2 Developing an understanding of the groundwater system

The two sections of this chapter summarise the major investigations and publications related to the groundwater systems of the northern Perth Basin (Figure 2). The first section summarises the findings of over 30 separate, government-funded hydrogeological investigations conducted over the past 100 or so years, and the main investigations undertaken by other agencies and private companies for mining, irrigated agriculture and geological purposes. The second section summarises surface water – groundwater interaction studies, including groundwater-dependent ecosystems (GDEs), wetlands, river baseflow and cave ecohydrology. Collectively, the publications referenced in this chapter capture the current state of knowledge of the groundwater systems of the northern Perth Basin.

2.1 Hydrogeological investigations

The groundwater resource potential of the northern Perth Basin was first recognised in the late nineteenth century and government investigations commenced early in the following century. The state government drilled exploratory bores for water and coal in the townships of Mullewa, Eradu, Mingenew, Geraldton, Dongara, Moora and Yardarino (Campbell 1910; Maitland 1913; Connolly 1954; Allen 1997). During World War II, the Royal Australian Engineers drilled water supply bores for army camps and airfields throughout the basin at Dandaragan, Gingin, Mingenew, Moora and Morawa (Allen 1997). Significant groundwater development began in the 1950s when new land was released under the War Service Land Settlement Scheme and drilling for stock and domestic supplies increased (Mory 1995a, 1995b). These bores, some of which were as much as 150 m deep in the Badgingarra–Eneabba area, were equipped with windpumps.

Prospects for farm water supplies, particularly in the northern part of the basin where groundwater salinity is relatively high, have been reported by the Geological Survey of Western Australia (GSWA) in both published (e.g. Berliat 1966) and unpublished (e.g. Laws 1980) hydrogeology reports. Groundwater salinity in this region was found to generally increase from west to east, and to be controlled by rock types, and partly by faults and topography. Town water supply development and private investigations by mining companies and agricultural developers have also contributed significantly to the hydrogeological knowledge of the northern Perth Basin.

The potential groundwater availability in the northern Perth Basin demonstrated by the early drilling investigations led to a period of systematic investigation conducted by the GSWA from 1963 to 1994, initially under the Federal Water Resources Assessment Program. Since 1995 groundwater investigations have been carried out successively by the former Water and Rivers Commission, the Department of Environment, and the Department of Water. These investigations, summarised in Table 1 and Figure 3, comprise a range of investigations that include:

- six major deep east–west borehole lines spaced about 50 km apart between Guilderton and Dongara

- one ‘infill’ deep regional investigation in the Swan Coastal Plain between Guilderton and Cervantes
- five shallow regional investigations covering the full extent of the Swan Coastal Plain from Gingin to Geraldton
- local investigations for various purposes, including those carried out jointly with the former Public Works Department and also former Water Authority of Western Australia focusing on town water supply development in strategic areas (Wicherina, Allanooka and Irwin View, Arrowsmith, Agaton and Jurien Bay)
- local investigations focused on surface water – groundwater interaction in the northern Perth Basin.

From these investigations, 709 monitoring bores were constructed in the northern Perth Basin and a subset are monitored at least twice a year for water levels. They can also be used for monitoring changes in salinity and hydrochemistry.

Collectively, these investigations have provided a broad baseline understanding of aquifer extents and thickness, depth to groundwater, groundwater recharge, flow and discharge, aquifer salinity, hydrochemistry, groundwater age and in some cases surface water – groundwater interaction and GDEs. This wealth of information has been captured in reports and has vastly improved the sustainable management of groundwater resources in the region.

Deep regional investigations

The GSWA commenced a systematic drilling program to investigate the stratigraphy and map the hydrogeology of the northern Perth Basin, and provide an ongoing regional assessment of available groundwater resources as early as 1963.

A total of six deep east–west borehole lines were drilled in the northern Perth Basin about 50 km apart to depths of up to 800 m. These are, in order from north to south: the Dongara Line, Eneabba Line, Watheroo Line, Moora Line, Gillingarra Line and the Gingin Line (Figure 2). Boreholes were completed for long-term water level and salinity monitoring where possible, and many sites included multiple bores screened at different depths and in different aquifers.

The first borehole line in the northern Perth Basin was the Gingin Line, drilled in 1965–66. The project drilled 11 bores and confirmed that the multilayered aquifer system previously mapped from Mandurah to Bullsbrook extended as far north as the Gingin area. An ‘abundance’ of domestic quality groundwater was found within the Upper Jurassic – Lower Cretaceous aquifers up to depth of 150 m (Sanders 1967a, 1967b).

