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ORIGINAL ARTICLE

Groundwater Resource Assessment and Conceptualization in the Pilbara Region, Western Australia

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Abstract

The Pilbara region is one of the most important mining hubs in Australia. It is also a region characterised by an extreme climate, featuring environmental assets of national significance, and considered a valued land by indigenous people. Given the arid conditions, surface water is scarce, shows large variability, and is an unreliable source of water for drinking and industrial/mining purposes. In such conditions, groundwater has become a strategic resource in the Pilbara region. To date, however, an integrated regional characterization and conceptualization of the occurrence of groundwater resources in this region were missing. This article addresses this gap by integrating disperse knowledge, collating available data on aquifer properties, by reviewing groundwater systems (aquifer types) present in the region and identifying their potential, and proposing conceptualizations for the occurrence and functioning of the groundwater systems identified. Results show that aquifers across the Pilbara Region vary substantially and can be classified in seven main types: coastal alluvial systems, concealed channel iron deposits, inland valley-fill aquifers, karstified dolomites, sandstone aquifers (West Canning Basin), Permian/Cenozoic Paleochannels, and Fractured Rock aquifers. Coastal alluvial systems show the greatest regional potential as water sources and are currently intensively utilised. Conceptually, the main recharge processes are infiltration of precipitation associated with cyclonic events and the interaction with streamflows during summer season, whereas the main discharge mechanisms correspond to evapotranspiration from riverine and coastal vegetation, discharge into the Indian Ocean, and dewatering of iron-ore bodies to facilitate mining activities. Important gaps in the knowledge relate to aquifer connectivity and accurate quantification of recharge/discharge mechanisms.

Keywords Pilbara · Regional review · Paleovalley aquifers · Channel iron deposit (CID) aquifers

1 Introduction and scope

The Pilbara region in Western Australia is one of the most important mining hubs of the country. Total iron-ore production in Western Australia alone in the period 2012–2013 represented a quarter of the world's production (AUD$56 billion) and amounted to 73% of the total value of the West Australian mineral and petroleum sales (Kneeshaw and Morris 2014). This region is also one of the World Wildlife Fund's Global 200 Ecoregions selected for its unique and rich biodiversity, containing highly valued environmental assets intrinsically connected to groundwater systems (DoW 2010). Moreover, riverine pools sustained by groundwater discharge, groundwater-fed wetlands, and groundwater-dependent vegetation have an intrinsic cultural value to the indigenous communities inhabiting this region (Brodie et al. 2012; Alaibakhsh et al. 2017). These aspects are all

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conditioned by the occurrence of aquifers and the variations of groundwater levels, which may fluctuate due to water abstraction and/or climatic cycles, among others.

In this region, groundwater abstraction is dominated by mining activities, ca. 360 Mm^3/year, with nearly 52% used for consumptive use (DoW 2013a). Water utilities are another major water consumer in the region (ca. 22 Mm^3/year), with the Onslow, West Pilbara, and Port Hedland water supply schemes (see Fig. 1 for location) accounting for more than 85% of the town water consumption (DoW 2013a). Future projections of consumptive water use for the Pilbara region indicate that consumption will increase between 2.5- and 3-fold by 2042 under a low- and medium-growth scenario, respectively (for details on these scenarios, see DoW 2013a). It is, therefore, anticipated that even a low-growth scenario will put substantial pressure on the current water sources identified in the region.

The Pilbara region has an extreme climate with high temperatures and cyclonic rainfall events shaping the landscape. Orographic features such as the Hamersley and Chichester ranges (and the distance from the coast) affect the spatial distribution of rainfall and delineate surface water drainages (Fig. 1). Given the semi-arid conditions, surface water is scarce, shows large inter-annual variability, and is, therefore, an unreliable source of water. In this context, groundwater has become a strategic resource to further develop this region. Similar areas around the globe show that intensive groundwater abstraction in the arid and semi-arid areas is a common and valuable water resource that promotes economic and social development, however, usually associated with serious administrative and inter-sectoral conflicts and environmental problems (Oyarzún and Oyarzún 2011; Custodio et al. 2016a, b).

Groundwater conceptualization and characterization in semi-arid/arid areas with the presence of important mining activities (and exposed to potentially extreme rainfall events as the Pilbara region) has been studied from different perspectives, mainly including mapping of groundwater potential using GIS (Lachaal et al. 2013); characterising regional and/or global groundwater recharge and discharge (Scanlon et al. 2006; Wada et al. 2014), addressing salinization and groundwater quality deterioration problems (Brahim et al. 2015), and more specifically, acidification of open pit mines; and management of resources for sustainability (McCullough and Lund 2006; Yihdego and Drury 2016). Groundwater potential can be characterised using remote-sensing products and GIS analysis in combination with multi-criteria analysis (Machiwal et al. 2011), whereas, in data-poor areas or poorly mapped regions, simple GIS techniques have proven as valuable tools for knowledge and data integration to aid resource management (see, e.g., VanderPost and McFarlane 2007).

Since the 1970s, several studies have explored the potential of local aquifers as source of water in the Pilbara region

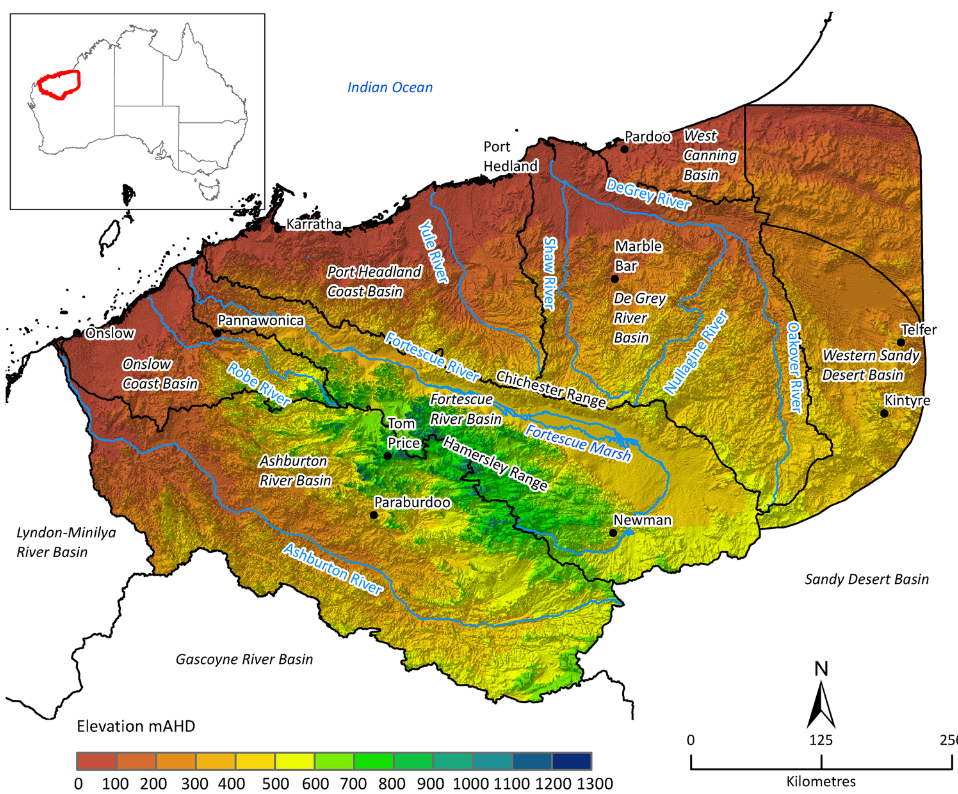

Fig. 1 Location of the study area. Surface elevation of the Pilbara region showing the main river basins and topographic features

(e.g., Davidson 1974, 1976; Leech 1979; Barnett and Commander 1986; Commander 1994a, b; Skidmore 1996; Wright 1997). More recently, Johnson (2004) described the availability of groundwater resources in the Pilbara region associated with four types of aquifers: unconsolidated sediment/surficial, chemically deposited, sedimentary (sandstone), and fractured rock aquifers, with the first three having major potential as groundwater source on the basis of bore yields. Haig (2009) performed a review of groundwater resources along coastal areas of the Pilbara region. This study concluded that further development of groundwater resources was required to meet long-term projected demand and identified the following prospective areas: Lower Fortescue River aquifer, Millstream aquifer, West Canning Basin (WCB) aquifers, Lower De Grey River aquifer, Lower Yule River aquifer, and Lower Robe River aquifer (see Fig. 1 and Table 1 for location and description).

A series of paleovalleys in the Canning Basin and the Paterson Province in the Western Sandy Desert Basin (Fig. 1) were investigated by English et al. (2012). They concluded that the paleovalley system of the Canning Basin was poorly understood and that coarse-grained sands and gravels infilling deep valley paleochannels constituted important aquifers in these areas containing groundwater of acceptable quality.

In a study restricted to the Hamersley Basin in the Pilbara region, Dogramaci et al. (2012) suggested that sporadic rainfall events larger than 20 mm contribute most to recharge of alluvial aquifers. Recharge–discharge mechanisms in the area, however, showed large spatial and temporal heterogeneity arising from the nature of rainfall events, catchments characteristics such as size, topography, and recharge through the regolith, and the high evaporation rates (Dogramaci et al. 2012, 2015).

More recently, HydroConcept (2014) performed a groundwater assessment of seven local aquifers located in the northwest Hamersley Range, southeast of Pannawonica town, and northwest of Tom Price town (Fig. 1). Although this study concentrated on the assessment of channel iron deposit (CID) aquifers as potential sources of groundwater, they identified valley-fill, calcrete, and CID aquifers as the most prospective in the area. Groundwater storage suitable for exploitation was estimated between 23 and 108 Mm^3 with average recharge rates between 3 and 10 Mm^3/year (HydroConcept 2014).

