



Are there biases in borehole databases of weathered basement aquifers affecting their reliability to estimate aquifer productivity?

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Abstract

Groundwater from weathered basement aquifers (WBAs) is a strategic water resource, but its potential for resource development remains poorly characterized. Meanwhile, groundwater abstraction from WBAs is growing to meet water and food security needs in most sub-Saharan African countries. In this study, the impact of the instructions given to water borehole drillers on the characterization of WBA properties was assessed by modelling WBA short-term productivity using a novel numerically based, stochastic modeling approach. The numerical modeling of 10,000 synthetic WBAs reveals systematic biases in borehole databases due to instructions given to water borehole drillers, such as the discharge target (Q_{target}) together with the maximum allowed borehole depth (Z_{max}) and the minimum allowed borehole depth (Z_{min}). Insufficient drilling depth below the base of the saprolite ($Z \leq 35$ m) leads to undersampling of deeper water-bearing fracture, causing an underestimation of aquifer productivity and fractured-layer thickness ($> 10\%$). These biases persist across discharge targets (0.5–10 m³/h) and are exacerbated by shallow drilling. Moreover, traditional borehole-database-processing methodologies, fail to account for instructions given to water borehole drillers, misrepresenting useful aquifer thickness (Lu) by up to 100%. To enhance accurate use of drilling databases, several approaches could be considered: (1) classify boreholes by exploration depth and instantaneous discharge, excluding shallow borehole data (≤ 35 m below the base of saprolite); (2) archive drilling instructions (Q_{target} , Z_{max} and Z_{min}) to contextualize data limitations; and (3) adopt robust indicators like specific capacity and depth-dependent yield instead of instantaneous discharge.

Keywords Weathered basement aquifer · Numerical modeling · Saprolite · Fractured layer · Borehole database

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Introduction

Groundwater is the largest readily accessible source of fresh-water, and its strategic importance is expected to grow under climate change, necessitating integrated management at both the regional and local scales (Kuang et al. 2024; Scanlon et al. 2023). In African regions with monsoon systems, particularly in semi-arid areas, surface water is mostly intermittent, vulnerable to climate change and pollution (Fovet et al. 2021). In Africa, groundwater resources, therefore, offer an important opportunity to provide an affordable and safe water supply, notably to rural communities (Cobbing 2020; Pointet 2022). In the western part of the continent, weathered basement aquifers (WBA) cover about 40% of the land area (Heckmann et al. 2022; MacDonald et al. 2012; Ofterdinger et al. 2019). Groundwater from WBAs shows a widespread availability (Calow et al. 2010; Cuthbert et al. 2019; Taylor et al. 2013), which will become increasingly important for achieving the United Nations sustainable development goals (SDGs), notably SDG 6 aims to ensure water availability and sanitation for all (Velis et al. 2017; Vouillamoz and Koita 2022), and for sustaining food production (Agrawal and Jain 2019; Villholth and Altchenko 2016), as yet only 5% of cultivable land is irrigated in Africa (Siebert et al. 2010).

Since the 1970s, the western African WBAs have been the subject of many drilling surveys, resulting in the drilling of several tens of thousands of boreholes (Tuinhof et al. 2011). The employed strategy consisted of drilling boreholes equipped mostly with hand pumps, implying a minimum instantaneous yield target of 0.5–1 m³/h. As a result of the growing water demand in West Africa, the water supply strategy is gradually being replaced by higher yield targets to meet the needs of larger villages or suburbs supplied by tap water networks (Vouillamoz and Koita 2022). These networks rely on boreholes equipped with motorized pumps (primarily electric), which motivates the national agencies to target higher discharge, e.g., 6 m³/h for Benin, 5 m³/h for Burkina Faso and 10 m³/h for Côte d'Ivoire.

The characteristics of all those boreholes, including instantaneous discharge, borehole depth, saprolite thickness, piezometric level, and depth to the main water-bearing fractures, were noted during drilling operations. They were later recorded in national databases in each country, each comprising several thousands to tens of thousands of borehole entries (see Courtois et al. 2010). These databases are used by several authors to infer various properties of WBA, and their upscaling and mapping with various approaches (Ahmed et al. 2018; Courtois et al. 2010; MacDonald et al. 2012).

Nevertheless, some studies have highlighted that key variables such as the borehole instantaneous discharge (Q) could be a biased variable, notably because it may depend on the

total depth of the borehole (Z) (Courtois et al. 2010; Dewandel et al. 2006; Wright 1992). Studies in the fractured layer of WBAs in India, and also in Oman, recognized that boreholes observations were generally limited to shallow depths and emphasized the need to account for a statistical bias in borehole data introduced by the unequal representation of depth ranges in the investigated boreholes, notably the deepest ranges (Dewandel et al. 2004, 2005, 2006). They defined a “quality ratio” that states that compliance is only reached for depths above which more than 50% of the boreholes cross the considered depth within the fractured layer. Such a potential bias in the context of WBA characterization using borehole databases has not yet been systematically investigated to determine its consequences. The central question then is whether these national borehole databases are reliable or biased and may lead to incorrect aquifer descriptions. With the increasing availability of large borehole databases and the growing number of regional studies conducted with them (Bianchi et al. 2020, 2023; Courtois et al. 2010; Cuthbert et al. 2019; Dewandel et al. 2006; Lachassagne et al. 2021; MacDonald et al. 2012, 2021; MacDonald et al. 2008), a scientific concern remains: To what extent can national borehole databases be used to accurately describe the overall hydrogeological properties of WBAs? This includes key variables such as (1) borehole instantaneous discharge, which is a proxy of the short-term aquifer productivity (Adeotan et al. 2025) and an indicator of aquifer permeability/transmissivity, and (2) the thickness of the fractured layer.

For this purpose, the conducted research consists of (1) developing a numerical model of a conceptual WBA, and simulating 10,000 realizations of the synthetic WBA; (2) designing a numerical experiment to generate several databases of 10,000 sets of synthetic boreholes based on the typical instructions given to water borehole drillers (such as the discharge target, maximum allowed depth, and minimum allowed depth subject to driller behavior); (3) assessing the impact of these instructions on WBA properties (instantaneous discharge, depth of the last water-bearing fractures) derived from such boreholes databases by comparison to the “true” aquifer properties for each aquifer realizations, and also to existing known methods used to infer aquifer parameters from such databases, as in Courtois et al. (2010); and finally (4) conducting a sensitivity analysis to assess to which extent the conclusions of this research are robust.

Material and methods

Conceptual model and numerical modeling of WBA

Conceptual model of WBA

Extensive studies, notably by Aoulou et al. (2021), Barker et al. (1992), Chilton and Smith-Carlington (1984),

Dewandel et al. (2005, 2006, 2004), Foster (1984), Lachassagne et al. (2001, 2014, 2021), Wyns et al. (2003, 2004), demonstrate that basement aquifers result from weathering processes rather than other geological processes. In West Africa, Precambrian basement aquifers form from long and intense weathering processes, enabled by their exposure within an intertropical climate zone over geological time scales with limited tectonic activity (Bianchi et al. 2020, 2023; Chardon 2023; Grimaud et al. 2014; Key 1992; Strakhov et al. 1967). This results in fairly thick weathering, covering of up to 200 m or more in some areas (Alle et al. (2018); Lachassagne et al. (2021)). The conceptual model of the weathered basement aquifers, validated by many studies and field observations worldwide, has been explained by Lachassagne et al. (2014, 2021, 2011) (Fig. 1).

Below the iron crust, where protected from erosion, lies the unconsolidated alterite or saprolite. This saprolite thickness ranges from 25 to 100 m. The fractured layer is located beneath the saprolite. Its thickness ranges from 50 to 200 m, and is almost twice that of the saprolite where the latter is not eroded (Wyns et al. 2003, 2004). The fractured layer is characterized by dense fracturing in the first few meters, with mostly subhorizontal fractures in granite-type rocks, followed by a decrease in fracture density with depth (Ayraud et al. 2008; Collins et al. 2020; Guihéneuf et al. 2014; Maréchal et al. 2004). The saprolite plays a hydrogeological capacitive role, and the fractured layer plays a transmissive role (Compaore et al. 1997;

Dewandel et al. 2006; Wyns et al. 2004). The base of the WBA is defined by the top of the unweathered impervious basement rock (Cho et al. 2003; Lachassagne et al. 2021). This conceptual model is the one adopted in this research (Fig. 1).

Numerical modeling of WBAs

The numerical modeling approach considers the conceptual model described previously and targets the short-term behavior of WBAs. In other words, it aims to simulate the results of airlift tests performed in the borehole at the end of drilling, and not the long-term (monthly, seasonal or interannual) behavior of these boreholes during abstraction. This “blowing discharge” variable has been considered for a long time as a reliable estimation of the short-term productivity of the aquifers, thus serving as a good proxy of their permeability/transmissivity (Adeotan et al. 2025).

Firstly, a simplifying hypothesis is assumed: the saprolite is modeled with a constant thickness of 25 m and its contribution to the “blowing discharge” at the end of drilling was considered null. In fact, the fractured layer is the major contributor (90–99%, Wyns et al. 2004) to the aquifer equivalent hydraulic conductivity (Courtois et al. 2010), and thus to the water borehole’s instantaneous discharge (Cho et al. 2003; Dewandel et al. 2006; Lachassagne et al. 2021). Therefore, the developed WBA numerical modeling approach simulates only the short-term behavior of the aquifer’s fractured layer.

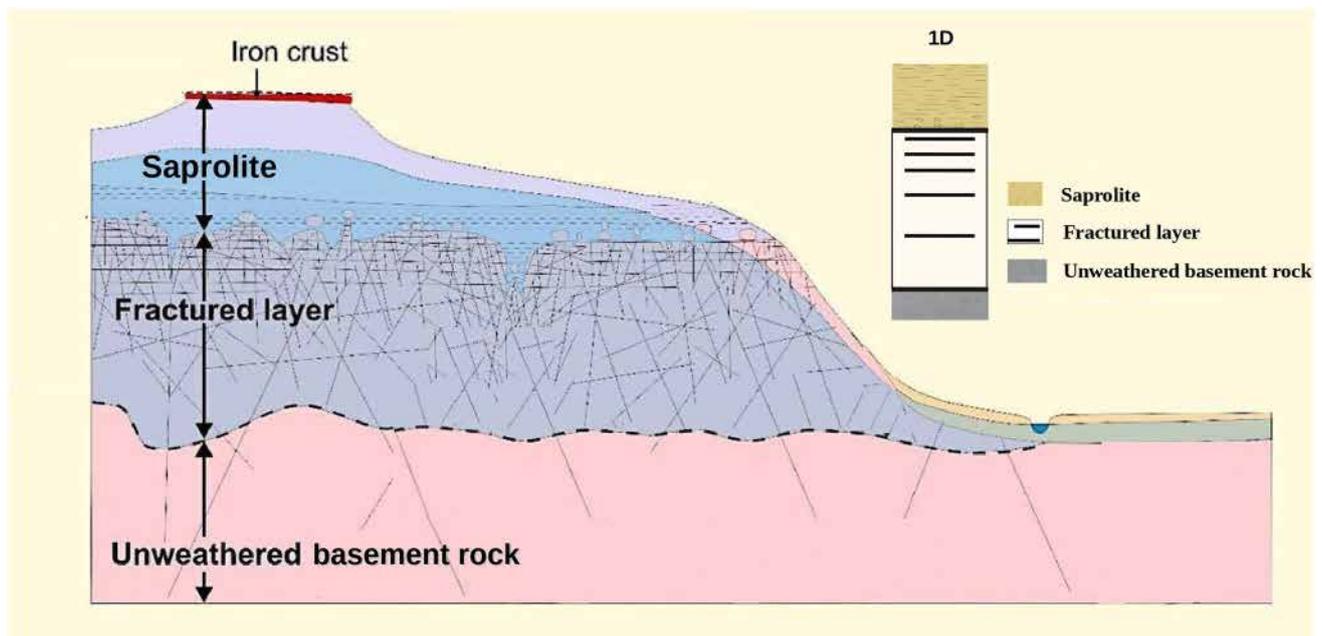


Fig. 1 Left: Hydrogeological conceptual model of weathered basement aquifer (modified from Lachassagne et al. 2021), and right: simplified hydrogeological conceptual model proposed for the current research

An extensive bibliographical review was performed to identify and describe the characteristics and parameters of the fractured layer and their statistical distribution laws. These characteristics include the thickness of the fractured layer, and the characteristics of the water-bearing fractures number, depth, and hydraulic conductivity (K) as described in the subsequent subsections (Fig. 2).

