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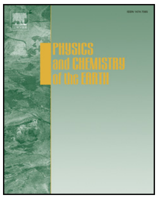

Hydrogeological conceptual model of large and complex sedimentary aquifer systems – Central Kalahari Basin

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ABSTRACT

Successful groundwater resources evaluation and management is nowadays typically undertaken using distributed numerical groundwater flow models. Such models largely rely on hydrogeological conceptual models. The conceptual models summarize hydrogeological knowledge of an area to be modelled and thereby providing a framework for numerical model design. In this study, an efficient data integration method for developing hydrogeological conceptual model of the large and hydrogeologically-complex, Central Kalahari Basin (CKB) aquifer system, was undertaken. In that process, suitability of 3-D geological modelling with RockWorks code in iterative combination with standard GIS (ArcGIS) was tested. As a result, six hydrostratigraphic units were identified, their heads and related flow system interdependencies evaluated and hydraulic properties attached. A characteristic feature of the CKB is a thick unsaturated Kalahari Sand Unit (KSU), that restricts the erratic recharge input to $< 1\ \mathrm{mm\,yr^{-1}}$ in the centre to about $5–10\ \mathrm{mm\,yr^{-1}}$ in the eastern fringe. The analysis of the spatial distribution of topological surfaces of the hydrostratigraphic units and hydraulic heads of the aquifers, allowed to identify three flow systems of the three aquifers, Lebung, Ecca and Ghanzi, all three having similar radially-concentric regional groundwater flow patterns directed towards discharge area of Makgadikgadi Pans. That pattern similarity is likely due to various hydraulic interconnections, direct or through aquitard leakages, and also due to the presence of the overlying unconfined, surficial KSU, hydraulically connected with all the three aquifers, redistributing recharge into them. The proposed 3-D geological modelling with RockWorks, turned to be vital and efficient in developing hydrogeological conceptual model of a large and complex multi-layered aquifer systems. Its strength is in simplicity of operation, in conjunctive, iterative use with other software such as standard GIS and in flexibility to interface with numerical groundwater model. As a result of conceptual modelling, fully 3-d, 6 layer numerical model, with shallow, variably-saturated, unconfined layer is finally recommended as a transition from conceptual into numerical model of the CKB.

1. Introduction

The successful groundwater resources evaluation and management is nowadays typically done using distributed numerical groundwater models. The reliability of such models is largely determined by realistic hydrogeological conceptual models, which summarize hydrogeological knowledge of a site to be modelled and thereby providing a framework for numerical model design. According to Anderson et al. (2015), hydrogeological "conceptual model is a qualitative representation of a groundwater system that conforms to hydrogeological principles and is based on geological, geophysical, hydrological, hydrogeochemical and other ancillary information"; hence it includes both, the hydrogeological framework and hydrological system characterization. A conceptual model is usually presented in a series of cross sections, fence diagrams and tables showing distribution of hydrostratigraphic units and boundary conditions with groundwater flow directions and hydrogeological parameter estimates. All these, are reconstructed from surface and subsurface data to help hydrogeologists understand the hydrogeological system behaviour and support quantitative modelling (Frances et al., 2014). The subsurface geological data such as lithology, structural geology and stratigraphy, are difficult to schematize due to geological heterogeneity and data scarcity (Trabelsi et al., 2013). Even more difficult is to characterize hydrostratigraphy, hydrogeological parameters, flow systems with their piezometric surfaces and interactions, all these assessed in this study.

Hydrogeological conceptual model setup usually involves analysis

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and integration of relevant geological and hydrogeological data using database tool such as a geographical information system (GIS) (Anderson et al., 2015; Trabelsi et al., 2013), although there is no standard widely accepted methodology in that respect (Brassington and Younger, 2010). 3-D geological modelling (Hassen et al., 2016) has not been frequently used in environmental studies in the past century due to a number of factors, among them high cost of software packages, necessary sophisticated hardware and often shortage of borehole information. However, only recently, the 3-D geological modelling has increasingly been used as a tool for synthesizing all available data types, leading to better understanding and more realistic presentation of a geological settings (Hassen et al., 2016). The demand for 3-D geological modelling and rapid increase of computer power, resulted in advancement in the 3-D modelling packages, which allowed development of efficient 3-D geological models on standard desktops (Royse, 2010), making them available to a wider scientific and commercial community (Raiber et al., 2012). Also this advancement has enabled 3-D geological models to move from the sole use in petroleum and mining industry to all geological disciplines (Royse, 2010), including hydrogeology (Gill et al., 2011). In groundwater studies, 3-D geological modelling is used to evaluate complexity of structural geological and hydrogeological subsurface heterogeneity, which is generally the basis for any hydrogeological conceptual model and therefore a very important step towards building a numerical distributed groundwater flow models (Bredehoeft, 2002; Robins et al., 2005; Tam et al., 2014). The 3-D geological models also assist in providing a check on the logic of the hydrogeological conceptualization (Gill et al., 2011), especially important in areas with high hydrogeological heterogeneity (Tam et al., 2014).

The usefulness of 3-D geological models in hydrogeological conceptualization of aquifers has been demonstrated worldwide, but only few of them address Africa, especially semi-arid regions, where groundwater is the only source of potable water. In the Northern Africa Hassen et al. (2016), constructed 3-D geological model to define the geometry of the Kasserine Aquifer System in Tunisia, which was further used in the development of hydrogeological conceptual model for future development of the 3-D numerical groundwater flow model. In Southern Africa, Lindenmaier et al. (2014) integrated all available geological information in a 3-D geological model to refine the hydrostratigraphy and to develop a 3-D aquifer map within the Cuvelai-Etosha Basin in Namibia. However, there has not been presented any regional hydrogeological conceptual model of the Central Kalahari Basin (CKB) (Fig. 1), especially not based on the 3-D geological model solution, addressing the complex, multi-layered, geological and hydrogeological CKB system heterogeneity. So far, only local studies within small parts of the CKB, summarised in the Botswana National Water Master Plan Review (Snowy Mountains Engineering Corporation and EHES Consulting Engineers, 2006), have been investigated using 3-D geological modelling.

The CKB is very important hydrogeologically to Botswana and neighbouring Namibia, as it hosts the most productive and exploited transboundary Karoo System Aquifers. A lot of research in the CKB has been carried out for possible occurrence of oil and coal bedded methane gas, rather than for groundwater potential. These researches included, for example, studies by Bordy et al. (2010), where they analysed the depositional environment of the Mosolotsane Formation, and other exploration works by international companies like for example Shell Oil Company. Hydrogeological studies in the CKB have been limited. Farr et al. (1981) evaluated groundwater resources in Botswana, including the CKB, but their study did not cover spatial distribution of hydrostratigraphic units. Considering CKB hydrogeology, only few recharge-related studies were published, all referring to CKB fringes (de Vries and Simmers, 2002; Mazor, 1982; Obakeng et al., 2007; Stadler et al., 2010). There are also some local, consultancy studies (Geotechnical Consulting Services (Pty) Ltd, 2014; Water Surveys Botswana (Pty) Ltd, 2008; Water Surveys Botswana (Pty) Ltd & Aqualogic (Pty) Ltd, 2007; Wellfield Consulting Services (Pty) Ltd, 2001, 2007, 2009, 2012), presenting local hydrogeological conditions of the CKB, based on borehole data. However, none of them attempted to integrate spatially all the available, fragmented data, to develop hydrogeological conceptual model of the CKB.

The main objective of this study was to develop an efficient method of integrating data from various sources and scales, to develop hydrogeological conceptual model of a large and complex multi-layered aquifer system, such as the CKB. Specific objectives of this study were: 1) to test suitability of 3-D geological modelling tool in: i) integration of data from various sources and scales; ii) modelling of hydrostratigraphic units in large and complex multi-layered aquifer systems; iii) its interfacing with GIS and numerical model; 2) to improve CKB understanding of: i) the spatial distribution of the hydrostratigraphic units and their hydraulic properties; ii) flow systems, their boundaries and interactions between different hydrostratigraphic units; 3) to adapt the hydrogeological conceptual model to its smooth conversion into regional, numerical model.

2. Description of the CKB study area

The majority of CKB (Fig. 1) is situated in the central part of Botswana ($\sim 181{,}000\ \mathrm{km}^2$) and in the small western part of Namibia ($\sim 14{,}000\ \mathrm{km}^2$). The CKB with its boundaries, is presented in Fig. 1. It is a large-scale hydrogeological basin, which formerly was a catchment of the fossil Okwa-Mmone River system (de Vries, 1984). Currently it is nearly flat area due to surficial accumulation of eolian sand, known as Kalahari Sand. About 90% of the CKB is occupied by Kalahari Desert characterized by semi-arid to arid climate because of its position under the descending limb of the Hadley cell circulation (Batisani and Yarnal, 2010). Most of the rainfall in the CKB is from convection processes such as instability showers to thunderstorms, several orders of magnitude smaller than the synoptic systems, like the Inter-Tropical Convergence Zone, which control the air-masses supplying the moisture (Bhalotra, 1987). Rainfall in the region is highly spatially and temporally variable (Obakeng et al., 2007), with highly localized rainfall showers (Bhalotra, 1987). Almost all rainfall occurs during the summer, i.e., from September to April. The average annual rainfall ranges from $380\ \mathrm{mm\ y}^{-1}$ in the southwestern to $530\ \mathrm{mm\ y}^{-1}$ in the north-eastern parts of the CKB.

2.1. General geology

Approximately two thirds of the CKB area, i.e. $\sim 128{,}000\ \mathrm{km}^2$, is occupied by the Kalahari Karoo Basin (KKB) rocks while the remaining $\sim 67{,}000\ \mathrm{km}^2$, by Pre-Karoo rocks (Fig. 2 and Fig. 3). The KKB is a sedimentary basin type structure (Catuneanu et al., 2005; Johnson et al., 1996) with areal extent of 4.5 million km^2. It extends over most of Southern African countries (Fig. 2) and is filled with a succession of sedimentary and volcanic rocks (Table 1), with a maximum vertical thickness of about 12 km (Johnson et al., 1996).

2.1.1. Pre-Karoo Groups

There are three Pre-Karoo rock Groups of Proterozoic age (Carney et al., 1994; Key and Ayres, 2000) (Fig. 3) on top of Archaean Basement: i) Ghanzi Group (weakly metamorphosed purple-red, arkosic sandstones, siltstones, mudstones and rhythmites) in the north-western part of the study area; ii) Waterberg Group (Reddish siliciclastic sedimentary rocks, mostly quartzitic sandstones and conglomerates) in the Southern tip; iii) Transvaal Super Group (interbedded reddish, grey and purple quartzites, carbonaceous siltstones and shales, cherts, limestones, ironstones and volcanics). There are also three Pre-Karoo rock Groups of Archaean age in the CKB (Carney et al., 1994; Key and Ayres, 2000) (Fig. 3): i) Gaborone Granite; ii) Kanye Formation composed of felsites; and iii) Okwa Complex composed of porphyritic felsite, granitic gneiss, microgranite and metadolerite.