While all these studies have advanced the knowledge about groundwater system in the Pilbara region, they are limited to a particular area at a time, do not provide a regional characterization of the aquifers present in the broader Pilbara region and their potential, and lack a conceptualization of groundwater systems at a regional scale. The objective of this work is to provide the most recent regional scale groundwater systems identification and characterization as

Table 1 Local aquifers with conceptual/flow models used to described groundwater resources in the Pilbara region

Groundwater area	Area (km^2)	Conceptual/flow model description
Millstream aquifer	1410	MODFLOW model consisting of six layers describing Dolomites, inland alluvial, and valley-fill systems. Main recharge mechanism is transient flooding events (streambed leakage) of the Fortescue River, while main discharge process is through outflows to surface pools and springs. Calibration: 1968–1995. Validation: 1996–2007 (SKM 2009)
Lower Fortescue aquifer	200	FEFLOW model consisting of six layers describing the coastal alluvial plain of the Lower Fortescue River and classified as (coastal) alluvial aquifer. The main recharge mechanism is localised recharge from the Fortescue River as a result of floods from extreme rainfall events, while the main discharge is evapotranspiration by coastal vegetation. Calibration 1983–2007. No validation. (MWH 2010a)
Lower Yule aquifer	2675	FEFLOW model consisting of six layers describing the coastal alluvial plain of the Lower Yule River and classified as (coastal) alluvial aquifer. Main recharge is localised recharge as streambed leakage resulting from flooding events of the Yule River, while the main discharge is evapotranspiration. Calibration 1972–2009. No validation. (MWH 2010b)
West Canning basin aquifer	26,100	MODFLOW model consisting of five layers describing the Wallal and Broome sandstone aquifers in the West Canning Basin. Main recharge occurs via rainfall infiltration (diffuse recharge) and regional throughflow from regional aquifers, while main discharge is outflowed to the Indian Ocean. Calibration 1975–2009. No validation. (Aquaterra 2010)
Lower De Grey aquifer	4500	FEFLOW model consisting of three layers representing the coastal alluvial plain of the Lower De Grey River and classified as (coastal) alluvial aquifer. The main recharge mechanism is streambed leakage resulting from flooding events of the De Grey River and secondary rainfall infiltration. The main discharge corresponds to evapotranspiration and groundwater abstraction. Calibration 1983–2009. No validation. (SKM Merz 2010a)
Lower Robe aquifer	714	FEFLOW model consisting of three layers representing the coastal alluvial plain of the Lower Robe River and classified as (coastal) alluvial aquifer. The main recharge mechanism is streambed leakage from the Robe River, while the main discharge corresponds to evapotranspiration. Calibration 1984–2008. No validation. (SKM 2010b)
Total modelled area	35,600	

well as the conceptualization of the occurrence and functioning of groundwater systems in this extremely arid region. For this, an extensive review and collation of existing and dispersed data on aquifer properties was performed. In addition, groundwater systems were characterised on the basis of the available information from a regional perspective, i.e., building on the previous studies to provide a first-ever regional synthesis. With this knowledge, the potential of the aquifers identified was assessed and the conceptualization of the functioning of these systems was proposed. This regional perspective will help improving the broader understanding of the groundwater systems in this region aiming at facilitating sustainable management of groundwater resources.

2 Materials and Methods

2.1 Study Area Description

The Pilbara region in the northwest of the state of Western Australia covers an area of ca. 289,000 km^2, equivalent to about 11% of the state's surface (Fig. 1). It extends between the coastal town of Onslow on the west and the Telfer/Kintyre mine sites to the east, and between Pardoo homestead on the north and the Ashburton River catchment to the south.

Two distinctive physiographic features of the area are the Hamersley and Chichester ranges (Fig. 1). They traverse the study area in a southeast–northwest direction, with the former containing the highest peaks in Western Australia (ca. 1250 m above Australian Height Datum, mAHD). These two ranges enclose the Fortescue Valley, which contains the Fortescue River and Fortescue Marsh, and form the headwaters of the main south—(Robe and Ashburton) and north–draining (Yule, Oakover and De Grey) rivers in the study area. A detailed description of the physiographic regions identified in the study area is provided by Pain et al. (2011).

Climate data on rainfall, temperature, relative humidity, and solar radiation were obtained from the SILO repository (Jeffrey et al. 2001) (https://www.longpaddock.qld.gov.au/silo/), and utilised in a regional climate assessment by Charles et al. 2015. Two data sets were available from SILO: the Patched Point Data set (PPD) and the Data Drill gridded data at 0.05° horizontal resolution. The PPD are point observations, whereas the gridded data are obtained by interpolation using a thin plate smoothing spline for daily climate variables and ordinary kriging for daily and monthly rainfall. A total of 93 PPD stations and about 10,000 grid cells are located within the study area.

The study area is located in a semi-arid region with influences of tropical cyclones linked to the Australian monsoon and exhibits high summer temperatures and irregular rainfall events, manifested by a large inter-annual variability. Average maximum temperatures exceed 35 °C between November and March with the lowest minimum temperatures of 6 °C or less in July in the far south (i.e., furthest from coast).

Annual average class A pan evaporation exceeds 3,000 mm over most of the region with the exception of the Hamersley Range (McFarlane et al. 2015a). Given the high temperatures and that potential evaporation (PE) can exceed annual rainfall by more than one order of magnitude, there is limited surface water resources in the Pilbara region.

For the period 1911–2012, mean annual rainfall was 299 mm, with a large inter-annual variability ranging between 48 mm (1924) and 731 mm (2000). September corresponds to the driest month of the hydrological year (average rainfall of 2 mm), whereas 60% of the annual rainfall concentrated in the wettest months (January to March) (Charles et al. 2015). A substantial increase in rainfall during the last decades relative to the long-term average value has been observed (Cullen and Grierson 2007; Taschetto and England 2009), with a significantly wetter period (average annual rainfall of 500 mm) recorded between years 1995 and 2001 (Fig. 2). The largest increase in monthly rainfall for the period 1961–2012 occurred in February, March, and December.

A detailed discussion on large-scale processes affecting the study area's climate as well as climatic trends and extremes is beyond the scope of this article. The reader is referred to Charles et al. (2015) for a discussion on these topics.

2.2 Geology of the Study Area

The study area encompasses the Archean-Proterozoic Pilbara Craton, parts of the Capricorn and Paterson orogens, small parts of the Neoproterozoic Officer Basin, and the Phanerozoic Carnarvon and Canning basins (GSWA 1990) (Fig. 3). The Pilbara Craton consists of the North Pilbara granite–greenstone terrane and the volcano-sedimentary rocks of the Hamersley Basin. The Capricorn and Paterson orogens consist of folded and faulted metamorphosed sedimentary rocks, with igneous rocks in the Gascoyne and Rudall complexes. The sediments of the Carnarvon and Canning basins are largely shallow dipping and not metamorphosed.

The North Pilbara granite–greenstone terrane and the Sylvania Inlier are composed of greenstone sequences (3650–2850 Ma, Nelson et al. 1999) of a variety of sedimentary and volcanic rocks, principally basalt, acid volcanics, schist, quartzite, chert, and banded iron formation (BIF). The Hamersley Basin sequence covers the southern part of the Pilbara Craton and extends over an area of approximately 40,000 km^2. It comprises the Mount Bruce Supergroup (2770 to near 2350 Ma), which consists of the volcanic

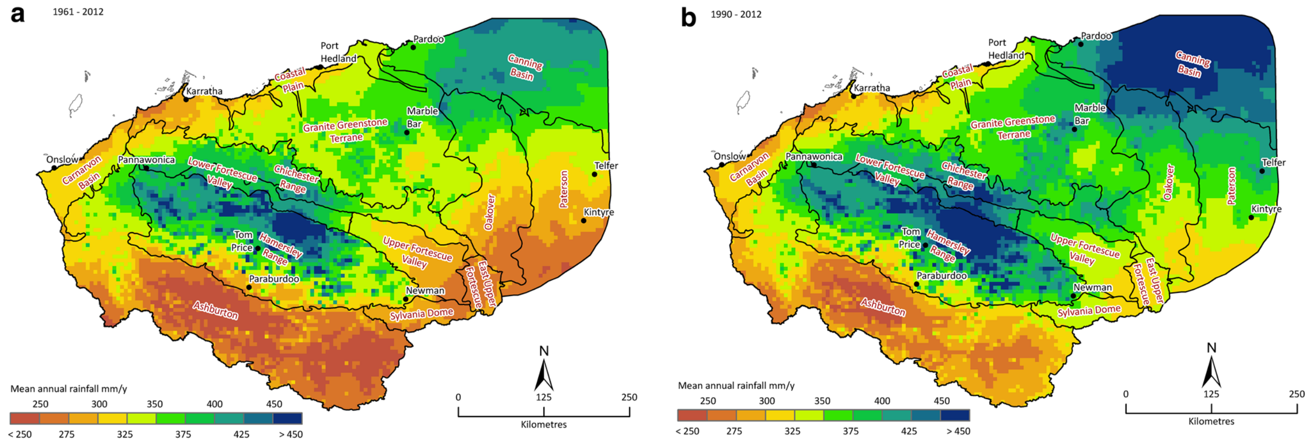

Fig. 2 Mean annual rainfall for the period **a** 1961–2012 and **b** 1990–2012 showing the substantial increase to east of the study area over the western section of the Canning Basin Source: Gridded data from SILO

