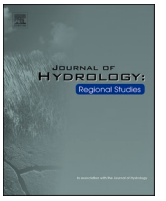
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A 3D geological model of the horn of Africa: New insights for hydrogeological simulations of deep groundwater systems

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ABSTRACT

Study Region: The area of interest comprises 1.6 million km^2 of the Horn of Africa, extending 60 km offshore the Gulf of Aden and Indian Ocean, and delimited by the Tana River in Kenya and the Rift Valley in Ethiopia.
Study Focus: Deep (> 400 m) groundwater resources are virtually unexplored in the Horn of Africa. One of the main challenges in this vast and sparsely documented area, is producing solid geological models. This paper presents a first-order assessment of the deep structure and water resources in the region, based on the integration of data from hydrogeological and Oil & Gas exploration. Public domain cross-sections, geological maps, and satellite data are reinterpreted, defining the extent of formations in the subsurface. The data integration benefits from using a multi-source modelling platform, subsurface mapping software from the Oil & Gas and hydrogeology sectors, and proprietary scripts.
New Hydrological Insights: The present study reveals new evidence of the presence of deep aquifer systems in the Horn of Africa. The model outputs include the extent, predicted thickness, salinity, and petrophysical properties of the potential aquifers. The results of this first extensive 3D subsurface model for the region provide new hydrogeological insights into potential transboundary aquifers and can be used as a baseline for further investigations and, ultimately, for quantifying the total water resources in the region.

1. Introduction

Large parts of East Africa are suffering from water scarcity, driven by low precipitation, high evapotranspiration, and contamination of shallow resources (FAO-SWALIM, 2012). In these arid regions, the available natural water resources are thus largely restricted to groundwater. In Somalia, which is increasingly affected by drought and extreme weather events, extraction of groundwater resources is generally limited to aquifers of up to a few 10–100 s of meters deep in the subsurface, and the extent of aquifers deeper than 400 m is still largely unknown (FAO-SWALIM, 2012). If developed, these deep aquifers could represent an additional source of fresh and low salinity water for local communities.

Worldwide conventional hydrogeological boreholes generally focus on shallow and easily exploitable aquifers (few 100 s of meters). However, there are examples of deeper fresh groundwater aquifers that have proved to be very productive (Margat and Van der

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Gun, 2013). Examples are the Nubian Sandstone Aquifer (El-Rawy and De Smedt, 2020; Gonçalvès et al., 2013; Mazzoni et al., 2018; Ruden, 2016; Sultan et al., 2007) which reaches depths of 3500 m; the Upper Mega aquifer system at the Arabian platform, at more than 450 m depth (Abotalib et al., 2019); and the Great Artesian Basin in Australia up to 3000 m deep (Fensham et al., 2021; Habermehl, 2020). In East Africa, a groundwater exploration project based in Tanzania, used for the first time Oil & Gas (O&G hereafter) data to identify a deep aquifer, which has since been exploited (Moe et al., 2017; Ruden, 2007). This deep coastal aquifer extends over an area of approximately 1000 km^2 and is ca. 1000 m deep on average (Moe et al., 2017; Ruden, 2007). In Somalia, the potential presence of deep freshwater aquifers has been indicated by previous authors (Quiroga, 2020; Quiroga et al., 2022), and this offers a new opportunity to expand the concepts driving exploration for current groundwater resources. However, a regional model of the distribution of these deep aquifers is still lacking.

Constructing a regional geological model for the Horn of Africa is the first fundamental step needed to evaluate the extent of these potential deep aquifers. This task is challenging, as data is scarce and its accessibility limited due to 1- the current social-political situation, which limits the opportunity to collect data from specific areas in the field, and 2- the loss of data previously acquired and stored in the country due to the civil war in the 1990 s. This study assembles the most updated and complete dataset of geological and hydrogeological data available in the wider region of the Horn of Africa, including Somalia, and uses a specifically built workflow to filter and analyze the data. The regional model builds upon the successful previous approach based on the integration of hydrogeological data, and geophysical and geological data acquired by the O&G industry. This novel approach resulted in the discovery of the Kimbiji aquifer in Tanzania (Moe et al., 2017; Ruden, 2007; Ruden, 2009). Our new 3D model of the Horn of Africa is entirely based on public domain information and enables the prediction of potential deeper aquifers.

The initial literature analysis included documents containing 261 cross-sections, which were subsequently filtered for completeness and quality (Fig. 1). The study workflow included the combined use of open access GIS analytical software (QGIS) and industry-standard software for subsurface (well & seismic) data interpretation, available under license (Petrel). In addition, the data input was filtered and cleaned using a proprietary script, and the data format was adapted to the requirements of the software. The scale of the maps upon which this work was based ranges between 1:100,000 (for local maps limited to a few locations) and 1: 2000,000 scale (for regional maps) (Abbate et al., 1993; Carmignani et al., 1983a; Carmignani et al., 1983b; Conti, 1989; Kazmin, 1972; Merla et al., 1979) and the grid spacing amongst the cross-sections varies from 5 km to $>$ 100 km, therefore producing a variable resolution.

The key outputs of the model include the maps of 13 formations, which are relevant for the hydrostratigraphic setting of the region. Further results are the analysis of freshwater indications in relation to the modelled surfaces, the integration of hydraulic heads derived from pressure tests in O&G wells (Quiroga et al., 2022), and of the values formation porosity and permeability of the most relevant modelled surfaces or hydrostratigraphic units. Finally, we use the model to predict the regional-scale distribution of aquifers based on the extent of the formations and their predicted thickness, and their lithological and petrophysical properties. Our approach to 3D geological modelling is applicable at a wide scale, for mapping the potential for deep fresh aquifers in other regions worldwide.

2. Background studies

2.1. Geographical, climatic and hydrogeological setting

The study area is approximately 1.6 million km^2 and covers, from west to east, from the Rift Valley in Ethiopia to 60 km into the Indian Ocean, and, from south to north, from the Lake and River Tane in Kenya to 60 km off the shoreline of the Gulf of Aden. This region covers the whole of Somalia and parts of eastern Ethiopia and northern Kenya, representing the majority of the Horn of Africa (Fig. 2). The area is characterized by relatively low relief in most of Somalia and areas of higher relief in Ethiopia, with mountains that are more than 4000 m high in the eastern part of the Ethiopian Highlands (Appendix A). In Somalia, the highest mountain is in the north, along the Gulf of Aden coast ($>$ 2400 m high). There are only two perennial rivers in Somalia, the Juba and Shebelle, which have vast seasonal variability and have their main catchments in the Ethiopian highlands (FAO-SWALIM, 2012). Elsewhere, the rivers are ephemeral and only flow for a few hours or days per year.

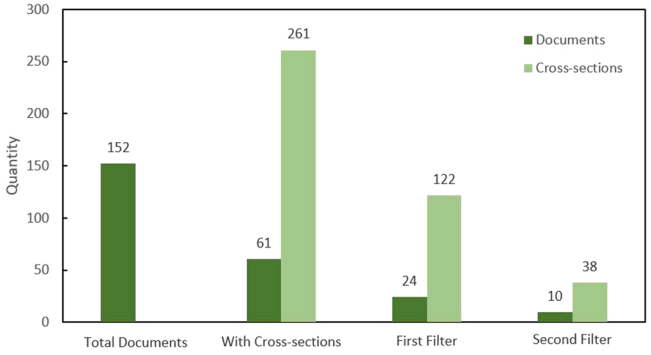


Fig. 1. Number of documents and cross-sections reviewed and used for the geological model creation in this study. First filter refers to documents with cross-sections in areas of interest and that could be georeferenced. The second filter refers to documents with cross-sections in depth.

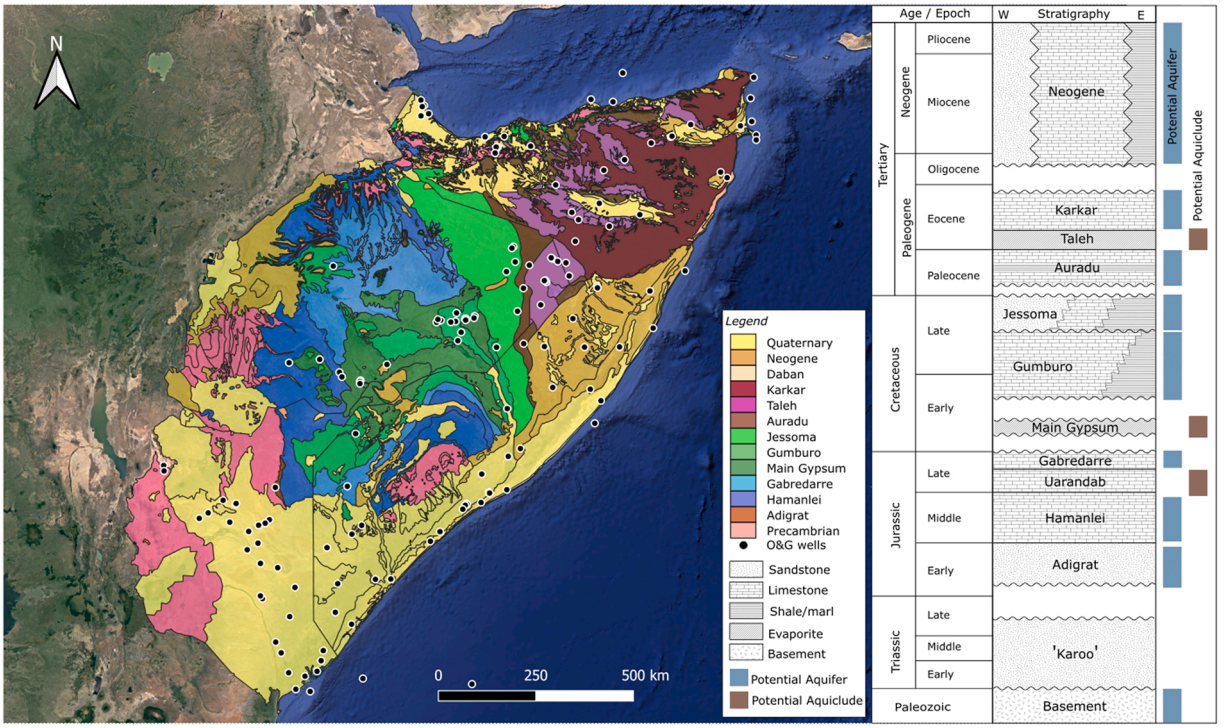


Fig. 2. Left: Geological map of the Horn of Africa, compiled and modified from several sources (Abbate et al., 1993; Kazmin, 1972; Merla et al., 1979). Oil and gas wells are marked as black dots. Right: Simplified stratigraphic column which corresponds to the hydrostratigraphic units used in the model. Compiled and modified after previous studies (Abbate et al., 2015; Kazmin, 1972) and the Geological Map published in 1962 by the Survey of Kenya (https://esdac.jrc.ec.europa.eu/content/national-atlas-kenya-geological-map). The Daban formation (Oligocene) is only present in the north of Somalia and therefore not included in the general stratigraphic column. Transboundary formation transitions can be abrupt, due to no entire alignment between different geological maps.