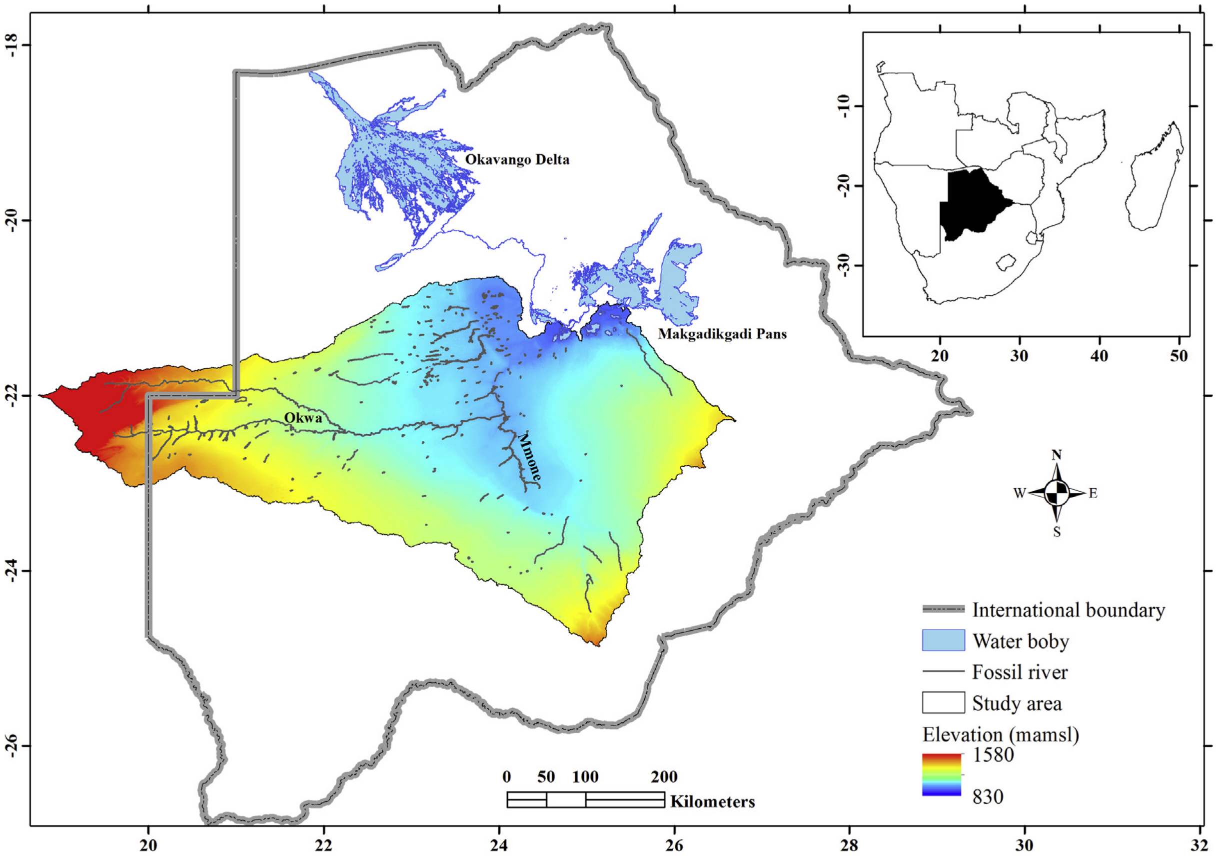

Fig. 1. Location, topography and surface water drainage of the Central Kalahari Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

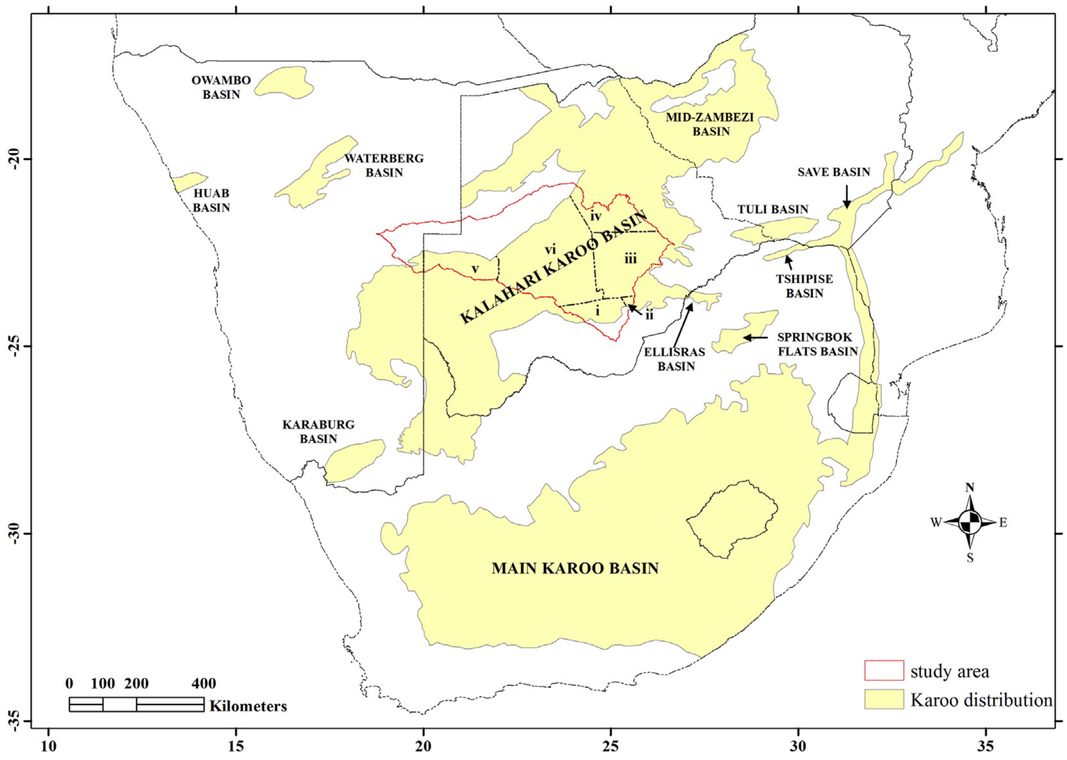

Fig. 2. Distribution of Karoo Basins in Southern Africa after Johnson et al. (1996). The Roman numerals denote the following CKB Kalahari Karoo Sub-Basins: i) Kweneng; ii) Mmamabula; iii) South-East Central Kalahari; iv) Northern-Belt Central Kalahari; v) Western-Central Kalahari; vi) South-Western Botswana. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

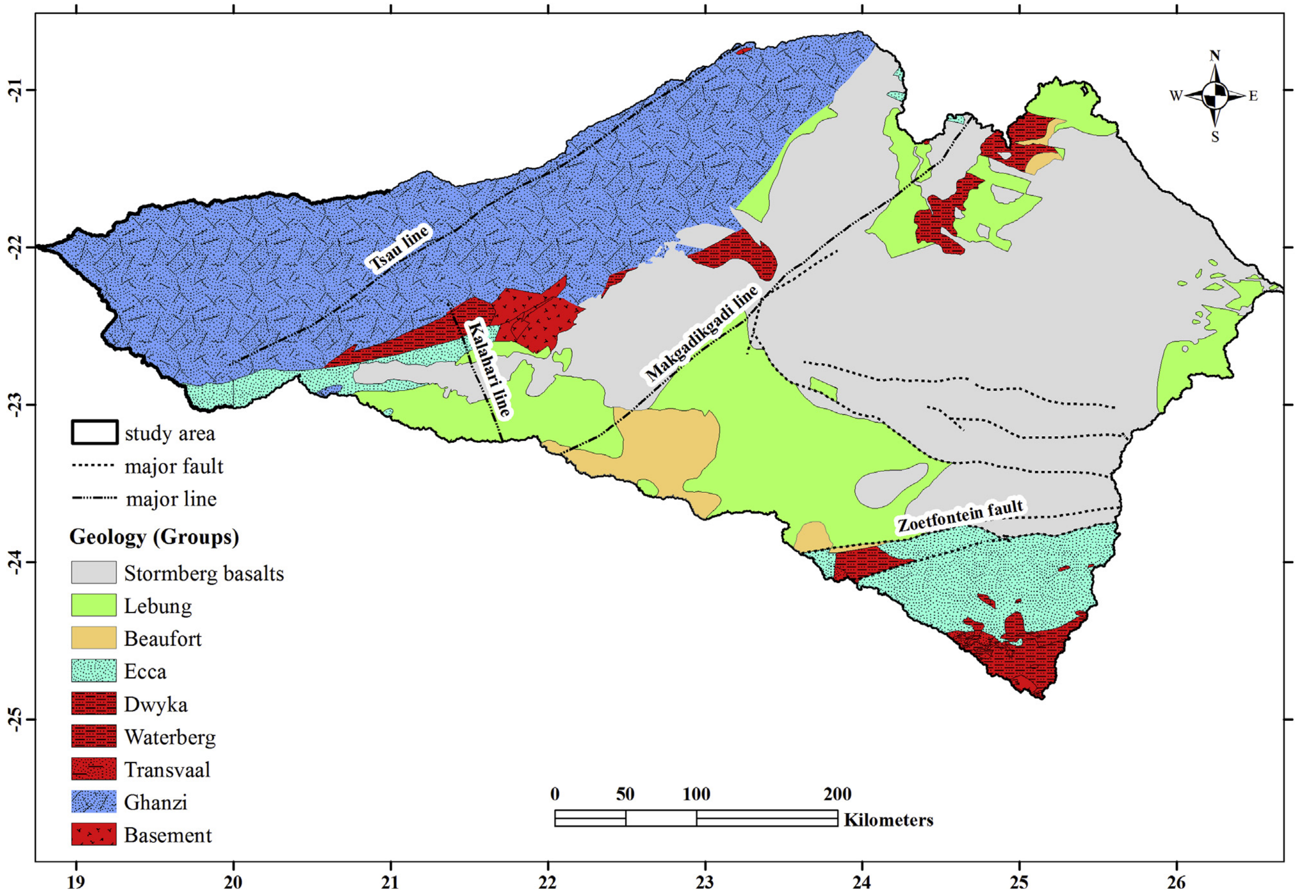

Fig. 3. The Pre-Kalahari Group geology of the Central Kalahari Basin, modified after Key and Ayres (2000) and Carney et al. (1994). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Stratigraphy and hydrostratigraphy of Karoo Supergroup in the CKB, modified after Smith (1984) to include Pre-Karoo and Kalahari Rocks; the colors correspond to hydrostratigraphic units and a dash-line defines a regional unconformity.

DESCRIPTION / AGE	Period	Karoo Division	Group	Sub-Basin						Hydrostratigraphy
				Kweneng (i)	Mmamabula (ii)	South-East-Central Kalahari (iii)	Northern-Belt Central Kalahari (iv)	Western-Central Kalahari (vi)	South-Western Botswana (v)	
CENOZOIC	Quaternary	Post-Karoo	Kalahari	Kalahari Group						Kalahari Sand Unit (KSU) (Unit1)
MESOZOIC	Jurassic	Upper Karoo	Stormberg Basalts	Stormberg Lava Group						Stormberg Basalt Aquitard (SBA) (Unit 2)
	Triassic		Lebung	Ntane Sandstone Formation					Nakalatlou Sst.	Lebung Aquifer (Unit 3)
				Mosolotsane Fm.			Ngwasha Fm. (North East Only)	Mosolotsane Fm.	Dondong Fm.	Inter-Karoo Aquitard (IKA) (Unit 4)
							Pandamatenga Fm.			
	Upper Permian	Lower Karoo	Beaufort	Kwetla Fm.	Thabala Fm.			Kwetla Fm.	Kule Fm.	
PALEOZOIC	Lower Permian		Ecca	Boritse Fm.	Korotlo Fm.	Serowe Fm.	Tlapana Fm.	Boritse Fm.	Otshe Fm.	Ecca Aquifer (Unit 5)
					Mmamabula Fm.	Morupule Fm.				
				Kweneng Fm.	Mosomane Fm.	Kamotaka Fm	Mea Arkose Fm	Kweneng Fm.		
				Bori Fm.		Makoro Fm.	Tswane Fm.	Bori Fm.	Kobe Fm.	
PROTEROZOIC	Mesoproterozoic		Dwyka	Dukwi Fm.					Middlepits Fm.	
									Khuis Fm.	
									Malogong Fm.	
		Pre-Karoo							Ghanzi Group	Ghanzi Aquifer (Unit 6)
ARCHAEAN			Waterberg, Transvaal, Gaborone Granite, Kanye Formation, Okwa complex							Basement Aquiclude

