

Temporal trends of groundwater levels in the Condamine catchment 2007-2013

Dr. Elad Dafny



March, 2014

Citation

Dafny E., 2014. Temporal trends of groundwater levels in the Condamine catchment – 2007-2013. Report prepared for CRDC project 11-12FRP00044 (DNRM, USQ and UNSW). University of Southern Queensland, Toowoomba, Australia.

Acknowledgement

The author thanks D. Mark Silburn, Andrew Biggs, Jenny Foley (DNRM) and Alice Melland (USQ) for constructive comments and thorough review of the draft version.

Abbreviations

ALMD - Automatic level monitoring devices
CGMA – Condamine Groundwater Management Area
CRAA - Condamine River Alluvial Aquifer
CRDC – Cotton Research and Development Corporation
DNRM- Department of Natural Resources and Mines
GAB- Great Artesian Basin
GWDB - Queensland Government Groundwater Database
MRV- Main Range Volcanics (geological unit)
USQ- The University of Southern Queensland
WCM- Walloon Coal Measures (geological unit)

Executive summary

Over 500 hydrographs of monitoring bores, located in the Condamine Catchment, were reviewed, analysed and clustered. Results indicate that the consistent trend of declining water levels occurred for several decades in most parts of the Condamine catchment and ceased in the late 2000s. In most bores in the Condamine catchment, current groundwater levels are higher by 1.5 – 8.5 m than the levels recorded in 2010. In other bores, groundwater levels stabilized since 2007. These trends are a cumulative result of (1) enhanced recharge during summer 2007/08 and summer 2010/11 flood events, and (2) restriction on water pumping in the CGMA.

The bore hydrographs testify to the conceptual mechanism of recharge and inter-connections between aquifers in the catchment: (1) Diffuse recharge occurs over the eastern and south-eastern rims of the catchment, (2) the elevated water table introduce higher fluxes toward the Condamine floodplain, and (3) the enhanced lateral fluxes combined with restricted pumping lead to stable water levels in the floodplain.

The current hydrological situation thus represents a step toward sustainable use of the groundwater resources. Nevertheless, the lateral fluxes from the eastern recharge zones are not constant and may decrease again should another drought period will take place in the Darling Downs region. It is suggested to keep the water allocation process in place and also to incorporate the effect of water table elevation in the eastern recharge areas, in the water allocation announcement equation.

Table of Contents

Executive summary	II
1 Introduction.....	1
1.1 Scope of the report	1
1.2 Aims and Objectives.....	2
2 Investigation area	3
2.1 Climate.....	4
2.2 Hydrology	5
2.3 Hydrogeology	7
3 Methodology	12
3.1 Data sources	12
3.2 Data analysis	13
4 Results.....	14
4.1 Rainfall.....	14
4.2 Stream flow discharge	16
4.3 Groundwater levels	19
4.3.1 Groundwater level trends	19
4.3.2 Timing of groundwater level rise	20
4.3.3 Extent of groundwater level rise.....	21
4.4 Hydrograph patterns	24
5 Discussion	31
5.1 Response to 2007/8 events.....	31
5.2 Response to 2010/11 events	33
5.3 Streams - groundwater connectivity.....	36
5.4 Rainfall/groundwater relationship.....	38
5.5 Pumping effects on hydrographs.....	39
5.6 Shallow horizons within the CRAA	40
5.6.1 Individual bores	40
5.6.2 Conclusions	42
5.7 Flooded bores.....	43
6 Summary	45
7 Reference.....	47
Appendix A - Bore hydrographs	48

Tables list

Table 1: Stratigraphic column.....	7
Table 2: List of selected stream gauging stations	13
Table 3: List of selected rain gauging stations	13
Table 4: Recent groundwater levels in respect to 2007-2010 levels.....	19
Table 5: Minimum groundwater level year in bores with rising water table	21
Table 6: Extent of groundwater level rise	21
Table 7: Distribution of hydrograph patterns	24
Table 8: Summary of hydrographs patterns	26

Figures list

Figure 1: Location map	3
Figure 2: Rain isohyets	4
Figure 3: Monthly time-series for the years 2000-2013.....	5
Figure 4: Schematic hydrogeological cross-section	8
Figure 5: Estimated recharge map (source: Hansen, 1999)	9
Figure 6: Water level maps in the Condamine floodplain.	10
Figure 7: Hydrograph of bore 42230058	11
Figure 8: Hydrograph of bore 42230018	11
Figure 9: Hydrograph of bores 42231318 and 42231317	12
Figure 10: Recent rainfall trends.....	15
Figure 11: Recent stream flow records	17
Figure 12: Recent (2007-2013) groundwater level changes.....	20
Figure 13: Groundwater initial rise year (2007-2012)	22
Figure 14: 2010-2013 groundwater levels rise.....	23
Figure 15: Spatial distribution of the hydrographs patterns	25
Figure 16: Bores show groundwater rise in 2007.....	32
Figure 17: Spatial distribution of hydrograph patterns B, C and E	33
Figure 18: Spatial distribution of hydrograph's patterns A, B and D	34
Figure 19: 2010-2013 Groundwater rise and Hansen (1999) Net Recharge map	36
Figure 20: Groundwater levels in selected bores and stream discharge.....	37
Figure 21: Comparison of bore 42231399 hydrographs with rainfall.	39
Figure 22: Sites with records of two water table horizons within the CRAA	43
Figure 23: Hydrographs of paired bores- flooded and unaffected.....	44

1 Introduction

In the previous decade (2000s), a prolonged drought occurred in south-east Queensland. For example, the average annual rainfall in Jondaryan, at the heart of the Condamine Catchment, was 546 mm, much lower than historical average (640 mm). These changes affected the water availability in the region, in terms of domestic users (water restriction), surface water (reduced flow in streams and dam storage) and groundwater (cap on water allocations). Contrarily, in recent years (2010-2013) two extreme floods have occurred and water restrictions were eased.

This report reviews the recent temporal trends of groundwater levels in the Condamine Catchment and its association with recent rainfall and stream flow series.

1.1 Scope of the report

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

The report presents the up-to-date conceptual understanding of the hydrogeology in the Darling Downs region (Condamine catchment), including the Condamine River Alluvial Aquifer (CRAA), followed by a detailed analysis of bores hydrographs. The latter is based solely on DNRM monitoring bores, which are spread throughout the area and generally have frequent water level monitoring. Data of private domestic & stock bores was excluded; however it is not expected to affect the result as usually it includes only one level record per bore rather than levels time-series.

Quantification of the inter-connectivity between the Walloon Coal Measures (WCM) and the CRAA is out of the scope of this review. This is due to the relatively small numbers of bores registered as penetrating the WCM and the uncertainty in the affiliated formation of other bores penetrating deep sandy section.

1.2 Aims and Objectives

The hydrogeological review had three primary aims:

- Identify recent trends of groundwater levels in the Condamine catchment, including the cotton growing area of the Condamine floodplain
- Indicate association between rainfall and flood events to groundwater levels trends
- Support the hydrogeological conceptual model for the basalt, alluvial and sedimentary aquifer systems within the investigation area

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

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

2 Investigation area

This investigation area covers the entire Condamine Catchment, south-east Queensland. The catchment, stretches over an area of about 24,600 km² (Figure 1), comprises a large floodplain surrounded by gentle highlands; the eastern part of the catchment runs along the Great Dividing Range.

Data from the area west of the Condamine floodplain and Condamine River (Fitz, Sandy, Wilkie and Wambo creeks) is scarce.

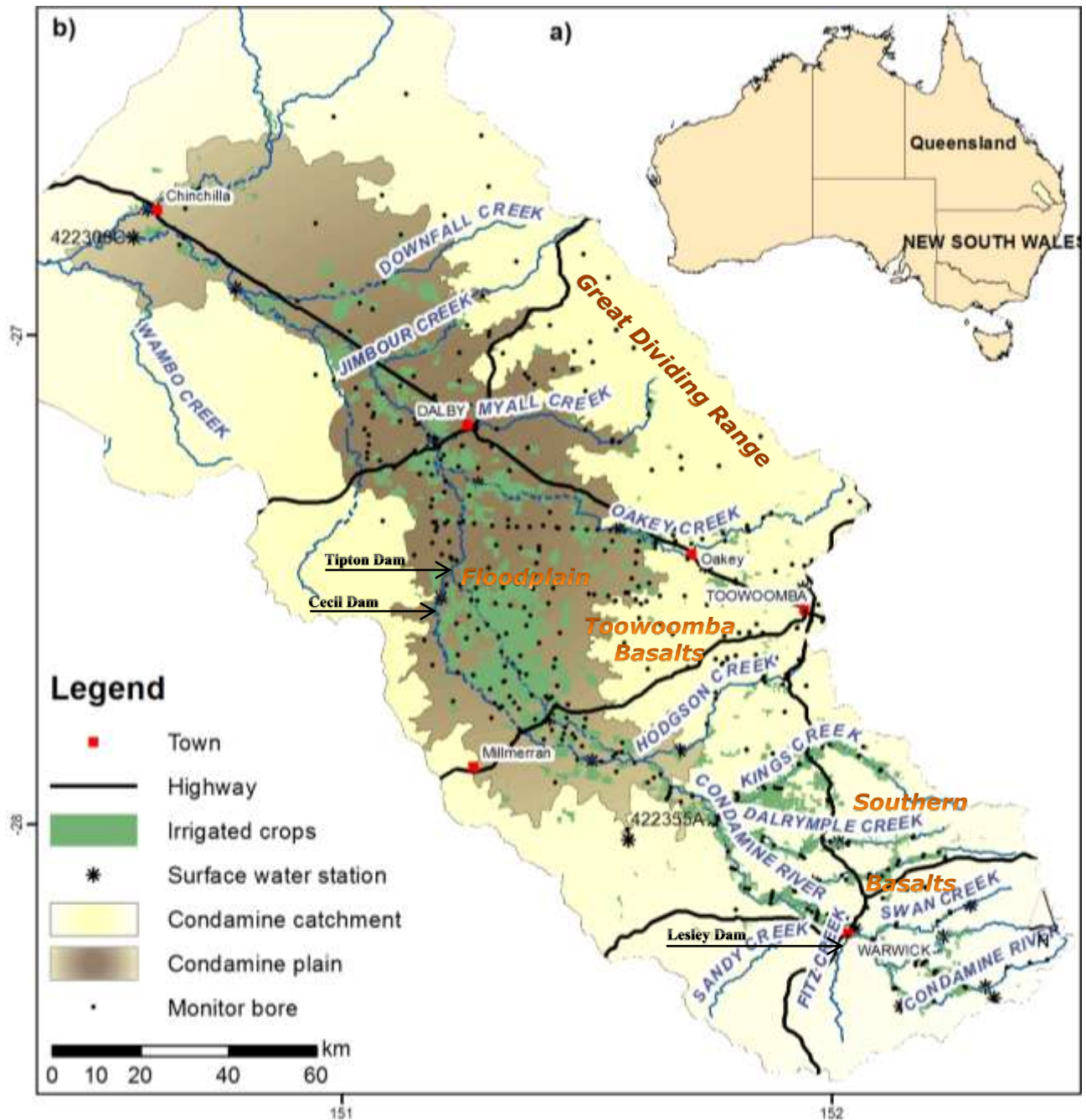


Figure 1: Location map

2.1 Climate

Most of the catchment is characterized by a semi-arid climate. Average rain varies between ~600-680 mm in the floodplain to ~700-800 mm on the eastern hilly area (Figure 2). The southern-most margin trends into a temperate climate with substantial higher rainfall, up to ~1100 mm/yr. Hot, dry summers (October-March) with prolonged drought periods common across the catchment.