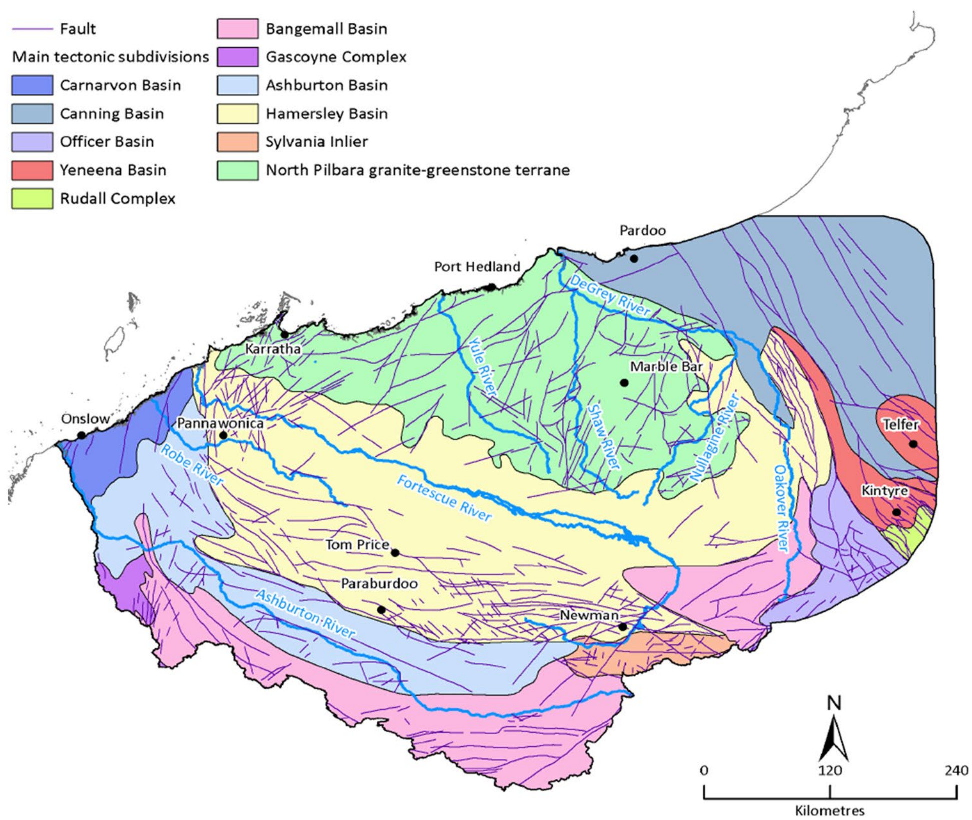

Fig. 3 Main tectonics subdivisions and major faults in the Pilbara region

sedimentary Fortescue, Hamersley, and Turee Creek groups (GSWA 1990) unconformably overlying the granite–greenstone terrane. The northern margin of the Hamersley Basin is the south dipping Fortescue Group which forms the 400 km-long Chichester Range. The Hamersley Range (Fig. 1) is formed by a syncline in the Hamersley Group. The Ashburton Basin lies unconformably on the Hamersley Basin and passes south-westwards into the Gascoyne Complex. Granite of the Gascoyne Complex is exposed in the western edge of the region, whereas the younger Mesoproterozoic Bangemall Basin separates the Ashburton Basin and Gascoyne Complex.

To the west, the Cretaceous and Cenozoic sequence of the northern section of the Carnarvon Basin is mostly fine-grained, with the only significant sandstone occurring at the base of the Cretaceous. The basal Cretaceous sediments crop out along the inland boundary of the Carnarvon Basin and pass laterally into the Birdrong Sandstone.

To the east, the Bangemall Basin (1300–1400 Ma) is represented by the Manganese Group which consists of shale, sandstone, dolomite, and minor conglomerate. Further east, the Yeneena Basin (younger than 900 M, Grey et al. 2005) and the Rudall Complex are present, which host the gold mineralisation at the Telfer mine and the uranium ore at the Kintyre mine, respectively. The neoproterozoic (700–850 Ma?) sandstones, shales, and dolomites occupying the area between the Bangemall and Yeneena Basins are assigned to the Officer Basin (Grey et al. 2005). The sedimentary rocks of the Officer and Yeneena basins are poorly exposed in the region, being largely covered with sand dunes, and their relationships are not clear (Grey et al. 2005).

To the northwest, the study area includes the south-western part of the Canning Basin, which is Australia's second–largest sedimentary basin (Ordovician to Cretaceous). The basal sediments of Permian age in the east are unconformably overlain by a Jurassic-to-Early Cretaceous sequence, which lies directly on Precambrian rocks. The Jurassic–Cretaceous sequence outcrops as isolated mesas along the inland margin and dips gently northwards below the coastal plain. The geology has been simplified in the literature to a basal Jurassic unit (Wallal Sandstone), and overlain by the Jarlemai Siltstone and the Broome Sandstone (Leech 1979; Haig 2009).

Tilting and uplift since the Cretaceous and early Cenozoic has led to the current drainage pattern (McFarlane et al. 2015a). The early Cenozoic drainage pattern in the Hamersley Range is shown by the distribution pattern of the CIDs (also known as Pisolite) and the presence of paleovalleys (Sect. 3.1 and Fig. 4). For example, the current

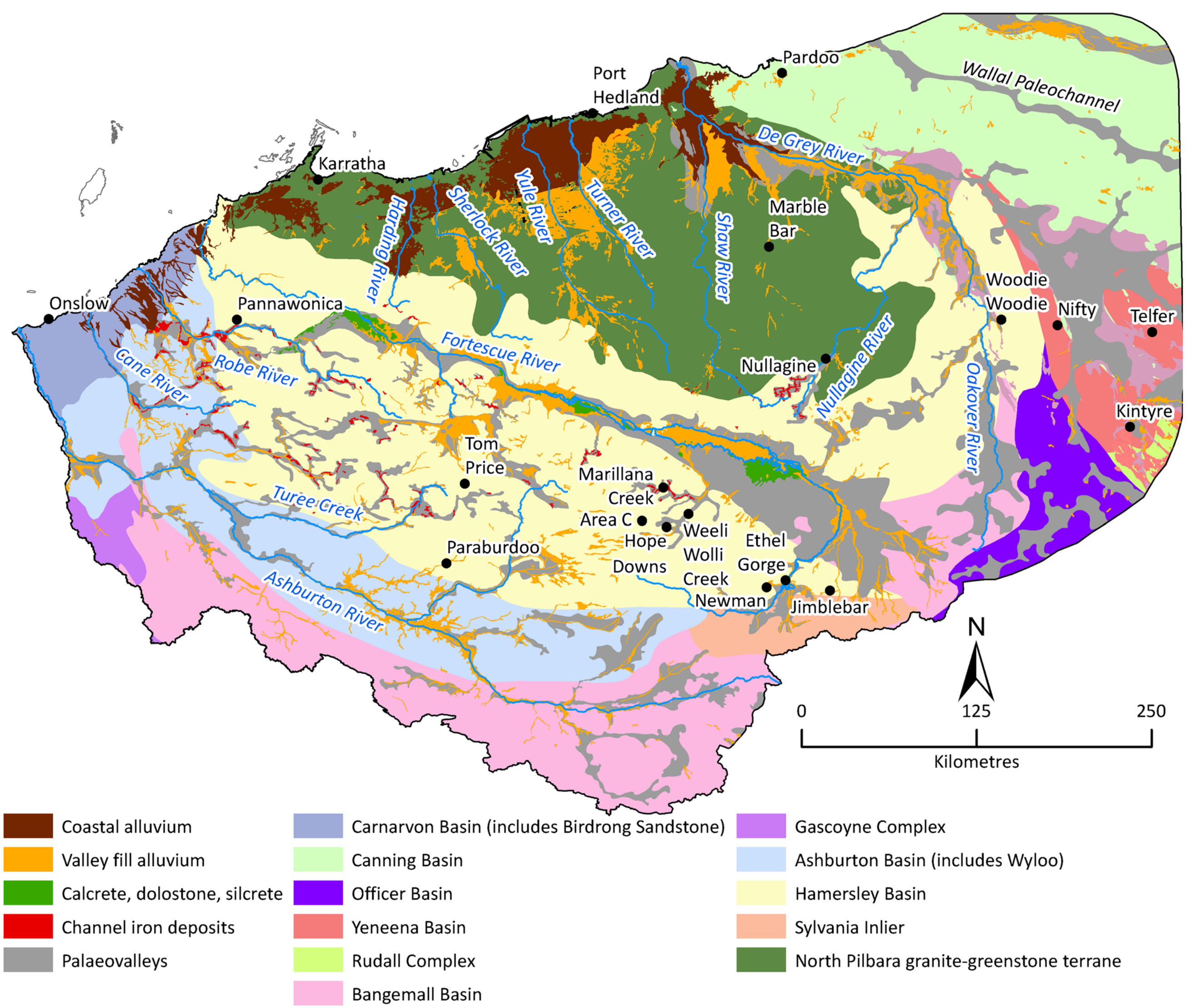

Fig. 4 Main aquifer types and geological features found in the study area

Fortescue Valley previously drained in the direction of the present Robe River, south of Pannawonica, but has now been diverted at Millstream by the lower Fortescue River, which exits the valley sediments to cut through bedrock north of Pannawonica (Fig. 1). Tilting is also responsible for creating a surface water divide in the Fortescue Valley with the upper part of the valley internally draining to the Fortescue Marsh (Fig. 1).

2.3 Methodology

The methodology employed in this work sits on a larger methodological scope employed to assess water resources in the Pilbara region. This methodology included GIS analysis and mapping of the existing data sets describing climate, hydrological, hydrogeological, and ecological assets features; climate data analysis and trends (Charles et al. 2015), hydrological and rainfall-runoff modelling, hydrogeological characterization, and assessment and groundwater-dependent ecosystem identification. In the following, only the methodological steps relevant to the scope of this article are described.

2.3.1 Aquifer Data and Literature Review

Extensive literature review was performed to collate data on aquifers' hydraulic properties (hydraulic conductivity, transmissivity, and storativity) and groundwater systems identified in the study area. More than 1200 reports on groundwater-related assessment/exploration covering the period 1967–2013 and made available by the Western Australian Department of Water were reviewed. Hydraulic properties were summarised from more than 1400 bore records and matched against aquifer types previously identified in the region. Hydraulic properties for the bores analysed were obtained through different methods such as pumping tests (constant- and varying-rate), single-well recovery tests, slug tests, and dual-porosity tests for the cases of fractured rock aquifers (Kruseman and de Ridder 2000). When more than one value was reported for the hydraulic properties of a given aquifer, this information was summarised in terms of the mean, median, range, and number of observations. It is worth emphasizing that most of these reports were associated with mining exploration activities and as such were highly clustered around mine sites describing localised conditions. The latter prevented the creation of regional aquifer property maps as a high degree of extrapolation would have been required, thus, adding considerable uncertainty to any potential regional mapping.

2.3.2 Aquifer Characterization

The existing public and confidential reports on groundwater exploration in the Pilbara region were reviewed and the aquifer systems were characterised in terms of geological features, representative (known) thickness, salinity values, and bore yields (when available). Whenever possible and given data constraints, the characterization of groundwater systems and aquifer properties followed Kovalevsky et al. (2004). Groundwater systems were described in terms of aquifer characteristics (confined, unconfined, leaky, etc.), recharge/discharge mechanisms, groundwater budget components, and (if available data) volume stored. Other properties such as chemical composition, groundwater head, and/or water table fluctuations could not be analysed in detail at regional scale given data constraints. Aquifer analysis included hydraulic properties and aquifer types (unconfined, confined, etc.) and when data were available analysis of geometry and dominant boundary conditions (Kovalevsky et al. 2004).

2.3.3 Groundwater System Conceptualization

The occurrence of these aquifers systems was further identified in the Pilbara region on the basis of the hydrogeological provinces defined by McFarlane et al. (2015a). Assessment of present and future potential of these aquifers as groundwater sources as well as critical gaps in the knowledge were identified and discussed.

