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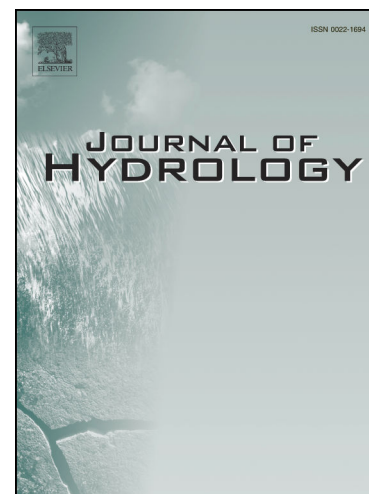
Characteristics of hydraulic conductivity in mountain block systems and its effects on mountain block recharge: Insights from field investigation and numerical modeling

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1 Characteristics of hydraulic conductivity in mountain block systems and its effects
2 on mountain block recharge: Insights from field investigation and numerical
3 modeling

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HLW: High-level radioactive waste; MBR: Mountain block recharge; MFR: Mountain-front recharge;
STEP: Scientific Expedition and Research Program; TDS: Total dissolved solid; URL: Underground
research laboratory; IQR: interquartile range

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Abstract

The process wherein groundwater flowing from mountain bedrock into lowland and adjacent alluvial aquifers, known as mountain-block recharge (MBR), is found across various climatic and geological settings. An understanding of the potential groundwater flow paths in mountain block systems is necessary for comprehending MBR spatial distribution. However, poorly characterized mountain block hydraulic properties, and especially a lack of direct measurements of hydraulic conductivity (K) at depths >200

m, limit the characterization and quantifications of the MBR processes. In this study, we analyze hydraulic data set, namely 555 in-situ K measurements at various depths from two borehole sections extending from mountain block to mountain front in a potential disposal site for high-level radioactive waste. The K dataset was categorized into two groups: one for bedrock and another for fault zones, which was further classified into fault core K , damage zone K , and general fault zone K . Using a permeability conceptual model and multiple scenarios numerical modelling, this study examined the potential flow paths of MBR processes, mainly focusing on the characteristics of K in bedrocks and the hydraulic role of fault zones in mountain block systems. The distribution of Bedrock K supports the assumption of decreased trend with depth. A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K) = -1.62 \cdot \text{Log}(z) - 6.52$, with low predictive power. This study illustrated the localized effects and spatially variable roles of fault zones in MBR within this particular hydrogeological configuration in Beishan, China. Our results provide insights into the MBR process in crystalline mountain block systems. Additionally, the hydraulic conductivity presented here provides data on the subsurface properties of mountain block systems in a crystalline area, and further facilitates the characterization and quantification of mountain-block recharge.

Keywords: mountain block recharge, mountain hydrogeology, fractured aquifer

49

50 **1 Introduction**

51 Mountainous areas play an important role in the global water cycle and constitute the
52 water source for numerous populated regions at lower elevations (Jódar et al., 2017;
53 Lone et al., 2021; Somers and McKenzie, 2020; Viviroli et al., 2020; Wilson and Guan,
54 2004). Water from mountainous areas recharges lowlands via mountain-front recharge
55 (MFR) and mountain-block recharge (MBR; (Aishlin and McNamara, 2011; Ajami et
56 al., 2011; Bresciani et al., 2018; Manning and Solomon, 2003; Markovich et al., 2019;
57 Peng et al., 2018; Taucare et al., 2020; Wilson and Guan, 2004). MFR refers to the
58 focused and net infiltration from perennial and ephemeral streams originating in the
59 mountain block, which occurs at the piedmont zone (Markovich et al., 2019; Wilson
60 and Guan, 2004). MBR refers to the groundwater flow from the mountain block into an
61 adjacent alluvial aquifer, and is also referred to as “inter-aquifer recharge” (Healy, 2010)
62 or “subsurface inflow” (Manning and Solomon, 2003). MBR may recharge adjacent
63 aquifers by two processes: diffuse MBR and focused MBR (Wilson and Guan, 2004).
64 Diffuse MBR occurs widely within mountain blocks, including the mountain front area
65 (Markovich et al., 2019; Wilson and Guan, 2004). Focused MBR corresponds to
66 groundwater flow through permeable colluvium-alluvium corridors in gullies or
67 canyons joining the adjacent basin, and oblique basement faults crossing the mountain

front area, which may promote groundwater flow into the adjacent basin (Figueroa et al., 2021; Markovich et al., 2019; Wilson and Guan, 2004).

Previous studies have largely focused on understanding the fundamental factors determining the location and extent of MBR, with the hydraulic conductivity (K) distribution within mountain bedrock and the role that fault zones play being two vital factors (Gleeson and Manning, 2008; Markovich et al., 2019; Welch et al., 2012; Wilson and Guan, 2004). K distribution was identified as one of the first-order controls of the rate and distribution of MBR (Forster and Smith, 1988; Gleeson and Manning, 2008; Haitjema and Mitchell-Bruker, 2005; Markovich et al., 2019; Welch et al., 2012; Wilson and Guan, 2004). The general conceptual model for mountain groundwater flow systems is composed of a higher- K “active” zone (the aquifer) that overlies a deep low- K zone (relatively impermeable bedrock) (Manning and Caine, 2007; Markovich et al., 2019; Welch et al., 2012). The existence of an “active” zone with $K > 10^{-8} \text{ m}^{-1}$ where active mountain groundwater flow can be produced, and a recharge rate greater than roughly 10 mm/year are prerequisites for the occurrence of MBR (Markovich et al., 2019). If some MBR exists, major faults near the mountain front can potentially either impede or enhance MBR. Theoretically, major faults oriented at a high angle to the MBR flow paths might act as barriers to MBR as the groundwater must flow across the fault zone to enter the adjacent aquifers (Chowdhury et al., 2008; Delinom, 2009;

Figueroa et al., 2021; Kebede et al., 2008). In contrast, obliquely oriented faults (more parallel to MBR flow paths) within the bedrock could act as conduits for groundwater flow and promote MBR (Figueroa et al., 2021). However, the results from field examination, hydrochemical, and groundwater age assessment provide evidence that the orientations of faults do not determine their role in mountain block hydrogeological processes (Caine et al., 2017; Kebede et al., 2008), and the oblique oriented faults could act as barriers to MBR. Therefore, the possible permeability structure and the actual hydraulic influence of mountain-block faults in MBR processes (impeding or enhancing) remain speculative.

Although the vital controls of the MBR process have been identified, the characterization and quantification of MBR processes remain challenging in mountain block hydrogeology because of the intrinsic heterogeneity of K distribution and fault zones and data limitation, particularly of subsurface data from the mountain block and mountain front (Markovich et al., 2019; Yao et al., 2017).

Several studies proposed to bypass determining actual K distribution by employing synthetic or semi-synthetic subsurface K structures in models (Engdahl and Maxwell, 2015; Gleeson and Manning, 2008; Voeckler et al., 2014; Wang et al., 2018a; Welch et al., 2012). Few studies are based on the actual K , using data sets at depths of 0–20 m (Ameli et al., 2018) and 10–200 m (Welch and Allen, 2014). Most of these works have

generally converged that the typical groundwater active circulation depth for fractured crystalline rock environments may extend to 200 m subsurface, with $K = 10^{-8} \text{ m}\cdot\text{s}^{-1}$ (Manning and Ingebritsen, 1999; Markovich et al., 2019; Rapp et al., 2020), surpassing the K data depth previously used. In addition, the target depth of geo-environmental systems engineering related to mountain groundwater systems is much deeper. For example, the site selection for long-term nuclear waste is targeted at 300–500 m (Tóth and Sheng, 1996; Voss and Provost, 2001; Wang et al., 2018b); whereas CO_2 geological storage target depths are $\geq 800 \text{ m}$ (Bickle, 2009; Gunter et al., 2004). In contrast, direct subsurface measurements of K at depths $> 200 \text{ m}$ are rare (Markovich et al., 2019). Therefore, studies providing access to a range of actual bedrock properties (especially K) at depths $> 200 \text{ m}$ should be prioritized in mountain block system hydrogeology.

In this study, we report a series of in-situ measured hydraulic conductivities ($n = 555$) from a crystalline mountain block system to complement hydrogeological databases at depths $> 200 \text{ m}$ in mountain systems. The data set includes K measured in crystalline bedrock ($n = 512$) and within fault zones ($n = 43$), ranging from 0 m to 592.3 m below the ground surface (mbgs). All data were obtained from the Beishan area, Gansu Province, China, a disposal site for high-level radioactive waste (HLW). Given the possibility of groundwater acting as a carrier of radionuclides, understanding the flow paths in MBR processes in the study area is critical for determining the safety of HLW

disposal. Based on a permeability conceptual model and numerical modelling built on in-situ measurements, this study explores the possible flow paths for MBR in this area, focusing on the K distribution, associated heterogeneity and the hydraulic role of fault zones.