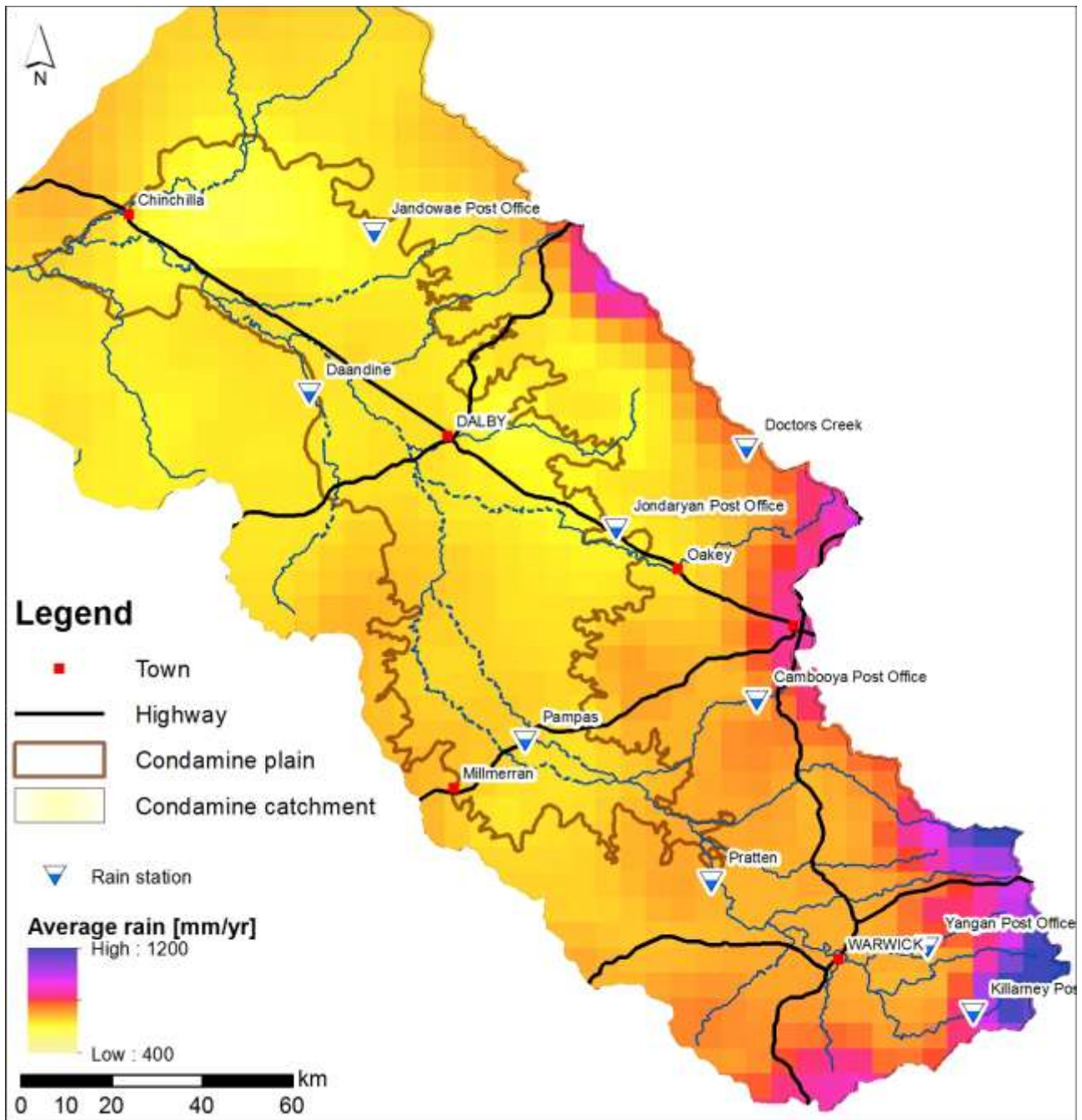


Figure 2: Rain isohyets (Source: BOM) and selected gauging stations (stations detail in Table 3).

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

A long-term water budget shows that in most parts of the catchment, total evaporation exceeds rainfall. Nevertheless, there are short-term periods where rainfall (+irrigation) exceeds evaporation and water may percolate to the unsaturated zone and recharged to the aquifer.

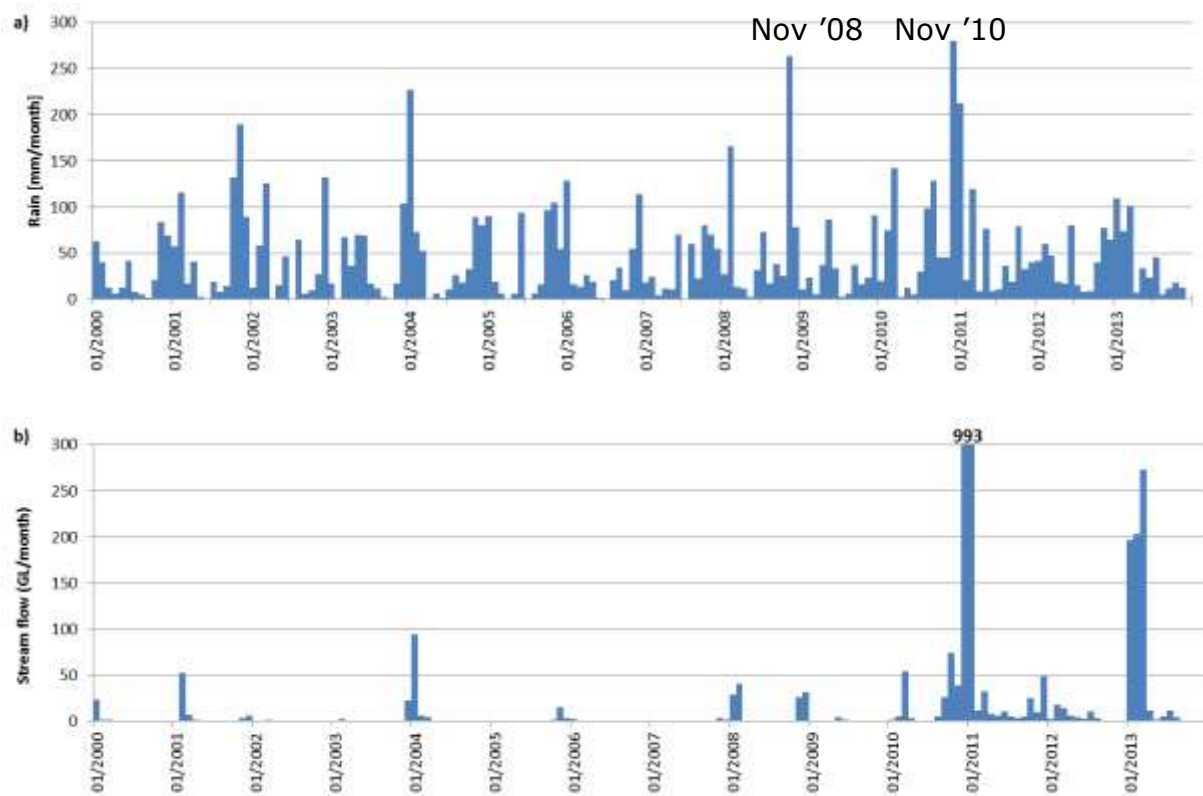


Figure 3: Monthly time-series for the years 2000-2013 of (a) rainfall in Jondaryan (source: BOM); (b) Condamine stream flow near Cecil Plains (source: DNRM).

2.2 Hydrology

Many streams drain the highlands surrounding the alluvial plain to form the Condamine River and the Condamine Catchment. These include the upper tributaries of the Condamine River- Kings, Dalrymple, Glengallan, Swan, Emu, Fitz and Sandy creeks; the eastern tributaries- Hodgson, Oakey, Myall, Jimbour and Downfall creeks and the northern tributary- Charleys Creek (Figure 1). All the Condamine tributaries,

but Oakey Creek, are intermittent. Hydrological stations were erected in the Oakey and Hodgson creeks, at the point where these streams enter the floodplain; a flood warning station is located in Myall Creek, at Dalby¹.

In the southern part of the Condamine floodplain the river splits into two branches- the 'North Branch' to the east and the 'Main Branch' to the west; both merging near Cecil-Plains (Figure 1). Under natural conditions, the North Branch was an intermittent stream, but since about 1989 has received pumped diversions from the main river channel (SKM, 2003).

Several weirs were erected along the river, including weirs for water supply near Warwick (Leslie Dam), Cecil-Plains and Tipton (Figure 1). Leslie Dam regulates the river flow downstream of Warwick, as water is released for irrigation ('regulated flows'). 'Unregulated flows', i.e., storm runoff occurs following intensive rainfall events, usually during the summer. The average annual discharge (including regulated and unregulated flows) of the Condamine River as it enters the alluvial plain is 115 GL/yr (stations 422355A). Along its course, the river drains several intermittent creeks, and as the river leaves the floodplain its average discharge is 581 GL/yr (station 422308C). Concurrently, water is being extracted from the river for irrigation either as 'regulated diversion' or as 'unregulated flows', pumped from the river when flows exceed nominated thresholds. The flow in the surface water system is extremely variable and the Condamine River may reduce to a series of drying ponds during severe droughts, or develop into a vast shallow flooded area.

Many farmers on the floodplain use furrow irrigation- water is supplied via head ditches and any surplus water is collected in tail drains, and re-circulated into large on-farm dams for future use. Thus, storm runoff, which would naturally drained into the major creeks, is captured by the tail ditch and stored on-farms as well (termed also 'surface water harvesting').

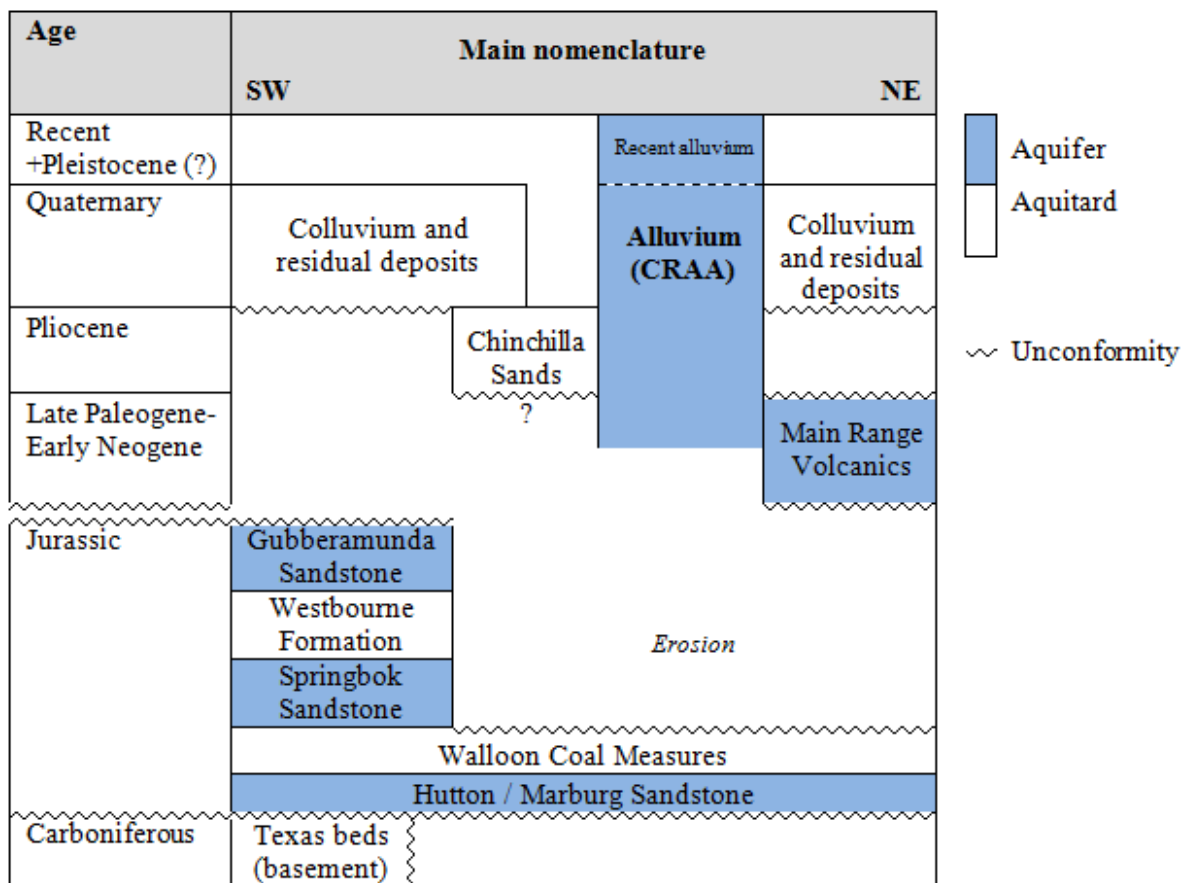
Apart from regulated diversions, pumped unregulated flow, and surface water harvesting, irrigation is based on groundwater extraction, mainly from the CRAA.

¹ http://www.bom.gov.au/qld/flood/brochures/condamine_myall_creek/condamine_myall_creek.shtml

2.3 Hydrogeology

The study area is characterised by its contrasting geology consisting (from bottom to top) of Jurassic sedimentary formations, including some coal measures, Tertiary basalts (Main Range Volcanics) and Quaternary-Recent Alluvium and Colluvium. These geological units define the three dominant hydrogeological units in the investigation area, namely the sedimentary basement aquifers (interlayered with less permeable units, as demonstrated in Table 1), which will be termed here GAB units, the basalt aquifers and the alluvial aquifers.

