PAPER

Assessing regional variation in yield from weathered basement aquifers in West Africa and modelling their future groundwater development and sustainability

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Abstract

A data-driven modelling approach was applied to quantify the potential groundwater yield from weathered crystalline basement aquifers in West Africa, which are a strategic resource for achieving water and food security. To account for possible geological control on aquifer productivity, seven major geological domains were identified based on lithological, stratigraphic, and structural characteristics of the crystalline basement. Extensive data mining was conducted for the hydrogeological parameterisation that led to the identification of representative distributions of input parameters for numerical simulations of groundwater abstractions. These were calibrated to match distributions of measured yields for each domain. Calibrated models were then applied to investigate aquifer and borehole scenarios to assess groundwater productivity. Considering the entire region, modelling results indicate that approximately 50% of well-sited standard 60-m-deep boreholes could sustain yields exceeding 0.5 L/s, and 25% could sustain the yield required for small irrigation systems (> 1.0 L/s). Results also highlighted some regional differences in the ranges of productivities for the different domains, and the significance of the depth of the static water table and the lateral extent of aquifers across all geological domains. This approach can be applied to derive groundwater maps for the region and provide the quantitative information required to evaluate the potential of different designs of groundwater supply networks.

Keywords Water supply · Numerical modelling · Africa

Introduction and background

For many rural communities in developing countries, local groundwater resources offer the best opportunity for an affordable safe water supply (United Nations 2022). This is particularly the case in Africa, although there has been limited progress in the development of groundwater and, as a result, rural water supply coverage here is amongst the lowest globally (WHO/UNICEF 2021). Conventionally, groundwater is developed through the drilling of boreholes that, equipped with handpumps, can serve communities of several hundred people (MacDonald et al. 2005). However, ambitious water supply targets associated with sustainable development goals (SDGs; United Nations 2018) and encouraged by the availability of off-grid solar energy solutions (Wu et al. 2017) and the demand for small-scale irrigation (Villholth 2013), has raised interest in the pumping of larger volumes of groundwater through motorised pumps. This African 'groundwater revolution' (Cobbing and Hiller 2019) is seen as a potential driver for economic and social transformation in many rural areas.

The increased demand for groundwater has highlighted the need to better understand the groundwater potential of the weathered crystalline basement aquifers that underlie over 40% of the land area of sub-Saharan Africa (MacDonald et al. 2008). Conceptualisations of these aquifers (Chilton and Foster 1995; Dewandel et al. 2006; Jones 1985; Lachassagne et al. 2021) typically include a superficial highly weathered unconsolidated section called regolith, which comprises a residual soil and saprolite layers (Chilton and Foster 1995). The regolith overlays a saprock

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layer, characterised by high-density horizontal fracturing with local brecciation and boulders (Wright 1992). The saprock transitions into a layer of relatively unaltered rock with significant fracturing in the upper section and reducing in density with depth. In the literature, the saprock and the fractured unaltered rock layers are sometimes described as a whole and combined into a fissured or fractured layer (e.g. Lachassagne et al. 2021). In this composite aquifer, most of the groundwater flow occurs in the water-bearing fracture zones at the base of the regolith (lower saprolite) and in the saprock layer, while the upper saprolite provides significant groundwater storage due to the high porosity, allowing water to drain towards the underlying productive zone (Lachassagne et al. 2021). The structure and mineralogical composition of each layer is the expression of a complex history of weathering cycles of the original crystalline basement rocks (Butt et al. 2000). Results of several hydrogeological characterisation studies in weathered basement aquifers on different continents (Collins et al. 2020; Macdonald and Edmunds 2014; Maréchal et al. 2004; Maurice et al. 2019) indicate a large variability in hydraulic conductivity and porosity of the different layers.

Weathered basement aquifers are generally local poorly productive aquifers (e.g. Ofterdinger et al. 2019). The sustainable yield for an abstraction borehole, that is the rate of pumping that can be maintained long term without causing undesirable environmental, economic and social impacts (Walton and McLane 2013; Zhou 2009), mostly depends on the number of water-bearing fractures intersected, and therefore on the lithology, tectonic and weathering history, as well as past and present climate (Dewandel et al. 2006). In weathered basement aquifers, sustainable yields from boreholes tend to be less than 0.5 L/s (MacDonald et al. 2012); some larger values (>2 L/s) are possible but are considered rare (Maurice et al. 2019). Groundwater quality in African basement rocks is generally good (Gurmessa et al. 2022; Lapworth et al. 2020) with local pockets of high salinity (Barbieri et al. 2019; Ricolfi et al. 2020) or high concentrations of fluoride (Sunkari and Abu 2019) and arsenic (Smedley 1996). Due to their low storage, crystalline basement aquifers are likely to have low resilience to climate change (MacDonald et al. 2021) and impacts on water quality are uncertain (Barbieri et al. 2021; Taylor et al. 2013). Historically, these aquifers have been mapped as poorly productive, with optimal zones for groundwater exploitation only identified locally using geophysical methods (e.g. Belle et al. 2019; Hazell et al. 1992). Rarely have attempts been made to map variations in basement aquifer properties across larger areas (Aoulou et al. 2021; Courtois et al. 2010).

As with most of SSA, although improvements have been made, West Africa still has a challenge to meet the targets of SDG6 ('Clean water and sanitation for all'; Nhamo et al. 2019). A high proportion of the region is underlain by weathered basement aquifers (Fig. 1). In this work, the potential for increased and sustainable exploitation of this type of aquifer is examined. Variations in aquifer properties and in sustainable borehole yields from weathered basement aquifers are investigated in West Africa by constructing hydrogeological domains from the regional geology and geomorphology, and then applying the process-based modelling approach proposed by Bianchi et al. (2020) to each domain to estimate statistical distributions of sustainable yields. In Bianchi et al. (2020), this modelling approach was only tested for the weathered basement aquifer in northern Ghana. Here, the previous analysis to a number of countries in West Africa and to different types of crystalline basements is expanded on.

The objectives of this study include: (1) verifying the effectiveness of the modelling approach for estimating sustainable yields across a number of countries in West Africa and geological domains; (2) investigating the degree of geological control on groundwater productivity and estimating the probability of sustainable yield values for each domain; (3) estimating transmissivity distributions for each domain and understanding suggested controls on this hydrogeological property; and (4) understanding the influence of aquifer extent and water-table depth on sustainable yields.

Materials and methods

The methodology adopted for investigating regional variability regarding the productivity of weathered basement aquifers in West Africa includes an extensive review of the geological and hydrogeological settings of West African countries, hydrogeological data mining, numerical modelling, including calibration and scenario analysis, and statistical analysis of modelling outputs. These different components are explained in the following.

Origin of weathered basement aquifers in West Africa and division into geological domains