Drilling of the Watheroo Line commenced in 1967 and was completed in 1972, consisting of 11 bore sites and 23 bores up to 762 m depth, from near Watheroo in the east to Jurien Bay in the west (Harley 1974). Drilling of the Watheroo Line restarted in 1971 and was completed in 1972. This drilling program proved up the presence of large fresh groundwater resources in the Superficial, Leederville–Parmelia, Yarragadee and Eneabba–Lesueur aquifers. The investigation also discovered that the Otorowiri Formation forms an important confining unit. In addition, the potentiometric surface can be deep beneath parts of the Dandaragan Plateau, as much as 113 m bgl (below ground level) in Watheroo Line bore WL4.

The Eneabba Line to the north was drilled between 1972 and 1974 and comprised 28 bores at 11 sites to a maximum depth of 800 m. The drilling program discovered very large fresh groundwater resources in the Yarragadee and Leederville–Parmelia aquifers (Commander 1978). It found that the Cattamarra and Eneabba–Lesueur aquifers contain large reserves of fresh to brackish groundwater. It also found a high geothermal gradient in the west of up to 5.5 ^{o}C per 100 m but lower gradients to the east.

The Eneabba Line investigation was followed by drilling of the Moora Line, which started in 1974. The Moora Line runs from Moora to the coast and consists of 19 bores of up to 801 m depth (Briese 1979). Soon after, the Gillingarra Line between Lancelin and Mogumber was drilled between 1981 and 1986. Twenty bores were drilled at eight sites to a maximum depth of 1200 m (Moncrieff 1989). These drilling programs demonstrated the presence of large fresh groundwater resources in the southern portion of the northern Perth Basin, principally beneath the Swan Coastal Plain and the western part of the Dandaragan Plateau.

The Dongara Line, extending east from Dongara, was completed in 1995 (Groves 1995; Irwin 2007). This investigation confirmed the Yarragadee aquifer as a major groundwater resource in the area, but also identified salinity increases with depth and near the coast where there is mixing with seawater. The investigation also found that the potentiometric surface can be very deep in the area, as much as 181 m bgl in Dongara Line bore DL4B. Also, the Leederville–Parmelia aquifer was identified east of the Dandaragan Scarp, where it yields fresh groundwater and the water levels are increasing as a result of land clearing in the region.

More recently, between 2013 and 2015, a series of four deep bore lines were drilled across the Swan Coastal Plain between Guilderton and Wedge Island to the west and the Gingin Scarp to the east. A total of 29 bores were installed at 12 sites to a maximum depth of 1022 m. This drilling program focused on the Leederville and Yarragadee aquifers, improving groundwater monitoring and refining the hydrogeological conceptualisation between the Gingin, Gillingarra and Moora lines. Significant fresh groundwater resources were confirmed in the Leederville and Yarragadee aquifers (Tuffs 2016).

Department of Water reports can be accessed at www.water.wa.gov.au or at www.wir.water.wa.gov.au.

Geological Survey of Western Australia reports can be accessed at http://geodocs.dmp.wa.gov.au/

