Lachlan Catchment

Groundwater Hydrographs

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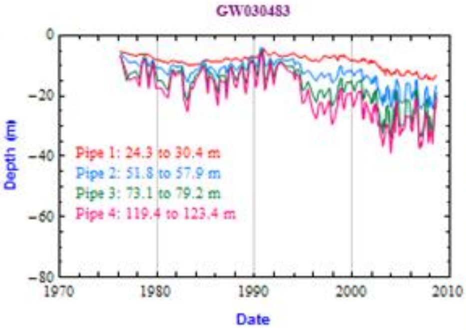

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Executive Summary

The hydrogeology of the Lachlan Catchment has been studied by numerous authors over the past 40 years, but there are still many gaps in our understanding of the groundwater systems and river-aquifer interactions. These shortfalls in our knowledge limit our capacity to manage water resources throughout the catchment. This document captures our current understanding of the hydrogeology of the catchment and provides a multidimensional spatial analysis of the groundwater monitoring bore standing water level (SWL) data. Based on the findings, recommendations for further research are presented.

Significant groundwater development in the Lachlan Catchment began in the 1970s, however extractions have increased substantially in the last 15 years. To monitor the impact of groundwater usage NSW state water management departments installed monitoring bores in relevant zones. The groundwater monitoring data are publicly available on the Pinneena Groundwater Works CD. This report presents all the hydrographs for the Lachlan Catchment, and examines the spatial and temporal trends displayed in these data. The primary goal of this project was to provide a plot of all the groundwater hydrographs in the catchment. A printout of the hydrograph set for 256 groundwater work locations within the Lachlan Catchment is presented in the Appendix.

The Water Sharing Plan for the *Lower Lachlan Groundwater Source 2003* came into effect on the 1st of February 2008. Through the implementation of this water sharing plan there have been changes to groundwater allocations in the Lower Lachlan. At some locations there has been a reduction in the water allocated per share, with the aim of improving the long term viability of the groundwater resource for all users and the environment; the water sharing plan for the Lachlan commenced in 2008. The groundwater hydrographs provide a record of

baseline conditions and can be used to assess the impact of variations in allocation and guide future management decisions.

Almost 40 years of groundwater hydrograph records enable long term groundwater level trends to be analysed throughout the alluvial regions of the catchment. Fluctuations in the groundwater level over long and short periods of time are analysed using traditional hydrograph plots and 3D plots to show the yearly and interdecadal impacts of groundwater extractions. The groundwater hydrograph data are interpreted in the context of existing geological knowledge, streamflow, rainfall, land use and groundwater usage data.

Within the Lachlan Catchment a balance needs to be achieved in the way water is managed if urban centres and farms dependent on the water are to prosper, while maintaining important wetlands at the end of the catchment. The headwaters of the Lachlan River commence near the township of Gunning, at the foothills of the Great Dividing Range. The river then flows in a westerly direction, terminating to the West of the Oxley Gauging Station, where it joins the Murray region. Wyangala Dam is the major reservoir of the upper Lachlan Catchment, while reservoirs in the lower catchment include Lake Brewster and Lake Carelligo. The major irrigation district of the upper Lachlan is located between Condobolin and Forbes, proximal to the Lachlan River, while areas to the north and west of Hillston represent the principle irrigation zones of the lower catchment.

Regionally, the Cenozoic alluvial aquifers of the upper and lower Lachlan represent two different hydrological systems. In the lower catchment alluvial sediments overly the western extremity of the Murray Basin, while sediments in the mid to upper Lachlan represent valley fill deposits overlying the folded and faulted units of the Palaeozoic Lachlan Fold Belt. It is the fresh groundwater hosted by these alluvial aquifers that is used for irrigation and in some case town water.

This study identifies zones in the upper and lower Lachlan, where aquifers within the alluvial sediments are locally hydraulically connected to the river, and zones where the deep aquifers are disconnected from the shallow aquifers and do not receive direct river recharge. The extent of the hydraulic connection between the alluvial aquifers and the immediate underlying sedimentary rock aquifers is poorly understood. Overall the lower catchment and the upper unconfined aquifer of the upper catchment have experienced no declines in the SWL over the past 20 years. The largest zone of groundwater depletion is along the tributary emanating from Lake Cowal; long term (1988-2008) declines in the SWL for this area exceed 30 m at slotted intervals 70 to 100 metres below the ground surface. Other zones of concern include the irrigation district between Condobolin and Forbes which exhibit reductions greater than 10 m in the groundwater level throughout the deeper portions of the aquifer (i.e. > 80 m). Due to the economic and social importance of this region further extensive hydrogeological and water chemistry investigations are required to better understand the recharge pathways. If the management goal is to reduce the decline in the groundwater level, then this region may require managed aquifer recharge.

Based on these findings it is suggested that a detailed 3D lithofacies model needs to be constructed for the upper and lower Lachlan catchments. This 3D model could then guide the construction of a coupled surface and sub-surface flow model. Also required is an extensive groundwater chemical investigation (with a focus on dating the ages of the groundwater zones) and coupled river and aquifer flow modelling, linked to the water chemistry investigations. The results of these investigations should help to inform water management decisions.

Contents

Introduction

Spatial and temporal trends in the standing water level (SWL) are a consequence of numerous processes (Tillman and Leake, 2010). To be able to understand these processes, spatial and temporal trends in the SWL need to be assessed in conjunction with groundwater extraction records, the local hydrogeology as well as the climate, streamflow and land use data (McCallum *et al*., 2009).

To examine the spatial and temporal effects of groundwater extractions on the SWL, bore hydrographs data were utilised. These hydrographs have been reviewed in the context of the climatic, streamflow and land use data as well as the hydrogeology. To further aid analysis of hydrograph data, 3D plots have been generated at varying spatial scales to give a sense of the yearly and interdecadal impacts of groundwater extraction within the Lachlan Catchment.

The primary goal of this project was to plot all the groundwater hydrographs in the catchment. A printout of the hydrograph set for 256 groundwater work locations within the Lachlan Catchment is presented in the Appendix.

Lachlan Area – Location

The Murray-Darling Basin has been separated into 18 contiguous regions by the Murray-Darling Basin Sustainable Yields Project. The Lachlan Catchment is situated in central New South Wales and bounded by four separate regions; to the north by the Macquarie-Castlereagh region, to the north-west by the Barwon-Darling region and to the west and south by the Murray and Murrumbidgee regions respectively (Figure 1); the eastern portion of the Lachlan is enveloped by the Great Dividing Range (CSIRO, 2008).

The Lachlan Catchment represents a narrow basin stretching approximately 560 km from east to west (Bent *et al*., 2007). It covers 85,532 km^2 or 8 percent of the Murray-Darling Basin and is based almost entirely around the Lachlan River (CSIRO, 2008). It is estimated that the region hosts a population in excess of 106,000; the major town centres comprising the region include Cowra, Young, Parkes, Forbes, West Wyalong and Condobolin (Figure 2; Lachlan CMA 2009).

The headwaters of the Lachlan River commence near the township of Gunning, situated between Yass and Goulburn, at the foothills of the Great Dividing Range and the river flows in a westerly direction. Other main tributaries emanating from the mountains converge by the time they have reached Forbes, resulting in one principle river (WCIC, 1972). The river anastomoses as it approaches the nationally significant Booligal Wetlands and Great Cumbung Swamp (Figure 2; O'Brien and Burne, 1994). To the west of the Oxley gauging station, the Lachlan River terminates and joins the Murray region; this occurs 46 km upstream from the confluence between the Lachlan and Murrumbidgee Rivers (CSIRO, 2008; Kemp and Rhodes, 2010).

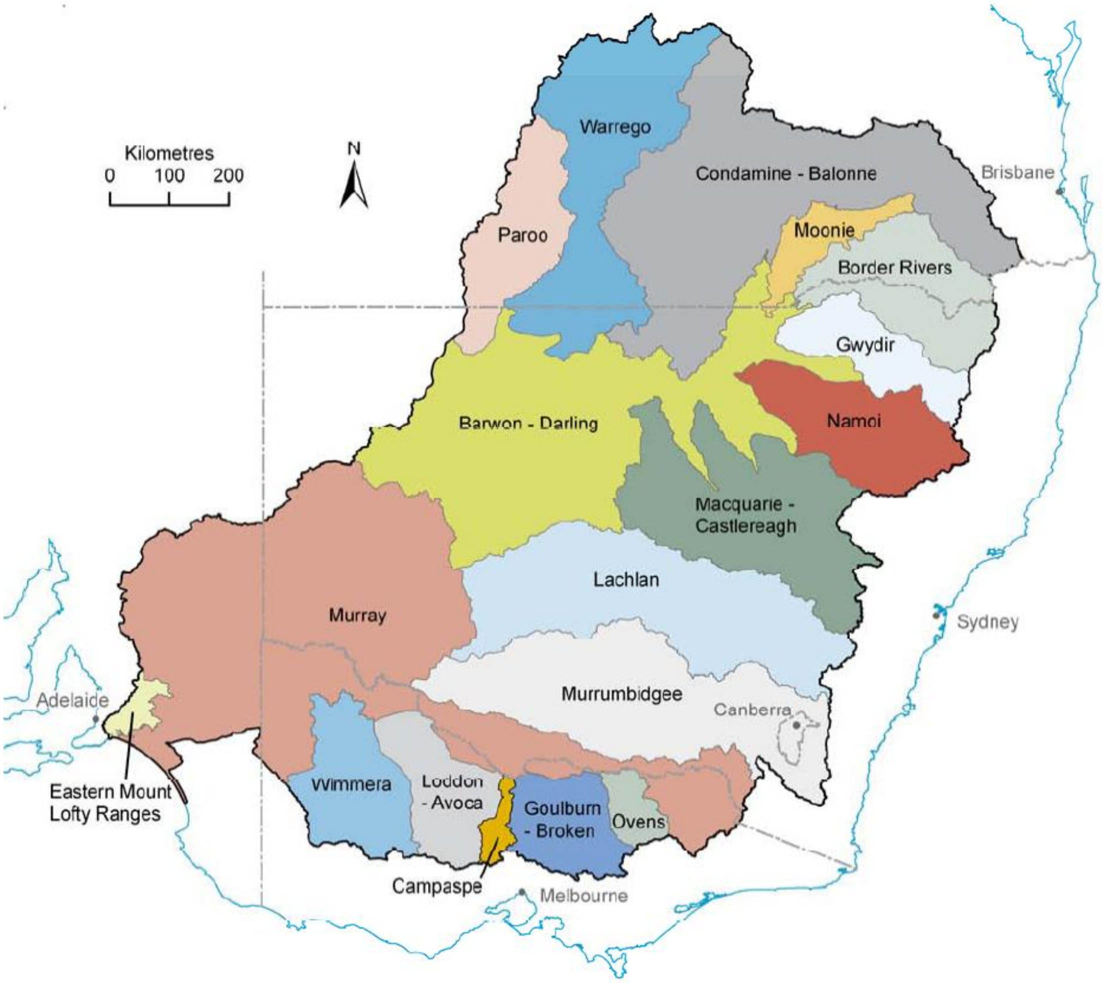


Figure 1. The regions comprising the Murray-Darling Basin (From CSIRO, 2008).

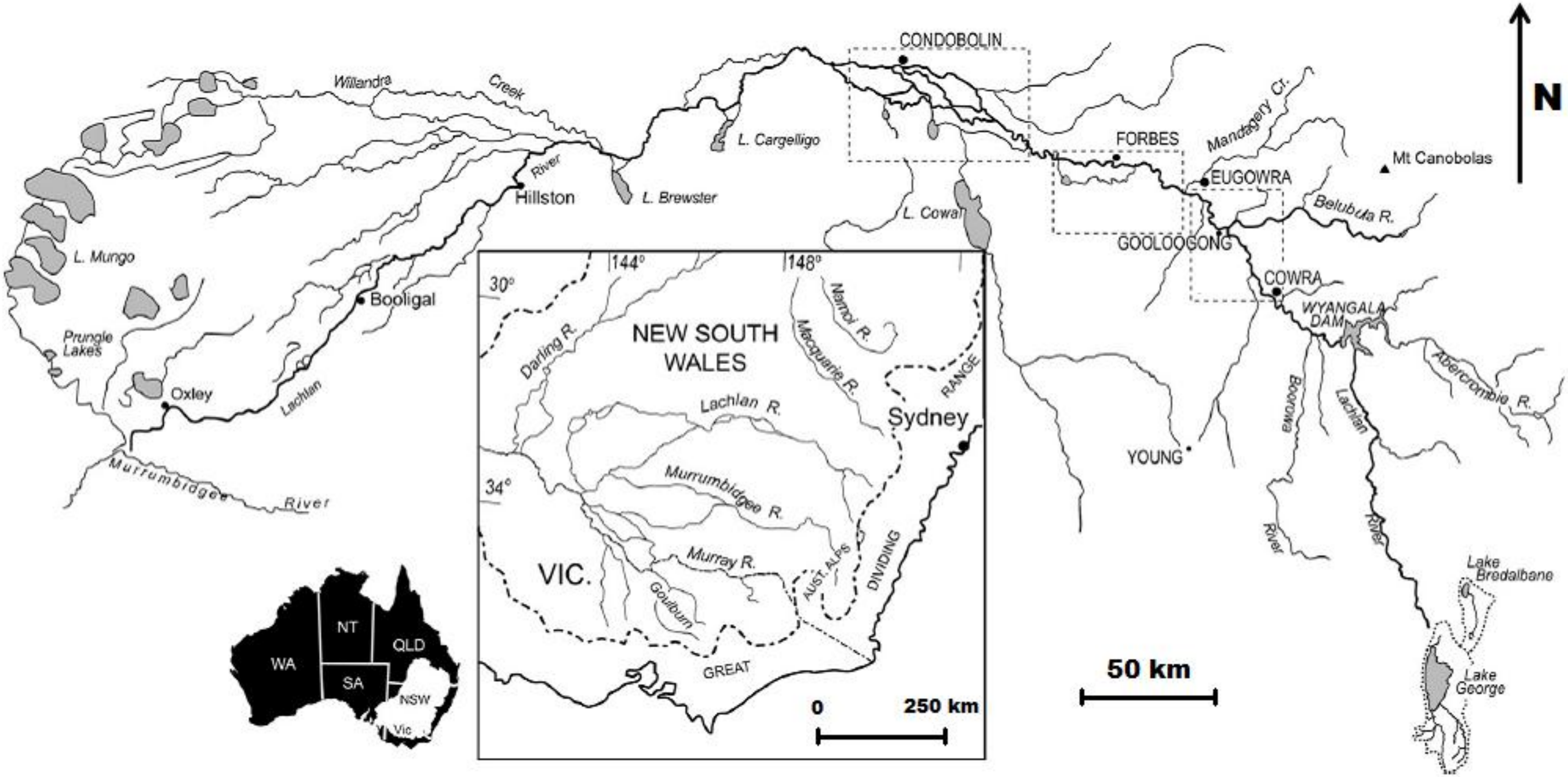


Figure 2. A schematic map of the Lachlan River and tributaries (From Kemp and Rhodes, 2010).

Lachlan Area – Topography

The Lachlan Catchment is diverse in its topographic relief. However, according to NSW Agriculture (2003) there are three broad north-south trending morphological zones which typify the Lachlan. These include the upper, mid and lower catchments; a topographic map of the Lachlan Catchment is provided in Figure 3 (NSW Agriculture, 2003).

The upper catchment, informally known as the tablelands includes the western slopes of the Great Dividing Range (NSW Agriculture, 2003; Lachlan CMA, 2009). This portion of the Lachlan is situated on a sequence of folded and faulted granites related to uplift of the SE Australian highlands in the late Palaeozoic. Folding and faulting was further extended by rifting along the eastern continental margin during the late Cretaceous (Bishop & Goldrick, 2010). The resultant landscape is elevated and undulating with a maximum height of approximately 1200 m.a.s.l.. (Figure 3; Kemp, 2010).

Water sourced from this mountainous terrain drains towards the west via the principle tributaries, namely the Lachlan and Abercrombie Rivers (Figure 2; Dent *et al.*, 2007). These rivers are moderately flowing with sandy to pebbly beds surrounded by densely vegetated to extensively cleared land (CSIRO, 2008; Lachlan CMA, 2009).

The mid-catchment refers to the region between Wyangala Dam and Lake Brewster (Figure 2; CSIRO, 2008). The prominent “mountain front” defining the upper catchment grades into more undulating country of mid-catchment towards the west in what is referred to as the slopes (Lachlan CMA, 2009). The slopes are generally cleared although pockets of native vegetation do exist. Principle perennial tributaries derived from the undulating terrain (i.e. Belubula River, Boorowa River and Mandagery Creek) are united upstream from Forbes forming one principle stream. Except in extremely wet years no perennial tributaries exist downstream of Forbes (i.e. the ephemeral Lake Cowal; Kemp 2010).

Between Forbes and Condobolin numerous effluent streams diverge from the Lachlan River, most of which ana-branch on the southern side and rejoin the main stream further down (Dent *et al*., 2007); according to Kemp and Rhodes (2010) these anabranches follow palaeochannel depressions. A number of streams do not rejoin the Lachlan however; these are most frequently encountered on the plains situated to the west of Condobolin and include Willandra Creek (WCIC, 1972). Approaching Condobolin alluvial plains predominate over the undulating landscape to the east. Alluvial plains comprise 78 % of the Lachlan Catchment with the majority of the sediment and water believed to have originated from the tablelands and slopes (Kemp, 2010).

The lower catchment is defined as the area west of Lake Brewster and is also dominated by alluvial plains (NSW Agriculture, 2003). Flows downstream of Hillston are diverted to distributaries for irrigation purposes or dissipate into the Booligal Wetlands, Great Cumbung Swamp and ephemeral lakes. In most years there is no flow of surface water from the Lachlan Catchment to the Murrumbidgee River (O'Brien and Burne, 1994).

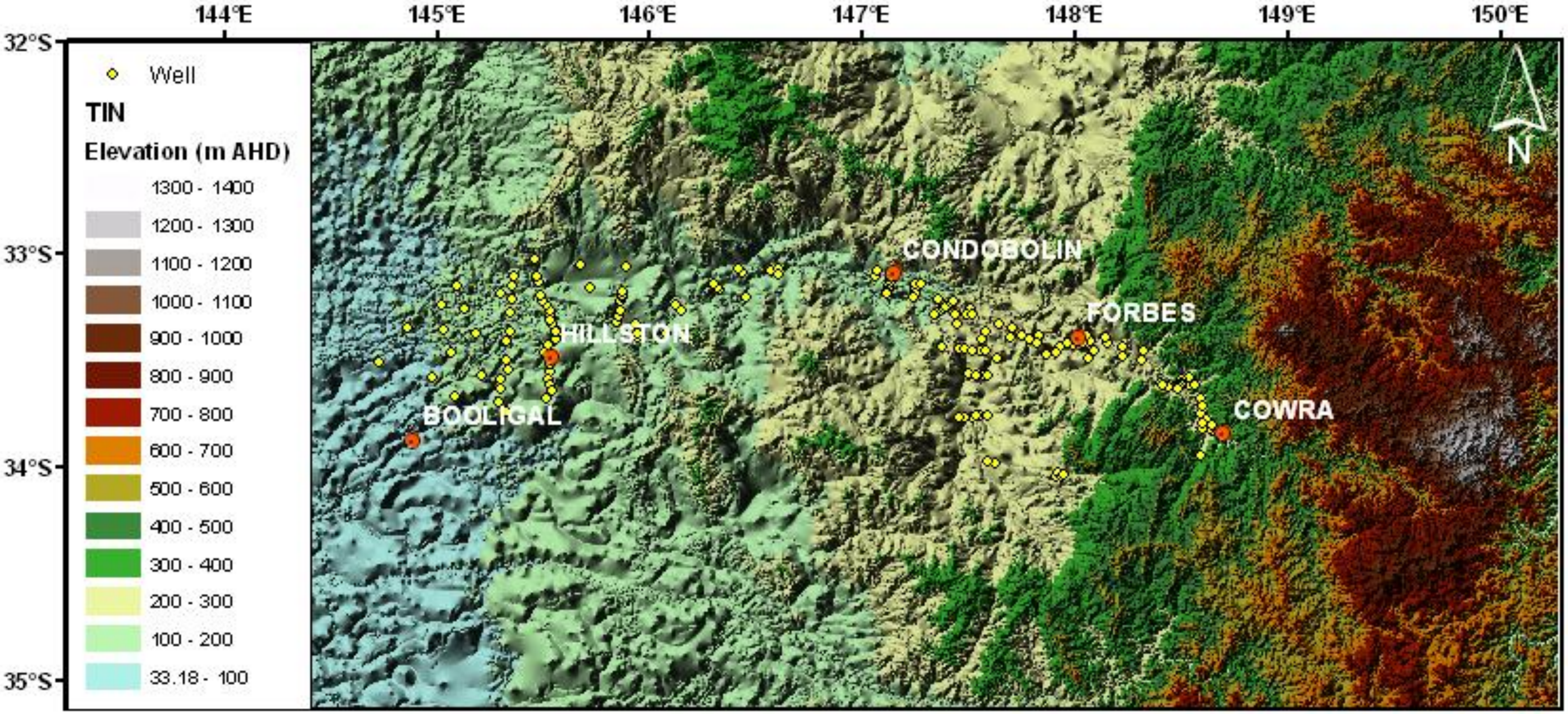


Figure 3. Topography of the Lachlan Catchment and the location of the major town centres. The bores utilised for the current study have are also shown on this map. For the corresponding bore ID numbers the reader is referred to Figure 34 (Modified from GSA, 2010).

Climate and Rainfall

Due to the vast and elongate nature of the Lachlan Catchment, and its diverse topographic relief, the climate varies both temporally and spatially throughout the catchment (NSW Agriculture, 2003; Dent *et al.*, 2007).

Overall the Lachlan Catchment exhibits a temperate climate (Kemp 2010) with an annual average rainfall of 461 mm. Figure 4A shows that the variability of the annual average rainfall between years is considerable. The fitted trendline on the graphs reveals no markedly significant change in rainfall between 1955 and 1995 (CSIRO, 2008).

Two primary weather systems exist within the catchment; a winter dominated southern pattern and a summer dominated northern pattern. As such, rainfall is greater in the southern regions of the catchment relative to the north during the winter months, while summer rainfall is dominant in the northern catchment (NSW Agriculture and Fisheries Division of Plant Industries 1990; Lachlan CMA, 2009). The resultant mean monthly average rainfall across the entire catchment is relatively static with the greatest variability occurring in the summer months (Figure 4B; NSW Agriculture, 2003; CSIRO, 2008).

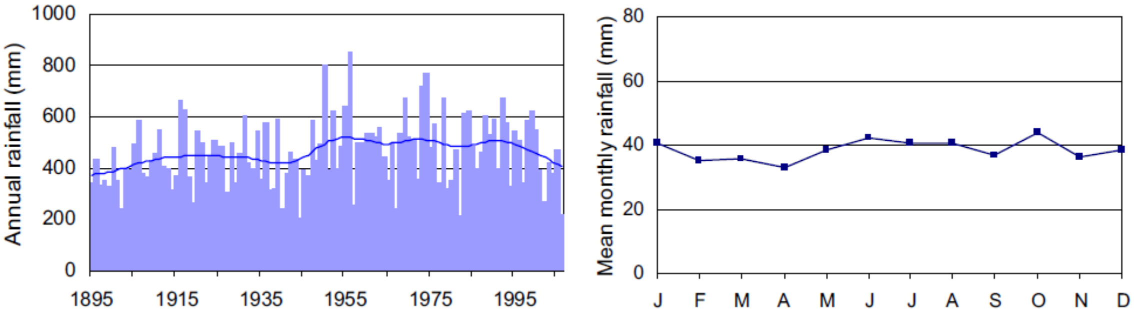


Figure 4. (A) Average annual rainfall histogram for the Lachlan Catchment from 1895 to 2007 (From CSIRO, 2008). (B) Mean monthly rainfall for the Lachlan Catchment from 1895 to 2007 (From CSIRO, 2008).

The eastern portion of the Lachlan Catchment is situated in undulating to mountainous terrain resulting in a sub-alpine environment while the semi-arid rangelands in the west are a consequence of the relatively flat landscape. Between the eastern and western portions of the catchment a transitional environment between sub-alpine and semi-arid rangelands exists (CSIRO, 2008). Lateral changes in precipitation and temperature throughout the catchment ultimately reflect the topographic profile resulting in an increasing thermal and decreasing precipitation gradient from east to west (NSW Agriculture, 2003; DLWC, 1989).

In the tablelands, rainfall levels do not vary significantly from month to month, and the annual average precipitation is 650 mm. During winter precipitation may reflect snowfall as well as rainfall in areas above 900 m.a.s.l.. (Kemp 2010). Towards the west, mean precipitation values decrease with distance (Figure 5) and elevation (Table 1), while the minimum, maximum and mean temperatures generally increase (Table 1; Figure 6; NSW Agriculture, 2003; DLWC, 1989). Annual potential evaporation exceeds the average annual precipitation levels irrespective of location within the catchment.

To assess rainfall data more critically the cumulative rainfall departure (CRD) methodology was applied. The CRD methodology is as follows:

1. The mean annual rainfall is calculated using total yearly rainfall for the period of the record;
2. The total individual rainfall for each year is then subtracted by the mean annual rainfall to determine the departure from the mean;
3. The cumulative departures are then plotted on a graph to allow for visual interpretation of the data.

Table 1. Climate statistics for major townships in the Lachlan Catchment. Note, some of the summary statistics are based on less than 20 years of monitoring; for a record of the years monitored the reader is referred to the Bureau of Meteorology (2010). Abbreviations: *Nd* = no data (Modified from Bureau of Meteorology, 2010).

	Blaney	Cowra	Forbes	Condobolin	Hillston
Elevation (m asl)	863	318	240	199	122
Mean daily max temperature (^{o}C)	18.3	22.2	24.4	24.6	24.3
Highest max temp (^{o}C)	37.5	42.5	45.1	45.7	46
Mean daily min temperature (^{o}C)	4.4	10	9.7	10.2	10.9
Lowest min temp (^{o}C)	-10.6	-4.2	-6.7	-8.1	-4.4
Mean daily evaporation (mm)	n.d.	3.8	n.d	n.d.	4.9
Annual evaporation (mm)	n.d.	1387	n.d.	n.d.	1789
Long-term annual evapotranspitation (mm)†	1172	1331	1437	n.d.	367
Annual Mean rainfall (mm)	767	627	447	410	365

Note:

† Long term evapotranspiration values are those obtained from NSW Agriculture (2003) which utilised the amount of evaporation and transpiration of a grass reference crop from Allen *et al.* (1998).

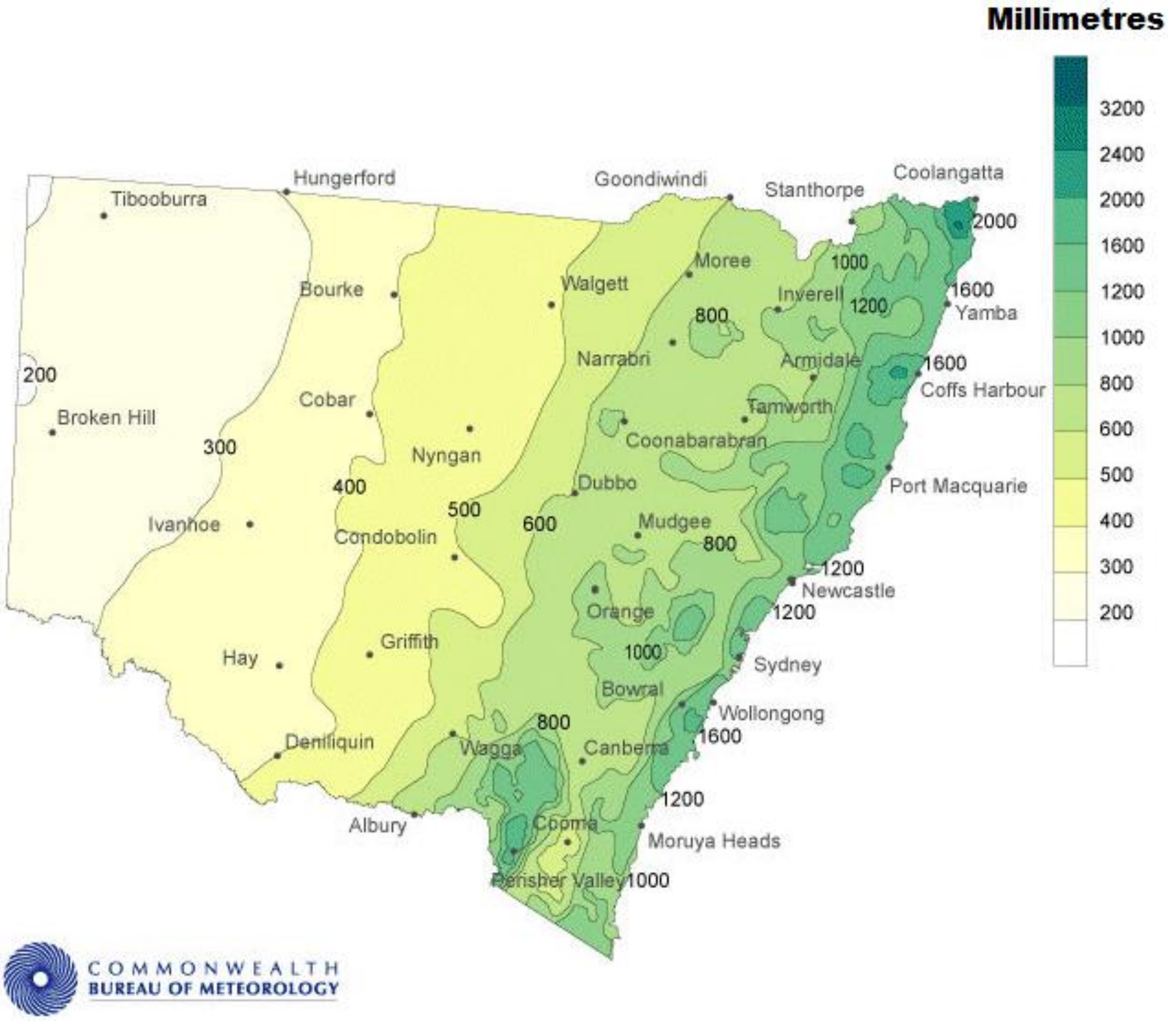


Figure 5. Annual average precipitation contour map for New South Wales (Modified from Bureau of Meteorology, 2010).

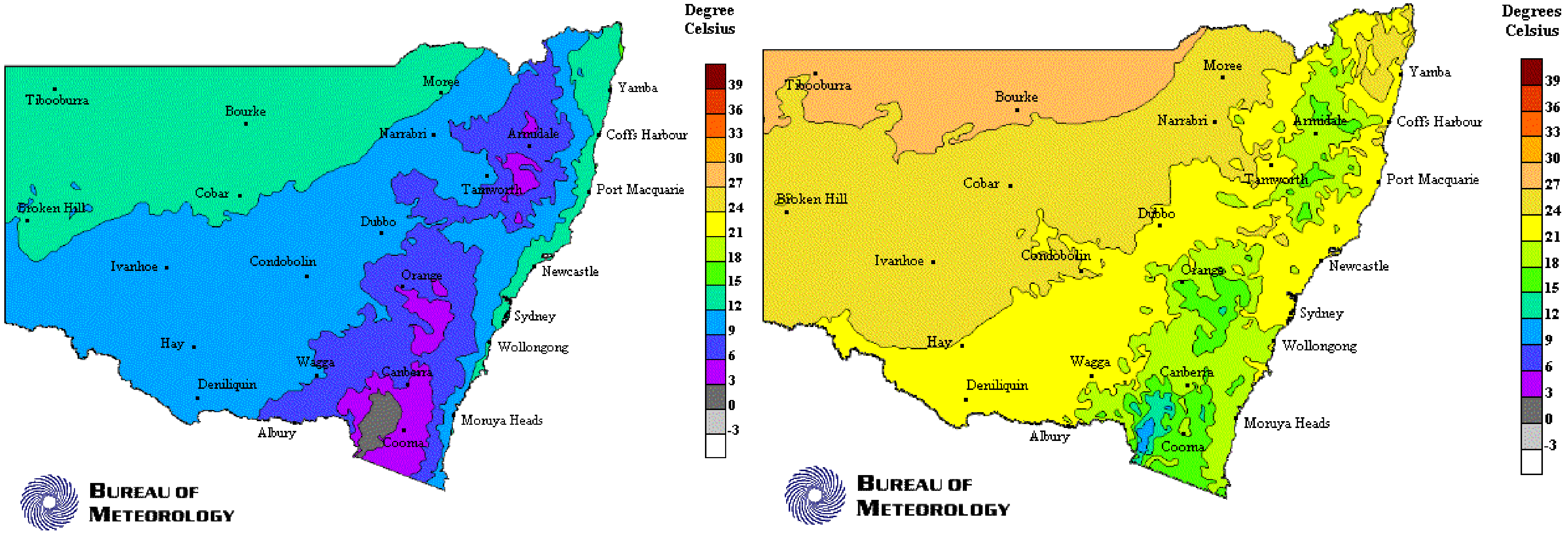


Figure 6. Average annual minimum temperature for New South Wales and (B) average annual maximum temperature for New South Wales. Within the Lachlan Catchment there is a general trend towards higher temperatures towards the west (Modified from Bureau of Meteorology, 2010).

CRD graphs can be used to indicate periods of relatively increased rainfall and relatively declining rainfall as upward and downward slopes respectively. Webster and Stewart (2004) suggest that the CRD procedure is only applicable when trying to quantify short-term precipitation trends as quantification of long-term trends often produces misleading and/or erroneous results in non-normally distributed datasets. CRD graphs were generated for the mid to upper and lower Lachlan Catchment utilising precipitation data collected during 1900 to 2009; precipitation data for the mid to upper Lachlan were collected from the Condobolin Retirement Village Weather Station while data for the lower Lachlan were sourced from the Hillston Airport Weather Station.

In the upper Lachlan there is an overall period of below average precipitation (a "dry run") from 1895 through to the late 1940s followed by a period of above average rainfall (a "wet run"). This wet run continued through to the start of the 21st Century and was preceded by a relatively steep dry run (Figure 7; Bureau of Meteorology, 2010).

The steady dry run experienced during the first half of the last century coincides with what was termed the 'dry phase' by Hogendyk (2007) during 1895 to 1946. The wet run commencing in the late 1940s exhibits sharp spikes during the 1950s and early to mid 1970s; this is not surprising as more than 4 floods were experienced in the Lachlan in 1950, 1952, 1956 and 1974 (Kemp, 2002). During this wet run there was one major drought event which occurred in the early 1980s and corresponds with a major trough in the CRD graph (Figure 7; DIPNR, 2003).

The lower Lachlan appears to have experienced more varied rainfall conditions with a relatively large dry run at the start of the last century, followed by two decades of varied rainfall (i.e. mid 1940s to the mid 1960s), proceeded by a long period of above average rainfall until the start of the 21st Century (Figure 8; Bureau of Meteorology, 2010).

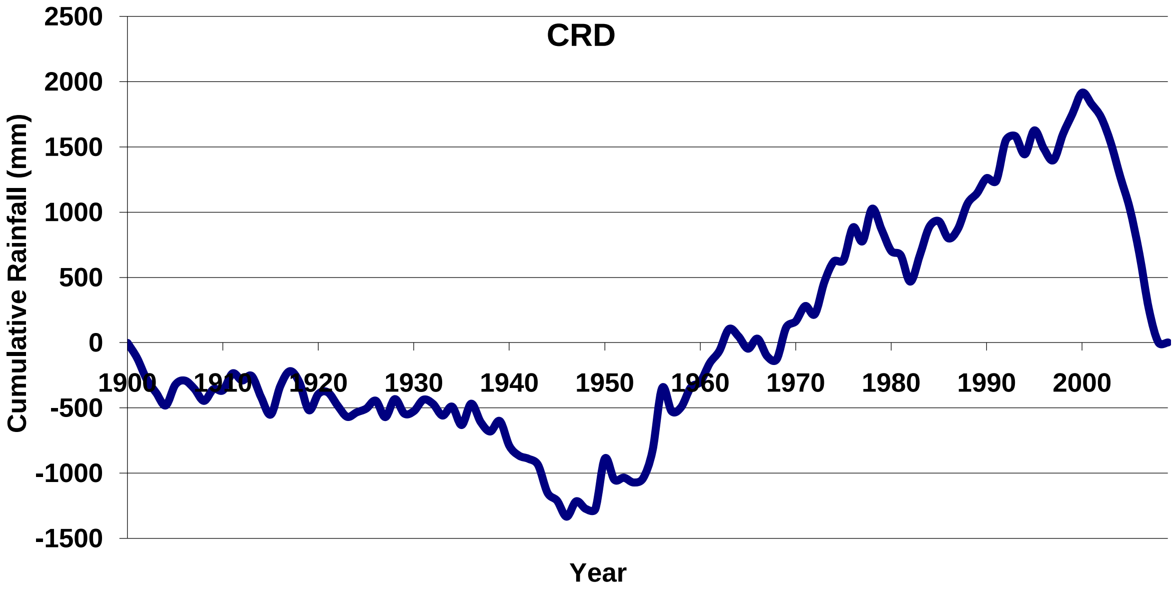


Figure 7. CRD graph for the Condobolin Retirement Village Weather Station located within the upper Lachlan Catchment (Modified from Bureau of Meteorology, 2010).

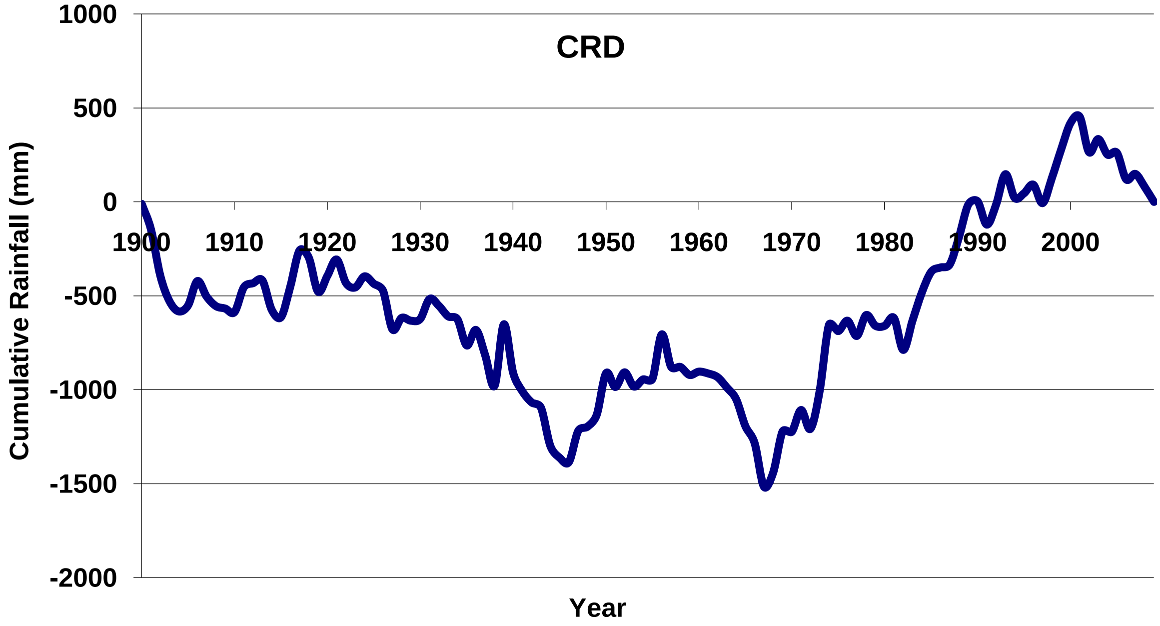


Figure 8. CRD graph for the Hillston Airport Weather Station located within the lower Lachlan Catchment (Modified from Bureau of Meteorology, 2010).

The dry run observed from 1900 till 1946 for the lower Lachlan can be also explained by the dry phase experienced during 1895 to 1946. This dry run experiences a greater departure from the mean relative to that experienced in the upper Lachlan; this appears to be a result of the heightened severity of the drought in the western regions (Figure 8; Hogendyk, 2007).

The steep dry run of the early to 1940s can be explained by severe droughts documented by DIPNR (2003) and MDBC (2006). This period was followed by a short wet run from 1946 to 1960 which was accompanied by 4 or more annual floods in the years of 1950, 1952 and 1956 (Kemp, 2002). The drought of the 1960s was responsible for the second lowest inflow rates in the basin's history and explains the 7 year decline in annual precipitation; this is followed by an extended wet run with the steepest jump in precipitation levels occurring from 1973 to 1974 coinciding with at least 4 documented floods in 1974 (Figure 8; MDBC, 2006; Kemp, 2010).

Regional Geology

As a consequence of its vast elongate nature the Lachlan Catchment crosses numerous geological terrains of varied geological complexity (Kingham, 1998). The upper and middle regions of the Lachlan Catchment are situated on a package of Palaeozoic rocks typifying the structural unit known as the Lachlan Fold Belt (LFB); while the majority of the lower catchment lies on Cenozoic aged alluvial sediments characterising the Murray Basin (Figure 9; Dent *et al*., 2007).

According to Coney (1992) the LFB comprises three primary lithotectonic assemblages. These include Early to Middle Cambrian greenstone belts, Ordovician-Silurian turbidite fan deposits, and early-mid Silurian to Late Devonian-Early Carboniferous aged volcaniclastics, metasediments and felsic to mafic volcanic and plutonic units (Coney, 1992; Chan, 1999).

The units of the LFB have been subjected to multiple deformation events. The Benambran orogeny of the late Ordovician – Early Silurian affected almost all of the LFB as it inverted the tectonic regime from an extensional, back-arc basin to a collisional thrust belt known as the Wagga-Omeo Zone (Scheibner and Basden, 1996). Subsequent to this, central and eastern portions of the LFB experienced rapid opening and closing of basins and deformation accompanying the Bowning-Bindi orogeny of the late Silurian-Early Devonian (Graham *et al*., 1996). As the LFB transitioned towards a mature continental margin orogen in the Silurian-Devonian, extensive orogenic granites were emplaced; this was accompanied by the deposition of sedimentary units and large scale, explosive volcanism. Following this further granites were emplaced during the Carboniferous, marking the completion of the formation of the LFB (Kingham, 1998). Subsequent rifting along the eastern continental margin in the Late Cretaceous further enhanced the uplift the LFB (Bishop and Goldrick, 2000). According to Kemp (2010) these events are responsible for folded and faulted granitic units which typify the undulating tablelands of the upper Lachlan Catchment.

Towards the central regions of the Lachlan, in the undulating country informally referred to as the slopes, it appears that the LFB has undergone flexure of faulting (Kemp, 2010). Evidence for this includes a prominent mountain front as well as less than 80 m of stream incision which is responsible for terraces that converge towards low gradient alluvial plains (Bishop and Goldrick, 1992).

The region of the Murray Basin relevant to the current study unconformably overlies and onlaps the LFB (Figures 9 and 10; NSW Department of Primary Industries, 2006). Basin formation was initiated approximately 90 MA in response to seafloor spreading between Australia and New Zealand (NSW Department of Primary Industries, 2005). Uplifting related to this tectonic event made subsidence possible leading to the development of the Murray Basin in the Cenozoic (Kingham, 1998). The basin is relatively broad and shallow, with the geological record indicating low levels of sediment supply as well as slow rates of subsidence (Brown and Stephenson, 1989). Numerous "trough structures" have been identified; the schematic boundaries of these troughs are shown in Figure 10. The Ivanhoe and Booligal Troughs are the only troughs situated within the Lachlan Catchment (Martin, 1984); the Booligal Trough located proximal to the Booligal wetlands (Figure 10) hosts sediments believed to be Devonian in age (NSW Department of Primary Industries, 2005).

Broadly speaking, the Cenozoic alluvial sediments within the Lachlan can be separated into two separate zones; those situated in the middle to upper Lachlan and those in the lower Lachlan. As these sedimentary units host the alluvial aquifers pertinent to this study their spatial distribution, geological characteristics and geological history will be addressed in greater detail in the following section. For a detailed geological map showing the spatial distribution of lithological and alluvial units the reader is referred to Figure 11.

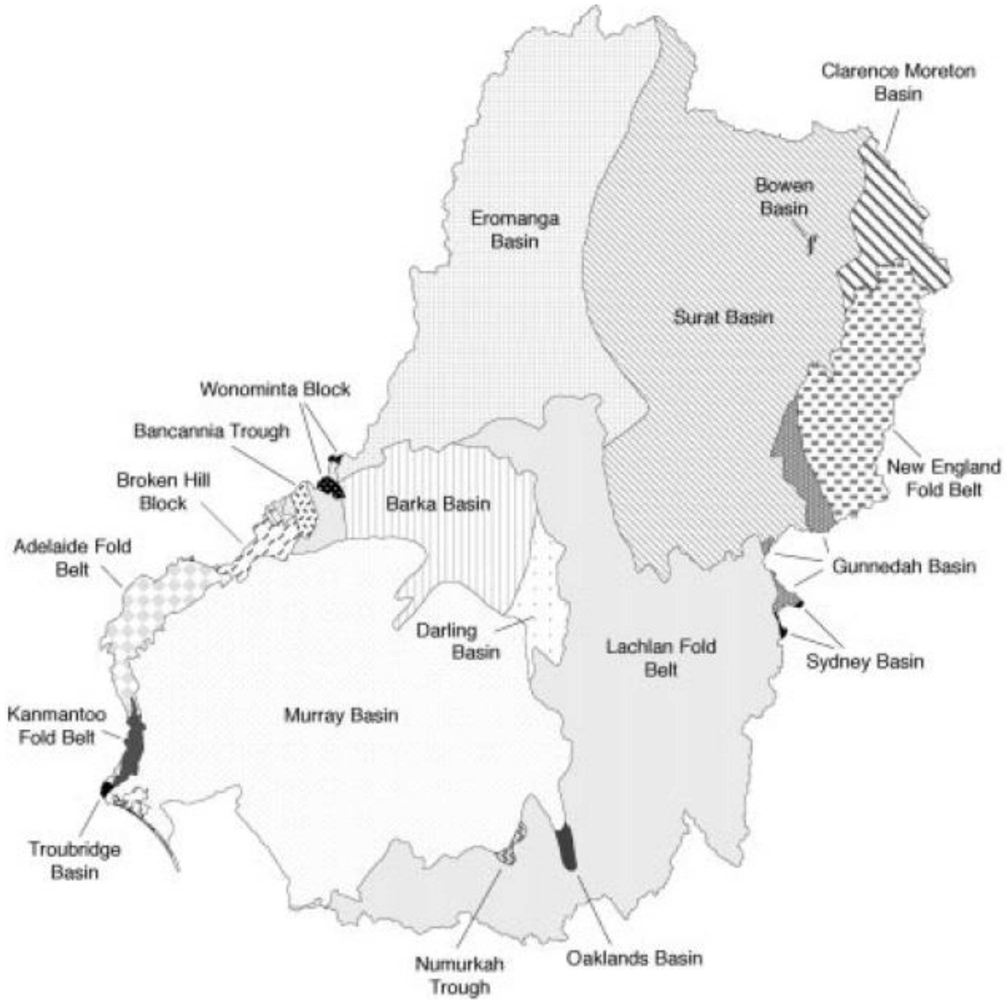


Figure 9. Tectonic units within the Murray-Darling Basin (Kingham, 1998).

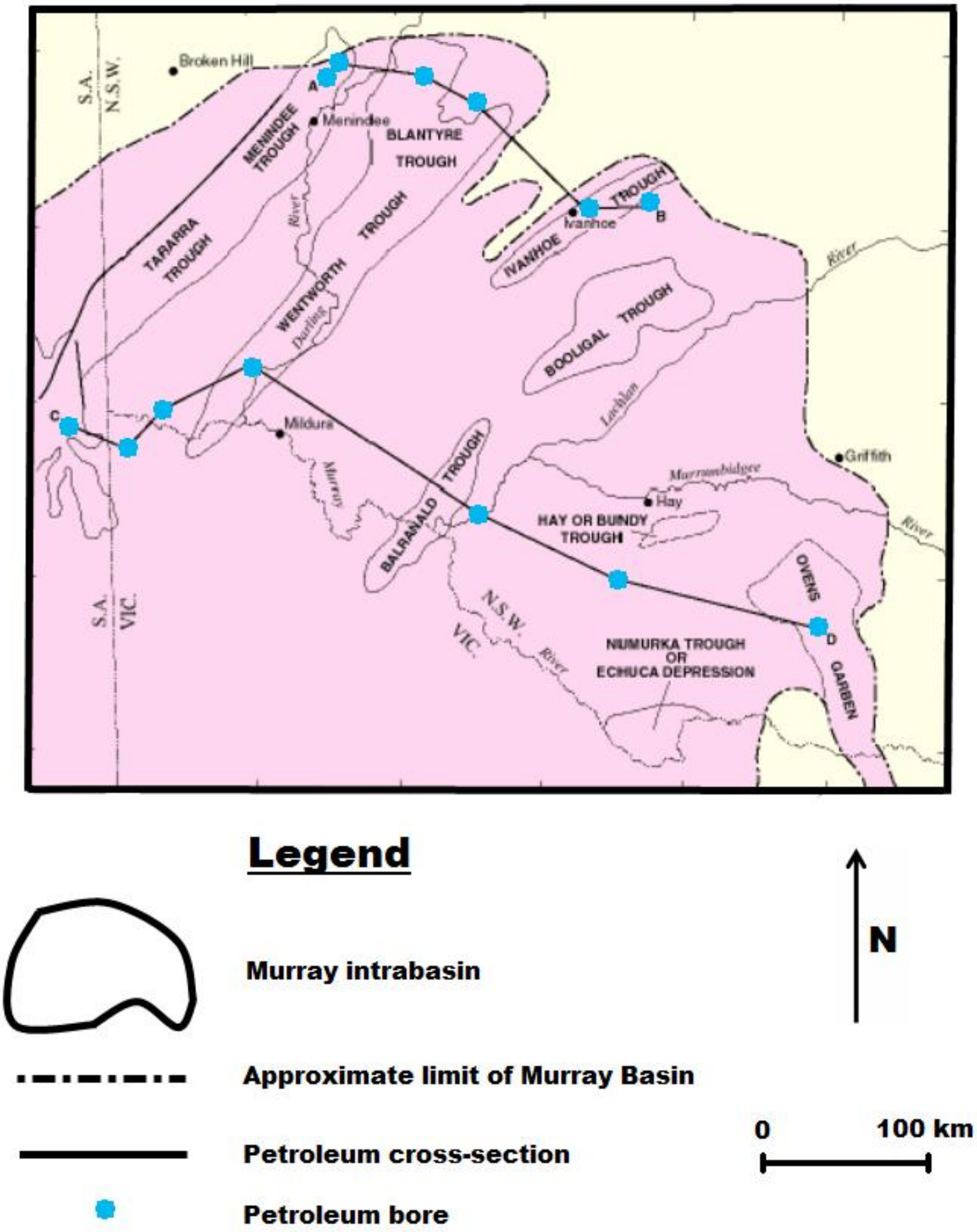


Figure 10. Crustal structure of the Murray Basin. Note that the region to the east of the Murray Basin within the Lachlan Catchment falls within the Lachlan Fold Belt (Modified from NSW Dept. of Primary Industries, 2006).

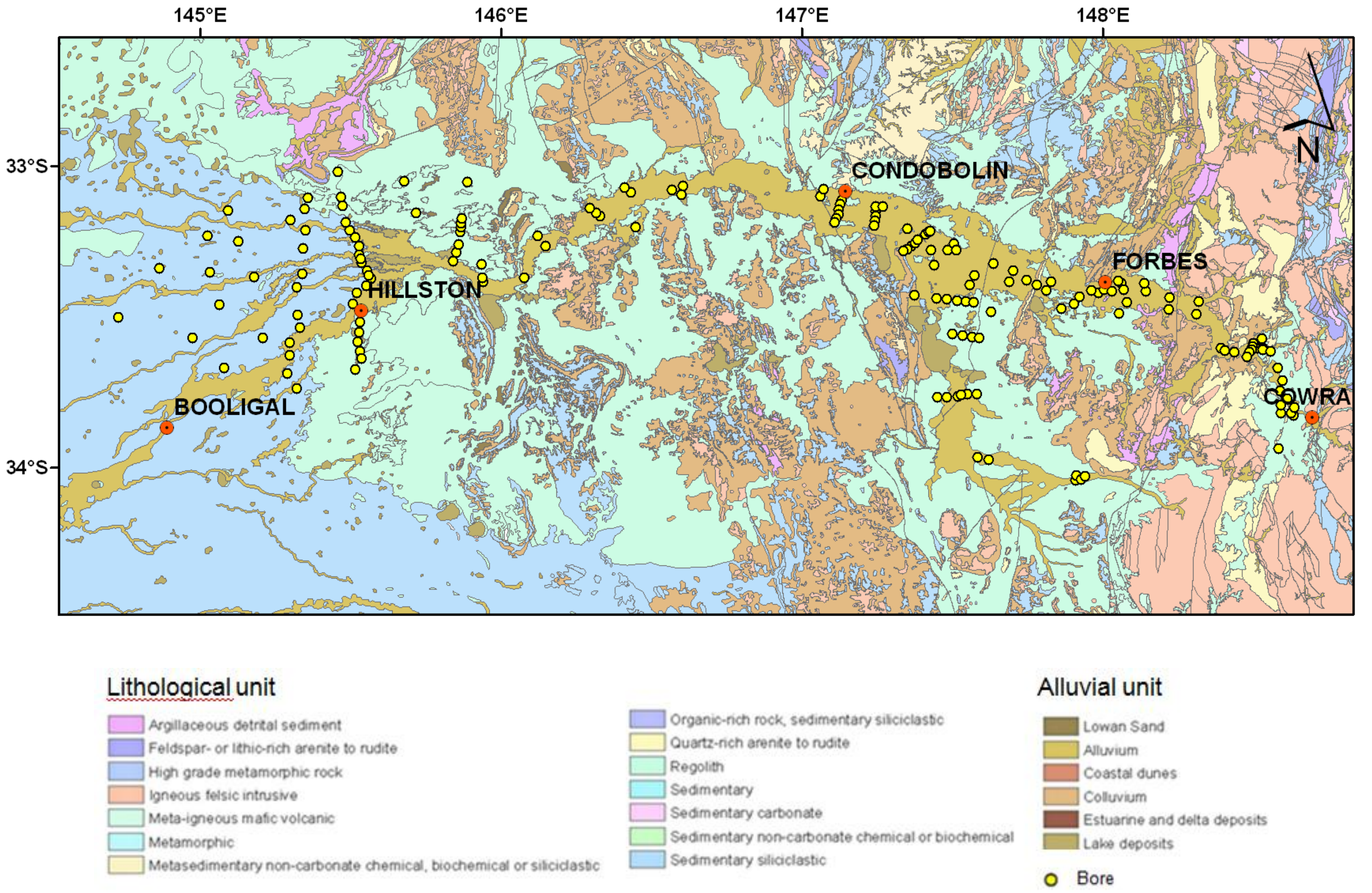


Figure 11. Geological map showing the spatial distribution of the lithological and alluvial units typifying Lachlan Catchment (Modified from GSA, 2010).

Local Geology

The Cenozoic alluvial sediments of the Lachlan Catchment can be separated into two separate zones; those situated in the middle to upper catchment and those in the lower catchment (Figure 12; CSIRO, 2008).

According to URS (2006) over half of the middle to upper Lachlan Valley is covered by the Central West Highlands (Figure 12). The Central West Highlands are characterised by the volcanic and sedimentary lithological units of the LFB. These units effectively act as a "bucket", enveloping the alluvial sediments of the middle to upper Lachlan (Figures 12 and 13; URS 2006; Dent *et al.*, 2007).

Alluvial sediments occupying the middle to upper section of the Lachlan Valley vary in regards to their vertical and lateral extent. Proximal to Cowra, alluvial sediments occupy an area ~ 3-5 km wide, this increases to 10 km approaching the juncture between the valley and the floodplains and can range from 24 to 32 km on the floodplains themselves (Adamson *et al.*, 1969). Bore drilling logs have shown that the alluvial sequence becomes thicker downstream; 3 km upstream from Cowra alluvium is 17 m deep increasing to 61 m approximately 6 km downstream of Cowra. The maximum depth reached in the middle Lachlan is 133 m in an area to the south of Forbes (Martin, 1987).

Downstream of Cowra a buried "valley in valley" structure has been recognised which may be attributed to uplift. This is characterised by an old valley maintaining a relatively constant depth of 27-30 m beneath the modern day drainage level, carved into by a more recent valley increasing in depth with distance downstream (1.6 m/km; Martin, 1987). The valley comprises two distinctly different Cenozoic alluvial formations; the lower formation is known as the Lachlan Formation which is unconformably overlain by the Cowra Formation. Elevated above both of these formations is the Glen Logan Gravel which is believed to be stratigraphically lower than the Cowra and Lachlan formations (Figure 12; Adamson *et al.*, 1969).

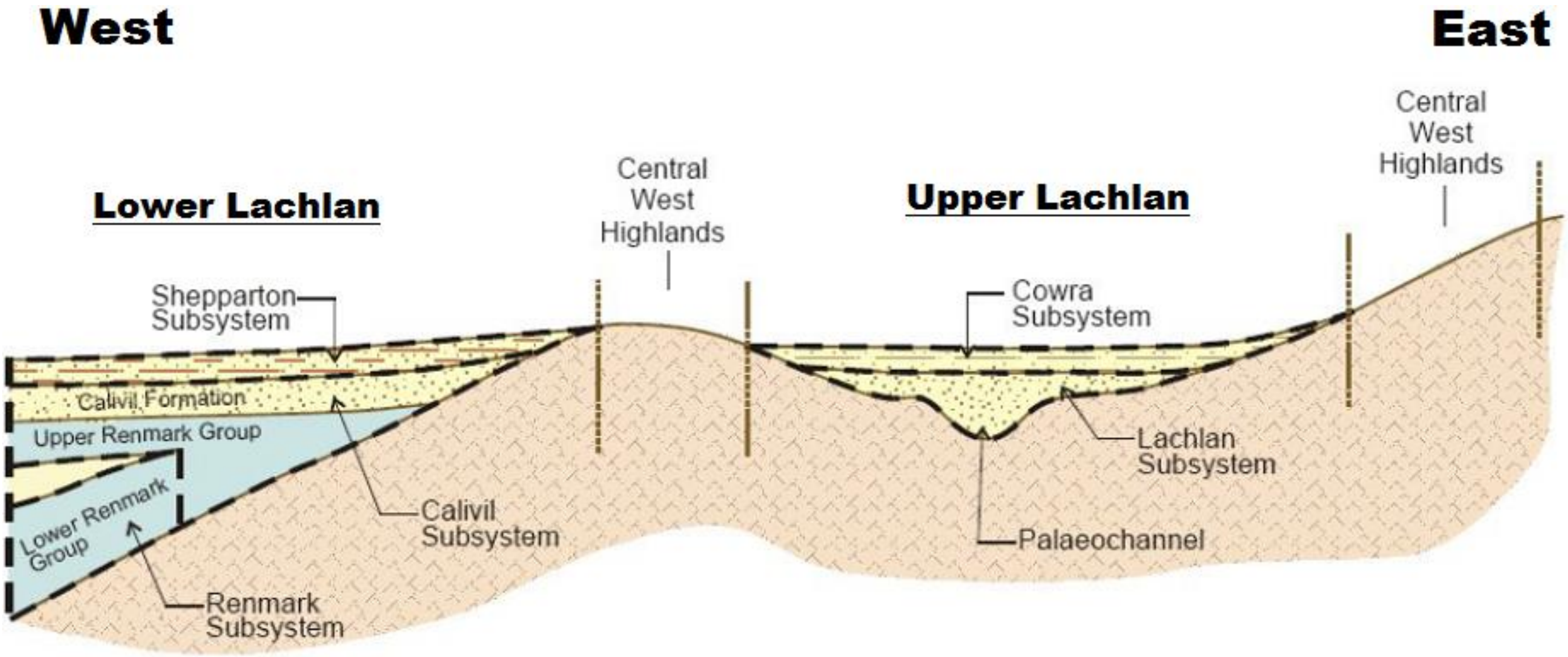


Figure 12. Schematic west-east geological cross-section of the Lachlan Catchment (Modified from URS, 2006).