The Precambrian basement of West Africa can be divided into three major lithological groups including Archean granite-gneiss-greenstone, Proterozoic metamorphic rocks, and Phanerozoic intrusive magmatic rocks (Key 1992). These lithologies and the associated weathered basement aquifers are expected to have different hydrogeological properties. In particular, Archean and Phanerozoic rocks, which are related to the development of major cratons and typically comprise massive granite and orthogneiss, tend to have low primary intergranular porosity and conductivity, but they can be associated with relatively productive weathered basement aquifers having a well-developed and relatively highly transmissive fracture zone (Lachassagne et al. 2021;
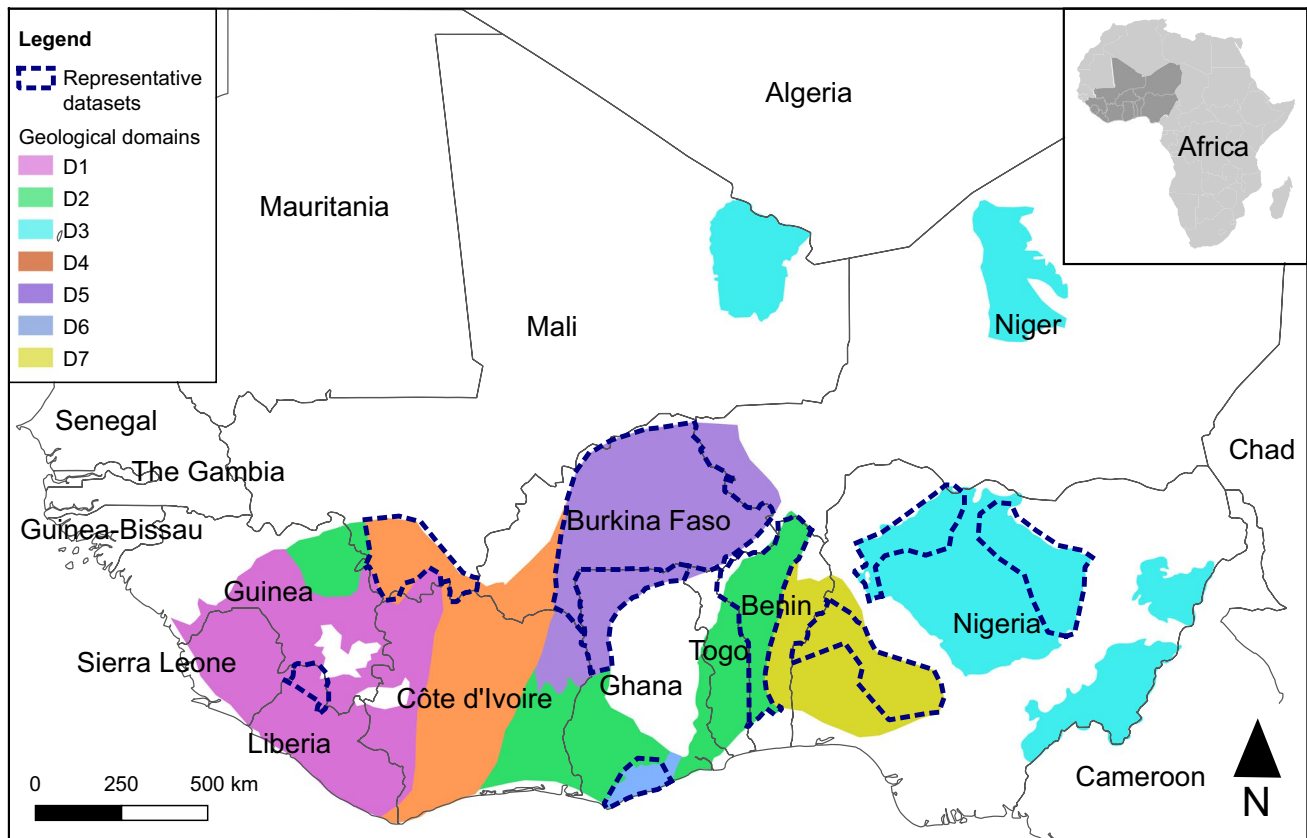
Fig. 1 Geological domains for areas of the crystalline basement in West African countries. Blue-dashed lines show the study areas of the reference data used for groundwater modelling

Pradhan et al. 2022). In contrast, Proterozoic metamorphic rocks, related to collisional and extensional tectonic events of the older cratons that are heavily sheared and schistose, are likely to have a higher intergranular porosity, but the productivity of the associated weathered basement aquifers depends on the dip of the foliation, with more favourable conditions when it is near vertical (Lachassagne et al. 2021).

The distribution, thickness, and stratigraphy (i.e. layering) of the regolith in West Africa, which are all important factors controlling groundwater productivity, are the result of a complex landscape history that extends from the Jurassic to the present day. The African Erosional Surface (AES) is a locally composite landscape surface on a continental scale that developed across Africa between 200–65 Ma (Burke and Gunnell 2008). In West Africa, the AES, which is best preserved in central Guinea and the western Ivory Coast, is an interior continental surface with pervasive lateritic weathering over a prolonged period of time, which has an extensive bauxite and ferricrete development (Chardon et al. 2006). During the last 65 Ma, four major uplifted pediments formed across West Africa (Chardon et al. 2018; Grimaud et al. 2015). The pediments represent long-term dissection and weathering of the AES. The extent, thickness, and

regolith stratigraphy of each pediment is locally variable, but show certain regional trends and similarities. Overall, each pediment represents the expression of repeated climatic cycles from semiarid to tropical climate (Grandin 1977). The four pediments form a series of gently dipping surfaces away from inland highs, including the intermediate land surface (24 Ma age), and the High (11 Ma), Middle (6 Ma) and Lower Glacis (3 Ma; Grimaud et al. 2015). Overall weathering and duricrust development decrease further down the pediment surfaces. The thickest saprolite and most extensive ferricrete are found on the upper pediment surfaces. The Middle and Lower Glacis have the thinnest saprolite and comprise conglomeratic regolith with clasts of ferricrete, eroded from older surfaces.

In summary, the long-term geological and geomorphological history of West Africa from the Archean to the Recent has resulted in large variability in the characteristics of both the crystalline basement and the overlying regolith across the region. Factors for aquifer productivity such as the basement lithology, the thickness of the regolith, or the extent of fracturing, are all expressions of this complex history, and high variability is expected throughout the region both at the local and regional scale.

For instance, regolith thickness is likely to be controlled by slope and the density of the drainage systems impacting erosion rates. In the attempt to constrain and classify this variability at the regional scale, a delineation into seven geological domains is proposed focussing on large-scale variations in bedrock lithology, major tectonic lineament density, and regolith thickness (Fig. 1; Table 1). This delineation is based on the interpretation of regional-scale geological maps, regional-scale models of long-term landscape evolution (e.g. Chardon et al. 2018) and various published regional studies. Therefore, it does not likely represent the local-scale complexity, while there is some degree of uncertainty in the delineation in areas lacking detailed data or not clearly assignable to a specific domain. The proposed geological delineation will be tested using the numerical modelling approach to understand if it can explain the differences in sustainable yields from weathered basements aquifers in West Africa.

The first domain, Domain 1 (D1), is mostly igneous basement with well-developed pediment surfaces. The area of D1, which includes Guinea, Liberia, Sierra Leone, and the western part of Ivory Coast, is dominated by the high and intermediate pediments, with complex and variable regolith sequences (Bowden 1997; Bowles et al. 2017).

Domain 2 (D2) is separated into three main areas in northern Guinea, Ivory Coast and Ghana and across Togo and Benin. The basement across the domain is mostly meta-volcano-sedimentary formations with minor proportions of plutonic igneous rocks. D2 includes the more distal and lowest pediments (Chardon et al. 2018). The regolith across the domain can be variable in thickness and capped with ferruginous duricrust of 25 cm to 2 m (Bayari et al. 2019; Koita et al. 2013). The thicker crust comprises reworked and cemented older crusts reflecting multiple climatic cycles.

Domain 3 (D3) covers the basement within the Trans-Saharan orogenic belt across Nigeria, Mali and Niger. The crystalline basement consists of plutonic and metamorphic rocks (mainly granites, migmatites, gneisses, quartzites and schists) with increased fracturing and shears associated with the orogenic belt (Hazell et al. 1992; Tijani et al. 2006).

The thickness of the regolith cover across the area is highly variable.

Domain 4 (D4) mostly covers central Ivory Coast and southern parts of Burkina Faso and Mali and comprises approximately equal coverage of volcano-sedimentary and igneous rocks. Similarly to D2, D4 has relatively well-developed higher pediment surfaces (Butt and Bristow 2013). The regolith is well developed comprising mostly saprolite with a ferricrete crust of variable age and thickness (Béziat et al. 2016).

Domain 5 (D5) mainly covers Burkina Faso and northern parts of Ivory Coast and Ghana. The basement is predominantly volcano-sedimentary with a small proportion of igneous basement and covers areas with well-developed middle to lower pediment surfaces. The regolith has a complex stratigraphy comprising saprolite with repeated Mn-Oxide layers and reworked regolith horizons in deeply weathered volcanic and sedimentary rocks capped with a ferricrete layer (Colin et al. 2005; Grimaud et al. 2015).

Domain 6 (D6) represents a small area (15,000 km^2) on the coast in southwest Ghana characterised by an igneous basement consisting mostly of granitoids (Leube et al. 1990; Taylor et al. 1992). Lastly, Domain 7 (D7) covers an area of nearly 150,000 km^2 in western Nigeria and eastern Benin. The basement of the domain is mostly igneous plutonic rocks (granites, granodiorites, migmatites), while the regolith has variable thickness and comprises a sequence of saprock, saprolite, and a ferricrete crust (Aizebeokhai and Oyeyemi 2018).

