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Groundwater abstraction and aquifer response in the Roe Palaeodrainage (1990–2001)

S.L. Johnson

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Department of Water
Level 4, 168 St Georges Terrace
Perth Western Australia 6000

www.water.wa.gov.au

Telephone +61-8-6364 7600
Facsimile +61-8-6364 7601
For more information about this report, contact

Seth Johnson
Section Manager, Groundwater Investigation

Department of Water
PO Box K822
Perth WA 6842

Telephone (08) 6364 6897
Facsimile (08) 6364 6525

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Contents

Figures

Tables

Summary

In the late 1980s, the introduction of new gold processing technologies (CIP – carbon-in-pulp and CIL – carbon-in-leach) and resultant expansion of the gold industry led to a rapid increase in groundwater demand. Mining companies developed numerous production borefields in the Tertiary palaeochannels to meet this demand for local hypersaline groundwater.

The palaeochannel aquifer in the Kalgoorlie region appears to have performed better than initially predicted. Large sections of the palaeochannel have reached steady-state condition, rather than continuing water level decline, suggesting that groundwater pumped is from leakage or recharge rather than storage depletion. Since 1997, many of the borefields have shown appreciable water level recovery because of the reduction of groundwater abstraction through improved water use efficiency and usage of alternative water sources (mine dewatering, flooded lakes and mine voids).

The concept of sustainable yield in palaeochannel aquifers is considered new thinking, which is different from current allocation and groundwater management practice. The fact that the groundwater system has reached equilibrium or steady-state conditions during extended periods of groundwater abstraction suggests that a sustainable yield can be estimated. The initial estimate of 10 GL/yr is for a combined palaeochannel length of about 110 km; therefore, the sustainable yield for the entire Roe Palaeodrainage (400 km in total) is conservatively estimated at about 35 GL/yr. Future reviews will confirm or modify this estimation of sustainable yield for the Roe Palaeodrainage.

As a sustainable yield can be determined, there is no need to discuss life of the groundwater resource in terms of years or decades. It is therefore assumed that the groundwater resource can maintain reliable hypersaline supplies in perpetuity providing sustainable abstraction rates are maintained. The groundwater resource will not become depleted by 2012 or 2022, as originally suggested by others, but rather large sections of the palaeochannel may completely recover to original water levels, assuming abstraction continues to decline.

1 Introduction

1.1 Overview

In the late 1980s, the introduction of new gold processing technologies (CIP – carbon-in-pulp and CIL – carbon-in-leach) and resultant expansion of the gold industry led to a rapid increase in groundwater demand. Mining companies developed numerous production borefields in the Tertiary palaeochannel aquifers to meet this demand for local hypersaline groundwater.

There have been numerous groundwater studies focused on the palaeochannels around Kalgoorlie (known as the Roe Palaeodrainage). BHP Engineering and Australian Groundwater Consultants (1988) and Commander et al. (1992) detailed the regional distribution of the palaeochannels and provided estimates of stored groundwater resources that contributed to the understanding of palaeochannel stratigraphy (Kern and Commander, 1993). Various groundwater consultants have been responsible for establishing the borefields and providing ongoing reviews of aquifer performance. CSIRO have also undertaken projects to estimate groundwater recharge (Turner et al., 1994), artificially recharge of flood waters from salt lakes into palaeochannels (Ali and Turner, 2000), and the long-term viability of groundwater abstraction (Turner et al., 1996).

Concerns about the water supply to the Goldfields in 1987 led to initial investigation of the palaeochannel resources. There has also been periodic interest shown by private industry to provide alternative water supplies to the local mining industry, including pipelines from Perth, the Officer Basin and the Kimberley. The work by Turner et al. (1996) encouraged this interest by suggesting that the palaeochannel groundwater resources in the vicinity of Kalgoorlie will become exhausted between 2012 and 2022. Rather than depletion of water resources, it is considered that the exhaustion of known mineral reserves is a greater concern for survival of the Goldfields. Flint and Searston (2003) showed that the amount of mineral exploration and discovery of mineral deposits significantly reduced in the late 1990s and early 2000s.

There have also been two comprehensive reviews to determine longevity or sustainability of the palaeochannel groundwater resource, including historical water use, availability and future water demand (Water Corporation, 1999; Department of Mineral and Petroleum Resources, 2002). Ion (1998) reviewed groundwater utilisation from the Roe Palaeodrainage between 1984 and 1996 and demonstrated that only a portion of the groundwater pumped came from storage with the remainder resulting from leakage.

More recently, Wharton (2002) provided some discussion on groundwater recharge into the palaeochannel aquifer (Black Flag Palaeochannel) near Paddington gold mine, 30 km north of Kalgoorlie. His work demonstrated that the groundwater levels in the palaeochannel sand aquifer have recovered because of a combination of reduced abstraction and inferred groundwater recharge.

1.2 Purpose and scope

There has been no previous systematic regional review of individual bore hydrographs and borefield abstraction to evaluate aquifer performance and longevity of the groundwater resource. A five-year review was recommended by Ion (1998), which was released initially as Hydrogeology Report 208 (Johnson, 2003). An initial review of groundwater monitoring data from selected borefields around Kalgoorlie showed widespread recovery or upward trends in water level. The purpose of this study is to provide some regional understanding of aquifer recovery and sustainability throughout the Roe Palaeodrainage. It will also determine aquifer response to extended periods of groundwater abstraction and the rates of recovery following cessation of abstraction.

In order to achieve the study objectives, the seven largest borefields (based on cumulative groundwater abstraction) surrounding Kalgoorlie were reviewed, including Kaltails, KCGM Northern and Southern borefields, New Celebration, Jubilee, Kanowna Belle and Paddington (Fig. 1). The selected borefields are regionally significant and considered representative of different scenarios, including borefields that have ceased operating, have reduced groundwater abstraction, or still at full production.

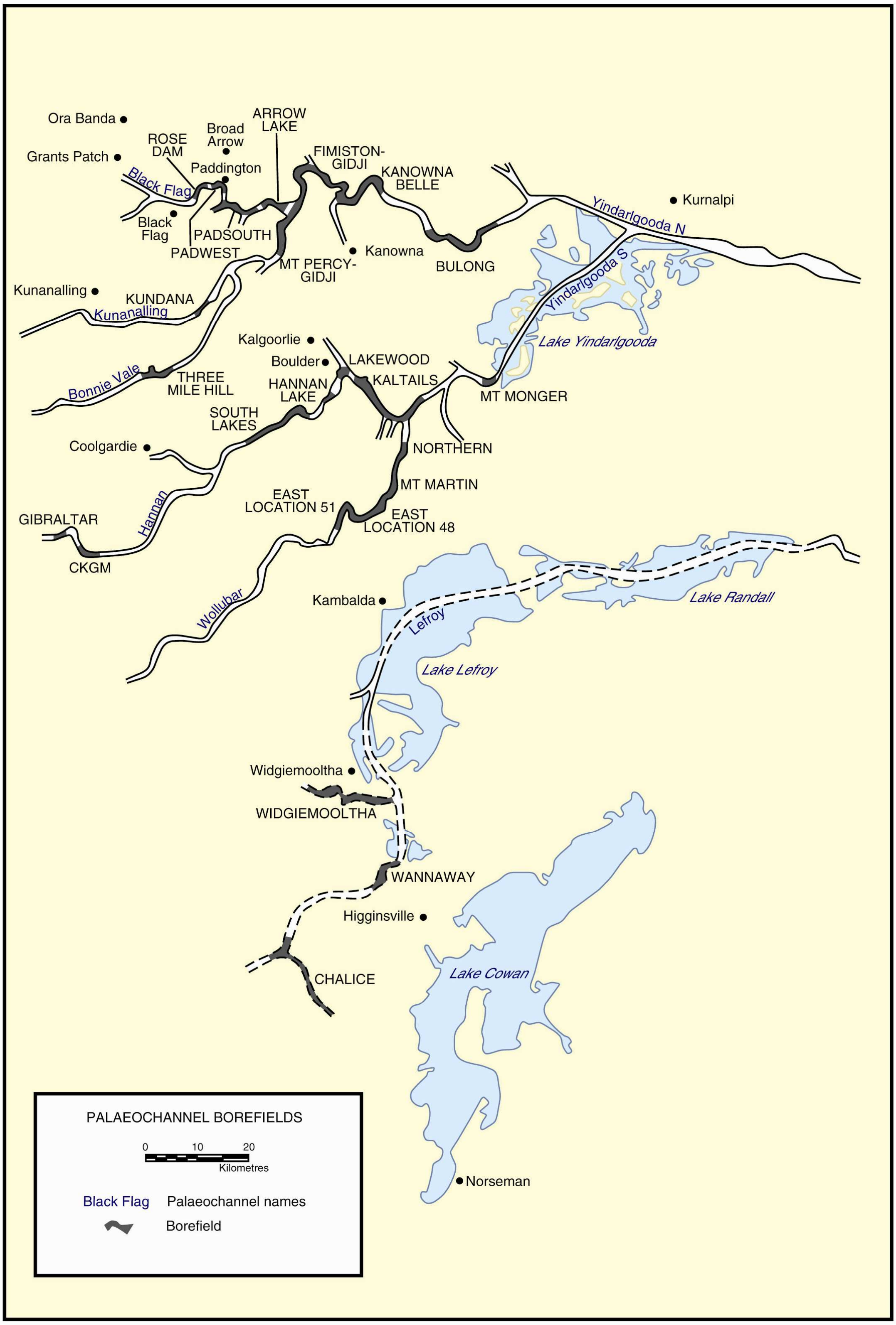

Figure 1 Location map showing palaeochannel borefields (after Ion, 1998)

2 Hydrogeology

Palaeochannels are former deep river valleys that eroded into the bedrock within the broad palaeodrainages and are now infilled with sediment (Fig. 2). In the vicinity of Kalgoorlie, the sedimentary sequence is commonly less than 60 m thick comprising basal Eocene sand overlain by plastic clay, in turn concealed by a thin alluvial cover (Kern and Commander, 1993). The basal sands range up to about 40 m thick and are about 1 km in width. In the Northern Goldfields, 300 km north of Kalgoorlie, the palaeochannel depth often reaches 130 m, comprising substantially thicker sequences of upper alluvium, which is locally replaced by calcrete (Johnson et al, 2000). The geological evolution and sedimentary deposition within these buried inset-valleys is discussed by De Broekert and Sandiford (2005).

