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Research paper

Hydrogeological conceptual model of Stampriet transboundary aquifer system in Southern Africa

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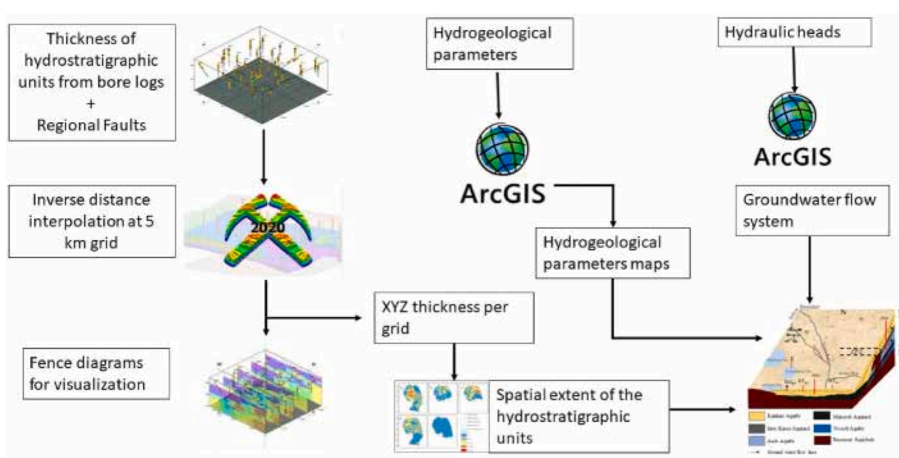
HIGHLIGHTS

- A hydrostratigraphic synthesis and 3D geological modelling enable a better definition of the STAS.
- A fourth aquifer (Dwyka) was added to the STAS.
- 42% increase of the size of STAS compared previous study.
- STAS and CKB are sub-basins of the same regional basin (Kalahari Karoo Basin).
- Faults and dolerite intrusions strongly influence aquifers geometry and groundwater flow.

GRAPHICAL ABSTRACT



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ABSTRACT

Stampriet Transboundary Aquifer System (STAS) is shared between Botswana, Namibia and South Africa with massive utilization especially in Namibia. However, the understanding of the comprehensive hydrogeological framework of the aquifer system is limited. This study aimed to develop a comprehensive hydrogeological conceptual model of the aquifer system which mainly entailed 3D hydrostratigraphic modelling using Rockworks 3D geological modelling software, analysis of regional groundwater occurrence and flow system, sources and sinks, hydraulic parameters and definition of STAS boundaries. Six hydrostratigraphic units composed of four aquifers, including a new one (the Dwyka), and two aquitards were identified. Analysis of the regional groundwater flow system revealed that groundwater flows in two directions, indicating presence of a regional

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groundwater divide. 3D hydrostratigraphic geometry revealed that groundwater flow in STAS is influenced by topography but also by faults such as the Zoetfontein Fault, which displaces the pre-Kalahari rocks vertically creating a barrier to groundwater flow. Hydrostratigraphic and 3D geometry work also led to a 42% increase of the size of STAS compared to the boundary initially delineated by UNESCO. The proposed hydrogeological conceptual model forms a basis for development of numerical integrated hydrological model to simulate surface-groundwater interactions, regional groundwater flow and aquifer development potential.

1. Introduction

Groundwater is the main water resource in arid and semi-arid areas where often surface water is scarce or polluted. Understanding aquifer replenishments, groundwater flow dynamics and the impact of exploitation of groundwater resources is thus vital for groundwater management. These processes are usually evaluated through numerical models that include all features characterizing the system (Anderson et al., 2015). However, the ability of numerical models to reproduce these processes to evaluate possible utilization of management scenarios is highly dependent on reliability and accuracy of a hydrogeological conceptual model (HCM). An HCM is a synthesis of what is known about the area of interest (Krešić and Alex, 2012) and provides a systematic overview of the hydrogeological system, properties and dominant processes relevant to the modelling objective. For quantitative groundwater assessment, an HCM may include information on hydrostratigraphy and spatial variability of hydraulic properties; groundwater flow pattern and direction, sources and sinks; boundary conditions; and field based water budget components (Anderson et al., 2015).

An HCM bridges the gap between hydrogeological characterization and groundwater modelling and is a major source of uncertainty in numerical modelling (Anderson et al., 2015; Gupta et al., 2012; Krešić and Alex, 2012). Conceptual model uncertainty arises from incorrect hydrogeological characterization due to data inadequacy and insufficient knowledge of a groundwater system (Enemark et al., 2019; Gupta et al., 2012). Propagation of that uncertainty into the numerical modelling may lead to biased parameter estimation through calibration, hence uncertainty in model predictions (e.g. simulated heads and flow) (Doherty and Welter, 2010; Ye et al., 2010). However, since a groundwater model is a simplification of reality, it is not possible to represent all hydrogeologic features, heterogeneities in subsurface properties and groundwater processes. All HCMs, so also numerical models, are therefore characterized by a certain level of uncertainty, which can only be reduced, but never eliminated (Anderson et al., 2015). The conceptual model uncertainty can be reduced either through a systematic integration of multi-source data that characterizes the system in question or by adopting the multi-model approach where alternative conceptualizations are developed and tested through the modelling process in parallel rather than sequentially (Enemark et al., 2019).

Development of an HCM typically entails the integration of surface and subsurface information such as topographic, geological, hydrometeorological, geomorphological, and hydrochemistry data. This is mostly done with an aid of geospatial analysis tools such as Geographical Information System (GIS), a combination of GIS and 3D geological modelling software or hydrogeological conceptualization tools built-in numerical modelling environments such as Groundwater Modelling System (GMS) (AQUAVEO, 2023) as used, for instance, by Gurwin and Lubczynski (2005), Vijai Singhal (2011) and Tam et al. (2014) among others. 3D hydrostratigraphic modelling in a standard GIS environment (e.g. ArcGIS) is based on definition of lithological classes and extrapolating these data from boreholes. However, while this approach provides some basic two-dimensional and three-dimensional visualization functions, there are many deficiencies in the ability to display and analyze complex multi-source spatial data especially in areas with high heterogeneity (Tam et al., 2014).

An alternative solution can be achieved by combining 3D geological modelling software such as Rockworks (2020) with standard GIS as used by Lekula et al. (2018), Shishaye et al. (2020a, 2020b) and Zahran (2020), to mention a few. Lekula et al. (2018) noted that 3D modelling software such as Rockworks are easier to use and require less time to learn while offering comparable capability to GMS. 3D geological modelling enables reliable delineation of the hydrostratigraphic framework to ensure reliable predictions of groundwater flow. 3D geometry also provides insights into the variability of the volume of each hydrostratigraphic unit, which in turn can be useful to estimate the available groundwater development potential (Shishaye et al., 2020a, 2020b). Rockworks also offers capability for exportation of results into ArcGIS for visualization and usage in subsequent numerical model. Some of the other 3D geological modelling software commonly applied in hydrogeological studies include Geomodeller (2023), GOCAD (2023), EarthVision (2023), GSI3D (2012) and Petrel (2023), to mention a few.

Stampriet Transboundary Aquifer System (STAS), the focus of this study, is a multi-layered sedimentary aquifer system shared between Namibia, Botswana and South Africa. It is a major source of groundwater, particularly in Namibia where it is predominantly used for irrigation, domestic use and livestock watering, and is a key component of human and economic development in the region (ORASECOM, 2007). A few local consultancy studies have been conducted in various parts of STAS (Fig. 2) including JICA (2002), who conducted a detailed groundwater resources assessment in the western part of the STAS (Aranos sub-basin) in Namibia. Stone and Edmunds (2012) estimated groundwater recharge rates using the chloride mass balance method for the same spatial extent as JICA (2002). They estimated a long-term average direct rainfall recharge rate, ranging from 7 $mm.y^{-1}$ to 46 $mm.y^{-1}$. WRC (2008) conducted a study in the north eastern part of the STAS in Botswana to assess the aquifers' potential to provide sufficient portable water for supply to villages in the region, referred to as the Matsheng Villages project, and to locate suitable areas to site boreholes for monitoring, exploration and production purposes; they found that Ecca Aquifer was most productive in this region. A number of studies have also been conducted in the south-eastern part of STAS to identify zones of greatest potential suitable for livestock and domestic use in the Bokspits and Middlepits Tribal Grazing Land Policy (TGLP) Ranch Blocks (DGS, 2000, 1994a; ORASECOM, 2022). They found that the Auob Aquifer had the highest potential but its utilization was limited by groundwater salinity. Four desalination plants have since then been installed in the region to mitigate shortage of water for domestic use and livestock watering (ORASECOM, 2022). Other studies include Peck (2009), Kamundu et al. (2019) and Kisendi (2016) who developed conceptual and numerical models for Aranos, Auob and upper SW Botswana sub-basins respectively.

The above-listed studies provide only local understanding of groundwater occurrence and flow system and do not take into consideration the transboundary nature of the aquifer system. Also, while the geology and hydrogeology of the aquifer system is comparatively well understood in Namibia, where it is referred to as Stampriet Artesian Basin, it is not well known in Botswana and South Africa. UNESCO (2016) made an attempt to delineate the boundary of STAS based on the occurrence of geological formations belonging to the ECCA Group within Auob and Nossob drainage basins which was later extended 'arbitrarily' eastwards into Botswana by UNESCO (2017a) (Fig. 2). However, based on the map of the distribution of Karoo sedimentary basins in Southern Africa (Fig. 1), as well as on the compiled in this study geological map (Fig. 3), it is possible that the aquifer system extends beyond this boundary. It is therefore important to integrate data from all the previous studies in order to give a better understanding of regional groundwater occurrence and flow in the STAS, as well as to establish links with the neighbouring regional hydrogeological study of Central Kalahari Basin (CKB) (Lekula et al., 2018).

This study, therefore, aims to develop a hydrogeological conceptual model of the whole of STAS through a systematic integration of multi-source data and 3D geological modelling. Specifically, this study aims to (1) assess the spatial distribution and geometry of the hydrostratigraphic units; (2) improve understanding of regional groundwater flow system, sources and sinks, boundaries and interaction between different hydro-stratigraphic units; and (3) define the spatial extent of STAS and propose a new boundary building on the study by UNESCO (2016).

This STAS study is part of Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) international project implemented by UNESCO International Hydrological Programme (UNESCO-IHP), which is aimed at gaining experience in Governance of Groundwater Resources in Transboundary Aquifers. GGRETA has three pilot studies of Transboundary Aquifer (TBA) systems: the Trifinio aquifer in Central America, the Stampriet aquifer system in Southern Africa and the Pretashkent aquifer system in Central Asia. As part of the GGRETA project, UNESCO and local stakeholders have been promoting the development of a groundwater model for the assessment and the sustainable management of the STAS (Kenabatho et al., 2021; Leblanc et al., 2021; UNESCO, 2016). In this paper, a new conceptual hydrogeological model of the STAS is proposed, which finally will be converted into numerical model in a further study.

2. Geographical, geological and hydrogeological setting of the study area

2.1. Geographical and hydrological setting of the study area

The aquifer system stretches from central Namibia into western Botswana and South Africa's Nothern Cape Province and is part of the hydrogeological Kalahari Karoo Basin (KKB). Since one of the objectives of this study was to determine the spatial extent of STAS, the study area consists of the whole Kalahari Karoo sedimentary basin, with more focus on the Aranos, South-West Botswana and Kalahari Gemsbok sub-basins (Fig. 1). The topography of the area is gently sloping with an elevation of 1500 m–750 m above mean sea level sloping from the northwest to the south (Fig. 2).