At the present day, the Horn of Africa has an arid to semi-arid climate in Somalia and coastal Kenya, and a savanna to sub-tropical climate in the Ethiopian highlands (Peel et al., 2007). The Horn of Africa has frequent occurrences of severe droughts and is equally plagued by floods. On average, the annual rainfall in the north, northeast, and the central plateaus is up to 300 mm in the wettest places, and between 500 mm and 600 mm in the Ethiopian highlands (O Dochartaigh et al., 2016). The precipitation is influenced by rainy seasons, which normally occur from April to May and October to November in Somalia. However, due to climate change, these two rainy seasons are increasingly absent in the Horn of Africa (Shukla et al., 2021).

Rainfall is not constant in time, neither is groundwater recharge (Fleitmann and Matter, 2009; Nicholson et al., 2020; Schaebitz et al., 2021; Tierney et al., 2015). Important recharge events most likely coincided with humid periods, thousands to up to a million years ago. Therefore, aquifers in arid regions can hold water that is dated to be thousands to millions of years old (Bierkens and Wada, 2019; Ram et al., 2020; Sultan et al., 2007). This is especially the case for aquifers that are at 400 m depth or even deeper. As these aquifers are isolated from modern day climate change, they could serve as a reliable water source when exploited sustainably. Therefore, understanding the paleoclimate and climate predictions for the future are as important as understanding the present-day recharge. The geological model described in this paper aims to contribute to the understanding of the pathways of recharge to deeper aquifers.

2.2. Geological setting

Studies on the geology of the Horn of Africa started in the early 1900's and until the post Second World War years (Currie et al., 1925; Gregory, 1900; Gregory, 1925; Stefanini, 1913; Stefanini, 1936; Weir, 1925). An increase in geological outputs followed the onset of O&G exploration in the area (Azzaroli and Merla, 1957; Azzaroli and De Angelis, 1965; Merla et al., 1979; Merla et al., 1979).

Significant contributions to understanding the regional geology of the study area were made by several authors before the civil war in 1991 (Barnes, 1976; Bosellini, 1989; Fantozzi et al., 1990; Kamen-Kaye and Barnes, 1979; Piccoli et al., 1986; Purcell, 1979; Schunemann, 1984). Between 1987 and 1991, Abbate and co-authors compiled maps, papers with regional and local maps, marine and subsurface geology, and subsequently published a comprehensive geological map (Abbate et al., 1993). More recent local geological studies covered the Anza basin (Bosworth and Morley, 1994; Morley et al., 1999), and Daroor and Nogal basins (Ali and Lee, 2019a; Ali and Watts, 2013; Ali and Watts, 2021; Ali and Lee, 2019b).

The geological history of the Horn of Africa is characterised by several rifting phases alternating with subsidence and tectonic

quiescence. This influenced the lithology and the permeability distribution of the sediments in the subsurface, and hence of the aquifers, with the Mesozoic to early Paleocene formations virtually unexplored for fresh groundwater. Most of the sedimentary units consist of marine and continental-margin sedimentary rocks of Mesozoic and Tertiary age, unconformably deposited on Pre-Cambrian basement metamorphic and igneous rocks (Fig. 2). The main sedimentary basins of the region include the Lamu, Anza, Mandera-Lugh, Coastal, Ogaden, Nogal, Daroor, and Buban basins, and the Bur Acaba high and Nogal uplift areas (Abiikar, 2012; Purcell, 1979) (Fig. 3). Alluvial and fluvial deposits of Quaternary/Holocene ages cover most of the southeastern coastal area (Fig. 2).

2.3. Stratigraphy

The Precambrian basement outcrops mainly in the coastal regions in Northern Somalia and in the Bur area in the south of Somalia. The Bur area has two different complexes: the Olontole formation and the upper Dinsor formation. The Olontole formation mainly has paragneisses and amphibolites, where the Dinso formation consists of metasediments where marbles and quartzites are dominant (Bakos and Sassi, 1980; D'Amico et al., 1981; Daniels, 1965). In Northern Somalia, basement rocks are uplifted and crop out on the surface (Sommavilla, 1977) with two distinct units: the upper Inda Ad formation and the lower Older formation (D'Amico et al., 1981; Daniels, 1965). The upper Inda Ad formation is characterized by an abundance of meta-sandstones, occurrence of meta-conglomerates and marbles and low-grade metamorphism. The Older formation consists mainly of metasediments and acid to basic metamorphic igneous rocks. Some carbonate rocks occur locally (D'Amico et al., 1981; Daniels, 1965).

During the late Carboniferous to Early Permian, the Horn of Africa had a predominantly continental setting, where most of the land was exposed and therefore had locally widespread subaerial erosion (Bosellini, 1989; Bosellini, 1992). The oldest sedimentary unit present in the area is the Adigrat formation (Late Triassic to Early Jurassic) (Fig. 2), which was mostly deposited in fluvial, fluvio-lacustrine and deltaic environments, upon a peneplained pre-Cambrian rock surface (Abbate et al., 2015; Mohr, 1971). The Adigrat formation represents the Mesozoic Pre-rift sequence and is regionally widespread. The basal contact with the underlying Paleozoic basement, and the 'Karoo' equivalent rift clastics in basal areas, is erosional (Bosellini, 1989; Bosellini, 1992; Luger et al., 1990). As the formation lacks the abundance of fossils, exact dating is difficult. Both the top and the base of the formation are interpreted to be diachronous. The top of the formation is gradually younger towards the north and northeast reaching Callovian to Kimmeridgian age. (Abbate et al., 1993; Merla et al., 1979; Piccoli et al., 1986). The Adigrat sandstone is exposed in the south of Ethiopia and Somalia, along the northern coast of Somalia (St. John, 2015) and in smaller outcrops in the north of Somalia (Fantozzi and Ali Kassim, 2002). Inland from the marine Jurassic facies of East Africa, continental Karoo-type sediments were deposited (Mohr, 1971).

In the Middle Jurassic, breakup of Pangaea occurred. A period of global highstand and a marine transgression resulted in the

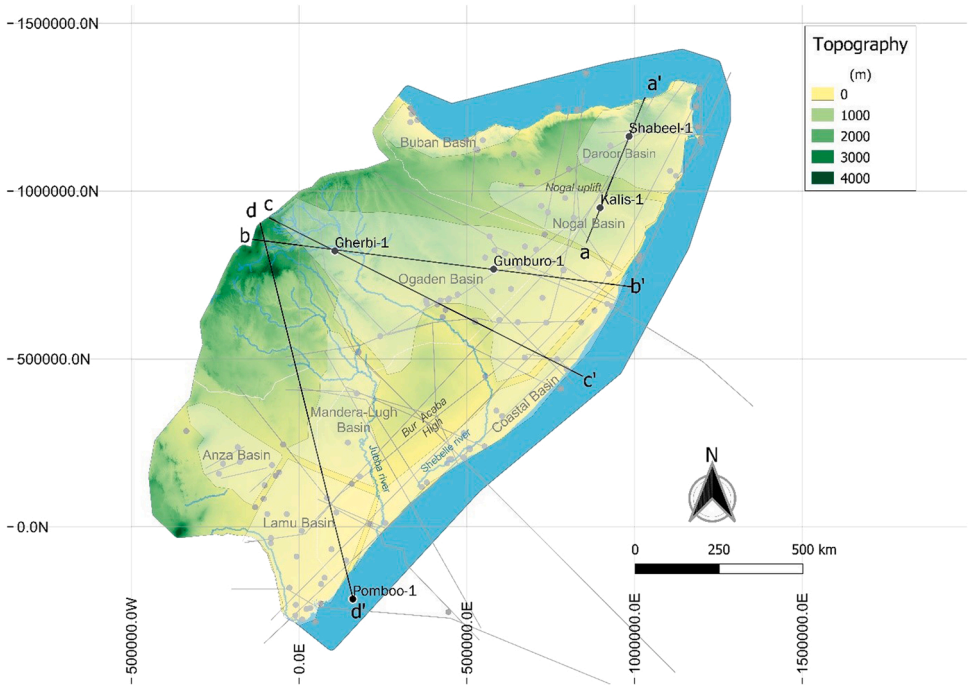


Fig. 3. Topography map of the study area. Cross-sections used to construct the 3D model are shown as light grey lines. O&G wells are marked as light grey dots. The main sedimentary basins are shown as transparent-white shades -modified from (Abiikar, 2012; Purcell, 1979). Four main produced cross-sections (a-a', b-b', c-c', d-d', shown in Figs. 8 to 11) are shown as black lines. Relevant O&G wells for freshwater analysis are marked as black dots, (for all the wells with indications of freshwater see Table 1 and appendix B).

deposition of the limestones of the Hamanlei formation, conformable over the Adigrat formation (Abbate et al., 1993; Merla et al., 1979; St. John, 2016) (Fig. 2). The Hamanlei formation consists of fossiliferous marine shelf carbonates, interbedded with shale and finer sand beds. In southern Somalia and in parts of Ethiopia, oolitic and coralline limestone beds are present. In northern Somalia anhydrite is interbedded with dolomite and limestone (map in Appendix C). The formation is Pliensbachian to Kimmeridgian in age (Abbate et al., 2015; Ali and Watts, 2016; Barnes, 1976; Bosellini, 1989). In the north of the study area, the Berriasian – Barremian interval is generally absent, and sediments of Aptian age are transgressing over Jurassic terrains from east to west. The Hamanlei formation is also referred to as the Meregh, Bihen formation and Baidoa formation (Ali and Watts, 2016; Angelucci et al., 1984; Angelucci et al., 1983). The upper parts of the Hamanlei formation usually show a high degree of fracturing and karstic cavities. The most extensive observed karst development is in the area near Borama (location in Appendix C) where the limestone has probably been exposed continuously since the Jurassic (FAO-SWALIM, 2012). This formation provides a good shallow aquifer system in the Awdal region (location in Appendix C), with numerous springs originating from karstified Jurassic limestones (Faillace, 1983; FAO-SWALIM, 2012).

