

Final Report of:
**“Deep Drainage under irrigated cotton –
surface and groundwater implications”**
Project Number : 2.02.17 (2008-2011)

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Executive Summary

Deep drainage (DD) - water that passes beyond the root zone – is an important process in irrigated cropping soils to ensure leaching of salts through the soil profile to deeper soil layers, the vadose zone (the zone between the rootzone and the watertable) or to groundwater. Salt can either be naturally present within some soils or be added through low quality irrigation water. Furthermore, excessive DD may cause water table rise to the rootzone with associated salts, so precluding the growth of salt sensitive species.

DD is also an economic negative, as costs of pumping and storage are not realised in increased yields or possible increased area under production. The loss of irrigation waters to DD is particularly important in drought years where the rare water resource must be carefully utilised to ensure crops attain maximum yield per unit volume of applied water.

The study reported here focused on DD water losses and the quality of those lost waters (in terms of salinity) on 7 irrigated cotton farms (all but one under traditional furrow irrigation management) in the upper Murray Darling basin (UMDB) near the towns of Boggabilla (2 sites), Dalby, Goondiwindi, Macalister, Pampas and St George.

Many regarded the advent of low volume irrigation devices (eg lateral moves) with their known capacity to increase water use efficiency (bales of cotton/unit water applied) as a “win win” situation; making minimum water go further, particularly as DD is almost zero. However, minimal or no DD equates to a reduced leaching fraction. This in turn can lead to a potential for increased rootzone salinity.

This project commenced in 2008 and monitored DD across irrigated cropping lands in the UMDP. There were 7 sites with lysimeters installed (each a commercial, irrigated cotton field) giving a total of 21 lysimeters. At each site, a lysimeter was installed near the head ditch, mid field and tail ditch in each field. One of these sites was irrigated with a lateral move and the remaining 6 with traditional furrow irrigation. One of the 6 furrow irrigated fields immediately adjoined the lateral move site, facilitating comparison of the two irrigation techniques in terms of DD. The water quality (salinity level) of all DD leachates was monitored at all sites.

Several hydrological models were tested, to investigate their capacity to predict DD.

Lastly, monitoring continued of the 16 “wet” inspection bores in the St George irrigation area (SGIA) to investigate their continuing dynamics and links with surface water events.

Principal results were:

(i) In 2008-09, DD was collected only at the Macalister site under a rainfed barley crop; all other sites being fallow. Five sites (including the lateral move site) were irrigated in 2009-10 with DD values up to 104 mm measured, though most values were <20 mm and the lateral move (as always) being zero. All sites were under irrigated cotton in 2010-11 (high cotton prices) but DD collected were very low

(all <12 mm) showing the incidence of very few irrigation events at all sites because of good and frequent in-season rains.

(ii) The DD data and related soil Chloride sampling under the lateral move and in the adjoining furrow irrigated field suggest salt build-up under the lateral, due to the lack of DD (ie no leaching fraction). It is emphasised that the chloride data sets to date are small and sampling will continue in both fields to mid-2013 (just before a new Project ends) to assess further these soil chloride trends.

(iii) As found previously, the EC of the leachates collected in the lysimeter collection bottles continued to be far greater than the EC of the irrigation waters applied to each field. This is seen as highlighting the potential for adverse off-site effects of poor water quality from DD. The maximum increases (60 fold) continued to occur at the St George site.

(iv) Testing of the four hydrological models (SODICS, HowLeaky?, SaLF and SIRMOD/FAO-56) provided results at variance to the lysimeter-measured, DD values. The simulated outputs, though based on field collected parameters, had no relation to the magnitude, or seasonal or in-field trends of the lysimeter DD data. More work is required to fully investigate these anomalies. In particular, the simulations may benefit from more detailed inputs of evapotranspiration, rain and irrigation volumes that better reflect seasonal variability of irrigated cotton production.

(v) Groundwater dynamics of the 16 “wet” inspection boreholes in the SGIA have been monitored since 1972 by manual dipping and since early 2007, by loggers set to log water levels on a 12 h interval. In the early to mid 1980s, the groundwater level in 50% of all the 16 wet inspection bores rose a range of 0.5 to 19 m towards the ground surface. Though these rises could have many causative factors, local growers linked them to the filling of on-farm water storages at approximately that time. These water levels have generally stayed at these elevated levels. Importantly, the water levels and their dynamics of the wet inspection bores illustrate more localised (small) groundwater mounds, rather than a broad groundwater mound under the SGIA. Two of the boreholes with the shallowest water levels showed a distinct rise in level, associated with the heavy rains and floods of March 2010 and January 2011. This result illustrates the continuing connectivity between surface water events and groundwater levels, at least for shallow, unconfined aquifers in the SGIA.

Layout of the Report

Following the Introduction, Aims and Methodology sections, this Report will be presented in three parts:

Part A will present the Deep Drainage results,

Part B will present the associated Hydrological Modelling, and

Part C will report on the Groundwater level changes with time in the St George irrigation area.

Introduction

Irrigated agriculture in Australia and the cotton industry in particular have become increasingly aware of water losses due to deep drainage (DD, expressed as mm/ha where 100 mm/ha = 1 ML/ha) in furrow-irrigated Vertosols (Silburn *et al.* 2004). Such data contradicted earlier beliefs that “clay soils don’t drain” (Hearn 1998). A review by Silburn and Montgomery (2004) suggested DD from furrow irrigated agriculture was between 50 and 300 mm/season with this study instrumental in changing the cotton industry’s view of “leak proof” Vertosols. Earlier work by Thorburn *et al.* (1990) estimated DD for 30 irrigated soils in southern Queensland, presenting values <100 mm/year for 13 sites, 100 to 200 mm/year for 6 sites, <200 mm/year for 11 sites and >500 mm/year for only two sites. Gordon (2000) measured seasonal DD in cotton using large lysimeters in Vertosols and reported values of 95 to 305 mm/year under drip irrigation and 165 to 180 mm/year under furrow irrigation on the Darling Downs, Queensland. Dalton (2003) calculated seasonal DD values under irrigated cotton of 100 - 200 mm using water balance measurements and concluded that “DD in surface irrigated cotton systems has remained a contentious issue and one that has not been well understood by the (irrigation) Industry”. Analysis of furrow advance data for 79 furrow irrigation events conducted by growers in southern Queensland found average DD losses of 42.5 mm per irrigation and potential annual losses of up to 250 mm (Smith *et al.* 2005).

Efficient irrigation water use is vital for the Australian cotton industry. In 1998 there were 535,400 ha of cotton grown, of which 76% was irrigated using 1,940 GL of water (ABARE 2009). In 2009, only 164,000 ha were harvested (ABARE 2009), reflecting the greatly reduced availability of irrigation water in a period of drought. Despite this decline, cotton remains the dominant irrigated summer crop in the upper Murray Darling Basin (UMDB) on clay soils, due to expectations of improved returns, relative to other summer crops (ABARE 2009). Further threats to sustainable crop production are rising water tables and ground water salinisation. Although cotton is generally regarded as a salt tolerant plant, yield is affected at a soil $EC_{(se)}$ of 7.7 dS/m (EC_{se} is the EC of a soil saturated extract) with a 50% reduction at 17 dS/m (Ahmad *et al.* 2002). The shallow root systems (<2 m) of irrigated annual crops including cotton result in less water extraction from deep in the soil profile, and annual crops provide no transpiration for much of the year, potentially resulting in more DD than for perennial vegetation (Williamson 1973).

Deep drainage occurs when water passes beyond the root zone, in one way a positive phenomenon by recharging ground water and removing excess soluble salts from the root zone, but also potentially negative due to excess pumping costs for “unused” water, and the potential for rising ground water tables and particularly if these are saline. Excessively high and uncontrolled DD is, therefore, economically and environmentally poor practice.

Direct methods of estimating DD include measured water balance (Dalton 2003), metering soil water flux (Dirksen 1974), lysimetry (Bethune and Wang 2004; Robinson *et al.* 2004) and tracers collected with drainage (Cook and Herczeg 1998). Despite the potential

accuracy of these methods, they have seen limited application in irrigated cotton, mainly because of installation time and complexities, small area of measurement in some cases, and high cost. Of these methods, lysimetry appears to have several areas of application. It is suitable for long-term measurement and relies on physical rather than chemical methods. A major potential problem in lysimetry studies has been preferential flow along the side walls of the lysimeters, but this has been addressed in recent designs (Corwin 2000).

One reason for using lysimetry in DD studies, such as here, is the ability to collect the DD leachate for salt analysis, hence to measure and rationalise salt fluxes in soils. To maintain a desirable salt concentration in the root zone of irrigated crops using poor quality water ($EC_{iw} > 0.65$ dS/m; EC_{iw} is the EC of the irrigation water) some leaching (ie DD) is required. Vervoort and Silburn (2002) suggested that in irrigated cotton a leaching fraction (LF) of 10-20% of applied water will provide, and probably exceed, this requirement. Previous lysimeter research and drainage modelling by Silburn and Montgomery (2004) have measured or predicted LF of up to 20% under irrigated cotton on Vertosols.

Project Aims

The underlying aim of this project was a “continuation of high quality data collection and interpretation towards technical input for correct development of farmer usable best management practices (BMPs) and enhanced community awareness of NRM issues”. The source of these outcomes is the existing network of deep drainage monitoring lysimeters, installed from 2005, across a wide variety of cotton soils and management types, and the related groundwater and soil salinity monitoring sites. Within this there were three specific aims:

- To continue 3 seasons of data collection (2008-11) at the current 7 lysimeter sites to gain industry-representative data in more typical (non-drought) seasons. The 7 sites were located at Boggabilla (the lateral move and adjoining field), Dalby (Dalby, Macalister, Pampas), Goondiwindi and St George
- To continue (3 seasons) of data collection from the site at Boggabilla with adjoining lateral move and furrow irrigated cotton fields, to better represent the water use efficiencies with this system, regarded industry-wide as strong potential for water use efficiencies (WUE).
- To continue (3 years) twelve hourly monitoring of groundwater levels in 16 monitoring boreholes (St George irrigation area) in association with local, concurrent rainfall and flood records, to investigate links between change in water table (aquifer) levels and surface water events.

This project commenced in July 2008 with funding from both the Cotton Research and Development Corporation and the Cotton Catchment Communities CRC. The project continued Project: 1.02.04 “Deep Drainage under Irrigated Cotton – Surface and Groundwater Implications” to ensure: (i) maximum value gained from Cotton investments in equipment and human inputs, and (ii) the collection of data sets from more “typical” (non-drought) seasons, to ensure correct formulation of BMPs. The current project continued to provide continuous monitoring of two key aspects of water for irrigated cotton: DD and sub-soil aquifers.

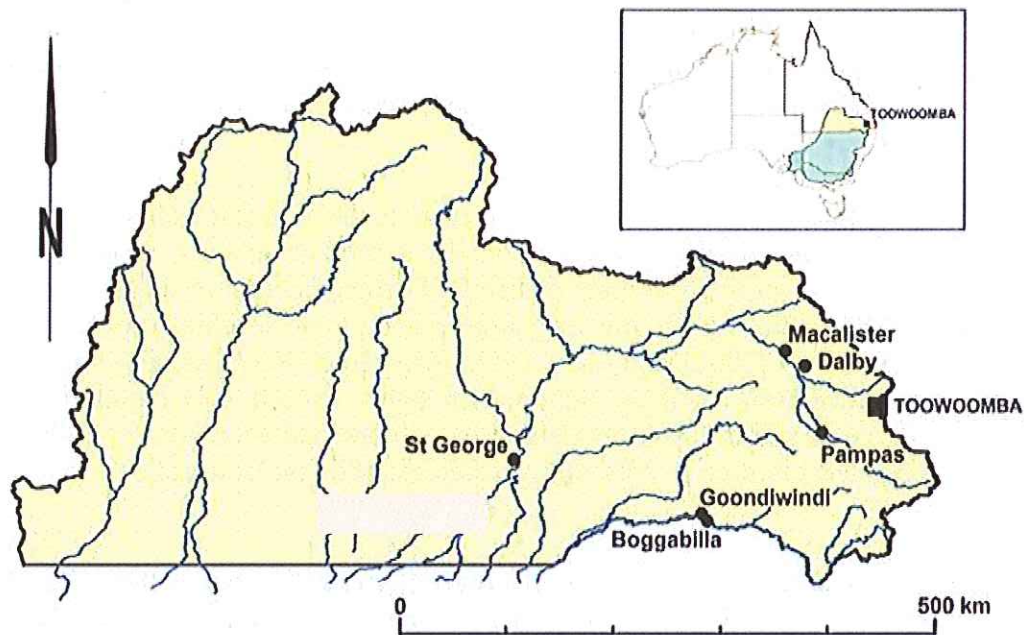


Fig. 1. Location of the 7 operational lysimeter sites.

Methodology

There were five distinct but inter-related parts to the methodology:

- Real-time monitoring of the 7 already-established lysimeter sites was continued for three years.
- Twice daily monitoring of water table levels was continued of the borehole loggers in the St George irrigation area (SGIA). Data was downloaded up to four times a year as the loggers were found to be unreliable and constantly stopping. The reason for the unreliability was a continuing manufacturer's fault, so all stopped loggers were replaced under warranty.
- Rainfall data and flood levels in the SGIA were recorded (on site pluviometers and Bureau of meteorology data) with the aim of checking if groundwater responses were triggered by surface water events.
- Creation of BMPs including alternate irrigation management and alternative irrigation systems towards the alleviation of DD, based on project results.
- Test hydrological models, using field data collected through the life of the Project, to simulate DD and compare to measured (lysimeter) results. Four different models were used (SODICS, HowLeaky?, SaLF and SIRMOD/FAO-56).

Part A: Deep Drainage

A.1. Lysimeters

Three seasons of data will be presented. The lysimeter data presented here has been fully reported in Gunawardena et al (2011). It sources from the 21 remaining, operational lysimeters. The lysimeters used, described as “confined, undisturbed, constant tension, non-weighing”, were installed in the period 2002 to 2007 to capture water passing 1.5 m depth at three in-field positions: (i) near the head ditch, (ii) mid-way between head and tail ditches, and (iii) close to the tail ditch.

- In 2008-09 all of the lysimeter sites were under bare fallow except for a sorghum crop under the lateral move (LM) at the Boggabilla site. Deep drainage was recorded at only one site - Macalister there were 41 mm (head) and 13 mm (mid) of DD when the field was under rain fed barley followed by bare fallow, after harvest (Table 1).

- In 2009-10 two sites were under fallow (Dalby and Pampas), one under sorghum (Goondiwindi) and all others were under cotton. A total of seven DD events were recorded in the range of 2 to 104 mm. The largest DD (104mm) was at St George (mid) with 70 mm out of this was from the pre irrigation. The second largest value was 52 mm at Macalister mid. At all other sites DD values were less than 18 mm.

- In the 2010-11 season all sites were under cotton apart from Boggabilla furrow that was fallow. Though most of the field was under cotton, the part (edge) of the field where the lysimeters are installed at both Macalister and St George was under a “catch crop” of field pea, hence was only watered once at St George and three times at Macalister. Hence, the irrigation regime did not represent that of a full cotton crop. In total there were 7 DD events, though with smaller DD values (1 to 12 mm) than in other seasons. It is believed that these small values resulted from the above average rainfalls in 2010-11 with in-season rainfall at the lysimeter sites ranging from 367 (3.7 ML) to 810 mm (8.1 ML) (Table1). As a result, there were far fewer irrigation events at almost all sites.

Table 1. Deep drainage (DD) calculated from the measured leachate volumes (mm) at the head, mid and tail locations of the nine DD monitoring sites. Also presented are the same DD data, expressed as the leaching fraction ($LF = (DD) / (\text{rain} + \text{irrigation}) * 100$) (Note; data up to 2008-09 have been published in AJSR: Gunawardena et al., 2011)

| Crop | In crop rain (mm) | Irrigation (mm) | Season | Head | | Mid | | Tail | |
|----------------------------------|-------------------|-----------------|--------|------|------|-----|------|------|----|
| | | | | DD | LF | DD | LF | DD | LF |
| <i>Boggabilla -Furrow</i> | | | | | | | | | |
| Fallow | 328 | - | 08/09 | 0 | - | 0 | - | 0 | - |
| Cotton | 320 | 400 | 09/10 | 14 | 1.94 | 2 | 0.28 | | |
| Fallow | 455 | - | 10/11 | 0 | - | 0 | - | 0 | - |
| <i>Boggabilla – Lateral move</i> | | | | | | | | | |
| Chick pea | 112 | 30 | 2008 | 0 | - | 0 | - | 0 | - |
| Sorghum | 328 | 60 | 08/09 | 0 | - | 0 | - | 0 | - |
| Cotton | 320 | 200 | 09/10 | 0 | - | 0 | - | 0 | - |
| Cotton | 455 | 239 | 10/11 | 0 | - | 0 | - | 0 | - |
| <i>Dalby</i> | | | | | | | | | |
| Fallow | 351 | - | 08/09 | 0 | - | 0 | - | 0 | - |
| Fallow | 466 | - | 09/10 | 0 | - | 0 | - | 0 | - |
| Cotton | 780 | 100 | 10/11 | 4 | 0.45 | 0 | - | 0 | - |
| <i>Goondiwindi</i> | | | | | | | | | |
| Mixed seed | 211 | * | 2008 | 0 | - | 0 | - | 0 | - |
| Fallow | 435 | - | 08/09 | 0 | - | 0 | - | 0 | - |
| Sorghum | 324 | - | 09/10 | 2 | 0.62 | 0 | - | 0 | - |
| Cotton | 367 | * | 10/11 | 0 | - | 0 | - | 0 | - |

| <i>Macalister</i> | | | | | | | | | |
|-----------------------|-----|-----|-------|----|------|-----|-------|---|------|
| Barley | 278 | 200 | 2008 | 41 | 7.09 | 6 | | 0 | - |
| Fallow | 298 | - | 08/09 | 13 | 4.36 | 0 | - | 0 | - |
| Cotton | 382 | 400 | 09/10 | 16 | 2.05 | 52 | 6.65 | 0 | - |
| Field pea/Cotton** | 810 | 0 | 10/11 | 7 | 0.86 | 3 | 0.37 | 0 | - |
| <i>Pampas</i> | | | | | | | | | |
| Sorghum | 390 | - | 08/09 | 0 | - | 0 | - | 0 | - |
| Fallow | 453 | | 09/10 | 0 | - | 79 | 17.55 | 7 | 1.55 |
| Cotton | 612 | * | 10/11 | 12 | | 1 | | 3 | |
| <i>St George</i> | | | | | | | | | |
| Wheat | 133 | * | 2008 | 0 | - | 0 | - | 0 | - |
| Fallow | 180 | - | 08/09 | 0 | - | 0 | - | 0 | - |
| Cotton | 548 | * | 09/10 | 18 | | 104 | | 0 | - |
| Field pea/cotton** | 351 | 0 | 10/11 | 0 | - | 8 | | 0 | - |

* Irrigation waters applied, not known.

** Lysimeter areas were under field pea, so minimally irrigated.

A.2. Solute Dynamics

Two sets of soil hydrology and related soil/water salt data will be presented to demonstrate some aspects of relationships between DD and solute dynamics, arising from the current Project.

Drainage solute dynamics

The EC of the DD leachates (EC_{leach} in dS/m) had been measured on all DD samples to date (from 2005). The EC_{leach} measured over the three years of the Project generally corresponded with the average EC_{leach} , measured over the previous five year period (Table 2). As found previously, the EC_{leach} of the leachates collected in the lysimeter collection bottles continued to be far greater than the EC of the irrigation waters (EC_{iw}) applied to each field. This is seen as highlighting the potential for adverse off-site effects of poor water quality from DD. The maximum increase of 60 fold occurred at the St George site. The smallest increase in EC_{leach} compared to waters applied (3 fold) was at the Macalister site, where the EC_{iw} (principally bore water) had an EC of 4.15 dS/m. The leachate at this site, however, had the largest EC_{leach} value (approx. 12 dS/m).