Hydrologically, STAS is part of Orange Senqu transboundary surface water basin. The drainage courses in the area include Auob and Nossob dry river valleys, which originate in the Anas Mountains near Windhoek, Namibia and extend to the south-east, joining at the southern tip of Kgalagadi Transfontier Park (KTP) and continue on as the Nossob River, which then joins the Molopo and Kuruman rivers at Bokspit (Fig. 2). The Auob and Nossob are both predominantly dry, only flowing short periods during abnormally high rainfall events and their flow dissipates within a short distance from the source (ORASECOM, 2009a, 2007; Spies, 2016). Both rivers remain an indication of a wetter era and are often referred to as fossil rivers (Spies, 2016). South of their junction, the Nossob River continues to the confluence with the Molopo and Kuruman Rivers at Bokspit (Fig. 2) and then continue south as Molopo River to join Orange River. There also exists large shallow endorheic depressions or pans, especially south of Molopo River and Kuruman Rivers, which

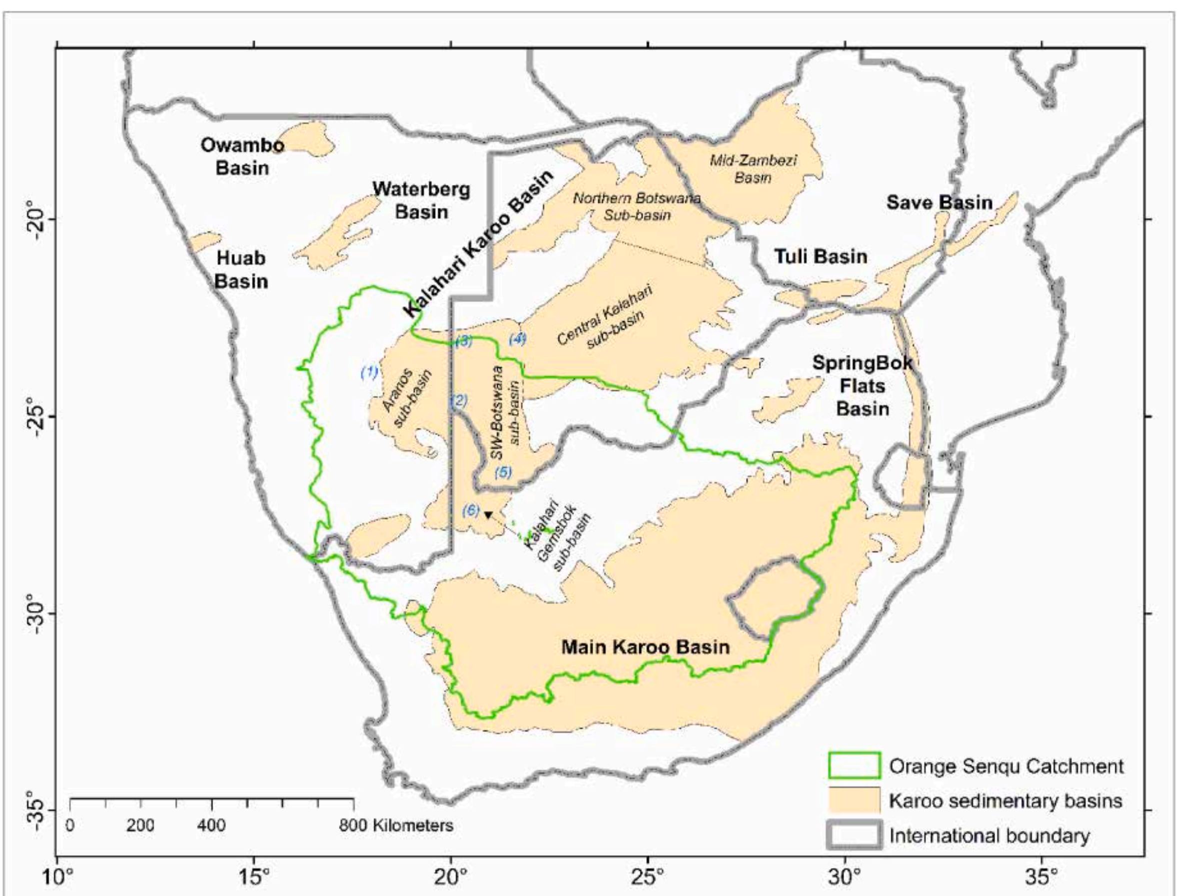

Fig. 1. Distribution of Karoo sedimentary basins in Southern Africa (after Johnson et al. (1996). The numbers indicate stratigraphy of the regions described in Table 1.

hold water periodically during wet seasons (Chiloane et al., 2020; Spies, 2016). As these rivers are generally dry and overlie the thick, unsaturated Kalahari sand, there is limited surface water-groundwater interaction in the STAS.

Rainfall in STAS normally occurs between October and April predominantly in form of thunderstorms (high intensity and short duration) and ranges between 150 and 250 mm/year (UNESCO, 2016). The highest rainfall months are from January to March whilst the lowest, are from June to September. The majority of the study area is covered by savannah grassland, sparse shrubs and acacia trees. Several species of Alien prosopis trees *(Prosopis* spp*)* including *Prosopis chilensis, Prosopis velutina, Prosopis juliflora, Prosopis glandulosa,* as well as their hybrids occur along Auob and Nossob Rivers (Strohbach et al., 2015; UNESCO, 2016) and south-eastern part of the study area around Bokspit (Mosweu et al., 2013; Muzila et al., 2011).

2.2. Geology and groundwater occurrence

The stratigraphy of STAS consists of Karoo Super Group, with its associated intrusions of dolerite, underlain by Pre-Karoo rocks and covered by a layer of Tertiary and Quaternary Kalahari sands. The pre-Kalahari geology of the study area is shown in Fig. 3 as compiled from various geology maps (JICA, 2002; Johnson and Wolmarans, 2016; Key and Ayres, 2000; Miller et al., 2008; ORASECOM, 2009b; Rose and Van Wyk, 2006; van Wyk, 1987a, 1987b)

2.2.1. Pre-Karoo group

The study area is bounded by Pre-Karoo rocks consisting of Nama and Damara Sequence to the west and south (JICA, 2002; Miller et al., 2008), Ghanzi Group to the north (Aldiss and Carney, 1992; Carney et al., 1994); and Olifantshoek Group to the south-east margin (Carney et al., 1994; Key et al., 1998), which also form the basement of the basin.

2.2.2. The Karoo super group

The Karoo Supergroup is an extensive volcano-sedimentary sequence that spans most of Southern Africa (Fig. 1), deposited in the Paleozoic (Carboniferous to Cretaceous) era (Johnson et al., 1996; SACS, 1980; Smith et al., 1984). The Karoo Supergroup in Southern Africa occurs in the Main Karoo Basin in South Africa, Kalahari Karoo Basin as well as a number of minor basins in South Africa, Namibia, Botswana, Zimbabwe, and Mozambique (Fig. 1), with the various basins being separated from one another by zones of non-deposition and of erosion (Catuneanu et al., 2005). The lithostratigraphy of Karoo Supergroup is subdivided into groups, formations and members based on general sedimentological traits. Different lithostratigraphic nomenclature is adopted in various Karoo basins and sub-basins. Johnson et al. (1996) compiled various stratigraphical classifications in each of the Karoo basins and correlated the lithostratigraphies in various basins to each other with the groups established in the main Karoo Basin in South Africa as the reference. Table 1 attempts to integrate the stratigraphy and hydrostratigraphy of Aranos, Kalahari Gemsbok and South-West Botswana sub-basins, while description of each group is given in the subsequent sections.

2.2.2.1. Dwyka group. The Dwyka Group consisting of Malogong and Khuis Formations was deposited in the late Carboniferous to the early Permian period and forms the base of the Karoo Supergroup (JICA, 2002; Key et al., 1998; Smith et al., 1984; Thomas et al., 1988). In Namibia and Botswana, Dwyka Group does not constitute an important aquifer within the study area and serves as an impermeable layer, except from the south-eastern area north of Molopo where they supply Gakhibane village (DGS, 1994b, 1994a; ORASECOM, 2009b). However, in South Africa, the Dwyka formation is classified as a fractured aquifer

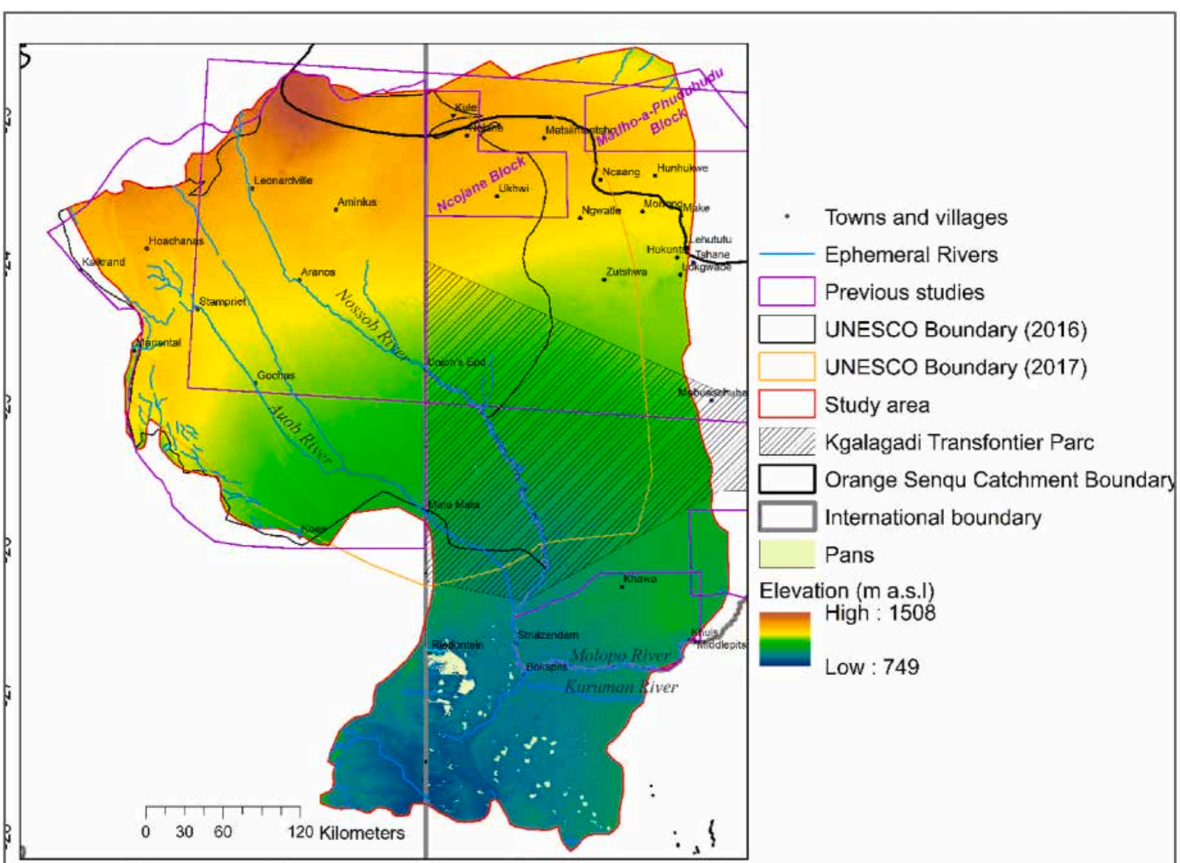

Fig. 2. Topography and hydrology of the study area and location of the studies conducted previously

and forms an important source of water to villages through spring intakes and production boreholes (Levin, 1980; ORASECOM, 2009b; Rose and Van Wyk, 2006).