On the basis of the aquifer properties and the characterization described above and through geological interpretation, a conceptualization for the occurrence and functioning of the aquifer systems across the Pilbara region was proposed and presented in graphical format. In addition, GIS mapping and analysis was performed to represent the main aquifers identified in the Pilbara region.

3 Results

3.1 Groundwater Occurrence in the Pilbara Region

Groundwater resources in the study area occur within seven main hydrogeological systems/aquifer types: (a) coastal plain alluvial aquifers; (b) channel iron deposits (CIDs); (c) inland alluvial systems and paleovalleys including calcrete and valley-fill aquifers; (d) karstified dolomites underlying inland valleys within the Hamersley Range; (e) sandstone aquifers including the Wallal and Broome (West Canning Basin) and the Birdrong (Carnarvon Basin); (f) Permian and Cenozoic paleochannels in the northeast of the study area; and fractured rocks sub-divided into (g) mineralised BIF of locally high yields and limited storage, and (h) fractured bedrock formations. From Figs. 3 and 4, we see that coastal alluvial aquifers occur in the coastal plain alluvium; CID aquifers are distributed mainly in the Hamersley Basin and in close link with the inland paleovalley/paleochannel systems; inland valley-fill and paleovalleys are well distributed over all the Pilbara region; karstified dolomites, although not seen in Figs. 3 or 4, underlain the Hamersley Basin; and the sandstone aquifers occur at the western end of the Canning Basin. Mineralised and Fractured rock aquifers have not specified boundary, but they occur mainly in the rocks of the Hamersley Basin and the granite–greenstone terrane in the study area.

Table 2 shows the occurrence of these aquifer types in the hydrogeological provinces defined by McFarlane et al. (2015a). The West Canning and Carnarvon basins have been grouped under the 'Sandstone' column given the nature of the major aquifer systems identified in these basins, whereas fractured rock aquifers have been sub-classified into areas where mineralised Banded Iron Formations (BIFs) occur. From Table 2, it is clear that fractured rock aquifers occur across a large area of the Pilbara region. This type of aquifer, however, is associated with locally fractured systems with limited prospects to provide groundwater at a regional scale (Commander et al. 2015a) and with mineralised BIFs dewatered to facility dry-mining operations. In addition, valley-fill and dolomite aquifers are present across most of the study area, but concentrated on the Hamersley Range, Upper and Lower Fortescue Valley, and Oakover and Ashburton river valleys. Most of these areas show the presence of paleovalley systems hosting a varied sequence of unconsolidated sediments. CIDs are the fourth most common aquifer type in terms of spatial distribution and recently have attracted a surge of attention as they need to be dewatered for mining purposes, raising environmental and water management issues.

Information on representative thicknesses, salinity values, bore yields, and references for the main documented aquifers in the study area is shown in Tables 3, 4, 5, 6, 7, and 8. Figure 4 shows the extent of these aquifers in the study area, which are further described and conceptualized in the following sections.

3.1.1 Coastal Alluvium Aquifers

These aquifers are distributed from the mouth of the Ashburton River near Onslow to the mouth of the De Grey River and are associated with the main rivers in the study area where they enter the coastal plain (Fig. 4, Table 3). The size of the alluvial aquifers is linked to the size of the river basin, with the aquifers associated with De Grey, Yule, and Fortescue Rivers being the most relevant in size. The type of alluvial sediments composing these aquifers is largely controlled by their provenance, i.e., type and distance of the bedload source: for example, bedloads from the Fortescue and Robe rivers are composed by cobbles derived from the volcanics and BIF of the Hamersley Basin. These aquifers can be unconfined, confined by finer sediments spread laterally and potentially transmit groundwater through vertical leakage (see Fig. 5 for examples).

Table 2 Main aquifer types identified in the study area and their presence in the hydrogeological provinces described in McFarlane et al. (2015b)

	Aquifer types							
	Coastal alluvial	CID	Valley-fill	Karstified Dolomite	Sandstone	Permian/Cenozoic paleochannels	Fractured rock[a]	
								Min BIF
Hydrogeological province								
Ashburton	–	✓	✓	✓	–	–	✓	–
Granite–greenstone terrane	–	–	–	–	–	–	✓	✓
Hamersley range	–	✓	✓	✓	–	–	✓	✓
Canning basin	–	–	–	–	✓	✓	–	–
Paterson	–	–	–	✓	–	✓	✓	–
Oakover	–	–	✓	✓	–	✓	✓	✓
Chichester range	–	–	–	–	–	–	✓	✓
Upper Fortescue valley	–	✓	✓	✓	–	–	✓	✓
Carnarvon basin	✓	✓	–	–	✓	–	–	–
Coastal plain	✓	–	–	–	–	–	✓	–
Lower Fortescue valley	–	✓	✓	✓	–	–	–	–
Sylvania dome	–	–	✓	–	–	–	✓	–
East upper Fortescue	–	–	–	–	–	–	✓	✓

[a]A sub-classification of *Fractured rock* has been defined for areas with occurrence of mineralised BIF

Table 3 Representative information about coastal alluvial aquifers in the study area (for locations, see Fig. 4)

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
De Grey River alluvium	70	500 [585–1000]	2000	Davidson (1974); Haig (2009); Commander et al. (2015a)
Yule River alluvium	60	< 500 [140–620]	4800	Davidson (1976); Haig (2009); Commander et al. (2015a)
Turner River alluvium	40	< 1000[a] [215–2000]	110–330 [650][b]	Haig (2009); DoW (2011); Commander et al. (2015a)
(Lower) Fortescue River alluvium	30	500–1000[c]	900 [100–500][d]	Commander (1994a); Haig (2009); Johnson (2004)
Robe River alluvium	15	450–1280	3000	Commander (1994b); Haig (2009); DoW (2012a)
Cane River alluvium	Up to 25	< 300[e] [500–1000]	170	Martin (1989); Haig (2009); Commander et al. (2015a)
Ashburton River alluvium	35–45	500–1200 2000–8000	2500	Yesertener and Prangley (1997); Haig (2009); Commander et al. (2015a)

[a]Only within 2 km from the river banks

[b]Value in brackets for the weathered bedrock aquifer in connection with the alluvial aquifer

[c]The value at the centre of the aquifer rises up to 1000 mg/L TDS on the edges of the alluvial aquifer

[d]Estimates in brackets correspond to the Fortescue River alluvium and may not represent the lower section of the river

[e]Salinity may peak as a result of large-flow events and high abstraction rates

Table 4 Representative information about CID aquifers in the study area (for locations, see Fig. 4)

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
Robe River and Bungaroo Creek (Pannawonica)	40–100	< 200	1500	HydroConcept (2014); Commander et al. (2015a);
Marillana and Weeli Wolli creeks	40–80	350–740[a]	500–2200	BHPBIO (2006); RPS Aquaterra (2011); Commander et al. (2015a)
Weelumurra and Caliwingina creeks (Pannawonica)	50	160–660	2600	HydroConcept (2014)

[a]Available only for Marillana Creek around the Yandi mine

Table 5 Representative information about valley-fill aquifers in the study area (for approximate locations, see Fig. 4)

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
Lower Fortescue Valley	Up to 150 [45][a]	200–1500	100–500 [< 1500][b]	Johnson and Wright (2001); Haig (2009); HydroConcept (2014); Commander et al. (2015a)
Upper Fortescue Valley	60 [up to 150][c]	<60000[d]	–	Johnson and Wright (2001); Skrzypek et al. (2013)
Hamersley range	<90	500–550	860	HydroConcept (2014); Commander et al. (2015a)
Turee Creek Catchment	50-80	140–1100	–	Commander et al. (2015a)
Newman area	40–120 [10–40]	<1250	600–5500[e]	Commander et al. (2015a)

[a]Value in brackets corresponds to the calcrete aquifer in the *Lower Fortescue Valley* around Millstream

[b]Values can reach high bore yields depending on the connectivity of aquifer (calcrete, conglomerate, and alluvium)

[c]Some creeks of the *Upper Fortescue Valley* can reach up to 150 m depth of alluvial sediments (e.g., Upper Weeli Wolli Creek)

[d]Hypersaline groundwater recorded in the vicinity of the Fortescue Marsh

[e]Values around Mt Whaleback, Ophthalmia, and Homestead Creek

Table 6 Representative information about karstified/weathered dolomite aquifers in the study area

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
Lower Fortescue Valley (around Millstream)	150	150–1500	<2000–5500	Johnson and Wright (2001); Johnson (2004); Haig (2009)
Different mine sites (Area C, Telfer)	–	1500–3000[a]	600–1550[b]	BHP 1997; Commander et al. (2015a)

[a]Around Telfer gold mine

[b]Around Area C mine site

Table 7 Representative information about sandstone aquifers in the study area (for approximate locations, see Fig. 4)

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
Broome Sandstone (Canning Basin)	10–130	1000–> 5000	<3000	Leech (1979); Johnson (2004); Aquaterra (2010); DoW (2012b); NTEC (2012); WorleyParsons (2013)
Wallal Sandstone (Canning Basin)	20–220	500–< 5000	600–3000	Leech, 1979; Johnson (2004); Haig (2009); Aquaterra (2010); DoW (2012b); NTEC (2012); WorleyParsons (2013)
Birdrong Sandstone (Carnarvon Basin)	30 [16–53][a] 400[b]	890–3450[a] [> 10000][c]	26–309[a]	Haig (2009); Commander et al. (2015b)

[a]Estimates for the upper Cane River area only

[b]Estimated around Onslow

[c]Salinity rises in excess of 10000 mg/L TDS along the coast

Table 8 Representative information about fractured rock aquifers in the study area (for approximate locations, see Fig. 4)

Main aquifer	Representative thickness [m]	Salinity [mg/l TDS]	Reported bore yields [m^3/day]	Main references
Harding River—Upper Maitland River (20 km west of Karratha)	30	100–2800	430	Haig (2009); Commander et al. (2015a)
Mine sites[a]	51	480–3000	1000	Commander et al. (2015a)
Mineralised BIFs[a]	–	200–1400	500	Johnson (2004); Commander et al. (2015a)