2 Study area

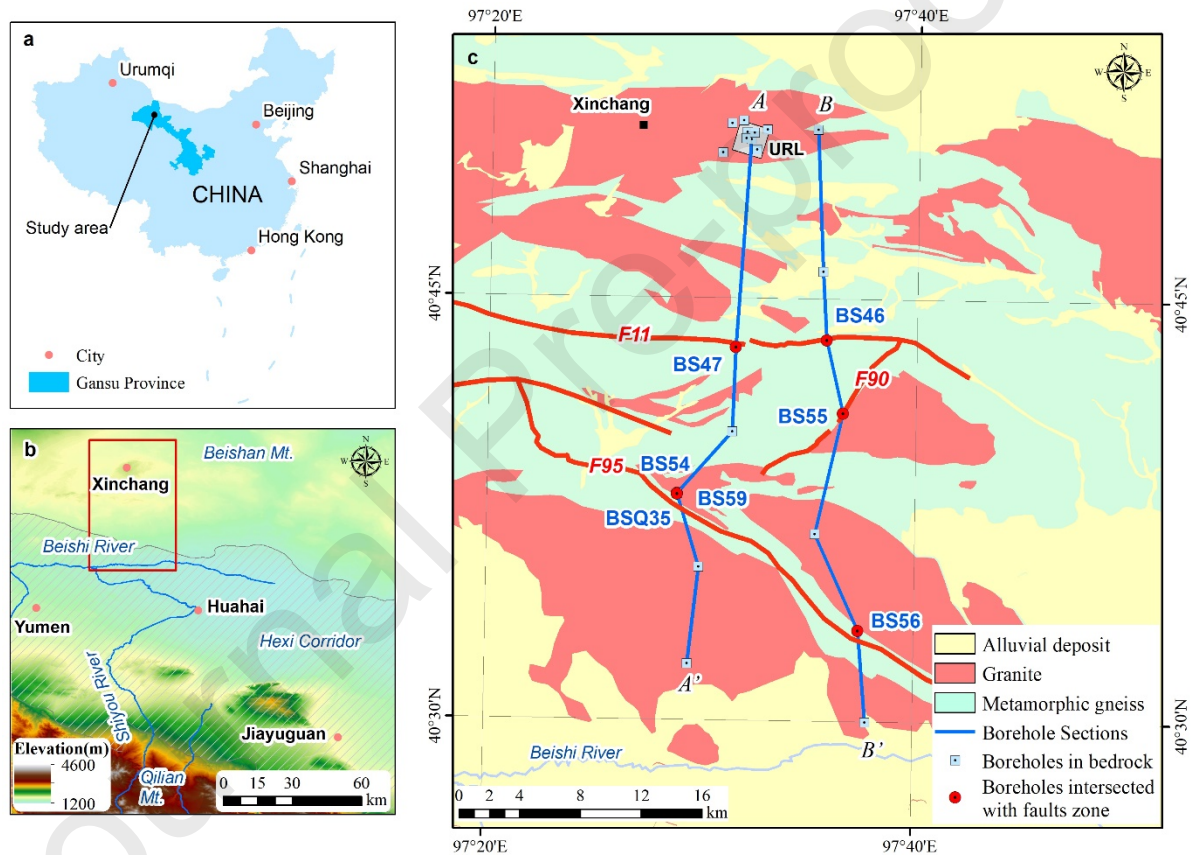


Figure 1. a. Location of the study area, b. topography of the study area, and c. borehole sections (where field data were obtained) and geology.

This study was conducted in the Beishan area situated in the Gansu Province of

northwestern China (Fig 1a). The study area is an inland mountain range covering an area of approximately 3,973.9 km² and is located north of the Huahai Basin in the Hexi Corridor, where multiple cities (including Yumen, Jiayuguan, and Huahai) with more than 9 million inhabitants are located. With an altitude ranging between 873 m and 2,556 m above sea level, the Beishan area primarily consists of low altitude mountains and small hills. The Xinchang Site, which is the prospective location for China's HLW repository and the location of China's first underground research laboratory (URL), is located to the southwest of the Beishan area and is approximately 60 km from the nearest city of Yumen (Fig 1b). The site covers an area of >100 km² with an altitude ranging between 1,400 and 1,800 m (Zhou et al., 2020)

Metamorphic rocks (mainly Ordovician or Silurian gneiss), intrusive rocks (mainly Permian granite) and sediments (mainly Quaternary clay and sandy loam weathered from gneiss and granite) comprise the main lithology of the study area, with occasional alluvium deposits (usually <10 m) in the ground (Peng, 2013; Wang et al., 2018b). The cores obtained from the Xinchang Site are dominated by gneissic biotite monzonitic granite and biotite granodiorite (Zhao et al., 2016).

The Beishan area is characterized by an arid climate with an annual average precipitation of 73.1 mm·yr⁻¹ and a mean annual potential evaporation of >3,000 mm (Zhou et al., 2020). Except for the Beishi River, a river originating from Qilian

Mountain and flows eastward passing the study area, no other perennial river is found within the area due to extreme drought, although ephemeral deluge can occur after brief precipitation events in the summer (Cao et al., 2017a; Cao et al., 2017b; Dong et al., 2009).

Several faults have been identified in the study area, including two major faults (F11 and F95), and several local faults (F90). The fault kinematics and architectures, as determined by surface geological mapping and borehole drilling, are provided in Table 1 (Gansu Geology Survey, 1978; Guo et al., 2003; Guo et al., 2014; Wang et al., 2018b). The F11 fault is located in a metamorphic gneiss south of the Xinchang Site and is approximately perpendicular to the mountain slope. F90 is the most representative of the secondary faults of F11 and is located in granite and metamorphic gneiss (Gansu Geology Survey, 1978). The F95 fault is an NW striking fault developed in metamorphic gneiss between two intrusive granite zones and extends directly from the mountain front to the Huahai Basin (Gansu Geology Survey, 1978; Guo et al., 2003; Guo et al., 2014; Wang et al., 2018b).

Table 1. Fault kinematics and architectures.

Section	Fault	Strike	Dip	Geology	Thickness
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					Total zone (m)	Fault core (m)	Damage zone (m)
A-A'	F11	W-SW	70	Metamorphic gneiss	-	10.6	-
	F95	NW-SE	78	Metamorphic gneiss	64.4	30.2	34.2
B-B'	F11	W-SW	60	Metamorphic gneiss	-	1.4	-
	F90	NE-SW	60	Granite & Metamorphic gneiss	52.4	-	-
	F95	NW-SE	75	Metamorphic gneiss	67.0	1.6	65.4

Hydrogeochemical characteristics reveal the evolution processes of groundwater by recording the interaction between groundwater and the aquifer medium. Accordingly, the hydrogeochemical data of groundwater in the Beishan area were comprehensively collected from published literature, revealing a range of pH values from 7.39 to 10.14, groundwater temperature between 8 and 17 °C, and a total dissolved solid (TDS) content of 0.7–19.0 g·L⁻¹ (Guo et al., 2014; Li, 2020; Wang et al., 2018b; Wang, 2015). In particular, high TDS was observed in shallow groundwater, indicating that the

groundwater underwent strong evaporation. Based on isotopic data and groundwater age, previous studies have also shown that groundwater in the study area is recharged primarily by local precipitation (Li, 2020). The groundwater flow is controlled by topography (Dong et al., 2009; Wang, 2015).

3. Methods

3.1 Hydraulic conductivity measurements, categories, and characterization

3.1.1 K measurements and categories

A total of 555 hydraulic conductivity measurements were obtained from 22 boreholes (Table 1). Boreholes were drilled through the surface weathering rock and into the bedrock, reaching a maximum depth of 690.7 m, permitting the characterization of the mountain block hydraulic conductivity. All data were obtained via in-situ tests (including constant-head injection, plug, or slug tests using packer systems); therefore, these data are all defined as bulk permeability instead of matrix permeability (Scibek, 2020; Scibek et al., 2016). The measuring intervals of in-situ tests differ from 12 to 50 m along the boreholes, and were also extended to 202 m to investigate the fault zones intersected by the boreholes.