2.2.2.2. Ecca Group. Ecca group overlies the Dwyka Group and its thickness increases eastwards with a reported thickness of over 380 m in the north-eastern part of the study area at Mashelheng Pan (Stoakes and McMaster, 1990) as cited by Key et al. (1998). In the Aranos sub-basin in Namibia and Kalahari Gemsbok in South Africa, the Ecca Group is subdivided from bottom to top into Nossob, Mukorob and Auob Members consisting mainly of siltstone, shale, and sandstone intercalated with coal bearing shales respectively (JICA, 2002; Zieger et al., 2021). Nossob, Mukorob and Auob Members correspond to Lower Kobe (Ncojane Sandstone), Upper Kobe and Otshe Formations of the South-West Botswana Sub-basin (Fig. 1) respectively, following Smith et al. (1984) nomenclature.

2.2.2.3. Rietmond Member. Within the study area, the Rietmond Member, consisting mainly of shales, occurs only in the Aranos sub-basin where it overlies the Auob Member. While WRC (2008) correlated the Rietmond Member to the Kule Formation of South West Botswana, according to Johnson et al. (1996), they are different formations with the Rietmond Member forming the upper part of the Prince Albert Formation (JICA, 2002; van Wyk, 1987b).

2.2.2.4. Beaufort Group. The Beaufort Group overlies the Otshe Formation in the north eastern part of the study area with a region of limited extent in the south (Fig. 3) which could be due to erosion at the end of the Beaufort times and after eruption of the Karoo Basalts (Key et al., 1998). It consists mainly of non-carbonaceous mudstone and is considered as an aquitard (WRC, 2008).

2.2.2.5. Lebung Group. The Lebung Group lies on top of the Beaufort Group in the north-eastern part of the study area and extends into Central Kalahari Basin (CKB). It is composed of Dondong and Nakalatlou Formations (WRC, 2008) which consist mainly of reddish-brown mudstone and reddish fine to medium grained sandstone, respectively.

2.2.2.6. Karoo Basalts. The Basalt lava forms the uppermost volcanic member of the Karoo Super Group. It consists of stacked basalt flows and is completely absent in most of the study area except of the north-western and north-eastern parts (Fig. 3). In the Aranos sub-basin it is referred to as the Kalkrand Basalt where JICA (2002) reported a thickness of up to 370 m, and is equivalent to the Stomberg Basalts of the Central Kalahari Basin (Lekula et al., 2018; WRC, 2008). The Kalkrand Basalts are well developed, and most water boreholes dug in this area encountered water inside the formation (JICA, 2002).

2.2.3. Post-Karoo geology

2.2.3.1. Dolerite sills. Post Karoo dolerite dykes and sills intrude the Karoo sequence, mostly favouring the Ecca-Rietmond and Ecca-Beaufort

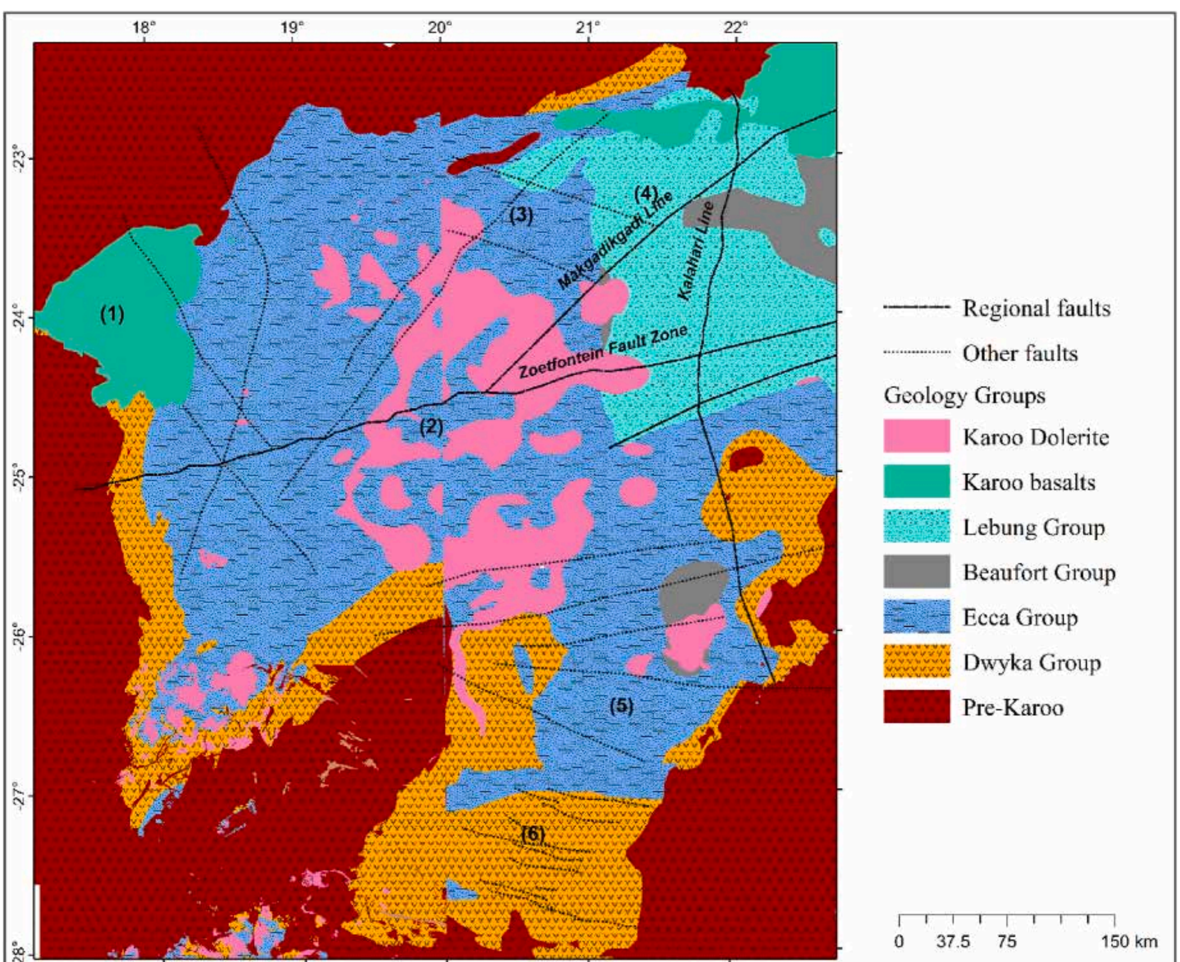

Fig. 3. Simplified Pre-Kalahari geology of STAS (Data sources: Namibia (JICA, 2002; Miller et al., 2008), Botswana (Key and Ayres, 2000) and South Africa (Johnson and Wolmarans, 2016; ORASECOM, 2009b; van Wyk, 1987b). The numbers indicate stratigraphy of the regions described in Table 1.

Table 1
Stratigraphy and hydrostratigraphy of the study area modified after (Johnson et al., 1996) Smith et al. (1984); JICA (2002); WRC (2008); UNESCO (2016).

Description / Period	Super Group	Group	Region: Kalkrand (1)	Ncojane (2)	Matlho-a-Phuduhudu (3)	Union's End (4)	Bokspit (5)	South of Kuruman River (6)	Hydrostratigraphic unit
Tertiary to Quaternary	Post Karoo	Kalahari	Kalahari group						Kalahari Aquifer
Cretaceous to Jurassic	Upper Karoo	Karoo Basalts	Kalkrand Basalts						Kalkrand Aquifer
Triassic		Lebung	Rietmond Member		Ntane Sandstone				Lebung Aquifer
				Dondong Formation					Inter Karoo Aquitard
Permian	Lower Karoo	Beaufort		Kule Formation					
		Rietmond							
		Ecca	Auob Member	Otshe Formation		Auob Member			Aoub Aquifer
			Mukorob Member	Upper Kobe Formation		Mukorob Member			Mukorob Aquitard
			Nossob Member	Ncojane Sandstone		Nossob Member			Nossob Aquifer
Mesoproterozoic		Dwyka	Dwyka	Khuis Formation			Khuis Formation		Dwyka Aquifer
				Malagong Formation			Malogong Formation		
Archaean	Pre-Karoo		Nama and Damara	Okwa Complex		Nama	Olifantshoek		Basement Aquiclude

Group contact and in places cut out the whole of the Rietmond Member and part of the Auob Member (JICA, 2002; ORASECOM, 2007).

2.2.3.2. Kalahari Group. Post-Karoo superficial deposits of the Kalahari Group cover the whole of the study area. From the bottom, it comprises: clayey gravel (Wessels Formation) and red to brown calcareous clay (Budin Formation); sandstone probably formed from Karoo Sequence; grit and conglomerate (Eden Formation) deposited under fluviatile conditions; calcrete (Mokalanen Formation) and sand (Gordonia Formation); clayey diatomaceous limestone (Lonely Formation) deposited in a lacustrine environment; and clay and sand (Goeboe Goeboe Formation) found in pans and rivers (Malherbe, 1984; Smith et al., 1984; Thomas et al., 1988).

2.3. Geological structures

Geological features, including faults, lineaments and dolerite sills have been defined in the STAS in previous studies through aeromagnetic, seismic and gravity data interpretation as well as through borehole analysis (Corner and Durrheim, 2018; JICA, 2002; WRC, 2008). The main features include the NE-SW trending Makgadikgadi Line; the east-west trending Zoetfontein Fault; and the north-south trending Kalahari Line (Aldiss and Carney, 1992; Key and Ayres, 2000) (Fig. 3). All the faults were digitised from Corner and Durrheim (2018).

3. Methods

Data collected by UNESCO-IHP through the GGRETA project (UNESCO, 2016) was used in this study. This data includes borehole logs, geological maps and hydrogeological reports done by government agencies and private consultants from the member countries. The SRTM 30 m digital elevation model obtained from https://earthexplorer.usgs.gov/was used to define the topography. To establish the link between STAS and CKB, the hydrogeological data of the CKB was obtained from Lekula et al. (2018).

3.1. Harmonization of the hydrostratigraphy across the basin and hydrogeological characterization

Different nomenclature in different literature sources is used to describe geology in various sub-basins of STAS. For instance, the nomenclature adopted in the SW Botswana sub-basin follows Smith et al. (1984) while in Aranos and Kalahari Gemsbok in South Africa (Fig. 1), by SACS (1980). It was therefore important to harmonize the nomenclature and definition of the hydrostratigraphic units across the basin. This process involved an identification of the lithology in every borehole log and a subsequent classification into the appropriate hydrostratigraphic units. A total of 431 boreholes were used.