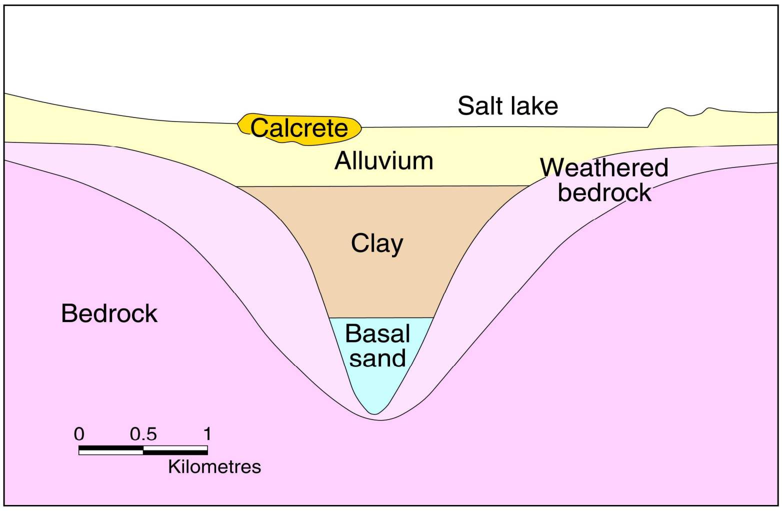

Figure 2 Palaeochannel cross section

The basal sands form the major regional aquifer. Palaeochannels act as regional drains with groundwater moving through the palaeochannel sand whilst receiving groundwater from surrounding bedrock. Pumping or depressurisation of the palaeochannel aquifer induces leakage from overlying clay and alluvium, as well as neighbouring bedrock aquifers.

Groundwater in the palaeochannel moves under very low hydraulic gradients in the trunk palaeochannels, and virtually all groundwater discharge is via evaporation from salt lakes. Groundwater recharge constitutes a very small proportion of rainfall with losses related to evaporation, utilisation by vegetation and runoff into the playa lakes (Turner et al., 1994). Direct recharge may occur in the upper reaches of the tributary palaeochannels, where lower salinity groundwater is present.

Groundwater salinity in the palaeochannels around Kalgoorlie ranges from 30 g/L (seawater is 34 g/L) in the west before increasing down-gradient to exceed 230 g/L in the eastern discharge areas. The increase in salinity is related to groundwater discharge from salt lakes; however, the salinity can vary along the trunk palaeochannels with accession of less saline groundwater from tributaries or bedrock features.

An important hydrogeological consideration of palaeochannels is the transition from confined to unconfined conditions as a result of groundwater abstraction. During the period of abstraction when the aquifer is confined, the groundwater storage in the palaeochannel aquifer is virtually unchanged, and groundwater is produced by aquifer compression, and leakage from the overlying alluvium and adjacent weathered bedrock. When the palaeochannel aquifer becomes unconfined, the groundwater storage in the palaeochannel itself is being depleted (Fig. 3) and contributes much more water than aquifer compression (confined storage).

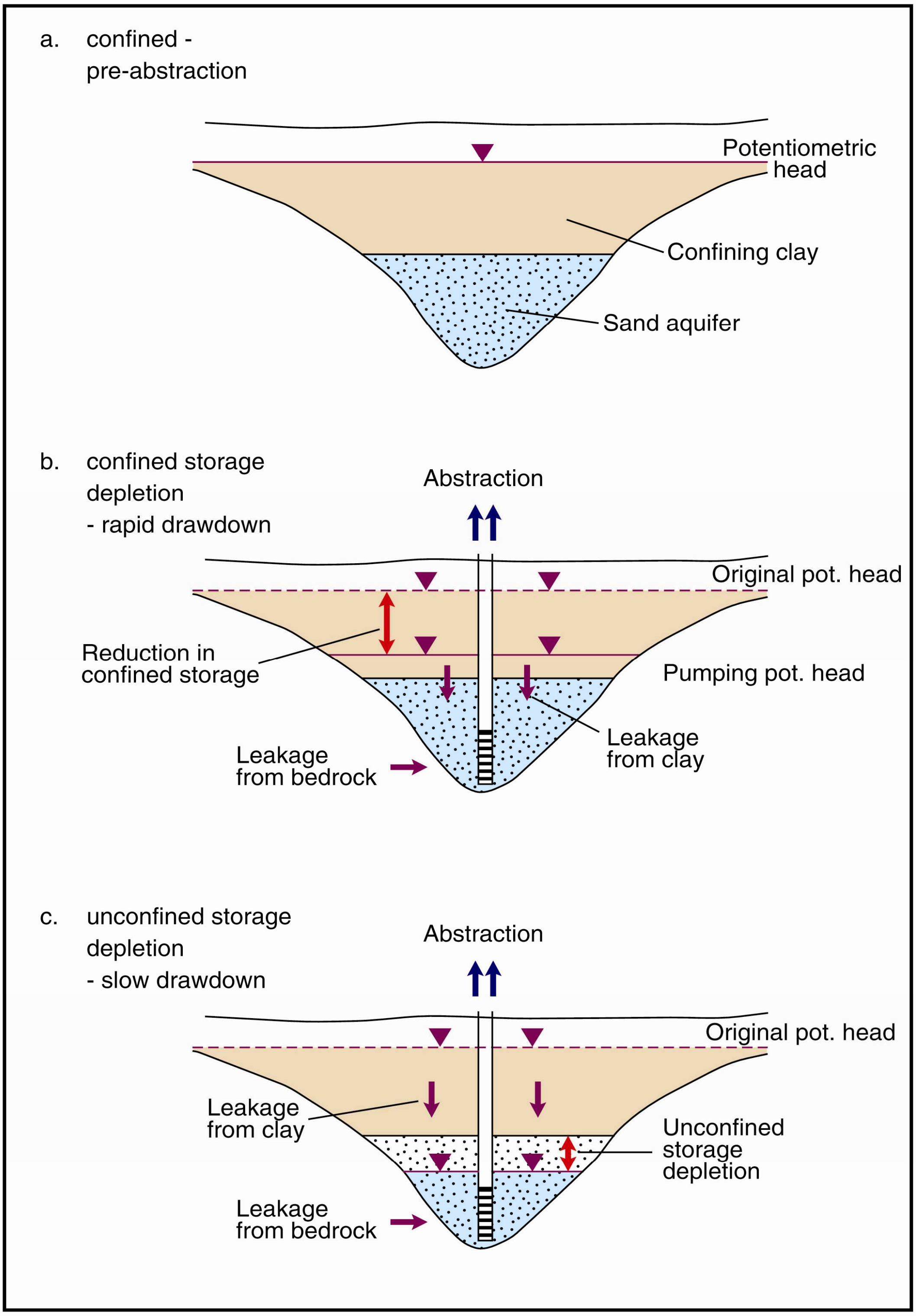

Figure 3 Diagrammatic section showing transition to unconfined state.

3 Groundwater abstraction

Ion (1998) reviewed groundwater utilisation from the Roe Palaeodrainage, including annual groundwater abstraction from all major borefields between 1984 and 1996. The key findings with respect to groundwater abstraction in the Roe Palaeodrainage were (1) licensed allocation in 1996 was 30.5 GL/yr; (2) actual usage in 1996 was 12.4 GL/yr, representing 39% of annual allocation; and (3) cumulative abstraction between 1985 and 1996 was 100.6 GL.

Figure 4 highlights the change in groundwater abstraction between 1986 and 2001. The main features are a rapid increase in groundwater utilisation in the late 1980s as new mines were established and borefields commissioned; abstraction was greatest and most steady until the mid-1990s (averaging about 10 GL/yr) before a significant reduction during the late 1990s. There is good correlation between groundwater abstraction and the gold price (particularly in the late 1990s); however, this relationship is not the prime reason for reduced groundwater abstraction.

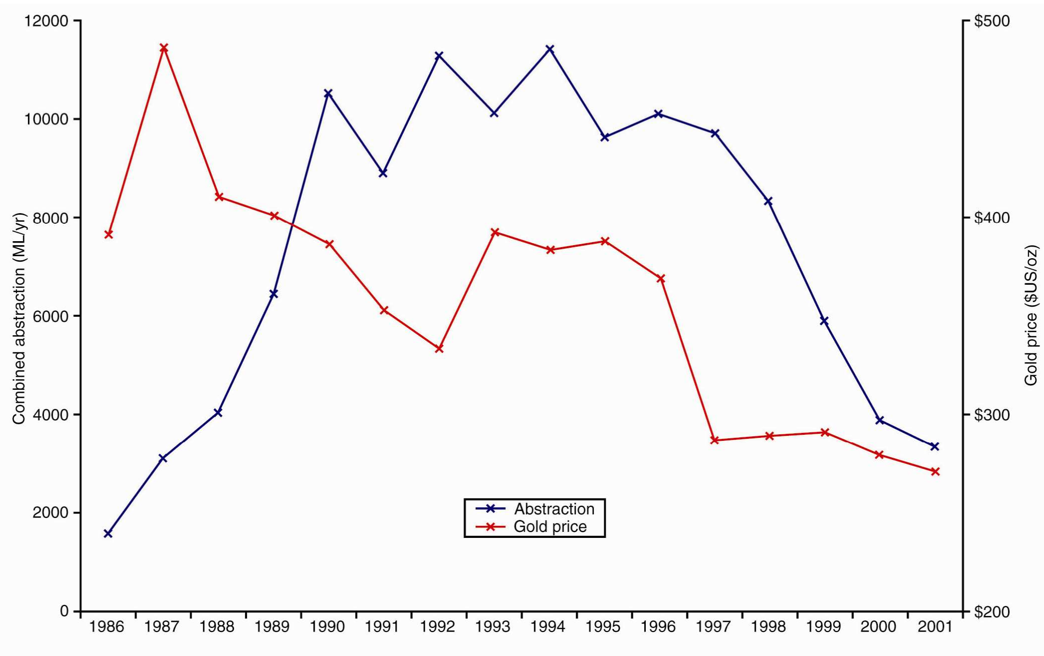

Figure 4 Groundwater abstraction versus gold price between 1986 and 2001

By the late 1990s, the gold industry had refined the CIP/CIL process, thus producing improved water use efficiencies (in particular tailings water recovery). Dewatering of the progressively larger opencut pits provides an alternative water supply, which is easier to consume during processing rather than disposal to the environment (salt lakes, injection etc.). Another alternative water source is the use of flooded water in either abandoned mine voids or salt lakes, which is generally of better quality than the local groundwater. Also many mining operations, such as Kaltails, have ceased or reduced ore processing.