Thickness of the fractured layer The fractured layer is characterized by a thickness (Fig. 2a) ranging from 50 to 200 m and its water-bearing fractures (Fig. 2b, see i–iii; Lachassagne et al. 2021). The characterization of thickness for many WBAs highlights that the fractured layer thickness rarely exceeds 50 m below the saprolite. Thus, the majority of water-bearing fractures are concentrated within the first 50 m beneath the saprolite, while fractures beyond this depth are significantly less frequent (Biémi 1992; Faillat 1986; Koita et al. 2013; Kouamé et al. 2010; Savané et al. 1997;

Soro 2017). Based on this understanding, this study considers that the fractured layer thickness of the numerical WBA is equal to 50 m.

Number of water-bearing fractures From a geological standpoint, geological logging (or coring) identifies several tens of fractures in the fractured layer (Aoulou et al. 2021; Dewandel et al. 2005, 2006, 2004; Lachassagne et al. 2021). These fractures are mostly subhorizontal in granite-type rocks and in vertically foliated rocks. They are randomly dipping in metamorphic folded rocks (no preferential orientation). Because of the permeability reduction processes in some of these fractures, very few of them (~0–5) remain permeable enough to be detected as “water strikes”, or “water-bearing fractures” during borehole drilling and logging, the others being “dry” (Aoulou et al. 2021; Dewandel et al. 2005, 2006, 2004; Lachassagne et al. 2021). These fractures then ensure the discharge of the water borehole. Sometimes, no fractures

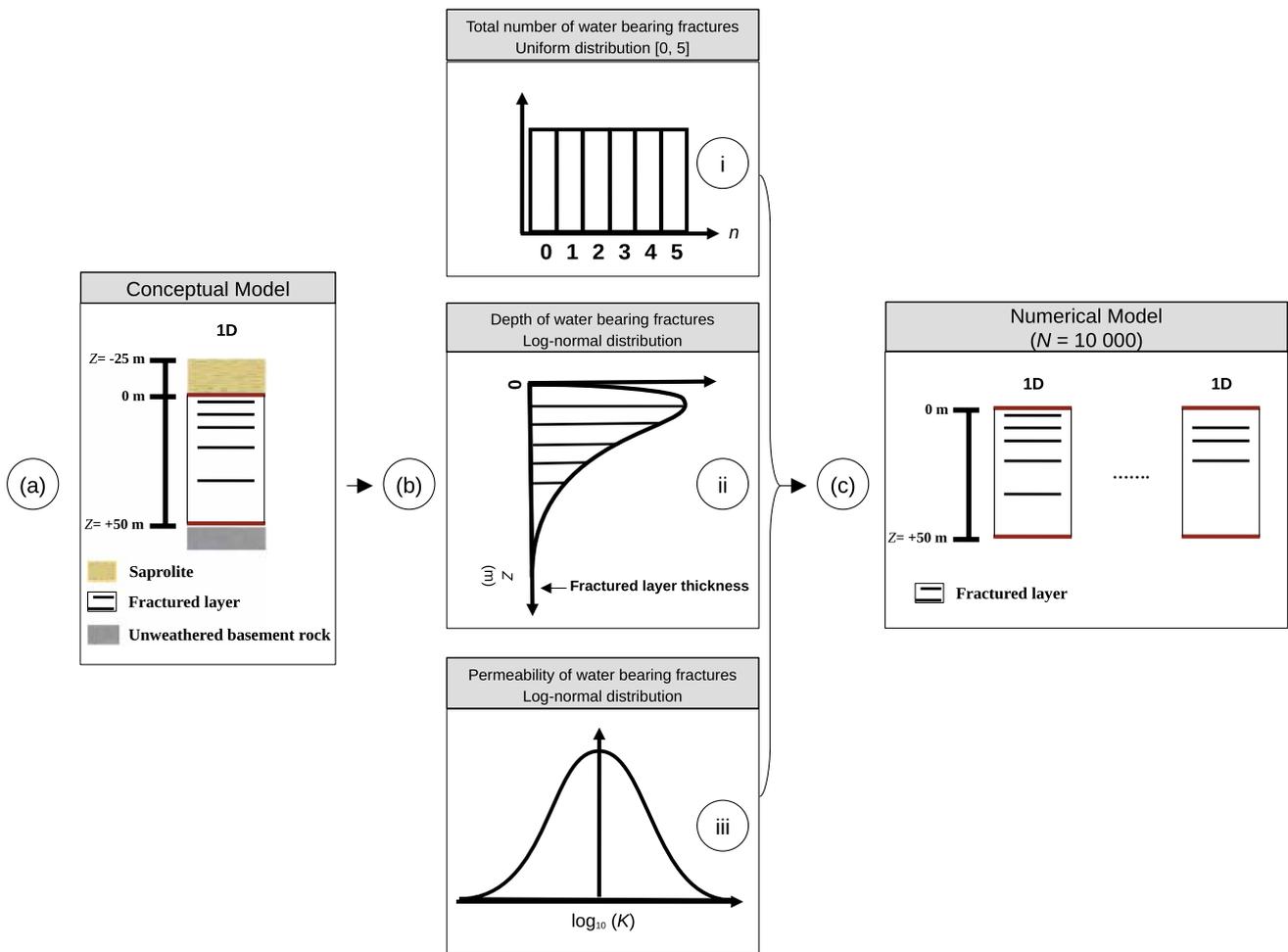


Fig. 2 The various steps of the numerical modeling of the Weathered Basement Aquifer (WBA): **a** conceptual model of WBA, **b** (i) histogram of the total number of water-bearing fractures (wbf) per water

boreholes, (ii) histogram of the depth of all water-bearing fractures, (iii) histogram of the “log” of the hydraulic conductivity of all water-bearing fractures, **c** generated numerical model

at all is permeable enough to ensure a significant discharge; hence, when modelling water-bearing fractures, their number was varied uniformly between zero and five in a given vertical log of the WBA (Fig. 2b, see i).

Depth of water-bearing fractures The fracture density decreases with depth towards the base of the weathering profile (the base of the fractured layer), and so does the density of the water-bearing fractures (Aoulou et al. 2021; Chilton and Foster 1995; Chilton and Smith-Carington 1984; Dewandel et al. 2006, 2004). The water-bearing fracture depths were assumed to follow a log-normal statistical distribution (Fig. 2b, see ii). A depth limit of 50 m was applied to truncate the log-normal statistical distribution of the water-bearing fractures, representing the maximum thickness of the fractured layer.

Hydraulic conductivity of water-bearing fractures Figure 2b (see iii) presents the histogram distribution of the hydraulic conductivity (K) of all the water-bearing fractures, whatever their depth. The K of the single water-bearing fracture does not show much variability with depth (Dewandel et al. 2006; Maréchal et al. 2004), which supports weathering as a unique origin. The observed decrease of the K of the fractured layer of the WBA and not of the individual water-bearing fracture with depth (see, for instance, Chilton and Foster 1995) is not a consequence of a lower permeability of the water-bearing fractures or of their “closure with depth because of lithostatic constraints”, but rather is due to their lower frequency and their disappearance in depth (Dewandel et al. 2006; Maréchal et al. 2004). Therefore, dense horizontal fracturing maintains relatively high K values in the fractured layer, as also indicated by flow-meter and packer tests data in African and Indian WBAs, with a geometric mean of the order of 10^{-5} m/s for individual water-bearing fracture (Bianchi et al. 2020, 2023; Dewandel et al. 2006; Maréchal et al. 2004). Therefore, each water-bearing fracture was assigned a permeability value, independently of its depth, using a log-normal distribution with a mean and standard deviation (SD) respectively equal to $\log_{10} 5 \times 10^{-5}$ and $\sigma = 0.32$ as characterized by (Dewandel et al. 2006, 2004) (Fig. 2b, see iii).

The set of synthetic WBAs Finally, a realization of the numerical model of WBA as presented in Fig. 2 is generated as follows: within the considered thickness of the fractured layer, zero to five water-bearing fractures were statistically uniformly and randomly drawn, with their depth following a log-normal statistical distribution. Then, for each water-bearing fracture, a K value was assigned following a log-normal statistical distribution. This numerical modeling approach was performed 10,000 times to generate a set of 10,000 realizations of the synthetic WBAs.

Generation of synthetic borehole databases

Instantaneous discharge of synthetic water-bearing fractures and boreholes

The discharge of each water-bearing fracture, was calculated using the analytical solution of Dupuit (1863) (Eq. 1). This estimation of the water-bearing fracture discharge is consistent with the works of Dewandel et al. (2006) and Maréchal et al. (2004), who were able to determine the vertical distribution of water-bearing fractures and their permeability by applying the analytical solution of Dupuit (1863) using data from packer tests and flow-meter profiles during injection tests. As such, the permeability of the matrix of the fractured layer, as well as potential leakage from the saprolite, has not been taken into account (see section “Numerical modeling of WBAs” and Maréchal et al. 2004). Additionally, it was considered that the piezometric level is at the top of the fractured layer.

$$Q_{\text{wbf}} = K_{\text{wbf}} \times \pi \times s \frac{(2 \times s + H)}{\ln\left(\frac{R_i}{r_w}\right)} \quad (1)$$

where the parameters are defined as follows:

Q_{wbf}	Instantaneous discharge of a water-bearing fracture
K_{wbf}	Permeability of the water-bearing fracture
H	Depth of the water-bearing fracture with reference to the bottom of the saprolite
s	Drawdown taken as equal to unity (instantaneous behavior of the WBA)
r_w	Borehole radius is taken as equal to the common radius of the boreholes which is 125 mm
R_i	Radius of influence = 1 m

The instantaneous discharge of a synthetic borehole of a given depth (Z) below the saprolite is then computed as equal to the discharge of all the water-bearing fractures found within the interval between the base of the saprolite and the depth (Z) (Eq. 2). This is in line with Adeotan et al. (2025), who found a strong correlation between the borehole instantaneous discharge and the cumulative discharge derived from each water-bearing fracture encountered during drilling.

$$Q_{\text{Borehole}} = \sum_0^Z Q_{\text{wbf}} \quad (2)$$

where the parameters are as follows:

Q_{Borehole}	Instantaneous discharge of the synthetic borehole
Q_{wbf}	Instantaneous discharge of each water-bearing fracture
Z	Borehole depth

Modeling of the water borehole driller's behavior

A comprehensive understanding of the instructions given to water borehole drillers and the behavior of the latter, notably in West Africa, was based on extensive experience with hydrogeological and drilling surveys. Additionally, studies, including those by Thierry (1982) in Bretagne and Corsica (France), and in Togo, have investigated the relationship between water borehole instantaneous discharge and depth, based on the typical standardized instructions given to and followed by water borehole drillers. While there are some exceptions regarding the adherence to these instructions, as highlighted by Maréchal et al. (2004) in India, they do not undermine the conceptual framework of the instructions described in the following subsections. These instructions are widely used in West Africa (e.g., Burkina Faso, Benin, Togo, Ivory Coast), as demonstrated by numerous drilling project tender documents and the subsequent operational practices by stakeholders (Adeotan et al. 2025). Three variables were used to model the instructions given to water borehole drillers: the instantaneous discharge target (Q_{target}), a maximum allowed depth (Z_{max}) and a minimum depth of the borehole (Z_{min}).

Borehole instantaneous discharge target For this research, a range of borehole instantaneous discharge targets (Q_{target}) were considered by different water supply strategies, particularly in West Africa, between 0.5 and 1 m³/h for hand pumps, and 5 and 10 m³/h for water supply networks serving larger populations (Vouillamoz and Koita 2022). A discharge target equal to 0.7 m³/h, commonly used as a threshold for hand pumps in West Africa, is also considered (CIEH and BURGEAP 1988).