Seven of the 22 boreholes have intersected fault zones. Data from all 555 hydraulic

conductivity measurements were classified into two categories based on the measured locations: Bedrock K , which refers to K obtained from in-situ tests conducted away from any fault zones ($n = 512$, shown as blue squares in Figure 2), and K measured in fault zones ($n = 43$, shown as circles in Figure 2). For K measured in fault zones, the data were further divided into three categories: Core zone K , which refers to the data obtained within the zone that is clearly identified as a fault core and isolated in the in-situ tests ($n = 2$, shown as yellow circles in Figure 2); Damage zone K , which refers to the data measured only within the fault damage zone ($n = 33$, shown as red circles in Figure 2); and General fault K , which refers to the data from test intervals including both fault damage zones and the main fault core zones ($n = 8$, shown as green circles in Figure 2). General fault K occurred due to either of two reasons: the isolation of the fault core zone or damage zone was not available for in-situ tests due to potential collapsibility of boreholes, or, it was difficult to clearly identify the damage and fault core zones within a fault zone.

The Bedrock K data ($n = 512$, shown as blue squares in Figure 2a) was divided into measurement depth intervals of 50 m, and the arithmetic mean, median, 10% and 90% confidence distribution of each interval were calculated. A linear regression of log hydraulic conductivity ($\log K$) over log depth ($\log z$) was performed on the Bedrock K data, considering the previous understanding that K decays exponentially with an

210 increase in depth (Achtziger-Zupančič et al., 2017).

211 3.1.2 Characterization of permeability structure

212 A vertical layer profile of the study area was created based on the data. Instead of
213 adapting detailed definitions and descriptions of weathering and fracture, the vertical
214 distribution of K and its relative differences established the primary principles for
215 constructing a conceptualized model of the mountain block systems.

216 From a hydrogeological perspective, a domain can be viewed as a pervious formation
217 with $K \geq 1.00 \text{ E-8 m}\cdot\text{s}^{-1}$, where active groundwater flow may be produced (Katsura et
218 al., 2009; Markovich et al., 2019; Welch and Allen, 2014). Therefore, a threshold value
219 of $K_0 = 1.00 \text{ E-8 m}\cdot\text{s}^{-1}$ was adapted to indicating K 's relative difference by depth in
220 bedrock. The probability $K > K_0$ (P) and the arithmetic mean K value of every 50 m
221 depth were calculated. Based on the calculated results and the vertical conceptual model
222 for fractured crystalline-rock mountain block system of Welch and Allen (2014), the
223 vertical permeability structure of the mountain block in the study area was then divided
224 into three layers: the Weathered Zone (including soil and highly weathered rock), the
225 Fractured Zone, and the Inactive Zone (relatively impermeable bedrock with majority
226 of $K < K_0$, where active groundwater may not be produced).

227 The permeability ratios (Scibek, 2020) can be used to quantify the “conduit” or “barrier”

magnitudes of a fault zone using the permeability of the general fault zone (or fault core) and host rock obtained at specific locations (ideally along the same drillhole or outcrop section). In this study, permeability (m^2) was replaced with hydraulic conductivity ($\text{m}\cdot\text{s}^{-1}$) in the calculation for data consistency, and therefore refers to this ratio as hydraulic conductivity ratio (K ratio).

$$K \text{ ratio} = \log_{10} \frac{K_{\text{General fault zone/ Core}}}{K_{\text{Host rock}}}$$

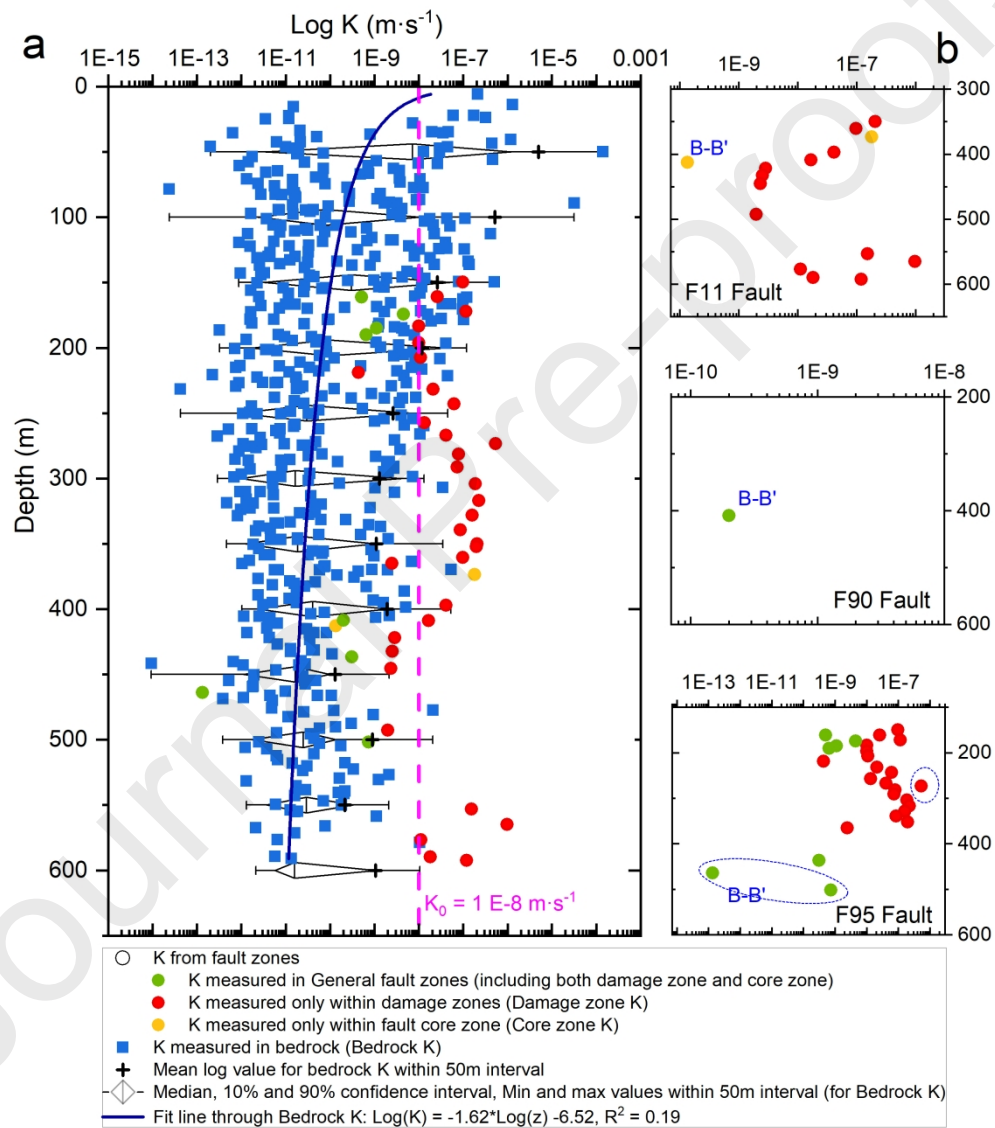
3.2 Groundwater flow analysis– numerical modelling

To investigate the flow behavior of faults in the study area, a 2D hydrogeological numerical model coupled with particle tracking was applied. MODFLOW-USG was used to simulate the hydrogeological processes of mountain blocks, and Darcy's Law Module was used to describe groundwater flow. We constrained the model based on the topographical section B-B', as well as the hydraulic properties described in Section 4.

241 4. Results

242 4.1 Characteristics of hydraulic conductivity

243 4.1.1 Hydraulic conductivity of bedrock



244

Figure 2. Distribution of hydraulic conductivity (K) with depth, a. Depth trend of K for bedrock (n = 512, shown as blue squares) and fault zones (n = 43, shown as circles) derived from in-situ hydraulic testing in 22 boreholes; b. K from three faults, i.e., F11 fault, F90 fault and F95 fault.

Figure 2a shows K distribution with depth in the study area, including Bedrock K ($n = 512$) and K from fault zones ($n = 43$). Both the highest hydraulic conductivity ($1.40 \text{ E-}4 \text{ m}\cdot\text{s}^{-1}$ at 50.0 m depth) and lowest hydraulic conductivity ($9.39 \text{ E-}15 \text{ m}\cdot\text{s}^{-1}$ at 441.5 m depth) were observed in Bedrock K . Only two of the 555 K data are greater than $1.00 \text{ E-}5 \text{ m}\cdot\text{s}^{-1}$, both within the depth less than 100.0 m. The hydraulic conductivity data is shown to be more scattered at shallow depths than at deeper ones, and shows substantial variance near the surface.

A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K) = -1.62 * \text{Log}(z) - 6.52$, with low predictive power ($R^2 = 0.19$). The slope of the regression reveals that the hydraulic conductivity averages 1.62 orders of magnitude per order of magnitude of depth change.