Table 1: Stratigraphic column (Dafny and Silburn, 2013)



Generally, the GAB units are exposed (and utilized) in the SW margins of the catchment, the alluvial aquifer in the central part of the catchment, and the basaltic aquifers in the eastern margins (Figure 4). Nevertheless, the spatial relations between the aquifers are complex, especially in the eastern margins where:

- In places, the basalts were not layered upon the sedimentary basement and the latter outcrops and is recharged

- The basalts were incised and dissected into discrete spatial hydrogeologic units, the larger of which is called 'Toowoomba Basalt', and stretches between Oakey and Kings creeks (Figure 1)
- In places, thin alluvial sequence covers the basalt sequence

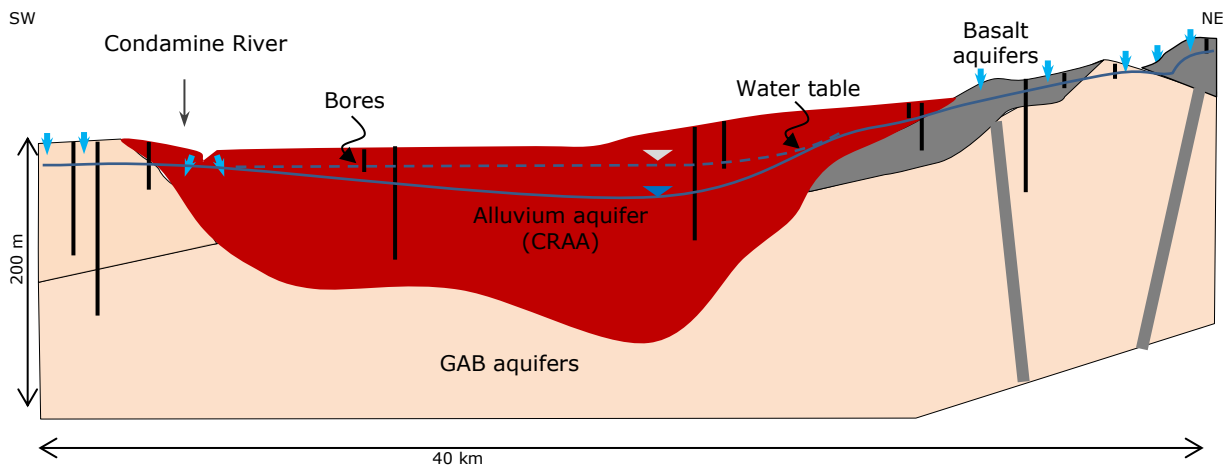


Figure 4: Schematic hydrogeological cross-section (not to scale) (white triangle – pre-pumping (1960s) water level, blue triangle – recent water level)

Recharge occurs over the eastern margins of the catchment, as rainwater percolates into the GAB and basaltic aquifers. An empirical attempt to map and estimate the recharge (Hansen, 1999) is shown in Figure 5. The map was produced based on estimations of leaching fraction over different soils, multiplied by the average annual rainfall; vegetation and irrigation effects were neglected.

Consequently, the eastern margins are the area where the highest heads occur; water flow is generally to the southwest in the GAB aquifers and corresponding to the topography in the basalt units. It is worth noting that several perched horizons occur in many places in the basalt sequence and that the basalt units discharge to streams, providing base-flow in wetter years.

On the other hand, the CRAA does not receive substantial quantities of direct recharge as the heavy clay soil hinder water percolation (except maybe at periods of excessive rain, floods or irrigation). Nevertheless, it receives substantial recharge from the Condamine River and lateral input from the adjacent aquifers, where the heads are higher (Huxley, 1982; Dafny and Silburn, 2013). The latter component includes inflow from shallow alluvial fans along the Condamine's tributaries. In other words, there are hydrological inter-connections between all the aquifers, as groundwater flow appears essentially continuous across the three aquifer systems (Pearce, et al., 2006); this

concept is supported by the data analysed in this report. It is important to note that while the extent of the recharge from the Condamine River to the aquifer is still not fully understood, in no section of the river are there conditions which allow the opposite situation, i.e., discharge from the aquifer to the river.

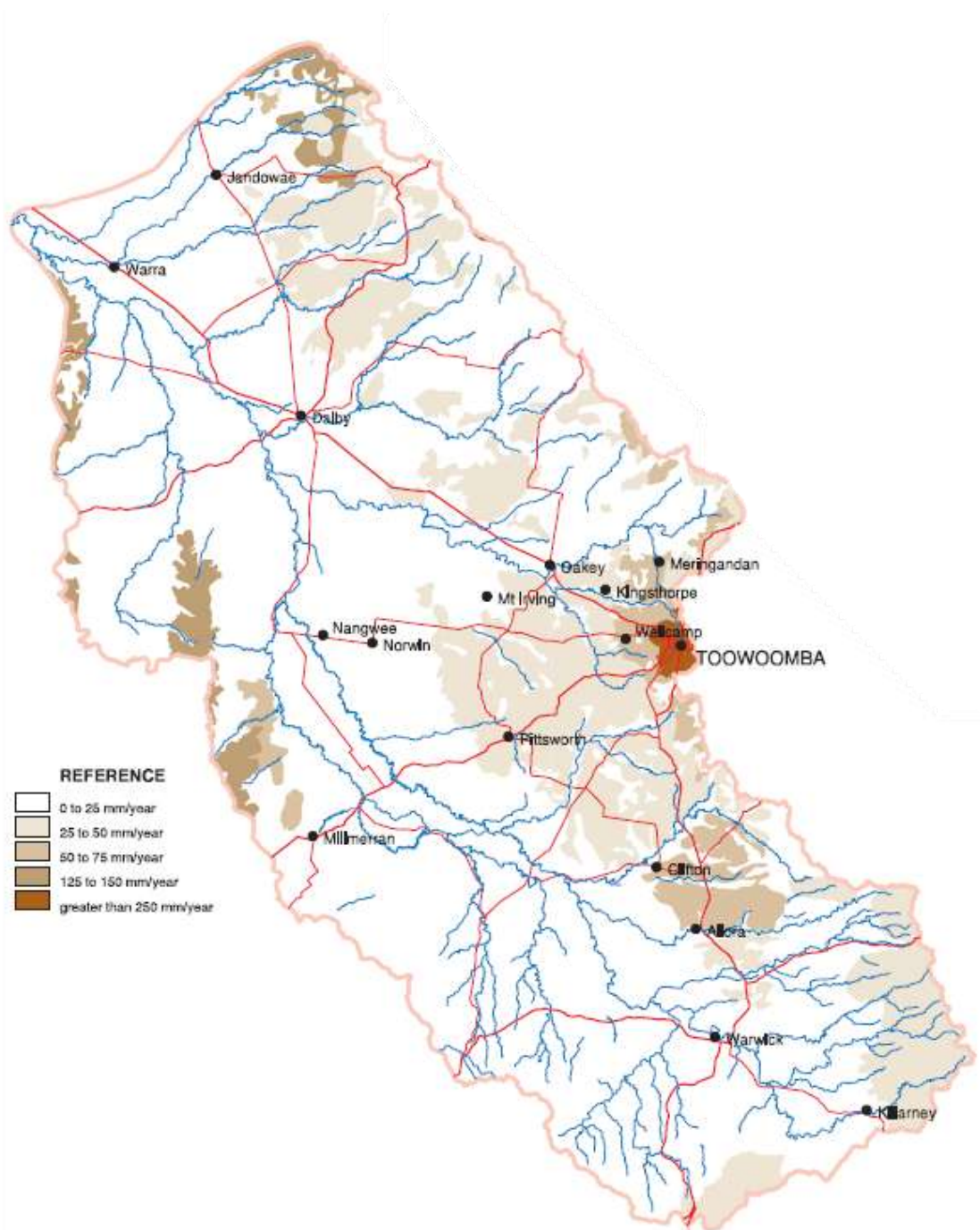


Figure 5: Estimated recharge map (source: Hansen, 1999)

Within the CRAA, groundwater flow was generally northward (Figure 6a). The aquifer was over-exploited during the last few decades, as groundwater was pumped for irrigation at an overall rate exceeding recharge. As a result, groundwater levels in the aquifer have dropped by 3-25 m from their pre-pumping elevations, and some shallow bores have dried-out; these settings are illustrated in Figure 4, while historical and current water levels in the CRAA are illustrated in Figure 6. The later map (Figure 6b) suggests that currently only the area NW of the Warra-Jandowae line drains toward the northern rims of the CRAA; the remainder draining towards several 'hydraulic lows' created by over-exploitation of the aquifer.

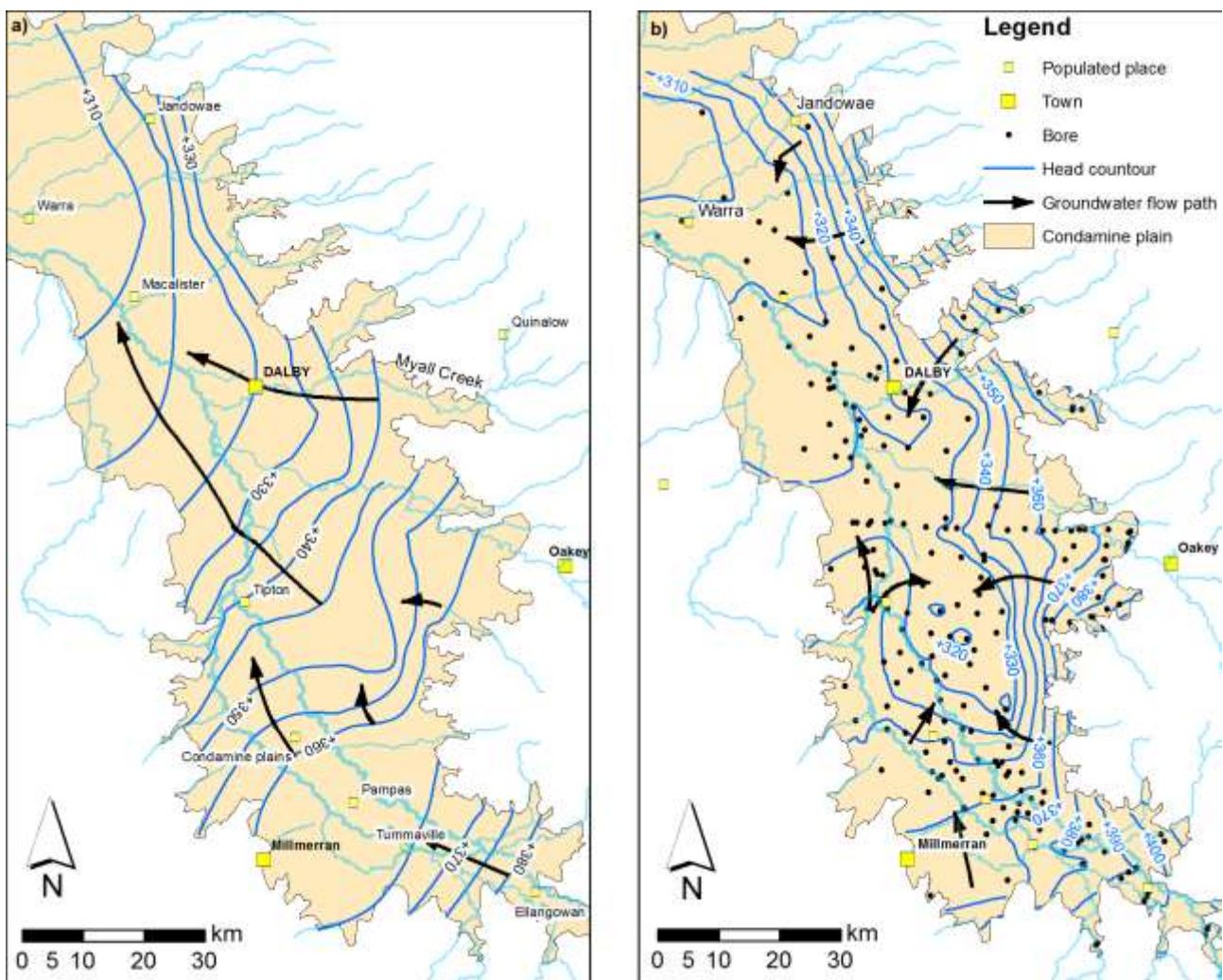


Figure 6: Water level maps in the Condamine floodplain (a) historical (1960s) levels (after KCB 2010); (b) 2011 levels (Dafny and Silburn, 2013).