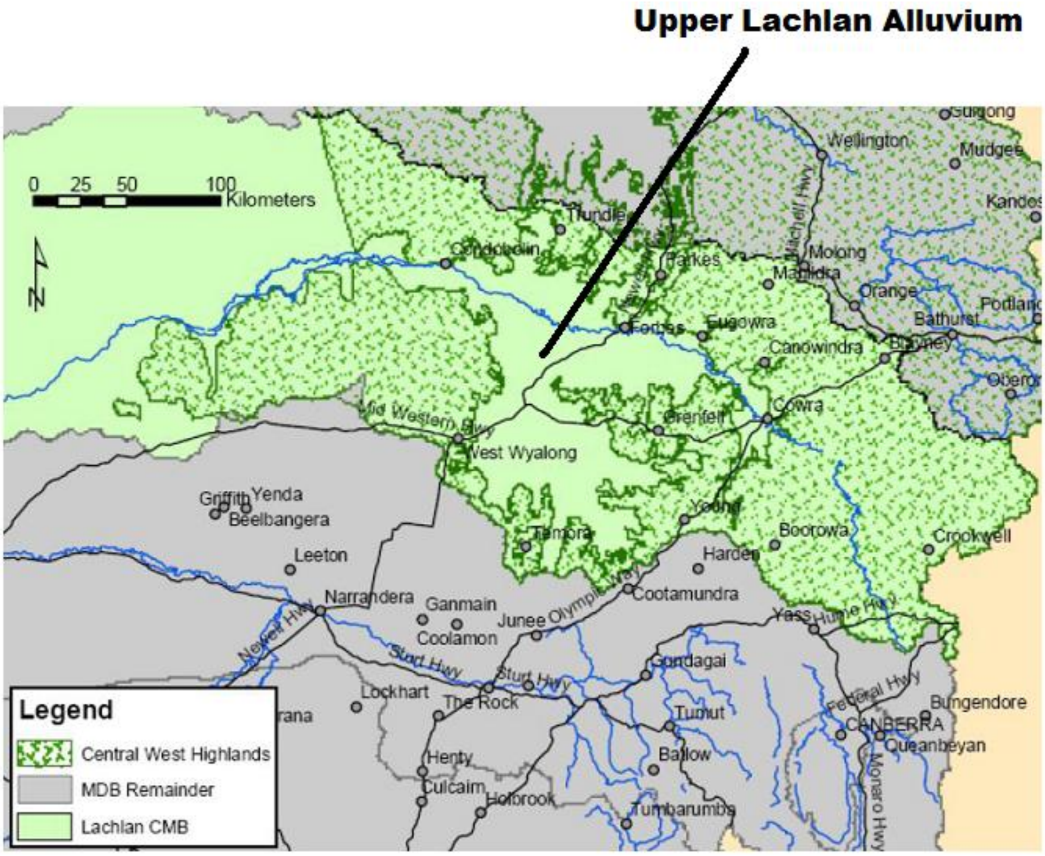


Figure 13. Extent of the Central Western Highlands. Note the Central Western Highlands envelopes the alluvial sediments of the middle to upper Lachlan Catchment (URS, 2006).

The Lachlan Formation is characterised by interbedded and interlensed sediments ranging from clays through to gravel. The sands and gravels are almost entirely composed of different varieties of quartz with occasional chert pebbles. A maximum thickness of 24 m was recognised for the gravels by Adamson *et al*. (1969). Curiously both the gravels and sands are barren of resistant rock types encountered in the catchment today (Martin 1987).

Clays of the Lachlan Formation are either carbonaceous or variegated. According to Adamson *et al*. (1969) and Martin (1987) the former are the most useful for palynological purposes as they contain pollen spores which may be utilised for dating the sequence and indicating climatic conditions. Carbonaceous clays occur as infrequently distributed lenses often less than 1 m in thickness with lenses up to 12 m having been recognised.

The Glen Logan Gravels are defined by medium to coarse grained gravel composed of quartz, set in a red-brown silty matrix. This formation often forms hill cappings or is located at other elevated positions. The complete absence of other rock types indicates that this unit has been redistributed. It has therefore been postulated (Adamson *et al*. 1969) that these gravels are the remnants of an older formation which is the source material for the Lachlan Formation. The most likely source appears to be quartz reefs situated in the Palaeozoic slates to the east of the Lachlan Valley.

The palaeontologic record suggests that the Lachlan Formation was deposited during the Pliocene. No such evidence was available in the palaeontologically barren Glen Logan Gravels, but the age of the Lachlan Formation in conjunction with a known period of peneplanation and sedimentation in the Miocene suggests they were deposited during this epoch (Adamson *et al*., 1969).

Subsequent to the deposition of the Lachlan Formation was a period of uplift which resulted in the deposition of the Cowra Formation on the eroded surface of the Lachlan Formation (Adamson *et al*., 1969). The Cowra Formation is thought to be Pleistocene in age, hosting gravel to clay size sediments. Clay to silt is generally brown in colour and occurs in thin layers; carbonaceous clays have been identified although occurrences to date have been extremely rare. Sands and coarse gravels are generally composed of resistant rock types encountered in the catchment today (Adamson *et al*., 1969; Martin, 1987; CSIRO, 2008).

Since deposition the Cowra Formation has been subjected to considerable levels of erosion; this is in part a result of a series of minor uplifts which have allowed drainage to rejuvenate, forming erosion terraces. Erosion terraces are most common upstream and steadily decline in their distribution and pronounced nature downstream (Adamson *et al*., 1969; Martin 1987). Cross-sections through the middle valley showing the distribution of the different Cenozoic alluvial sediments are provided in Figure 14.

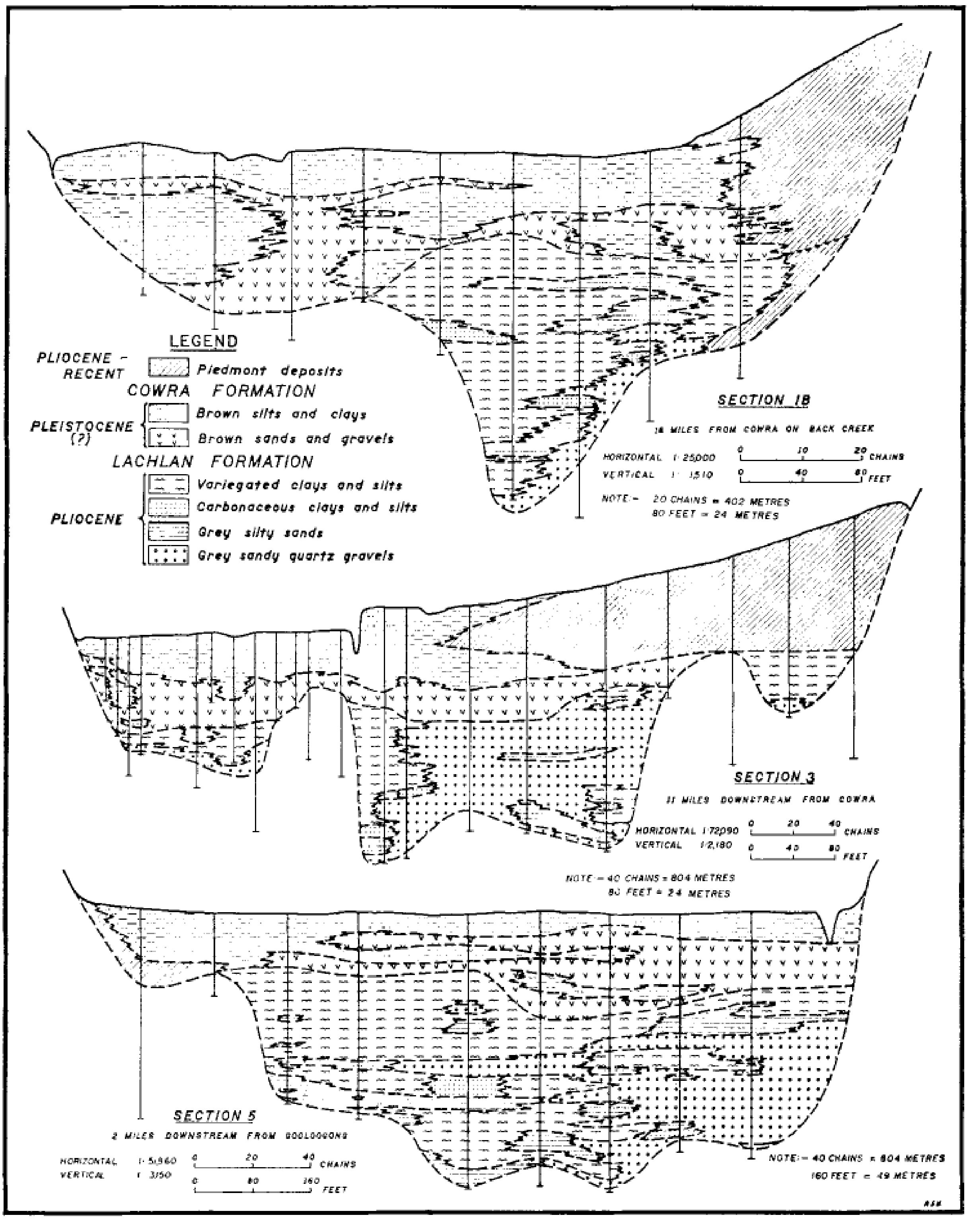


Figure 14. Cross-sections of the valley middle Lachlan and the distribution of alluvial sediments they host (Modified from Adamson *et al.*, 1969).

As mentioned previously, the stratigraphy of the lower catchment differs to that of the middle and upper catchments (Figure 12). The geology of the western region, incorporating the Murray Basin, has been explained in detail by Martin (1984), Martin (1987), Mampitiya (2002), Dent *et al*. (2007) and summarised in the stratigraphic column provided in Table 2.

The pre-Paleogene basement of the Murray Basin is relatively shallow compared to surrounding basins. There are however basement features known as troughs which are significantly deeper; these include the Ivanhoe and Booligal Troughs (Figure 10; Martin, 1984). As such the overlying alluvial sequence is on the whole thinner in comparison to surrounding basins. At the basin's edge (i.e. towards the east) the thickness of alluvial sediments ranges from 100 to 170 m and increases towards the basins depocentre. The thickest recorded alluvial sequence was identified within the Ivanhoe trough with the depth from the top of the alluvial sequence to the basement being approximately 270 m (Martin, 1987).

The basal unit in this portion of the catchment is the Warina Sands. This unit is only found in deeper portions of the basin and characterised by coarse-grained quartz sands hosting carbonaceous and dark grey clay lenses. Overlying these sands is the Renmark Group of the Olney Formation; the Olney is primarily composed of variably consolidated grey carbonaceous clays as well as quartzose sands and fine gravel; sporadic layers of peat and lignite have also been identified. This formation is at its thickest (i.e. 40-60 m) approaching the depocentre of the basin and thins drastically eastward to the point where it is almost non-existent at Hillston (Figure 15). The base of the Olney is considered to have been deposited during the Eocene epoch, while the upper units belong to the mid-Miocene (Martin, 1987; Mampitiya, 2002; Dent *et al*., 2007).

Unconformably overlying the Olney is the Calivil Formation which is believed to be late Miocene in age. The Calivil primarily comprises fine gravels and coarse sands interbedded with lesser quantities of carbonaceous and kaolinitic clay. The average thickness of these alluvials throughout the Lachlan is 40 m (Figure 16).

The uppermost Shepparton Formation overlies the Calivil and comprises variegated clays with sporadic sand interbeds. The average thickness of this unit is 20 m; towards the west this formation is dominated by shoe-string gravels. Quaternary alluvial and colluvial sand and gravel deposits have been recognised towards the central west highlands (Figure 12; Martin, 1987; Mampitiya, 2002; Dent *et al*., 2007). The lateral extent of the Shepparton Formation is provided in Figure 17.

Table 2. Stratigraphy of the western Lachlan. Note there is presently a limited understanding of the Quaternary sediments and although they may represent distinctly different units they have been amalgamated for hydrological purposes (Modified from Martin, 1984; Martin, 1987; Mampitiya, 2002; Dent *et al*., 2007).

Era	Period	Epoch	Approximate Age (MA)	Lithological Description	Formation
Cenozoic	Quaternary	Late-Pleistocene to Holocene	Recent to 1.8	Alluvial and colluvial sand and gravel deposits	Various
Cenozoic	Neogene to Quaternary	Pliocene to Pleistocene	0.5 to 5.5	Variegated clays and sporadic interbeds of sand	Shepparton
Cenozoic	Neogene	Late-Miocene	1.8 to 5.5	Fine gravels and coarse sands interbedded with lesser quantities of carbonaceous and kaolinitc clay	Calivil
Cenozoic	Paleogene to Neogene	Eocene to mid Miocene	10 to 53.5	Variably consolidated carbonaceous clays, quartzose sands, fine gravel and sporadic layers of peat and lignite	Olney (Renmark Group)
Cenozoic	Paleogene	N/A	N/A	Quartzose sands	Warina Sands
Major unconformity					
Paleozoic	Devonian to Carboniferous	Early-Devonian to Late Devonian-early Carboniferous	354 to 410	Metamorphosed and folded volcanics and slate	Lachlan Fold Belt (Basement)

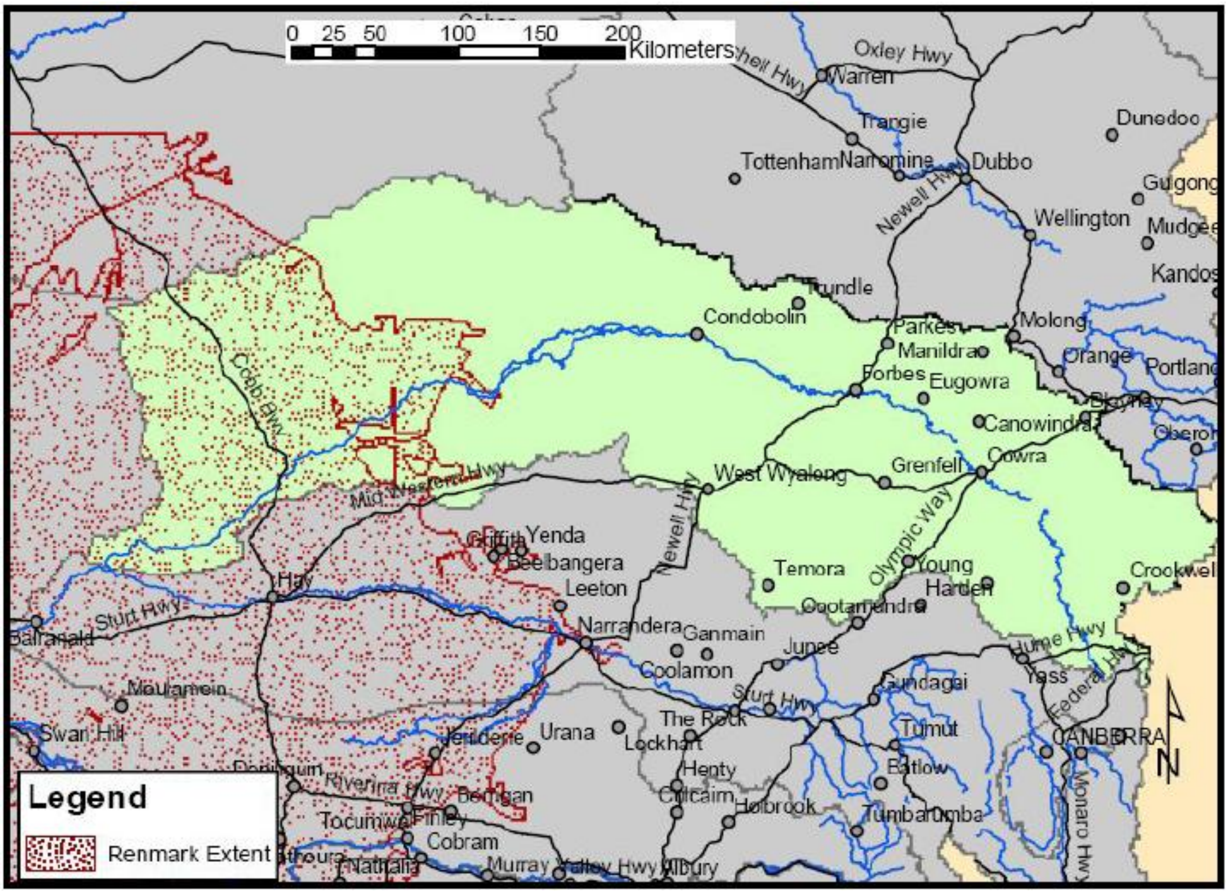


Figure 15. Lateral extent of the Olney Formation (Renmark Group; Modified from URS, 2006).

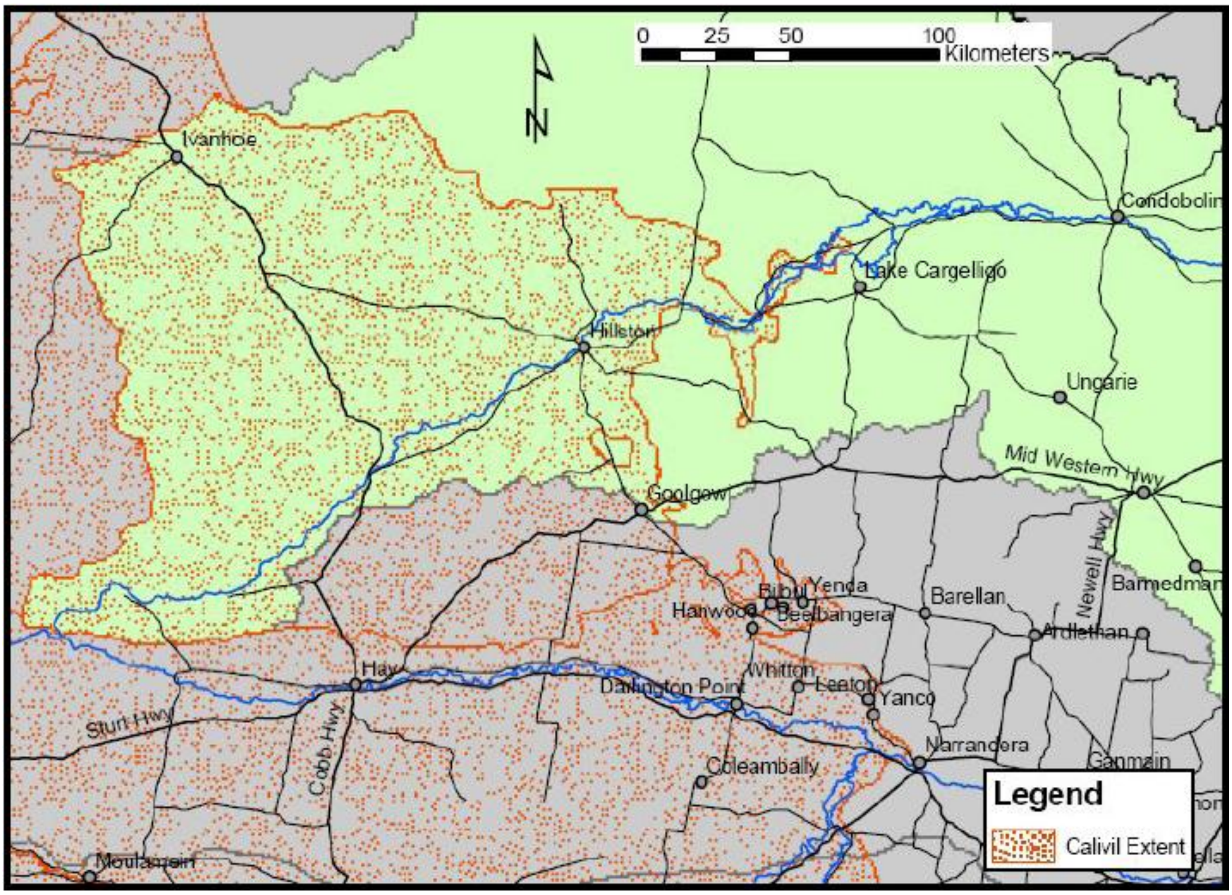


Figure 16. Lateral extent of the Calivil Formation (Modified from URS, 2006).

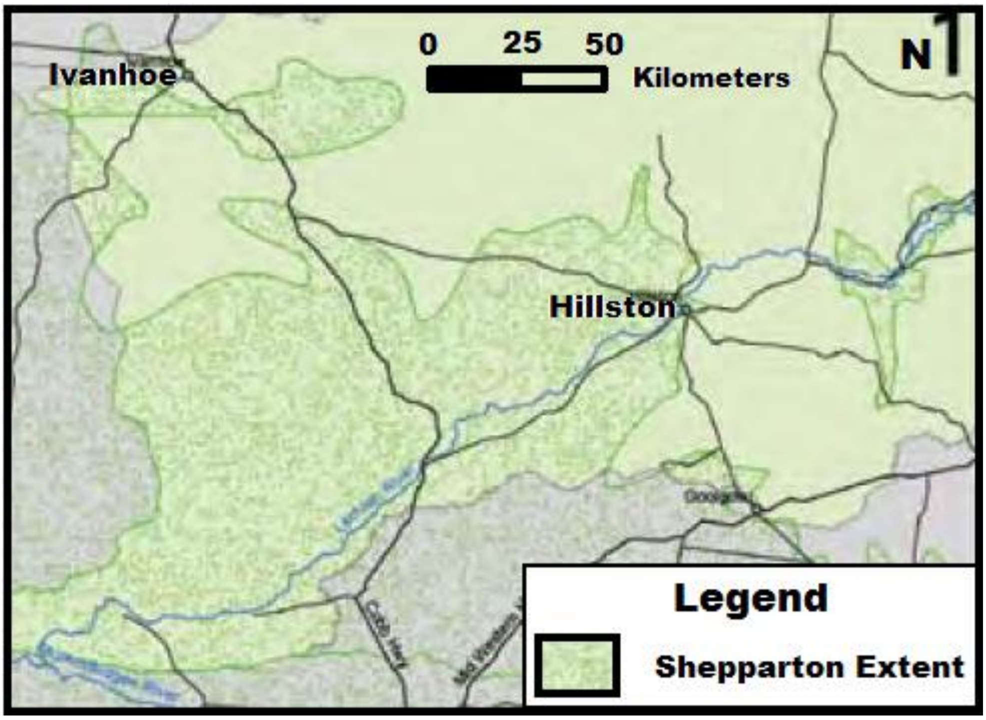


Figure 17. Lateral extent of the Shepparton Formation (Modified from URS, 2006).

Hydrogeology

Groundwater in the Lachlan Catchment is primarily extracted from two alluvial aquifers; the lower and middle to upper Lachlan alluvial aquifers (Figure 18). Both the lower and middle to upper aquifers host multiple hydrologeological subsystems. This section of the report will address the hydrogeological characteristics of each of the major subsystems within the Lachlan Catchment and look at the connectivity between subsystems. Hydrogeological subsystems are assessed rather than individual aquifers due to the varied spatial distribution of aquifers within geological formations; this is in part due to the heterogeneous composition of the different geological formations (URC, 2006; NRC, 2006; Dent *et al*., 2007; CSIRO, 2008).

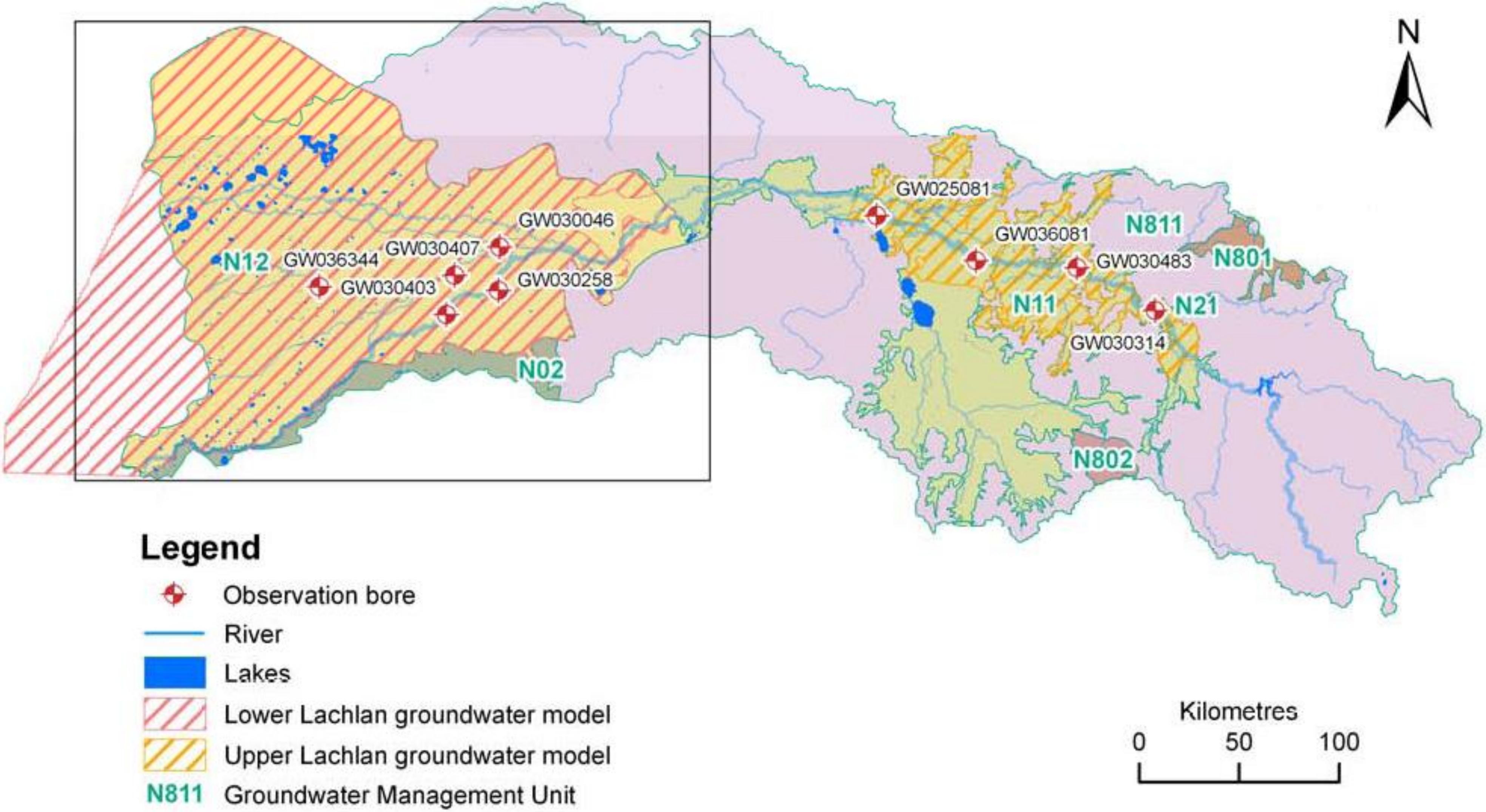


Figure 18. The lower and upper aquifers of the Lachlan Catchment (Modified from CSIRO, 2008).

Hydrogeology – Lower Lachlan Catchment

The aquifers of the lower Lachlan are contained within the Renmark Group and the Calivil and Shepparton Formations. The sediments of the Renmark Group immediately overlie the Palaeozoic basement and are completely covered by alluvium of the Calivil and Shepparton Formations (URS, 2006). According to NRC (2006), in the western portion of the lower Lachlan the Renmark Group can be separated into three distinct units; these being the Lower, Middle and Upper Renmark Group. The Lower Renmark Group comprises sand-sized sediments overlain by the clays and peats of the Middle Renmark while the Upper Renmark Group is typically dominated by sands and gravels. The clays of the Middle Renmark essentially act as an aquitard. Hydrograph records in the semi-confined Lower Renmark Group are distinctly different to those in the Upper Renmark Group (Figure 12; URC, 2006; NRC, 2006; CSIRO, 2008).

In the western portion of the lower Lachlan only the leaky confined aquifer of the Lower Renmark Group belongs to the Renmark hydrogeological Subsystem. In the east however, the Olney Formation thins out and the separate units of the Renmark Group become indistinguishable resulting in a single, hydraulically connected body (Figure 12; URC, 2006; NRC, 2006; CSIRO, 2008).

The sands and gravels of the overlying Calivil Formation are hydraulically connected to the Upper Renmark Group. Thus for hydrological purposes the Calivil Formation and Upper Renmark Group have been combined to form the Calivil Subsystem (a leaky confined aquifer); the main aquifer in the Lower Lachlan Catchment (Figure 12; NRC, 2006; URS, 2006).

The Shepparton Formation hosts clays and sands typifying the uppermost, unconfined aquifer in the lower Lachlan known as the Shepparton Subsystem. According to NRC (2006) the Shepparton Subsystem is partially connected to the underlying Calivil Subsystem (Figure 12; Ife and Skelt, 2004; URC, 2006; NRC, 2006; Dent *et al.*, 2007; CSIRO, 2008).

In the western regions there are essentially three aquifers with the clays of the Middle Renmark Group acting as a hydraulic divide between the Calivil and Renmark Subsystems. In the east an absence of the Middle Renmark Group has resulted in two main hydrogeological subsystems; the Shepparton Subsystem and the Calivil Subsystem comprising the Calivil Formation and the Renmark Group (Figure 12; URC, 2006; NRC, 2006; CSIRO, 2008).

Groundwater in the Renmark Subsystem flows towards the North-West maintaining a reasonably consistent hydraulic conductivity throughout its entirety (Dent *et al.*, 2007). Vertical movement throughout the aquifer is vital as the Renmark Subsystem exhibits no surficial expression and therefore relies on water passing through the upper hydrogeological Subsystems (URS, 2006).

Groundwater movement through the Calivil Formation travels in a west northwest direction in the northern portions of the aquifer and west southwest in the southern portions. Hydraulic conductivity through the Calivil Subsystem varies spatially with rates of 1 m/day in the east increasing to 20-50 m/day towards the west. A map illustrating the potentiometric surface for the Calivil Formation is provided in Figure 19 (URS, 2006; NRC, 2006; Dent *et al.*, 2007).

The Shepparton Formation is essentially dry throughout the catchment as it is above the watertable in the north, northwest (generally beneath the Willandra Creek system) and east becoming progressively saturated towards the south and west; as a result, the watertable generally lies in the Calivil Formation. When the water table is situated within the Shepparton Formation it is located at a depth of 5-10 m (Mampitiya, 2002). Overall the Shepparton Subsystem is of little importance to the Lachlan Catchment as an aquifer, although it does act as a conduit for fluid flow to the stratigraphically lower, more significant aquifers (URS, 2006; NRC, 2006; Dent *et al.*, 2007; CSIRO; 2008).

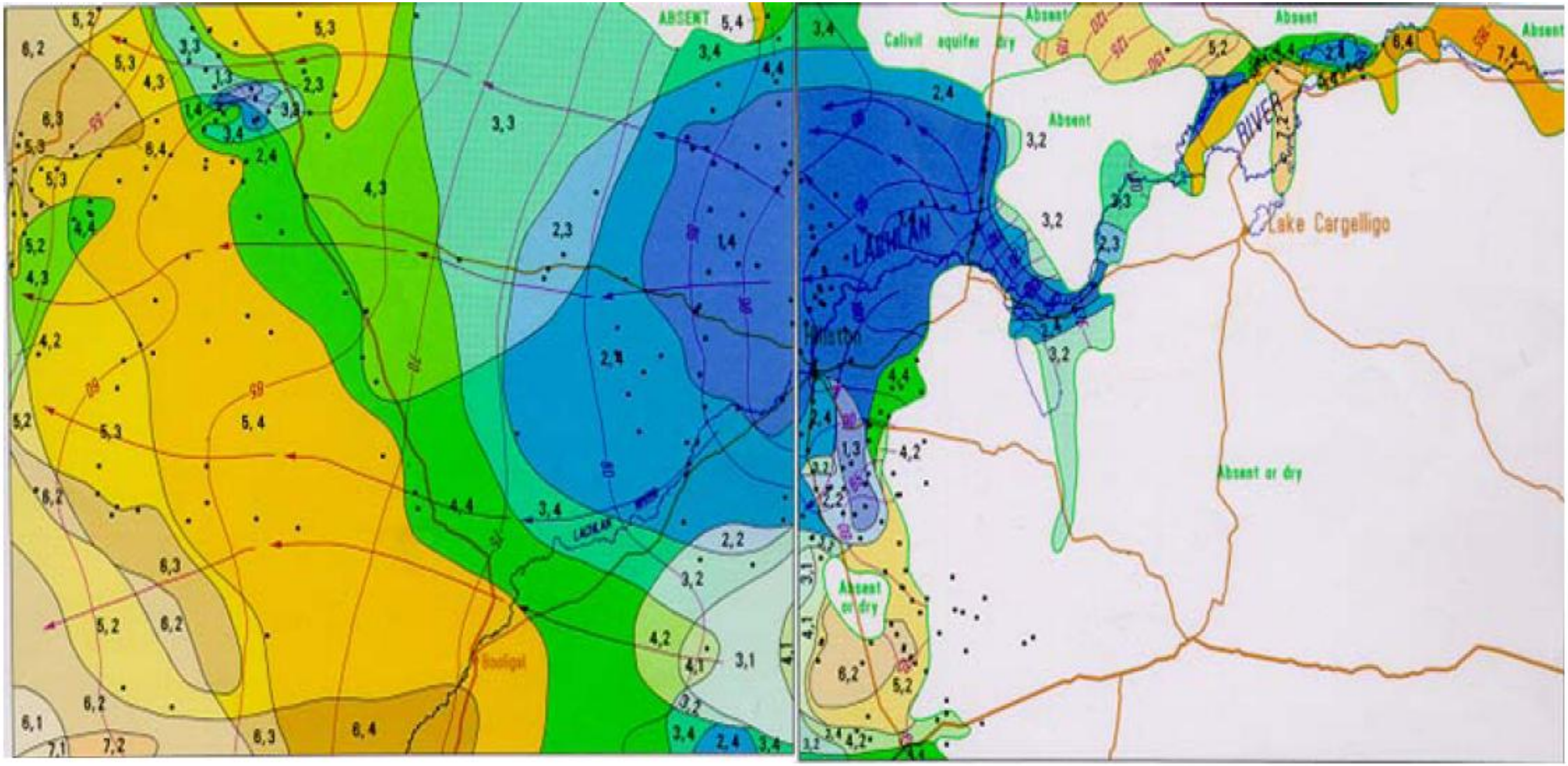


Figure 19. Potentiometric surface and salinity classes for the Calivil aquifer (Modified from NRC, 2006).

All streams passing through the alluvial plains flow across the Shepparton Formation. East of Lake Brewster, at the eastern margin of the alluvial plains the Lachlan River is hydraulically connected to the surface aquifers; this is generally not the case downstream. There is however an ephemeral riverine network just to the west of the Lachlan Catchment where in the right conditions it is likely to produce a watertable of sufficient height to establish hydraulic connection with the surface waters (Figure 20; Braaten and Gates, 2003; NRC, 2006).

According to the CSIRO (2008) the streams throughout the lower Lachlan are influent streams. However, due to the hydraulic connectivity in the east these are only considered "medium" level losing streams. As the water table falls well below that of the Lachlan River in the west, constant leakage to the lower aquifers occurs resulting in a "high" level losing stream. According to Dent *et al.* (2007) the hydraulic separation of the water table and river can partially be explained by the clayey formations in the river bed of the Lachlan (Figure 21; CSIRO, 2008).

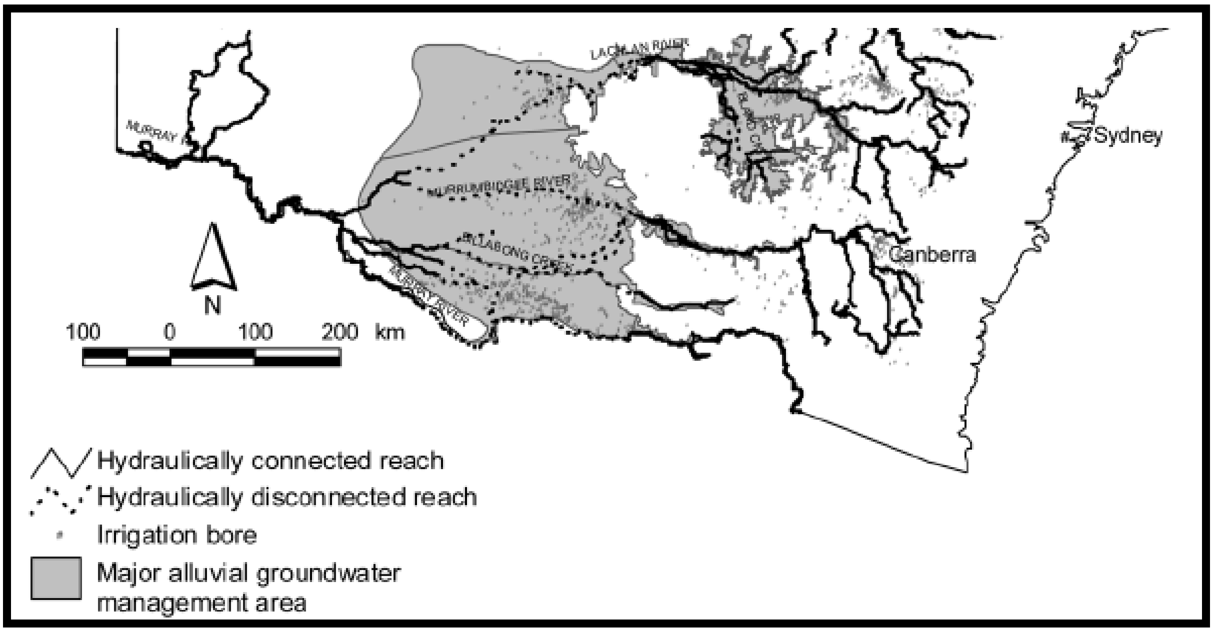


Figure 20. Hydraulic connection of the tributaries of the Riverine Plain, NSW (Modified from Braaten and Gates, 2003).

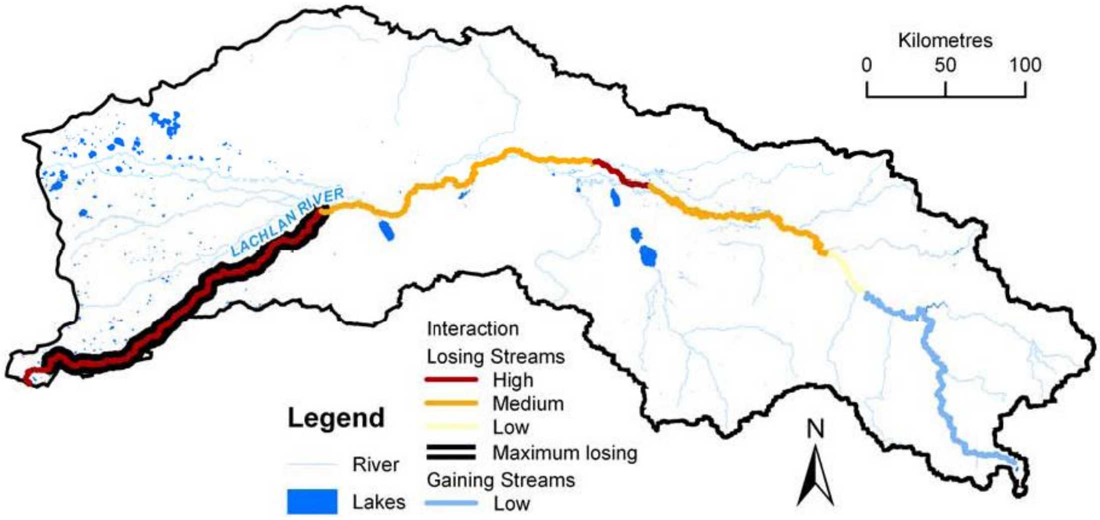


Figure 21. Connectivity between streams and groundwater throughout the Lachlan Catchment (Modified from CSIRO, 2008).

Hydrogeology – Upper Lachlan Catchment

The mid to upper Lachlan Catchment hosts aquifers in the fractured rock aquifers of the Central West Highlands as well as unconsolidated alluvial Cenozoic sediments.

The upper Lachlan Catchment is dominated by the outcropping volcanic and sedimentary units of the LFB known as the Central West Highlands (Figures 12 and 13). As the aquifers of the Central West Highlands are of little importance to the current study, the hydrology of this subsystem will be only briefly addressed. For more detailed descriptions of this subsystem the reader is referred to URS (2006).

The Central West Highlands hosts numerous fractured rock aquifers in different lithological units including basalt, granite and consolidated sediments. Although the permeability of these units is inherently low, secondary porosity has developed as a consequence of dissolution of limestone and the intense fracturing related to deformation. Recharge to the aquifers of the Highlands is primarily via seasonal rainfall with fractured rock aquifers receiving the highest rates of recharge on hilltops and slopes where the soil cover is thin.

Groundwater discharge accompanies geomorphic features (i.e. breaks-of-slope), physical boundaries (i.e. change in soil texture), lithological controls (i.e. change in porosity and/or permeability in adjacent units) or structural controls (i.e. following fault planes and joints). Discharge into streams is received as washoff and baseflow (URS, 2006).

The significant alluvial hydrogeological Subsystems in the mid to upper Lachlan include the Lachlan and Cowra Subsystems. The Lachlan Subsystem occupies the palaeochannel within a river valley and comprises highly conductive, coarse alluvial sands and gravels; the river valley is constrained by the outcropping units of the Central West Highlands (Figures 12 and 22). As the Lachlan Subsystem is situated within a relatively narrow palaeochannel it forms a laterally constrained belt which can be seen in Figure 23 (URS, 2006; Barnett and Muller, 2008).

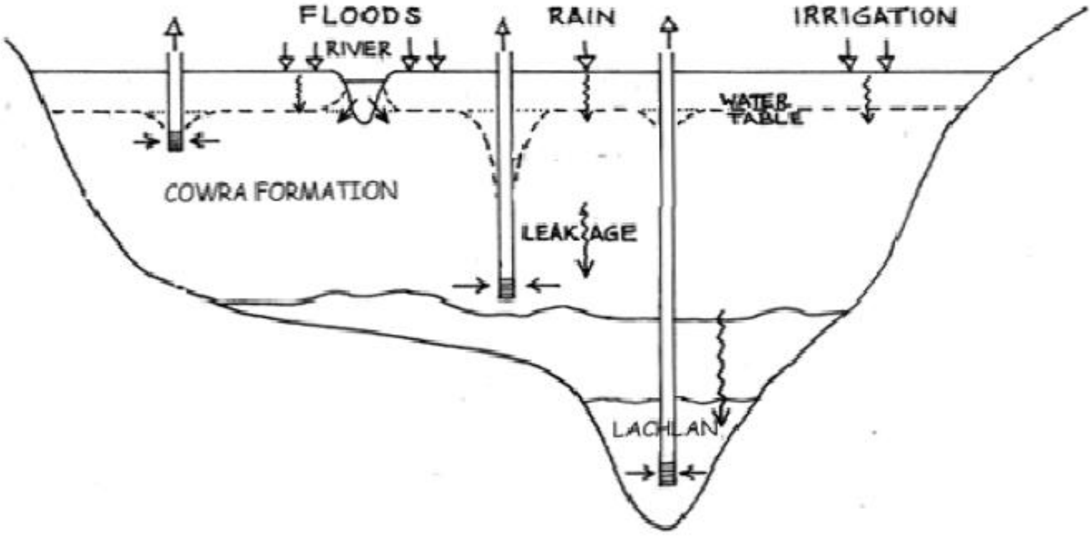


Figure 22. Conceptual model for groundwater-surface water interactions in the upper Lachlan Catchment (Barnett and Muller, 2008 modified from Merrick pers. comm.).

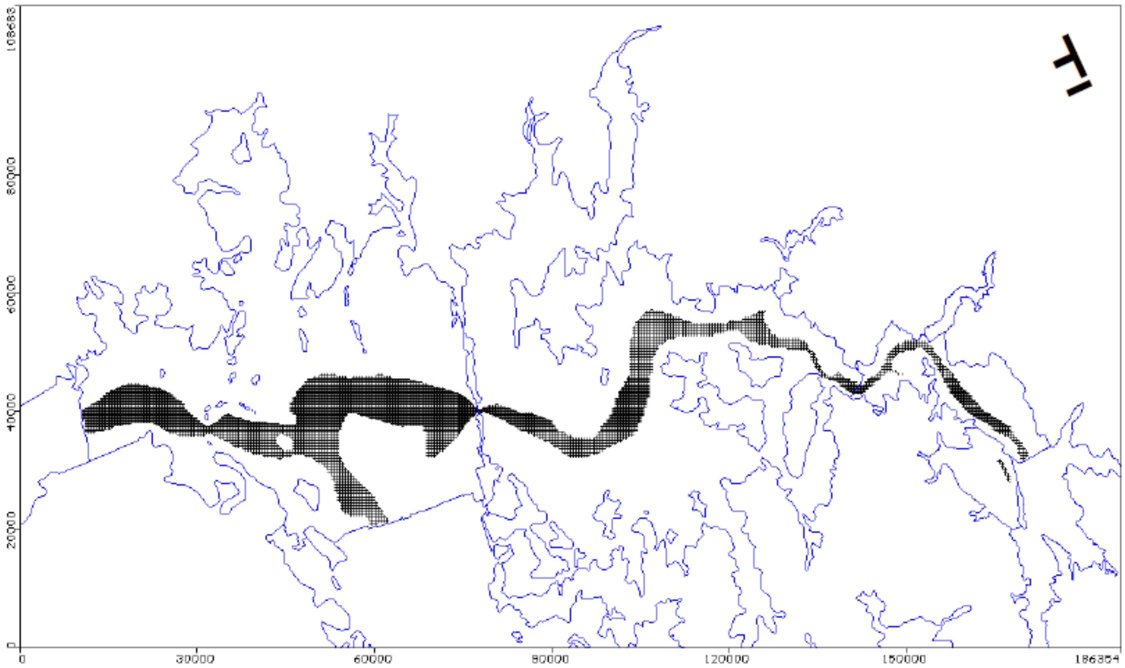


Figure 23. Lateral extent of the Lachlan Subsystem according the New South Wales Department of Energy and Water (Modified from Barnett and Muller, 2008).

The laterally extensive units of the Cowra Subsystem (Figure 24) overlies the Lachlan Subsystem. This hydrogeological subsystem is defined by alluvial channel sands and floodplain clays and according to CSIRO (2008) is the upland equivalent of the Shepparton Subsystem. Although the Cowra Subsystem occupies a substantially large area laterally, much of this is unsaturated and exhibits a thickness generally < 40 m usually lying immediately above the Palaeozoic basement. Previously the Cowra Subsystem has been considered to be an unconfined aquifer; however, the presence of shoestring sands and interbedded silts and clays would suggest that the aquifer is semi-confined in some portions. The Cowra Formation is important as it acts as a conduit for fluids percolating downwards to the Lachlan Subsystem (Figure 22; URS, 2006; Barnett and Muller, 2008; CSIRO, 2008).

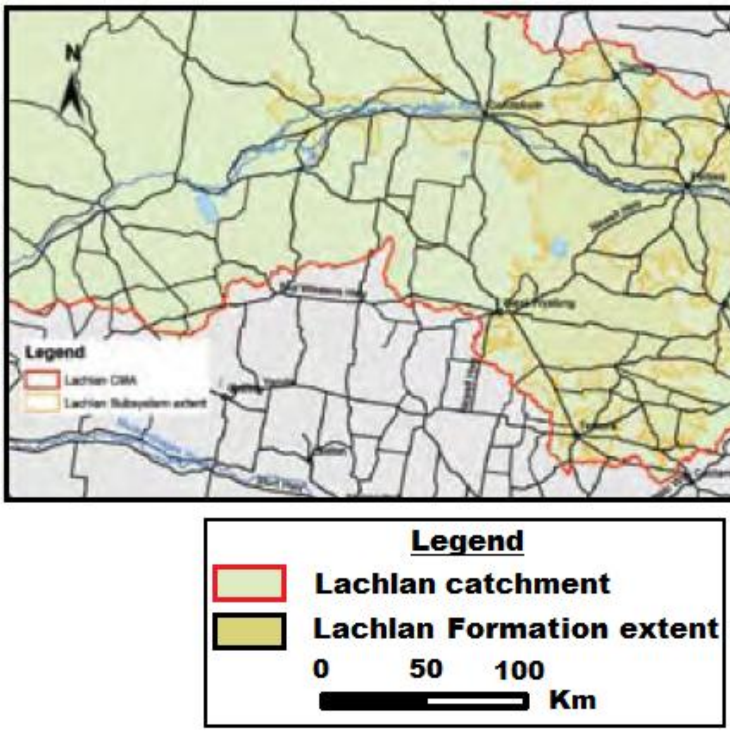


Figure 24. Lateral extent of the Lachlan Subsystem (Modified from URS, 2006).

Between Hillston and Cowra the Lachlan River and Cowra Subsystem are highly connected. The Lachlan River is an influent stream losing medium levels of water to the Cowra Subsystem. Adjacent to the irrigation district proximal to Lake Cowal the Lachlan River is considered to be a high level influent stream and approaching Cowra only low levels of water are lost to groundwater. Upstream of Cowra the Lachlan River is an effluent stream receiving low levels of input from the underlying saturated zone (Figures 21 and 22; Barnett and Muller, 2008; CSIRO, 2008).

Although laterally constrained, the Lachlan Subsystem is the major aquifer in the Upper Lachlan as a consequence of its conductive nature compared to the shallow, low yielding sediments of the Cowra Subsystem. The potentiometric contours for the Lachlan can be seen in Figure 25 and suggest that water flows in a westerly direction at an elevation of 270 m Australian Height Datum (AHD) near Cowra progressing down to Lake Cargelligo to < 150 m AHD (URS, 2006).

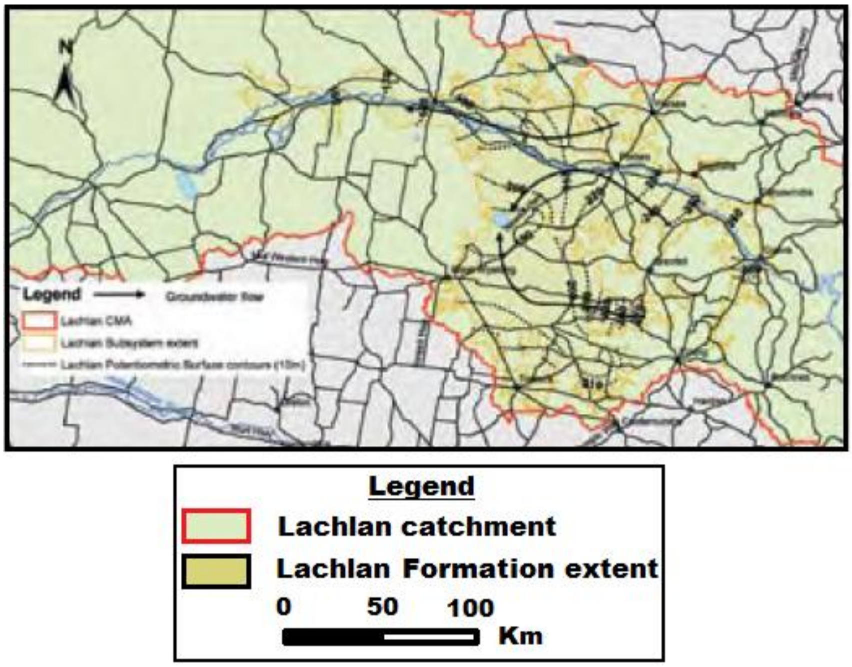


Figure 25. Potentiometric contours for the Lachlan Subsystem (Modified from URS, 2006).

Streamflow

Streamflow throughout the Lachlan River is highly variable both spatially and temporally as a function of the different hydrological (i.e. connectivity between surface and groundwater) and climatic conditions experienced throughout the Lachlan Catchment (Allen *et al.*, 1998; CSIRO, 2008; Bureau of Meteorology, 2010).

Rainfall and runoff varies significantly between and within years (Chiew *et al.*, 2003). According to McMahon *et al.* (1992) the interannual variability of streamflow in Australian and South African rivers is approximately twice as large when compared with rivers located elsewhere in the world. In saying this, streamflow is strongly seasonal with the greatest levels occurring in the last two months of winter and the first month of spring. Following this a step reduction in flows occurs through the remainder of spring proceeded by relatively static, low flow rates throughout summer and autumn (Figure 26; Armstrong *et al.*, 2009). High levels of flow appear to correspond with climatic data which reports the largest effective evaporation values (and therefore highest levels of runoff) in the months of June, July and August (CSIRO, 2008; Kemp, 2010). Large levels of streamflow in winter may be further accentuated by the lower variability of winter rainfall relative to the rest of the year (NSW Agriculture, 2003).

Annually the upper Lachlan River experiences higher levels of streamflow compared to the lower Lachlan (Figure 27). The proportion of streamflow reaching downstream gauging stations from upstream gauges is also greater in the upper reaches of the river relative to the mid to lower portions (Figure 28; Armstrong, *et al*., 2009).

The response in the streamflow graph is almost identical at Forbes and Booligal. This is not surprising as there is little to no input into streamflow downstream of Forbes; as such, changes in streamflow experienced in Forbes are essentially going to be felt further downstream (Figure 27; WCIC, 1972; Kemp, 2010).

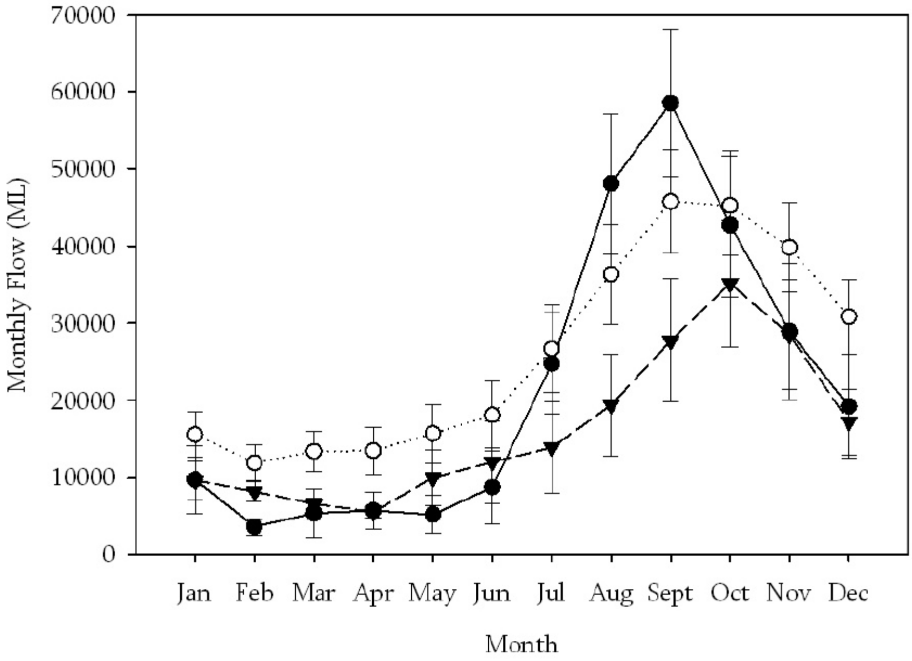


Figure 26. Average monthly flow (± SE) on the Lachlan River at Booligal. Note solid line with filled circles denotes monthly flow prior to river regulation (1908-1930), dotted lines with open circles represent flow post regulation while the dashed lines with filled triangles are values calculated after maximum extraction (1982-2007).

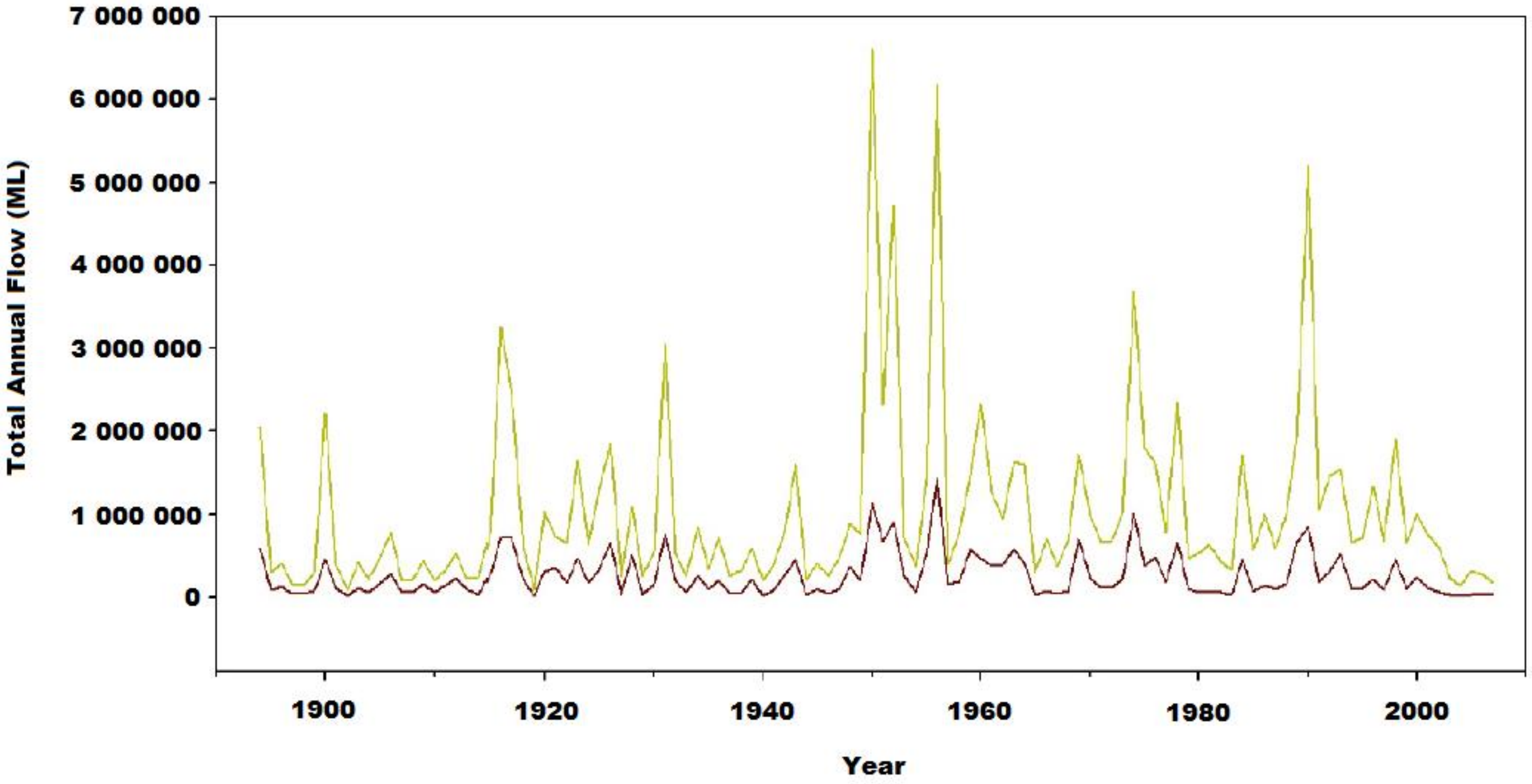


Figure 27. Annual stream flow (ML) for the Lachlan River from 1894 to 2007 at Forbes (yellow line), situated in the upper catchment and Booligal (brown line) located in the lower catchment (Modified from Armstrong *et al.*, 2009).