3.2. 3D modelling of hydrostratigraphic units

After verification and classification of lithologic units into respective hydrostratigraphic units, the borehole data which included XY coordinates, depth, elevation and thickness of each hydrostratigraphic unit and also XY coordinates representing the location of the regional structures (Makgadikgadi Line, Kalahari Line and Zoetfontein Fault Zone) was imported into Rockworks (2020) for interpolation. Both, kriging with the automatic variography offered by Rockworks and inverse distance weighting (IDW) with power two interpolation methods, were tested. In contrast to the findings of Bamisaiye (2018), the inverse distance weighting was found to give a better correlation with existing geological records for the study area as also reported by Lekula et al. (2018). A grid spacing of 5 km was used and a 3-D hydrostratigraphic model was generated through 3D interpolation iteratively until satisfactory results were obtained. That model was used to generate other outputs including 2-D cross-sections along selected transects across the study area. For visualization of the model layers and subsequent use in the numerical model, 3-D data points detailing thickness of each hydrostratigraphic unit were exported from Rockworks as XYZ files, then imported and interpolated in ArcGIS to produce spatial extent of each unit. This enabled estimation of the geometry and thickness of each hydrostratigraphic unit.

3.3. Regional groundwater flowpaths and boundary conditions

To determine the groundwater flow system in STAS, water level data was obtained from various consultancy reports including JICA (2002), WRC (2008), DGS (1994b) and ORASECOM (2022) for Namibia and Botswana while for the South African STAS area, the data was requested and downloaded from https://www.dws.gov.za/groundwater/NGA.aspx, which is the national groundwater archive.

For each aquifer, the water levels were converted to hydraulic heads and interpolated in ArcGIS using the IDW method with power two. Potentiometric maps were then derived from the interpolated heads to get the flow direction for each aquifer. Hydrogeological boundary conditions were defined by, first examining the spatial extents of each aquifer trying to identify physical boundaries, followed by the regional potentiometric maps, to deduce the regional flow system. Where no physical boundaries exist along the margin of the study area, the external boundary conditions were defined along marginal streamlines defined as perpendicular to the potentiometric lines. Potential interaction between aquifers was assessed by analysing their corresponding heads in respect to each other.

3.4. Estimation of aquifer hydraulic properties

STAS aquifer transmissivity and storage coefficient data were extracted from 58 pumping tests (8 for Kalahari, 43 for Auob and 7 for Nossob) documented in groundwater consultancy reports (JICA, 2002; WRC, 2008). However, this data was deemed insufficient to represent the hydraulic parameters of the whole of STAS especially for the Kalahari and Nossob aquifers. Therefore, ranges of values were obtained from the literature based on lithological units which will be optimised through zonation in the numerical model in further research.

3.5. Sources and sinks

The groundwater input to the aquifer system is through diffuse rainfall recharge which is limited in STAS, given the thick unsaturated zone and remains difficult to quantify. Rainfall recharge, via local depression and the drainage network, is often referred as the dominant recharge process in arid areas (Wheater et al., 2010). However, it has seldom been documented and quantified in the STAS.

The groundwater output from the aquifer system is through evapotranspiration, abstraction and groundwater outflow through the north-eastern boundary. The potential recharge and discharge areas based on environmental tracer data were identified from studies conducted by JICA (2002), Kirchner et al. (2002) and Stone and Edmunds (2012) and a review by Tweed (2021) in Namibia, and Levin (1980),Verhagen (1983),Toens and Partners (1997) as reviewed by Rose and Van Wyk (2006) in South Africa. Groundwater abstraction estimates were derived from various reports (JICA, 2002; ORASECOM, 2022, 2009a; UNESCO, 2016; WRC, 2008), for different parts of STAS where the aquifer is utilised.

4. Results

4.1. Harmonization of the stratigraphy across the basin and hydrogeological characterization

Eight hydrostratigraphic units underlain by impermeable basement, were defined in this study; they include (counting from the top): Kalahari Aquifer, Kalkrand Basalt Aquifer, Lebung Aquifer, Inter-Karoo Aquitard, Auob Aquifer, Mukorob Aquitard, Nossob Aquifer and Dwyka Aquifer (Table 1). The Lebung Group was split into two Formations with the Nakatlalou Formation (Ntane Sandstone), which occurs only at the north-eastern tip of the study area and extends into the CKB forming the Lebung Aquifer. The Dondong Formation of Lebung Group was combined with the underlying Beaufort Group and the Rietmond Member of the Aranos sub-basin to form the Inter-Karoo Aquitard. Karoo dolerite sills were found to occur at different hydrostratigraphic units within the study area. From a hydrogeological point of view, the sills are aquitards except where they are weathered or fractured and therefore, where they occur above, in between or below the Rietmond and Beaufort formations, they were considered to be part of the Inter-Karoo Aquitard. The Ecca Group was split into Auob Aquifer, Mukorob Aquitard and Nossob Aquifer. The Dwyka Group represented by fractured aquifer (Fig. 5 E–E' and G-G'), occurs in the south.

Seven hydrostratigraphic cross-sections across the study area were generated (Figs. 4 and 5), from the 3D hydrostratigraphic model, to visualize key findings. These cross-sections enabled visualization of the geometric interrelations between the hydrostratigraphic units relative to each other, influence of geological structures on the layers and the hydrogeological relationships between the sub-basins. For instance, cross-section AA', CC', and DD' show the limited extent of the Kalkrand Basalts and Lebung Aquifers within the study area. The Inter-Karoo Aquitard and Ecca layers pinch out against the Kalkrand Basalt to the west and against the Pre-Karoo rocks to the north west and south-east as depicted by cross-sections AA' and EE' respectively. BB' shows that at the central part of the Aranos sub-basin, the Inter Karoo Aquitard has been eroded and therefore the Kalahari and Auob Aquifers are hydraulically connected. The north-south cross-section DD', which cuts across the South-West Botswana sub-basin shows the absence of the upper Karoo Formations south of the Zoetfontein Fault Zone while EE' and FF' show the absence of the Auob Aquifer in the south-western part of the study area. In that region, the Inter-Karoo Aquitard is represented only locally by the dolerite sills. Cross-section DD' shows the displacement of the Karoo Group vertically by the Zoetfontein Fault zone, while at the intersection between Zoetfontein Fault and Makgadikgadi line, the Karoo sequence is cut of completely as portrayed by cross-section GG'. That area is also characterised by presence of Karoo dolerites and sills and dykes (Fig. 3). The west-east hydrostratigraphic cross-section HH' (Fig. 5) extending from the western edge of STAS to the eastern edge of CKB was generated to establish the link between the two basins.

4.2. Regional groundwater flow pattern

As shown in Fig. 7, the general groundwater flow in the Kalkrand Basalt Aquifer (Fig. 3) is from north to south-west into the neighbouring Fish Orange Basin. This agrees with the findings of JICA (2002) who applied an outflow boundary on the southern part of the Kalkrand Basalt Aquifer. Within the Auob River sub-catchment (Fig. 2), groundwater flow is similar to surface water flow, i.e., from north-west to south-east and eventually southwards while in the Nossob River sub-catchment, groundwater flow exhibits a split into a north-eastward flow towards Central Kalahari Basin in Botswana and ultimately into Makgadikgadi Pans and south-eastward and then southward towards Orange River. The flow in the south-east of STAS, along the Molopo sub-catchment, is from the north east to south west and then southwards, similar to surface water flow system.

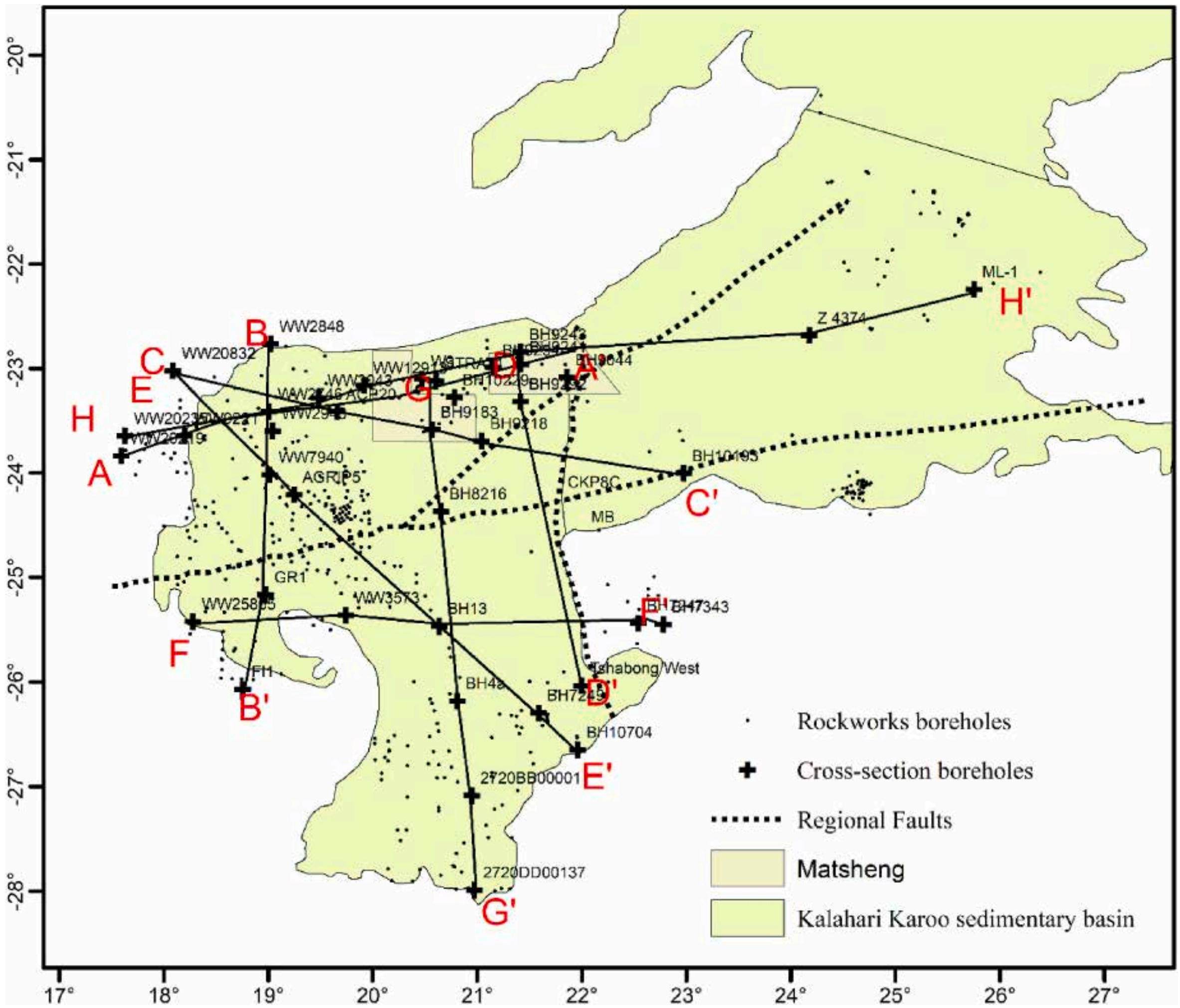

Fig. 4. Location of boreholes used to construct the 3D hydrostratigraphic model in Rockworks. Cross section boreholes are those along the transects selected for visualization of the hydrostratigraphic cross-sections presented in Fig. 5.

4.3. Hydrostratigraphic units and their geometry

Fig. 8 shows the spatial extent and thickness of the modelled hydrostratigraphic units within STAS, for each 5 km grid and the average thickness, spatial coverage and total volume of each unit is shown in Table S 1. Kalahari Aquifer is absent in the south west where the Dwyka Group outcrops and its thickness varies from less than 10 m in the north-west and south, to more than 200 m in the central part of the Aranos sub-basin (Fig. 8 a) where the Inter-Karoo Aquitard has been partially or completely eroded and the Kalahari aquifer is hydraulically connected with the Auob Aquifer (Fig. 5 BB').