The seasonal nature of the pumping (and recharge) leads to dynamic seasonal fluctuations of the water table, i.e., water levels decrease by several meters during the irrigation season (October-February) and recover in the following months (usually by April). These trends can be seen only where frequent monitoring is taking place, such as in several bores which are equipped with automatic level monitoring devices (ALMD) (Figure 7). Similarly, direct recharge events are characterized by a sharp rise in water level followed by an exponential recession as the water flow away (Figure 8).

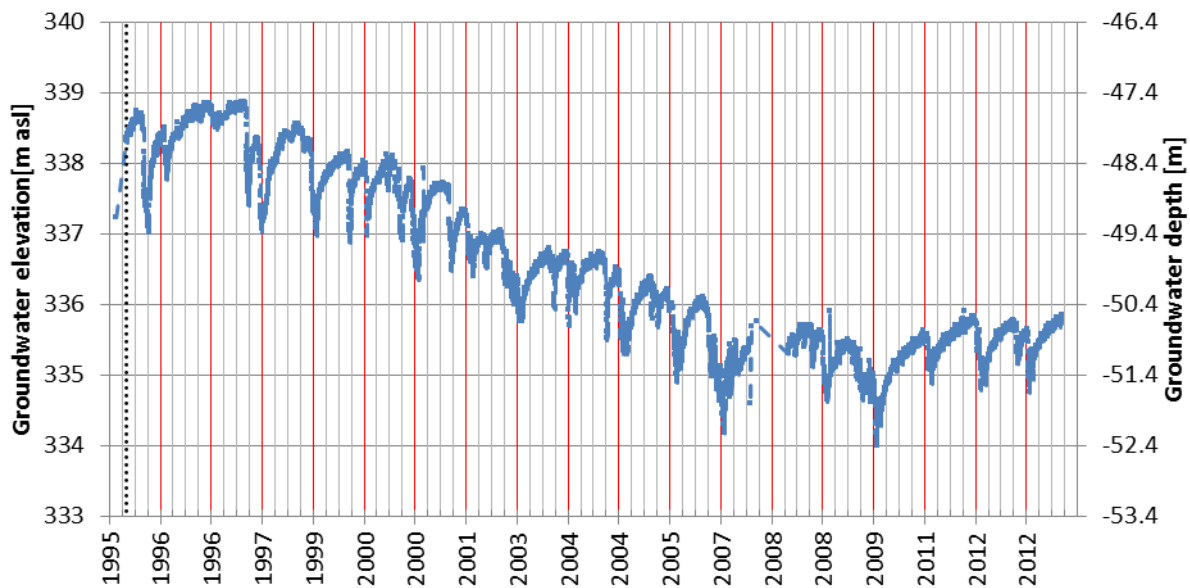


Figure 7: Hydrograph of bore 42230058, equipped with ALMD since 1995. Sharp water levels declines are due to pumping in a nearby irrigation bore; recovery is achieved within 6-12 months. (Data source: GWDB)

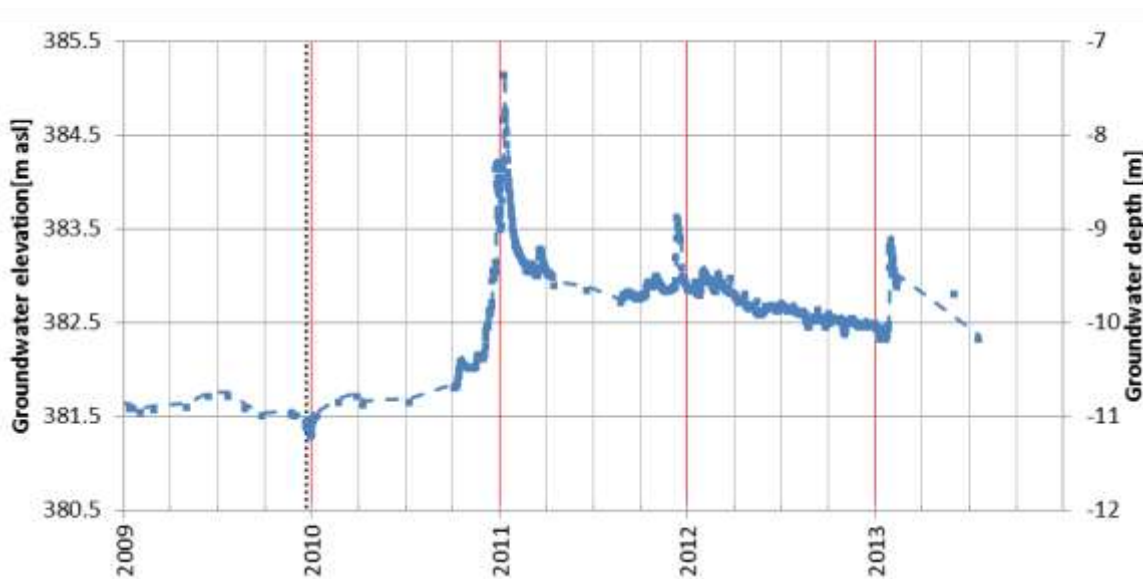


Figure 8: Hydrograph of bore 42230018, equipped with ALMD since 2010. Sharp water levels rises are due to discrete recharge events followed by exponential recessions. (Data source: GWDB)

In places, there is evidence for two different water tables within the CRAA. For example, where pairs of shallow and deeper pipes are installed in the same bore or where shallow and deeper bores were drilled adjacent to each other (Figure 9). The appearance, extent, groundwater level trends and explanation for such behaviour is the subject of this report and will be explained in detail in following sections.



Figure 9: Hydrograph of adjacent bores 42231318 and 42231317 (both near Dalby), drilled to depth of 44 m and 120m, respectively. (Data source: GWDB)

3 Methodology

3.1 Data sources

Bore data was extracted from the Queensland Government Groundwater Database (GWDB), which is managed by DNRM. The database includes groundwater depth records for 594 monitoring bores in the Condamine catchment; 504 of these bores (85%) were selected for analysis, as they contain some records for years 2007-2010 and 2012-2013. Other bores, which do not have records for these years, were excluded as temporal interpretation for 'current trend' is practically impossible.

Surface water data (stream flux) was extracted from the Queensland Government DNRM Water Monitoring Data Portal website (DNRM web site, 2013). Seven gauging stations are located along the Condamine River, and three others were selected along Hodgson, Gowrie and Oakey creeks. Some creeks, such as Myall Creek, do not have any gauging station and stream flow data is unavailable. The raw data included many footnotes relating to the accuracy of the measurement, such as estimations, poor or fair reading; these were overlooked when stream flow time series were created.

Rainfall data was extracted from the Australian Bureau of Meteorology website (BOM web site). Nine stations with long-term records, going back to the late 19th century in several cases, and which spread through the catchment, were selected.

The data was extracted in December 2013, and was censored at 1/12/2013.

Table 2: List of selected stream gauging stations

Station	Location	Location (Order) along the Condamine
422308B	Condamine River at Chinchilla	7
422310C	Condamine River at Warwick	1
422316A	Condamine River at Cecil Weir	4
422323A	Condamine River at Tummaville	3
422332A	Gowrie Creek at Oakey (act 'till 2012)	
422333A	Condamine River at Loudouns Bridge (Dalby)	5
422336A	Condamine River at Brigalow	6
422352A	Hodgson Creek at Balgownie	
422355A	Condamine River at Talgai tailwater	2
422359A	Oakey Creek at Jondaryan (act from 2011)	

Table 3: List of selected rain gauging stations (source: BOM; locations in Figure 2)

Station	#	Opened	Lat.	Lon.	Elevation [m]	Annual average [mm/y] ¹
Doctors Creek	41024	1906	-27.21	151.85	612	717
Cambooya	41011	1887	-27.71	151.87	476	682
Jandowae	41050	1898	-26.78	151.11	362	661
Jondaryan	41053	1887	-27.37	151.59	382	636
Killarney	41056	1889	-28.33	152.3	507	636
Pratten	41083	1898	-28.07	151.78	609	671
Yangan	41120	1912	-28.2	152.21	536	706
Pampas	41250	1959	-27.79	151.41	390	635
Daandine	41297	1905	-27.1	150.98	331	661

Notes: ¹ For the entire historical record, up to 2013

3.2 Data analysis

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

1)
$$WL = Ref + WD$$

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

The hydrographs of 504 bores were manually analysed for temporal trends. In most, no uniform trends were found (for example, a step rise in 2010 followed by rather stable heads in 2011-2013). For this reason, current levels were characterised as either above, similar to or below 2007-2010 levels. In a minor portion of the hydrographs (3%), even such a distinction could not be reached, as data are scarce.

The bores were clustered according to hydrograph shape into eight groups (titled A-H). All of the hydrographs are presented in Appendix A, in accordance with this grouping. Hydrographs show groundwater elevation in the period 2000-2013 (that is, until the end of 2013) but with varying vertical scale. Representative cases from each group were compared with rainfall and stream flow data to assess potential responses to the recharge events based on visual appraisals.

4 Results

4.1 Rainfall

Rainfall in recent years at nine rain gauging stations through the catchment is presented in Figure 10. Each diagram shows the annual rainfall (columns), the running 5-year average (black line), the long-term historical average since erection of the station (red line) and two decade's average (purple lines) - the first for 2000-2009 and the second for 2011-2013. An extreme rainy year was recorded in the entire basin in 2010; this year was not included in the 2011-2013 average.

In all stations, the 2010s average exceeds the 2000s average and the running 5-year average substantially increased just before 2010. In some stations, the 2010s average exceeds the long-term average. To conclude, an increase in the overall rainfall occurred over the entire catchment, especially on its eastern rims.

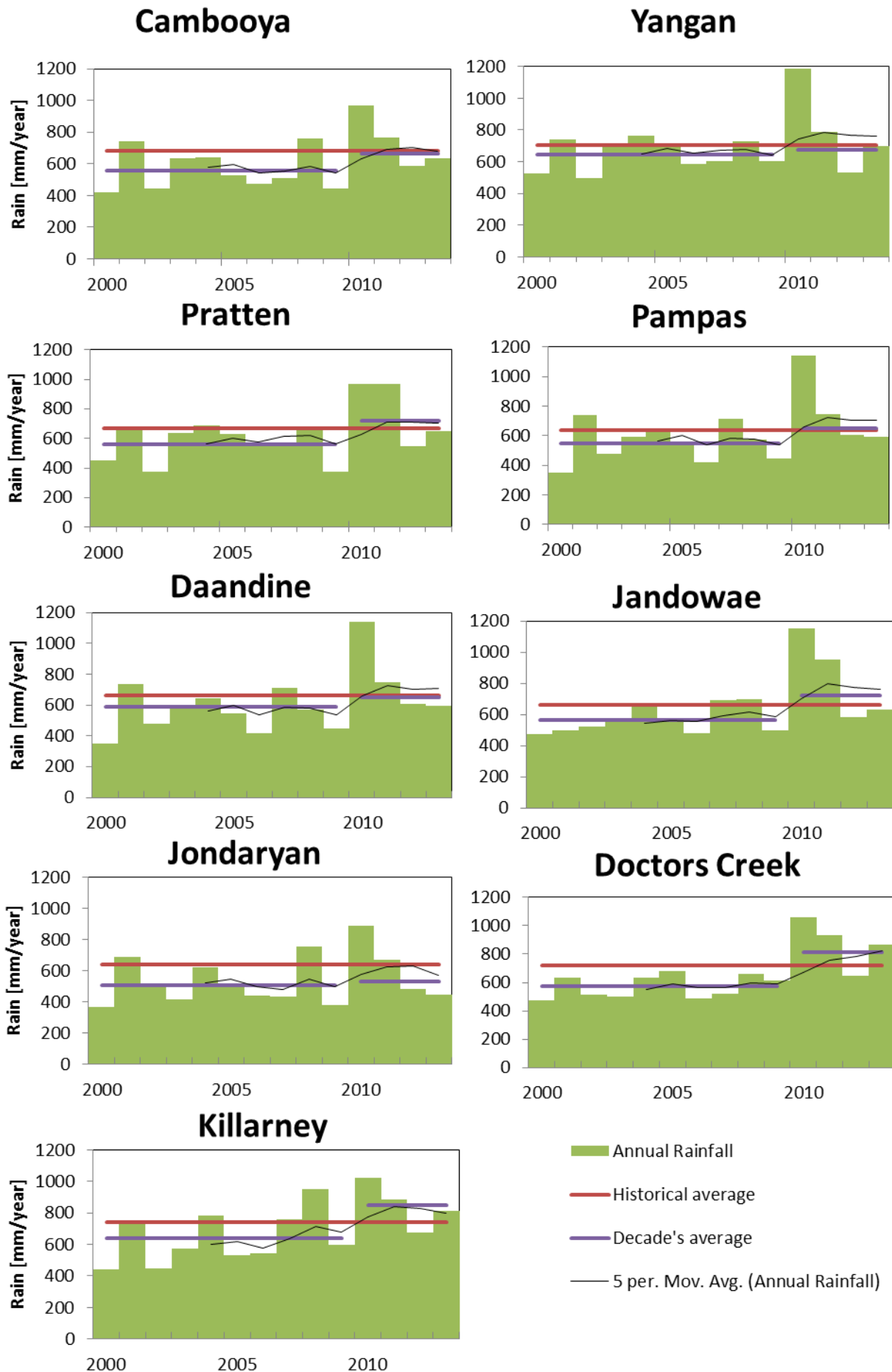


Figure 10: Recent rainfall trends (stations location in Figure 2 and Table 3)

4.2 Stream flow discharge

Stream flow (discharge) at seven gauging stations, located along the Condamine River, is presented in Figure 11 (note that Cecil Plains station is presented twice, to allow better comparison with upstream and downstream stations). Each diagram shows the monthly discharge (columns) in GL (Giga-litre, equivalent to 10^6 cubic meters).