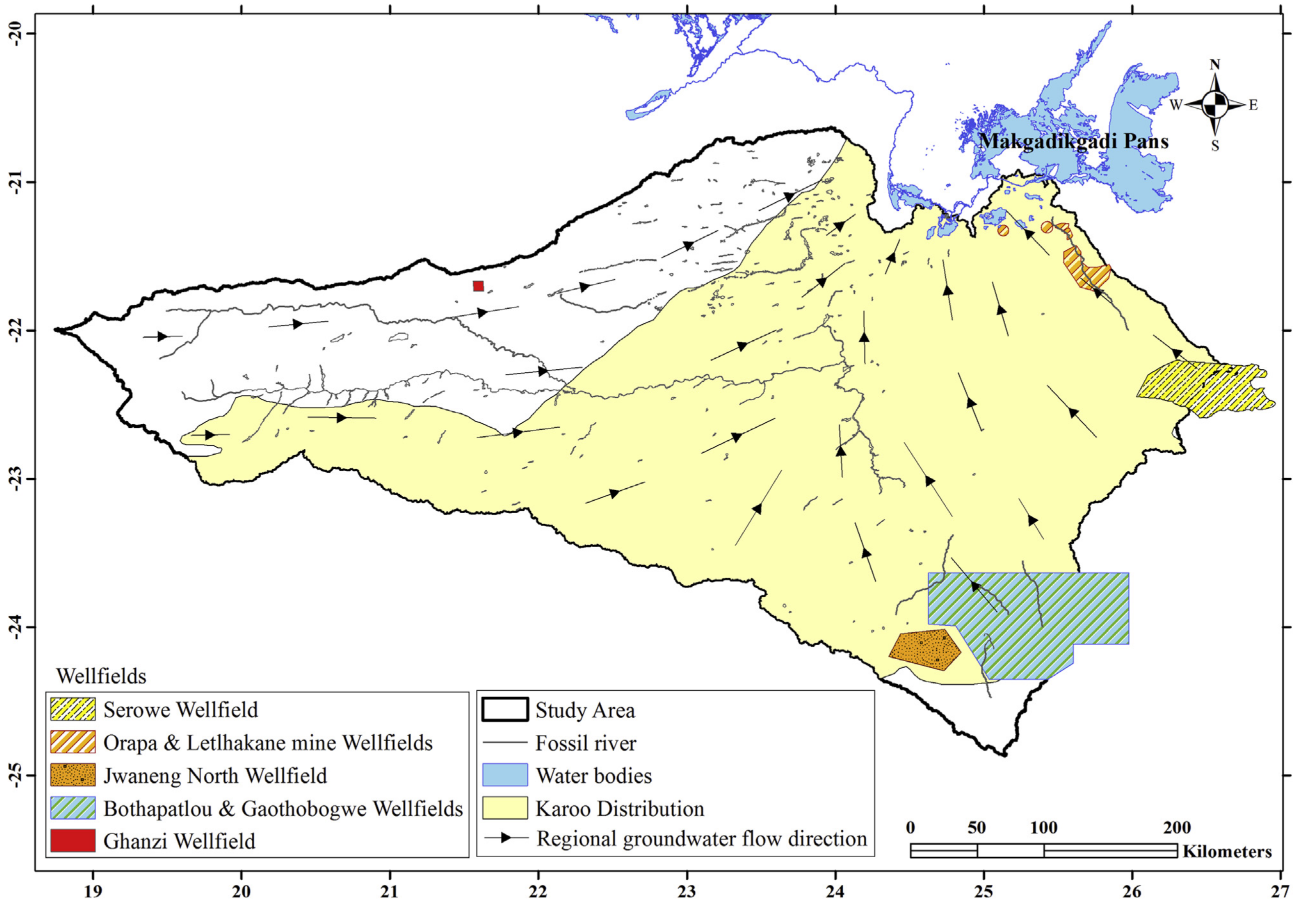

Fig. 4. General inter-layer groundwater flow pattern and major wellfields in the Central Kalahari Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.1.2. *Karoo Supergroup*

The Karoo Super group Formation, in which the CKB groundwater resources occur, has been sub-divided by Smith (1984) into the Lower Karoo (Dwyka, Ecca and Beaufort Groups) and Upper Karoo (Lebung and Stormberg Groups) based on a regional unconformity (Table 1). Only the Karoo Groups that are present in the CKB and have hydrogeological importance are described. As such, the Dwyka Group is not considered.

2.1.2.1. Ecca Group. The Ecca Group is divided into different formations in different Sub-Basins (Table 1). Generally this group consists of inter-layered sandstone, siltstone, mudstone with carbonaceous mudstones and coal seams (Smith, 1984). Thicknesses of different units corresponding to different formations vary spatially, so it is difficult to define their boundaries, particularly that most of the boreholes drilled in the area did not reach the bottom of the Ecca Group. The Ecca Group represents the principal aquifer in the South-Western Botswana and Kweneng Sub-Basins (Smith, 1984) (Figs. 2 and 3).

2.1.2.2. Beaufort Group. The Beaufort Group follows conformably from the Ecca Group and is characterized by a largely argillaceous, non-carbonaceous and multi-coloured (yellow, brown, green, greenish grey, purple, cream, white and light grey) sequence of mudstones and subordinate siltstones, with minor fine to coarse grained sandstone intercalations (Smith, 1984). The Beaufort Group subcrops under the Kalahari Sand in the southern CKB (Fig. 3).

2.1.2.3. Lebung Group. The Lebung Group lies uncomformably on the Beaufort Group. It is composed of sandstone and mudstone formations, which have local names in different Karoo Sub-Basins (Table 1, Figs. 2 and 3). In the Lebung Group, there is a downward progression from medium to fine grained, well sorted, reddish to white, massive but fractured sandstones to an argillaceous reddish brown mudstones and siltstones (Smith, 1984). The Ntane and Nakalatlou Sandstone Formations (Table 1) are the principal aquifers, with the former covering the majority of CKB (Smith, 1984).

2.1.2.4. Stormberg Basalt Group. This group forms the uppermost, volcanic unit of the Karoo Super Group (Table 1), which has spatially limited extent (Fig. 3). It consists of an extensive, and locally thick (>100 m) sequence of tholeiitic flood basalts. That basalt is characterized by weathered green to reddish purple, amygdaloidal lava flows, dark grey when fresh (Smith, 1984).

2.1.3. *Post-Karoo Group*

2.1.3.1. Kalahari Group. Post-Karoo (Table 1), superficial deposits of the Kalahari Group (commonly termed 'Kalahari Beds' or 'Kalahari Sands'), cover the whole study area and have variable thickness ranging from about 6 to more than 200 m. This group comprises a discordant and highly variable sequence of loose to poorly consolidated sand, silcrete and calcrete intercalations of variable proportions, subordinate to minor ferricrete, silcretized/calcretized sandstones and mudstones (Smith, 1984). The large Kalahari Sand thickness, limits recharge in the CKB (Mazor, 1982).

2.2. *Structural geology*

The principal structural elements in the CKB have been defined using aeromagnetic, seismic and gravity data interpretation (Haddon, 2005; Hutchins and Reeves, 1980). The major structural features in the CKB are: the N-S trending Kalahari Line, the NE-SW trending Makgadikgadi Line, the NE-SW trending Tsau Line and the E-W trending Zoetfontein Fault (Carney et al., 1994) (Fig. 3). The Makgadikgadi and Kalahari Lines are major thrust faults, which originated ∼2 Ga ago (Carney et al., 1994). The Kalahari Line defines the western edge of the Kapvaal Craton while the Makgadikgadi Line, the north-western edge of the Zimbabwe Craton (Carney et al., 1994; Key and Ayres, 2000; Pouliquen et al., 2008). The Tsau Line is a series of thrust faults along the strike of the Ghanzi meta-sediments (Ramokate et al., 2000). The Zoetfontein Fault developed during major orogenic episodes in the Lower Proterozoic Era (Smith, 1984). Previous studies by Dietvorst et al. (1991) and Bureau de Recherches Géologiques et Minières (1991) have clearly indicated that movement of pre-existing structures subsequent to lithification in the Zoetfontein Fault, together with the development of the complex fracture pattern, plays a significant role in the hydrogeology of the Karoo strata and has a major influence on the yields of boreholes.

2.3. Hydrogeology

The hydrogeological regime of the CKB study area is significantly influenced by geology. The principal aquifers in the CKB are: Ecca Aquifer, Lebung Aquifer and the Ghanzi Aquifer (Table 1). It is remarkable that despite deep occurrence of groundwater (>60 meters below ground surface), in majority of the CKB, the main regional groundwater flow (Fig. 4) follows the topography, i.e. it is directed from the higher elevated areas along the water divides in the west, south and east, towards lowest depression area around Makgadikgadi Pan (de Vries et al., 2000). There are no permanent surface water bodies in the study area and thus de Vries et al. (2000) characterized the CKB as a closed surface water basin with an internal groundwater drainage system, outflowing towards a natural discharge area of Makgadikgadi Pans (Fig. 4).

Groundwater replenishment by diffuse recharge is of paramount importance in the CKB since that recharge dictates the amount of groundwater safe yield that can be extracted sustainably from aquifers. However, the high potential evapotranspiration rates due to large vapour pressure deficit, the thick (typically >60 m) sandy unsaturated zone, and abundant ‘thirsty’ Kalahari plants very efficient in taking up unsaturated zone moisture (Lubczynski, 2009), do not favour aquifer replenishment. Such environmental conditions prompted researchers to challenge occurrence of groundwater recharge. For example de Vries (1984) had ruled out groundwater recharge in the Kalahari stating that the current piezometric surface is a residual-fossil feature, resulting from its decay since the last fluvial period, which ended 12 millennia ago. However, later in his other studies, he admitted few mm per annum recharge occurring at the CKB fringes (de Vries et al., 2000). Also Mazor (1982) showed active recharge in Kalahari fringes, i.e. in Morwamusu and Kweneng areas, despite the thick Kalahari Sand of about 100 m. These observations were confirmed by recent environmental tracer and groundwater flow modelling studies, which stated that CKB recharge is only incidentally present, being restricted to very wet years/seasons (such as for example 1999–2000), occurring every 5–10 years (Obakeng et al., 2007); in the eastern fringe of the CKB, where the mean annual rainfall is ∼450 mm, the mean annual recharge is in order of 5–10 mm yr^{-1} while in the central CKB where the mean annual rainfall is ∼350 mm, the mean annual recharge is <1 mm (de Vries et al., 2000; de Vries and Simmers, 2002; Gieske, 1992; Lubczynski, 2006, 2009; Obakeng et al., 2007; Selaolo, 1998). The recharge in the far western CKB in Namibia, has not been investigated yet.

Groundwater, wellfield abstractions from aquifers in the CKB, are located in the inhabited fringes of the CKB (Fig. 4) as documented by Snowy Mountains Engineering Corporation and EHES Consulting Engineers (2006). The main groundwater abstractor in the CKB is the Debswana Diamond Mining Company (DDMC), at three locations; Jwaneng, Letlhakane and Orapa mines.

The Jwaneng mine, in the South-Eastern part of CKB, utilizes the Jwaneng North Wellfield where groundwater is abstracted from the Ecca aquifer. The Orapa and Letlhakane mines, in the North-Eastern part of the CKB, have a series of wellfields where groundwater is abstracted from the Lebung Aquifer (Fig. 4). Water supply abstraction for major villages from the Ecca Aquifer in the southern part of the CKB, takes place at Gaothobogwe Wellfield, adjacent to the Jwaneng North Wellfield and at the recently developed Bothapatlou Wellfield. In the eastern part of the CKB, at the Serowe Wellfield, groundwater abstraction is from the Lebung Aquifer and in the North-Western at Ghanzi Wellfield, the abstraction is from the Ghanzi Aquifer (Fig. 4) (Snowy Mountains Engineering Corporation and EHES Consulting Engineers, 2006). There are also some minor abstractions from all the three aquifers for settlement water supply and livestock watering.