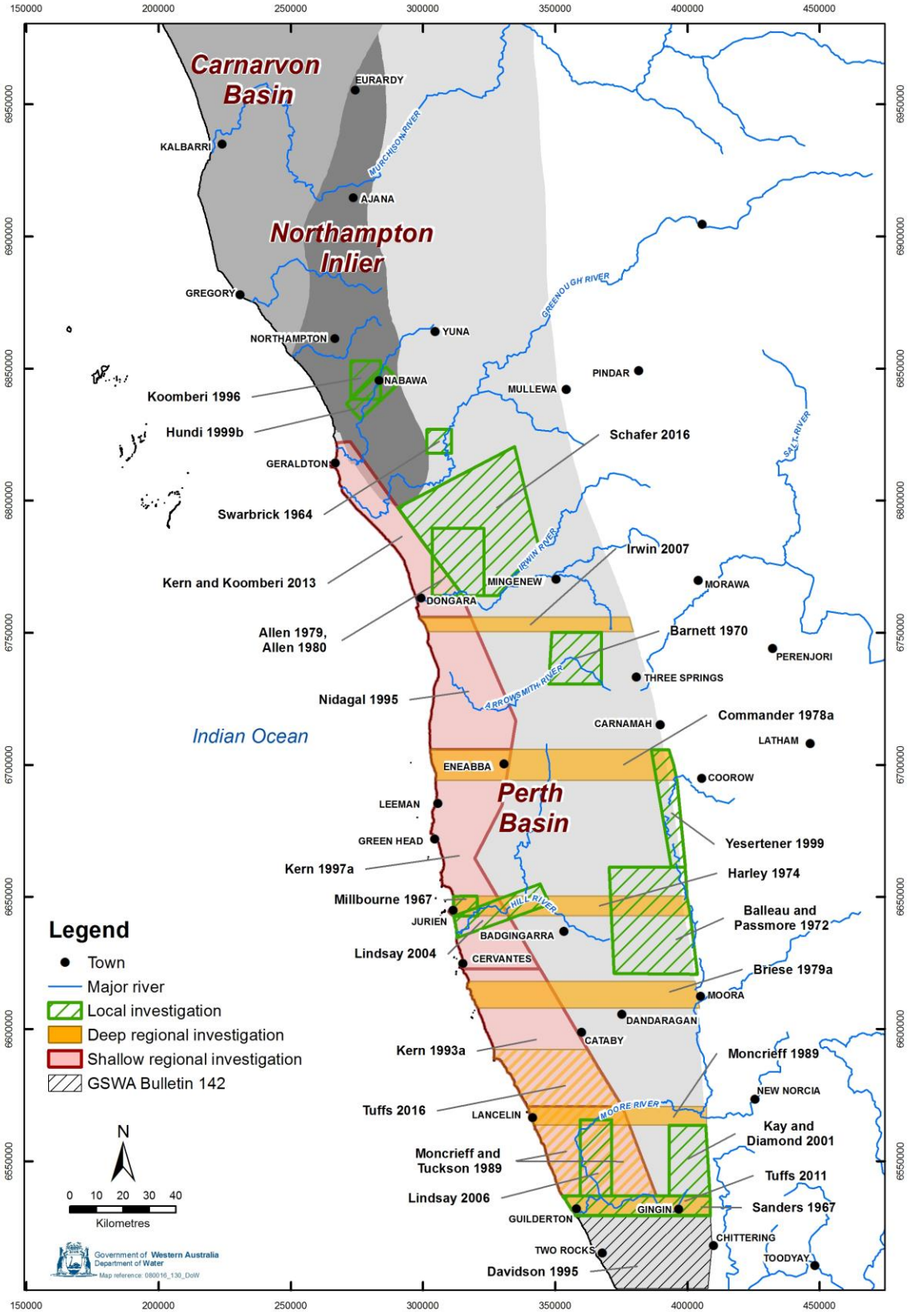

Figure 2 *Northern Perth Basin bulletin study area and the main hydrogeological investigations compiled in the bulletin*

Table 1 State government groundwater investigation programs in the northern Perth Basin

Program	Prefix	Sites	Bores	Year	Reference
Deep regional investigations					
Gingin Brook Line	GB	5	6	1965–66	Sanders 1967a
Watheroo Line	WL	12	23	1967–72	Harley 1974
Eneabba Line	EL	11	28	1972–76	Commander 1978a, b
Moora Line	ML	9	19	1974–77	Briese 1979a, b
Gillingarra Line	GL	8	20	1981–86	Moncrieff 1989
Dongara Line	DL	5	10	1990–95	Groves 1995; Irwin 2007
North Gingin	NGG	12	29	2013–15	Tuffs 2016
Shallow regional investigations					
Gingin	GG	11	11	1973	Allen 1975
Salvado	S	22	31	1976–80	Moncrieff & Tuckson 1989
Cataby Shallow	CS	35	65	1985–87	Kern 1988
Leeman Shallow	LS	34	68	1990–93	Nidagal 1994; Kern 1997
Greenough Shallow	GS	19	25	1994	Kern & Koomberi 2013
Mid West GDEs	Various	10	38	2009–12	Boniecki & Ryan 2010; Ryan 2012b
Local investigations					
Arrowsmith	AR	54	54	1963–67	Barnett 1969
Wicherina	–	5	5	1964	Swarbrick 1964b
Jurien Bay	JB	12	12	1965–66	Milbourne 1967
Allanooka	A	90	90	1965–98	Allen 1980
Agaton	A	16	18	1967–69	Balleau & Passmore 1972
Irwin View	IV	24	24	1974–77	Allen 1980