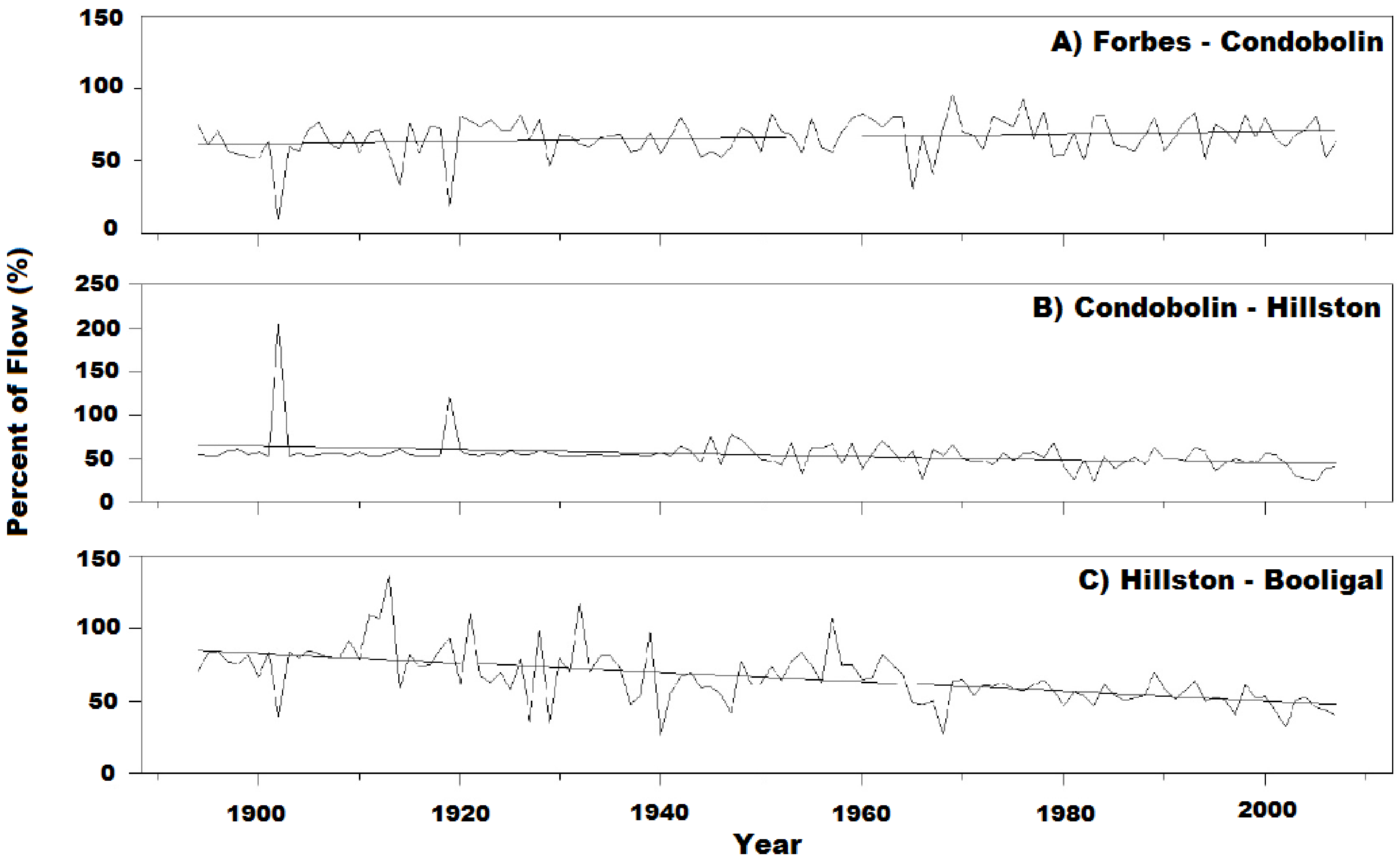


Figure 28. Percentage of flow (%) received at the gauging stations downstream from the upstream gauging stations for the years 1894 to 2007 (Modified from Armstrong *et al.*, 2009).

Land Use and Dam Levels

The Lachlan Catchment covers an area of approximately 85,532 km^2 or 8 percent of the Murray-Darling Basin and is based almost entirely around the Lachlan River (CSIRO, 2008). Major townships include Boorowa, Young, Cowra, Parkes, Forbes, West Wyalong, Condobolin, Hillston and Booligal (Figure 2, NSW IC, 2007) with an estimated population for the region exceeding 106,000; 22 % of whom are employed by the natural resource sector (Lachlan CMA 2009). According to Lachlan CMA (2009) the Lachlan Catchment accounts for 14 % of the total agricultural production in NSW (NSW IC, 2007).

Land use statistics are provided in Table 3 and as such only a brief description is required here. By area the largest enterprise is dryland pasture, with the land being used mainly for broadacre grazing. This is followed by dryland cropping and irrigated agriculture. Although comparatively smaller compared to its dryland counterpart, irrigated agriculture is still a lucrative industry with 0.6 % of the entire catchment (by area) contributing 20.8 % of the total production. Irrigation production statistics are given in Table 4 (NSW IC, 2007; CSIRO, 2008).

Proximal to the township of Young stone fruit is grown, while grapes are the dominant crop grown at Cowra. Lucerne, other summer fruits and cotton dominate irrigated agriculture on the alluvial plains in the mid to lower valleys (NSW IC, 2007). By area, the largest irrigation districts appear to be to the west, north and east of Hillston and between Condobolin and Forbes on the southern side of the Lachlan River. Irrigation is also extensive upstream of Cowra on the southern side of the Lachlan River (Figure 29; Dent *et al.*, 2007; CSIRO, 2008). Principle cotton growing areas within the region are located close to Hillston (Figure 30; Dowling 2005).

Major reservoirs in the catchment include Wyangala Dam, Lake Cargelligo and Lake Brewster. Wyangala Dam is the located 50 km upstream of Cowra (Figure 2) and is the major water storage for the Lachlan. The original dam was constructed in 1935 with enlargements completed in 1971. Wyangala currently has the capacity to store 1,200,000 ML and is fed by the Abercrombie and Lachlan Rivers. Lake Cargelligo and Lake Brewster are situated between Hillston and Condobolin (Figure 2) and are used to store water for irrigation purposes; the storage capacity of these lakes is 36 000 ML (CSIRO, 2008).

Time series plots of reservoir volume in storage (GL) for the Wyangala Dam and Lake Cargelligo reservoirs are provided in Figures 31 and 32 respectively. The essentially dry conditions experienced in the last decade coincide with low storage levels at Wyangala Dam (Figures 4, 7 and 8). The effects of the drought are also evident at Lake Cargelligo, although oscillating patterns of high water storage have also been observed during this 10 year drought period. Effective storage for Wyangala Dam is currently 12 %, Lake Cargelligo 68 % and Lake Brewster is essentially empty.

Table 3. Land use statistics for the Lachlan Catchment in the year 2000 (CSIRO, 2008).

Land use	Percent	Ha
Dryland pasture	62.6	5,349,800
Dryland crops	15.5	1,328,600
Irrigated crops	0.6	47,900
Cereals	*25.3*	*12,100*
Cotton	*5.2*	*2,500*
Horticulture	*3.3*	*1,600*
Orchards	*6.7*	*3,200*
Pasture and hay	*55.3*	*26,500*
Vine fruits	*4.2*	*2,000*
Native vegetation	19.6	1,676,900
Plantation forests	0.8	64,200
Urban	0.1	12,400
Water	0.8	71,700
Total	**100**	**8,551,500**

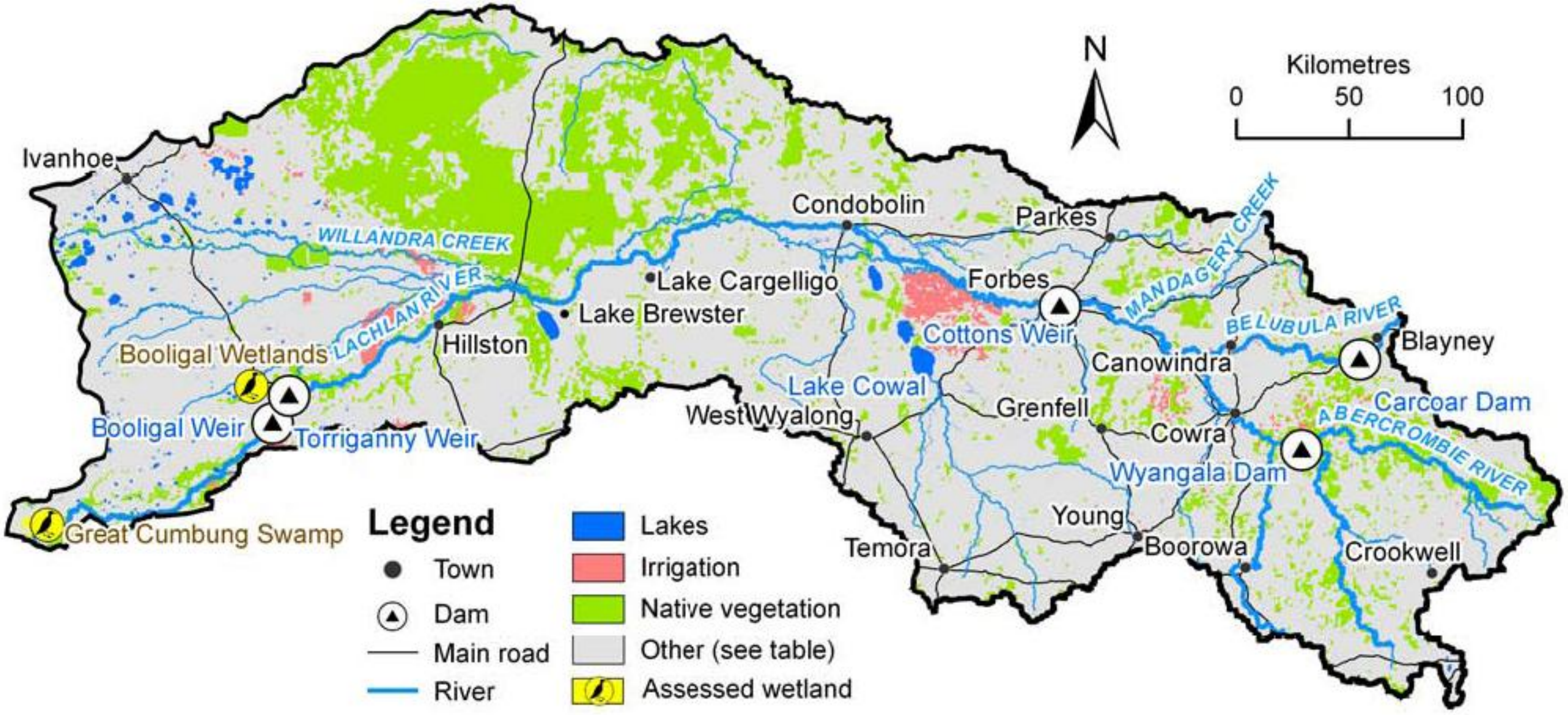


Figure 29. Land use map for the Lachlan Catchment (From CSIRO, 2008).

Table 4. Summary statistics for the irrigated agriculture in the Lachlan Catchment for 2000/2001 (Modified from NSW IC, 2007).

Irrigated Agriculture	Total Production that is Irrigated (%)	Value of irrigated production ($ millions)
Pastures for stock feed	54.5	11.8
Crops for hay	24	0.9
Cerals for grain	9.5	51.1
Other crops	66	104.7
Vegetables	99.9	36.5
Fruit (excluding grapes)	63.7	23.1
Grapes	80	11.8
Livestock slaughterings	5.5	15.5
Livestock products	8.6	19.2
Total	20.8	274.9
NSW Total	30.7	2713

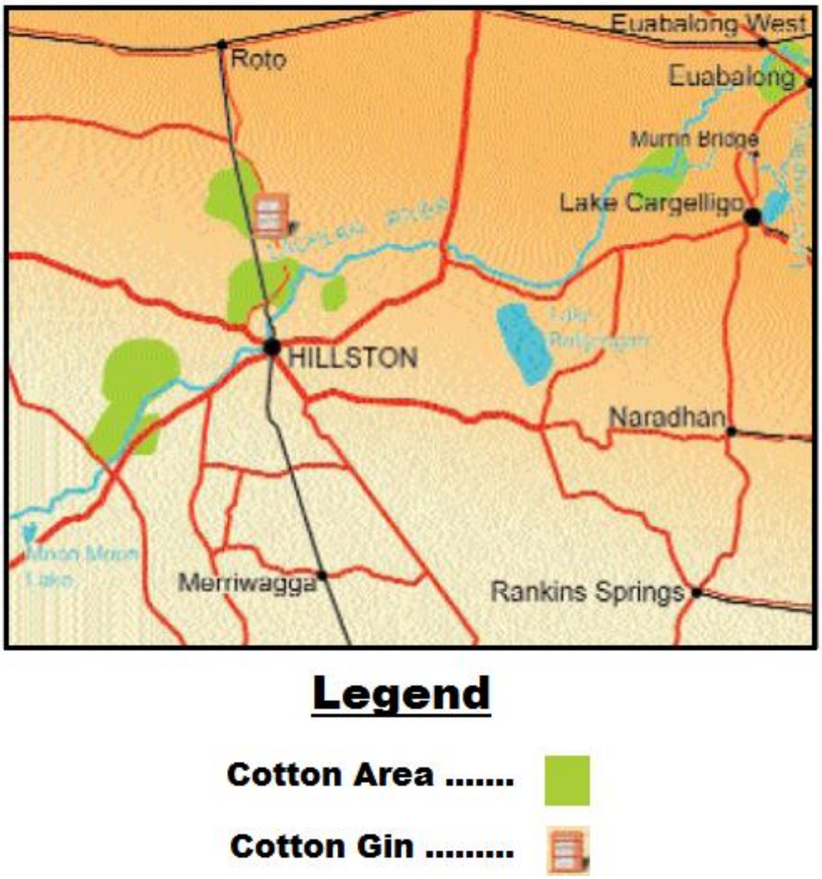


Figure 30. Principle cotton growing districts in the Lachlan Catchment (Modified from Dowling, 2005).

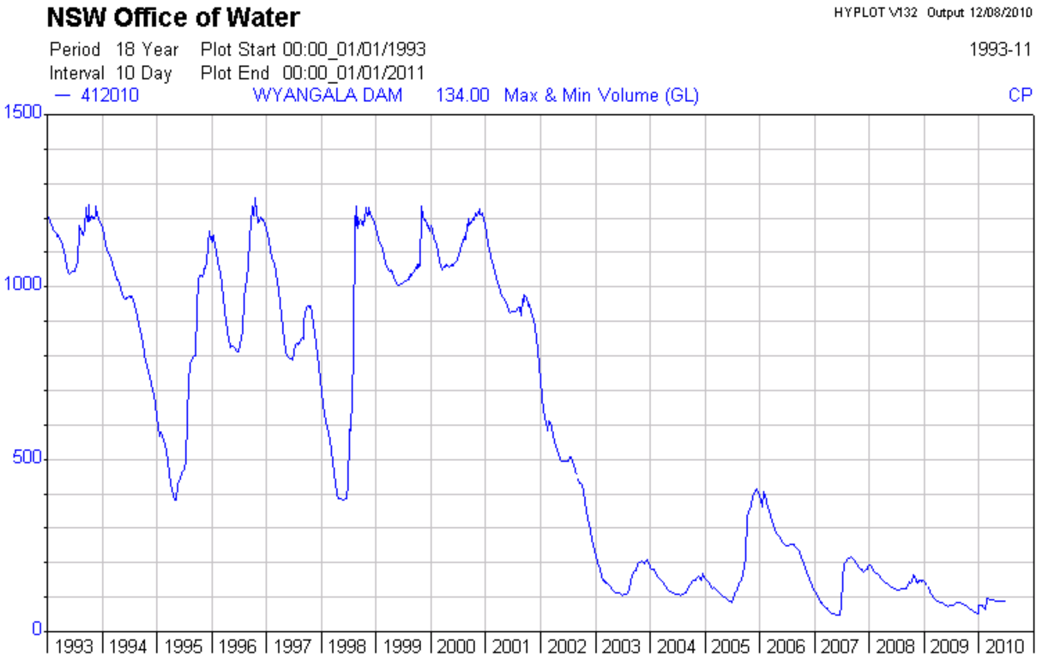


Figure 31. Wyangala Dam storage in gigalitres (GL) (Data from NSW Office of Water, (http://waterinfo.nsw.gov.au/water.shtml?ppbm=STORAGE_SITE&da&3&dakm_url, 02/Aug/2010).

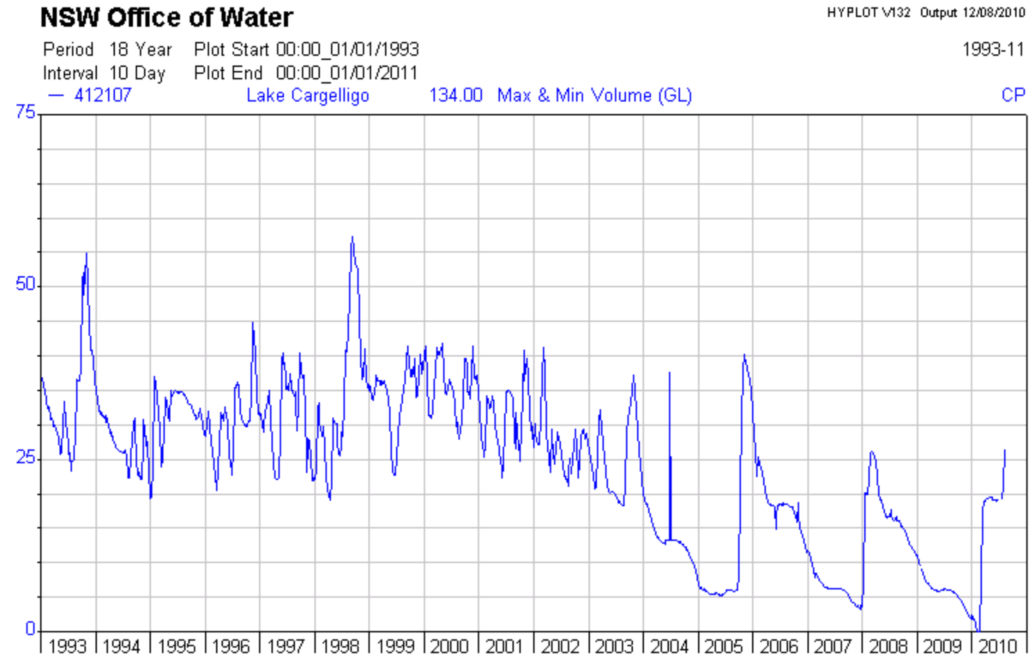


Figure 32. Lake Cargelligo storage in gigalitres (GL) (Data from NSW Office of Water, (http://waterinfo.nsw.gov.au/water.shtml?ppbm=STORAGE_SITE&da&3&dakm_url, 02/Aug/2010).

Wetlands and Native Vegetation

Native vegetation in the Lachlan Catchment has been substantially altered as a consequence of urban development, mining, agriculture and by the introduction of invasive flora and fauna. As a result, State and Commonwealth legislation has listed 121 faunal and floral species as threatened. Biodiversity in the Lachlan is rich with 1,579 known vascular plant species and native vegetation accounting for approximately 20 % of the catchment by area (Figure 29; Lachlan CMA, 2006; CSIRO, 2008).

Numerous wetlands are found within the Lachlan Catchment, many of which are considered to be of national significance (Table 5); the most notable of these include the Booligal Wetlands and the Great Cumbung Swamp (Figure 29).

Table 5. Wetlands of national significance situated within the Lachlan Catchment (CSIRO, 2008 Modified from Environment Australia, 2001).

Site Code	Wetland	Area (ha)
NSW040	Lake Cowal/Wilbertroy Wetlands	20,500
NSW043	Booligal Wetlands	5,000
NSW044	Cuba Dam	1,680
NSW045	Great Cumbung Swamp	16,000
NSW047	Lachlan Swamp (Part of mid-Lachlan Wetlands)	6,600
NSW048	Lake Brewster	6,140
NSW049	Lake Merrimajeel/Murrumbidgil Swamp	300
NSW051	Merrowie Creek (Cuba Dam to Chillichil Swamp)	2,500

The Booligal Wetlands comprise the Booligal Swamp and Little Gum Swamp and are associated with Murrumbidgil Swamp and Lake Merrimajeel Swamp further downstream. These wetlands are located near the township of Booligal and are characterised by low-gradient braided channels and depressions adjacent to and on the Muggabah and Merrimajeel Creeks (Armstrong *et al*., 2009). The wetlands are temporary, requiring moderate to large flood events, usually occurring in the winter to spring months; by summer the majority of the wetlands are dry (Moore, 1992; Environment Australia, 2001; CSIRO, 2008; MDBA, 2010).

The Great Cumbung Swamp is a terminal reed swamp which includes the Great Cumbung Swamp, its surrounding floodplains and Baconian Swamp. These wetlands are situated near the township of Oxley and are adjacent to the Murrumbidgee River and Lowbidgee Wetlands (Figure 29; Lachlan CMA, 2006). Like the Booligal Wetlands the Great Cumbung Swamp represents temporary wetlands which are dependent on flood flows. On average, significant flooding occurs every ten years as a result of rainfall in the upper catchment. In extremely wet years water from the Great Cumbung Swamp has been known to flow into the Murrumbidgee River (Brady *et al*., 1998; CSIRO, 2008; MDBA, 2010).

During times of flooding both the Booligal Wetlands and the Great Cumbung Swamp are known to be inhabited by a large number of waterbirds. For information pertaining to these birds and the ecology of the Lachlans Wetlands the reader is referred to Magrath (1992) and MDBA (2010).

Legislation

There are numerous pieces of legislation pertinent to the catchments comprising the Murray-Darling Basin. One of the most relevant to this report includes the *Water Management Act* 2000. The primary object of the Act is stipulated in Section 3 and as is follows:

> *"to provide for the sustainable and integrated management of the water sources of the State for the benefit of both present and future generations…"*

To achieve this object the Minister is required under s 50 of the Act to develop and implement water sharing plans for NSW. Water sharing plans define the water sharing arrangements between water users (persons and enterprises utilising water) and the environment. Specific objectives vary from plan to plan but the primary aim of each of the water sharing plans is to protect rivers and groundwater aquifers as well as their associated ecosystems. It also puts guidelines in place which provide greater clarity for water users in relation to their water access rights.

Water sharing plans concerned with surface water arrangements in the Lachlan Catchment include the *Lachlan Regulated River Water Source 2003* (DIPNR, 2004a) and the *Mandagery Creek Water Source 2003* (DIPNR, 2004b) The *Lachlan Regulated River Water Source 2003* and the *Mandagery Creek Water Source 2003* both commenced on the 1st July 2004; although the former of these was suspended on the same day under s 49A of the Act as the Minister was satisfied that there was a severe water shortage. As such, the rules pertaining to distribution in s 60(1) of the Act were suspended and instead the rules of distribution stipulated in s 60(3) were adopted. These rules give first priority to domestic landholders, followed by the environment and then by persons using water for stock and/or other enterprises.

The Water Sharing Plan for the *Lachlan Regulated River Water Source 2003* applies to the regulated portions of the Lachlan River (but not to the regulated portion of the Belubula River) as well as replenishment flows shown in Figure 31 (DIPNR, 2004a). The Water Sharing Plan for the *Mandagery Creek Water Source 2003* applies to 6 management zones comprising the Mandagery Creek and its associated tributaries (Figure 32). These management zones include Zone 1 – Bourimbla Creek, Zone 2 – Lower Boree Creek, Zone 3 – Mid Mandagery Creek, Zone 4 – Lower Mandagery Creek, Zone 5 – Upper Boree Creek and Zone 6 –

To date the only Water Sharing Plan concerned with groundwater arrangements is the *Lower Lachlan Groundwater Source 2003*; currently no Water Sharing Plans have been devised for the upper Lachlan Catchment or anywhere else in the region. The Water Sharing Plan for the *Lower Lachlan Groundwater Source 2003* came into effect on the 1st February 2008. This applies to unconsolidated aquifers of the lower Lachlan Catchment (Figure 33). As the Water Sharing Plan estimates recharge to be 108 GL/year, this same volume of water has been set as the annual extraction limit. Of this 108 GL, 97.828 % or 105.654 GL are extracted by those with access licences, the remainder is utilised for basic rights and town water (CSIRO, 2008; NSW DWE, 2008b).

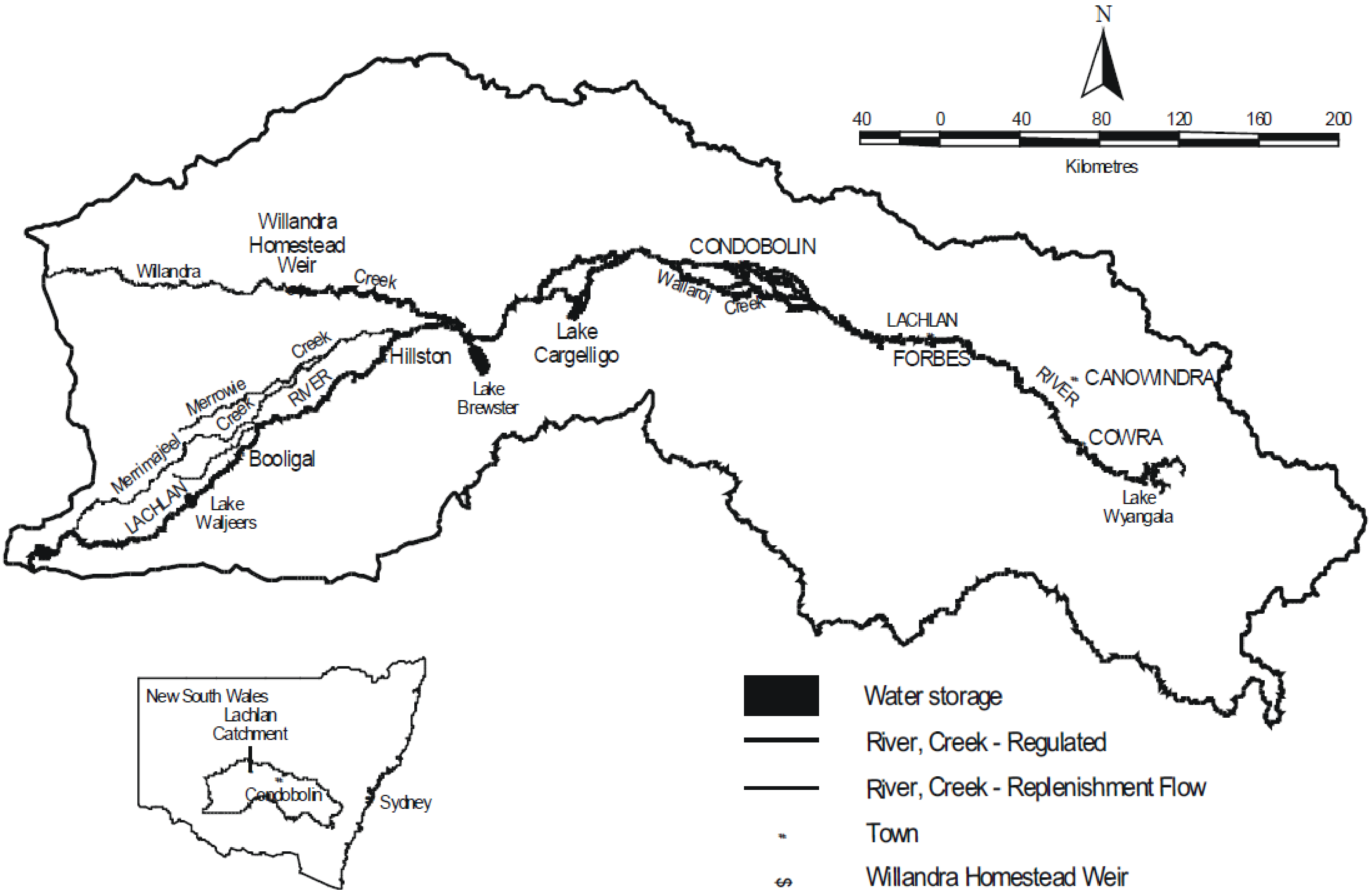


Figure 31. The area covered by the Water Sharing Plan for the Lachlan Regulated River Water Source 2003 (From DIPNR, 2004a).

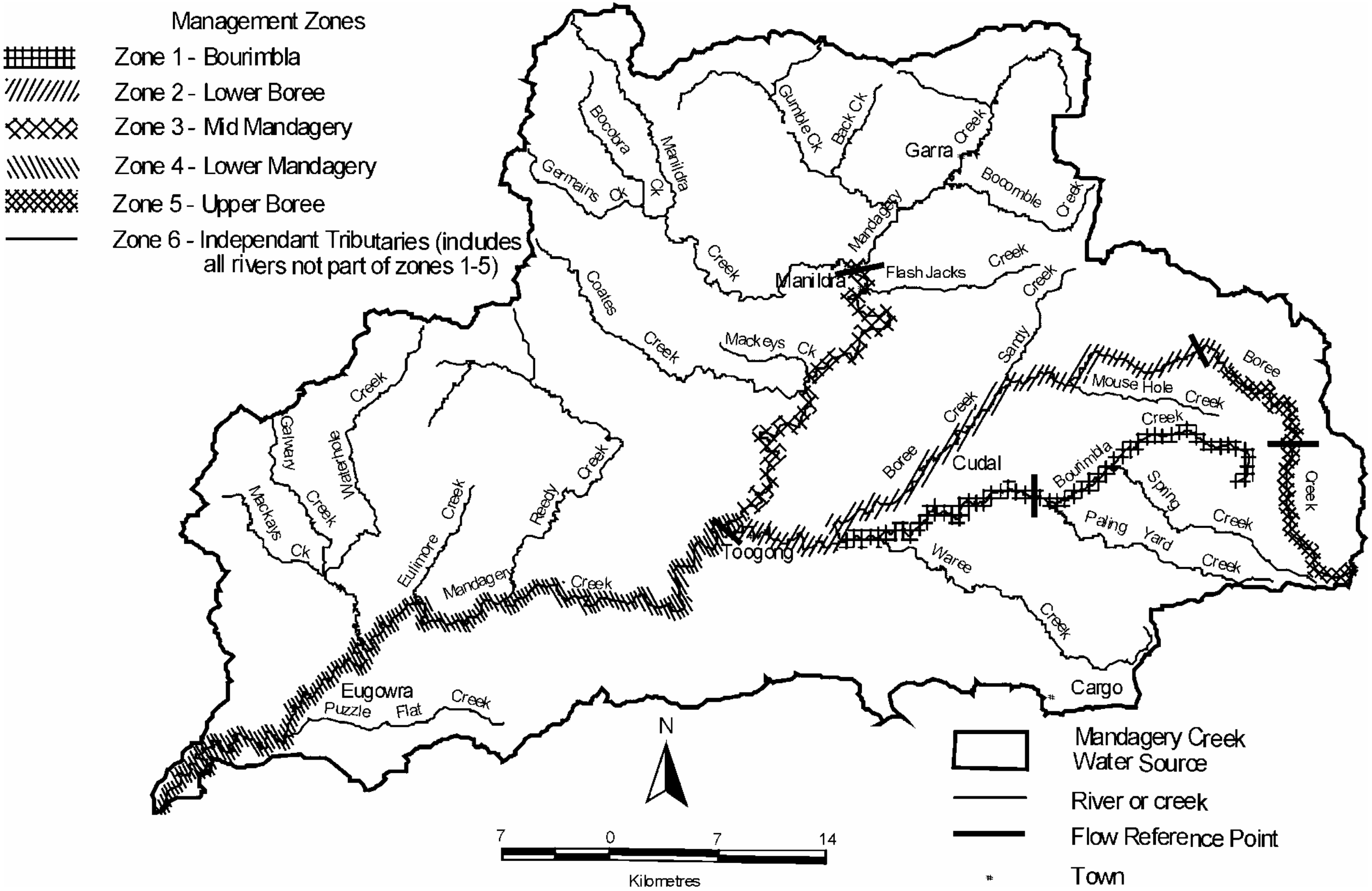


Figure 32. The zones pertaining to the Water Sharing Plan for the Mandagery Creek Water Source 2003 (From DIPNR, 2004b).

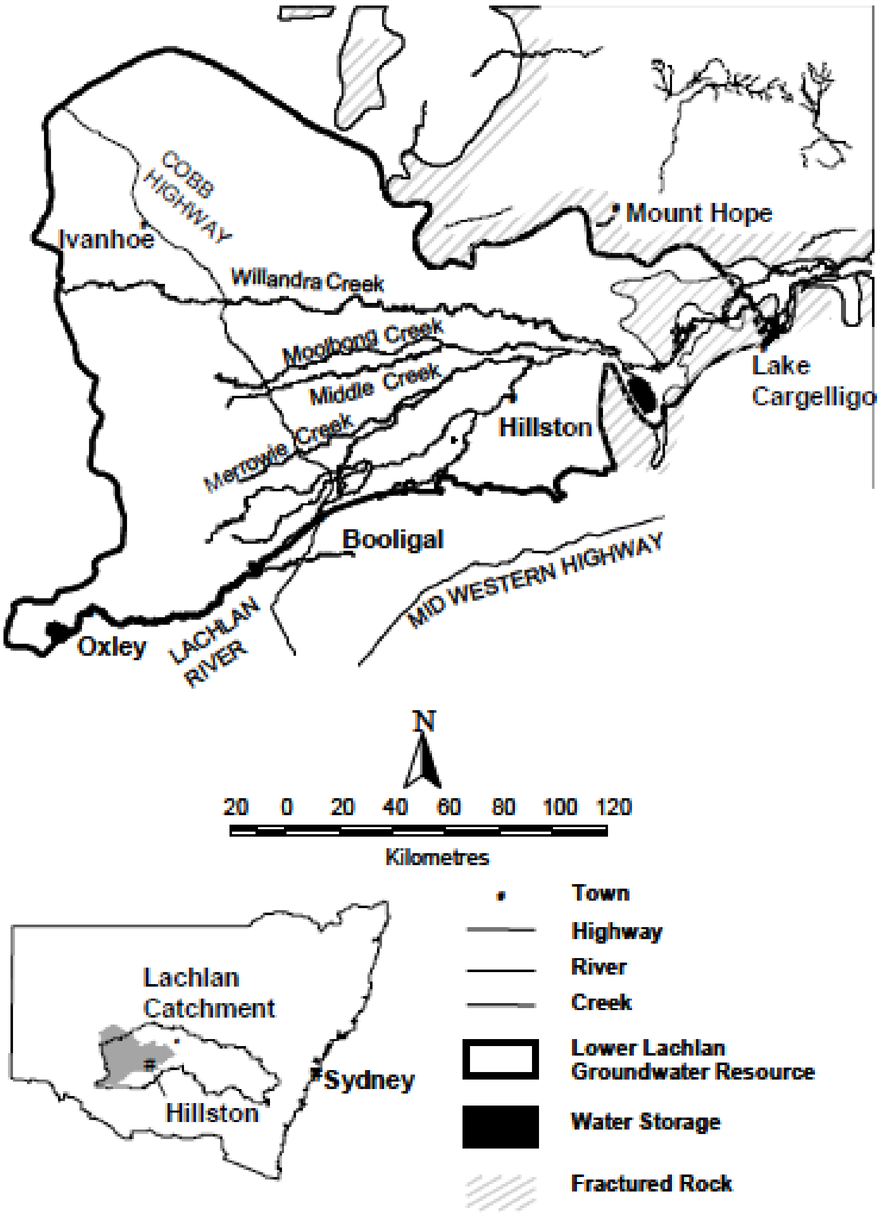


Figure 33. Location map for the lower Lachlan Catchment. The area constrained by the extent of the lower Lachlan groundwater resource is covered by the Water Sharing Plan for Lower Lachlan Groundwater Source 2003 (From NRC, 2006).

Groundwater Usage

To date long term groundwater extraction information is not readily available in a single coherent document. However, CSIRO (2008) alludes to trends in groundwater usage for the lower Lachlan and provides some figures pertaining to groundwater usage in the upper Lachlan.

According to CSIRO (2008) the 1970s saw significant development in groundwater for the lower Lachlan. In the latter part of the 1990s a rapid increase in groundwater extractions was observed following the drought of the mid-1990s. MDBC (2007) reported that extractions from the lower Lachlan alluvium were 122.47 GL/year for 2004/05.

In the upper Lachlan alluvium 65 GL/year of groundwater was extracted in the 2004/2005 growing season. Annual groundwater extraction data are presented in Figure 34. Groundwater extraction in the early 1980s and mid 1990s was below 10 GL/year. The late 1990s saw an increase in usage in response to the drought of the mid 1990s. High levels of extraction have persisted over the last decade as groundwater is used to offset the limited surface water supplies available due to drought conditions.

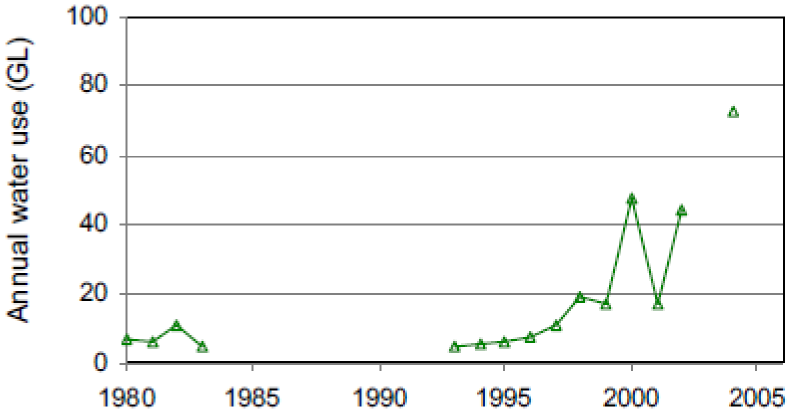


Figure 34. Annual groundwater extraction from the upper Lachlan alluvium (From CSIRO, 2008).

Study Area

The locations of the bores utilised for hydrograph analysis as well as their identification numbers are provided in Figure 35. For the corresponding digital elevation model the reader is referred to Figure 3.

Bore Hydrograph Data

The groundwater hydrograph data were sourced from the NSW Groundwater Pinneena CD 2009 v 3.1 (http://waterinfo.nsw.gov.au/pinneena/gw.shtml, 2/Aug/2010). A subset of the information from the CD was extracted for all bores within the Lachlan Catchment boundary.

The Lachlan database includes:

- location and elevation data ;
- construction details and methods of bores and pipes;
- drillers' logs;
- extended groundwater monitoring levels for 141 groundwater work locations;
- purpose and use information for each bore; and
- the water bearing zone.

Bores that had suspected errors (sudden jumps in water levels, zero reading etc) were removed from the 3D analysis of the hydrograph data. Groundwater hydrograph sets with minor errors (spikes in years not analysed) were used. Further quality control is needed, but was beyond the scope of the project. It is expected that such an extensive database would have errors, given that the data have been collected over several decades, were manually measured, manually entered into the database, and transferred between various databases. The majority of the data are sufficient for examining the major spatial and temporal trends recorded in the groundwater monitoring bore standing water level. The SWL is typically measured from the top of the casing to the top of the water within the pipe (units, metres below the casing top). The terms groundwater head and groundwater level are used when the SWL is converted to a height above the Australian height datum (units, metres above sea level).

Mathematica (http://www.wolfram.com/, 2/Aug/2010) scripts were written to extract the information from the database. At each groundwater works location there can be one or more holes. Within each hole there can be one or more pipes. Each pipe can have one or more slotted intervals. On the hydrographs the highest and lowest slotted levels reported were used to indicate the total length of the aquifer for which the head was being measured. For some bores the slotted interval information was not on the Pinneena CD or the information was ambiguous. For such cases the information was not added to the hydrograph plots. Comprehensive details on the *Mathematica* scripts are given in Kelly *et al.* (2010). In the 3D plots below the data were plotted at the midpoint of the slotted interval(s).

Plotting the absolute fluctuation or relative difference over time in 3D at the midpoint of each pipe's slotted interval requires no assumptions about assigning the screened section of a bore to a specific aquifer. The 3D analysis is then used to assign each pipe to an aquifer.

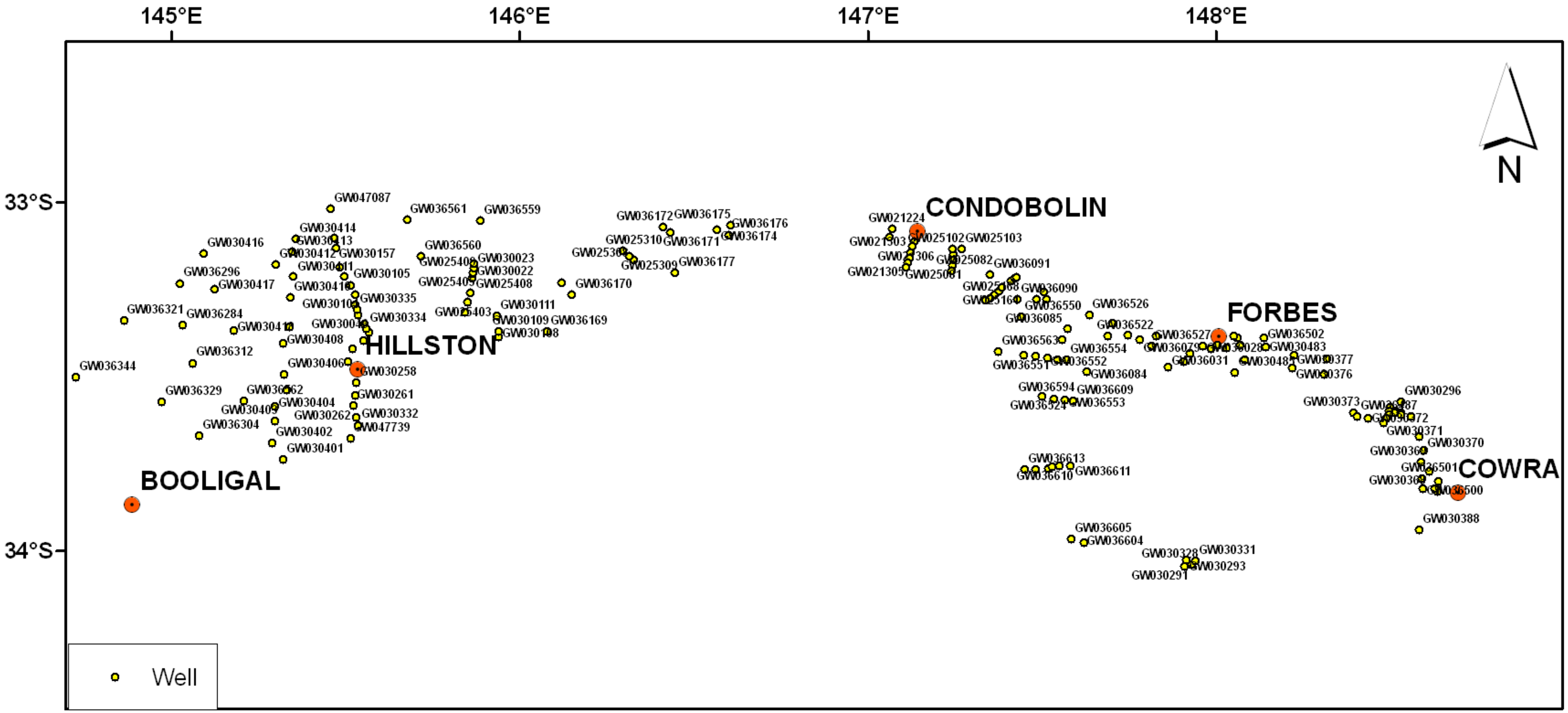


Figure 35. Bores utilised for the current study and their ID numbers.

Bore Hydrographs

Spatial and temporal trends in the groundwater level are a consequence of numerous processes (Tillman and Leake, 2010). To be able to better understand these processes, spatial and temporal trends in the groundwater level need to be assessed in conjunction with groundwater extraction records, the local hydrogeology and climate, streamflow and land use data (McCallum *et al*., 2009).

As the use of groundwater expanded in the catchment groundwater monitoring bores were installed to monitor the impact. The SWL is measured in these bores 4 or more times per year. Plots of all available hydrographs for the Lachlan are presented in Appendix 2. The hydrograph data have also been used to develop 3D images of the yearly fluctuation in the SWL and to examine long-term changes in SWLs. Two time periods were used to assess variability in the SWL both spatially and temporally.

To examine the hydraulic connectivity throughout the aquifer systems and assess the effect of seasonal pumping on the alluvial aquifers of the upper and lower Lachlan Catchments, the SWL fluctuations were calculated for a single year (i.e. Figure 36). The year 2006 was selected for analysis because this was a year when the majority of the sites were measured, annual rainfall was low (Figures 7 and 8) and groundwater usage was relatively high (Figure 34). Once calculated, the maximum difference in the SWL within one year for each groundwater monitoring bore was plotted in 3D at the midpoint of the slotted interval(s) (Figures 37 and 38).

To analyse the long term impact of groundwater extraction and to detect any decline in the recovered SWL, the difference between the 1988 and 2008 recovered SWL was calculated (Figure 39). This interval of time was selected to get a balance between the length of the record and coverage across the catchment. The recovered SWL is the level recorded throughout the year closest to the ground surface and usually occurs in June or July before the beginning of the pumping season, which runs from late August until February. Recovery of the SWL is important for the health and functioning of the aquifer and for the economic benefit of its users. During the pumping season the SWL drops and if usage is in balance with recharge the SWL recovers to the level of pre-development over time (sometimes this requires a flood recharge event). If the SWL falls over time this indicates that usage is in excess of recharge for that time period. The relative difference in the SWL for each of the bores has been plotted in 3D so that long term gains and losses can be identified and reviewed in light of land use practices and climatic events (Figure 40).

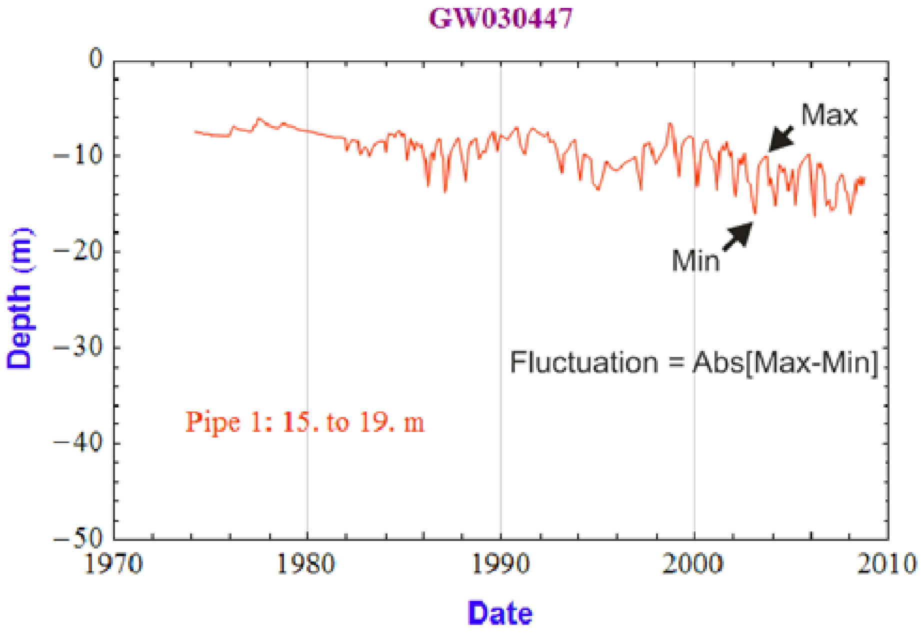


Figure 36. Method for determining the absolute fluctuation in the SWL in 2004.

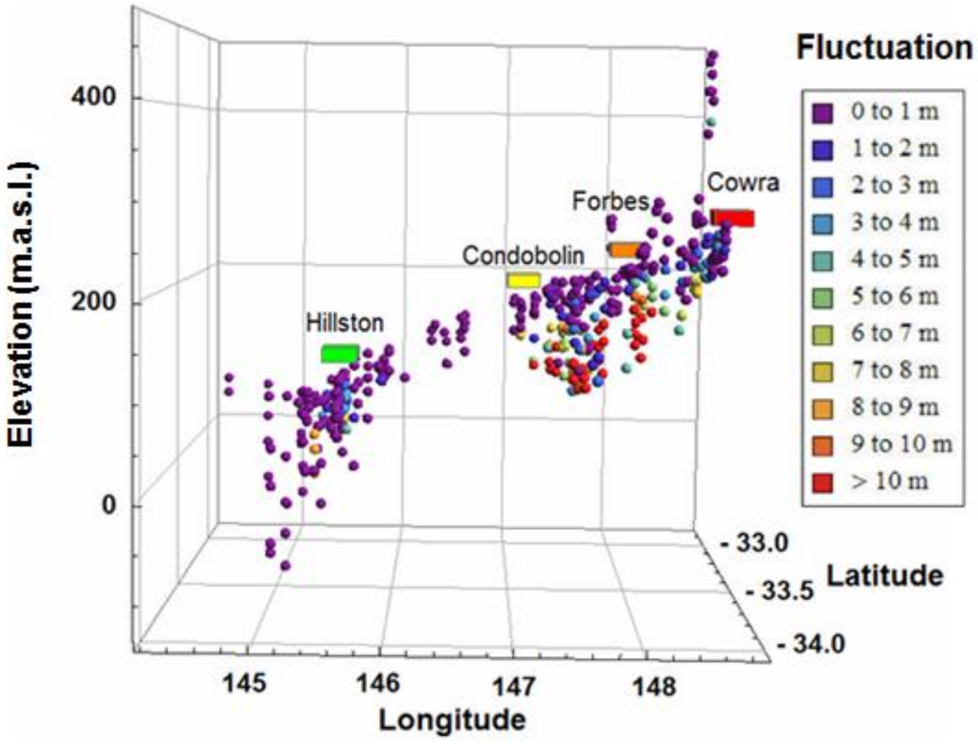


Figure 37. Side view of the absolute fluctuation in the standing water levels for the year 2006.

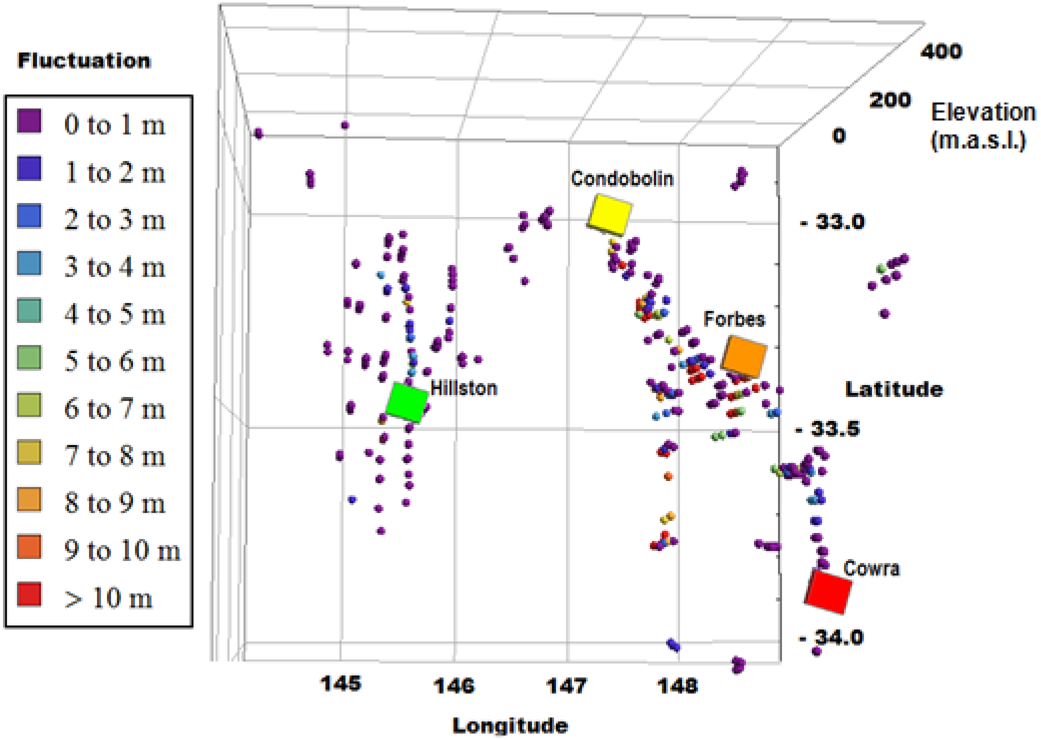


Figure 38. Overhead view of the absolute fluctuation in the standing water levels in year 2006.

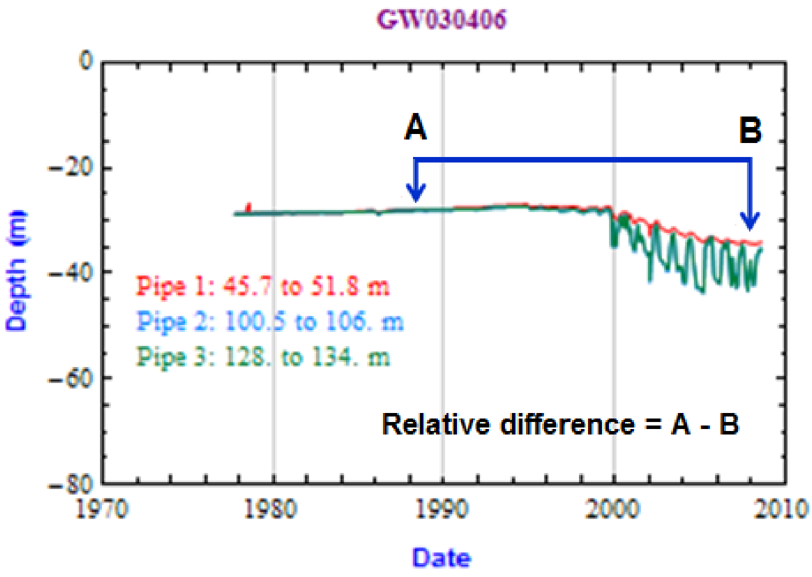


Figure 39. Method for determining the relative change in the recovered SWL between 1980 to 1994.

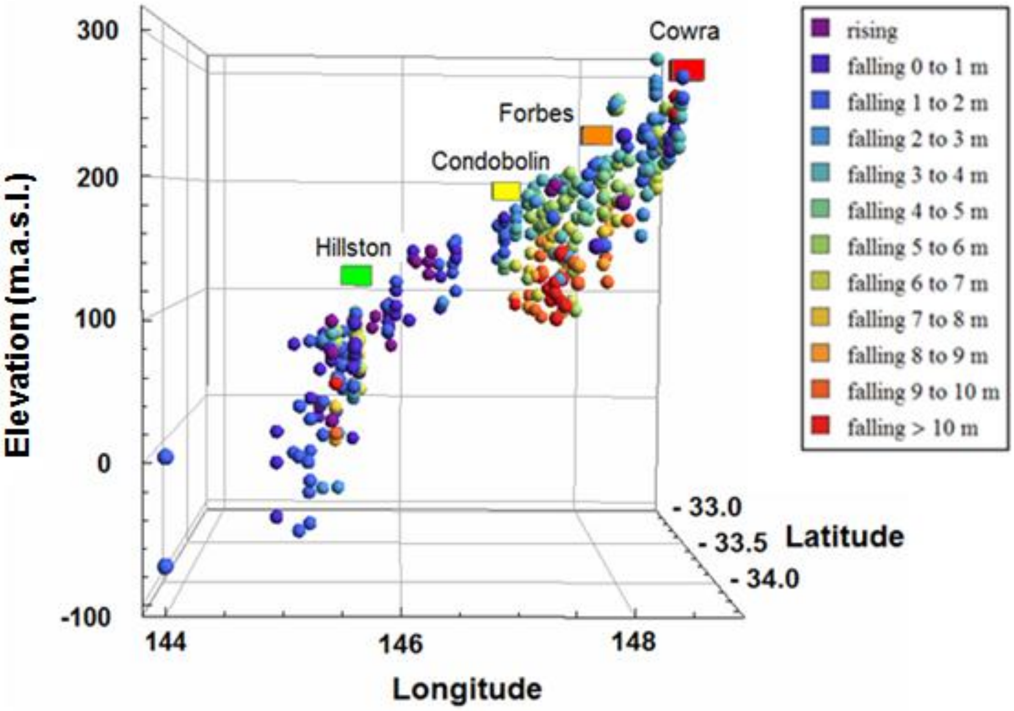


Figure 40. Side view of the relative difference in the standing water levels between 1988 and 2008. Each data point is plotted at the midpoint of the slotted interval(s) in each monitoring bore.

Short Term Head Fluctuation Analysis

Groundwater extraction imposes stress on aquifers resulting in a decline in the standing water level. The area affected by pumping is proportional to the period of time and rate that the pump has been running. Changes in SWL occur vertically and laterally from the site of pumping and are reflected in bore hydrographs as changes in the SWL. Where a sedimentary sequence is hydraulically connected the change in the SWL will be the same throughout the entire sequence. If however, an impermeable layer (i.e. a clay layer) within the sedimentary sequence impedes the flow of water and pressure transfer between the pump at depth and the ground surface then the SWL will only change at depth.

