

Temporal trends in groundwater levels in the Lower Balonne 2000-2014

Dr. Elad Dafny



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Cover Photo

Distribution canal at the SGIA, May 2014 (Elad Dafny)

Abbreviations

CRDC – Cotton Research and Development Corporation

DNRM- Department of Natural Resources and Mines

GWDB - Queensland Government GroundWater DataBase

SGIA – St George Irrigation area

USQ- The University of Southern Queensland

Executive summary

Groundwater levels at the outskirts of the Balonne floodplain and the newer irrigation areas away from St George have remained relatively stable over the last decade, reflecting no association with temporal changes of rain and river flow within the same period. In contrast, there are several bores, located along the major streams, which indicate an induced streambed recharge during the 2010-2013 high flow period; this evidence, along with groundwater level contours and soil mapping, suggest that streambed recharge is probably more substantial in areas where the stream incises lighter textured soils, e.g., Sodosols.

The groundwater levels under the 'original' St George Irrigation Area (SGIA) and another irrigated area (Kia Ora farm and surroundings), where groundwater has not been intensively monitored, are rising continuously, as deep drainage is accumulating at the water table. The deep drainage is roughly estimated to be in the order of 45-120 mm/yr, which coincide with the overall range for irrigated cotton in Australia.

It is highly recommended to recommence the frequent monitoring scheme in the SGIA, which ceased in the late-2000s. It is also recommended to initiate monitoring at other irrigated areas which are not monitored at the moment. This will allow better risk management in the future.



Photo: Cotton Harvest near Dirranbandi, 2014

Table of Contents

1	Introduction.....	1
1.1	Scope of the report.....	1
1.2	Aims and Objectives.....	1
2	Investigation area	2
2.1	Climate.....	4
2.2	Hydrology	5
2.3	Hydrogeology.....	7
3	Methodology.....	10
3.1	Data sources.....	10
3.2	Field excursion	11
3.3	Data analysis	14
3.4	Analytical calculations	14
4	Results and discussion	14
4.1	Stream flow discharge.....	14
4.2	Groundwater levels	16
4.2.1	St George Irrigation area	23
4.2.2	The central floodplain	26
4.2.3	The southern floodplain.....	28
4.3	Streambed recharge.....	28
4.3.1	Spatial considerations.....	28
4.3.2	Temporal considerations	30
4.3.3	Summary	33
4.4	Deep-drainage under the irrigated areas.....	33
4.5	Flooded bores.....	34
5	Summary	36
6	Reference.....	37

Appendix A - Bore hydrographs

Appendix B – Field work log and results

Tables list

Table 1: List of selected stream gauging stations	10
Table 2: Groundwater levels changes in bores of the SGIA.....	24

Figures list

Figure 1: Location maps..	3
Figure 2: Rain in St George	4
Figure 3: Stream discharge in the studied area	6
Figure 4: Schematic hydrogeological cross-section (not to scale)	7
Figure 5: Standing groundwater level elevation (Pearce et al., 2006).	8
Figure 6: Soils map	9
Figure 7: Google earth image of the studied area showing the measured bores	12
Figure 8: Recent stream flow records	15
Figure 9: Number of bores being monitored by DNRM in the study area	16
Figure 10: Groundwater levels - 2004	17
Figure 11: Groundwater levels – 2006	18
Figure 12: Groundwater levels – 2008	19
Figure 13: Groundwater levels – 2010	20
Figure 14: Groundwater levels – 2012	21
Figure 15: Groundwater levels – 2014	22
Figure 16: Groundwater levels changes in the SGIA (1972-2014)	25
Figure 17: Groundwater levels changes in the central portion (2000-2014)	27
Figure 18: Groundwater levels changes in the southern portion (2000-2014)	29
Figure 19: Schematic groundwater level contour lines under three cases of hydraulic connection between aquifer and river	30
Figure 20: Annual stream discharge near St George (station #422201) (a) and groundwater depth at bore #0079 (b) and #0155 (c)	31
Figure 21: Annual stream discharge near the braiding point (station #422205) (a) and groundwater depth at bore #0085 (b) and #0086 (c)	32
Figure 22: Measure and reconstructed heads (a) in bore #0087 for the period 2010-2014, and (b) in bore #0139 for the period 2009-2012	35

1 Introduction

The lower Balonne catchment, between St George and the QLD-NSW border, comprises a broad floodplain where irrigated cropping occurs extensively. The extensive aquifers under the floodplain are regarded as having low recharge rates under non-irrigated land uses (Herczeg 2004; Tolmie et al. 2011). Previous studies observed a trend of rising groundwater level under one of these irrigated areas (the SGIA), and attributed this trend to deep-drainage from surplus irrigation water which percolated downward. Despite these findings and recommendations (Pearce and Hansen, 2006), the extensive monitoring scheme which took place in this area until 2006 was reduced substantially; in 2013, only one bore out of 24 was monitored.

This report reviews the recent changes and trends in groundwater levels in the lower Balonne catchment, particularly in the irrigated areas. The analysis is based on existing data, and to a large extent, on new field data collected in May 2014. Results and recent trends are then compared to previous studies.

1.1 Scope of the report

The current report was made as an integral part of the DNRM project – ‘The impact of improved WUE on paddock and catchment health’, sponsored by the Cotton RDC. Two of the project aims are to ‘Understand recent groundwater trends in cotton growing areas in the QMDB and risks posed to landscape health, and options for management’ and ‘Determine likely groundwater rise, timeframes and severity for groundwater and salt discharges, and management responses’.

The report presents the up-to-date conceptual understanding of the hydrogeology in the Lower Balonne River catchment (Pearce and Hansen, 2006; Pearce et al., 2006; Murphy, 2009), including the St. George irrigation area, followed by a detailed analysis of bores hydrographs. The latter is based solely on DNRM monitoring bores, which are spread throughout the area. Data of private domestic & stock bores was excluded; however, it is not expected to affect the result as usually these include only one level record per bore rather than levels time-series.

1.2 Aims and Objectives

The hydrogeological review had three primary aims:

- Identify recent trends of groundwater levels in the Lower Balonne, including the cotton growing areas around St. George and Dirranbandi

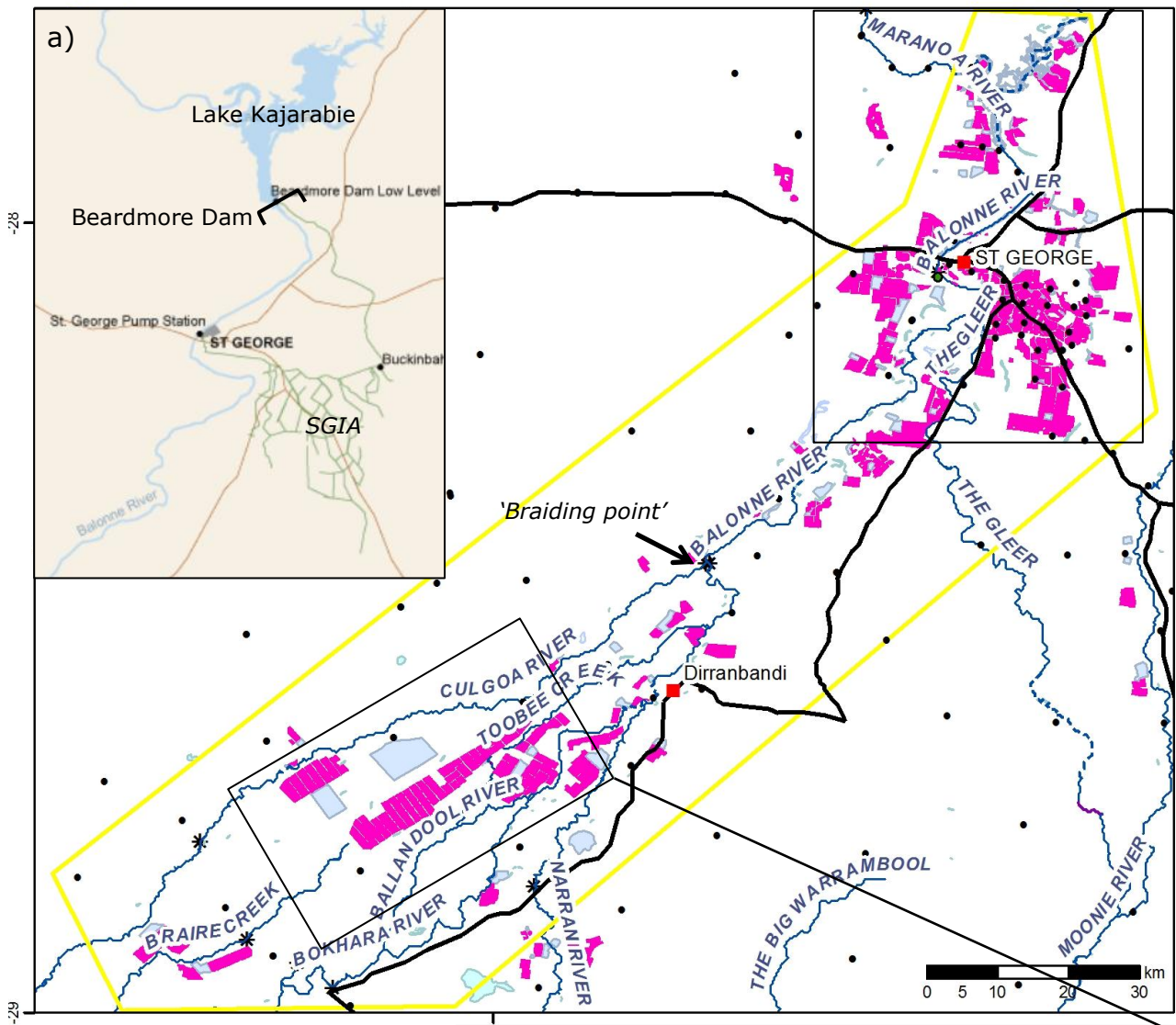
- Indicate association between rain and flood events to groundwater levels trends
- Support the hydrogeological conceptual model for the alluvial and sedimentary aquifer systems within the investigation area

In turn, the gathered information will be used to achieve the project aims by-

- Identifying possible risks for cotton growing areas due to groundwater level rise or fall
- Identifying areas where further (new) irrigation schemes are likely to affect landscape health
- Identifying areas where data are not available, and
- Recommend further management and monitoring

2 Investigation area

The investigation area covers part of the lower Balonne River Catchment, south-east Queensland. It stretches from St. George in the NE, through Dirranbandi, and to Hebel, located at the QLD-NSW border in the SW, over an area of about 7,200 km² (Figure 1). The area includes two major cotton irrigation projects- the St George Irrigation Area (SGIA) and the Cubbie Station (insets a and b in Figure 1). Ground elevation decrease from ~200 m asl near St George to ~175 near Dirranbandi and ~150m near Hebel.



Legend

- DNRM bore
 - Town
 - Highway
 - ▭ Investigation area
 - Irrigated crops
- AHGFWaterbody**
- Lake
 - Reservoir
 - Swamp
- * Surface water station

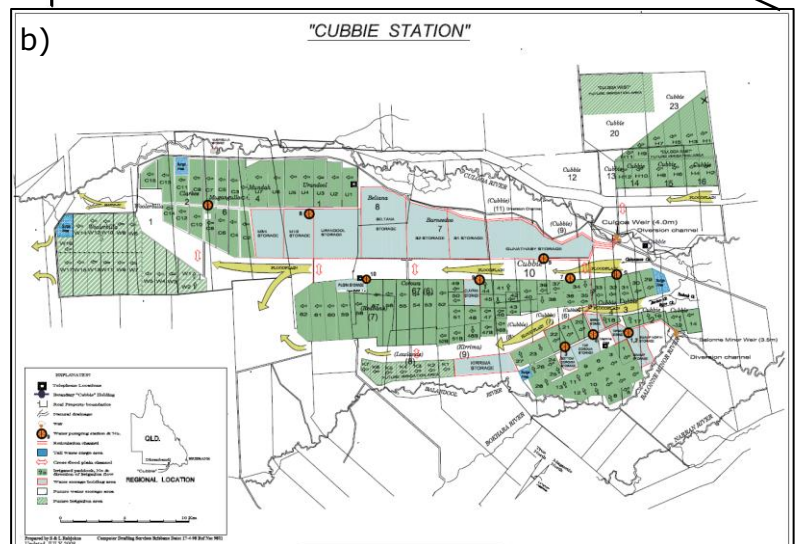


Figure 1: Location maps. Inset (a) from IMA irrigation website, inset (b) from Cubbie Station website.

2.1 Climate

The studied area is characterized by a semi-arid sub-tropical climate. The average annual rainfall decreases westward, and varies between ~520 mm near St. George (Figure 2a) to ~420 mm near Hebel. Hot, dry summers (October-March) with prolonged drought periods are common.

The rainfall is summer dominant and highly variable, with occasional periods of high-intensity rain and runoff, and extended periods of severe drought (Figure 2) and low stream flow (Figure 3b). Most recently, dry conditions occurred in SE Queensland from 2001 onward (National Climate Centre, 2006), up to 2009.

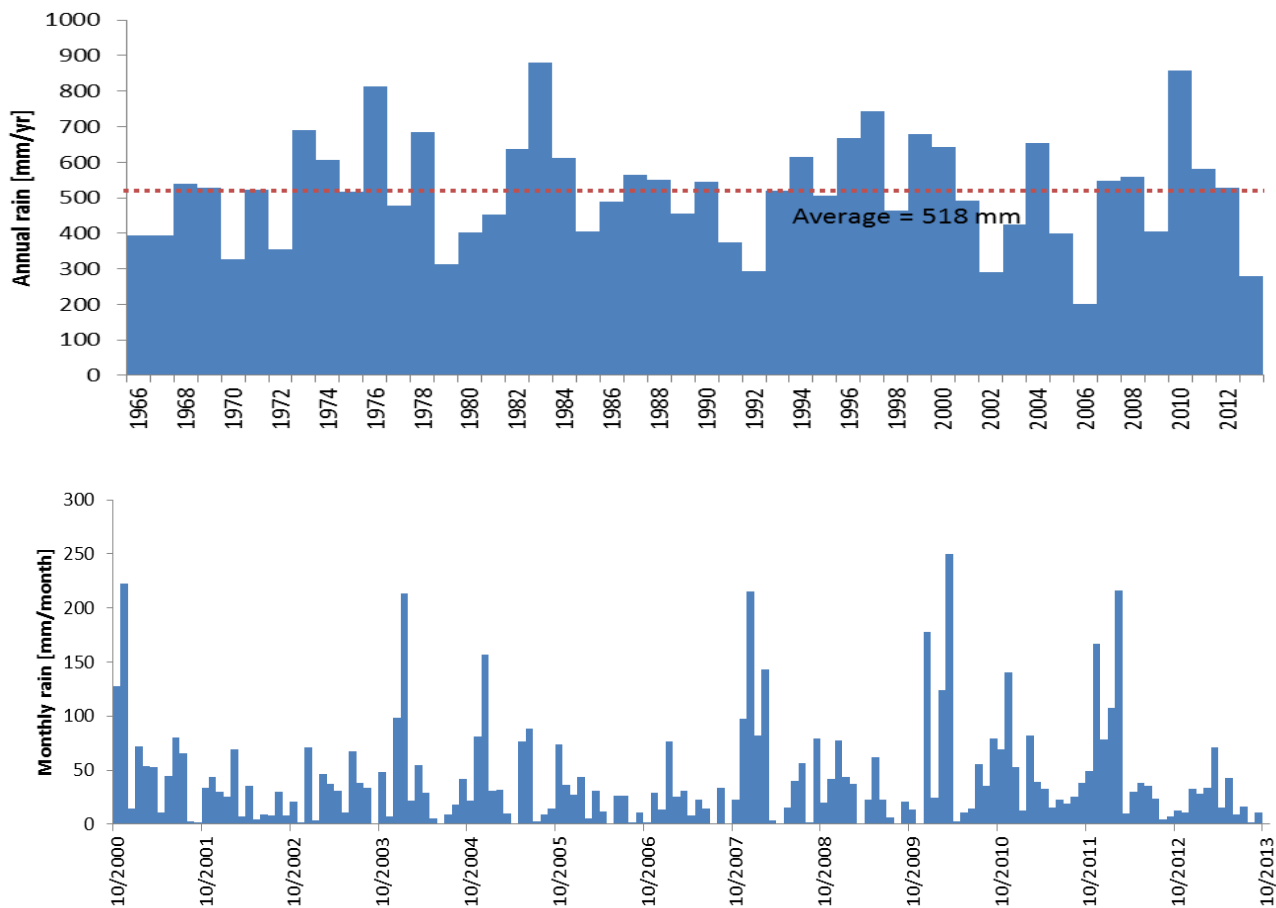


Figure 2: Rain in St George (source: BOM): (a) Annual time series for the years 1966-2013, and (b) monthly time-series for the years 2000-2013.

2.2 Hydrology

The studied area is part of the Balonne River Catchment. In its NE corner, the Maranoa River joins the Balonne River and both flow into Lake Kajarabie (Figure 1). The lake was formed following the construction of E.J. Beardmore Dam in 1972 and holds up to 81,800 ML of water at an average depth of 2.4 meters¹. The Balonne River also passes through the Jack Taylor Weir, constructed near St. George in 1953, and continues to flow in a south-west direction for about 50 km. About 20 kilometers north of Dirranbandi it forms a braided stream system, including the Culgoa, Toobee, Ballandool, Bokhara, Braire and Narran rivers (Figure 1). With the exception of the latter, all these braided rivers confluence downstream to form the Darling River.

The average annual discharge of the Balonne River as it enters the studied area is 1,150 GL/yr (Weribone station, #422213A). The flows are highly variable and (as with many Queensland systems) prone to extreme high inflow events. For example, in the period of 1969-2013, there were 8 years where discharge was greater than 2,300 GL/yr and 18 years where stream flow was less than 575 GL/yr (i.e., double and half the average, respectively) (Figure 3). The highest discharge, ~8,200 GL of water, was recorded in 2010/11; of which, 5,550 GL of the flow occurred in January 2011. The average annual discharge at the downstream end of the studied area is ~ 900 GL/yr (cumulative average of 5 stations).

An 112-km network of open channels and pipes, with manually operated gravity flow control structures, drain and distribute water toward the St George Irrigation Area (SGIA)- a 10,000 ha area on the east bank of the Balonne River (Figure 1a). The system supplies ~50 GL/yr through 178 off-takes, extending 32 kilometres south-east of St George². In addition, large quantities of water are being diverted from the Culgoa River for irrigation at Cubbie Station. It is estimated that the farm diverts 200-500 GL/yr for irrigating 13,000 hectares of cotton³.

The surface-water balance for 'average' years (1150 (GL inflow) = 900 (GL outflow) + 250 (GL irrigation diversion)) suggests that the 'losses', i.e., river recharge to the aquifer, are small (smaller than the estimation's precision of ~50 GL/yr), in agreement with some of the previous estimates (Murphy, 2009). In contrast, losses along the

¹ <http://www.sunwater.com.au/schemes/st-george>

² <http://www.lmairrigation.com.au/stgeorge>

³ http://www.melaleucamedia.com.au/01_cms/details.asp?ID=35

Narran River, between Dirranbandi and Hebel, were calculated in one instance, to be 518 ML (Eastern Australia Agriculture Pty Ltd, 2009); this volume is equivalent to ~ 8000 L/m per event, and when extrapolated to the entire stream system, potential losses are totalled to be ~ 3 GL/yr. Substantial streambed recharge was also assumed by Pearce et al. (2006), but a quantitative analysis did not accompany this.

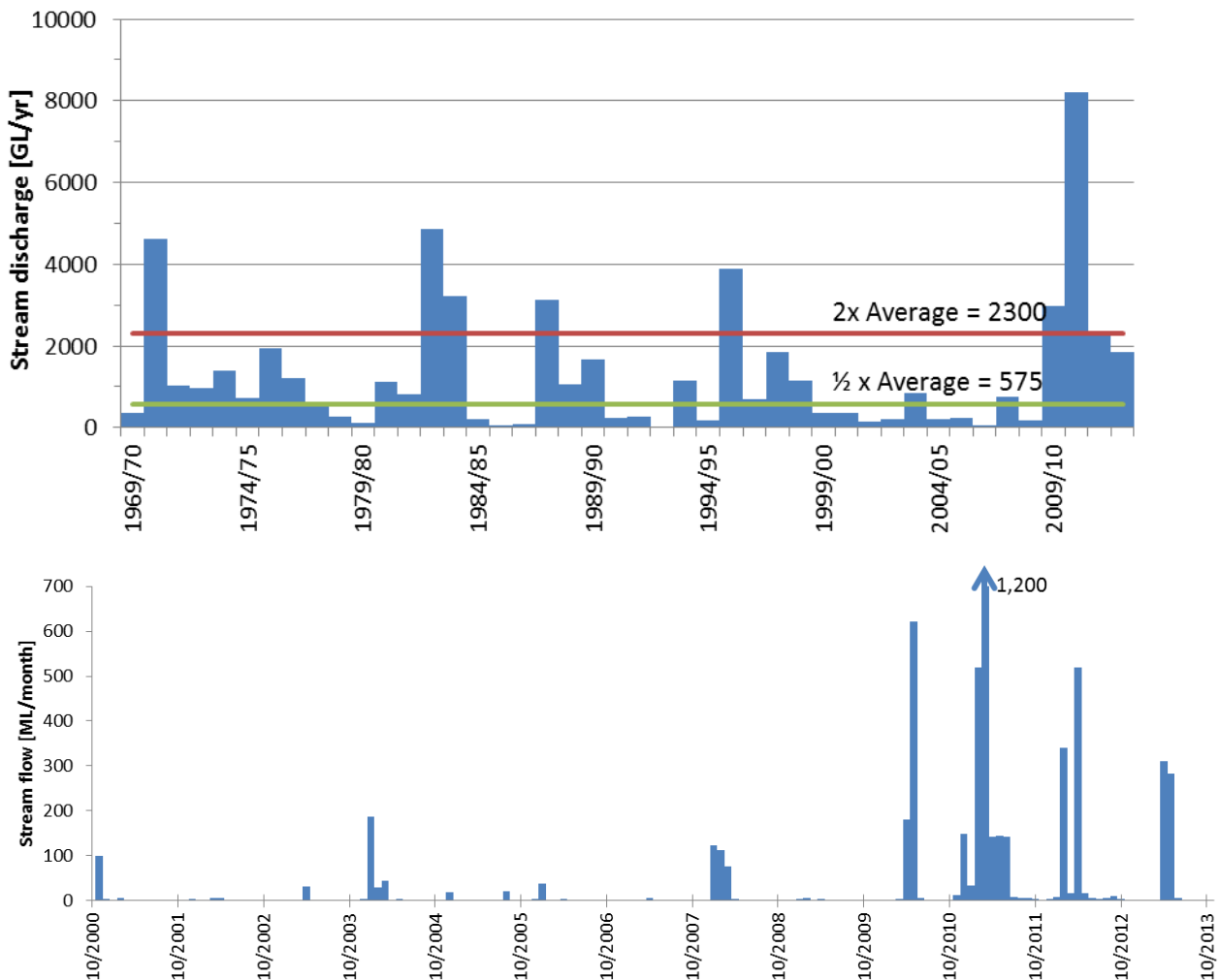


Figure 3: Stream discharge in the studied area (source: DNRM): (a) annual time series of the Balonne River (Weribone station, #422213A) and (b) monthly time series of the Culgoa River (Whyenbah site, #422204A).

2.3 Hydrogeology

The study area is comprised of the Cretaceous Griman Creek Formation, overlain by young fluvial-alluvial sediments. The Griman Creek Formation accumulated as part of the larger Surat Basin and consists of marine and terrestrial sediments. In later stages, it was incised in an NE-SW direction and filled by younger sediments (see photo below).



Photo: Griman Creek Formation rocks outcrop downstream of Beardmore Dam

These geological units define the three dominant hydrogeological units in the investigation area, namely the Griman Creek Fm. aquifer, and two alluvial aquifers (lower and upper), separated by a clayey, leaky aquitard (Figure 4). The upper alluvial aquifer extends throughout and beyond the studied area (Figure 5), while the lower alluvial aquifer is much narrower and is prolonged in the NE-SW direction.

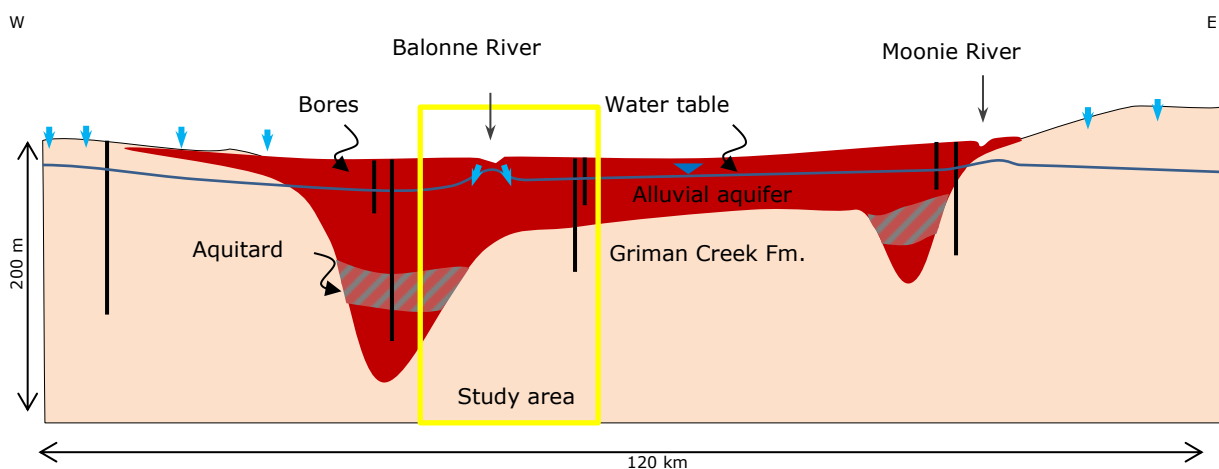


Figure 4: Schematic hydrogeological cross-section (not to scale)

Recharge (blue arrows in Figure 4) to the alluvial aquifer occurs largely as (1) 'streambed recharge' along the Balonne River and (2) rainfall, mainly through the Kandosols, stretching to the north of the study area (Figure 6) (Pearce et al., 2006). Explicit assessment of the streambed recharge is unavailable. Nevertheless, on one occasion, losses along the Narran River, between Dirranbandi and Hebel, were calculated to be 518ML⁴; this volume is equivalent to ~ 8000L/m per event.