Program	Prefix	Sites	Bores	Year	Reference
Mt Hill	–	6	6	1977–96	Allen 1980
Nabawa	NAB	10	10	1994–95	Koomberi 1995
Chapman Valley	WRC	14	14	1998	Hundi 1999a, b
Yarra Yarra Lakes	YR	5	28	1999	Yesertener 1999a, b
Red Gully	RG	3	3	2000	Diamond 2000
Hill River	HRM	2	2	2004	Lindsay 2004
Gingin Superficial (Cowalla)	GS	10	10	2006	Lindsay 2006
Gingin Brook	GGB	16	32	2008	Tuffs 2011
Allanooka–Casuarinas	AC	17	28	2010–11	Schafer 2016

Shallow regional investigations

In the 1970s investigations began into the shallow aquifers of the Swan Coastal Plain between Guilderton in the south and Geraldton in the north. These investigations installed 200 monitoring bores (Figure 4). The first shallow drilling program to install monitoring bores in the Superficial aquifer was conducted in 1973 on the northern Gnangara Mound by the Metropolitan Water Authority. This program constructed 11 monitoring bores between Gingin and Guilderton (GG series). This was followed by the installation of the GB series of monitoring bores in 1977.

The first systematic investigation by the GSWA was the Salvado project between 1976 and 1980, consisting of 31 bores drilled across the Swan Coastal Plain between Guilderton and Lancelin (Moncrieff & Tuckson 1989).