Hydrogeological conceptualisation and parameterisation of weathered basement aquifers in West Africa

For each geological domain, a comprehensive review of the available data in published local and regional studies focussing on West Africa was conducted with the aim to define a representative range of values and statistical distributions for the parameters considered by the adopted stochastic modelling approach. This approach follows two steps. In the first

Table 1 Geological domains for the crystalline basement in West Africa. The values reported for D4 and D5 refer to the ratios between igneous and metamorphic rocks

Domain	Basement lithology	Countries	Covered area (km^2)
D1	Igneous	Guinea, Sierra Leone, Liberia, Ivory Coast	330,000
D2	Meta-sediment	Ghana, Togo, Benin, Ivory Coast, Guinea	270,000
D3	Plutonic and metamorphic	Nigeria, Niger, Mali	460,000
D4	Volcanic-volcano-sedimentary (50:50)	Ivory Coast, Mali, Burkina Faso	275,000
D5	Volcanic-volcano-sedimentary (70:30)	Burkina Faso, Ghana, Ivory Coast	250,000
D6	Igneous	Ghana	15,000
D7	Plutonic	Nigeria, Benin	150,000

step, one-dimensional (1D) vertical profiles of hydraulic conductivity and effective porosity (i.e. specific yield) are generated based on the established conceptualisation of the weathered profile in crystalline basement aquifers (e.g. Chilton and Foster 1995), which includes the following layers from top to bottom: the residual soil (RS), upper saprolite (US) and lower saprolite (LS) layers, the saprock layer (SR) and the unweathered fresh rock layer (FR). In the second step, a radial flow model is applied to simulate groundwater abstraction considering the generated profiles of hydraulic conductivity and specific yield. A complete list of the input parameters required for the modelling approach and their descriptions are provided in Table S1 in the electronic supplementary material (ESM), while further details about the methodology can be found in Bianchi et al. (2020). These parameters include the thickness of the different layers, maximum and minimum values of the hydrogeological properties along the profile, as well as others, such as the depth to the water table and the lateral extension of the aquifer.

The range of values and statistical distributions of the input parameters for different geological domains are also provided in Tables S2–S12 in the ESM. Here follows a summary of the parameterisation of each geological domain starting from D1, for which the main sources of information were the analysis of direct (74 borehole logs) and indirect (2D electrical resistivity profiles) hydrogeological data in the basement aquifer system of NW Liberia (Elster et al. 2014), and the results of a nationwide hydrogeological survey in Sierra Leone considering geological and tectonic maps analysis, remote sensing, and analysis of 1,033 borehole records (Fileccia et al. 2018). Input data for D2 were based on an integrated assessment of groundwater resources in Benin based on the spatial analysis of hydrogeological parameters taken from national boreholes database (Barthel et al. 2009; El-Fahem 2008), investigations of groundwater resources in southern Ghana (e.g., Anornu et al. 2009) and Benin (Vouillamoz et al. 2014), and numerical modelling studies (e.g. Dickson et al. 2019). Sources of data for D3 include a series of studies of the crystalline basement aquifers in northern Nigeria (e.g., Acworth 1981; Edet and Okereke 2005; Hazell et al. 1992), while studies of groundwater potential in Mali (Delgado 2018; Díaz-Alcaide et al. 2017), which consider the analysis of more than 25,000 boreholes, provided the necessary information for the input data for D4 (DNH 2010). The comprehensive hydrogeological studies of Carrier et al. (2011), focussing on northern Ghana, and Courtois et al. (2010), focussing on Burkina Faso, were the main sources of data for D5, together with a number of local investigations in these two countries (e.g. Dapaah-Siakwan and Gyau-Boakye 2000; Vouillamoz et al. 2005). Input data for D6 were mostly taken from investigations of the basement aquifer in the Ochi-Narkwa basin in southern Ghana (Ganyaglo et al. 2017a, b). Lastly, a number of studies of

the hydrogeological characteristics of the Precambrian Basement Complex in the Kwara State region in western Nigeria were the sources used for the parameterisation of D7 (e.g., Aizebeokhai et al. 2018; Houston 1992; Ifabiyi et al. 2016; Talabi et al. 2020).

For all the geological domains, the total thickness of the regolith, which includes the RS, US, and LS layers, was assumed following a normal distribution with mean and standard deviation values estimated from available data. Mean values for the normal distributions range from 8 m for D1 to 26.5 m for D5 (Tables S2–S12 in the ESM), while the standard deviations are between 2 and 4.5 m. Very scarce data exist for determining the distribution of the RS layer in the different domains. For simplicity, a uniform distribution with maximum and minimum values based on values reported in the literature was used. Similarly, uniform distributions were also assumed for the parameters controlling the thickness of the LS and SR layers. Again, the maximum and minimum values of these parameters were adjusted to be consistent with the range of values reported in the sources. Boxplots of the resulting distributions of thickness values for the saprolite (US + LS) and SR layers for the different geological domains are shown in Fig. 2. In general, it is observed that thickness can vary several meters within each domain, and there is a high degree of data overlap amongst the domains. D1 is characterised by relatively thin saprolite (< 15 m) and saprock layers (<10 m), whereas D2 is characterised by the highest variability in the thickness of the saprolite with values ranging from a few meters up to almost 30 m. Likewise, the thickness of the saprock layer in this domain can be very thin or nonexistent or reach a thickness in the order of 10–15 m. In D3 and D7, the thicknesses of the two layers are generally comparable, while in D5 although the saprolite tends to be very thick, with values reaching almost 40 m, the saprock layer is much thinner and
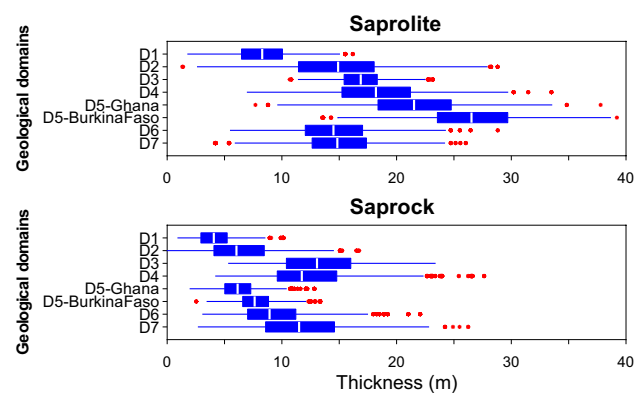
Fig. 2 Boxplots of the thickness values of the saprolite (US+LS) and saprock (SR) layers in the different geological domains assumed in the numerical models. The red points are outliers between 1.5 and 3 times the interquartile range

generally does not exceed 10 m in thickness. This is true for both the Ghana and Burkina Faso subdomains, although the saprolite of D5 in Burkina Faso tends to be thicker than in the Ghanaian subdomain. Considering the thickness of the saprock, which is generally the most transmissive zone in weathered basement aquifers, and therefore important for aquifer productivity, D3, D4, and D7 rank at the top, being the only ones with median values (vertical white lines in the boxplots) exceeding 10 m.

Numerical simulation of groundwater abstraction and estimation of sustainable yields

The axisymmetric numerical radial flow model developed by Bianchi et al. (2020) was applied to quantify the sustainable yields for the 1D of weathered basement aquifer profiles in the different geological domains. The model assumes an abstraction borehole at the centre of the radial domain. An impervious boundary is assumed at the bottom, while a specified flux condition representing net recharge is applied to the top. On the lateral boundary, no-flow conditions are assumed for the cells representing within the regolith and SR layers, while a head-dependent flux condition is assumed for the cells within the FR layer. A uniform static groundwater level is assumed at the beginning of the 5-year simulation period. As in Bianchi et al. (2020), the aquifer is assumed to receive recharge only for 4 months (i.e. wet season) every year. The recharge rate is kept constant over the simulation period. For each daily time step, the model estimates the abstraction rate that can be sustained without causing a decline in groundwater head in the borehole below the elevation of the productive zone at the base of the LS and the SR layers. This rate represents an estimation of the sustainable yield of the weathered basement aquifer profile since it does not cause excessive depletion of groundwater storage or excessively lower water levels resulting in a substantial deterioration of the productivity. At the end of the simulation, the average of the daily rates over 4 years, with the first simulated year being considered as spin-up time, is considered as the representative sustainable yield for the considered aquifer profile. It is important to clarify that this value represents the best-case scenario in which the hydraulic efficiency of the borehole is 100%. The equivalent transmissivity of the profile is also estimated based on the application of the Thiem equation (see Bianchi et al. 2020 for details). The generation of 1D profiles and the numerical model were implemented in a stochastic Monte Carlo framework to produce ensemble distributions of the outputs by providing sets of values for the 13 input parameters. One thousand Latin-hypercube (LH) independent random samples were generated from the distributions of each input parameter. In the absence of reliable data regarding the lateral extent of the weathered basement aquifers, a constant value of 3,000 m

was initially assumed such that this parameter has basically no effect on the calculated maximum sustainable yield. In fact, as shown by the results of the sensitivity analysis performed on the model input parameters (Bianchi et al. 2020), the lateral extent is a relevant parameter for the simulated yields, only for extents not exceeding 500 m to 1 km. However, the effect of this parameter on the simulated yields for different geological domains will be investigated later in the paper. The thicknesses of the different layers, as well as the range of values of other parameters, including the depths of the boreholes and the depth of the static water table, are consistent with borehole data in the literature (see Tables S2–S12 in the ESM). Water-table and borehole depths were assumed to follow uniform distributions within the reported minimum and maximum values for domains lacking specific information regarding the type of distribution of these two parameters (e.g. D1). Where this information was available (e.g. D3), or just for the depth of the boreholes (e.g. D7), normal distributions were assumed with mean and standard deviation values consistent with actual borehole and literature data. Over the different domains, water-table depth varies between a few metres to up to 20 m below ground surface. Values tend to be shallower for D1, D2, D6 and D7 with values under 10 m. The ranges of effective recharge rates for the different domains correspond to the confidence intervals of the long-term average (LTA) values for the period 1970–2019 published by MacDonald et al. (2021).