Rainfall recharge rates estimated from groundwater chloride mass balance indicate low rates of less than 1 mm/yr on average (Herczeg, 2004). These rates are consistent with deep drainage rates measured using soil chloride mass balance for native vegetation to the east of St George (e.g. 0.2-0.3 mm/yr for Coolabah woodland near Nindigully; Tolmie et al., 2011). Consistent with this low recharge, the groundwater is generally moderately to highly saline, with fresh water only found in the upper aquifer at some locations near the river (Herczeg, 2004).

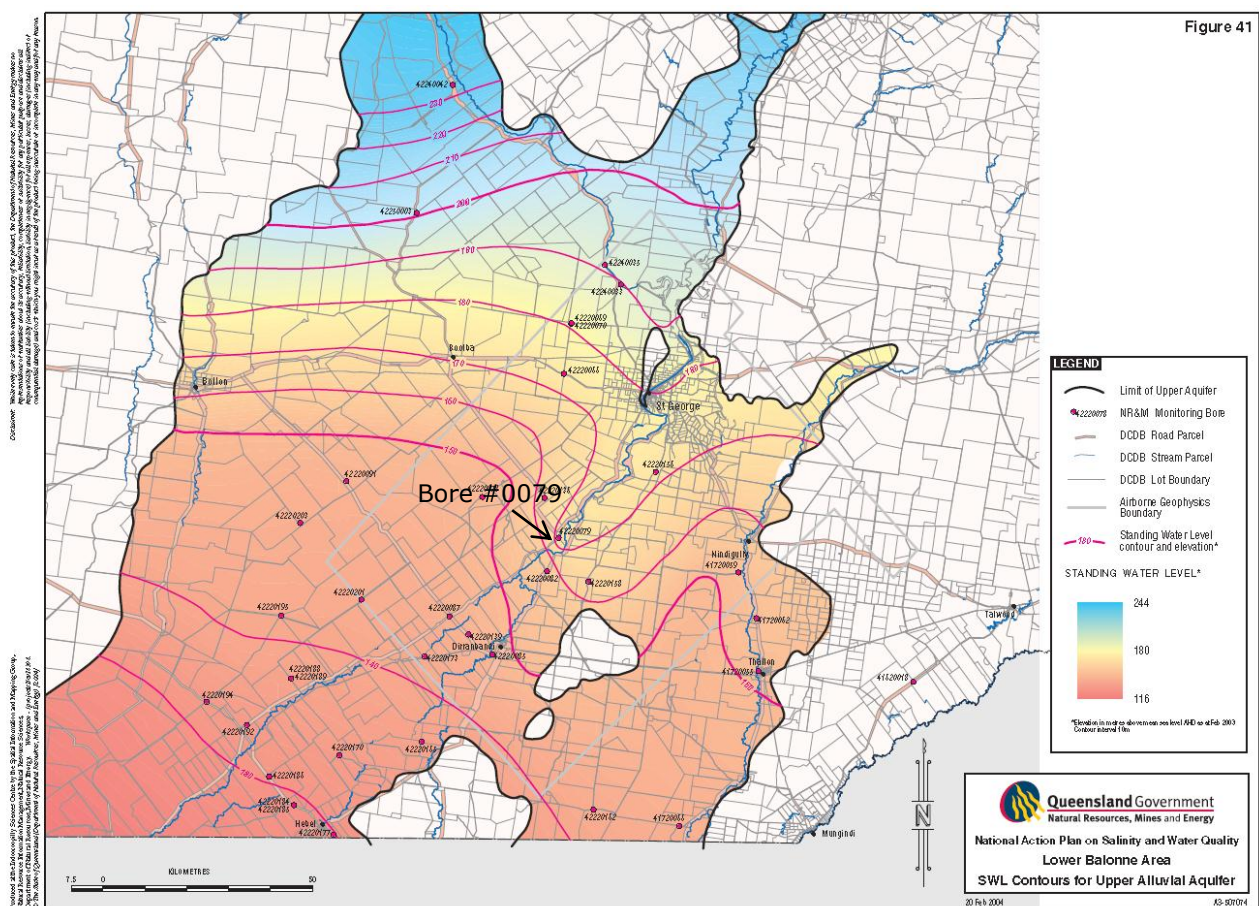


Figure 5: Standing groundwater level elevation contours for the Upper Alluvial Aquifer in the Lower Balonne region (Pearce et al., 2006).

⁴ http://www.pc.gov.au/__data/assets/pdf_file/0020/91613/sub045.pdf

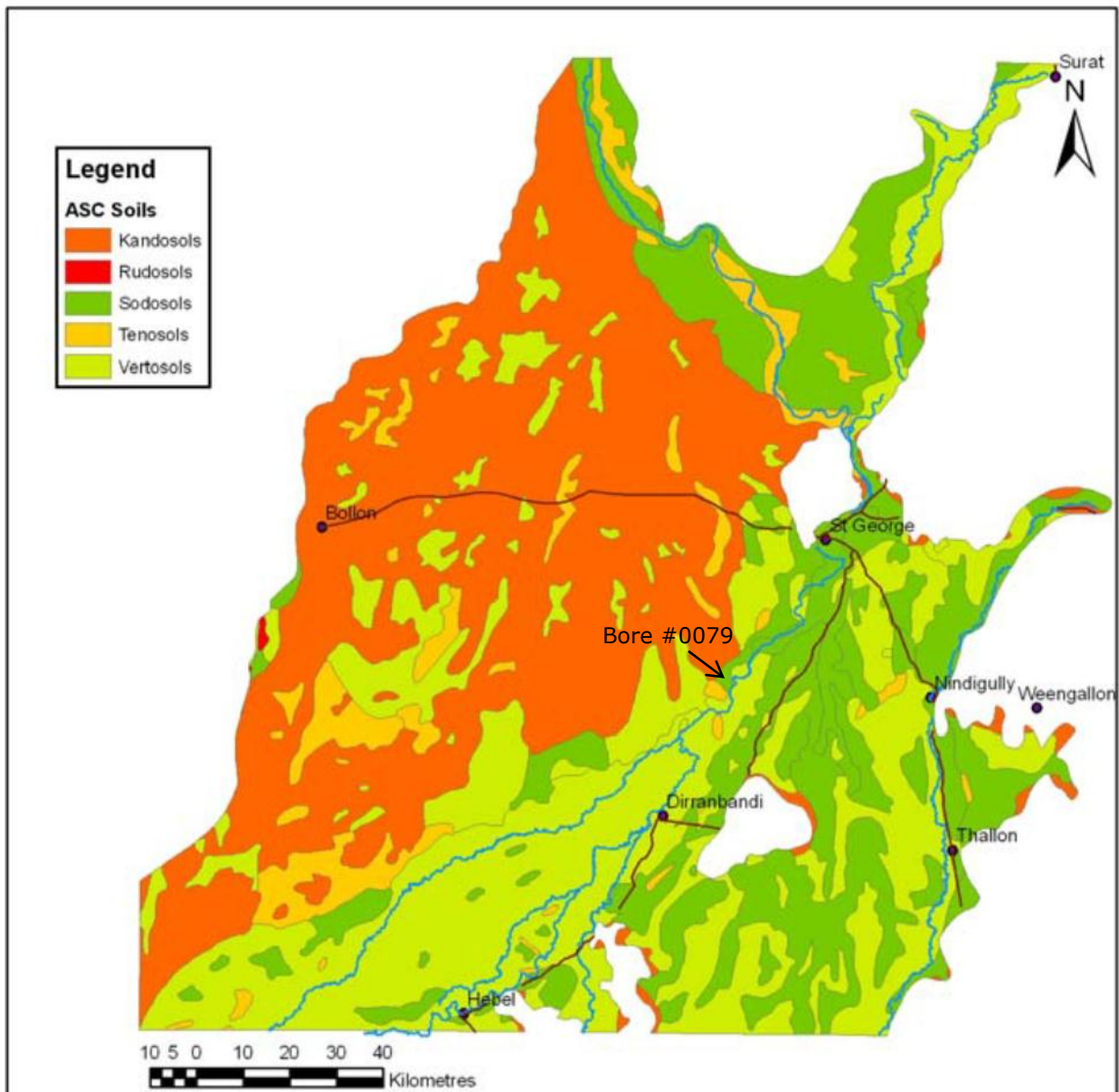


Figure 6: Soils based on the Australian Soil Classification system

Additional 'artificial' sources of recharge were suggested to explain the observed trend of rising groundwater levels, from 1978 to 2006, across the SGIA (Pearce and Hansen, 2006). These are (3) deep-drainage from the SGIA fields and (4) leakage from the extensive network of earth supply channels and drains associated with the irrigation area. The deep-drainage has been estimated to be 68 mm/yr and 90 mm/yr from Vertisols and Sodosols, respectively (Pearce et al., 2006). The possible leakage from the channels and drains has not been estimated so far.

3 Methodology

3.1 Data sources

Bore data was extracted from the Queensland Government GroundWater DataBase (GWDB), which is managed by DNRM. The database includes groundwater depth records for 81 monitoring bores in the studied area; 79 of these bores were selected for analysis, as they contain some records for the years 2000-2013. Nevertheless, data for the recent years (2012-2013) include records of no more than 17 bores per year. Additional measurements from 25 bores were taken during this study as described below.

Cubbie Station installed ~30 piezometers which are being reviewed annually (Dr. Pat Hulme, personal communication). This information is private and hence not available for this report.

Surface water data (stream discharge) was extracted from the Queensland Government DNRM Water Monitoring Data Portal website (DNRM web site, 2013). Eight gauging stations are located within the study area, and additional upstream station was added as a reference (Table 1). Five of the gauging stations are located downstream from the Balonne braiding point, and their cumulative discharge serves as an indication for the overall flow through this section. The raw data include many footnotes relating to the accuracy of the measurement, such as estimations, poor or fair reading; these were disregarded when stream flow time series were created.

Rain data was extracted from the Australian Bureau of Meteorology website for the St George station (closed at 2001) and St George airport station (2002-2013) (BOM web site).

The data was extracted in January 2014 and was censored at 31/12/2013.

Table 1: List of selected stream gauging stations

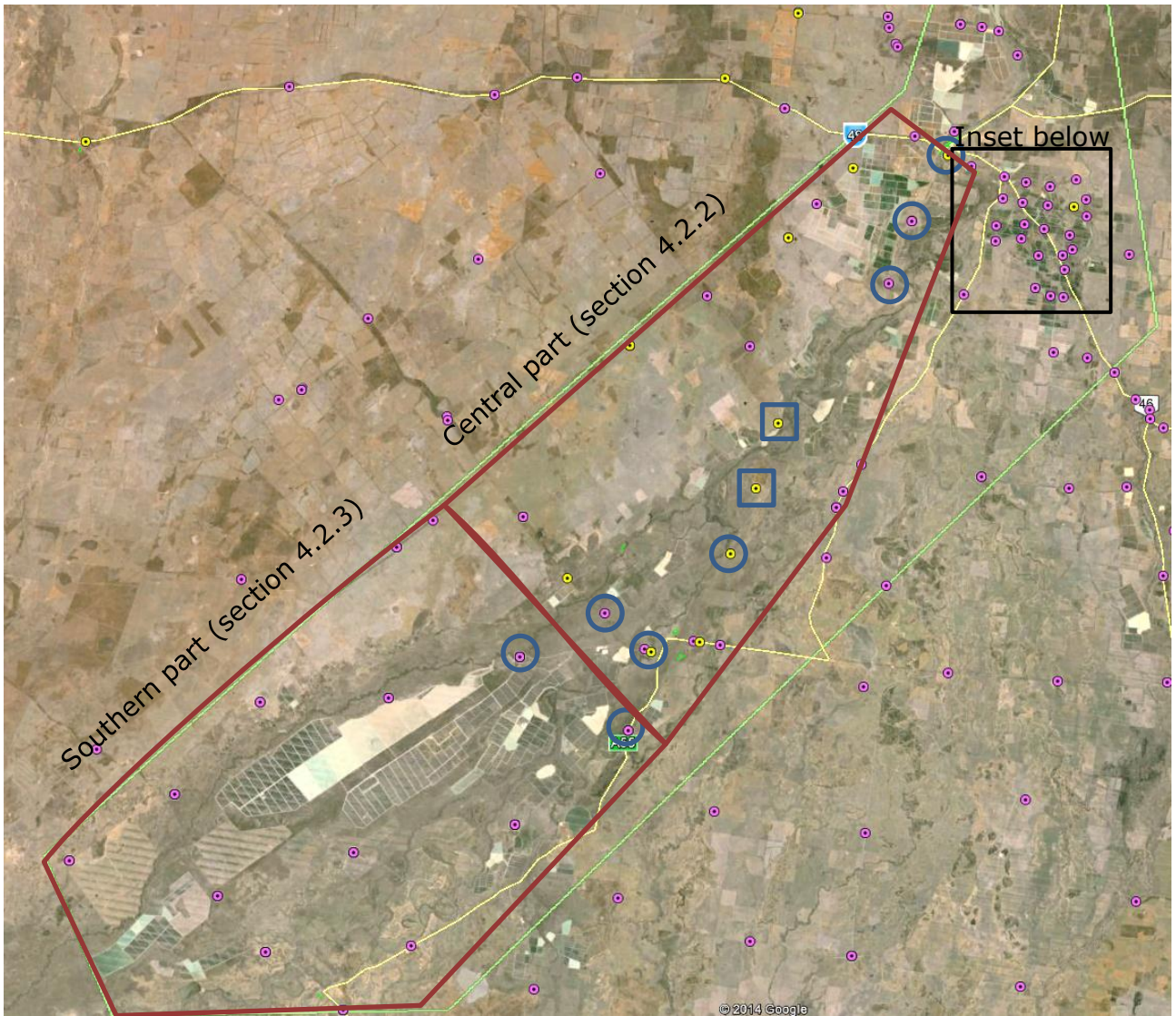
Station	Location	Location (Order) downstream
422201E	Balonne River at St George (replaced by 'F' in 2012)	2
422204A	Culgoa River at Whyenbah	3a
422205A	Balonne—minor River at Hastings	3b
422206A	Narran River at Dirranbandi—Hebel Road	4b-iv
422207A	Ballandool River at Hebel Bollon Road	4b-ii
422208A	Culgoa River at Woolerbilla	4a
422209A	Bokhara River at Hebel	4b-iii
422211A	Briarie Creek at Woolerbilla-Hebel Road	4b-i
422213A	Balonne River at Weribone	1

3.2 Field excursion

Field data from 25 bores was collected by the author during an excursion to the study area in 5-6th of May, 2014 (Figure 7). Data included bore total depth, groundwater depth, salinity (EC) and temperature (Table B1; Appendix B). In eight bores, water was purged and sampled (Table B2; Appendix B). The weather was calm and dry, with a mean daily temperature of 16-18 °C.

Total depth was measured by dropping a weighted tape measure into the bore, and measuring the length of the tight cord. Groundwater depth, salinity (EC) and temperature was measured using a Solinst 103. Purging and sampling were performed using a 1 litre PVC bailer. Initially, five litres were purged from the bore. Water level was measured again, and once the level had recovered, an additional two litres were collected from the bore's perforation depth. Bottles and assigned equipment were rinsed three times with the collected water. Samples were stored, unfiltered, in a 1 litre PVC bottle ('Type A'), kept sealed and cool at all times. A 'YSI pro' multi-meter; was used to measure temperature, salinity (EC and TDS), pH, Eh, Oxygen level (concentration and %DO) and Nitrate (NO_3^-) concentration of the collected groundwater samples.

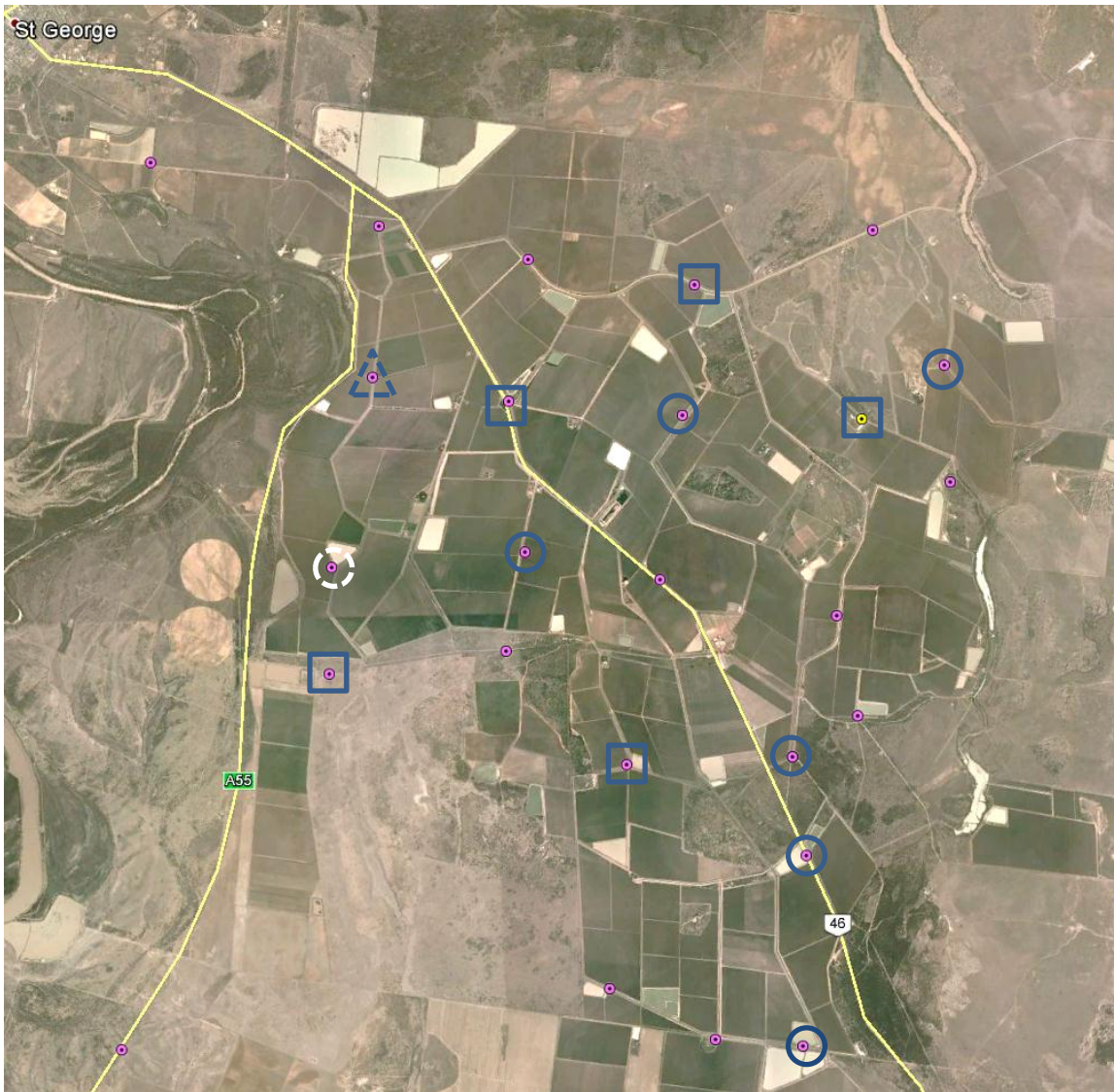
The collected data were reported to DNRM.



Legend

- | | | | |
|----------|---|-------------------------|---|
| Measured | ○ | Current monitoring bore | ● |
| Sampled | □ | Past monitoring bore | ● |

Figure 7: Google earth image of the studied area showing the 2014 measured bores



Legend

- | | | | |
|-------------|---|-------------------------|---|
| Measured | ○ | Current monitoring bore | ● |
| Sampled | □ | Past monitoring bore | ● |
| Not located | ○ | | |
| Faulty | △ | | |

Figure 7 (continue): Google Earth image of SGIA showing the 2014 measured bores

3.3 Data analysis

The GWDB contains time series of groundwater depths (WD), i.e., the depth of the water table from a reference point, which is found slightly above the surface elevation. These data are given as negative values, and were transformed into absolute water levels (WL) using equation 1 and the reference point elevation (Ref):

$$1) \quad WL = Ref + WD$$

For consistency, water depths are presented as negative values and water elevation as positive values, representing elevation above mean sea level (AMSL); all values are given in meters. In the following report, the use of the latter was preferred for consistency.

3.4 Analytical calculations

Some inconsistencies between measures taken at individual bores and measures taken at adjacent bores were identified and attributed to sediment clogging. Rudimentary analytical equations were developed to stress the dynamic interaction between the water column in such bores and the head in the aquifer. These equations are shown below, in section 4.5. The equations were set in a Microsoft excel spreadsheet. Optimization using root mean square (RMS) method to fit measured values was done by changing key parameters.

4 Results and discussion

4.1 Stream flow discharge

Cumulative stream flow (discharge) at four points, arranged in the downstream direction, is shown in Figure 8 (note the logarithmic scale). Each diagram shows the monthly discharge (columns) in ML (Mega-litre, equivalent to 10^3 cubic meters).

The records show the seasonal flow pattern, with low discharge during the winter months (sometimes reaching below the station's discharge threshold) and intermittent 'floods' in the summer, usually between December to March. Discharge in the last four years (2009/10-2012/13) was substantially higher than that of the 1999/2000 through 2008/9 discharge (Figure 3a).

The discharge decreases in the downstream direction. For example, the January 2004 flow event reduced from ~468 ML near St. George to 415 ML near the braiding point and to 92 ML (cumulative) in the downstream stations; and the March 2011 flow event

reduced from 5.9 GL to 4.3 GL and 3.4 GL, respectively. The decrease in the discharge is associated with extensive diversion of flood water for irrigation in the study area but may also imply that recharge to the aquifer occurs in high flow years. For perspective, Cubbie Station storage capacity near Dirranbandi is 462 GL. It should be noted that temporal data of actual diversion volumes for irrigation were not available.

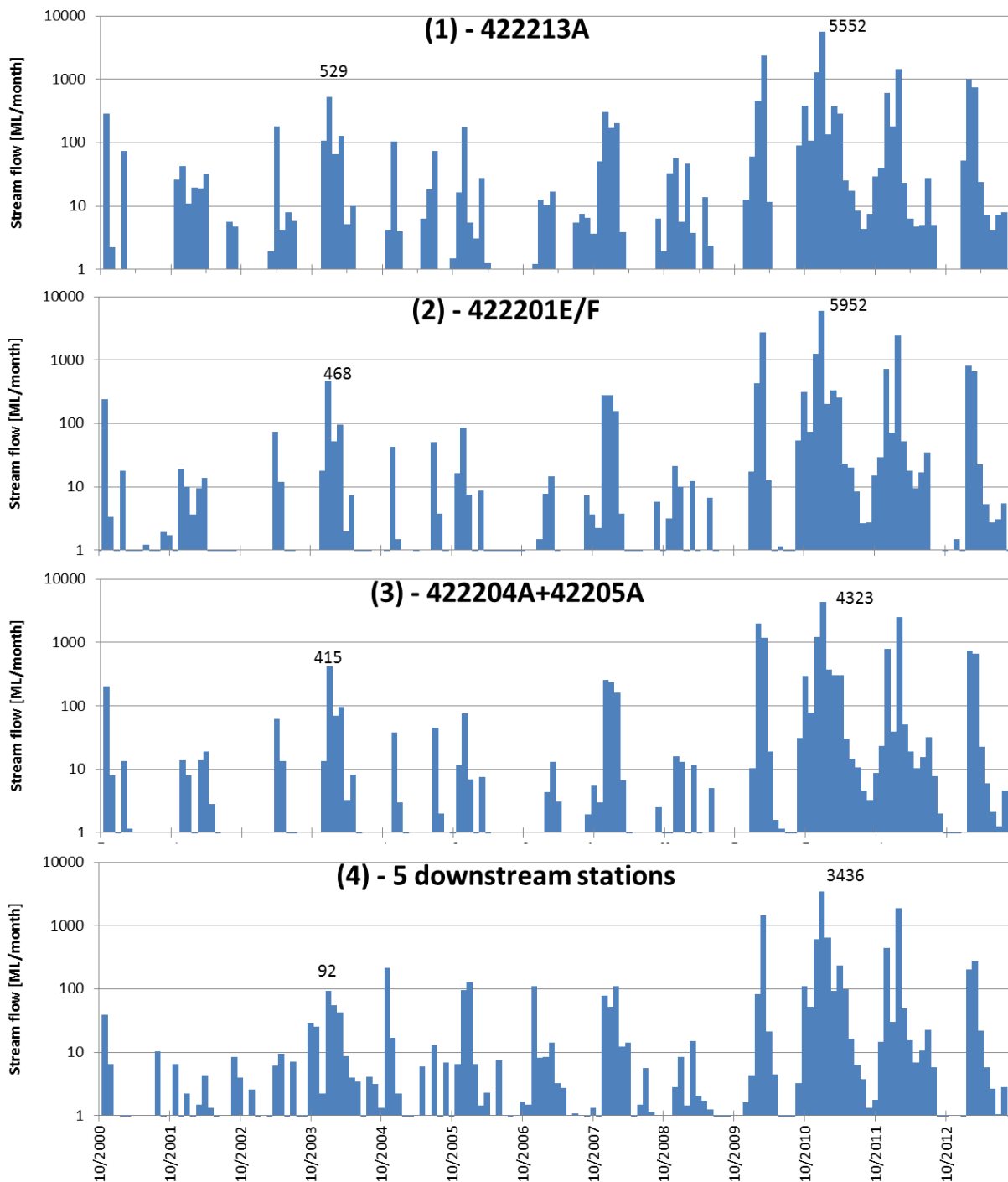


Figure 8: Recent stream flow records (stations location in Table 1).

4.2 Groundwater levels

Data collection from bores in the study area was at its peak in 2004-2006, with ~70 bores being monitored, and decreased over the last decade; in 2013, only 16 bores were monitored (Figure 9). This obstructs the ability to analyse and map spatial and temporal trends of groundwater levels. The following figures provide the average groundwater levels collected in the study area by years (Figure 10, Figure 11, Figure 12, Figure 13, Figure 14); the last figure shows the data obtained in this study, for 2014 (Figure 15).

Individual bores hydrographs are shown in Figure 16, Figure 17, Figure 18 and appendix A; the latter also shows the groundwater depth beneath the ground surface. There are no apparent common trends of the groundwater table, beside the notion that many of the bores show stable groundwater elevation, at least for substantial periods of time while several others show on-going rising trends. The following discussion is made with respect to three sub-zones: the SGIA, the central portion and the southern portion of the study area (see in Figure 7). All the bores included in the discussion are located in the Balonne basin (4222) and are identified by the four last digits of their respective RN.