Kalahari Aquifer is separated from Auob Aquifer by the underlying Inter-Karoo Aquitard which is spatially discontinuous (Fig. 5 b). Inter-Karoo Aquitard is the thickest in the north and north-east (>150 m) and it wedges into basement rocks to the south and north-west of STAS. The locations where Inter-Karoo Aquitard is missing are potential 'hydraulic windows' for the groundwater recharge from the Kalahari into the Auob Aquifer.

The Auob Aquifer constitutes the main aquifer of the STAS. Its thickness varies from 0 m in the north-west and south where it wedges out, probably due to erosion, and increases north-eastwards to >200 m (Fig. 8 c) towards CKB. Depth to the top of Auob is spatially variable and is largely determined by the deepening of the basin towards the east (Fig. 5 CC') and the reduction of the Karoo Super Group thickness southwards.

Mukorob Aquitard underlies the Auob Aquifer and is a confining unit to the underlying Nossob Aquifer. Similar to the Auob aquifer, it wedges out to the north-west and south and its thickness increases eastwards to ~180 m (Fig. 8 d). It confines the Nossob Aquifer in most of the study area, apart from a small region south of Union's End (Fig. 9 a) where the Nossob aquifer is overlain either by dolerites or Kalahari layer.

The Nossob Aquifer extends between the overlying Mukorob aquitard and underlying Dwyka Group. Similarly, to Auob and Mukorob, it wedges out to the north-west and south. It has an average thickness of ~30 m (Fig. 8 e), although that estimate is not precise, as not many boreholes reach and pass through the Nossob Aquifer and for the same reason, its spatial extent to the north-east is uncertain.

The Dwyka Aquifer which is part of Dwyka Group, underlies the Nossob Aquifer in the south and its thickness increases from ~50 m in the west to more than 500 m in the east (Fig. 8 f).

4.4. New boundary of STAS and proposed boundary conditions

Based on the hydrostratigraphy and the general groundwater flow system, a new boundary of STAS is proposed. It consists of the Aranos, South-West Botswana and Kalahari Gemsbok sub-basins of KKB (Fig. 1) with slight modifications. To the north-west at Kalkrand Basalt (Fig. 3), the boundary was adjusted along the groundwater divide (Fig. 7), to exclude areas where the flow is towards the Fish-Orange River sub-catchment located south of STAS, which excluded the Kalkrand Aquifer initially considered to be part of STAS by JICA (2002) and UNESCO (2016). The boundary to the north-east in Botswana, was

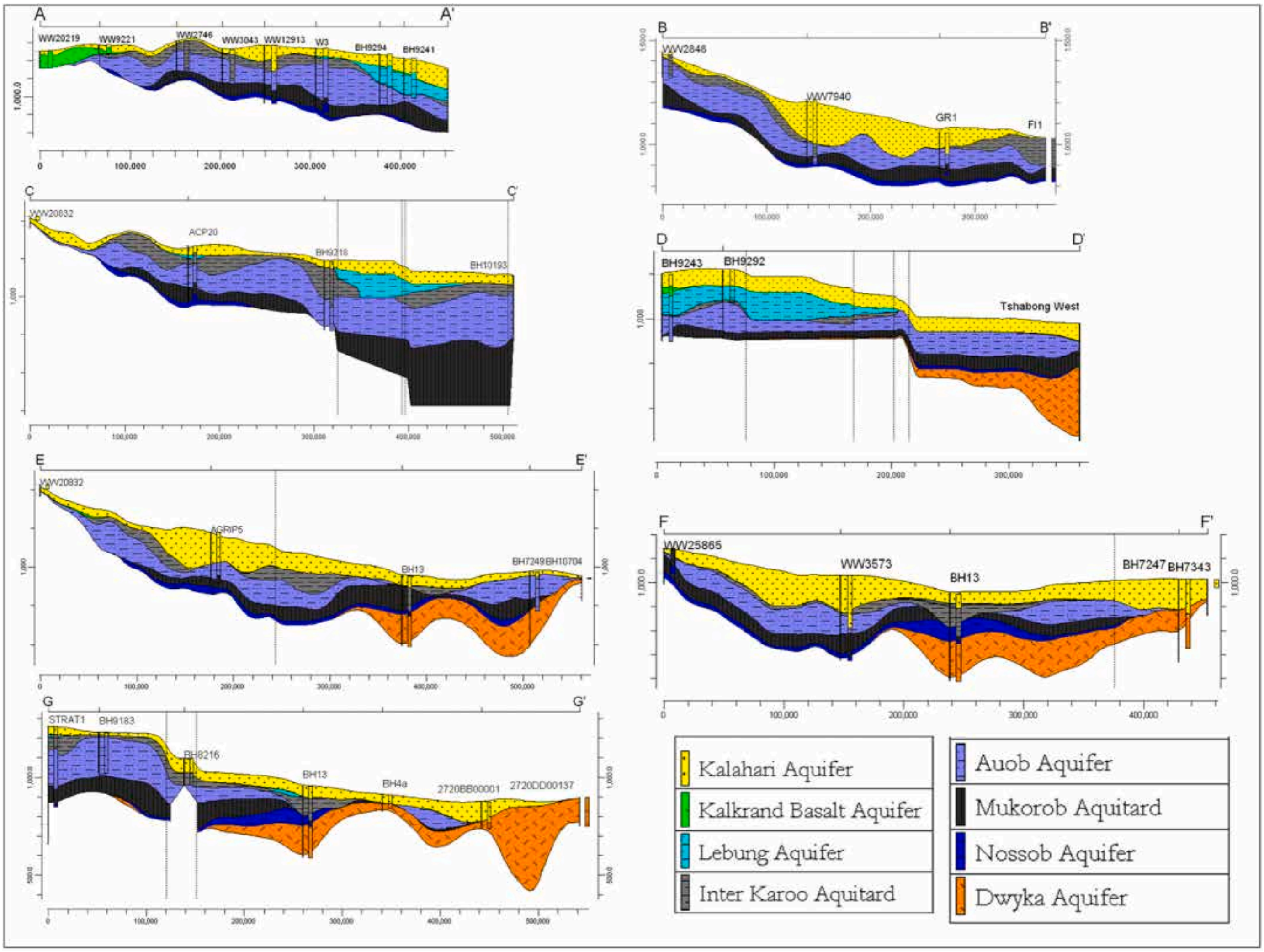

Fig. 5. Hydrostratigraphic cross-sections from the transects in Fig. 4 – vertical dashed lines represent faults

defined based on hydrostratigraphy following cross-section AA' (Figs. 4 and 5), especially at borehole W3 where all the layers start dipping north-eastward towards CKB and Lebung Aquifer begins, hence excluding both Lebung and Stomberg Basalt from the STAS. To the South, the boundary was extended to include the whole of Kalahari Gemsbok sub-basin to the end of the Kalahari Karoo Basin.

The boundary conditions were defined based on hydrostratigraphy, groundwater flow system and saturated thickness in the case of the upper phreatic Kalahari Aquifer. The groundwater flow system in the Kalahari Aquifer is mainly from the north-west to south east (Fig. 9 a) and its saturated thickness varies both in space and time, increasing after significant recharge and decreasing afterwards due to downward leakage and groundwater evapotranspiration. Groundwater level is shallowest west of Auob River at ~10 m and deepest in the central part at >100 m below the ground surface. In Botswana, the Kalahari is mostly unsaturated and groundwater occurs as highly localised perched aquifers mainly associated with calcrete pans and fossil river valleys (DGS, 2000; ORASECOM, 2022; WRC, 2008). A lateral head dependent inflow boundary was defined to the north-west while all the other boundaries were defined as no flow boundaries as they are parallel to the flow lines and there exists a shallow groundwater divide between STAS and CKB in this aquifer to the north-east and in the south Kalahari is completely unsaturated.

The flow system in the Auob and Nossob Aquifers is bidirectional i.e. from north-west to north-east and south-east. Although the Karoo Super Group wedges out against Pre-Karoo Formations in the north-west (Fig. 3), it is hypothesised that there could be inflow into Auob and Nossob Aquifers through this boundary depending on whether the Pre-Karoo Formations hold water or not and if there is a flow hydraulic gradient. This boundary was, thus, defined as a potential head dependent inflow boundary (Fig. 9a and b) and a head dependent lateral outflow, into the neighbouring CKB, was defined to the north-east for both aquifers. All the other external boundaries were defined as no flow boundaries as they are parallel to the groundwater flowlines. In the south, both Auob and Nossob are wedging so the groundwater could be evapotranspired or leaking upward into the Kalahari Aquifer or downward into Dwyka, depending on the hydraulic window contacts and vertical hydraulic gradient.

There is no sufficient data to analyze the flow system in Dwyka aquifer but it is conceptualized to be from the north east to south-west, similar to surface water flow. STAS is bounded to the south by Pre-Karoo rocks and therefore there is possibly no outflow to the south and all the outflow is through evaporation through the pans that are abundant in the southern part of STAS (Fig. 2).

4.5. Sources and sinks

Generally, STAS is characterised by low rainfall and high potential evapotranspiration resulting in soil moisture deficits hence low groundwater recharge potential under normal rainfall conditions.

Groundwater recharge is highly variable in space and time, as depicted by research conducted in various parts of STAS. In the western part in Namibia, groundwater recharge mechanism has been investigated through isotope analysis (JICA, 2002; Kirchner et al., 2002; Tweed, 2021) and chloride mass balance method (Stone and Edmunds, 2012). The environmental tracer (δ^{18}O, ^{3}H and ^{14}C) data indicates that sinkholes and river channels are potential recharge areas during the wet season. The sinkholes, mostly located in the western STAS area, are the result of the karstification of the Kalahari calcrete (Figure S 1). Slight depressions in the landscape drain runoff towards these sinkhole areas, which then act as points of focused recharge to the Kalahari aquifer. However, delineation of the extent of these areas, as analysed by Tweed (2021), was limited by the availability of hydrochemical sampling data, as such showing a strong bias towards the western and central areas of Kalahari and Auob aquifers in Namibia.

In the southern part of the study area in the vicinity of Molopo, Nossob and Kuruman Rivers in South Africa, three potential recharge areas, including the south-western Dwyka sub-outcrop area (Fig. 3), the Kuruman River and the pan system (Fig. 2) were identified by Levin (1980). They found out that recharge occurs as collection of water in fissures and contact zones of outcrop surfaces and where the Kalahari layer is thin (Levin, 1980). This was affirmed by Toens and Partners (1997) in Rose and Van Wyk (2006), who reported high ^{14}C and ^{3}H concentrations in areas where the Kalahari Group is thin or absent (i.e., south-western parts of the study area which indicates rapid recharge, while much lower ^{14}C and declining ^{3}H concentrations were observed in areas covered by thick Kalahari Layer (i.e., area north of Matamata (Fig. 2), which indicated slower recharge rate. Active recharge occurs on the Kuruman River bed during flooding and is dependent on heavy rainfall in the river catchment area. The effect of the recharge on the water quality and water level is restricted to the river bed and decreases sharply away from the river channel (Levin, 1980), as depicted by a freshwater lens, representing relatively young groundwater, that is restricted both laterally and vertically possibly due to presence of an impervious or semi-impervious layer (Verhagen, 1983). The water level beneath most of the pans in the southern part of STAS is shallow and rapidly deepens away from the pans. During rainy seasons, the salt on the pans dissolves and the salt solution moves downwards to the water table (Levin, 1980). Downward leakage from Kalahari Aquifer into Auob Aquifer occurs at the central part of STAS where there is a large hydraulic window. Environmental isotope investigations in the south-east show no evidence of recent recharge into the Auob and Nossob aquifers (DGS, 1994a).