The separation of Africa and Madagascar marked the end of rifting and the onset of a steady phase of regional subsidence (Bosellini, 1989; Bosellini, 1992). A transgression related to this drifting phase resulted in the deposition of a shaly succession over most of East Africa, referred to as the Uarandab formation (Fig. 2). The Uarandab formation is a marly and shaly limestone of Callovian/Oxfordian to Kimmeridgian age (Ali Kassim et al., 2002; St. John, 2016) and it is considered one of the main source rocks for hydrocarbons in the area (Hunegnaw et al., 1998; Plummer et al., 1998). The formation is deposited in an open, deep-marine and low energy environment, and it is also referred to as the Anole formation (Bosellini, 1989; Bosellini, 1992; Bruni and Fazzuoli, 1976; Shigut, 1998; St. John, 2016).

The Gabredarre formation overlies the Uarandab formation, and it consists of a shallowing-upwards, well-bedded limestone, composed of bioclastic calcarenites, oolitic grainstones and thin shaly and marly interbeds, which are prograding towards the east (Bosellini, 1989) (map in Appendix C). In the north of Somalia, the Gabredarre formation is referred to as the Gawan formation (Ali and Lee, 2019a; MacFadyen, 1933). In the Ogaden Basin, the Gabredarre formation represents a passive-margin sequence (Hunegnaw et al., 1998). The Gabredarre formation is only found in northern Somalia due to the effects of post-Jurassic erosion (Ali and Watts, 2016).

During the Early Cretaceous, central Somalia was a shallow gulf, largely surrounded by land. In this embayment, dolostones and sulfates (Main Gypsum formation, Fig. 2) accumulated in sabkhas, lagoons, and shallow water (Abbate et al., 2015; Bosellini, 1989; Bosellini, 1992). This succession records several sea-level oscillations and represents the final stages of the Mesozoic flooding in the Ogaden basin (Abbate et al., 2015). The anhydrite and gypsum deposits are mostly in eastern Ethiopia and parts of northern Somalia. In the coastal Somalia to the Indian Ocean, Early Cretaceous deposits are mostly shaly limestones and limestones (Purcell, 1979). In the Lamu embayment the Lower Cretaceous deposits are characterized by marine grey shale and shaly limestones (Peterson, 1985). To the southeast, a major fluviatile system (the Ambar sandstone) prograded northeast into a wide, restricted marine shelf (Bosellini, 1989).

The Gumburo formation is composed of limestones, with fossiliferous beds and shaly, dolomitic and evaporite beds and was deposited between Aptian – Turonian (Fig. 2). The formation is also referred to as the Mustahil, Ferfer and Belet Uen formations or the Gira sequence (Bosellini, 1989; Bosellini, 1992; St. John, 2016). This period of deposition was marked by relative tectonic quiescence, with a stable shallow–marine carbonate shelf and open deep-marine conditions in the most easterly part of the study area.

The transgressive Jessoma sequence overlies a major early Maastrichtian unconformity caused by regional uplift and faulting, and the formation of east – west trending horsts and grabens (Bosellini, 1989; Bosellini, 1992; Tuck-Martin et al., 2018). The Jessoma formation gradually changes from sediments of fluvial and shallow marine origin, with continental fluvial sandstones in the west, through marginal, shallow marine shelf carbonates to deep-water basinal shales in the east (Bosellini, 1989; Bosellini, 1992) (map in Appendix C).

During the late Paleocene to early Eocene, the transgression created an open shallow marine carbonate shelf across the Horn of Africa, resulting in the deposition of the first marine deposits after the Upper Cretaceous to Lower Paleocene emersive phase; the Auradu formation (Fig. 2) (Carbone et al., 1993; MacFadyen, 1933). The Auradu formation also marks the last major marine flooding of the Africa craton (Carbone et al., 1993). The Auradu formation overlies the Jessoma formation unconformably and covered the northeast of the area of interest and the Daroor Basin with shallow marine limestones (Bosellini, 1989; Bosellini, 1992) (Appendix D and C). The Auradu formation deposits are rich in corals, mollusks, and foraminifers, and represent an important karstified shallow groundwater aquifer in north Somalia (FAO-SWALIM, 2012) (map in Appendix C). The base is diachronous, and in most parts of central and NW Somalia this is attributed to the Paleocene or early Eocene (Bosellini, 1989; Bosellini, 1992), while in the NE of Somalia it contains marine faunas of Maastrichtian age (Luger et al., 1990).

The regressive Taleh formation, deposited in Eocene, consists of mostly evaporites with shelf limestones and dolomite (Bosellini, 1989; Bosellini, 1992). Massive to banded anhydrite was mostly deposited in the Nogal and Daroor basins, whereas in the central and southern part of Somalia deposited shelf limestones and shallow marine sands (Boeckelmann and Schreiber, 1990). The anhydrite is often altered to gypsum on the present-day surface. The Taleh formation can be karstified, with examples of karstic caves in the gypsum at Sool Plateau, north Somalia (FAO-SWALIM, 2012).

The Karkar formation deposited during a following transgression event in the Late Eocene, depositing marly, nodular limestones, containing rich shallow marine fauna (Azzaroli, 1950; Stefanini, 1925). The formation is characterized by alluvial and deltaic deposits in the northeast of the study area. At the base there are laminated claystones, interbedded with gypsum and anhydrite (Bosellini, 1989; Bosellini, 1992). The Karkar formation is only deposited in the northeastern part of the study area, indicating that probably most of the Horn of Africa was being uplifted and exposed at this time. Karstic springs exist in the Karkar formation in northern Somalia (FAO-SWALIM, 2012).

The most recent rifting event, related to the opening of the Gulf of Aden, started in the Oligocene. In the early Oligocene the eastern part of the study area was subaerially exposed, most likely because of a major tectonic uplift and deformation. The Oligo-Miocene succession is now mostly restricted to a narrow and discontinuous coastal belt (Bosellini, 1986; Bosellini et al., 1987). The Oligo-Miocene syn- and post-rift sequences, outcropping in the northeastern coast of Somalia, are referred to as the Guban series (Azzaroli and Merla, 1957; Fantozzi, 1996). Equivalent series are the Duban formation and Hafun series (Stefanini, 1937). A regional marine transgression occurred in the Late Oligocene-Miocene, followed by a Miocene highstand (Bosellini, 1989; Bosellini, 1992). The Quaternary deposits are characterized by alluvial deposits, dune fields and beach deposits (Fantozzi and Ali Kassim, 2002). These deposits outcrop in southern Somalia, around Mogadishu, and near the Juba and Shabelle rivers (Abbate et al., 1993).

3. Material and methods

The basis of the geological model shown in this study is the digitization and integration of several cross-sections collected from earlier hydrocarbon exploration reports, geological reviews, and research studies of the Horn of Africa. 152 documents were reviewed to extract 38 cross-sections, the formation tops from 63 oil wells (Fig. 3), and the geologic maps. The gathered data were integrated into the 3D model as shown in Fig. 3 and Appendix E1. The spatial coverage of the data is variable, with the Daroor, Nogal, east Ogaden, Coastal and Anza basins showing good coverage, with an irregular grid of 5–100 km spacing (Fig. 3). Data coverage in the central regions is sparser, with a spatial resolution between 10 km and 500 km. The reliability of the references was rated based on the input information, where the quality indicator “A” is given to studies that had access to seismic and/or oil well drilling data, “B” to publications based on previous studies but with little or no access to oil data, and “C” when no documented sources were presented by authors with presumed access to relevant data (Appendix E2).

A lithostratigraphic, chronostratigraphic, and facies review was carried out to ensure uniformity in formation names throughout the area of study. For example, in the Ogaden Basin, the Gumburo Sandstone is part of the Karoo sediments from the Late Permian - Early Triassic, while in Northern Somalia, Gumburo is a formation from the Cretaceous which consists mainly of carbonates. For this study, the name Gumburo refers to the carbonate formation from the Cretaceous. Another example is the Karoo and Adigrat sandstones. In the past, the failure to recognize the Permian sedimentary cycle in Ethiopia, and the presence of Triassic continental sandstones in Kenya, have complicated regional and local correlations of this unit (Purcell, 1979). In the Coastal and Lamu basins the sandstone sediments from the Permian and Triassic are named Karoo, while in the Ogaden, Nogal and Daroor basins these are referred to as Adigrat in the literature. For this study, the authors refer the Permian and Triassic sandstones to the Adigrat formation.

3.1. Workflow

The main methodological challenge of this study was bridging the gap between the file types, and proprietary formats used for reservoir interpretation and modelling in the O&G industry software (Petrel), and the ones handled by hydrogeological (ModFlow) and surface geospatial data software (QGIS). In order to address this challenge, and achieve the integration between the typical hydrogeological studies (focused on surface and shallow geology) and O&G reservoir characterization data (focused on deeper formations) a specific workflow was created, which includes Python scripts to enable file format conversion, data filtering and cleaning. This workflow is repeatable and consists of iterative steps between QGIS and Petrel, and Python and Visual Modflow Flex (VMF) software (Fig. 4) to integrate O&G well logs and seismic data (e.g. in.las format) with hydrogeological data derived from images or text files.