Generally, the records testify for seasonal flow pattern, with very low (below threshold) discharge during the winter months and intermittent 'floods' in the summer, usually between December to March, in the following year. Most stations show such flow events in the summer of 2000/1, 2003/4, 2007/8, 2008/9, 2010/11 and 2012/13. Discharge generally increases in the downstream direction, with the exception of Tummaville station (The latter probably reflects some fault in the measuring method and not exhaustion of the stream flow due to extraction of the river water). For example, the February 2010 flow event is almost doubled from ~250 GL near Warwick to 455 GL near Talgai, to 993 GL near Cecil Plains and to 2196 GL near Brigalow. The increase in the discharge is associated with the additional drainage of the Condamine tributaries; however it is not evenly spread. For example along a 39 km section, in between Cecil Plains and Dalby stations, which drain the North Branch, Ashall Creek and Oakey Creek, discharge increase is minor. In contrast, along the 58 km section, in between Dalby and Brigalow stations, which drain Myall, Jimbour and Cooranga creeks from the east and Wilkie and Braemar creeks from the west, the discharge is almost doubled.

When compared with the rain, a general association between high rainfall and high flow events is shown, as expected (Figure 3). However, this association is not linear- i.e. the same amount of monthly rain may not have significantly influenced the flow in several years yet caused severe flooding in other years. This is the case for the November 2008 and November 2010 rain events (260-270 mm), respectively (Figure 3). In turn, this suggests that run-off is affected by other parameters, such as humidity and temperature (potential evaporation), rain intensity, antecedent rainfall, etc., all leading to varying degrees of soil saturation.

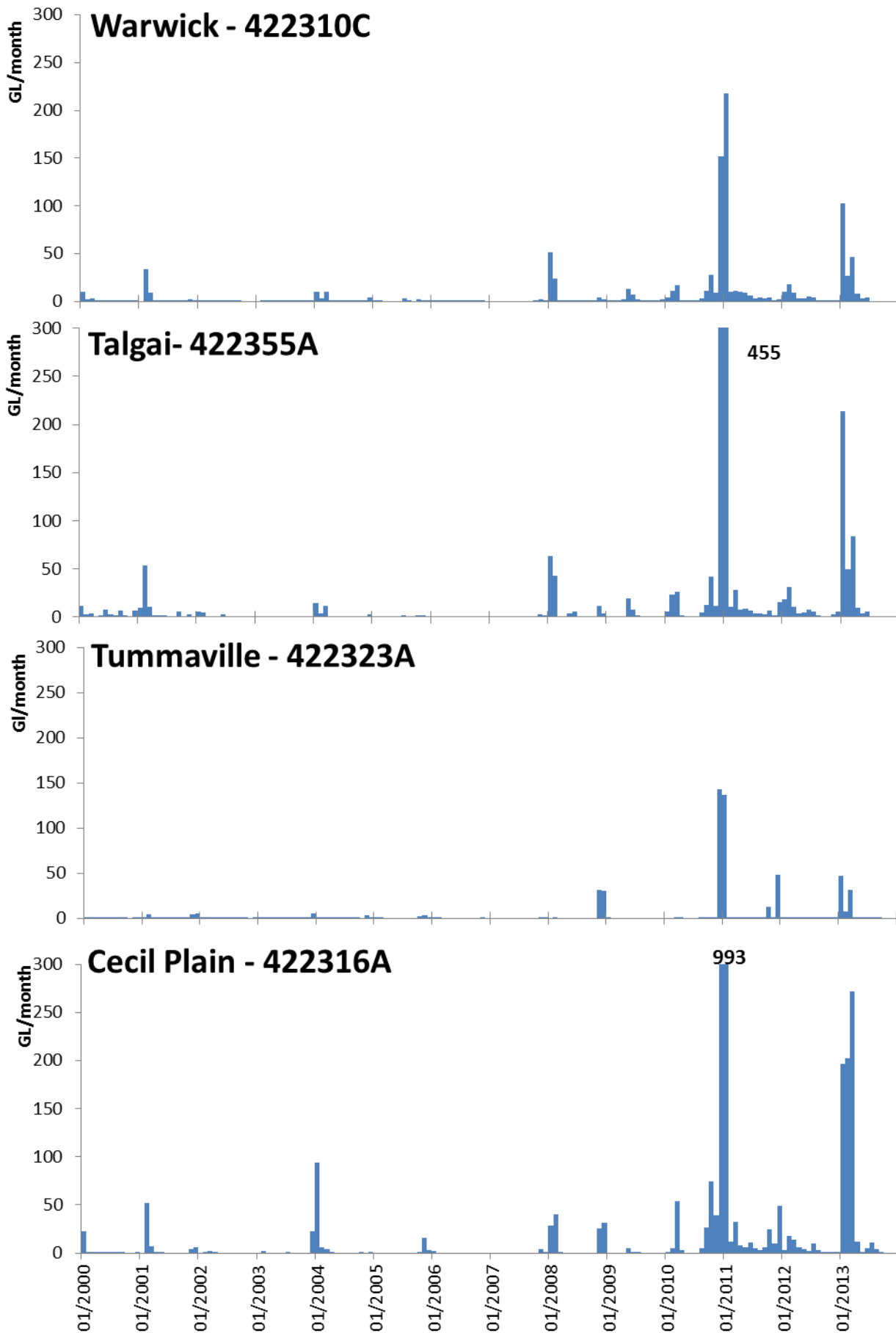


Figure 11: Recent stream flow records (stations location in Figure 2 and Table 2)

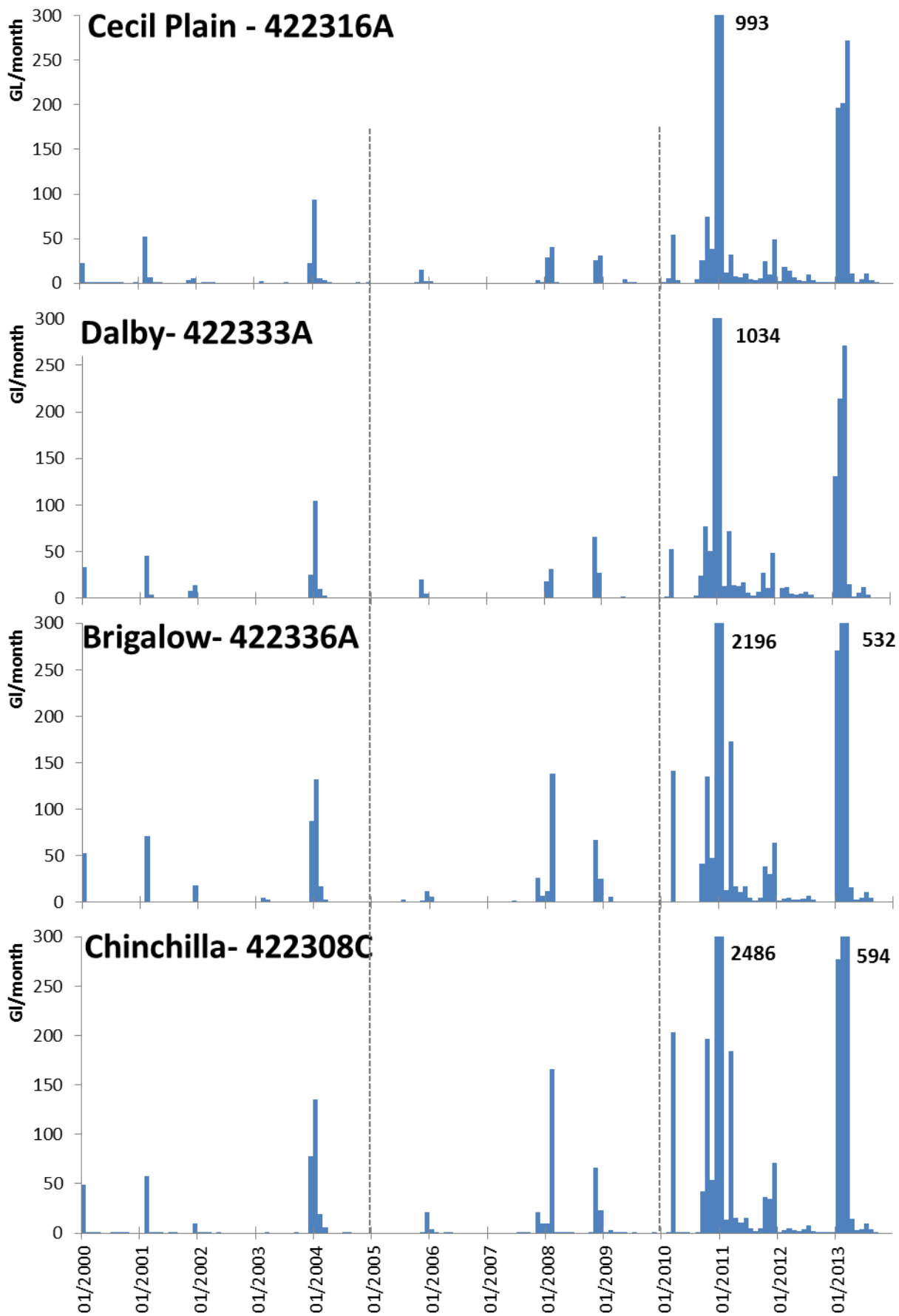


Figure 11: Recent stream flow records (stations location in Figure 2 and Table 2)

4.3 Groundwater levels

Data from 491 hydrographs of bores throughout the Condamine Catchment indicate, with a sufficient confidence, the actual groundwater levels relative to 2007-2010 levels; 13 additional hydrographs were found to be non-indicative (Table 4). The 2007-2013 and the 2010-2013 increments in groundwater levels were captured and analysed on statistical and spatial bases. Hydrographs were collated into 8 major groups and enable enhanced insights regarding recharge and connectivity mechanisms as will be discussed in the following sections.

4.3.1 Groundwater level trends

In most parts of the catchment, the current groundwater levels (2012-2013) are above the 2007-2010 levels (Figure 12, Table 4). Stable trends (similar levels) were recorded in 86 bores (17% of total), most of which are spread in the central part of the Condamine floodplain, and between Dalby and Warra; both are major irrigation areas. Lower levels and falling trends were recorded in nine bores (1.8% of total), five of which are located along the western rims of the Condamine floodplain.