4.1.2 Fault zone hydraulic conductivity

Figure 2b shows 43 K measured in fault zones (2 Core zone K , 33 Damage zone K , and 8 General fault zone K), revealing the permeability of three faults: F90, F95 and F11.

For F11, two Core zone K were measured in boreholes at different locations that showed a large variance: $1.80 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$ in the western part (A-A'), and $1.34 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ in the eastern part (B-B'). All Damage zone K of F11 were obtained from the same borehole located in the western part (A-A') and are distributed within 2 orders of magnitudes ($1.97 \text{ E-}9 \text{ m}\cdot\text{s}^{-1} - 9.71 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$).

The overall hydraulic conductivity of F90 (including fault core and damage zone) was low permeable with a General fault zone K of $2.00 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$. For F95, General fault zone K obtained from the western part (B-B') ranged from $1.33 \text{ E-}13 \text{ m}\cdot\text{s}^{-1}$ to $7.31 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$, with the ones from the western part (A-A') showing a larger variance. Damage zone K were all centralized between $4.31 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ and $5.35 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$.

4.2 Mountain-basin conceptual model

4.2.1 Bedrock permeability structure

Based on the calculated results and the vertical conceptual model for fractured crystalline-rock mountain block system of Welch and Allen (2014), the vertical permeability structure of the mountain block in the study area can be classified into three layers: 0–50 mbgs for the Weathered Zone (including soil and highly weathered rock), 50–350 mbgs for the Fractured Zone, and >350 mbgs for the Inactive Zone (relatively impermeable bedrock with majority of $K < K_0$).

The arithmetic mean value of K was $4.80 \text{ E-}6 \text{ m}\cdot\text{s}^{-1}$, $1.01 \text{ E-}7 \text{ m}\cdot\text{s}^{-1}$, and $9.08 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ for the Weathered Zone, Fractured Zone, and Inactive Zone respectively. The proportion of $K \geq K_0$ was 48.28% within the Weathered Zone, whereas it decreased to 13.22% within the Fractured zone and to 2.24% within the Inactive Zone (350–600 m).

To better reveal the hydraulic properties of each layer, the interquartile range (IQR) measure of statistical dispersion was used to remove extreme K values in each layer. Subsequently, the arithmetic mean K values of the three layers were recalculated as $1.16 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$ for the Weathered Zone, $5.69 \text{ E-}9 \text{ m}\cdot\text{s}^{-1}$ for the Fractured Zone, and $9.08 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$ for the Inactive Zone.

4.2.2 Permeability structure of faults

Table 3 lists the calculated K ratios of faults, indicating their potential permeability structures in the study area. The K ratio of F11 in the western part (A-A') was 2.64, which indicates a potential conduit for groundwater; however, the ratio in the eastern part (B-B') was -1.81, which suggests a potential barrier for groundwater. This inconsistency in hydraulic properties implies possible spatial variability in permeability structure for the same fault.

In contrast to F11, F95 shows consistency in K ratios: -0.75 and -0.53 for the western part (A-A') and the eastern part (B-B') respectively, indicating that F95 may impede

groundwater flow and acts as a “barrier”. K ratio of -0.96 for F90 also suggests a potential “barrier” for groundwater flow.

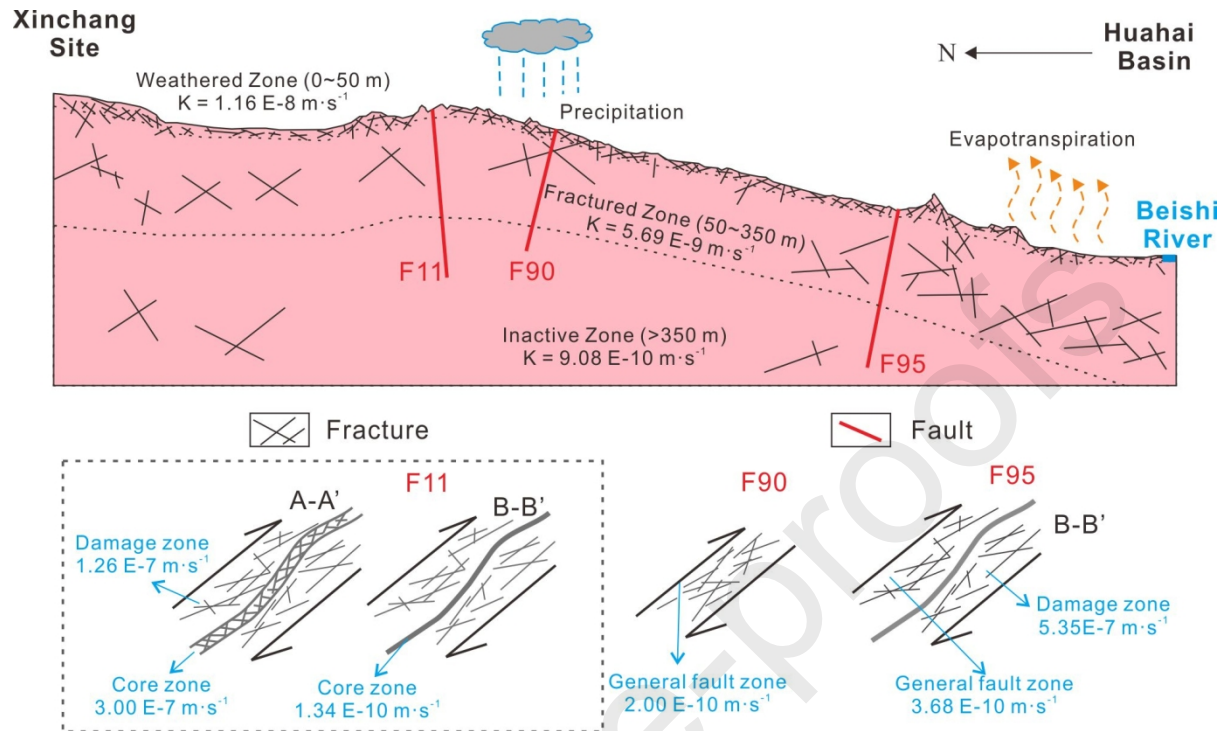
*Table 2 Fault information and calculated K ratios (*represented averaged values)*

Section	Fault	General fault zone K	Core zone K	Host rock K	K ratio
A-A'	F11	-	3.00E-7	4.15E-10*	2.86
	F95	1.41E-9*	-	7.89E-9*	-0.75
B-B'	F11	-	1.34E-10	8.74E-9*	-1.81
	F90	2.00E-10	-	1.84E-9*	-0.96
	F95	3.68E-10*	-	1.25E-9*	-0.53

4.2.3 Conceptual model

A conceptual hydrogeological model of the study area is shown in Figure 3. Based on the permeability structures of bedrock and faults, the 2D conceptual model was vertically divided into three layers. The arithmetic mean K values with extreme values removed by the interquartile range (IQR) method were selected to represent each zone. Three faults (F11, F90, and F95) were considered in this conceptual model. The hydraulic conductivity of F95 and F90 were labelled according to the information obtained on the eastern part (B-B'). However, their hydraulic impact remains the primary source of uncertainty in this conceptual model for characterizing groundwater flow patterns in the study area.

307



308

Fig 3. Conceptual hydrogeological model of the study area, and the permeability structures of faults (A-A', B-B' representing the sections where hydraulic conductivity was measured).

4.3 Groundwater flow patterns in study area – numerical model results

4.3.1 Model scenarios and setup

The following four field scenarios were developed based on the permeability conceptual model built in Section 4.2: homogeneous permeability, layered permeability, layered permeability with low permeable core zone of F11, and layered permeability

with high permeable core zone of F11. All scenarios were simulated in steady state flow, with Scenarios 3 and 4 designed to investigate the potential hydrogeological role of F11, F90, and F95 faults. The scenario details are as follows:

Homogeneous scenario: Served as the baseline model, where an arithmetic mean K value of the weathered zone calculated in Section 4.1 ($1.16 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$) was applied to represent the general hydraulic conductivity. This approach maintained a constant hydraulic property of the model domain, allowing the results to reflect a direct control of topography on groundwater flow patterns within the study area.

Layered: without faults (Layered permeability field) scenario: Here, the permeability was consistent with the conceptual model in Section 4.2.3, except for the faults. This scenario did not include faults, an appropriate assumption when controlling for the vertical distribution of K along the hydrogeological conditions of mountain blocks.