Two main sets of data were collected and used for the regional mapping: geological and structural maps, and cross-sections. These data are derived from hydrocarbon exploration reports, geological reviews, and research studies of the Horn of Africa, including published papers and conference presentations (Appendix E2). Maps and cross-sections were extracted as pdf or image (.jpg/.png) files and later georeferenced in QGIS where the corner-point coordinates were extracted. Subsequently, maps were imported as surface images in Petrel. Surface geology maps were also imported as shape files (.shp) and converted to surfaces by using elevation data.

A similar approach was used with cross-sections; in addition, the collection of cross-sections was filtered by 1- area of interest; 2- availability of location information that allowed georeferencing and 3) vertical units available in depth units (rather than in two-way-travel-time (TWT), which is a common format for seismic data derived cross-sections) (Fig. 4). The location maps of the selected cross sections were then georeferenced in QGIS. Finally, the selected cross-sections were loaded into Petrel with their location maps, which

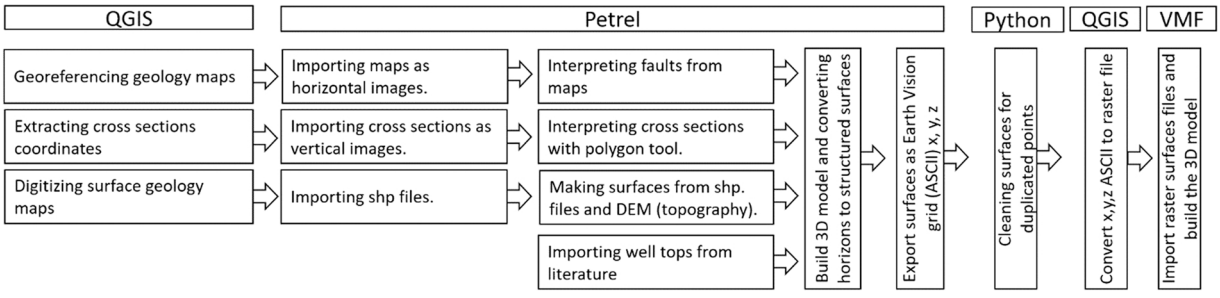


Fig. 4. Workflow used to produce a 3D geological model from data of public domain (open access and/or published).

were used for spatially locating the cross-sections. For each cross-section, the interpreted formation tops were digitized and reinterpreted where needed, using the 'polygon' tool in Petrel, while faults were interpreted or digitized from geological maps using the 'insert fault' tool. Tops or horizons in terms of geological age (e.g., top of Jurassic) were converted to formation tops based on their lithological and chronostratigraphic description, and based on the correlation with well data, where available. Finally, the polygons were converted into surfaces to be used as an input for the 3D geological model.

Faults from surface geology maps (Abbate et al., 1993; Kamen-Kaye and Barnes, 1979) and satellite imagery (source: Google Earth) were digitized and included in the initial database (Appendix A). As the aim was to produce a first pass, large-scale model, only the faults that were likely to have an impact on the regional aquifer distribution, and had been interpreted on cross-sections, were selected. The number of faults therefore appearing in the 3D model (appendix D) is a much-reduced subset of the total number of faults originally interpreted (Appendix A).

Surface geology, well tops, and contour maps found in the literature were also integrated into the structural modelling process. After the 3D geological model was built in Petrel, horizons were converted to structure surfaces and exported in ASCII (x,y,z) format. The resulting surfaces and faults were separately imported in Visual Modflow Flex, where the final hydrogeological model and grid were built.

4. Results

The data collection and analysis allowed us to extract the building blocks of the 3D geological model consisting of mapping the extent of the main geological units, associating them with the indications of freshwater in deep formations from O&G wells, the level of confinement, and estimations of porosity and permeability in the mapped units. The constructed model and resulting maps are very regional as the main purpose of the study is to introduce the methodology and the new hydrogeological insights of the potential cross-boundary aquifers linked to the overall water recharge in the highlands of Ethiopia (Ruden, 2017).

4.1. Mapping of main surfaces

The definition and correlation of the units across the entire Horn of Africa region pose a real challenge, mostly due to differences in lithological description and interpretation (e.g., different facies, hiatuses) and nomenclature assigned to time-equivalent units. In order to address this issue, and minimize potential correlation errors, we established a combination of several criteria for surface selection, including stratigraphic relevance, regional extent, importance in the hydrogeological context and data control. Ultimately, surface definition was primarily based on lithostratigraphy, but where formations were coeval over the entire area, also on geological age.

The reinterpretation of geological maps and cross-sections across the regions allowed producing regional maps that show the extent and depth of the main formations in the 3D geological model. These formations are considered the main hydrostratigraphic units that build our 3D model. Priority was given to the following formation tops, which are, from oldest to most recent (see Fig. 2):

- The Paleozoic weathered and fractured basement (Fig. 5a, Appendix D and F). This formation is one of the most important and prolific reservoirs of water in rural Africa. In the geological model, one of the largest basement outcrops is in the Bur Acaba area

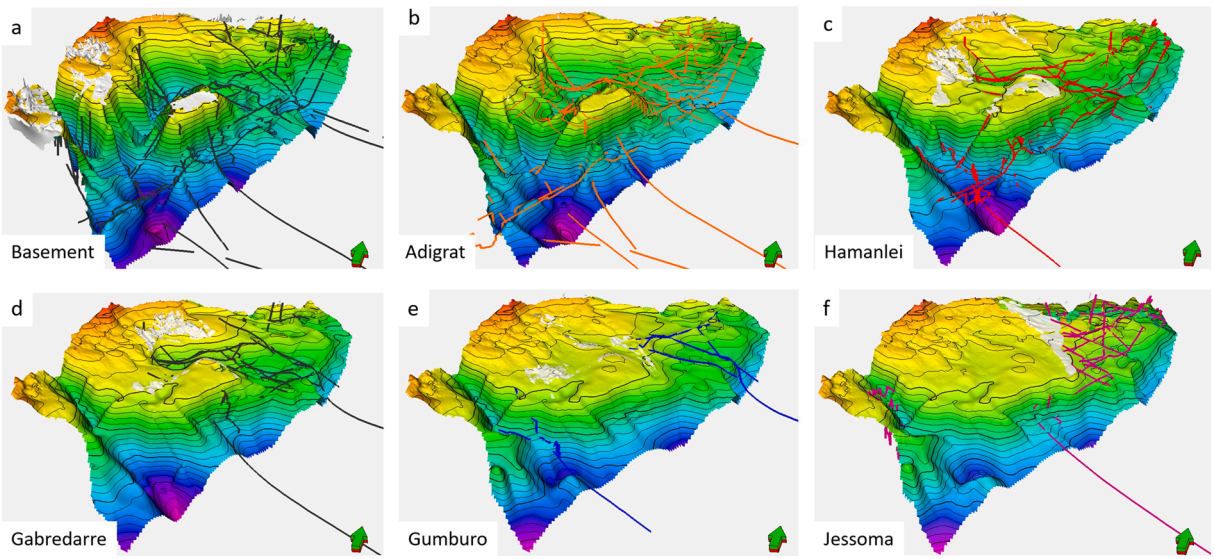


Fig. 5. Examples of formation surfaces built from interpreted lines (see Appendix D for full-size figures). Deep formations such as Basement, Adigrat and Hamanlei are well characterized, mostly thanks to the availability of published O&G data (including gravimetric and seismic data). Outcrops of each formation are shown in white.

(absolute age 615 My). The fissured zones of the crystalline rocks are a potential infiltration route for water, however, the quality of the water from fissures in the region is generally poor. Moreover, wells with water of very good quality but with a limited yield are found in fault zones (Faillace, 1983). For this study, the top 300 m of the basement formation along the area of study (Fig. 5a) is assumed to be a potential aquifer with fair vertical permeability, while the deeper basement is considered a confining bed/aquitard.

- The Adigrat formation (Fig. 5b, Appendix D and F). This is a fine to coarse-grained feldspathic sandstone with limestone intercalations of Late Triassic to Early Jurassic age. In the highlands of Ethiopia, the Adigrat sandstones represent a potential aquifer and also a pathway of deep groundwater to the east coast. To reduce the complexity of the model, the Karoo and Adigrat sandstone are modelled as a single unit as having similar lithology and petrophysical properties (Fig. 5b).
- The Hamanlei formation (Fig. 5c, Appendix D and F). This formation was deposited in the Late to Middle Jurassic and consists primarily of limestone with some intercalations of shale and sandstone. This formation is expected to play an essential role in transporting water from the western highland recharge areas to the deep sedimentary basins. Hamanlei formation suggests that groundwater circulation takes place mainly in this zone. Karst normally conveys water at much higher flow velocities than traditional porous or fractured aquifers. In hydrogeological terms, karst aquifers are characterized by high flow velocities, low residence time, and low storage volumes (Ruden, 2017). Therefore, water in karstic aquifers is less prone to mineralization than the slower-moving counterpart in porous or fractured rocks.
- The Gabredarre formation (Fig. 5d, Appendix D and F). This is also referred to as Dawan formation, and it was deposited in the Late Jurassic. In the Lamu and Ogaden basins, this formation consists mainly of grey argillaceous and calcareous marlstones, with interbedded argillaceous limestones and dolomites. The lateral variation in lithology throughout the study area required independent modelling of the surface, in order to assign the specific petrophysical properties, according to the facies.
- The Main Gypsum Formation (Appendix D). It outcrops over large areas of the western basin and extends into the Mandera-Lugh Trough, where it consists of gypsum and limestone with interbedded shales. The Ambar sandstone in the Mandera-Lugh basin, and the Gorrahei carbonates in Ethiopia are chronostratigraphically equivalent. The Main Gypsum is considered a potential aquitard because of its low porosity and permeability.
- The Gumburo Formation (Fig. 5e, Appendix D and F). This includes the the Belet Uen, Ferfer and Gira formations, and was deposited in the Late Cretaceous (Fig. 5e). The formation consists mainly of highly fractured limestone in the Nogal and part of Daroor basins, while in the western side of the model, the lithology changes to siliciclastic shoreline and continental sediments (Purcell, 1979). The secondary porosity of the Gumburo formation in the carbonate facies makes it suitable for conveying and storing groundwater.
- The Jessoma formation (Fig. 5f, Appendix D and F). This formation underlies much of the Ogaden basin and extends to the Buban, Daroor and Nogal basins and Horn of Africa. It consists of fine-grained sandstones in the east, transitioning to shallow carbonates in the west, from the Late Cretaceous to the early Tertiary age. In places, this formation has a deep water table (several 100 s meters), holds saline water, and is difficult to drill (Kebede, 2012). Kebede (2012) also reports potable water and frequent 'loss of circulation' problems in this formation while drilling. Pathways for water transfer are still poorly understood and reside either in limestone members within the sandstone series, or alternatively within fractures and faults networks (Kebede, 2012); in either case, the observed water circulation may imply significant water potential.
- The Auradu formation (Appendix D and F). It consists of massive limestone beds alternating with chalky and gypsiferous beds and calcareous shales deposited since the Paleocene. Drilling operations in the Auradu formation are considered difficult due to circulation losses when drilling through karst (Kebede, 2012). Nonetheless, other authors (Ullah, 2016) highlight that the most productive water well of the northeast of the area of interest (at 50 L/s) was drilled in this formation in Ceerigabo.
- The Taleh formation (Appendix D). This was deposited in the Early Eocene, and it is a typical evaporitic formation deposited in a shallow sea in arid climate. It consists of a sequence of massive and dense anhydrite beds with intercalations of limestone and gypsum. Lateral changes of facies from gypsum and anhydrite to limestone are known in some places (FAO-SWALIM, 2012). Due to the low permeability of this formation, the Taleh formation is a potential aquitard.
- The Karkar (Late Eocene) and Daban formations (Oligocene) (Appendix D). These formations are Neogene and Quaternary in age, and have been modelled separately. For the purposes of this study, they are both considered part of the shallow aquifers system.