Table 4: Recent groundwater levels in respect to 2007-2010 levels

Current level	Number of bores	% of all
Above	396	79%
Similar	86	17%
Below	9	2%
Non-indicative	13	3%
Total	504	100%

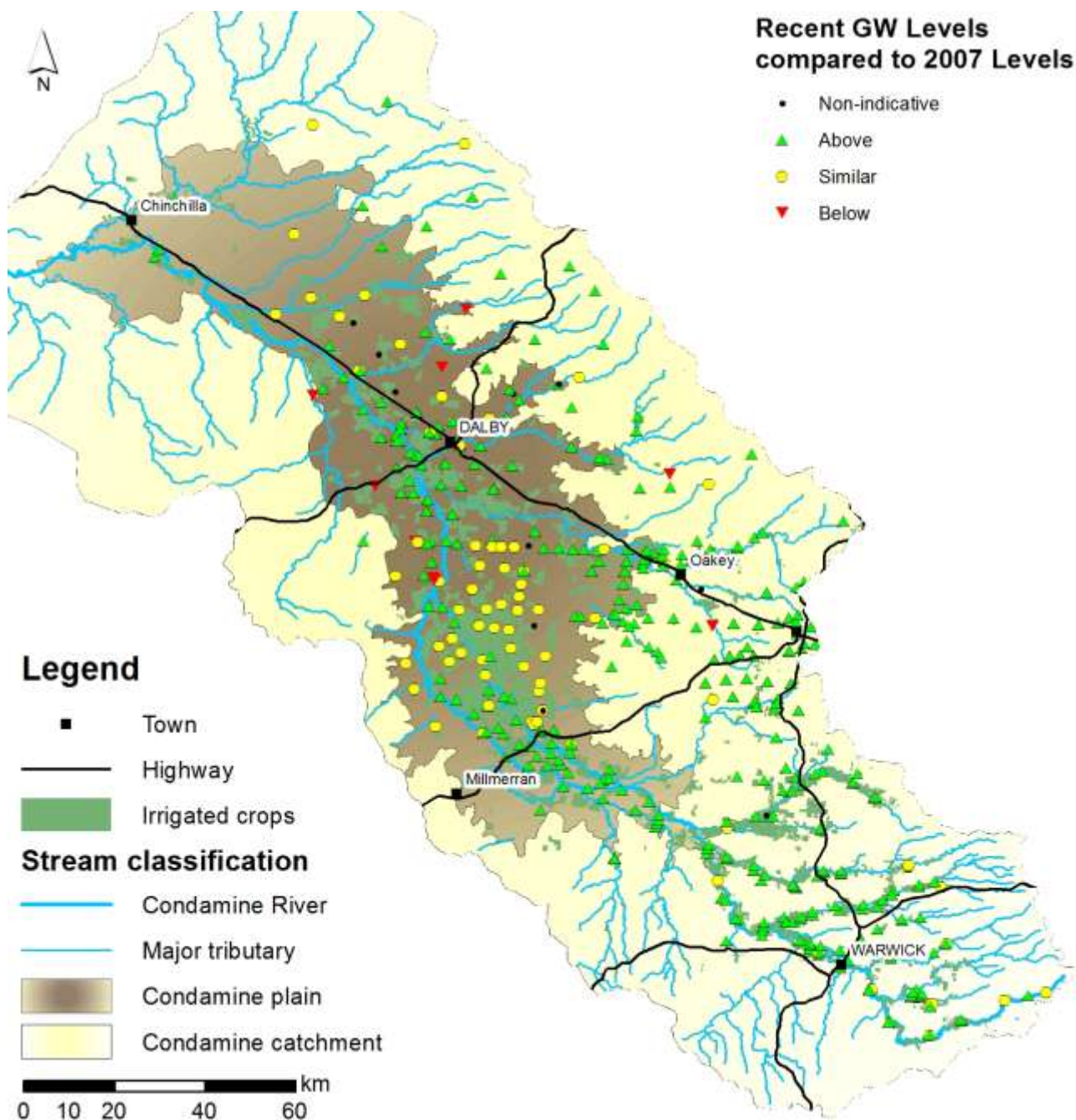


Figure 12: Recent (2007-2013) groundwater level changes

4.3.2 Timing of groundwater level rise

Most hydrographs show a continuous decrease in groundwater levels prior to, and in the mid-2000s. This trend ceased in most bores between the years 2007 (27% of rising bores) and 2010 (58% of rising bores) when groundwater level stabilized or increased; Table 5 lists the years in which minimum levels were recorded in the rising bores. Many bores which show an initial increase in 2007 are located at the upper tributaries and the uppermost part of the Condamine River (Ellangowan – Millmerran); several others are located around Dalby and near Oakey (Figure 13).

Table 5: Minimum groundwater level year in bores with rising water table

Year of minimum level record	Number of bores	% of all
<2007	19	5%
2007	105	27%
2008	28	7%
2009	6	2%
2010	229	58%
2011	9	2%
Total	396	100%

4.3.3 Extent of groundwater level rise

Some of the groundwater level statistics in the rising bores are presented in Table 6. Overall, there are about much more data points for 2010 statistics than for 2007 statistics; the reason is that in 264 bores (384-120=264; Table 6) levels still decreased between 2007 and 2010 and statistics are therefore of no added value. It is apparent that the overall groundwater level increase since 2007 is higher than the increase since 2010 in all percentiles. The maximum values however are biased by three data points which show significant higher values than all the rest. Neglecting these points, the maximum for 2010 is ~14 m in respect to maximum from 2007 of ~18m.

Table 6: Extent of groundwater level rise (P = percentile)

Statistics	Rise since 2007 [m]	Rise since 2010 [m]
n	120	384
Max	17.78	25.95 [#]
P-90%	7.90	7.67
P-75%	5.55	4.13
P-50%	3.34	2.34
P-25%	2.14	1.35
P-10%	1.26	0.62

Note: [#] value is affected by few data points. See text for explanation.

Overall, the largest increase in groundwater levels was recorded in the 'Toowoomba basalt' zone (Figure 14). Moderate increases occurred in the 'Southern basalt' zone and near Dalby, and mild increases occurred in other areas along the Condamine floodplain. Bores that were 'stable' (no clear rise) are concentrated in the central Condamine alluvia, between Pampas (Gore Highway) and Oakey Creek, the area of greatest long term pumping. Inconsistent rise in several other areas will be discussed in the following sections.

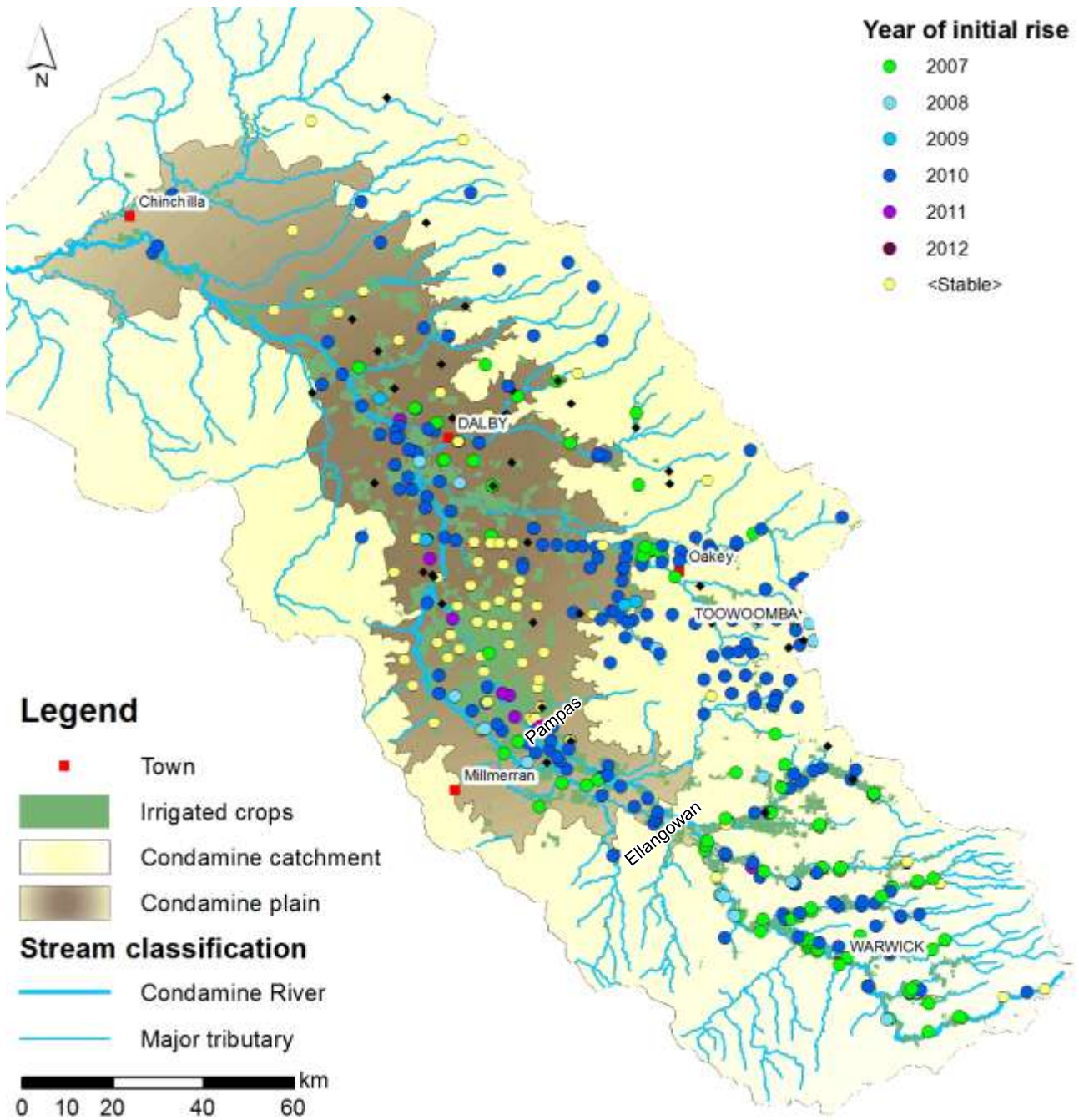


Figure 13: Groundwater initial rise year (2007-2012)

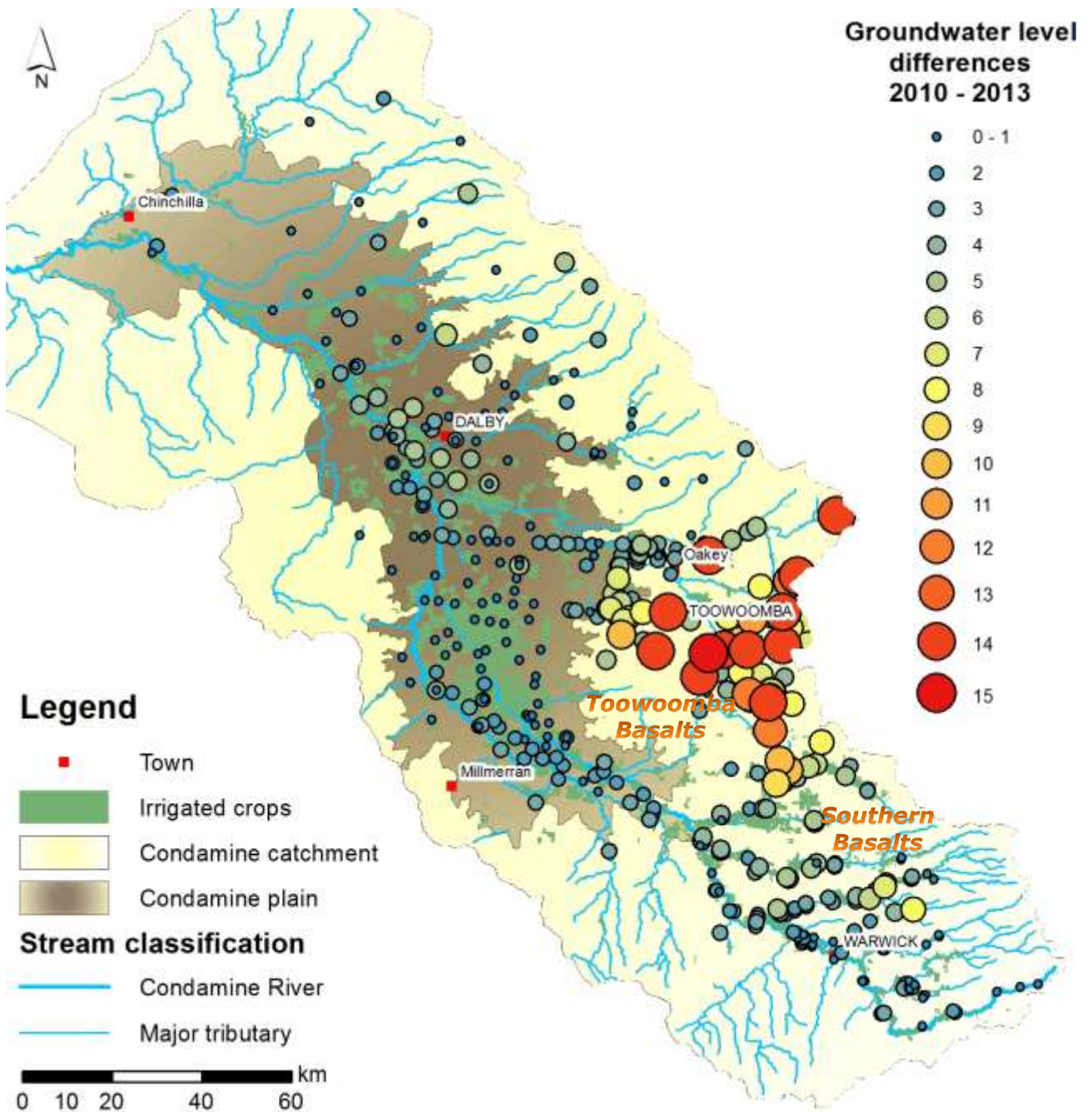


Figure 14: 2010-2013 groundwater levels rise (in meters)

4.4 Hydrograph patterns

Eight patterns (marked A-H) which collate, with sufficient confidence, 87% of the analysed hydrographs, were detected following a manual visual classification of bore hydrographs; five of which (A-E) represent 76% of all bores (Table 7). Against a background of previous falling levels, patterns A, B, D and E represent bores that recovered (i.e. rose) in various stages since 2007 or 2010 (69 % of bores), E having a distinct continuous rise (12%). Pattern C were falling and then have been steady since 2007 (7%), indicating a balance been recharge and pumping/discharge. Pattern H bores have been rising continuously prior to 2007 (1%). Pattern F bore have continued falling since 2000 (2%). Pattern G bore have been steady or unresponsive (8%). Other bore hydrographs could not be sufficiently classified into one of the identified pattern as they either present a hybrid pattern or a unique pattern. Some patterns include several 'variants', i.e., they share the same major attributes but are distinguish in minor attributes. The patterns, their major attributes and variants are presented in Table 8. The spatial distribution is presented in Figure 15. It is important to note that the classification process was done manually, and as such in some cases is subjective to a certain degree.