Figures 37 and 38 illustrate the SWL fluctuation due to pumping stress for the year 2006. Absolute fluctuation in the SWL for the lower Lachlan is on the whole minor, typically ranging from 0-3 m (purple and blue spheres; Figures 37 and 38); there is however one monitoring hole which exhibits a fluctuation in the SWL greater than 8 m (yellow spheres; Figures 37 and 38), and others with fluctuations values of approximately 4 m (green spheres; Figures 37 and 38). The green through red spheres highlight where the bulk of the groundwater was extracted in 2006.

Areas where there is hydraulic connection throughout all levels of the alluvial sequence can be identified in the 3D fluctuation dataset by spheres which have the same colour at all depths. It needs to be noted that in areas of limited or no groundwater extractions it is not possible to use this method to map aquifer connectivity.

Figure 41 identifies the different hydraulic zones recognised in the lower Lachlan based on bore hydrographs and provides a representative hydrograph for each zone. The location of the slotted intervals for the monitoring bores used in Figure 40 as well as their palynology is provided in Appendix 1. Not surprisingly, only areas located proximal to irrigation zones (identified in Figures 29 and 30) exhibited noticeable fluctuations in the SWL as well as those holes located near the Lachlan River or its tributaries (Figure 2).

The olive green zone is situated within or close to an irrigation district, 2-15 km from the Lachlan River. Downward trends in these hydrographs over the last decade have identified three separate aquifers, while only two could be discerned further to the north. Hydrographs indicate that there is some leakage from the upper aquifers to the lower aquifer (Bore GW030406, Appendix 2). The bright green zone is also located within an irrigation district not far from the Lachlan River. Hydrographs suggests that this zone hosts at least two aquifers; with moderate connectivity existing between the upper to the lower aquifers (Figure 41).

In the eastern portion of the lower Lachlan, the yellow zone located outside of the irrigation district experiences no change in the SWL with depth since there is no pumping stress being placed on the aquifer systems. Other hydraulic zones experiencing similar hydraulic responses include those from the brown, purple, cyan, navy and red zones (Figure 41).

Pink, orange and grey hydraulic zones show subtle drawdowns over the past decade. This could be related to climatic events or the peripheral impacts of irrigation. At GW03284 there is a slightly greater decrease in the SWL for pipe 2 compared to pipe 1, indicating the presence of a hydraulic impeding layer(s).

There does not appear to be any correspondence between the hydrographs in Appendix 2 and the stratigraphy or palaeostratigraphy for the lower Lachlan (Appendix 1). A detailed lithofacies model and a new water chemistry investigation, including dating with isotopes, coupled with a surface and sub-surface flow model is required for this region to quantify the extent of recharge and to define the nature and extent of the different aquifer systems.

In 2006 the absolute fluctuation in the SWL for the upper alluvial sequence in the upper Lachlan is minor, typically ranging from 0-3 m (purple and blue spheres; Figures 42 and 43). Fluctuations generally exceed 4 m for the mid to lower portions of the alluvial sequence with many of the monitoring holes experiencing fluctuations in the SWL greater than 10 m (red spheres; Figures 42 and 43). The largest losses appear to be occurring in the irrigation district between Condobolin and Forbes and along the tributary emanating from Lake Cowal.

In Figures 37 and 38 the purple spheres extend across most of the shallow measurement points, while yellow and red spheres occur in the deeper portions of the aquifer system. This suggests the presence of a regional extensive aquitard.

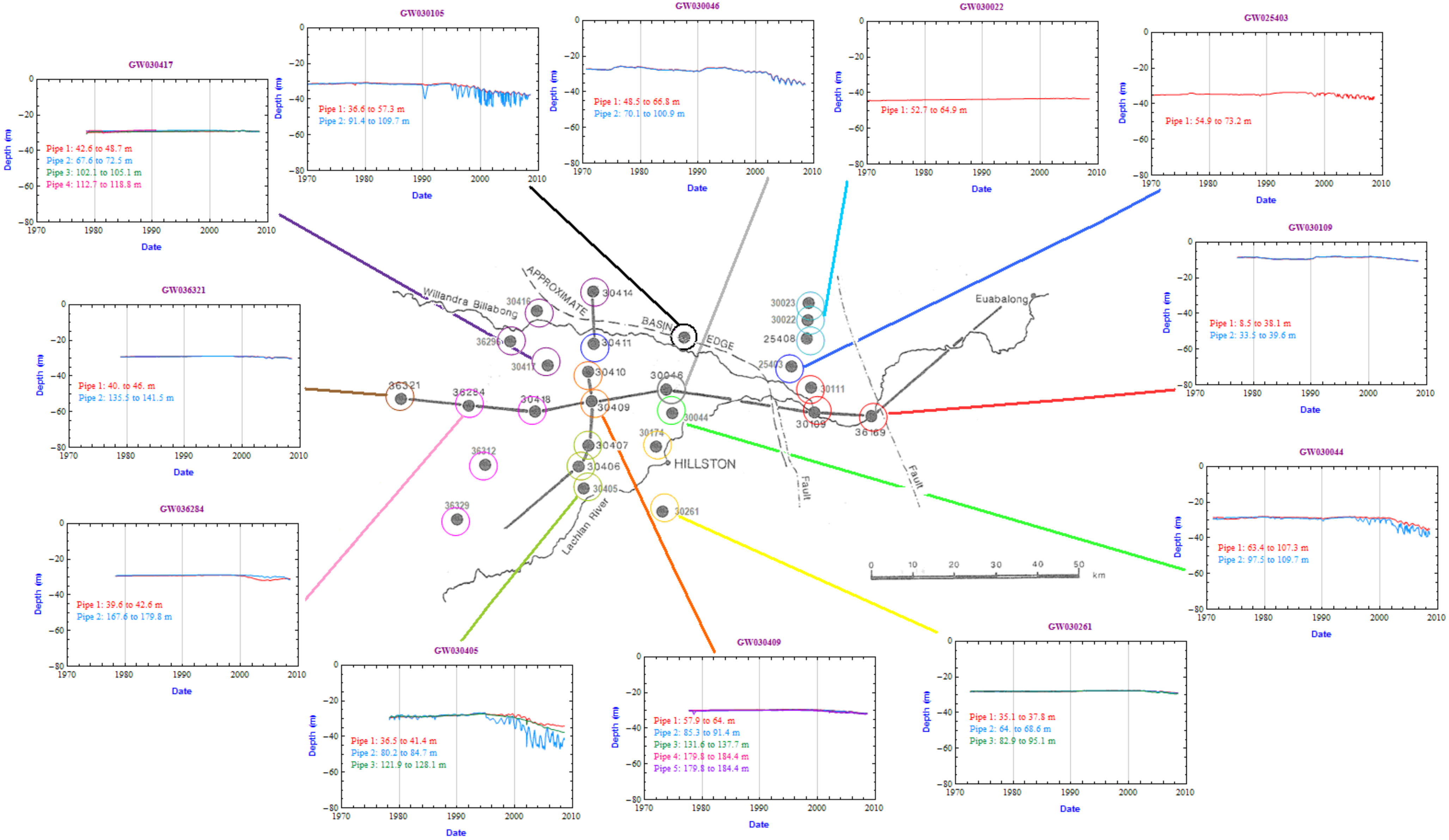


Figure 41. Lower Lachlan bore hydrographs.

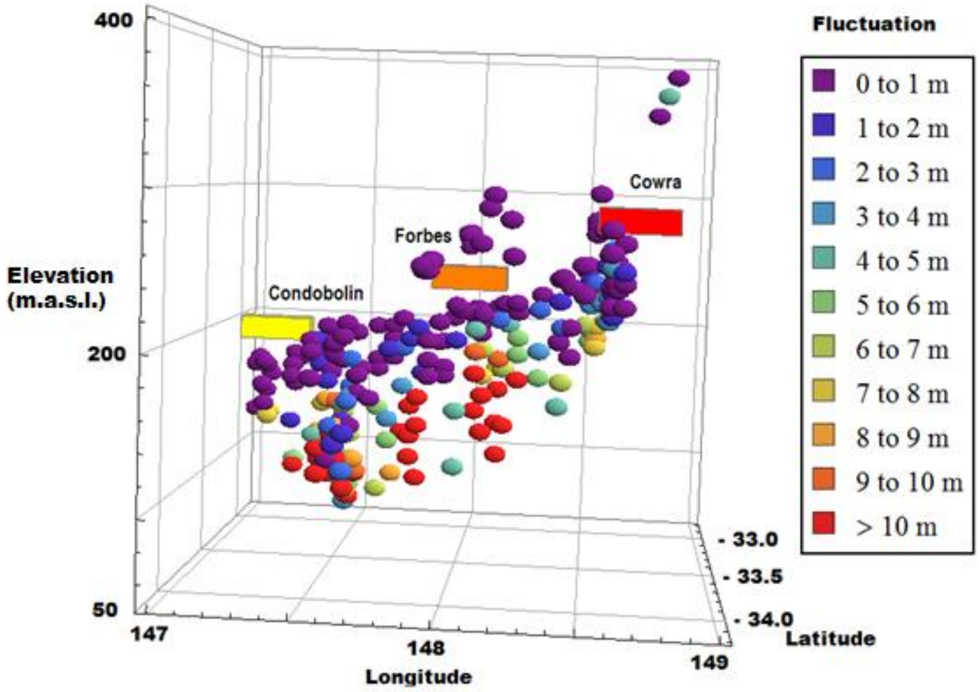


Figure 42. Side view of the absolute fluctuation in the standing water levels in year 2006 for the upper Lachlan Catchment.

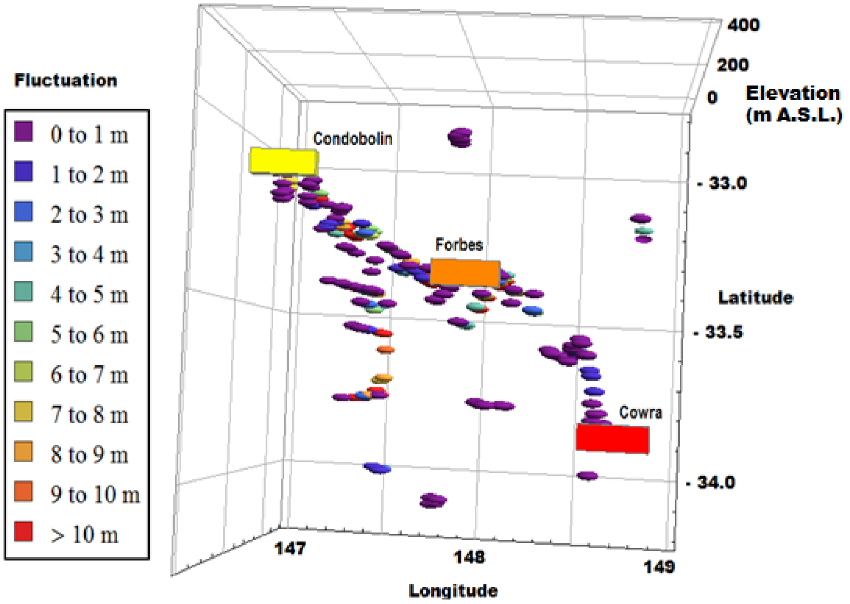


Figure 43. Overhead view of the absolute fluctuation in the standing water levels in year 2006 for the upper Lachlan Catchment.

Figure 44 identifies the different hydraulic zones recognised in the upper Lachlan based on bore hydrographs and provides a representative hydrograph for each zone. Immediately south of Condobolin, close to the Lachlan River there are no significant irrigation districts (Figure 29). Pumping stresses in these regions are low, explaining the minimal fluctuations in the SWL (i.e. GW025081) which make it impossible to determine hydraulic connectivity with depth.

Near the Lachlan River, between Condobolin and south of Forbes, deep and shallow portions of the aquifer system differ in their response to pumping stresses. In the irrigation district, south-east of Condobolin (Figure 29) two aquifers were recognised with low hydraulic connection between them (i.e. GW025151). Further upstream, but still within the irrigation district, there appears to be a moderate degree of connectivity between the upper and lower aquifers (i.e. GW036089), reflected by the decline and fluctuation in monitoring bores located near the surface and to depths of 30 m. Approaching Forbes irrigation is still the primary land use and drawdowns over the past decade have identified 3 aquifers with moderate levels of leakage between the unconfined upper and the middle aquifer systems. Higher levels of hydraulic connectivity can be observed between the middle and lower aquifers (i.e. GW036080; Figure 44).

Further away from the Lachlan River peripheral effects of irrigation have only become evident over the last decade. Responses to pumping are defined by subtle drawdowns throughout the alluvial sequence and small yet obvious differences in the SWL between upper and lower portions of the aquifer system (i.e. GW036550). South of Forbes upper and lower aquifers exhibit a relatively high level of connectivity (i.e. GW030373; Figure 44).

Between Forbes and Cowra most monitoring bores exhibit little or no difference in the SWL with depth (i.e. GW030359) indicating high connectivity at all depths, with the exception of GW030247 which displays a dampened response to pumping in pipe 1 (Figure 44).

The majority of monitoring bores near the tributary running from Lake Cowal to the Lachlan River only have a single slotted interval, or multiple intervals at similar depths, thus indentifying multiple aquifers is not possible. One of the few which has multiple intervals (i.e. GW036552) identified three aquifers, with pipes 1and 2 displaying reduced responses to the pumping impacts displayed in pipe 3. Maximum drawdowns occur at bore GW036597 in the southernmost portion of the tributary adjoining Lake Cowal (Figure 44).

Away from the Lachlan River and its associated tributaries slotted intervals are generally located in the upper to middle portions of the alluvial sequence; these bores show no significant difference in the SWL with depth (i.e. GW030388). In the North west of the region bore GW090017 indicates an upper unconfined aquifer overlying a semi-confined aquifer (Figure 44).

This report also recommends a detailed lithofacies model and a new water chemistry investigation (including dating with isotopes), coupled with a surface and sub-surface flow model for the upper Lachlan to quantify the extent of recharge and define the nature and extent of the different aquifer systems indicated by the bore hydrographs displayed in Figure 44.

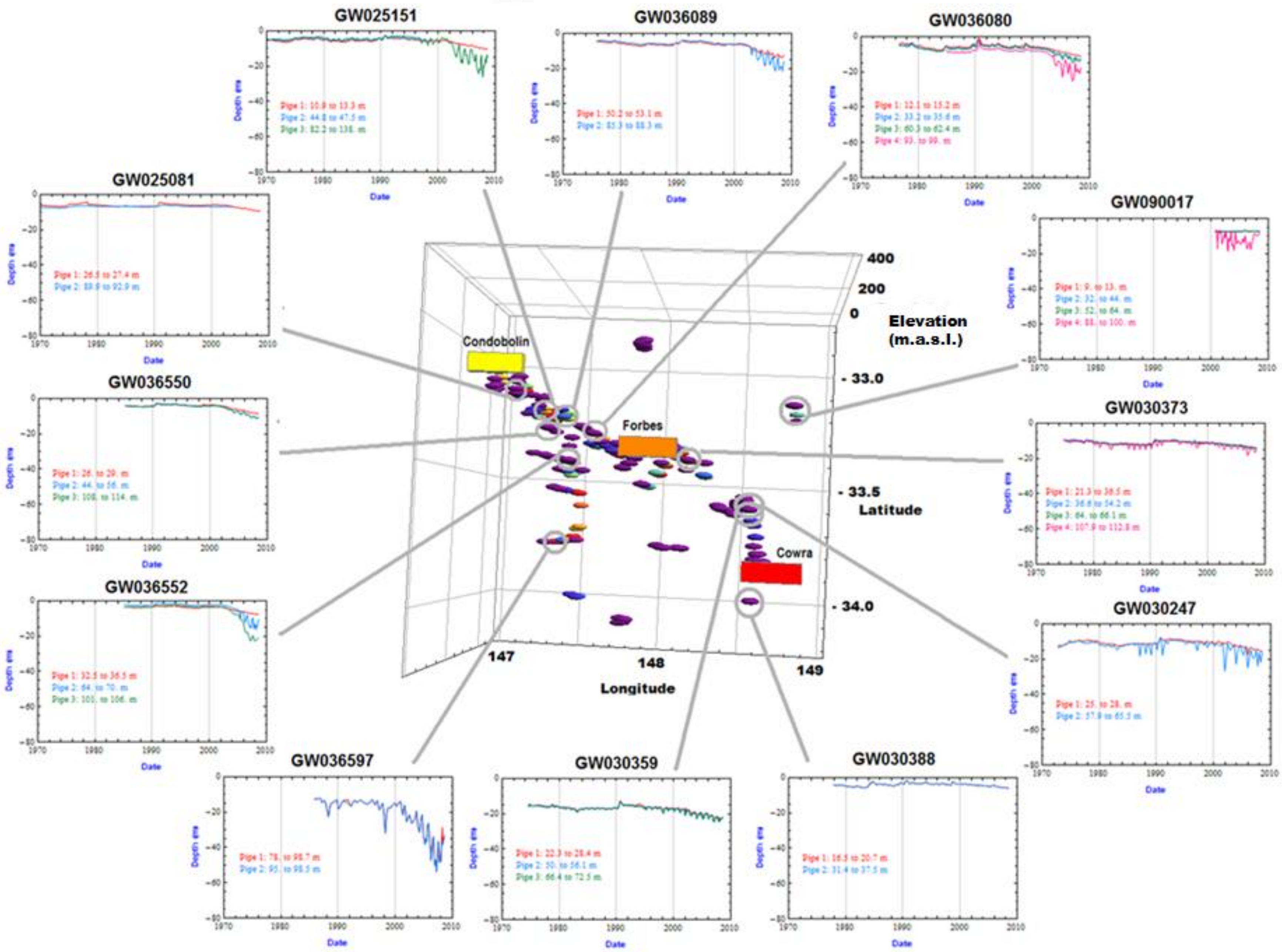


Figure 44. Lower Lachlan bore hydrographs.

Long Term Trends in the Standing Water Level

The relative difference in the SWL was determined for each location (Figure 39), tabulated in a histogram (Figure 45) and plotted in 3D at the midpoint of the slotted interval (Figures 40 and 46). At the majority of the monitoring locations the SWL has decreased by 0 to 4 m (Figure 45). The largest fall in the SWL was 13 m (i.e. GW030405) and 31.75 m (i.e. GW036553) in the lower and upper catchments respectively; both of these monitoring sites are located within irrigation districts. The maximum rise in the SWL was 1.33 m at bore GW036594 to the south of the irrigation approaching the base of the tributary leaving the Lake Cowal.

Most of the bores in the lower catchment show little change or a rise in the SWL. Only bores located in the olive and bright green hydraulic zones (Figure 41) have declined significantly in the last 20 years, typically in the order of 5 to 7 m (green to light green spheres); these locations include GW030405, GW030406, GW030173, GW030044, GW030045, GW030046, GW030104 and GW036561. These monitoring sites are located within or immediately adjacent to the irrigation district. In the upper catchment there appears to be a strong visual relationship between areas of irrigation and significant declines in the SWL with irrigation districts typically reporting losses of 5 to 8 m, especially at deeper levels within the alluvial sequence (green to yellow spheres). The largest declines over the last 20 years have occurred in the tributary emanating from Lake Cowal adjacent to the largest irrigation district by area in the Lachlan (red spheres). Monitoring bores within this region experiencing the largest drawdowns are GW036611, GW036596, GW036597, GW036595, GW036609, GW036553, GW036552 and GW036523. Maximum drawdowns occur at bore GW036597 in the southernmost portion of the tributary adjoining Lake Cowal.

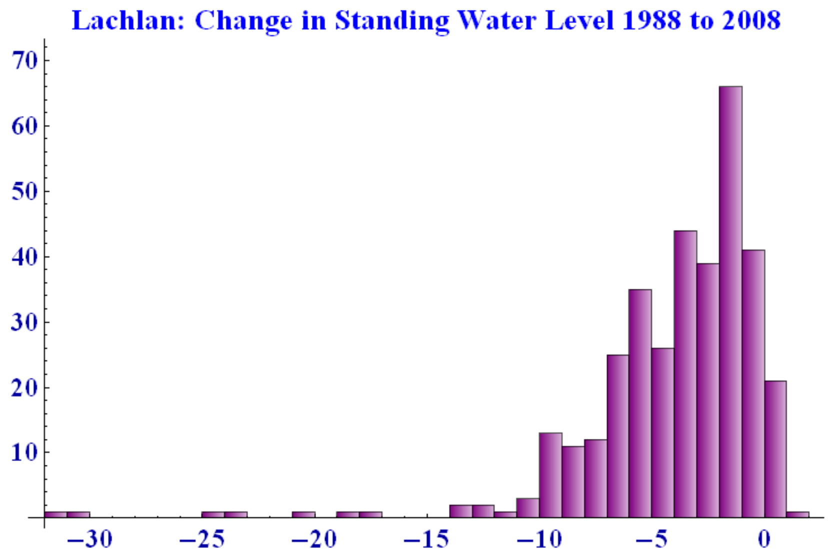


Figure 45. Histogram of the relative difference in the standing water level between 1998 and 2008 for groundwater monitoring bores in the Lachlan Catchment. Negative values indicate falling standing water levels.

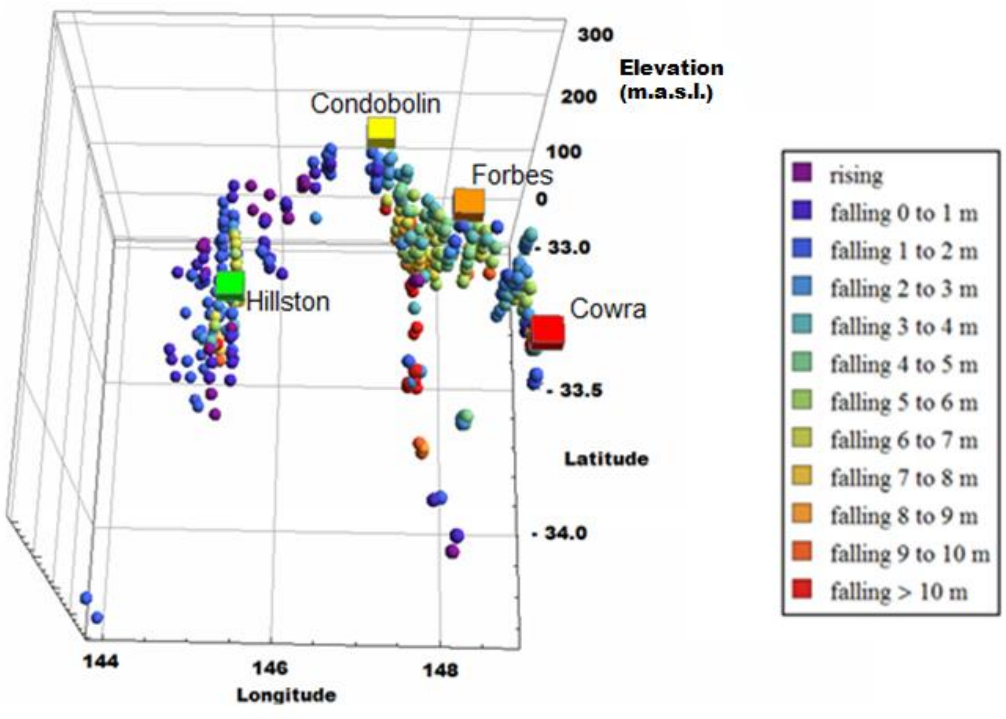


Figure 46. Overhead view of the relative difference in the standing water levels between 1988 and 2008.

In the lower Lachlan, hydrographs for bores located distal to rivers are essentially flat reporting little to no change in SWL form 1988 and 2008 (i.e. the brown, purple, cyan and yellow hydraulic zones; Figure 41). Areas from the blue hydraulic zone display no change in the SWL until 1998, at which time an oscillating pattern is evident indicating extraction impacts (Figure 41). Other aquifers close to the river (i.e. the red hydraulic zone; Figure 41) show a well defined flood response in the early 1990s and a subtle decline in SWL in the last decade.

The upper Lachlan experiences very different trends in hydrographs from 1988 to 2008. Outside of the irrigation district but still near the Lachlan River, the hydrograph response is comparable from Condobolin to south of Cowra (i.e. GW025081, GW030388 and GW030373; Figure 44). The SWL is relatively flat with the exception of the flood responses in the 1970s and 1990. Over the last decade there has been a subtle decline in the SWL corresponding to the drought.

Monitoring sites adjacent to the Lachlan river during wet periods do not show the impact of pumping, but during the drought last decade a decline in the SWL is clearly evident (for example see bores, GW030359 and GW036089; Figure 44). Throughout most of the irrigation districts the SWL had not varied much with depth until the recent drought. Different responses to the pumping are clearly observable in the upper unconfined and lower semi-confined aquifers (for example see bores GW036089 and GW036552; Figure 44). This is a consequence of the rate of groundwater extraction exceeding recharge, with the biggest drawdowns occurring in the deepest portions of the alluvial sequence. A similar pattern, but an order of magnitude lower, is observable at the periphery of the irrigation district (GW036550; Figure 44).

Towards Lake Cowal the hydrographs have exhibited an oscillating pattern with sharp declines in the late 1980s and 1990s. The drop in the SWL over the past decade is greater here than anywhere else within the catchment (i.e. GW036597).

Conclusion

Groundwater hydrographs provide important insights into the impact of groundwater extractions and irrigation on water resources and the subsequent effects on the environment. Almost 40 years of groundwater hydrograph records enable long term groundwater level trends (both spatial and temporal) to be analysed throughout the alluvial regions of the catchment.

Relative variations in the SWL analysed in the 3D plots and in association with the groundwater hydrograph plots helped to determine the hydraulic connectivity throughout the alluvial sequence of the lower and upper Lachlan Catchment.

Over most of the lower Lachlan catchment the fluctuation in the SWL due to pumping stresses is low which makes it difficult to differentiate between separate aquifer systems using hydrograph data. Two to three aquifers were identified in the irrigation district near Hillston with variation in the hydraulic connectivity between the upper and lower aquifers. In the upper Lachlan Catchment there clearly is an unconfined aquifer overlying a semi-confined aquifer system.

The long term (1988-2008) relative difference in the groundwater monitoring bore SWL analysis shows the impact of groundwater extraction throughout the upper and lower Lachlan Catchment. In the lower catchment monitoring bores located away from irrigation, the Lachlan River and its tributaries report no change in the SWL from 1998 to 2008. Areas near the river but away from irrigation districts have the same essentially flat hydrograph reading until 1998 at which time a steady and small, yet obvious oscillating pattern is evident; this is likely to be river response. This response is not surprising as this portion of the Lachlan River is highly connected to the groundwater aquifers (Braaten and Gates, 2003). Bores within 5 km of the river show clear flood responses to the

1990 flood. Subtle declines in the SWL over the past decade also coincide with drought (Figure 4, 7 and 8).

Bores within the irrigation districts of the lower Lachlan show similar features as those near rivers (i.e. relatively flat till 2000, flood response in the 1990s, etc), although pumping stresses associated with these districts have amplified the effects of drought from 2000 to 2008; especially in the lower portions of the alluvial sequence. These same effects are obvious on the periphery of the irrigation districts, but an order of magnitudes less.

In the upper Lachlan the SWL measurements indicate significant groundwater usage in excess of recharge. In the upper Lachlan, both the long term trend and yearly fluctuation groundwater hydrograph data in this district indicate the existence of an unconfined aquifer overly a semi-confined aquifer system across most of the region. From 1988 to 2008 most of the bore hydrographs in the upper Lachlan display a drawdown in excess of 4 metres, with drawdowns in excess of 10 metres in most monitoring bores along the tributary adjoining Lake Cowal.

To better understand aquifer connectivity a 3D geological model could be built using core logs data available from NSW PINNEENA CD 2009. This would enhance the understanding of the alluvial aquifer geometry, highlighting possible buried bedrock highs which could act as hydraulic impediments for flood and river recharge. Geological structures can have serious implications for the sustainable management of the groundwater resources. Groundwater is clearly being extracted at a rate higher than recharge in the irrigation districts close to Hillston and between Condobolin to Forbes. These regions need detailed investigations to better understand from where and at what rate the deeper semi-confined aquifers are being recharged.

Water storage in the Lachlan Catchment has decreased over the last decade since dam releases, rainfall, stream flow and flood recharge have been at historically low levels, and groundwater usage has been at historically high levels. The high connectivity between rivers and groundwater in the region (Braaten and Gates, 2003) in conjunction with the river response identified in hydrographs suggest that extraction bores near rivers are maximising leakage from the rivers to the underlying aquifers. This process cannot be inferred from the groundwater hydrographs alone. A more extensive stream-aquifer water balance study is required to quantify the extent of surface and sub-surface coupling. For bores several kilometres away from the river the aquifer system is being depressurised.

If the management goal is to not deplete the aquifers, and river and aquifer interactions are to be balanced with environmental goals, then surface and ground water need to be managed as one resource. We also need to have a good understanding of the hydraulic connections throughout the catchment, and how to balance the variable inputs with the outputs. For the Lachlan Catchment there already exist several water balance models (Dent et al. 2007; CSIRO, 2008) that demonstrate a moderate ability to predict groundwater responses for variable rainfall, river flow, flooding, and usage. To advance our knowledge of river and aquifer connectivity, and connectivity throughout the aquifer system, we must interpret the groundwater hydrographs in the context of a comprehensive 3D lithofacies model supported by extensive chemical investigations, examining both the major ion chemistry and dating the ages of the groundwater zones.

References

Adamson C.L., Branagan L.R., Hall R., McElroy C.T., Moye D.G., Relph R.E., Sharp K.R., Stapledon H., Whiting J.W., Williamson W.H., & Wynn D.W. 1969. Cainozoic rocks outside the Murray Basin. *Australian Journal of Earth Sciences* **16**, 543-557.

Allen R.G., Pereira L.S., Raes D., & Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements, irrigation and drainage paper 56, Food and Agriculture Organisation, Rome.

Armstrong J.L., Kingsford R.T., & Jenkins K.M. 2009. The effect of regulating the Lachlan River on the Booligal Wetlands – the floodplain red gum swamps. Wetlands & Rivers, School of Earth & Environmental Sciences, University of New South Wales.

Barnett B.G., & Muller J. 2008. Upper Lachlan groundwater model calibration report. *A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. CSIRO. Pp. 1-66.

Bishop P., & Goldrick G. 2000. Geomorphical evolution of the east Australian continental margin. *In Summerfield, M.A. (Ed). Geomorphology and Global Tectonics. Wiley.* Pp. 225-254.

Braaten R., & Gates G. 2003. Groundwater-surface interaction in inland New South Wales: a scoping study. *Water, Science and Technology* **48**(7), 215-224.

Brady A., Shaikh M., King A., Ross J., & Sharma P. 1998. The Great Cumbung Swamp: assessment of water requirements. Tech. rep., New South Wales Department of Land and Water Conservation, Sydney.

Brown C.M., & Stephenson A.E. 1991. Geology of the Murray Basin (1:1 000 000 scale map). Bureau of Mineral Resources, Canberra.

Bureau of Meteorology. 2010. Bureau of Meteorology < http://www.bom.gov.au/>. (retrieved 15 July 2010).

Chan R.A. 1999. Palaeodrainage and its significance to mineral exploration the Bathurst region. Tech. rep., Cooperative Research Centre for Landscape Evolution and Mineral Exploration, Canberra.

Chiew F.H.S., Zhou S.L., & McMahon T.A. 2003. Use of seasonal streamflow forecasts in water resources management. *Journal of Hydrology* **270**, 135-144.

Coney P.J. 1992. The Lachlan Fold Belt of Eastern Australia and Circum-Pacific tectonic evolution. *Tectonophysics* **214**, 1-25.

CSIRO 2008. *Water availability in the Lachlan. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. CSIRO. Pp. 1-133.

Department of Infrastructure, Planning and Natural Resources (DIPNR). 2003. Lachlan River Drought Continues, News Release.

Department of Land and Water Conservation (DLWC), 1989. Water Resources of the Lachlan Valley. NSW. DWLC, N.S.W., Australia.

Dent B, Merrick N., Kelly B., Milne-Home W., & Yates D. 2007. Groundwater knowledge and gaps in the Lachlan Catchment management area. Tech. rep., National Centre for Groundwater Management, University of Technology, Sydney.

Dowling D. 2005. *Cotton Yearbook 2005*. Greenmount Press.

Environment Australia. 2001. A directory of important wetlands in Australia. Third edition. Environment Australia, Canberra.

<http://www.environment.gov.au/water/publications/environmental/wetlands/pubs/directory.pdf>

Graham I.T., Franklin B.J., Marshall B., Leitch E.C., & Fanning M. 1996. Tectonic significance of 400 Ma zircon ages for ophiolitic rocks from the Lachlan fold belt, eastern Australia. *Geology* **24**, 1111-1114.

Geoscience Australia (GSA). 2010. Geoscience Australia < http://www.ga.gov.au/>. (Retrieved 15 July 2010).

Hogendyk, G., 2007. The Macquarie Marshes - an ecological history. Tech. rep., Institute of Public Affairs.

Kelly, B., Giambastiani, B., Andersen, M., McCallum, A., Greve, A., and Acworth, I. (2010) "Development of a 3D Geological Mapping and Database Interface to Support Interconnected Groundwater and Surface Water Management", A report by the Connected Waters Initiative, UNSW and National Centre for Groundwater Research and Training for the Cotton Catchment Communities CRC and the National Water Commission, Raising the National Water Standards, Groundwater Project, Final Report, 310 pages.

Kemp J. 2002. The geomorphology, hydrology and quaternary palaeochannels of the Lachlan Valley, NSW. PhD thesis, Australian National University, Canberra.

Kemp J. 2010. Downstream channel changes on a contracting anabranching river: The Lachlan, southeastern Australia. *Geomorphology* **Article In Press**

Kemp J., & Rhodes E.J. 2010. Episodic fluvial activity of inland rivers in southeastern Australia: Palaeochannel systems and terraces of the Lachlan River. *Quaternary Science Reviews* **29**, 732-752.

Kingham R. 1998. Geology of the Murray-Darling Basin – simplified lithostratigraphic groupings. Tech. rep., Australian Geological Survey Organisation, Canberra.

Lachlan Catchment Management Authority (CMA). 2006. *Lachlan Catchment Action Plan 2006*. Lachlan Catchment Management Authority. Pp. 207.

Lachlan Catchment Management Authority (CMA). 2009. *Annual Report 2009*. Lachlan Catchment Management Authority. Pp. 1-73.

McCallum A.M., Andersen M.S., Kelly B.F.J., Giambastiani B., & Acworth. 2009. Hydrological investigations of surface water-groundwater interactions in a sub-catchment in the Namoi Valley, NSW, Australia. In: Trends and Sustainability of Groundwater in Highly Stressed Aquifers eds.: Taniguchi M. et al. Proc. of the Joint IAHS & IAH Congress, Hyderabad, India, 6th - 12th of September 2009. IAHS Publ. 329, 2009, 157-166.

Magrath MJL. 1992. Waterbird study of the lower Lachlan and Murrumbidgee Valley Wetlands in 1990/91. New South Wales Department of Water Resources, Sydney.

Mampitiya D. 2002. Lower Lachlan groundwater model: model development, calibration and use. Tech. rep., NSW Department of Land Water and Conservation, Centre for Natural Resources, 68

Martin H.A. 1984. The stratigraphy palynology of the Murray Basin in New South Wales. III. *The Lachlan area. Journal and Proceedings of the Royal Society of New South Wales* **117**, 45-51.

Martin H.A. 1987. Cainozoic history of the vegetation and climate of the Lachlan River region, New South Wales. *Proceedings of the Linnean Society* **109**, 214-257.

McMahon T.A., Finlayson B.L., Haines A.T., Srikanthan R. 1992. *Global runoff-continental comparisons of annual flows and peak discharges*. Catena. Pp. 166.

Moore C. 1992. *Water management plan for the Booligal Wetlands Ibis Rookery Preservation Strategy*. Department of Water Resources. NRMS Project N167. Forbes.

Murray Darling Basin Authority (MDBA). 2010. Assessing environmental water requirements. Tech. rep., Murray Darling Basin Authority, Canberra.

Murray Darling Basin Commission (MDBC). 2006. River Murray System – Drought Update. Tech. rep., Murray Darling Basin Commission. Canberra.

Murray Darling Basin Commission (MDBC). 2007. Updated summary of estimated impact of groundwater extraction on stream flow in the Murray-Darling Basin. Tech. rep., Murray Darling Basin Commission. Canberra.

Natural Resources Commission (NRC). 2006. Scientific expert review for the lower Lachlan groundwater sharing plan. Tech. rep., Natural Resources Commission, Sydney.

NSW Agriculture. 2003. Lachlan Catchment Irrigation Profile. Report prepared by New South Wales Agriculture for the Water Efficiency Advisory Unit, Dubbo.

NSW Agriculture & Fisheries Division of Plant Industries. 1990. Horticulture in the Lachlan Valley. Tech. rep., NSW Agriculture & Fisheries Division of Plant Industries, Sydney.

NSW Department of Infrastructure, Planning and Natural Resources (DIPNR). 2004a. A guide to the Water Sharing Plan for the Lachlan Regulated River water source. Tech. rep., NSW Department of Infrastructure, Planning and Natural Resources, Forbes.

NSW Department of Infrastructure, Planning and Natural Resources (DIPNR). 2004b. A guide to the Water Sharing Plan for the Mandagery Creek water source.

Tech. rep., NSW Department of Infrastructure, Planning and Natural Resources, Forbes.

NSW Irrigators Council (IC). 2007. Lachlan Valley Fact Sheet. < http://www.nswic.org.au/pdf/catchment_profiles/Lachlan.pdf>

NSW Department of Primary Industries. 2005. Statewide tectonics. Tech. rep., NSW Department of Primary Industries, Orange.

NSW Department of Primary Industries. 2006. Murray Basin – geological overview. Tech. rep., NSW Department of Primary Industries, Orange.

NSW Department of Water and Energy (DWE). 2008a. Water Sharing Plan: lower Lachlan groundwater source. Information for groundwater licence holders on the commencement of the Water Sharing Plan. Tech. rep., NSW Department of Water and Energy, Sydney.

NSW Department of Water and Energy (DWE). 2008b. Water Sharing Plan for the Lower Lachlan Groundwater Source 2003. Effective from 1 February 2008 and ceases on the 30 June 2018. New South Wales Department of Water and Energy. NSW Government Gazette.

O'Brien P.E., & Burne R.V. 1994. The Great Cumbung Swamp; terminus of the low-gradient Lachlan River, eastern Australia. AGSO Journal of Australian Geology and Geophysics **15** (2), 223-233.

Scheibner E., & Basden H. 1996. Geology of New South Wales – Synthesis. Volume 1 Structural Framework. Geological Survey of New South Wales, Memoir Geology 13(1), 295.

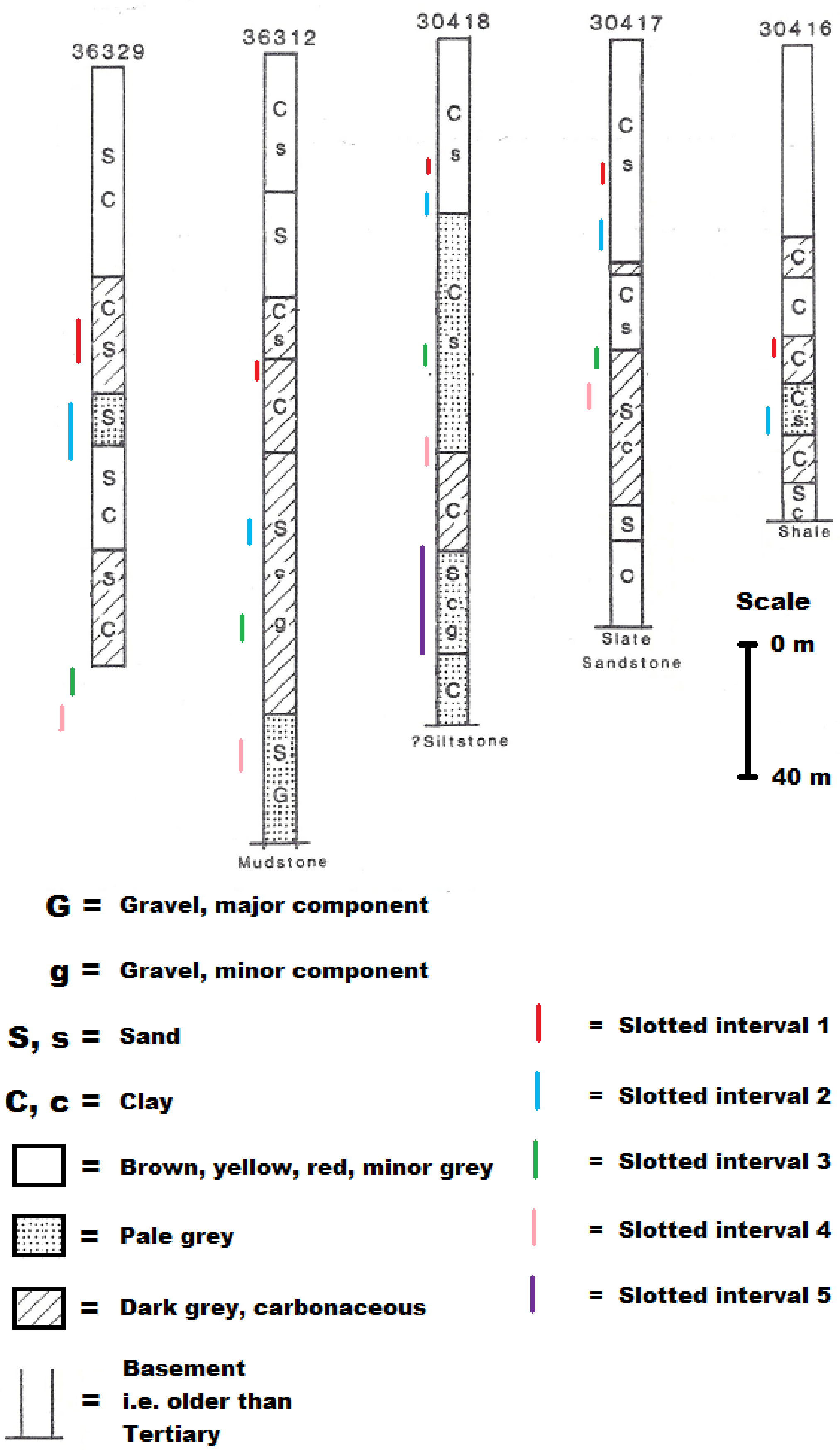
Tillman F.D., and Leake S.A. 2010. Trends in groundwater levels in wells in the active management areas of Arizona. *Hydrogeology Journal* Inpress.

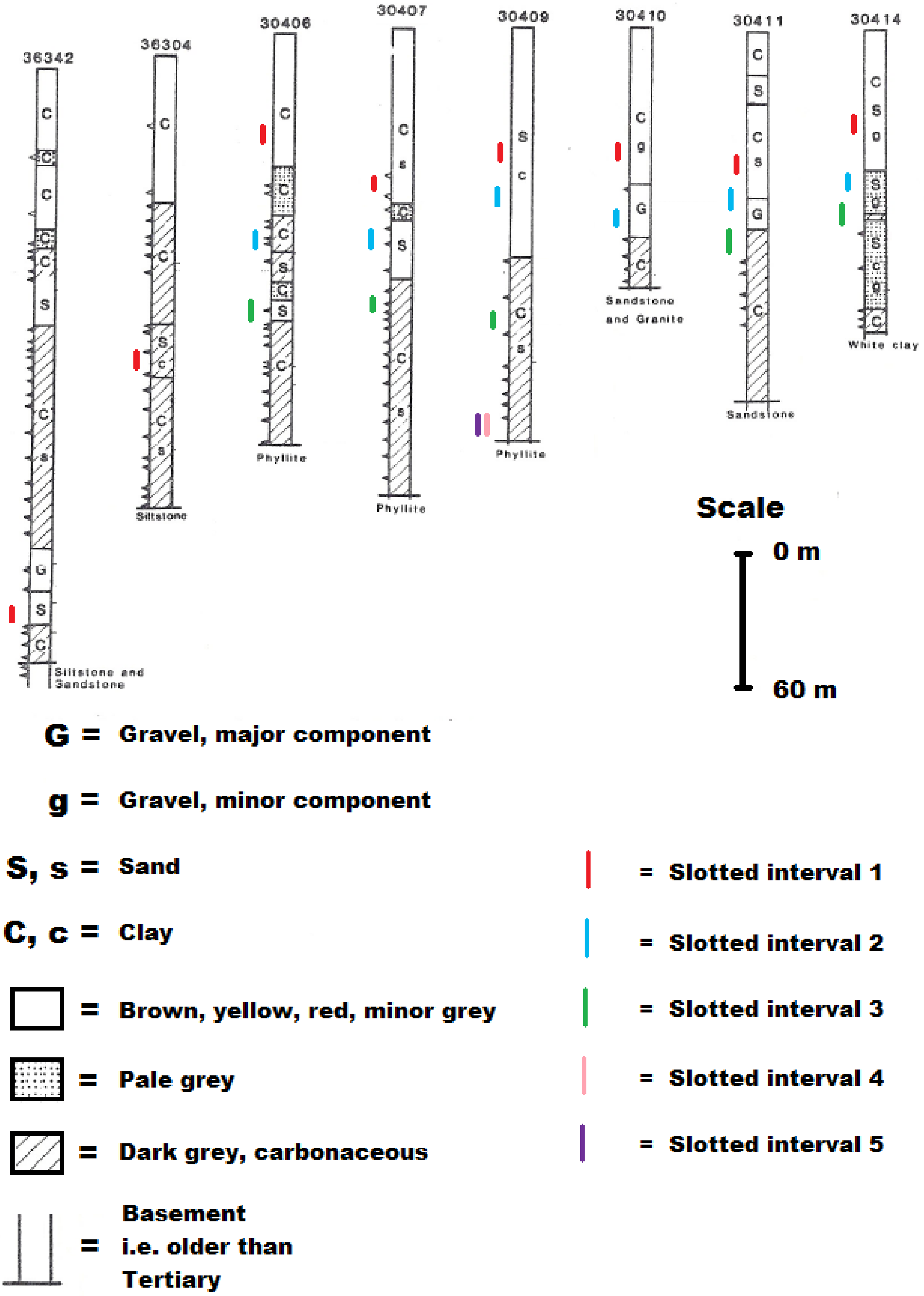
URS 2006. Introducing groundwater in your catchment. Tech. rep., URS, Southbank.

Webster K., & Stewart M. 2004. A critical analysis of the cumulative rainfall departure concept. *Groundwater* **42**, 935-938.

WCIC 1972. *Water Resources of the Lachlan Valley*. Water Conservation and Irrigation Commission.

Appendix 1 – Location of Slotted Intervals

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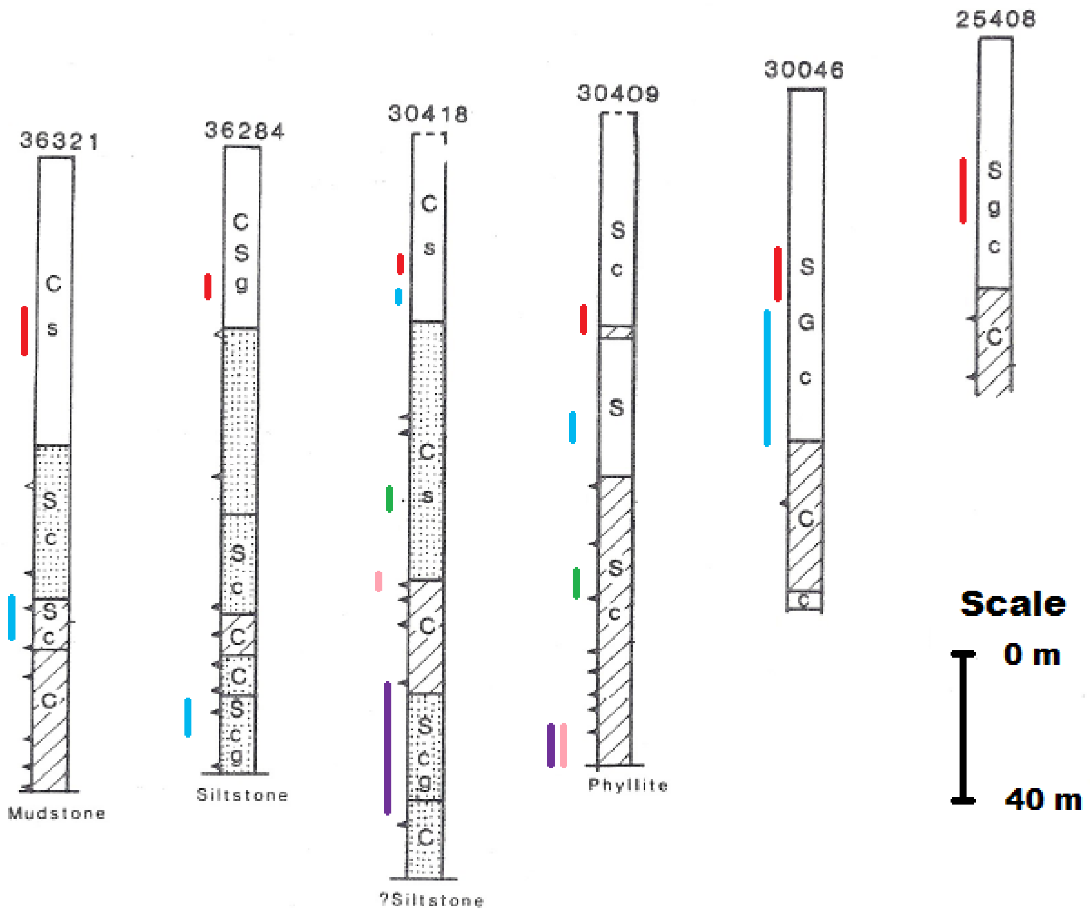
Siltstone and Sandstone
Siltstone
Phyllite
Phyllite
Phyllite
Sandstone and Granite
Sandstone
White clay
Scale
0 m
60 m
G = Gravel, major component
g = Gravel, minor component
S, s = Sand
C, c = Clay
= Brown, yellow, red, minor grey
= Pale grey
= Dark grey, carbonaceous
= Basement i.e. older than Tertiary
= Slotted interval 1
= Slotted interval 2
= Slotted interval 3
= Slotted interval 4
= Slotted interval 5