Borehole maximum allowed depth Regarding the maximum allowed borehole depth (Z_{max}), drillers are often advised to stop the drilling at a depth between 60 and 80 m, if Q_{target} is not yet reached. Bianchi et al. (2020, 2023) considered a maximum borehole depth of 60 m to be the most representative of typical borehole depths to assess regional variations in yield from WBA in West Africa. Furthermore, boreholes drilled beyond 60 m depth in a quest of reaching the discharge target, are not so common, less than 30%, and only 10% are drilled beyond 80 m—see, for instance, Aoulou et al. (2021); Courtois et al. (2010); Dewandel et al. (2006). Consequently, the usual maximum depth (Z_{max}) considered in this research was set to be equal to 60–80 m, which is 35–55 m below the base of the 25-m-thick saprolite in the model. The variation of the maximum allowed depth below the base of the saprolite (Z_{max}^*) was considered, ranging from 5 to 55 m.

Minimum borehole depth Moreover, following these instructions, water borehole drillers tend to adapt if they reach the discharge target at a shallower depth than Z_{max} . In such cases, drilling often continues until a minimum borehole depth

(Z_{min}) is reached that provides financial margin benefits and, in some realizations, allows for the proper installation of borehole equipment or meets other technical requirements. In this study, a scenario of Z_{min} stating that the Z_{min} is taken as half of the maximum allowed depth below the saprolite $*Z_{\text{max}}$.

Synthetic borehole databases

Based on the aforementioned instructions given to water borehole drillers (Q_{target} , Z_{max} and Z_{min}) (Fig. 3), a numerical experiment was conducted to generate synthetic borehole databases. These instructions state that if the discharge target (Q_{target}) cannot be obtained in the WBA, drilling ceases at the maximum allowed depth (Z_{max} ; Fig. 3a). Otherwise: (1) if the discharge target is reached before the maximum allowed depth (Z_{max} , drilling ceases at the crossing of the water-bearing fractures, satisfying at least the discharge target Q_{target} (Fig. 3b); (2) if the Q_{target} is obtained at a depth $< Z_{\text{min}}$, the water borehole drillers continue drilling until the minimum borehole depth (Z_{min}) (Fig. 3c).

The generation of the synthetic borehole databases therefore involved: (1) sampling each realization of the synthetic WBA; (2) computing the instantaneous discharge of each borehole (Q_{Borehole}) as the cumulative sum of the water-bearing fractures encountered while following the instructions given to the water borehole driller (cf. section “Instantaneous discharge of synthetic water-bearing fractures and boreholes”); (3) considering the depth of the borehole (Z_{Borehole}) as the depth at the end of the drilling; (4) and taking all the other useful parameters (number of water-bearing fractures, depth of the last water-bearing fractures intersected by the synthetic borehole (Z_{Borehole}^*), instantaneous discharge, etc.).

Assessment of the impact of the instructions given to water borehole drillers

The impact of the instructions given to water borehole drillers was assessed on the estimation of WBA properties (instantaneous discharge, depth to the last water-bearing fractures) and existing borehole database processing methodologies, such as that developed in Burkina Faso by Courtois et al. (2010). This methodology has been chosen because of its use by other authors (e.g. Aoulou et al. 2021; Kouamé et al. 2010; Kouassi et al. 2024) notably in Côte d'Ivoire. It aims to provide an estimation of the “optimal” well length or useful thickness (Lu)—that is, the length beyond which it is not necessary to drill since the small gain in discharge will not justify the increased drilling cost. This methodology evaluates the Lu and the resulting mean discharge for the “theoretical well” that would intersect the entire useful thickness of the fractured layer “ $Q_M(Lu)$ ”, see Courtois et al. (2010) for a detail of the overall methodology. Moreover, in this paper, a critical analysis of the methods was achieved using a mathematical approach.

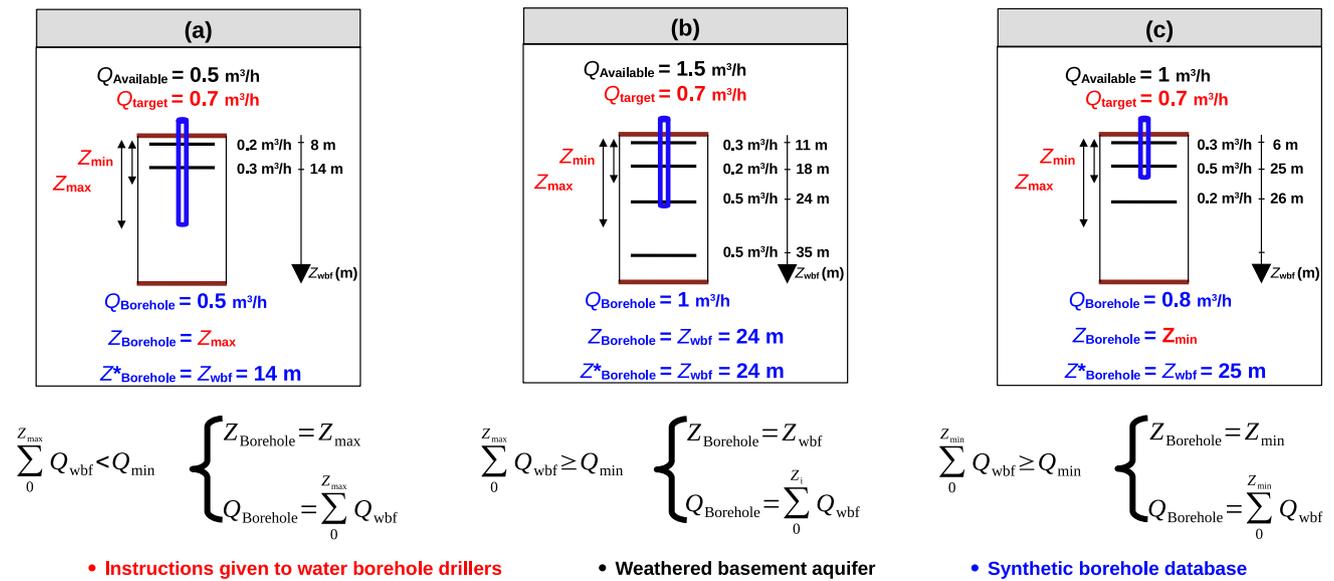


Fig. 3 Example of the generation of a synthetic borehole database following the instructions given to water borehole drillers. In red: Instructions given to water borehole drillers; in black: WBA properties; in blue: parameters obtained in the synthetic borehole database

The assessment of the impact of the instructions given to water borehole drillers is then computed as described in Table 1, using the following two formulas (Eq. 3)

$$\begin{aligned}
 \text{Difference}_X(\%) &= \frac{1}{10000} \left(\sum_{i=1}^{10000} \frac{X_{\text{Borehole}} - X_{\text{Available}}}{X_{\text{Available}}} \right) \times 100 \\
 \text{Difference}_X &= \frac{1}{10000} \left(\sum_{i=1}^{10000} X_{\text{Borehole}} - X_{\text{Available}} \right)
 \end{aligned} \quad (3)$$

where:

X	Variable of interest
$X_{\text{Available}}$	Reference value of the variable
X_{Borehole}	Estimated value of the variable
$\text{Difference}_X(\%)$	Estimated relative difference in the variable
Difference_X	Estimated absolute difference in the variable

Sensitivity analysis

The sensitivity analysis involved analyzing in two steps: (1) the sensitivity of the WBA numerical model to a variation of its parameters, and (2) the sensitivity of the drillers' behavior model to the minimum borehole depth, the most uncertain parameter in the model (Table 2). The first step was undertaken by changing (1) the statistical distribution of hydraulic conductivity for schist-type rocks instead of granite, and (2) the statistical distribution of water-bearing depth, either shallow or deep, as presented in Table 2. Moreover, the second step consists of changing the minimum borehole depth Z_{min}

considered by water borehole drillers as presented in Table 2. The values considered for the sensitivity analysis are based on the literature review conducted (see Bianchi et al. (2020, 2023); Chilton and Foster (1995); Chilton and Smith-Carington (1984); Courtois et al. (2010); Guo et al. (2024); Lachassagne et al. (2021); Raj (2020); Staněk and Géraud (2019)). The impact of these differences was assessed using Eq. (3).

Results

Conceptual model and numerical modeling of WBAs

With respect to the numerical modeling approach, the resulting characteristics of the 10,000 realizations of the synthetic WBAs' fractured layer is presented in Fig. 4. Firstly, there are no water-bearing fractures in 16.7% of the 10,000 realizations of the synthetic WBA (Fig. 4a). Secondly, the parametrization (Fig. 4c–e) shows that WBA hydraulic conductivity (K) decreases from the top of the fractured layer until it reaches its base where there are less water-bearing fractures. The highest permeability part of the WBA (Fig. 4e) is encountered in the 5–10-m interval below the base of the saprolite, which is consistent with the depth distribution of water-bearing fractures below the base of the saprolite (Fig. 4b). This is also consistent with observation performed on real databases (e.g. Aoulou et al. 2021) and the physical heterogeneity in a WBA described by Bianchi et al. (2020, 2023), Chilton and Foster (1995), Chilton and Smith-Carington (1984), Courtois et al. (2010), and Lachassagne et al. (2021).

Table 1 Summary of the assessment of the impact of the Instructions given to water borehole drillers. *wbf*: water-bearing fractures

Component	Variable	Reference value (model)	Estimate value (borehole)	Impact metrics	Hydrogeological significance
Weathered basement aquifer properties	Instantaneous discharge (Q)	$Q_{Available}$: discharge from full WBA thickness in model	$Q_{Borehole}$: discharge from synthetic borehole	Eq. (3)	Quantifies underestimation of the instantaneous discharge due to incomplete sampling of the aquifers
	Depth to deepest wbf (Z)	$Z_{Available}$: depth to deepest wbf in WBA model	$Z_{Borehole}^*$: depth to last wbf intersected by the synthetic borehole	Eq. (3)	Quantifies underestimation of the depth to the deepest wbf or of the fractured layer thickness due to incomplete sampling of aquifer
Courtois et al. (2010) methodology	Useful thickness (Lu)	$Lu_{Available}$: depth at which 80% of cumulative Q is reached in WBA model	$Lu_{Borehole}$: depth at which 80% of cumulative Q is reached using synthetic borehole databases	Eq. (3)	Measures inconsistency of the Courtois et al. (2010) methodology based on different synthetic borehole databases
	Mean discharge over useful thickness [$Q_M(Lu)$]	$Q_M(Lu)_{Available}$: mean discharge over $Lu_{Available}$ from full model	$Q_M(Lu)_{Borehole}$: mean discharge over $Lu_{Borehole}$ from synthetic boreholes databases	Eq. (3)	Measures inconsistency of the Courtois et al. (2010) methodology based on different synthetic borehole databases

Analysis of the generated synthetic borehole databases

Figure 5 shows the distribution of the instantaneous discharge of the 10,000 realizations of the synthetic WBA (bold blue line). The 10,000 realizations of the synthetic WBA instantaneous discharge (sum of the water-bearing fracture discharges within each WBA), as if each borehole would have reached the bottom of the fractured layer, 50 m below the base of the saprolite ranges from 0 to 14.5 m³/h, and has a mean $\mu = 1.94$ m³/h and a standard deviation $\sigma = 2.1$ m³/h. The distribution is skewed toward low Q where the low (< 1 m³/h) Q of synthetic WBAs accounts for almost 40%, while high (≥ 10 m³/h) of synthetic WBAs accounts for less than 1%. The highest percentage of low depth and low Q (< 1 m³/h) results from the unproductive fractured layer ($Q = 0$ m³/h) of the synthetic WBAs, which have no water-bearing fractures (cf. Fig. 4a). Figure 5 shows the distribution of the last water-bearing fracture depth (below the saprolite) within the 10,000 realizations of the synthetic WBA. This distribution has a mean $\mu = 17$ m and a SD of $\sigma = 12$ m. It represents the depth at which a given synthetic borehole has explored all the water-bearing fractures of the WBA.