[a]Around Tom Price, Paraburdoo, and Jimblebar orebodies

The main recharge mechanism is streamflow leakage during flow (and flood) events, which take place just a few weeks during the hydrologic year (Haig 2009; Commander et al. 2015a). This recharge will depend on the duration and magnitude of the streamflow and the available storage capacity in the aquifer, and is in agreement with recharge processes described for similar hyper-arid environments with the presence of ephemeral rivers (Dahan et al. 2008). Estimates for the period 1968–2009 (through groundwater modelling) report values between 12 and 28 Mm^3/year for the local aquifers of the lower Fortescue, lower Yule, and Lower De Grey rivers (Rojas et al. 2015a, b). The main discharge mechanisms are evapotranspiration from riverine and coastal vegetation, groundwater abstraction in those aquifers that have been developed (Lower De Grey River aquifer), and discharges to the Indian Ocean. Estimates for the period 1968–2009 report values for evapotranspiration at about 14 Mm^3/year for the lower Fortescue and lower Yule aquifers, whereas estimates for the Lower De Grey aquifer are about 85 Mm^3/year. Discharges to the Indian Ocean have been quantified as 46 Mm^3/year for the lower De Grey aquifer (Rojas et al. 2015b). In terms of salinity, available data on Total Dissolved Solids (TDS) show that these aquifers contain fresh groundwater, with exceptional brackish conditions for the Ashburton River Alluvium. Figure 5 shows a conceptualization of the coastal alluvial aquifers around the lower sections of the Fortescue, Yule, and Robe rivers, highlighting the interbedded sections of sandy and clay/silty

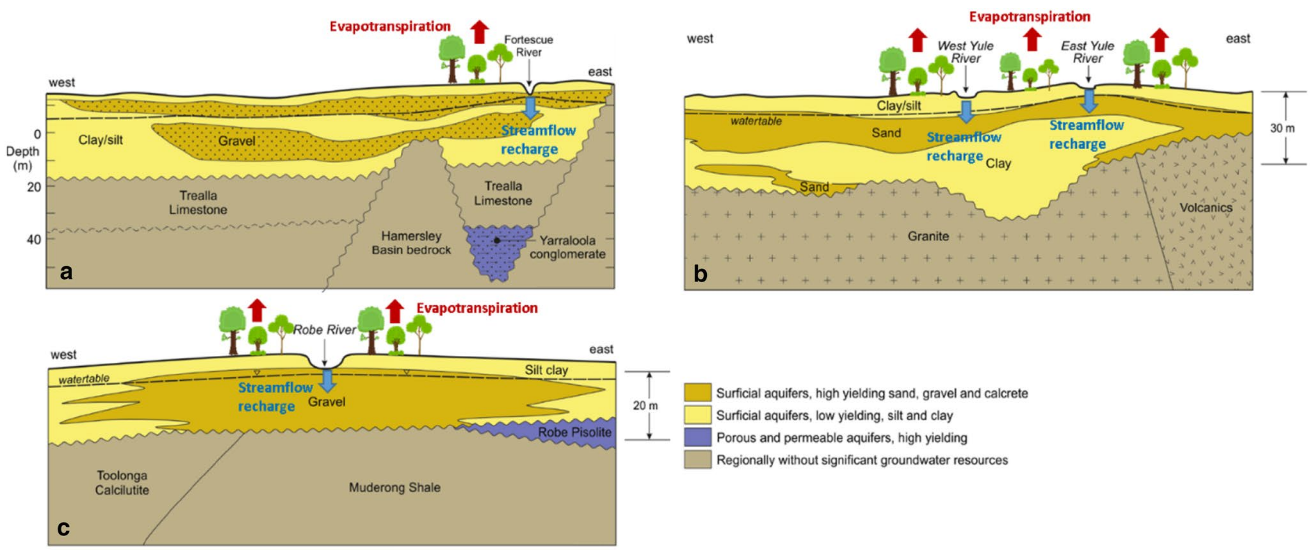

Fig. 5 Conceptual cross sections across the coastal plain alluvial aquifers in **a** Fortescue, **b** Yule, and **c** Robe rivers. Streamflow recharge is the main recharge mechanism, whereas evapotranspiration from vegetated areas in close proximity to rivers and in areas of shallow groundwater levels is the main discharge mechanism. Another discharge conceptualized corresponds to groundwater outflows to the Indian Ocean (perpendicular to these cross sections)

materials defining series of localised interconnected aquifers and aquitards.

These aquifers have been extensively studied and a good understanding of their potential as sources of current supply schemes exists (DoW 2013b). However, challenges to develop these sources relate to aquifer reliability due to the infrequency of groundwater recharge events (Haig 2009), build-up of salts and their periodic flushing (Commander et al. 2015a), prevention of saltwater intrusion due to groundwater abstraction, sustaining water quality for the most beneficial use (potable water), and maintaining groundwater and pool levels to sustain groundwater-dependent ecosystems (GDEs) (DoW 2013b).

3.1.2 Channel Iron Deposits' (CIDs) Aquifers

CIDs, also known as Pisolite or Robe Pisolite, have been described and investigated in the past (Morris and Ramanaidou 2007), but only recently they have been assessed as potential sources of groundwater (HydroConcept 2014). CID aquifers are concealed iron-rich highly porous and permeable deposits underlying current valleys and paleovalleys. Documented CID aquifers are concentrated around the paleovalleys of the Hamersley Basin and southwest of Pannawonica in the Ashburton Basin (Fig. 4, Table 4). The CID aquifers are composed of basal ferruginous sediments derived from BIFs of the Hamersley Group, highly porous and permeable, capable of significant yields, and show thicknesses of up to 100 m and typical widths of less than 1 km (HydroConcept 2014). Given its nature, CIDs are mostly overlain by leaky aquifers and can behave as unconfined aquifers when in hydraulic connection with overlying sediments, and also as confined aquifers when overlain by poorly transmissive sediments.

The main recharge mechanism is downward leakage from overlying aquifers (HydroConcept 2014), whereas the main discharge mechanism corresponds to dewatering for mining and for supplementing the existing water schemes (Commander et al. 2015a) (Fig. 6b, c). Conceptually, in most cases, CIDs (or Pisolite or Robe Pisolite as referred in Fig. 6) are hydraulically connected with overlying valley-fill sediments forming inland alluvial aquifer systems and they exchange downward fluxes to underlying karstified/fracture dolomite aquifers of regional extent (e.g. Wittenoom Dolomite, Fig. 6a, b). Available TDS data suggest that groundwater in these aquifers can be classified as fresh (see Table 4).

CIDs have been increasingly mined from below the water table as surficial iron-rich deposits have become exhausted (Pfautsch et al. 2015); this has originated considerable volumes of surplus water from dewatering. The CID aquifers show a substantial potential to supplement the existing water supply schemes; however, there is an important challenge in managing these aquifers as they are both an iron-ore resource and a source of freshwater (HydroConcept 2014).

3.1.3 Valley-fill and Inland Alluvial Aquifers

Valley-fill aquifers occur along the Fortescue, Oakover, and part of the De Grey river valleys (Fig. 4, Table 5), with valleys and paleovalleys in the Hamersley Basin showing a

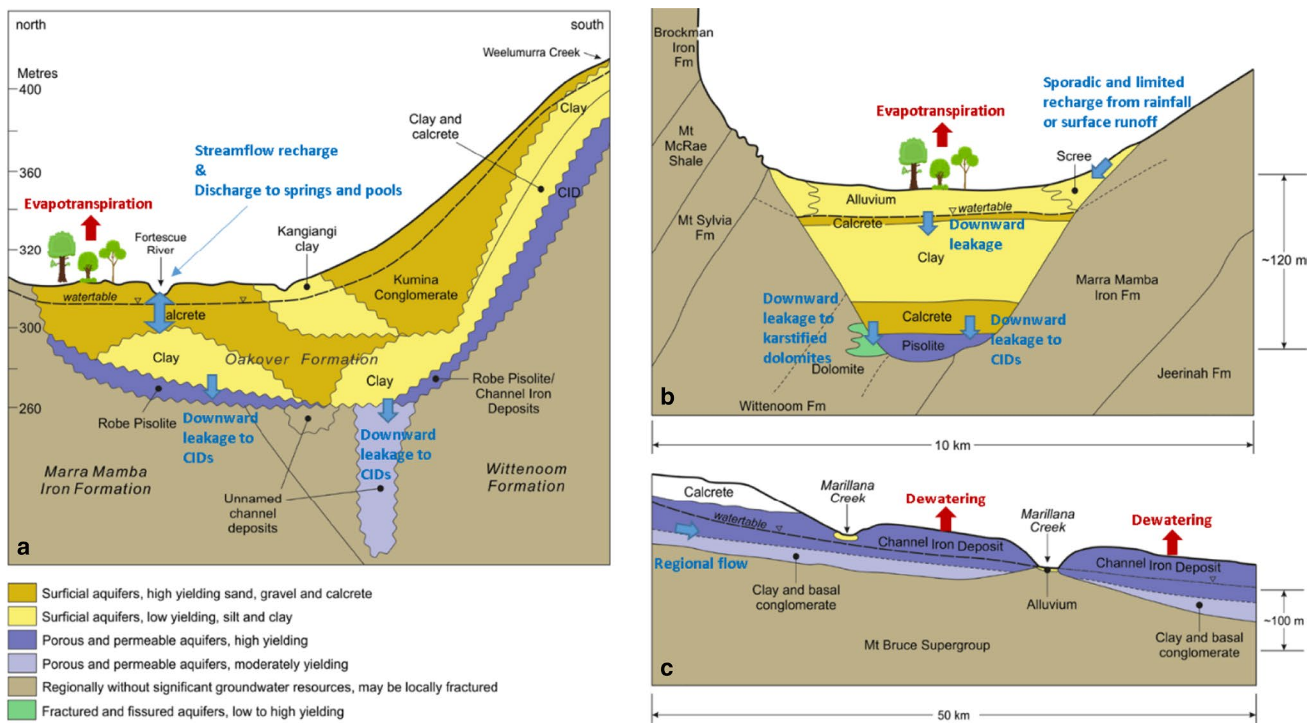

Fig. 6 Conceptual cross sections across valley-fill aquifers in **a** lower Fortescue valley, and **b** upper Fortescue valley (e.g., Fortescue Marsh); and **c** conceptual longitudinal section around the Marillana Creek in the Hamersley range area

common sequence: CIDs at the bottom, overlain by calcrete, lacustrine clay, and varying alluvium from gravel to clay, with an upper layer of calcrete commonly developed in the zone of watertable fluctuation. These aquifers develop high transmissivity and secondary porosity in calcrete deposits and groundwater usually occurs in interconnected karstified dolomites, CID, calcrete, and gravel aquifers (Figs. 6a, b). Hydraulic connectivity of these aquifers, however, depends on local conditions and the presence of confining units (Johnson and Wright 2001; HydroConcept 2014). Given the complex nature of these aquifers, they can be described as unconfined, confined, leaky, and patchy. Groundwater recharge takes place through streamflow infiltration in those river sections cutting valley-fill sediments or the outcrops of calcrete/CID deposits (e.g., Fortescue River around Millstream, Fig. 6a), and through scree on the valley flanks (Fig. 6b). Estimates of recharge in the valley-fill aquifers in the central Pilbara Region vary from 0.09 to 17 Mm^3/year/km length of valley and depend on factors such as frequency, flow volume, and duration of surface flows (Johnson and Wright 2001). The main discharge mechanisms correspond to outflows to river springs and pools, evapotranspiration, and direct evaporation where the water table is close to the surface (HydroConcept 2014) (Fig. 6a).