G = **Gravel, major component**

g = **Gravel, minor component**

S, s = **Sand**

C, c = **Clay**

☐ = **Brown, yellow, red, minor grey**

▦ = **Pale grey**

▨ = **Dark grey, carbonaceous**

‖ = **Basement i.e. older than Tertiary**

| = **Slotted interval 1**

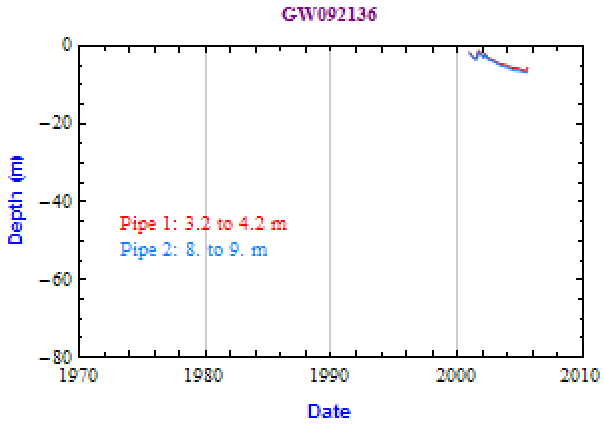
| = **Slotted interval 2**

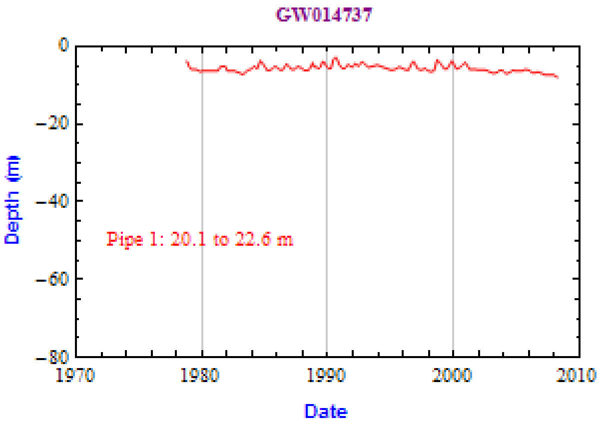
| = **Slotted interval 3**

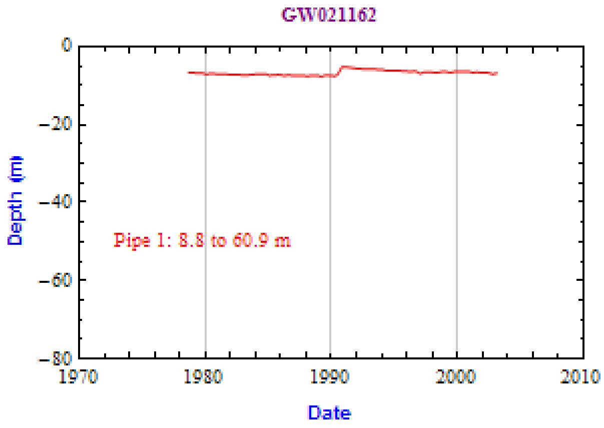
| = **Slotted interval 4**

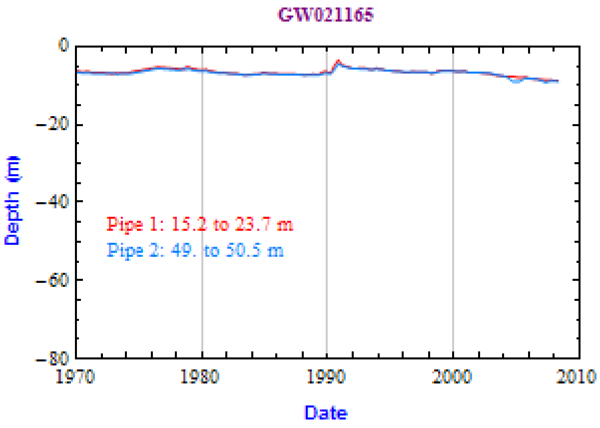
| = **Slotted interval 5**

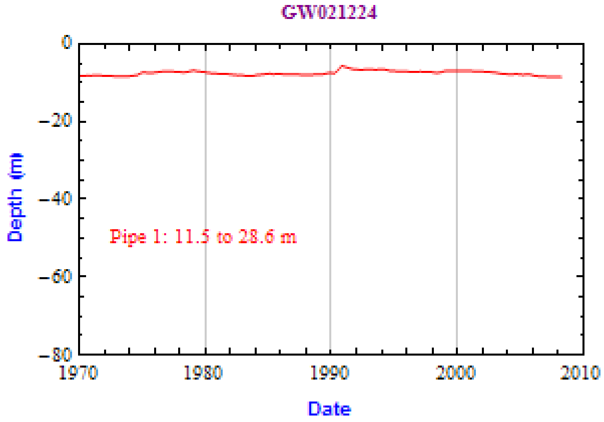
Appendix 2 – Borehole Hydrographs







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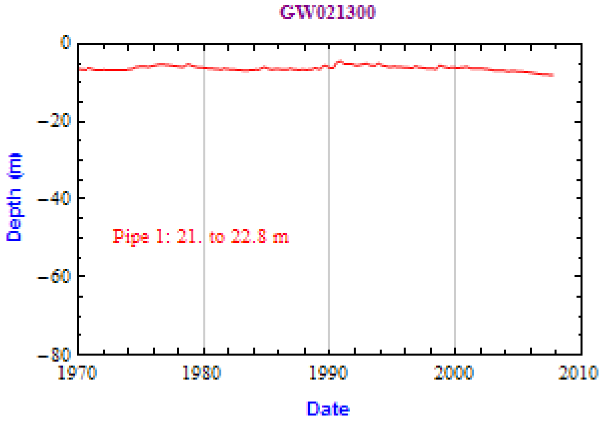
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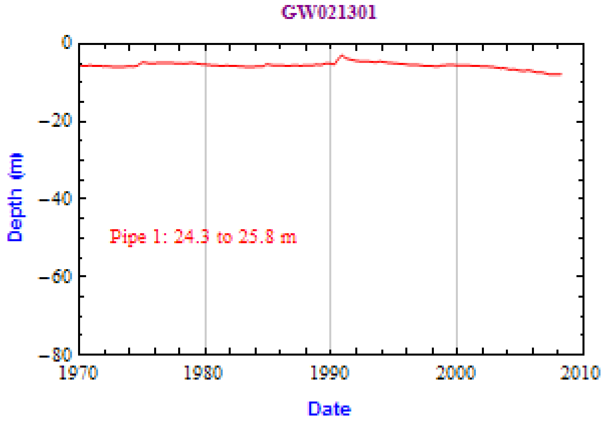
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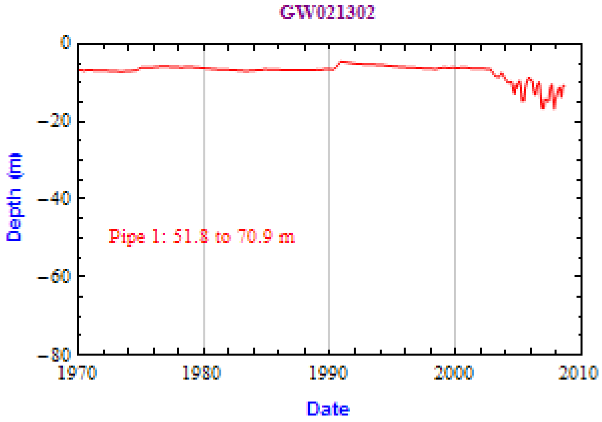
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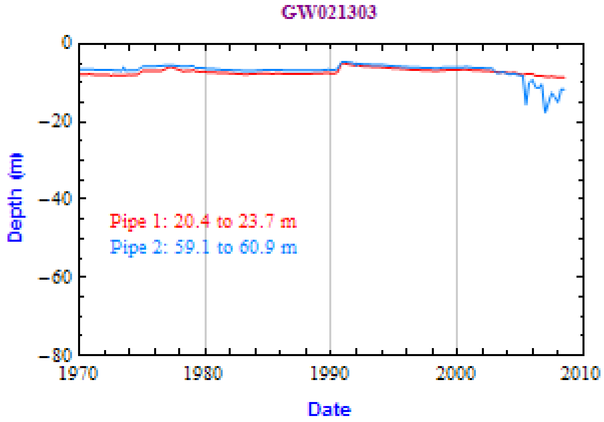
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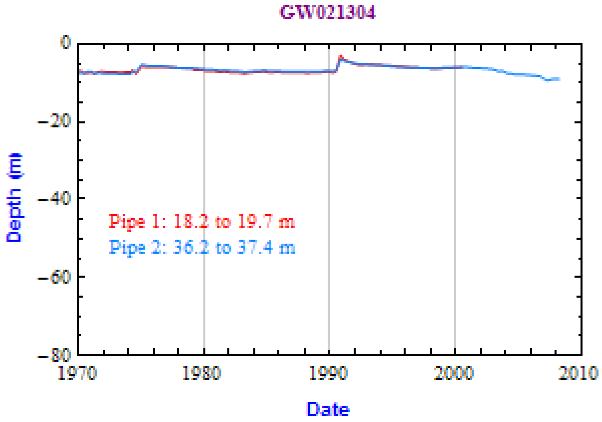
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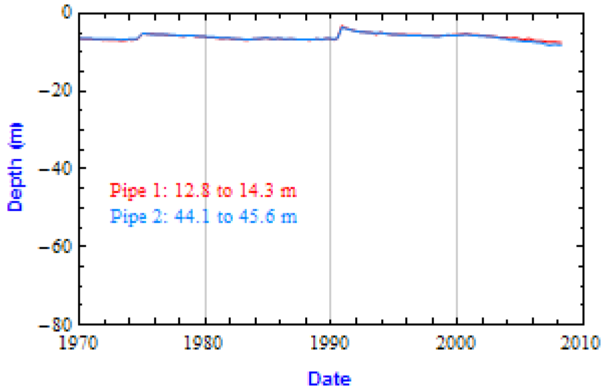
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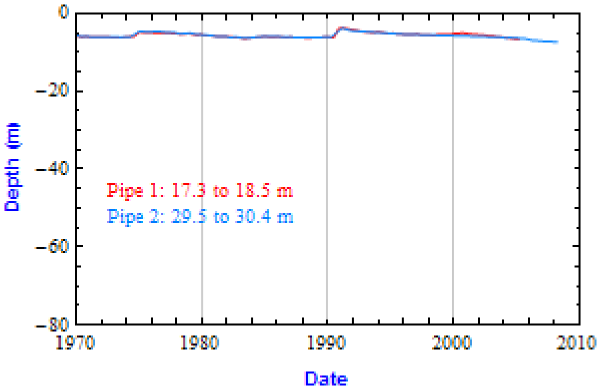
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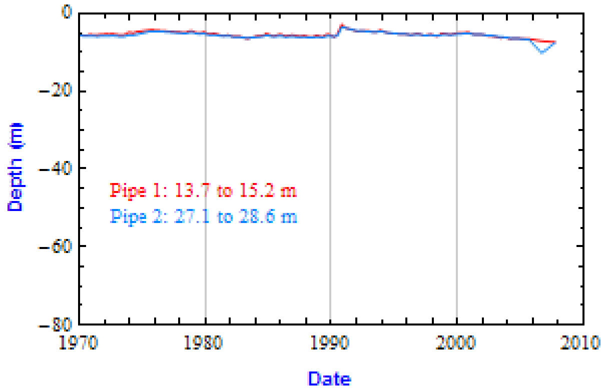
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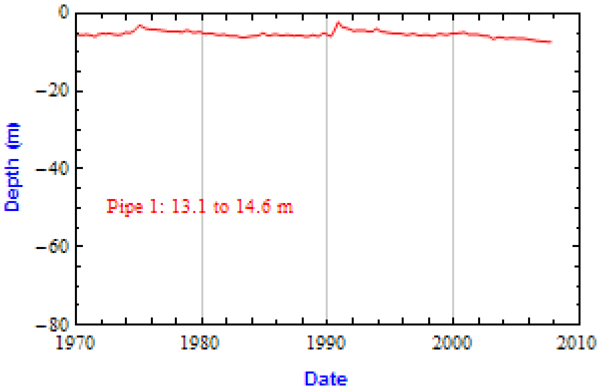
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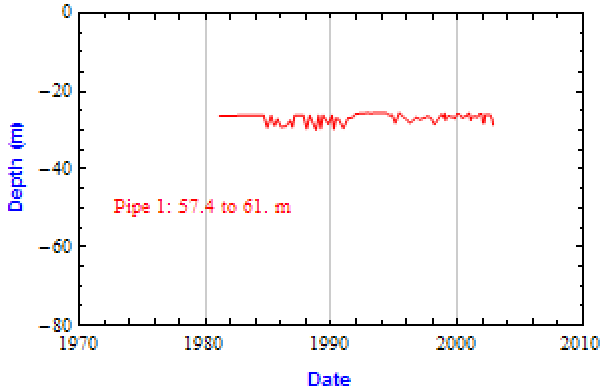
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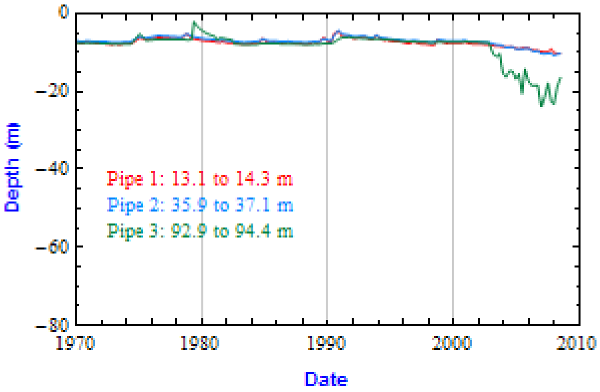
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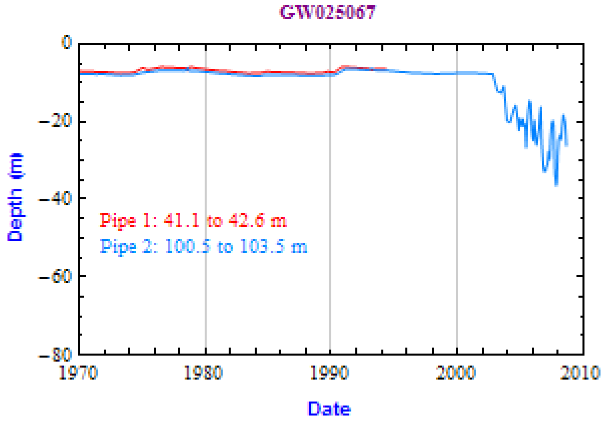
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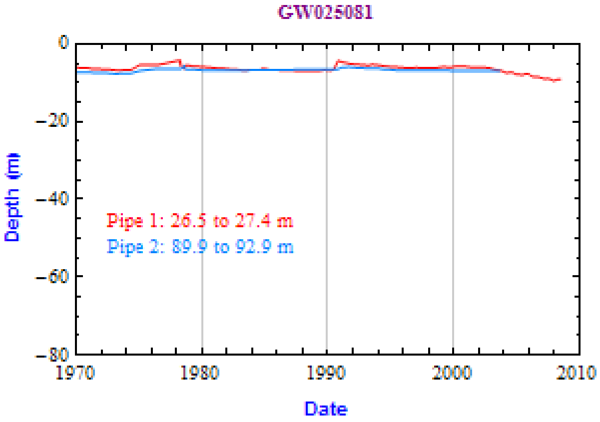
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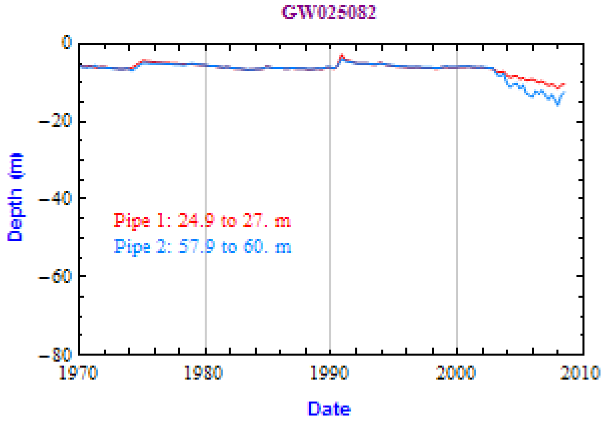
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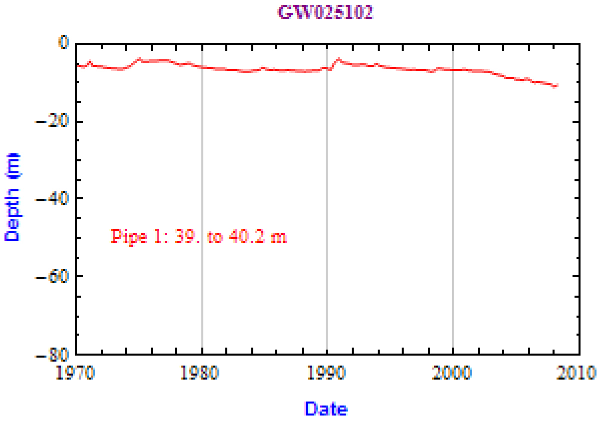
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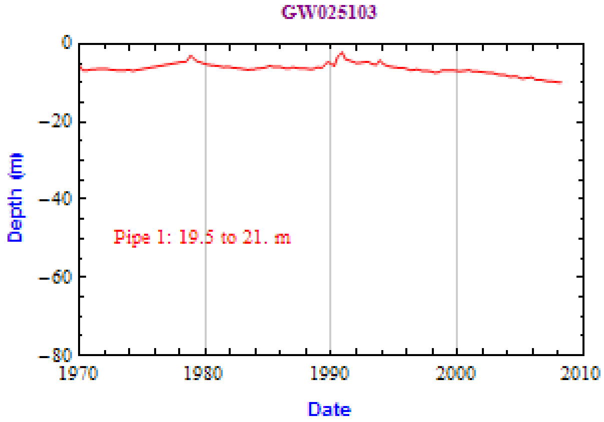
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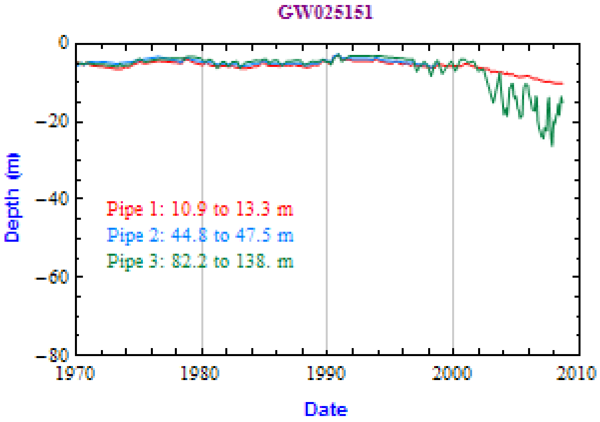
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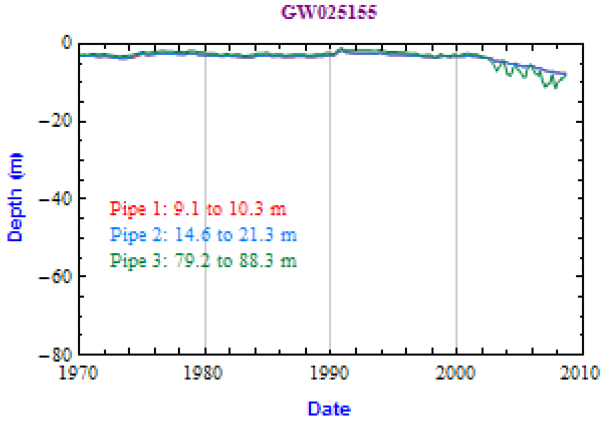
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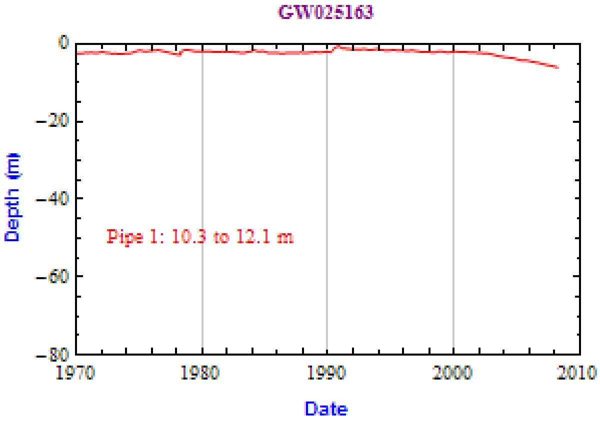
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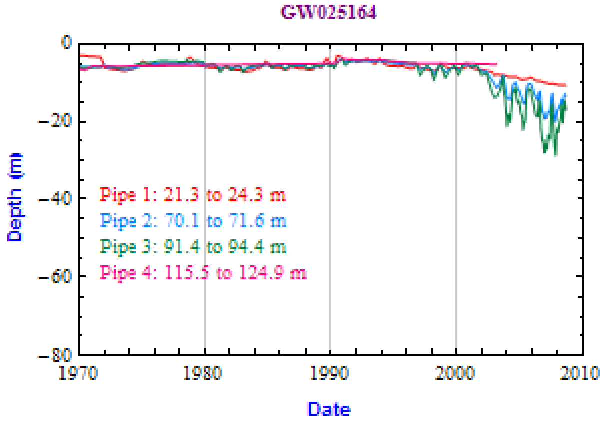
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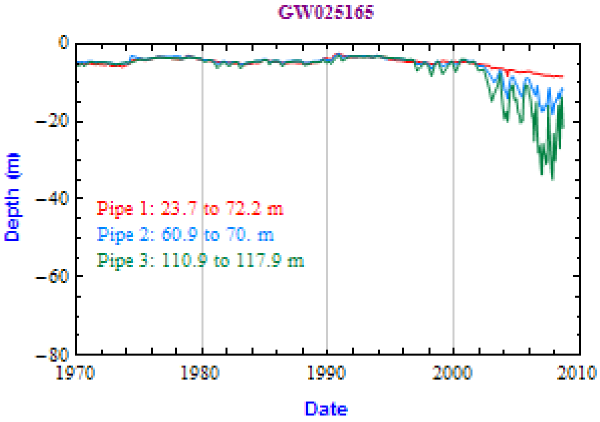
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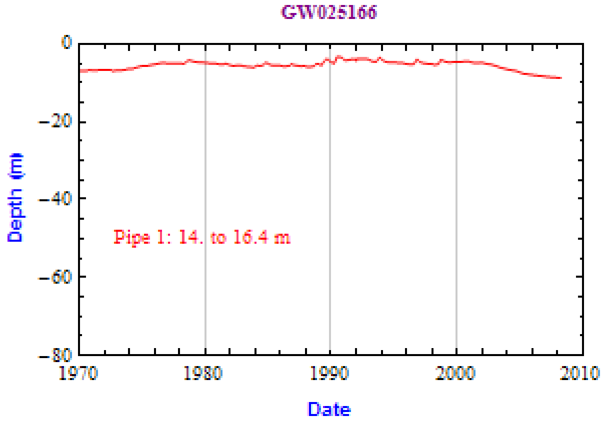
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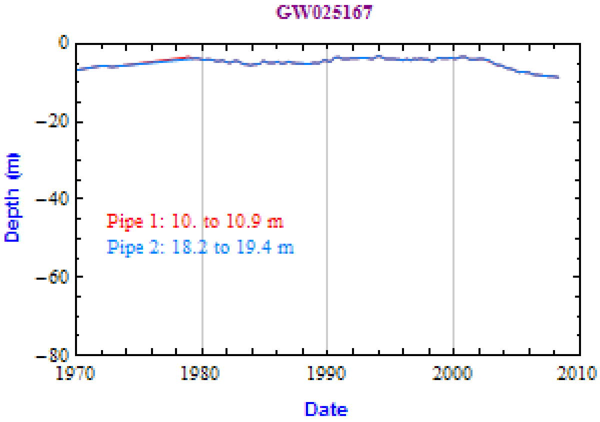
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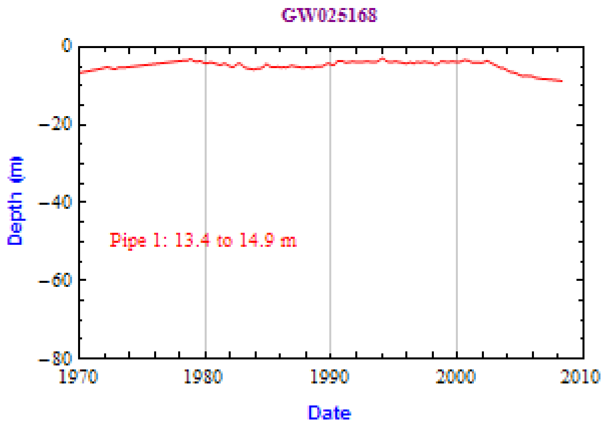
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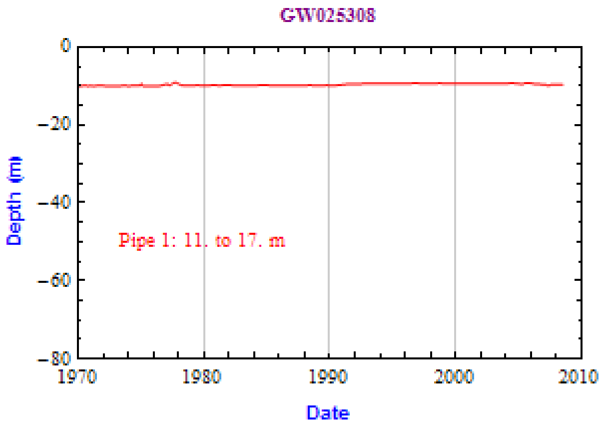
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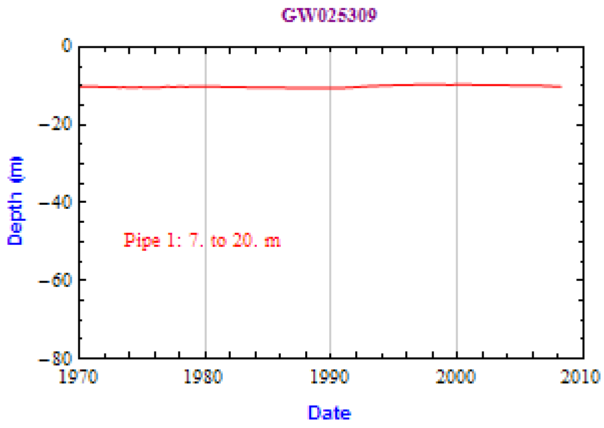
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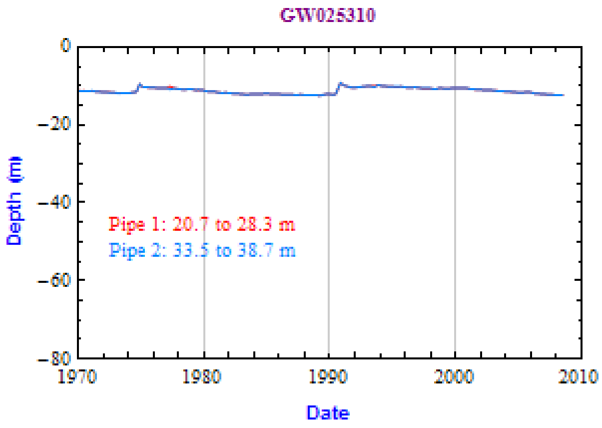
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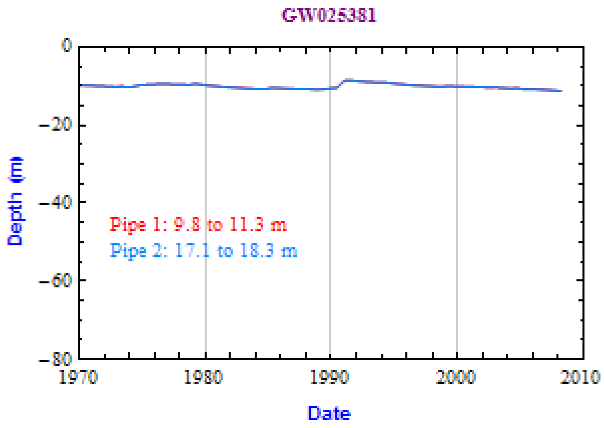
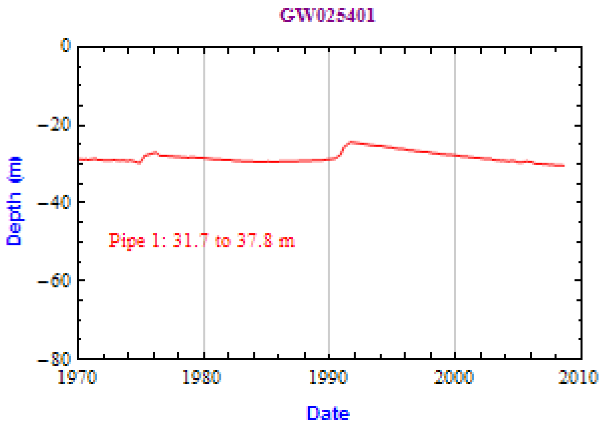
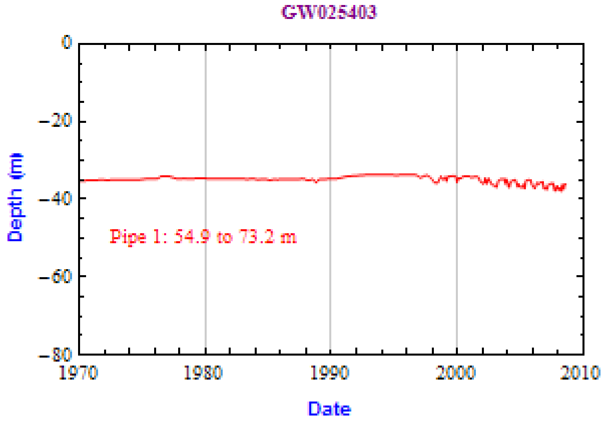
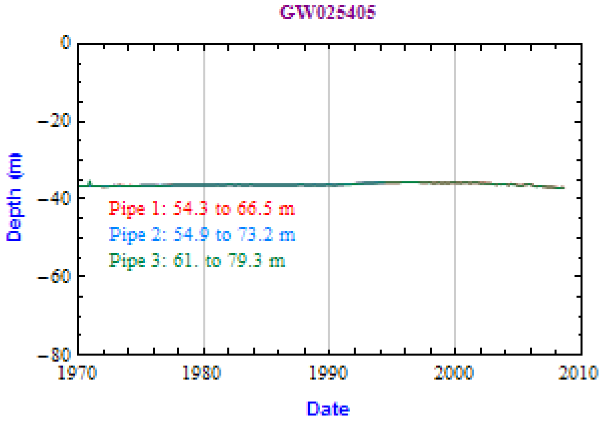
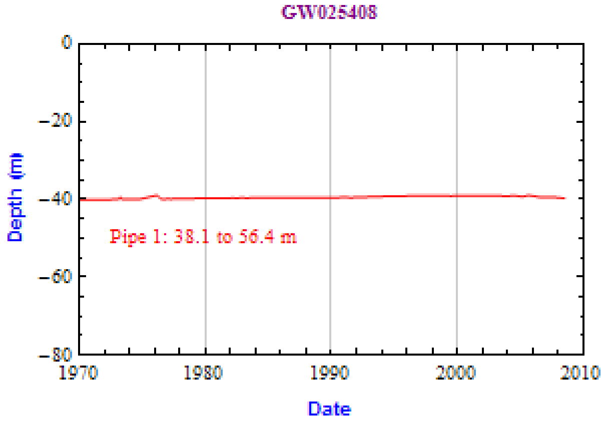
2010
Date

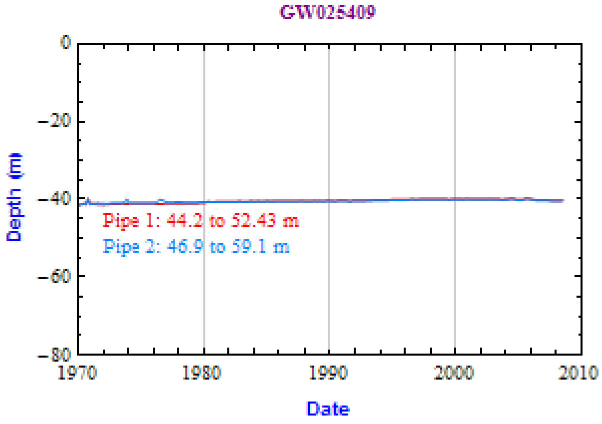

GW025381
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 9.8 to 11.3 m
Pipe 2: 17.1 to 18.3 m
1970
1980
1990
2000
2010
Date

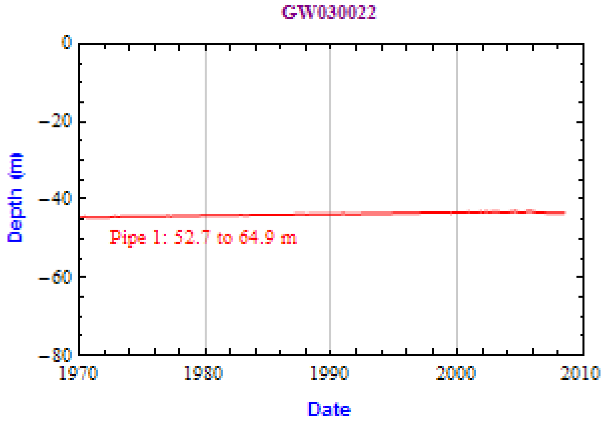

GW025401
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 31.7 to 37.8 m
1970
1980
1990
2000
2010
Date

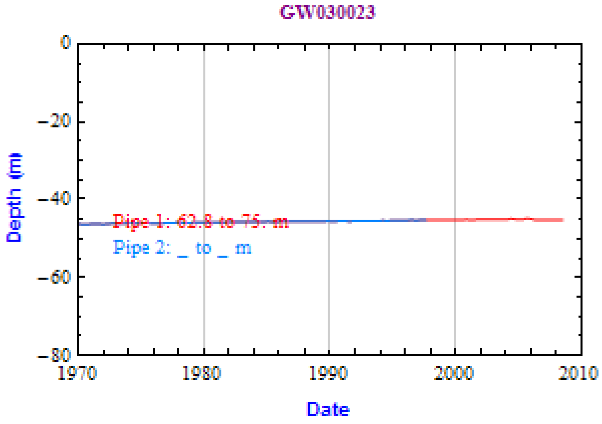

GW025403
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 54.9 to 73.2 m
1970
1980
1990
2000
2010
Date

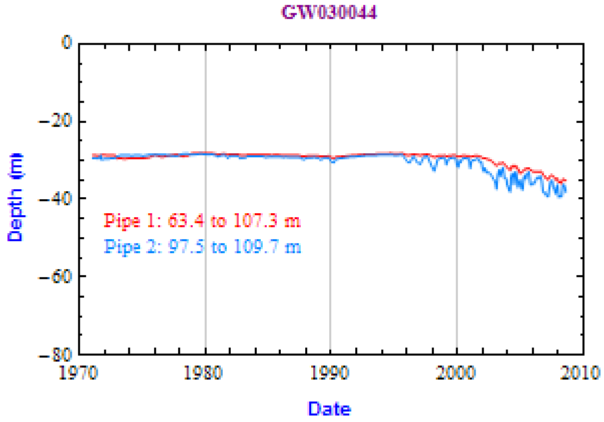

GW025405
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 54.3 to 66.5 m
Pipe 2: 54.9 to 73.2 m
Pipe 3: 61. to 79.3 m
1970
1980
1990
2000
2010
Date

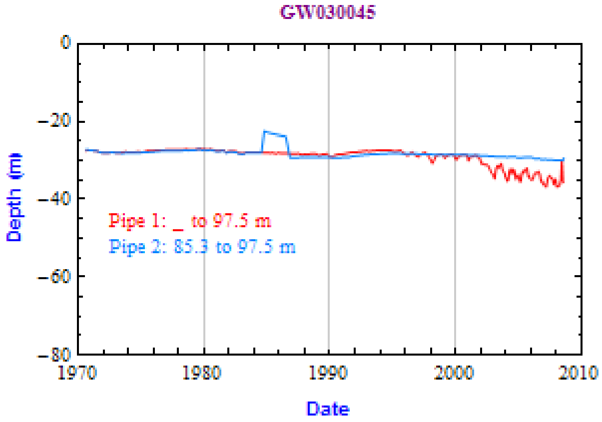

GW025408
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 38.1 to 56.4 m
1970
1980
1990
2000
2010
Date

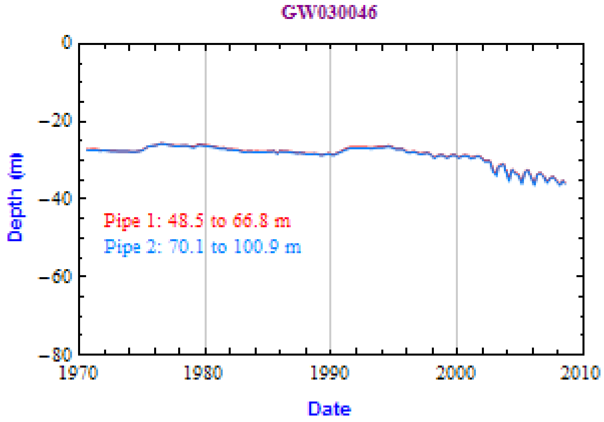

GW025409
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 44.2 to 52.43 m
Pipe 2: 46.9 to 59.1 m
1970
1980
1990
2000
2010
Date

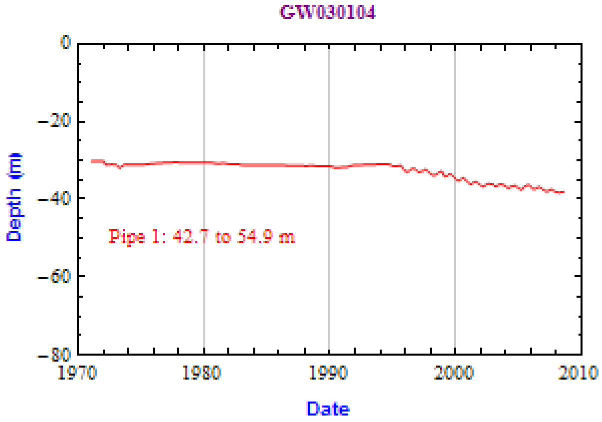

GW030022
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 52.7 to 64.9 m
1970
1980
1990
2000
2010
Date

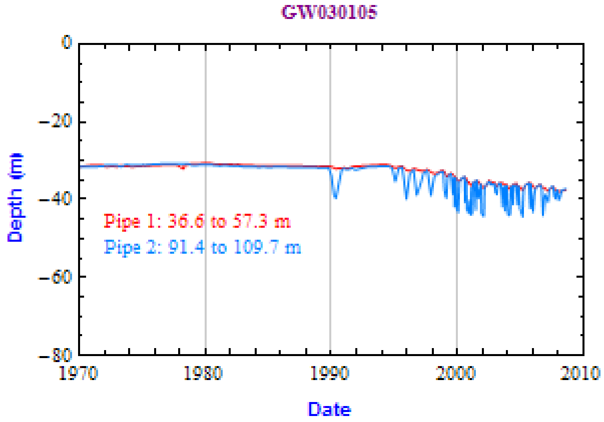

GW030023
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 62.8 to 75. m
Pipe 2: _ to _ m
1970
1980
1990
2000
2010
Date

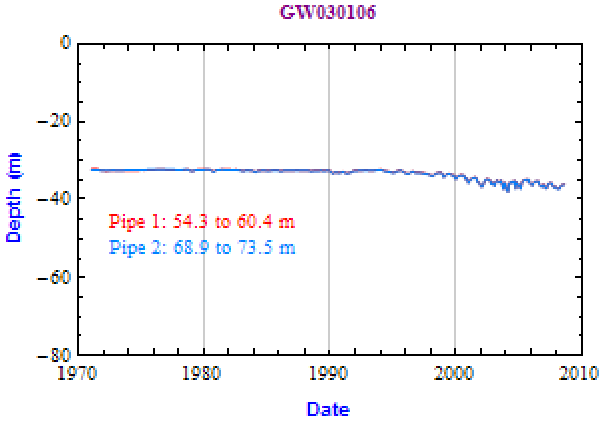

GW030044
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 63.4 to 107.3 m
Pipe 2: 97.5 to 109.7 m

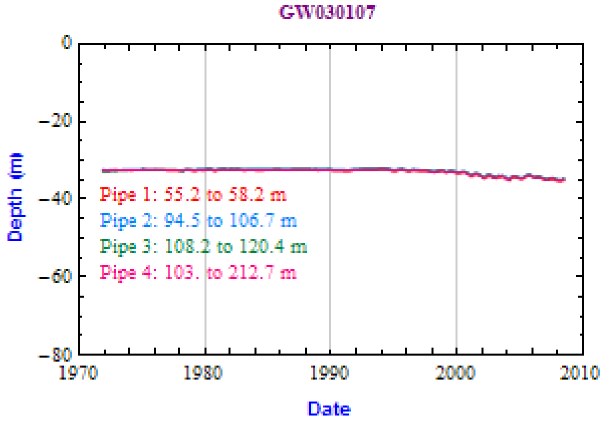

GW030045
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: _ to 97.5 m
Pipe 2: 85.3 to 97.5 m

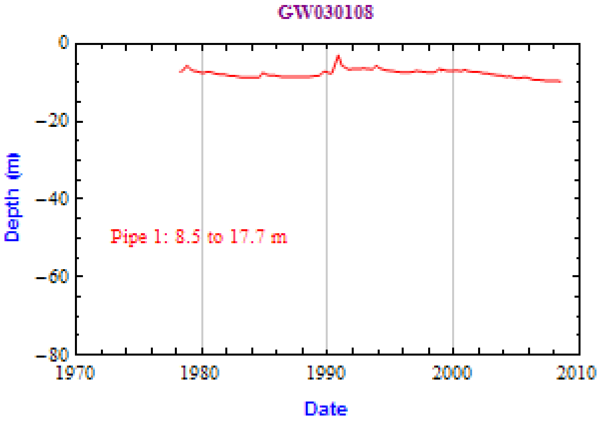

GW030046
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 48.5 to 66.8 m
Pipe 2: 70.1 to 100.9 m

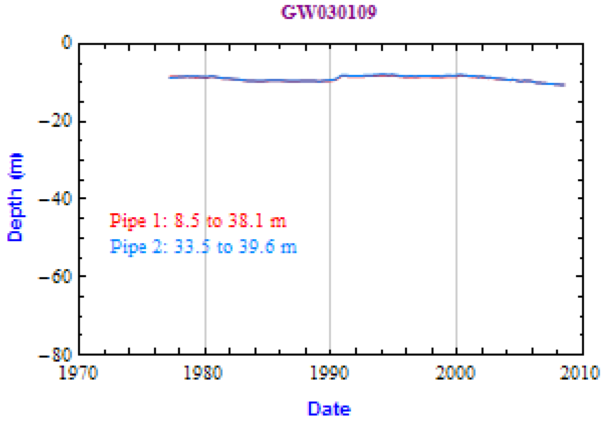

GW030104
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 42.7 to 54.9 m

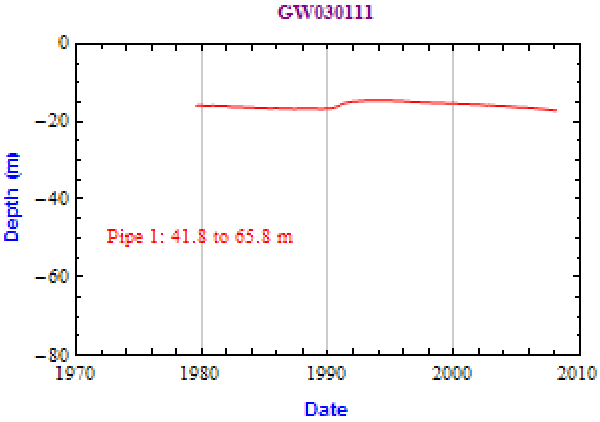

GW030105
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 36.6 to 57.3 m
Pipe 2: 91.4 to 109.7 m

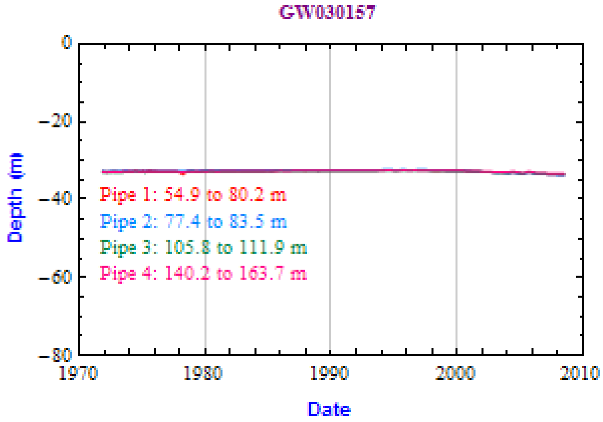

GW030106
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 54.3 to 60.4 m
Pipe 2: 68.9 to 73.5 m

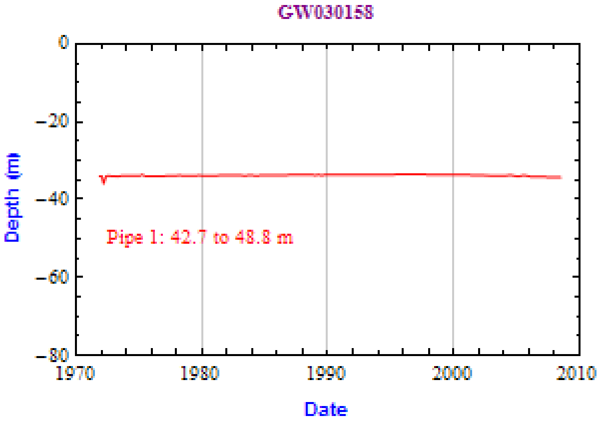

GW030107
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 55.2 to 58.2 m
Pipe 2: 94.5 to 106.7 m
Pipe 3: 108.2 to 120.4 m
Pipe 4: 103. to 212.7 m

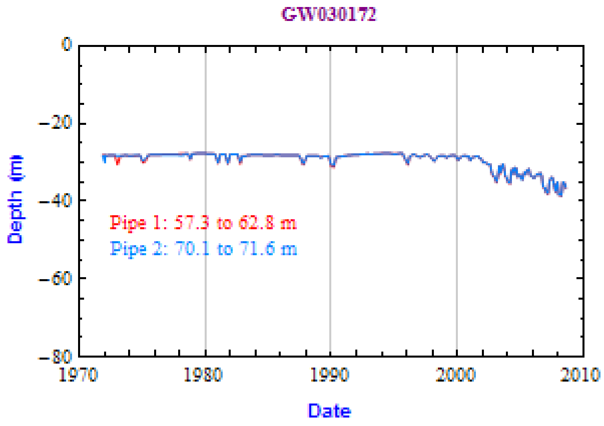

GW030108
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 8.5 to 17.7 m

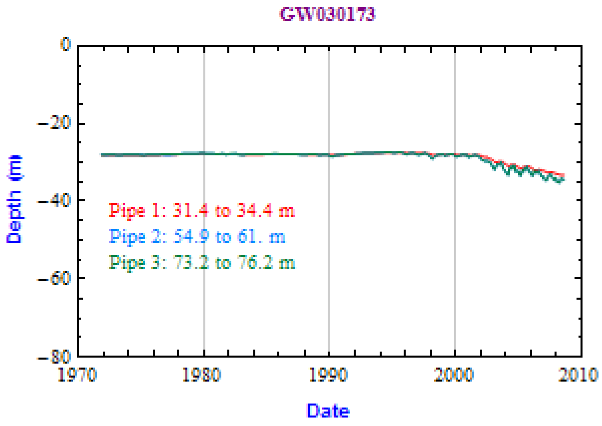

GW030109
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 8.5 to 38.1 m
Pipe 2: 33.5 to 39.6 m

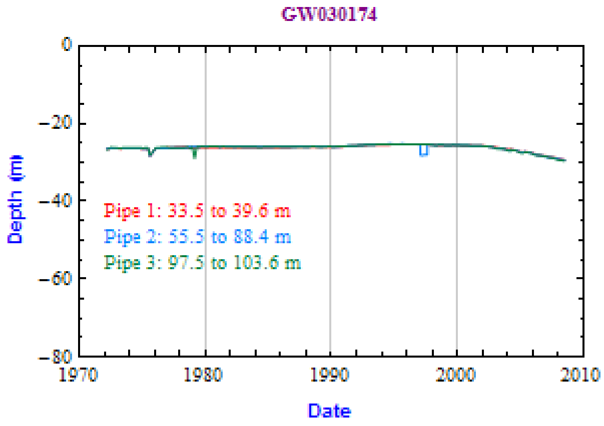

GW030111
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 41.8 to 65.8 m

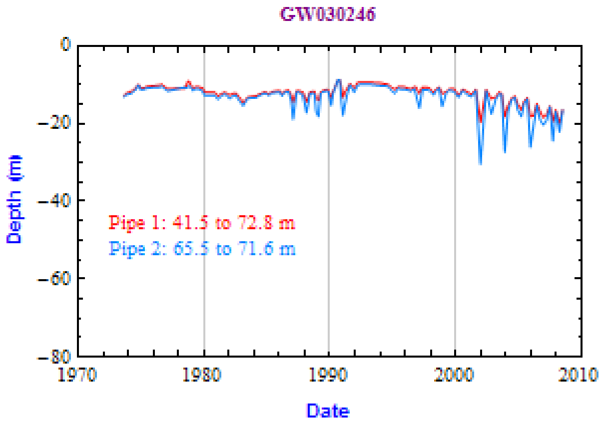

GW030157
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 54.9 to 80.2 m
Pipe 2: 77.4 to 83.5 m
Pipe 3: 105.8 to 111.9 m
Pipe 4: 140.2 to 163.7 m

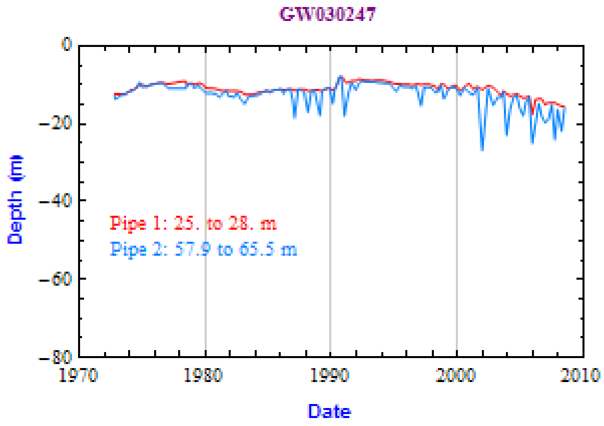

GW030158
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 42.7 to 48.8 m

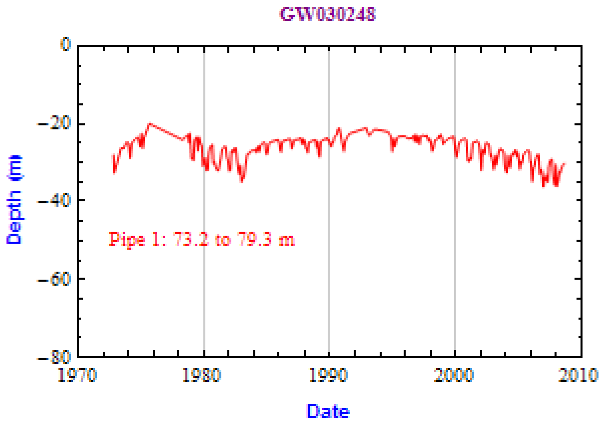

GW030172
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 57.3 to 62.8 m
Pipe 2: 70.1 to 71.6 m

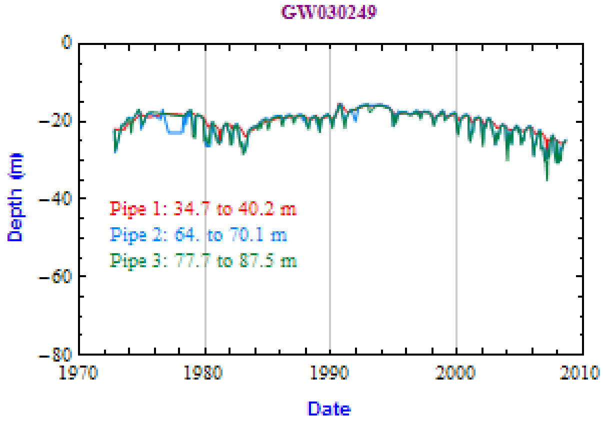

GW030173
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 31.4 to 34.4 m
Pipe 2: 54.9 to 61. m
Pipe 3: 73.2 to 76.2 m

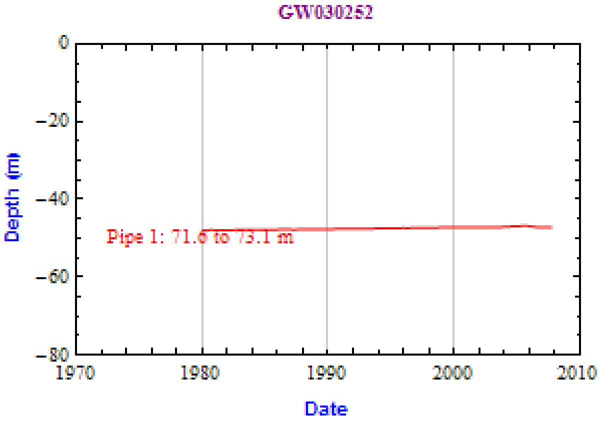

GW030174
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 33.5 to 39.6 m
Pipe 2: 55.5 to 88.4 m
Pipe 3: 97.5 to 103.6 m

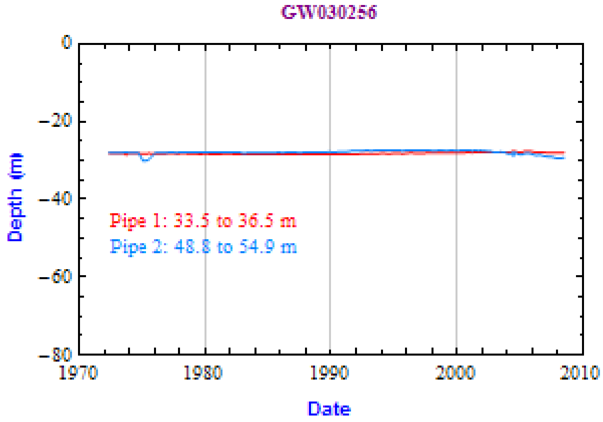

GW030246
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 41.5 to 72.8 m
Pipe 2: 65.5 to 71.6 m

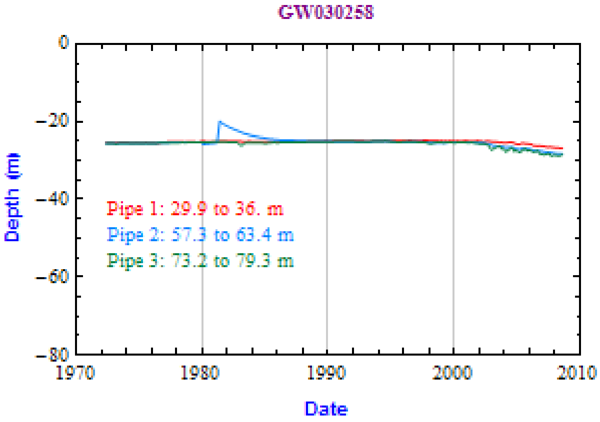

GW030247
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 25. to 28. m
Pipe 2: 57.9 to 65.5 m

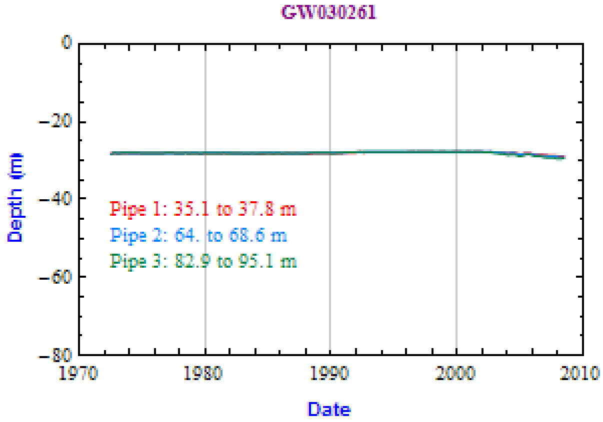

GW030248
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 73.2 to 79.3 m

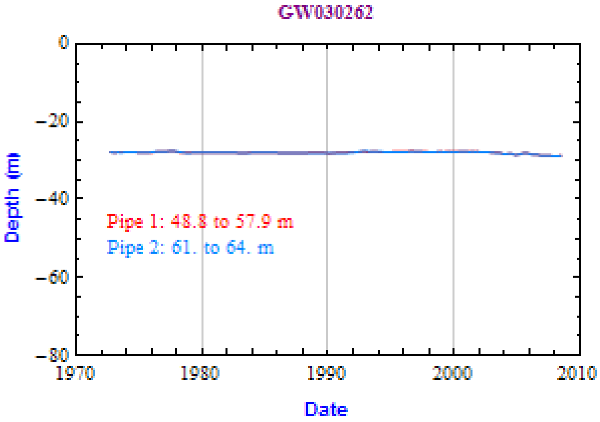

GW030249
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 34.7 to 40.2 m
Pipe 2: 64. to 70.1 m
Pipe 3: 77.7 to 87.5 m
1970
1980
1990
2000
2010
Date

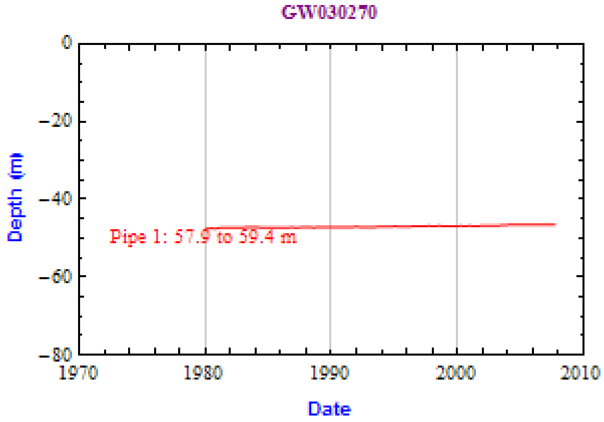

GW030252
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 71.6 to 73.1 m
1970
1980
1990
2000
2010
Date

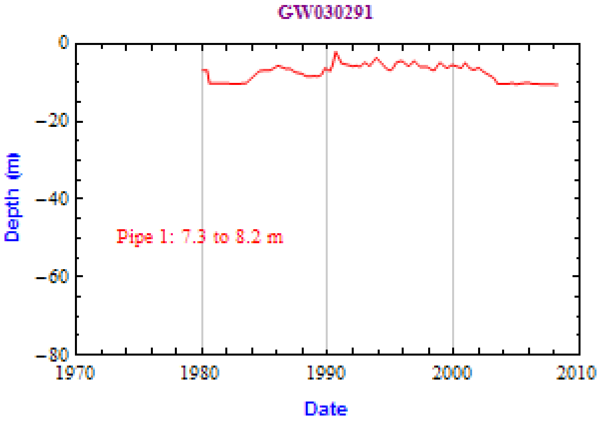

GW030256
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 33.5 to 36.5 m
Pipe 2: 48.8 to 54.9 m
1970
1980
1990
2000
2010
Date

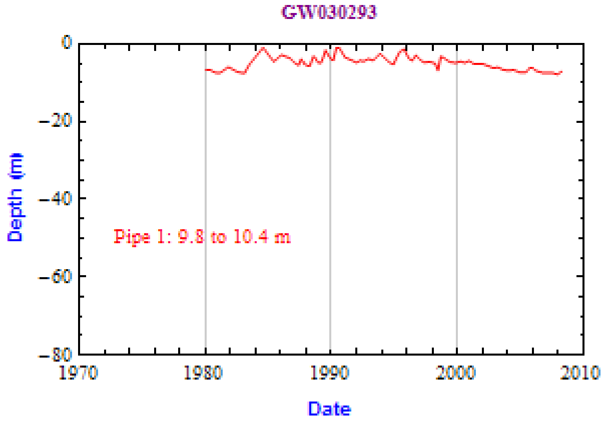

GW030258
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 29.9 to 36. m
Pipe 2: 57.3 to 63.4 m
Pipe 3: 73.2 to 79.3 m
1970
1980
1990
2000
2010
Date

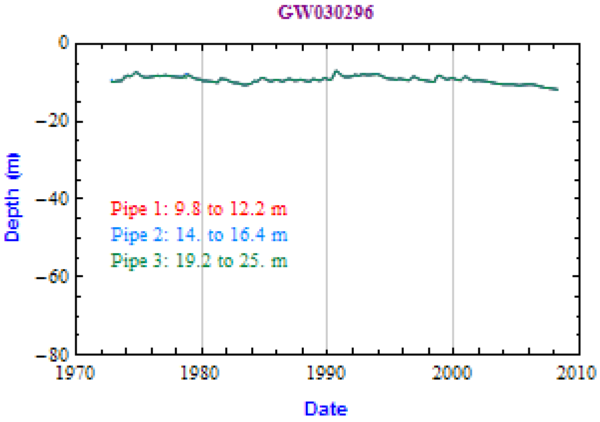

GW030261
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 35.1 to 37.8 m
Pipe 2: 64. to 68.6 m
Pipe 3: 82.9 to 95.1 m
1970
1980
1990
2000
2010
Date

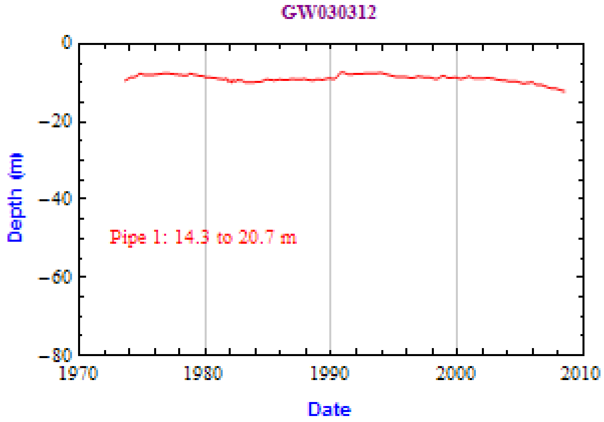

GW030262
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 48.8 to 57.9 m
Pipe 2: 61. to 64. m
1970
1980
1990
2000
2010
Date

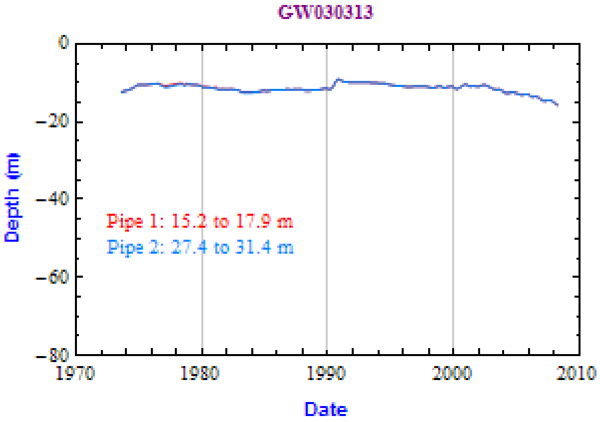

GW030270
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 57.9 to 59.4 m
1970
1980
1990
2000
2010
Date

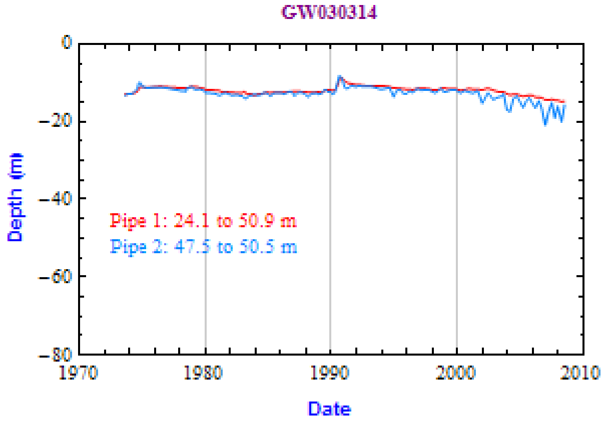

GW030291
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 7.3 to 8.2 m
1970
1980
1990
2000
2010
Date

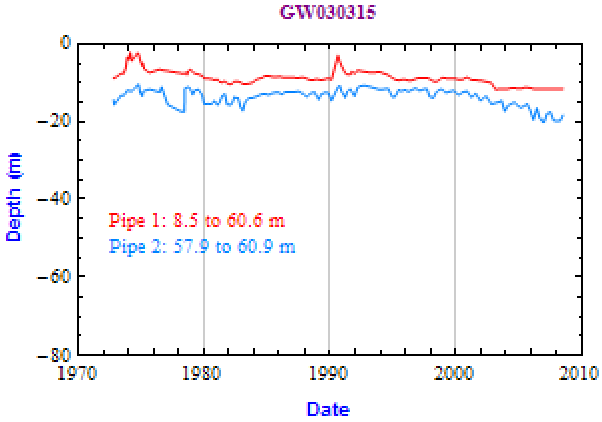

GW030293
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 9.8 to 10.4 m
1970
1980
1990
2000
2010
Date

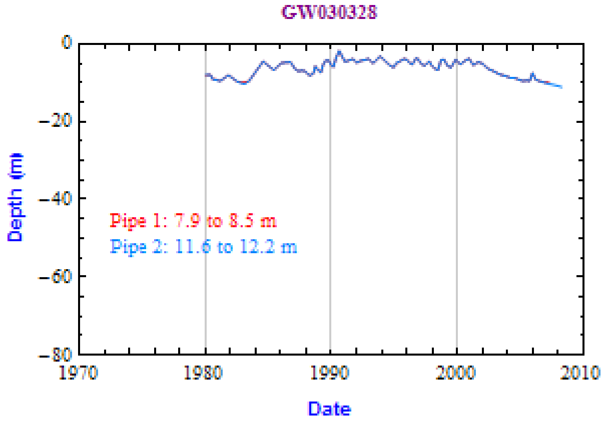

GW030296
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 9.8 to 12.2 m
Pipe 2: 14. to 16.4 m
Pipe 3: 19.2 to 25. m
1970
1980
1990
2000
2010
Date

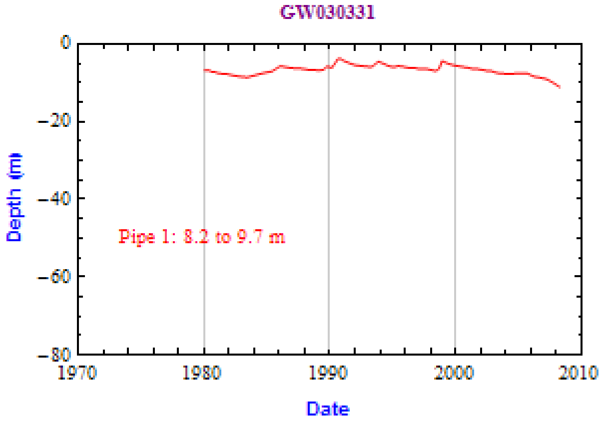

GW030312
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 14.3 to 20.7 m
1970
1980
1990
2000
2010
Date