The dominant discharge mechanism from the unconfined Kalahari aquifer is by evapotranspiration which occurs mainly from the unsaturated zone, especially along the dry river channels and from the salt pans in the south. However, the deep-rooted plants such as Prosopis spp (Figure S 2) can also withdraw groundwater (Braune et al., 2013; UNESCO, 2016), although the stable isotope data (δ^{18}O and δ^{2}H) indicate greater impact of evaporation than transpiration (Kirchner et al., 2002). Lateral groundwater outflow through Auob and Nossob Aquifers across the north-eastern boundary towards Central Kalahari sub-basin (CKB) and ultimately into Makgadikgadi Pans (Lekula et al., 2018), constitute the other discharge of groundwater of the STAS aquifer system.

Water resources of STAS are mainly utilised in Namibia where irrigation accounts for 47% of groundwater abstraction, followed by stock watering at 37.5%, and domestic use at 15%, while a small portion of less than 1% is used for tourism. In the area there are over 7000 abstraction boreholes for various purposes and only 1% of the total annual groundwater abstraction comes from Nossob aquifer, whereas 33% comes from the Auob aquifer and 66% from the Kalahari aquifers. A hydro census conducted by JICA (2002) estimated the total abstraction from Namibian part of STAS to be ~15 million cubic metres per annum. Another hydrocensus by UNESCO (2016) estimated that the abstraction had increased by ~30% to 20 million cubic metres per annum. In Botswana, Ncojane wellfiled consisting of six boreholes tapping the Auob Aquifer was established in 2007 during the WRC (2008) project to meet the water demand of the village centres in the Kgalagadi North District referred to as the Matsheng Villages. The total recommended amount of abstraction from the wellfield is ~3.5 million cubic metres per annum. In the south-east three production boreholes supplying the Bokspits Ranches were reported by ORASECOM (2022) with an annual abstraction of 85,249 m^3 reported in 2020. More groundwater utilization in this area is limited by very high salinities in the Ecca aquifers and parts of Kalahari Aquifer and also by low yield from the latter (DGS, 1994a). Nevertheless, four desalination plants have since been installed in the region to mitigate water shortage (ORASECOM, 2022). In South Africa, the aquifer system is utilised within the Kgalagadi Transfrontier Park abstracting mostly the Kalahari Aquifer and for domestic and livestock watering in the Mier settlement with an estimate of ~1.5 million cubic metres per annum (ORASECOM, 2009a). This totals to ~35.85 m^3 per annum although it could be more due to unaccounted, illegal groundwater abstractions.

4.6. Hydraulic parameters

Hydraulic properties reflect spatial heterogeneity of an aquifer system and determine aquifer flows and connectivity across aquitards. The parameter values are usually obtained from field tests such as pumping tests or slug tests. However, most boreholes in the STAS were drilled for production but without pumping test; as such the available data is not representative of the whole system. Therefore, ranges of values for hydraulic conductivities, specific yield and specific storage were adopted from literature, based on lithology (sand, sandstone and siltstone for Kalahari, Auob and Nossob aquifers respectively and shale for both aquitards), to enable estimation of water resources of STAS. These parameters will be optimised in the numerical model in a follow-up study. The adopted values of hydraulic conductivity range between four to five orders of magnitude with the ones for sand ranging between 10^{-3} m d^{-1} to 10 m d^{-1}, sandstone between 10^{-6} m d^{-1} to 10^{-1} m d^{-1}, siltstone between 10^{-7} m d^{-1} to 10^{-3} m d^{-1} and shale between 10^{-9} m d^{-1} to 10^{-4} m d^{-1} (Domenico and Schwartz, 1990; Freeze and Cherry, 1979; Kuang et al., 2020). Values of specific storage were obtained from recent review studies conducted by Kuang et al. (2020) and Chowdhury et al. (2022). Based on the reviewed field tests, specific storage of sandstone and shale range between 10^{-5} m^{-1} to 10^{-7} $m^{-1}$and 10^{-6} m^{-1} to 10^{-7} m^{-1}orders of magnitude respectively. The values of specific yield for the phreatic Kalahari Aquifer which range between 0.21 and 0.35 were obtained from Johnson (1967).

5. Discussion

5.1. Hydrogeological characterization and regional groundwater flow system

A 3D hydrogeological conceptual model of STAS was developed, through systematic integration of data from various sources, to assess the physical, process and spatial variability structures of the aquifer system. The physical structure, which includes the extent and geometry of hydrostratigraphic units (Enemark et al., 2019; Gupta et al., 2012) was defined through an iterative process using Rockworks 3D geological modelling code. The first and most important step was to harmonize the hydrostratigraphic units across the basin. The hydrostratigraphic units were identified through a comprehensive analysis of lithological information from borehole logs and potential groundwater occurrences following a similar study by Lekula et al. (2018) in the neighbouring CKB. Rockworks offered various capabilities not available in a GIS environment such as flexibility in data management and processing, a range of ways to visualize the results such as through 2D cross-sections, and exportation of results into ArcGIS for visualization and usage in subsequent numerical model. Rockworks also provides flexibility to update the 3D model and therefore as more drill logs become available, the conceptual model can be updated and re-computed for more accurate hydrogeological representation.

The 3-D hydrostratigraphic model showed that the overall lithological and hydrostratigraphic setting of the Kalahari Karoo Basin varied based on the geological and deformation processes that had occurred in the basin over time. For instance, absence of Upper Karoo Formations i.e., Karoo Basalts and Lebung Group, and part of Lower Karoo i.e. Beaufort and upper part of Ecca Group in the western and southern parts of STAS, could be due to non-deposition or as a result of erosion after Karoo deposition and during the post-Gondwanan period (Catuneanu et al., 2005). Within STAS, thick Kalahari sands are found where the Rietmond Member has been eroded partially or completely. Part of this area has been intruded by post-Karoo dolerite sills and where there are no dolerite sills, the Kalahari and Auob Aquifers are hydraulically connected. The Karoo Basalts are absent in most of the studied area except the western edge (known as Kalkrand Basalts) where they are quite fractured and weathered and several production boreholes have been drilled through the formation (JICA, 2002). That formation exists in most of CKB (referred to as Stomberg Basalt) where it forms a confining unit to the Lebung Aquifer (Lekula et al., 2018), which pinches out at a short distance west of the Kalahari line (Fig. 3).

The Ecca Group of STAS is subdivided into three formations/members, each forming a single hydrostratigraphic unit. In contrast, in CKB, Mukorob Member/Upper Kobe Formation and Nossob Member/Lower Kobe Formation/Ncojane Sandstone are considered as one formation, the Bori Formation (Catuneanu et al., 2005; Johnson et al., 1996), which together with overlying Kweneng and Boritse Formations, form the Ecca Aquifer of CKB (Lekula et al., 2018). The Kweneng Formation is equivalent to the Auob of STAS (Catuneanu et al., 2005; Johnson et al., 1996). The whole of KKB, apart from a small portion in the south-western tip where the Dwyka Group outcrops, is overlain by sediments of Kalahari Group. The Dwyka Group forms the lowest Karoo Group across the KKB and apart from the southernmost part of STAS in South Africa and part of south-western Botswana where it is considered a fractured aquifer, it is generally considered as an aquiclude.

STAS boundary as defined by UNESCO (2016) was initially delineated based on the occurrence of Ecca geological group within Auob and Nossob River basins. That boundary was later extended eastwards by extending the contour lines arbitrarily trying to identify a possible no-flow boundary (UNESCO, 2017a). This was based on the assumption that groundwater flow was a replica of surface topography. While this is a useful simplification, it may introduce bias in instances when topography is not the primary determining factor. Thus, when assessing the groundwater flow system, the combined effect of topography, climate, and geology on groundwater flow patterns should be examined (Zhang et al., 2022a). Shishaye et al. (2020b) recommends comparing potentiometric surface to surface water flow in order to identify other aspects such as geological structures that may influence groundwater flow. Application of this method in this study revealed that Ecca groundwater flow in the northern part of STAS was not entirely controlled by topography, as surface water flows south-eastwards while groundwater flows both south-eastwards and north-eastwards indicating presence of a groundwater divide. Similar results were observed by ORASECOM (2009b) who analysed groundwater flow system in the Molopo-Nossob surface water sub-catchment of Orange River Catchment.

Inclusion of regional faults in 3D geological modelling revealed that at the intersection between Zoetfontein Fault and Makgakgadi line, the Karoo sequence is displaced vertically (Fig. 6, GG') hence altering the groundwater flow direction. This area is also characterised by intrusion of dolerite dykes and sills which could also form a barrier to groundwater flow. This is in agreement with Reeves and Hutchins (1982) who stated that "in southern Botswana, the Zoetfontein Fault appears to have a post-Karoo vertical displacement of several hundred metres and therefore cuts out the Karoo rocks and brings Archaean granite-greenstone terrain, overlain by Proterozoic platform sediments, close to the surface (below only Kalahari cover)". This divides the SW Botswana sub-basin into two, with groundwater in the northern part (Ncojane sub-basin) flowing north-eastwards into CKB and ultimately into Makgakgadi pans and the southern part (Nossob sub-basin) flowing south-wards towards Molopo River. Similar results were observed by Lekula et al. (2018) in the south-eastern part of CKB where the Zoetfontein Fault displaced the Karoo Group vertically upthrown to the north and cuts off the Ecca Aquifer. The zone south of the Zoetfontein fault, is characterised by absence of Upper Karoo Formations.

Proper conceptualization of groundwater flow system was crucial as it enabled external boundary conditions to be defined realistically. The new proposed boundary of STAS covers an area of approximately 154,000 km^2 of which 41% in Botswana, 39% is in Namibia and 20% in South Africa. A head dependent outflow boundary in the Ecca aquifers was identified at the north-eastern boundary of STAS at the contact with CKB which is in contrast to UNESCO (2017a) and Lekula et al. (2018) who applied a no flow boundary. This means that CKB is part of a larger regional groundwater flow system and not a laterally closed groundwater flow system like was hypothesised by Lekula et al. (2018) and both CKB and STAS are sub-basins of the larger hydrogeological KKB. STAS is bounded by Pre-Karoo rocks to the south and Rose and Van Wyk (2006) describe the flow in the southern part of the STAS as retarded, indicative of a stagnant system. DGS (1994a) reports similar flow system north of Molopo River within Botswana and attributes the slow flow system to be the cause of the high salinities. The discharge mechanism in the south could thus be only through evaporation through the salt pans.