The interpretation and mapping of the Basement, Adigrat, and Hamanlei formations is supported by good data coverage and distribution, providing solid structural control for the base of the model (Fig. 5). These formations have been extensively described in the literature, except in the Lamu basin and south of the Mandera Lugh basin, where O&G wells did not reach the Jurassic. The vertical extent of the Jurassic and older formations in these two basins is instead based on gravimetry maps and interpretations published by previous authors (Abbate et al., 2015; Kamen-Kaye and Barnes, 1979; Piccoli et al., 1986; Schunemann, 1984). The top part of the model is controlled by the topography, and the outcrops of formations as shown on geological maps. These formations were digitized from surface geology maps, and subsequently updated or reinterpreted using satellite imagery, where needed.

4.2. Distribution of hydrostratigraphic units: facies maps and predicted thickness

The potential extent of the hydrostratigraphic units used in our model is defined by the current extent (after erosion) of the related formation, and by the facies, which is directly linked to their original depositional environment. Existing facies maps were used to characterise the expected lithology and quality of aquifer (Bosellini, 1992; Purcell, 1979), while the thickness of the unit is derived from the interpretation of the related formation on the Petrel 3D model. Figs. 6 and 7 show such examples for the Adigrat formation, while facies and thickness maps for all the formations are presented in Appendix C and G.

Due to the size of the area of study and the limited data available, the grid resolution of the constructed model was set to 10 × 10 km. Therefore, input data with a spatial resolution higher than 10 km is not considered and smoothed by the model. As a consequence, in areas with high data coverage such as the Nogal and Daroor basins, the resulting surfaces do not accurately cross the interpreted formation tops. Thus, the regional thickness maps do not always represent the correct local thickness of formations, and they should be used only as an indication of where there is a good chance of finding the targeted formations.

4.3. Freshwater indications in oil exploration data

The distribution of the hydrostratigraphic units obtained with the 3D geological model was cross-checked against the freshwater indications found in O&G exploration wells, in order to ground-truth their potential as aquifers. Quiroga et al. (2022) used the combination of resistivity, gamma-ray, spontaneous potential, density, neutron-porosity, and photoelectric effect logs with Drill Stem (DST) and Repeat Formation tests (RFT) to identify formations filled with freshwater in northern Somalia and Somaliland. Table 1 summarizes the findings of freshwater reported in the literature over the area of study. For the purposes of this study, water with a concentration of less than 5000 mg/l TDS (Total Dissolved Solids) is considered freshwater. Water ranging from 5000–10,000 mg/l TDS is considered brackish. Water in excess of 10,000 mg/l TDS is considered saline.

From north to south, the regions that reported the most freshwater indications in deep aquifers are: the Daroor, the Nogal, the Ogaden Basin and the Lamu basin. A series of vertical cross-sections extracted from the 3D model have been selected to indicate the structure of the geological formations together with the related freshwater indications in these key areas (Figs. 8 to 11, location in Fig. 3).

The northern part of the Horn of Africa is particularly rich in indications of deep freshwater aquifers, but this could be due to a data bias, as they are the basins with the highest data coverage. Occurrence of low salinity deep water in the Nogal basin was documented in connection with O&G exploration in the well Nogal-1 (Ali and Lee, 2019b). The Jessoma Formation was interpreted to be flushed by fresh water that could have migrated by juxtaposition from the Auradu formation (Ali and Lee, 2019a; Ali and Lee, 2019b). Quiroga (2020) and Quiroga et al. (2022) report the potential for fresh deep groundwater in the Daroor and Nogal basins after analysing data from seven wells drilled for hydrocarbon exploration in the Nogal and Daroor basins (Table 1, and Appendix B). The formations that have indications of low salinity water are the Auradu (limestone), Jessoma (sandstone and limestone), Gumburo (highly fractured

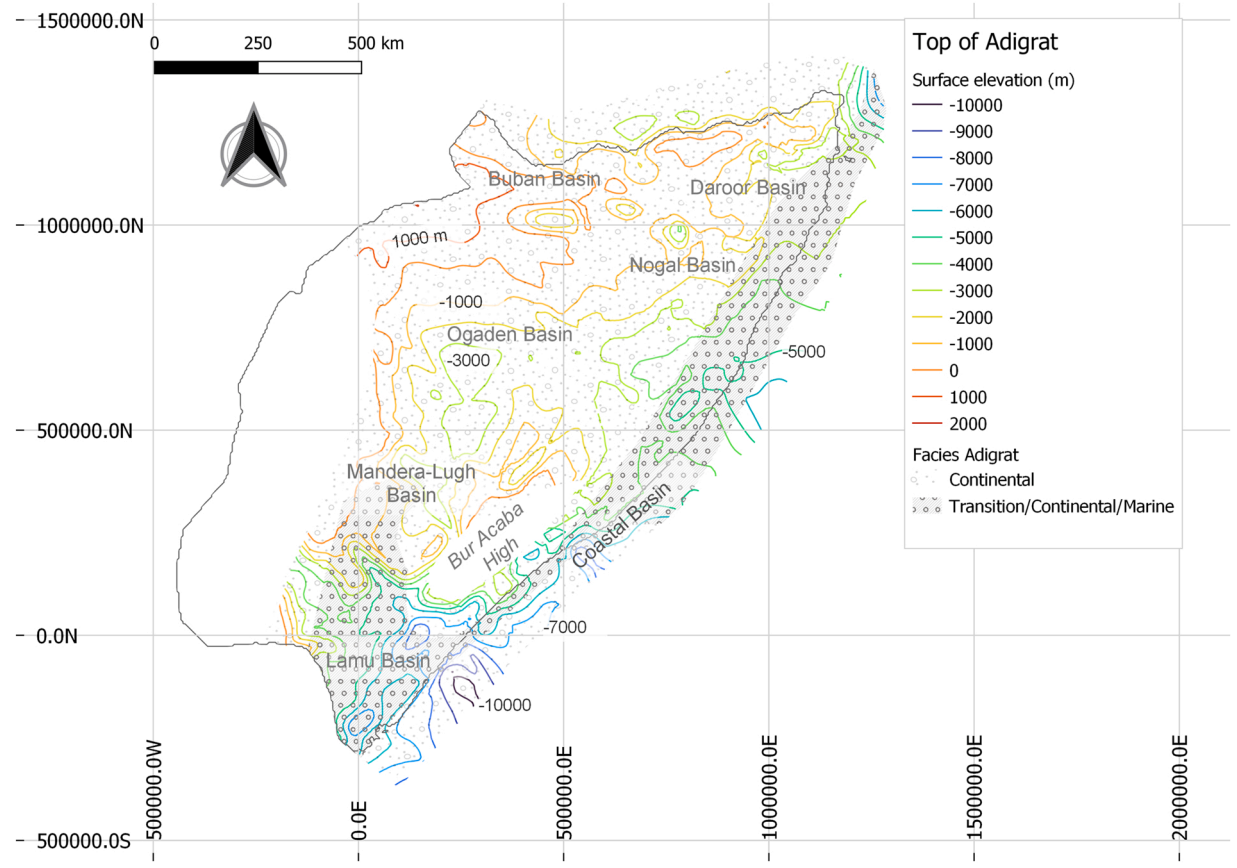


Fig. 6. Adigrat formation facies and elevation map.
Modified from Purcell (1979), Bosellini (1992); and unpublished O&G reports.