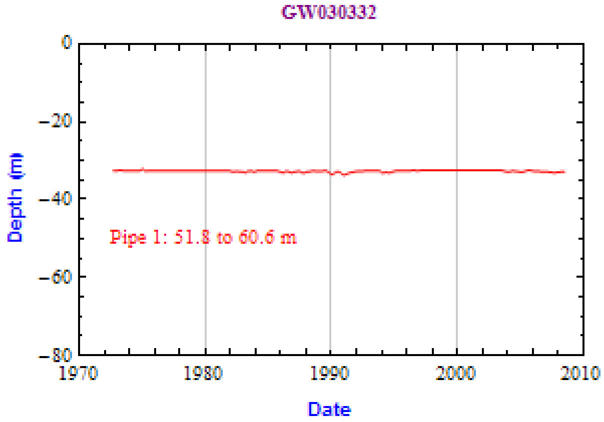

GW030313
Depth (m)
0
−20
−40
−60
−80
Pipe 1: 15.2 to 17.9 m
Pipe 2: 27.4 to 31.4 m
1970
1980
1990
2000
2010
Date

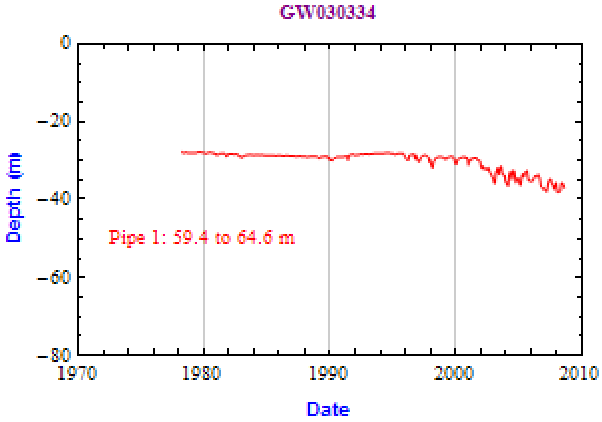

GW030314

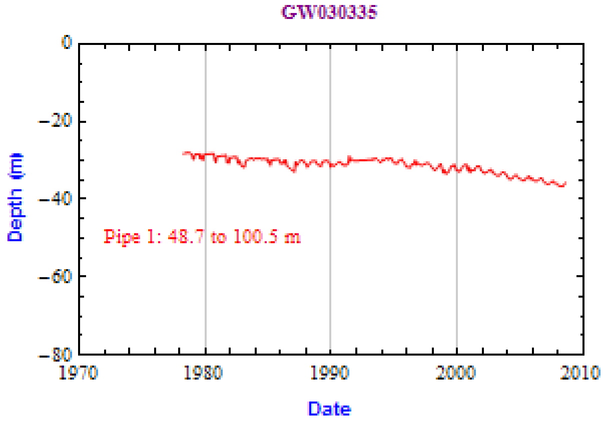

GW030315

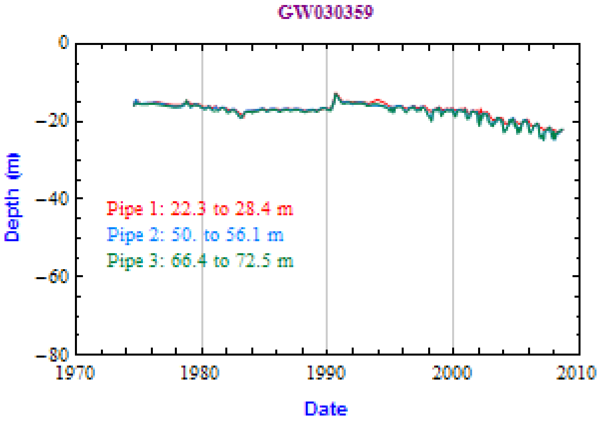

GW030328

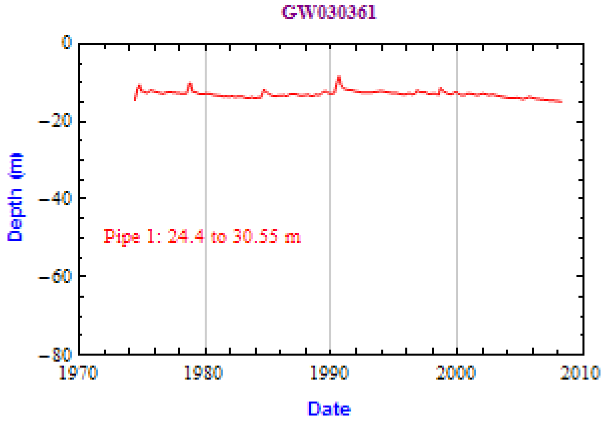

GW030331

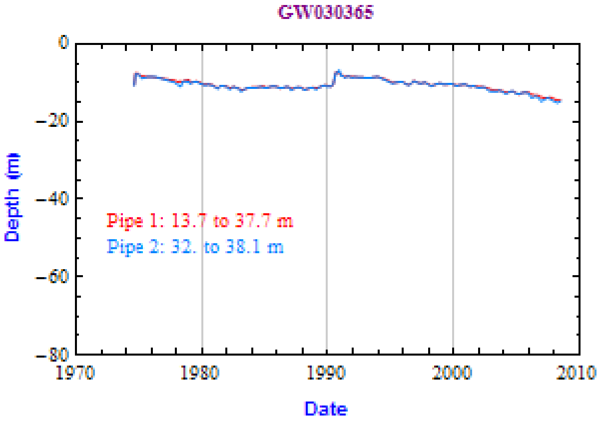

GW030332

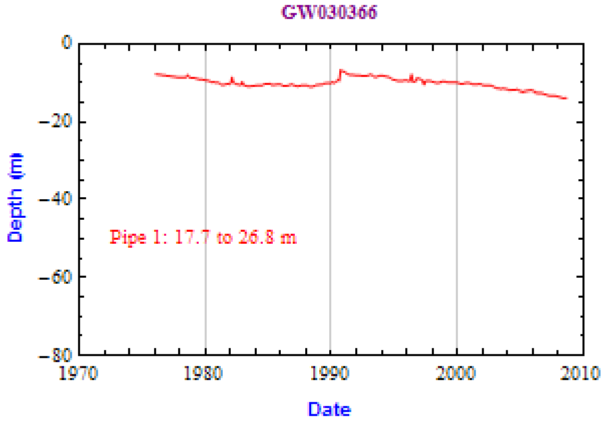

GW030334

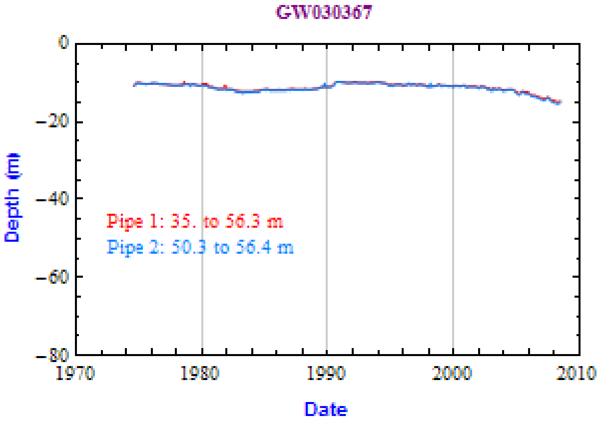

GW030335
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 48.7 to 100.5 m

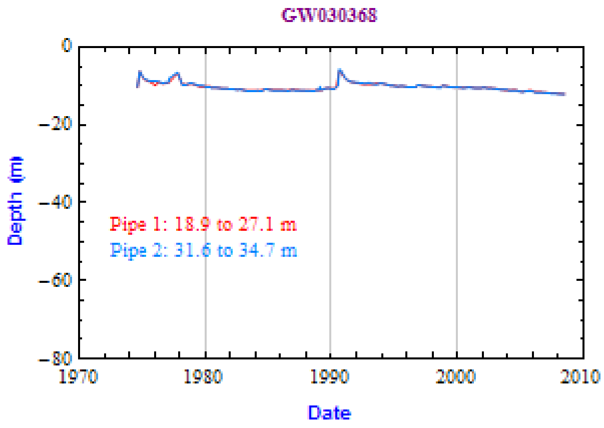

GW030359
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 22.3 to 28.4 m
Pipe 2: 50. to 56.1 m
Pipe 3: 66.4 to 72.5 m

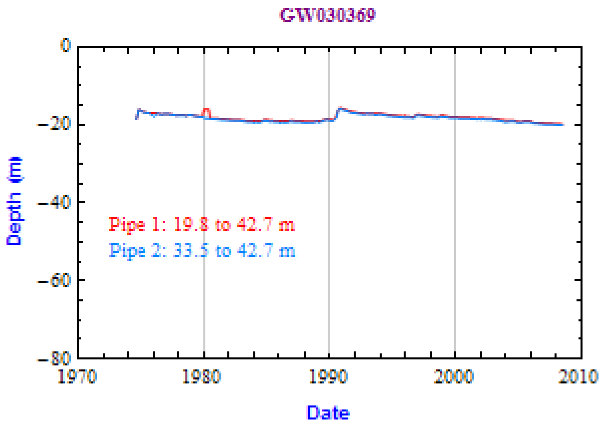

GW030361
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 24.4 to 30.55 m

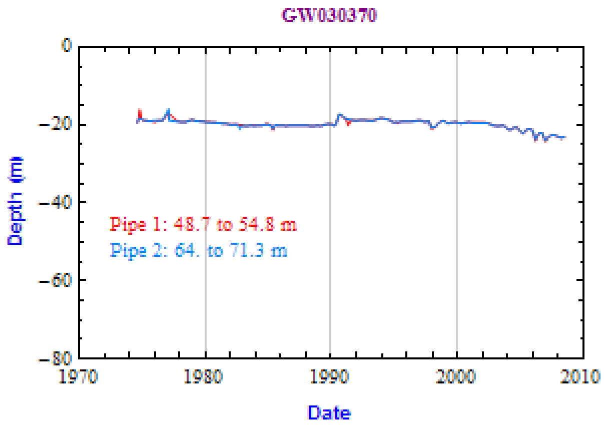

GW030365
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 13.7 to 37.7 m
Pipe 2: 32. to 38.1 m

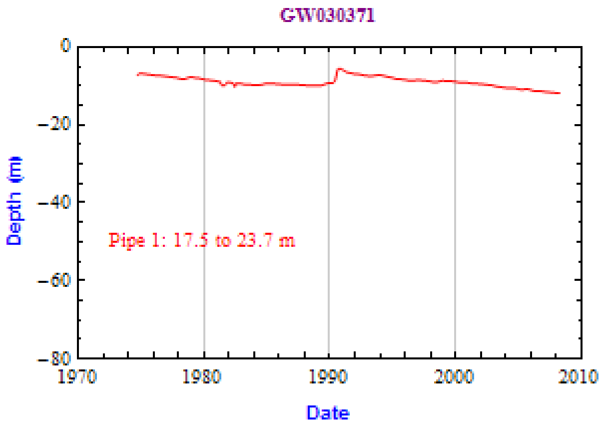

GW030366
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 17.7 to 26.8 m

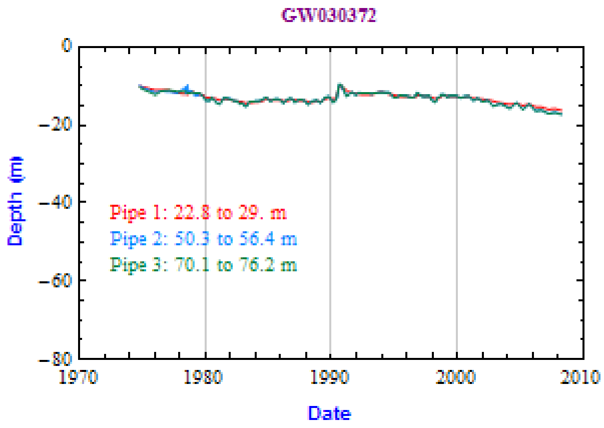

GW030367
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 35. to 56.3 m
Pipe 2: 50.3 to 56.4 m

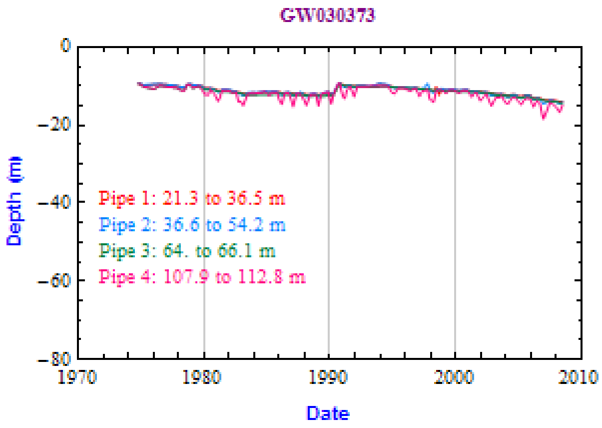

GW030368
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 18.9 to 27.1 m
Pipe 2: 31.6 to 34.7 m
1970
1980
1990
2000
2010
Date

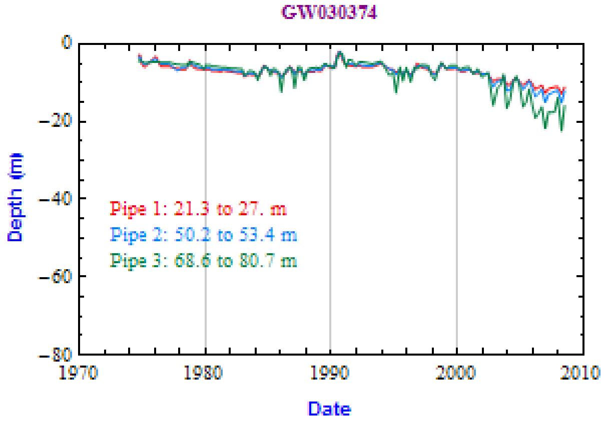

GW030369
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 19.8 to 42.7 m
Pipe 2: 33.5 to 42.7 m
1970
1980
1990
2000
2010
Date

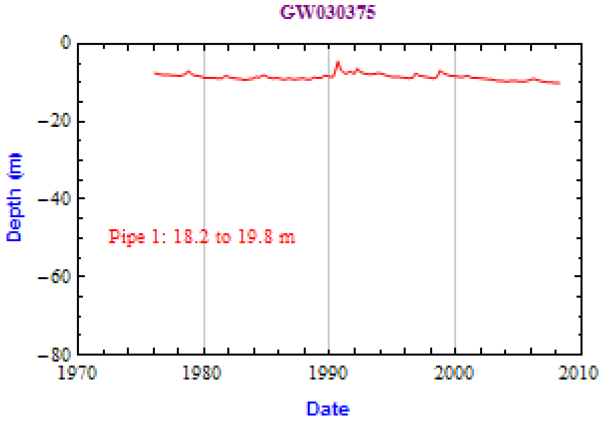

GW030370
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 48.7 to 54.8 m
Pipe 2: 64. to 71.3 m
1970
1980
1990
2000
2010
Date

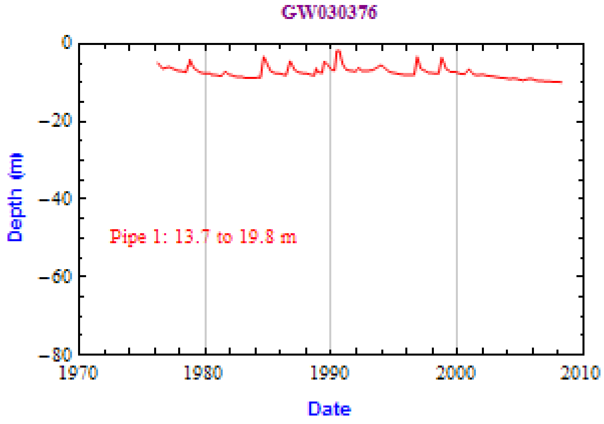

GW030371
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 17.5 to 23.7 m
1970
1980
1990
2000
2010
Date

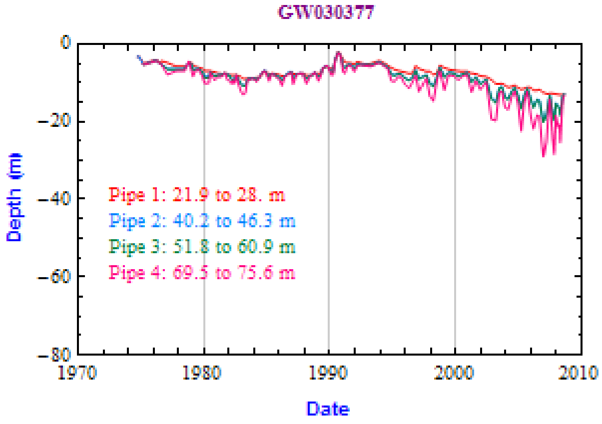

GW030372
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 22.8 to 29. m
Pipe 2: 50.3 to 56.4 m
Pipe 3: 70.1 to 76.2 m
1970
1980
1990
2000
2010
Date

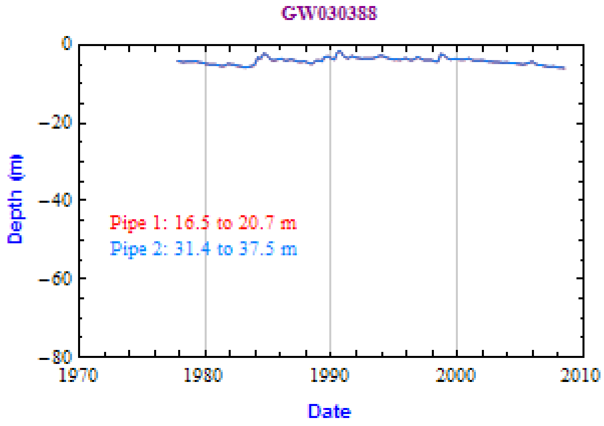

GW030373
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 21.3 to 36.5 m
Pipe 2: 36.6 to 54.2 m
Pipe 3: 64. to 66.1 m
Pipe 4: 107.9 to 112.8 m
1970
1980
1990
2000
2010
Date

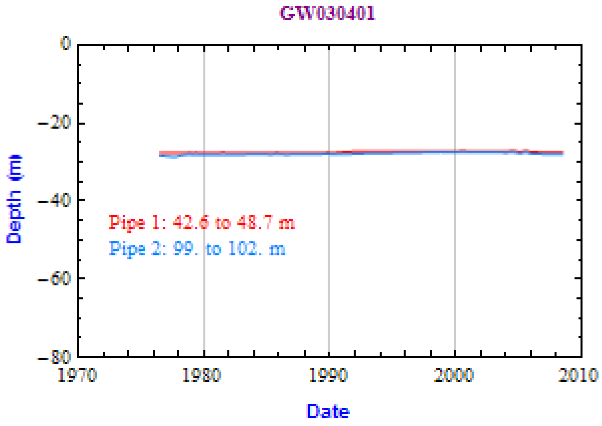

GW030374
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 21.3 to 27. m
Pipe 2: 50.2 to 53.4 m
Pipe 3: 68.6 to 80.7 m

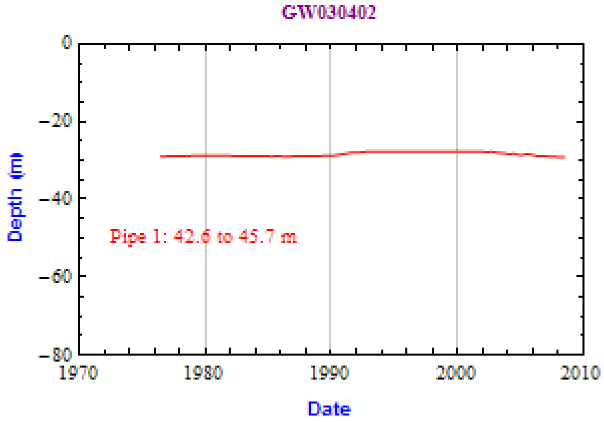

GW030375
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 18.2 to 19.8 m

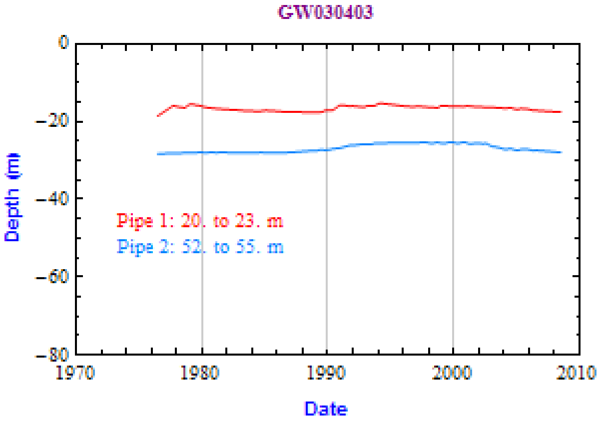

GW030376
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 13.7 to 19.8 m

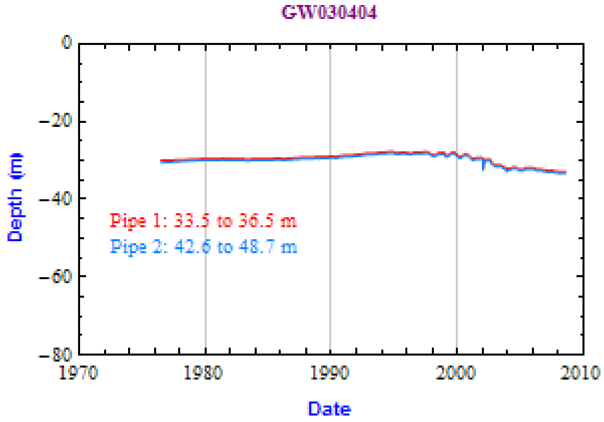

GW030377
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 21.9 to 28. m
Pipe 2: 40.2 to 46.3 m
Pipe 3: 51.8 to 60.9 m
Pipe 4: 69.5 to 75.6 m

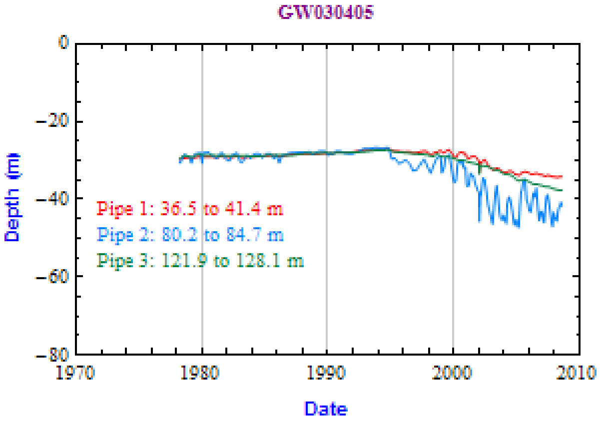

GW030388
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 16.5 to 20.7 m
Pipe 2: 31.4 to 37.5 m

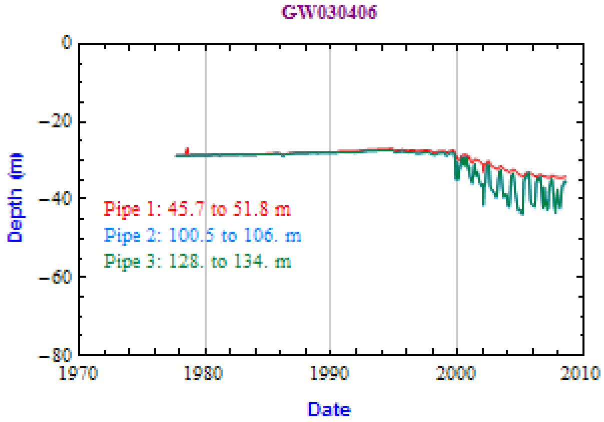

GW030401
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 42.6 to 48.7 m
Pipe 2: 99. to 102. m

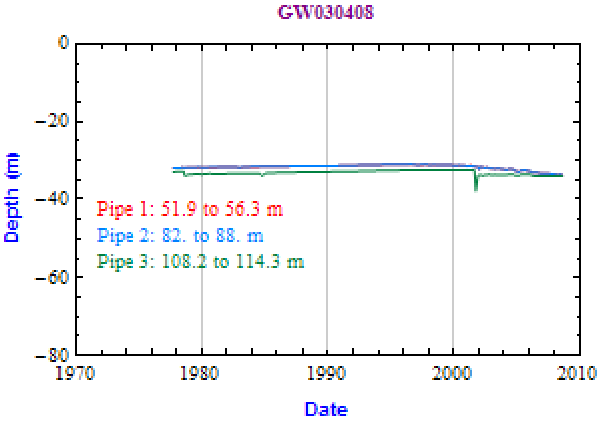

GW030402
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 42.6 to 45.7 m
1970
1980
1990
2000
2010
Date


GW030403
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 20. to 23. m
Pipe 2: 52. to 55. m
1970
1980
1990
2000
2010
Date

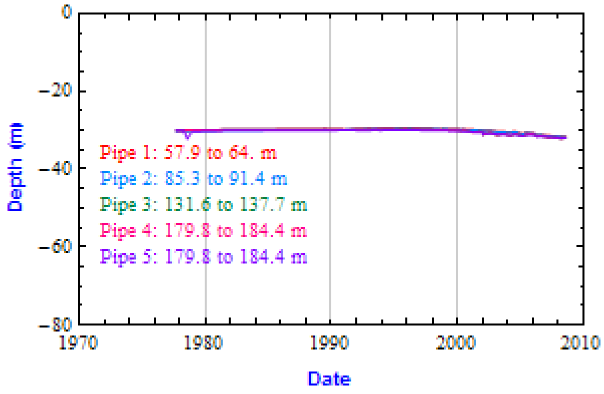

GW030404
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 33.5 to 36.5 m
Pipe 2: 42.6 to 48.7 m
1970
1980
1990
2000
2010
Date


GW030405
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 36.5 to 41.4 m
Pipe 2: 80.2 to 84.7 m
Pipe 3: 121.9 to 128.1 m
1970
1980
1990
2000
2010
Date

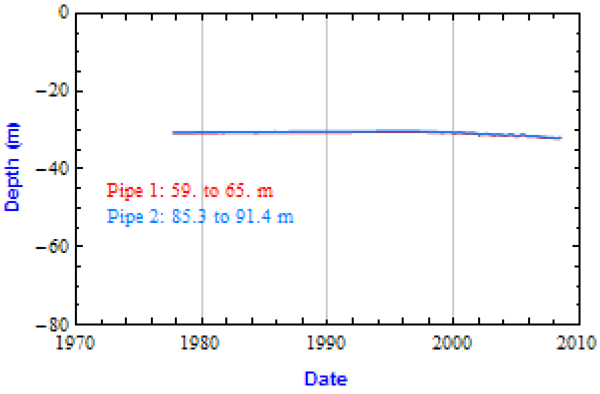

GW030406
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 45.7 to 51.8 m
Pipe 2: 100.5 to 106. m
Pipe 3: 128. to 134. m
1970
1980
1990
2000
2010
Date


GW030408
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 51.9 to 56.3 m
Pipe 2: 82. to 88. m
Pipe 3: 108.2 to 114.3 m
1970
1980
1990
2000
2010
Date

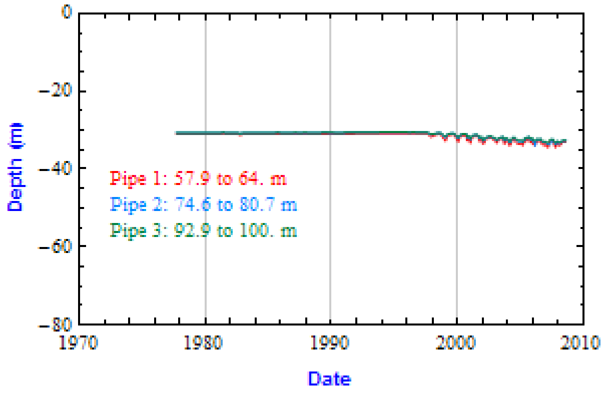
GW030409



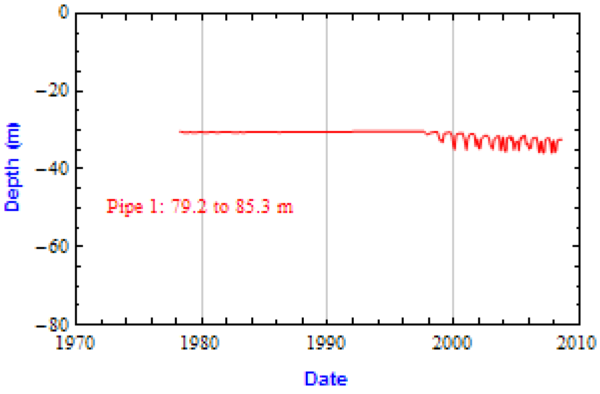
GW030410



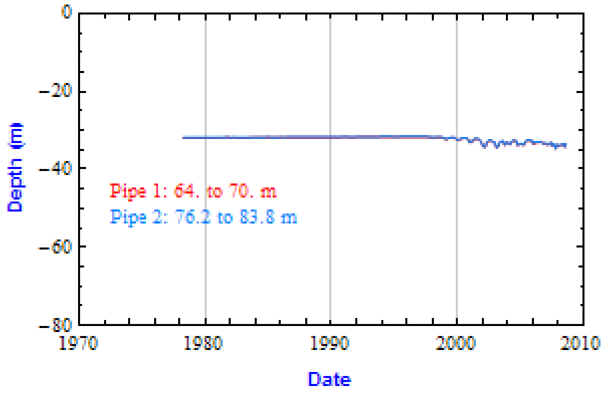
GW030411



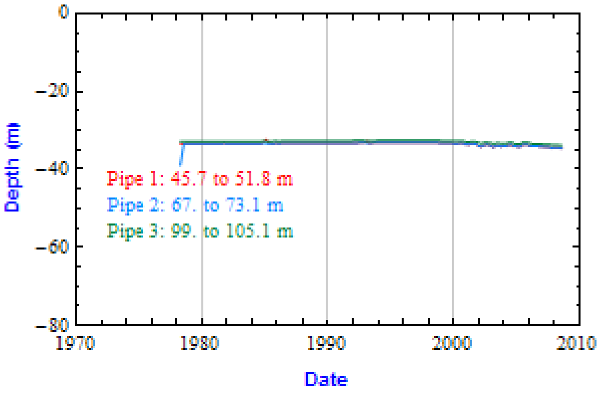
GW030412

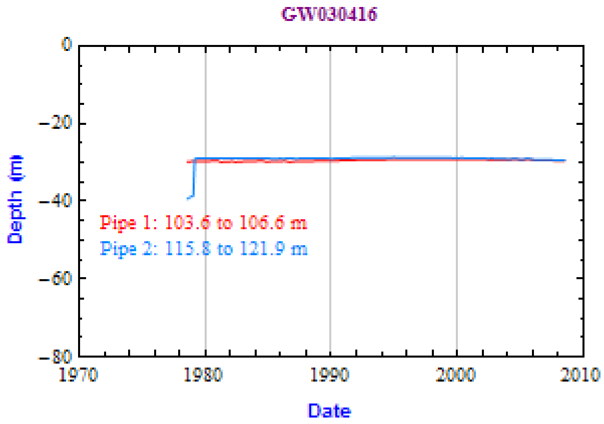


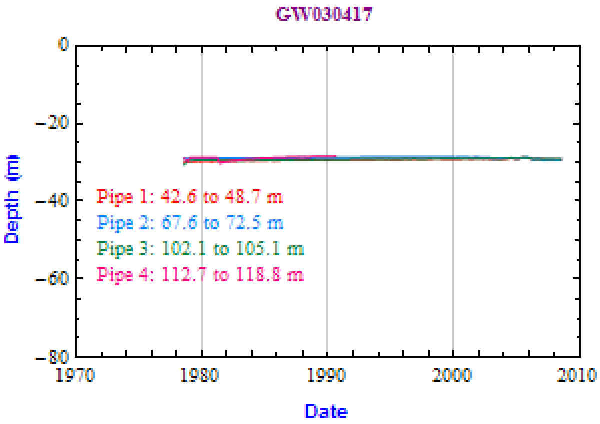
GW030413

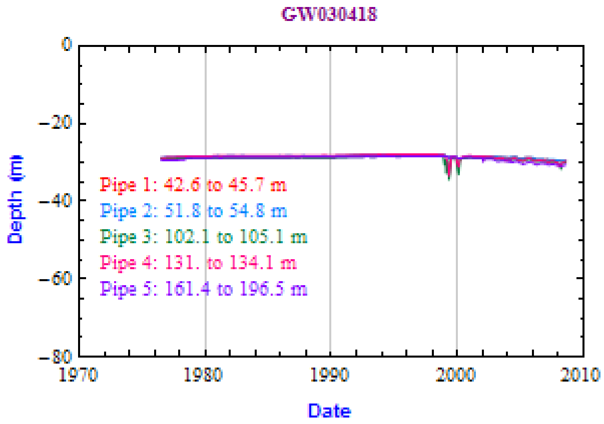


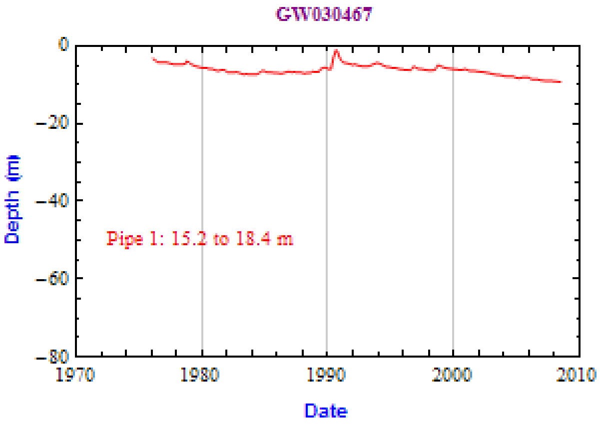
GW030414

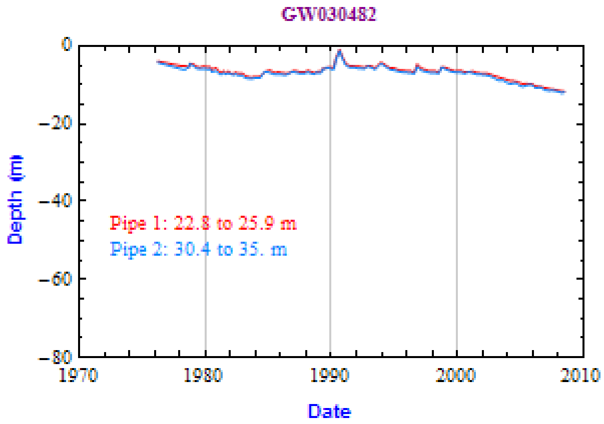


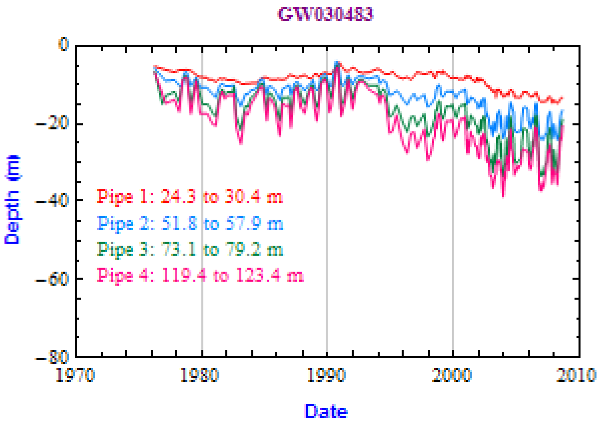

GW030416
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 103.6 to 106.6 m
Pipe 2: 115.8 to 121.9 m

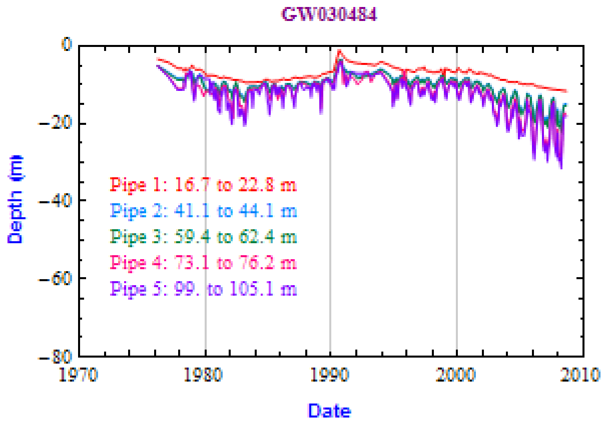

GW030417
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 42.6 to 48.7 m
Pipe 2: 67.6 to 72.5 m
Pipe 3: 102.1 to 105.1 m
Pipe 4: 112.7 to 118.8 m

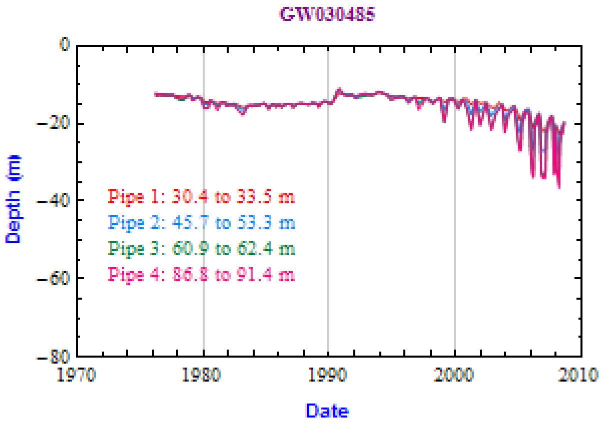

GW030418
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 42.6 to 45.7 m
Pipe 2: 51.8 to 54.8 m
Pipe 3: 102.1 to 105.1 m
Pipe 4: 131. to 134.1 m
Pipe 5: 161.4 to 196.5 m

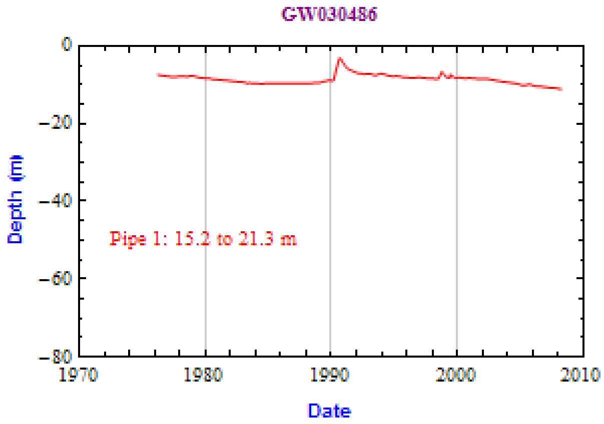

GW030467
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 15.2 to 18.4 m

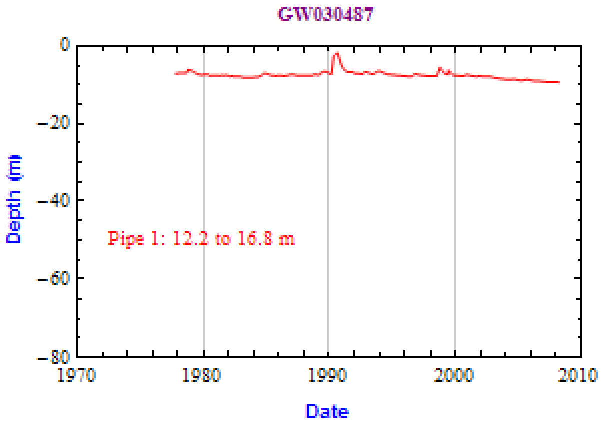

GW030482
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 22.8 to 25.9 m
Pipe 2: 30.4 to 35. m

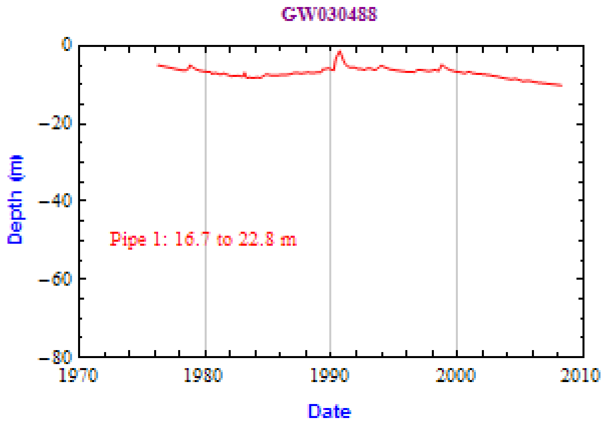

GW030483
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 24.3 to 30.4 m
Pipe 2: 51.8 to 57.9 m
Pipe 3: 73.1 to 79.2 m
Pipe 4: 119.4 to 123.4 m

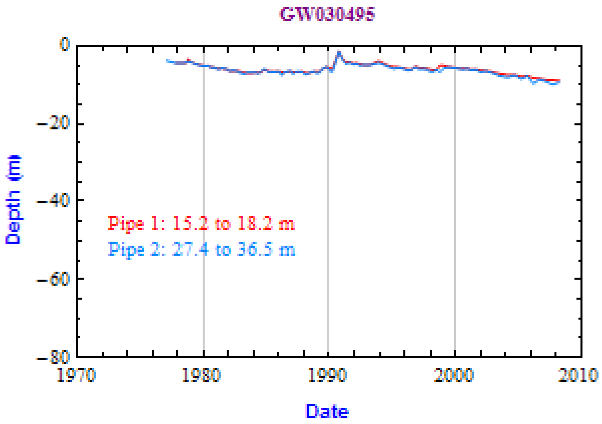

GW030484
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 16.7 to 22.8 m
Pipe 2: 41.1 to 44.1 m
Pipe 3: 59.4 to 62.4 m
Pipe 4: 73.1 to 76.2 m
Pipe 5: 99. to 105.1 m

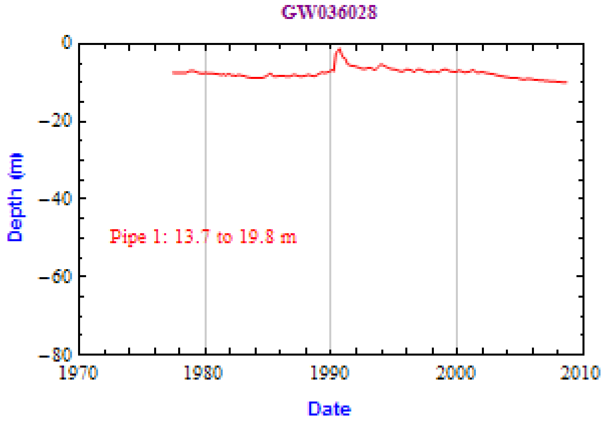

GW030485
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 30.4 to 33.5 m
Pipe 2: 45.7 to 53.3 m
Pipe 3: 60.9 to 62.4 m
Pipe 4: 86.8 to 91.4 m

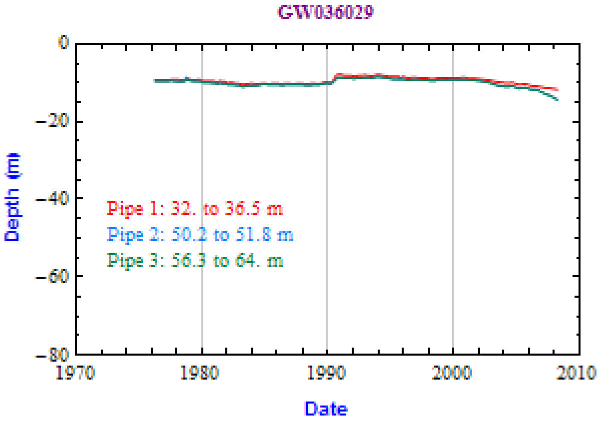

GW030486
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 15.2 to 21.3 m

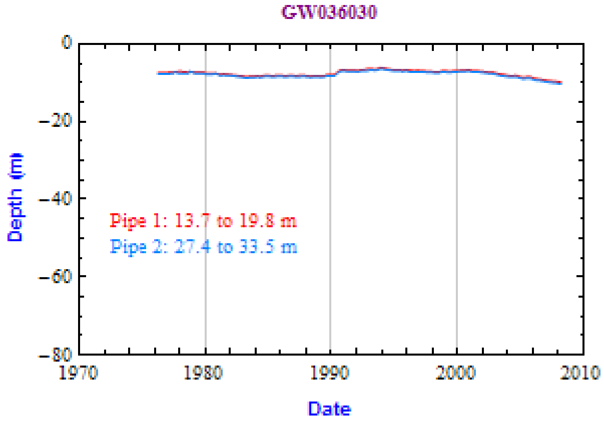

GW030487
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 12.2 to 16.8 m

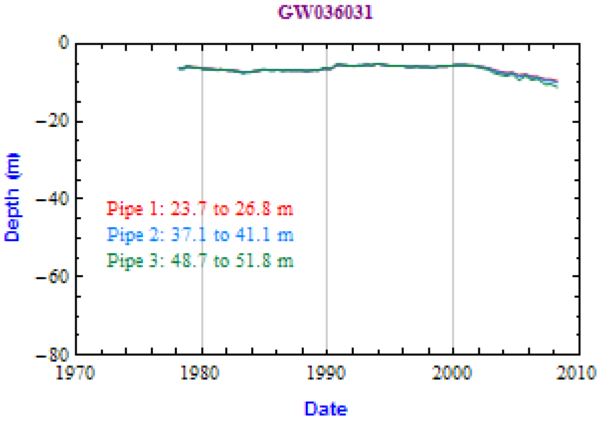

GW030488
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 16.7 to 22.8 m

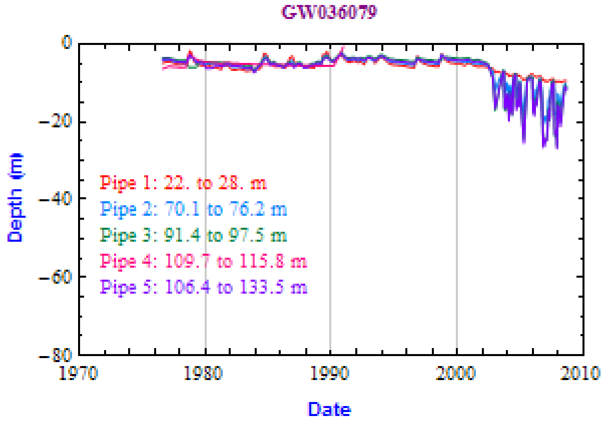

GW030495
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 15.2 to 18.2 m
Pipe 2: 27.4 to 36.5 m

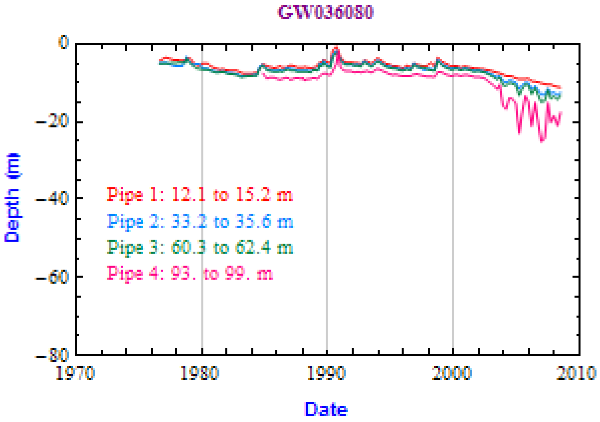

GW036028
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 13.7 to 19.8 m
1970
1980
1990
2000
2010
Date

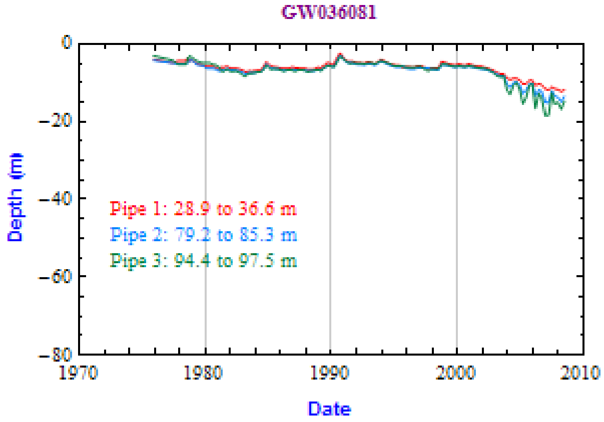

GW036029
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 32. to 36.5 m
Pipe 2: 50.2 to 51.8 m
Pipe 3: 56.3 to 64. m
1970
1980
1990
2000
2010
Date

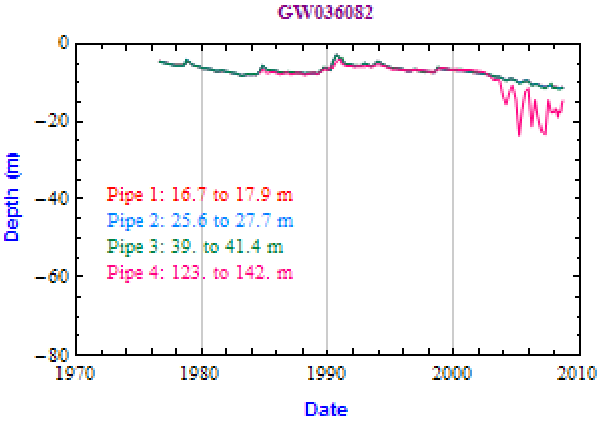

GW036030
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 13.7 to 19.8 m
Pipe 2: 27.4 to 33.5 m
1970
1980
1990
2000
2010
Date

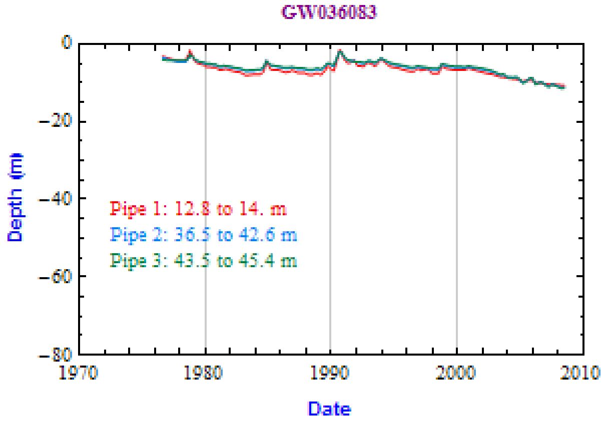

GW036031
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 23.7 to 26.8 m
Pipe 2: 37.1 to 41.1 m
Pipe 3: 48.7 to 51.8 m
1970
1980
1990
2000
2010
Date


GW036079
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 22. to 28. m
Pipe 2: 70.1 to 76.2 m
Pipe 3: 91.4 to 97.5 m
Pipe 4: 109.7 to 115.8 m
Pipe 5: 106.4 to 133.5 m
1970
1980
1990
2000
2010
Date


GW036080
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 12.1 to 15.2 m
Pipe 2: 33.2 to 35.6 m
Pipe 3: 60.3 to 62.4 m
Pipe 4: 93. to 99. m
1970
1980
1990
2000
2010
Date


GW036081
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 28.9 to 36.6 m
Pipe 2: 79.2 to 85.3 m
Pipe 3: 94.4 to 97.5 m


GW036082
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 16.7 to 17.9 m
Pipe 2: 25.6 to 27.7 m
Pipe 3: 39. to 41.4 m
Pipe 4: 123. to 142. m


GW036083
Depth (m)
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−20
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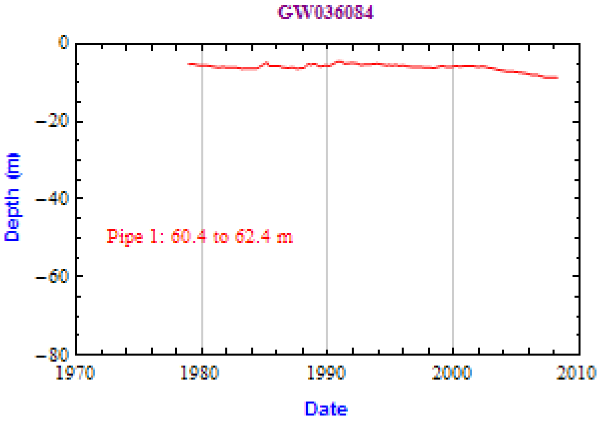
1970
1980
1990
2000
2010
Date
Pipe 1: 12.8 to 14. m
Pipe 2: 36.5 to 42.6 m
Pipe 3: 43.5 to 45.4 m


GW036084
Depth (m)
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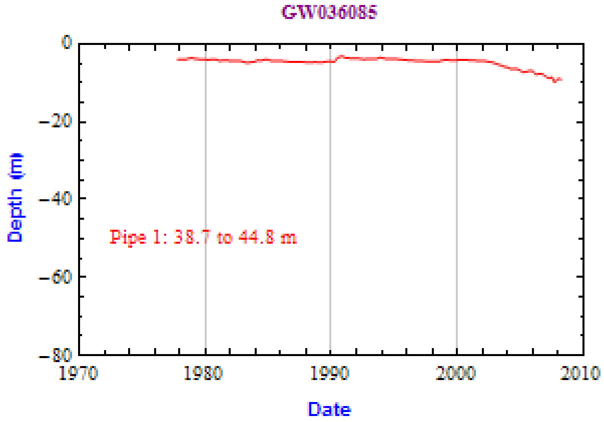
1970
1980
1990
2000
2010
Date
Pipe 1: 60.4 to 62.4 m


GW036085
Depth (m)
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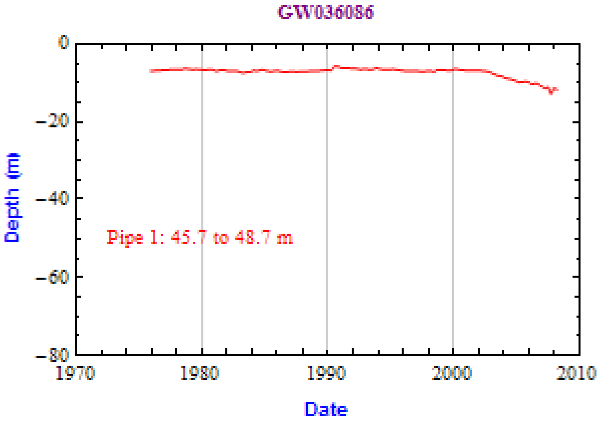
1970
1980
1990
2000
2010
Date
Pipe 1: 38.7 to 44.8 m


GW036086
Depth (m)
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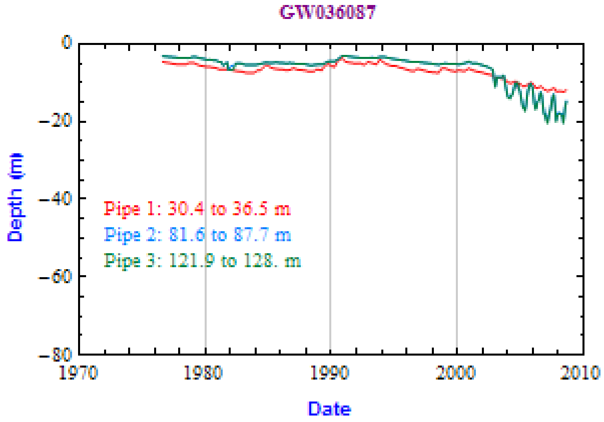
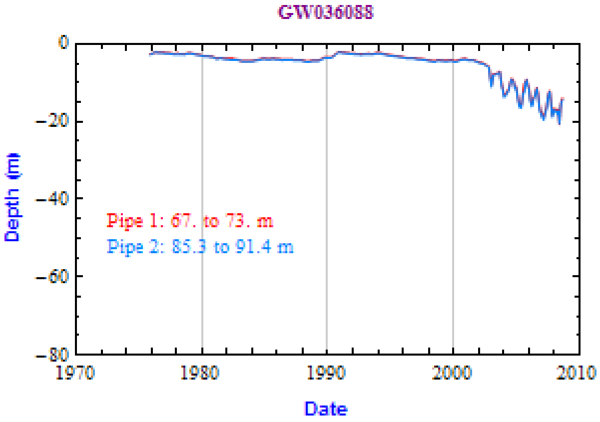
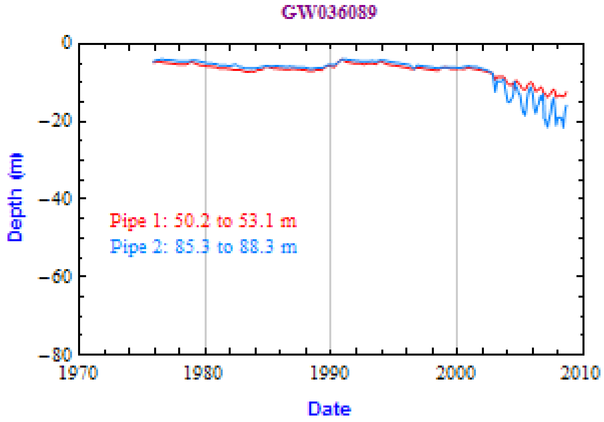
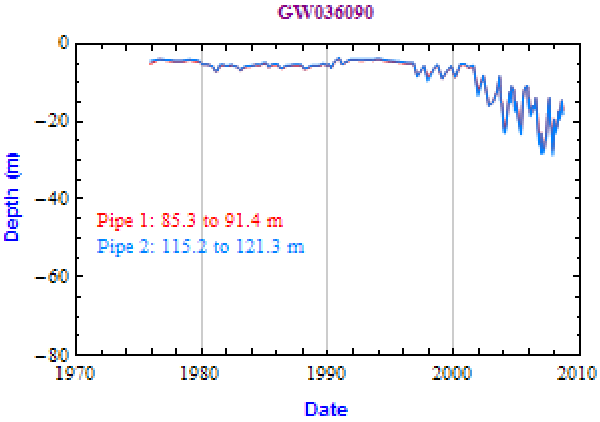
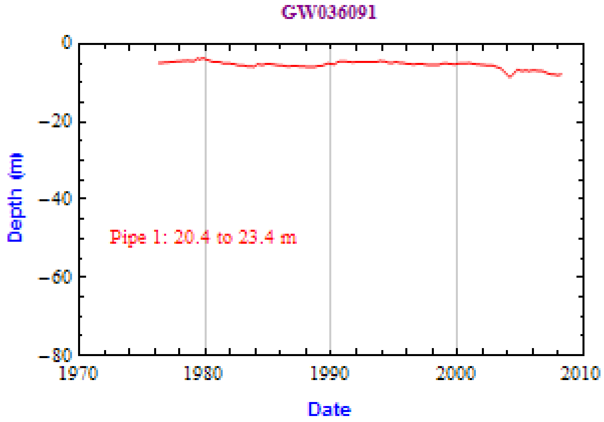
1970
1980
1990
2000
2010
Date
Pipe 1: 45.7 to 48.7 m