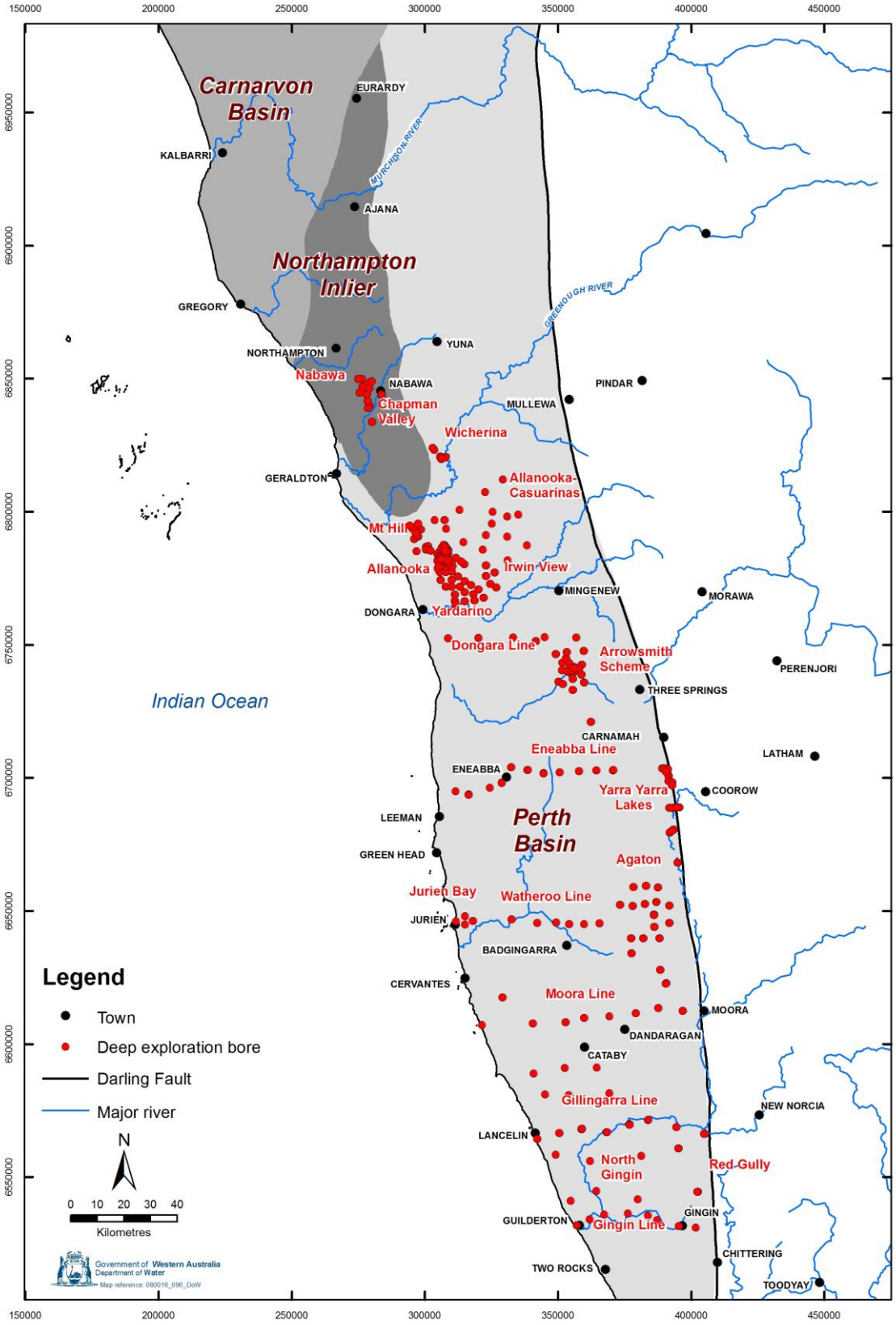

Figure 3 Deep exploration bores

The Cataby Shallow project extended the bore network to the north from Lancelin to Cervantes. This is the largest shallow investigation to date, comprising 68 bores at 35 sites (Kern 1988). Both the Cataby Shallow and Salvado projects confirmed the presence of a large fresh groundwater resource, up to 60 m thick, in the Superficial aquifer that could be used for irrigated agriculture and town water supply.

The Leeman Shallow project extended the network to Dongara, with 64 bores drilled between Leeman and Dongara (Nidagal 1994; Kern 1997). Major freshwater resources were found in the Yarragadee and Lesueur Sandstone component of the Eneabba–Lesueur aquifers. This investigation determined the saturated thickness of the Superficial aquifer as generally less than 20 m with groundwater salinity increasing to the north. It also confirmed that groundwater is generally brackish to saline in the Cattamarra aquifer and Eneabba Sandstone component of the Eneabba–Lesueur aquifer.

The Greenough Shallow project was completed in 1994, with 26 shallow bores installed between Dongara and Geraldton (Koomberi 1994b; Kern & Koomberi 2013). This investigation found that groundwater in all aquifers was generally brackish to saline, except in the eastern portion of the coastal plain where fresh groundwater can occur locally in the Superficial and Yarragadee aquifers.

Local-scale investigations

Town water supply investigations

Numerous investigations have been undertaken as part of town water supply development. Drilling and monitoring information on each of these sources has been collected by the Water Corporation and its predecessors (Public Works Department and Water Authority of Western Australia).

The Arrowsmith investigation in the Parmelia aquifer commenced in 1963 to identify suitable water supplies for towns located on the eastern edge of the basin and adjacent Yilgarn Craton (Barnett 1969). The investigation drilled 54 bores in the Arrowsmith River region, 10 km west of Arrino, resulting in the development of the Arrowsmith Scheme that supplies water to Mingenew, Arrino, Morawa and Perenjori.

Investigations for the Agaton project in the Leederville–Parmelia aquifer in the late 1960s were undertaken as part of the Northern Comprehensive Water Supply Scheme, which aimed to develop an integrated piped water supply scheme through much of the state's northern agricultural area and Goldfields region (Balleau & Passmore 1972). Although significant groundwater resources were discovered, the area was never developed as an integrated water supply scheme.

Investigations for Geraldton's town water supply were conducted as early as 1927 (Swarbrick 1964b), resulting in the development of the Wicherina borefield. Following increased demand and declining water quality in the Wicherina borefield, the Allanooka, Irwin River and Mount Hill investigations were initiated in the late 1960s to identify a suitable replacement water source (Allen 1964, 1965). Over 100 bores were drilled at the Allanooka, Mount Hill and Wye Springs borefields. Abstraction from the Allanooka borefield commenced in 1967, with the scheme supplying Geraldton, Dongara, Port Denison, Walkaway, Narngulu, Mullewa and

Eradu. A further 17 bores were drilled between 1974 and 1977 to augment the scheme (Allen 1979, 1980). Since then, the Water Corporation has installed additional monitoring and production bores. Further investigation drilling has been conducted by the Department of Water in the Casuarinas area to the north and east of Allanooka (Schafer 2016).

The Water Corporation recently conducted investigations of the Superficial and Eneabba–Lesueur aquifers near Jurien Bay to expand the town water supply. This included drilling 40 new bores (Baddock & Lach 2003) and investigating potential environmental impacts of groundwater abstraction (Froend et al. 2002).

Several smaller investigations to improve hydrogeological understanding and identify new water sources have taken place at Nabawa and Chapman Valley north of Geraldton (Koomberi 1995; Hundi 1999a, b), in the Yarra Yarra region (Yesertener 1999 a, b), and in the Gingin area (Diamond 2000; Tuffs 2011).

For more information on groundwater use for town water supply, including the locations of water supply wells and pipelines, refer to Section 6.2.