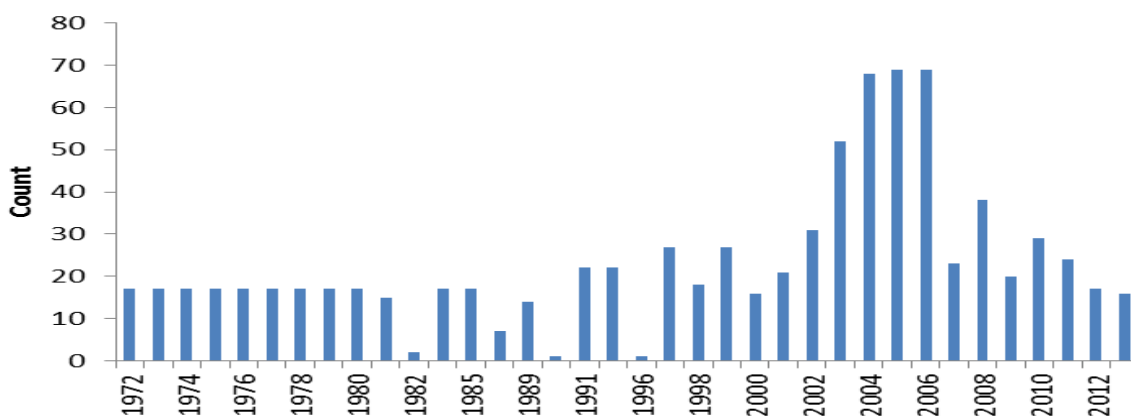


Figure 9: Number of bores being monitored by DNRM in the study area

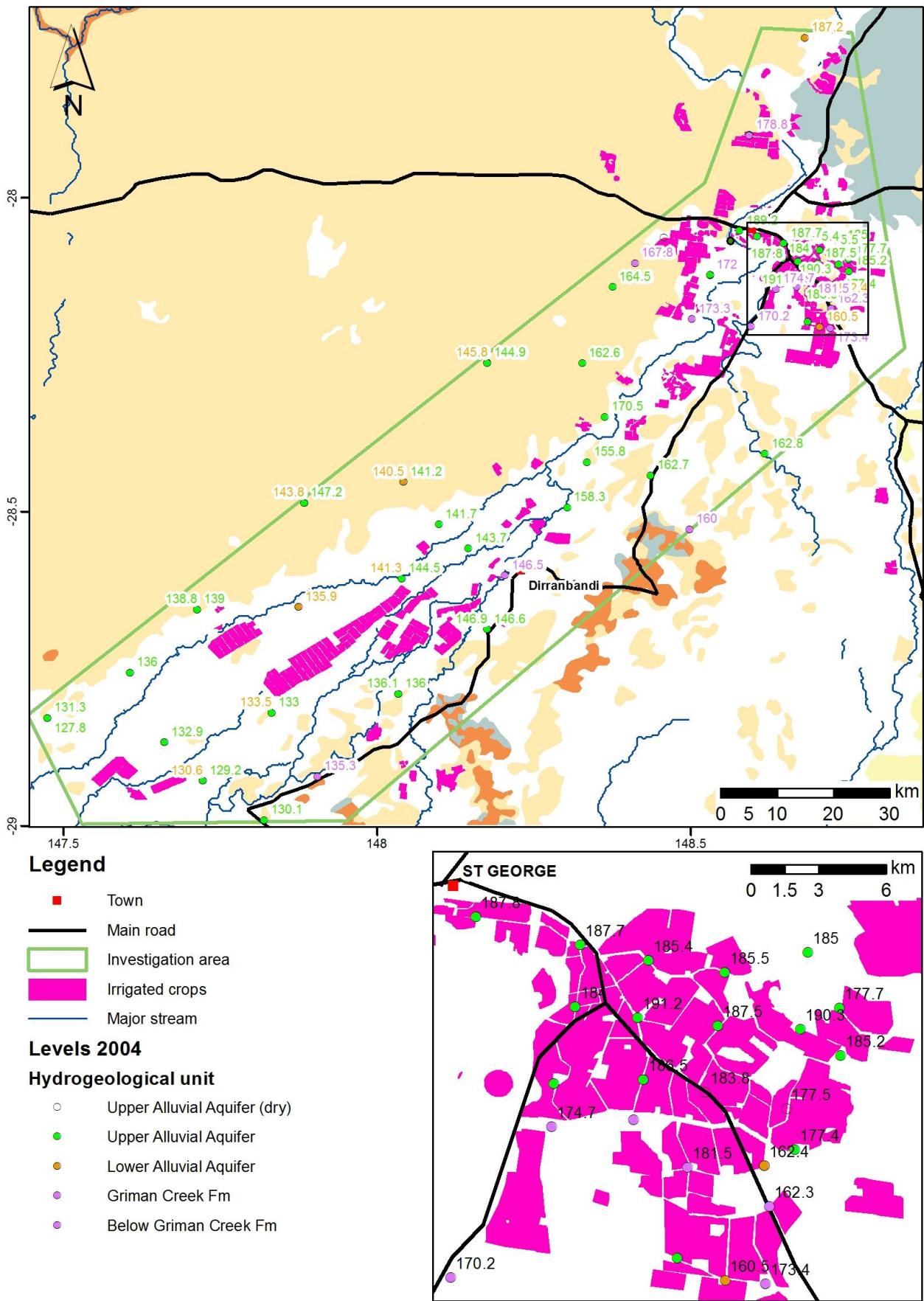


Figure 10: Groundwater levels - 2004

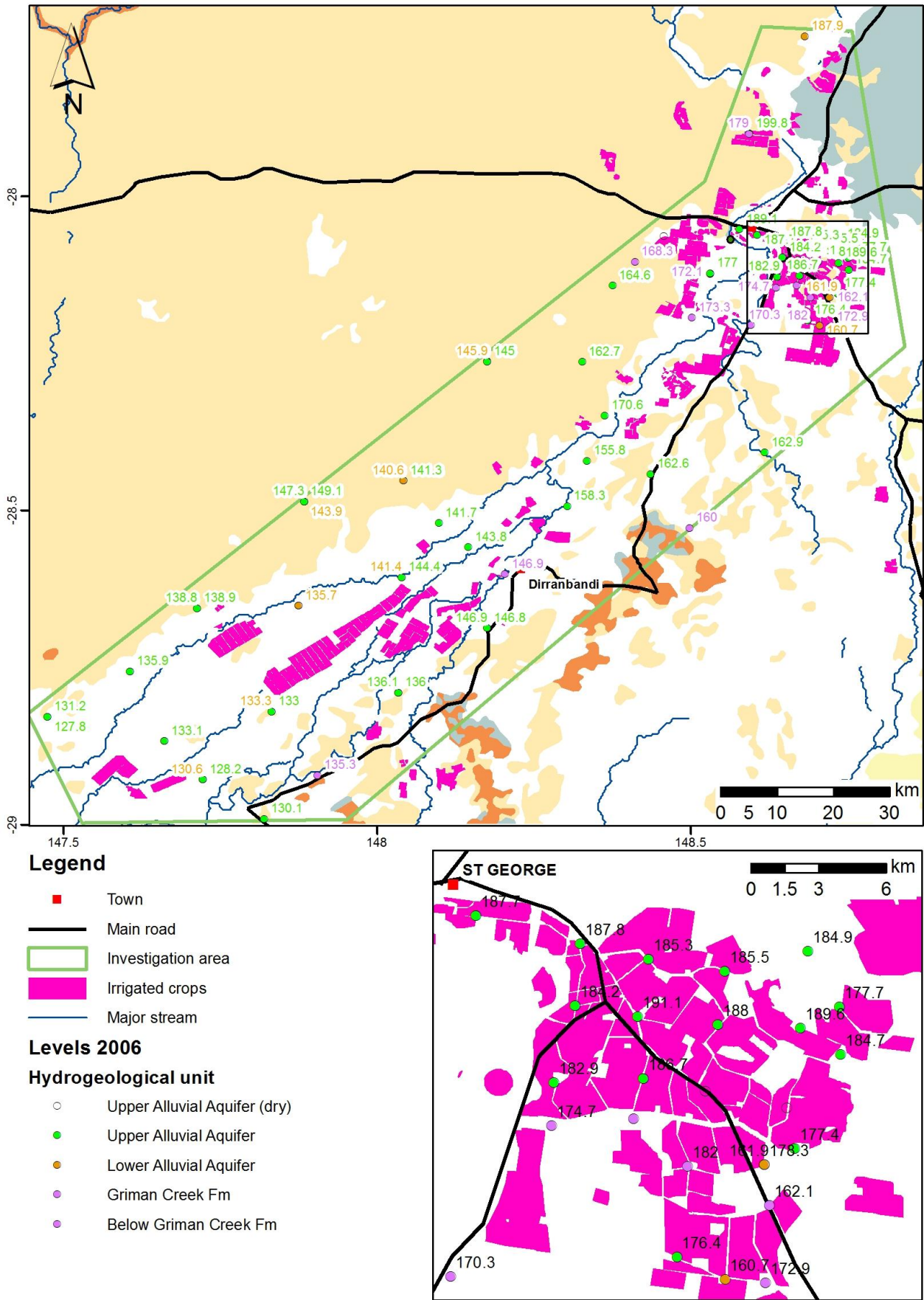
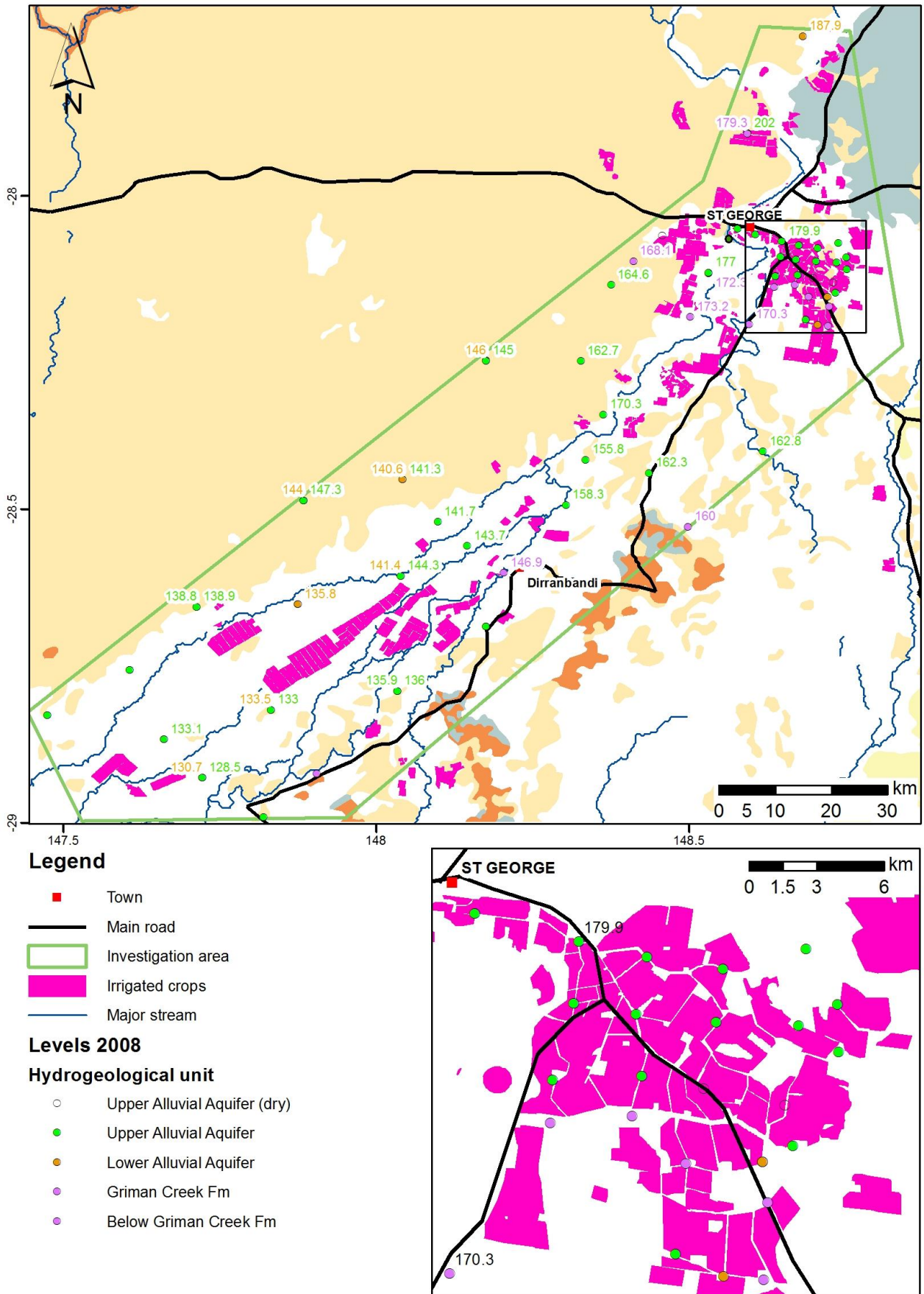
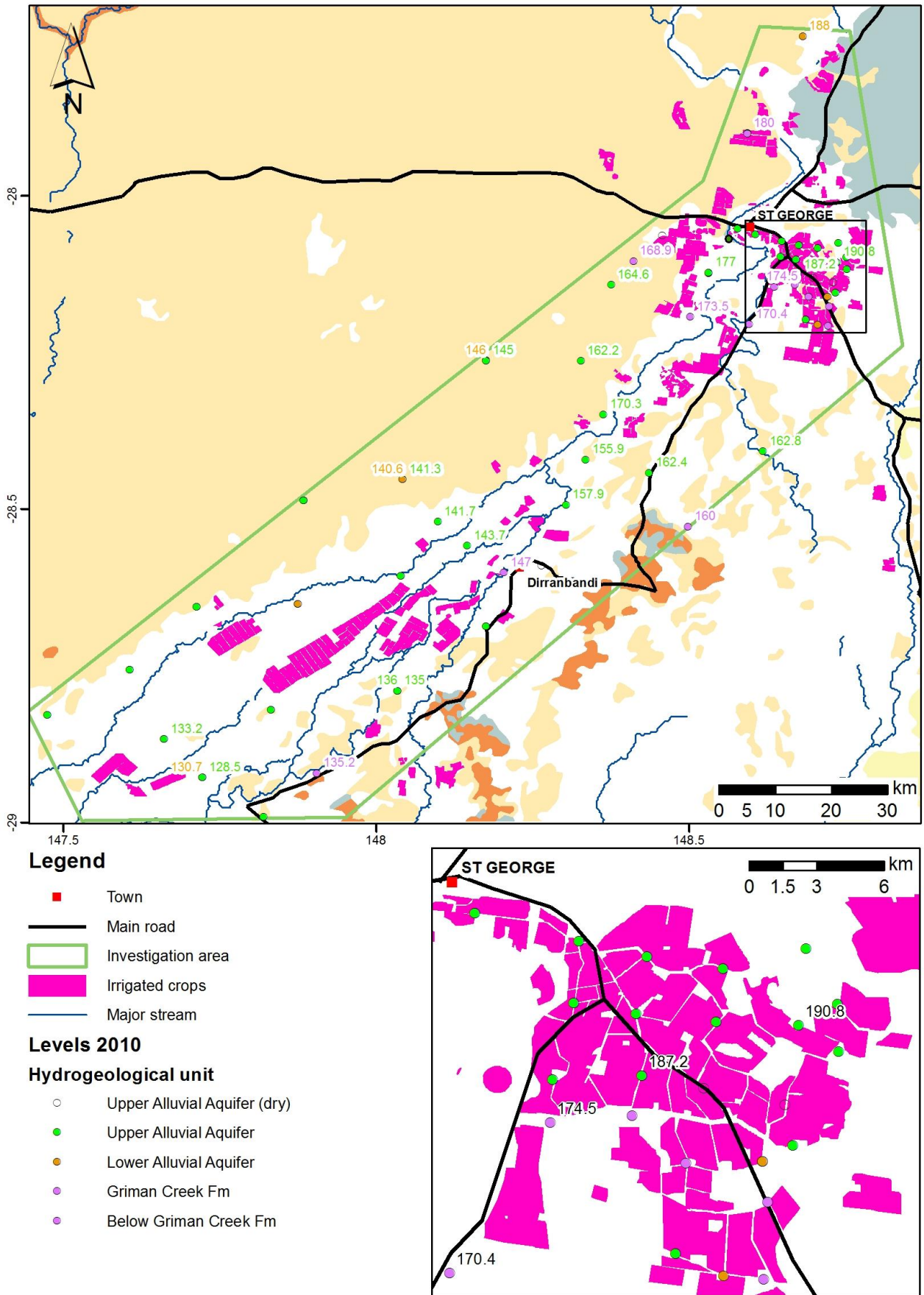
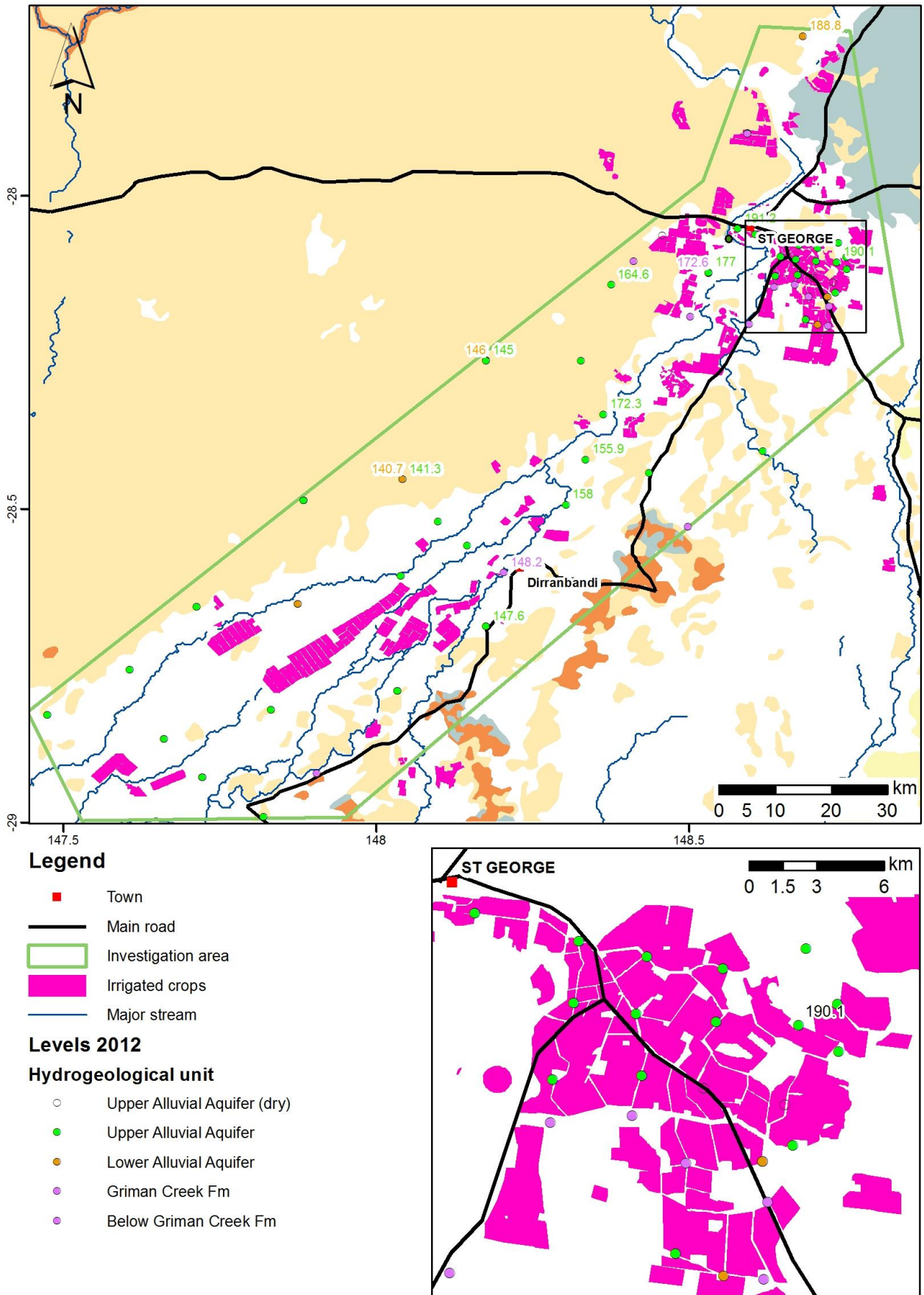
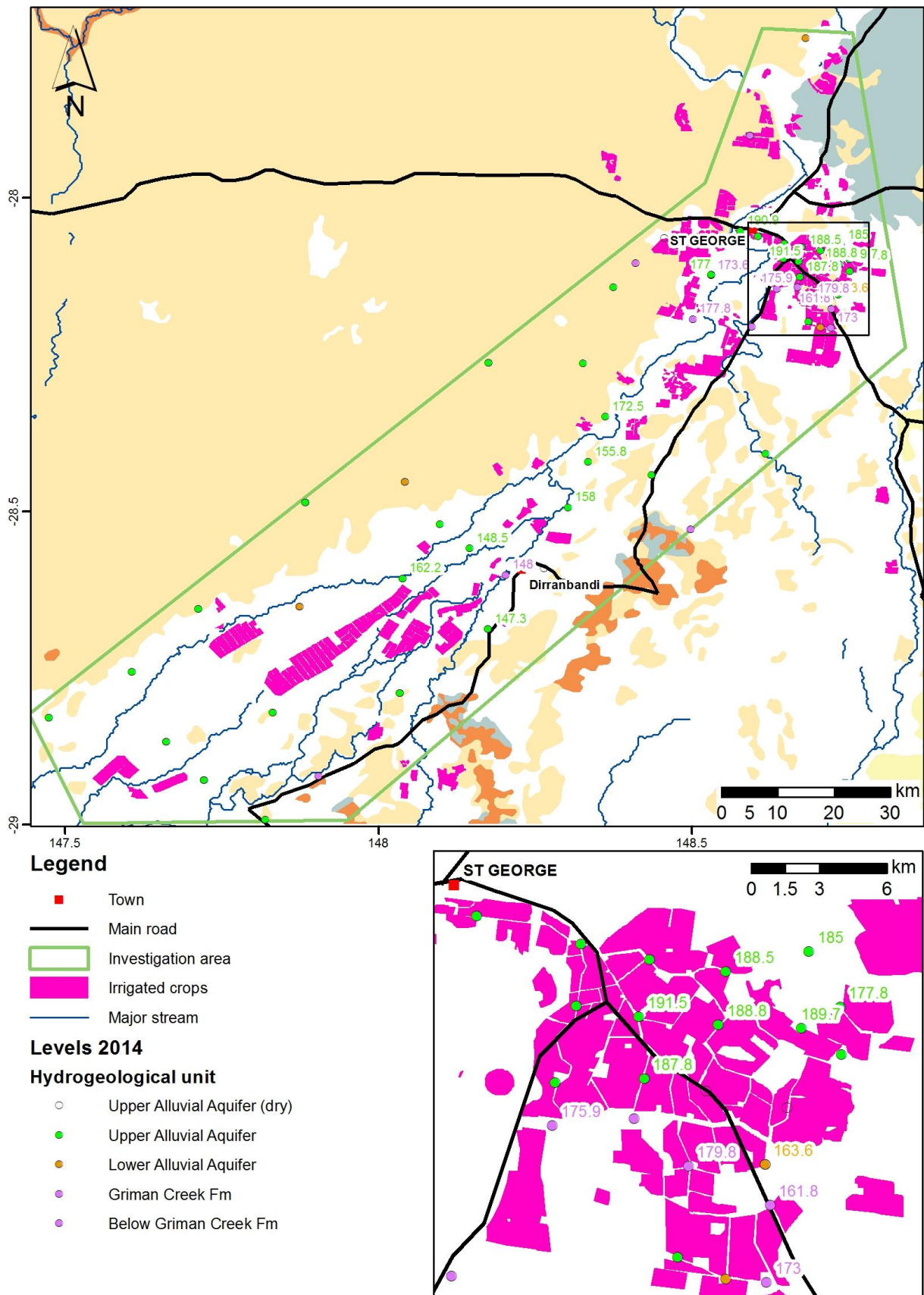


Figure 11: Groundwater levels – 2006









4.2.1 St George Irrigation area

The SGIA has 24 bores (Table 2), spatially spread in a grid structure (Figure 16). Most of these bores were monitored until 2006, and enabled changes in groundwater level to be traced under the irrigated zone (Pearce and Hansen, 2006). Nevertheless, currently only one bore is included in the DNRM monitoring net and overall, for the period 2010-2013 there are only scattered records of groundwater levels from 4 bores. During the field excursion, levels were measured in 13 bores in the SGIA. Trends, for the periods of 1978-1997, 1998-2006 and 2006-recent are collated in Table 2; current trends are shown in Figure 16.

Continuous data loggers ("*micro Diver*") were found on the field trip in nine bores in the SGIA. Enquiry with DNRM staff suggests that the data loggers have been installed in 2006 and have not been read since 2007.

Three bores (#0027, #0024, and #0030), which are located at the heart of the SGIA, show an on-going rise of groundwater levels. Of these, in two (#0027 and #0024) the long-term trend is similar to the current on-going rise of ~15 cm/yr. Bore #0030 shows on-going rise with different rates. In two other bores (#0020, #0023), 2014 groundwater levels were found to be higher than 2006-7 by 2.9 – 0.7 m, but no conclusive trend was observed. Bore #0020 was dry at least until 2002, while now it contains water. Three bores, at the eastern outskirts of the SGIA (#0025, #0053 and #0034) show rather stable levels. Of these, bore #0025 shows moderate on-going rise in the past with some fluctuations, however the current level resembles those of 2006. In one bore (#0032) the current groundwater level is apparently lower than 2006, but as this bore has demonstrated very high fluctuation in the past, this cannot lead to a conclusive remark.