4 Borefield performance

This section reviews the long-term performance of the selected borefields around Kalgoorlie. The emphasis has been to compare changes in groundwater level with respect to abstraction or recharge regimes, in order to determine the impact of groundwater abstraction on the palaeochannel aquifer. All comments by groundwater consultants on the longevity and sustainability of the groundwater resources have also been included and referenced.

4.1 KCGM Borefields

Kalgoorlie Consolidated Gold Mines Pty Ltd (KCGM) operate the Fimiston open pit (Kalgoorlie Superpit) and Mt Charlotte underground on the eastern side of Kalgoorlie–Boulder. Large-scale open pit mining at Fimiston commenced in 1989 with the KCGM operations expected to continue until 2015. The gold ore is processed at the Fimiston mill, east of the open pit.

KCGM is the largest groundwater consumer in the region, abstracting more than 45 GL of groundwater (equating to nearly a third of cumulative regional abstraction between 1988 and 2000). The water supply for ore processing and dust suppression is derived from four borefields — Mt Percy, Gidji, South Lakes / Hannan Lake; and Lakewood. In 2000, KCGM amalgamated these borefields into two borefields for licensing purposes forming a Northern Borefield (GWL 54900) including Mt Percy and Gidji Borefields and a Southern Borefield (GWL 52283) including South Lakes / Hannan Lake, Hannan East (not yet commissioned) and Lakewood Borefields.

For the purpose of this review, the four original borefields have been kept separate to facilitate better comparison and interpretation. There is also an Eastern Borefield (formerly known as Trafalgar Borefield) that is not included as these production bores are positioned within alluvial deposits rather than the palaeochannel aquifer.

4.1.1 Gidji Borefield

The Gidji Borefield consists of 15 production bores (prefixed G1 to G15) with groundwater abstraction having commenced in June 1989. By the end of 1999, cumulative groundwater abstraction from the borefield was about 25 GL. Groundwater abstraction peaked in 1993 (3.2 GL), before progressively declining during the late 1990s (1.6 GL in 1999).

A hydrographic analysis and aquifer performance evaluation was undertaken based on the aquifer review for Gidji borefield by Peter Clifton & Associates (2000a). Prior to abstraction, standing groundwater levels in production bores were 20 to 35 m above the top of the aquifer. All production bore hydrographs show initial declining trends following commencement of borefield abstraction in 1989. Decline in groundwater level (about 15 to 20 m below initial water levels) had diminished in G1 to G4 during 1991 with the other bores (G5 to G15) declining until 1994 or 1995. Following the initial decline, most production bores approached quasi steady-state (or equilibrium) conditions until 1998, except for G1, G2 and G7 where slight recovery trends were related to lower abstraction. Reduced borefield abstraction from 1998 to 1999 has resulted in appreciable recovery of water levels (2–3 m/yr), particularly in the western portion of the borefield.

In December 1998, there was at least 10 m of confined pressure head remaining in the aquifer. After a decade of abstraction, all production bores are still drawing groundwater from the confined palaeochannel sand aquifer, suggesting that the aquifer is capable of sustaining greater production rates. Peter Clifton & Associates (2002a) concludes that most groundwater abstracted from the borefield has been derived from leakage from surrounding bedrock, overlying formations or unidentified tributary palaeochannels. Other important observations are that the monitoring bore hydrographs show similar trends to the nearby production bores, and groundwater chemistry has not changed during borefield life.

4.1.2 Mt Percy Borefield

The Mt Percy Borefield consists of four production bores (prefixed MP1 to MP4) and three nearby observation bores (GL1 to GL3). Groundwater abstraction commenced in October 1985 and by the end of 1999, cumulative groundwater abstraction from the borefield had been 8.7 GL. Groundwater abstraction peaked between 1988 and 1991 (averaging about 0.8 GL/yr), before lessening in the late 1990s (0.3 GL in 1999).

The following evaluation of aquifer performance is based on the aquifer review for Mt Percy Borefield (Peter Clifton & Associates, 2000b). Prior to abstraction, standing groundwater levels in production bores were about 25 m above the top of the aquifer. All production bore hydrographs show initial declining trends following commencement of borefield abstraction in 1985. The decline in groundwater level (about 20 to 25 m below initial water levels) had ceased in all production and monitoring bores by 1991.

There was a short period of quasi steady-state conditions (at or slightly above the top of aquifer) before recovery of water levels in early 1992 owing to reduced groundwater abstraction. This recovery is important as the nearby Gidji Borefield was still at full production. The resumption of abstraction in 1992 produced subsequent water level decline before re-establishing the previous steady-state conditions. Post-1998 recovery of water levels can be observed in all production and monitoring bores resulting from reduced or no abstraction.

Peter Clifton & Associates (2000b) established that water levels fluctuate in response to variations in bore abstraction, but stabilise at or above the top of the aquifer. All bores have remained in confined condition throughout the entire period of groundwater abstraction. Another important observation is that bores MP3 and MP4 show some periods of improvement in groundwater salinity (TDS).

4.1.3 South Lakes / Hannan Lake Borefield

The South Lakes / Hannan Lake Borefield comprises 14 production bores. In late 1991, groundwater abstraction commenced from the South Lakes section comprising 12 production bores (S1 to S12). The Hannan Lake section, located to the east of the South Lakes section, consists of two production bores (H1 and H2) that were commissioned in late 1992. By the end of 1999, cumulative groundwater abstraction from the borefield was 11.6 GL. Groundwater abstraction from the borefield remained fairly constant between 1992 and 1998 (averaging about 1.5 GL/yr), before lessening in the late 1990s (0.8 GL in 1999).

Hydrographic analysis and aquifer performance was evaluated using the aquifer review for South Lakes / Hannan Lake Borefield by Peter Clifton & Associates (2000c). There are subtle hydrogeological variations in aquifer response between the South Lakes and Hannan Lake sections, which require separate discussion.

South Lakes section

Prior to abstraction, standing groundwater levels in production bores were about 18 m above the top of the aquifer. All production bore hydrographs show rapid declining trends following commencement of borefield abstraction. The groundwater level (10 to 15 m below initial water levels) had stabilised in all production and monitoring bores by 1992. In all production bores, there was an extended period of quasi steady-state conditions (about 10 m above the top of the aquifer) between 1992 and 1997. For operational purposes and spreading long-term groundwater drawdown, the borefield is divided into two sections (Bores S1 to S6; Bores S7 to S12) producing different aquifer responses.

Bores S1 to S6 show slight water level recovery associated with reduced groundwater abstraction (1995–96); 10 m of water level decline due to resumption of abstraction (1997); establishment of a lower steady-state water level (about 5 m above the top of the aquifer); and another period of water level recovery due to reduced abstraction (post-1999). Bores S7 to S12 show slight declining trends from increased abstraction (1996) before steady water level recovery associated with low rates of abstraction from these bores (1997 to present). All bores have remained in confined condition throughout the entire period of groundwater abstraction. Other important observations are that monitoring bore hydrographs show similar trends to nearby production bores, and groundwater chemistry has not changed over the period of groundwater abstraction.

Hannan Lake section

Prior to abstraction, standing groundwater levels in production bores were about 12 m above the top of the aquifer (NB: initial water levels were depressed by earlier abstraction at South Lake — up-gradient; and Lakewood — down-gradient). The two production bores (H1 and H2) show different hydrographic trends after the initial decline in water level associated with commencement of abstraction. Bore H1 made the transition from confined to unconfined conditions quickly and has moved between these conditions frequently responding to changes in abstraction (short-term recovery periods in 1995 and 1996 with sustained recovery of 20 m between mid-1997 and 2000). Water levels in Bore H1 have always remained within 5 m of the top of the aquifer and an additional 15 m of saturated aquifer is available. Bore H2 was slightly different with, water levels reaching a quasi steady-state at the top of the aquifer until late 1996 when there was rapid transition from confined to unconfined conditions; however, water levels have steadily recovered (5 m/yr) from mid-1997.

Monitoring data for 2000–01 (Peter Clifton & Associates, 2002b) showed water levels in KMT 4 (Observation Bore at H1) returning to initial water levels during early 2001. Water level recovery is closely related to abstraction with total production also varying significantly with 243 ML in 1997, 1400 ML in 1998, 88 ML in 1999 and only 26 ML in 2000.

4.1.4 Lakewood Borefield

The Lakewood Borefield is the closest to the Fimiston Mill (8 km south) and comprises two production bores (LW5 and LW6) with four observation bores (LW1 to LW4). The production bores were constructed in 1984 with abstraction commencing in 1986. By the end of 1998, cumulative groundwater abstraction from the borefield had been 4.8 GL. Groundwater abstraction peaked between 1989 and 1992 (averaging about 0.5 GL/yr), before lessening in the late 1990s (0.35 GL in 1998).

Hydrographic analysis and aquifer performance evaluation were undertaken using the aquifer review for Lakewood Borefield (Peter Clifton & Associates, 2000d). Bore LW 1 has been infrequently monitored, providing an incomplete hydrograph. Bore LW2 is not located within the palaeochannel and shows water level fluctuation in the bedrock aquifer, although it is important to note that no significant impacts from groundwater abstraction can be observed. Monitoring bores LW3 and LW4 show the most useful hydrographic data with LW3 positioned in the vicinity of production bore LW6, while bore LW4 is positioned between the Lakewood and Kaltails Borefields.

Prior to abstraction, standing groundwater levels in LW3 and LW4 were about 25 m above the top of the aquifer. The hydrographs of LW3 and LW4 show initial declining trends (about 15 m) related to the commencement of borefield abstraction. The declining trend had diminished by late 1989; however, the aquifer had transitioned from confined to unconfined conditions. Water levels have remained steady (about 2 m below the top of the aquifer) suggesting quasi steady-state conditions for the twelve years of abstraction between 1990 and 2001.