Related to interpretation of the EC_{leach} data, the soil EC values ($EC_{1.5}$) measured across all sites at 1.5 m depth (data presented in the Final report to CCC-CRC and CRDC, 2005) ranged from 0.1 to 1.8 dS/m. These values equate to EC_{sc} values of 0.6 to 10.8 dS/m. These EC_{sc} values (derived from the soil $EC_{1.5}$) are likely to be somewhat less than the EC of any leached soil solution because soils wetter than field capacity will drain. For Vertosols, field capacity is typically 45% volumetric water capacity, whereas saturation is typically 55%, and hence a conversion factor of approximately 1.22 may be applied to determine the EC of the soil water at field capacity (EC_{FC}). Using this conversion, the calculated values of EC_{FC} range from 0.7 to 13.2 dS/m for the Project sites. The EC_{leach} was slightly larger than these values (3.7 to 13.4 dS/m) showing that salt moved out of the soil profile with drainage.

Table 2. The average electrical conductivity (EC_{leach} ; dS/m) of leachates collected over five years (2003-08) – these data being from an earlier phase of the current project - and the annual average (of all leachate samples collected) for each of the recent three seasons (2008-09 to 2010-11).

| Site | Five year average (dS/m) | 2008-09 (dS/m) | 2009-10 (dS/m) | 2010-11 (dS/m) |
|---------------------|--------------------------|----------------|----------------|----------------|
| Goondiwindi | 3.7 | - | 4.8 | - |
| Pampas | 4.1 | - | - | 3.9 |
| Boggabilla (furrow) | 8.8 | - | 8.8 | - |
| St George | 9.0 | 13 | 11.3 | 8.8 |
| Dalby | 12.1 | - | - | 12.7 |
| Macalister | 13.4 | 20.3 | 17.1 | 19.3 |

- no DD measured

Soil solute dynamics

To monitor the change in soil salts under the two different irrigation practices at the Boggabilla site, soil cores were collected when the lysimeters were installed (September, 2005), then 48 and 56 months later for the LM and furrow sides, respectively. All cores were taken within a 2 m radius of each lysimeter (head, mid and tail in the LM and furrow fields) and soil chloride was determined on selected 0.1 m increments to 1.5 m. One core was taken at each of the six field locations in 2005 and three cores at each location in 2009.

Laboratory analysis showed both fields ranged in clay content from 40 – 50% to 1.5 m depth at all lysimeter locations, and there was no appreciable difference in soil EC profiles of the two adjacent sites when the initial samples were taken, all values being <1 dS/m throughout. Irrigation water quality at the Boggabilla site is very good ($EC = 0.24$ dS/m, $SAR = 1.1$, $Cl = 18.5$ mg/L) with water sourced from nearby Whalan creek, a tributary of the Macintyre river.

Results of the 2005 and 2009 core analysis showed that soil chloride increased at 81% of the sampled depths under the LM (where data was available in both years; ie 13 of 16 data comparisons) in the 48 month period (Fig. 2). Lack of replication in the 2005 sampling precluded statistical comparisons, but the tail location showed large chloride increases below 0.5 m (up to 39% at 55 cm) and at the head below 1 m (up to 25% at 1.45 m). Conversely, chloride decreased at the mid location for the two sampled depths below 0.5 m (Fig. 2). The largest overall increase was at 1.5 m depth at the head location (227 mg/kg of chloride; a 25% increase). These considerable increases in chloride at deeper layers at the head and tail locations demonstrate the requirement of additional LF for long term salinity management under the LM. In the furrow irrigated field change in chloride was very small for the mid and tail, the only large increase in soil chloride being at the head location (Fig. 3). Rationalisation of this result will require further sampling with more replication across more occasions to better determine site variability. The DD totals with furrow irrigation (over the three irrigation seasons; 2005-6, 2007-8 and 2009-10) show little difference between head and mid locations (138 and 129 mm, respectively), hence do not aid rationalisation of change in Cl with time.

Since lysimeter installation at these two sites (2005), the volumes (ML) of water applied through the LM and to the furrow irrigated field have been recorded; as too have the cotton yields (bales/ha) in the seasons when cotton was grown. The average of these data

clearly show water use efficiency (yield per megalitre) under the LM was far better than with traditional furrow irrigation. On average the LM used 64% less water for equivalent yield.

Almost zero DD was measured under the LM. This site has a calculated leaching requirement (LR) for cotton of 0.6 % (of the total seasonal rain plus irrigation), based on the cotton salinity threshold and the measured quality (EC) of the irrigation water. With furrow irrigation, this value was exceeded in 5 out of 6 occasions, over three field locations, inferring excessive irrigation. Noteworthy is that other, less salinity tolerant crops have far greater LR values; eg 2.9% for maize. As there was no DD under the LM, the LR was never exceeded, hence possibly explaining the chloride build-up under the LM, reported above. Under the LM, the chloride results suggest the need for additional LF. The study supports the need for continual monitoring of root zone salinity, particularly as the farmer also grows less salt-tolerance crops than cotton (e.g. chickpeas).

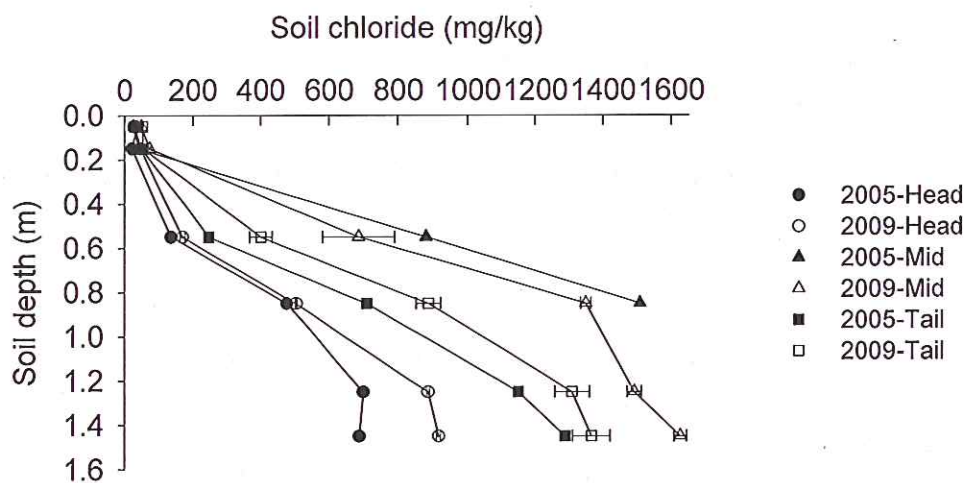


Fig. 2. Change in soil chloride at the head, mid and tail locations under the lateral move at the Boggabilla site over four years. The SD (\pm) for the 2009 values is shown.

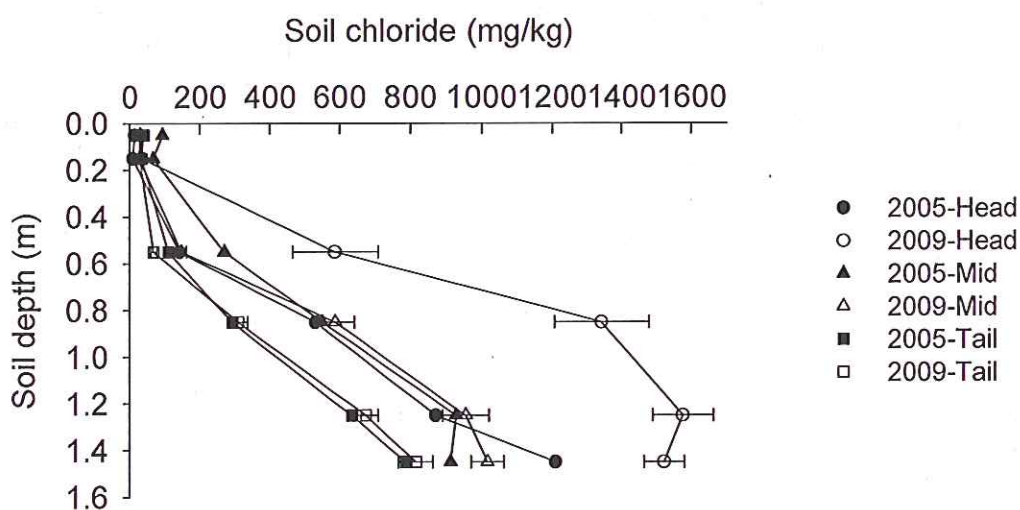


Fig. 3. Changes in soil chloride at the head, mid and tail locations under furrow irrigation over four years at the Boggabilla site. The SD (\pm) for the 2009 values is shown.

Part B. Hydrological modelling

Various modelling tools were tested, using field data collected within the Project from the lysimeter sites, to (i) test the performance of these model in accurately predicting DD and (ii) investigate the “readiness” of these models to adequately predict DD for various soil types and climatic conditions, that may be encountered elsewhere in the irrigated cropping areas of the upper Murray Darling basin.

Four different models (SODICS, HowLeaky?, SaLF and SIRMOD/FAO-56) were tested.

B.1. SODICS

The SODICS (Solute Dynamics In Clay Soils) model, developed by Rose et al (1979), estimates soil water movement from changes in soil Chloride (Cl^-) concentration over time. Changes in Cl^- concentrations are equated to inputs (infiltrating rain plus irrigation) and outputs (the translocation of salt from the soil profile). Because many clay soils in northern Australia contain large amounts of salts that are slowly leached by rainfall or irrigation, the SODICS model has many potential applications in estimating long-term DD and identifying salinity hazards. SODICS has been used extensively to provide information about the “leakiness” of cultivated fields in rainfed agriculture (Tolmie et al. 2003) and has been used in a few studies of irrigated agriculture (e.g. Thorburn et al. 1990).

The SODICS model was applied to soil chloride data (Cl^-) collected from five of the DD sites over the period 2002 to 2007. The Cl^- data was obtained from the analysis of soil cores sampled to 1.5 m, immediately surrounding each of the lysimeter locations at the five sites, and cut into 0.1 m sample depths.

Results of the SODICS analysis showed that almost all the predicted DD values at all field locations in the five sites were negative, showing a “drainage deficit” (ie water was not draining from the soil). The exception was St George (N) where the head and tail locations had DD values of 254 and 64mm, respectively (Table 3). Note that the St George (N) site no longer exists as it was decommissioned in 2008.

Considering all sites, and based on the initial (2002) and final (2007) Cl^- values, the SODICS model calculated significant increases in stored salt to 1.35m depth at all sites (Table 3). It also appeared that all sites were far from reaching steady state (where the salt exiting the soil profile is replaced by salt from the applied waters). It should be noted, however, that most of the soil samples were taken during winter from bare fallow fields, so it is possible that the Cl^- increase with increasing depth, down the soil profile was due to upward movement of salt outside the irrigation season. This hypothesis, however requires testing (i.e. coincidence of salinity “spikes” with sampling time).

Table 3. Estimation of DD using SODICS simulation. Outputs based on changes in soil chloride profiles from 2002 to 2007; drainage at 1.35m depth. The sum of DD measured by lysimetry for each of the head, mid and tail locations from 2002 to 2007 is given in [square brackets]. **Note:** the St George (S) site is the current “St George” site and the Dirranbandi and St George (N) sites were lysimeter sites, established in an early phase of this project and now de-commissioned.

| Site | Location | DD (mm) | Start Cl ⁻ (t/ha) | Final Cl ⁻ ¹ (t/ha) | Leached (%) | Years to 90% steady state | SS drainage (mm/Yr) |
|----------------------|----------|---------------|---------------------------------|--|----------------|------------------------------------|---------------------------|
| Macalister | Head | -144 [274] | 39.0 | 64.6 | -66 | No | 0.5 |
| | Mid | -74 [147] | 38.0 | 54.4 | -43 | No | 0.5 |
| | Tail | -234 [84] | 31.1 | 58.4 | -88 | No | 0.6 |
| Goondiwindi | Head | -667 [526] | 0.9 | 4.5 | -416 | No | 33.1 |
| | Mid | -796 [320] | 0.4 | 6.3 | -1333 | No | 58.6 |
| | Tail | -232 [76] | 1.6 | 3.9 | -139 | No | 18.1 |
| St George (S) | Head | -283 [163] | 3.7 | 7.3 | -109 | No | 8.1 |
| | Mid | -181 [321] | 1.0 | 1.9 | -88 | No | 33.6 |
| | Tail | -248 [138] | 2.1 | 4.2 | -98 | No | 14.0 |
| St George(N) | Head | 254 [51] | 6.7 | 4.0 | 40 | 21 | 4.8 |
| | Mid | -83 [77] | 9.5 | 12.6 | -32 | No | 2.2 |
| | Tail | 62 [2] | 17.6 | 14.9 | 15 | 65 | 1.2 |
| Dirranbandi | Head | -14 [11] | 13.6 | 14.4 | -6 | No | 1.9 |
| | Mid | -101 [22] | 5.3 | 7.4 | -40 | No | 4.8 |
| | Tail | -180 [182] | 7.6 | 12.4 | -62 | No | 3.3 |

To investigate the outputs of the SODICS model for a shorter time period, the soil Cl⁻ profiles from the Macalister site for the 2003 and 2004 period were selected. SODICS showed the greatest DD at the mid location (456 mm) while the tail had the least (163 mm) and DD at the head between the two (378 mm). Though the magnitude is 3 to 4 times that of the measured DD values, the “trend” was in agreement with the (lysimeter)

collected DD values for the irrigated cotton crop in the 2004-5 season where 41, 101 and 0 mm were recorded at the head, mid and tail, respectively.

B.2. HowLeaky?

HowLeaky? is a daily time step model of the soil water balance. It is a one-dimensional model that represents an area with uniform climate, soil and vegetation. HowLeaky? accounts for inputs from rainfall and irrigation and estimates runoff, transpiration, soil evaporation and deep drainage. Where input data are available, it can also estimate soil erosion and pesticide, nutrient and solute transport, albeit with less precision. Errors in predictions arise from errors and unknowns in the input parameters and limitations of the mathematical representations in the model.

Analyses were conducted for the 2004-05 season where, for five of the lysimeter sites, all the required input parameters were available and enabled the construction of required fields on soil, vegetation and climate for simulations. The simulation outputs showed that there was no similarity between the simulated DD values and DD measured in the same season by the lysimeters (Table 4).

Table 4. Water balance components derived from HowLeaky? simulations for the 2004-05 irrigated season at five deep drainage monitoring sites. Soil water deficit (SWD) was set to 75 mm and irrigating to saturation for simulation. The average DD (average of of head, mid and tail) of the 2004-05 season from the lysimeters is given in [square brackets].

| Water balance components (mm) | Dalby | Goondiwindi | Macalister | Pampas | St George |
|-------------------------------|-----------------|-----------------|-----------------|------------------|-----------------|
| Rainfall | 199 | 251 | 206 | 242 | 251 |
| Irrigation | 711 | 592 | 652 | 503 | 826 |
| Runoff | 6.2 | 7.3 | 13 | 89.9 | 73.2 |
| Soil Evaporation | 191 | 199 | 163 | 176 | 154 |
| Transpiration | 518 | 489 | 475 | 525 | 471 |
| Deep drainage | 304 [56] | 259 [49] | 294 [27] | 15.1 [80] | 475 [71] |

B.3. SaLF

The “Salt and Leaching Fraction” (SaLF) model (Shaw and Thorburn, 1985) was run for each of the soil lysimeter sites, using the soil chemistry data, from each of the head, mid and tail locations separately (as individual soil cores had been collected from each of these locations at time of lysimeter installation).

SaLF analysis is based on the assumption that DD is related to the soil hydraulic conductivity, which in turn is influenced by the amount of clay (%), clay mineralogy (defined by the ratio of CEC/clay %) and exchangeable sodium percentage (ESP) of the soil at any given site. The soil physico-chemical properties used in the current analysis were clay (%), soil CEC (meq/100g), air dried moisture content (%), annual rainfall (mm), seasonal irrigation amount (mm), EC of the irrigation water (dS/m) and soil ESP at 0.9 m depth (meq/100g).

Simulations were conducted for a variety of irrigation seasons at each site; in this way the soil physico-chemical data remained the same but the seasonal irrigation amount and the EC of the irrigation water (or rain water) varied between seasons (Table 5). Predicted DD

for all sites, apart from Boggabilla (LM) were usually far smaller and mostly totally dissimilar to the actual DD values measured by the lysimeters. In particular, the Boggabilla (F), Dalby, Goondiwindi and St George predicted data had no similarity to the measured DD. This dissimilarity was for both seasonal and in-field location values.

Table 5. Deep drainage predicted by SaLF simulations for head, mid and tail locations at each lysimeter site. The actual DD values measured in that season at the head, mid and tail are given in the [square brackets]. **Note:** the St George (S) site is the current “St George” site and the Dirranbandi and St George (N) sites were lysimeter sites, established in an early phase of this project and now de-commissioned.

| Site | | Deep drainage (mm) | | |
|------------------------|-------------------|--------------------|--------------|----------|
| | Crop/season | Head | Mid | Tail |
| Boggabilla (F) | Cotton/ '05 – '06 | 9 [105] | 16 [87] | 14 [92] |
| | Fallow/ '06 – '07 | 0 | 0 | 0 |
| | Cotton/ '07 – '08 | 6 [19] | 10 [40] | 9 [1] |
| Boggabilla (LM) | Cotton 05 – 06 | 3 [31] | 2 [0] | 3 [0] |
| | Fallow 06 – 07 | 2 [0] | 1 [0] | 2 [0] |
| | Cotton 07 – 08 | 2 [0] | 1 [0] | 2 [0] |
| Dalby | Cotton 04 - 05 | 169 [39] | 175 [95] | 522 [34] |
| | Soybean 05- 06 | 162 [0] | 168 [0] | 490 [0] |
| | Sorghum 06 - 07 | 19 [0] | 18 [17] | 136 [0] |
| Dirranbandi | Cotton 03 - 04 | 9 [11] | 14 [21] | 17 [176] |
| | Cotton 05 - 06 | 6 [0] | 10 [1] | 12 [6] |
| Goondiwindi | Sorghum 03 - 04 | 8 [235] | 3 [101] | 4 [21] |
| | Cotton 04 - 05 | 9 [104] | 4 [23] | 5 [19] |
| | Sunflower 05 - 06 | 5 [0] | 2 [1] | 3 [11] |
| Macalister | Cotton 04 - 05 | 92 [41] | 118 [101] | 100 [0] |
| | Cotton 05 - 06 | 38 [12] | 48 [10] | 41 [0] |
| | Cotton 06 - 07 | 65 [31] | 83 [26] | 71 [0] |
| | Barley 07 - 08 | 1.5 [72] | 1.9 [6] | 1.6 [0] |
| Pampas | Cotton 04 - 05 | 91 [71] | 72 [106] | 185 [72] |
| St George | Cotton 03 - 04 | 7 [104] | 5 [91] | 4 [18] |
| | Cotton 04 - 05 | 6 [40] | 4 [92] | 4 [50] |
| | Field pea 05 - 06 | 3 [5] | 2 [37] | 2 [33] |
| | Cotton 06 - 07 | 4 [0] | 3 [33] | 3 [0] |

B.4. Water balance by SIRMOD / FAO-56

Hydrological inputs and outputs of each of the fields where lysimeters had been installed were used to run SIRMOD simulations: irrigation (I), precipitation (P),

evapotranspiration (ET), runoff (R), change in soil water storage (ΔS) and Infiltration (In).

$$\text{Infiltration (In)} = \text{DD} = (\text{I} + \text{P}) - (\text{R} + \text{ET} + \Delta S)$$

The field input parameters for the SIRMOD simulations were gathered from *Irrimate*® irrigation monitoring equipment; specifically Irrimate advance sensors that measured (irrigation) water advance down the field and siphon flow meters that measured volumetric input and irrigation duration for each irrigation. Data from the on-site weather stations was used to calculate evapotranspiration (ET), using FAO-56. DD was calculated as follows (assuming ΔS is negligible)

$$\text{DD} = (\text{P} + \text{I}) - \text{ET}$$

Measurements were collected from two field sites in the 2003-04 season and five sites in the 2004-05 season to estimate DD by SIRMOD and FAO-56 methods (Table 6). In general DD simulated by SIRMOD and FAO-56 showed no similarity to the measured DD values.