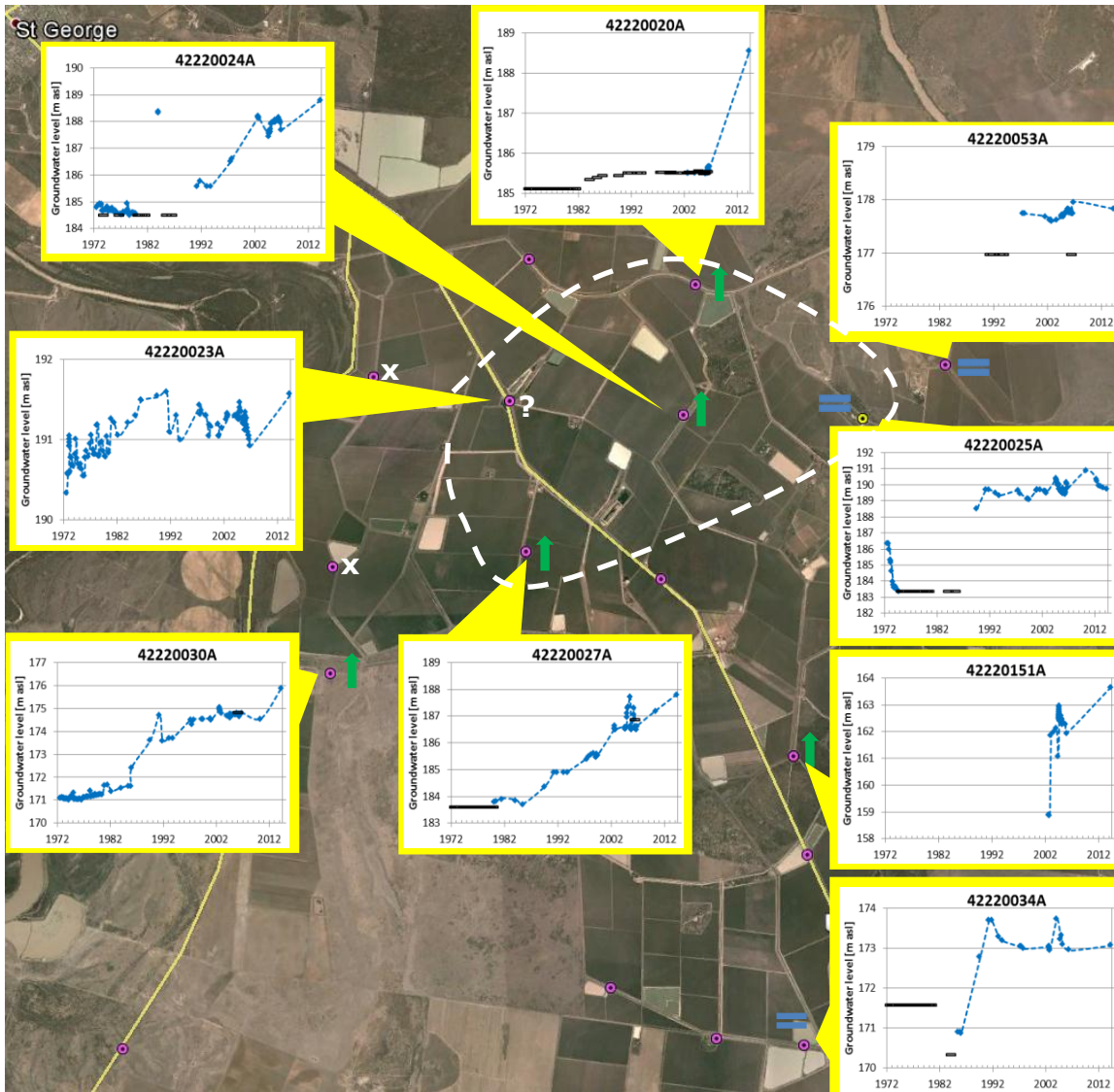
It should be noted that the groundwater depths in individual bores (#0020, #0023, #0024, #0025 and #0027) are less than 10 m below the ground surface elevation (~200 m asl); the area contained these bores is delimited by dash white line in Figure 16.

Table 2: Groundwater levels changes in bores of the SGIA

Rn	Aquifer ¹	First	Last	1978	-	1997	1998	-	2006	2007	-	2013/14
42220018	U	07/1972	12/2008	Dry			Dry; occasional limited water at the bottom			-		
42220019	U	07/1972	01/2007	Dry; occasional limited water at the bottom			Dry; occasional limited water at the bottom			-		
42220020	U	07/1972	05/2014	Dry			Dry; signs of rise during 2006			Rise of 2.9 m		
42220021	U	07/1972	12/2006	Dry			Dry			Dry		
42220022	U	08/1972	12/2006	Dry			Dry; signs of rise in 2004-2006			-		
42220023	U	08/1972	05/2014	Rise; ~5cm/yr up to 1992			Stable with mild fluctuations			Rise of 42 cm		
42220024	U	08/1972	05/2014	Rise; ~15cm/yr up to 1997			Stable with mild fluctuations			Rise of 75cm		
42220025	U	09/1972	05/2014	Dry up to 1985; Rise; 6m gap between '85 – '89			Rise; 7cm/yr			Stable with mild fluctuations		
42220026	U	08/1972	08/2006	Recover from a previous decline up to '81; Stable; 1m Rise in 1992			Stable 1993-2002 Fall? Last record of dry bore					
42220027	U	08/1972	05/2014	Rise; 15cm/yr between 1985-2002			Stable 2002-2006			Rise; 15cm/yr 2006-2014		
42220028	U	08/1972	12/2006	Dry			Dry			-		
42220029	U	08/1972	07/2011	Dry			Dry			Dry		
42220030	G	08/1972	05/2014	Rise; 3.5m			Stable			Stable up to 2010; Rise of 1.3 m		
42220031	G	08/1972	07/2011	Dry			Dry			Dry		
42220032	G	08/1972	05/2014	Dry up to 1985; Rise 170cm/yr 1985-1993			Rise 38cm/yr 1993-2006			Fall of 1 m		
42220033	G	08/1972	05/2014	Dry			Dry; occasional limited water at bottom			Dry		
42220034	G	08/1972	05/2014	Dry			Dry; occasional limited water at bottom			Stable		
42220053	U	05/1991	05/2014	Stable with mild fluctuations			Stable with mild fluctuations			Stable		
42220054	U	05/1991	12/2006	Rise; 17cm/yr			Rise; 48cm/yr up to 2004			-		
42220055	U	05/1991	12/2006	Dry			Dry			-		
42220063	U	02/1990	12/2006	Dry			Dry			-		
42220151	L	09/2002	05/2014	-			3m rise between 2002-2003; Stable			Rise of 1.7 m		
42220152	U	09/2002	05/2014	-			Dry			Dry		
42220209	L	02/2004	12/2006	-			Rise; 11 cm/yr			-		

Notes:

- 1) U = Upper Alluvial Aquifer; L= Lower Alluvial Aquifer G= Griman Creek Formation Aquifer
Bold – bores measured during this study.



Legend

Current trends

- Rise ↑
- Stable =
- Inconclusive ?
- Unavailable x

Bores symbol

- Current monitoring bore ●
- Past monitoring bore ●

Hydrographs symbol

- Reading —●—
- Dry =
- (and total depth)

Figure 16: Groundwater levels changes in the SGIA (1972-2014)

4.2.2 The central floodplain

In the area between St George – Bollon Rd. in the north, Dirranbandi – Bollon Rd. in the south and the Balonne River in the east, there are 19 monitoring bores; seven of which are included in the current DNRM monitoring scheme (Figure 17).

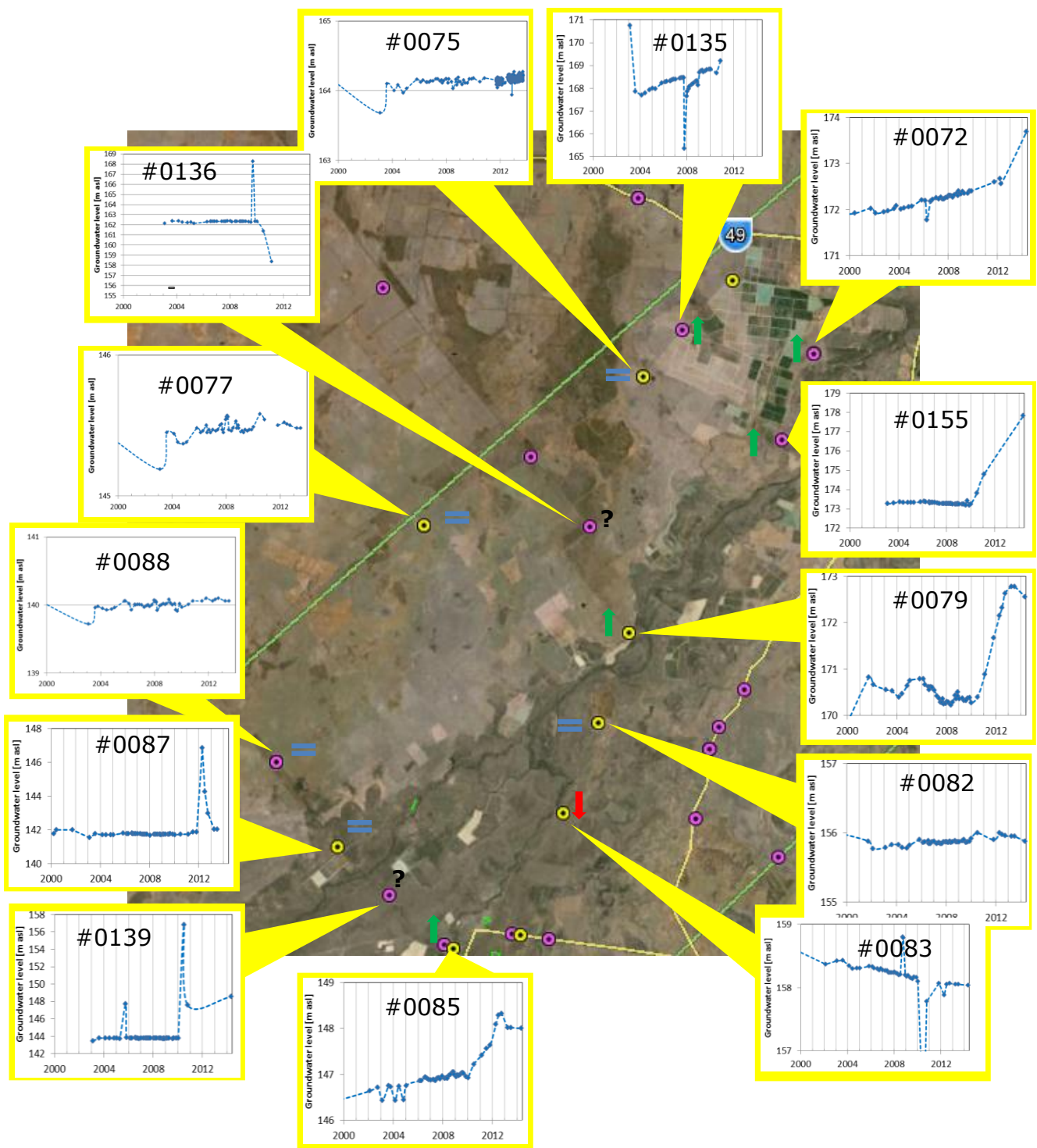
Two bores in the north show on-going trend of rising groundwater level since monitoring commenced: Bores #0072 and #0135, with rising rates of 3.5 cm/yr and 13.8 cm/yr, respectively. The recent level record of bore #0072 suggests that the 2012-2014 rising rate was even higher (55 cm/yr). These two bores are located near irrigation areas. Additionally, a rising rate of 5 cm/yr was recorded in bore #0085, which located south of Dirranbandi.

Bores #0155, #0079 and #0085, located relatively close to the main streams, show rising groundwater elevation since 2010. The linear 2010-2014 rising rate is 103 cm/yr, 87 cm/yr and 54 cm/yr respectively. The bore locations, the timing of the rising trends and the high rising rates, suggest that these hydrographs should be interpreted in the context of streambed recharge, as explained below.

Five bores, located beyond and within the floodplain, show stable groundwater levels over 8-12 years. In turn, this suggests rather steady hydrological conditions (i.e., water balance) in the aquifer.

Two bores (#0139 and #0087), located in the floodplain, demonstrate 1-2 upward peaks with a temporal rise of 4-13 m followed by full-partial recessions to previous levels. Recent measurement of bore #0139 shows that its total depth is less than the depth of the casing, suggesting poor interconnectivity with the aquifer. The latter measurement and its location in the floodplain, support the hypothesis that this bore was filled from its top by flood water- perhaps several times since its erection (e.g. 2005 and 2010), and clogged by the fine sediments which were suspended in the water. In this context, the 2014 measure should be interpreted as a response to a recent flooding event, independent from the event which occurred in 2010. The same conclusion can be made for bore #0087, with the exception that the flooding event of this bore happened in 2012.

One bore (#0083) shows falling groundwater levels for the past decade, with a rate of -3.5 cm/yr. This trend was not captured in other bores in the study area and should be further addressed. It should be note that the absolute levels in this bore are higher than expected, considering the general hydraulic gradient trend in the area.



Legend

Current trends

- Rise
- Stable
- Fall
- Inconclusive

Bores symbol

- Current monitoring bore
- Past monitoring bore

Hydrographs symbol

- Reading
- Dry
- (and total depth)

Figure 17: Groundwater levels changes in the central portion of the studied area (2000-2014)

4.2.3 The southern floodplain

In the area south of Dirranbandi – Bollon Rd. there are 29 monitoring bores nested in 13 sites; only one (#0086) is included in the current DNRM monitoring scheme (Figure 18). The others were monitored from 2003 until 2008-2010 and current trends are thus unknown.

Generally, the hydrographs show rather stable groundwater elevations, with mild seasonal fluctuations. This conclusion however should be considered subject to the infrequent measurements and to the overall short monitoring period. It seems that the 2014 high groundwater level in bore #0173 should be considered in the framework of flooded bores as mentioned above for bores #0087 and #0139. Similarly, bore #0086 hydrograph can be interpreted as induced streambed recharge.

4.3 Streambed recharge

4.3.1 Spatial considerations

Some of the previous studies assumed that one of the recharge sources in the study area is the fluvial system of the Balonne River (Pearce et al., 2006). Indeed, streambed elevations are found at least 10 m above the water table elevation, hence may be considered as a potential recharge source. However, a substantial streambed recharge should lead to a 'Divergence' pattern of groundwater level contours near the contributing rivers (Figure 19c). Along the Balonne River, this pattern is seen only between St George and bore #0079 (Figure 5). Along the other sections, groundwater level contours seem to be perpendicular to the rivers channels, indicating no hydraulic connection between the river and the aquifers (Figure 19a).



Legend

Current trends

Inconclusive ?

Unknown ?

Bores symbol

Current monitoring bore ●

Past monitoring bore ●

Hydrographs symbol

Reading —●—

Dry =

(and total depth)

Figure 18: Groundwater levels changes in the southern portion of the studied area (2000-2014)

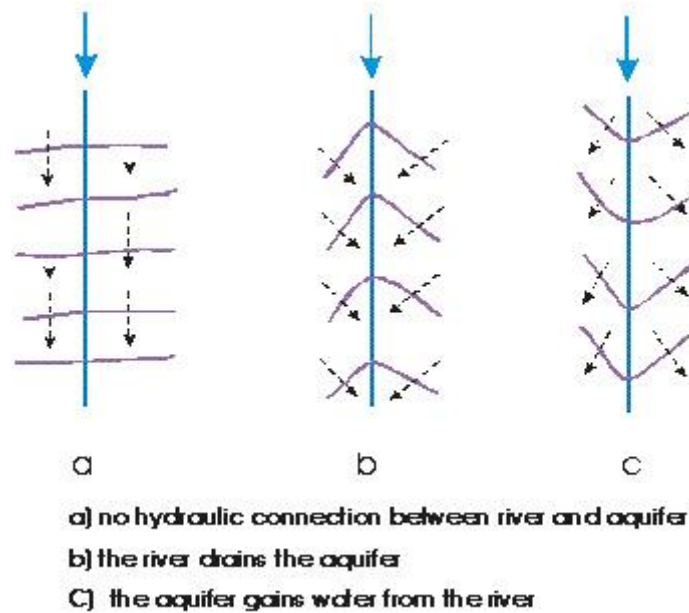


Figure 19: Schematic groundwater level contour lines under three cases of hydraulic connection between aquifer and river

Soils distribution may provide an explanation for the above pattern: The soils along the upper section (St George – bore #0079) are typified by Sodosols while those along the downstream section are typified by Vertisols (Figure 6). When eroded and transported, Sodosols may provide sandy sediments which, in turn, accumulate on the streambed; these sediments are considered more permeable than the clayey products of Vertisols hence it is reasonable to assume that the surface water leakages are higher along the upper section.

4.3.2 Temporal considerations

Typically, streambed recharge rates increase at high flood periods, as the depth of the water in the stream (and its width) increases and due to scouring of the streambed in high flows. However, it may or may not have an immediate effect on the groundwater table elevation, in accordance with the timescales and storage capacity of the vadose zone (i.e., porosity, hydraulic conductivity and the depth of the water table).

In the study area there is some evidence that suggests the mechanism of induced recharge during periods of high stream flow or large floods occurs in two sections:

1) Downstream of St George (Figure 20):

Bore #0079 hydrograph shows a 3 m rise in groundwater level in the period 2010-2013, in chorus with the substantial increase of the discharge of the Balonne River (i.e., the recent severe floods of Mar-2010, Jan-Feb-2011 and Mar-2012). A mild decrease in the head occurred in the hydrological year 2013/2014 in association with lower discharge in the river. It is reasonable to assume that this rise is due to the streambed recharge. The 5 m groundwater level rise in bore #0155, in the same period can also be attributed to this effect as reconstructed in the grey curve.

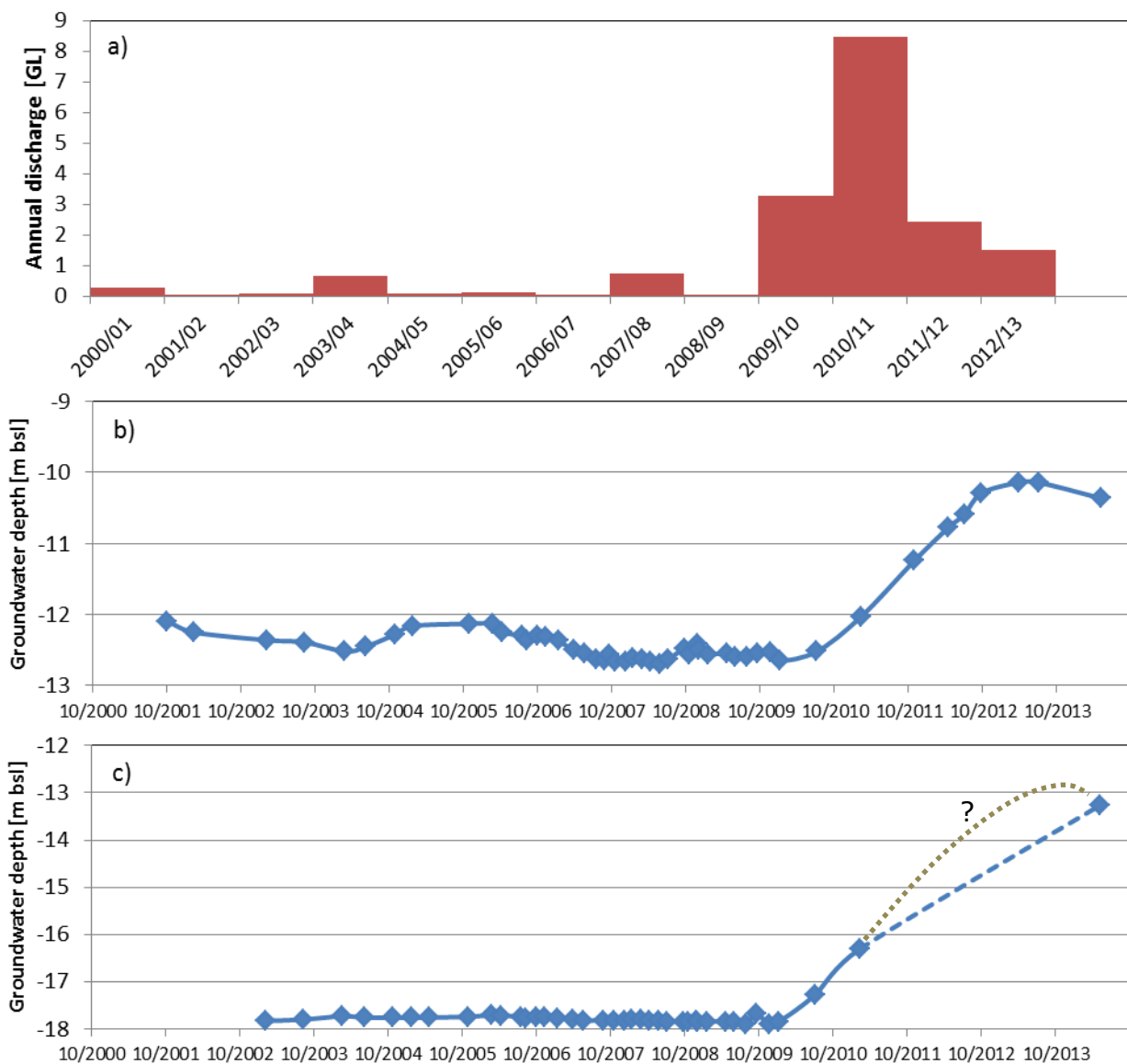


Figure 20: Annual stream discharge near St George (station #422201) (a) and groundwater depth at bore #0079 (b) and #0155 (c).

2) Downstream of Dirranbandi (Figure 21):

Bore #0085 hydrograph demonstrates a 1.7 m rise in groundwater level in the period 2010-2012, in chorus with the substantial increase of the discharge of the Balonne River (i.e., the recent extreme floods of Mar-2010, Jan-Feb-2011 and Mar-2012). A mild decrease in the head occurred in the hydrological year 2012/2013 in association with lower discharge in the river. Again, it is reasonable to assume that this rise is due to recharge from the streambed. The 1 m groundwater level rise in bore #0086 (relative to the 2006 level), can also be attributed to this effect, as reconstructed in the grey curve.

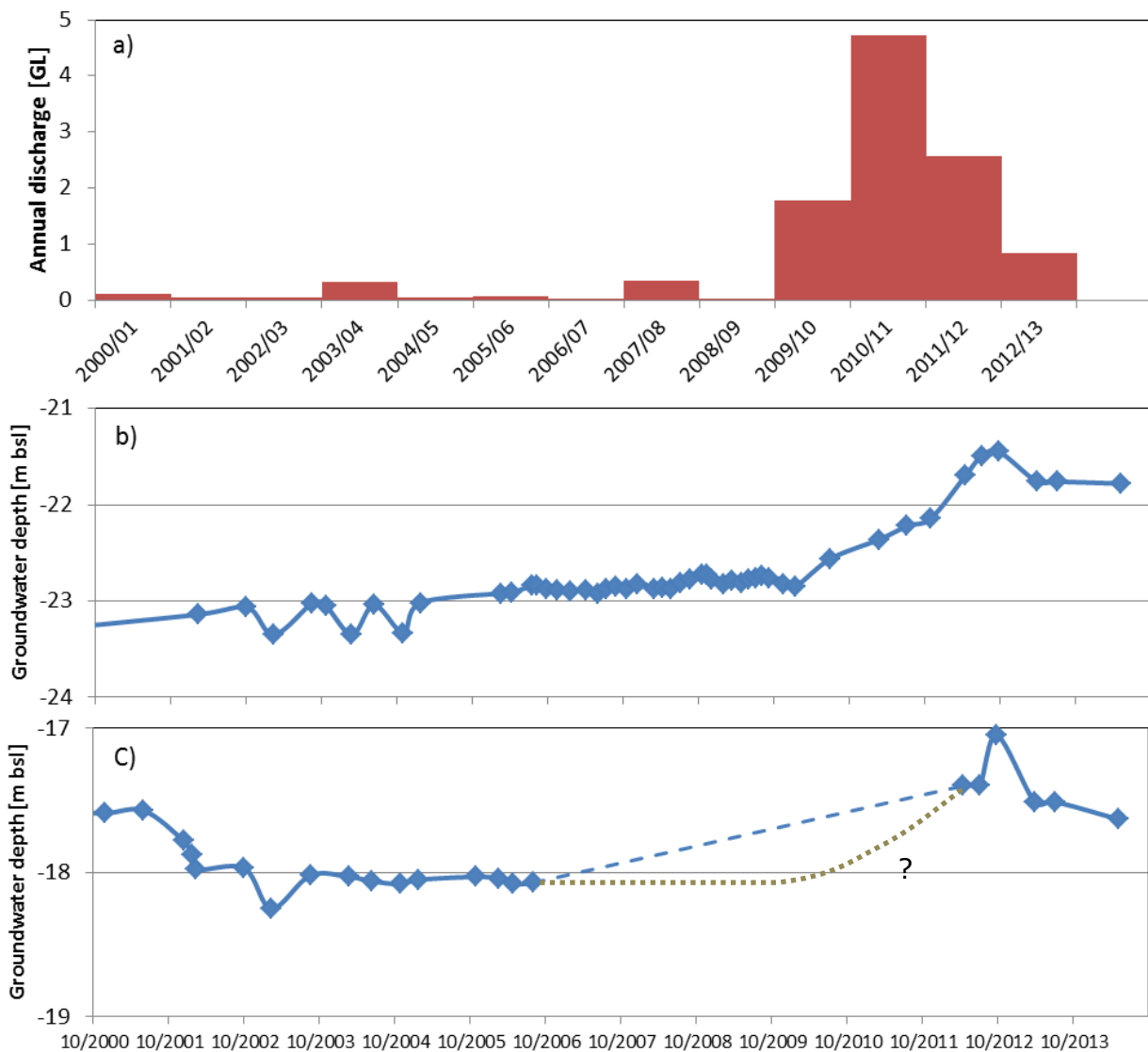


Figure 21: Annual stream discharge near the braiding point (station #422205) (a) and groundwater depth at bore #0085 (b) and #0086 (c).

It is worth noting that the nearby bores #0082 and #0083, which both penetrated the upper alluvial aquifer, did not show any temporal changes in the groundwater levels corresponding to the flood events.

4.3.3 Summary

In agreement with previous literature, it is concluded that streambed recharge is a localised recharge source for the upper alluvial aquifer; it occurs in places where channels incise light texture soils, and affect bores located in the vicinity to the major streams. Evidence suggests that streambed recharge is induced by high flow in the rivers; however, this hypothesis needs further investigation and quantification. The total volume of recharge from streams relative to diffuse recharge is unknown, though one source indicates an average of 8 KL / m stream during a single event. Continuous or frequent long-term monitoring is recommended in order to identify recharge patterns.