Peter Clifton & Associates (2002b) surmised that groundwater abstraction at Lakewood Borefield did not cause any significant depletion of the unconfined groundwater storage in the palaeochannel. This is seen as significant since about 10 GL had also been abstracted from the Kaltails borefield (downstream) over the same period. Groundwater chemistry did not significantly change during the period of groundwater abstraction.

4.2 Kaltails

The Kaltails Re-treatment Project (referred to as Kaltails), operated by Normandy Mining, is located 10 km southeast of Kalgoorlie. The processing of gold tailings ceased in 1999 and the site is currently closed and undergoing rehabilitation. Processing water demand was primarily from the Kaltails Borefield with additional water from tailings recovery and use of excess flotation water from Kalgoorlie Consolidated Gold Mines (KCGM).

The Kaltails Borefield was operational between 1990 and September 1999 with a cumulative groundwater abstraction of 18.4 GL. Annual abstraction peaked in 1991 (3 GL) and average abstraction was about 1.8 GL/yr. The borefield comprises 15 production bores (Bores 1 to 15) spaced at 1200 m intervals and nine observation bores (KT1 to KT5; KT8 to KT11) along the 17 km of palaeochannel.

High-quality monitoring records for the borefield (whilst in full production) were compiled by various groundwater consultants acting on behalf of Normandy Mining: Australian Groundwater Consultants (1989–91), Mackie Martin (1992–94), PPK (1995–98) and Aquaterra in 1999. Since the commencement of rehabilitation in late 1999, Normandy Mining has undertaken all monitoring and reporting requirements.

Bore hydrographs have been compiled showing water level change throughout the borefield life (1990–2003). On the commencement of pumping, groundwater levels declined between 2 to 9 m of drawdown throughout the borefield. By late 1990, most of the borefield was expressing unconfined conditions with water levels ranging from the top of the aquifer to 5 m below the top of the aquifer. Water levels remained steady between 1991 and 1999 (fluctuating within a few metres in response to pumping) suggesting quasi steady-state conditions. There was some indication of water level decline (about 0.5 m per year) in the western portion of the borefield (PPK, 1996a) associated with increased and extended groundwater abstraction from Bores 4 and 5.

The hydrograph for Bore 5 shows a direct relationship between water level decline and groundwater abstraction (Fig. 5). Periods of no water level change or steady-state condition are associated with lower groundwater abstraction of both 130 ML/yr (1993–95) and 200 ML/yr (1997–99). In contrast, there is appreciable water level decline of about 4 m resulting from increased abstraction rates of 320 ML/yr (1996–97). It can therefore be suggested that the sustainable yield of Bore 5 is about 200 ML/yr (or 550 kL/day).

During the final two years of borefield abstraction (1998 and 1999), the declining trends had ceased with another quasi steady-state condition reached (about 8 m below the top of the aquifer). The flat hydrographs and quasi steady-state conditions suggested a balance between pumping and groundwater throughflow / leakage into the borefield. Since the cessation of pumping, water levels have started to recover slightly.

The Kaltails Borefield is an important case study for understanding groundwater recovery and aquifer performance in palaeochannels, as (1) the borefield ceased abstraction in September 1999; (2) the aquifer was largely unconfined throughout the abstraction period; and (3) water level monitoring should highlight the transition from unconfined to the original confined conditions. Since ceasing groundwater abstraction in late 1999, water levels throughout the borefield have steadily recovered (in the order of 0.5 m/yr); however, by 2003 the borefield was still unconfined in the western portion and confined in the eastern portion.

In late February 2003, water levels were monitored throughout the Kaltails Borefield to determine the rate and spatial extent of groundwater recovery. East of Bore 5 (equating to 80% of the total borefield), there has been widespread recovery of water levels in the order of 2 m since ceasing abstraction, suggesting recovery rates of 0.5 to 1 m/yr. There are large sections of the borefield (about two-thirds) that are still unconfined, explaining the slow rates of water level recovery. Bores 1 to 4 have shown recent water level decline of 1 to 2 m, which suggests that groundwater abstraction from KCGM Lakewood Borefield has increased significantly during early 2003, responding to a higher gold price.

Groundwater in the borefield is hypersaline, ranging between 96 g/L and 160 g/L TDS, with lower salinity in the western portion than in the eastern portion. There have been large fluctuations in groundwater salinity through the life of the borefield. An observed trend of increasing salinity can be related to reduced abstraction and, alternatively, decreasing salinity related to increased abstraction (most evident in 1997 and 1998 data). There is also an increasing HCO_3 concentration towards the east, which is believed to be related to the presence of carbonate in the basement rocks (PPK, 1996a). There has been no monitoring of groundwater quality since ceasing abstraction.

4.3 New Celebration / Jubilee

In 2001, New Celebration gold mine (previously owned by Newcrest) was purchased by South Kal Mines Pty Ltd (a subsidiary of Harmony Gold) resulting in an amalgamation of the New Celebration and Jubilee mining operations. The mining operations are located about 40 km south of Kalgoorlie and 20 km north of Kambalda.

Water supplies for ore processing, dust suppression and desalination are abstracted from four borefields; Northern, Mt Martin (AUR), East Location 48 (also known as

New Celebration Borefield) and East Location 51 (previously Jubilee Borefield). The New Celebration Borefield has been operating since 1986 with total groundwater abstraction of 16.9 GL (1986–2000). Abstraction peaked at 1.95 GL/yr (1990) before declining in the late 1990s to about 0.6 GL/yr. In contrast, total groundwater abstraction from Jubilee Borefield has been 8 GL (1988–2000) with a peak of 1.1 GL/yr (1989) and remaining steady since 1996 (averaging 0.4 GL/yr).

The hydrogeology in the New Celebration / Jubilee Borefields is different from that of the other palaeochannel borefields. There are large sections of the confined clay eroded/removed, resulting in unconfined conditions throughout much of the Woolubar Palaeochannel (prior to groundwater abstraction). The Northern Borefield is the exception with the basal sand aquifer in partial confined condition beneath the clay.

The following hydrographic analysis utilised data presented in the aquifer review by IT Environmental (2001). In the New Celebration Borefield, water levels declined by 5 to 10 m in the first three years of pumping. Following this initial drawdown, water levels either remained flat (fluctuating within a few metres in response to pumping) suggesting quasi steady-state conditions, or recovered slightly throughout the 1990s.

4.3.1 Northern Borefield

Prior to groundwater abstraction, the Northern Borefield was in partial confined condition with water levels about 2 to 3 m above the top of the aquifer. On the commencement of abstraction, the borefield quickly moved from confined to unconfined conditions. There has been 6 to 7 m water level decline throughout the borefield; however, there is more than 20 m of saturated aquifer still available. Water level decline ceased by the mid-1990s with the establishment of quasi steady-state conditions with some bores showing slight water level recovery of 0.5 m/yr (1999–2001) in response to lower abstraction. The Northern Borefield is under-utilised with only 21 ML abstracted in 2000–01 because of factors concerned with distance from the mill and groundwater salinity (East Location 48 and 51 are closer with improved salinity).

Groundwater salinity in the Northern Borefield is increasing (particularly since 1997) with the exception of the southern most bore (NP1). The best examples are NP5 and NP6, where groundwater salinity has increased from 100 g/L (1997) to 130 g/L. IT Environmental (2001) suggest that the salinity increase is related to groundwater movement and recovery from the north during periods of low abstraction.

4.3.2 Mt Martin (AUR) Borefield

The Mt Martin (AUR) Borefield was decommissioned in 1990; hence, any water level fluctuation or response is related to abstraction from the Northern and East Location 48 Borefields. Since the mid-1990s, the water levels have remained relatively flat throughout this section of the palaeochannel. IT Environmental (2001) noted that there is reversal of groundwater gradient in the southern portion of the AUR Borefield