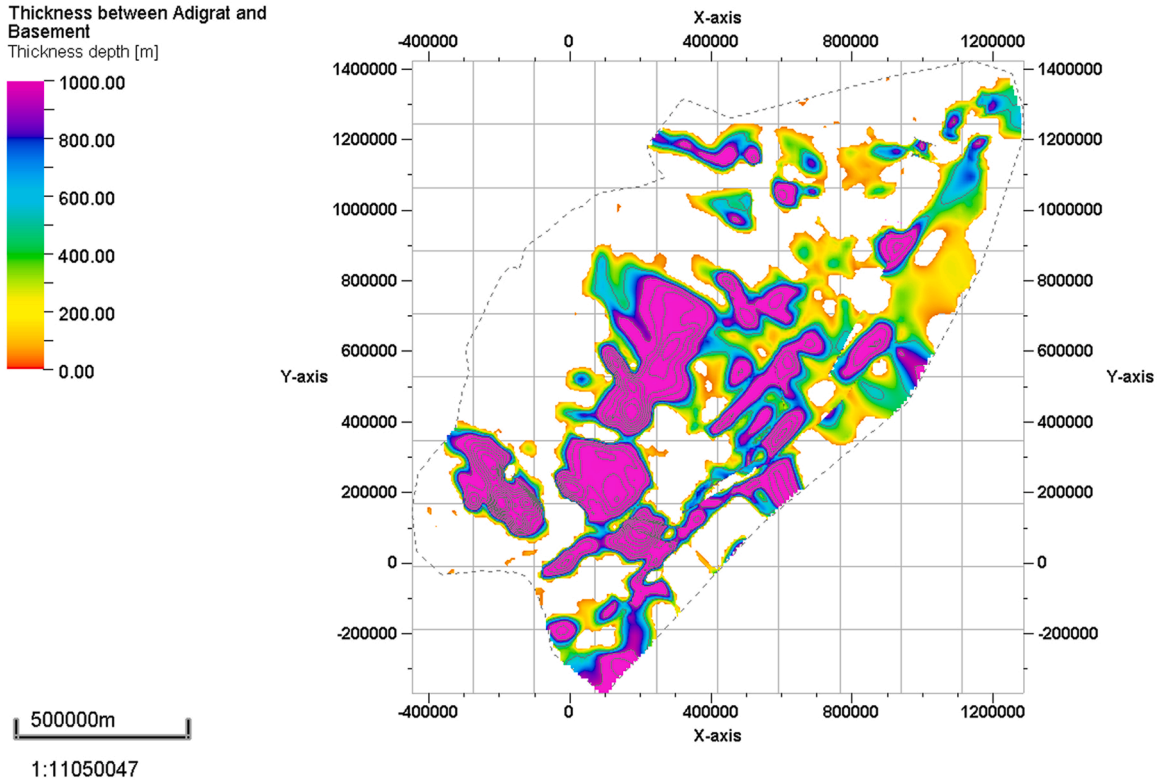


Fig. 7. Map of thickness between the Adigrat formation and the Basement.

limestone, sandstone and shale), Gabredarre (limestone and anhydrite), Hamanlei (limestone and sandstone) and Adigrat (sandstone and interbedded limestone) formations.

In the Ogaden basin, the Gherbi-1 well, drilled in 1974 by Teneco on the northwest flank of the basin, tested fresh water from the Adigrat formation (sandstone). The Upper Hamanlei formation (limestone and anhydrite) in this well tested salt water (Purcell, 1979). The Gumburo-1 well, drilled by the Sinclair Petroleum Company in 1950, tested freshwater in the Gumburo formation (carbonate/marl/evaporites), and brackish to salty water in the Hamanlei formation (carbonate) (Piccoli et al., 1986).

In the eastern Ogaden region, the well Abred-1 was drilled and abandoned in 1963 without significant hydrocarbons shows. The Cretaceous section tested fresh water and the Hamanlei and Adigrat formations yielded salt water (Purcell, 1979). The Cretaceous formations in the Ogaden basin, which are interpreted to be flushed with freshwater, are present at greater depths in the Lamu basin. The offshore well Pomboo-1, drilled by Woodside in 2007 on a thrust anticline, encountered a thick Late Cretaceous clastic sequence which included Campanian sands, and no hydrocarbons were encountered (Davison and Steel, 2018).

4.4. Hydraulic properties of the potential aquifers

Porosity and permeability data have been collected from O&G studies and reports for the Adigrat, Gumburo, Jessoma and Auradu formations (Fig. 12). The Adigrat formation shows average porosities of 5 – 15%, and values of up to 20% in Ethiopia (Purcell, 1979). In the northern part of the study area, the well Buran-1 encountered 2.5 mD of horizontal permeability in the upper section of the Adigrat formation, up to 450 mD for the middle and lower Adigrat, and a maximum of 50 mD of vertical permeability. In the Nogal basin, the well Burhisso-1 reported a horizontal and vertical permeability of, respectively, 180 mD and 125 mD.

The Gumburo formation has permeabilities of 0.5 – 8 mD in Buran-1 and 11–13 mD in Yaguri-1. In the lower Gumburo, the well Burhisso-1 encountered a horizontal permeability of 9 mD and a vertical permeability of 14 mD (Fig. 12).

The well Buran-1 encountered good reservoir properties in the Jessoma formation with average porosities of 20–40%. The well reported horizontal permeabilities of 280 – 840 mD and vertical permeabilities of 140 – 920 mD. In the Burhisso-1 well the permeabilities of the Jessoma formation ranged from 260 to 510 mD, and up to 1200 mD in Shabeel North-1 in the same formation (Fig. 11).

Limited information is available from the Auradu formation, as it is found at relatively shallow depths and therefore not a target for oil prospects. In the Buran-1 well permeabilities were reported between 81 and 145 mD in the Auradu carbonates (Fig. 12).

Equivalent freshwater heads and distribution can be derived from pressure data recorded in onshore and offshore petroleum wells (Varma and Michael, 2012). The level of confinement of the potential aquifers in the Nogal and Daroor basins is determined from oil exploration data in Quiroga et al. (2022) (Table 2). Although the aquifers are confined, the pressure is not sufficient for the wells to be artesian in the two basins. Oil well exploration data on the other basins are necessary to derive further conclusions on the level of

Table 1
Freshwater indications summary table. Modified after Quiroga et al. (2022). (*) Salinity is not specified by the authors: Dagah Shabel-2 in (Ali and Lee, 2019b), Abred-1, Gherbi-1, Gumburo-1 (Purcell, 1979). For well locations see Appendix B.

					Method			
Well	Top MD	Top TVDSS	Base TVDSS	Formation	SP	Archie (NaCl ppm)	DST (NaCl ppm)	Core (NaCl ppm)
Shabeel North-1	1168	659.0	721.0	Auradu		700		
		721.0	1139.0	Auradu	Positive	700		
	1852	1343.0	1400.0	Jessoma		2203		
		1400.0	1421.0	Jessoma		2203	3465	
		1421.0	1458.0	Jessoma	Positive	2203	3465	
	1967	1458.0	1471.0	Jessoma	Positive	7004		
		1471.0	1573.0	Jessoma		7004		
	2082	1573.0	1658.0	Jessoma		6515		
		1744.0	1763.0	Gumburo	Positive			
		1850.0	2041.0	Gumburo	Positive			
Shabeel-1		650.0	769.9	Auradu	Positive			
	1279	769.9	800.9	Auradu	Positive	7744		
	1310	800.9	1129.9	Auradu	Positive	283		
	1840	1330.9	1511.9	Jessoma	Positive	5583		
	2021	1511.9	1774.0	Gumburo		3140		
		1774.0	1868.9	Gumburo	Positive	3140		
		1868.9	1900.0	Gumburo	Positive			
Buran-1		-535.8	-531.9	Auradu				1153
		-78.6	-76.8	Jessoma				494
		84.1	90.6	Jessoma			1000	1483
		433.6	437.6	Gumburo				988
		464.1	468.6	Gumburo				988
		525.6	531.6	Gumburo				824
		643.1	647.6	Gabredarre				988
		735.6	743.6	Gabredarre				1483
		1496.6	1503.6	Adigrat				1647
		1529.6	1537.6	Adigrat				1483
		1552.6	1567.6	Adigrat				2636
Kalis-1		297.3	314.3	Auradu	Positive			
		445.3	456.3	Auradu	Positive			
		727.3	740.3	Auradu	Positive			
		944.3	992.3	Jessoma	Positive			
		1032.3	1054.3	Jessoma	Positive			
		1078.3	1095.3	Jessoma	Positive		4942	
		1172.3	1211.3	Jessoma	Positive			
		1266.3	1309.3	Gumburo	Positive			
		1760.3	1798.3	Gumburo	Positive			
		1820.3	1832.3	Gumburo	Positive			
		2004.3	2009.3	Gumburo	Positive			
		2138.3	2144.3	Gumburo	Positive			
		2156.3	2164.3	Gumburo	Positive			
		2143.3	2242.3	Gumburo	Positive			
Nogal-1		1553.14	1592.14	Jessoma	Positive			
		2530.14	2541.14	Gumburo	Positive			
		2609.14	2629.14	Gumburo	Positive			
Yaguri-1		669.4528	687.4528	Hamanlei-Adigrat			2965	
		674.4528	720.4528	Adigrat			3500/2535	
Burhisso-1		700.14	707.14	Gumburo			1647	
		846.14	855.14	Adigrat			1647.390691	
Dagah Shabel-2 (*)				Adigrat				
Abred-1 (*)				Cretaceous				
Gherbi-1 (*)				Adigrat				
Gumburo-1 (*)		176	195	Gumburo				

confinement of the rest of the system.

4.5. Potential extent of the deep aquifers

The results from our analysis show the potential stacked aquifers in areas with significant data control based on the 3D geological model, and on the data on freshwater occurrences from O&G data, shallow wells and springs (Faillace, 1983; FAO-SWALIM, 2012; Quiroga, 2020; Quiroga et al., 2022; Ullah, 2016)ah, 2016) (Fig. 13). Significant aquifer potential is observed regionally for the Adigrat, Hamanlei, Gabredarre, Gumburo, Jessoma, Auradu units. Of these units, while the most recent and shallowest, i.e., Auradu and Jessoma (Cretaceous to Paleocene) have been previously recognised as regional or local aquifers, the oldest ones, i.e., Adigrat, Hamanlei, Gabredarre and Gumburo (Jurassic to Cretaceous) are here reported for the first time as potential deep aquifers.

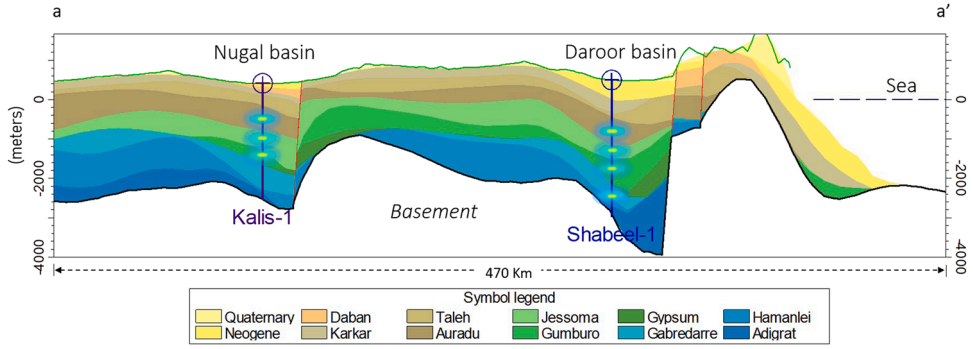


Fig. 8. Vertical cross-section of the resulted 3D model across the Nogal basin in northern Somalia, with the Kalis-1 and Shabeel-1 well. Formations with freshwater indications are highlighted on each well. Main faults are shown in red. Location of cross-section in Fig. 3.

