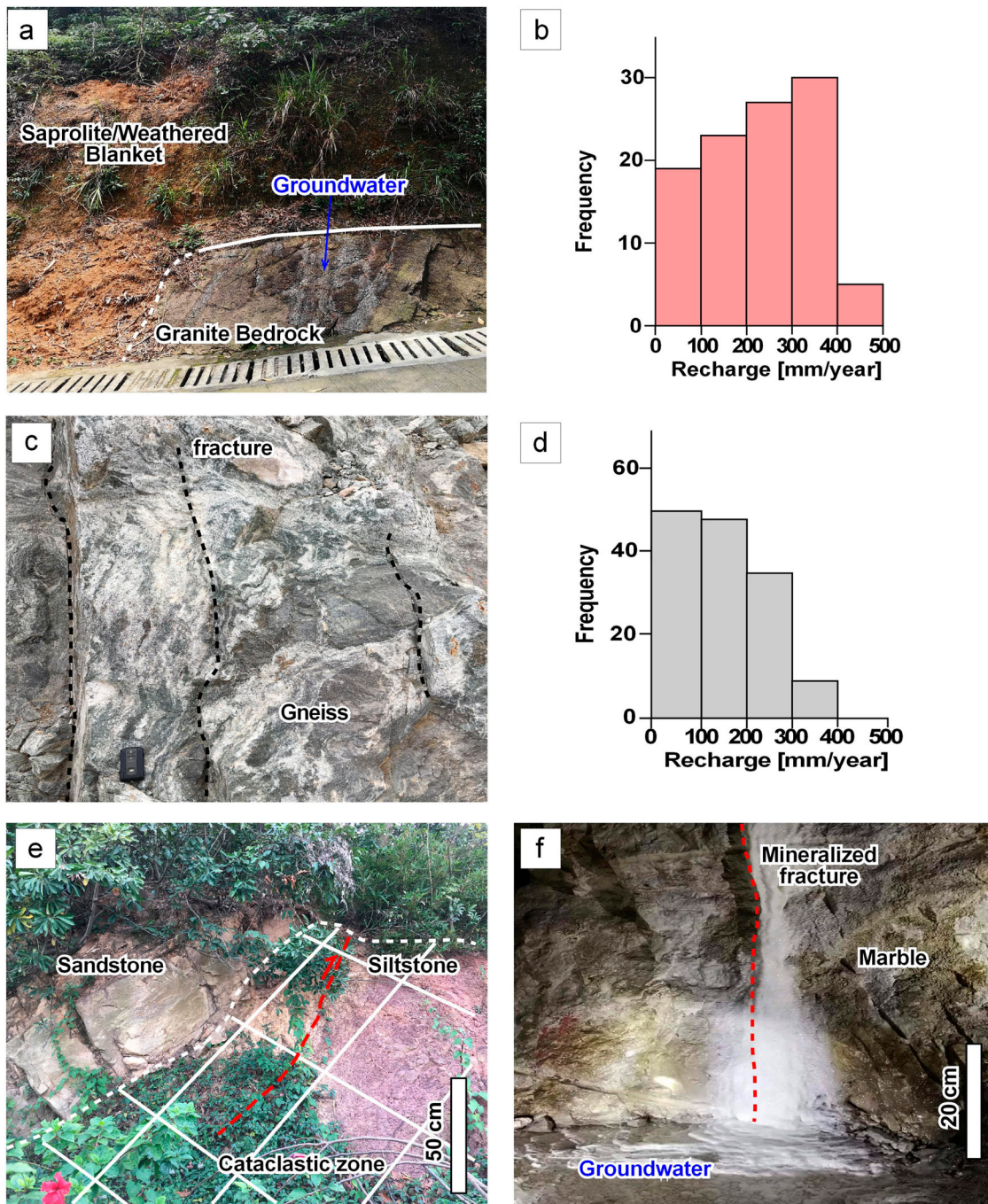
throughout the basin because of the flat morphology. In the urban areas, pressurized water-supply pipes leak from fractures and cracks recharging the shallow aquifers (Lerner, 2000). On the other hand, urban sewers in free flow condition drain groundwater when the groundwater table close to the ground level (Lancia et al., 2019b). As a result of this favorable condition, leakage represent a minor issue throughout the delta. In urban areas, the main pollution sources are chemical spillages, urban waterlogging and illegal discharge of factories to channels and streams.

In rural areas, the hydrogeological setting is similar. Continental and marine sediments with different grain size create multi-layer aquifers, up to 90 m thick. Clay lenses are aquitards and sand layers the aquifers. Irrigation with surface water mixed with domestic sewage and outdated septic tanks spread contaminants into the shallow aquifers (Huang et al., 2018; Lu et al., 2008). Clay lenses preserve confined aquifers from contaminant; currently, urbanization and industrialization do not affect the confined groundwater resources of karst aquifers and is limited on the fractured aquifers. However, groundwater overexploitation of confined aquifers should be avoided in polluted areas as it will accelerate cross-contamination from shallow aquifers. These conceptual models are schematized in the Main Map.

## 7. Conclusions

The hydrogeological setting of the Pearl River Delta is synthetized and represented via mapping and





**Figure 4.** Field evidence from Pearl River Delta: (a) contact between saprolite/weathered blanket (aquifer) and granite bedrock (aquitard), ephemeral groundwater discharge into a road ditch; (b) recharge rate frequency distribution for catchments characterized by the intrusion unit; (c) gneiss with sparse fractures; (d) recharge rate frequency distribution for catchments characterized by basement unit and/or Mesozoic to Paleozoic terrigenous unit; (e) contractional tectonic contact between sandstone and siltstone intersected by a cataclastic zone that locally increases rock-mass permeability; (f) karstified and mineralized fracture in marble with flowing groundwater, observed during tunneling.

conceptual models. With a recharge rate up to 500 mm/year, shallow aquifers of the mountain sectors contribute to river and streams as the bedrock is generally impervious. Along the delta, groundwater resources have a poor quality due to saline intrusions and complex geochemical processes. Below the Quaternary deposits, pristine confined aquifers (fissured and karstified) can contribute to satisfy the increasing groundwater water demand via water-wells. In urban areas, leakage from sewers is not a major issue as

groundwater likely seeps into the sewers throughout the basin. Main contaminant sources are chemical spillages, urban waterlogging, and illegal discharge of factories into channels and streams. Confined aquifers are sensitive to pollution when groundwater dynamics are altered by human activities. In rural and urban areas, new policies are recommended including irrigation with clean water, a modernization of the septic tanks and construction of sewers and water treatment plants. If shallow aquifers are polluted, exploitation of

confined aquifers should be discouraged to avoid contamination.

## Software

Collected data from literature and field activity were stored in a geodatabase and represented in a GIS environment (ArcGis 10.6.1 version).

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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