The valley-fill aquifers support relevant spring-fed GDEs around the Weeli Wolli creek and in the Millstream aquifer area (see Table 1 and Fig. 4). Groundwater in the valley-fill aquifers is usually fresh to brackish, with exception of the Fortescue Marsh (see Fig. 1), a closed basin in the Upper Fortescue Valley, where hypersaline groundwater has been reported (Table 5).

Valley-fill aquifers show the largest potential when hydraulically connected with underlying fractured bedrocks or karstified dolomites (Commander et al. 2015a). In the study area, the most relevant aquifer of this type corresponds to the calcrete aquifer around Millstream in the Lower Fortescue valley, which supplied water for the West Pilbara Supply Scheme for over 40 years (Fig. 4) (Haig 2009). Figure 6a and b shows typical cross sections of valley-fill aquifers along the Fortescue valley in the study area, where the interbedded layers of alluvium, calcrete, and silt/clay materials define the main inland alluvial aquifers.

3.1.4 Karstified/Weathered Dolomite Aquifers

The karstified dolomite of the Wittenoom Formation is probably the most important regional aquifer among the Archean–Proterozoic rocks in terms of occurrence (Table 2). It underlies the major valleys of the Hamersley Range and the valley of the Oakover River, and is prospective for groundwater where it underlies thick sequences of valley-fill (Johnson 2004) (Fig. 6b, Table 6). Dolomite in the study area is highly variable in nature, from massive to highly karstified (Commander et al. 2015a). Hydrogeological data for the dolomite formations in the Oakover (Carawine dolomite) and Ashburton (Duck Creek dolomite) river valleys are limited and their characteristics and properties are, therefore, largely unknown (Johnson 2004; Commander et al. 2015a). The most documented area corresponds to the Millstream aquifer in the Lower Fortescue Valley (Figs. 4, 6b, Table 6), where the Wittenoom Dolomite reaches 150 m thickness and can have cavities up to 0.5 m thick, thus, showing high transmissivities (Haig 2009). At the same time, karstified dolomite aquifers have been developed for water supply around mining sites in Tom Price, Hope Downs, Area C, Jimblebar and Telfer (Commander et al. 2015a) (Fig. 4). Available data on TDS suggest that groundwater in this aquifer can be classified as fresh in the Wittenoom Dolomite around the Millstream area and brackish around the Area C and Telfer mine sites (Table 6).

The main recharge mechanism corresponds to vertical leakage from overlying inland alluvial aquifers, whereas groundwater abstraction is the main discharge process in those aquifers developed to supply mining operations.

Due to the limited information available and the highly variable nature of the dolomite formations in the study area, it is difficult to assess the potential of this aquifer type at regional scale. Nonetheless, the extent of the dolomite formations guarantees a substantial potential for groundwater development at regional scale, when these aquifers are hydraulically connected with overlying aquifers.

3.1.5 Sandstone Aquifers—Broome, Wallal, and Birdrong Aquifers

Both the Broome and Wallal Sandstone aquifers occur in the West Canning Basin, Australia's second-largest sedimentary basin, whereas the Birdrong Sandstone aquifer occurs in the Carnarvon Basin (Fig. 4, Table 7).

The unconfined Broome Sandstone aquifer is saturated only in a narrow coastal strip of ca. 20 km (WorleyParsons 2013) (Fig. 7a). The main recharge mechanism is by direct infiltration of rainfall, with rates ranging between 3 and 6% of total annual rainfall, whereas the main discharge corresponds to outflows to the Indian Ocean, minor evapotranspiration along the coast by phreatophytes, and outflows to the southwest towards the coastal alluvial aquifer of the De Grey River (Haig 2009).

The confined Wallal Sandstone aquifer shows a greater volume and better water quality than the Broome Sandstone aquifer (Haig 2009), with Johnson (2004), suggesting that it holds a larger storage than any aquifer in the Pilbara region.

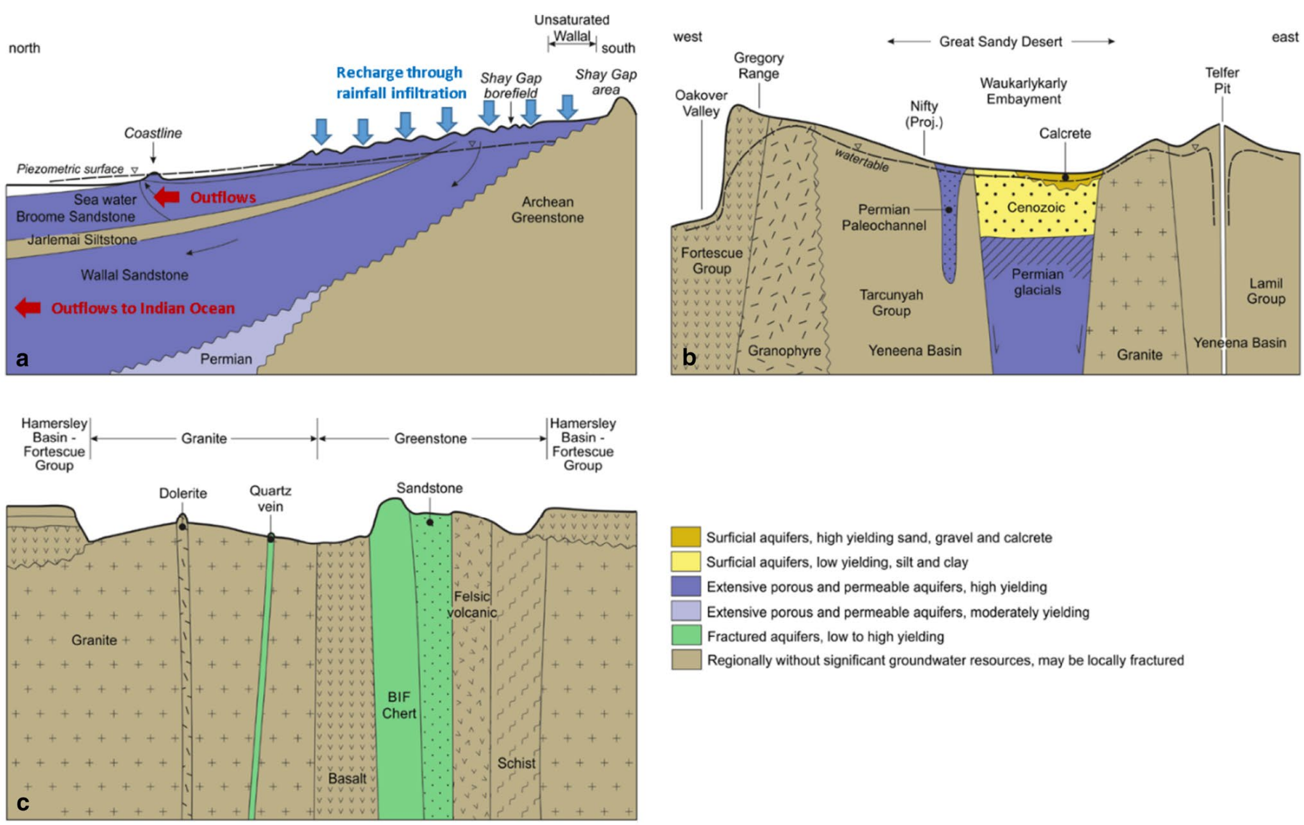

Fig. 7 Conceptual cross sections across **a** sandstone aquifers in the West Canning Basin, **b** Permian/Cenozoic paleochannels in the Paterson Province, and **c** typical BIF and fractured sandstones aquifers in the granite–greenstone terrain of the Pilbara region

Estimates by Haig (2009) suggest a resource of 21 Mm^3 of which 14 Mm^3 is fresh water. The Wallal aquifer increases in thickness from south to north, and groundwater flow is from east-southeast to northwest to the Indian Ocean (Fig. 7a). The main recharge mechanism is from direct infiltration of large intense rainfall events along the southern margin of the West Canning Basin where the confining unit (Jarlemai Siltstone) is absent (Meredith 2009), whereas the main discharge is outflows to the Indian Ocean (offshore) (Haig, 2009).

The confined Birdrong Sandstone is the only significant aquifer in the Carnarvon Basin (Commander et al. 2015b). Artesian conditions are present over much of the coastal plain being mostly confined by the Muderong Shale (Yesertener and Prangley 1997).

Data on TDS suggest that these sandstone aquifers can contain fresh to brackish groundwater, with the Wallal and Broome aquifers showing the largest potential, and the high salinities observed for the Birdrong Sandstone limiting the potential for this aquifer (Table 7).

It is recognised by several authors that the sandstone aquifers in the West Canning Basin show potential as water resource in the study area (Johnson and Wright 2001; Johnson 2004; Haig 2009; Commander et al. 2015a; Rojas et al. 2015b). Out of these aquifers, the Wallal Sandstone shows the largest potential given the considerable groundwater storage and relatively good quality compared to the Broome Sandstone aquifer (Table 7). Nonetheless, there exist important gaps in the knowledge about the functioning of these aquifers related to potential hydraulic connections with the coastal alluvial system of the De Grey River, the role of regional eastern groundwater fluxes as recharge and the origin of this recharge, and vertical interactions between the Broome and Wallal sandstone formations along the coastal line, where artesian wells have been reported (Commander et al. 2015a).