Furthermore, the distribution of borehole instantaneous discharge ($Q_{Borehole}$) and the depth to the deepest water-bearing fracture ($Z_{Borehole}^*$) derived from the generated synthetic borehole databases are presented as a dotted line in Fig. 5. Figure 5a shows that synthetic borehole databases generated with a low discharge target ($Q_{target} = 0.5$ m³/h) bias the distribution of instantaneous discharge toward lower values, a consequence of omitting deep water-bearing fractures, which is obviously more salient for low Z_{max}^* than for high Z_{max}^* . This omission of deep water-bearing fractures is a result of the maximum allowed borehole depth (Z_{max}^*) when it is shallow compared to the actual depth of the true last water-bearing fracture ($\mu = 17$ m, with many exceeding 30 m) (Fig. 5a). Moreover, for discharge targets equal to 0.5 m³/h, Fig. 5a and Fig. S1 of the electronic supplementary material (ESM) show that it is not necessary to drill water boreholes more than about 40 m below the base of the saprolite to accurately fit the WBA Q distribution. This means that a Q of 0.5 m³/h can be reached before about 40 m for the majority of the synthetic WBAs. Finally, the difference between the distribution of the instantaneous discharge and the last water-bearing fracture depth of the synthetic boreholes for discharge targets equal to 0.5 and 10 m³/h is minor (Fig. 5a, b). This highlights the fact that, among the instructions given to water well drillers, the depth target of the boreholes has likely more importance than the Q_{target} , which is logical, as the instruction “maximum allowed depth of the synthetic boreholes” implies stopping drilling at a given depth whatever the obtained discharge, whereas, as discharge is quite low in WBAs, the instruction “discharge target” induces the

Table 2 Sensitivity analysis parameters: μ , σ are respectively the mean and standard deviation of the depth (Z_{wbf}) and hydraulic conductivity (K_{wbf}) of water bearing fractures and minimum borehole depth (Z_{min})

Parameters		Initial value of parameters	Variation of parameters
Synthetic WBA	Z_{wbf} (m)	Log-normal distribution $\mu = 2.4$; $\sigma = 0.75$	Log-normal distribution $\mu = 2.4$; $\sigma = 0.5$ Log normal distribution $\mu = 2.4$; $\sigma = 1$
	K_{wbf} (m/s)	Log-normal distribution $\mu = \log_{10} 5 \times 10^{-5}$ and $\sigma = 0.32$	Log-normal distribution (Schist) $\mu = \log_{10} 10^{-5}$ and $\sigma = 0.32$ Log-normal distribution (Granite) $\mu = \log_{10} 10^{-4}$ and $\sigma = 0.32$
Drillers' behavior	Z_{min} (m)	$Z_{min} = 0.5 \times Z_{max}$	$Z_{min} = x \times Z_{max}^*$ where $x = \{0, \frac{1}{4}, \frac{2}{4}, \frac{3}{4}, \frac{4}{4}\}$

wbf water-bearing fractures

drilling of quite deep boreholes, whatever the given instruction. In other words, only unrealistic discharge targets that are very low (below $0.5 \text{ m}^3/\text{h}$ for the simulated WBAs) would have an impact on the results. Logically, this slight difference in estimated instantaneous discharge and depth to the deepest water-bearing fracture below the base of the saprolite is also observed for the different discharge targets of 0.7 , 1 and $5 \text{ m}^3/\text{h}$, as presented in Figures S2, S3 and S4 of the ESM.

Assessment of biases due to the instructions given to water borehole drillers

The box plots of the differences in instantaneous discharge (Fig. 6a) and depth of the last water-bearing fractures (Fig. 6b), between the complete WBA and the synthetic borehole database, as defined by Eq. (3), show that (1) the differences are systematically negative, meaning that they lead to the underestimation of Q and the last water-bearing fracture depth; (2) there are very limited differences between high and low discharge targets, (3) low Z_{max}^* values imply higher absolute median, mean and interquartile range than higher Z_{max}^* values; (4) relative differences show similar values whether considering instantaneous discharge or depth of the last water-bearing fractures. For typical Z_{max}^* of 25 – 35 m , Q differences are confined to less than 1 – $2 \text{ m}^3/\text{h}$, which is a 5 – 15% difference, while the last water-bearing fracture depth difference is confined to less than 10 – 20 m , that is, 10 – 20% . Although not negligible, these percentages remain acceptable. Moreover, the median and mean tend to be closer to the lower quartile (Q1) than to the upper quartile (Q3; Fig. 6a, b). Most data points cluster near Q1, while a long right-hand tail extends toward higher values. Consequently, the upper whisker, representing values up to 1.5 times the interquartile range (IQR) above Q3, extends significantly farther than the lower whisker. The numerous data points beyond $Q3 + 1.5 \times \text{IQR}$, typically classified as

“outliers”, are in fact a statistically expected feature of the log-normal-like distribution and should not be interpreted as anomalies. Figure 6a, b also shows that the relative difference in the estimation of the depth to the deepest water-bearing fracture ($Z\%$) and instantaneous discharge ($Q\%$) varies considerably with the borehole depth below the base of the saprolite. Typically, only boreholes deeper than 35 m below the base of the saprolite exhibit a relative difference in $Z\%$ and $Q\%$ below 10% . Those depths deeper than 35 up to 55 m represent the usual borehole depth below the base of saprolite commonly observed within borehole databases used by Courtois et al. (2010) and Aoulou et al. (2021).

Furthermore, Fig. 7 presents the estimate of the useful thickness (Lu) and mean discharge $Q_M(\text{Lu})$, based on the synthetic borehole databases obtained under various types of instructions given to water borehole drillers. The real useful thickness that contains 80% of the total instantaneous discharge from the $10,000$ synthetic WBA realizations occurs within the first 22.5 m . The real mean discharge of the $10,000$ synthetic WBA realizations is equal to $1.94 \text{ m}^3/\text{h}$ (Fig. 7). The estimated useful thickness (Lu) and mean discharge $Q_M(\text{Lu})$, (Fig. 7), differ greatly from those obtained using the generated synthetic borehole database with all boreholes reaching the deepest fracture of the aquifer. This shows that the borehole database influences the estimation of the useful thickness, which contradicts the intended interpretation of Lu, since it should remain approximately constant across the same $10,000$ realizations of the synthetic WBA. The method developed by Courtois et al. (2010) is parameterized based on borehole depth below the base of the saprolite and does not show consistent results.

Sensitivity analysis

As already described, the sensitivity analysis involved both (1) the sensitivity of the WBA numerical model to its parameters; and (2) the sensitivity of the drillers' behavior model to the minimum borehole depth.

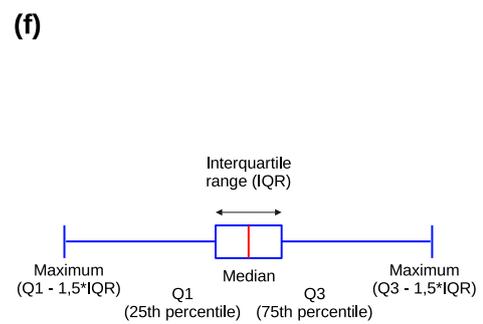
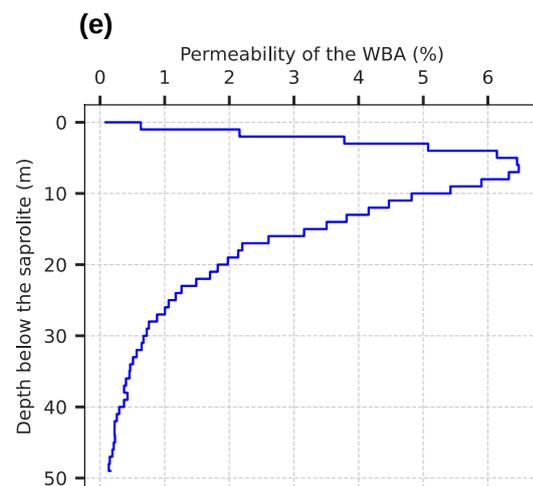
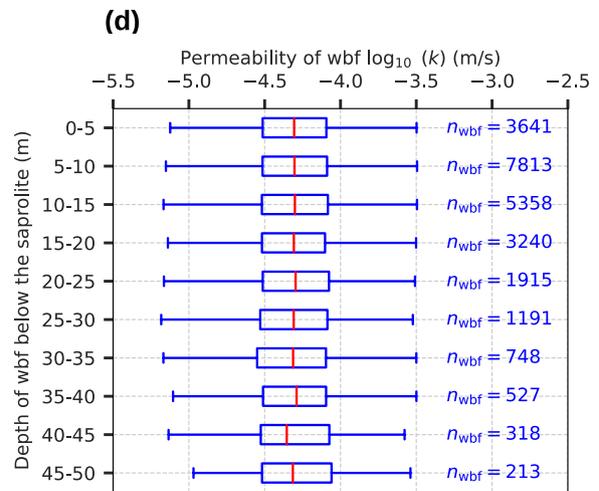
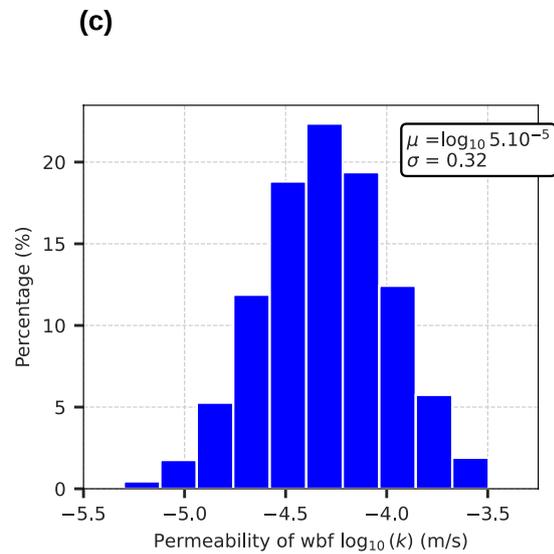
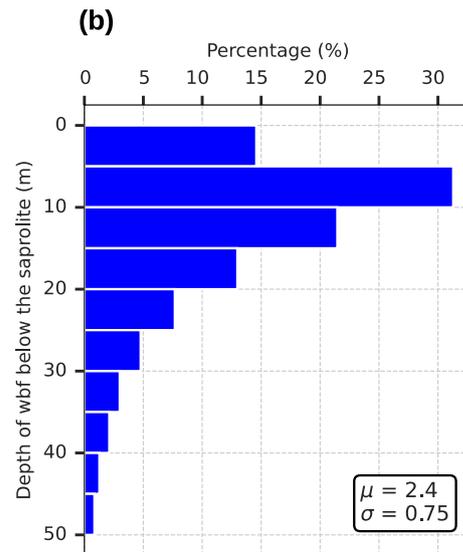
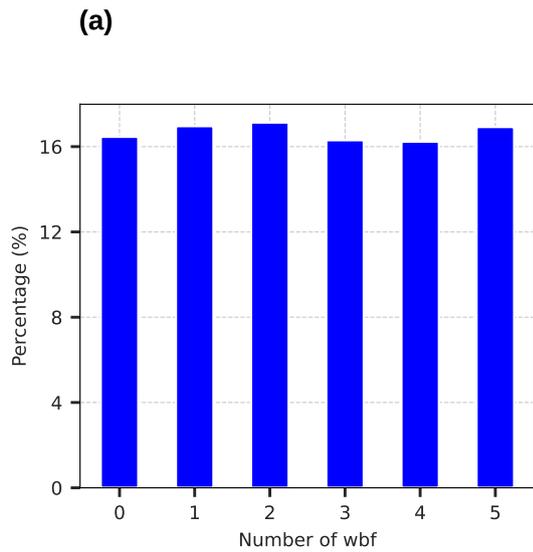


Fig. 4 Control of the conformity of the input parameters in the obtained synthetic WBA: **a** Number of water-bearing fractures (wbf); **b** Depth of the water-bearing fractures (wbf); **c** Permeability of the water-bearing fractures (wbf); **d** Permeability of the water-bearing fractures (wbf) as a function of their depth below the saprolite; **e**) Average permeability percentage (sum of the water-bearing fractures, wbf) permeability per 1-m layer divided by the sum of the permeability of all water-bearing fractures (wbf) in the 10,000 realizations of the synthetic WBAs) of the 10,000 realizations of the synthetic WBA as a function of their depth below the saprolite; **f** legend used for box-plot in this research; with, n_{wbf} the number of water-bearing fractures (wbf)

Parameters of WBA

The sensitivity analysis conducted on selected parameters of the synthetic WBA, specifically hydraulic conductivity and the depth distribution of water-bearing fractures below the base of the saprolite, shows minimal variation in the already presented results.