Table 6. Deep drainage estimated from SIRMOD simulations (R, rainfall; I, amount of irrigation water that infiltrated the soil profile; ET, crop evapotranspiration; DD and LF for two cotton seasons. The actual DD values measured in that season at the head, mid and tail are given in the [square brackets].

| | | R (mm) | I (mm) | ET (mm) | DD (mm) | LF (%) |
|-------------------------|------|--------|--------|---------|-----------|--------|
| <i>2003/2004 Season</i> | | | | | | |
| St George | Head | 386 | 873 | 1255 | 4 [104] | 0.3 |
| | Mid | 386 | 790 | 1255 | 0 [91] | - |
| | Tail | 386 | 558 | 1255 | 0 [18] | - |
| Goondiwindi | Head | 379 | 534 | 843 | 70 [235] | 7.7 |
| | Mid | 379 | 479 | 843 | 5 [101] | 1.7 |
| | Tail | 379 | 289 | 843 | 0 [21] | - |
| <i>2004/2005 Season</i> | | | | | | |
| St George | Head | 394 | 1144 | 1300 | 238 [40] | 15.5 |
| | Mid | 394 | 1051 | 1300 | 145 [92] | 10.0 |
| | Tail | 394 | 814 | 1300 | 0 [50] | - |
| Goondiwindi | Head | 390 | 1287 | 1340 | 337 [104] | 20.1 |
| | Mid | 390 | 1183 | 1340 | 233 [23] | 14.8 |
| | Tail | 390 | 746 | 1340 | 0 [19] | - |
| Macalister | Head | 305 | 1275 | 1402 | 178 [41] | 11.3 |
| | Mid | 305 | 1103 | 1402 | 6 [101] | 0.4 |
| | Tail | 305 | 449 | 1402 | 0 [0] | - |
| Dalby | Head | 248 | 1006 | 1180 | 74 [39] | 5.9 |
| | Mid | 248 | 958 | 1180 | 26 [95] | 2.2 |
| | Tail | 248 | 789 | 1180 | 0 [34] | - |

| | | | | | | |
|---------------|------|-----|------|------|-----------|-------------|
| Pampas | Head | 486 | 1059 | 1332 | 213 [71] | <i>13.8</i> |
| | Mid | 486 | 1005 | 1332 | 159 [106] | <i>10.7</i> |
| | Tail | 486 | 770 | 1332 | 0 [62] | - |

Part C

Groundwater level changes with time in the St George irrigation area

Introduction

The investigation of water level changes with time in the groundwater inspection bores of the St George (south) irrigation area (SGIA) commenced in mid-2006. Data collection (twice daily logging and routine, manual dips) continued to March 2011. This section of the Final Report will (i) present these data, (ii) aim to rationalise them in terms of above ground events (rainfall, floods and irrigation infrastructure construction) and (iii) consider if evidence exists of a threat of rising groundwater under the SGIA.

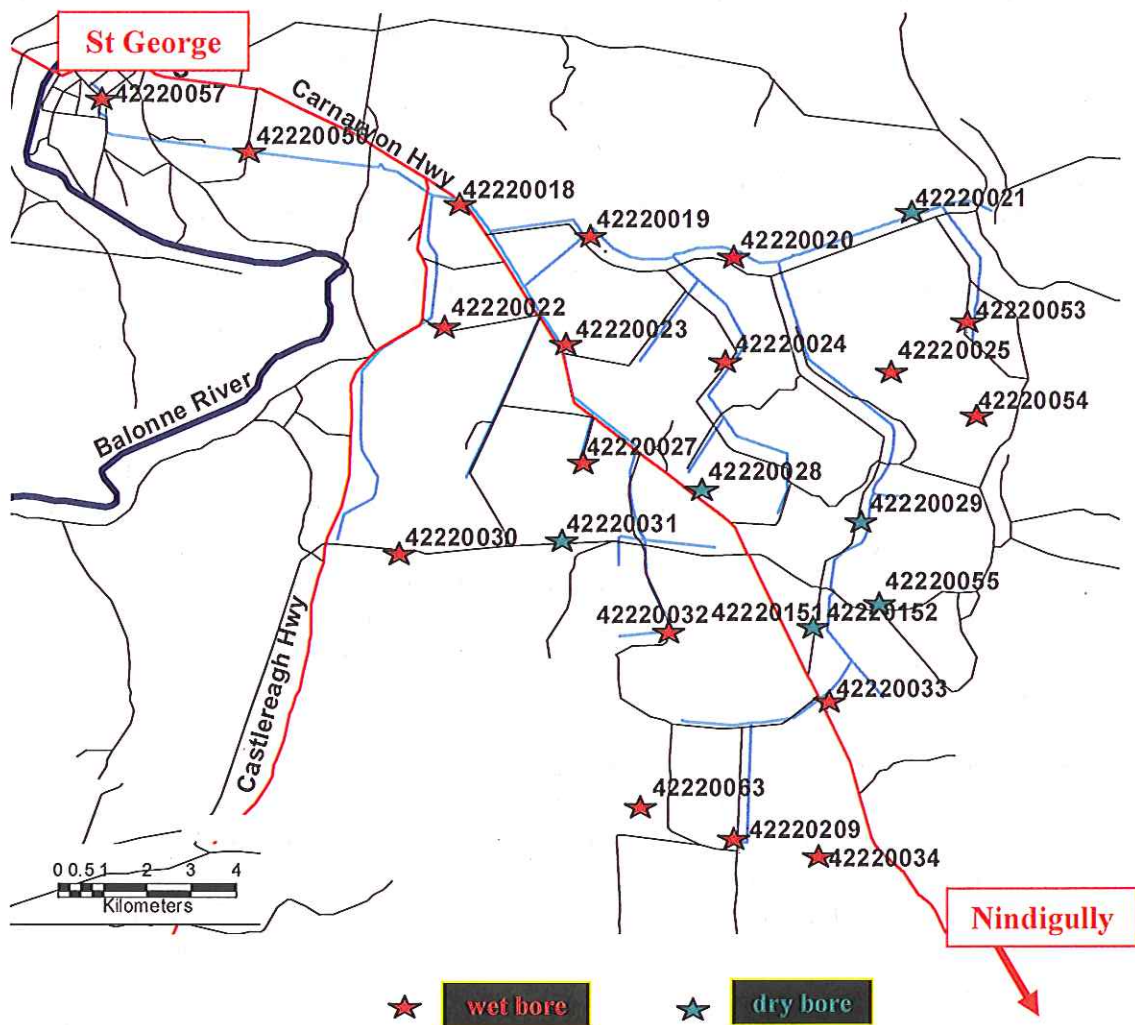


Fig. 4. Location of dry and wet inspection bores in St George Irrigation Area

The SGIA lies to the south east of the town of St George on the Balonne River (Fig. 4) and was opened to irrigation *via* the original St George supply channel in the mid 1950's by the Queensland Irrigation and Water Supply Commission. The initial scheme was devised for fat lamb fodder production, and consisted of construction of the Jack Taylor Weir in 1953 and subsequent irrigation of approximately 2,700 ha of land *via* the original St George supply channel. The next phase of expansion occurred in the early 1970s, with the construction of Beardmore Dam on the Balonne River (1972) and subsequent construction of the Buckinbah supply channel, and the Buckinbah and Moolabah Weirs on the Thuraggi watercourse. This expansion enabled the current total of 9,470 ha of irrigable land. Cotton is the main crop, although cereals, oilseeds and fodder are also grown.

There are a total of 24 observation boreholes within the irrigation area (Fig. 4). Of these, 16 have been found to contain water (hereafter termed the "wet" boreholes) and the remainder have (apparently) been dry, since installation. One borehole (Registered Number 42220026) has been destroyed without trace. All boreholes consist of 50 mm diameter PVC pipe, perforated with cut "slots" at a selected depth to monitor groundwater levels, and protected on the surface with a metal sheath.

Drillers' logs and historic water level collection

During installation of the inspection boreholes, records were kept ("drillers' logs") of the type and depths of materials being removed, and bore construction details such as the depth of slots cut into the PVC pipe. Subsequently, water level records of the boreholes in the investigation area have been monitored manually from installation by tape measure.

Early project field methods

From 11 - 15 December 2006, DERM staff conducted down-borehole video investigations, using an AUSLOG "Mighty Cam" system. The sixteen "wet" inspection bores were investigated with colour video footage taken to the end of each borehole. The purpose was to determine the condition of the inspection boreholes, specifically the integrity of casings and joints, the nature and location of slots, and the general effectiveness of these bores as monitoring bores, particularly with knowledge that many of the bores were drilled more than 30 years ago.

To log groundwater levels in the wet boreholes, 16 Divers DI 501 loggers were purchased and each programmed to log water level twice daily (midday and midnight). As required, to provide the important correction for barometric pressure, a Divers Baro logger was also purchased and programmed to log on the same interval as the DI 501s. All loggers were suspended on stainless steel wire such that the loggers were suspended at least 2 m under the current water level, in each bore. The Baro logger was located in the centre of the "nest" of wet boreholes and was suspended on stainless steel wire 1 m under the protective PVC cap at borehole 4222023. Logger installation occurred on two separate occasions: in the weeks commencing 11 December 2006 and 22 January 2007.

Logger reliability was a constant problem over the 4 years of data logging with loggers persistently ceasing to function. This is evident in the plots of the logged data (Appendix 1) as data gaps, when the logger was installed in the borehole but had malfunctioned and there was no data collection. The reason for the unreliability was a

continuing manufacturer's fault, so all malfunctioning loggers were replaced under warranty. Manual dips continued to be recorded in the four years of data logging. A manual dip was taken on every site visit when the loggers were downloaded.

RESULTS

C.1. The location of inspection boreholes

The details of each bore are in Table 7. Additionally, Fig. 5 presents a visual representation of each borehole in terms of stratigraphy (from borehole logs where available), ground surface elevation, standing water level (December 2006 data), presence / position of slots, and presence of a sump (below the slots). All of these data were obtained from the Groundwater Database (GWDB) of Queensland Government.

Installation of the 23 boreholes spanned a 30 year period, from 1972 to 2002 (Table 1). This wide range of ages adds to the heterogeneity of several aspects of the boreholes including physical considerations such as borehole depth and construction (eg slot type and location) but also an apparent change in the philosophy governing borehole location.

- The bores drilled in the 1970s were placed immediately beside channels (except two: 42220028 and 42220031), specifically to monitor potential channel leakage.
- In the mid 1980s, on-farm water storages were constructed, so some boreholes were located alongside these (eg 42220034), apparently to test if the storages were leaking and causing groundwater rise. The most recent bores (including 42220209) were drilled as part of the National Action Plan for Salinity and Water Quality (NAP) initiative¹. These bores tend to be deeper, have more detailed logs of stratigraphy, and utilise tools like down-hole geophysics to aid interpretation of results.

The various ages of bores is also reflected in the nature and placement of slots and sumps in the boreholes. The down-hole camera observations showed that slots were present in all boreholes, though these ranged from vertical, horizontal or angled cuts with varying aperture size and spacing. Video inspection also showed that most bores (all but five) have sumps (where the PVC extends below the slotted section) and that all the sumps have been drilled with holes (approx. 3 mm drill bit), to drain the water once the regional water table fell below the casing.

Table 8 presents field notes of the proximity of the wet and dry inspection bores to local physical structures that may have an impact on the presence/absence of water in the bore, the water level (SWL ie metres below surface) of the water, and the dynamics of this level. Recorded were phenomena such as proximity to water carrying channels and on-farm storages, land use around the bore, and the seasonality of water in these channels and storages.

The majority of inspection boreholes (14 of 23) are located beside channels, and several of these (5) are also located next to on-farm storages. Two bores are located in natural, treed areas. However, there appears to be minimal correlation between the

¹ The general aim of the National Action Plan for Salinity and Water Quality was to provide new knowledge and developing methodologies for improved natural resource management in the Murray Darling Basin of southern Queensland, and more specifically to understand the processes and controls on salinity in the region.

location of bores to potential supply phenomena and whether a bore is dry or wet, and the level of water in the bore. For example, both 42220031 and 4222054 are in treed “reserves” / grazing land, some distance from water bodies. However, the former is wet and the latter dry. Of the bores installed in the 1970s (42220018 to 4222034) all but two (42220028 and 42220031) are located besides channels. However, six of these are dry bores.

Table 7. Information for the 16 wet inspection bores in the St George Irrigation Area. *SWL is the standing water level which is the depth from soil surface to the water surface within the inspection borehole, measured during field visits in September 2006.

** GCF is the Grimman Creek Formation.

| RN | Easting | Northing | Elevation | Date of Installation | Depth of bore (m) | Presence of Water | SWL* (m) (09/06) | Aquifer |
|----------|---------|----------|-----------|----------------------|-------------------|-------------------|------------------|----------|
| 42220018 | 661916 | 6893592 | 197.78 | 1972 | 11.30 | Wet | - 9.90 | Alluvial |
| 42220019 | 664587 | 6892891 | 197.83 | 1972 | 12.59 | Wet | - 12.39 | Alluvial |
| 42220020 | 667605 | 6892258 | 197.80 | 1972 | 12.26 | Wet | - 12.12 | Alluvial |
| 42220023 | 664129 | 6890356 | 196.78 | 1972 | 12.48 | Wet | - 5.87 | Alluvial |
| 42220024 | 667258 | 6889976 | 197.18 | 1973 | 12.76 | Wet | - 9.23 | Alluvial |
| 42220025 | 670497 | 6889774 | 196.01 | 1973 | 12.92 | Wet | - 6.19 | Alluvial |
| 42220027 | 664310 | 6887636 | 196.33 | 1972 | 12.20 | Wet | - 9.68 | Alluvial |
| 42220030 | 660500 | 6885644 | 194.82 | 1972 | 26.26 | Wet | - 20.01 | GCF** |
| 42220032 | 665987 | 6883738 | 193.75 | 1972 | 31.07 | Wet | - 17.57 | GCF |
| 42220033 | 669167 | 6881968 | 192.99 | 1972 | 32.80 | Wet | - 31.10 | GCF |
| 42220034 | 668965 | 6878541 | 193.28 | 1972 | 22.97 | Wet | | GCF |
| 42220053 | 672030 | 6890679 | 196.97 | 1989 | 20.05 | Wet | - 19.01 | Alluvial |
| 42220054 | 672048 | 6888574 | 196.26 | 1989 | 18.20 | Wet | - 11.49 | Alluvial |
| 42220056 | 657841 | 6894915 | 199.58 | 1990 | 18.80 | Wet | - 11.87 | Alluvial |
| 42220057 | 655035 | 6895917 | 199.63 | 1989 | 14.56 | Wet | - 10.49 | Alluvial |
| 42220209 | 667393 | 6878738 | 192.52 | 2002 | 41.14 | Wet | - 31.69 | GCF |

C.2. Stratigraphy and slot locations

Information from the bore logs (where available) in terms of stratigraphy, the location of slots and the stratigraphy at the slots location is given in Table 9 and Fig. 5. Generally, records of the early borelogs (1970s) gave simple descriptors of materials removed during drilling. Evident from Table 9 is that the placement of slots is not consistent in terms of either depth or material (at that depth). There seems to have been a rationale with the 1970s bores to drill to and slot at approximately the same depth (11.6 m to 12.2 m), irrespective of what materials occurred at that depth. This depth represents the total length of two lengths of PVC casing. At this depth, some of the bores tap sands and gravels, and others tap clay rich materials.

C.3. General Condition of Bores (down hole video inspections)

In general, the outcome of the down borehole monitoring demonstrated that the majority of bores were in good condition, with sound casing and joints, and clean slots. A few cracks in the casing were found (for example 42220019 had a crack at the join between the casing and the slotted section; not considered problematic as located close to the slotted section). Worse were gaps between PVC casing sections in bore 42220033, that appeared to be leaking water from outside the bore casing. Several

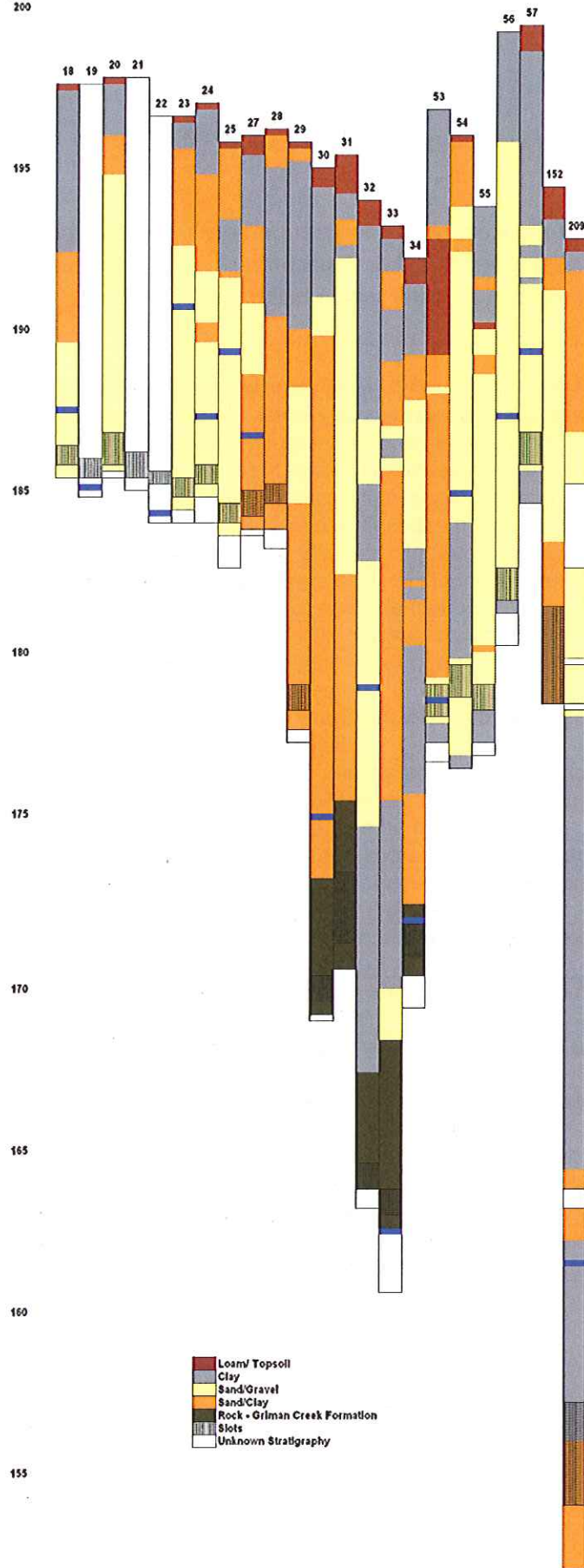


Fig. 5. Schematic cross-section of the wet inspection bores in St George irrigation area; stratigraphy (from borehole logs), ground surface elevation, recent standing water presence / position of slots, and presence of sump (below slots). The “y” axis (ASL) is given as metres above sea level.

bores had slots that were clogged with silt (42220022) or an algae like substance (422200209).