4.4 Deep-drainage under the irrigated areas

Another important recharge source is deep-drainage under irrigated areas (Silburn et al., 2013). Where deep-drainage exceeds the subsurface hydraulic transmissivity, a groundwater mound may develop. In the study area, results suggest that the previously-identified groundwater 'mound' under the SGIA (Pearce and Hansen, 2006) is still rising. The long-term average rate of groundwater rise, as calculated for bores #0024 and #0027 is ~150 mm/yr (all units in this section are in mm/yr to help with interpretation). Recent measurements (bores #0020 and #0151) show that it may reach higher rates of 200-380 mm/yr. Assuming a vadose zone porosity of 30%, these rates of rise are equivalent to deep drainage rates of 45-114 mm/yr. This range resembles previous estimation of deep-drainage rates from furrow irrigated cotton in this region (68-90 mm/yr; Pearce et al. (2006)) and the overall range of deep-drainage under furrow irrigated cotton in Australia (50-100 mm/yr; (Silburn et al., 2013)). Groundwater depth under this area varies between -20 m to -5 m. Mitigation of deep drainage losses may be required in those parts where current groundwater depths are relatively shallow (for example, -5.2 m at bore #0025); continuous and extensive program for monitoring these shallow groundwater levels is recommended.

Deep drainage is also assumed to occur in the irrigated area ~10 km to the west of St George. Using the above assumptions, observed rising groundwater levels rates of 50-138 mm/yr (bores #0072 and #0135) are equivalent to deep drainage of 15-41 mm/yr. Groundwater depth in this area is -18 to -13 m.

At the moment, there are no available data from bores around Cubbie Station to support, reject or estimate rates of deep-drainage there.

4.5 Flooded bores

The upward spikes in the hydrographs of bores #0087 and #0139, located in the floodplain, may be interpreted as an artificial effect due to bores flooding and clogging. A reasonable scenario for such clogging would be when low permeability fluvial sediments, which entered the bore from the surface in a period of flooding, settle inside the casing and now serve as a hydraulic barrier between the water column in the bore and the water table in the aquifer. The involved fluxes and pressures can be represented in the following rudimentary analytical equations:

$$2) \quad q_t = \frac{\Delta h_t}{\Delta l} * K = \frac{(h_{aq,t} - h_{in,t})}{\Delta l} * K$$

$$3) \quad Q_t = q_t * \Delta t * A = q_t * \Delta t * \pi r^2$$

$$4) \quad h_{in,t+1} = h_{in,t} - \frac{Q_t}{\pi r^2}$$

where q_t is the Darcian flux (positive in the outward direction) in a given time (t), Δh is the difference in head between the water column in the pipe and the head in the aquifer, K is the hydraulic conductivity of the accumulated sediments, Δl is the thickness of the accumulated sediments, r is the casing radius, h_{in} is the head inside the bore, Q_t is the Darcian discharge in a given time period and A is the cross-section area.

For the purpose of the exercise, it was assumed that the groundwater table in the aquifer rises sharply following a recharge event and recedes slowly according to equation 5:

$$5) \quad h_{aq,t} = h_{aq,0} - \alpha (t - t_0)$$

where t_0 is the flood date, $h_{aq,0}$ is the head immediately following the flood, $h_{aq,t}$ is the head at day t following the flood, and α is an empirical linear coefficient to describe the head recession in the aquifer.

Furthermore, it was assumed that the maximum head during the flood was equal to the surface elevation, and the clogging sediments section was 5 m thick. Accumulation of such sediments is believed to be the reason for reducing the total depth of bore #0139 by ~6.2 m (bore #0087 was not measured in the field excursion). Fitting was done by changing t_0 , α , h_0 and K to achieve the best match with the measured data.

For both bores, best fitting was achieved (Figure 22) when α is set to 0.0035 m/yr, and K to $4 \pm 0.1 \text{ e}^{-2} \text{ m/d}$. The latter value is in the range of hydraulic conductivities of silt sediments.

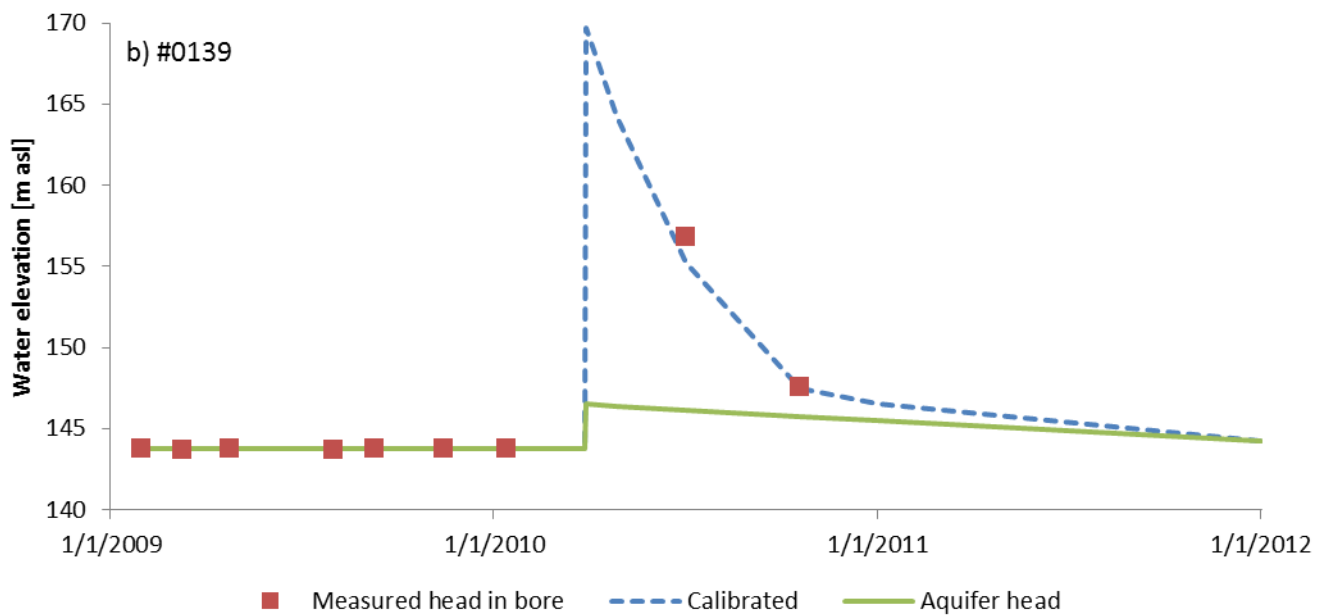
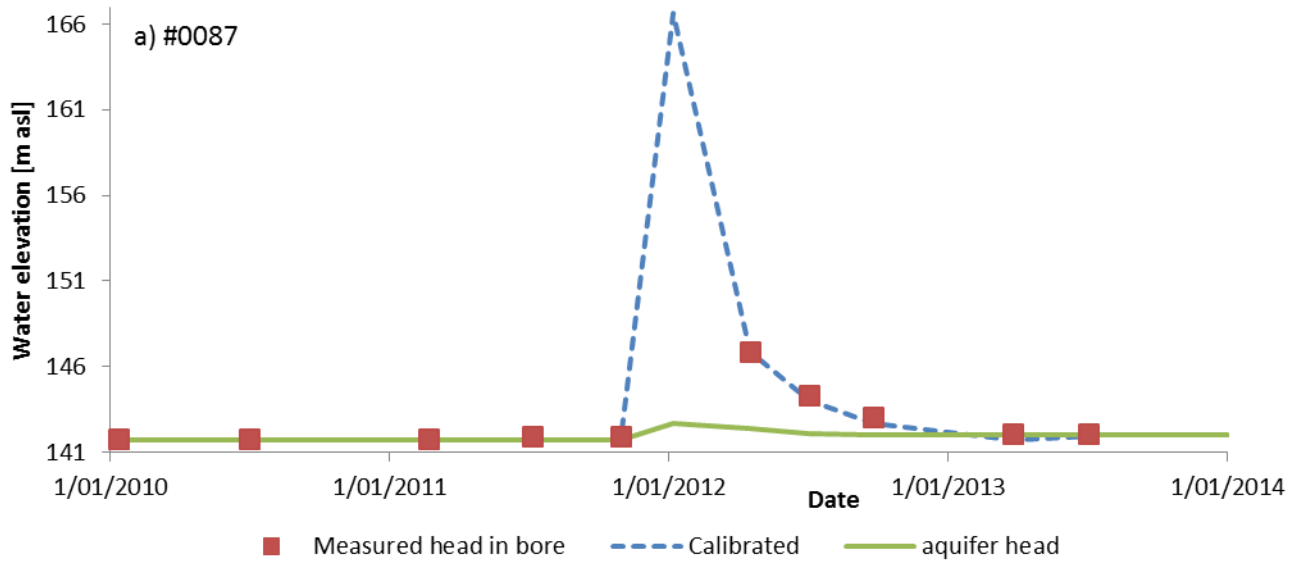


Figure 22: Measure and reconstructed heads (a) in bore #0087 for the period 2010-2014, and (b) in bore #0139 for the period 2009-2012

Similar analysis can be carried out for other bores and may assist in identifying clogged bores. Frequent monitoring is recommended to understand this effect; changes in the total depth are an obvious indication of accumulation of sediments inside the casing. Regardless, clogged bores can be cleaned and restored by a relatively simple procedure.

5 Summary

The current report reviews the on-going trends and current changes of groundwater levels in the lower Balonne catchment based on the existing database and newly collected field data. Lack of information in many of the bores hinders conclusive remarks to be made. Nevertheless, the following can be summarized:

- Groundwater at the northern and southern outskirts of the floodplain has remained relatively static, reflecting no association with temporal changes in possible recharge sources (rain, seasonal irrigation and river flow).
- The previously identified groundwater mound under the SGIA is continuing to accumulate, at a rate in the order of 10-40 cm per year.
- The estimated deep drainage rate under the SGIA is in the order of 45-120 mm per year.
- Deep drainage probably also occurs under the irrigated area west of St George (Kia Ora and surrounding farms), at rates similar to the SGIA area.
- Substantial streambed recharge is probably limited to areas where the stream incises lighter textured soils, e.g., Sodosols.
- Evidence suggests that the groundwater recharge from the streambed was induced during high flow periods along two sections of the rivers- south of St George and near Dirranbandi.

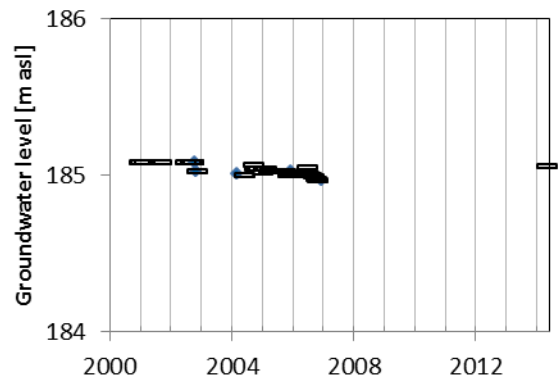
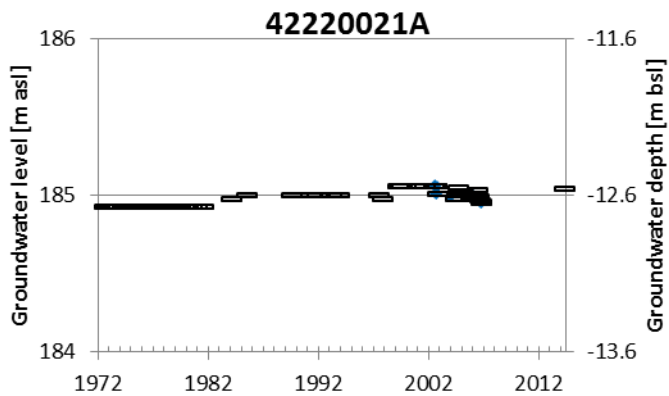
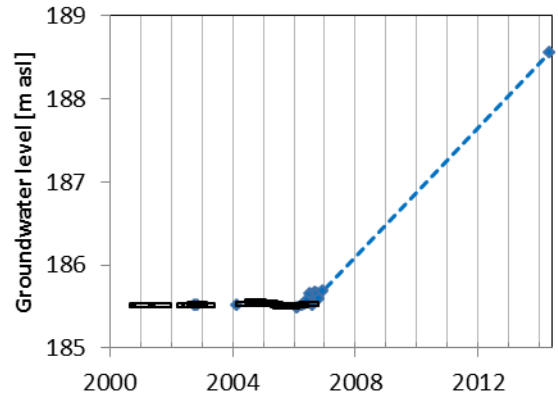
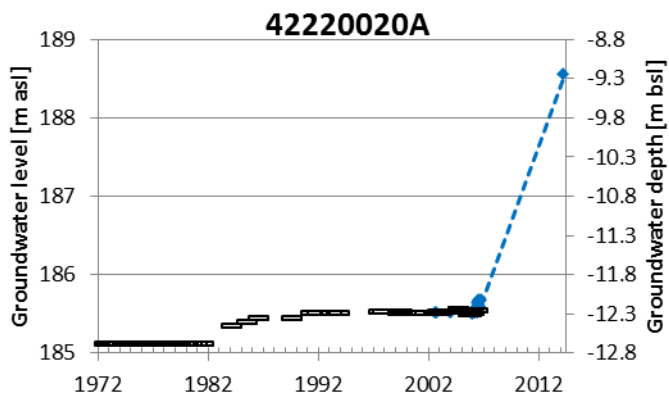
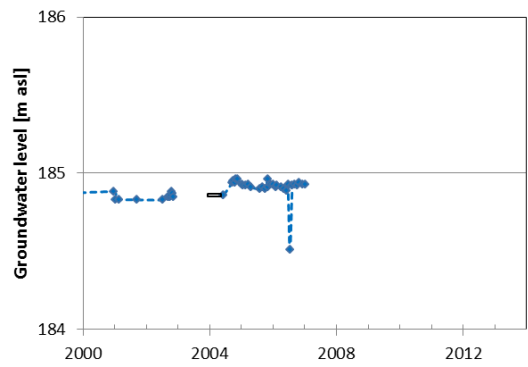
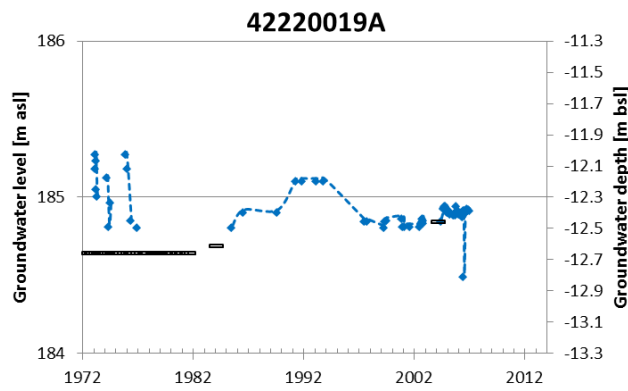
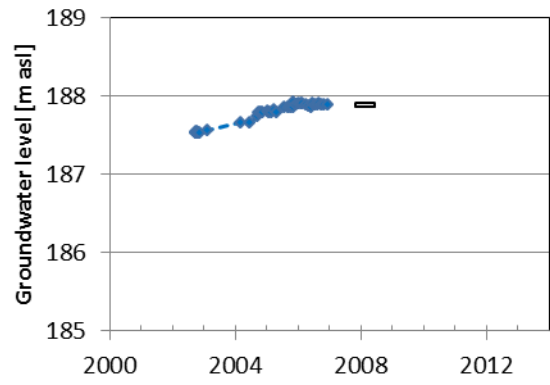
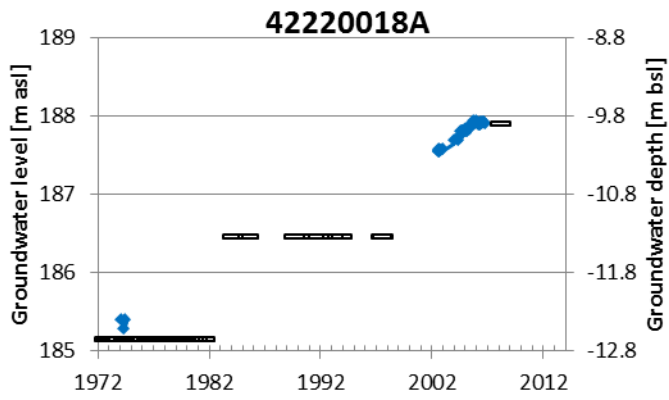
It is strongly recommended to monitor the existing bores more frequently, to retrieve and use the data of the continuous data loggers and to drill new monitoring bores in the irrigated area west of St George. It is also possible to clean the silted existing bores in the floodplain, downstream from the braiding point.

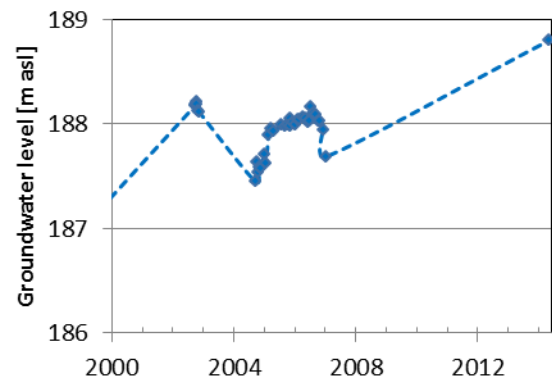
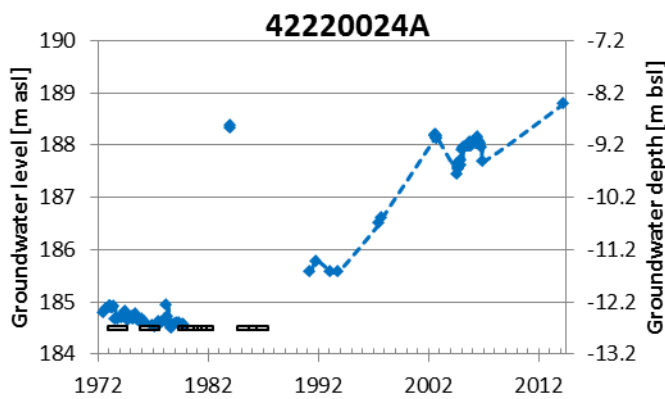
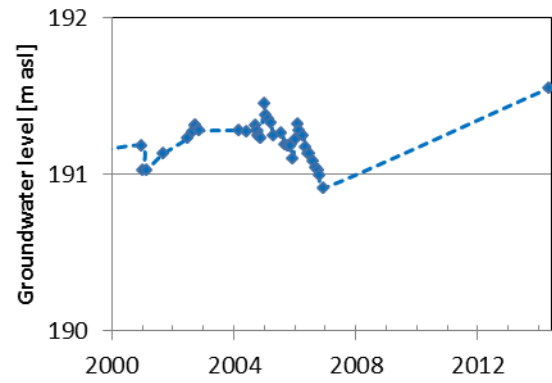
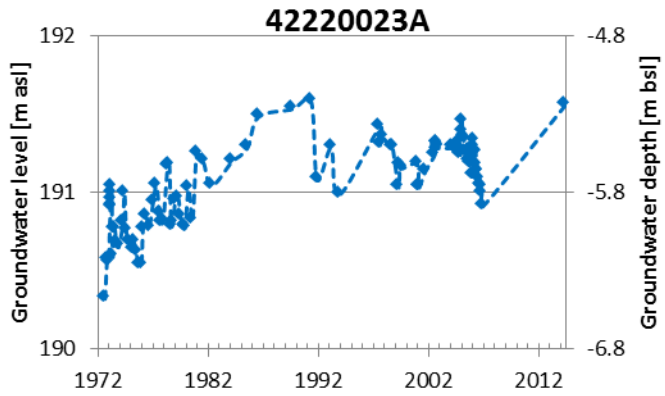
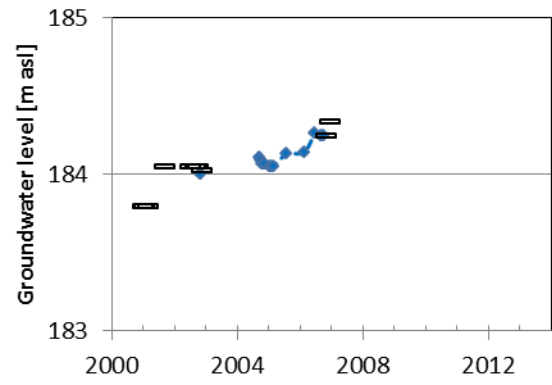
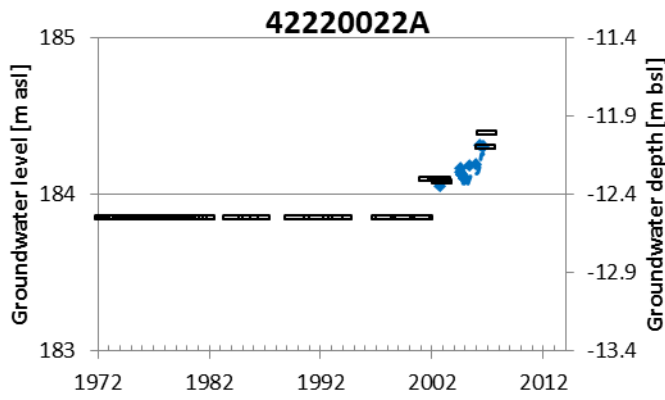
6 Reference

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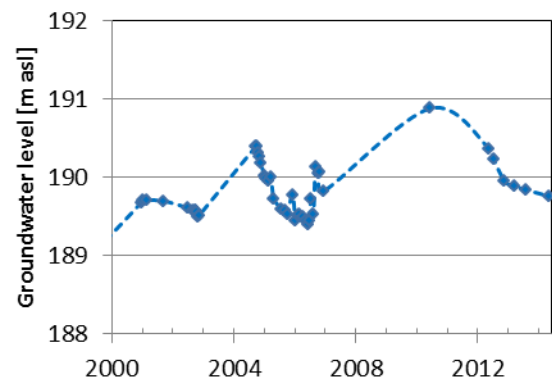
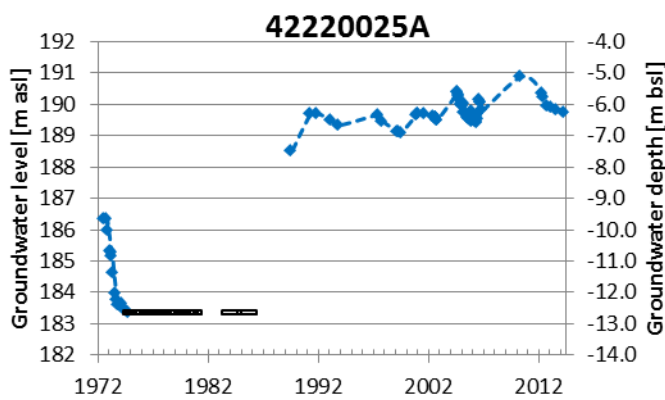
Appendix A - Bore hydrographs

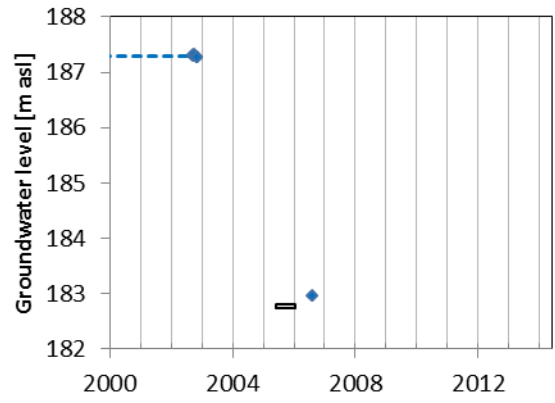
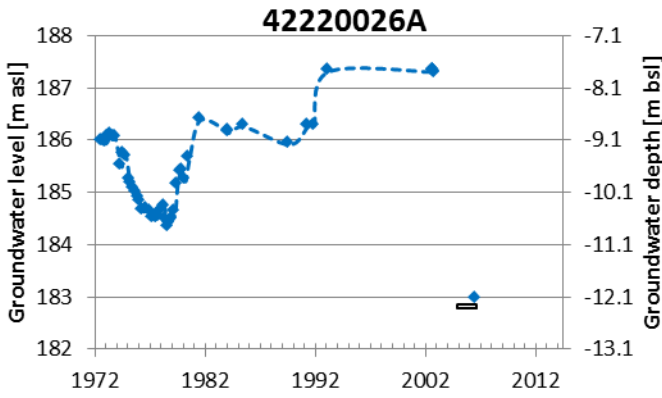
- The following graphs are hydrographs of bores within the study area. In each row, the left graph presents groundwater level and depth below the reference point (match) for the years 1972-2014 data, while the right graph presents 2000-2014 groundwater levels.
- The vertical scales of the graphs are varied according to represented range.
- Black marks represent incidents in which bores have been found dry, and the total depth of the bore at the same date (instead of groundwater level).
- Exceptional or anomalous historical records are remarked at the bottom of some graphs.



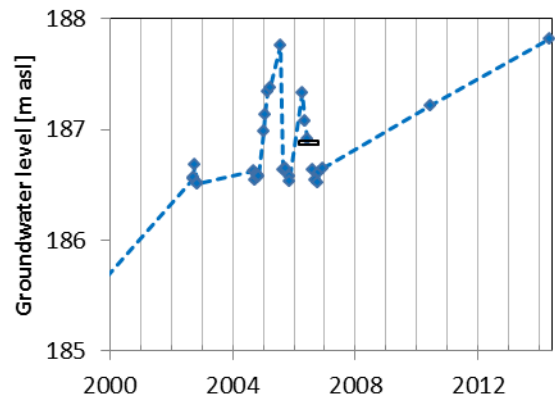
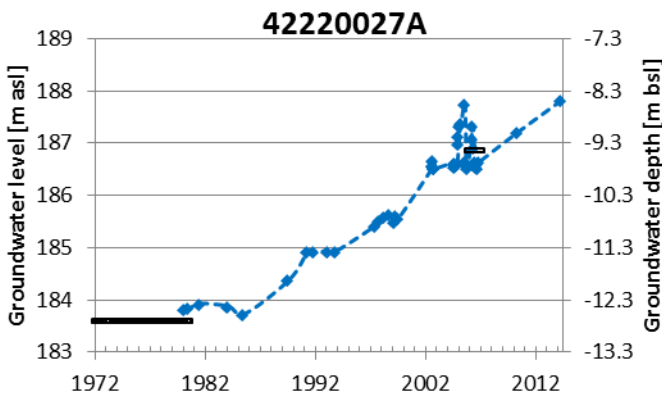


10/2/1984- erroneous reading ?