Water-bearing-fractures depth distribution The sensitivity analysis conducted on the distribution of water-bearing fractures was carried out by modifying only the standard deviation to assess the impact of water-bearing fracture extension. The results show some changes compared to the initial assessed impact of the instructions given to water borehole drillers, but all are below 10%. These changes are primarily linked to the percentage of water-bearing fractures being higher or lower than this reference within the first meters. Finally, in reality, the small percentage of water-bearing fractures observed at the contact between the saprolite and the fractured layer is, as reported in the literature, due to difficulties in clearly identifying the transition zone between the saprolite and the fractured layer. Additionally, this is also attributed to the dewatering of this interface in cases where the water table lies below the base of the saprolite (Figs. 8a and 9a).

Hydraulic conductivity Variation of the statistical distribution parameters (only the mean $\mu_1 = 5 \times 10^{-5}$ m/s; $\mu_2 = 10^{-5}$ m/s) of K , while maintaining a constant SD, shows limited impact of the instructions given to water borehole drillers on the estimation of hydrogeological properties. Two important results should be highlighted. First, there is no major impact from this parameter; however, the bias, whether for instantaneous discharge (Q) or the depth of the last water-bearing fractures decreases for $Q \geq 0.5$ m³/h when K is reduced. This suggests that achieving the discharge target becomes more difficult, leading to deeper water boreholes, and therefore a reduction in the under-sampling of the WBA. This effect is clearly visible for K with a mean $\mu = 10^{-5}$ m/s. The lower the K of the aquifer, the lower impact of the Q_{target} instruction. Under-sampling is reduced (for the same Q_{target}) because greater depth is

required to reach the discharge threshold. The opposite is logically observed for the higher K value, but without any great impact as a result of the normal range of water-bearing fracture permeability value rarely exceeding $\mu = 10^{-4}$ m/s (Figs. 8b and 9b).

Parameters regarding the instructions given to water borehole drillers

The consideration of the impact of a change in the value of Z_{min} in the current results was made by comparing the outcomes in the absence of Z_{min} to different scenarios where Z_{min} was set as a percentage of Z_{max}^* . This variation primarily affects borehole databases generated with low discharge targets (e.g., $Q \geq 0.5$ m³/h). In contrast, a discharge target of $Q_{target} \geq 10$ m³/h is difficult to obtain within the maximum allowed borehole depth, resulting in uniform differences both for the instantaneous discharge and the depth of the last water-bearing fractures across all variations of Z_{min} . The estimated differences are particularly significant across all the different cases. A reduction of the undersampling is systematically observed when compared to the absence of Z_{min} , and reaches up to 30% both for the instantaneous discharge and the depth of the last water-bearing fractures. These findings further emphasize the strong influence of borehole depth on the reliability of WBA property estimations derived from borehole databases (Figs. 10 and 11).

Discussion

The WBA model

The first step of this research involved developing a realistic weathered basement aquifer (WBA) model to simulate its short-term productivity behavior, based on key aquifer parameters. This was achieved by incorporating recent advances in the conceptualization of WBAs (e.g. Lachasagne et al. 2021), as well as parameters and their ranges, from a review of the literature.

Regarding aquifer productivity, the model suggests that discharge from water-bearing fractures increases with depth. This is a consequence of the use of the Dupuit equation (Eq. 1), where instantaneous discharge (Q) is proportional to the hydraulic head, itself a function of depth. This aligns notably with the works of Adeotan et al. (2025) and Bianchi et al. (2020, 2023), who report a positive correlation between saturated thickness and borehole yield in West Africa. In this research, the piezometric level was assumed to be at the limit between the saprolite and the fractured layer. Bianchi et al. (2023), in their regional analysis of WBA instantaneous discharge spatial variations across West Africa, noted that water-table depths range from a few meters to approximately

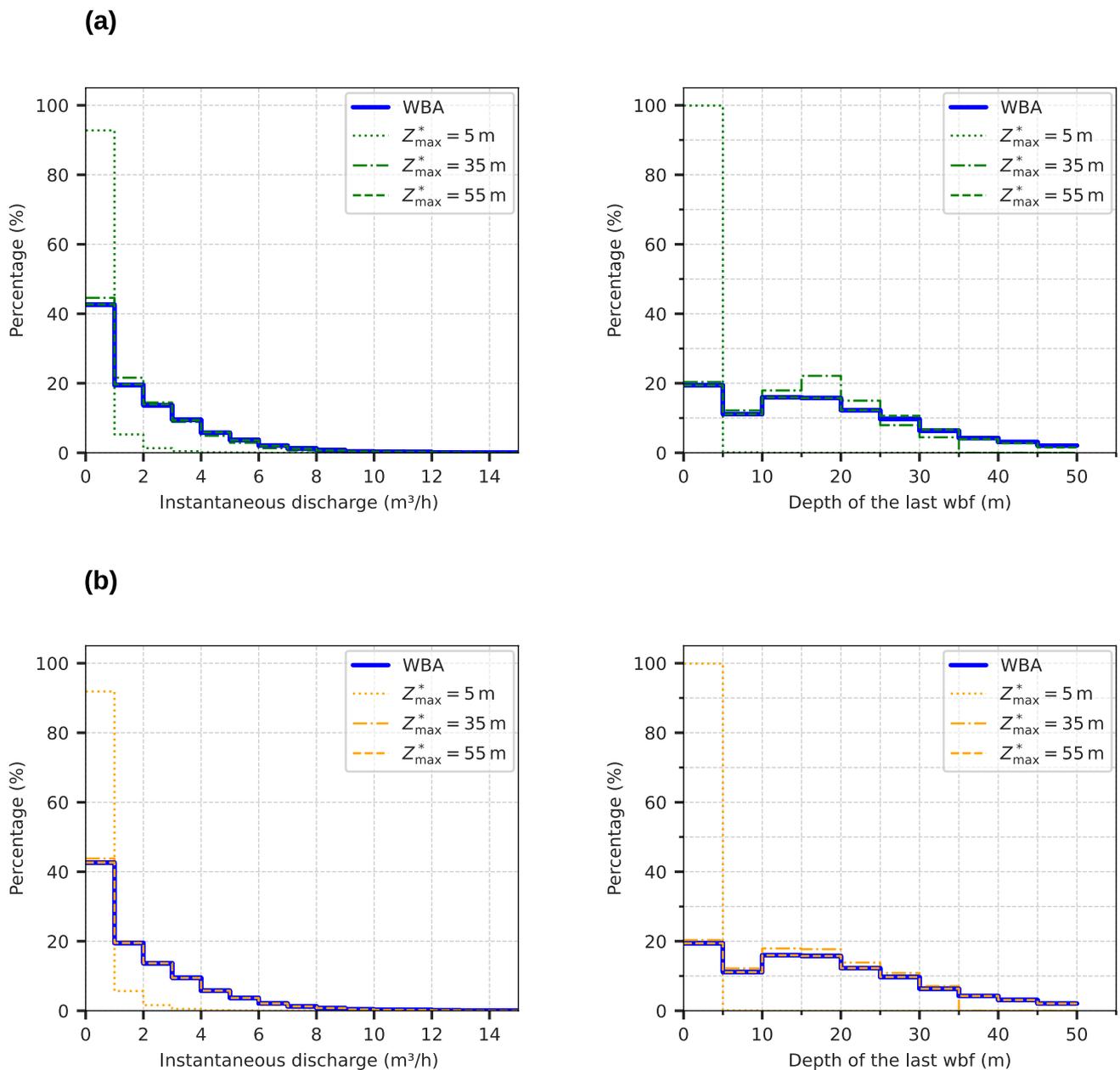


Fig. 5 Distribution of the borehole Instantaneous discharge (m³/h) (left) and the depth of the last water-bearing fracture depth below the saprolite (right) for **a** $Q_{\text{target}} = 0.5 \text{ m}^3/\text{h}$ and **b** $Q_{\text{target}} = 10 \text{ m}^3/\text{h}$ and

$Z_{\text{max}}^* = 5, 35$ and 55 m below the saprolite (dotted line) compared to complete WBA (bold line)

20 m. Accordingly, the water-table depth was changed and set to 20 m for this analysis. A sensitivity analysis of this parameter shows only slight variations in Q . In fact, shifting the piezometric level 5 m upwards into the saprolite layer caused an increase in the productivity of the WBAs by +20%, estimated for the mean discharge), yet important in the context of WBA productivity. The 20% increase (+0.4 m³/h) in discharge caused by the higher piezometric level does not have much impact on the main conclusions of the study. As it slightly increases water

borehole discharge, it slightly increases the undersampling bias (less than 1%) and, therefore, does not affect our overall conclusions (Fig. S6 of the ESM).

The WBA model was used to assess the impact of the instructions given to water borehole drillers on the estimation of hydrogeological parameters. In this context, an analysis of the database processing methodology of Courtois et al. (2010) was undertaken and further analysis is presented below (cf. section : Accuracy of the Courtois et al. 2010 methodology).

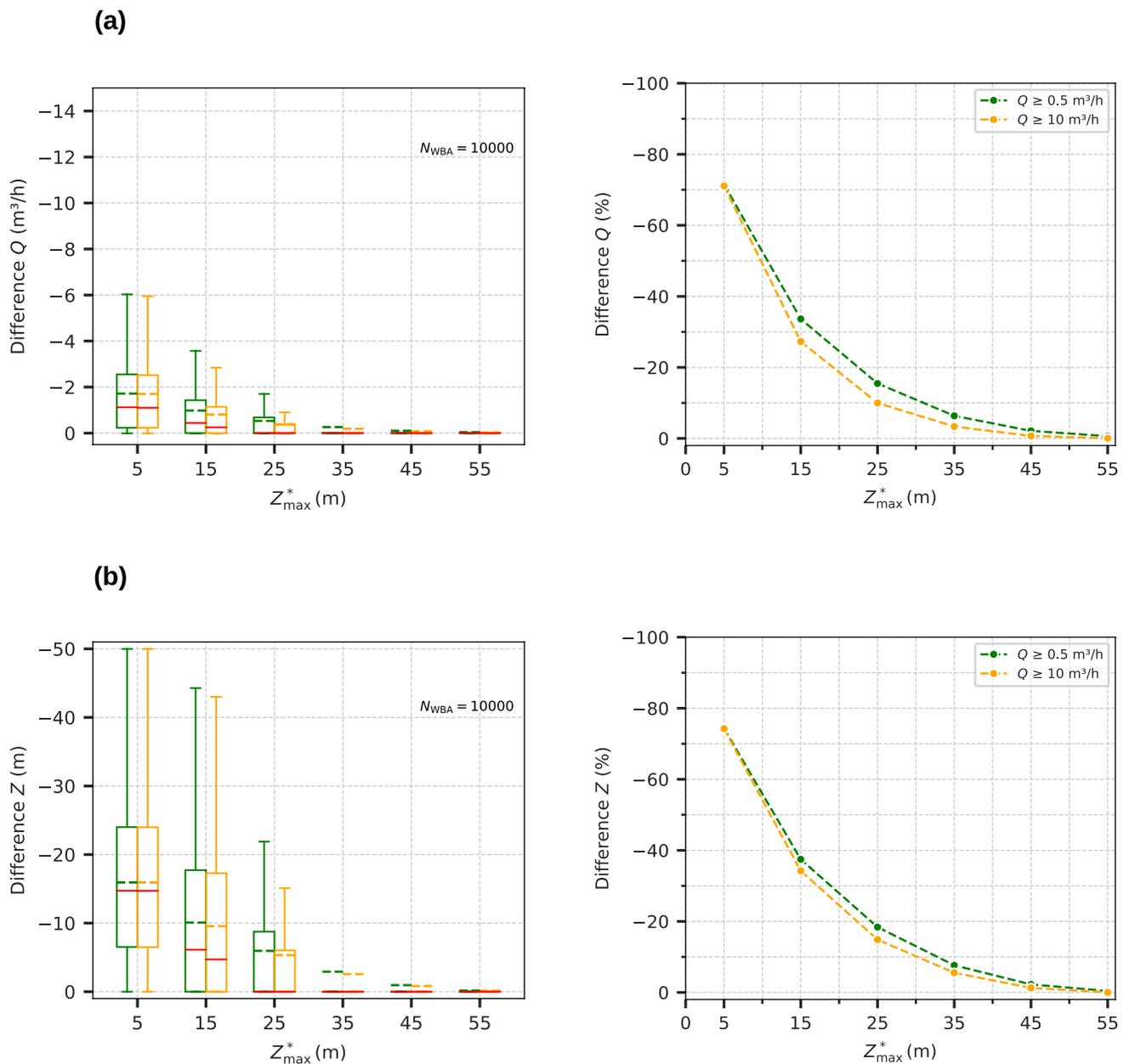


Fig. 6 Average difference, for different instructions given to water borehole driller, for **a** borehole instantaneous discharge (m³/h) and **b** depth of the deepest water-bearing fractures below the saprolite (m) for $Q=0.5$ m³/h and $Q=10$ m³/h and $Z_{max}^*=5$ to 55 m (dotted line)

compared to complete WBA (bold line); The dashed line represents the median of the box plot, whereas the red line represents the mean of the box plot

This model of WBA may be used for several other applications beyond the one proposed in this paper—for instance, modeling the long-term discharge of water boreholes, providing that conceptualization and data are available at least to infer fracture connectivity. Beyond its current applications, the model offers flexibility for broader use. Future research could focus on site-specific parameterization through probabilistic numerical modeling. Such refinement

would strengthen the model’s capability to characterize aquifer productivity and geometry, making it a practical tool for evaluating groundwater dynamics in basement rock environments. Furthermore, the model can serve as a calibration framework to correct systematic biases present in national borehole databases, which often stem from historical drilling protocols, thereby enhancing the reliability of aquifer property estimations.