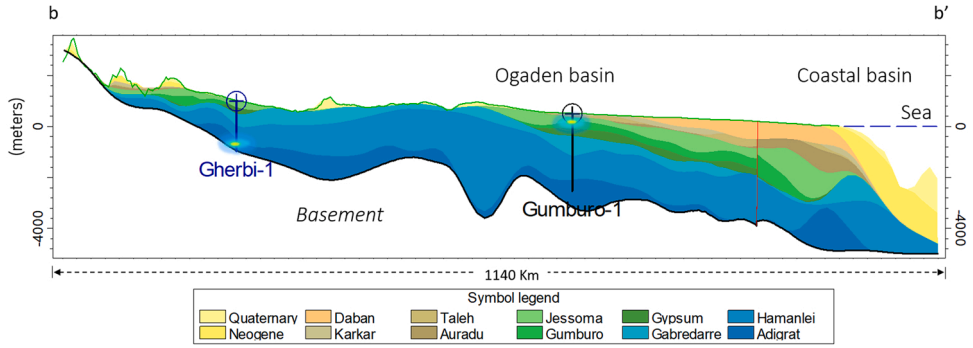


Fig. 9. Vertical cross-section of the resulted 3D model across the Ogaden Basin Gherbi-1 and Gumburo – 1 wells. Formations with freshwater indications are highlighted on each well. Main faults are shown in red. Location of cross-section in Fig. 3.

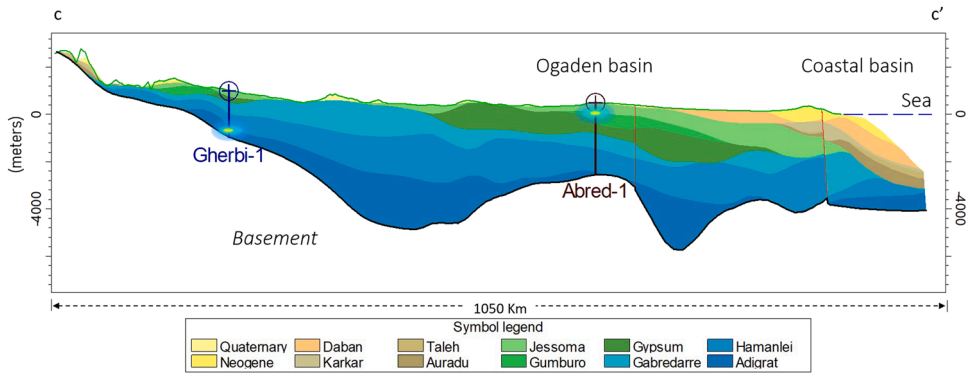


Fig. 10. Cross-section of the resulted 3D geological model across the Ogaden Basin Gherbi-1 and Abred-1 wells. Formations with freshwater indications are highlighted on each well. Main faults are shown in red. Location of cross-section in Fig. 3.

It should be considered that the predicted maps do not guarantee the presence of sufficient thickness of the formation far from the control points where the surfaces have been extrapolated. To map viable aquifers in targeted follow-up studies, it is important to go back to the local data and/or construct more localized models with higher grid resolution. The recommended use of the maps is twofold: for water resources exploitation, only in areas close to the O&G wells with indications of freshwater, and for the definition of larger potential prospecting areas, in areas far from oil wells control, by re-gridding and adding new data.

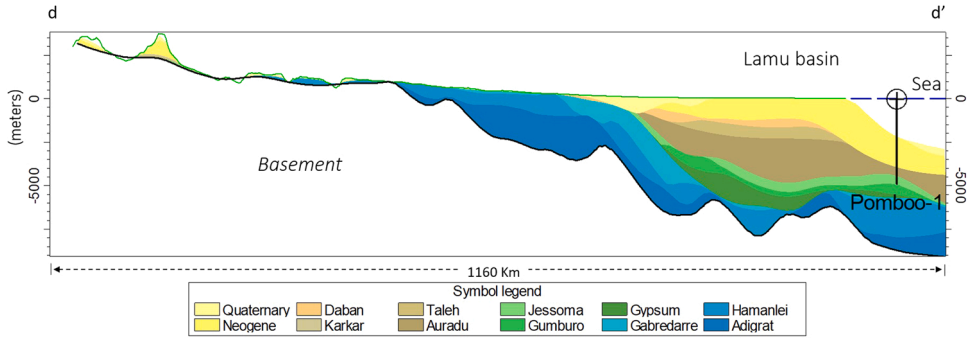


Fig. 11. Vertical section of the model crossing from the Ethiopian highlands to the Lamu basin Pombo well in Kenya, where young formations are thicker and Cretaceous formations have been found at greater depths. Location of cross-section in Fig. 3.

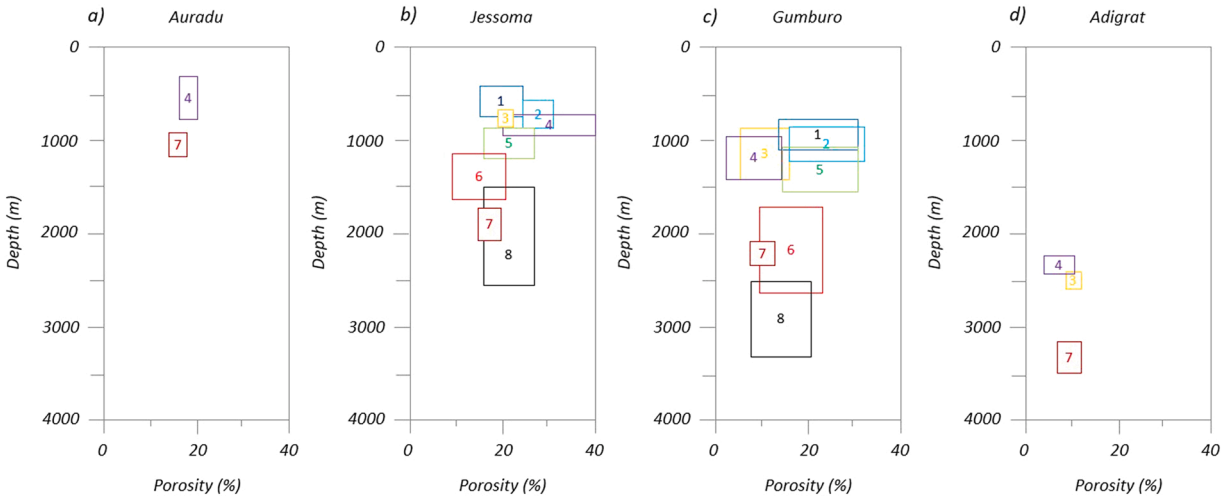


Fig. 12. Compiled average porosities of (a) Auradu, (b) Jessoma, (c) Gumburo and (d) Adigrat Formations in exploration wells drilled in the Nogal and Daroor basins. 1. Yaguri-1; 2. Las Anod-1; 3. Burhisso-1; 4. Buran-1; 5. Faro Hills-1; 6. Kalis-1; 7. Shabeel-1; 8. Nogal-1.
Modified from (Ali and Lee, 2019a; Ali and Lee, 2019b).

Table 2
Equivalent hydraulic heads in some wells from Northern Somalia, assuming water density of 1 g/cm3. (*) Measured from the sea level, positive values mean water level below the sea level.

Basin	Wells		Pressure test		Equivalent hydraulic head* (m)
	Name	Elevation (KB)	Formation	DST/RFT depth TVDSS*	
Daroor	Shabeel-1	509.1	Jessoma	1430.9	-292.6
	Shabeel North-1	509.0	Jessoma	1400.0	-206.0
	Buran-1	853.4	Auradu	-534.0	-594.0
			Jessoma	83.5	-469.1
			Adigrat	1525.9	-223.0
Nogal	Kalis-1	423.7	Auradu	235.0	-220.9
			Jessoma	836.1	-130.7
			Jessoma	1079.3	-122.0
			Gumburo	1307.1	-118.1
			Gumburo	1613.3	-117.2
	Yaguri-1	720.6	Adigrat	669.5	-340.5
			Adigrat	674.5	-370.7

Source:Modified from Quiroga et al. (2022).