Environmental hydrogeology investigations

Investigations to assist managing agricultural land include a review of the impacts of rising groundwater levels and development of secondary salinity on biodiversity and agriculture in the West Midlands region (Carter & Deshon 2002). McConnell (2000) carried out an investigation of the Nebru catchment in the upper Arrowsmith River. This work concluded that the Urella Fault might act as a groundwater barrier and therefore reduce the risk of saline groundwater leakage from the Nebru catchment into the Perth Basin.

Studies of waterlogging due to rising groundwater and increased runoff from extensive clearing have also been undertaken in the Moora Group at Moora townsite (Deshon 2001) and in the Jingemai Dolomite, 28 km east of Mingenew (Speed et al. 2004). The Department of Agriculture and Food, Western Australia (DAFWA) carried out a hydrogeological assessment of rising groundwater levels in the Tumblagooda aquifer and potential saline land degradation near Adjana (Speed 2003).

Drilling and aerial electromagnetic survey have been conducted in the Gillingarra – West Koojan area for the Moore Catchment Council (Moore Catchment Council 2008). More recently, DAFWA carried out local drilling near lakes Indoon and Logue in 1999 as part of their long-term monitoring program (R Speed 2016 pers. comm.). There have also been drilling programs focused on surface water – groundwater interactions, including the characterisation of GDEs (Stelfox 2001; Lindsay 2004; Tuffs 2011; Ryan 2012a).

Other groundwater investigations

Groundwater investigations by mining companies for irrigated agriculture and geological studies have also contributed significantly to the hydrogeological knowledge of the northern Perth Basin. The information from many of these investigations is synthesised in this bulletin, and the main references are outlined here.

The mineral sands deposits at Eneabba and Cataby and their water requirements have driven a number of groundwater investigations (Baxter 1977). Water supply drilling for the Eneabba area began in 1971, with more than 40 production bores constructed in the

Superficial, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers (e.g. AGC 1974, 1975; Rockwater 1977, 1980b, 1995; Commander 1980).

Similar investigations were carried out in the Cataby area in the 1980s and 1990s for the Cooljarloo mineral sands deposit, with over 30 bores drilled in the Superficial and Yarragadee aquifers (Rockwater 1992; AGC 1989b). Other significant investigations for mineral sands projects have also been conducted near Jurien Bay (AGC 1975; McPhar Geophysics Pty Ltd 1975).

In the 1980s an investigation in the Hill River area was undertaken to prove groundwater resources for a proposed coal-fired power station (AGC 1989b). While the power station was never constructed, the three production bores with aquifer test data and nine monitoring bores contributed significantly to the understanding of the hydrogeology of the Hill River area. More recently, investigations have been undertaken for a proposed coalmine in the Cattamarra Coal Measures, west of Eneabba (Rockwater 2009), which included drilling and aquifer tests of four production bores and construction of 16 monitoring bores.

Groundwater supplies have been investigated by two magnetite mining projects with several investigation bores constructed in both the Leederville–Parmelia and Yarragadee aquifers in the Arrowsmith River and Mingenew areas to assess groundwater resources for process and slurry transport (Aquaterra 2005; Rockwater 2008).

Since the 1990s large irrigated agriculture projects have also undertaken significant investigations to assess groundwater resources. Several horticultural operations in the Dinner Hill area have undertaken localised investigations of the Leederville–Parmelia aquifer to prove up the resource (Woodward Clyde 2000a; ERM 2001a; Water Direct 2004; Aquaterra 2004; Pennington Scott 2006). Irrigated fodder crop operations have also installed several deep Yarragadee bores north of Eneabba (Worley 2004); near Badgingarra (Pennington Scott 2009b); in the Cataby area (Pennington Scott 2009c); as well as in the Eneabba–Lesueur aquifer west of Eneabba (GRC–Dames & Moore 1990). Most recently an investigation for an irrigated almond project included the drilling of five deep bores in the Yarragadee aquifer and three bores in the Leederville–Parmelia aquifer near Eneabba (Pennington Scott 2007, 2008b, 2009a, 2009b).