Calibration and validation of the simulated yields

Parameters defining the vertical profile of hydraulic conductivity (K_{max} and K_{rock} in Table S1 of the ESM), which are the most influential for the simulated yields (Bianchi et al. 2020), were assumed to follow a lognormal distribution. Mean and variance of these distributions were calibrated by matching the empirical cumulative distribution functions (eCDF) of the model outputs to available datasets of yield and specific capacity (for D3 only). These reference data were taken from the published studies listed in Table 2, while their areas of investigation are shown in Fig. 1. The yields reported in the reference datasets are primarily values measured during pumping tests. For D1, the model was calibrated to match the eCDF of the yields measured in 44 successful boreholes in Lofa county, Liberia. Borehole data from steady-state pumping tests indicate that measured yields range between 0.08 and 1.4 L/s, with a median value of about 0.5 L/s (Elster et al. 2014). Compared to other datasets, the yield data for D1 are representative of a much smaller area (Table 2; Fig. 1). This limitation has to be factored in when extrapolating the modelling results and interpretations to the entire geological domain, which covers large areas of Liberia, Sierra Leone, and Guinea.

Table 2 Reference data for model calibration

Domain	Country	Type of observations	Measurement method	Number of observations	Covered area (km²)	Source
D1	Liberia	Yield	Pumping tests	44	9,400	Elster et al. (2014)
D2	Benin	Yield	Pumping tests	2,198	60,400	Barthel et al. (2009)
D3	Nigeria	Specific capacity	Pumping tests	1,517	97,000	Hazell et al. (1992)
D4	Mali	Yield	Average borehole rates	1,326	44,400	DNH (2010)
D5	Ghana	Yield	Pumping tests	576	38,600	Carrier et al. (2011)
D5	Burkina Faso	Yield	Air lift tests	14,645	190,000	Courtois et al. (2010)
D6	Ghana	Yield	Unknown	41	14,300	Ganyaglo et al. (2017a)
D7	Nigeria	Yield	Pumping tests	213	55,700	Houston (1992)

Yield data for calibrating the models for D2 are based on the national water resources database of Benin—Banque des données intégrées (BDI), Barthel et al. (2009). The database contains yield measurements from constant rate, step-draw-down, and long-duration tests and lithological classifications of the basement aquifers for more than 5,000 boreholes. Data from a subset of 2,198 boreholes located within the boundaries of D2 were used as a reference. This work refers to this yield data for D2 as "undifferentiated" and several basement aquifer lithologies including gneiss and quartzite, more or less altered and fractured, are included. A different subset of reference yields was extracted that specifically refer to boreholes in weathered schists. Undifferentiated yield ranges from 0.01 to >100 L/s with a median value of about 0.4 L/s, whereas yields in the weathered schists are generally higher with a median value of 0.6 L/s.

Specific capacity data derived from short duration (maximum 4 h) pumping tests in 1,517 boreholes in the Kano, Sokoto and Bauchi states in northern Nigeria were used for calibrating the model for D3. The eCDF of the combined data for the three states indicates high variability with 90% of the boreholes exceeding 1.00 m³/day/m and about 10% exceeding 28 m³/day/m (Hazell et al. 1992). Two subsets representing different lithologies of the parent rock of the weathered basement aquifer in the Kano state were also considered. These subsets include boreholes in weathered metamorphic rocks (i.e. migmatites, quartzites, schists and gneiss) and in weathered granitoids, with the latter showing generally higher productivity as indicated by a comparison of the median values of the specific capacity data (6.0 vs. 2.9 m³/day/m).

The reference data for D4 were extracted from the national database of borehole data in Mali (DNH 2010), which includes information regarding average yield and borehole depth amongst other parameters. The eCDF of 1,326 yield values representing the average borehole rates per village within the boundaries of this geological domain was used for model calibration. The reference data show moderate variability around a median value of about 1 L/s.

About 80% of the boreholes can produce yields in excess of 0.5 L/s, but only 25% have yields between 2 and 20 L/s, with the vast majority under 10 L/s.

Simulations of groundwater abstractions from the D5 weathered basement aquifer were calibrated by matching the eCDFs of two sets of reference yield data. The first set, which is the same used in Bianchi et al. (2020), consists of yields from pumping tests in 576 successful boreholes (i.e. yield > 0.1 L/s) in the Precambrian basement aquifer in northern Ghana (Carrier et al. 2011). The median yield from these boreholes is about 0.5 L/s with a range of values between 0.1 and 5.5 L/s. The second dataset includes instantaneous discharge (i.e. air lift data) from more than 14,000 boreholes in the Precambrian basement in Burkina Faso (Courtois et al. (2010). Apart from the geographical location of the study area, this dataset differs from the Ghanaian counterpart because it also includes unsuccessful (zero discharge) boreholes, which explains the evident shift towards lower values in the cumulative distribution. According to Courtois et al. (2010), unsuccessful boreholes represent about 24% of the entire borehole data, while only 23% of the boreholes can sustain yields greater than 3.6 m³/h (equivalent to 1.0 L/s), which is considered a threshold for the supply of a small village (Chilton and Foster 1995). The eCDFs of the Burkina Faso and the northern Ghana datasets become more similar for higher yields. For instance, the values corresponding to the 80th and 90th percentiles of the distribution of yields for the Ghana case study are equal to 1.0 and 1.8 L/s, which are comparable to the corresponding values (0.9 and 1.6 L/s) for the Burkina Faso dataset.

It was not possible to find in the literature, reference sets of values of yield or specific capacity values for D6. Therefore, the calibration of the model for this domain simply relied on the information provided by Ganyaglo et al. (2017a). In this work, a range between 0.1 and 3.0 L/s is reported for 41 boreholes, with an average yield of 0.5 L/s. It is unknown if these values refer to pumping tests or are actual abstraction rates. These values were used as a

reference for the range and the mean of the simulated yield values.

The calibration of the model for D7 considered the eCDF of yield data from 213 boreholes in the Kwara State. Yields were tested for up to 3 days and the results extrapolated to a 12-h to a 200-day safe yield value (i.e. the maximum yield not exceeding the long-term recharge), taking into account interference drawdowns within the wellfield (Houston 1992). Statistical analysis of these data indicates that about 50% of the boreholes can sustain a yield above 1 L/s, while approximately 10% can discharge more than 5 L/s. These yield values were the result of testing the boreholes at or above a certain rate for up to 3 days, and then extrapolating the results to a long-term sustainable yield (200 days). As explained by Houston (1992), for yields above 1 L/s, the extrapolation was performed by multiplying the observed specific capacity by the maximum drawdown estimated from the difference between the static water level and the top of the main production zone. This approach presents some similarities to the way the proposed numerical model calculates the maximum available yield. Because of the extrapolation, lower yields (<1 L/s) have higher reliability than higher values.

Scenario analysis

Once calibrated, the stochastic models were applied to investigate the variability in productivity of weathered basement aquifers in the different geological domains and in different scenarios of borehole depth, static water-table depth, and aquifer lateral extent. In the first scenario, a set of 1,000 model runs were performed with a generic 60-m-deep open borehole. This uniform depth was chosen because it is deep enough to simulate the abstraction of groundwater from all the layers of the weathered basement aquifer profile in all the domains. All the other parameters (Tables S2–S12 in the ESM), including distributions of thicknesses of the different layers, water-table depths, and hydraulic conductivity parameters, remained unchanged from the set of simulations matching reference data.

Two additional numerical experiments were conducted to investigate how aquifer productivity responds to changes in static water-table depth and aquifer extent. This study focused on these two parameters because the water-table depth is a relevant parameter for aquifer productivity (Bianchi et al. 2020), while the lateral aquifer extent, apart from being an influential parameter, can be highly variable and generally hard to assess in real-world situations. Therefore, a comparison between different scenarios can provide insight regarding the sensitivity of productivity with respect to this parameter.