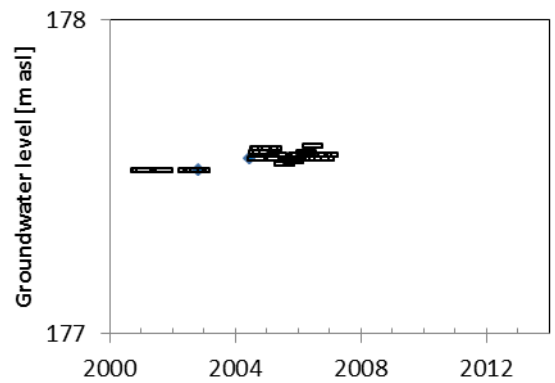
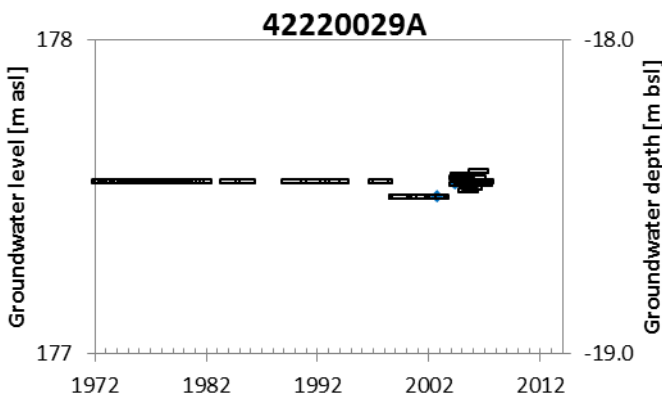
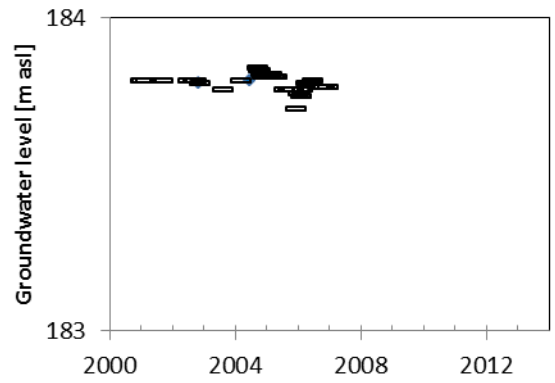
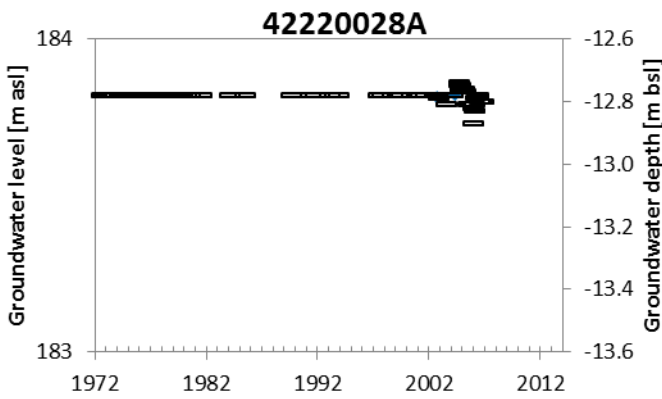


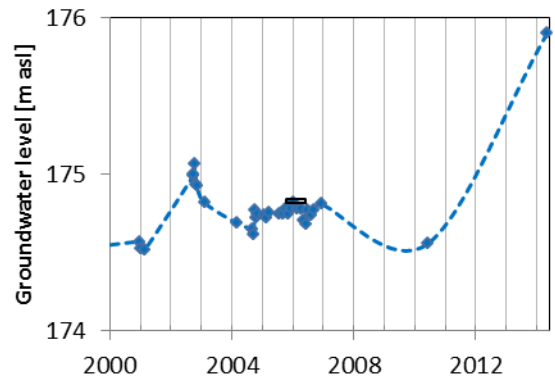
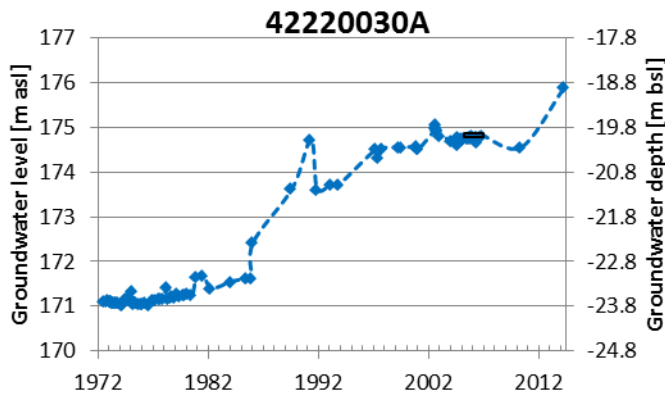


Jun 2006 – erroneous dry reading ?

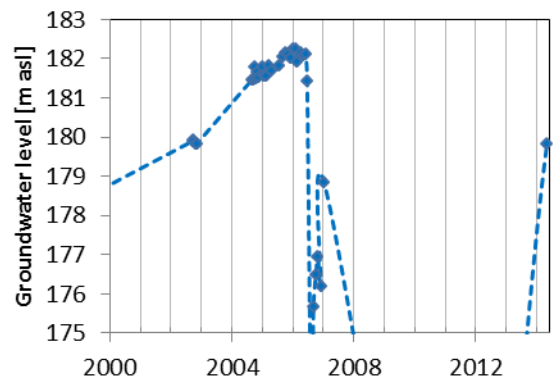
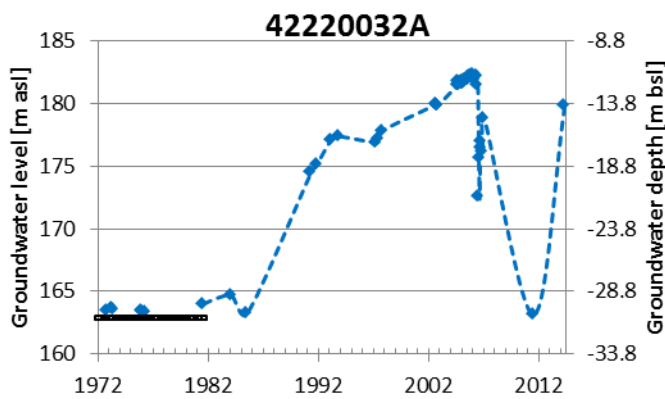


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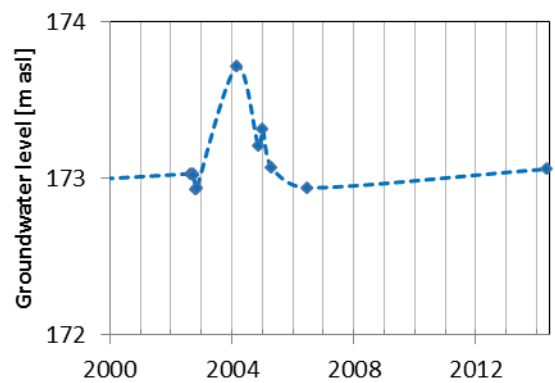
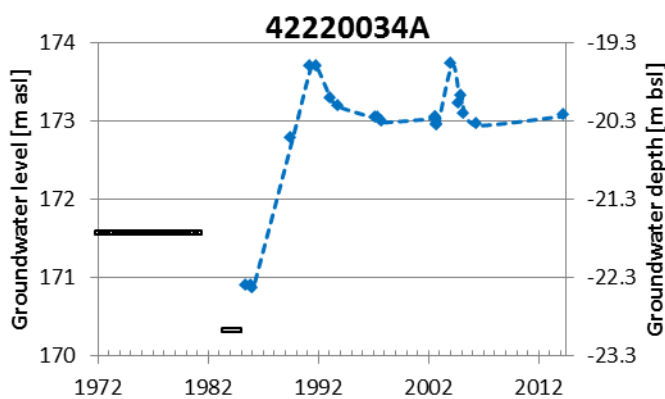
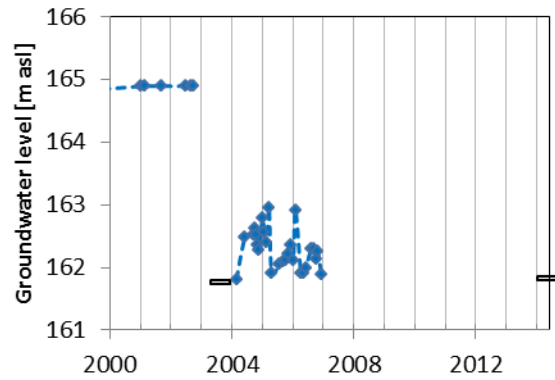
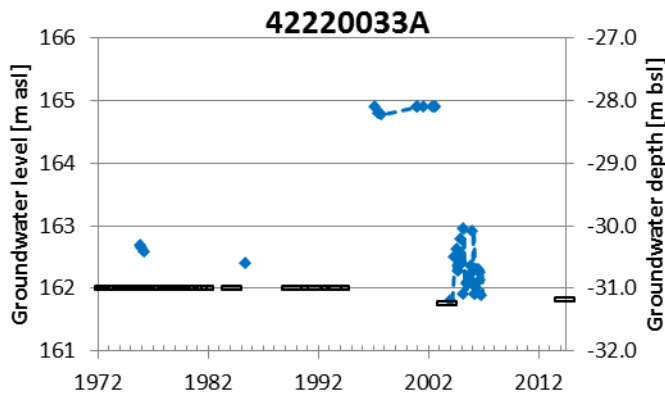


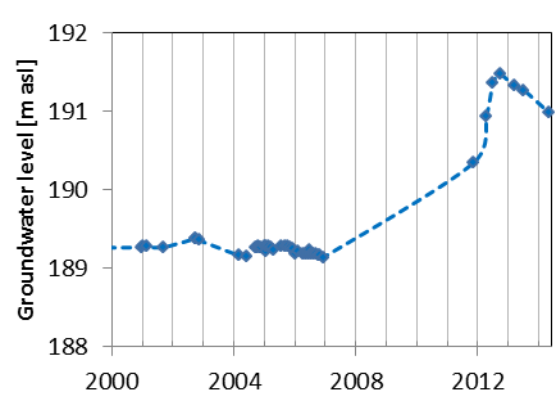
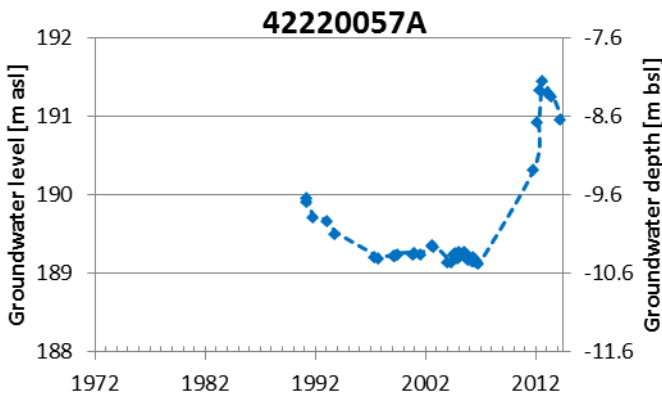
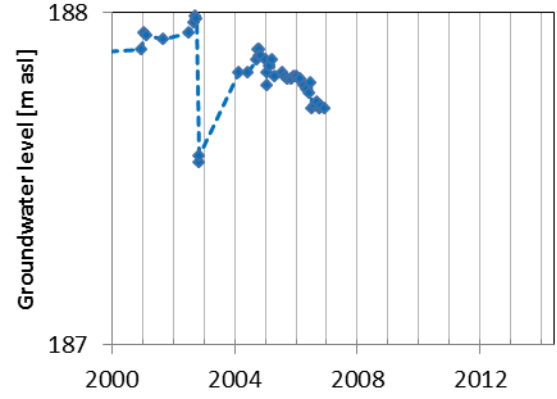
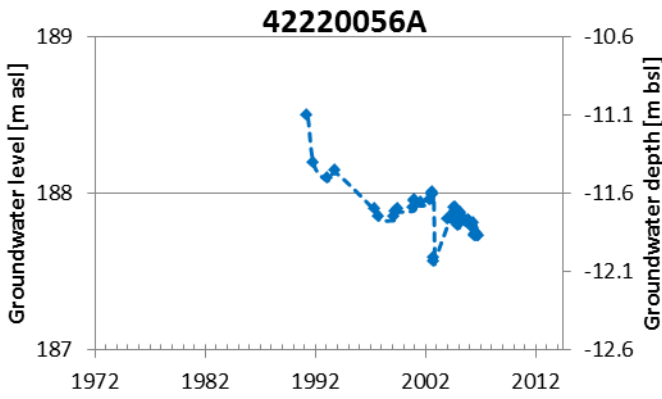
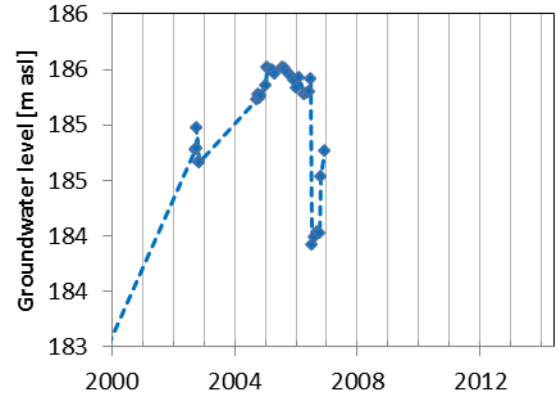
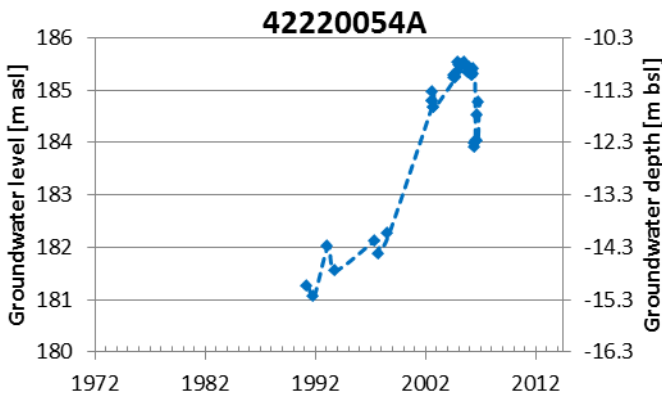
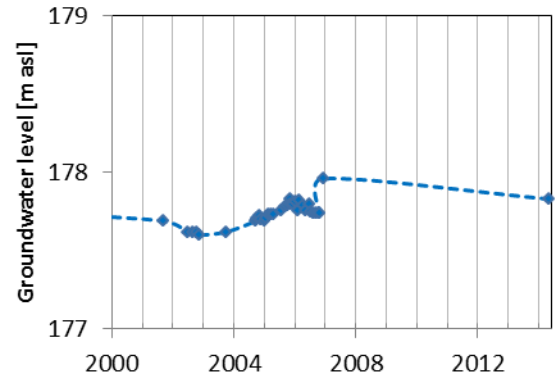
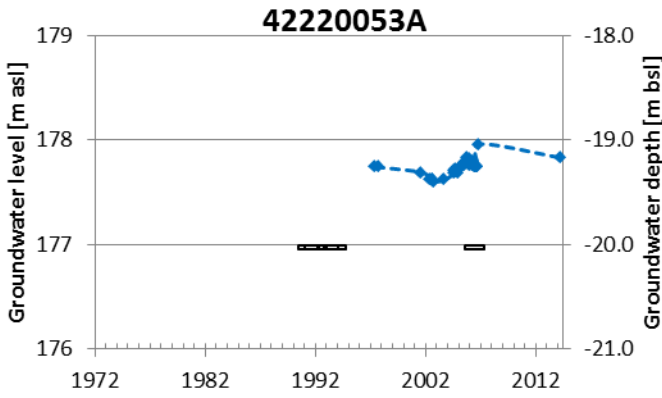


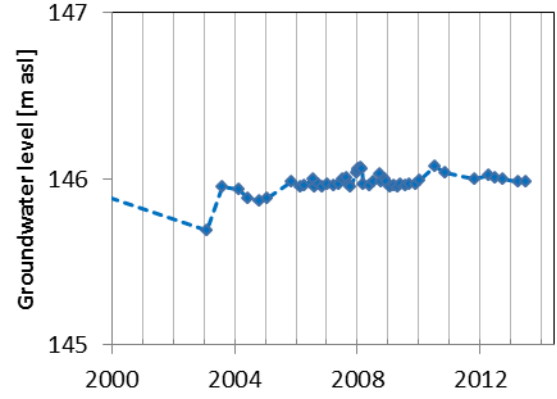
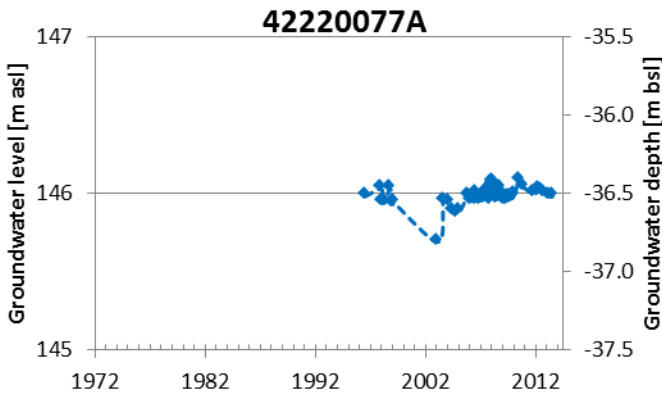
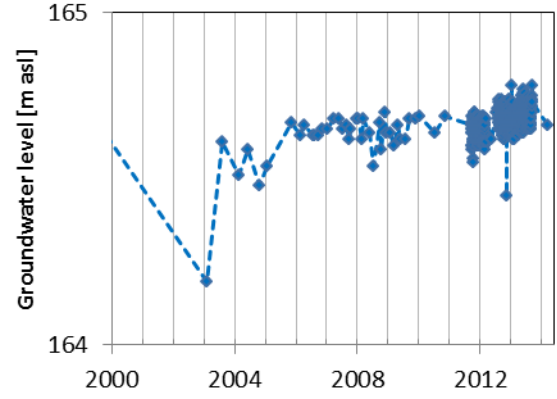
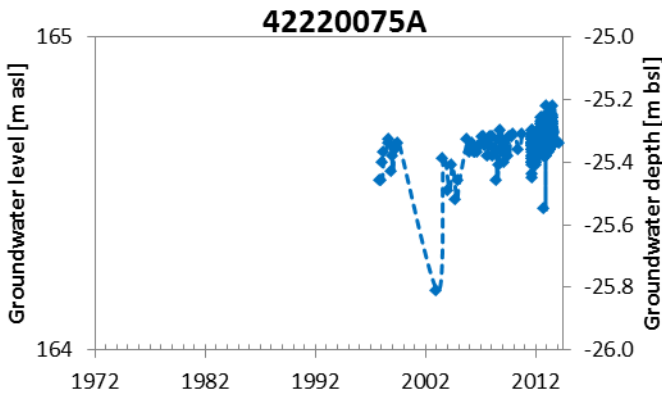
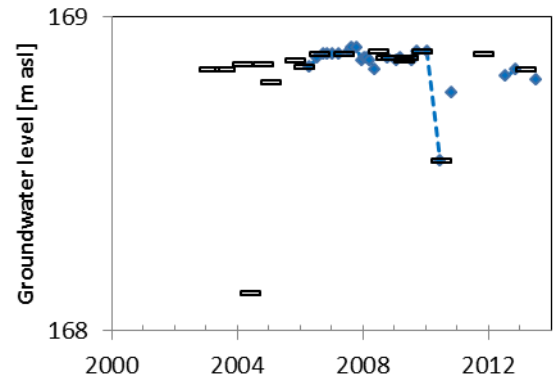
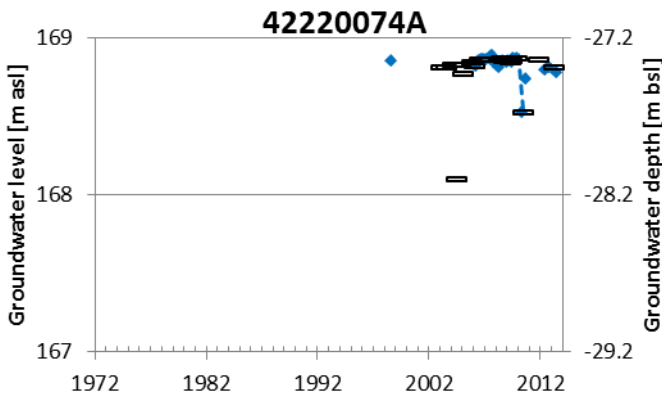
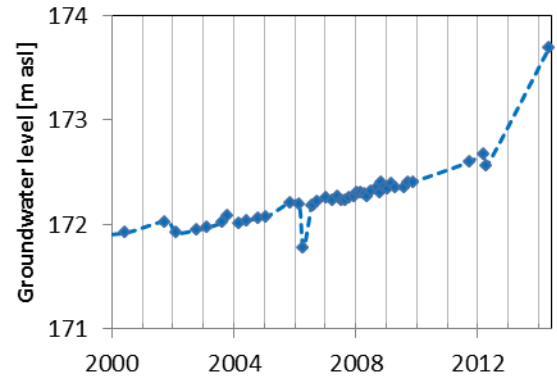
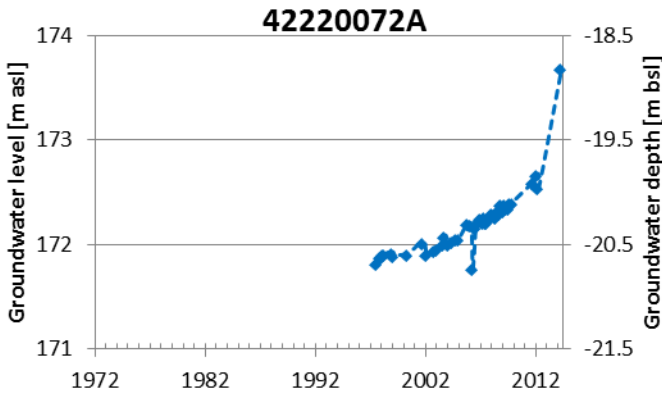
Jun 2006 – erroneous dry reading ?

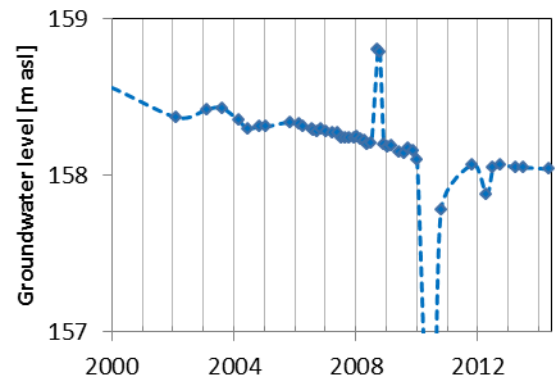
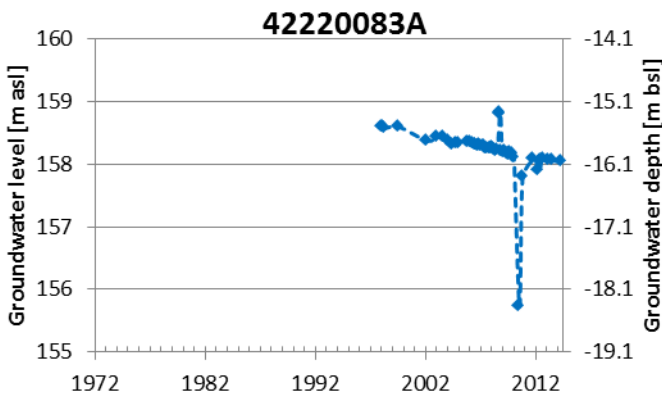
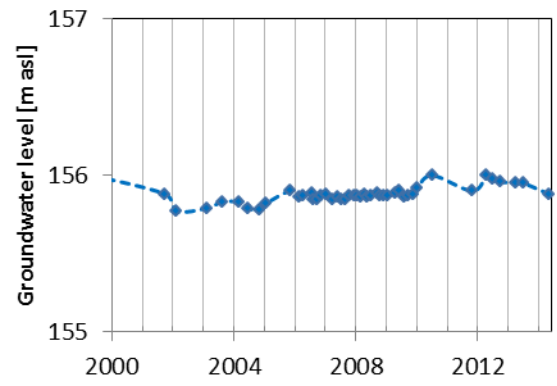
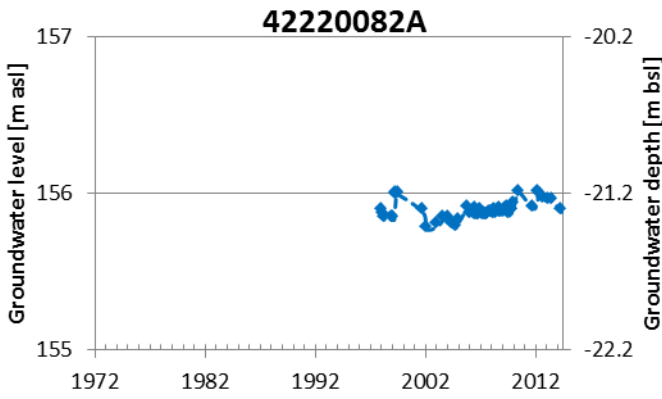
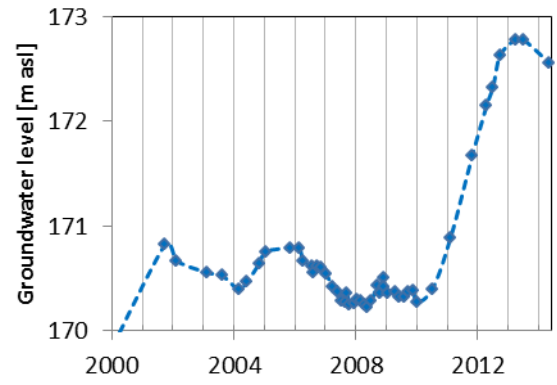
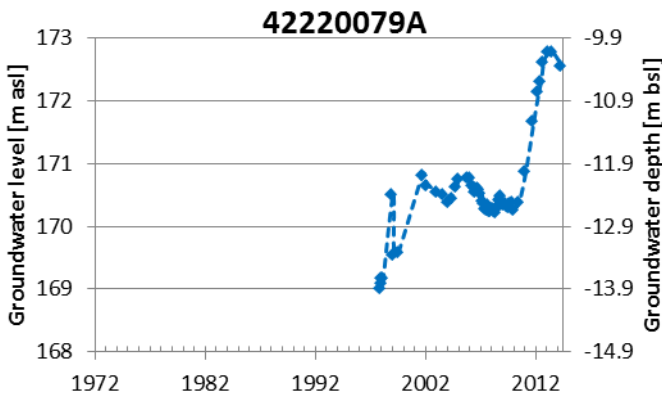
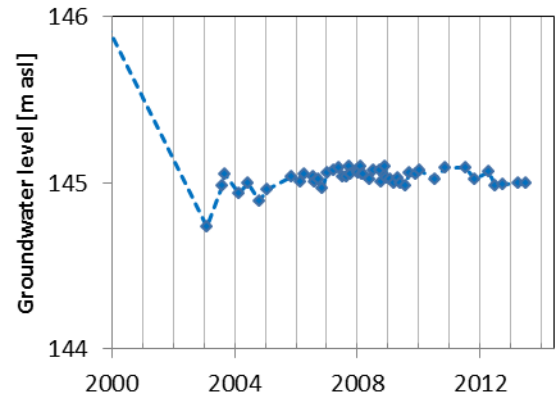
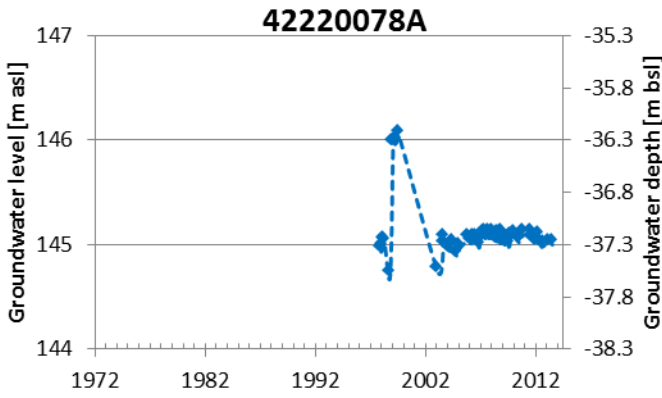