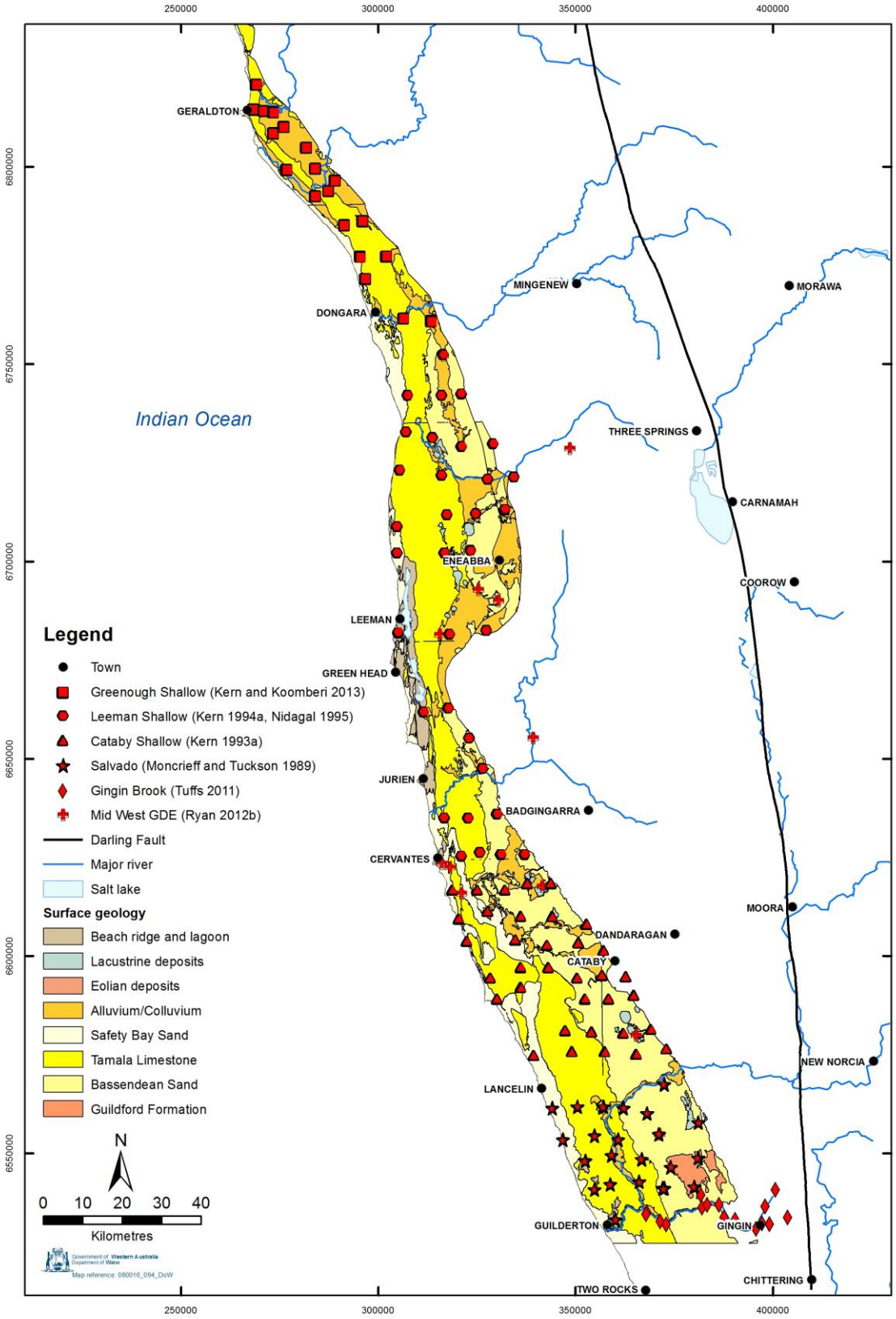

Figure 4 Shallow regional investigations

2.2 Environmental water investigations

Numerous investigations into environmental water requirements and GDEs across the northern Perth Basin have been published since 1995. The major findings of many of these studies are summarised in the department's HG11 report (Rutherford et al. 2005).

Groundwater-dependent ecosystem studies

V & C Semeniuk Research Group (2001) and PPK (2001) studied GDEs of the northern Perth Basin. These studies mapped potential groundwater-dependent wetlands, vegetation and caves. To do the latter, PPK (2001) considered both depth to groundwater and Normalised Difference Vegetation Index (vegetation 'greenness') of satellite imagery.

Following these studies were several studies of ecological and social water requirements of the Moore River (Strategen 2005, 2006) and ecological water requirements of the Hill River (Wetland Research and Management 2005).

Rutherford et al. (2005) generated a depth-to-groundwater contour map of the northern Perth Basin based on data from the state monitoring network, along with interpretations by PPK (2001) and Davidson et al. (2004). They produced conceptual models of 98 potential GDEs, and mapped remnant vegetation over shallow groundwater.

In 2007 the Northern Agricultural Catchments Council and the Department of Water consulted the northern Perth Basin community on their visions and desires for groundwater (Northern Agricultural Catchments Council 2007). The report documents consultation with representatives of the Noongar and Yamatji Indigenous groups, including information on the relevance and history of specific GDEs, and songlines in general, many of which are strongly defined by water in the landscape.