3.1.6 Permian and Cenozoic Paleochannels

The aquifers associated with Permian and Cenozoic paleochannels concentrate on the eastern and northeastern regions of the study area around the Great Sandy Desert, the Oakover Valley, and the Canning Basin (Figs. 4, 7b). They form part of paleodrainage systems (Roach et al. 2010a) and have only recently been investigated as potential groundwater sources (English et al. 2012). Aquifer properties are poorly documented but drilling around the Nifty and Kintyre mine sites revealed Permian sediments up to 100 m deep (Roach et al. 2010a) and fresh water from basal sand-gravel sequences of the Paterson Formation (English et al. 2012). Groundwater recharge seems to occur episodically from monsoon-related events that travel inland and recharging through present-day drainage lines that intersect these features, whereas data on isotopes for groundwater suggest that evapotranspiration is a dominant discharge process (English et al. 2012).

On the basis of extensive AEM survey data, Roach et al. (2010b) suggest that the Wallal paleochannel (Fig. 4) must contain low salinity groundwater unlike other paleochannels in the area. Further evidence to support this is the fact that this paleovalley does not drain large salt lakes observed in the area, thus not receiving saline groundwater. English et al. (2012), however, suggest that there are no drill holes or bores along this paleochannel to confirm this contention.

The Wallal paleochannel and the system of paleochannels located in the northeastern section of the Pilbara region show some potential as groundwater source with large volumes of reasonably good-quality groundwater stored in diverse aquifers receiving some modern recharge (English et al. 2012). This modern recharge would occur over decadal timescales associated with irregular inland incursions of cyclonic weather systems. Up to date, however, limited data are available to further quantify the potential of Permian and Cenozoic paleochannel aquifers in the Pilbara region.

3.1.7 Fractured Rock Aquifers

Fractured rock aquifers occur across the greater part of the study area (Table 2), but do not contain regionally substantial groundwater resources (documented data for these aquifers are shown in Table 8). They can, however, locally provide water supply and feed springs and pools supporting GDEs (Barron and Emelyanova 2015). These unconfined aquifers occur in the upper weathered zone of basement rocks (granite) where secondary porosity has been developed due to weathering, fractures, joints, and quartz veining, or where they are brittle (greenstone) (Haig 2009) (Fig. 7c) and in BIFs where weathering and/or ore mineralisation has enhanced well-developed solution features (Johnson 2004). Given the importance mining has in the study area, this type of aquifer has been further sub-divided into those occurring in rocks of the granite–greenstone terrane and in iron-rich deposits showing well-developed fractures due to ore mineralisation, i.e., mineralised BIFs (Table 2).

High-permeability mineralised BIFs occur in zones of the Marra Mamba and Brockman iron formations of the Hamersley Range (Figs. 1 and 4). Potential for these aquifers is limited and restricted to localised groundwater supplies, providing in some cases substantial water volumes as part of dewatering mineralised ore bodies. Groundwater in orebodies such as Tom Price, Paraburdoo, and Jimblebar (Fig. 4) is commonly compartmentalised and stand-alone water supplies have been developed (Commander et al. 2015a).

As stated, potential for these aquifers is limited and restricted to localised supplies, showing a relative significance to sustain GDEs through groundwater-fed springs and pools. They can provide, however, substantial water volumes as part of dewatering mineralised ore bodies. Available data on TDS indicate that these aquifers are classified as fresh to brackish in the study area (Table 8).

3.2 Aquifer Types and Hydraulic Properties

Table 9 summarises the main hydraulic properties obtained for the aquifers identified across the study area. In terms of available data, fractured rock aquifers show the largest number of available measurements (941), with mineralised BIFs adding 229 measurements, and thus, a high degree of confidence on these estimates can be expected. Coastal alluvium, CIDs, and valley-fill aquifers follow with available data measurements between 293 and 626. Karstified dolomites and Permian Cenozoic paleochannels are below 200 data measurements, whereas sandstone aquifers (restricted only to the Wallal and Broome sandstones in the West Canning Basin) record less than 100 data measurements. Caution must be considered when interpreting the data for these last two aquifers given the sparse number of available measurements. Available data are highly clustered around mine sites and current water utilities sites in the coastal alluvial aquifers, and given the diverse hydrogeological conditions and groundwater systems identified in the Pilbara region, the creation of regional aquifer property maps through interpolation of the available data is highly questionable and most likely plagued by uncertainties. High values for transmissivity are associated with higher values of hydraulic conductivity recorded in highly productive wells, and by definition, T estimates are

Table 9 Summary of properties (K: hydraulic conductivity, T: Transmissivity, and S: Storativity) for the aquifers identified in the Pilbara region obtained through pumping tests, single-well recovery tests, and dual-porosity tests

Aquifer type	Statistic[a]	K (m/day)	T (m^2/day)	S (–)
Coastal alluvium aquifers	Mean	15.23	1053.30	1.11×10^{-2}
	Median	16.40	510.00	6.10×10^{-4}
	Range	374.90	10,998.00	2.50×10^{-1}
	No. of observations	191	263	172
CID (channel iron deposit) aquifers	Mean	14.85	1449.88	1.05×10^{-2}
	Median	15.90	740.00	8.75×10^{-4}
	Range	305.86	20,992.00	1.90×10^{-1}
	No. of observations	122	177	124
Valley-fill aquifers	Mean	7.44	931.05	4.17×10^{-3}
	Median	8.80	274.00	4.00×10^{-4}
	Range	375.00	9999.40	8.90×10^{-2}
	No. of observations	87	125	81
Karstified/weathered dolomite	Mean	1.56	1328.59	4.02×10^{-2}
	Median	2.14	380.00	2.00×10^{-3}
	Range	390.00	24,991.75	3.00×10^{-1}
	No. of observations	46	75	39
Sandstone aquifers (West Canning Basin)	Mean	12.63	1478.79	2.05×10^{-4}
	Median	8.50	222.00	1.60×10^{-4}
	Range	217.40	16,317.00	5.87×10^{-4}
	No. of observations	34	39	10
Permian/Cenozoic paleochannels	Mean	3.28	961.51	2.06×10^{-2}
	Median	3.23	100.00	3.58×10^{-3}
	Range	195.90	9033.20	1.80×10^{-1}
	No. of observations	34	40	29
Fractured rock aquifers	Mean	2.26	638.06	1.27×10^{-2}
	Median	6.04	140.00	6.00×10^{-4}
	Range	420.00	10,500.00	6.40×10^{-1}
	No. of observations	322	407	212
Mineralised BIF aquifers	Mean	3.42	951.09	3.31×10^{-2}
	Median	5.17	427.00	3.00×10^{-3}
	Range	769.00	9999.80	5.00×10^{-1}
	No. of observations	80	92	57
	Total no. of observations	940	1243	730

[a]Mean for hydraulic conductivity is geometric mean

reasonable when linked to the typical thickness observed in the seven aquifer types identified.

Figure 8 shows a five-point summary for the aquifers across the study area. Coastal alluvium and CID aquifers are comparatively similar in terms of hydraulic conductivity and transmissivity; however, the spread in terms of storativity is larger for coastal alluvium aquifers possibly due to the presence of finer and more varied sediments in the depositional environment of the coastal alluvial plains. Valley-fill aquifers show a lower mean value and larger spread in hydraulic properties, and smaller storativity (on average) compared to the coastal alluvium and CID aquifers, which can be explained by the varied sediments composing the valley infills. Karstified dolomites show a larger storativity compared to the previous aquifers, thus reflecting the weathered/karstified nature of the aquifers, which is also reflected by a larger spread in hydraulic conductivity. Despite having a limited number of observations, sandstone aquifers show a similar conductivity and transmissivity than coastal alluvium and CID aquifers; however, the storativity is at least one order of magnitude smaller. Permian and Cenozoic paleochannel aquifers show slightly lower mean values for hydraulic conductivity compared to coastal alluvium, CID, and valley-fill aquifers, whereas transmissivity is comparatively smaller and shows more spread than the previous aquifers. Storativity, however, is comparatively higher (ca 0.04). Values for the fractured rock aquifers reflect the highly heterogeneous nature of these aquifers showing large ranges for hydraulic conductivity and storativity compared to all other aquifers.

In terms of potential as groundwater source, and on the basis of the data presented in Table 9 and Fig. 8, coastal alluvium, CID, and valley-fill aquifers show reasonably good hydraulic properties and a good number of measurements for a reliable estimation. While the sandstone aquifers of the West Canning Basin showed limited measurements, they show potential given the large extent which they cover in the study area. Karstified dolomites and Permian/Cenozoic paleochannels show slightly lower conductivities and transmissivities but larger storativity, with a lower number of measurements for reliable estimation. The fractured rock aquifers including the Mineralised BIFs aquifers show the largest number of measurements for a reliable estimation of potential concentrating almost half the observations available. These aquifers show reasonable values for the hydraulic properties (high storativity and reasonable hydraulic conductivity) but are confined to localised conditions so showing a limited potential at regional scale. In particular, data on the hydraulic properties for the sandstone aquifers of the West Canning Basin, valley-fill aquifers, and karstified dolomites show that these aquifers present the highest potential at regional scale. Nonetheless, more data describing the hydraulic and physical–chemical properties of these aquifers are required for a thorough description.

4 Discussion

The methodological approach allowed the identification of seven aquifer systems in this work, which align well with hydrogeological systems previously identified in local and sub-regional studies (Johnson 2004; Haig 2009; HydroConcept 2014). The previous sub-regional assessments suggest that coastal alluvium, valley-fill, and karstified dolomite aquifers show major potential as groundwater resource. More recently, HydroConcept (2014) suggested that local CID aquifers in the northwest Hamersley Range area (Fig. 1) showed some potential. This work shows that other groundwater systems such as karstified/weathered dolomites and the Cenozoic/Permian paleochannels show potential to provide good-quality groundwater but have been poorly documented.