Table 8. Location of the wet and dry inspection boreholes in respect to water carrying channels, irrigated cotton fields, other types of vegetation and on-farm storages (and their seasonality in relation to water level changes).

| RN | Site description – with respect to proximity to water bodies | Presence of Water |
|----------|---|-------------------|
| 42220018 | beside channel (permanently water filled) no fields nearby | Wet |
| 42220019 | beside channel (permanently water filled) close to cotton fields | Wet |
| 42220020 | beside channel (seasonally water filled) close to cotton fields | Wet |
| 42220021 | beside channel (seasonally water filled) close to cotton fields | Dry |
| 42220022 | beside channel (seasonally water filled) close to cotton fields | Dry |
| 42220023 | beside channel (permanently water filled) beside road | Wet |
| 42220024 | between 2 channels (one permanently water filled, the other seasonal) close to cotton fields | Wet |
| 42220025 | beside channel (permanently water filled) beside road | Wet |
| 42220027 | In a channel – on edge; (seasonally water filled) between cotton fields | Wet |
| 42220028 | beside highway, distant from supply channel but in middle of cotton fields | Dry |
| 42220029 | beside channel (seasonally water filled) and tail ditch of cotton field | Dry |
| 42220030 | beside channel (always water filled) and farm storage (seasonally full) on edge of cotton field area | Wet |
| 42220031 | In a treed area – hundreds of metres from channels and fields | Dry |
| 42220032 | beside channel (seasonally water filled) and farm storages (seasonally full) in middle of cotton fields | Wet |
| 42220033 | beside highway and large farm storage (seasonally full) in middle of cotton fields | Wet |
| 42220034 | between three farm storages and one channel (all seasonally water filled) in middle of cotton fields | Wet |
| 42220053 | beside channel (seasonally water filled) and in middle of cotton fields | Wet |
| 42220054 | in a treed area – 200 metres from channels, storages and fields | Wet |
| 42220055 | beside channel (permanently water filled) | Dry |
| 42220056 | beside channel (permanently water filled) close to drip irrigation field | Wet |
| 42220057 | beside channel (permanently water filled) no fields nearby | Wet |
| 42220152 | beside channel (permanently water filled) close to cotton fields | Dry |
| 42220209 | at southern end of irrigation area, channels nearby (permanently water filled) between cotton fields and edge of irrigated land | Wet |

Table 9. Depth of slots and stratigraphy at that depth for each of the wet and dry inspection boreholes.

| RN | Location of slots (m) | Stratigraphy at Slots | Presence of Water |
|----------|-----------------------|---------------------------------|-------------------|
| 42220018 | 11.60 – 12.22 | Sand, fine to medium | Wet |
| 42220019 | 11.60 – 12.20 | N/A | Wet |
| 42220020 | 11.20 – 12.48 | Sand, gravel, fine to v. course | Wet |
| 42220021 | N/A | N/A | Dry |
| 42220022 | 11.60 – 12.22 | N/A | Dry |
| 42220023 | 11.60 – 12.20 | Sand, fine to medium, claybound | Wet |
| 42220024 | 11.60 – 12.20 | Sand and gravel | Wet |
| 42220025 | 11.58 – 12.20 | Sand, fine to v. course | Wet |
| 42220027 | 11.53 – 12.20 | Sand, clayey, fine to course | Wet |
| 42220028 | 11.72 – 12.32 | Sand, clayey, fine to medium | Dry |
| 42220029 | 17.32 – 17.98 | Sand, clayey, fine to v. course | Dry |
| 42220030 | 25.10 – 25.70 | Multicoloured rock | Wet |
| 42220031 | 22.38 – 24.23 | Multicoloured rock | Dry |
| 42220032 | 29.81 – 30.48 | Multicoloured rock | Wet |
| 42220033 | 29.81 – 30.47 | Multicoloured rock | Wet |
| 42220034 | 20.66 – 21.33 | Multicoloured rock | Wet |
| 42220053 | 18.60 – 19.60 | Sand, medium, clay | Wet |
| 42220054 | 17.00 – 18.00 | Sand, medium, clay | Wet |
| 42220055 | 15.60 – 16.60 | Sand, clay | Dry |
| 42220056 | 17.10 – 18.10 | Sand and medium gravel, clay | Wet |
| 42220057 | 13.10 – 14.10 | Gravel and sand, sandy clay | Wet |
| 42220152 | 13.00 – 16.00 | N/A | Dry |
| 42220209 | 36.00 – 39.00 | Sand, v. fine to medium, clay | Wet |

C.4. Historic groundwater levels – data presentation and interpretation

Presentation and interpretation of the data of the historic and recent bore water levels is a major part of this Report.

Hydrographs of all bore water levels from historic and recent data for the wet inspection bores are presented in Appendix 1. Two graphs are presented for each inspection borehole: the historic data, derived from manual dips from time of bore installation to late 2006 and the twice a day logged data from the Divers loggers, from late 2006 (or early 2007) to February 2011; approximately 50 months of daily records.

C.5. Associated data sets

To aid interpretation of the historic and recent water level data, several types of data can be presented, that may have some bearing on the water level responses – hence aid in their interpretation.

- (i) Local farmers informed the authors that the construction and filling of “on farm water storages” in the SGIA commenced in the mid 1980s. Till then, all irrigation water came directly from the network of supply channels, emanating from Beardmore dam. The filling of these on farm storages represented a significant change in the amounts and periodicity of water storage in the SGIA; the storages remaining completely or partly full, year round.
- (ii) Though the average annual rainfall in St George is 520 mm, there have been many instances, in the lifetime of the inspection boreholes (1972 onwards) of intense rain. Fig. 6 presents the daily rainfall totals from early

1970 to mid 2011. Several, very large daily rainfall totals are marked. In order of daily totals > 100 mm, in descending order:

- a. (i) 219 mm (4/3/1982),
 - b. (ii) 192 mm (23/5/1983),
 - c. (iii) 138 mm (13/1/1974),
 - d. (iv) 130 mm (17/1/2004),
 - e. (v) 126.8 (2/3/2010)
 - f. (vi) 105 mm (10/12/2004).
- (iii) The town of St George and its surrounding area have experienced several major floods in the period from 1972 to present. For the time period under consideration, major flood events were recorded in 1975, 1976, 1983 (twice), 1988 and 1996; and more recently in March 2010 and January 2011 (Fig. 7 and Table 10). Generally these floods have occurred in the first half of the year although records indicate that they may also occur in late spring. This corresponds well with the six greatest daily rainfall totals in (ii), above, where five occurred in the period December to March.

Table 10. Summary data (metres) of the flood history of the Balonne River at the St George flood gauging station.

| | May 1983 | April 1988 | April 1990 | January 1996 | March 2010 | early January 2011 | late January 2011 |
|----------------|-------------|---------------|---------------|-----------------|---------------|--------------------------|-------------------------|
| metres: | 11.17 | 9.90 | 12.24 | 10.98 | 13.39 | 13.20 | 12.49 |

C.6. Historic and recent groundwater level data

The historic and recent data for all the wet boreholes are plotted in Fig. 8 on a common Y-axis (being SWL – water level in metres below land surface). In these graphs, the yellow lines and symbols are the historic (manual dip) data and the pink lines and symbols are the recent electronically-logged data.

Several comments can be made on the data values and trends in Fig. 8 that influence the potential to fully interpret the data presented in Appendix 1. These generalities will be further investigated for individual boreholes, later.

- (i) There is an almost 30 m differential in SWL across the range of inspection boreholes (5 m to 35 m SWL), reflecting each of (a) the complex stratigraphy of the study area (evident in Fig. 5) (b) that the slots in boreholes were placed at different levels (Fig. 5) presumably to monitor water level changes of different aquifers and (c) the different total lengths of the inspection bores with a 28 m range in lengths (eg 42220020 is 12.3 m, 42220033 is 32.7 m, 42220209 is 40.7 m).
- (ii) Location of slots at different levels causes them to be located in different geologic materials, so presumably materials of different water permeability and storage. For example, (a) 42220018, 42220020, 42220023, 42220024 and 42220025 are slotted in sand/gravel deposits, (b) 42220027, 42220028 and 42220029 are slotted in sand/clay deposits, and (c) 42220030, 42220031, 42220032, 42220033 and 42220034 are slotted

in Grimman creek formation (Fig. 5) which is a Cretaceous period sediment composed of sandstones, siltstones and mudstones.

- (iii) Continuity of data collection has been variable in terms of logging interval (a range of more than 2 per year to less than 1 per year). In particular, the 1970s and the early 2000s tended to be data rich but the 1980s and 1990s were data poor (Fig. 8). These vagaries in data collection cause difficulties in accurately relating groundwater response to the “above ground” phenomenon, presented above – including periods of heavy rain and local flooding.

The hydrographs of individual bores, presented in Appendix 1, will firstly be reviewed with general, across bore similarities/dissimilarities, and secondly data from individual bores with data of interest will be presented. Both sets of results will be interpreted as best as possible, considering the vagaries of differences in bore installation time, bore depths, slot locations and materials at slot location – as described above.

- (i) One of the most outstanding responses of bore water level in this study was the rapid and (often) large rise in groundwater level in the mid 1980s. As detailed below, 8 bores (that is 50 % of all wet bores in the SGIA and 73% of the 11 early installed (1972) bores) rose a range of 0.5 to 19 metres, commencing in the five year period from July 1981 to 1986.
- a. 42220018: had two rises – 0.7 m from July 1981 to February 1981, then 1.5 m from July 1997 to October 2005 (Fig. 9).
 - b. 42220019: had a small rise of 0.5 m from February 1984 to May 1991 (Fig. 10).
 - c. 42220024: had a large rise of 3.7 m from July 1986 to October 2002 (Fig. 13).
 - d. 42220025: had a very large rise of 6.7 m from July 1985 to May 1991 (Fig. 14).
 - e. 42220027: had a slow and steady rise of 4 metres from July 1985 to July 2005 (Fig. 15).
 - f. 42220030: had a two phase, very large rise of a total of 8 metres from December 1985 to May 1991 (3 metres), then to October 2002 (1 metre) (Fig. 16).
 - g. 42220032: had by far the greatest rise – of 19 metres from July 1985 to February 2006, then a dramatic 10 meter drop, to rise again 8 metres within a few months (Fig. 17). Of note in this bore is the “overnight” drop of over 5 metres on the 4 August 2010 (12.5 metres to 17.8 metres) that recovered 3.9 metres by 15 February 2011 to 14.1 metres.
 - h. 42220034: had a rapid 3.3 metre rise from February 1984 to May 1991 (Fig. 19).

Noteworthy is that the above mid 1980s rises occurred over a wide a range of slotted depths and materials at the slots (Fig. 5). The range of starting depths (in the mid 1980s) was 18 m (12.1 to 30.04 m).

The cause of this pattern of rises remains uncertain. However, as presented above, this was the period when on-farm storages began to be built in the SGIA, greatly increasing the quantity and periodicity (year round

presence) of surface water. Also, this period witnessed the two largest ever daily total rainfalls in St George town: 219 mm (4/3/82) and 192 mm (23/5/83) (Fig. 6). Lastly, St George had two flood peaks in 1983 (Table 10), no doubt associated with the May 1983 rain.

Generally, following the rises that commenced in the mid 1980s, the depth of water table in the 8 bores has risen (relatively) little, though there have been fluctuations in level, as reported below for selected bores.

- (ii) The only other, early installed bore (1972) that had a dramatic rise was 42220033. There was a rapid 3 metre rise from November 1993 to April 1997, then a drop of 3 metres from September 2002 to August 2003 (Fig. 17). Interpretation of this rise does not seem linked to heavy rainfall as 1993 was, generally a low rainfall period (Fig. 6), hence there were no floods in that period. This bore is located immediately beside a large storage but its construction date is unknown.
- (iii) In terms of the more recently installed bores (from mid 1991 onwards):
 - a. 42220053: was installed in May 1991, then had a rapid rise of 0.9 metres from November 1993 to July 1997
 - b. 42220054: was installed in May 1991 but had a rapid, large rise of 5.5 metres, to the present date (last sampling was February 2011)
 - c. 42220209: was installed in February 2004 and is the deepest bore water level of all the bores (commencing at 31.6 metres). There has been a slow and steady rise in this bore, totalling 1 metre from time on installation to one of the last logging occasions; January 2011 (Fig. 24).
- (iv) Two of the recently installed bores (also the two bores most closely located to St George town) have shown large decreases in groundwater levels since installation in May 1991:
 - a. 42220056 dropped almost 1 metre to November 2002 and with some fluctuations has remained almost at that lower level (Fig. 22).
 - b. 42220057 has dropped 1.2 metres to January 2010, though then rose 0.6 m to the last sampling date of February 2011 (Fig. 23).
- (v) The two bores with the shallowest ground water levels (42220023 and 42220025) seems to have been influenced both by the mid-1980s groundwater rise, as well as by recent heavy rain and associated flood events.
 - a. 42220023 rose slowly from its initial depth of 6.5 metres (1972), to 5.2 metres in April 1982 and peaking at 5.2 metres in May 1991 (Fig. 12). The recent logged data show a pronounced rise associated with a period of prolonged heavy rain in January-March 2010 when the bore level rose from 5.45 metres to 4.97 metres; a level generally maintained with the highest ever reading of 4.82 metres in late January 2011 (Fig. 12).
 - b. 42220025 rose almost 6.7 metres between July 1985 and May 1991 (Fig. 14). Generally, that water level has been maintained but the recent logged data shows two apparent rises in water level associated

with periods of heavy rain: a small rise in January – February 2008 and a dramatic and rapid rise of almost 1.2 metres from January 2011, associated with the heavy rain and associated flooding at that time. The highest level reached at that time (4.53 metres on 25 April 2011) is the highest ever recorded water level in the SGIA. Since then the water level in that bore has slowly dropped one metre, to 5.55 metres at time of the last reading (15 July 2011) (Fig. 14).

- (vi) Two bores have shown very evident cyclical change in water levels.
 - a. Bore 42220024 had two up/down cycles of water level with an almost 3 metre change in water level (Fig. 13). The cycles do not appear linked to rainfall patterns, nor winter/summer cycles.
 - b. Bore 42220027 has 10 or 11 distinct high/low cycles over the period from early 2007 to February 2011 (Fig. 15). The suggestion is that these may be linked to pumping water from this aquifer (though water pumping in the SGIA is rare) as four of the lowest water levels (2/9/2007, 20/9/2008, 25/9/2009 and 25/11/2010) correlate with the start of the irrigation season, and four of the high water levels (23/4/2008, 4/3/2009, 16/3/2010 and 15/2/2011) correspond with the end of the cotton season (when irrigations cease).

D. Conclusions

Conclusions on each of the three parts of this Report will be presented first, followed by an attempt to bring the findings of the three parts together.

Deep drainage measurements continued to be collected at the head, mid and tail locations in 10 sites, all commercial cotton growing fields, for the three years of the project. Some of these lysimeters were installed in 2003, so have been running continuously for up to 8 years. The decision to fully re-fit all pumps, solar panels and batteries at all lysimeter sites at the start of this project proved most useful, as the above-ground lysimeter apparatus ran faultlessly for the three years. The drought years up to 2010 caused many of the sites to be under bare fallow or rainfed crops, causing only one set of DD values to be collected (Macalister) in 2008-09. More sites (5) were irrigated in the 2009-10 season with seven recorded DD events with a season-maximum of 104 mm at St George mid. Most of the other values were <20mm. All sites were under irrigated cotton in 2010-11, linked to rising cotton prices and good seasonal rains. Again there were 7 DD events though with very small values recorded (all <12 mm), showing the incidence of very few irrigation events at all sites because of good and frequent in-season rains.

The EC of the DD leachates measured over the three years of the Project generally corresponded with the average EC measured over the previous five year period. The EC of the leachates continued to be far greater than the EC of the irrigation waters applied to each field. This is seen as highlighting the potential for adverse off-site effects of poor water quality from DD. The maximum increases, of 40 and 60 fold, continued to occur at St George (N) and (S), respectively. The largest EC values of the leachates continues to be at the Macalister site with an average value of 12 dS/m. This site has mostly been irrigated with bore water (EC of 4.15 dS/m) for many years.

The DD data and related soil Chloride sampling (over a 4 year period) under the lateral move and in the adjoining furrow irrigated field at Boggabilla appear to suggest salt build-up under the lateral, due to the lack of DD (ie no leaching fraction). It is emphasised that the chloride data sets to date are small and there are plans to repeat this sampling in both fields in late 2011, then mid 2013 (just before a new Project ends) to assess further these soil chloride trends.

Testing of the four hydrological models (SODICS, HowLeaky, SaLF and SIRMOD/FAO-56) provided results at variance to the lysimeter-measured, DD values.. Their output, though based on many field collected parameters, bore no resemblance to the magnitude, or seasonal or in-field trends of the lysimeter DD data. Work is already underway to fully investigate these anomalies with focus on the HowLeaky? model. In particular, the model may benefit from more detailed inputs of rain, evapotranspiration and irrigation volumes that better represent the seasonal variations through irrigated cotton crops. The latter perhaps derived from SIRMOD analysis (using advance sensors and siphon flow meters).

The groundwater monitoring work at St George has highlighted several trends, based on the historic groundwater levels and the more recent logged data. The strongest two were the dramatic rise in groundwater levels in some bores in the mid-1980s. There was a 0.5 to 19 metres rise in water table levels commencing from 1981-1986 across >70% of the 1972 installed bores. Generally, these higher levels have been maintained to date, showing the rise is probably more attributable to the installation and filling of on-farm storages in the SGIA, than recorded heavy rain and associated flooding in 1983. The highest recorded water level in an inspection bore was 4.53 metres (below the soil surface of 42220025), so some distance below the commonly accepted 2 metre level that could cause salt intrusion into surface soils from capillary rise. This shallow water level is almost directly attributable to the combination of “once in a lifetime” rainfall and associated flooding of January 2011 and the level dropped 1 metre in the following 5 months. Furthermore, in the SGIA, there are only 2 inspection bores, of a total of 24 wet and dry bores, where the water level is <5 metres below the surface (42220023, 42220025) and a further 5 where the water level is <10 metres below the soil surface (42220018, 42220024, 42220027, 42220054, 42220057). More generally, it has proven most difficult to present “overall” trends in groundwater response for the whole irrigation area; not surprising considering the heterogeneity of bore age and depths, slots in terms of depth and material at that depth, and the various distances of bores from local potential contributing phenomena like channels and storages. It is intended (budget permitting) to continue logging the wet inspection boreholes through to 2013.

The four main data sets presented here – deep drainage, soil and water salinity levels, hydrological modelling and borehole water dynamics – are undoubtedly inter-related. The DD values from all sites are far less than in the early years of this project (2003 to 2005) when up to 200 mm of DD was measured. It is believed that Cotton growers are beginning to understand and implement the “best management practices” (BMPs) suggested earlier. As such, these BMPs are perhaps the best way to bring together the data in this report since the data presented herein has caused minimal change in advised BMPs from the 2003 to 2008 period. The most important message is to “get water on and off the field as quickly as possible”; to greatly reduce water ponding that has clearly been shown to give large DD values. Secondly, a rapid pre-irrigation may

prove useful in closing many of the major cracks (from the dry ending of a previous crop), hence greatly reduce DD from subsequent irrigation events. The need to minimise DD is further emphasised by the continuing large EC values of the DD leachates – always far greater than the irrigation waters being applied. Thirdly, based on the chloride data from the field under the lateral move at Boggabilla, the almost total lack of DD appears to be increasing soil salt levels, and emphasises the need for routine EC and chloride monitoring of both soil and water (irrigation water and leachate if possible). If salts are accumulating in the rootzone, then a routine flushing of the soil may be required (the lateral on “high” flow, cracked soil after a dry (weather) harvest, in winter on a fallow field – to reduce ET).

E. Future potential research focus

- a. Accurate prediction of DD and other water balance component is vital to irrigated landscapes with ever increasing salinity risk. It is not practicable to directly measure water balance with lysimetry across all catchments, hence there is demand for application of modelling tools. The HowLeaky? model requires further validation to predict water balances of irrigated fields closer to reality. Investigation of how this may be achieved will be gained by careful investigation of model itself for various irrigation managements, soil types, in-season weather and cropping system scenarios.
- b. Contemporary issues associated with irrigation systems that improve WUE, particularly long-term sustainable adaptations of such technologies (towards developing BMP's) requires careful monitoring of long term salinity balances in a range of irrigated landscapes.

Reference

Gunawardena, T.A., McGarry, D., Robinson, J.B., Silburn, D.M. (2011). Deep drainage through Vertosols in irrigated fields measured with drainage lysimeters. *Australian Journal of Soil Research*. **49**, 343–354.