3. Methodology of setting up CKB conceptual model

The hydrostratigraphic unit modelling, system parameterization, flow system analysis, preliminary water balance and hydrogeological boundary conditions were used as steps in development of an efficient method of integrating data from various sources at various scale, for setting up hydrogeological conceptual model of a large and complex, CKB multi-layered aquifer system.

3.1. Borehole and spatial data

Borehole information, spatial geological data (including shapefiles), geological bulletins and hydrogeological reports done by groundwater consults were sourced from Botswana Geoscience Institute (BGI, former Department of Geological Survey) and Department of Water Affairs (DWA). The geological shapefiles for Namibia were downloaded online. Water levels were sourced from DWA, DDMC and Directorate of Water Resources Management in Namibia (DWRM). The digital elevation model (DEM) at 90 m spatial resolution was obtained from Shuttle Radar Topography Mission (SRTM) (Jarvis et al., 2008). The developed borehole database contained altitudes, lithological logs, water strikes and rest water levels. Published Botswana geological map (Key and Ayres, 2000) as well as hydrogeological reports from groundwater consultants (Geotechnical Consulting Services (Pty) Ltd, 2014; Pacific Consultants International and SANYU Consultants INC, 2002a,b; Water Surveys Botswana (Pty) Ltd, 2008; Water Surveys Botswana (Pty) Ltd & Aqualogic (Pty) Ltd, 2007; Wellfield Consulting Services (Pty) Ltd, 2001, 2007, 2012) provided additional geological information and hydrogeological data like aquifer transmissivity and hydraulic conductivity.

3.2. Geological modelling and hydrostratigraphic units

The RockWorks version 17 software package, further referred to as RockWorks, was used for geological and hydrogeological data analysis and management, and for modelling topologiacl surfaces and visualization of hydrostratigraphic units and cross-sections. The RockWorks, an easy to use software for 3-D modelling of subsurface geology (Trabelsi et al., 2013) and hydrostratigraphy, handles spatial, surface and subsurface data providing several methods of gridding and interpolating borehole data to build 3-D spatial model, including inverse distance, kriging, distance to point and triangulation. In this study, five km node spacing and the inverse distance interpolation method with power two, was chosen due to its ability to optimally interpolate faulted surfaces by giving less weight to far distant points, thus representing faulted surfaces better.

A six hydrostratigraphic units’ schematization (Anderson et al., 2015) for the CKB system (right column of Table 1) was deduced and proposed, based on detailed analysis of borehole data and related geological formations, subsurface lithology and groundwater occurrence. For example, in Mmamabula Sub-Basin, the stratigraphic Lebung Group consisting of Ntane and Mosolotsane Formations, was split into two hydrostratigraphic units, the Lebung Aquifer represented by Ntane Sandstone Formation and the Inter-Karoo Aquitard represented by argillic Mosolotsane Formation combined with underlying Thabala Formation of the Beaufort Group characterized by similar argillic composition. After systematic identification of the six hydrostratigraphic units, spatial definition of these units was further elaborated in the RockWorks.

Individual borehole coordinates, elevations, hydrostratigraphic unit intervals, deduced from borehole lithological logs, and digitised major faults from geological shapefiles were added to RockWorks Borehole Manager tool for interpolation. The 3-D solid model of hydrostratigraphic units was then generated and analysed. This was an iterative process until the satisfactory hydrostratigraphic thicknesses replicating their known spatial representation was achieved. Different fault angles were also tested and a 90^0 block faulting angle was set for all the regional faults. Also spatial location of boreholes used for hydrostratigraphic unit modelling were considered adequate to address issues of aquifer wedging and hydrostratigraphic displacement due to faulting as some of them were beyond the CKB model domain. Where borehole lithological logs were insufficient, spatial extent of the hydrostratigraphic units was constrained by geological shapefiles, which have been deduced using geophysical methods. For visual presentation, the vertical interval of hydrostratigraphic units were exaggerated 200 times. The resultant 2-D cross sections, drawn along sections of interest, were then used to visualize the spatial extent of hydrostratigraphic units.

The thicknesses of individual hydrostratigraphic units were exported from the 3-D geological model as XYZ files and further used to display and examine their spatial extent using ArcGIS 10.4 GIS software, further referred to as ArcGIS. That data export was done because of ArcGIS superior visual display.

3.3. System parameterization

The CKB aquifer transmissivity data (T) were extracted from 358 pumping tests documented in groundwater consultant reports (Geotechnical Consulting Services (Pty) Ltd, 2000, 2014; Pacific Consultants International and SANYU Consultants INC, 2002a,b; Water Surveys Botswana (Pty) Ltd & Aqualogic (Pty) Ltd, 2007; Wellfield Consulting Services (Pty) Ltd, 2001, 2007, 2012). As log-normally distributed spatial property, the T data were interpolated using inverse distance of power two. That interpolation was carried out in ArcGIS software. The aquifer hydraulic conductivities (K) were derived from T, dividing them by corresponding aquifer thicknesses. The aquifer storage parameters were extracted from 116 piezometric pumping tests data and lithology of borehole logs documented in groundwater consultant reports. The data to estimate aquitards' K and unsaturated zone parameters were also assigned based on groundwater consultancy reports and general literature guidelines addressing hydraulic conductivities of semi-permeable lithological units (Brassington, 1998; Freeze and Cherry, 1979).

3.4. Flow system analysis

Flow system of multi-layered CKB is complex, despite the fact there are no surface water bodies interacting with groundwater; there are only ephemeral rivers and streams, infiltrating water into subsurface shortly after intense rains. Consequently there is only diffuse rain-recharge, which is erratic and on average in order of only few millimetres per year at most and only following a wet year (de Vries et al., 2000; Obakeng et al., 2007). Hydraulic heads for each aquifer were defined from the borehole groundwater level data acquired from DWA, DDMC and DWRW. The hydraulic heads of each aquifer were spatially interpolated using kriging method in ArcGIS, despite sparsely distributed boreholes in some parts of the CKB. In locations with large separation distances between boreholes, artificial control points were used. The interpolated heads defined potentiometric maps which further determined groundwater flow directions. The aquifer flow systems, locally connected with overlying unconfined Kalahari Sand Unit (KSU) are: i) Lebung Aquifer; ii) Ecca Aquifer; iii) Ghanzi Aquifer. In the flow system analysis, particular attention was dedicated not only to aquifer interactions with KSU but also to interrelations between the three flow systems, each interaction pair regulated by leakance of an intra-aquitard.

3.5. Preliminary water balance

The only input of water in the CKB is precipitation. The main output is evapotranspiration and other two small output contributors are: i) groundwater abstraction for habited areas and for wildlife and ii) groundwater outflow towards Makgadikgadi Pans discharge area (Fig. 4).

3.6. Hydrogeological boundary conditions

In definition of boundary conditions, first physical boundaries such as spatial extent of hydrostratigraphic units, surface topography and major tectonic structures were analysed. Next, the result of that analysis was cross-referenced with the regional potentiometric maps, extending outside the CKB, to deduce regional flow directions. In case of no distinct physical boundaries, that analysis allowed to delineate external groundwater outflow boundaries, external no-flow boundaries along (parallel to) major streamline directions and characterize internal boundaries such as preferential flow lines along major fault systems and barriers of groundwater flow.

4. CKB conceptual model

4.1. Geological modelling and hydrostratigraphic units

The six-hydrostratigraphic units within the Karoo Super Group Formation and the Pre-Karoo rocks are identified based on lithological and hydrogeological analysis and are marked by different colors in Table 1: i) Kalahari Sand Unit (KSU); ii) Stormberg Basalt Aquitard (SBA); iii) Lebung Aquifer; iv) Inter-Karoo Aquitard (IKA); v) Ecca Aquifer; and vi) Ghanzi Aquifer. They are also presented spatially in series of hydrostratigraphic cross-sections in Fig. 5 and Fig. 6. These cross-sections present spatial extent and thicknesses of the hydrostratigraphic units, geometric and inter-hydrostratigraphic relationships, particularly around the regional faults.

4.1.1. Kalahari Sand Unit (KSU)

The KSU, is the first surficial unit, composed of sandy, unconsolidated to semi-consolidated deposits. It is the only hydrostratigraphic unit with continuous spatial extent in the whole CKB. Its thickness is spatially variable, ranging from 6 m in the western part to more than 100 m in the central and northern parts of the CKB (Figs. 6 and 7a). The characteristic feature of this unit is that 80–100% of its thickness is unsaturated so only its bottom part is locally saturated. If directly underlain by any of the aquifers, i.e. Lebung, Ghanzi or Ecca, then it is in hydraulic contact with that aquifer. The KSU is not productive within the CKB, therefore it is not referred as an aquifer, even though perched saturated units occur in its profile.

4.1.2. Stormberg Basalt Aquitard (SBA)

The SBA is a hydrostratigraphic unit non-uniformly distributed, composed of sparsely-fractured basalt (Fig. 3). Its thickness is spatially variable ranging from 0 to ~200 m, due to the block faulting and basin morphology (Figs. 6 and 7b). The SBA has been eroded in the southern

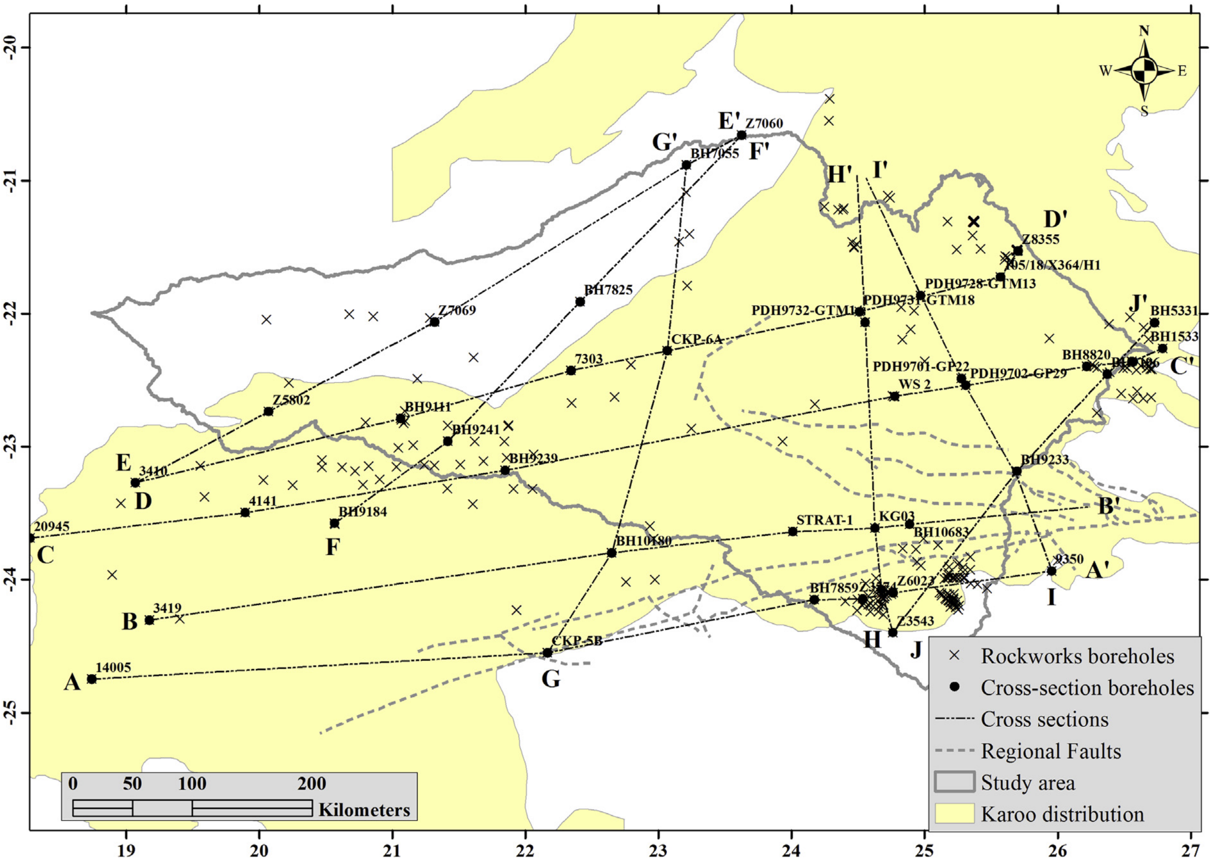

Fig. 5. Spatial distribution of boreholes used in RockWorks database and locations of 10 selected hydrostratigraphic cross-sections in the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