For assessing the influence of the water table, the results of the previously described simulations considering a 60-m-deep borehole, which in this context represents the "base-case" scenario, were compared to those of two additional sets of 1,000 model runs in which the uniform distributions of static water-table levels were shifted by a maximum of 5 m from the values of the base case towards lower ("shallower" scenario) or greater ("deeper" scenario) depths. In the deeper scenario, the 5-m lowering of the water table was applied to all the considered case studies to represent the combined effects of overexploitation of the groundwater resources or climatic variations. For certain runs of the shallower scenarios (e.g. D4), the raising of the water table by 5 m would have resulted in artesian conditions of the weathered basement aquifer. To prevent such unrealistic conditions, the shift in the uniform distribution of water-table depths was adjusted to match a minimum value of 0.5 m below ground surface.

In the previous work focussing on northern Ghana (Bianchi et al. 2020), a minimum lateral extent of the aquifer of approximately 400 m was found to be the threshold to sustain moderate yields (1–5 L/s). The corresponding threshold for yields below 0.5 L/s was estimated to be in the order of 200 m. Here, this analysis was extended to other geological domains by performing sets of 1,000 model runs considering different scenarios of incremental lateral aquifer extent (100, 250, 500, 1,000 and 3,000 m). As for the other scenarios, a 60-m borehole was considered, while input values for all the parameters, except for the lateral extent, are the same as for the calibrated models.

Results and discussion

Simulations of reference data and model accuracy

The estimated eCDFs of simulated yields for the different geological domains are generally in good agreement with the corresponding reference data (Fig. 3). For D1, simulated yields are particularly accurate in matching the distribution of yields above the 20th percentile of the distribution, while the eCDF of simulated values tends to be skewed towards lower values. However, the reliability of the lower tail of the reference distribution has to be considered low given the small number of data ($n = 44$), with only three values below the 10th percentile (0.27 L/s). This discrepancy is also explained by the bias in the reference data towards higher values, given that only successful boreholes with a yield greater than approximately 1,000 L/h, or 0.28 L/s, were considered (Elster et al. 2014).

Implemented models of abstraction from a D2 weathered basement aquifer can match the reference yield data from Benin with good accuracy both for the "undifferentiated" and for the "schists" datasets. A small discrepancy between the modelled and reference distributions can be observed for the undifferentiated case between the 40th and the 60th
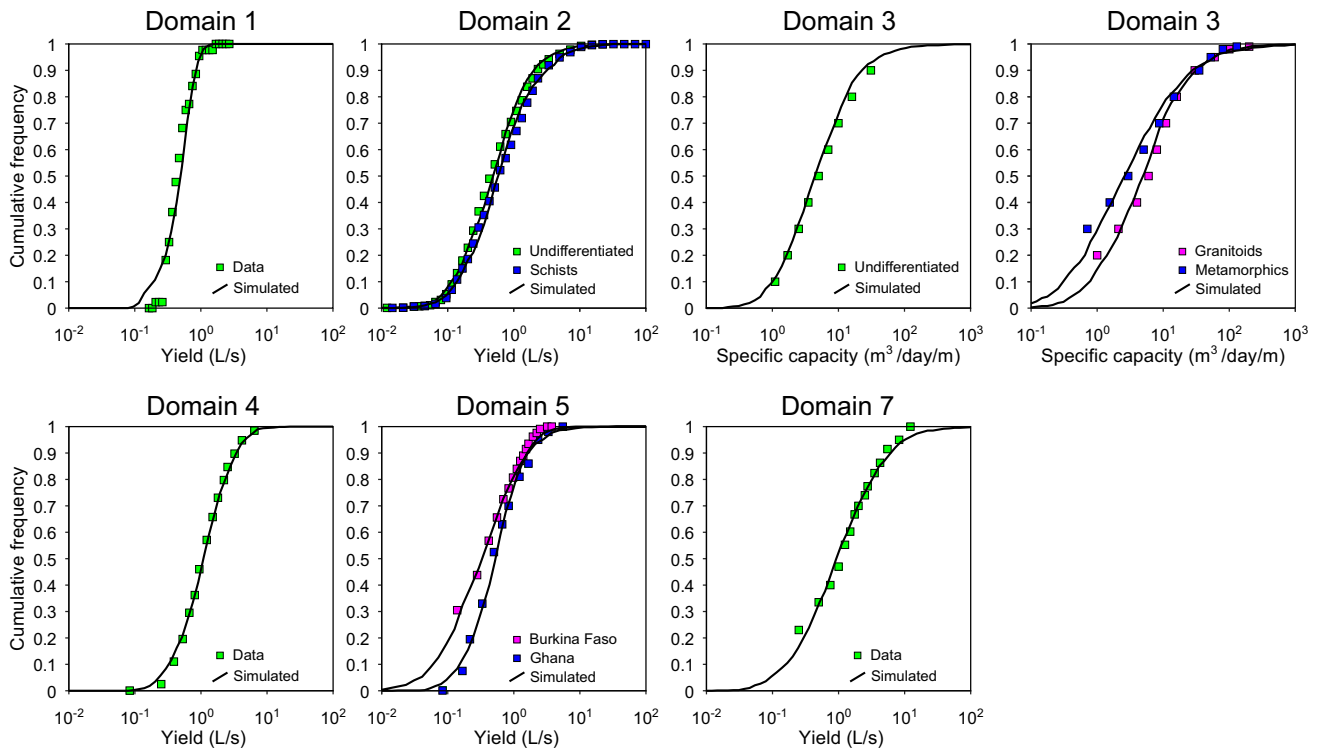
Fig. 3 Comparison between the empirical cumulative distributions (eCDF) of the simulated (black lines) and reference data (square symbols)

percentile of the distribution, although the overestimation of the model is within a 10% error, as shown by a comparison between the median values of the simulated yields (0.49 L/s) and the reference data (0.45 L/s). A maximum of 15% underestimation error is produced by the model when simulating yields between the 60th and the 80th percentile of the reference distribution.

A small general underestimation of the reference eCDF is also observed for the model reproducing the specific capacity of the weathered basement aquifer in D3. In this case, the discrepancy ranges between 3% around the 20th percentile, increasing towards higher values, up to 27% for values above the 90th percentile (27 m^2/day/m). Conversely, when the two smaller subsets based on lithology are considered, namely "Granitoids" and "Metamorphics" in Fig. 3, the model is more accurate in reproducing the upper tails of the two subset distributions as shown by the almost perfect match between simulated and reference 80th and 90th percentiles (15.5 vs 16.0 m^3/day/m and 30.9 vs 30.0 m^3/day/m, respectively). For these subsets, the study of Hazell et al. (1992) does not report the lower tails of the specific capacity distributions so it was not possible to provide a meaningful comparison between simulated and reference data. From the simulated eCDF, it can be said that the specific capacity of the weathered metamorphic basement is more skewed towards lower values.

The models simulating yields in D4 and in the two cases of D5 are accurate with errors generally within 5%. Overall, the highest discrepancy is observed for the simulation of the upper tail of the yields of the case study in Burkina Faso (D5) where the model tends to provide an overestimation of the reference yield distribution. However, as shown by Courtois et al. (2010), only a small number of boreholes in the reference data have yields above 1.6 L/s corresponding to the 90th percentile of the simulated yield distribution. Therefore, the upper tail of the reference population of yield values is likely misrepresented in the reference eCDF.

The mean of the simulated yields for D6 is equal to 0.5 L/s, with 95% of the values falling between 0.1 and 1.7 L/s. The maximum simulated yield is 3.6 L/s. These simulated values are comparable to the statistics of measured yields in 42 boreholes reported by Ganyaglo et al. (2017a). For D7, there is also good agreement between simulated and reference data. As shown in Fig. 3, the model is particularly accurate in reproducing the bulk part of the reference eCDF, i.e. from the 25th up to the 90th percentiles, with discrepancies between the two curves ranging from 1 to 16% (7% on average). The model tends to overestimate the upper tail of the reference distribution; however, high yield values are very scarce in the reference borehole data (see Fig. 9 in Houston 1992); therefore, similar to other domains, the reliability of the upper tail of the reference distribution is very low.