Layered: low K fault (Layered permeability field scenario with low permeable core zone of F11) scenario: Building upon the former scenario, but considering three faults (F11, F90, and F95). F11 and F95 were conceptualized as damage zones and fault cores. The measurements of the western part (B-B') of F95 were used to represent this fault: an average of General Fault zones K ($3.68 \text{ E-}10 \text{ m}\cdot\text{s}^{-1}$) was assigned to the core zone (as no measurement was available within the F95 fault

core); the measured Damage zone K ($5.35 \text{ E-7 m}\cdot\text{s}^{-1}$) was used for damage zone.

For F11, the lower measured value of $1.34 \text{ E-10 m}\cdot\text{s}^{-1}$ was selected to represent the permeability of F11 fault core (Figure 3), and the damage zone hydraulic conductivity was $1.26 \text{ E-7 m}\cdot\text{s}^{-1}$.

Layered: high K fault (Layered permeability field with a highly permeable core zone of F11) scenario: Building upon the former scenario, but replacing the K value of F11 fault core zone with $3.00 \text{ E-7 m}\cdot\text{s}^{-1}$.

The upper boundary of this model was conceptualized as a constant-head boundary to reflect the high correlation between hydraulic head and topography within the study area. At this boundary point, the groundwater head was identical to the ground elevation. The Beishi River, located at the foot of the mountain bedrock, was also regarded as a constant-head boundary; whereas the lateral and lower boundaries were specified as no-flow boundaries. Precipitation and evaporation were not considered in the model. While the study area has a typical arid climate (low precipitation, high evaporation), this assumption is appropriate as the model simulates the general topography and hydraulic properties of groundwater flow patterns under steady state flow. This approach allows for a clearer understanding of the groundwater flow pattern response to change in hydraulic properties (e.g., fault zones).

The model domain was divided into 39,056 unstructured grids, and the meshes were

required to be finer around the model boundaries and faults. Meshing quality was examined to ensure that each fault zone contained multiple elements was fully described in the model. Particle tracking was employed to investigate the differences in groundwater flow paths between model scenarios. A total of 2,038 particles were set up along the ground boundary, and their traces were recorded and exported.

4.3.2 Model results

Simulation results for the four scenarios are shown in Figure 4, where multiple types of streamlines distributions are presented (only representative streamlines were showed for distinguishability). Multiple types of streamlines (A, B, C, and D) are labelled to illustrate the differences in groundwater flow patterns: A represents the streamlines reaching deep positions; B represents the streamlines at the location of F11; C represents the streamline at the location of F90; D represented the streamlines at the location of F95.

While A streamlines are commonly observed in the *Homogeneous* scenario (Figure 4a), they are absent in the layered scenarios. B streamlines in the *Layered: without faults* scenario (Figure 4b) differ from those in the *Layered: low K fault* scenario (Figure 4c), but they are similar to those in the *Layered: high K fault* scenario (Figure 4d), implying impacts caused by the changes in permeability of the F11 fault core. In the *Layered:*

low K fault scenario, groundwater is hindered from flowing across the F11 fault zone but is driven along the damage zone. However, the B streamlines in *Layered: high K fault* indicate groundwater flowing across the F11 fault zone. The C and D streamlines in the *Layered: low K fault* and *Layered: high K fault* scenarios show the same distribution as F90 and F95 had identical permeabilities in these scenarios. In both scenarios, C and D streamlines suggest impeded groundwater flow compared with that in the *Layered: without faults* scenario.

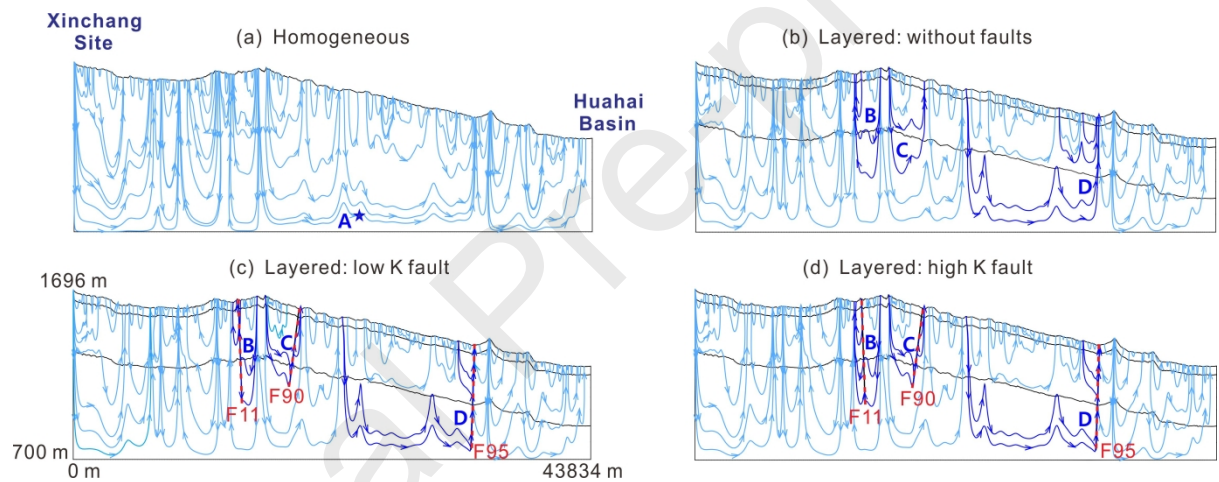


Figure 4. Streamline distributions of four model scenarios: A, B, and C represent observed streamlines to highlight the differences in groundwater flow patterns.

5. Discussion

5.1 Depth trend of Bedrock K in crystalline basement

The crystalline basement, being mostly granite and gneiss, is generally low-

conductivity media where interconnected fracture porosity and permeability determine groundwater flow behaviors (Rutqvist and Stephansson, 2003). The permeability of crystalline rocks varies in space both horizontally and vertically due to fracture interactions, and the vertical permeability is generally assumed to decrease with depth (Achtziger-Zupančič et al., 2017; Brace, 1980; Manning and Ingebritsen, 1999; Ranjram et al., 2015; Stober and Bucher, 2007). The decrease with depth was also observed in the K obtained in crystalline bedrock composed of gneiss and granite within 600 mbgs in this study (Fig 2a). High hydraulic conductivity values were mostly observed within depths of <100 m (especially within depths <50 m). The range between the maximum and minimum K decreased with depth from approximately 9 orders of magnitude ($1\text{E-}14$ to $1\text{E-}4 \text{ m}\cdot\text{s}^{-1}$) near the surface to approximately 4 orders of magnitude in the deepest interval ($1\text{E-}12$ to $1\text{E-}8 \text{ m}\cdot\text{s}^{-1}$). As lithology may be of less importance in crystalline rock permeability at near-surface depth (<1,000 m), the higher and more scattered K values near the surface may indicate greater sensitivity to weathering and tectonic setting alteration (Achtziger-Zupančič et al., 2017; Ranjram et al., 2015).

A total of 91% of Bedrock K is distributed between $1.03 \text{ E-}12 \text{ m}\cdot\text{s}^{-1}$ – $9.82 \text{ E-}8 \text{ m}\cdot\text{s}^{-1}$, which is generally less permeable than Carnmenellis Granite (Cornwall, UK) of similar depth (Watkins, 2007). As shown in Figure 5, the K range in the study area is of smaller

400 values and larger variance than that in the Black Forest area of Germany, which has a
401 similar lithology of gneiss and granite (Stober and Bucher, 2007). The discrepancy is
402 also obvious in the logarithmic fits for the depth trend of permeability. The resulting
403 trend for Bedrock K in our study area yields a smaller slope and intercept than that
404 derived in the Black Forest area by Stober and Bucher (2007), as well as the depth trend
405 derived for a global database in crystalline rock by Achtziger- Zupančič et al. (2017).
406 The slope and intercept are also substantially significantly lower than the widely cited
407 curve derived by Manning and Ingebritsen (1999). This lack of agreement is expected
408 as these fits are derived to describe permeability at larger depths than those reported in
409 this study. Although Bedrock K in our study area verified the assumption of a decreased
410 trend with depth, the low predictive power ($R^2 = 0.19$) demonstrated the invalidity of a
411 consistent and generalizable equation capable of describing the K - z relationship in a
412 crystalline basement. Similar results were reported for the analysis of crystalline rock
413 datasets (Ranjram et al., 2015; Snowdon et al., 2021; Stober and Bucher, 2007).