part of the Zoetfontein Fault, where significant uplifting occurred resulting in a horst structure as seen in Fig. 6 sections H-H, I-I and J-J. The thickest SBA of more than 200 m, is in the CKB centre, which likely is a result of sufficient space release after deepening of the basin (Fig. 6 sections C-C′ and H-H′ and Fig. 7b). The thick SBA in central part of Zoetfontein Fault zone can be attributed to significant down-faulting of the graben structure, thus preserving the original stratigraphy of the basin. The SBA is considered as highly heterogeneous aquitard.

4.1.3. Lebung Aquifer

The Lebung Aquifer, is one of the most productive aquifers in the CKB. It is composed of dual porosity sandstone characterized with spatially varying thickness, ranging from zero meters in the north-western part of the CKB where it wedges out and also in the southern part of the Zoetfontein Fault where it has been eroded as a result of significant uplifting, to ~230 m in the north-eastern and south-western parts of the CKB (Fig. 7c). The depth of the top of the Lebung Aquifer is also spatially variable, being significantly influenced by deepening of the basin towards the CKB centre and by regional faulting, mainly by Zoetfontein Fault (Fig. 6), being the deepest in the central part of the CKB where it also coincides with the thickest SBA. Where overlain by SBA, the Lebung Aquifer is confined but where the SBA is missing, it is hydraulically connected with the overlying KSU creating one unconfined aquifer (provided KSU is saturated at its bottom part) as can be seen in Fig. 6 sections B-B′,C-C′ and H-H’. In the western part of CKB, where IKA is absent, the Lebung Aquifer is hydraulically connected with the underlying Ecca aquifer.

4.1.4. Inter-Karoo Aquitard

The IKA, is composed of inter-changing low permeability mudstones and siltstones, underlying the Lebung Aquifer and overlying the Ecca Aquifer. It has low, spatially variable permeability, ranging from nearly impermeable to semi-permeable. Its thickness is spatially variable, ranging from zero meters in the north-western and southern part of the CKB, to ~250 m in the central part (Fig. 7d). The depth to the top of the IKA is also spatially variable and significantly controlled by deepening of the basin towards central CKB and also by regional faults (Fig. 6). The low permeability of this unit ensures a very low groundwater exchange between the Lebung and the underlying Ecca Aquifers, thus acting as an aquitard confinement to the Ecca aquifer (Snowy Mountains Engineering Corporation and EHES Consulting Engineers, 2006). Where the IKA is absent, the Ecca Aquifer is in hydraulic contact with the overlying Lebung Aquifer, but in locations where the Lebung Aquifer and the SBA are missing, the Ecca Aquifer is hydraulically connected with the KSU.

4.1.5. Ecca Aquifer

The Ecca Aquifer is composed of an alternating sugary-grained sandstone with coal seams, characterized by smooth transition between different formations (Smith, 1984). It has a spatially varying thickness ranging from zero in the north-western CKB where it wedges out, to ~290 m in the southern part of the Zoetfontein Fault, where significant uplifting was followed by erosion of the SBA, Lebung Aquifer and even IKA (Fig. 7e) so that Ecca is directly overlain by KSU. The thickness of the Ecca Aquifer in the north-eastern part of the CKB is uncertain due to limited amount of borehole data penetrating the whole Ecca Aquifer thickness. Depth to the top of the Ecca aquifer is spatially variable and is largely controlled by deepening of the basin towards central CKB and the graben and horst structures of the Zoetfontein Fault zone (Fig. 6). The Ecca Aquifer is the deepest in the southern part of the CKB around the Zoetfontein graben structure, where all the stratigraphic units of the Karoo Super Group are present, representing the original Karoo

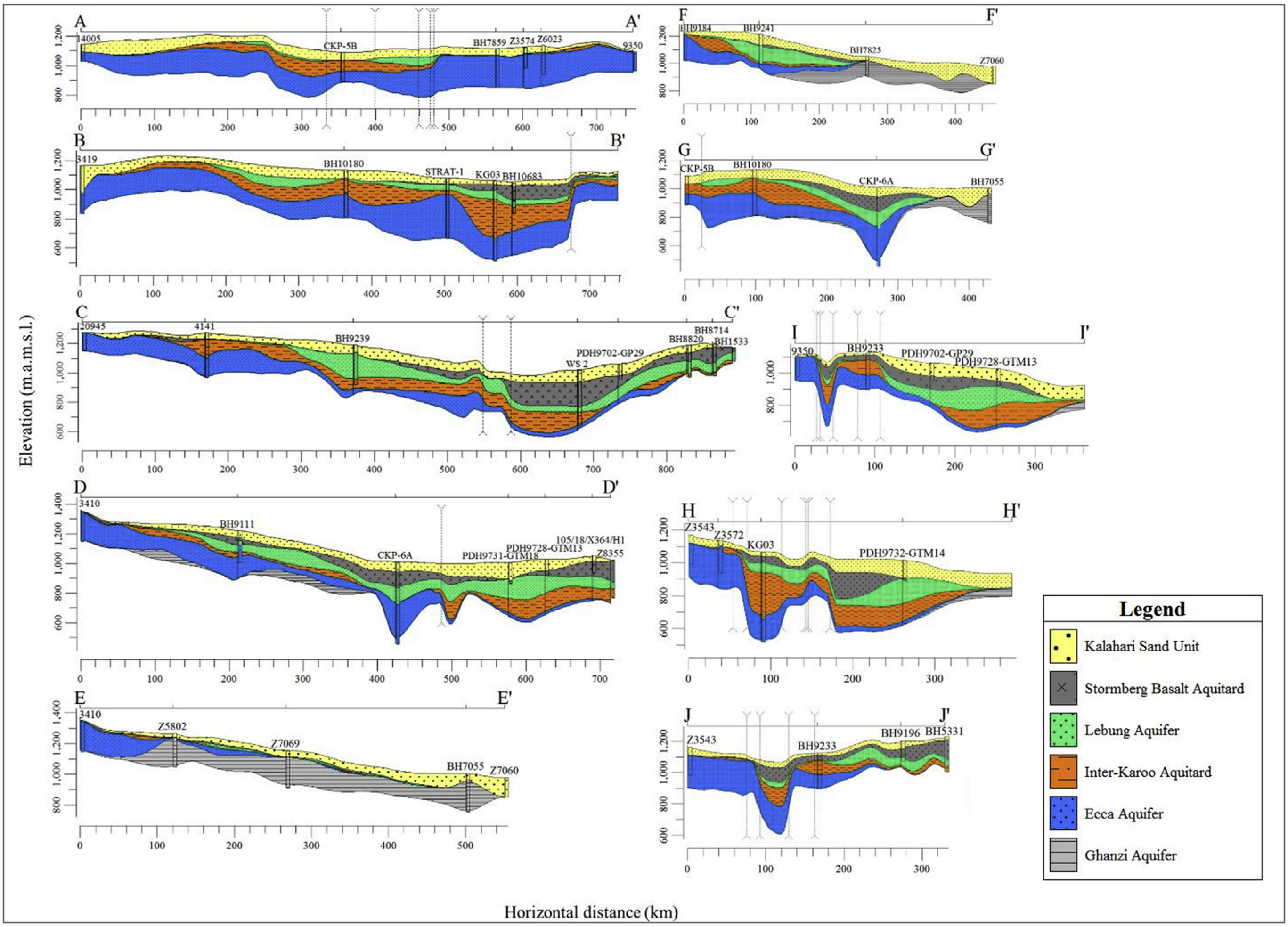

Fig. 6. Hydrostratigraphic cross-sections - vertical dashed lines show locations of faults. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sedimentation (Snowy Mountains Engineering Corporation and EHES Consulting Engineers, 2006). The Ecca Aquifer is confined where overlain by IKA (Fig. 6). Where the IKA is absent, the Ecca Aquifer is hydraulically connected with the overlying Lebung Aquifer and where the Lebung Aquifer and the SBA are missing, it is hydraulically connected with the KSU creating one unconfined aquifer (Fig. 6). The direct hydraulic contact between Ecca and Lebung Aquifers can be seen in Fig. 6 in sections D-D′ and I-I′ while between Ecca Aquifer and KSU in section H-H′ and J-J’.

4.1.6. *Ghanzi Aquifer*

The Ghanzi Aquifer is a sandwich of fractured arkosic sandstones, siltstone, mudstone and rhythmite; at nearly all its spatial extent is directly overlain by the KSU, the two being in hydraulic contact. It is only present in the north-western part of the CKB (Fig. 7f). Its thickness is spatially variable, ranging from zero due to wedging towards centre of CKB, to ~230 m (Figs. 6 and 7f) towards the north-western CKB. The depth to the top of the Ghazi Aquifer is also spatially variable, shallow where the KSU is the only overlying hydrostratigraphic unit and deeper towards the basin centre, as can be seen in Fig. 6 sections E-E′ and F-F’.

4.1.7. *Basement Aquiclude*

Basement aquiclude is represented by the impermeable unit underlying the deepest aquifer unit in a given location of the flow system. It can be Dwyka, Waterberg, Transvaal, Gaborone Granite, Kanye Formation or Okwa Complex (Table 1).