Six hydrostratigraphic units including, from the top, Kalahari Aquifer, Inter-Karoo Aquitard, Auob Aquifer, Mukorob Aquitard, Nossob Aquifer and Dwyka Aquifer were identified in the STAS. The unconfined Kalahari Aquifer plays a major role in the rainfall storage and spatio-temporal distribution of sub-surface fluxes (Lekula et al., 2018). The plant interception and thick unsaturated zone in combination with large

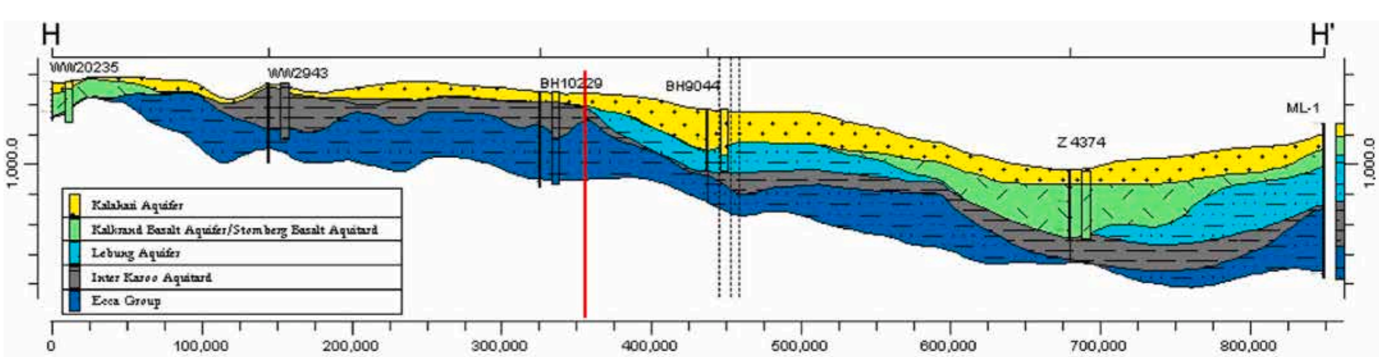

Fig. 6. West-north-east cross-section cutting across northern STAS into CKB. Auob, Mukorob and Nossob hydrostratigraphic units of STAS have been combined into Ecca Group for better interpolation. The red vertical line is an approximation of the boundary between STAS and CKB based on hydrostratigraphy. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

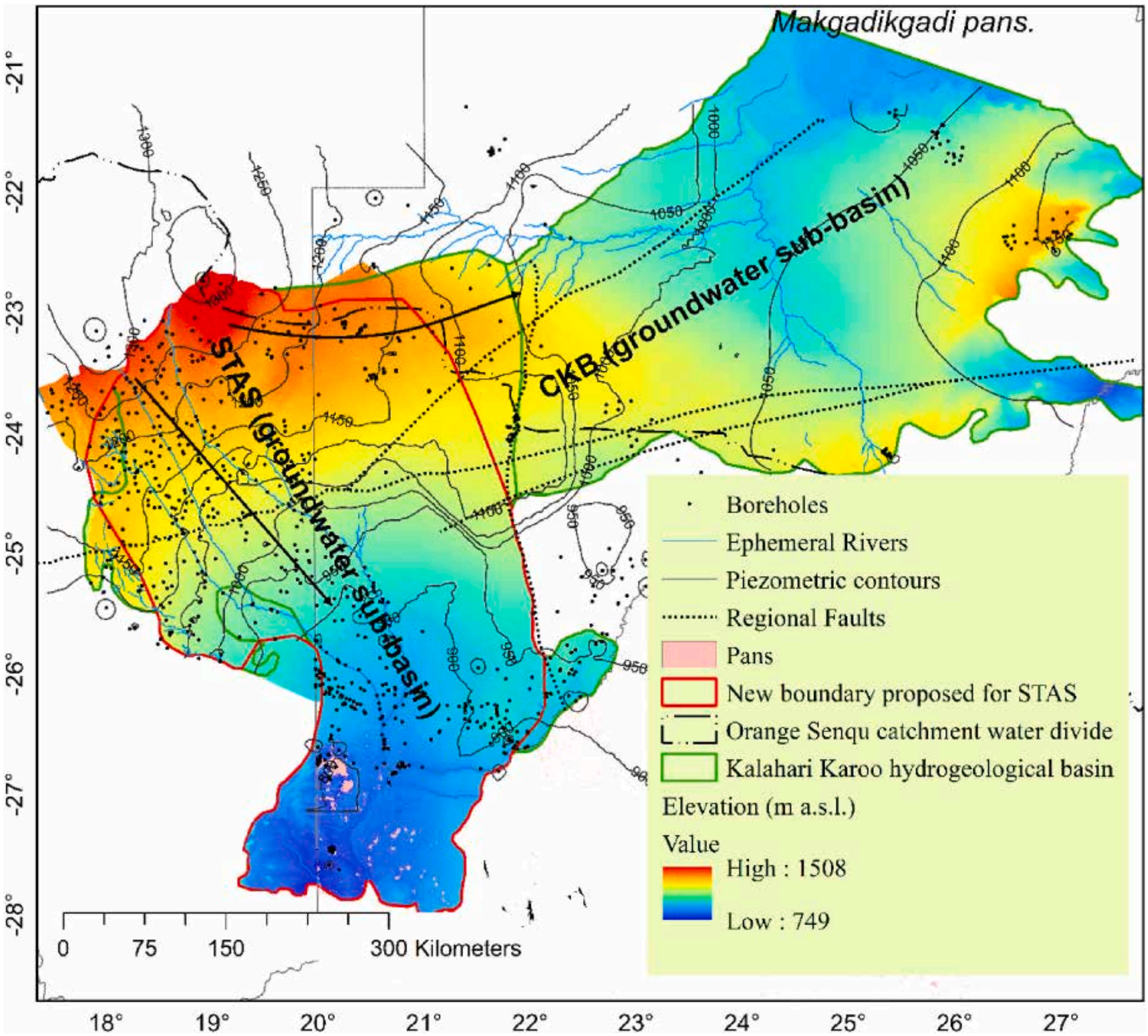

Fig. 7. Regional surface water and groundwater flow pattern in STAS and CKB and the proposed new boundary of STAS. Surface water flow is represented by the rivers and follows topography while groundwater flow is represented by the piezometric contours. The arrows show the general groundwater flow direction

vapour pressure deficit due to aridity, causes evaporation of infiltrated water after a rain event and consequently most of the rain water does not reach the water table. Presence of deep-rooted vegetation, such as Acacia and Prosopis spp, withdrawing water not only from the unsaturated zone but potentially also from groundwater, also implies large interception and transpiration processes.

Environmental tracer data, highlights areas of water exchange between the Kalahari and Auob aquifers; these coincide with the location of faults and areas where the Inter-Karoo Aquitard thickness is less than 3 m (Tweed, 2021). The Nossob Aquifer is characterised by low groundwater yields, although the piezometric level is very shallow and exhibits sub-artesian to artesian conditions in some areas in the Aranos sub-basin in Namibia, hence the basin is commonly referred to as the Stampriet Artesian Basin. The Nossob Aquifer is confined by the Mukorob Aquitard throughout nearly the whole STAS and thus it is assumed that in majority of its extent, it is not hydraulically connected with the overlying aquifers. According to Kirchner et al. (2002) the Nossob groundwater is 17500–40000 years old and as such they classified it as fossil water. The Dwyka Aquifer is hydraulically connected to Nossob and the Kalahari Aquifers.

5.2. Implication for groundwater management and future work

This study provides a systematic overview of the 3D hydrogeological system, properties and dominant processes as well as delineation of a new boundary of STAS. Use of 3-D geological modelling enabled reliable delineation of the hydrostratigraphic framework to improve understanding of the hydrogeology of STAS as well as to ensure reliable predictions of groundwater flow. These provided insights into the spatial extent and variability of the thickness of each hydrostratigraphic unit, which is useful for estimation of groundwater development potential. The aquifer thicknesses from Rockworks are also easily transferrable into the groundwater model to define the aquifer geometry. Reliable estimation of the aquifer geometry will reduce uncertainties propagated into the numerical groundwater flow model, hence more accurate quantitative estimation of water resources of STAS. The new boundary of STAS is ~67000 km^2 (i.e., 42%) more than the area previously reported in Phase 1 of the GGRETA project (UNESCO, 2016), implying that more settlements, inhabitants and industrial developments could be reliant on this strategic aquifer system than previously thought, and therefore proper groundwater management is key in this area.

A schematic diagram summarizing the important elements of the conceptual model of STAS, including the hydrostratigraphic units, sources and sinks, boundary conditions, groundwater flow system is presented in Fig. 10. Six hydrostratigraphic units (four aquifers and two aquitards) are proposed. The hydrogeological conceptual model of STAS, which is mainly qualitative, forms the basis for a quantitative numerical model. 3D integrated hydrological model (IHM) is

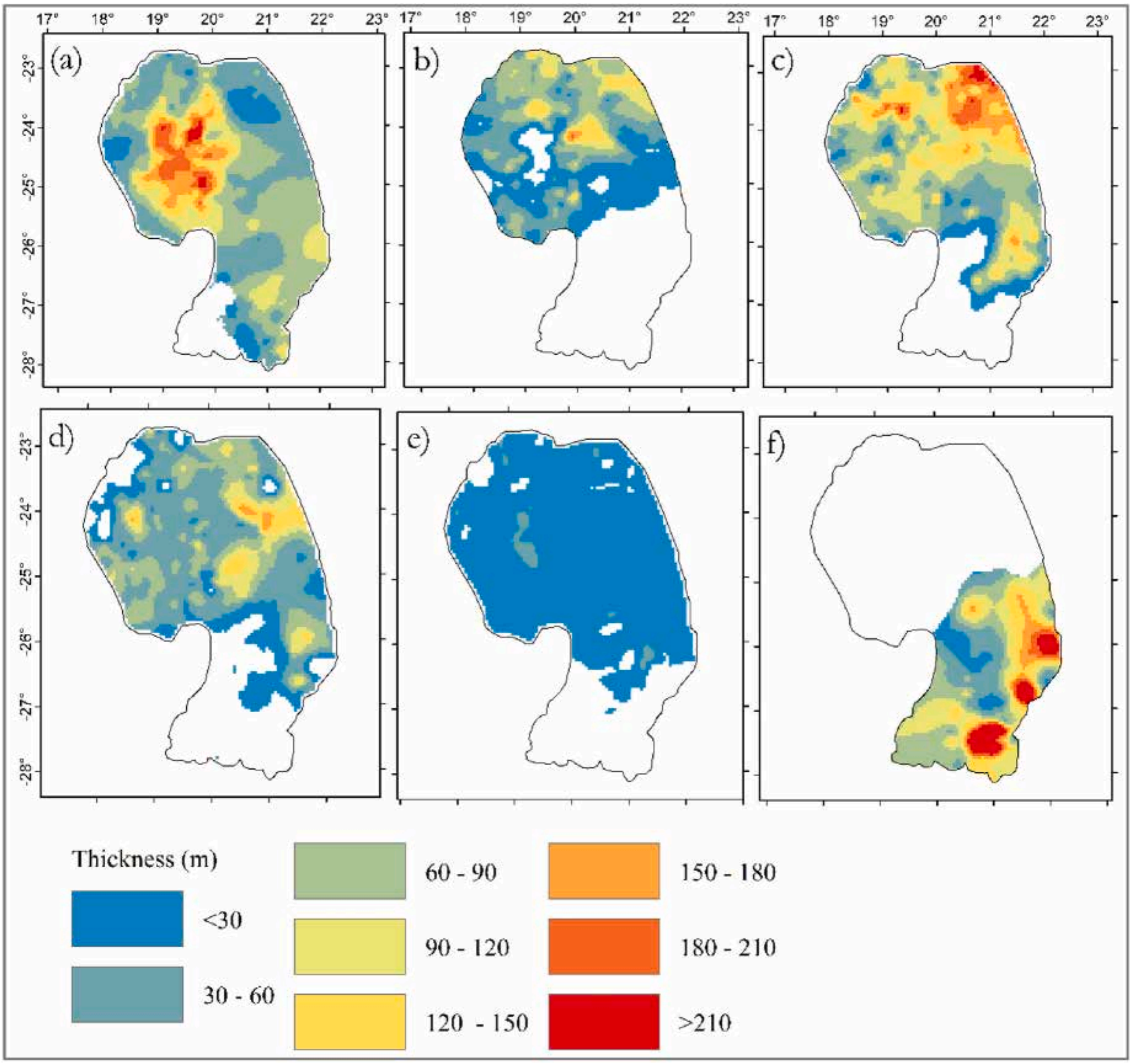

Fig. 8. Spatial extent and thickness of the hydrostratigraphic units: a) Kalahari, b) Inter-Karoo Aquitard, c) Auob Aquifer, d) Mukorob Aquitard, e) Nossob Aquifer and f) Dwyka Aquifer

recommended, as it allows for most realistic integration of surface and groundwater fluxes (Balugani et al., 2017; Daoud et al., 2024; Lubczynski et al., 2024; Zhang et al., 2022b), simulation of the role of the unsaturated zone on the water balance dynamics, simulation of groundwater flow in all three spatial dimensions, realistic simulation of pinching out of aquifers and provides opportunity for particle tracking option to determine groundwater residence time (Anderson et al., 2015).