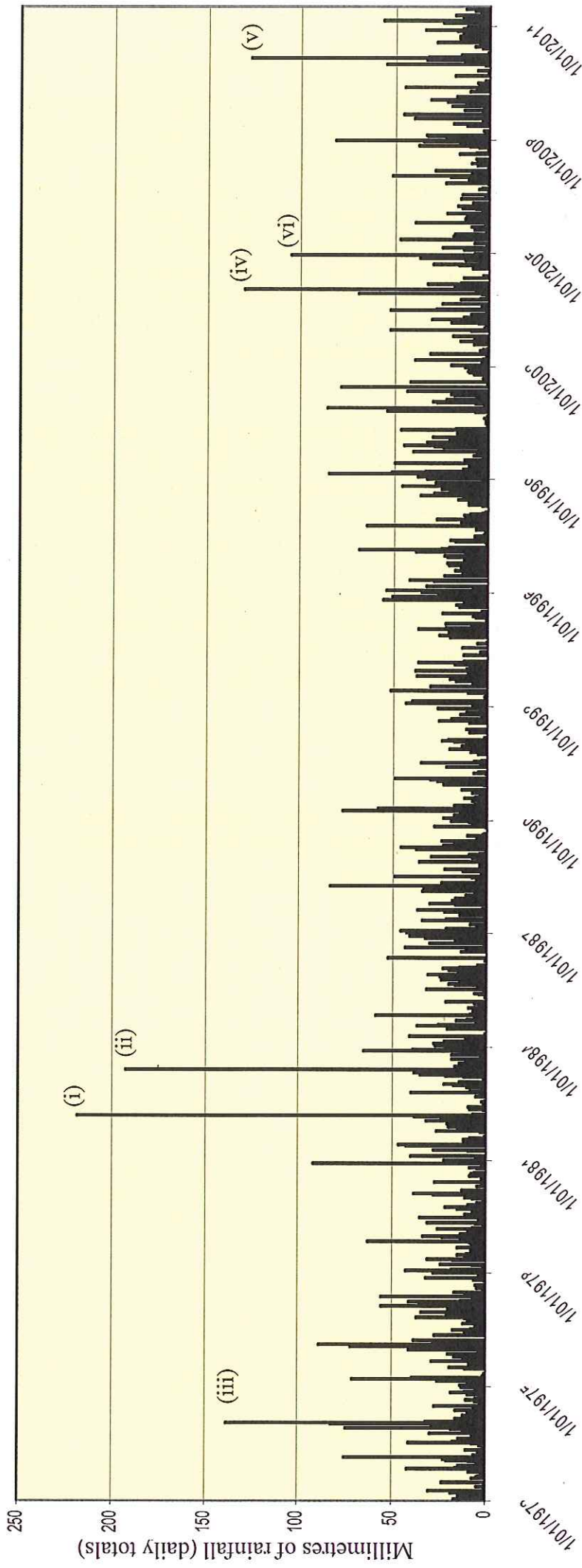


Fig. 6 Daily rainfall totals, St George Post Office, from 1st January 1970 to 14 July 2011. The six daily totals >100 mm are marked: (i) 219 mm (4/3/82), (ii) 192 mm (23/5/83), (iii) 138 mm (13/1/74), (iv) 130 mm (17/1/04), (v) 126.8 mm (2/3/10) and (vi) 105 mm (10/12/04).

Balonne R at St George (manual)
Highest Annual Flood Peaks

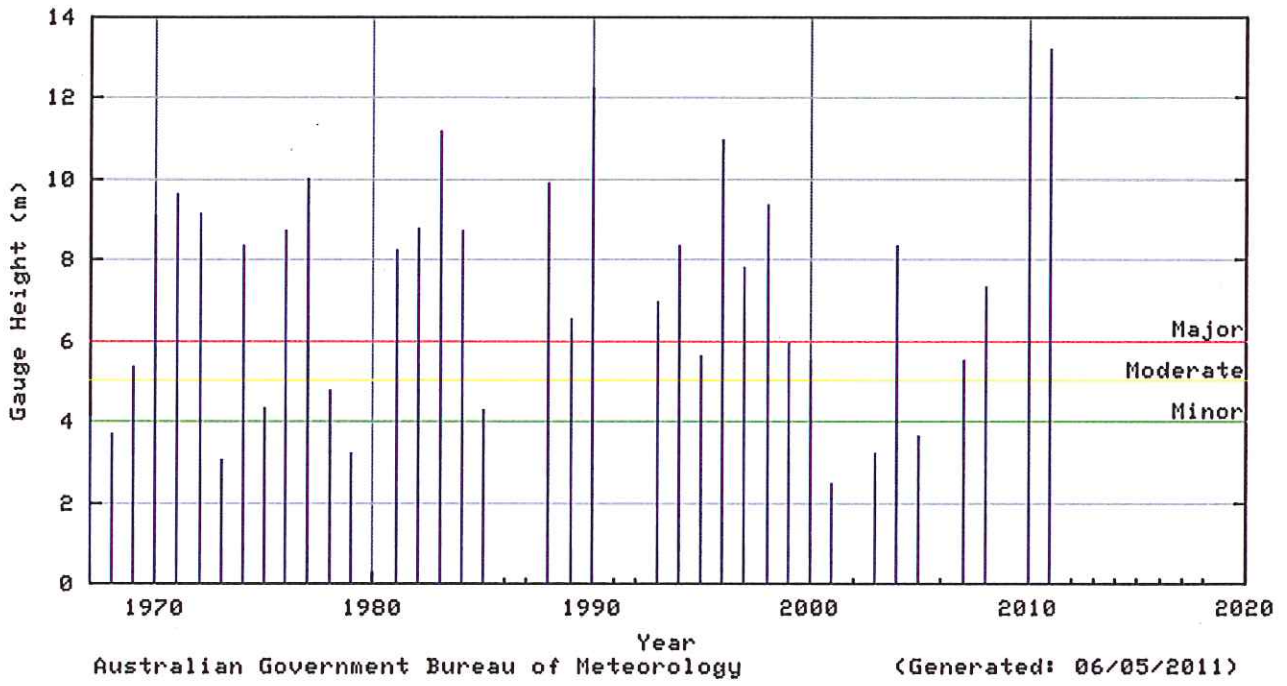


Fig.7. Highest recorded flood peaks of the Balonne River at St George township.

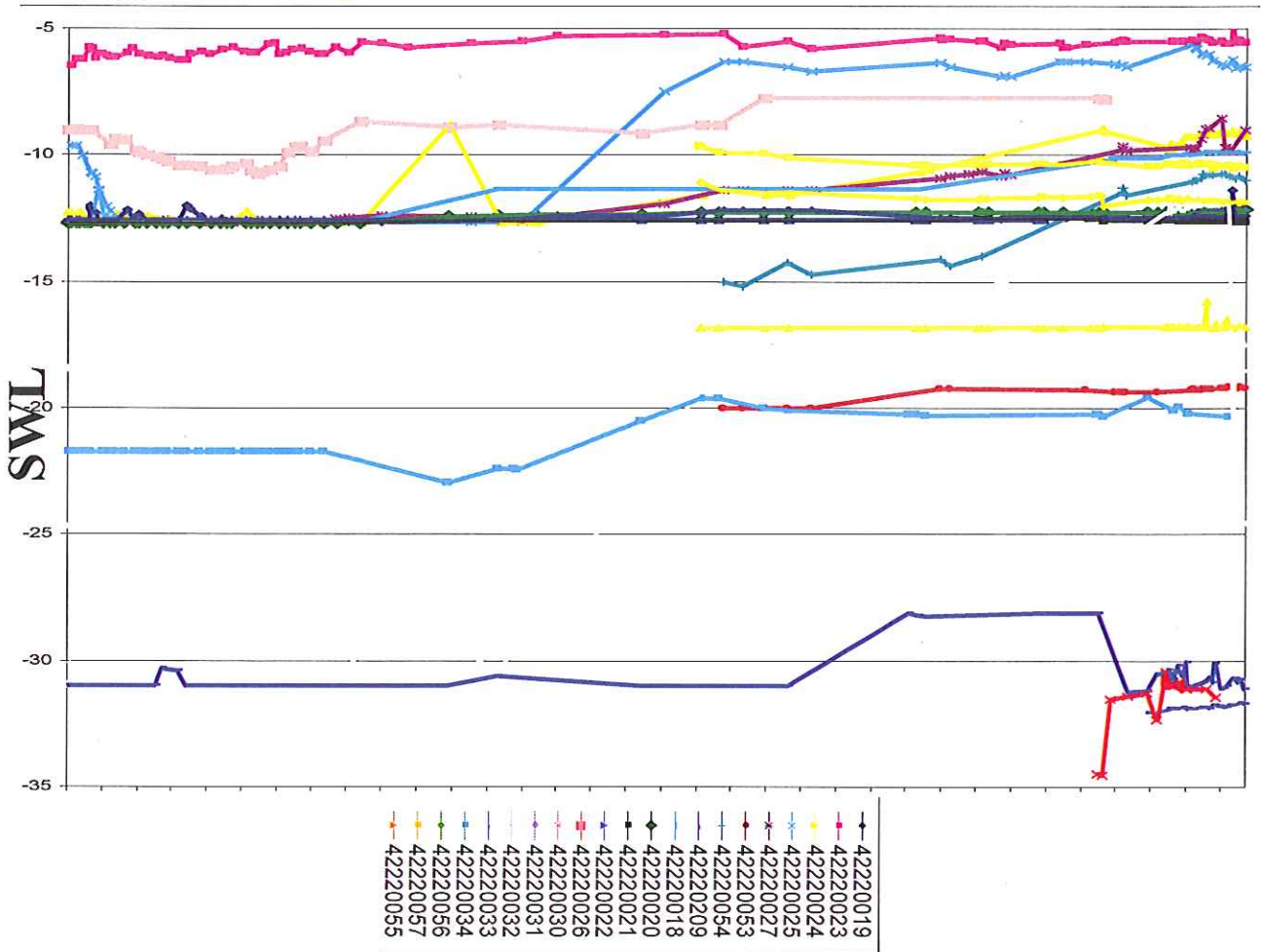


Fig 8. Historic water level borelogs for all the St George wet inspection boreholes, plotted for SWL ie metres below land surface.

Appendix 1

Historic Water Level Graphs (borelogs) of the St George Inspection Bores

Two graphs are presented for each of the wet inspection boreholes: (i) the historic data, mostly from 1972 and sourced from manual dipping of water levels, together with (ii) the more recent, twice daily (12 h interval) water level data, presented separately to seek out short term variations in water table depths.

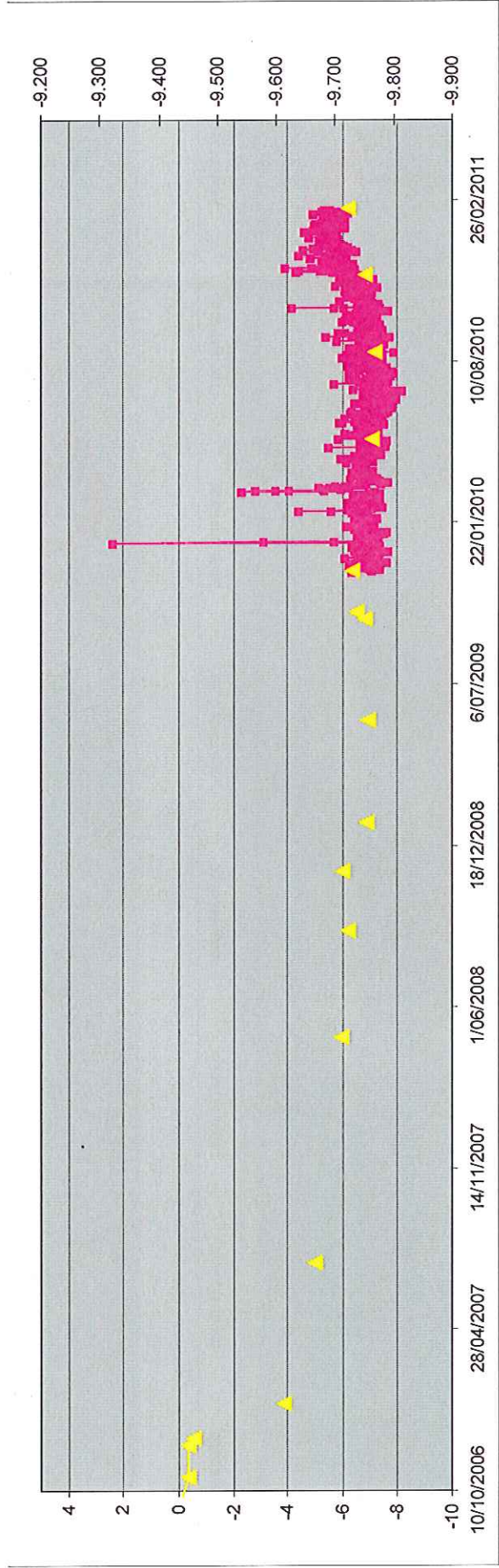
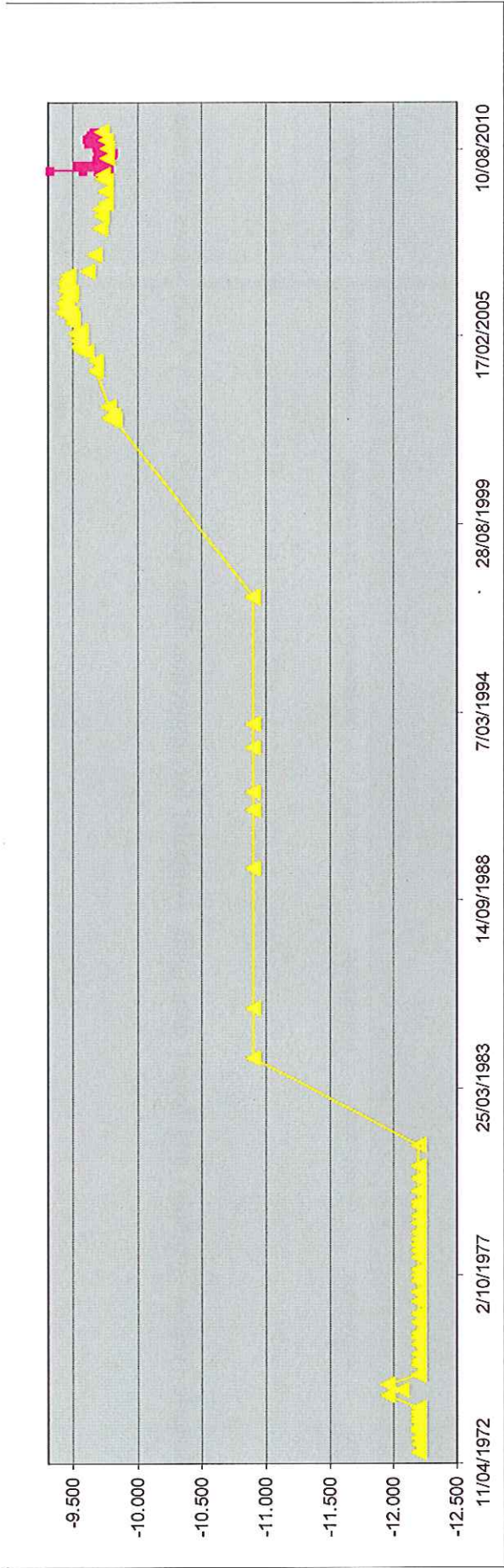


Fig. 9. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220018. The "y" axis shows the data-collection timeline.

Depth below ground surface (metres)

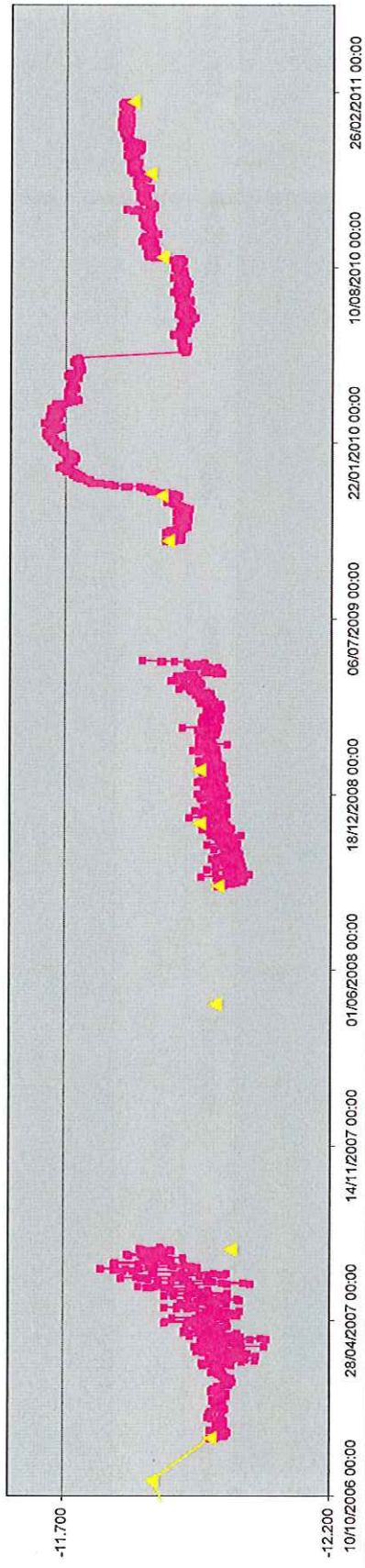
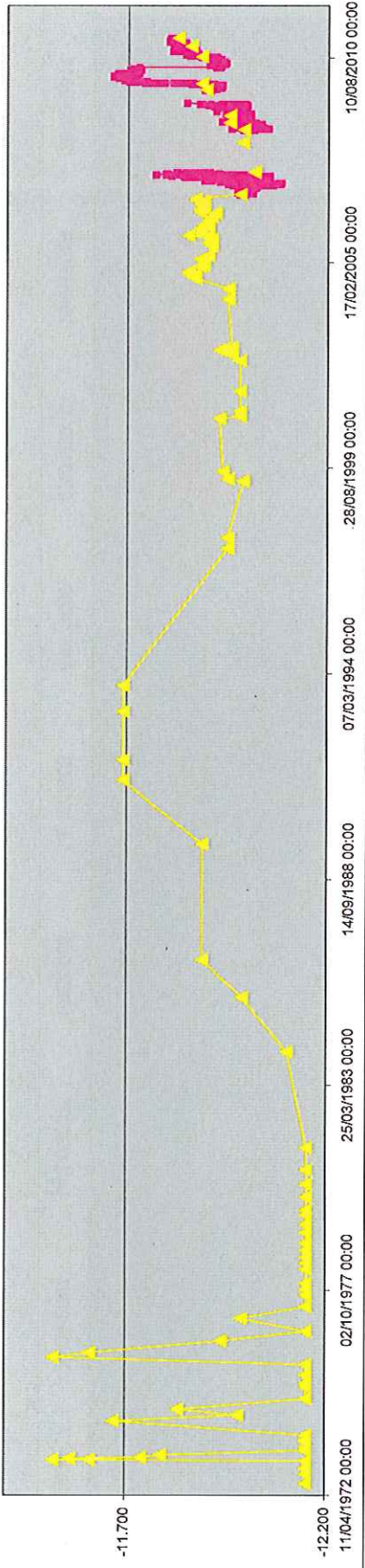


Fig. 10. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220019. The “y” axis shows the data-collection timeline.

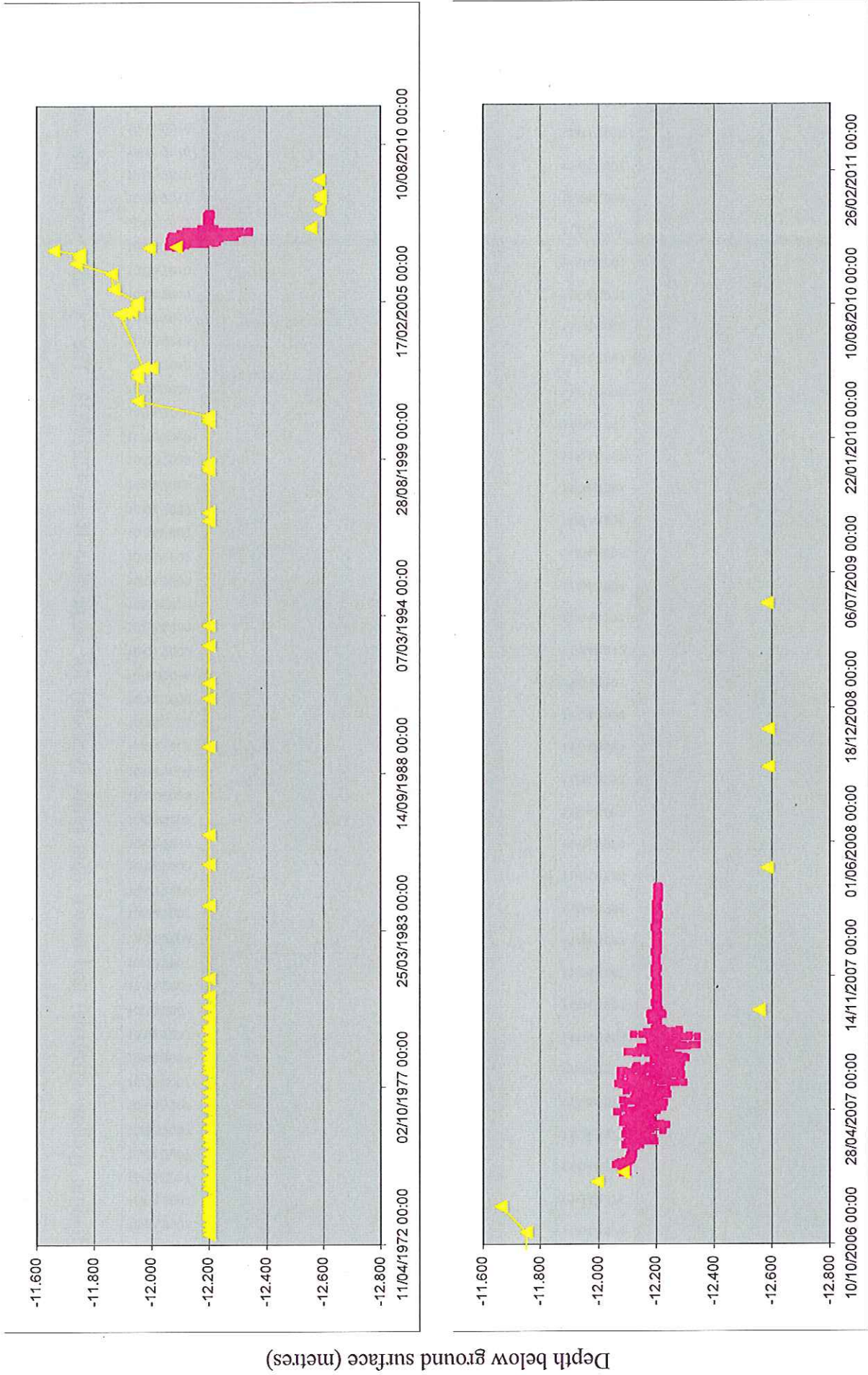


Fig. 11. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220022. The “y” axis shows the data-collection timeline.