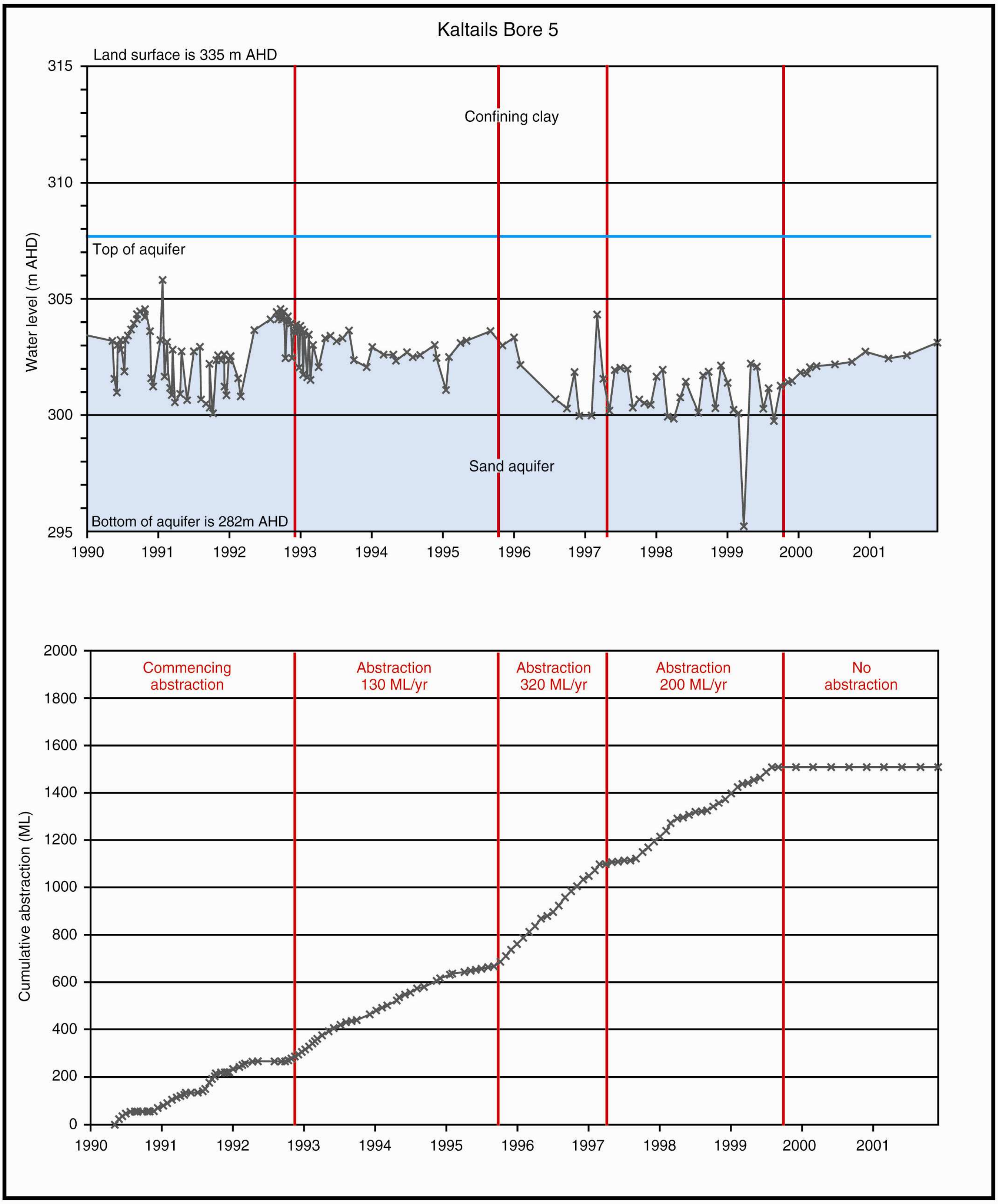

Figure 5 Water level change and cumulative abstraction in Kaltail Bore 5

(near MM6), which is related to historical abstraction from surrounding borefields. There has been no long-term monitoring of groundwater salinity in the borefield.

4.3.3 East Location 48 Borefield

The East Location 48 Borefield has always exhibited unconfined conditions. In response to commencing abstraction, initial drawdown was about 9 m (3 m/yr) with the declining trend ceasing in 1990. Water levels over the past decade have been steadily recovering at about 0.5 m/yr. Increased recovery can be observed in Bore HW5 related to greatly reduced abstraction and/or recharge from the nearby playa lake system (IT Environmental, 2001). There is a lower rate of recovery in the southern portion of East Location 48 Borefield (about 0.2 m/yr) related to continuing abstraction from the East Location 51 Borefield.

Groundwater salinity in the East Location 48 Borefield is generally stable. The only exception is Bore NC7 with an appreciable improvement in salinity decreasing from 130 g/L in 1989 to 80 g/L in 2001. IT Environmental (2001) suggest that water improvement is related to fresher, recharge water entering the groundwater environment via playa lakes. However, it is possible that lower salinity groundwater is contributing from a southern tributary, which is inferred to join the main palaeochannel near NC7.

4.3.4 East Location 51 (former Jubilee) Borefield

Hydrographic analysis was undertaken based on data from the aquifer review (IT Environmental, 2001). In the East Location 51 Borefield, water levels steadily declined at about 0.5 m/yr, rather than the rapid water level decline in the other Borefields, because abstraction was progressively increased and the aquifer was initially unconfined. Drawdown effects in the borefield are greatest (up to 7 m) in the eastern portion where abstraction is greatest (JP1, JP2 and JPA), whereas there is only 2 m of water level decline in the upstream, western areas (JP3). There is still between 10 and 15 m of saturated aquifer available.

During the 1990s, water level decline continued throughout most of the borefield. The only exception is the decommissioned Bore JP3 exhibiting steady recovery (0.1 m/yr) between 1993 and 2001. Since 1999, quasi steady-state conditions have become established in the remainder of the borefield suggesting groundwater abstraction is balanced with groundwater throughflow and leakage.

The groundwater salinity in the East Location 51 Borefield has remained stable. There have been only short-term fluctuations that cannot be related to any abstraction or rainfall event.

4.4 Kanowna Belle

Kanowna Belle gold mine, operated by Delta Gold, is located 18 km northeast of Kalgoorlie. Mining operations commenced in 1993 with processing water supplies obtained from five production bores (KB1 to KB5) in the Yindarlgooda North Palaeochannel. Groundwater monitoring is undertaken in eight observation bores, which are positioned in the palaeochannel aquifer. Since 1993, total groundwater abstraction has been 6.8 GL (1993–2000) with annual abstraction peaking at 1.24 GL (1994) but remaining relatively consistent (averaging about 0.8 GL/yr).

There are excellent monitoring records completed on behalf of Kanowna Belle gold mine by PPK (1993–99) and Aquaterra (since 1999). The borefield has remained in confined conditions with water levels remaining 20 to 30 m above the top of the aquifer. All bore hydrographs show a close relationship between groundwater abstraction and water level response. On the commencement of pumping, groundwater levels declined by 15 to 20 m throughout the borefield. In response to pumping, water levels have fluctuated within a 10 m variation between 1993 and present. Groundwater abstraction from individual bores results in the lowering of water levels, and reduced abstraction produces water level recovery. Many of the bores show water level recovery of greater than 10 m/yr following short-term cessation of abstraction, which is related to the confined nature of the palaeochannel aquifer.

The bore hydrographs have remained relatively uniform with no signs of unconfined conditions and storage depletion (PPK, 1996b). Aquaterra (2001) concluded that abstraction from Kanowna Belle is having no impact on the regional aquifer, as groundwater abstraction is balanced with groundwater throughflow and leakage. There is a long-term trend of increasing groundwater salinity from 180g/L in 1992 to 220g/L in 2001.

4.5 Paddington

The Paddington gold mine, operated by Paddington Gold Pty Ltd, is located 32 km north of Kalgoorlie. Mining operations commenced in the mid-1980s. Water supplies for ore processing, dust suppression and desalination are derived from five borefields (Padsouth, Padwest, Rose Dam, Broad Arrow and Arrow Lake). There are 18 production bores (Padsouth — PW21-32; Padwest — PW29-32; Rose Dam — PW35-38; Broad Arrow — PW40; Arrow Lake — PW41) distributed along a 20 km section of the Black Flag Palaeochannel. Groundwater monitoring is also undertaken in 26 observation bores, which are positioned in the palaeochannel aquifer and adjacent basement aquifers. The borefields have been operating since 1984 with a total groundwater abstraction of 15.6 GL (1986-2001) and annual abstraction remaining relatively consistent (averaging about 1 GL/yr).

Wharton (2002) undertook groundwater modelling of the Black Flag Palaeochannel, as utilised by Paddington gold mine, to propose that significant groundwater recharge (associated with rainfall and flooding events) was entering the palaeochannel aquifer. The main conclusion was that water levels in the palaeochannel sand aquifer had almost completely recovered because of a combination of reduced abstraction and inferred groundwater recharge. There are many unanswered questions about groundwater recharge and leakage; however, it is evident that groundwater abstraction at Paddington has not resulted in long-term storage depletion.

4.5.1 Padsouth

Padsouth Borefield comprises eight production bores (PW21–28) and 12 observation bores positioned in the palaeochannel aquifer and two bores (AL1 and AL3) in the basement rocks. The borefield has generally remained in confined conditions. Some bores have experienced short periods of unconfined condition; however, water levels have reached a quasi steady-state either at or just beneath (2–3 m) the top of the aquifer, or quickly recovered to regain confined conditions.

All bore hydrographs show a close relationship between groundwater abstraction and water level response. The trends of water level decline, steady-state and recovery are most evident in production bores PW21, 22, 24 and 28. The hydrograph for Bore PW21 and nearby observation bore AL15 shows initial water level decline (20 m) responding to sustained abstraction at a rate of 20 000 kL/month; steady-state conditions from mid-1997 to mid-1999 due to reduced abstraction (15 000 kL/mth); 10 m recovery between mid-1999 and late 2000 due to reduced abstraction (<5000 kL/mth); and recent slight decline in response to increasing abstraction of 8000 kL/mth.

Rockwater (2002) noted that groundwater levels in Padsouth rose between mid 1997 and mid-2000 because of reduced abstraction and infiltration of water from significant rainfall events during those years. In reviewing the hydrographs, there is no direct correlation between water level recovery in the palaeochannel aquifer and individual rainfall events; however, observation bores AL1 and AL3 positioned in the bedrock aquifer show water level recovery in response to rainfall. It is likely that direct groundwater recharge occurred throughout the catchment with recharging water entering the palaeochannel via leakage from adjacent bedrock aquifers and overlying alluvial sequences and associated flooded salt lakes.

4.5.2 Padwest

Padwest Borefield comprises four production bores (PW29–32) and three observation bores (AL1, 4 and 10). Groundwater abstraction is greatest from Bores PW31 and 32. The borefield has generally remained in confined conditions with water levels often 5 m above the top of the aquifer. The hydrograph for observation bore PW10 shows a short period of unconfined condition reflecting groundwater abstraction from nearby production bores. All bore hydrographs show similar long-term trends, with declining water levels (about 8 m) until mid-1997 responding to groundwater abstraction; steady recovery in water levels between late 1997 and mid-2001; and recent declining water levels with increased or renewed abstraction.

The recovery in Bore PW31 (about 10 m between 1997 and 2001) is particularly unusual, as water levels have risen during a period of increased groundwater abstraction (Fig. 6). The hydrograph for Bore PW31 provides the first conclusive evidence for groundwater recharge into the palaeochannel aquifer. It is probable that additional (recharging) water has entered the palaeochannel aquifer, implying some form of groundwater recharge. Rockwater (2002) suggested that this water level rise in the Padwest Borefield is related to reduced abstraction and infiltration of water from significant rainfall events during those years, although groundwater abstraction had actually marginally increased.

The hydrographs show no direct correlation between water level recovery in the palaeochannel aquifer and individual rainfall events. There are no bedrock monitoring bores in the Padwest Borefield; however, there are likely to be similar aquifer responses as those observed in Padsouth. It is likely that direct groundwater recharge was occurring throughout the catchment with recharging water entering the palaeochannel via leakage from adjacent bedrock aquifers, overlying alluvial sequences and nearby flooded salt lakes.

4.5.3 Rose Dam

Rose Dam Borefield comprises four production bores (PW35–38) and four observation bores (RD1–4). Most groundwater abstraction is from Bore PW37. All bore hydrographs show similar long-term trends with subtle water level fluctuations responding to groundwater abstraction. The borefield has remained in confined conditions with water levels reaching the top of the aquifer. Production Bores PW36 and 37 were occasionally unconfined, reflecting pumping effects; however, the observation bores show the borefield was typically confined.