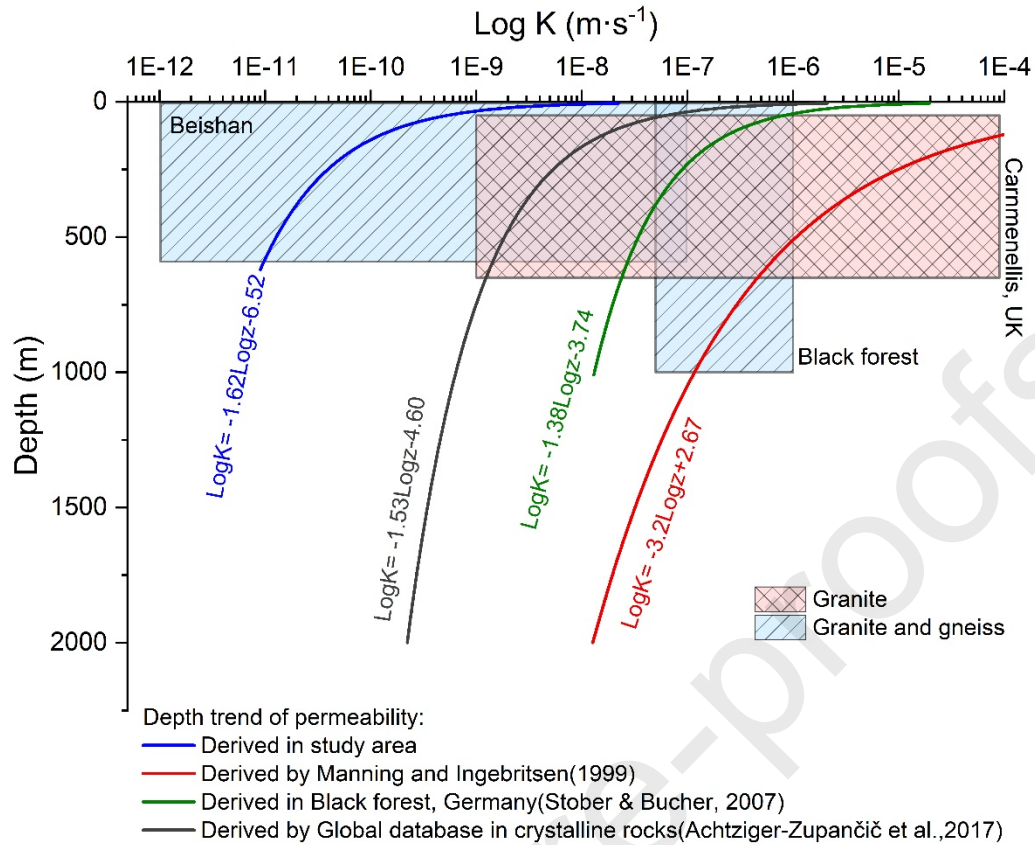


Figure 5. Comparison of hydraulic conductivity (K) ranges and the depth trends in crystalline bedrock.

5.2 Permeability and flow behaviors in fault zones

The permeability and flow behaviors in three faults (F11, F90, and F95) in this mountain hydrogeological system are shown in Figures 3 and 4.

Fault zones created by brittle formation are composed of distinct components with different permeability: fault cores and damage zones (Bense et al., 2013; Caine et al., 1996; Rawling et al., 2001; Scibek, 2020). For a single fault, groundwater flows mainly

through connected open fractures in the damage zone; the proportion of damage zone thickness to total fault thickness (F_a) enables the description of fault architecture and flow behavior (Caine et al., 1996). With a F_a value close to 1 (0.98), the western part (B-B') of F95 is likely to be of the "distributed conduit" type. However, the same fault was identified to be a potential "barrier" according to the permeability ratio (Table 3) and simulated streamlines from 2D numerical modelling. This suggested the complex and combined role of F95 in this particular hydrogeological setting. With low conductivity for the general fault zone, the groundwater was hindered from flowing across the F95 towards the south in this two-dimensional model. Nevertheless, the existence of a relatively more permeable damage zone with higher conductivity ($5.35 \text{ E-7 m}\cdot\text{s}^{-1}$) in F95 suggests potential flow along the damage zone towards the southeast.

For F11, the discrepancy in fault core conductivity causes the spatial variability in permeability structures, and thus affects the flow behavior in numerical modelling. Groundwater flow was impeded from flowing across the F11 fault zone in the *Layered: Low K fault* scenario (corresponding to the measurements on the western part A-A'), acting as a barrier in MBR processes (Bresciani et al., 2018; Figueroa et al., 2021). However, the flow was allowed to pass the same fault zone in the *Layered: High K fault* scenario (corresponding to measurements on the western part B-B'), connecting groundwater from both sides of fault zone (Roques et al., 2014). Consequently, the F11

fault zone partially impedes groundwater flow from flowing south, likely acting as a combined “conduit-barrier.” Similar flow behavior and discontinuity in permeability of faults have been examined with numerical modelling (Mechal et al., 2016) and field investigation (Caine et al., 2017). The large discontinuity of the fault in the eastern Española Basin, Rio Grande rift, New Mexico, indicated that it was unlikely to systematically impede groundwater flow (Caine et al., 2017).

According to simulated streamline C in Figure 4, F90 is likely a barrier for groundwater flow in the study area. However, all three faults show only localized impact on streamline distribution, indicating the limitation of faults’ effects on the hydrogeological process for this particular mountain bedrock groundwater system.

5.3 Possible MBR processes in the Beishan area

The streamline distributions in Figure 4 indicates no groundwater flow directly from the Xinchang Site to the Huahai Basin under the control of topography and generally low hydraulic conductivity in the Beishan area. Streamline A observed in the *Homogeneous* scenario was absent in all Layered scenarios, indicating the vertical heterogeneity of K might hinder groundwater from developing deeper circulation and therefore may prejudice diffuse MBR to the Hauhai Basin.

Although as an oblique-oriented fault, the F90 is likely to act as a hydraulic barrier to

diffuse MBR with available data. Groundwater flow towards the Huahai basin was impeded from crossing the fault core zone of the obliquely oriented fault F95 in the 2D section. However, the damage zone with relatively high conductivity and large thickness may also function as a conduit driving groundwater flow within the connected fractures, which is referred to as focused MBR. Consequently, the F95 is likely to act as a combined “conduit-barrier”, impeding diffuse MBR while permitting focused MBR.

The spatial variability in permeability results in the difference in the hydraulic role of F11. As C streamlines shown in Fig 4, the F11 was unlikely to systematically and significantly impede diffuse MBR by allowing groundwater flow across its core in partial sections. Therefore, the F11 may also act as a combined “conduit-barrier” for MBR in the study area.

Despite its spatial discontinuity and small thickness in the study area, the canyons of alluvial sediment could present a potential flow path for focused MBR (Markovich et al., 2019), especially within the mountain front area near the Huahai Basin. This process corresponds to the groundwater recharge through focused infiltration contributed by ephemeral streams, which is associated with rainy events or snowmelt (Taucare et al., 2020) and is highly sensitive to local weather. Indeed, the absence of snow and rare rainy events in the study area suppress focused MBR through canyons.

6. Conclusion

This study examines the potential flow paths of MBR processes, mainly focusing on the vertical heterogeneity of K and the hydraulic role of fault zones in hydrogeological settings. We also provide a series of hydraulic conductivity data obtained by in-situ measurements from a crystalline mountain block system at various depths (0–592.34 m). We deciphered the flow paths originating from the Xinchang Site, Beishan area, and feeding adjacent aquifers in the Huahai Basin using a permeability conceptual model and numerical simulations of bedrock sections. These findings help to explain the MBR processes critical in determining the safety of a future HLW disposal site. The primary conclusions are as follows:

- Most Bedrock K (91%) is distributed between $1.03 \text{ E-12 m}\cdot\text{s}^{-1}$ – $9.82 \text{ E-8 m}\cdot\text{s}^{-1}$, which is generally lower than that in other sites with similar depth or lithology (Stober and Bucher, 2007; Watkins, 2007). Higher K values and larger variance were observed at shallow depths (<100 m, and especially <50 m), supporting the assumption that permeability is generally decreasing with depth. A logarithmic fit to Bedrock K ($\text{Log } K = -1.62 \text{ Log } z(\text{m}) - 6.72, R^2 = 0.19$) shows a smaller slope and intersect than those derived by Achtziger-Zupančič et al. (2017), Manning and

Ingebritsen (1999), and Stober and Bucher (2007). The discrepancy in data and trend line, as well as the low predictive power R^2 , suggesting the ineffectiveness of a consistent and generalizable relationship between hydraulic conductivity and depth in a crystalline basement.