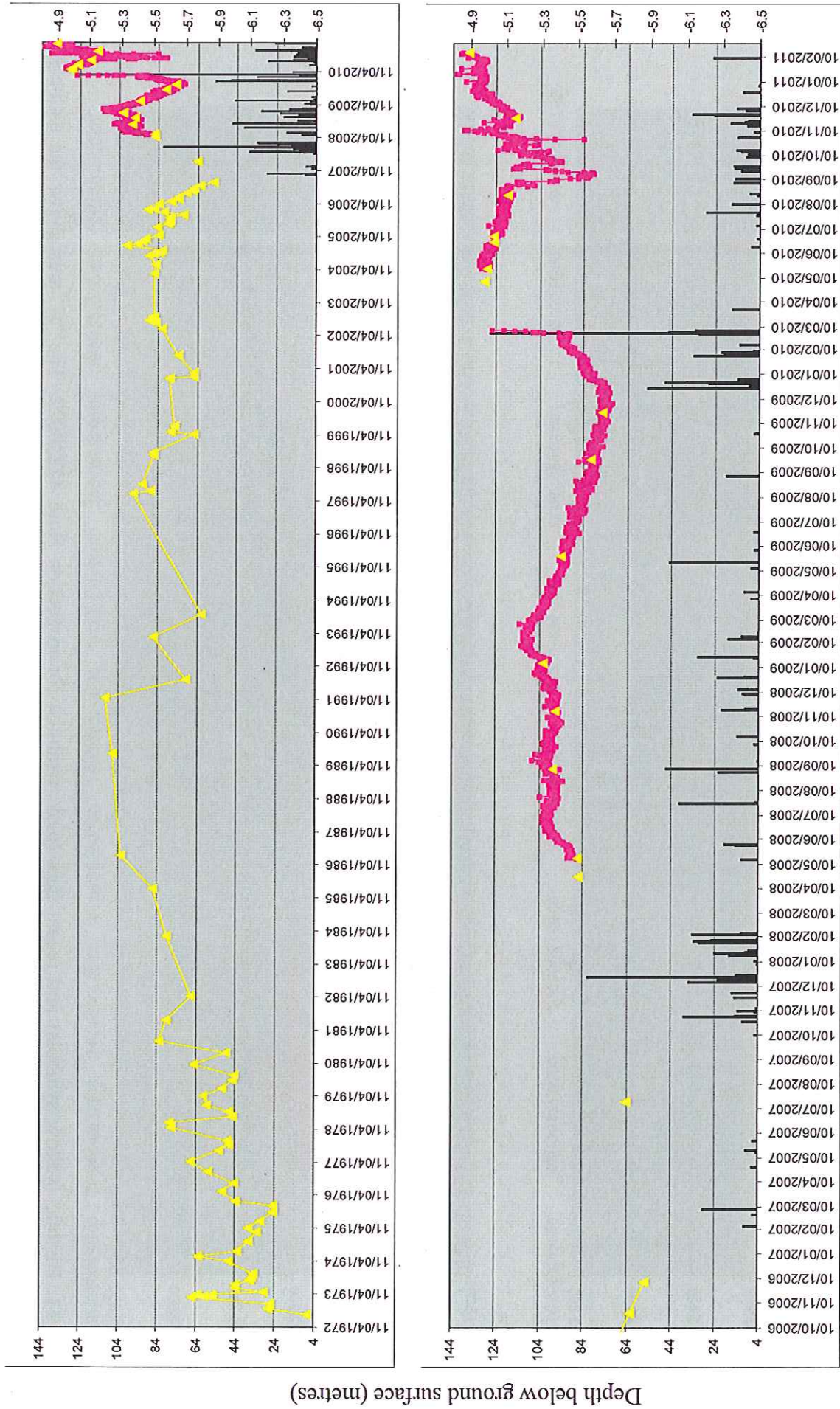
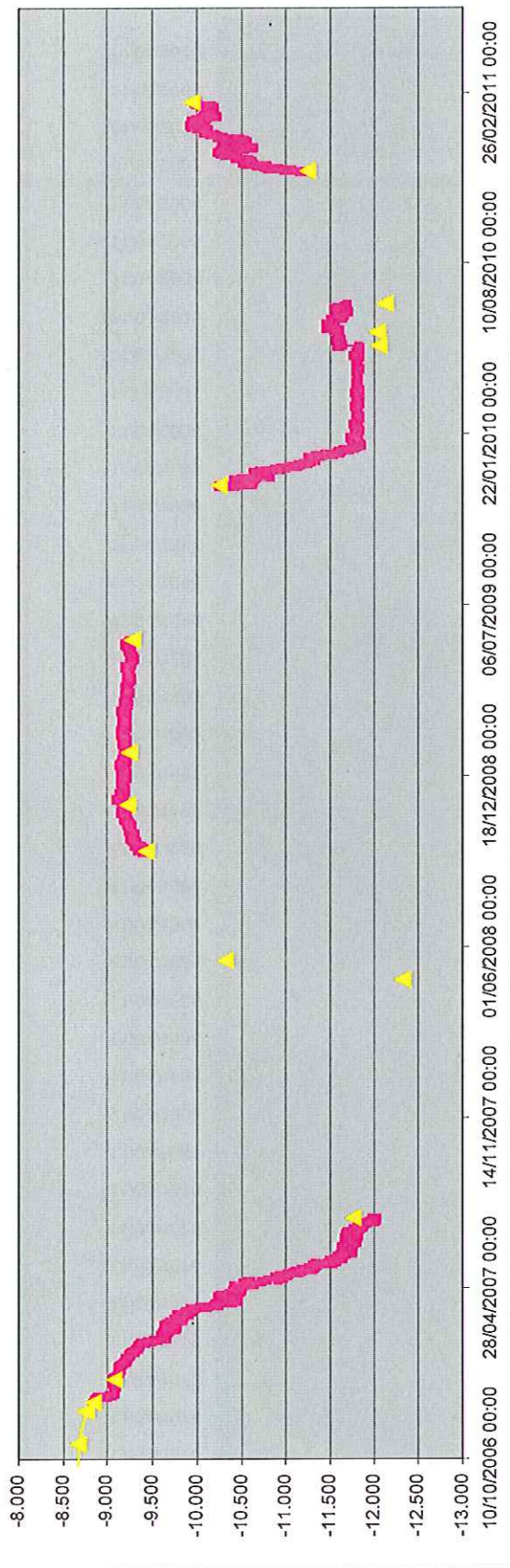
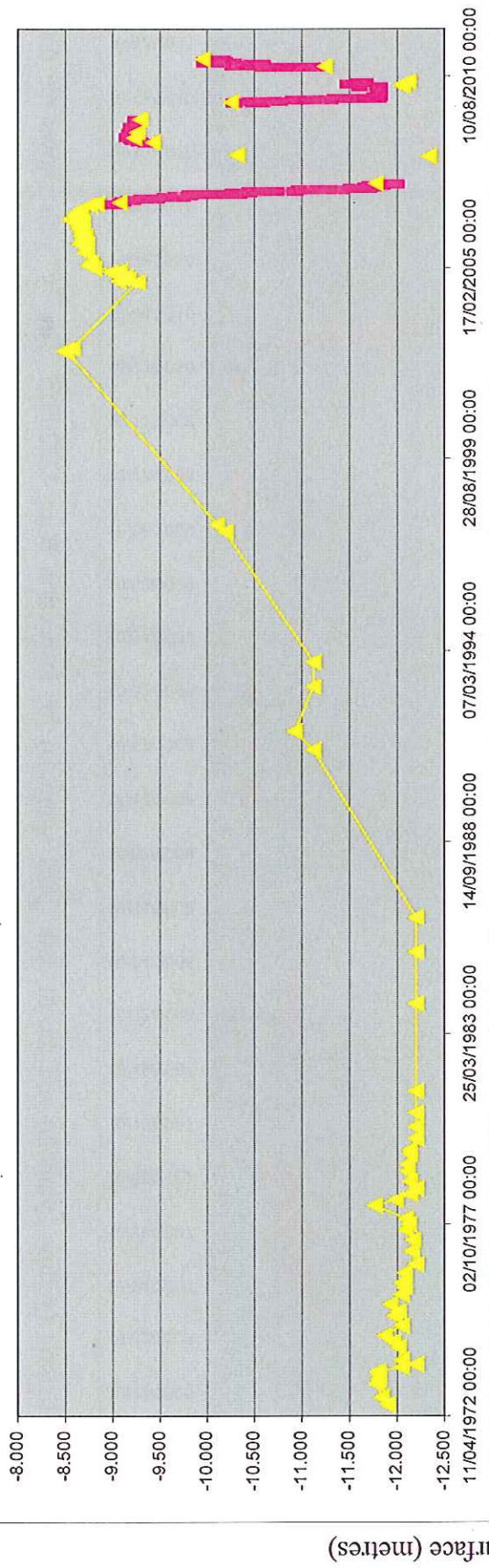


Fig. 12. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220023. The “y” axis shows the data-collection timeline.



Depth below ground surface (metres)

Fig. 13. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220024. The “y” axis shows the data-collection timeline.

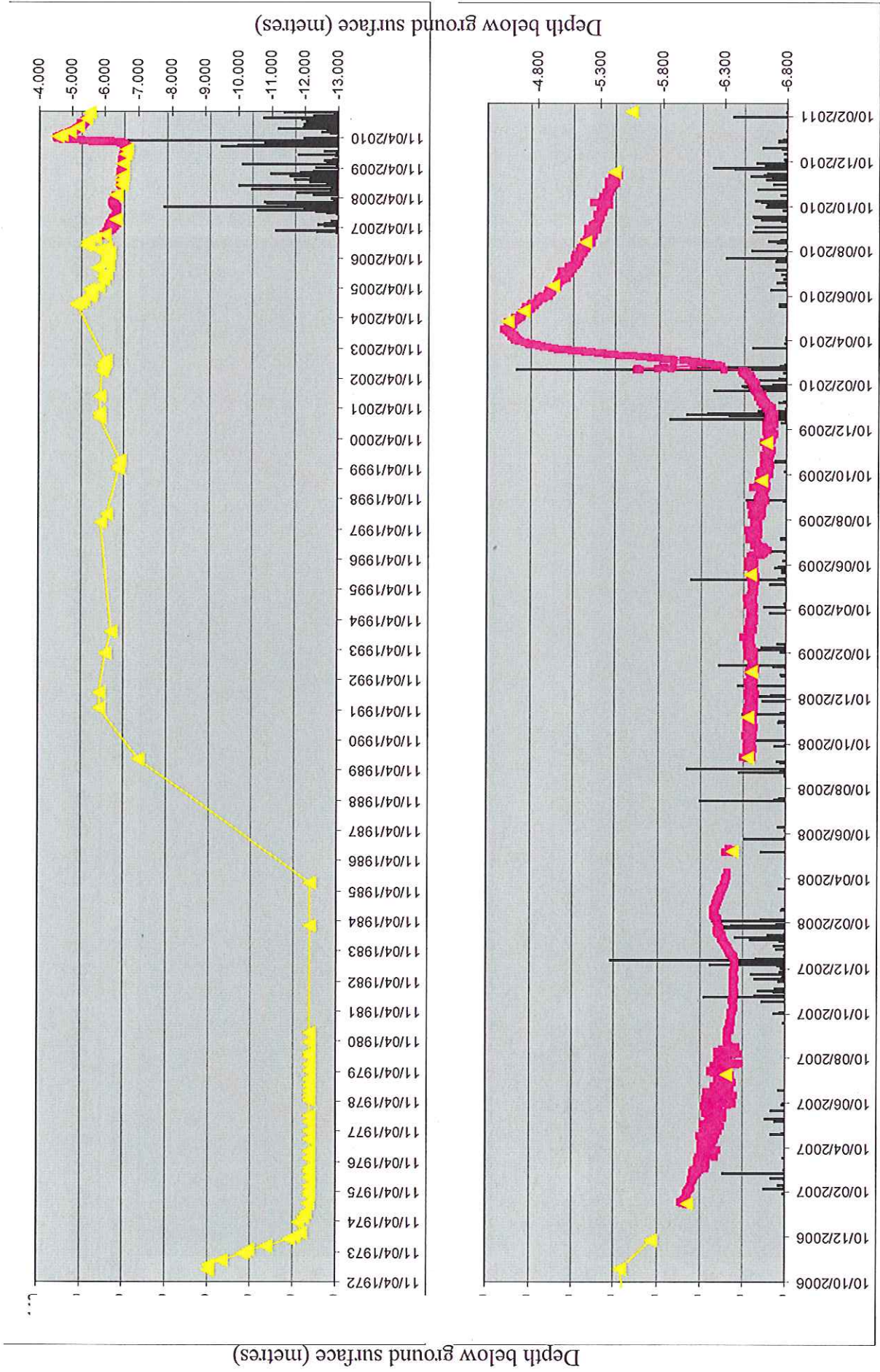


Fig. 14. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220025. The "y" axis shows the data-collection timeline.

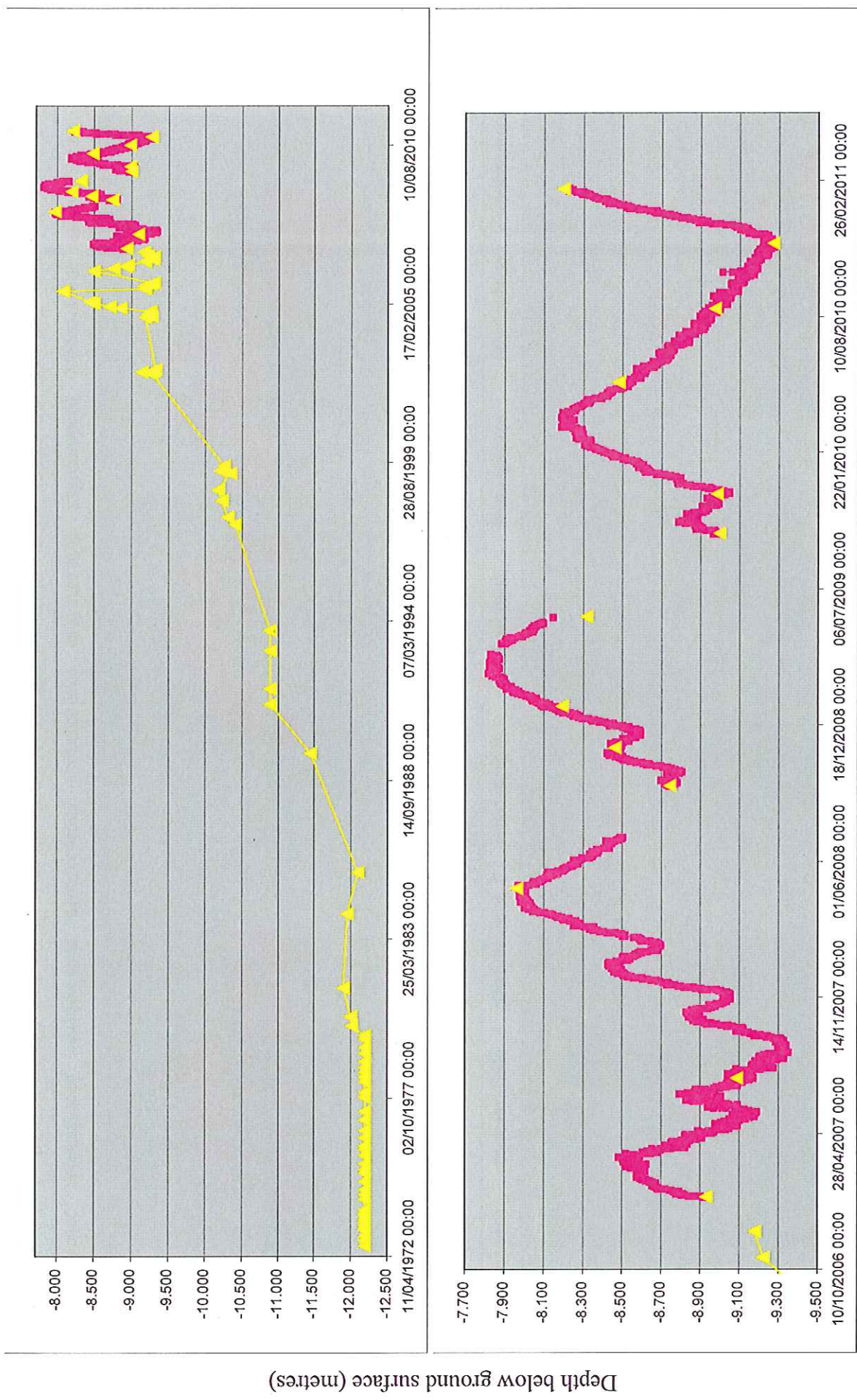


Fig. 15. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220027. The “y” axis shows the data-collection timeline.

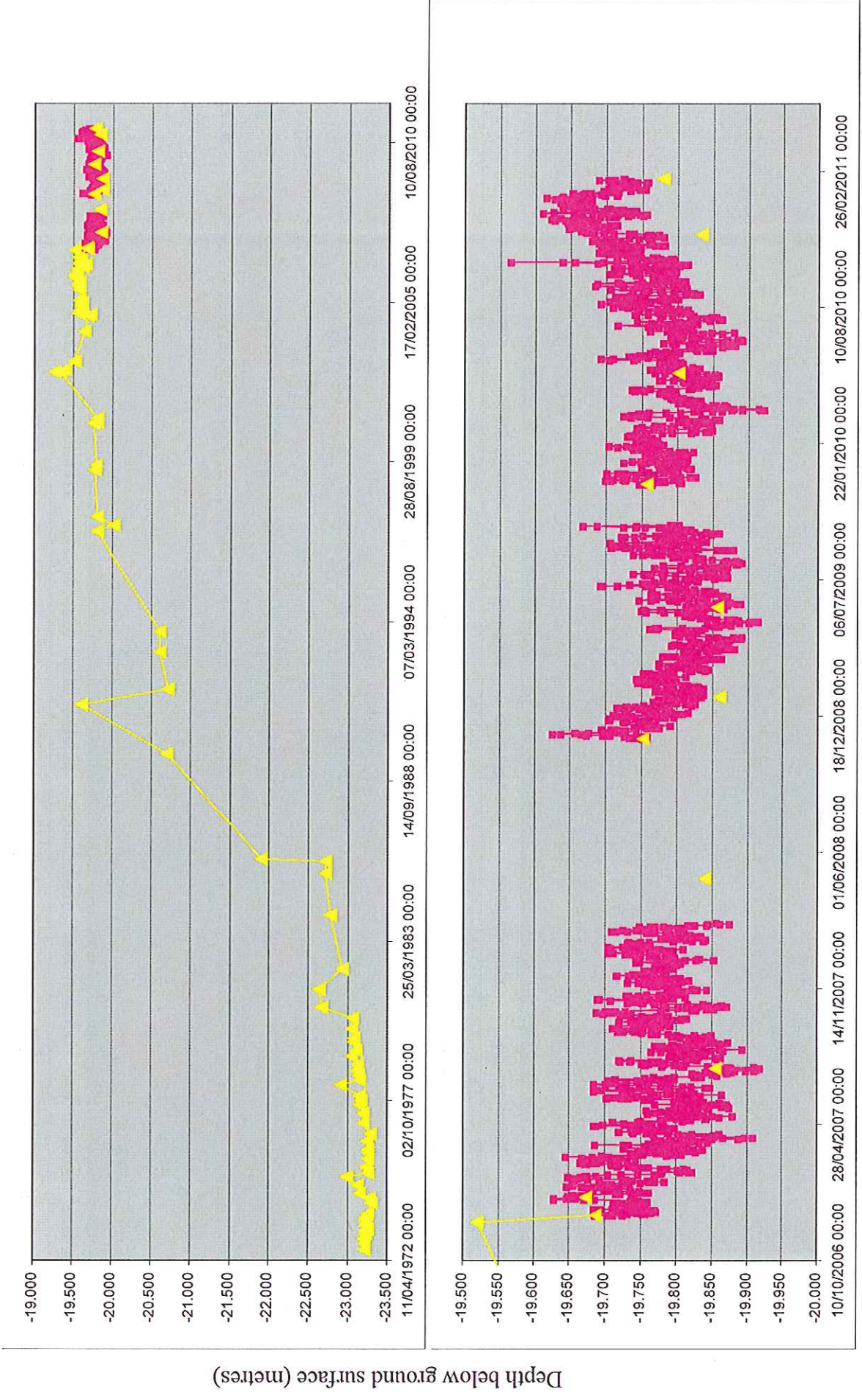


Fig. 16. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220030. The “y” axis shows the data-collection timeline.