At the same time, this work shows that there is major potential at regional scale for accessing groundwater of good quality in the sandstone aquifers contained in the West Canning Basin, with the confined Wallal aquifer showing the

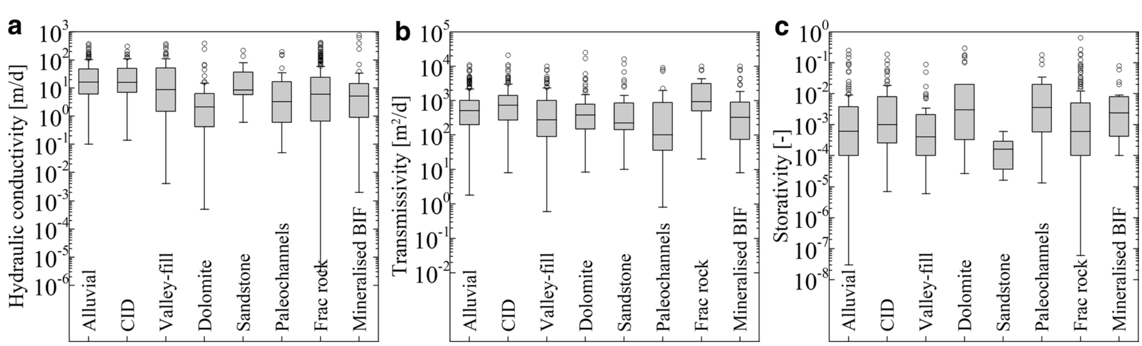

Fig. 8 Boxplots for the hydraulic properties collected for the aquifers identified in the Pilbara region. *Alluvial* coastal alluvial, *CID* channel iron deposit, Valley-fill, Dolomite karstified/weathered dolomite, *Sandstone* Wallal and Broome aquifers of the West Canning Basin, Permian/Cenozoic *Paleochannels*, *Fractured* rocks, *BIF* Banded Iron Formations

largest potential. This is in agreement with the increasing number of studies and water resource assessments of this aquifer implemented in recent years (see, e.g., DOW Department of Water (DoW) 2012b, 2013b). However, aspects of relevance for the future development of the Wallal sandstone aquifer need to be considered: (a) potential hydraulic connection with the coastal alluvium of the De Grey aquifer at the western limit of the WCB aquifer, (b) quantification of the effective offshore discharge, (c) potential vertical connection between confined and unconfined aquifers along the coastline, and (d) the role of the regional groundwater through flows as source of recharge and their potential connection with the Oakover River in the vicinity of the Wallal embayment. Up to date, these aspects are relatively unknown and remain as critical knowledge gaps and efforts should be invested to improve our understanding on these aspects of the flow system.

Our work confirmed the relevance of the coastal alluvium aquifers to support the existing water supply schemes in the study area. These aquifers are well investigated, easily accessible, and currently developed but show some challenges related to the need to protect groundwater-dependent riverine vegetation, uncertainty due to the infrequency of groundwater recharge events, and the prevention of saltwater intrusion due to groundwater abstraction (DOW 2013b). This work has identified additional knowledge gaps for these aquifers: (a) interaction between surface water and groundwater is poorly documented, (b) identification of processes enabling the flushing of salts, and (c) description and extent of the inland migration of the saltwater wedge are aspects that require data collection for a better understanding and quantification.

Valley-fill aquifers were identified in this work as a potential source of fresh groundwater, especially when multiple aquifers are hydraulically interconnected. Our analysis identified the relevance of karstified dolomites when in hydraulic connection with valley-fill aquifers (e.g., Millstream aquifer). Difficulties in assessing the opportunities for the development of these aquifers, however, are related to the ephemeral nature of the river courses in the Pilbara region, which limits local recharge from rivers, and the degree of interconnection of the multiple aquifer systems. Therefore, the interconnection of the multiple aquifer systems present in inland groundwater systems (e.g., valley-fill, calcrete, CID, and karstified dolomite) needs to be assessed as well as the quantification of the effective recharge. Despite their relevance, these aquifers are poorly studied and current assessments are limited to local conditions around mine sites and existing well fields (e.g., Millstream aquifer).

An emerging major water resource, not previously considered as a significant regional groundwater resource, is the concealed CID aquifers present in the Pilbara region. The groundwater resources of the CIDs have not been extensively studied in the region, but recent evaluation around the northwest of the Hamersley Range shows that there is a large potential as water source in the CIDs (HydroConcept 2014). Our analysis suggests that this type of aquifer could yield substantial volumes of good-quality groundwater at a regional scale. A major challenge to manage these aquifers, however, relates to both its nature as iron-ore resource and source of freshwater (HydroConcept 2014). Historically, surplus water resulting from mine dewatering has been discharged to the environment, but water resources planning could now account for potential use of the surplus water. Remaining challenges and knowledge gaps for their characterization are associated with the assessment of connectivity of CIDs with overlying and underlying aquifer formations and the quantification of vertical flux exchanges.

Paleochannels containing Permian and Cenozoic sediments have been identified in the east and northeast region of the study area but are poorly documented from a hydrogeological perspective. Despite of the previous investigations, the concealed non-saline paleochannel systems have only recently been investigated as potential groundwater sources (English et al. 2012). Our analysis revealed that groundwater resources associated with these paleochannels supply water to mining operations (Telfer and Kintyre) in the area and that a potential groundwater resource receiving some modern recharge corresponds to the Wallal paleovalley (Fig. 4), which is believed to contain relatively fresh water unlike other paleovalleys in the area (Roach et al. 2010b). However, there are limited hard data to confirm the presence of a suitable aquifer or to further characterise the potential associated with Permian and Cenozoic paleochannel aquifers in the study area.

Analysis of data and reports suggests that localised storage and potential in fractured rock aquifers is associated with the development of secondary porosity due to mechanical features or ore mineralisation. Given the nature of these aquifers, which may vary from nearly impermeable to highly fractured formations, it is difficult to anticipate a regional significance for this aquifer type as water source. This work, however, confirms that fractured rock aquifers have been extensively documented as part of mining exploration activities and that these systems constitute important local water sources supplying mine sites and supporting relevant GDEs.

Conceptually, the dominant recharge processes for the aquifers analysed in this work correspond to episodic and localised streamflow (river) recharge associated with overflow or flooding events of the main rivers, and direct infiltration of rainfall (diffuse recharge) on those areas (e.g., West Canning Basin) affected by cyclonic rainfall events. Despite a number of local studies attempting to characterise the recharge mechanisms of coastal alluvium aquifers, a full understanding of this process for other relevant aquifers is required for a better quantification of renewable groundwater resources (Dogramaci et al. 2012, 2015; Commander et al. 2015a). The dependence of groundwater recharge on high-intensity rainfall events is consistent with groundwater isotope data showing a similar composition than rainfall as well as groundwater of different ages along different flow paths (McCallum et al. 2017). The assessment of the groundwater recharge in the Pilbara region, however, is a challenging task given the arid nature of the study area and the large variability of rainfall, which is hard to fully capture given the limited number of rainfall stations in the study area (Ahooghalandari et al. 2015). As suggested by Houston (2002), flooding recharge events in arid and semi-arid areas are usually non-linear and difficult to quantify for resource evaluation. A good quantification of both localised recharge process as well as the diffuse recharge remains important knowledge gaps identified in this work. A better understanding of these processes will allow a better quantification of the vertical flux exchanges defining the recharge rates for underlying aquifers such as karstified dolomites and CIDs.

In terms of groundwater discharge, the dominant (natural) process corresponds to evapotranspiration, mainly in riverine areas and the coastal plain, and discharges into the Indian Ocean for the coastal alluvium and main sandstone (Wallal and Broome) aquifers. Riparian vegetation covers approximately 4% of the Pilbara region, with ca. 11% of the riparian vegetation being exclusively groundwater-dependent (Alaibakhsh et al. 2017). Despite the relatively small extent, evapotranspiration rates are significant given the climatic conditions of the study area. Nonetheless, a better understanding of evapotranspiration (as the main natural discharge process) is required in those aquifers where this process is relevant. The groundwater outflows into the Indian Ocean are relatively undocumented and not quantified, and this remains a major knowledge gap.

Understanding the functioning of the recharge and discharge processes and the collection of data explaining these processes in the aquifers identified are a priority for sustainable management of these resources. At the same time, climatic fluctuations and the impact of climate change on the main recharge processes may pose additional challenges to characterise the available groundwater resources for the future development of this region. The occurrence and the characteristics of the aquifers identified in the Pilbara region suggest that there might be significant volumes of groundwater of reasonable quality available; however, this resource must be managed in line with the protection of environmentally sensitive areas (groundwater-dependent ecosystems) and to ensure productive sectors and population access to safe water.

5 Conclusions

This work presents the most recent regional-scale assessment and conceptualization of groundwater resources in the Pilbara region. By reviewing extensive literature and data on hydraulic properties, aquifers are further categorised into seven main hydrogeological systems and a conceptualization of the functioning of these systems is proposed.

Coastal alluvium aquifers, inland aquifers comprising valley-fill, calcrete, and karstified dolomites, and the Wallal Sandstone aquifer of the West Canning Basin show potential to provide groundwater of acceptable quality at a regional scale. Other less studied aquifer systems such as CID aquifers and inland paleovalleys/paleochannels show some potential but require the collection of data on hydraulic properties, groundwater quality, aquifer geometry, and accessibility to groundwater resources to fully assess their potential at regional scale. Only limited regional potential is expected from fractured rock aquifers occurring in the study area. Given the arid nature of the Pilbara region, however, localised fractured/mineralised rock formations may provide substantial water resources to support mining activities or groundwater-dependent ecosystems at local scale.

Major renewable groundwater resources are generally associated with significant rivers, and are recharged by infiltration of streamflow and flood water. Up to date, a moderate understanding of the main recharge process for some of the aquifers exists (streamflow recharge); however, developing these aquifers to meet future water demands will require the collection of more data and a thorough understanding of the main recharge and discharge mechanisms dominating the water balance. Important challenges remain to manage these groundwater resources and they relate to surface water–groundwater interactions, infrequency and uncertainty of groundwater recharge associated with cyclonic rainfall events, risk of saline intrusion at coastal alluvium aquifers, hydraulic connectivity between adjacent aquifers (e.g., Coastal alluvium of the lower De Grey River and Wallal sandstone aquifers), description and quantification of evapotranspiration processes and offshore submarine discharges in the Wallal sandstone aquifer, and the coordination of ore exploitation and groundwater resources development in the CID aquifers for a better water management.

There is an impending need to augment the groundwater monitoring bores in the CIDs and paleochannel aquifers as well as to provide regional or sub-regional watertable maps to assess large-scale groundwater conditions. Currently, highly clustered data on aquifer properties, the diverse aquifer types identified in this region, poorly described systems such as Permian paleochannels, and the vast dimensions of the study area, make the creation of these regional/sub-regional maps a challenging task. Although partially analysed here, groundwater quality issues such as salt mobilisation and the risk of saltwater intrusion should be given a proper consideration for future water resource development plans of the coastal alluvium aquifers and inland valley-fill aquifers exposed to hypersaline fluxes (e.g., Fortescue Marsh).

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Compliance with ethical standards

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

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