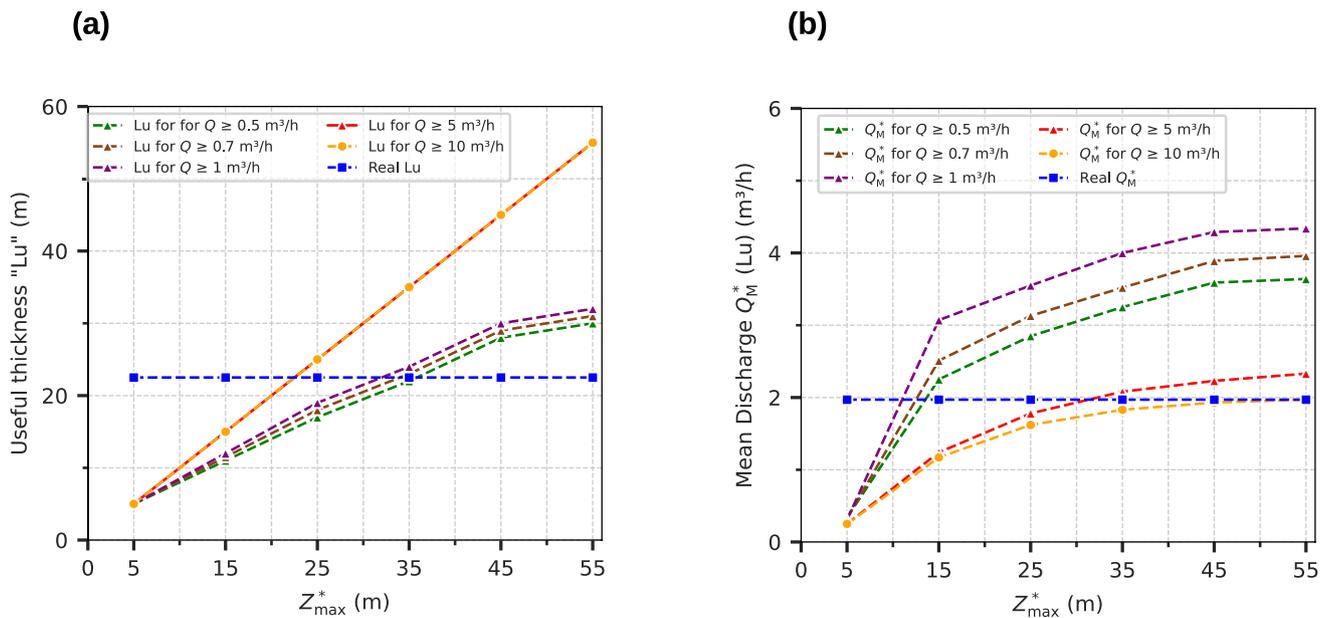


Fig. 7 Average difference, for different instructions given to water borehole driller, for **a** useful thickness (Lu) and **b** the mean discharge, Q_M (Lu)

Modeling the instructions given to water borehole drillers

A model was developed to show how instructions given to water borehole drillers impact key hydrogeological parameters (depth of the last water-bearing fractures, instantaneous discharge, etc.), and consequently, the reliability of borehole databases. The instructions given to the water drillers were conceptualized based on field experience and consisted of a discharge target, a maximum allowed depth, and a minimum allowed depth. In drilling projects, maximum allowed depth and discharge target are always predefined in tender documents and operational practices, and are guided by clear performance objectives. The model allows for a realistic evaluation of how such instructions given to water borehole drillers impact WBA hydrogeological-properties estimation. Though these three instruction types were focused on, the framework is adaptable to other instruction sets aimed at optimization.

Finally, critics may point to the model's simplification of saprolite thickness variability. However, this was addressed by introducing variability in the maximum permitted drilling depth below the base of the saprolite, thereby capturing saprolite profiles in a range of conditions from thick (low Z_{max}) to thin (high Z_{max}).

Impact of the instructions given to water borehole drillers on the quality and use of borehole databases

The results demonstrate that processing historical WBA borehole databases can induce systematic biases linked to the type of instructions given to water borehole drillers. These biases are systematically negative, meaning that they lead to the underestimation of the key parameters of the studied aquifer (e.g., instantaneous discharge and depth of the last water-bearing fractures). These biases are all related to a single process: the vertical undersampling of the WBA resulting from its incomplete drilling (under exploration). It should, however, be noted that this under-sampling introduces a bias into the databases but is not in itself a disadvantage when drilling, since the number of water-bearing fractures decreases with depth; the undersampling of aquifers does not necessarily reduce water borehole productivity in itself, but it does reduce the likelihood of having higher discharge.

This bias is mainly linked to the maximum allowed depth given to water borehole drillers rather than to the instantaneous discharge target, as the first type of instruction has a direct impact on aquifer undersampling. A very small maximum allowed depth (5–25 m) compared to the fractured

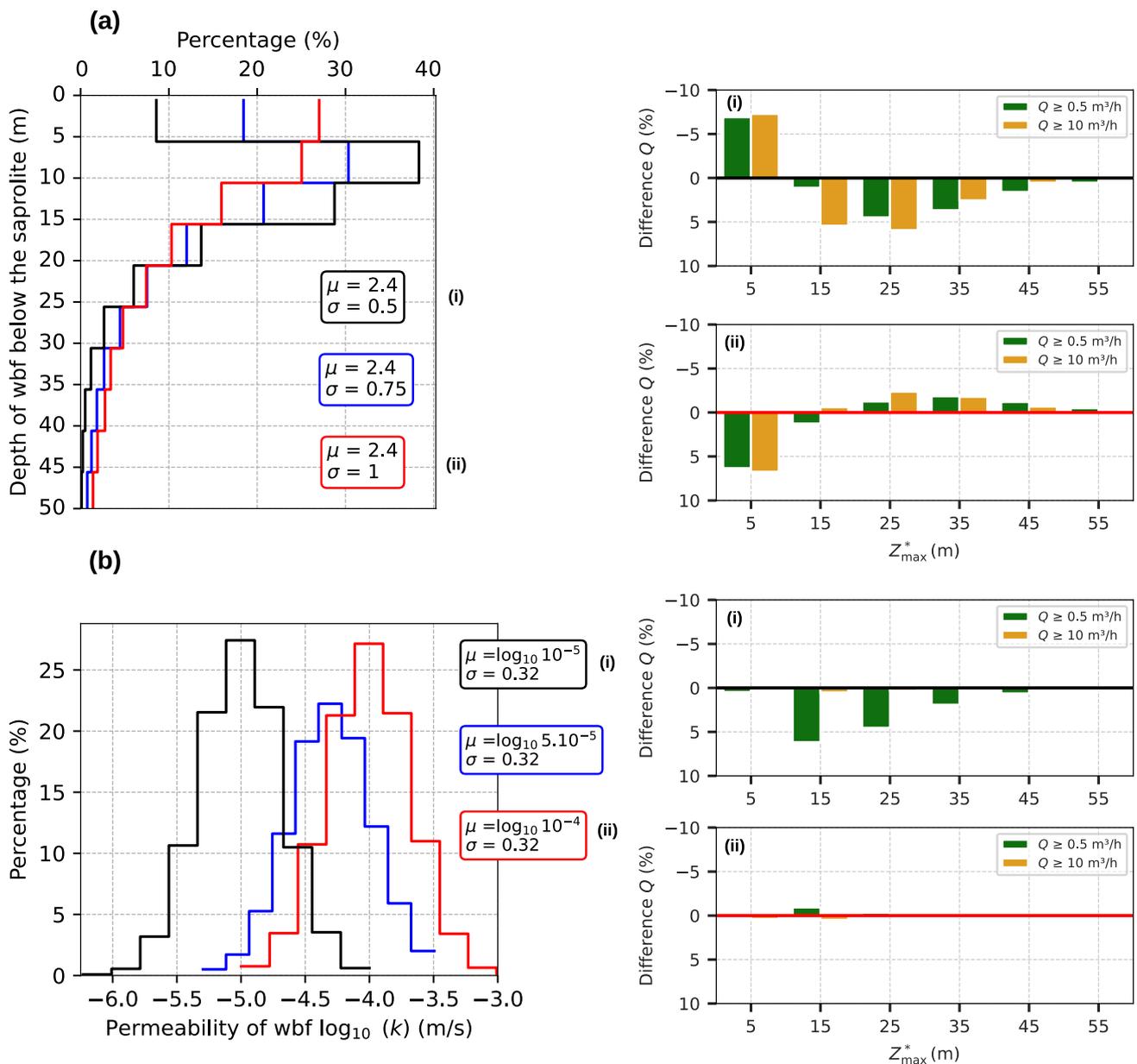


Fig. 8 Impact of a variation **a** of the water-bearing fracture (wbf) hydraulic conductivity (upper left) on the average difference of the estimate of the instantaneous discharge (upper right), **b** and of the water-bearing fracture depth distribution (lower left) on the aver-

age difference on the estimate of the instantaneous discharge (lower right), under different instructions given to the water borehole driller ($Q=0.5 \text{ m}^3/\text{h}$ and $Q=10 \text{ m}^3/\text{h}$ and $Z_{\text{max}}^*=5$ to 55 m) compared to the initial model parameter represented in blue

layer thickness (50 m), in this case, induces a strong bias. To minimize a bias effect in database analyses, only data obtained from drilling at least 70% of the thickness of the fractured layer (35 m below the base of the saprolite in the present case) should be considered, since the biases become quite low. This comes as a refinement of the quality ratio proposed by Dewandel et al. (2004, 2005, 2006).

As saprolite thicknesses and total borehole depth are often recorded in databases, this is realistic and pragmatic advice.