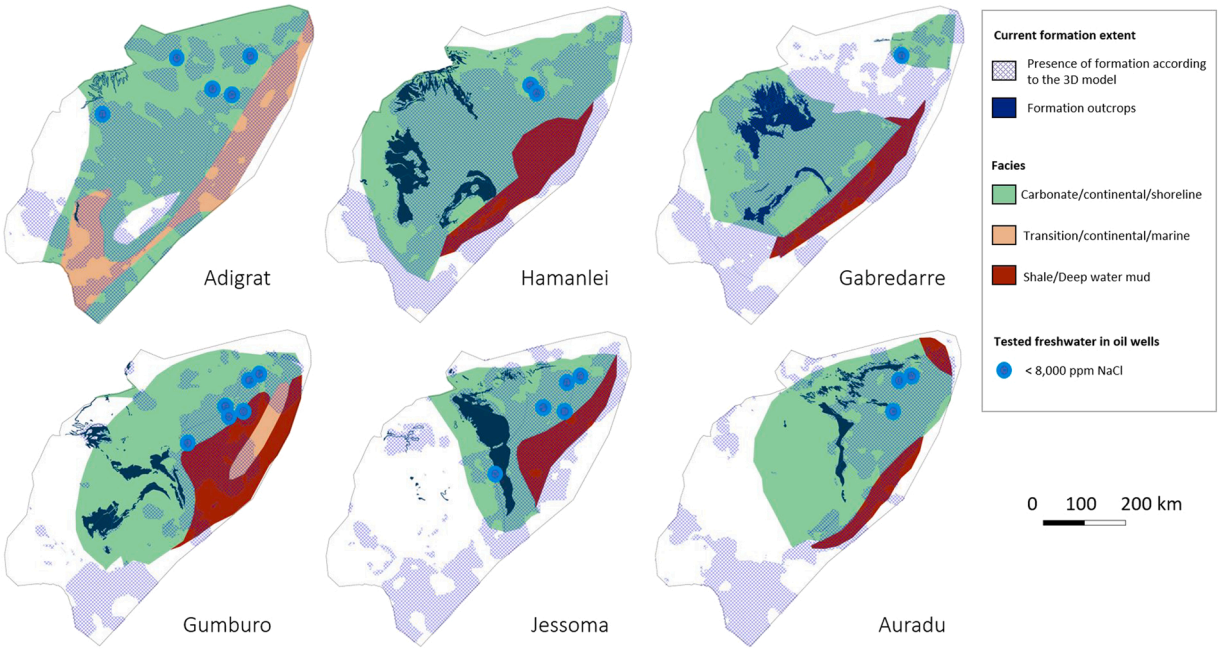


Fig. 13. Potential extent of the formations with indications of freshwater. See Appendix H for full-scale figures for all the potential aquifers.

5. Discussion

5.1. Aquifer potential of the hydrostratigraphic units

The results of this study show that amongst the 13 geological units analysed regionally, six are potential aquifers (Adigrat, Hamanlei, Gabredarre, Gumburo, Jessoma, Auradu) (Appendix H) and three are potential aquitards (Taleh, Main Gypsum and Uarandab) (Fig. 1). However, lateral lithology variability in certain units, such as the Main Gypsum, might determine local changes to this regional hydrostratigraphic setting, and should be addressed on a case-by-case basis.

The regional geological model presented in this study can be used as the initial input for groundwater simulations to understand the flow and pressure conditions at the boundaries of the more localized hydrogeological models, and to select relevant focus areas. In the Horn of Africa, the basement outcrops extensively in the highlands of Ethiopia, where it is overlain by permeable carbonate formations. This study confirms that this specific geological setting is especially suitable for deep groundwater storage and flow towards the east coast. The high potential for deep ($>$ 400 m) freshwater has been demonstrated by a combination of low salinity water observations, favorable physical properties and the extent of aquifers at considerable distance (several 100 s of kilometers) from the recharge areas. The depth of recorded freshwater occurrences can be significant and reaches up to $>$ 2000 m TVD for values of $<$ 5 g/l NaCl (Quiroga, 2020; Quiroga et al., 2022). However, the regional extent of the aquifers as shown in the results of this study can provide a possible range of depths at various locations, which can be explored in the context of other factors such as local water demand vs supply, and socio-economical and political considerations, to define the exploitability of deep groundwater in a defined region.

The geological model shows regionally consistent good aquifer properties, with high permeability and porosity values in the Jessoma and Auradu units. Lower values and less favorable aquifer properties were recorded for the Adigrat and Gumburo units. However, currently, the information available is more limited for deeper units, such as Adigrat and Gumburo. If available, further data on permeability and secondary porosity across the entire model could help determine the groundwater travel time and its preferential pathways, and possibly more favorable physical property distribution for the deeper units. Currently, data from the O&G wells drilled in the region is only partly published and available. If additional information is added to the model, it can be used to provide further insights and help develop a complete hydrogeological model for the Horn of Africa region.

The data collected in this study also suggest the potential relevance of structural features such as faults, to either facilitate or limit the flow of groundwater at depth, by putting aquifers in juxtaposition or by compartmentalising them. Furthermore, the extensive presence of carbonate formations points to karst development as a potential important feature for the creation of permeability and groundwater flow regionally (Ruden, 2017). A thorough analysis of the timing of faults versus the age of sediments, and of the degree and type of karstification of the units, will be instrumental to understand the role of these two factors in facilitating vertical connection between aquifers. If there is vertical communication between the aquitards and aquifers, the high sulfate content (SO4-) of gypsum and anhydrite rocks from the aquitards (such as the Main Gypsum and Taleh units) could contaminate the underlying formations, which further study will have to establish through the geochemical analysis of water samples from the deep aquifers.

5.2. Limitations to the model and way forward

Constructing a 3D geological model from data of the public domain in such a vast area, where deep hydrogeology is sparsely documented, has limitations due to the use of information from heterogeneous sources, which are different in terms of coverage, scales and accuracy. Even though a data quality assessment was performed in this study (Appendix E2), it only refers to the amount of data available for this study, and it is inevitable that there is a large variation in the reliability of the cross-sections and of the mapped geological units. The main factor behind the uncertainty in data analysis is the heterogeneity of interpretations published by several sources, given the fact that not all authors have access to the same data. Some interpretations used extrapolation and interpolation methods with limited source information. For example, in the case of the Lamu Basin, a difference of more than 2000 m is observed for the top of the Basement formation between two different sources (Piccoli et al., 1986; Schunemann, 1984). This produces uncertainty in stratigraphic correlations, and in the definition of physical properties derived from interdisciplinary sources. As another example, the differences between O&G and hydrogeological methods used to calculate hydraulic heads from O&G pressure tests carry an implicit uncertainty related to the density and viscosity of the water and should be addressed if any more exact data are needed in the planning stage for any drilling activities.

The spatial distribution of equivalent hydraulic heads, assuming a homogeneous aquifer with water of uniform density, can provide information on the regional groundwater flow paths, which in turn could be used to calibrate the groundwater flow modelling in future work. However, in the case of a variable-density formation water environment, representing the flow of the water with hydraulic heads can be challenging, and other factors should be considered, such as: aquifer geometry, pressure, temperature and salinity, the buoyancy component, porosity, and permeability (Bachu, 1995; Bachu and Michael, 2002; Davies, 1987; Jorgensen et al., 1982; Lusczynski, 1961; Oberlander, 1989; Post et al., 2007).

To provide further refinement to the 3D geological model, future work should include:

- The quantification of uncertainty, and definition of acceptable error ranges by means of statistical analysis. This is particularly relevant if the data points constitute a significant statistical sample;
- The improvement of the compatibility of surfaces made in Petrel with the hydrological modelling software. ModFlow was chosen in this current study, but as this software is not able to handle eroded or pinching-out formations, the geological units are currently modelled as continuous surfaces, with zero thickness when absent, which is not ideal as it may not represent the actual geology;
- The estimation of daily water recharge and its geospatial distribution to assess the sustainability of the system, in terms of extraction;
- The integration of water chemistry composition and aquifer properties into the model, to identify preferential groundwater flow paths and travel time;
- The construction of more localized geological models (e.g. for each basin), with the definition of the boundary conditions and the initial conceptual model based on the results of the current regional groundwater modelling;
- The implementation of a conceptual model which includes the vertical structure of the aquifers (hydrostratigraphic sections), proposing different case scenarios that could meet the actual boundary conditions.

Additionally, identifying new sources of water in arid and semi-arid countries characterized by extreme poverty requires cross-sectoral approaches. The use of existing data and technology from the O&G industry for the characterization of deeper aquifers can now be considered a potential solution next to the more conventional approaches such as water harvesting, desalination, and shallow groundwater. However, a thorough cost-benefit analysis and feasibility of different solutions need to be considered when planning for the exploration and exploitation of these resources.

6. Conclusions

This study illustrates the ability of defining a 3D geological model entirely based on published and open access data, in vast and logistically challenging territories of the East African regions struck by water scarcity. Furthermore, it paves the way to other regional hydrogeological studies where an interdisciplinary approach can provide new input data to models, and improve their calibration.

The new 3D geological model of the Horn of Africa shows the full extent of a series of units that potentially host deep aquifers in the region. After reviewing 152 documents of public domain, the regional geological model was constructed based on 38 cross-sections, unpublished reports, formation tops from 63 oil wells, and open access geological maps. The lithology variations with depth, the facies maps of the Horn of Africa, and the 3D model were used to define the vertical structure of the aquifers and to build a first regional deep hydrostratigraphic model.

Importantly, the workflow used is cross-disciplinary, integrating hydrogeological data with public domain data from O&G exploration studies. The differences in file formats, stratigraphic units and measurements collected in the two disciplines have been overcome with a workaround to combine O&G with hydrogeology software. The results from this study can be used to build a full hydrogeological model of the region, and ground-truth it with the collected evidence for deep freshwater in deep wells previously drilled by the O&G industry, and with the values of hydraulic heads calculated from their pressure tests.

Aquifer properties such as porosity, permeability and pressure were transferred from the hydrocarbon context and used in the hydrogeology context with due considerations. Due to the deeper reach compared to conventional hydrogeological data (geophysical and wells); it is important to note that hydrocarbon exploration data is irreplaceable in the identification of deep aquifers.

Based on the cross-correlation of the mapped hydrostratigraphic units with the observed regional freshwater indications, six

regional units were identified as potential aquifers: Adigrat, Hamanlei, Gabredarre, Gumburo, Jessoma, Auradu. Of these units, while the most recent and shallowest, i.e., Auradu and Jessoma (Cretaceous to Paleocene) have been previously recognised as regional or local aquifers, the oldest ones, i.e., Adigrat, Hamanlei, Gabredarre and Gumburo (Jurassic to Cretaceous) are here reported for the first time as potential deep aquifers. The recommended use of the maps is twofold: 1) for water resources exploitation, only in areas close to the O&G wells with indications of freshwater, 2) for the definition of larger potential prospecting areas, in areas far from oil wells control, by re-gridding and adding new data.

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CRediT authorship contribution statement

Elizabeth Quiroga: Conceptualization, Data curation, Methodology, Project administration, Formal analysis, Writing, Visualization. **Claudia Bertoni:** Conceptualization, Investigation, Formal analysis, Writing. **Manon van Goethem:** Writing, Visualization, Data curation. **Lara Antonia Blazevic:** Investigation, Formal analysis, Writing. **Fridtjov Ruden:** Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101166.

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