4.2. *System parameterization*

The KSU is not a productive aquifer in the CKB, so there are no parametric estimates from pumping tests. However, that sandy, permeable and relatively homogeneous unit, plays an important role in redistribution but also restriction of groundwater recharge to underlying aquifers because of its large thickness. The horizontal and vertical hydraulic conductivities of the KSU, obtained from Snowy Mountains Engineering Corporation and EHES Consulting Engineers (2006), range from 1.0 to 15.0 md^{-1} and from 0.1 to 2.0 md^{-1} respectively. The SBA is represented by a secondary porosity basalt rock type that has negligible storage (Snowy Mountains Engineering Corporation and EHES Consulting Engineers, 2006) and low, fracture-based, vertical hydraulic conductivity in order of 3.0×10^{-4} md^{-1} (Brassington, 1998; Freeze and Cherry, 1979). The K of the Lebung aquifer presented in Fig. 8a, varies from less than 0.1 to more than 10.0 md^{-1}, which is in the range typically associated with sandstones (Brassington, 1998; Freeze and Cherry, 1979) while the T, from 10.0 to 100.0 m^2d^{-1} (Fig. 8d). The relatively uniform K and T in the central part of the CKB of Lebung Aquifer is uncertain due to data limitation, hence it needs to be optimised during the numerical model simulation. The IKA is composed of semi-permeable layer sequence of siltstones and mudstones, which can be characterized by a horizontal hydraulic conductivity ranging from 8.6×10^{-7} to 1.2×10^{-3} and vertical hydraulic conductivity ten times lower than the horizontal hydraulic conductivity (Brassington, 1998; Freeze and Cherry, 1979). The low IKA vertical K assures limited hydraulic contact between Ecca and Lebung aquifers. The K and T of the

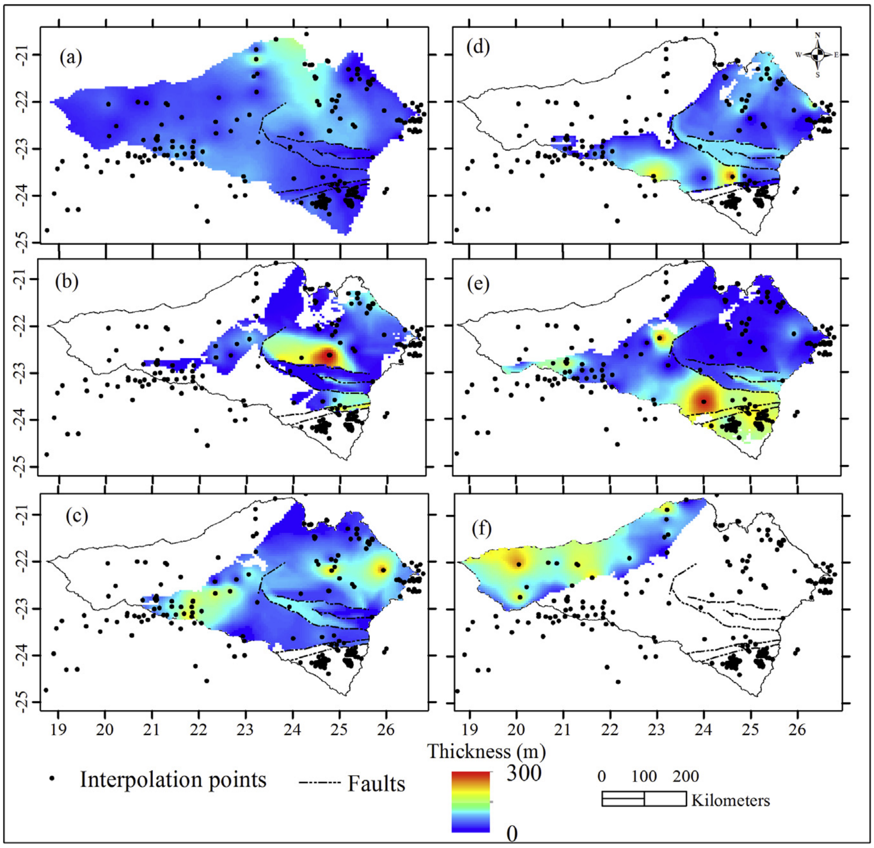

Fig. 7. Thickness of the six hydrostratigraphic units in the Central Kalahari Basin. Alphabetic letters denotes: a) Kalahari Sand Unit; b) Stormberg Basalt Aquitard; c) Lebung Aquifer; d) Inter-Karoo Aquitard; e) Ecca Aquifer; f) Ghanzi Aquifer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

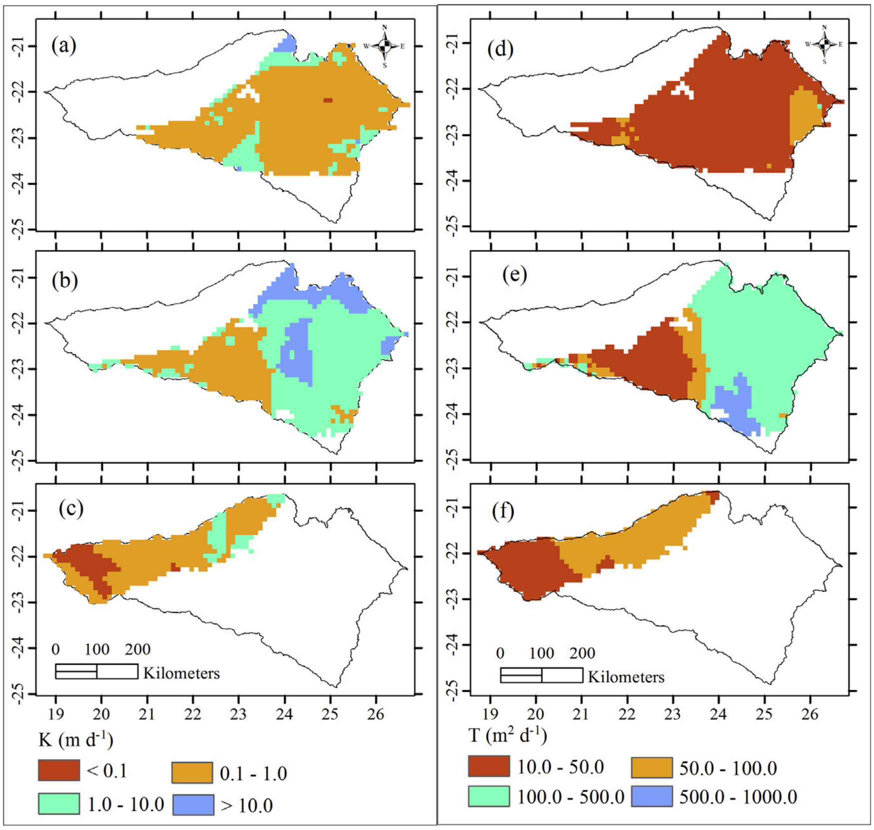

Fig. 8. Aquifer hydraulic conductivity (K) and transmissivity (T) in the Central Kalahari Basin: a) Lebung Aquifer K; b) Ecca Aquifer K; c) Ghanzi Aquifer K; d) Lebung Aquifer T; e) Ecca Aquifer T; f) Ghanzi Aquifer T. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

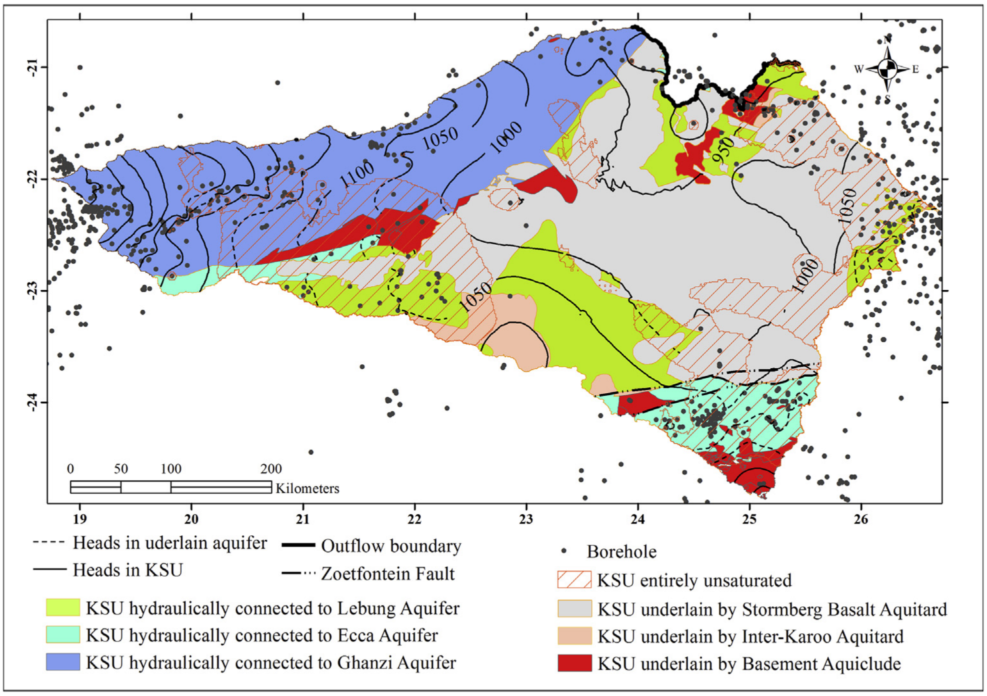

Fig. 9. Hydraulic heads and boundary conditions of an unconfined Kalahari Sand Unit (KSU) and Ghanzi Aquifer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Ecca Aquifer (Fig. 8b and e, respectively) are highly spatially variable, ranging from low values in the eastern side of the CKB, to large values in the western side, where locally $K > 10\ \mathrm{md}^{-1}$ and $T > 500\ \mathrm{m}^2\mathrm{d}^{-1}$. The large area with T in range 100–500 $\mathrm{m}^2\,\mathrm{d}^{-1}$ in the north-eastern part of CKB is uncertain due to limited amount of data, hence it needs to be optimised during the numerical model simulation. The Ghanzi Aquifer is hydraulically connected with KSU. Like in the case of Ecca Aquifer, the K and T of metamorphic, fractured-arkosic composition changes spatially from low values in the western part to higher in the eastern part (Fig. 8c and f, respectively), with K ranging from less than 0.1–10.0 $\mathrm{m\,d}^{-1}$ and T from 10.0 to 100.0 $\mathrm{m}^2\,\mathrm{d}^{-1}$.

4.3. Flow system, water balance and hydrogeological boundary conditions

4.3.1. Kalahari Sand Unit

The potentiometric map of the unconfined Kalahari Sand Unit (KSU) is presented in Fig. 9. This map considers a number of possibilities regarding KSU hydraulic relation with underlying units. Where the KSU is underlain by aquifers, such as Lebung, Ecca or Ghanzi, and the potentiometric surface is above the KSU bottom, then the lowest part of the KSU is saturated (continuous isolines); if the potentiometric surface is below the KSU bottom, then the KSU profile is entirely unsaturated (dashed isolines). If the KSU is underlain by aquitard or aquiclude and the potentiometric surface is above the KSU bottom, then the lowest part of the KSU is saturated, as unconfined layer isolated from the bottom; otherwise, the KSU is entirely unsaturated.

The flow pattern of the KSU is radially-concentric (Fig. 9). It converges from western, eastern and southern no-flow boundaries defined along the CKB watershed divides, towards the northern, Makgadikgadi Pans groundwater outflow boundary. That pattern, matches also the pattern of underlain aquifers and the regional pattern of groundwater flow, postulated by de Vries (1984) and de Vries et al. (2000). In the central-eastern part of the CKB, the KSU is saturated, being either on top of the SBA or hydraulically connected with underlain Lebung Aquifer. In the north-western part of the CKB, the KSU is in hydraulic connection with Ghanzi Aquifer, while the connection with Ecca occurs only within a little strip in the western area.

The thickness of the saturated part of the KSU profile, vary spatially from zero (stripped areas in Fig. 9) to 25 m (KSU thickness map not presented), hence the saturated thickness of the KSU is non-uniformly distributed. Regarding temporal variability of the saturated KSU thickness, it has to be noted that after substantial recharge, that thickness may gently increase, afterwards gradually declining due to downward leakage or due to groundwater evapotranspiration. In the KSU, there are also localized, perched layers, which however play negligible role in the CKB flownet system, eventually only in redistribution of recharge; therefore, the Kalahari perched layers are neglected in the regional CKB groundwater flow model.

4.3.2. Lebung Aquifer

The Lebung Aquifer has a spatially limited extent. Like the KSU, its hydraulic heads show a radially-concentric pattern, converging from western, southern and eastern no-flow boundaries, towards the northern Makgadikgadi Pans groundwater outflow boundary (Fig. 10). In the peripheral zone of the CKB, where the Lebung Aquifer is directly overlain by KSU (Fig. 10), they both create one hydraulically connected, unconfined aquifer. That hydraulic connection allows for recharge from the KSU into the Lebung Aquifer. In the remaining area, the Lebung Aquifer is confined by overlaying SBA although according to Smith (1984), there is localized leakage across the SBA due to relatively scarce fracture systems. It is interesting that the directions of the vertical leakages across the overlying SBA and the underlying IKA, are spatially variable. Those leakage directions depend on the potentiometric surface of the Lebung Aquifer relative to the overlying KSU and underlying Ecca aquifer, while the leakage rates across the SBA and IKA depend on the respective leakances.