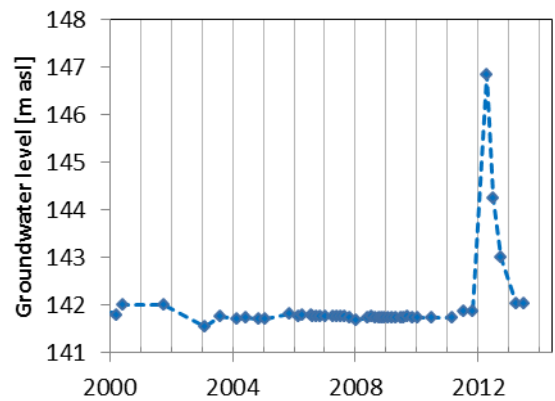
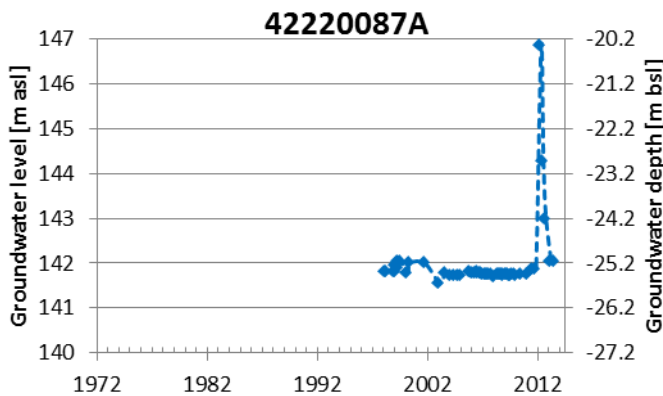
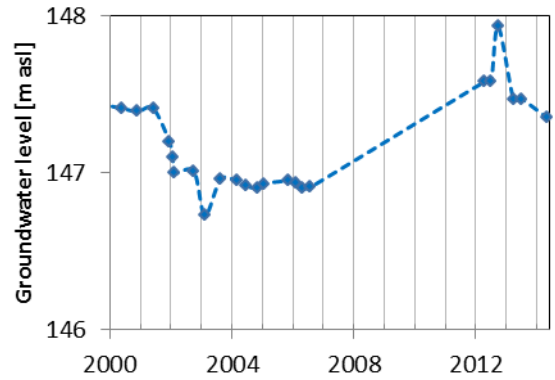
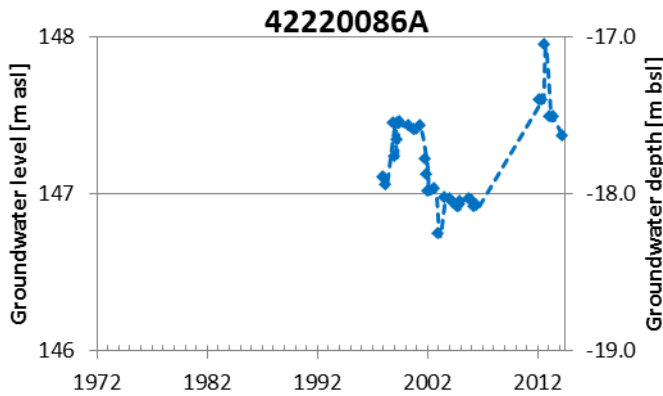
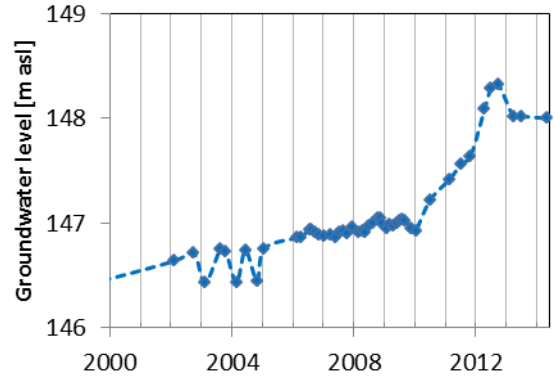
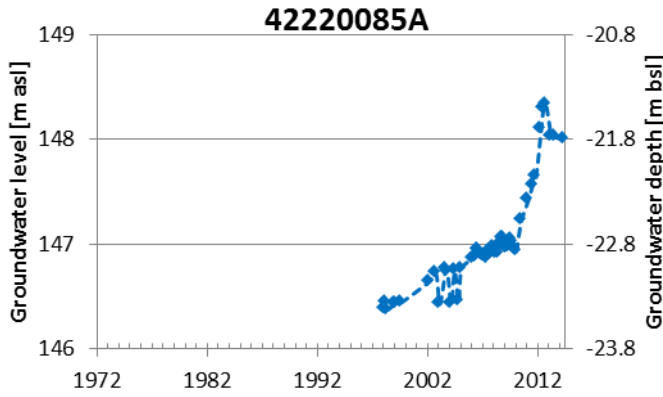
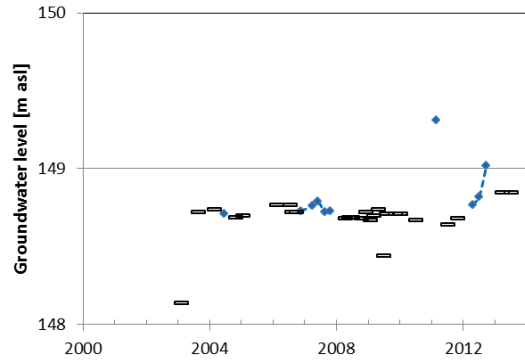
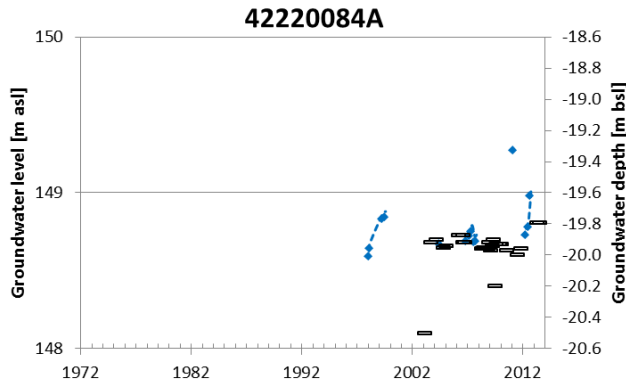
8/7/2011 – erroneous reading ?

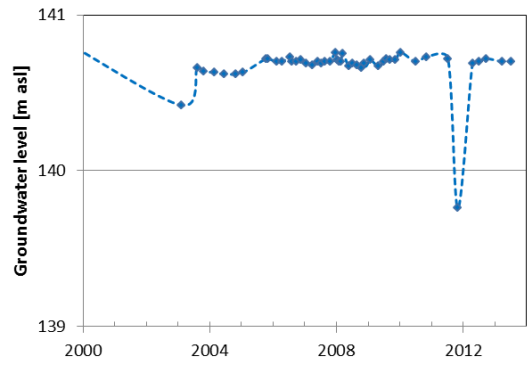
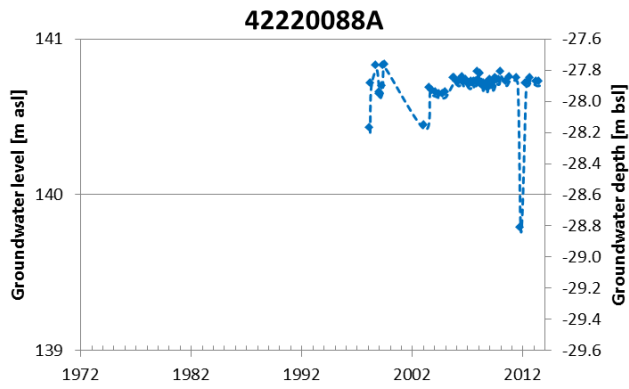




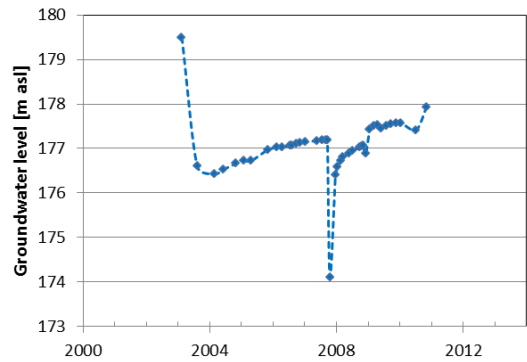
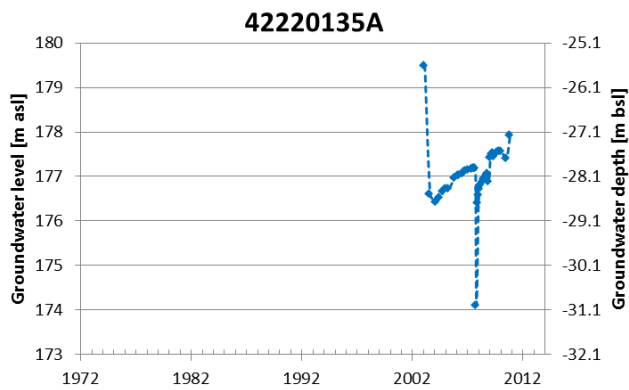
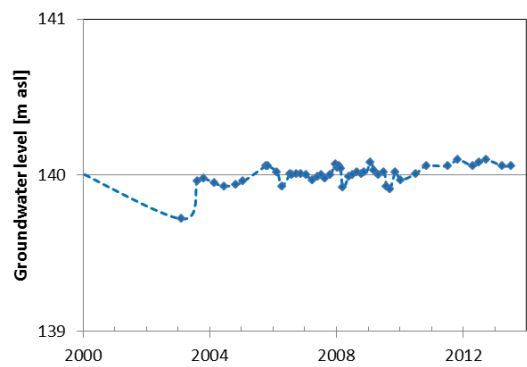
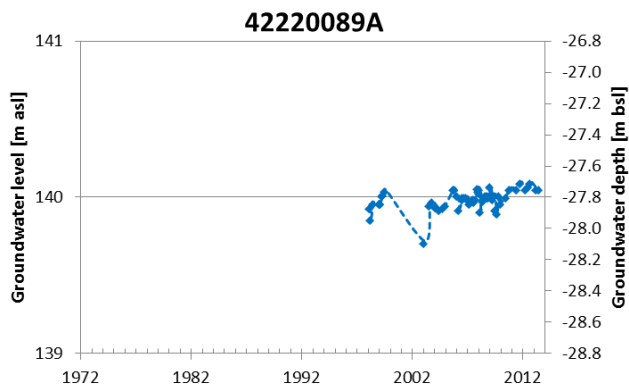




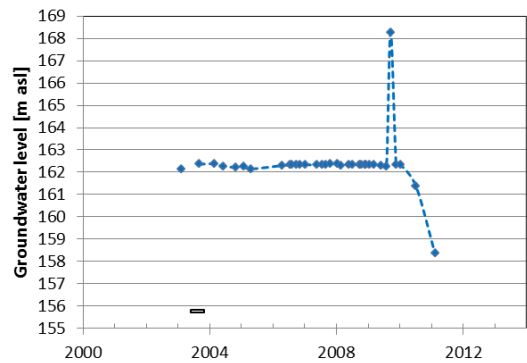
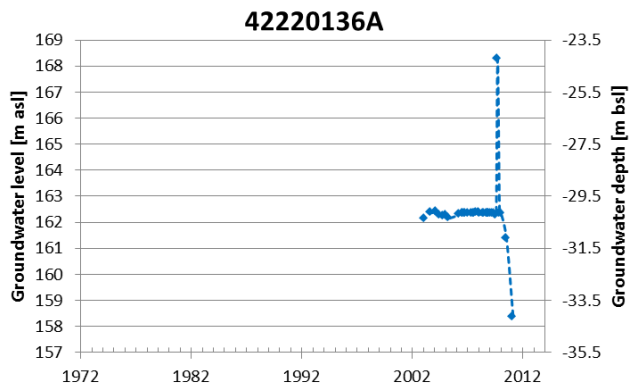




31/8/2012- erroneous reading ?

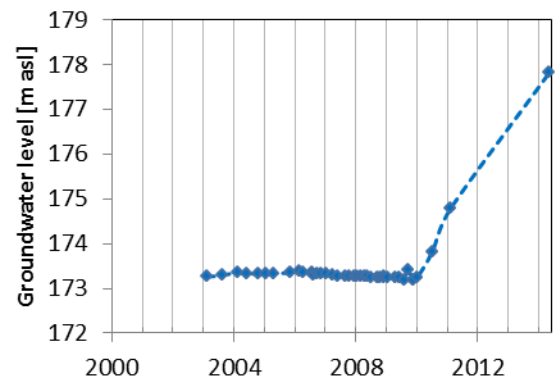
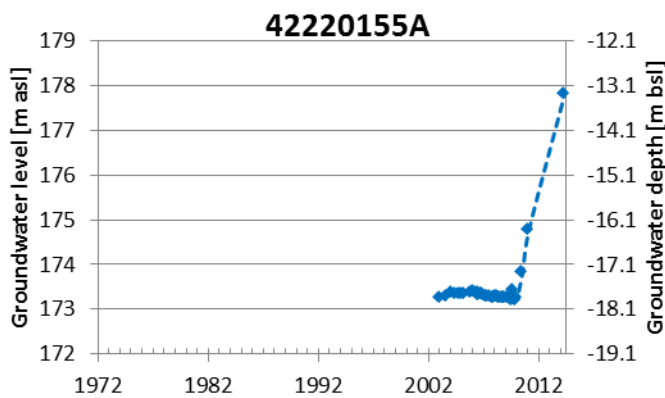
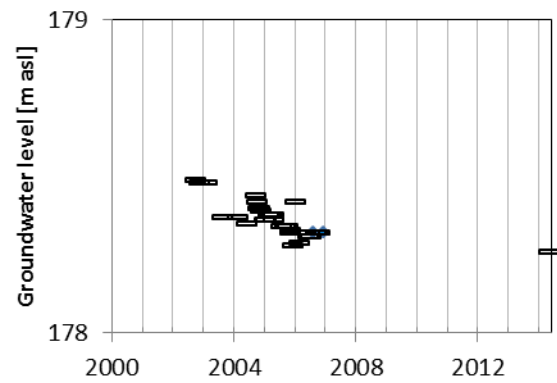
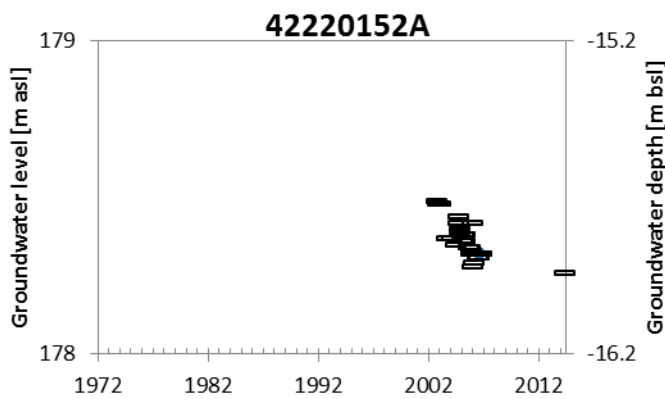
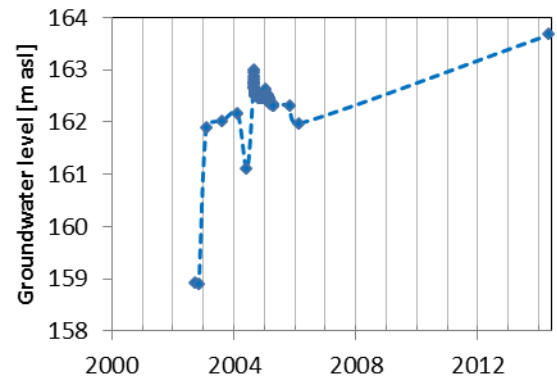
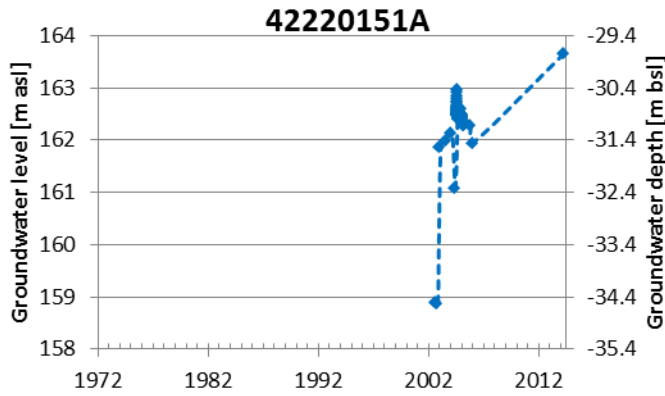
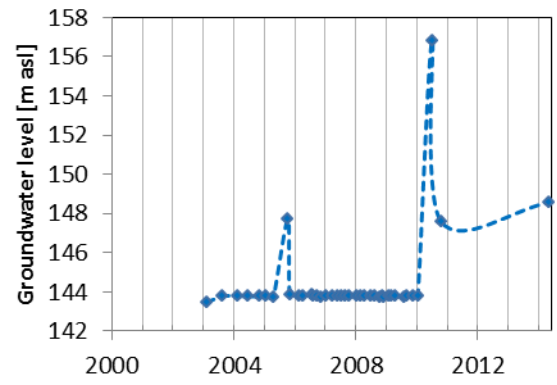
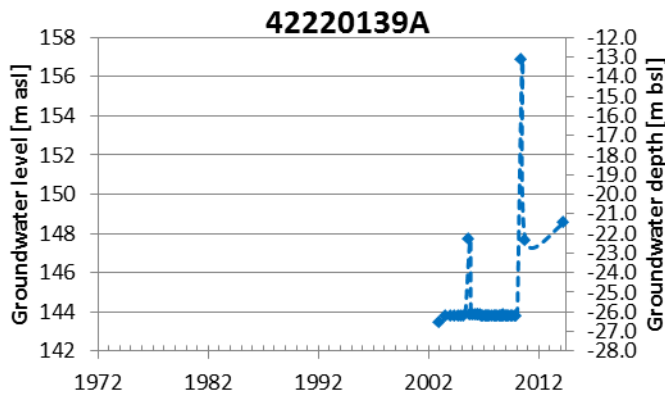


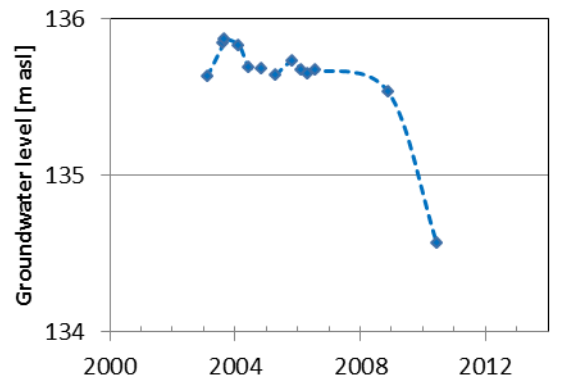
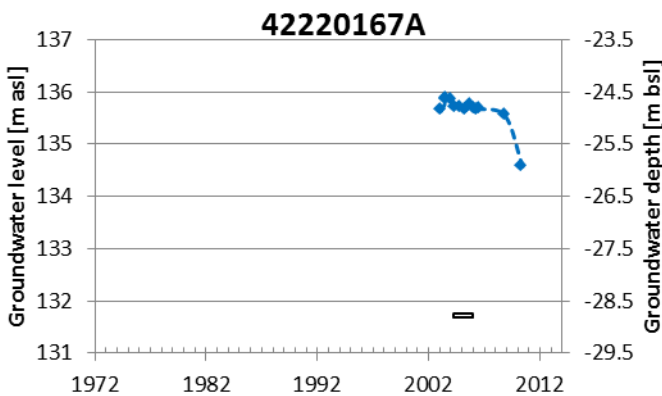
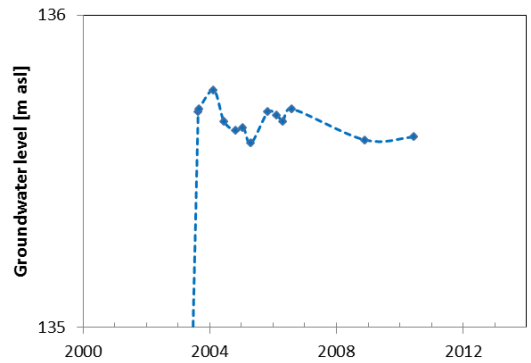
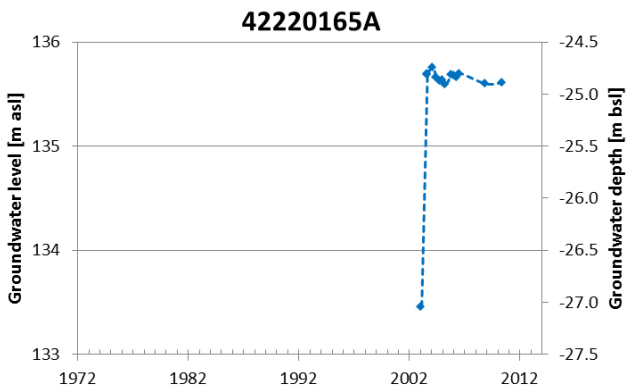
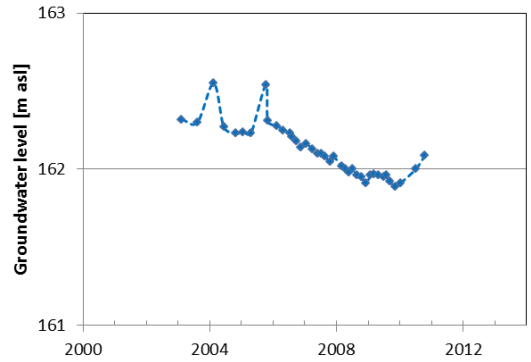
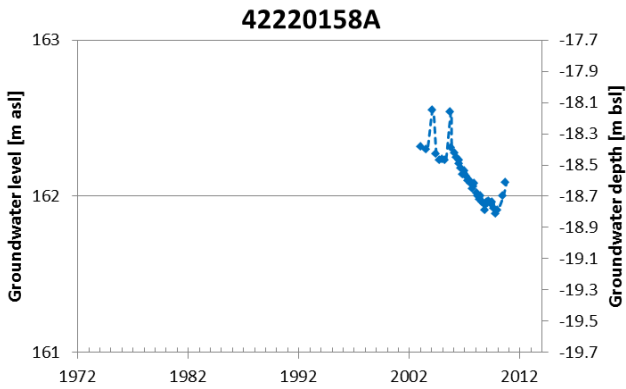
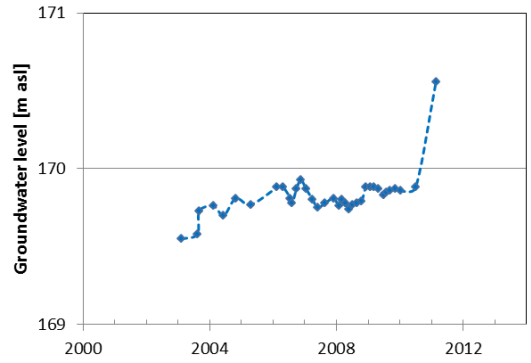
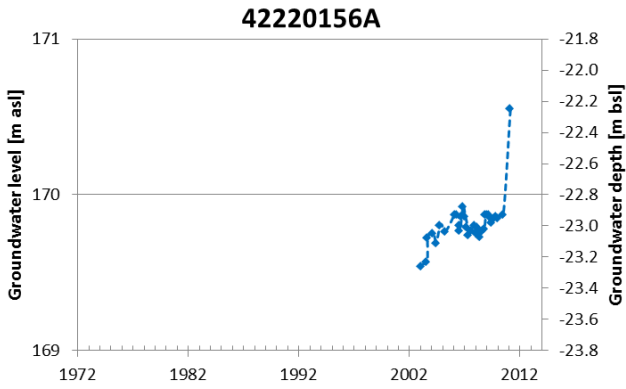
17/10/2007 – erroneous reading ?