5.3. Uncertainty and limitations

Hydrogeological conceptual models are usually developed using different data sources often with inherent uncertainties (Anderson et al., 2015). The uncertainties also arise because the models are created from point observations which are not always representative of the whole sub-surface. The major sources of uncertainties as identified by other authors include data density, data quality, geological complexity and geological interpretations (Lekula et al., 2018; Moya et al., 2014; Raiber et al., 2012; Shishaye et al., 2020a, 2020b). In respect to 3D hydrostratigraphic modelling the main area of low confidence was within and around Kgalagadi Transfrontier Park in Botswana, where no borehole logs were available. The pre-Kalahari geological map of Botswana (Carney et al., 1994; Key and Ayres, 2000; Smith et al., 1984) was used to assess and adjust the Rockworks model output through an iterative process in order to improve the accuracy in this region. Most of the wells used to produce the 3D hydrostratigraphic model did not penetrate the whole Ecca Group, particularly in Botswana and South Africa leading to higher uncertainty in the modelled thickness of the deeper layers in these areas. This uncertainty is less in Namibia where ~18% of the boreholes penetrate into the Nossob aquifer and they are well spatially distributed. The uncertainty increases eastwards into Botswana where only a handful of the boreholes penetrate into the Kobe Formation and only 3 within the study area intercepts the whole Ecca Group. Nonetheless, since real geology is complex, it is not necessary to bring all the complexity of geology into a descriptive groundwater model (Anderson et al., 2015; Krešić and Alex, 2012) and thus the results attained were considered satisfactory.

Another source of uncertainty in STAS is due to lack of sufficient data to define the groundwater flow system per aquifer in the north-eastern part of the STAS, especially for Kalahari and Nossob Aquifers and to map the saturated thickness of Kalahari Layer. The flow system of the Kalahari is dependent on whether the Kalahari is saturated at the boundary or not and also on spatial variability of the Kalahari saturation, but the data to define it is scarce. Other sources of uncertainty

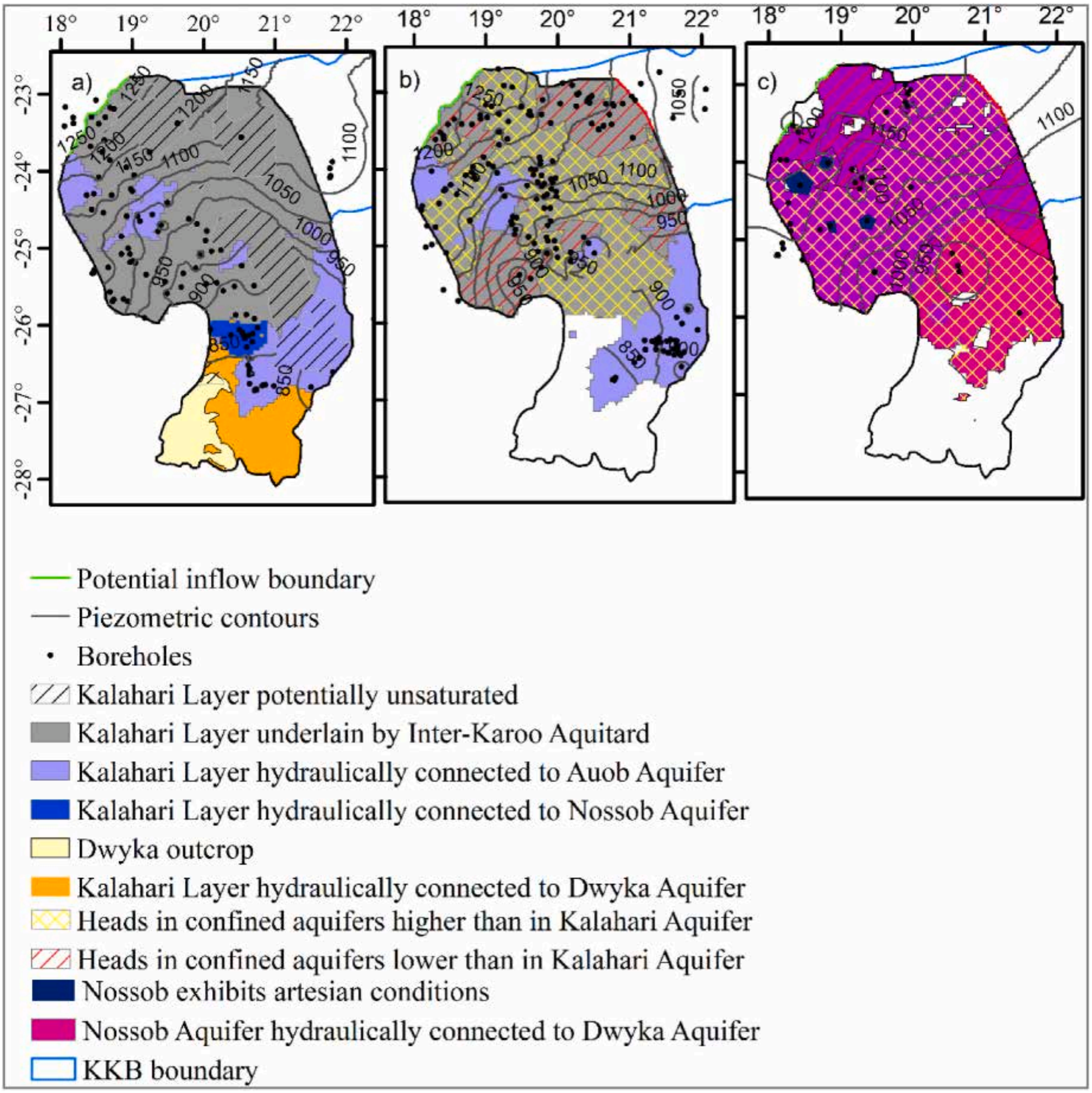

Fig. 9. Groundwater flow system and boundary conditions per aquifer: a) Kalahari Aquifer; b) Auob Aquifer; and c) Nossob Aquifer

include, the potential hydraulic connection with the underlying aquifers, especially in the north-east and south where the available data is scarce, as well as mapping potentiometric surface of the Nossob Aquifer to define location of artesian conditions and eventual hydraulic contacts with the overlying aquifers.

6. Conclusions

This study characterizes the 3D hydrogeological settings of STAS, the connectivity of the aquifers, the regional groundwater flow system, boundary conditions, hydraulic properties and the sources and sinks. Use of 3-D geological modelling code such as Rockworks proved to be vital as it allowed integration of various data types from different sources such as drill logs and regional faults. Two regional groundwater flow systems, one to the north east into CKB and ultimately into the Makgadikgadi Pans and another one to the south towards the Orange River were identified from analysis of groundwater level data, indicating presence of a groundwater divide. Comparison of the groundwater flow system to the surface water flow system and surface topography showed that groundwater flow in Kalahari was influenced by topography but in Ecca Aquifers (Auob and Nossob) also by geology and geological structures.

Six hydrostratigraphic units, including four aquifers and two aquitards were identified in STAS. The study also proposes a new boundary of STAS, highlights the distinctiveness of the geometries and extents of each hydrostratigraphic unit, and defines external boundaries which include inflow boundaries at the north-west and outflow boundary at the north-east. The environmental tracer data, as reviewed from different literature, highlights river channels, karstic sinkholes located in the western part of STAS in Namibia, outcrops, where the Kalahari is thin and the pan system in the southern part of STAS as potential recharge zones. River channels and the pan system also act as discharge areas through evapotranspiration. The environmental tracer data also highlights the faults and areas where the Inter Karoo Aquitard is less than 3 m as potential areas of interaction between the Kalahari and Auob Aquifers. The results from this study are fundamental inputs into the follow up numerical modelling studies for the assessment of groundwater potential estimation, recharge estimates and scenario simulation for sustainable groundwater management in STAS.

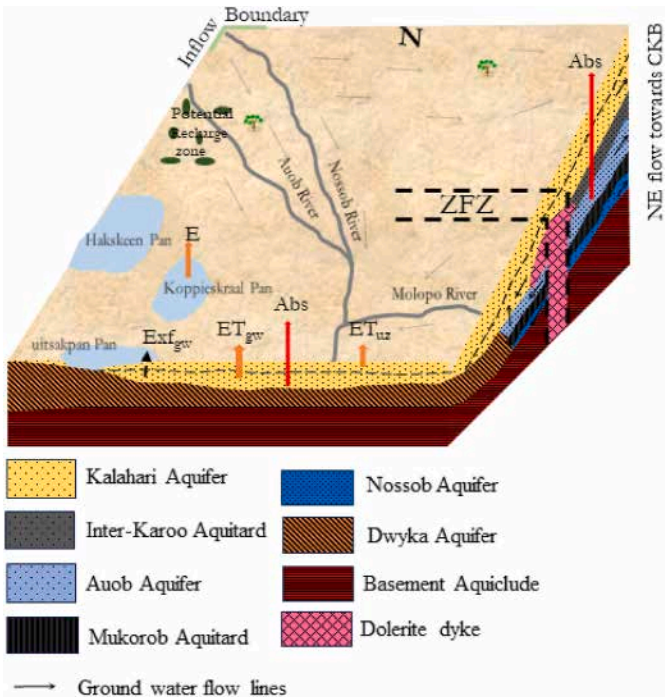

Fig. 10. Three-dimensional schematization of the hydrogeological conceptual model showing the geometry, sources and sinks, groundwater flow system and boundary conditions of the study area (not to scale): Abs – abstraction; ET_{gw} - groundwater evapotranspiration; ET_{uz} - unsaturated zone evapotranspiration; Exf_{gw} - groundwater exfiltration; N - north; ZFZ - Zoetfontein Fault Zone

CRediT authorship contribution statement

Irene Kinoti: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marc Leblanc:** Writing – review & editing, Supervision. **Moiteela Lekula:** Writing – review & editing. **Sarah Tweed:** Writing – review & editing. **Piet Kebuang Kenabatho:** Writing – review & editing. **Albert Olioso:** Writing – review & editing, Supervision. **Maciek W. Lubczynski:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2024.101301.

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