At the southern part of the CKB, the groundwater flow system of the Lebung Aquifer is delimited by graben and horst discontinuity structures of the Zoetfontein Fault zone, schematic of which is presented in Fig. 11. Considering structural position of the Lebung Aquifer at the northern side of the fault, it is likely that this aquifer is in hydraulic contact across the fault with the Ecca Aquifer at the southern side, although that connection requires additional investigations.

The radially-concentric groundwater flow pattern in the Lebung

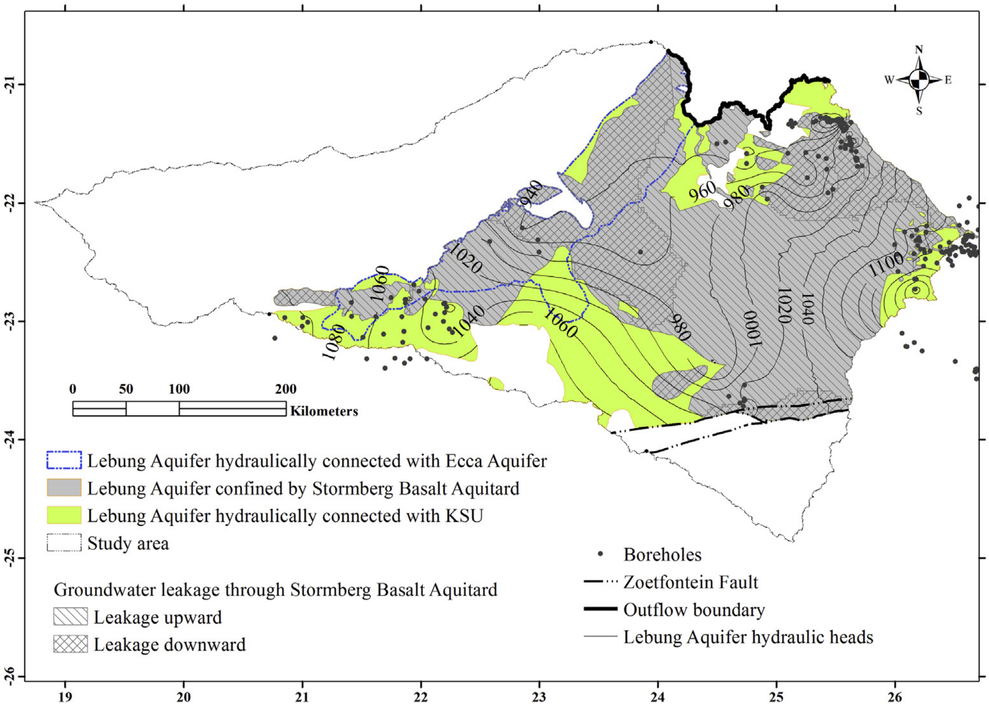

Fig. 10. Hydraulic heads and boundary conditions of Lebung Aquifer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

aquifer (and in KSU) implies its relatively simple water balance, where the Darcian lateral flow originated from water exchanges with overlying and underlying layers, is discharged at the northern outflow boundary and also by groundwater evapotranspiration as well as some well abstractions.

4.3.3. *Ecca Aquifer*

The flow pattern of the Ecca Aquifer is similar to the flow patterns of the Lebung Aquifer and KSU, i.e. the hydraulic heads show a radially concentric pattern converging from western, southern and eastern no-flow boundaries towards the northern outflow boundary at the Makgadikgadi Pans (Fig. 10). That similarity is influenced by good hydraulic Ecca Aquifer connections with: i) KSU in the southern part, towards south of Zoetfontein Fault (Figs. 9, Figs. 11 and 12) and in the western part (Fig. 12); with ii) Lebung Aquifer wedging at the north-western part (Fig. 12 as well as the cross-sections in Fig. 6); and with iii) Ghanzi Aquifer towards north-west.

The majority of the Ecca Aquifer within the CKB is confined by Inter-Karoo Aquitard (IKA) separating it from Lebung aquifer. The spatially variable vertical, upward or downward, leakage in the IKA, as presented in Fig. 12, is constrained by relative positions of the potentiometric surfaces of the Ecca and Lebung aquifers and by IKA

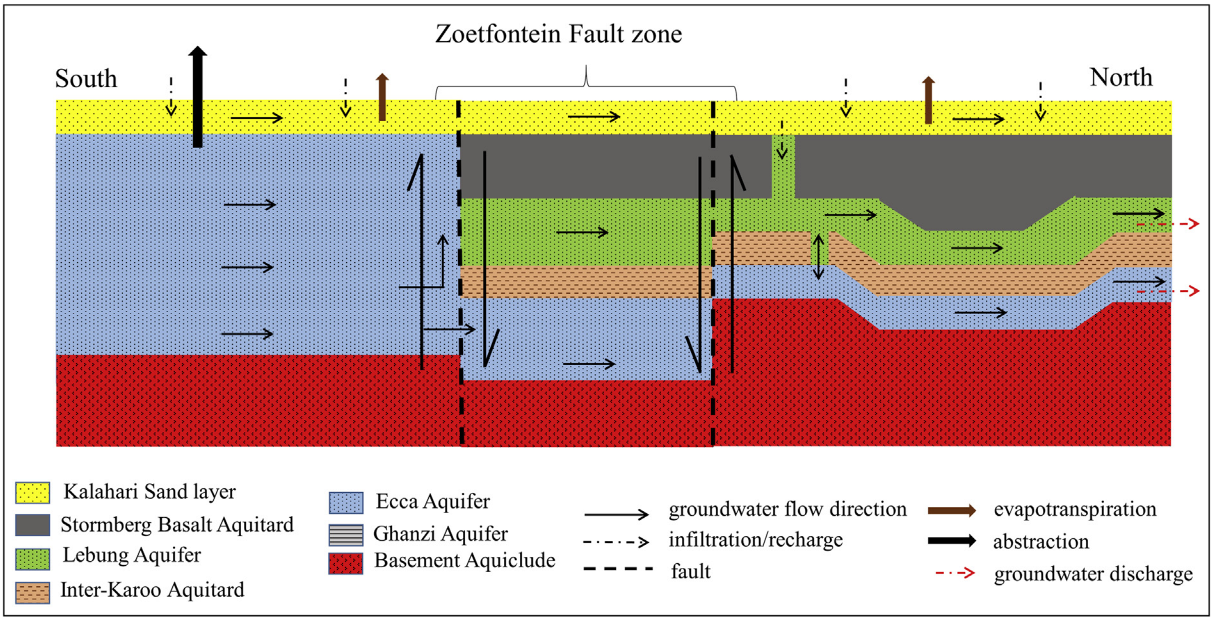

Fig. 11. Schematic of flow system adjacent to Zoetfontein Fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

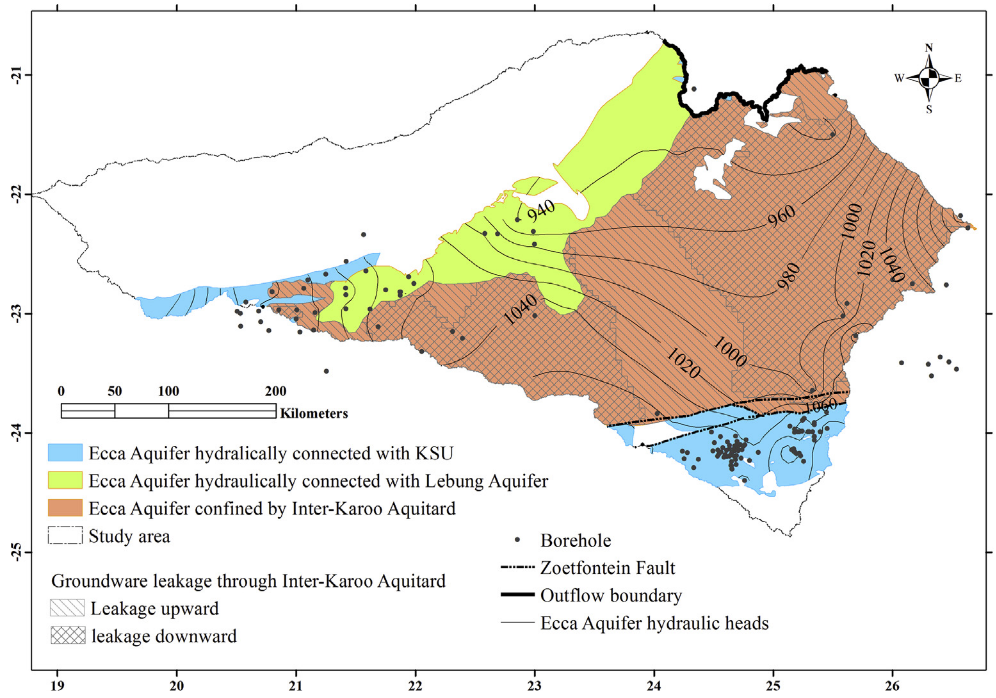

Fig. 12. Hydraulic heads and boundary conditions of Ecca Aquifer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

leakance.

It is hypothesized that the Ecca Aquifer (like Lebung) represents laterally closed system. It exchanges groundwater only with overlying layers (and losses some water by groundwater evapotranspiration and abstractions at wellfields located south of the Zoetfontein Fault, see Fig. 4), so that nearly-all the Ecca groundwater is discharged at the northern outflow boundary as the external boundaries are no-flow boundaries. The physical, wedging boundaries at the north-western and southern limits are reliable no-flow boundaries. The remaining external boundaries can be assigned as hydraulic no-flow boundaries along streamlines, in directions perpendicular to equipotential lines; however, some sections of these boundaries, particularly those under thick IKA, are uncertain as not sufficiently documented by adjacent boreholes. Nevertheless, if there is some flow across these boundaries, it is expected that it is negligible although at the current state of knowledge that hypothesis cannot be proved or rejected. Once numerical model is setup and calibrated, that hypothesis can be tested.

4.3.4. *Ghanzi Aquifer*

The Ghanzi Aquifer (Fig. 9), is the only aquifer present in the north-western CKB. In the large part of the CKB extent, it is directly overlain by KSU, so prone to recharge, and it is hydraulically connected with saturated KSU (continuous isolines) forming jointly one unconfined aquifer. The Ghanzi groundwater flow pattern, like of all other aquifers, is directed towards the northern outflow boundary of the Makgadikgadi Pans. In the south-eastern direction, the Ghanzi Aquifer is hydraulically connected with the Ecca Aquifer (Fig. 6 section E-E' and Fig. 9) and possibly also with Lebung Aquifer (Fig. 6, G-G). Considering that groundwater flow direction is parallel to the contacts with Ecca and Lebung aquifers, it is expected that the groundwater exchange with these aquifers is negligible. This means that all the water recharged through KSU into the Ghanzi Aquifer, except of groundwater evapotranspiration loses and Ghanzi Wellfield abstraction, is discharged at the northern outflow boundary.

5. Discussion

Systematic integration of various Central Kalahari Basin (CKB) data sets from various sources in the 3-D geological model, resulted in development of the hydrogeological conceptual model of the CKB (Table 1 and Fig. 13). The first important step in the model setup, was the definition of hydrostratigraphic units. Such definition requires good geological and hydrogeological knowledge. In this study, geology was pretty well defined from investigation boreholes and from geological studies of Key and Ayres (2000), Carney et al. (1994) and Smith (1984), although conversion of stratigraphic and lithological units into hydrostratigraphic units was still challenging due to not always clear regional meaning of Groups, Sub-basins and Formations and their inter-dependencies. Table 1, attempted to regulate that issue, proposing six hydrostratigraphic units, namely: Kalahari Sand Unit, Stormberg Basalt Aquitard, Lebung Aquifer, Inter-Karoo Aquitard, Ecca Aquifer and Ghanzi Aquifer.