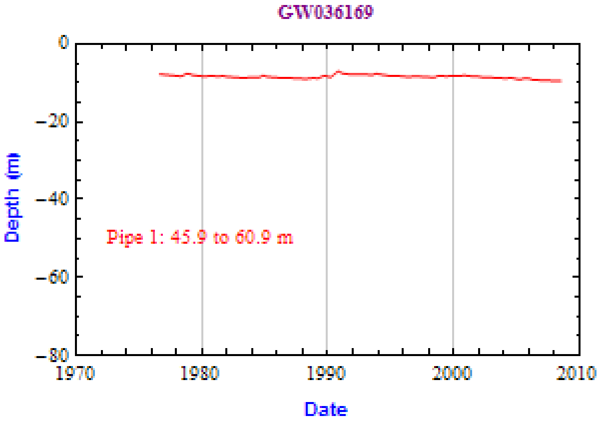

GW036087

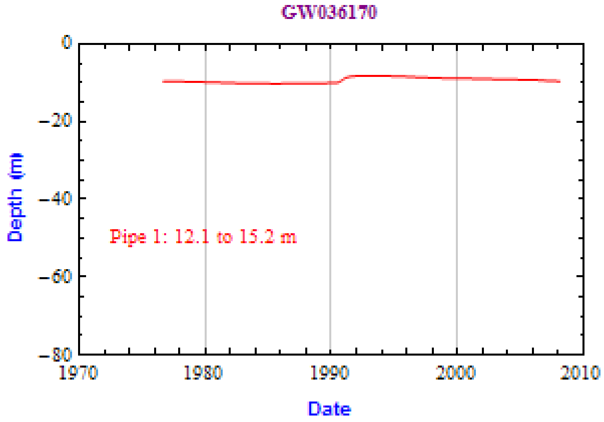

GW036088

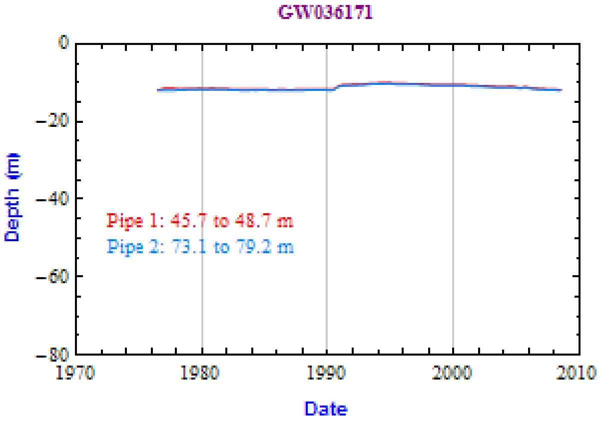

GW036089

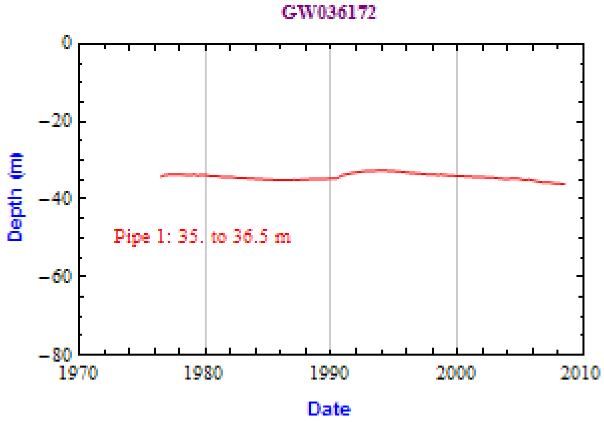

GW036090


GW036091


GW036169


GW036170
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 12.1 to 15.2 m
1970
1980
1990
2000
2010
Date


GW036171
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 45.7 to 48.7 m
Pipe 2: 73.1 to 79.2 m
1970
1980
1990
2000
2010
Date


GW036172
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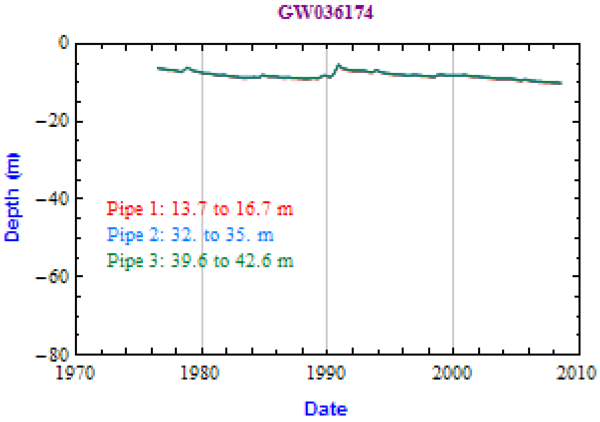
−60
−80
Depth (m)
Pipe 1: 35. to 36.5 m
1970
1980
1990
2000
2010
Date


GW036174
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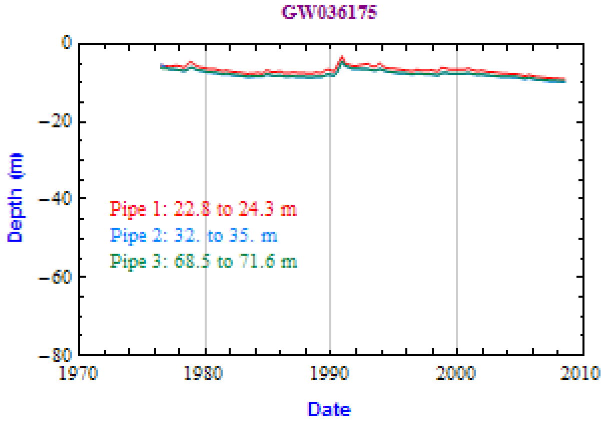
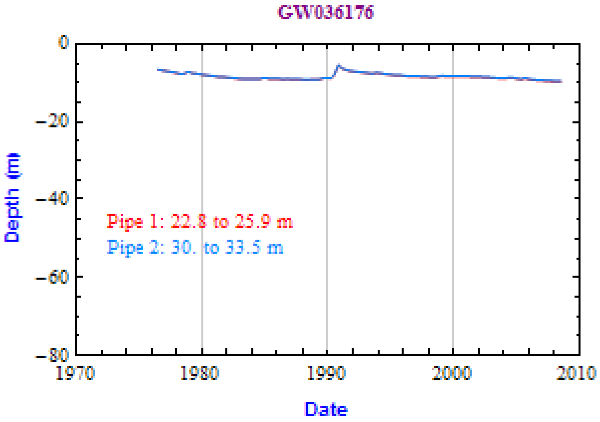
−20
−40
−60
−80
Depth (m)
Pipe 1: 13.7 to 16.7 m
Pipe 2: 32. to 35. m
Pipe 3: 39.6 to 42.6 m
1970
1980
1990
2000
2010
Date


GW036175
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 22.8 to 24.3 m
Pipe 2: 32. to 35. m
Pipe 3: 68.5 to 71.6 m
1970
1980
1990
2000
2010
Date


GW036176
0
−20
−40
−60
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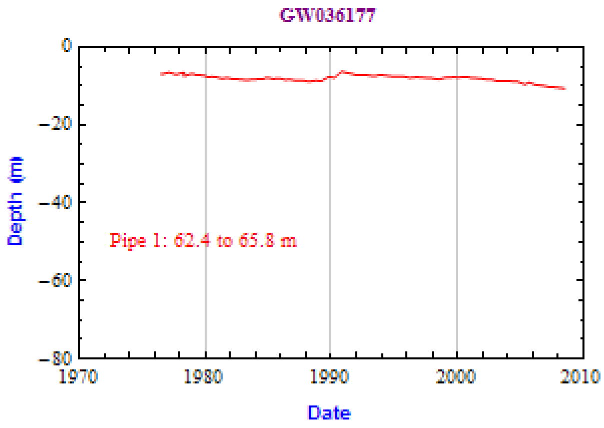
Depth (m)
Pipe 1: 22.8 to 25.9 m
Pipe 2: 30. to 33.5 m
1970
1980
1990
2000
2010
Date


GW036177
0
−20
−40
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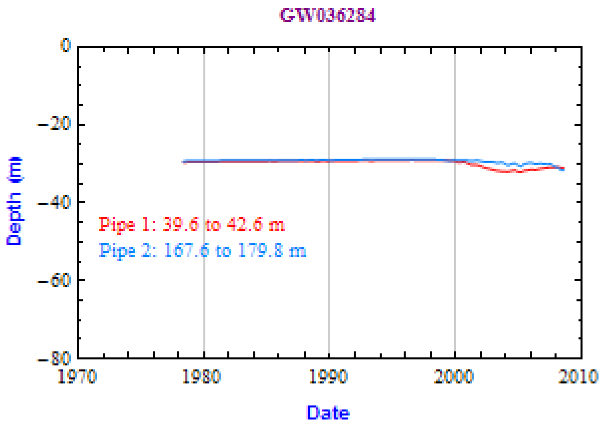
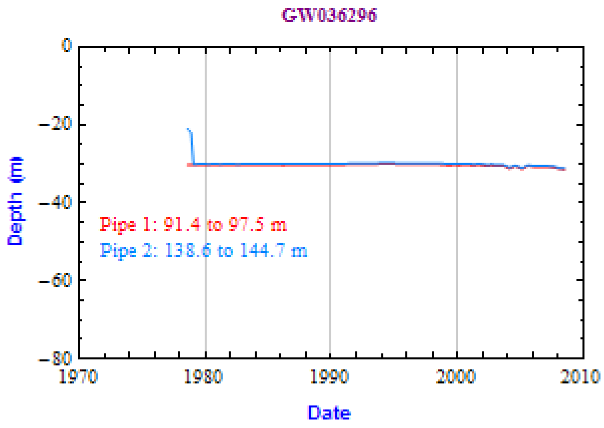
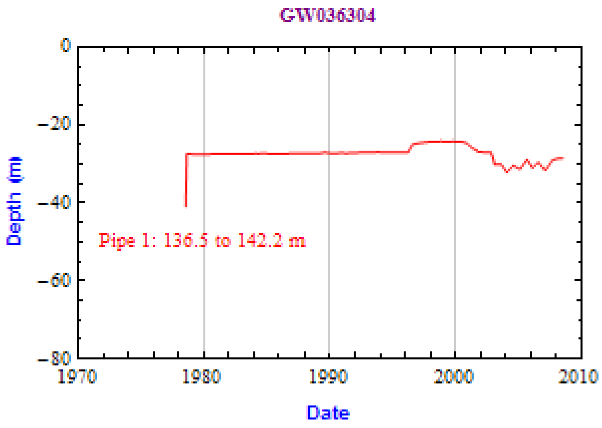
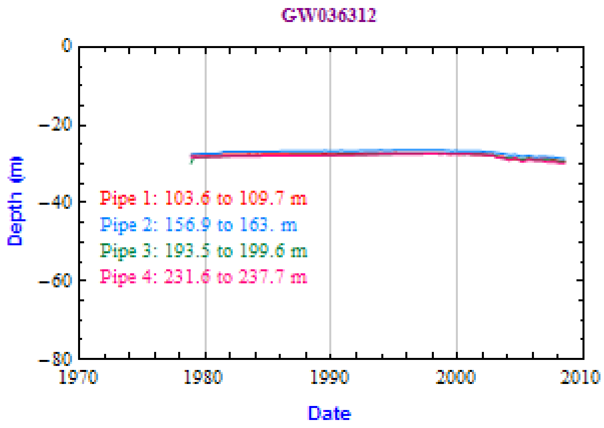
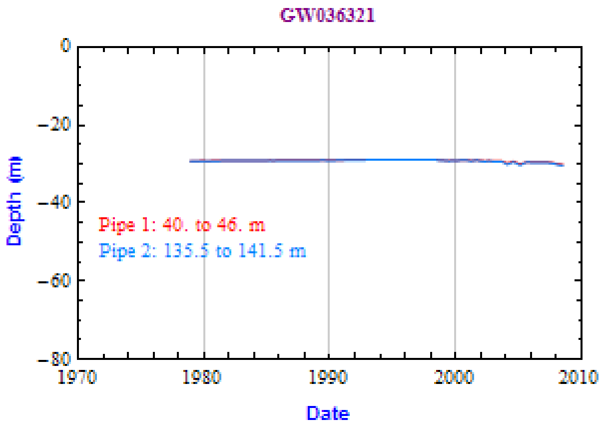
−80
Depth (m)
Pipe 1: 62.4 to 65.8 m
1970
1980
1990
2000
2010
Date

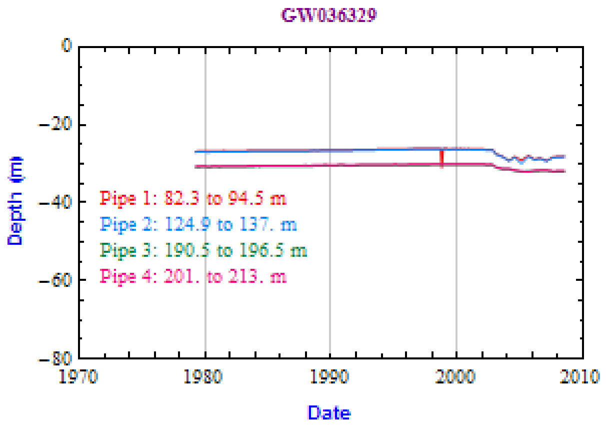

GW036284
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 39.6 to 42.6 m
Pipe 2: 167.6 to 179.8 m
1970
1980
1990
2000
2010
Date


GW036296
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 91.4 to 97.5 m
Pipe 2: 138.6 to 144.7 m
1970
1980
1990
2000
2010
Date


GW036304
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 136.5 to 142.2 m
1970
1980
1990
2000
2010
Date


GW036312
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 103.6 to 109.7 m
Pipe 2: 156.9 to 163. m
Pipe 3: 193.5 to 199.6 m
Pipe 4: 231.6 to 237.7 m
1970
1980
1990
2000
2010
Date


GW036321
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 40. to 46. m
Pipe 2: 135.5 to 141.5 m
1970
1980
1990
2000
2010
Date


GW036329
Depth (m)
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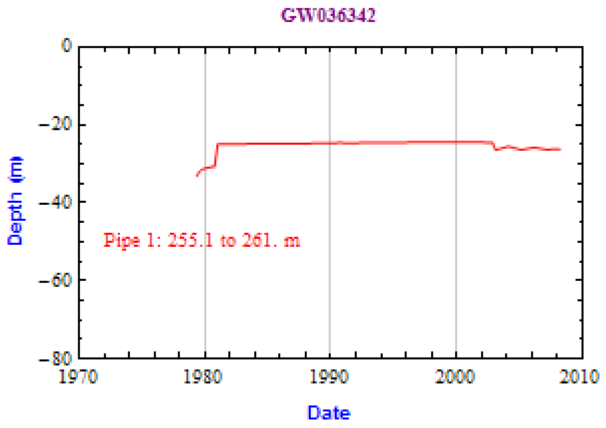
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 82.3 to 94.5 m
Pipe 2: 124.9 to 137. m
Pipe 3: 190.5 to 196.5 m
Pipe 4: 201. to 213. m


GW036342
Depth (m)
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−20
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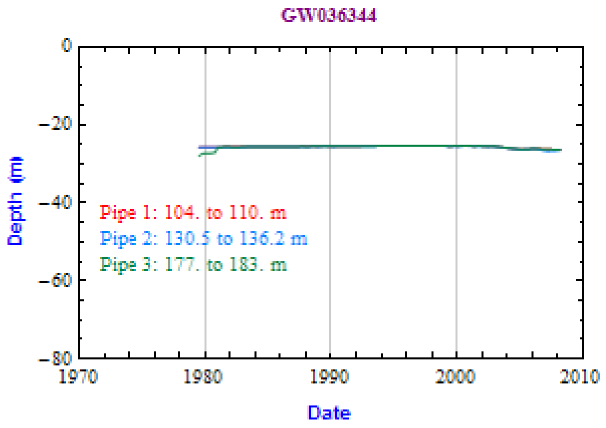
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 255.1 to 261. m


GW036344
Depth (m)
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−20
−40
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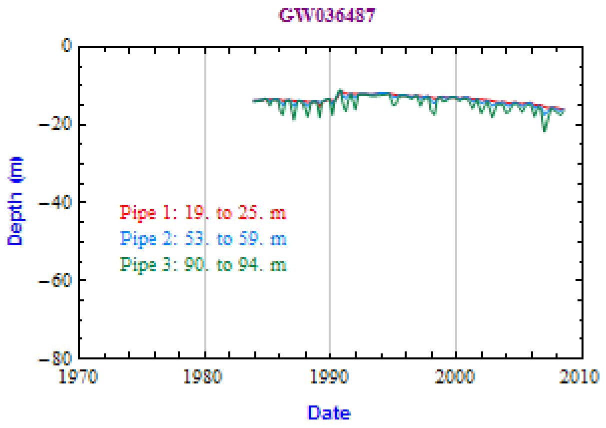
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 104. to 110. m
Pipe 2: 130.5 to 136.2 m
Pipe 3: 177. to 183. m


GW036487
Depth (m)
0
−20
−40
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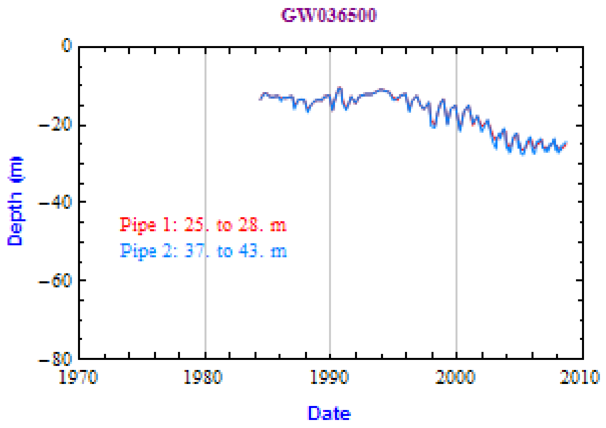
1970
1980
1990
2000
2010
Date
Pipe 1: 19. to 25. m
Pipe 2: 53. to 59. m
Pipe 3: 90. to 94. m


GW036500
Depth (m)
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−40
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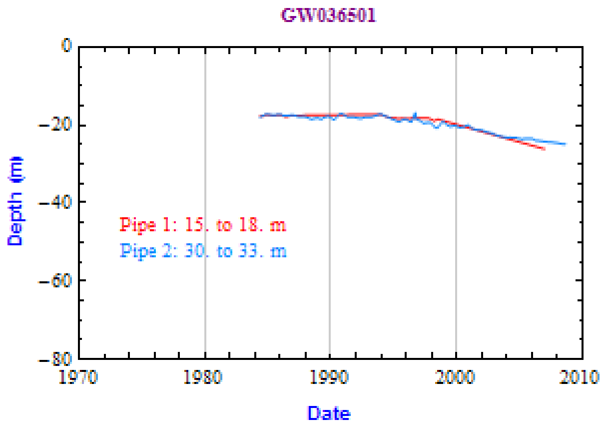
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 25. to 28. m
Pipe 2: 37. to 43. m


GW036501
Depth (m)
0
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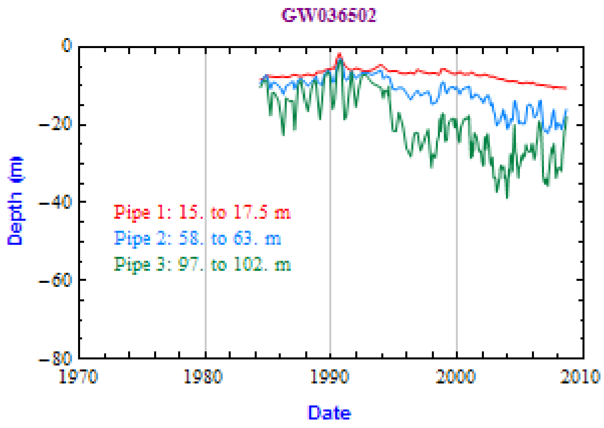
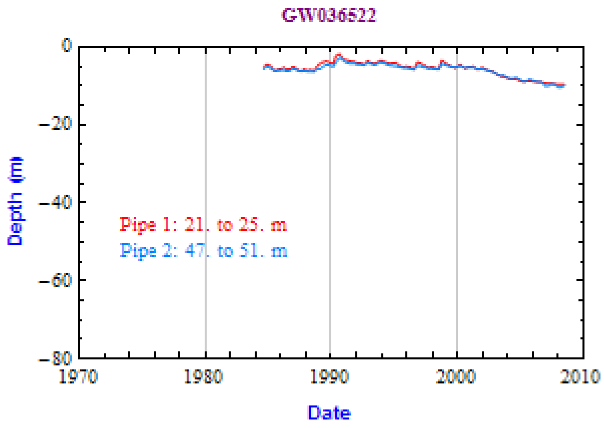
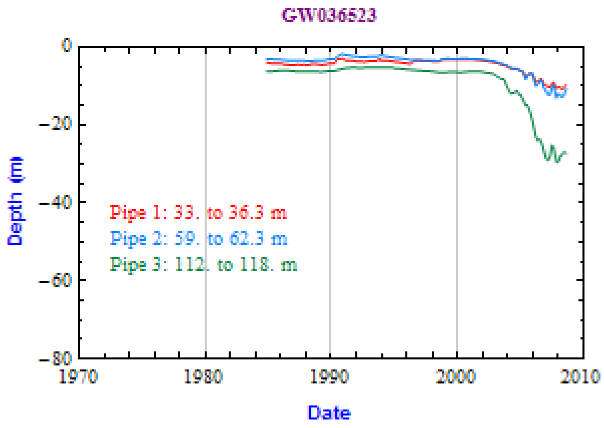
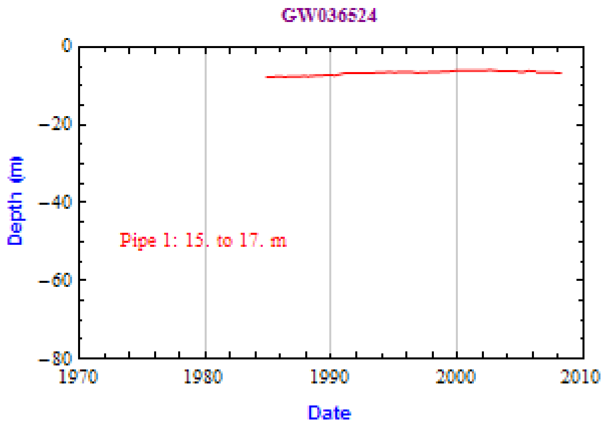
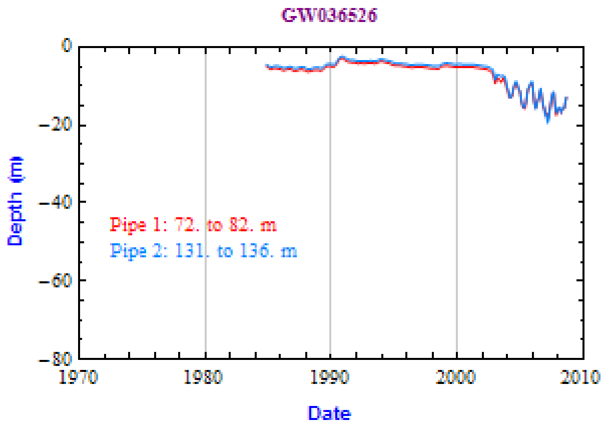
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 15. to 18. m
Pipe 2: 30. to 33. m

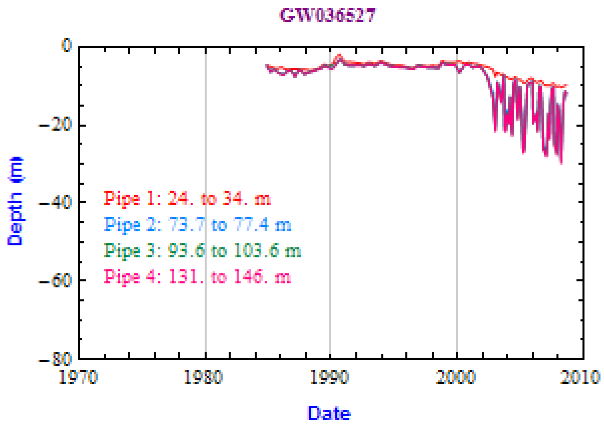

GW036502

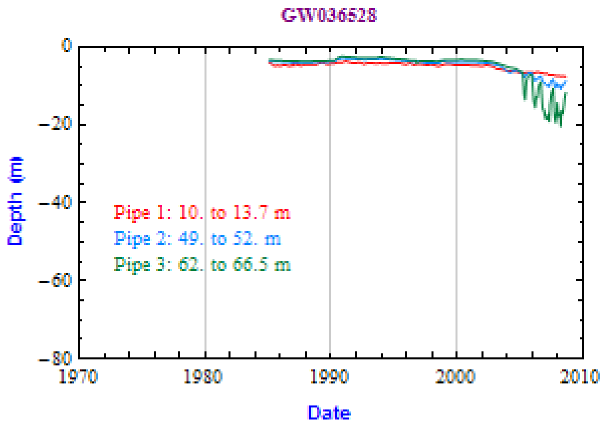

GW036522


GW036523


GW036524


GW036526


GW036527


GW036528
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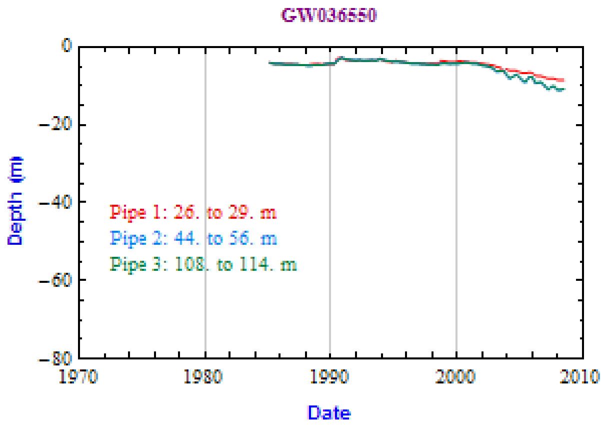
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 10. to 13.7 m
Pipe 2: 49. to 52. m
Pipe 3: 62. to 66.5 m


GW036550
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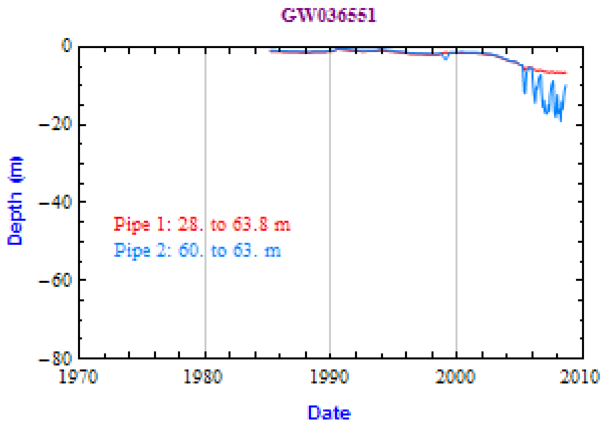
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 26. to 29. m
Pipe 2: 44. to 56. m
Pipe 3: 108. to 114. m


GW036551
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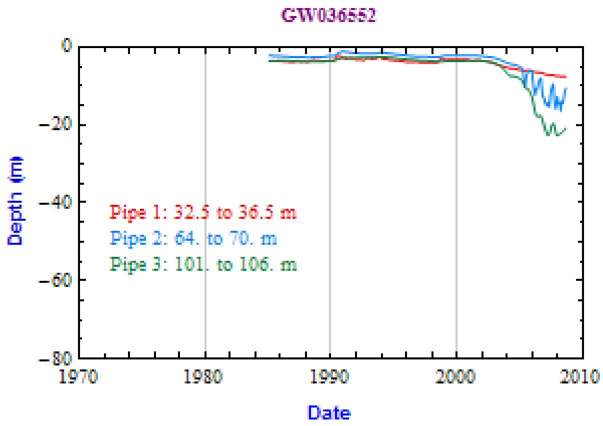
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 28. to 63.8 m
Pipe 2: 60. to 63. m


GW036552
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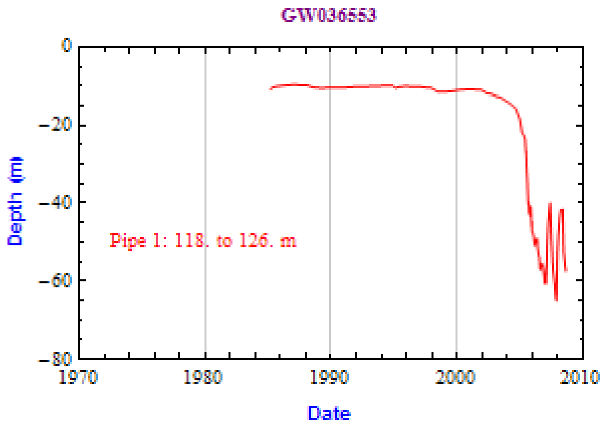
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 32.5 to 36.5 m
Pipe 2: 64. to 70. m
Pipe 3: 101. to 106. m


GW036553
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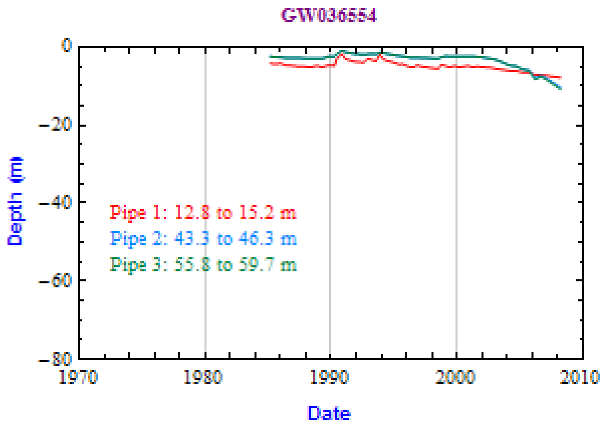
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 118. to 126. m


GW036554
0
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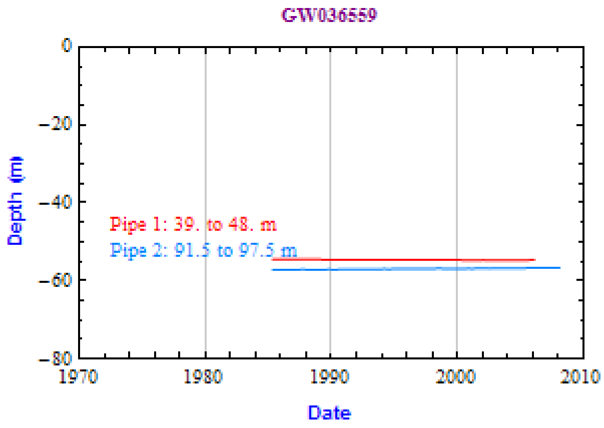
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 12.8 to 15.2 m
Pipe 2: 43.3 to 46.3 m
Pipe 3: 55.8 to 59.7 m


GW036559
0
−20
−40
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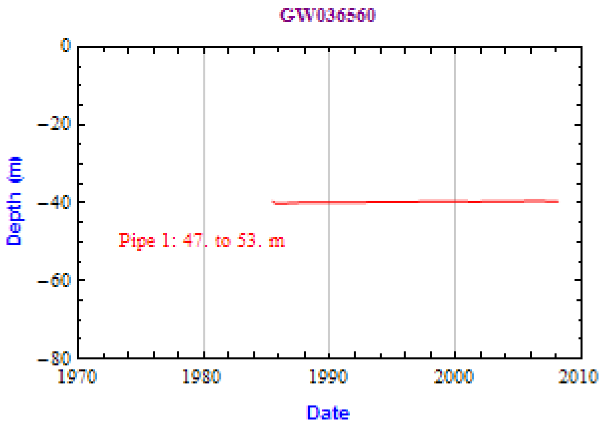
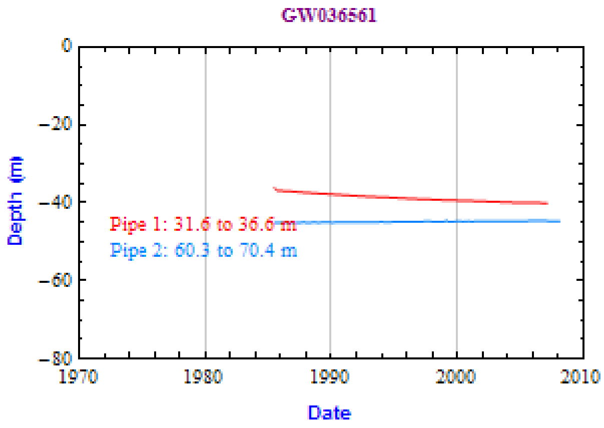
−80
Depth (m)
Pipe 1: 39. to 48. m
Pipe 2: 91.5 to 97.5 m
1970
1980
1990
2000
2010
Date


GW036560
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 47. to 53. m
1970
1980
1990
2000
2010
Date


GW036561
0
−20
−40
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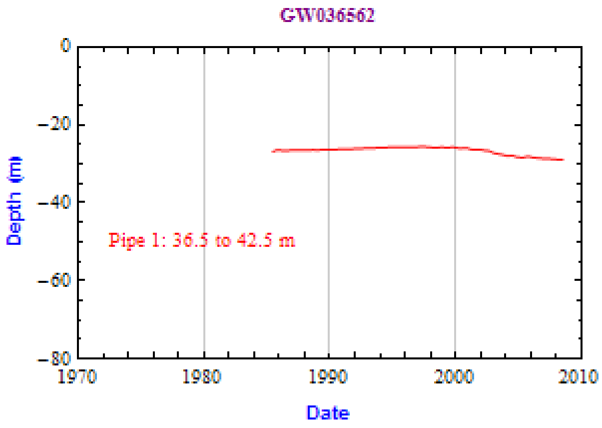
−80
Depth (m)
Pipe 1: 31.6 to 36.6 m
Pipe 2: 60.3 to 70.4 m
1970
1980
1990
2000
2010
Date


GW036562
0
−20
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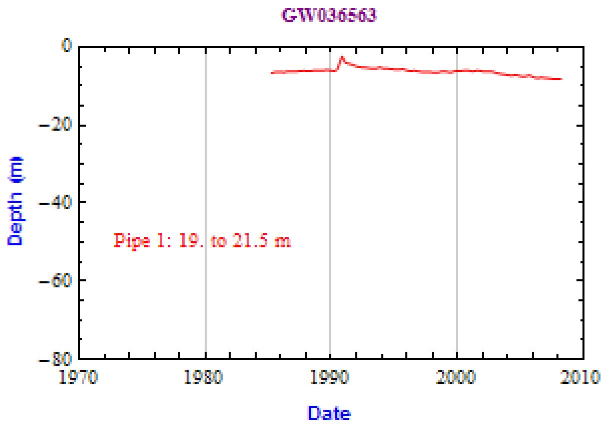
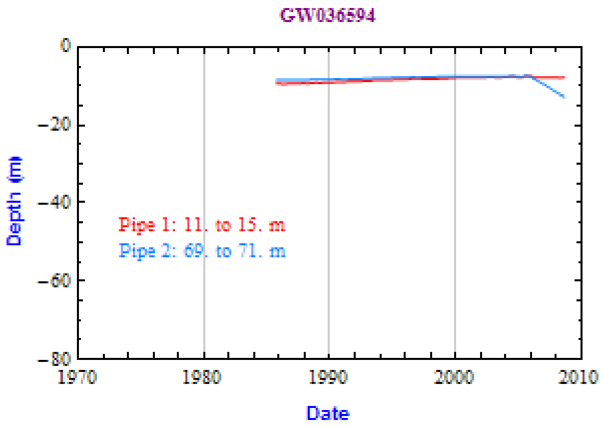
−80
Depth (m)
Pipe 1: 36.5 to 42.5 m
1970
1980
1990
2000
2010
Date


GW036563
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 19. to 21.5 m
1970
1980
1990
2000
2010
Date


GW036594
0
−20
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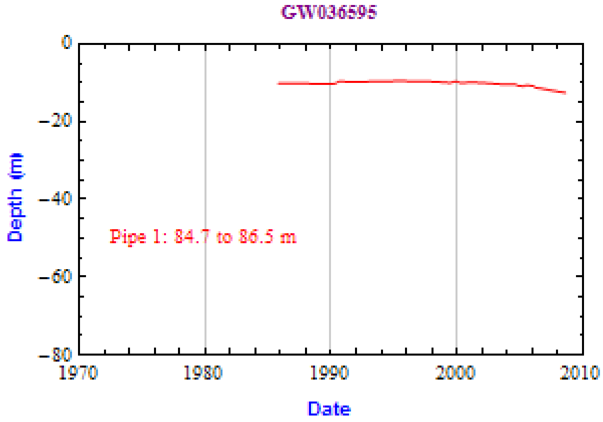
Depth (m)
Pipe 1: 11. to 15. m
Pipe 2: 69. to 71. m
1970
1980
1990
2000
2010
Date


GW036595
Depth (m)
0
−20
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−60
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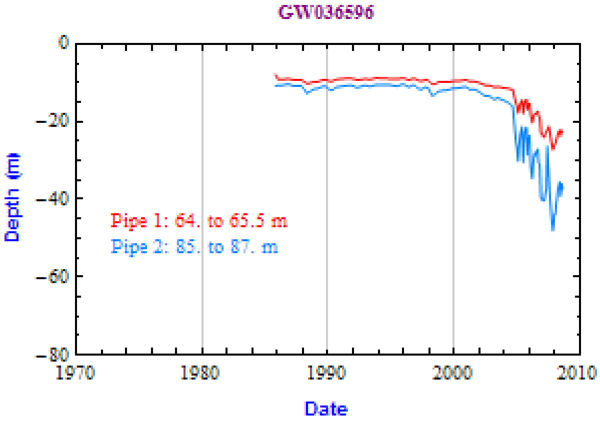
1970
1980
1990
2000
2010
Date
Pipe 1: 84.7 to 86.5 m


GW036596
Depth (m)
0
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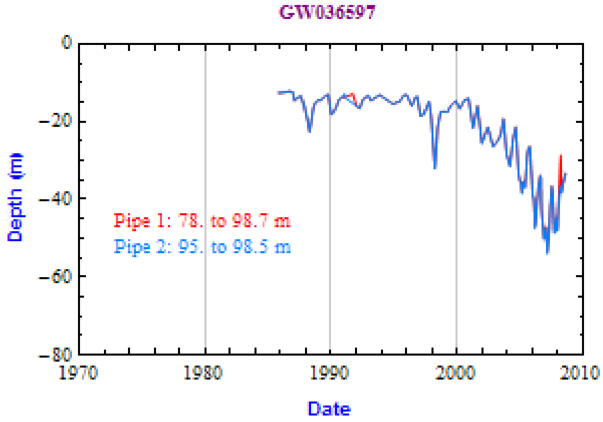
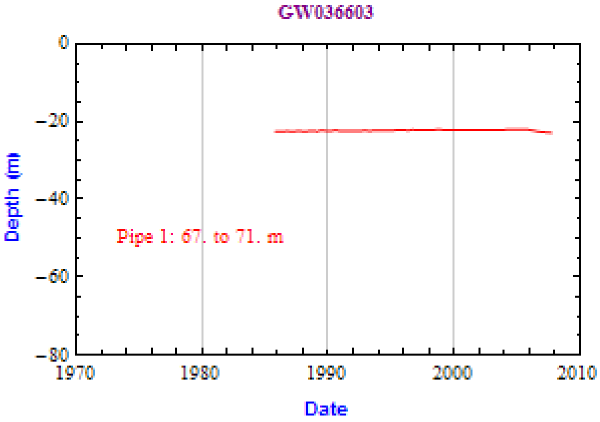
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 64. to 65.5 m
Pipe 2: 85. to 87. m


GW036597
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 78. to 98.7 m
Pipe 2: 95. to 98.5 m


GW036603
Depth (m)
0
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−40
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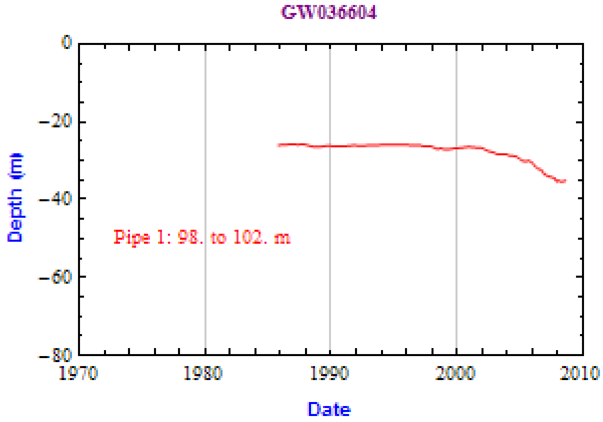
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 67. to 71. m


GW036604
Depth (m)
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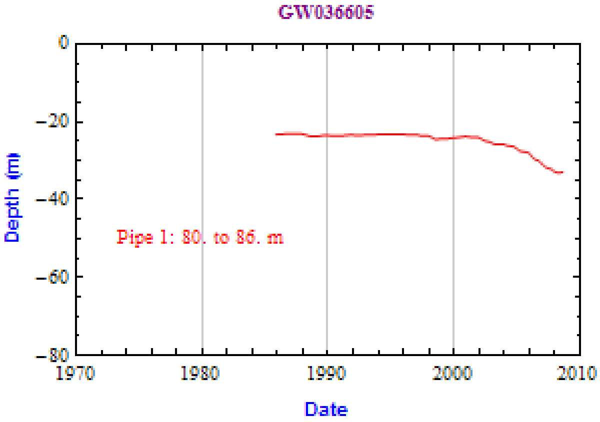
1970
1980
1990
2000
2010
Date
Pipe 1: 98. to 102. m


GW036605
Depth (m)
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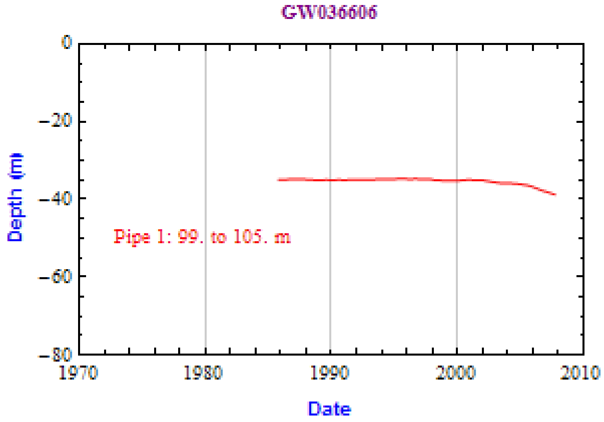
1970
1980
1990
2000
2010
Date
Pipe 1: 80. to 86. m


GW036606
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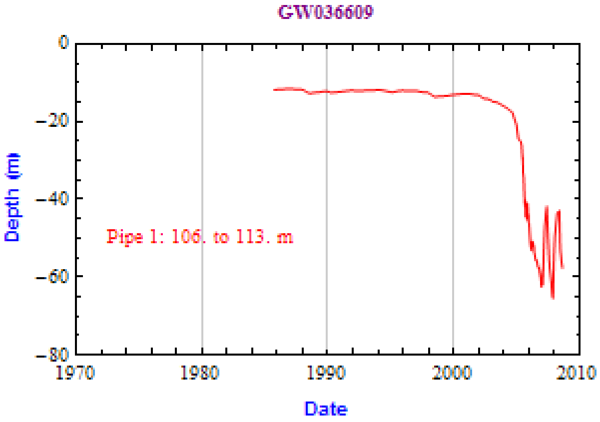
Depth (m)
Pipe 1: 99. to 105. m
1970
1980
1990
2000
2010
Date


GW036609
0
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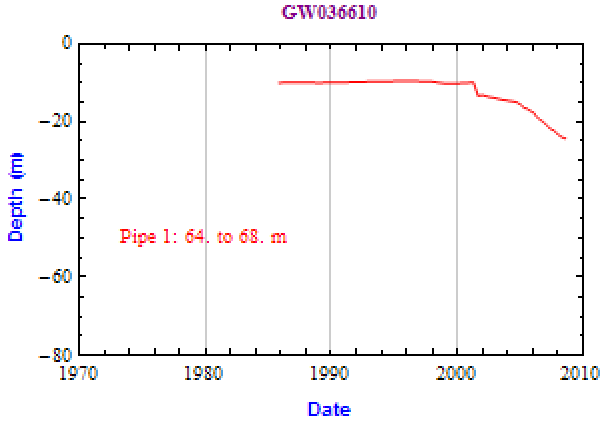
Depth (m)
Pipe 1: 106. to 113. m
1970
1980
1990
2000
2010
Date


GW036610
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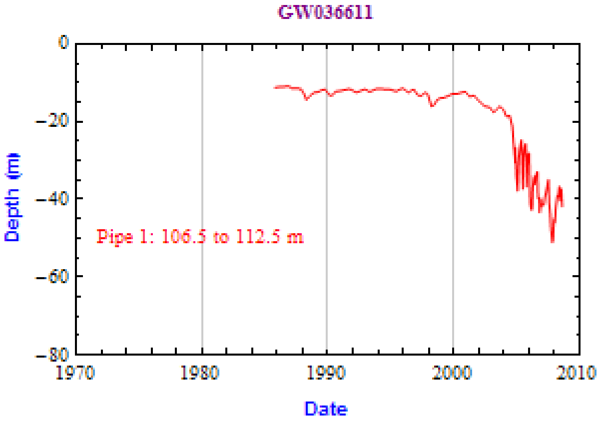
Depth (m)
Pipe 1: 64. to 68. m
1970
1980
1990
2000
2010
Date


GW036611
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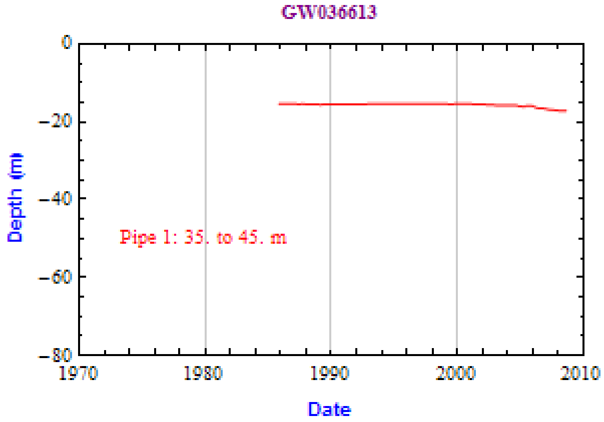
Depth (m)
Pipe 1: 106.5 to 112.5 m
1970
1980
1990
2000
2010
Date


GW036613
0
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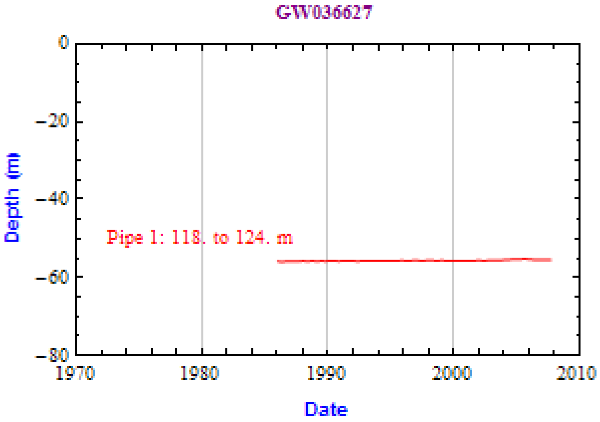
Depth (m)
Pipe 1: 35. to 45. m
1970
1980
1990
2000
2010
Date


GW036627
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−20
−40
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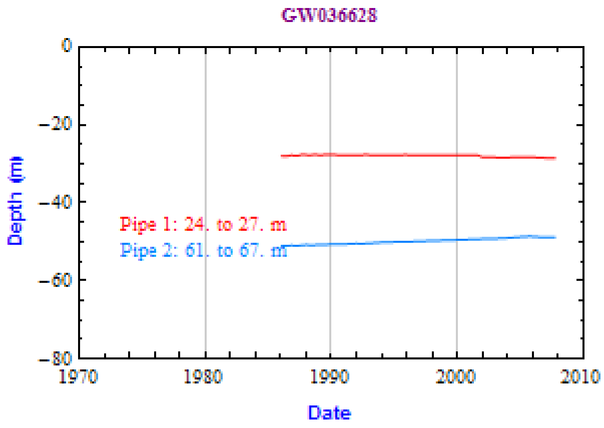
−80
Depth (m)
Pipe 1: 118. to 124. m
1970
1980
1990
2000
2010
Date


GW036628
Depth (m)
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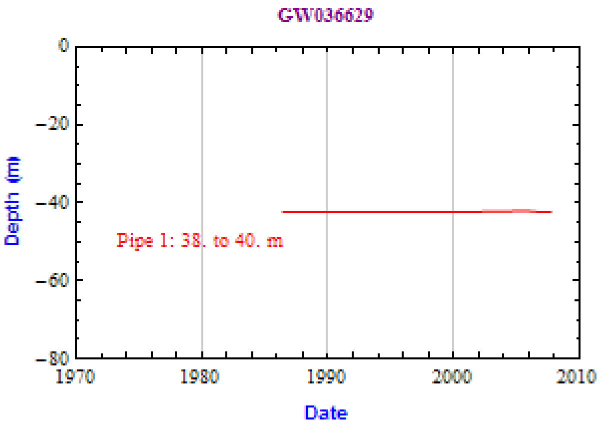
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 24. to 27. m
Pipe 2: 61. to 67. m


GW036629
Depth (m)
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−40
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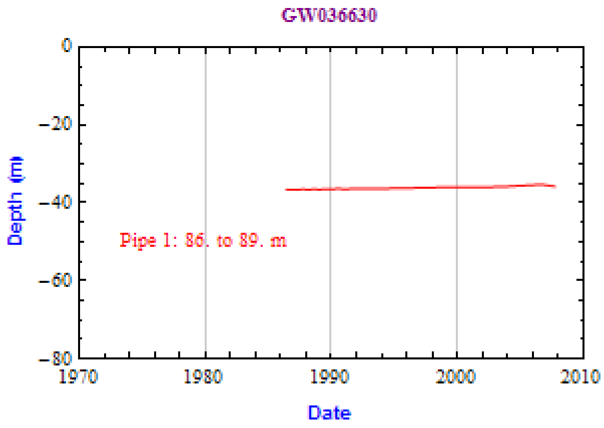
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 38. to 40. m


GW036630
Depth (m)
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−20
−40
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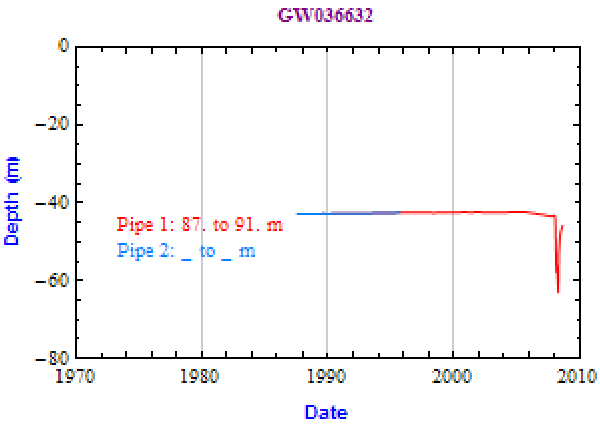
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 86. to 89. m


GW036632
Depth (m)
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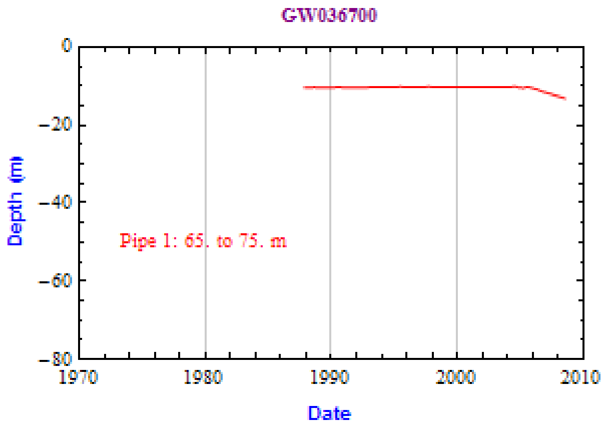
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 87. to 91. m
Pipe 2: _ to _ m


GW036700
Depth (m)
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−40
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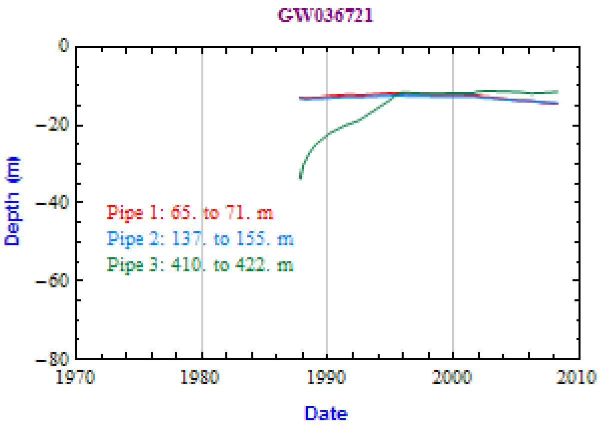
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 65. to 75. m


GW036721
Depth (m)
0
−20
−40
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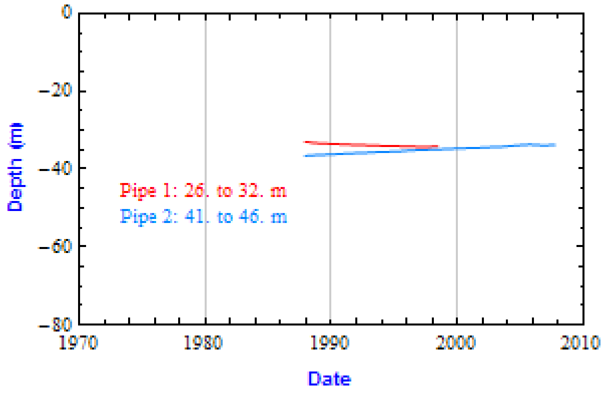
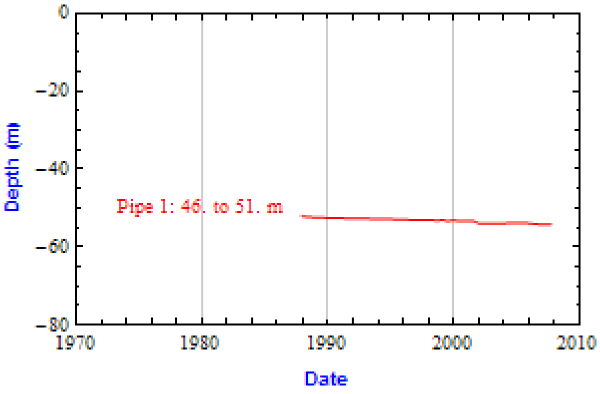
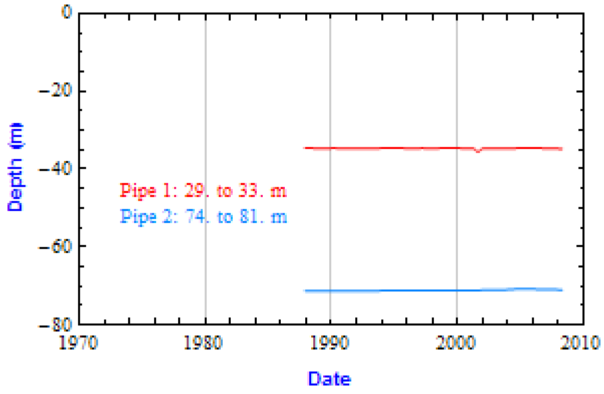
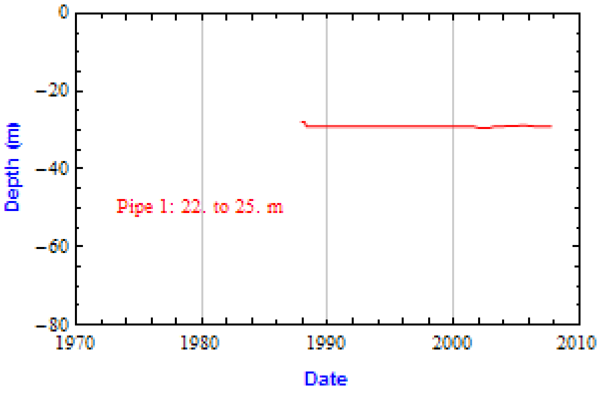
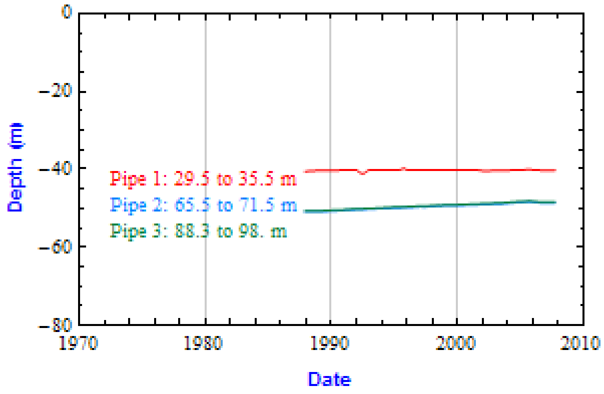
1970
1980
1990
2000
2010
Date
Pipe 1: 65. to 71. m
Pipe 2: 137. to 155. m
Pipe 3: 410. to 422. m

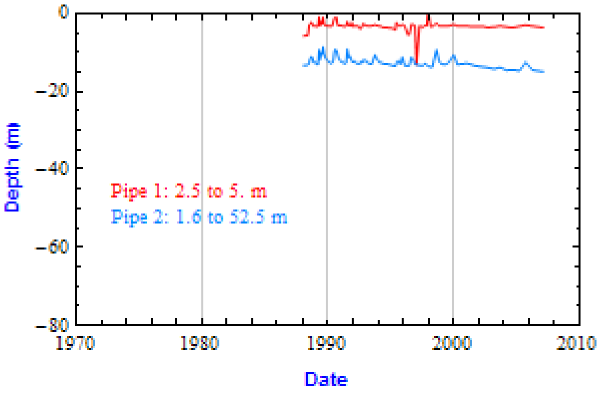

GW036735

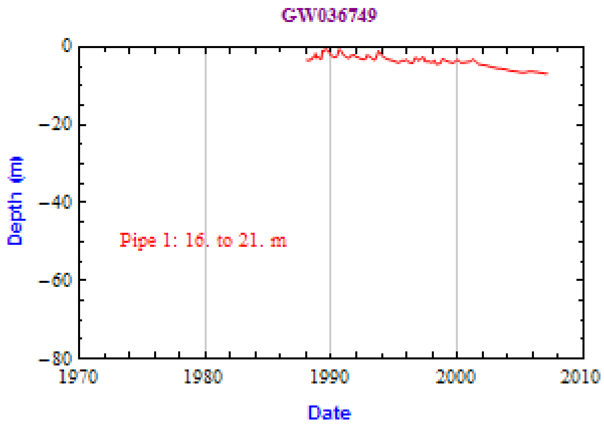

GW036737


GW036738


GW036739


GW036741


GW036748


GW036749
Depth (m)
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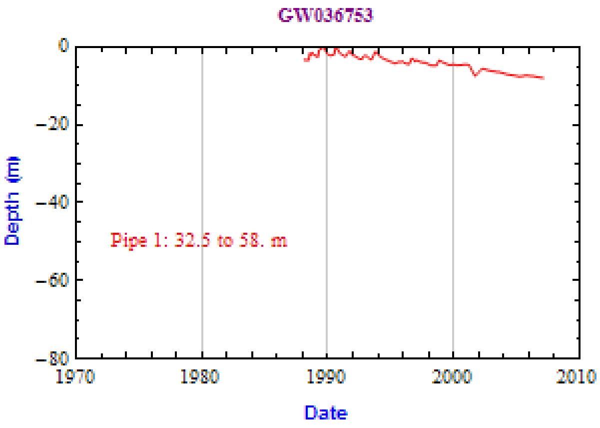
−20
−40
−60
−80
Pipe 1: 16. to 21. m
1970
1980
1990
2000
2010
Date