Transmissivity of the weathered basement aquifers in the different geological domains

The calibrated stochastic models provide estimates of the equivalent or bulk transmissivity of the simulated weathered-basement-aquifer profiles for the different case studies, which are directly linked to productivity. Bianchi et al. (2020) investigated this relationship showing that transmissivities as low as 1.5 m²/day are sufficient to sustain a hand pump (yield = 0.1 L/s), while the threshold for successfully deploying solar-powered pumps (yield > 0.5 L/s) require transmissivities above 6 m²/day. Thresholds for moderate (>1 L/s) and high (>5 L/s) yields were found to be equal to 9 and 37 m²/day transmissivity, respectively. Boxplots of the distributions of estimated bulk transmissivity for the different geological domains are compared in Fig. 4, while statistics are reported in Table S13 in the ESM. Excluding some very high outliers resulting from the unlikely combination of extreme values for the assigned thickness of the saprolite and hydraulic conductivities of the profile (K_{max} and K_{rock}), the estimated transmissivity values fall within a range of values reported by several studies of hydrogeological characterisation of weathered basement aquifers (e.g., Chilton and Foster 1995; Holland 2012; Maurice et al. 2019; Taylor and Howard 2000). For instance, for the D1 case study, Elster et al. (2014) report transmissivity values averaging 13.6 m²/day, which is consistent with the average transmissivity of the simulated profiles (14.6 m²/day). Also, the mean transmissivity of 16 pumping tests in the Precambrian basement aquifer of northern Ghana was found equal to 17 m²/day (Carrier et al. 2011), which is also in very good agreement with the corresponding value estimated in this work (15.8 m²/day). A further example of agreement between the transmissivity data produced in this work and available literature data is for D6, for which Ganyaglo et al. (2017a) report transmissivity values ranging from 0.3 to 35.7 m²/day. Simulated transmissivities for D7 have a somewhat comparable range (1.5–48.9 m²/s), even though this model
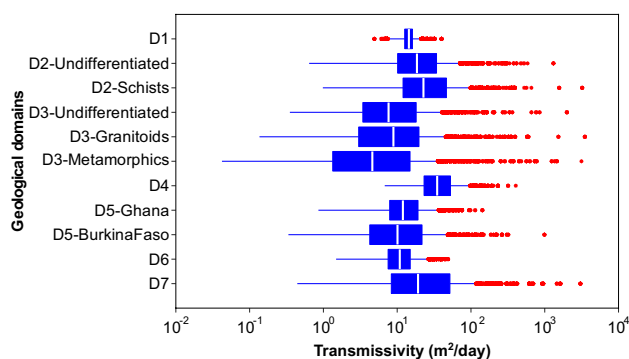
was not calibrated by matching the eCDF of reference data. The consistency between simulated and reported transmissivities for all the domains is further indirect indication that the implemented models can be considered representative of the complex hydrogeology of weathered basement aquifers.

The comparison of median transmissivity values suggests that there is moderate variability between the different geological domains, as values range from a minimum of 4.7 m²/day (D3-Metamorphics) up to 34 m²/day (D4). In terms of investigating a possible lithological factor for the difference in transmissivity, it is notable that schistose rocks in D2 tend to have slightly higher transmissivities than undifferentiated (i.e. mostly gneiss and quartzite) weathered basements aquifers, while for D3, the granitoid basement rocks produce weathered aquifers with higher transmissivities than those resulting from the alteration of metamorphic rocks. Based on the median values alone, the difference in the transmissivity between the two lithologies is equal to a factor of 1.85 in favour of the granitoid basement. For D5, the data from Burkina Faso seem to suggest lower aquifer transmissivity than the data for northern Ghana. However, this difference is likely the effect of the exclusion of unsuccessful boreholes from the northern Ghana dataset, given the similarity in the median and 3rd quartile values (10.1 vs 12.4 m²/day, and 22.7 vs 19.4 m²/day, respectively).

From the comparison of the interquartile ranges (IQR) and absolute ranges of the different cases, it emerges that some domains have lower variability than others. In particular, transmissivity distributions for domains 1, 4 and 6 are characterised by less variability as shown by values of the IQR not exceeding 10 m²/day. The spread of values is particularly evident for D3 (particularly for the metamorphic case) and D7, with absolute ranges spanning more than two orders of magnitude.

For each case, estimated transmissivity distributions are the results of the combination of the assigned distributions in thicknesses of the saprolite and saprock (Fig. 2), which were based on literature data, and calibrated distributions of the parameters defining the hydraulic conductivity profiles (K_{max} and K_{rock}). The generally higher transmissivity of the profiles for D4 compared to the other domains is, for instance, the result of relatively thick lower saprolite and saprock layers combined with the highest estimated mean for the lognormal distributions of K_{max}. Amongst the different domains, these mean values range from –4.6 for D4 (equivalent to 2.1 m/day) to –6.1 (0.07 m/day) for D3, which has generally lower transmissivity values than the other domains, although the thicknesses of saprolite and saprock layers are more comparable. Estimated mean values for the lognormal distributions of bulk rock conductivity K_{rock} range from a value of –5.8 (0.13 m/day) for D4 to –7.1 (0.007 m/day) for D3-Metamorphics, with an average mean value of –6.3 (0.04 m/day). In comparison, the average of the estimated mean values for

Fig. 4 Box plots of the transmissivity distributions for the different domains

the lognormal K_{max} distribution is equal to –5.4 (0.3 m/day). Similarly, the variability in simulated transmissivity distributions is controlled by the assigned variability in the thicknesses of the saprolite and saprock (Fig. 2), as well as by the variance of the distributions of K_{max} and K_{rock}. Estimated variances of the lognormal distributions of K_{max} for the different case studies range from 0.1 to 1.2, with an average of 0.73. The lowest estimated variance was estimated for D1, which resulted in smaller variability in transmissivity for this domain. For D4, the combination of high variability in the thicknesses of the saprolite and saprock layers with low variability in K_{max}, resulted in moderate variability in transmissivity. High variances (>0.8) were estimated for domains D3 and D7, hence the wider spreading in transmissivity values for these two domains. For K_{rock}, estimated variances of the lognormal distribution values range from 0.05 to 0.9. The highest values were estimated for the metamorphic case of D3 and for D7.

Productivity of a 60-m-deep borehole

The results of the stochastic simulations for a generic 60-m borehole for all the geological domains are compared in Fig. 5 and reported in Table S14 in the ESM. Following the work of MacDonald et al. (2012), the ensembles of simulated yields were binned into the following six classes of productivity: (1) "very low productivity" with yields below 0.1 L/s; (2) "low productivity" with yields between 0.1 and 0.5 L/s; (3) "low-moderate productivity" with yields between 0.5 and 1.0 L/s; (4) "moderate productivity" with yields between 1.0 and 5 L/s; (5) "high productivity" with yields between 5 and 20 L/s; (6) "very high productivity" with yields exceeding 20 L/s. The frequency of simulated values within each class was then used to estimate the probability of the different classes of productivity for all the domains and for a "combined" case resulting from the aggregation of all the simulation data.

In general terms, the productivity of weathered basement aquifers estimated in this work, although very variable, is low and in line with previous assessments (e.g.

Edmunds 2012; MacDonald et al. 2012). For the combined case, about 50% of the simulated yields were below a 0.5 L/s threshold, and about 13% of these fell into the very low productivity class. Low-moderate and moderate yields equally represented about 23% of the yields, while only about 4% exceeded the 5 L/s threshold of the high productivity class.

From the comparison of aquifer productivity in the different geological domains, some differences can be observed. Simulated yields for domains 1 and 4 fell into a smaller number of classes, indicating lower variability compared to the other domains. For these domains, the probability of abstractions sustaining high yields above 5 L/s is also very low (3.5% in D4) or zero. The other domains show a wider degree of productivity with yields falling into at least five classes. Simulation results for D2 indicate that the main differences between the two cases, "undifferentiated" and "schists", are the probabilities of low productivity (44% vs 32%) and high productivity boreholes (3.5% vs 7%), highlighting the higher potential of boreholes sited in weathered schists aquifers. Of all the domains, D3 presents the highest probability of very low productivity, with percentages ranging from 24% in "granitoids" up to 46% in "metamorphics". A high percentage of very low productivity boreholes (about 20%) is also observed for the Burkina Faso case study of D5. Focussing on higher yields, D4 has the highest probability of moderate productivity boreholes (48%), while the domain with the highest probability of high productivity boreholes is D7, with about 12% of the simulated yields exceeding 5 L/s.