- No direct groundwater flow from the Xinchang Site to the Huahai Basin was observed according to the simulated streamlines. The vertical heterogeneity of K distribution restrained groundwater from deeper circulation, and may suppress diffuse MBR in the study area.
- Spatial variability of measured K in fault cores of fault F11 induces discontinuity in permeability, and therefore the difference in hydraulic roles to MBR. F11 is approximately perpendicular to the MBR flow direction, whereas it might act as a combined “conduit-barrier” according to the distribution of simulated streamlines in study area (Figure 4).
- With low conductivity of general fault zones, obliquely oriented faults F90 and F95 act as hydraulic barriers to diffuse MBR. However, the damage zone of relatively high conductivity could function as a conduit driving groundwater flow within connected fractures, promoting focused MBR of study area.

In summary, based on in-situ K data ($n = 555$), this study suggests the possible flow paths of MBR in a crystalline mountain block system, providing insights into the

characteristics of K in mountain bedrock. The study also provides insights into the localized effects and spatially variable roles of fault zones in hydrogeological processes within this particular hydrogeological configuration in Beishan, China. In addition, the hydraulic conductivity data presented here can provide information on the subsurface properties of mountain block systems in crystalline areas, and further facilitate the characterization and quantification of mountain block recharge.

CRedit authorship contribution statement

Yunmei Fu: Conceptualization, Investigation, Methodology, Software, Formal analysis, Visualization, Writing - original draft. **Yanhui Dong:** Funding acquisition, Methodology, Project administration, Supervision, Writing - review and editing. **Liheng Wang:** Investigation, Writing - review and editing. **Olivier Bour:** Visualization, Writing - review and editing. **Maria V. Klepikova:** Visualization, Writing - review and editing. **Zihua Zong:** Resources, Investigation. **Zhifang Xu:** Supervision, Writing - review and editing. **Zichao Zhou:** Resources, Investigation.

Declaration of 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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Abstract

The process wherein groundwater flowing from mountain bedrock into lowland and adjacent alluvial aquifers, known as mountain-block recharge (MBR), is found across various climatic and geological settings. An understanding of the potential groundwater flow paths in mountain block systems is necessary for comprehending MBR spatial distribution. However, poorly characterized mountain block hydraulic properties, and especially a lack of direct measurements of hydraulic conductivity (K) at depths >200 m, limit the characterization and quantifications of the MBR processes. In this study, we analyze hydraulic data set, namely 555 in-situ K measurements at various depths from two borehole sections extending from mountain block to mountain front in a potential disposal site for high-level radioactive waste. The K dataset was categorized into two groups: one for bedrock and another for fault zones, which was further classified into fault core K , damage zone K , and general fault zone K . Using a permeability conceptual model and multiple scenarios numerical modelling, this study examined the potential flow paths of MBR processes, mainly focusing on the characteristics of K in bedrocks and the hydraulic role of fault zones in mountain block

systems. The distribution of Bedrock K supports the assumption of decreased trend with depth. A logarithmic fit through Bedrock K and depth pairs resulted in $\text{Log}(K) = -1.62 \cdot \text{Log}(z) - 6.52$, with low predictive power. This study illustrated the localized effects and spatially variable roles of fault zones in MBR within this particular hydrogeological configuration in Beishan, China. Our results provide insights into the MBR process in crystalline mountain block systems. Additionally, the hydraulic conductivity presented here provides data on the subsurface properties of mountain block systems in a crystalline area, and further facilitates the characterization and quantification of mountain-block recharge.

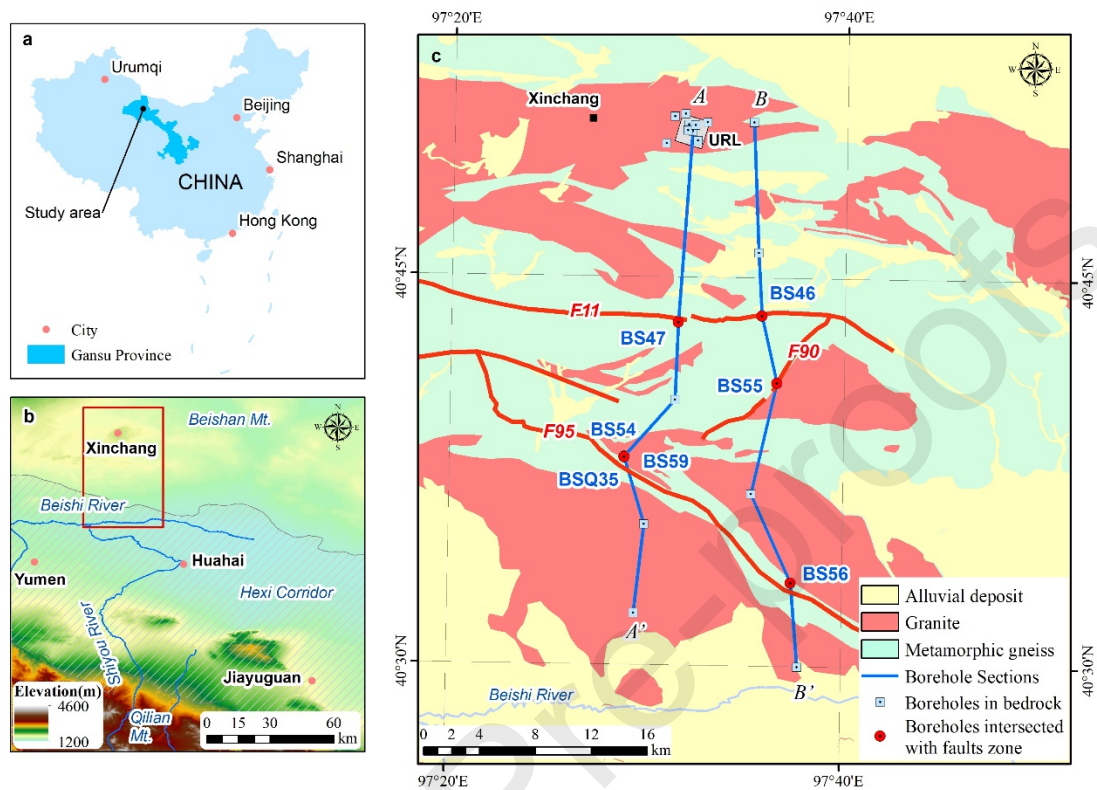
Keywords: mountain block recharge, mountain hydrogeology, fractured aquifer

Declaration of interests

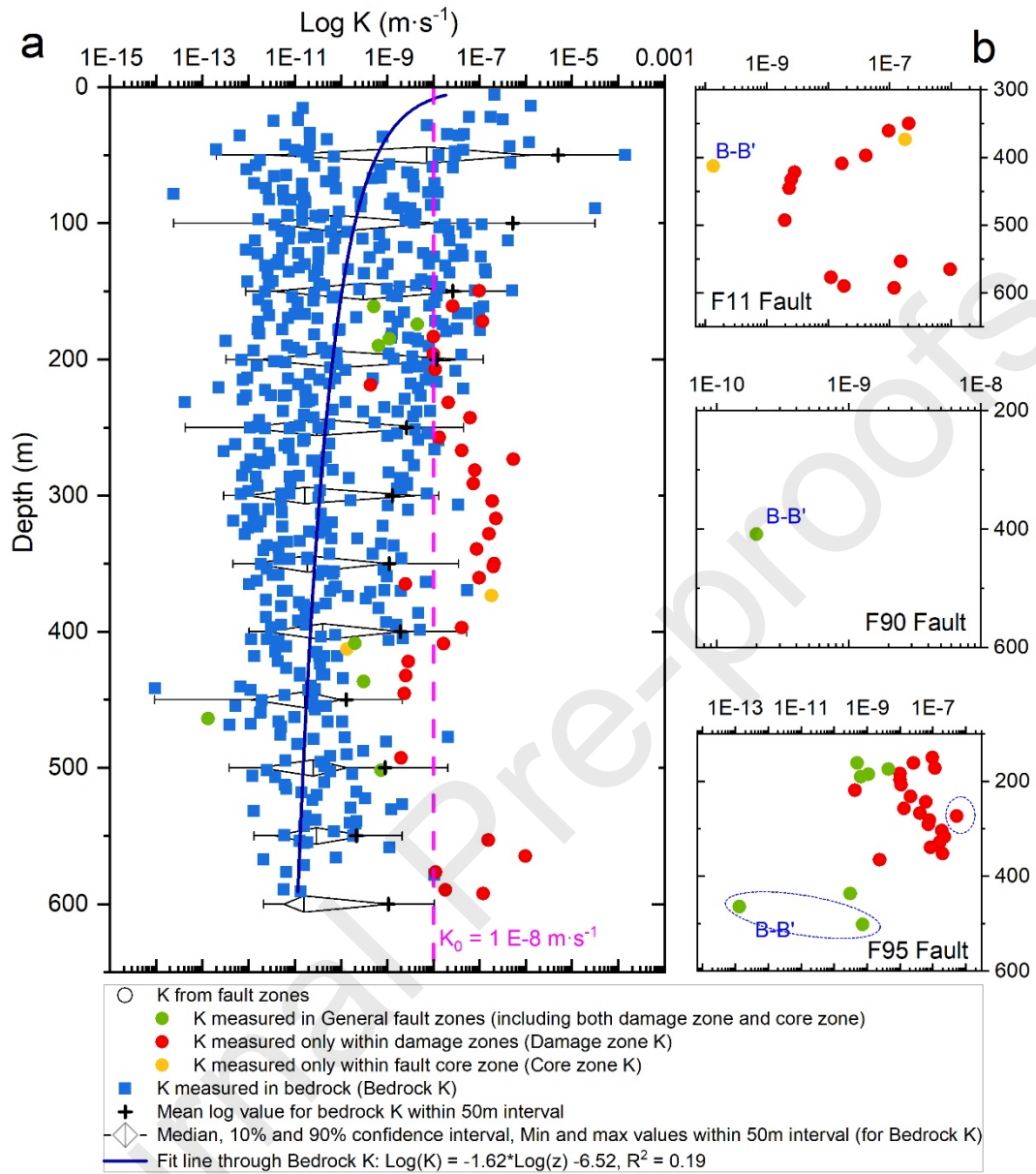
☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