Table 7: Distribution of hydrograph patterns

Pattern	Number of bores	% of total
A	111	22%
B	81	16%
C	37	7%
D	96	19%
E	59	12%
F	9	2%
G	38	8%
H	7	1%
x	66	13%
Total	504	100%

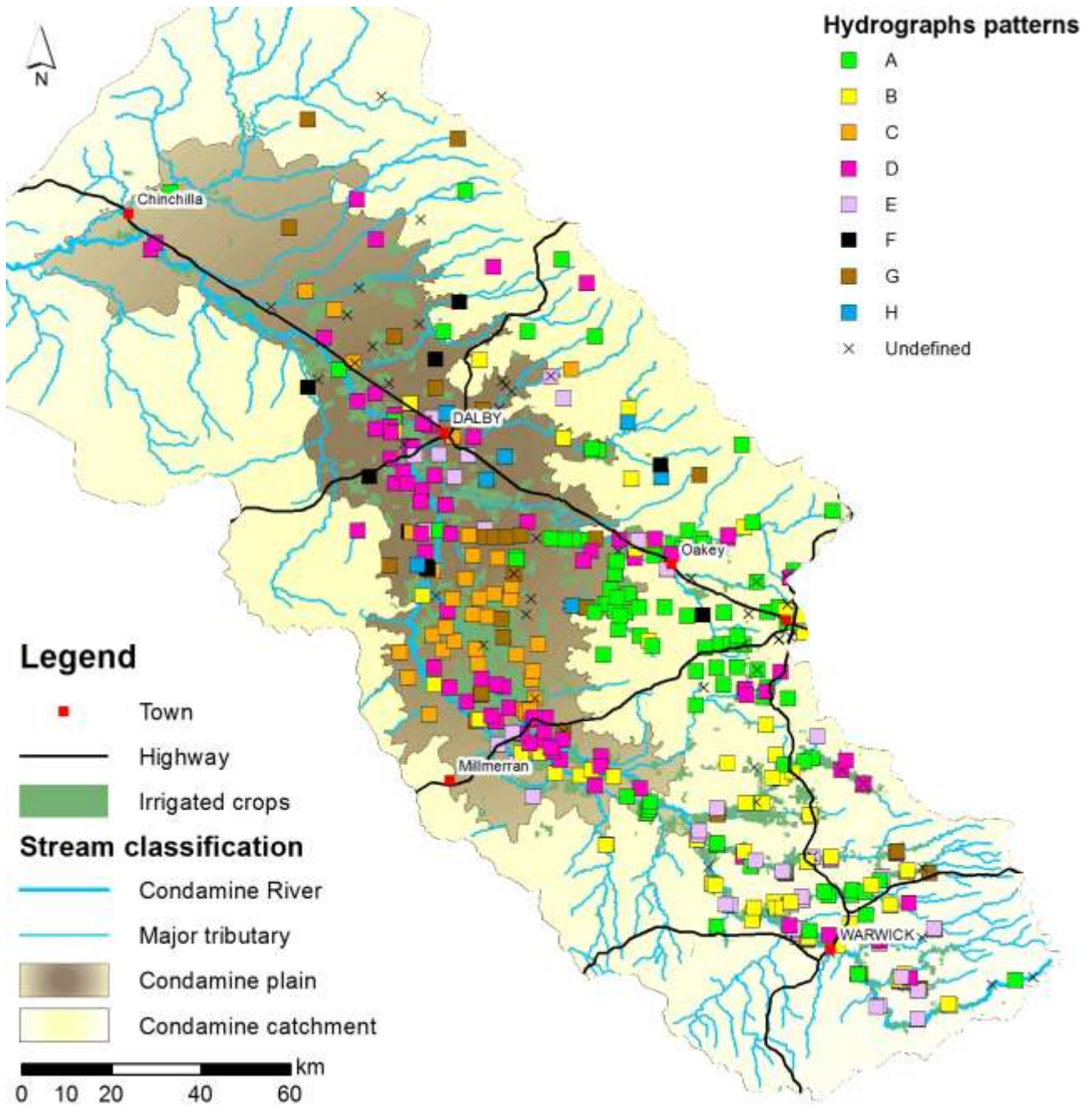

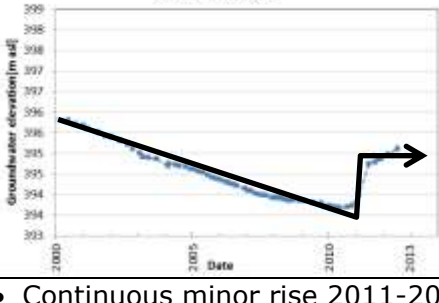
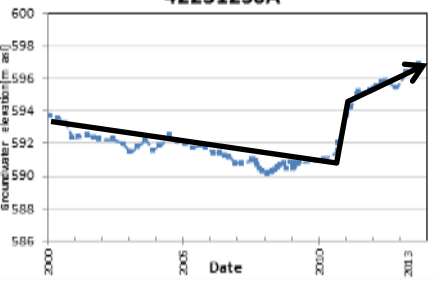
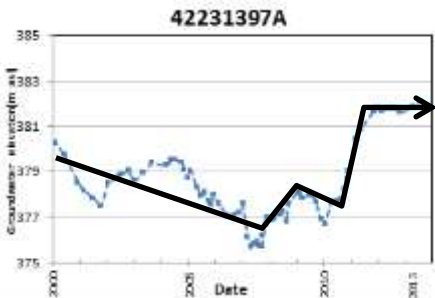
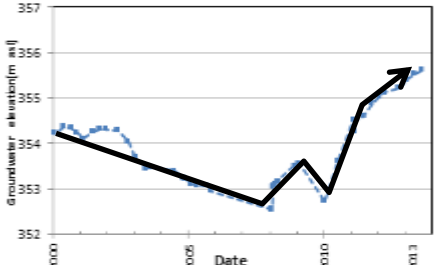
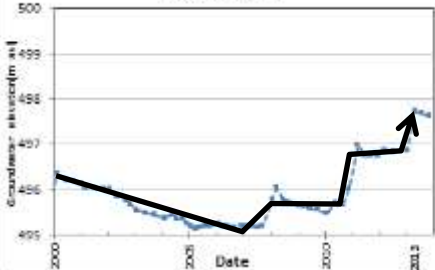


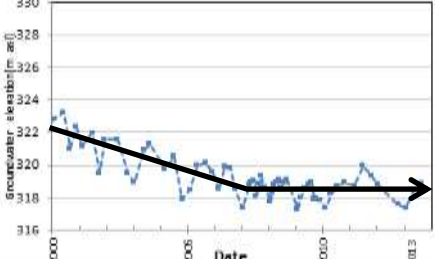
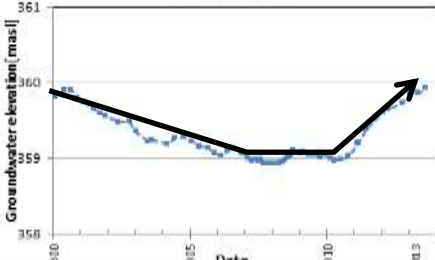
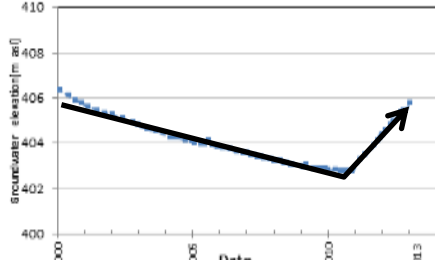
Figure 15: Spatial distribution of the hydrographs patterns

Table 8: Summary of hydrographs patterns

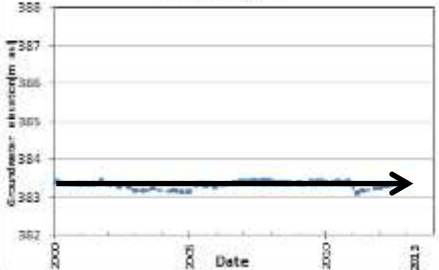
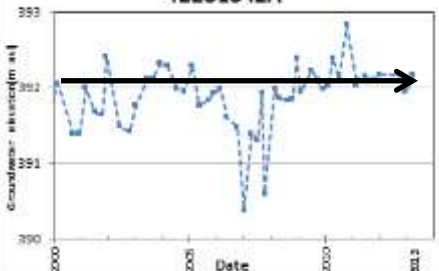
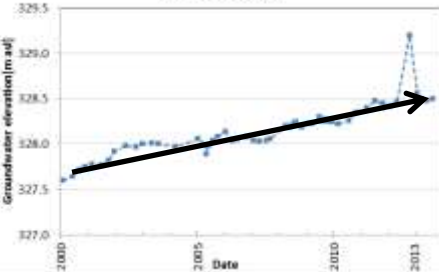
(# Interpretation discussed in following section)

Pattern	Major attributes	Variance	Interpretation [#]
A	<ul style="list-style-type: none"> Decrease or stable levels 2007-2010 Sharp rise in 2010 	<ul style="list-style-type: none"> Prototype 	<ul style="list-style-type: none"> Deficit water balance (WB) 2000-2007 Balanced recharge/lateral flow 2007-2010 Direct recharge during 2010/11 flood/rain event Balanced recharge/lateral flow in the following years
		<ul style="list-style-type: none"> Decrease WT until late 2010 	<ul style="list-style-type: none"> Deficit WB 2000-2010 Direct recharge during 2010/11 flood/rain event. Balanced recharge/lateral flow in the following years
		<ul style="list-style-type: none"> Continuous minor rise 2011-2013 	<ul style="list-style-type: none"> Deficit WB 2000-2010 Direct recharge during 2010/11 flood/rain event. Surplus recharge/lateral flow in the following years

B	<ul style="list-style-type: none"> • Rise (sharp or minor) in 2007 • Sharp rise in 2010 	<ul style="list-style-type: none"> • Prototype 	<ul style="list-style-type: none"> • Deficit WB 2000-2007 • Surplus lateral flow following the 2007 flood/rain event. • Deficit WB 2009-2010 • Direct recharge during 2010/11 flood/rain event • Balanced recharge/lateral flow in the following years
	<ul style="list-style-type: none"> • Continuous rise 2011-2013 		<ul style="list-style-type: none"> • Deficit WB 2000-2007 • Surplus lateral flow following the 2007 flood/rain event. • Deficit WB 2009-2010 • Direct recharge during 2010/11 flood/rain event • Surplus recharge/lateral flow following
	<ul style="list-style-type: none"> • 'Ramp-up' rise since 2007 		<ul style="list-style-type: none"> • Deficit WB 2000-2007 • Surplus lateral flow following the 2007 flood/rain event. • Balanced recharge 2009-2010 • Direct recharge during 2010/11 flood/rain event • Balanced recharge following • (Direct recharge following the 2012/13 flood/rain event)

C	<ul style="list-style-type: none"> • Decreasing levels before 2007 • Stable from 2007 onward 	<p style="text-align: center;">42231373A</p> 	<ul style="list-style-type: none"> • Deficit WB 2000-2007 • Lateral flow balance pumping 2007-2013 • No direct recharge • Often accompanied by seasonal fluctuation due to nearby pumping effect
D	<ul style="list-style-type: none"> • Decreasing levels before 2007 • Stable or decreasing levels 2007-2010 • Continuous rise 2010-2013 	<ul style="list-style-type: none"> • Prototype <p style="text-align: center;">42231415A</p> 	<ul style="list-style-type: none"> • Deficit WB 2000-2007 • Lateral flow balance pumping 2007-2010 • Lateral flow exceeds pumping 2010-2013 • No direct recharge
	<ul style="list-style-type: none"> • Fall 2000-2010 	<p style="text-align: center;">42231301A</p> 	<ul style="list-style-type: none"> • Deficit WB 2000-2010 • Lateral flow exceeds pumping 2010-2013 • No direct recharge

E	<ul style="list-style-type: none"> Falling levels prior to 2007 On-going rise since 2007 	<ul style="list-style-type: none"> Prototype 	<ul style="list-style-type: none"> Deficit WB 2000-2007 Lateral flow exceed pumping 2007-2013 No direct recharge
		<ul style="list-style-type: none"> Stable 2011-2013 Conjunction with Sharp rise in 2007 and/or 2010 	<ul style="list-style-type: none"> Deficit WB 2000-2007 Lateral flow/recharge exceeds pumping 2007-2013 Possible effect of direct recharge in 2010/11
F	<ul style="list-style-type: none"> Falling water levels 		<p><u>Bores away from pumping zones:</u></p> <ul style="list-style-type: none"> Deficit water balance <p><u>Bores adjacent to pumping zones:</u></p> <ul style="list-style-type: none"> Bore not respond to external pressures → clogged?