4.5.4 Broad Arrow / Arrow Lake

Broad Arrow (PW40) and Arrow Lake (PW41) Borefields are located down-gradient of Padsouth and comprise a production and observation bore at each site. The borefields have remained in confined condition with water levels more than 10 m above the top of the aquifer. Bore hydrographs remained relatively flat between 1995 and 1999, suggesting steady-state conditions, followed by water level recovery in 2000 and 2001, returning to pre-mining water levels resulting from reduced groundwater abstraction. Unlike Padsouth (upstream), there is no significant water level recovery (1997–99) in Broad Arrow / Arrow Lake Borefields, thus implying no groundwater recharge. However, there are appreciable changes in groundwater salinity with salinity increases coinciding with major rainfall events suggesting flushing of salts from the lake.

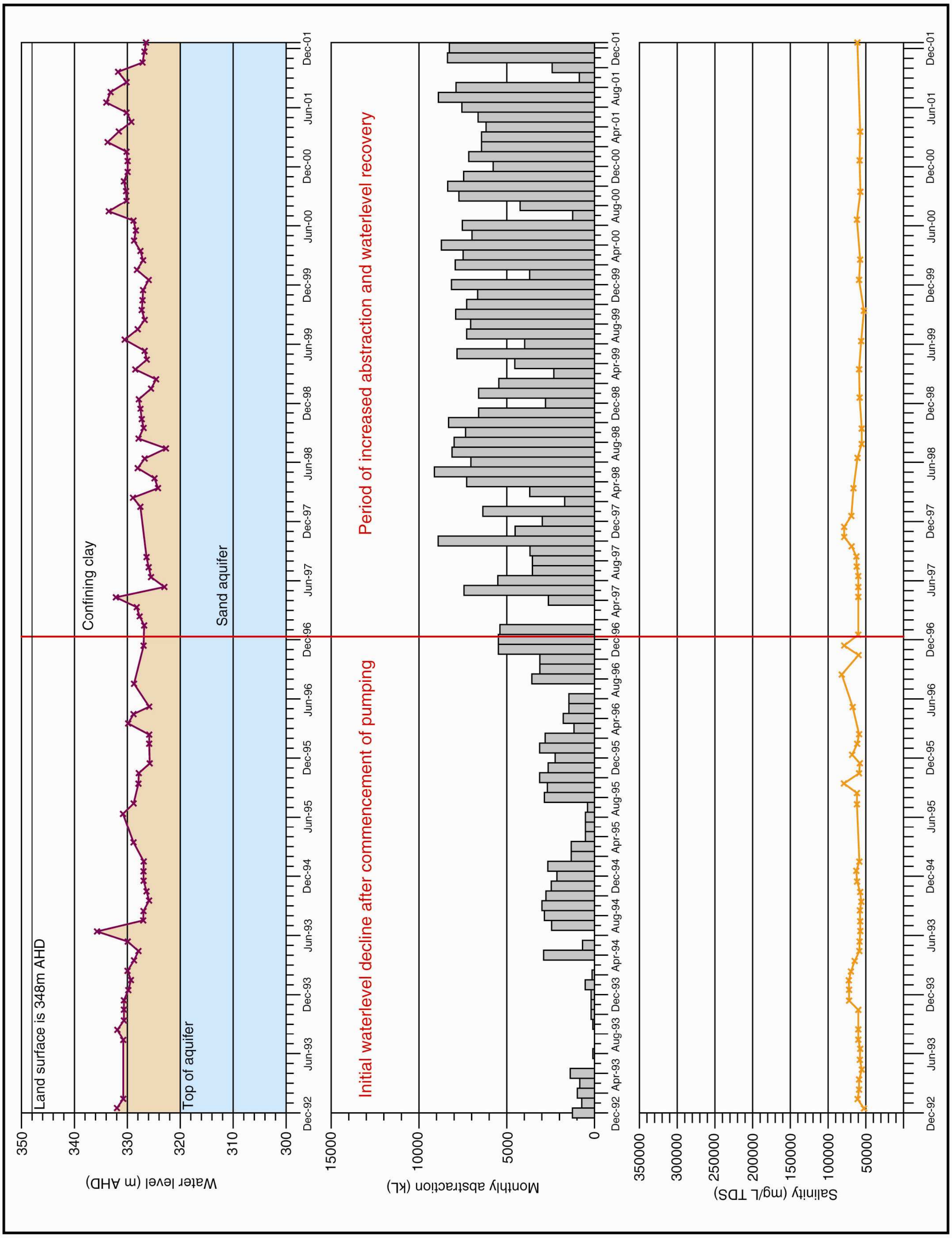

Figure 6 Hydrograph for PW31 showing water level recovery and increased groundwater abstraction (1997 onwards). Sourced from Rockwater (2002)

5 Impact on the groundwater resource

The palaeochannel aquifer in the Kalgoorlie region has been affected over a 20-year period, as a result of groundwater abstraction since 1984. Bore hydrographs show a direct relationship between groundwater abstraction and water level response. There is little to no water level fluctuation related to significant rainfall events, although some individual bores have unusual responses that may be attributable to groundwater recharge. The main findings and understanding of aquifer response and groundwater resource condition from the review of bore hydrographs are discussed below.

5.1 Aquifer response to unconfined or confined conditions

The initial aquifer condition, either confined or unconfined, appears to have a major impact on the extent and rate of drawdown, establishment of steady-state conditions and water level recovery. The transition between confined and unconfined condition results in different water level response and rates of change. The three main aquifer responses are as follows:

- Aquifers that remain confined — rapid drawdown, quasi steady-state and rapid recovery (Fig. 7);
- Aquifers that start confined then become unconfined — rapid drawdown to top of aquifer, quasi steady-state; slow recovery until confined conditions recur (Fig. 8); and
- Aquifers that are unconfined — slow drawdown, quasi steady-state and slow recovery (Fig. 9).

5.1.1 Drawdown

On the commencement of borefield abstraction, there is appreciable drawdown in the palaeochannel aquifer. All production bores show initial drawdown, in the order of 5 to 10 m over a period of two to three years.

The main factor influencing the rate of drawdown is the initial aquifer conditions (confined or unconfined). In confined conditions, the rate or steepness of drawdown is considerably greater with a water level decline of about 3 to 5 m/yr, with groundwater being abstracted from confined or elastic storage (e.g.; KCGM, Paddington and Kanowna Belle). However, water level decline in the unconfined aquifers tend to be considerably slower at 1–2 m/yr, with groundwater abstraction depleting the sand aquifer (e.g.; Kaltails and New Celebration).

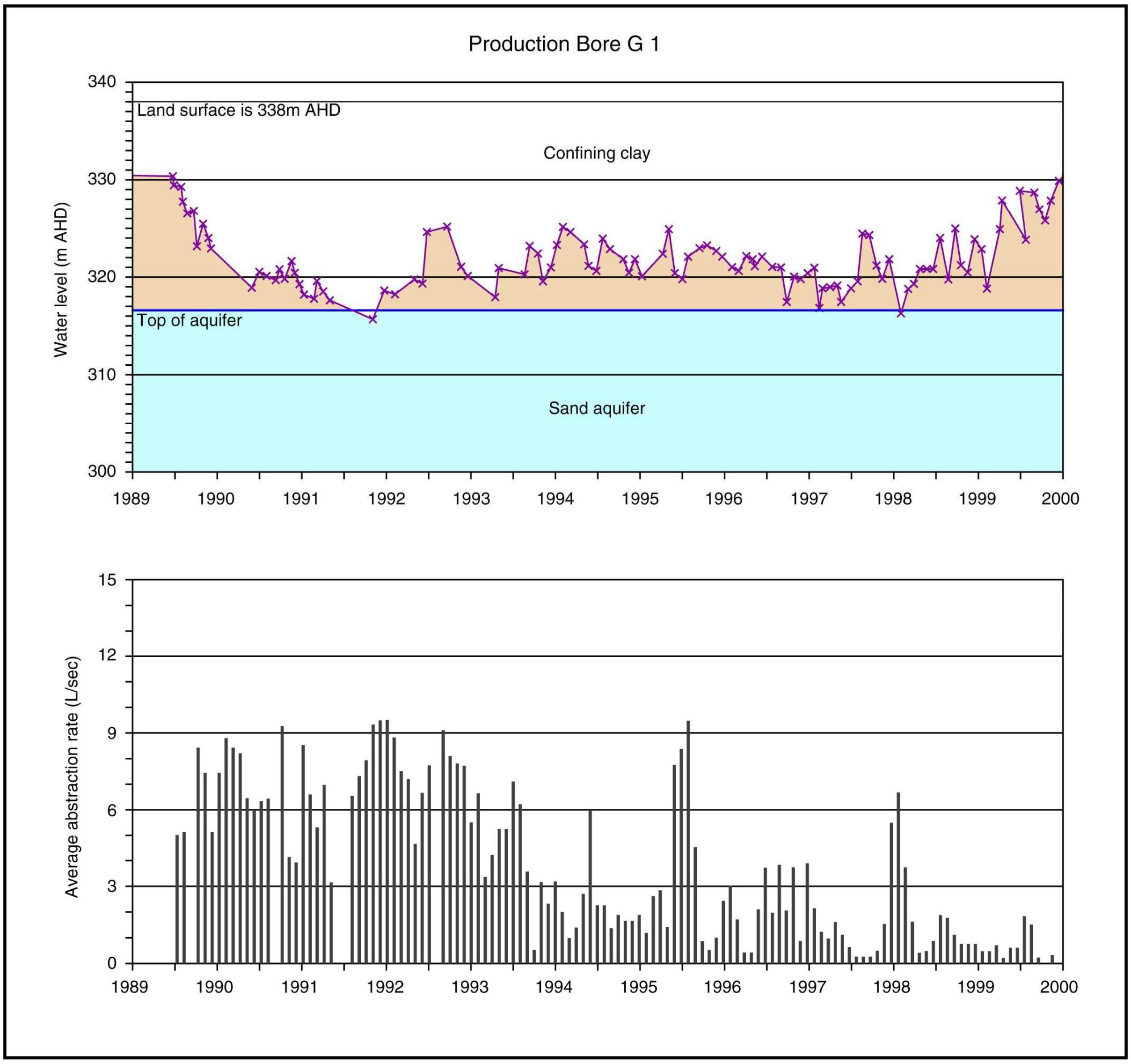

Figure 7 Confined aquifer response in Bore G1 — KCGM Gidji Borefield. Note that blue line represents top of aquifer. Sourced from Peter Clifton and Associates (2000c)