The GDE Vulnerability in the Mid West project (2009–12) drilled monitoring bores, analysed lithology, groundwater and acid sulfate potential (Boniecki & Ryan 2010, Ryan 2012b), characterised ecosystems (Casson 2012; Pinder & Quinlan 2015; Susac 2012) and conducted aerial electromagnetic surveys (GroundProbe Geophysics 2011a; 2011b) at 10 representative GDEs between the Moore and Irwin rivers. The study confirmed the importance of confined aquifers to ecosystems of high conservation priority. It also noted that while risk to ecosystems from abstraction is commonly attributable to drawdown, abstraction might also present a water quality risk to ecosystems, for example through inducing movement of saltwater–freshwater boundaries (Lam 2013), or through generation of acid sulfate soils.

Wetland studies

The V & C Semeniuk Research Group (1994) evaluated wetlands between Lancelin and Dongara to support nomination of individual wetlands to the Register of the National Estate. Their approach was to identify the natural groupings of wetlands and to assign them to a type, or consanguineous suite. This was to support selecting a variety of wetland types for recognition for their conservation significance.

Bennelongia Environmental Consultants (2010) completed a 'snapshot' literature review of wetlands between the Moore and Murchison rivers. They identified significant wetlands and

watercourses, along with their ecological communities, flora and fauna. Some references relevant to the northern Perth Basin's GDEs include volumes of the 1993–96 series *Wetlands of the Swan Coastal Plain* (e.g. Hill et al. 1996, which formed the basis for the Geomorphic Wetlands Swan Coastal Plain spatial dataset); surveys of lake geomorphology and salinity management in the Yarra Yarra catchment (Boggs et al. 2007; GHD 2006), surveys of the Hutt River catchment (Quinlan et al. 2009); and plant, animal and water quality surveys on parts of the Murchison River (Gibson et al. 2000; Halse et al. 2000).

River baseflow studies

Four major river baseflow studies have characterised how rivers traversing the northern Perth Basin gain from, and lose to, various aquifers along their lengths (Johnson 2000; Stelfox 2001; Lindsay 2004; Tuffs 2011). The rivers of the northern Perth Basin can therefore be conceptualised as a series of connected yet distinct GDEs, with a variety of conceptual models applying along their lengths.

Stelfox (2001) assessed the groundwater–river interactions of the Coonderoo and Moore rivers in the context of concerns around secondary salinity and its potential impacts on groundwater quality. Saline river water was found to recharge the aquifer on the Swan Coastal Plain. Groundwater south of Gingin Brook was found to have elevated nutrient concentrations, with potential implications for the health of Gingin Brook and the lower Moore River and its estuary. There has also been investigation of the hydrodynamics of the Moore River estuary in relation to variable patterns of groundwater, marine water and surface water contributions over time (Cousins 2003).

Lindsay (2004) assessed the relationship between the Hill River and groundwater. Over its course, the river traverses aquifers that are in places artesian, supplying water to the river via springs and seeps. The effect of rising groundwater levels on baseflow was noted, with this effect attributed to land clearing.

Tuffs (2011) drilled monitoring bores and analysed lithology and groundwater to investigate surface water – groundwater interaction along Gingin Brook, confirming the various contributing aquifers. The report noted the potential for groundwater and surface water abstraction to impact baseflows, as well as drying climate. This study followed work by Johnson (2000) that assessed the hydrogeology of five perennial brooks of the Dandaragan Plateau (Gingin, Lennard, Nulila, Breera and Yalyal brooks) as primarily fed by springs and seeps along the stream banks. The report noted landholder observations of declines in stream flow over 1992–2000, as well as substantial groundwater level declines in one contributing aquifer, attributable primarily to abstraction.

Cave studies

V & C Semeniuk Research Group (2001) and PPK (2001) both reported on caves of the northern Perth Basin. PPK (2001) mapped caves between Geraldton and Cervantes, and the V & C Semeniuk Research Group (2001) reported that there were no recorded caves between Grey and Yanchep, but this might be through lack of knowledge as opposed to their confirmed absence, given the existence of karst.

Susac (2009) produced a comprehensive literature review and report on karst biodiversity, palaeontology and hydrology of the Northern Agricultural region, for the Northern Agricultural Catchments Council. The report provides information on individual caves, in the context of a literature review on how selected caves interact with aquifers and surface water. Susac (2012) nominated one high value representative of each of seven subterranean ecosystem types, based on available information and expert cave knowledge.