Because the ratio between the borehole discharge target given to drillers (Q between $0.5\text{--}2 \text{ m}^3/\text{h}$, and often higher) and the median aquifer productivity ($1.94 \text{ m}^3/\text{h}$ in this case), which is intrinsically low in WBA, is not far from 1, the discharge target instruction is not a strong bias driver. In other words,

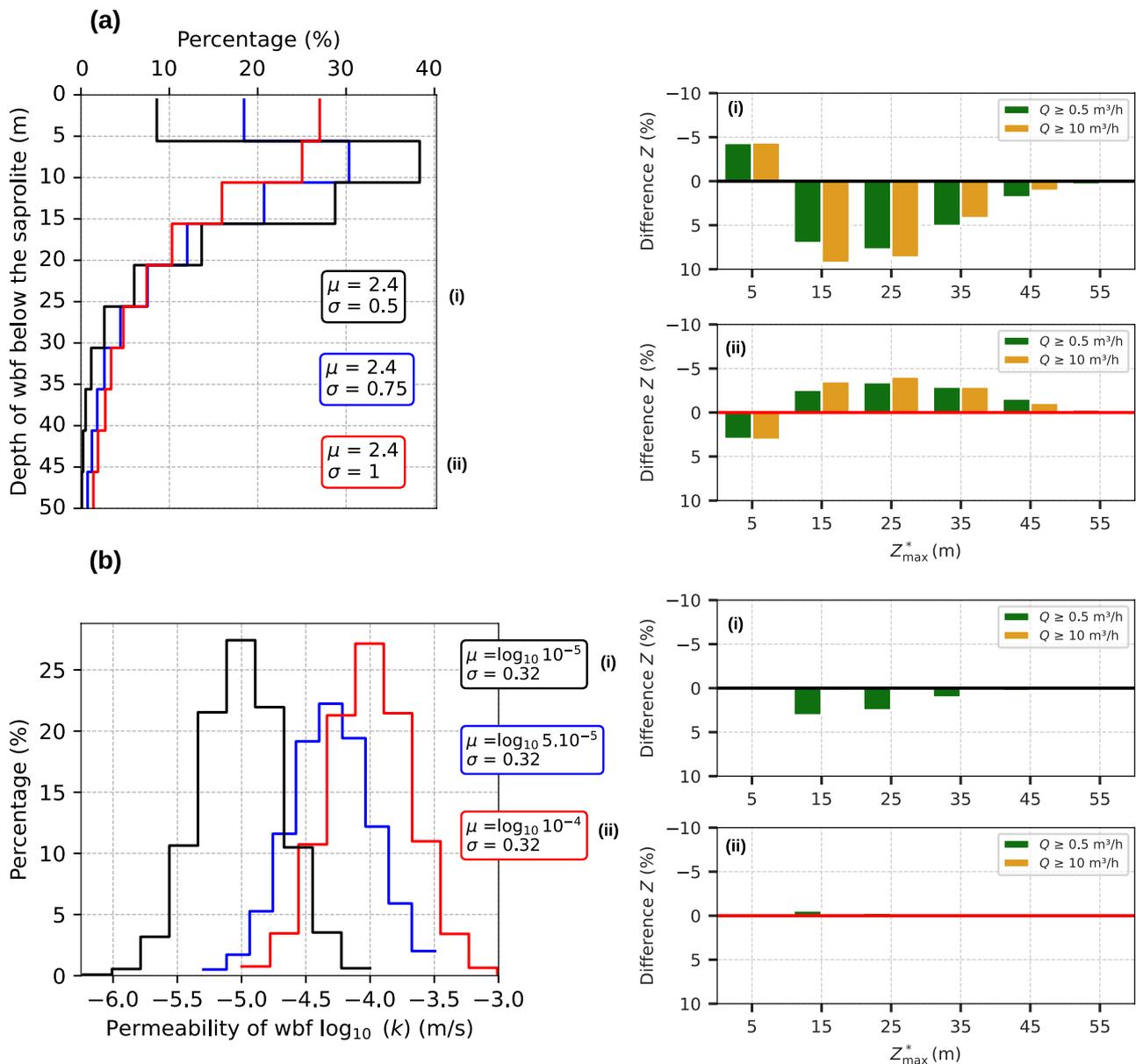


Fig. 9 Impact of a variation **a** of the water-bearing fracture (wbf) hydraulic conductivity (upper left) on the average difference on the estimate of the depth of the last water-bearing fractures (upper right), **b** and of the water-bearing fracture depth distribution (lower left) on

the average difference on the estimate of the depth of the last water-bearing fractures (lower right), under different instructions given to the water borehole driller ($Q=0.5 \text{ m}^3/\text{h}$ and $Q=10 \text{ m}^3/\text{h}$ and $Z_{\text{max}}^*=5$ to 55 m) compared to the initial model parameter represented in blue

the bias would be much higher in higher-productivity WBAs where instructions given to drillers would be of the same order of magnitude (Q between 0.5 – $2 \text{ m}^3/\text{h}$). As the discharge target given to drillers tends to increase with time, notably with the rather recent quest for “high-discharge wells,” this under-sampling bias should be lower in recent datasets than in older ones.

This 10% underestimation threshold must, however, be considered with care, as it hides the very high variability of WBA hydrodynamic properties. The result is thus only valid for databases with a high number of boreholes.

Therefore, existing databases can still be used, provided certain precautions are taken. For instance, shallow boreholes, drilled insufficiently below the saprolite, should be excluded from the analyzed datasets. A best practice recommendation would also be to archive additional parameters in borehole databases, especially key instructions given to water borehole drillers such as Q_{target} and Z_{max}^* , Z_{min}^* .

Moreover, it is important to note that the current recommendations (e.g., drilling at least to a depth of 35 m below

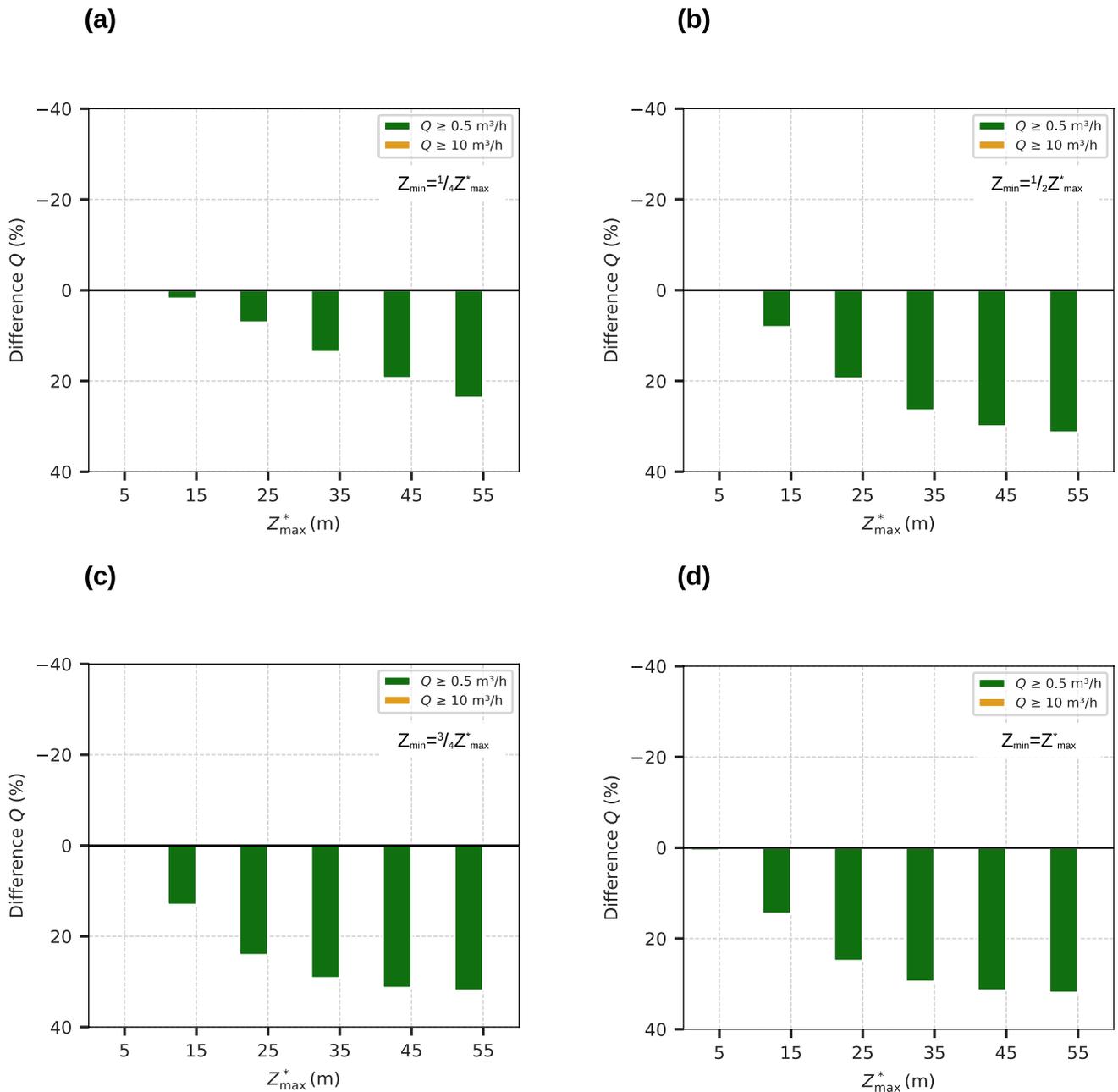


Fig. 10 Impact of a variation of the minimum borehole depth below the saprolite on the average difference on the estimate of the instantaneous discharge, compared to the case where Z_{\min} does not exist: **a** $Z_{\min} = 1/4 Z_{\max}^*$; **b** $Z_{\min} = 2/4 Z_{\max}^*$; **c** $Z_{\min} = 3/4 Z_{\max}^*$; **d** $Z_{\min} = Z_{\max}^*$

the base of the saprolite) are based on the stratiform conceptual model. In the (rare) cases where a borehole intersects a local deepening of the weathering profile (saprolite + fractured layer), resulting from a lithological contact, a vein, a dike, an ancient joint or fault, etc. (Dewandel et al. 2005, 2006; Lachassagne et al. 2021; Roques et al. 2016), these guidelines may not apply, as the hydrogeological conceptual model is different, and the saprolite + fractured layer may

locally be much deeper. A perspective of interest would be to identify, within water borehole databases, such configurations (with notably the saprolite being much thicker than at neighboring boreholes), and to gather them in a subdatabase whose properties could then be studied. Case studies in Burkina Faso, Togo, and Chad demonstrate that structured data categorization improves hydrogeological assessments (Adeotan et al. 2025; Ani et al. 2025; Nouradine et al. 2024).