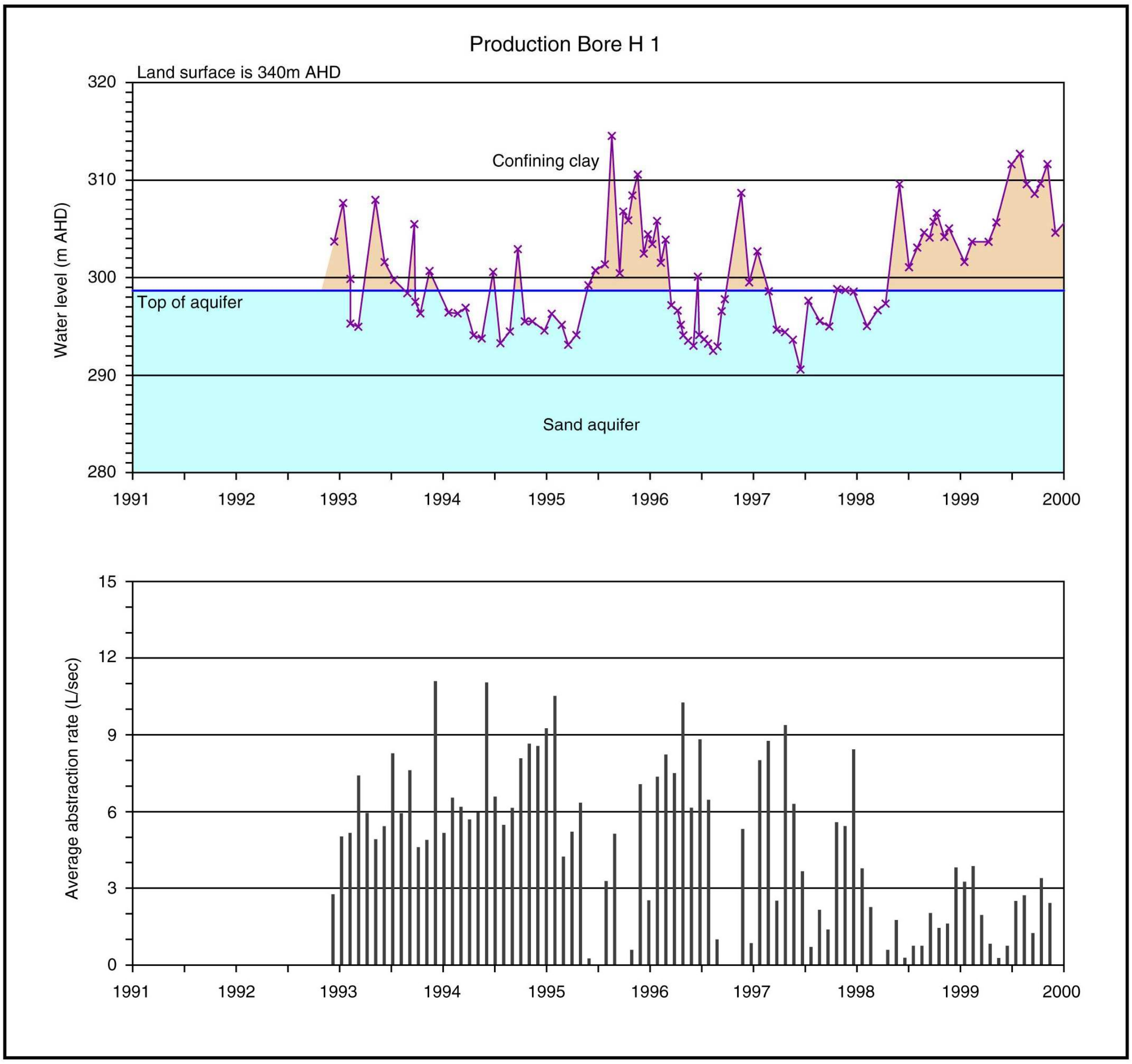

Figure 8 Confined to unconfined aquifer response in Bore H1 — KCGM Hannan Lake Borefield. Note that blue line represents top of aquifer. Sourced from Peter Clifton and Associates (2000c)

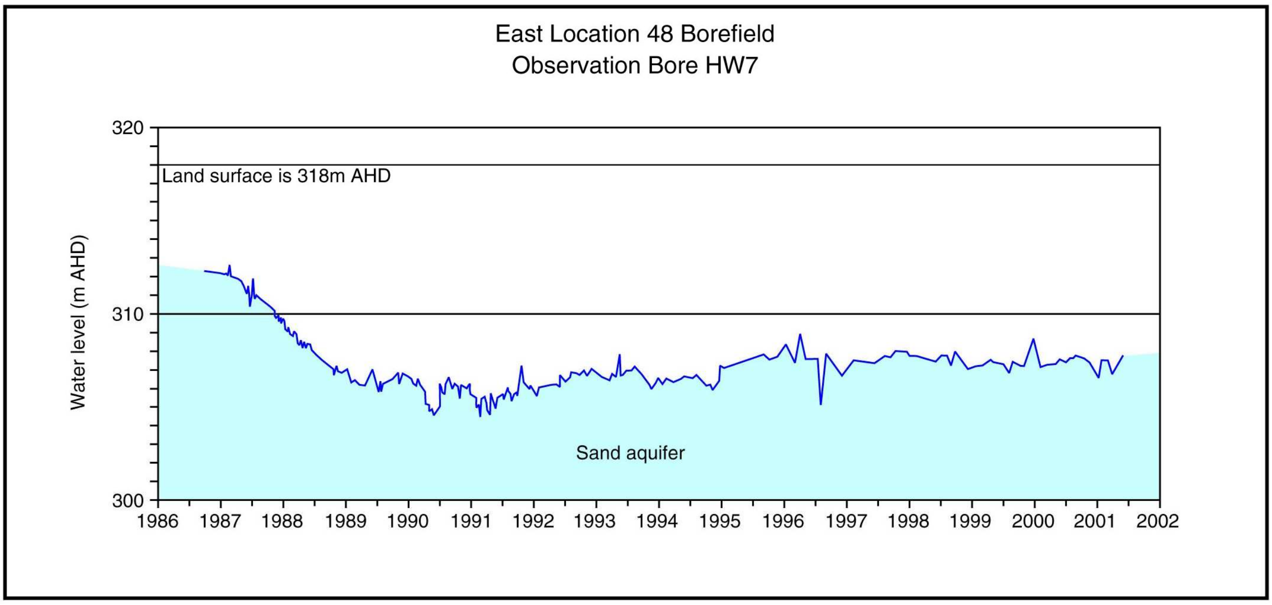

Figure 9 Unconfined aquifer response in Bore HW7—- East Location 48 Borefield. Note that no confining clay layer present. Sourced from IT Environmental (2001)

5.1.2 Steady-state conditions

There are no cases where water level in the palaeochannel aquifer has continued to decline throughout the life of the Borefield that contradicts the predictions by Turner et al. (1996). After the initial drawdown, the water level tends to stabilise or establish a quasi steady-state equilibrium representing a balance between inflows from leakage, throughflow or indirect recharge and groundwater abstraction. Many borefields have experienced extended periods of steady-state condition, under constant pumping or abstracting regimes.

The steady-state level often tends to coincide with the top of the aquifer or the clay/sand interface. The position of the steady-state level is largely dependent on the original water level, extent of confined condition and rate of groundwater abstraction. In places, the aquifer has become unconfined due to continuing abstraction, but no bores have had to be taken out of production, and all borefields have more than 10 to 20 m of saturated aquifer available.

5.1.3 Recovery

Since the mid-1990s, reduced groundwater abstraction from the palaeochannel aquifer has resulted in upward trends or water level recovery. As is the case of water level decline, the rate of recovery is closely related to the prevailing aquifer condition (confined/unconfined). There is rapid (2 to 3 m/yr) recovery associated with confined conditions and significantly slower (<0.5 m/yr) recovery in unconfined conditions.

The extent of recovery has been so significant in the confined aquifer that water levels in some borefields have returned to original or pre-mining levels, even though groundwater is being abstracted from other borefields (e.g.; Paddington). The recovery trends observed in the KCGM Mt Percy Borefield are significant, as they demonstrate that water levels can recover even though neighbouring borefields are still at full production.

The long-term recovery of water level in the unconfined aquifer is slow and more subdued. The main borefields with unconfined conditions (New Celebration and Kaltails) are showing recovery trends. The closure of the Kaltails Borefield (1999) and the continuing monitoring of water level recovery will be important in order to understand the length of recovery time required for an unconfined aquifer, as well as to observe the transition from unconfined to confined conditions.

The identification of water level recovery in the palaeochannel aquifer demonstrates significant leakage into the palaeochannel aquifers. The hydrographs clearly show extended periods of water level recovery, although further work is required to understand the recovery mechanism in the palaeochannels.

5.2 Groundwater recharge

Natural groundwater recharge into the palaeochannel aquifer around Kalgoorlie has been previously considered as negligible (Turner et al., 1994; Commander et al., 1992), partly because the aquifers are full and the outflow is low due to very low hydraulic gradients. Based on groundwater modelling and observations of more frequent, intense rainfall, Wharton (2002) postulated that significant groundwater recharge induced by pumping is now entering the palaeochannel aquifer.

Bore hydrographs reviewed in this study show no apparent relationship between water level recovery in the palaeochannel aquifer and rainfall events, although there are watertable and salinity variations in individual bores at Paddington and New Celebration suggesting indirect recharge or leakage processes may be active. The few monitoring bores in the basement aquifer show noticeable watertable response to rainfall events; hence, it can be postulated that the surrounding catchment is receiving groundwater recharge.