GW036753
Depth (m)
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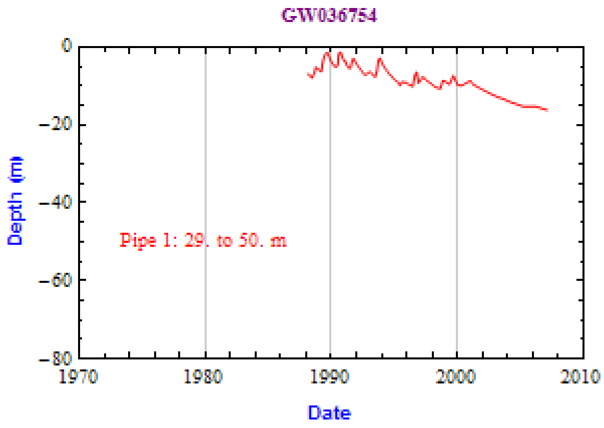
−20
−40
−60
−80
Pipe 1: 32.5 to 58. m
1970
1980
1990
2000
2010
Date


GW036754
Depth (m)
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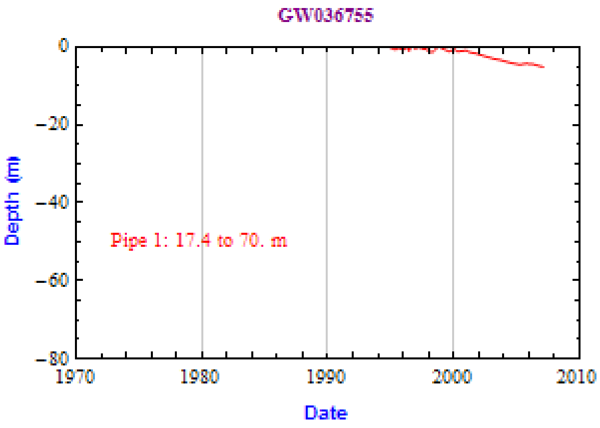
−20
−40
−60
−80
Pipe 1: 29. to 50. m
1970
1980
1990
2000
2010
Date


GW036755
Depth (m)
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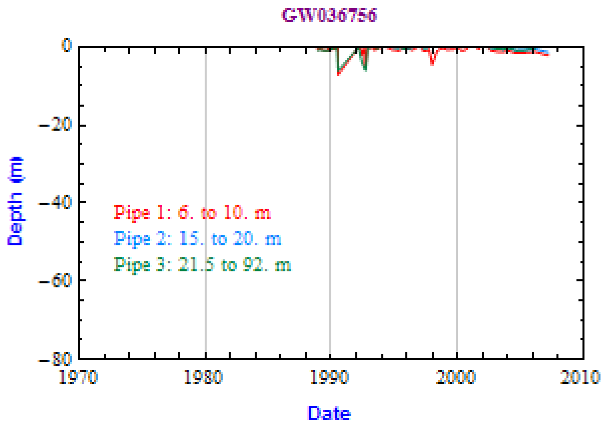
−20
−40
−60
−80
Pipe 1: 17.4 to 70. m
1970
1980
1990
2000
2010
Date


GW036756
Depth (m)
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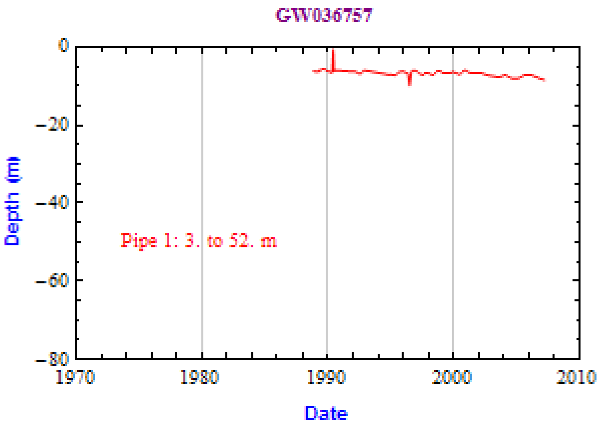
−20
−40
−60
−80
Pipe 1: 6. to 10. m
Pipe 2: 15. to 20. m
Pipe 3: 21.5 to 92. m
1970
1980
1990
2000
2010
Date


GW036757
Depth (m)
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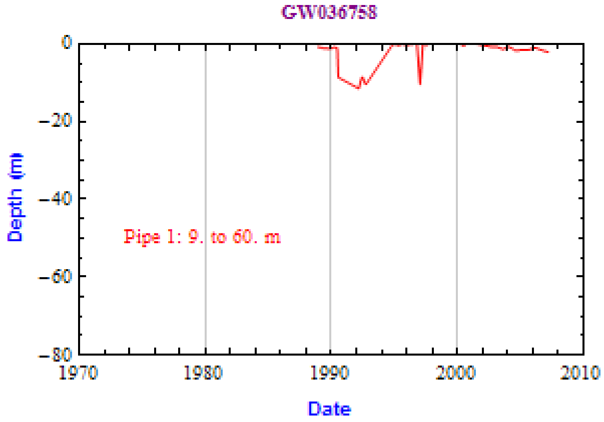
−20
−40
−60
−80
Pipe 1: 3. to 52. m
1970
1980
1990
2000
2010
Date


GW036758
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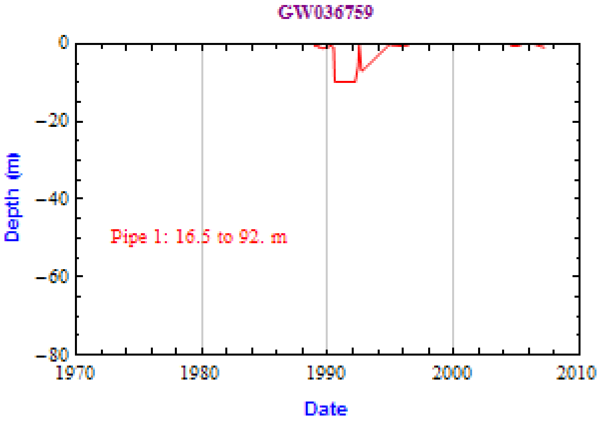
−40
−60
−80
Depth (m)
Pipe 1: 9. to 60. m
1970
1980
1990
2000
2010
Date


GW036759
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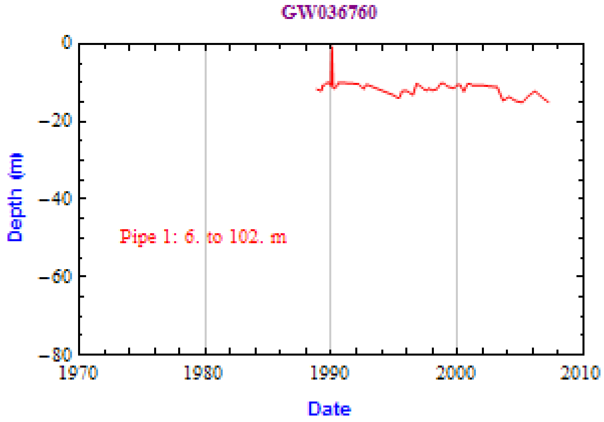
−20
−40
−60
−80
Depth (m)
Pipe 1: 16.5 to 92. m
1970
1980
1990
2000
2010
Date


GW036760
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−40
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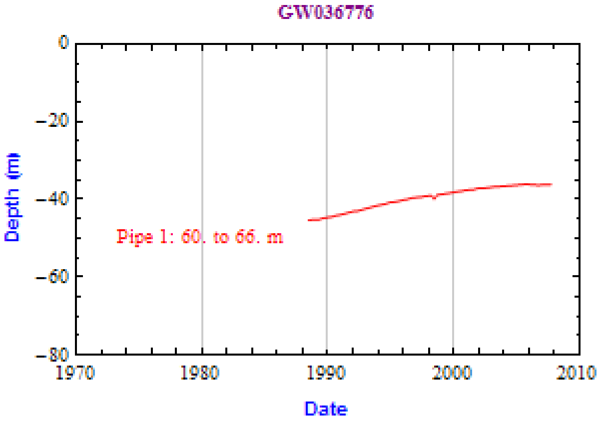
−80
Depth (m)
Pipe 1: 6. to 102. m
1970
1980
1990
2000
2010
Date


GW036776
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−40
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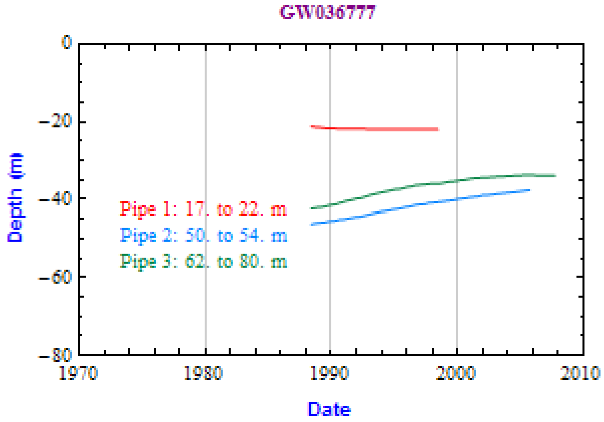
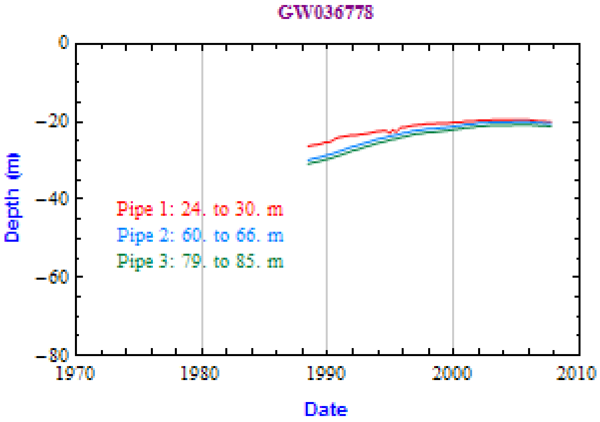
−80
Depth (m)
Pipe 1: 60. to 66. m
1970
1980
1990
2000
2010
Date


GW036777
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 17. to 22. m
Pipe 2: 50. to 54. m
Pipe 3: 62. to 80. m
1970
1980
1990
2000
2010
Date


GW036778
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−40
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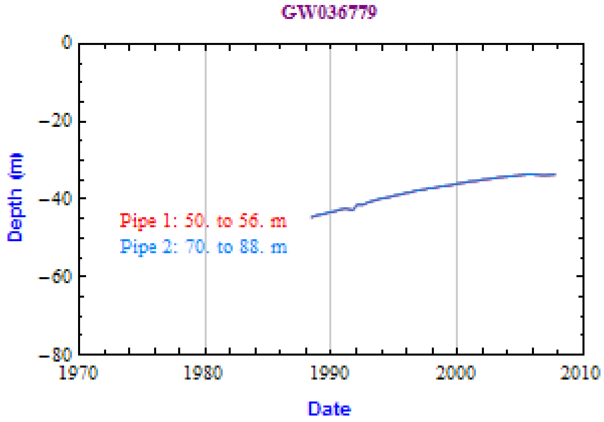
−80
Depth (m)
Pipe 1: 24. to 30. m
Pipe 2: 60. to 66. m
Pipe 3: 79. to 85. m
1970
1980
1990
2000
2010
Date


GW036779
Depth (m)
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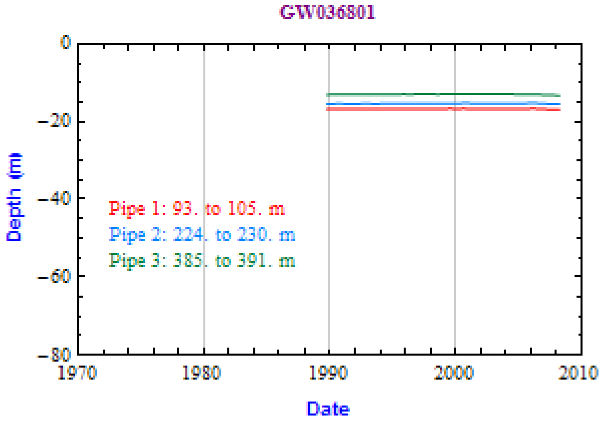
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 50. to 56. m
Pipe 2: 70. to 88. m


GW036801
Depth (m)
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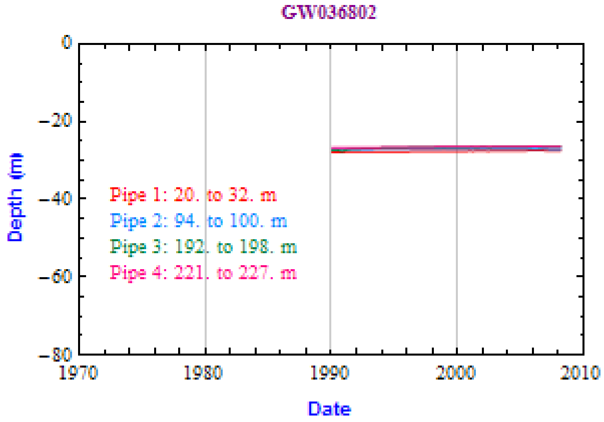
1970
1980
1990
2000
2010
Date
Pipe 1: 93. to 105. m
Pipe 2: 224. to 230. m
Pipe 3: 385. to 391. m


GW036802
Depth (m)
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−40
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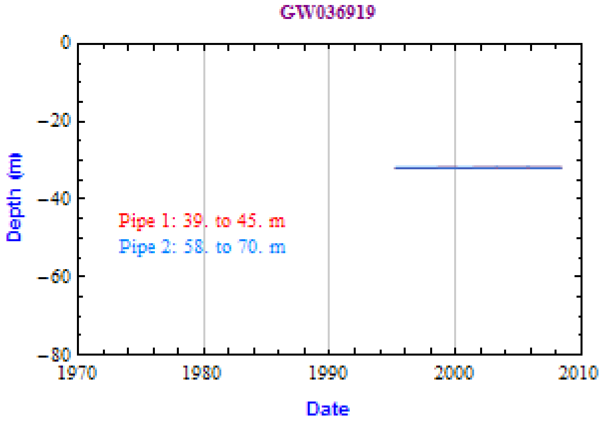
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 20. to 32. m
Pipe 2: 94. to 100. m
Pipe 3: 192. to 198. m
Pipe 4: 221. to 227. m


GW036919
Depth (m)
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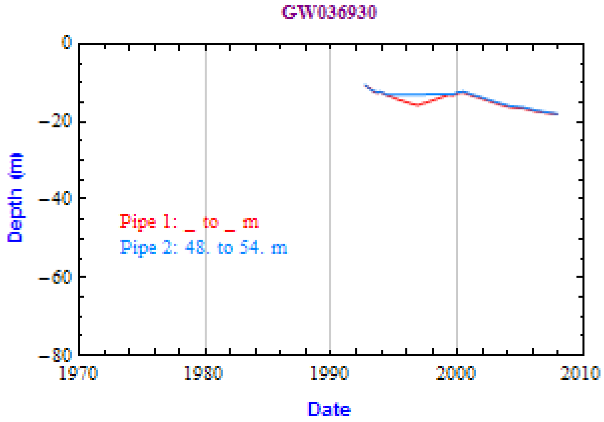
1970
1980
1990
2000
2010
Date
Pipe 1: 39. to 45. m
Pipe 2: 58. to 70. m


GW036930
Depth (m)
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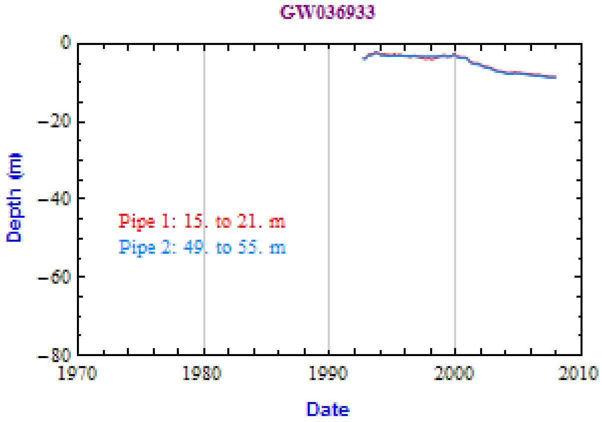
−80
1970
1980
1990
2000
2010
Date
Pipe 1: _ to _ m
Pipe 2: 48. to 54. m


GW036933
Depth (m)
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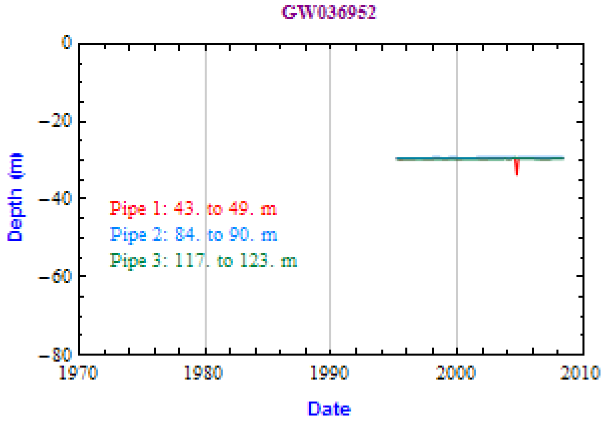
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 15. to 21. m
Pipe 2: 49. to 55. m


GW036952
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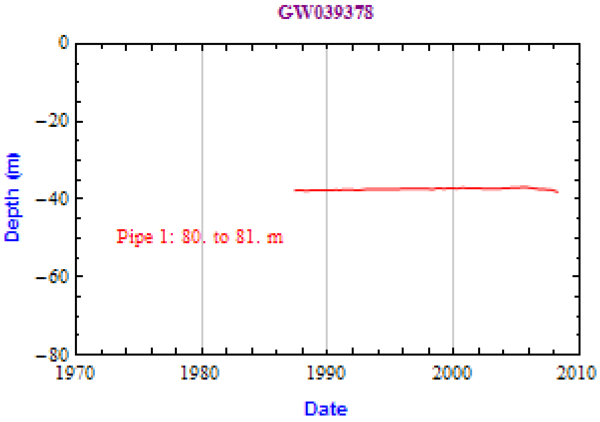
−40
−60
−80
Depth (m)
Pipe 1: 43. to 49. m
Pipe 2: 84. to 90. m
Pipe 3: 117. to 123. m
1970
1980
1990
2000
2010
Date


GW039378
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−40
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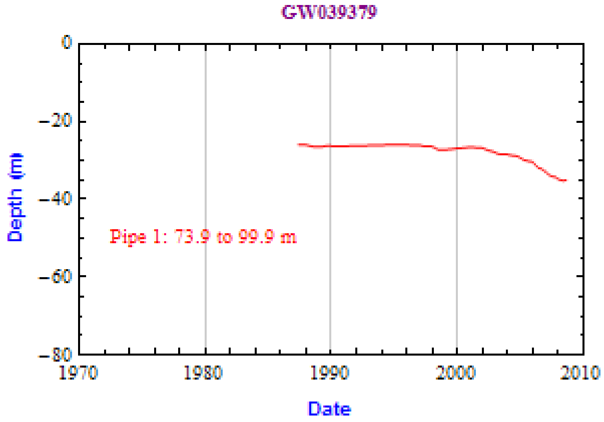
−80
Depth (m)
Pipe 1: 80. to 81. m
1970
1980
1990
2000
2010
Date


GW039379
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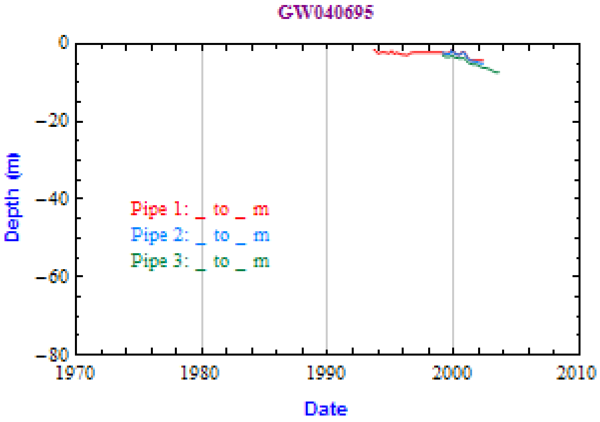
−40
−60
−80
Depth (m)
Pipe 1: 73.9 to 99.9 m
1970
1980
1990
2000
2010
Date


GW040695
0
−20
−40
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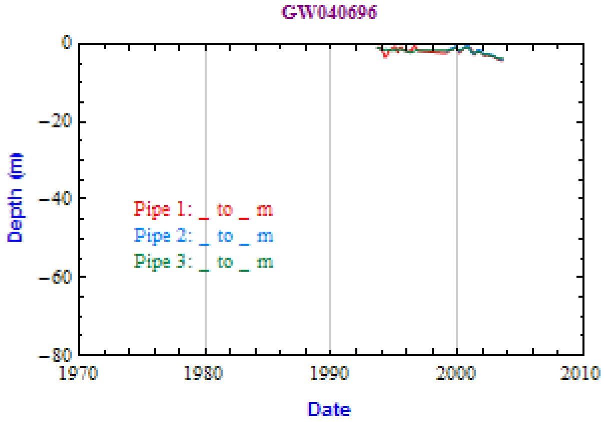
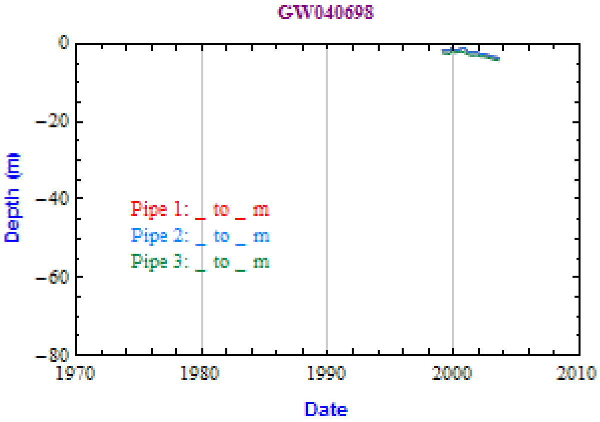
−80
Depth (m)
Pipe 1: _ to _ m
Pipe 2: _ to _ m
Pipe 3: _ to _ m
1970
1980
1990
2000
2010
Date


GW040696
0
−20
−40
−60
−80
Depth (m)
Pipe 1: _ to _ m
Pipe 2: _ to _ m
Pipe 3: _ to _ m
1970
1980
1990
2000
2010
Date


GW040698
0
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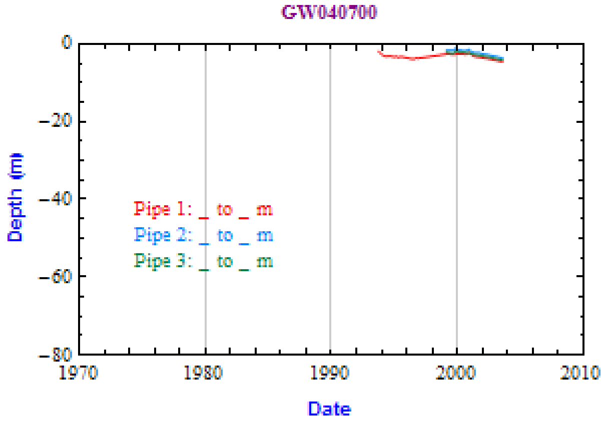
−80
Depth (m)
Pipe 1: _ to _ m
Pipe 2: _ to _ m
Pipe 3: _ to _ m
1970
1980
1990
2000
2010
Date


GW040700
Depth (m)
0
−20
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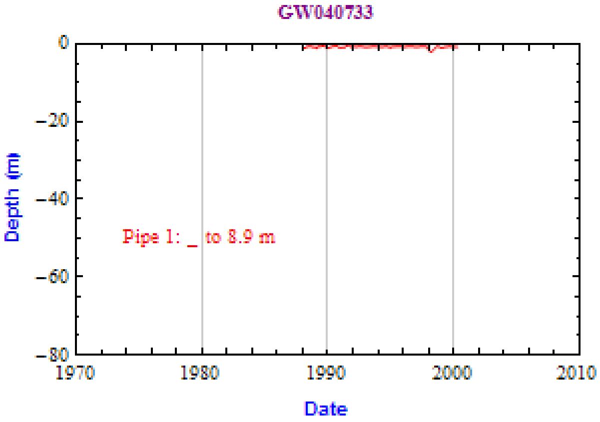
1970
1980
1990
2000
2010
Date
Pipe 1: _ to _ m
Pipe 2: _ to _ m
Pipe 3: _ to _ m


GW040733
Depth (m)
0
−20
−40
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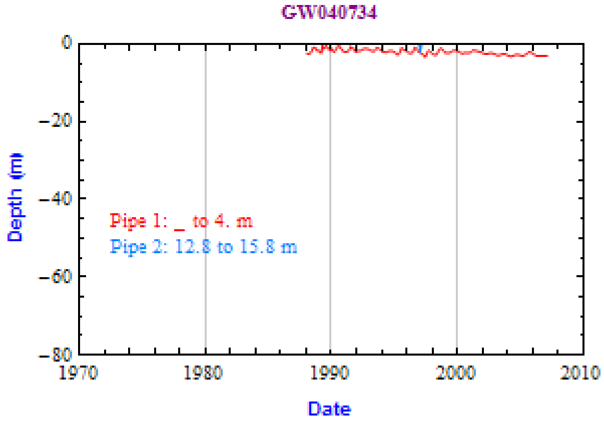
−80
1970
1980
1990
2000
2010
Date
Pipe 1: _ to 8.9 m


GW040734
Depth (m)
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−20
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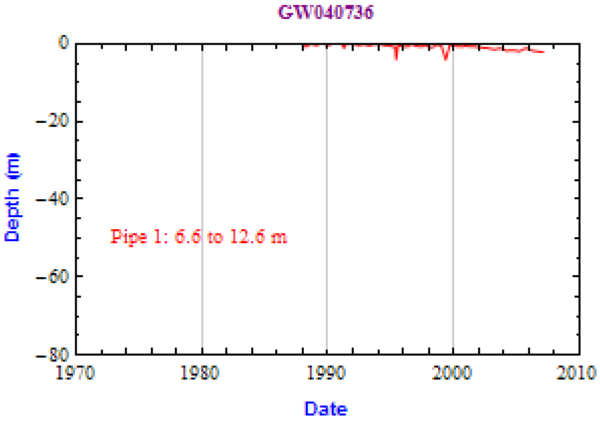
−80
1970
1980
1990
2000
2010
Date
Pipe 1: _ to 4. m
Pipe 2: 12.8 to 15.8 m


GW040736
Depth (m)
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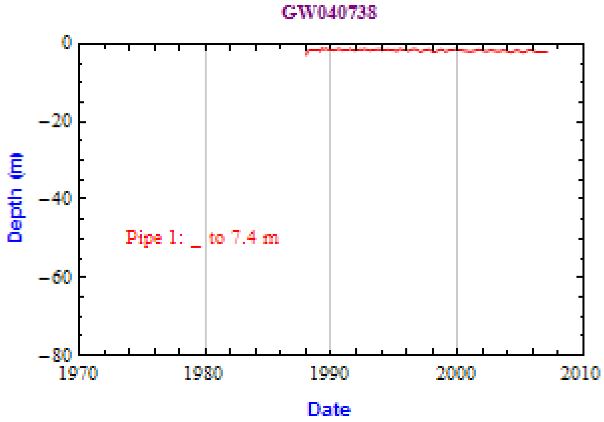
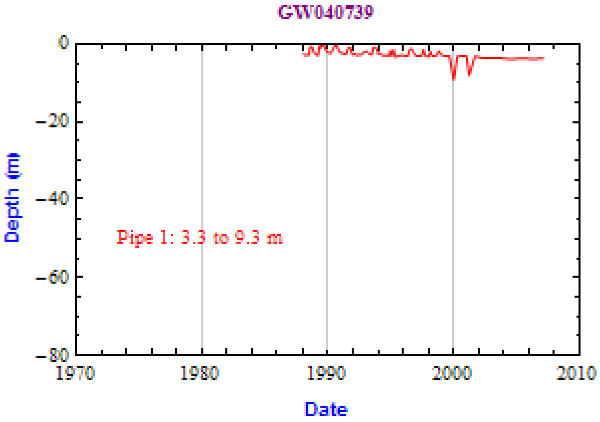
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 6.6 to 12.6 m


GW040738
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: _ to 7.4 m


GW040739
Depth (m)
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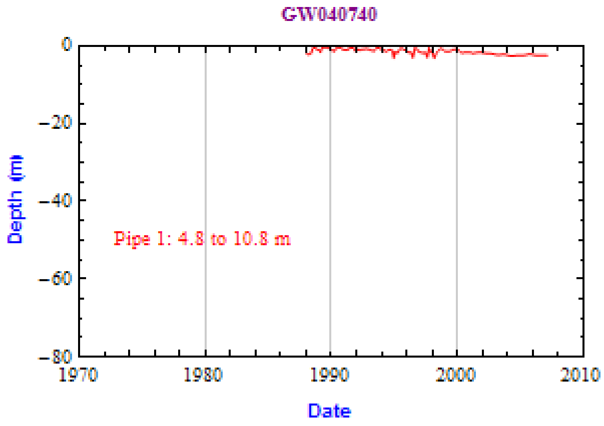
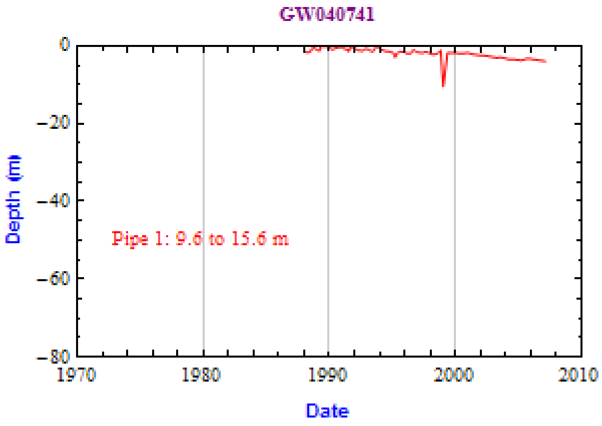
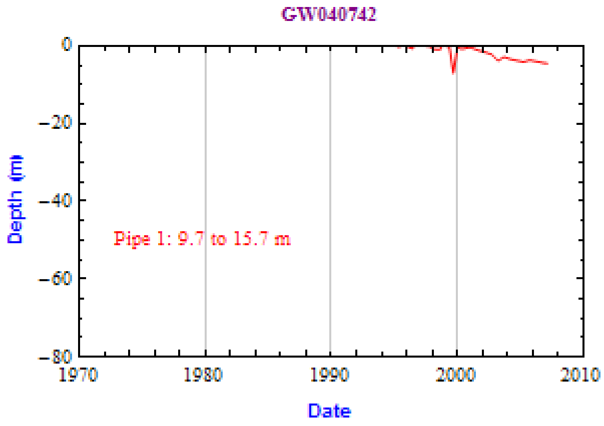
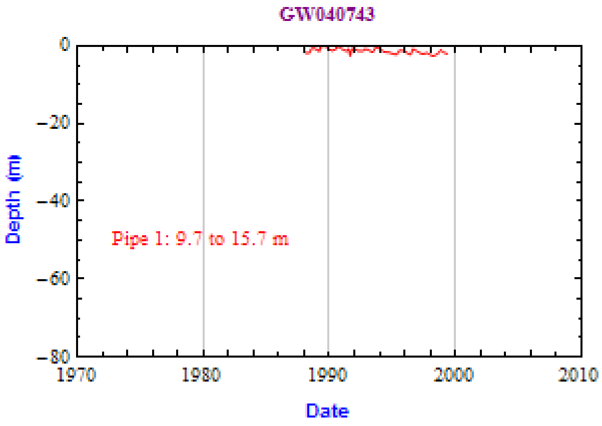
1970
1980
1990
2000
2010
Date
Pipe 1: 3.3 to 9.3 m


GW040740
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 4.8 to 10.8 m
1970
1980
1990
2000
2010
Date


GW040741
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 9.6 to 15.6 m
1970
1980
1990
2000
2010
Date


GW040742
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 9.7 to 15.7 m
1970
1980
1990
2000
2010
Date


GW040743
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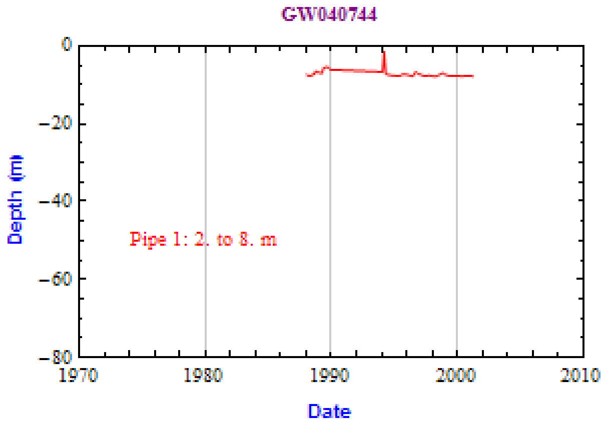
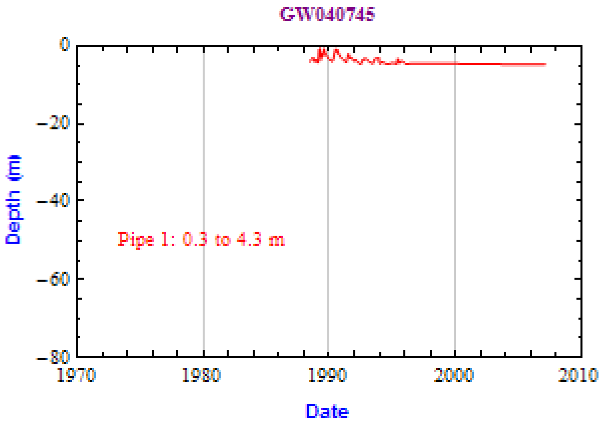
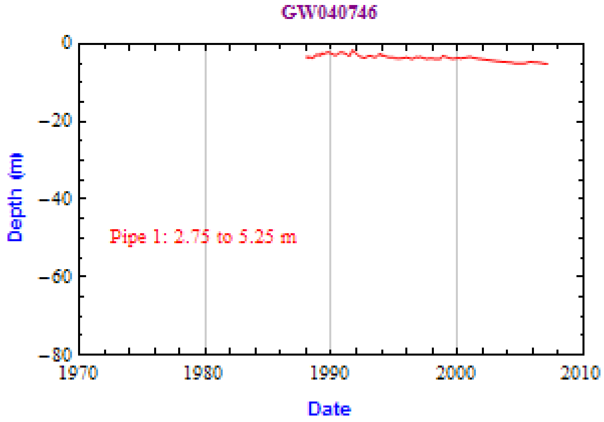
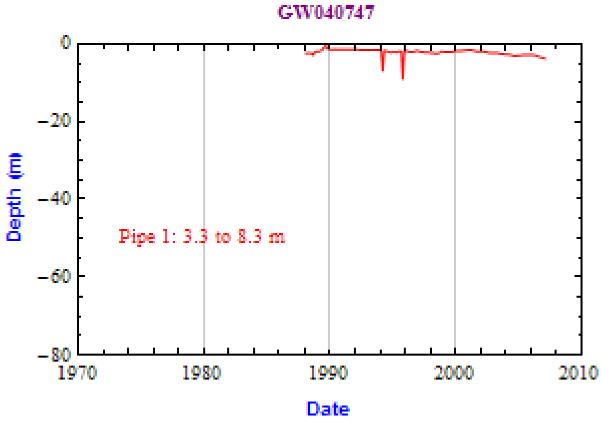
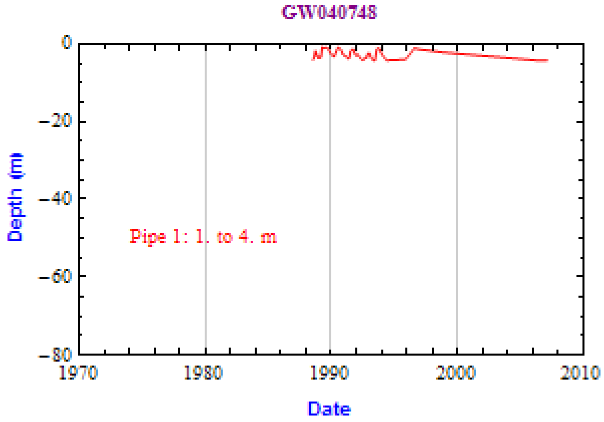
−20
−40
−60
−80
Depth (m)
Pipe 1: 9.7 to 15.7 m
1970
1980
1990
2000
2010
Date


GW040744
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 2. to 8. m
1970
1980
1990
2000
2010
Date


GW040745
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 0.3 to 4.3 m
1970
1980
1990
2000
2010
Date


GW040746
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 2.75 to 5.25 m
1970
1980
1990
2000
2010
Date


GW040747
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 3.3 to 8.3 m
1970
1980
1990
2000
2010
Date


GW040748
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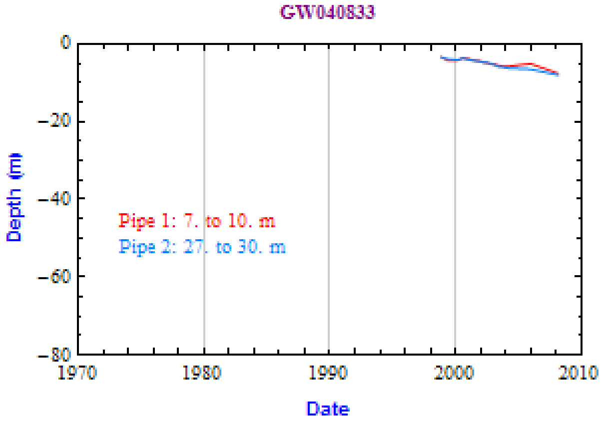
−20
−40
−60
−80
Depth (m)
Pipe 1: 1. to 4. m
1970
1980
1990
2000
2010
Date


GW040833
0
−20
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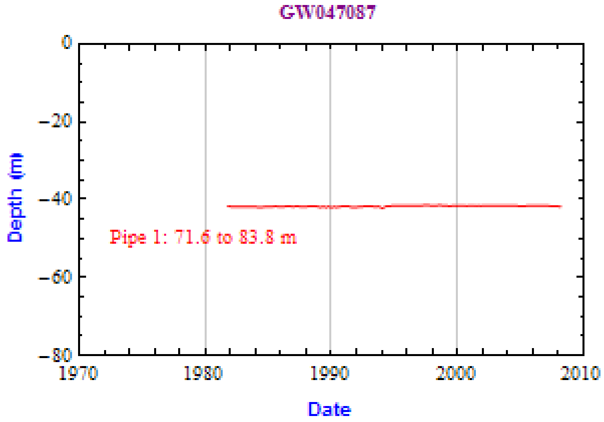
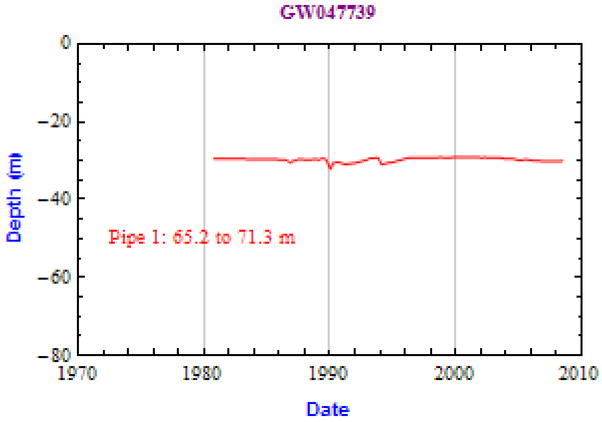
−60
−80
Depth (m)
Pipe 1: 7. to 10. m
Pipe 2: 27. to 30. m
1970
1980
1990
2000
2010
Date


GW047087
0
−20
−40
−60
−80
Depth (m)
Pipe 1: 71.6 to 83.8 m
1970
1980
1990
2000
2010
Date


GW047739
0
−20
−40
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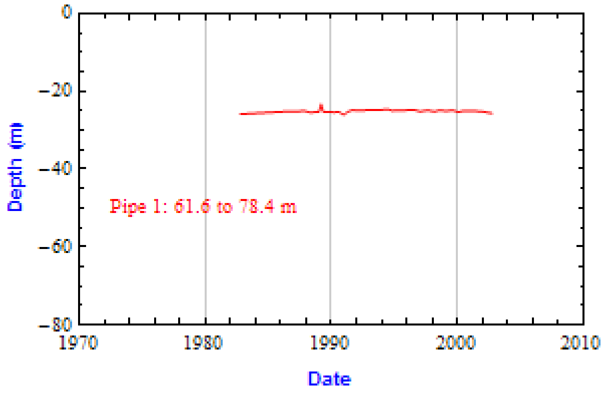
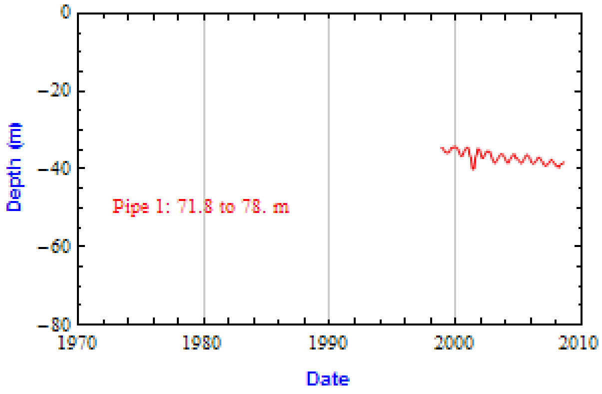
−80
Depth (m)
Pipe 1: 65.2 to 71.3 m
1970
1980
1990
2000
2010
Date

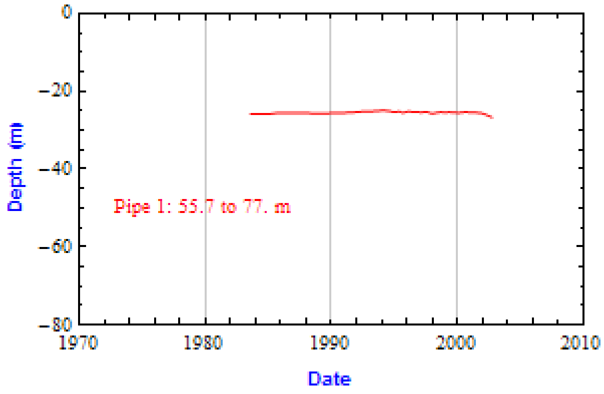
GW053765



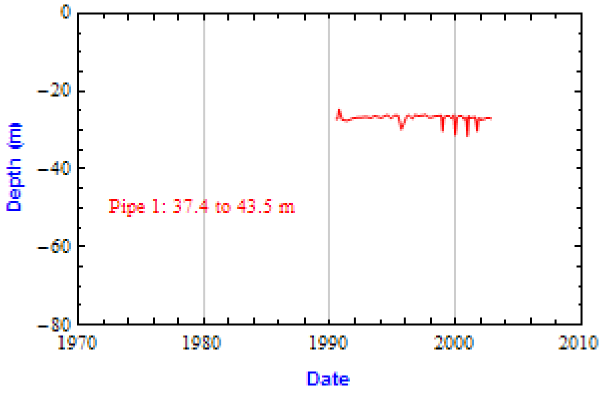
GW059094



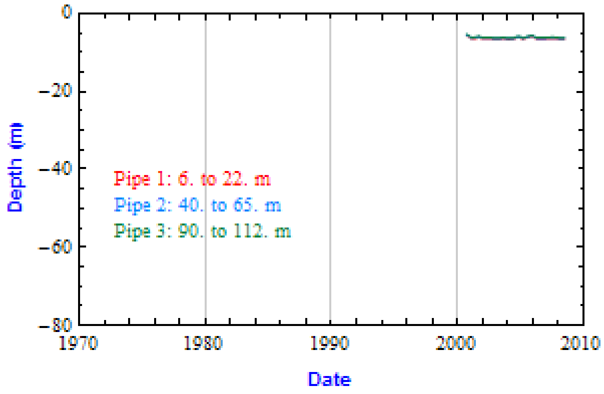
GW059422



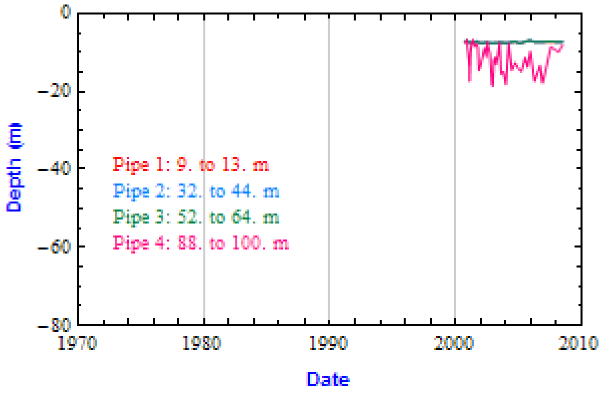
GW060153

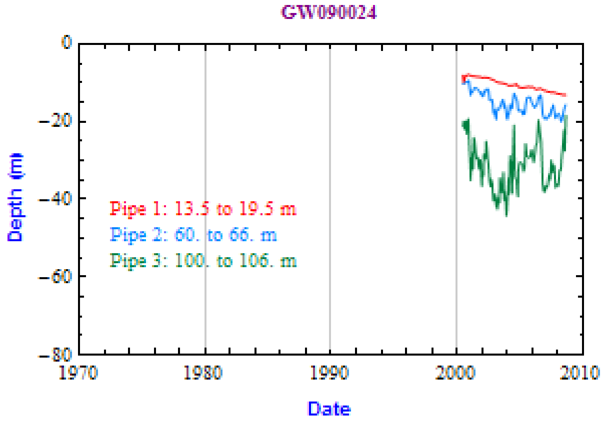


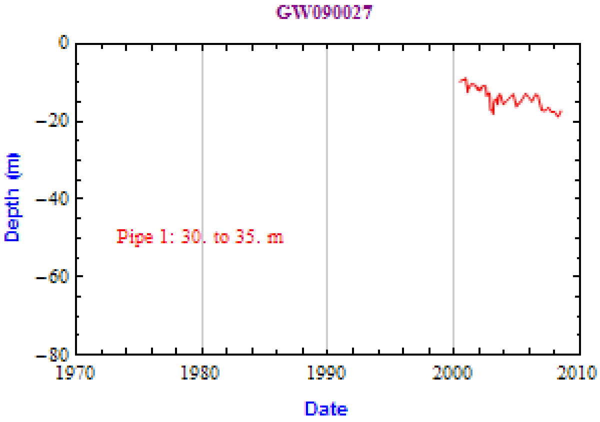
GW090016

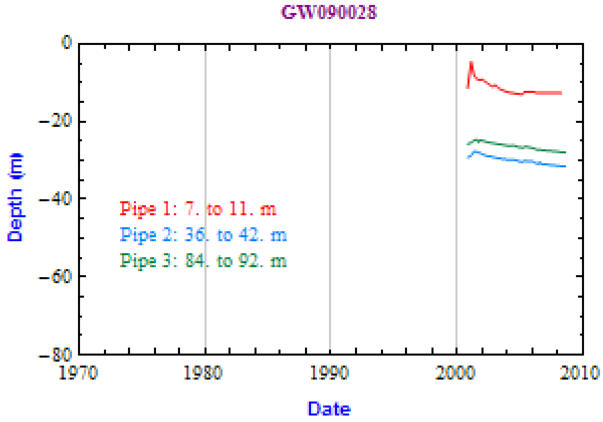


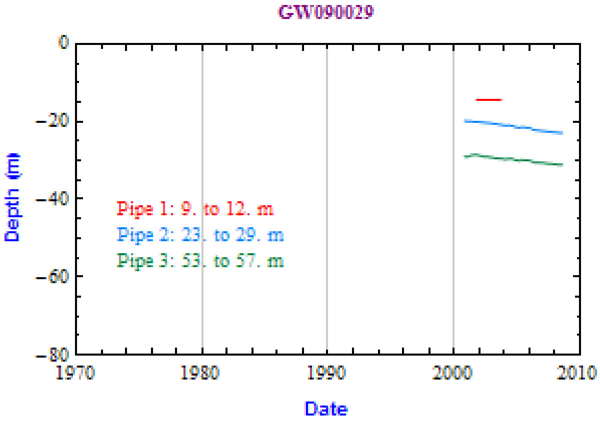
GW090017




GW090024
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 13.5 to 19.5 m
Pipe 2: 60. to 66. m
Pipe 3: 100. to 106. m


GW090027
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 30. to 35. m


GW090028
Depth (m)
0
−20
−40
−60
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 7. to 11. m
Pipe 2: 36. to 42. m
Pipe 3: 84. to 92. m


GW090029
Depth (m)
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−20
−40
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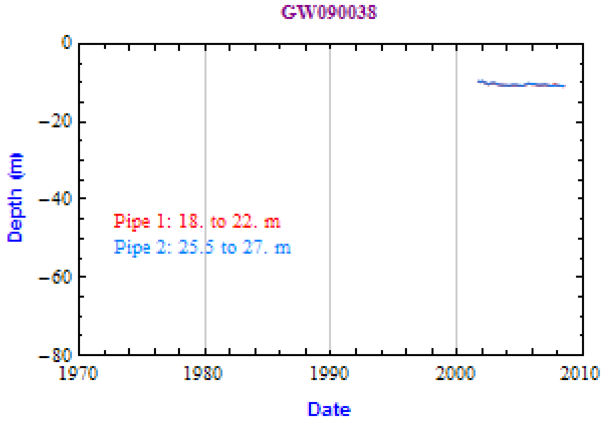
1970
1980
1990
2000
2010
Date
Pipe 1: 9. to 12. m
Pipe 2: 23. to 29. m
Pipe 3: 53. to 57. m


GW090038
Depth (m)
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−40
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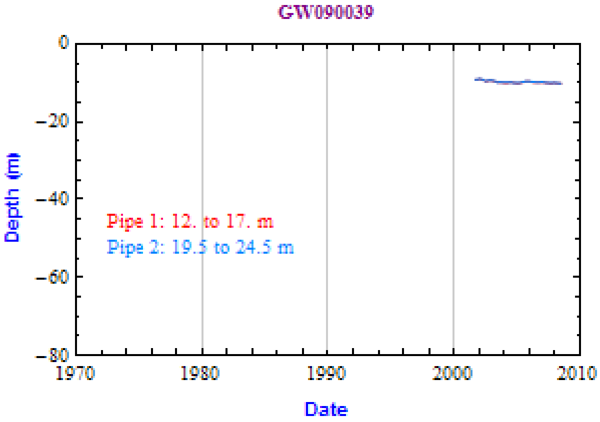
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 18. to 22. m
Pipe 2: 25.5 to 27. m


GW090039
Depth (m)
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−20
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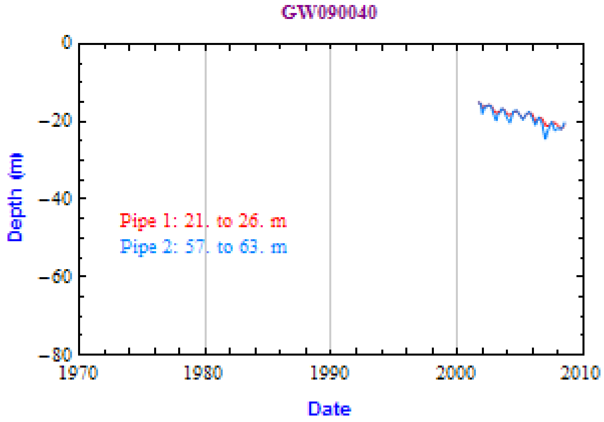
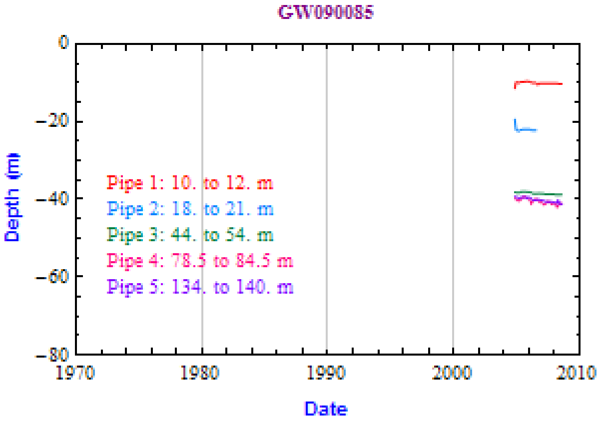
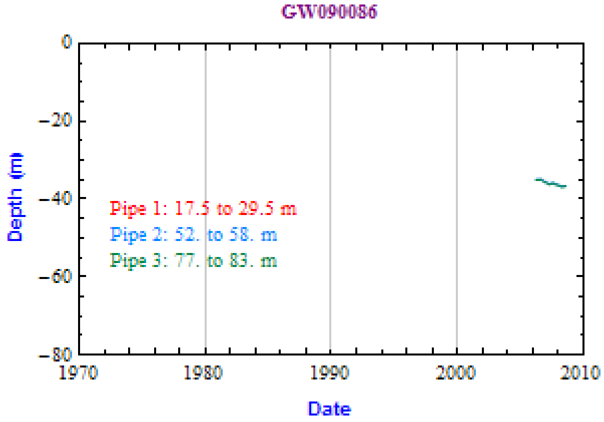
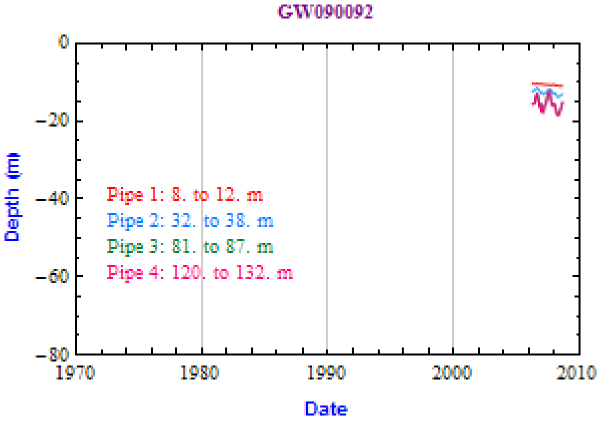
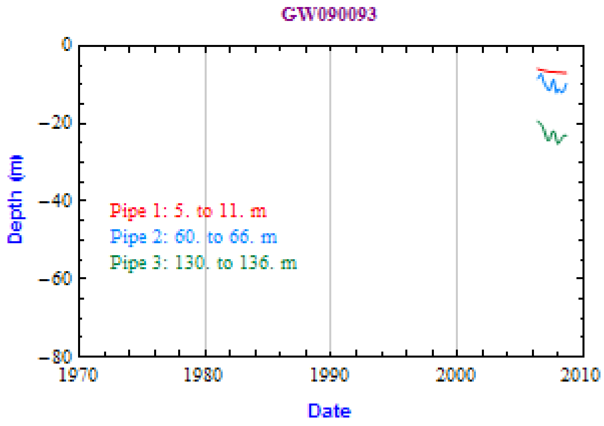
−80
1970
1980
1990
2000
2010
Date
Pipe 1: 12. to 17. m
Pipe 2: 19.5 to 24.5 m

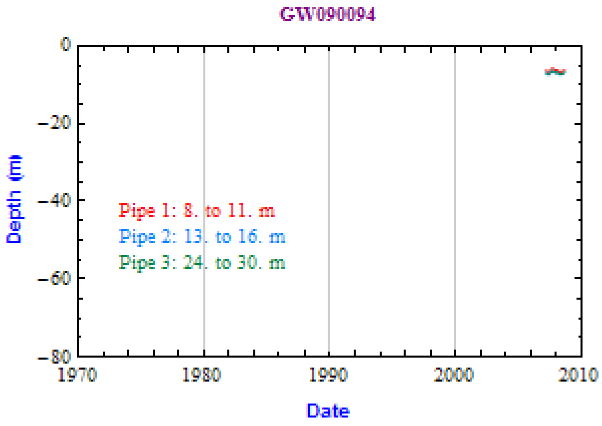

GW090040

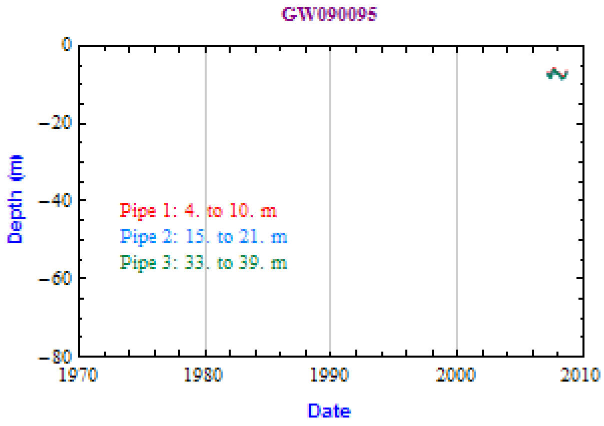

GW090085


GW090086


GW090092


GW090093
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 5. to 11. m
Pipe 2: 60. to 66. m
Pipe 3: 130. to 136. m


GW090094
0
−20
−40
−60
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 8. to 11. m
Pipe 2: 13. to 16. m
Pipe 3: 24. to 30. m


GW090095
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−20
−40
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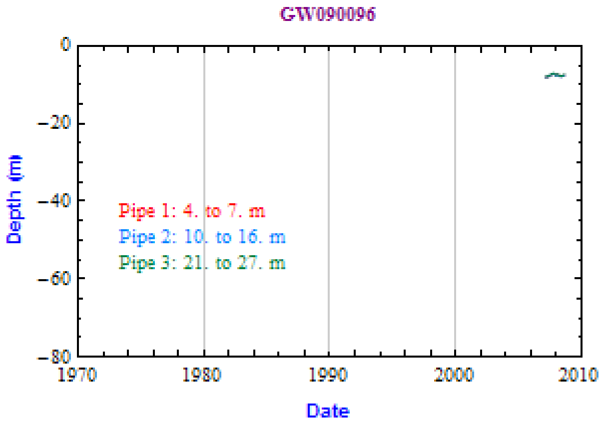
−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 4. to 10. m
Pipe 2: 15. to 21. m
Pipe 3: 33. to 39. m


GW090096
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−20
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−80
Depth (m)
1970
1980
1990
2000
2010
Date
Pipe 1: 4. to 7. m
Pipe 2: 10. to 16. m
Pipe 3: 21. to 27. m