Simulated results provide some general insights regarding the issues of borehole siting and assessing groundwater potential in real-world weathered basement aquifers. Boreholes in geological domains where simulations show a high probability of yields falling into the lowest category of productivity, may in fact have a higher risk of being unsuccessful or technically dry, at least within the range of hydrogeological conditions considered for the simulations. This may be particularly relevant for countries like Benin (D2), Burkina Faso (D5), Togo (D2), Ghana (D5) and the western part of Ivory Coast (D2). For


Fig. 5 Simulated probability of occurrence of productivity classes for a well-sited 60 m borehole for the different geological domains. Classes: very low productivity (<0.1 L/s), low productivity (0.1–0.5 L/s), low-moderate productivity (0.5–1.0 L/s), moderate productivity (1–5 L/s), high productivity (5–20 L/s), very high productivity (>20 L/s)
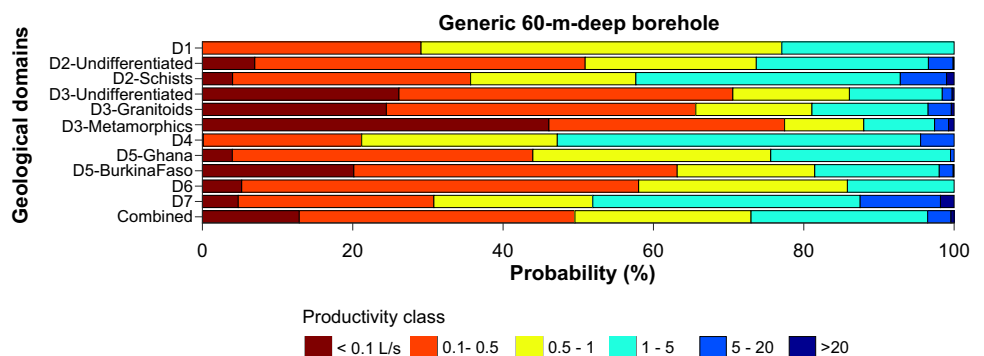
instance, in agreement with the simulations of this study, the percentage of technically dry boreholes in Burkina Faso is almost 25% (Courtois et al. 2010). Conversely, simulated data seem to suggest that countries within D1 and D4 may have a lower risk of unsuccessful boreholes, although the potential for high-yielding boreholes is also relatively low. Another general consideration is that because of the high variability in simulated productivity, as shown by all the domains having productivity levels ranging from very low to very high, site-specific hydrogeological characterisation may be the only effective way to locate boreholes with long-term sustainable yields. In this regard, the characterisation of the hydraulic conductivity around the interface between the regolith and the saprock (K_{max}), and the thickness of these two layers, are particularly important, given the impact these parameters have on borehole productivity (Bianchi et al. 2020)

Influence of saturated thickness on aquifer productivity

In Fig. 6, the productivity of the 60-m-deep borehole scenario (base case) is compared to the shallower and deeper water-table scenarios. Overall, a shallower static water-table results in increased productivity as shown by a decrease in the proportions of yields belonging to the very low and low classes and a corresponding increase in the proportions of moderate to high classes. For the combined case, an 18% reduction from the cumulative probabilities of very low or low yields (< 0.5 L/s) in the base case is estimated for the shallower scenario, while a 22% corresponding increase is estimated for the deeper scenario. The probability of low-moderate and moderate yields (0.5–5 L/s) increases by about 14% in the shallower scenario and it is reduced by about 22% in the deeper scenario. The probability of high yields
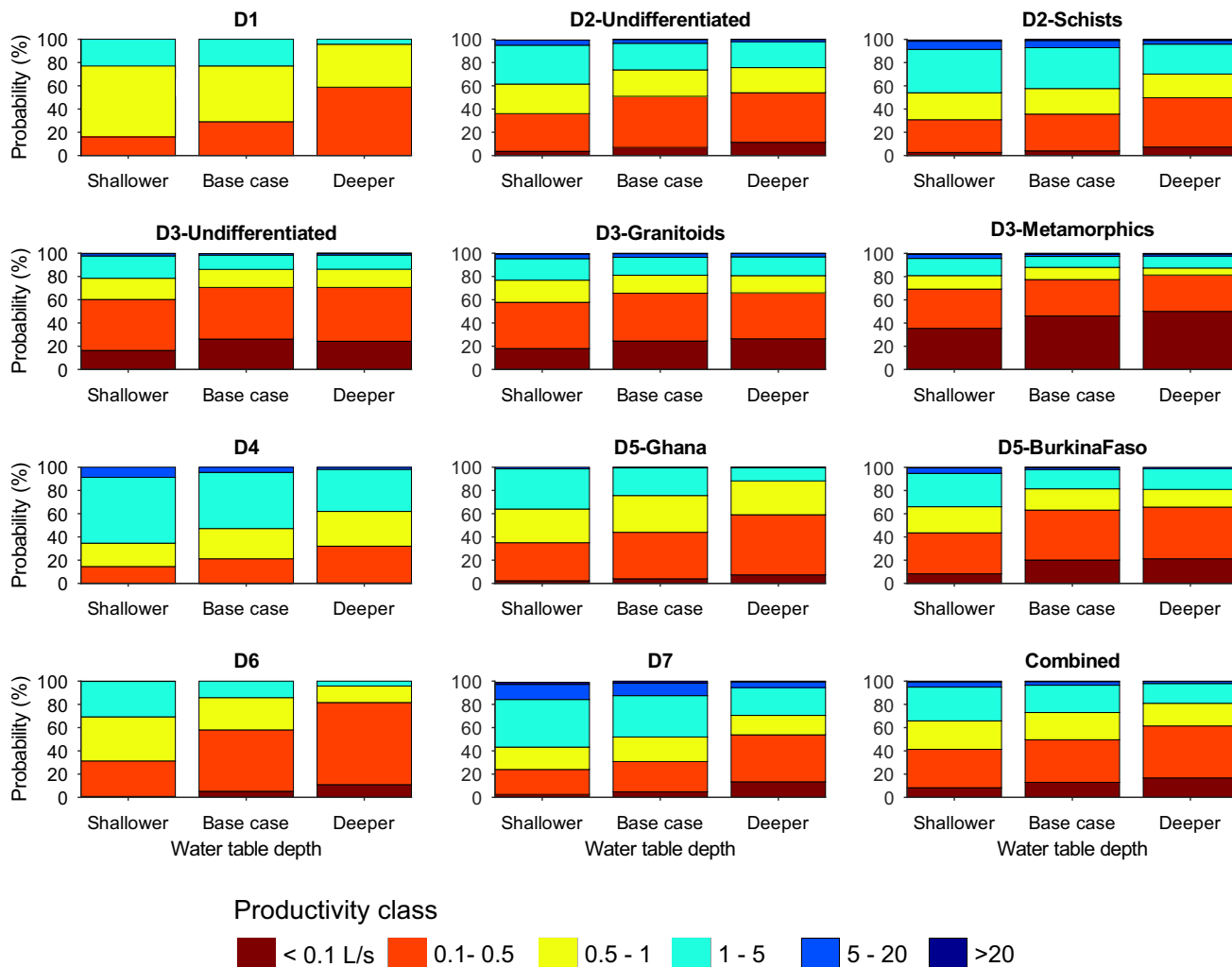
Fig. 6 Influence of the water-table depth on groundwater productivity: the base-case water table, and water tables that are 5 m shallower or 5 m deeper than the base case

exceeding 5 L/s is also reduced to about 2% in the deeper scenario, while it is estimated in the order of 5% in the shallower scenario. This general correlation between aquifer productivity with the saturated thickness of the weathered aquifer profile, which has been observed in previous studies (e.g., Chilton and Foster 1995) and in simulations of the northern Ghana case study (Bianchi et al. 2020), is consistent across the geological domains, although it is more evident in certain domains and for certain classes of productivity. For domains D1, D4, D5-Ghana, D6 and D7, the trend of higher incidence of low productivity classes (i.e. more orange and red colours in Fig. 6) with the deeper water table, and therefore thinner saturated profiles, is clear. For D2, the increase in productivity with a shallower water table in the "schists" case study is mostly confined to the low productivity classes, while the probability of moderate and higher yields (yellow and light and dark blue in Fig. 6) remains relatively unchanged with respect to the base case. For the different cases of D3, the deeper scenario shows only a slight reduction in productivity compared to the base case, while the shallower case has a noticeably lower probability of very low yields. A similar trend is also observed for the Burkina-Faso case of D5. The interpretation of these trends is quite complex being the result of a combination of different factors in the stochastic model. From the analysis of the assigned distributions of thicknesses for the different layers in the weathered basement profile and for the static water-table depth in the base cases, it seems that the productivity of domains characterised by relatively deep static water tables and thick regolith are less sensitive to a decline in the groundwater level, while their productivities improve relatively well in response to increases in saturated thickness (i.e. shallower water table). This is still rather speculative, and further numerical and field investigations outside the scope of this study are necessary for a better understanding of the interplay between different factors.