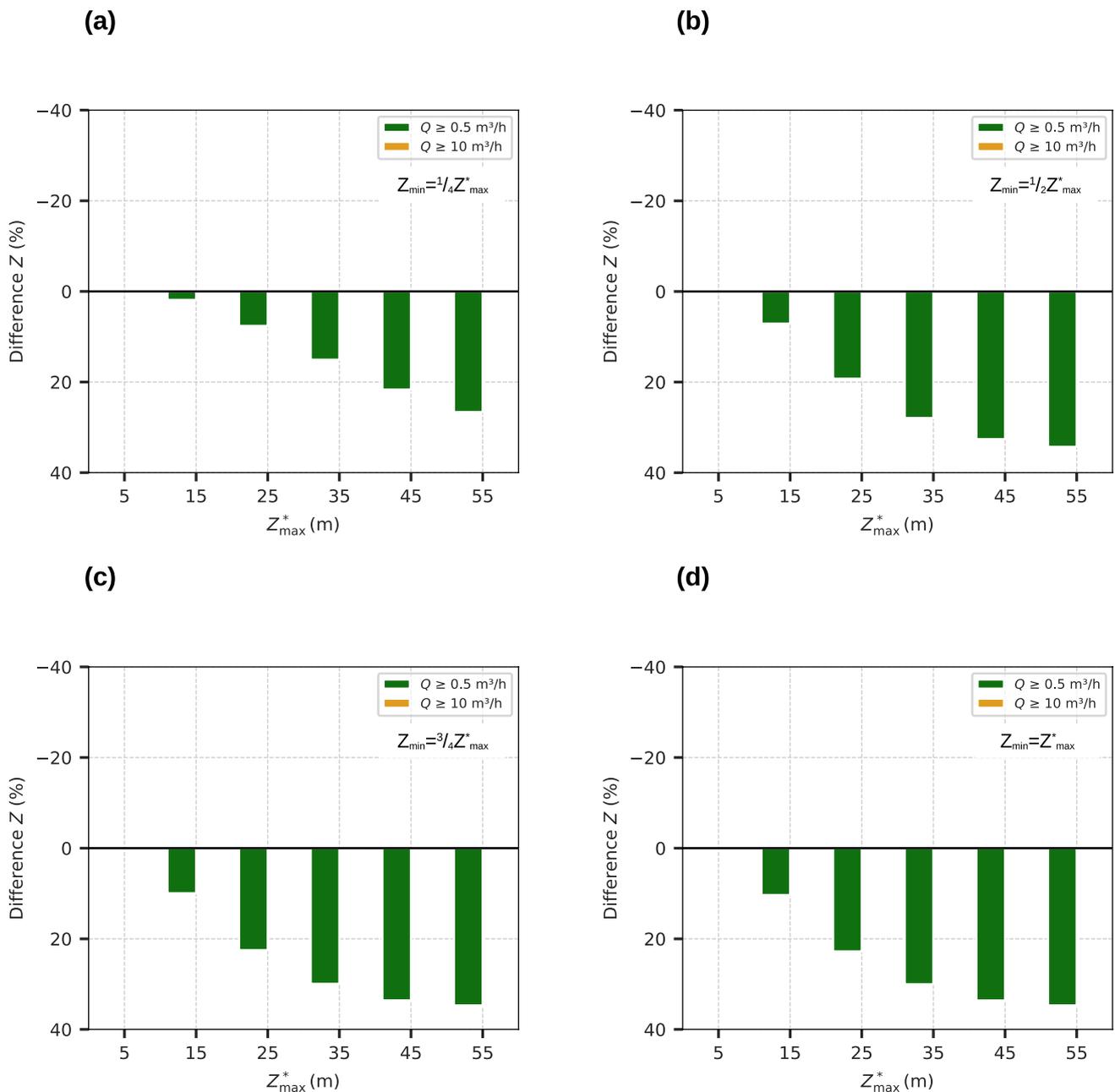


Fig. 11 Impact of a variation of the minimum borehole depth below the saprolite on the average difference on the estimate of the saturated thickness, compared to the case where Z_{\min} does not exist: **a** $Z_{\min} = 1/4 Z_{\max}^*$; **b** $Z_{\min} = 1/2 Z_{\max}^*$; **c** $Z_{\min} = 3/4 Z_{\max}^*$; **d** $Z_{\min} = Z_{\max}^*$

Accuracy of the Courtois et al. 2010 methodology

The results show that the methodology of Courtois et al. (2010), specifically designed to infer, from WBA borehole databases, the useful thickness and the mean discharge of WBAs, totally fails in its objectives, particularly in estimating the WBA's useful thickness Lu, regardless of the instructions given to water borehole drillers (Fig. 7). In fact, the Courtois et al. (2010) methodology only achieves the objective of

estimating (on average) the useful thickness of the WBA Lu in a few cases: low discharge target ($Q_{\text{target}} \geq 0.5$ to $0.7 \text{ m}^3/\text{h}$), $Z_{\max}^* = 35 \text{ m}$ (Fig. 7c). Apparently, this is due to the fact that, for no real physical reason, the result curves cross, on average, the actual Lu value at this point. The Courtois et al. (2010) method was analyzed using a simple mathematical framework and shows that the Courtois' curve is mainly driven by borehole density with respect to depth of the borehole (i.e. the number of boreholes available at a given depth; see below).

Biases due to instructions given to water borehole drillers' behavior shed new light on the Courtois et al. (2010) methodology for interpreting borehole databases

Here, a mathematical framework is proposed to show that the curve underlying the Courtois' methodology for identifying the useful thickness of an aquifer is not only driven by the actual linear discharge but also by the linear density of borehole depth and, subsequently, by the driller's behavior. Lu refers to a depth limit beyond which the cumulative percentage of linear discharge in function of the borehole depth below the base of the saprolite should experience a dramatic change highlighting an abrupt reduction in the linear discharge of the WBA, which is, supposedly, the point detected by Courtois' method in the plot of the cumulative percentages of the linear discharge with respect to borehole depth below the base of the saprolite.

More formally, considering the graph presented by Courtois et al. (2010), the cumulative linear discharge can be expressed as:

$$S(z + dz) = S(z) + \int_z^{z+dz} q(z) \cdot f(z) dz = S(z) + q(z) \cdot f(z) dz \quad (4)$$

where $q(z)$ is the linear discharge with respect to depth z ; $S(z)$ is the cumulative sum of the linear discharge with respect to depth z ; and $f(z)$ is the borehole density at the depth z .

If, over a given interval of depth, $a < z < b$, the function $S(z)$ is linear (i.e. it graphs as a straight line), it means that for all z in $[a, b]$:

$$\frac{S(z + dz) - S(z)}{dz} = \text{Const} \quad (5)$$

Which by Eq. (4) means that for all z in $[a, b]$:

$$q(z) \times f(z) = \text{Const} \quad (6)$$

Thus, over ranges of depth where $S(z)$ varies linearly with respect to z , the linear discharge at depth z is inversely proportional to the borehole density for that depth. This shows that the flattening of the cumulative percentage of the linear discharge curve at greater depths can be explained either by a reduction of $q(z)$ as intended by the Courtois' method, but can also simply be driven by a much smaller number of boreholes at higher depths—i.e., $f(z)$ diminishes. This reduction is likely due to the fact that most drilling operations are stopped earlier once the desired discharge is achieved.

Simulations were used to deconvolute the effect of $q(z)$ from the effect of $f(z)$ on the bending of the cumulative curve in Courtois' method. Under the same geological and hydrological conditions, namely under the same WBA model developed in section "Numerical modeling of WBAs", two different water-borehole driller behaviors were compared: one receiving instructions to reach a discharge target equal to $0.5 \text{ m}^3/\text{h}$ (Fig. 12a), and a second one drilling at a random depth chosen between 0 and 35 m under the base of the saprolite. The resulting synthetic cumulative discharge of linear discharge curves in Fig. 12b does not display any inflection patterns, while the curve in Fig. 12 is remarkably similar to those observed in actual datasets. This supports the

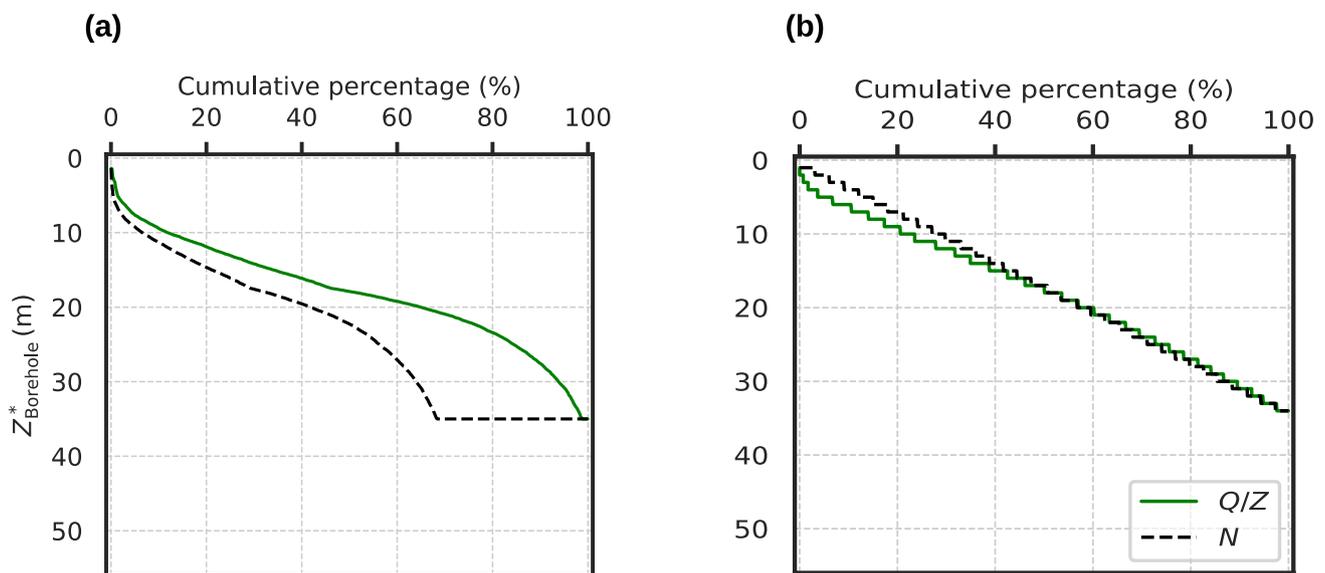


Fig. 12 Cumulative percentage of linear discharge (Q/Z) and the number of water boreholes (N) with respect to depth below the base of the saprolite. **a** Borehole database simulated with driller behavior,

i.e. $Q_{\text{target}} = 0.5 \text{ m}^3/\text{h}$ and $Z_{\text{max}}^* = 35 \text{ m}$ and $Z_{\text{min}}^* = \frac{1}{2} Z_{\text{max}}^*$, **b** Borehole database simulated with uniform random depth of drilling ranging from 0 to 35 m below the base of the saprolite

hypothesis that the apparent linear discharge decline originates not from aquifer properties, but from the borehole density (with respect to the depth, i.e. $f(z)$), which is in turn determined by the instructions given to water borehole drillers. Altogether, the authors claim that this study points out a very strong flaw in the foundations of the Courtois et al. (2010) methodology.

Conclusions

Numerical modeling of 10,000 synthetic weathered basement aquifers (WBAs) reveals systematic biases in borehole databases as a result of the instructions given to water borehole drillers. Insufficient drilling depth relative to the real thickness of the fractured layer leads to undersampling of deeper water-bearing fractures, causing an underestimation of aquifer productivity and fractured-layer thickness. These biases persist across discharge s ($0.5\text{--}10\text{ m}^3/\text{h}$) and are exacerbated by shallow drilling ($< 35\text{ m}$ below saprolite), which omits critical water-bearing fractures (wbfs). Traditional methodologies, such as Courtois et al. (2010)'s approach, fail to account for the bias because of the instructions given to the water borehole drillers, misrepresenting the useful aquifer thickness (Lu) by up to 100%. To enhance database reliability, several approaches could be considered: (1) classify boreholes by exploration depth below the saprolite and instantaneous discharge, excluding shallow borehole data ($< 35\text{ m}$ below saprolite), (2) archive drilling instructions (Q_{target} , Z_{max} and Z_{min}) to contextualize data limitations, and adopt robust indicators such as specific capacity and variations of discharge with depth instead of instantaneous discharge. Moreover, several refinements could be made based on this study: (1) integration of subvertical geological features (veins and faults) into WBA models to refine fracture connectivity estimates; (2) development of standardized protocols for ex-post evaluations of drilling campaigns to identify site-specific biases; (3) optimization of drilling depths using empirical depth-yield relationships, balancing resource investment and diminishing returns. This study underscores the urgency of reconciling drilling practices with aquifer heterogeneity to advance sustainable groundwater management in sub-Saharan Africa. By prioritizing data transparency and model refinement, stakeholders can mitigate systemic biases and unlock the full potential of WBAs for water and food security.

Appendix

Nomenclature

Q_{target}	Instantaneous discharge target
Z_{max}	Maximum allowed borehole depth
Z_{min}	Minimum borehole depth
$Q_{\text{Available}}$	Instantaneous discharge available in the realizations of the synthetic WBA
$Z_{\text{Available}}$	Fractured layer thickness of the realizations of the synthetic WBA
Q_{Borehole}	Instantaneous discharge of the synthetic borehole
Z_{Borehole}	Depth of the synthetic borehole below the base of the saprolite
Z_{Borehole}^*	Depth to the last water-bearing fracture below the saprolite in the synthetic borehole
$Lu_{\text{Available}}$	Useful thickness estimated using the Courtois et al. (2010) methodology and the 10,000 realizations of the synthetic WBA
Lu_{Borehole}	Useful thickness estimated using the Courtois et al. (2010) methodology and the 10,000 set of synthetic borehole databases
$Q_{\text{M}}(\text{Lu})$	Mean discharge over the useful thickness estimation using the Courtois et al. (2010) methodology and the 10,000 realizations of the synthetic WBA
$Q_{\text{M}}(\text{Lu})_{\text{Borehole}}$	Mean discharge over the useful thickness estimated using the Courtois et al. (2010) methodology and the 10,000 set of synthetic boreholes

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Data Availability The datasets and code generated and/or analyzed during the current study will be made available on request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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