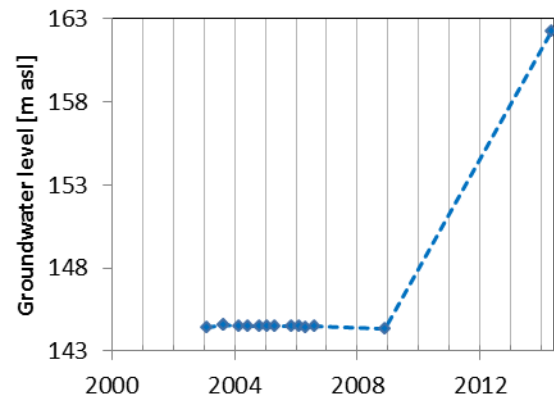
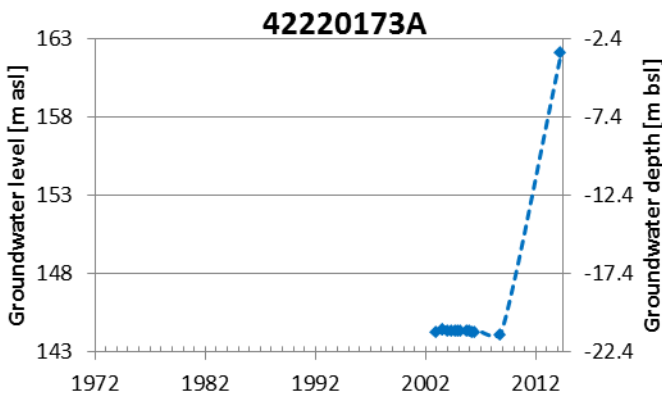
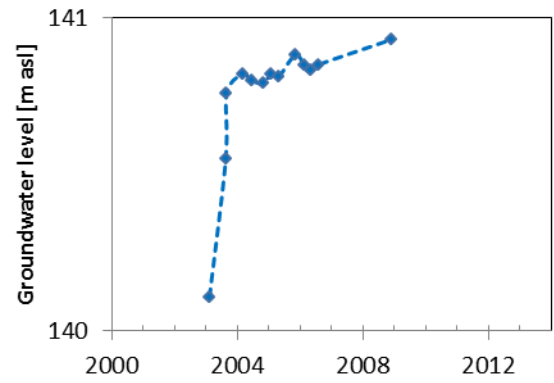
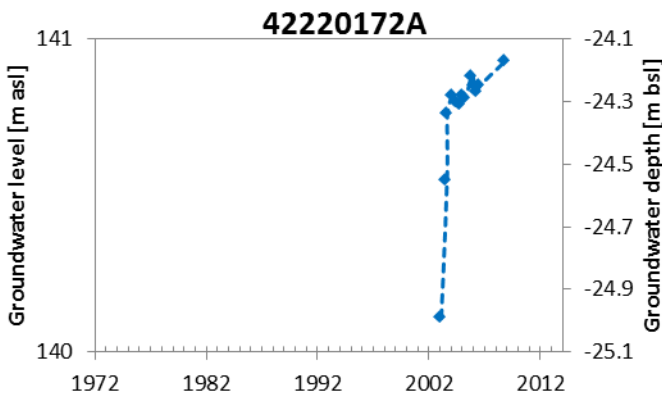
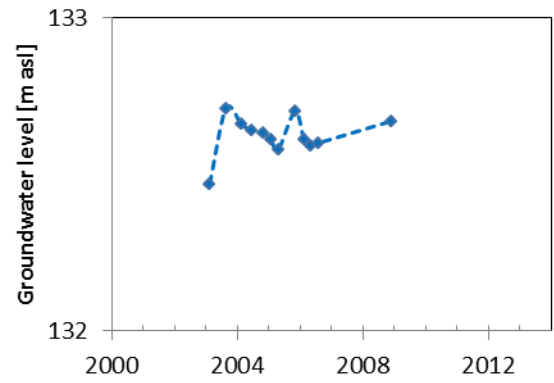
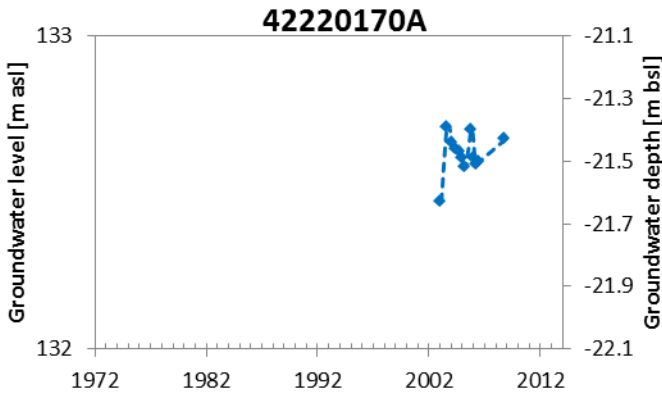
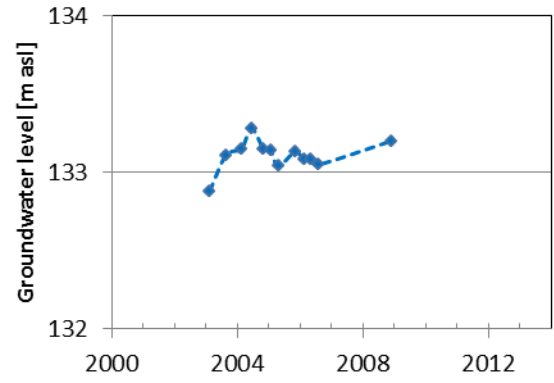
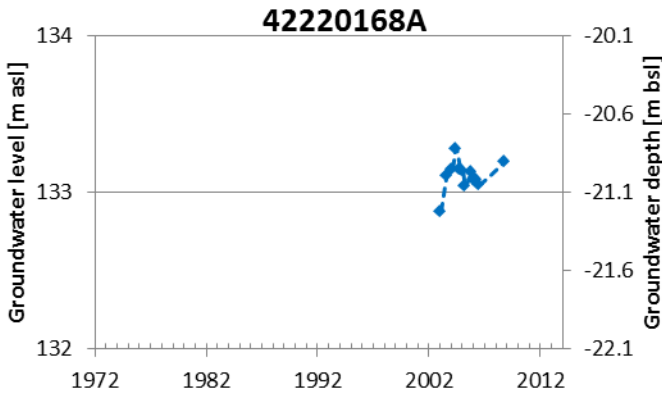


16/9/2009 erroneous reading ?

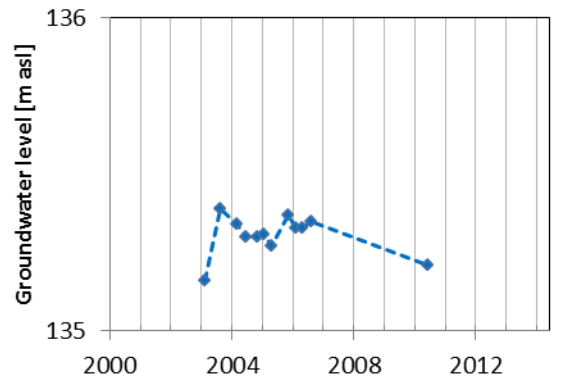
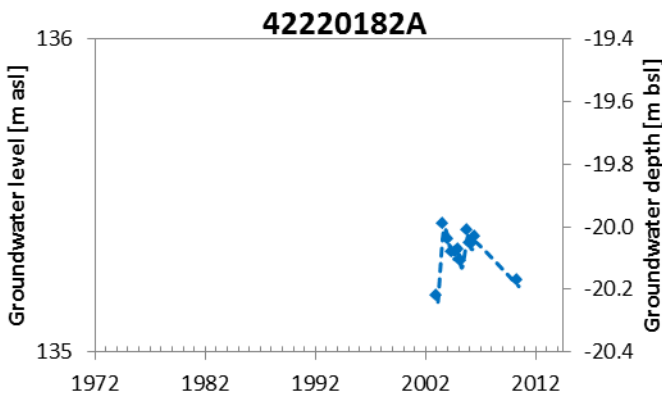
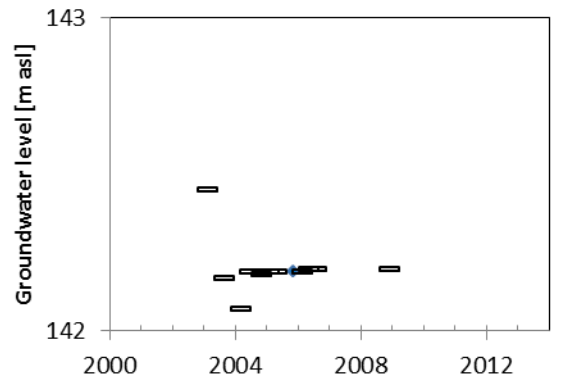
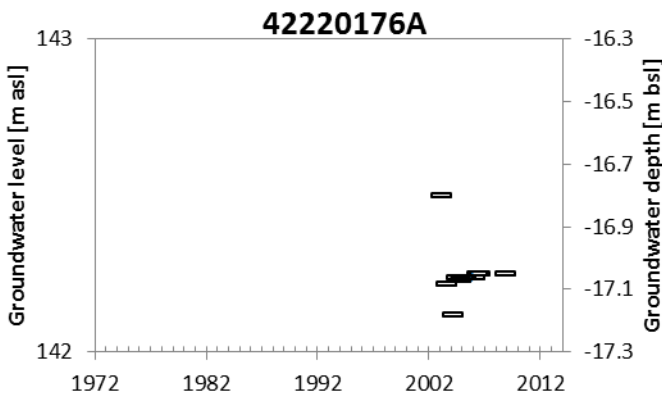
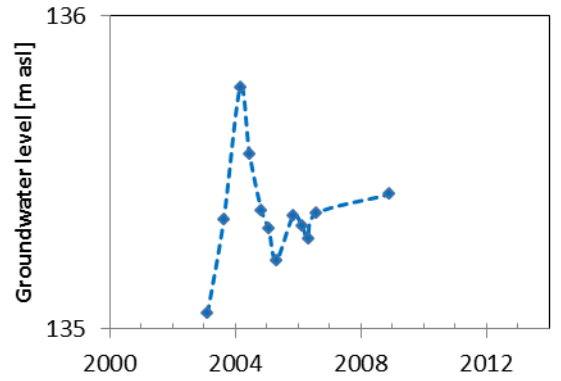
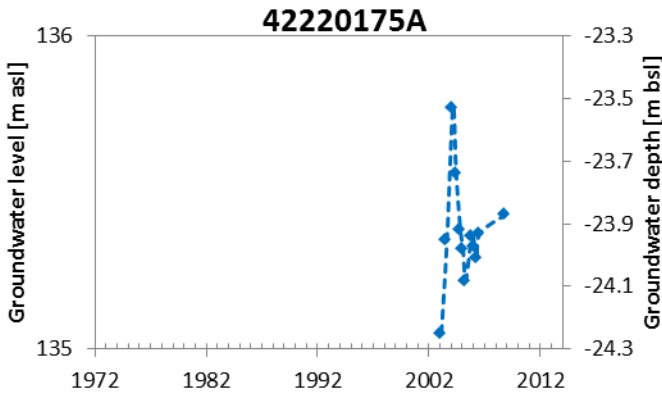
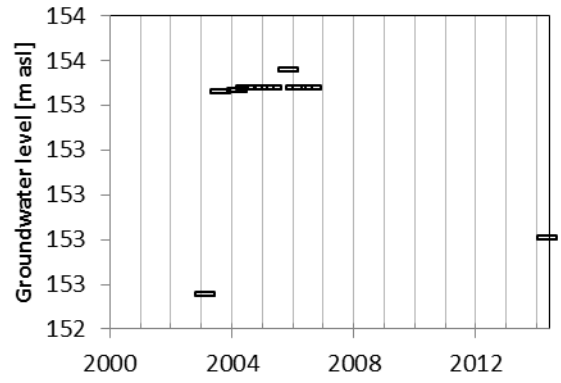
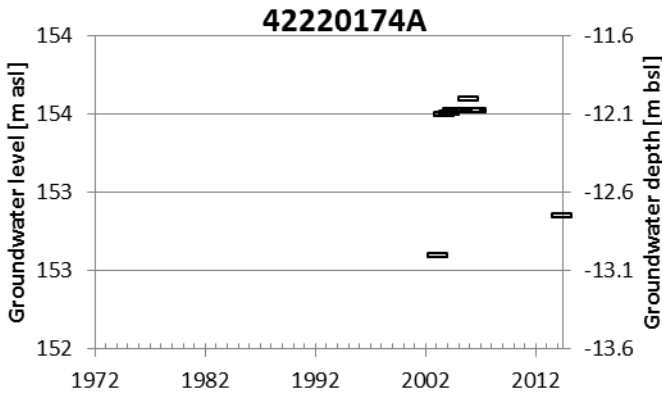
2009-2011 trend - ??

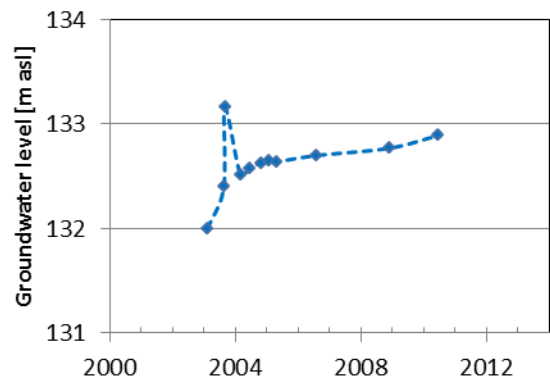
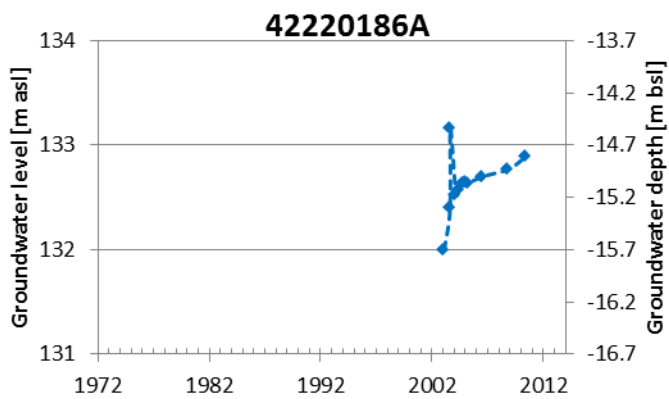
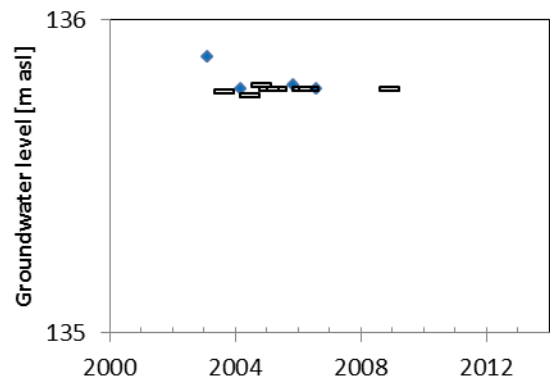
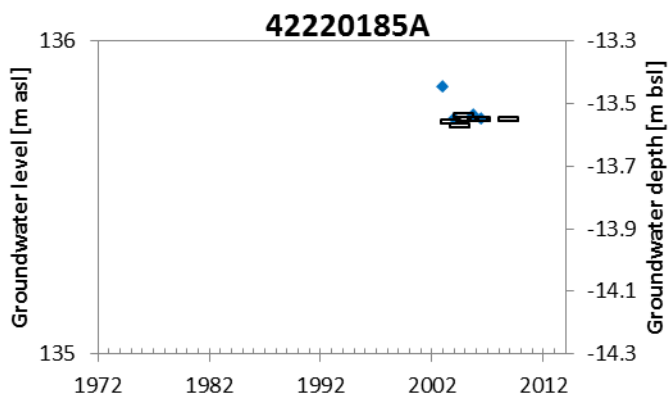
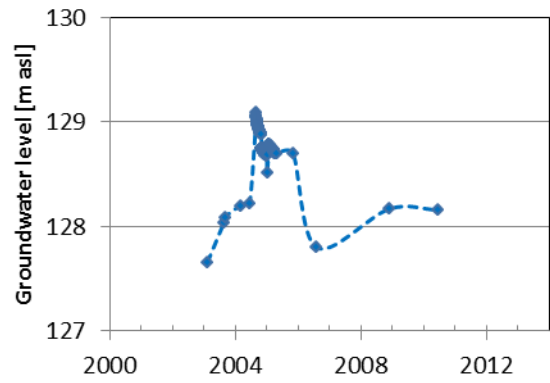
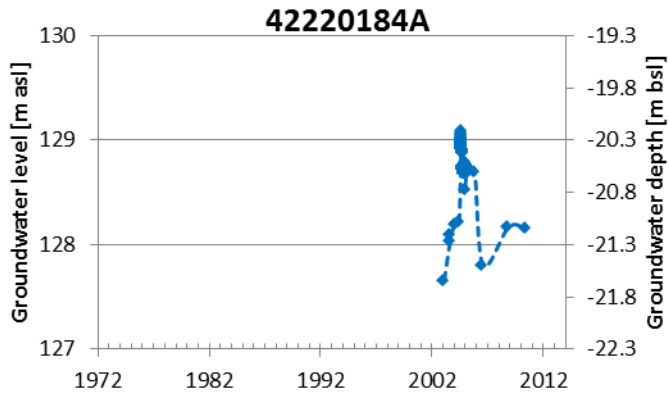
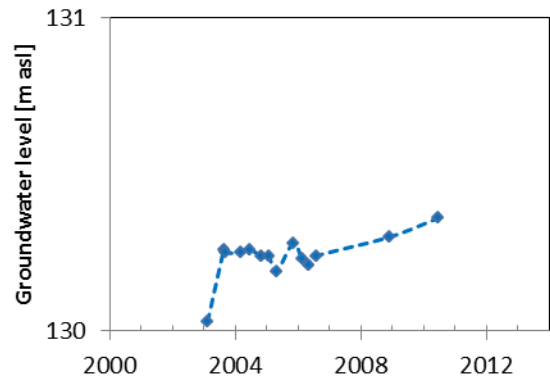
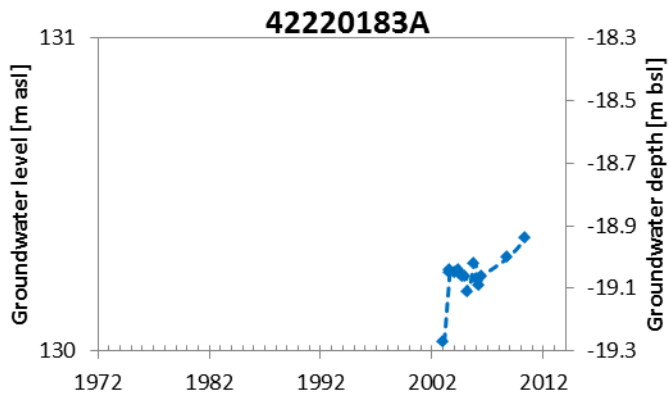


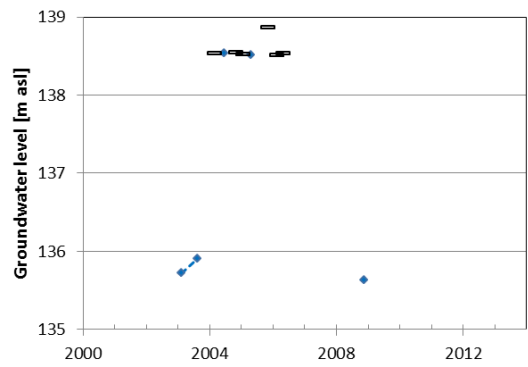
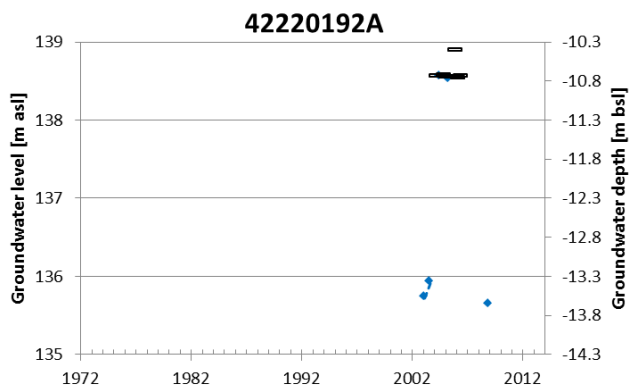
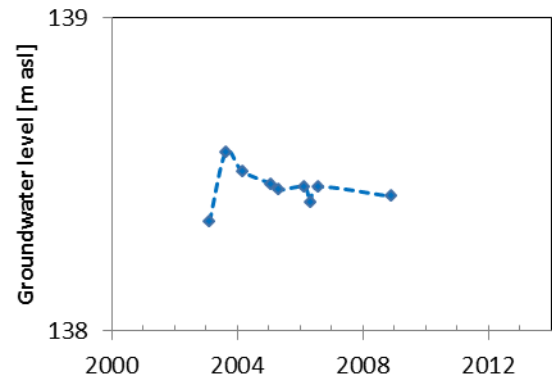
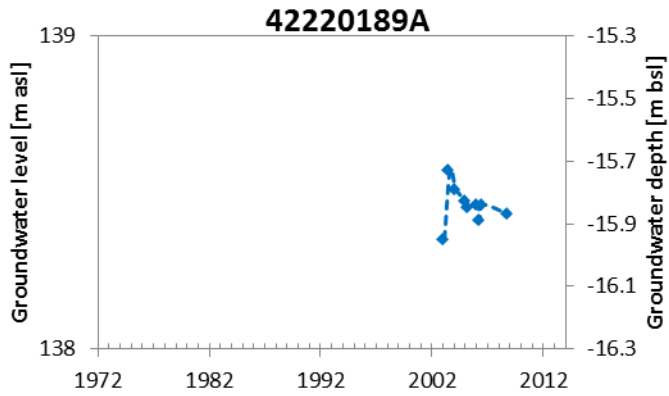
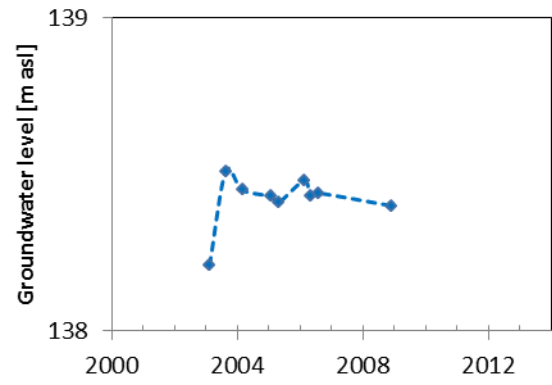
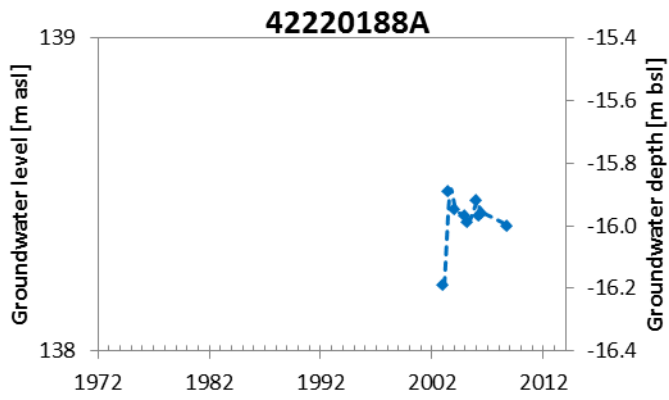




5/5/2014 - flooded?







Appendix B – Field work log and results

Table B1: Field work log and Solinst-103 readings

Date	RN	Purged & Sampled	TD [m]	GWD [m]	Temp °C	EC µS/cm	Remarks
5/05/2014	42220027		12.16	-8.51	22.7	730	Eq. w/ micro Diver
	42220030	Yes	26.34	-18.92	22.6	1374	Eq. w/ micro Diver
	42220022						Bulbbard fell; micro Diver stuck ~1m below casing
	42220023	Yes	12.46	-5.23	23.3	434	Eq. w/ micro Diver
	42220020	Yes	12.28	-9.25	23.2	1380	Eq. w/ micro Diver
	42220021		12.56	Dry			Collapse of granular material in the bottom of pipe
	42220024		12.79	-8.38	22.0	2333	Bend- the bailer not fit in the casing; eq. w/ micro Diver
	42220053		20.05	-19.14	22.5	9330	Eq. w/ micro Diver
	42220025	Yes	12.88	-6.25	22.6	430	Eq. w/ micro Diver
	42220151		74.90	-29.76	24.4	4368	
	42220152		15.94	Dry			
	42220033		31.16	Dry			
	42220034		23.02	-20.22	22.0	6014	Eq. w/ micro Diver
	42220032	Yes	31.06	-13.93	23.0	1506	Moisture in the lower ~10 cm
	6/05/2014	42220057	Yes	14.50	-8.65	22.1	3120
42220072			39.37	-18.84	23.7	4330	Stratified- fresh (165 µS/cm) water down to a depth of -35.5m
42220073			15.37	Dry			
42220155			38.41	-13.27	23.2	93	
42220079		Yes	21.84	-10.36	23.7	777	
42220082		Yes	31.66	-21.30	23.3	>6,900 *	Stratified- fresh (240 µS/cm) water down to a depth of -29 m
42220083		Only purged	20.00	-16.04	22.8	976	Water were purged and measure (black water; EC=939 µS/cm) but not sampled.
42220139			43.54	-21.41	21.8	146	
42220085			43.15	-21.78	22.2	958	
42220086			24.82	-17.63	22.6	19,200	Stratified- fresh (289 µS/cm) water down to a depth of -22.5m
42220174			12.05	Dry			
42220173			27.80	-3.36	22.0	250	
42220172			>100m	#	22.3	9,250	Stratified- fresh (240 µS/cm) water down to a substantial depth (not measured)

* Sensor has not stabilized.

Record corrupted.

Table B2: YSI-pro readings

RN	Sample code	Temp °C	EC (before purge) µS/cm	EC (after purge) µS/cm	pH	Eh	NO3 (mg/l)	DO (mg/l)
42220030	ED28	22.6	1374	1394	7.55	-30	2.7	3.1
42220023	ED30	23.3	434	500	6.53	28.4	0.6	1.0
42220020	ED25	23.2	1380	1634	7.16	-9.2	2.4	3.9
42220025	ED27	22.6	430	472	6.92	5	0.9	2.0
42220032	ED29	23	1506	1484	7.2	-10.9	3.9	3.0
42220057	ED26	22.1	3120	3930	7.54	-31	5.1	2.1
42220079	ED31	23.7	777	860	6.68	20	0.6	2.1
42220082	ED32	23.3	>6900	7787	6.1	50.6	4.4	1.3