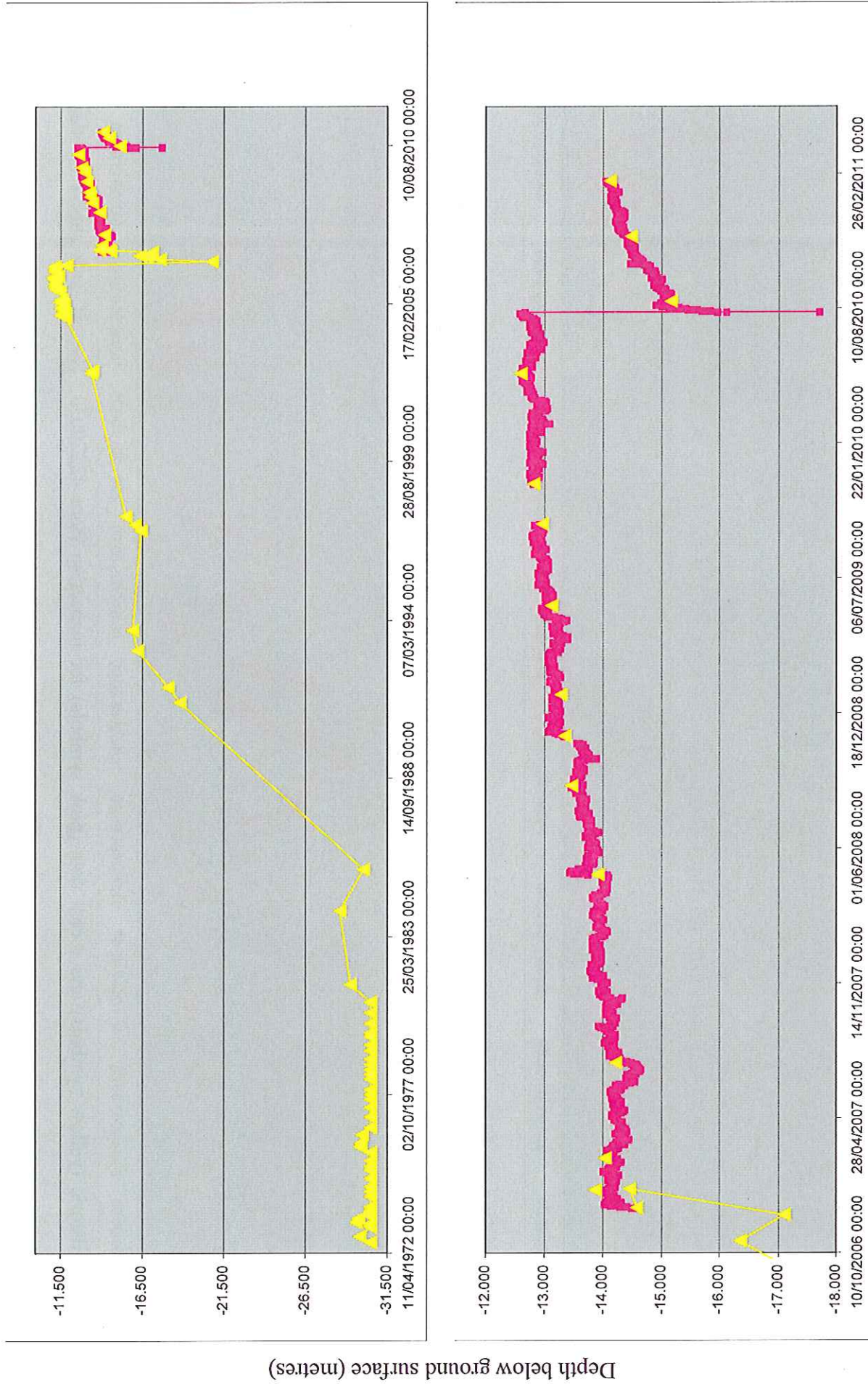


Fig. 17. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220032. The “y” axis shows the data-collection timeline.

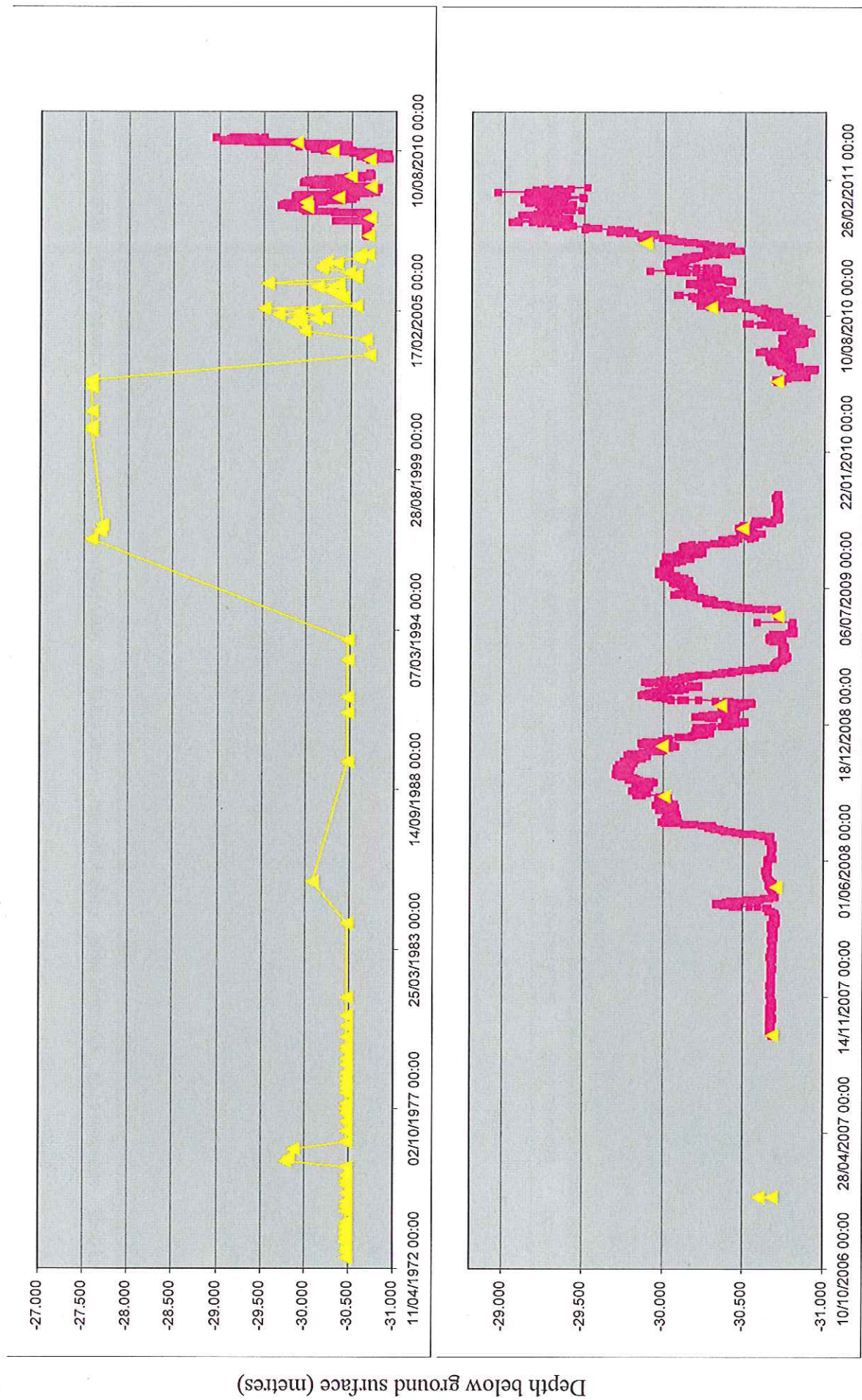


Fig. 18. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220033. The “y” axis shows the data-collection timeline.

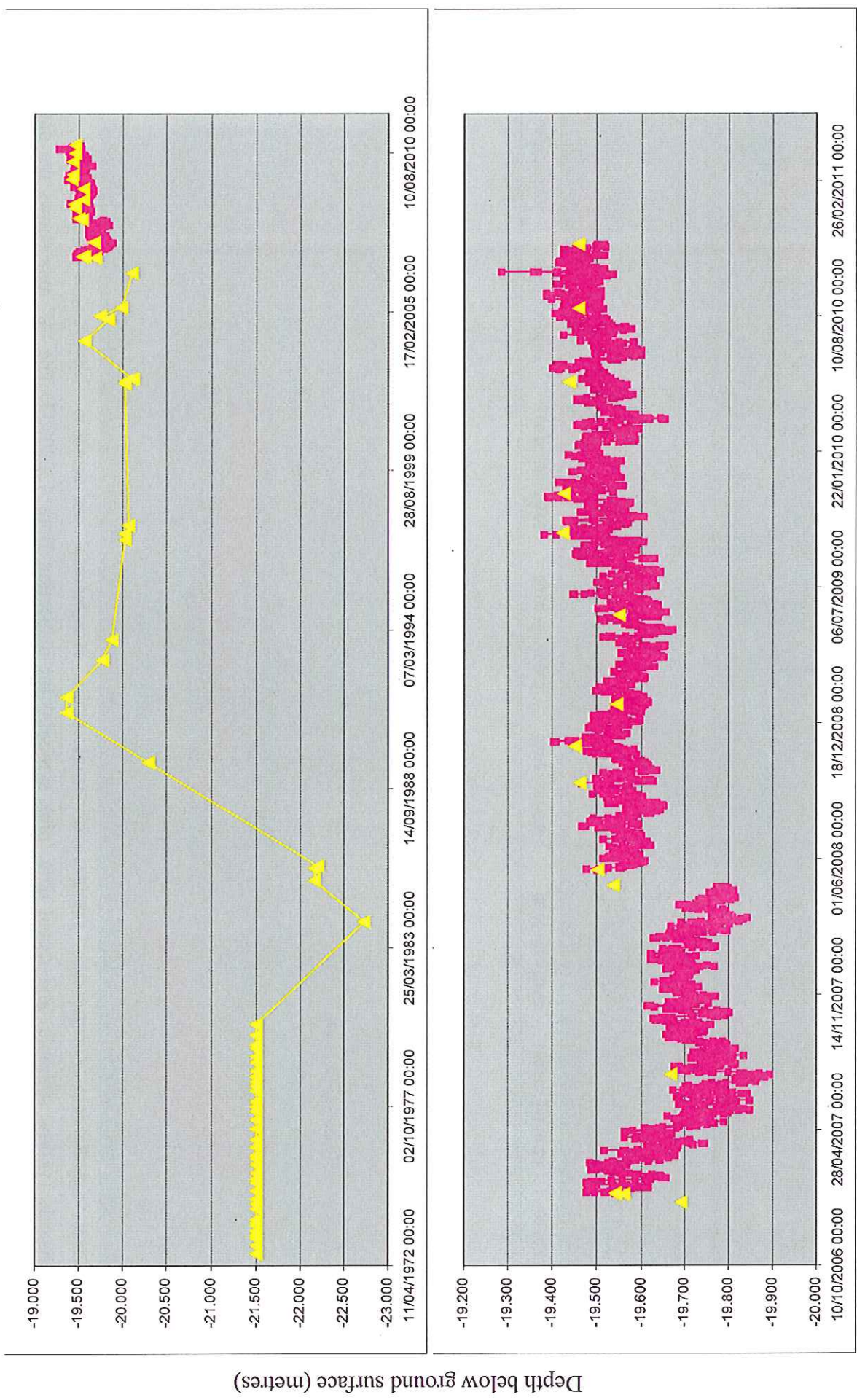


Fig. 19. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220034. The “y” axis shows the data-collection timeline.

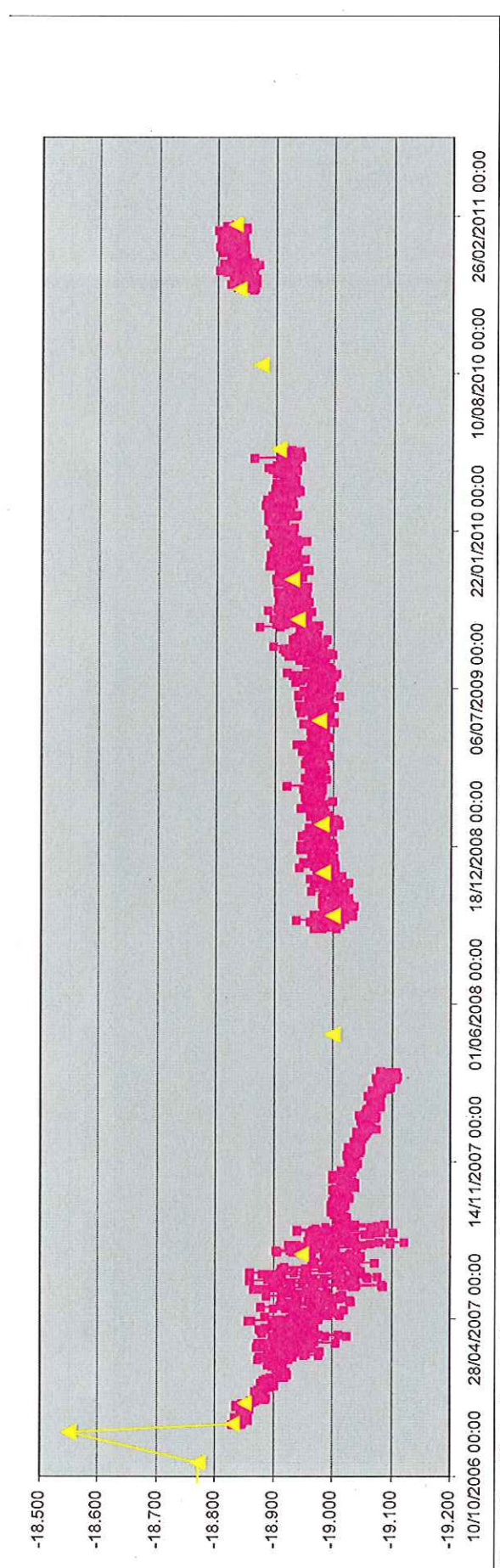
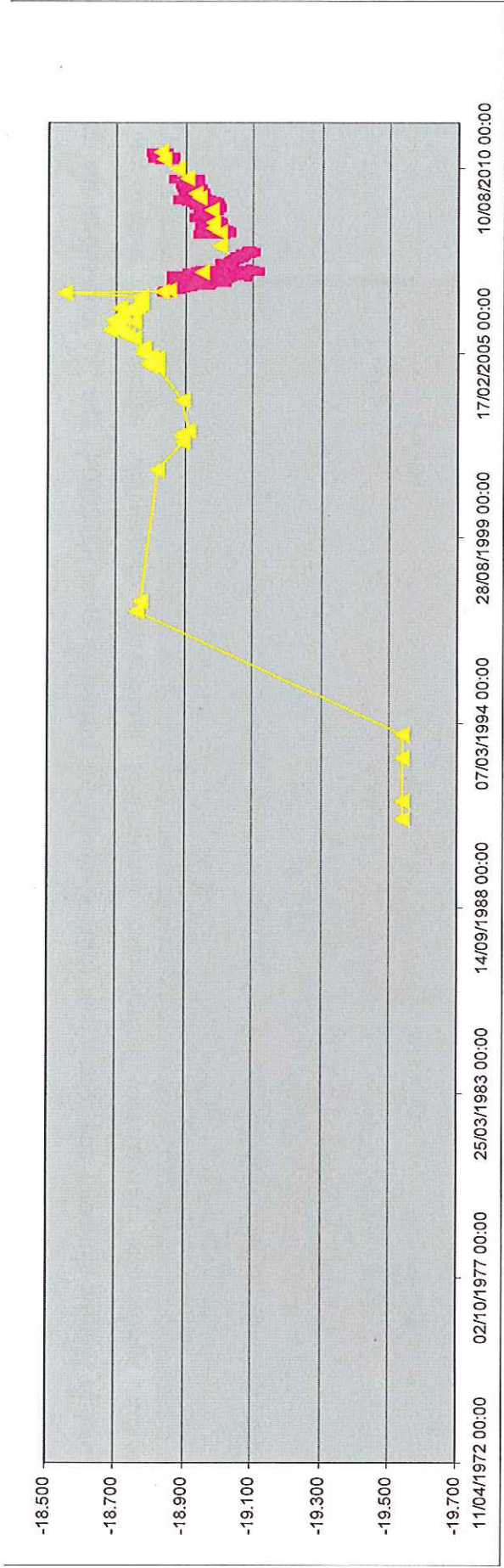


Fig. 20. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220053. The “y” axis shows the data-collection timeline.