Influence of aquifer lateral extent on productivity

Figure 7 presents a series of plots for the geological domains showing groundwater productivity in different scenarios of aquifer lateral extent. As expected, the distributions of simulated maximum allowable yields are more skewed towards low productivity classes for smaller lateral extents. However, as the lateral extent increases, there is an initial sharp decline in the probability of low productivity classes until a threshold lateral extent value above which the productivity remains practically unchanged for all the scenarios. For instance, the probability of low yields (<0.5 L/s) in D4 decreases from 43 to 23% between the scenarios with 100 and 250-m lateral extent, and then to 21.5% for the scenario with a 500-m value. Scenarios considering longer extents for this domain have similar percentages (e.g. 21.1% in the

3,000-m scenario). Considering moderate to high yields (>1 L/s), estimated probabilities range from 22% in the 100-m scenario to 53% in the 3,000-m scenario. However, a 51% value was estimated already for the 500-m scenario. Similar observations can be made for all the case studies in Fig. 7. Although the value of the threshold above which productivity remains unaffected by changes in the lateral extent varies slightly amongst the different geological domains, it is estimated to be between 250 and 500 m for most of the domains, as well as in the combined case. These threshold values, which are only valid within the ranges of values of annual net recharge assumed by the models, may be helpful in identifying the minimum distances between adjacent boreholes for sustainable water supply schemes.

Summary and conclusions

The modelling approach of Bianchi et al. (2020) was applied to investigate sustainable groundwater productivity from weathered crystalline basement aquifers in West Africa. Lithological, stratigraphical, and structural analyses of the crystalline basement in the region led to the identification of seven geological domains. Extensive data mining from previously published literature was conducted to estimate hydrogeological parameters for each domain. Identified representative distributions of hydrogeological parameters, also estimated by means of inverse modelling, were used as input for simulations of yields that were matched with reference data from selected case studies for each domain. Calibrated models were then applied to simulate scenarios of borehole depth, static water-table depth, and aquifer lateral extent to quantify ranges of productivity and their sensitivity, providing insights for borehole siting and sustainable resource management. The major conclusions of this work are the following:

- The good agreement between distributions of simulated and measured yields for the representative case studies in different geological domains expands the results of Bianchi et al. (2020) and provides further confirmation that this modelling approach can provide reliable estimates of borehole productivity in weathered basement aquifers.
- Estimated equivalent transmissivities of representative vertical profiles of aquifer heterogeneity indicate moderate to high variability with values ranging by two or more orders of magnitude for most case studies. From the comparison of distributions for the different domains, however, a clear influence of the parent rock lithology on the transmissivity of the weathered basement aquifers does not emerge, although geological domains are somewhat different in terms of median and interquartile
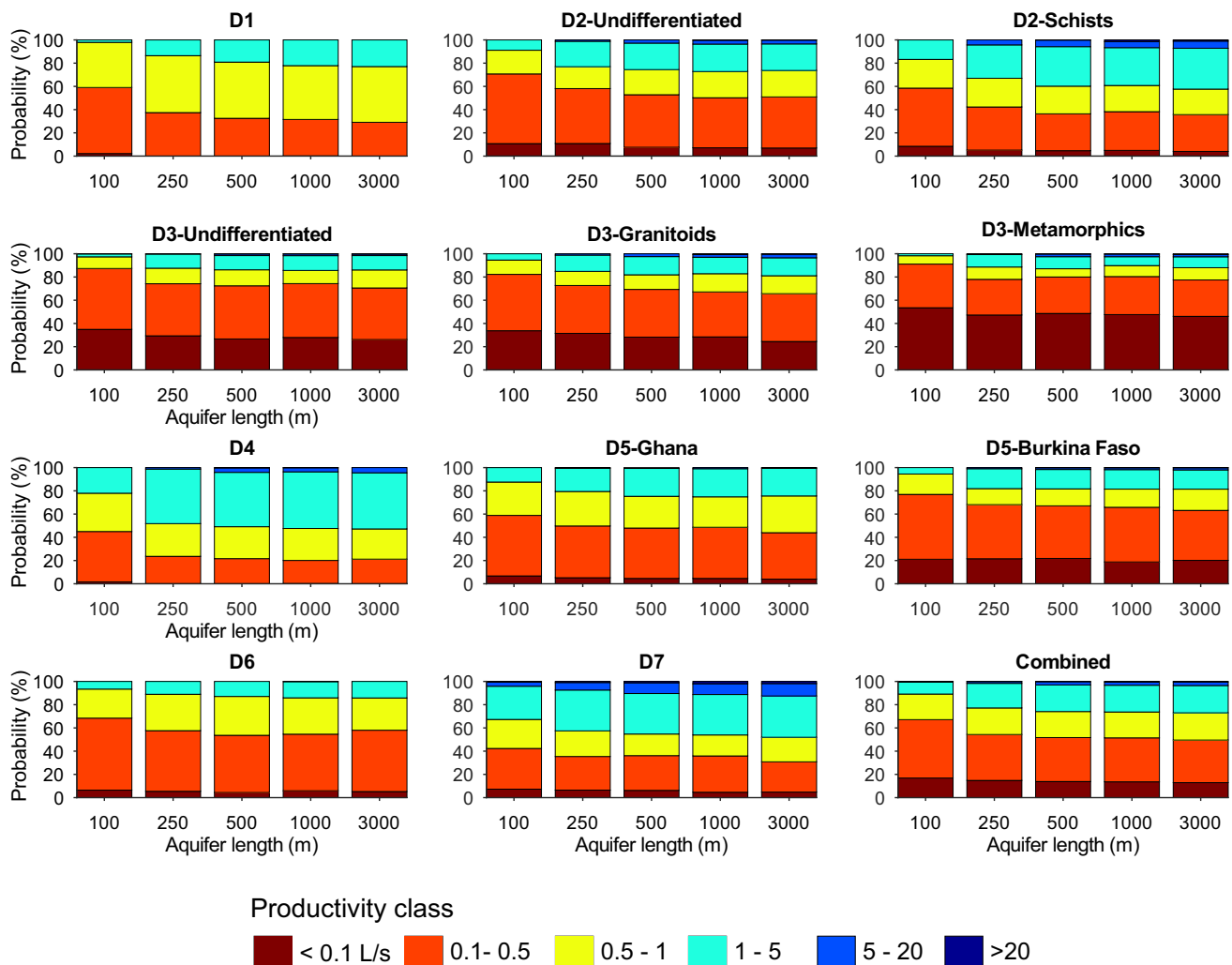
Fig. 7 Influence of the lateral extent of the aquifer on groundwater productivity

range values. This uniformity in transmissivity distributions confirms that the weathering processes of the parent-rock-control hydraulic properties of the basement aquifers (e.g. Lachassagne et al. 2021).

- In West Africa, the probability that a well-sited 60-m-deep borehole can provide yields exceeding 0.5 L/s is estimated to be in the order of 50%. There is a 13% probability that the weathered basement aquifer will not be able to sustain hand pumps (<0.1 L/s) or that the borehole will be technically dry, even if well sited. Approximately one borehole out of four could sustain moderate abstractions (>1.0 L/s).

- Simulations considering the scenario of a generic 60-m-deep borehole also indicate regional differences in groundwater productivity. For instance, D3 (north Nigeria) showed the highest variability in productivity and the highest risk of unproductive boreholes. This risk is quantified in the order of one in every four boreholes in granitic basement

rocks, up to almost one in every two boreholes in metamorphic rocks. Conversely, simulation results for other domains are more promising for the employment of higher-yielding pumps (>5 L/s), with the highest probability of being able to sustain such yields estimated in the order of one in every eight boreholes for D7 (eastern Nigeria and western Benin).

- Scenarios using a range of depths of the static water table indicate an indirect relationship between this parameter and the productivity of weathered basement aquifers. A 5-m drop in groundwater level, mimicking aquifer overexploitation and/or reduction in the net groundwater recharge, resulted in 22% overall increase in the probability of low-yielding boreholes and a close to 50% reduction in the probability of high-yielding boreholes. The increase in productivity observed for shallower water-table conditions is a common feature of all the case studies, although it is more evident for certain geological domains and for low-yield boreholes.

- There is a direct relationship between sustainable groundwater productivity and the lateral extent of the aquifer. Simulations assuming long-term averages of the net recharge values and different scenarios of aquifer lateral extent highlight a rather sharp decline in productivity when the lateral extent is less than a threshold ranging between 100 and 1,000 m for the different case studies.

In sub-Saharan Africa, groundwater in weathered basement aquifers represents a fundamental resource that can help achieve food security in rural communities (e.g. Mac-Allister et al. 2020) and drive economic and social development (World Bank Group 2018). Numerical modelling tools can help to fully unlock this potential by providing quantitive data for groundwater maps (BGR et al. 2022) and supporting the design and optimisation of supply networks for irrigation and water security.

Declarations

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

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