Classification of the hydrogeological system of CKB into six hydrostratigraphic units was crucial for the development of the 3-D, CKB hydrostratigraphic model, presented in the form of cross-sections in Fig. 6. A comprehensive analysis of the geological formations (Table 1), lithological information from borehole logs and potential groundwater occurrences, were used not only as the basis for identifying hydrostratigraphic units but also for defining their spatial extents. This was in contrast to the study by Allen et al. (2008), where hydrostratigraphic units and their spatial extents, were deduced from borehole lithological descriptions only. In locations with inadequate borehole information, the geological shapefiles (Fig. 3) were used to constrain the spatial distribution of the hydrostratigraphic units and to fill in the missing information in spaces between borehole logs. This process was achieved through flexible, iterative modelling, applying combination of RockWorks and ArcGIS software.

Utilisation of 3-D geological modelling codes such as RockWorks, is particularly suitable for 3-D hydrostratigraphic models of large scale and complex aquifer systems such as proposed in this study, as it conveniently integrates available data of lithology, stratigraphy, structural geology, tectonics and most importantly hydrogeology, providing

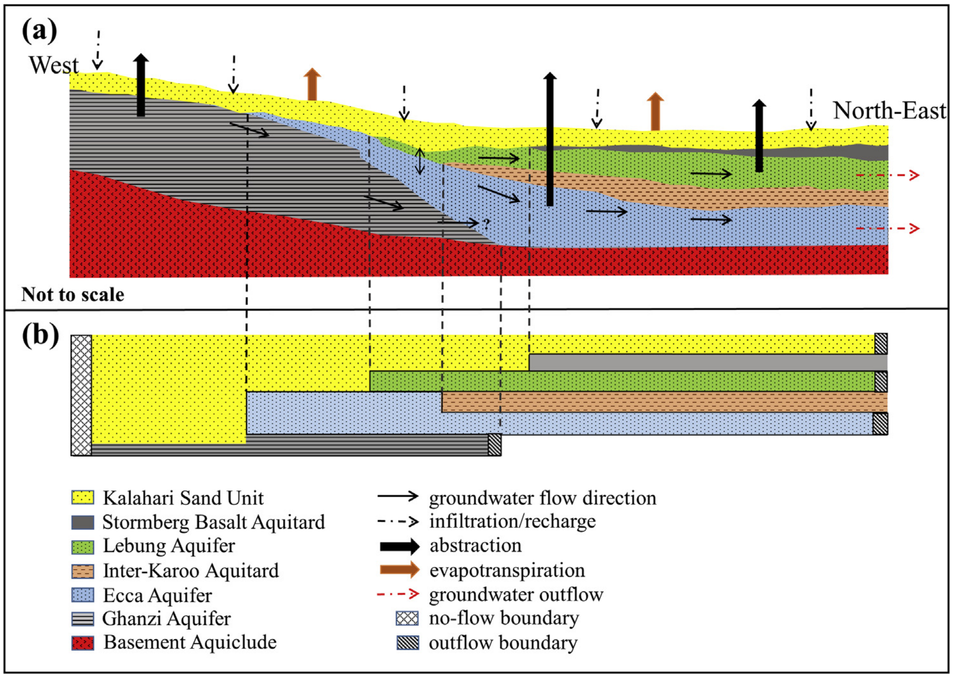

Fig. 13. Schematic diagrams of: **a)** hydrogeological conceptual model of the Central Kalahari Basin; **b)** numerical model schematization. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

opportunity of exporting any topological data of any required surface, for follow up numerical model. The RockWorks code, seems to be handier than software-based, hydrostratigraphic conceptualization built-in numerical modelling environments such as Groundwater Modelling System (GMS) for example used by Gurwin and Lubczynski (2005). This is mainly, because 3-D modelling codes such as RockWorks, are simpler in operation, requiring much less time to learn, while maintaining comparable capability i.e.: i) flexibility in data processing (e.g. database and conceptual model can be easily upgraded with new available data at any processing stage), particularly needed for the assessment of hydrostratigraphic information; ii) suitability for handling large data sets without compromising their computation time (Allen et al., 2008); iii) easy interfacing with any follow up numerical modelling code.

In hydrogeological conceptual models, hydraulic properties reflect spatial heterogeneity of a system and determine aquifer flows and aquitard leakages. Therefore, spatial system heterogeneity has to be defined carefully by assigning hydraulic parameters applying all information available for each hydrostratigraphic unit separately. Those parameters are further used in a numerical model, so will further be confirmed, eventually adjusted, during numerical model calibration (not part of this study). For the CKB aquifers, hydraulic parameters were assigned mainly based on pumping tests while for the KSU and for aquitards, based on lithology description of borehole logs. All the assigned hydraulic parameters fell in the ranges of their standard ranges as described in Freeze and Cherry (1979) and Brassington (1998).

In numerical model simulations, so also in setting up conceptual models, the shallowest, unconfined layer, is often meant as the one that is responsible for redistribution of recharge but not having large importance in lateral groundwater flow (Gurwin and Lubczynski, 2005; Hassan et al., 2014). Such layer, as in the CKB is the KSU, can be optimally modelled by variably-saturated numerical solutions, for example offered by MODFLOW-NWT unsaturated-zone flow (UZF1) Package (Niswonger et al., 2006). In that solution, the net recharge is inherently estimated, based on driving forces of precipitation and potential evapotranspiration and parameterization of surface, unsaturated and saturated zones. In the case of the CKB, the parameterization of the unsaturated zone, nearly entirely embedded within the KSU, is uncertain because of its large thickness (typically more than 60 m) and little hydraulic information about it, as the majority of investigation studies focusses on layers below the KSU.

The large thickness of unsaturated zone, and pretty dense and "thirsty" Kalahari vegetation with world-deepest roots and large potential evapotranspiration, imply large interception, transpiration and evaporation processes (Lubczynski, 2000, 2009), all three restricting the net recharge (R_n) replenishment of groundwater resources. As a result, the R_n is erratic and if present, then very low, i.e. in order of few mm per year only. Considering that spatial distribution of Kalahari woody vegetation is relatively uniform and that the Kalahari soil is quite homogeneous (Obakeng et al., 2007), it can be assumed that the KSU thickness, plays a major role in spatio-temporal redistribution of subsurface fluxes so also in R_n. That thickness, as defined in RockWorks, varies spatially from ~60 m at the eastern fringe, through more than 100 m at the central part of the CKB where recharge is unlikely, to less than 10 m at the western edge of the CKB, where the largest recharge, possibly more than 10 mm y^{-1} is expected, although to our knowledge, that recharge has not been validated yet.

In a conceptual model setting, it is important to characterize all groundwater flow systems of a study area. As the saturated part of the unconfined KSU is pretty thin (or not present) and underlain by any of the aquifers, Lebung, Ecca or Ghanzi (Fig. 9), then they jointly create flow system with that underlying aquifer. This means that in total there are three flow systems in the study area, Lebung, Ecca and Ghanzi, each of them eventually hydraulically connected with saturated bottom part of KSU. It is remarkable that all the three flow systems, have similar radial flow pattern, with groundwater moving from external boundaries towards northerly located Makgadikgadi Pans discharge area (Figs. 4, Fig. 9, Figs. 10 and 12). Such pattern was also postulated by de Vries et al. (2000).

Despite similar patterns of the three flow systems, there are substantial differences between their hydraulic heads. Such differences do represent driving forces of the vertical leakages across the aquitards. The shallowest, SBA aquitard, is spatially limited. It confines Lebung Aquifer, separating it from KSU. That confinement and related leakage depend on SBA leakance, i.e. on thickness and vertical hydraulic conductivity of the basalt, i.e. fracture openings and density of fractures

(Fig. 10). The Inter-Karoo Aquitard (IKA) has also important hydraulic role constraining leakage between Lebung and Ecca aquifers emphasized by locally large head difference. The IKA is composed of semi-permeable siltstone and mudstone so its vertical hydraulic conductivity is dependent on the lithological composition, i.e. mainly on the contribution of sandy fraction. It is remarkable that at the majority of the IKA extent, there is downward leakage because of the higher Lebung Aquifer heads than the Ecca Aquifer heads while the opposite leakage direction occurs only in the central part of the basin (Fig. 12). Such pattern follows Toth flownet system concept (Toth, 1963) and is typical for the hydraulics of sedimentary basins (Verweij, 1993). Considering parameterization of the two aquitards for the future numerical model setup, the leakances are unknown, so the preliminary-assigned, lithology-based leakances have to be calibrated within the numerical model (not part of this study).

The reliability of hydrogeological conceptual models are limited by available data quantity and quality. For example, in the CKB, the Ecca Aquifer thickness is generally uncertain because of limited number of boreholes penetrating the whole Ecca sequence. This particularly refers to the locations from central, towards the north and north-eastern part of the CKB, where large deepening of the basin takes place. In these locations, most of the boreholes are terminated either within the IKA or just after they intersect the Ecca. This problem is mitigated by presence of sparsely distributed deep exploration boreholes, penetrating the whole Karoo sequence, although such boreholes are pretty scarce. Nevertheless, Voss (2011) have argued that it is not necessary to bring all the complexity of geology into a descriptive groundwater model system just because real geology “looks” complicated thus bringing more uncertainties, hence the use of the sparsely distributed deep exploration borehole logs is deemed adequate.

Conceptual models serve as the critical background step for assembling numerical models. Therefore a transition between the two should be as smooth as possible. For that purpose, a simplified schematic diagram of the CKB hydrogeological conceptual model next to the corresponding, simplified proposal of numerical model schematization is presented in Fig. 13. In that proposal, the only source of water input into the CKB is precipitation. The main water output is evapotranspiration with other two, much smaller output contributors being groundwater abstraction for inhabited areas and wildlife and lateral groundwater outflow towards Makgadikgadi Pans’ discharge area.

Transition of hydrogeological conceptual models into numerical models is not straightforward. It varies with software packages and with their interfacing requirements (Cox et al., 2013). The proposed transition of the CKB conceptual model (Fig. 13a) into numerical model is presented in Fig. 13b. Considering that transition, still choice can be made for either quasi 3-D or full 3-D numerical model schematization (not part of this study). In quasi 3-D solution, there are only lateral flows in the aquifers and vertical leakages in the aquitards, the latter assumed not to have any storage. According to Anderson et al. (2015), the quasi 3-D numerical models have been surpassed by time because of such simplifying assumptions. In the case of the CKB, the main disadvantage of the quasi 3-D schematization is that it does not permit for realistic simulation of the spatial aquifer wedging typical in the CKB and also not for particle tracking option to determine groundwater residence time. As such, for the numerical modelling of the CKB, a fully 3-D numerical schematization is recommended.

6. Conclusions

This study has shown that a systematic approach of using 3-D geological modelling code such as RockWorks, is vital when developing hydrogeological conceptual models of complex-multi layered aquifer systems. Its strength is in simplicity of operation and iterative conjunctive use with other GIS-type of software. The RockWorks code supported in this study by ArcGIS, was useful in improving understanding of the spatial distribution of the CKB hydrostratigraphic units and their hydraulic properties. Besides, it allowed to define flow system interactions and contributed to definition of external and internal physical CKB boundaries. Therefore, the methodology presented in this study is highly recommended for development of conceptual models, particularly of large sedimentary, multi-layered hydrogeological systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.pce.2018.05.006.

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