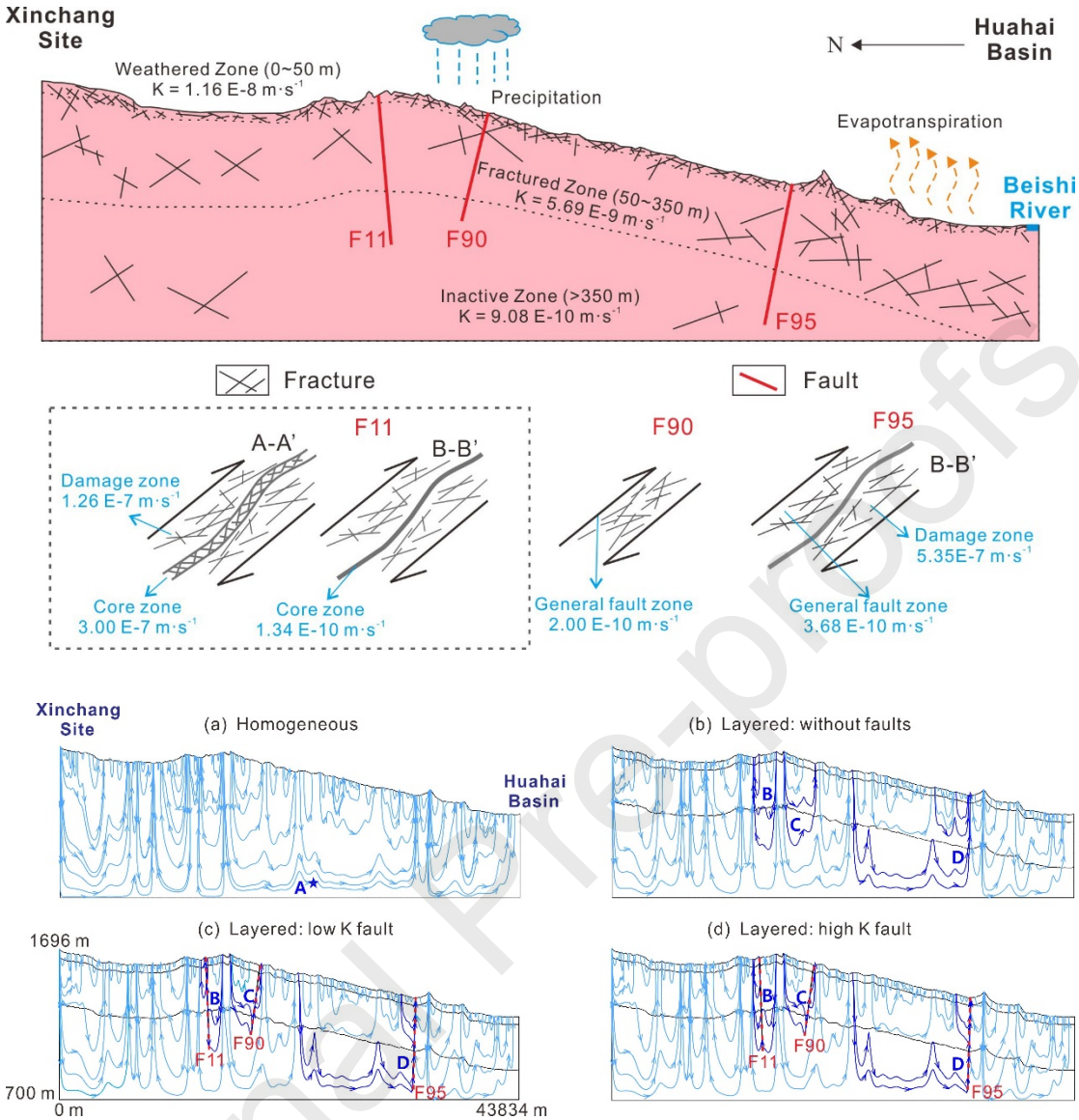
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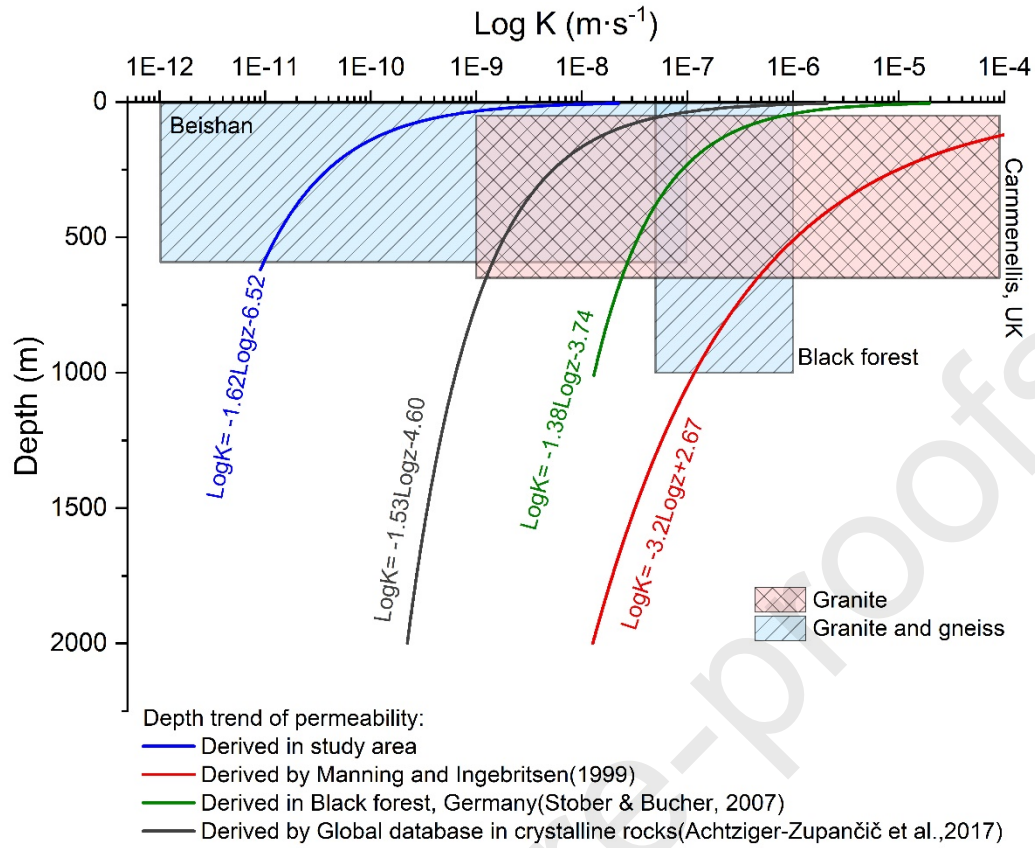


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Highlights

- Potential flow paths of MBR process in crystalline mountain block systems were explored based on hydraulic conductivity data up to ~592.34 m depth.
- Characteristics of hydraulic conductivity for bedrock and fault zones including core zones and damage zones were reported.
- Spatial discontinuities in the permeability may exist for the same fault, which lead to its role can be either a conduit or a barrier in the MBR process.