It is often difficult to conceptualise groundwater recharge into the palaeochannel aquifer because of the presence of the confining, impermeable clay. Rather than water moving through the clay, Johnson (2000) suggested that the dominant recharge mechanism is downward leakage and groundwater movement through the weathering profile. Commander et al. (1992) noted that water levels in the weathered bedrock are higher than in the palaeochannels, thereby demonstrating that groundwater flow is from the bedrock into the palaeochannel. In addition, the depressurisation of the aquifer resulting from groundwater abstraction will enhance the possible recharge of the palaeochannel aquifer.

Wharton (2002) indicated that the flooded salt lakes are an important component in understanding groundwater recharge. The salt lakes are spatially offset from the palaeochannel axis, with most lakes generally overlying weathered basement. The combination of depressurisation and permeability in weathered bedrock means that significant induced recharge may also leak from the flooded lakes through the weathering profile and into the sand aquifer.

As discussed in Section 4.6.2, the hydrograph for Bore PW31 (Fig. 6) is important for understanding aquifer performance and behaviour, as it implies appreciable groundwater recharge or leakage into the palaeochannel aquifer. An important consideration is that groundwater salinity in PW31 did not change during the same period; however, there may be a long time required before quality changes appear in a bore.

There is no evidence of direct groundwater recharge (i.e.; aquifer response to rainfall) into the palaeochannel aquifers, although hydrographs in the bedrock show that groundwater recharge is occurring throughout the catchment. It is therefore likely that the palaeochannel aquifer is indirectly recharged via downward leakage from adjacent bedrock aquifers, overlying alluvial sequences and flooded salt lakes. Ion (1998) showed that only a portion of the groundwater pumped came from storage with the remainder resulting from leakage. It can be assumed that leakage into the palaeochannel aquifers will increase in proportion to the lowered hydraulic heads.

5.3 Variations in groundwater salinity

Groundwater salinity in most borefields has not changed significantly during 20 years of abstraction. In general, the salinity has remained relatively stable with no observable trends and only subtle periodic change and fluctuation. However, there are a number of exceptions where the groundwater salinity has shown either a long-term improvement (less saline) associated with recharge, or deterioration (more saline) related to groundwater abstraction.

Deteriorating groundwater salinity suggests that groundwater abstraction is affecting groundwater quality in the palaeochannel, although the changes are generally subtle and there is no loss of beneficial use. The Kanowna Belle Borefield shows a long-term trend of increasing groundwater salinity from 180 g/L in 1992 to 220 g/L in 2001. Groundwater salinity in the Northern Borefield (New Celebration) has risen from 100 g/L in 1997 to 130 g/L in 2001, relating to groundwater movement and recovery from the north during periods of low abstraction. In the Arrow Lake / Broad Arrow Borefield at Paddington, there is increasing salinity associated with major rainfall events, suggesting flushing of salts from Arrow Lake.

Examples of improved or reduced groundwater salinity are less common. One production bore (NC7) in East Location 48 Borefield has shown an appreciable reduction in salinity from 130 g/L in 1989 to 80 g/L in 2001 (Fig. 10). IT Environmental (2001) suggest that water improvement is related to fresher, recharge water entering the groundwater environment via playa lakes; however, it is possible that lower salinity groundwater is contributing from an undefined southern tributary. Bores MP3 and MP4 in KCGM's Mt Percy Borefield show reduced salinity associated with extended periods of abstraction.

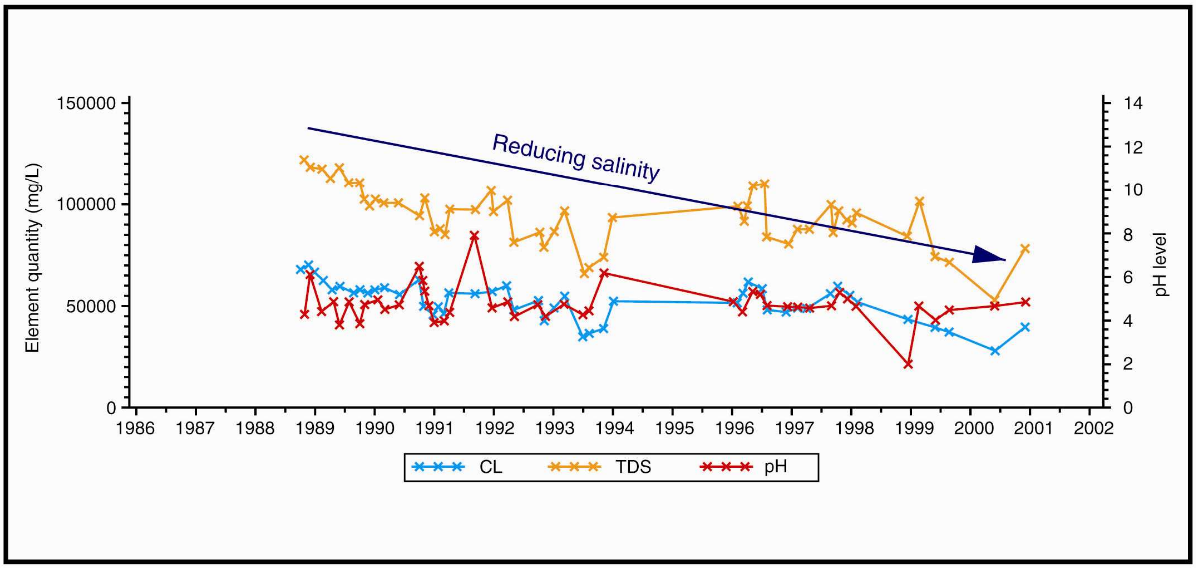

Figure 10 Salinity trends in Bore NC7. Sourced from IT Environmental (2001).

5.4 Aquifer sustainability

Turner et al. (1996), considering aquifer storage alone, indicated that ongoing groundwater abstraction from the palaeochannel aquifer would result in continuing water level decline and eventual storage depletion by 2012 to 2022. The key finding of this study and comments by other groundwater consultants in borefield monitoring reports show that leakage is becoming more significant and that the groundwater resources in the palaeochannel aquifer are more robust than initially predicted.

The longevity or sustainability of the palaeochannel aquifer is largely dependent on balancing borefield abstraction against groundwater inflows. Most borefields in the Kalgoorlie region have reached quasi steady-state conditions at some stage and more recently many are showing signs of extended water level recovery because of reduced groundwater abstraction.

Table 1 shows the period of steady-state condition and corresponding volume of groundwater abstraction for each borefield. Most borefields reached steady-state conditions between 1995 and 1997 with combined borefield abstraction at about 10 GL/yr. Therefore, it can be suggested that the palaeochannel aquifer, utilised by the largest regional borefields, has a sustainable yield of at least 10 GL/yr. The sustainable yield for the entire Roe Palaeodrainage will be significantly larger, as only a quarter of the groundwater resource has been assessed in this study.

Table 1. Steady-state conditions and groundwater abstraction for the major borefields

Borefield name	Period of steady-state conditions	Average annual groundwater abstraction (ML/yr)
Kaltails	1993 – 1998	1735
New Celebration	1992 – 1997*	1145
South Lake & Hannan Lake (KCGM)	1993 –1996	1580
Gidji (KCGM)	1994 –1998	2520
Mt Percy (KCGM)	1993 –1998	585
Lakewood (KCGM)	1990 –2001	355
Kanowna Belle	1995 –1997	980
Jubilee	1999 –2001	190
Paddington	1996 –1998	860

** some bores show water level recovery*

5.5 Groundwater management implications

Groundwater abstraction is regulated by the Department of Water according to the Goldfields Groundwater Area Management Plan (Water Authority, 1994). This plan allows for the mining of brackish (>2000 mg/L) and saline groundwater, referred to as managed depletion, in contrast to other areas of Western Australia where groundwater is allocated on an average sustainable basis. Mining is considered to be beneficial use for the saline groundwater resources.

The concept of sustainable yield in palaeochannel aquifers is considered to be new thinking. The fact that the groundwater system has reached equilibrium or steady-state conditions during extended periods of groundwater abstraction suggests that a sustainable yield can be estimated. The initial estimate of 10 GL/yr is for a combined palaeochannel length of about 110 km; therefore, the sustainable yield for the entire Roe Palaeodrainage (400 km in total) is conservatively estimated at about 35 GL/yr. Future reviews will better quantify the sustainable yield of the Roe Palaeodrainage.

6 Conclusions and recommendations

This review of the palaeochannel aquifer in the Kalgoorlie region, focusing on the period between 1999 and 2001, has demonstrated that the aquifer system has performed better than initially predicted. Large sections of the palaeochannel have reached a steady-state condition, rather than continuing water level decline, which implies that groundwater abstracted is from leakage or recharge rather than storage depletion. There appears to be more than sufficient hypersaline groundwater resources available for utilisation of the mining industry. It is not considered that hypersaline groundwater resources will constitute a limiting factor in mining development.

Bore hydrographs show that the water level declines rapidly in the first three years upon the commencement of groundwater abstraction. After the initial drawdown, the water levels stabilise or establish a quasi steady-state equilibrium representing a balance between inflows from leakage, throughflow or indirect recharge and groundwater abstraction. Since 1997, many of the borefields have shown appreciable water level recovery because of the reduction of groundwater abstraction through improved water use efficiency and usage of alternative water sources (mine dewatering, flooded lakes and mine voids).

The concept of sustainable yield in palaeochannel aquifers is considered new thinking, which is different from current allocation and groundwater management practice. Although, the existing Goldfields Management Plan allows for the mining of saline groundwater, this study suggests that such groundwater may be allocated on a sustainable basis. A sustainable yield of 10 GL/yr has been estimated for the major regional borefields from about 110 km of palaeochannel; therefore, the sustainable yield for the entire Roe Palaeodrainage (400 km in total) is conservatively estimated at about 35 GL/yr.

There is no need to discuss life of the groundwater resource in terms of years or decades. As a sustainable yield can be determined, the groundwater resource can maintain reliable hypersaline supplies assuming that sustainable abstraction rates are maintained. The groundwater resource will not become depleted by 2012 or 2022 but rather large sections of the palaeochannel may have completely recovered to original water levels, assuming abstraction continues to decline.

It is recommended that another five-year review is undertaken in 2008 to assess water level change and aquifer performance in the palaeochannel aquifer around Kalgoorlie. This will enable a comparison to be made between review periods and provide some longer term understanding of aquifer sustainability.

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Contributors

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