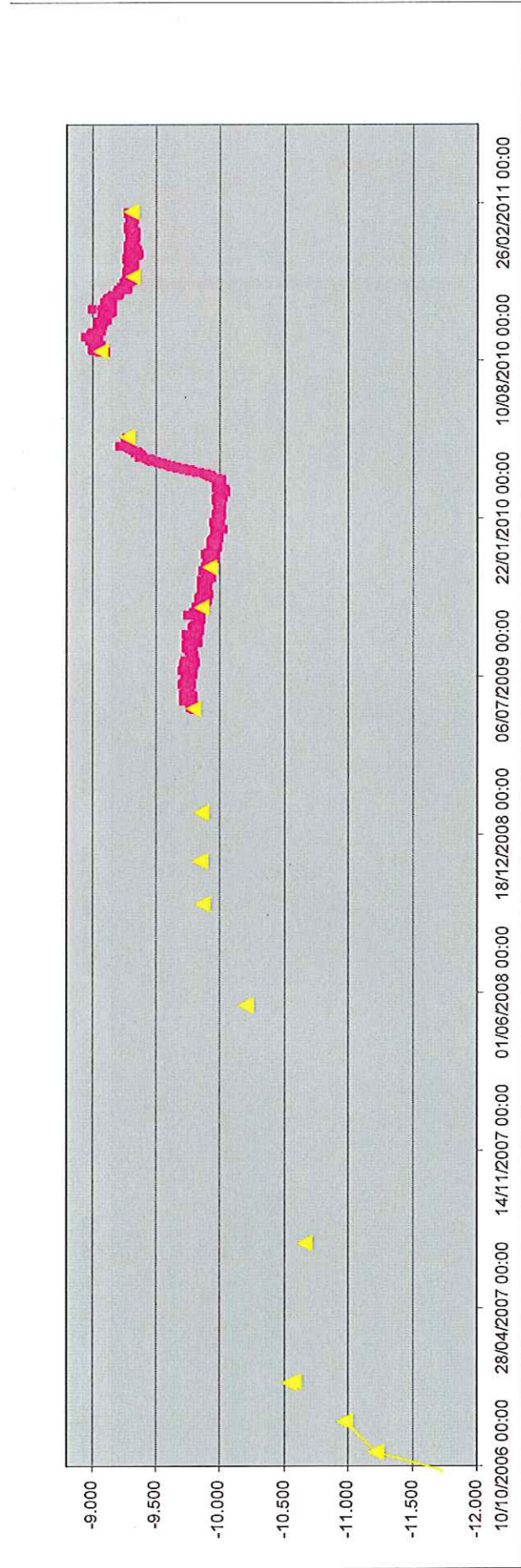
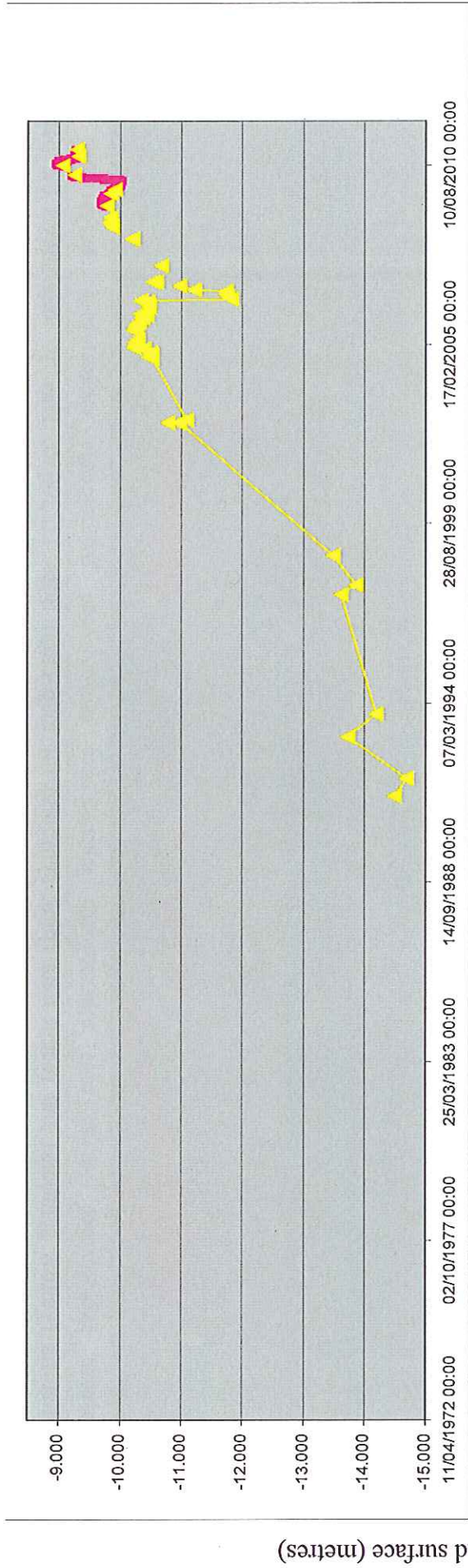


Fig. 21. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220054. The “y” axis shows the data-collection timeline.

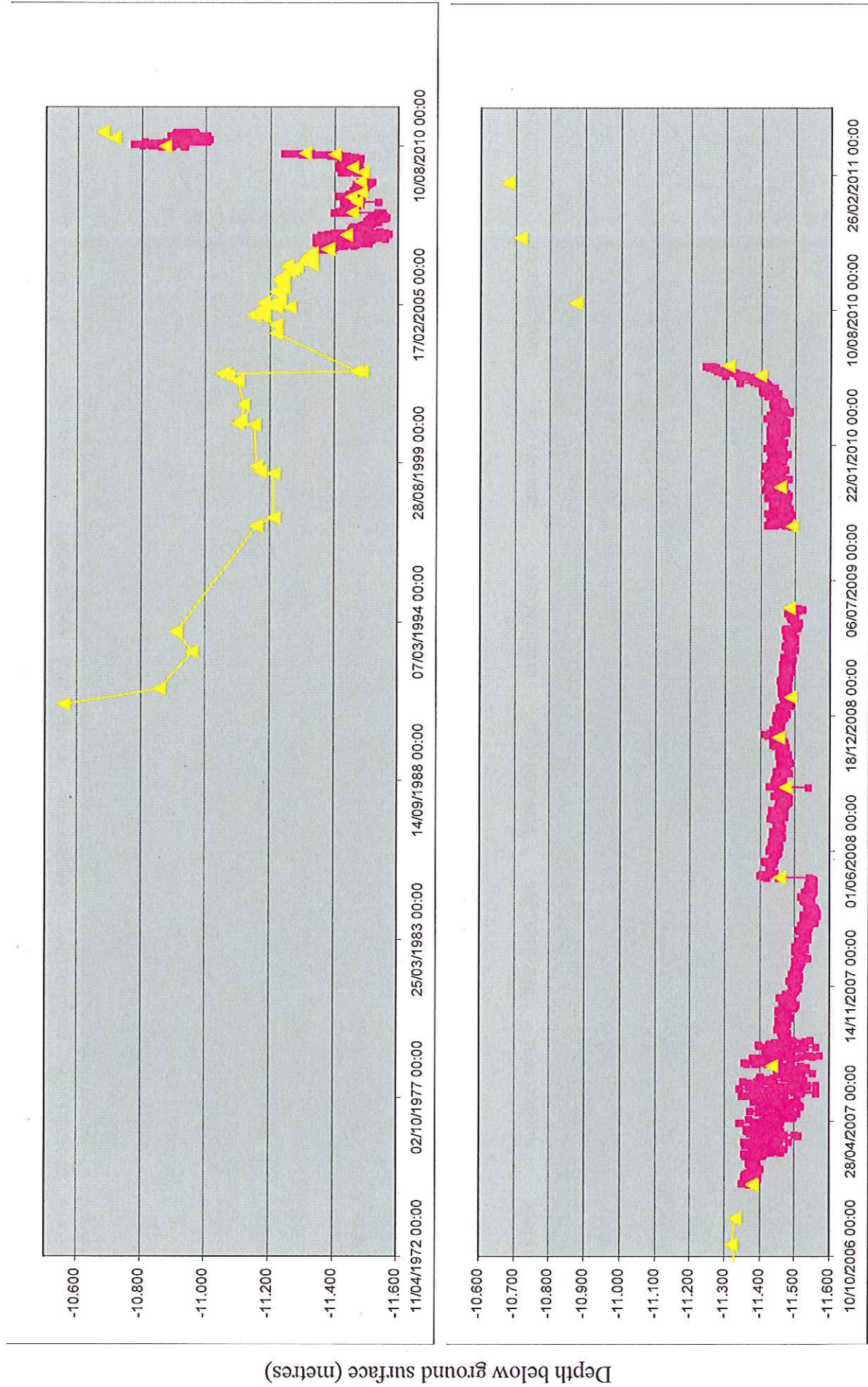


Fig. 22. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220056. The “y” axis shows the data-collection timeline.

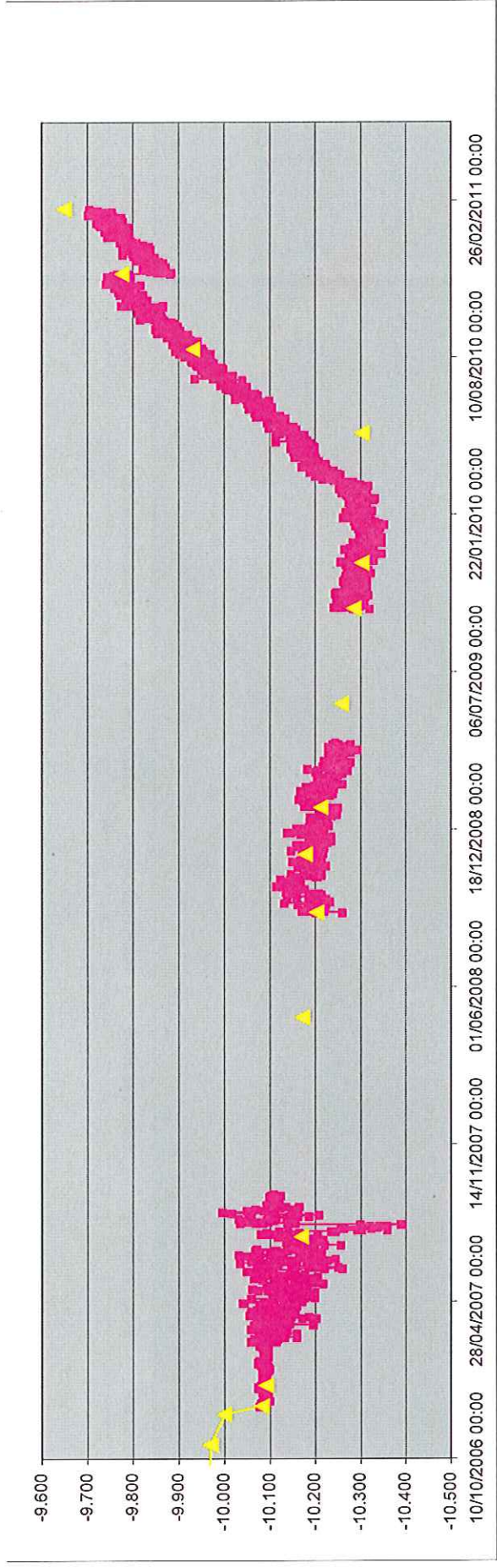
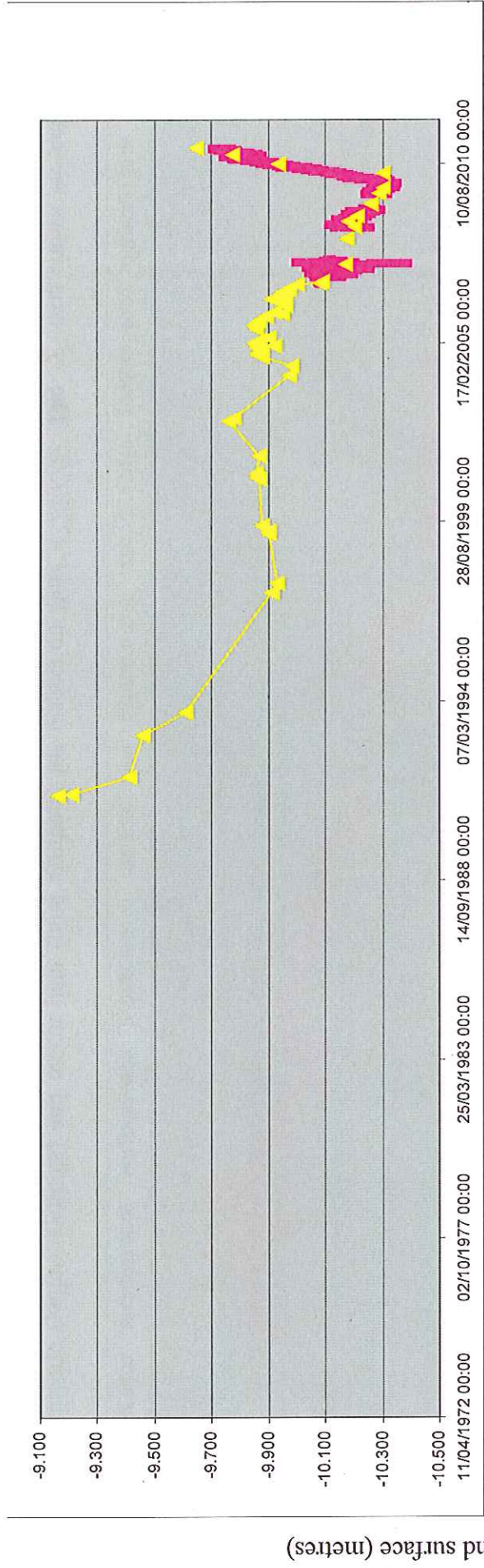


Fig. 23. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220057. The “y” axis shows the data-collection timeline.

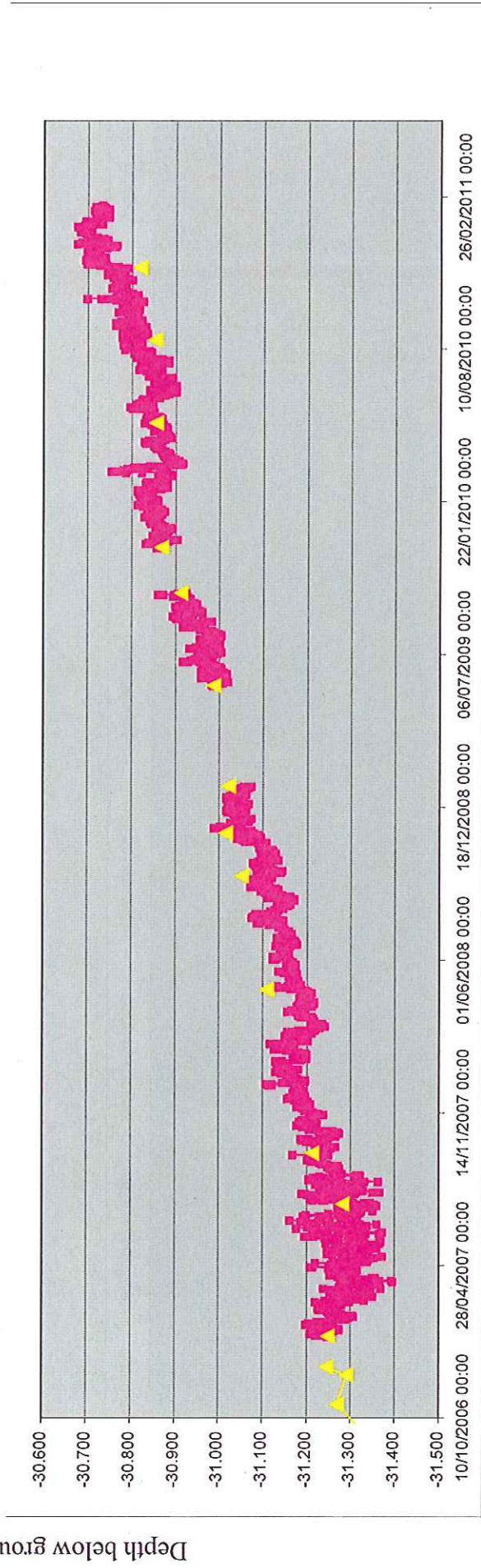
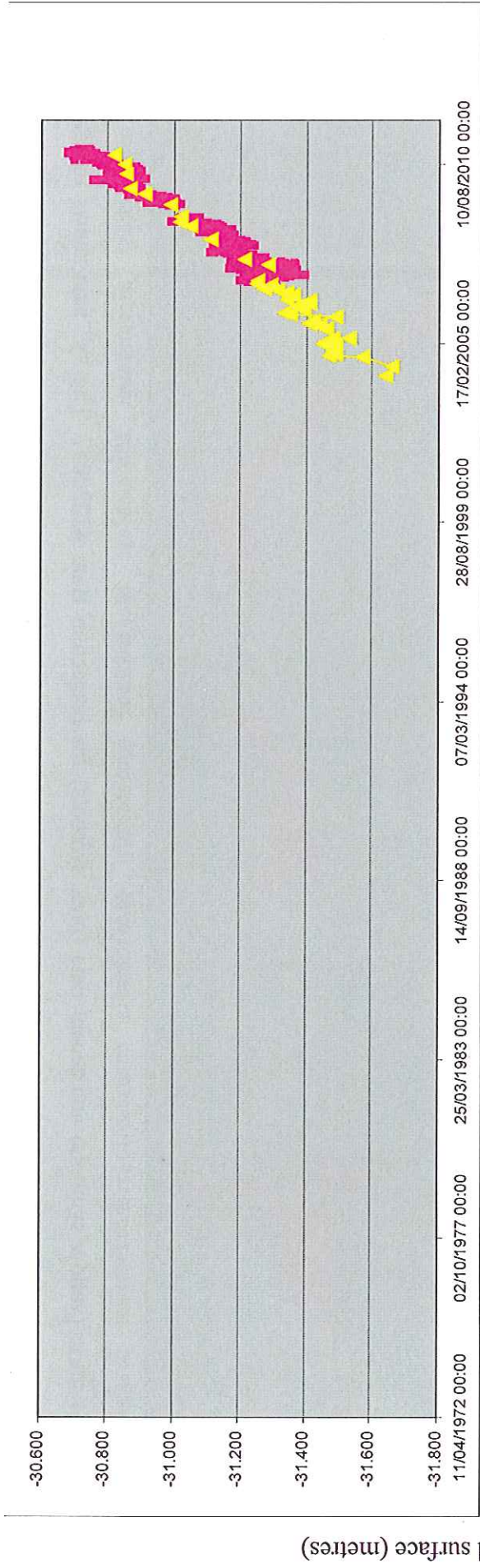


Fig. 24. Historic (yellow symbols) and recent data (pink symbols) for inspection Bore 42220209. The “y” axis shows the data-collection timeline.

Publications arising from the Deep Drainage project – under irrigated crops in the Upper Murray Darling Basin (2004 – 2011)

Refereed Journal

1. Gunawardena TA, McGarry D, Robinson JB, Silburn DM (2011) Deep drainage through Vertosols in irrigated fields measured with drainage lysimeters. *Australian Journal of Soil Research* 49 (4) 343-354.

Conference Papers

2. Gunawardena TA, Robinson JB, McGarry D (2011) Testing the SODICS model: Does it provide useful estimates of deep drainage in clay soils? In “5th World Congress of Conversation Agriculture incorporating - Farming System Design Conference”. 26-29 September 2011, Brisbane, Australia.
3. Gunawardena TA, McGarry D (2011) Lateral Move Irrigators- Innovative Engineering Solution For Improved Water Use Efficiency – But Risk Of Root Zone Salt Accumulation ? In “SEAg 2011 Conference” 28 – 30th September, Surfers Paradise, Australia.
4. McGarry D, Gunawardena TA, Foley J. (2010) Controlling deep drainage for improved WUE – and possible links with ground water movement. In “proceedings of the 15th Australian Cotton Conference.” 10 – 12 August 2010, Broadbeach, Australia.
5. Gunawardena TA, McGarry D, Gardner EA (2010) Will increased Water Use Efficiency lead to salt accumulation in the root zone? A comparison of adjacent lateral move and furrow irrigation. In “Proceedings of the Irrigation Australia 2010 National conference 8 -10 June” Sydney, Australia.
6. Gunawardena TA, McGarry D, Gardner EA, Stirzaker R (2008) Managing Deep Drainage for Improved WUE: Solute Monitoring and Ground Water Response in the Irrigated Landscape. In “Proceedings of the 14th Australian Cotton Conference.” 12 – 14 August 2008, Broadbeach, Australia.
7. Gunawardena TA, McGarry D, Gardner EA, Stirzaker R (2008) Improved Irrigation Efficiency through controlling Deep Drainage, and monitoring solute signatures and groundwater response. In “Proceedings of the Irrigation Australia 2008 National conference 20 -22 May” Melbourne, Australia.
8. McGarry D, Gunawardena TA, Gardner EA, Millar (2006) Deep drainage and irrigation management. In “Proceedings of the 13th Australian Cotton Conference.” 8 – 10 August 2006, Broadbeach, Australia.
9. McGarry D, Gunawardena TA, Gardner EA, Millar (2006) Deep drainage under irrigated cotton – surface and ground water implications. In “Proceedings of the Irrigation Australia 2006 National conference 9 – 11 May” Brisbane, Australia.

10. McGarry D, Gunawardena TA, Gardner EA, Millar G, McHugh AD (2005) Improved measurement and prediction of deep drainage under irrigated cotton fields in the Condamine – Balonne – McIntyre catchments and likely ground water responses. *Irrigation conference 2005 Townsville May 18-19.*

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11. Gunawardena TA, McGarry D (2007 – 2008). Eight technical reports on deep drainage studies on eight commercial cotton farms (Boggabilla p38, Dalby p31, Dirranbandi p32, Goondiwindi p34, Macalister p34, Pampas p33, St George south p36, and St George north p29). Provided to individual Grower-co-operators.
12. Gunawardena TA, McGarry D (2008) To present evidence of minimal effects of soil disturbance on Deep Drainage quantities as a result of installation procedures for the barrel (drainage) lysimeters at the ACRI site, Narrabri. Technical report, Department of Natural Resources and Water, p5.
13. Gunawardena TA, McGarry D, Gardner EA, Millar GE (2006) Improved measurements and prediction of deep drainage in Vertosols under irrigated cotton in the Condamine – Balonne – McIntyre catchments. Technical report No. 01/06, Department of Natural Resources, Mines and Water, p60.