G	<ul style="list-style-type: none"> • Stable water levels 	<p style="text-align: center;">42231308B</p> 	<p><u>Bores away from pumping zones:</u></p> <ul style="list-style-type: none"> • Inflow balanced outflow <p><u>Bores adjacent to pumping zones:</u></p> <ul style="list-style-type: none"> • Bore not respond to external pressures → clogged?
	<ul style="list-style-type: none"> • With seasonal fluctuations 	<p style="text-align: center;">42231342A</p> 	<ul style="list-style-type: none"> • Inflow balanced outflow • Pumping does not exceed potential yield
H	<ul style="list-style-type: none"> • Rising water levels 	<p style="text-align: center;">42230162A</p> 	<ul style="list-style-type: none"> • Lateral flow/diffusive recharge exceeds pumping

5 Discussion

As stated above, the study area comprises three major inter-connected aquifers, namely the GAB aquifers, the basalt aquifers and the alluvium aquifer (CRAA). The former two are fed mainly by diffuse recharge (rain water) and to a lesser degree, along the major creeks, by percolating stream water. The latter is fed by recharge from the Condamine River, and lateral flows from adjacent hydrological units.

Excessive rain will therefore be expected to induce a sharp rise in groundwater levels in the GAB and basalt aquifers. Excessive flow in the streams is expected to induce a rise in groundwater levels in shallow bores located along the creeks in all aquifers. Increased lateral fluxes, under higher hydraulic gradients, will tend to increase groundwater levels in a mild and continuous manner (provided that the outputs are not dramatically changed in the same period of time).

The studied period (2000 – 2013), in which on-going drought was followed by several rainy/flood years, supplies an opportunity to evaluate the actual trends in the groundwater levels and to analyse the recharge process and the inter-connectivity. These issues are discussed here by analysing patterns A-E. The three other patterns (F-H) do not show an association with climate/rain events and are not concentrated in specific area; thus it seems that the conditions which impact them are localized, and hence out of the scope of this report.

5.1 Response to 2007/8 events

Summer 2007/8 marks a key turning point for the groundwater balance of the Condamine catchment. Groundwater levels at most of the bores in the upper Condamine tributaries and the upper section of the main branch (above Pampas, Figure 17, Figure 16) have started to rise (pattern E) or show signs of temporary rise (pattern B). The same pattern appears in several bores located south of Dalby, while groundwater levels at most bores in the central irrigation zone stabilized (pattern C).

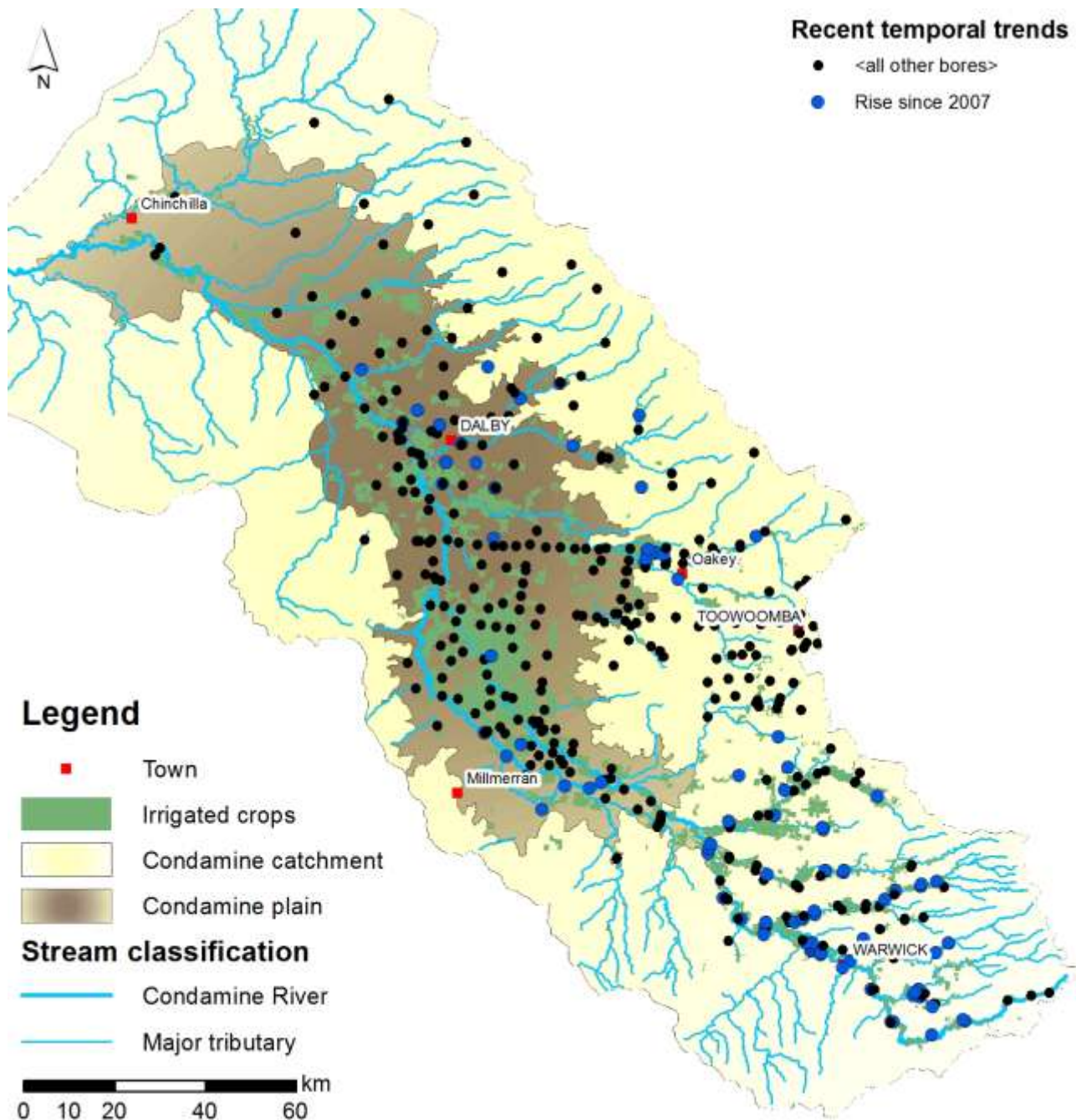


Figure 16: Bores show groundwater rise in 2007

These trends testify to a transition from a deficit groundwater balance to surplus or balanced water budget, which is allied to two processes:

- Reduction of water allocations in the CGMA: Announced entitlements were reduced from 70% in previous years to 60% in subarea #3 of the CGMA and from 100% to 80% in all other parts of the CGMA (White, et al., 2010).
- Enhanced localized recharge during the summer of 2007/8 and the following induced flood flow: rain in the SE (as evident in Killarney, for example) and near

Toowoomba (Jondaryan) was relatively high, and above average (Figure 10). It is hypothesised that due to this excessive rain period, the upper soils have been saturated to the point where it produce both run-off and recharge.

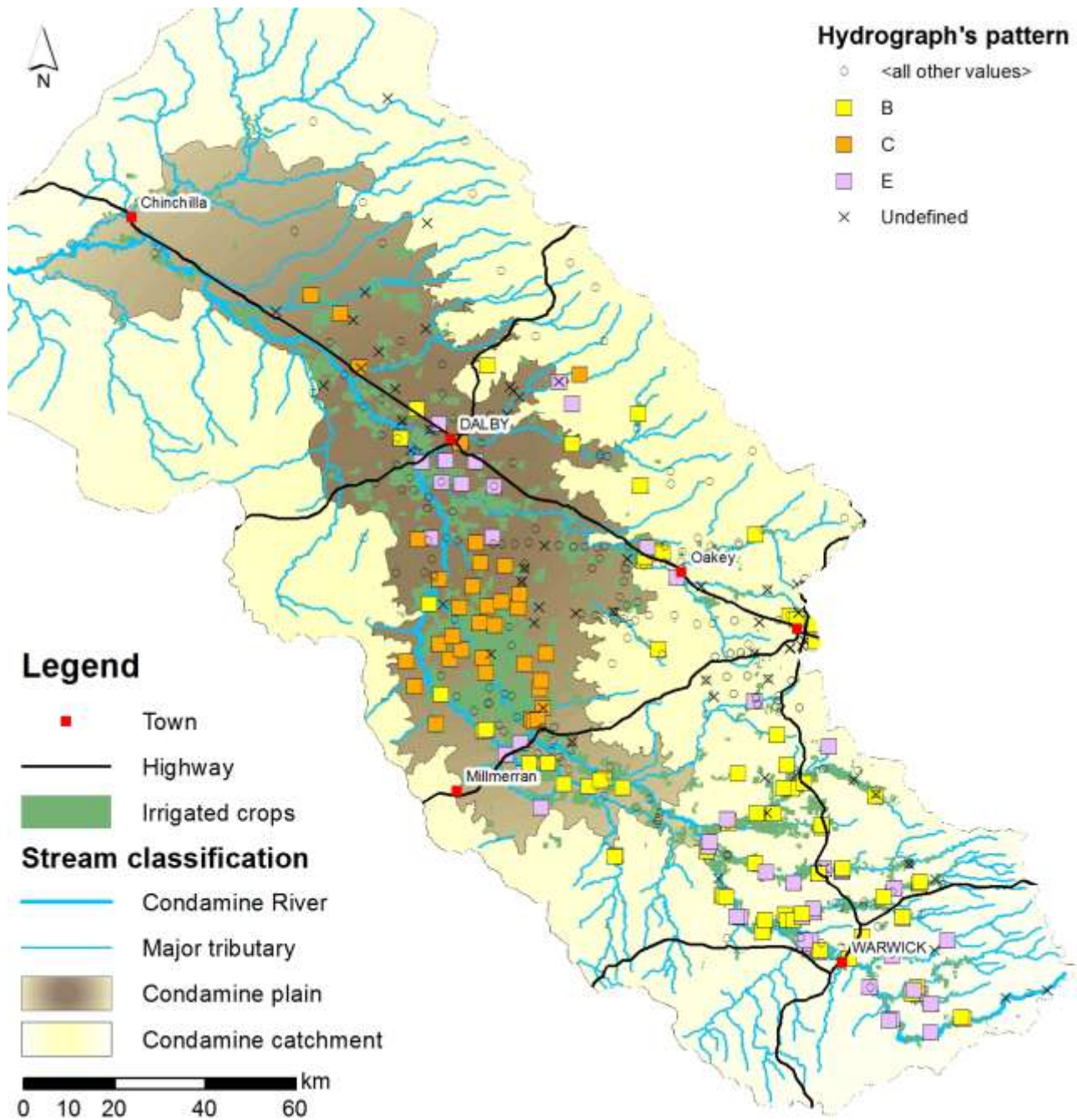


Figure 17: Spatial distribution of hydrograph patterns B, C and E

5.2 Response to 2010/11 events

The climate event of summer 2010/11 was yet another substantial milestone to the groundwater storage. Most of the bores in the SE recharge areas (at least 92 bores which accounts for 38% of total) show a sharp increase of groundwater level (patterns A and B, Figure 18). The sharp increase is a distinctive sign of direct recharge, i.e.

recharge which percolates in excess, to the same hydrological unit which the bore is monitoring. These bores are clustered in the recharge zone, east of the Condamine floodplain. Pattern A is distributed in the 'Toowoomba basalt' zone and pattern B in the upper tributaries and along the main branch of the Condamine. This indicates diffuse recharge and stream recharge from the Condamine River, respectively.

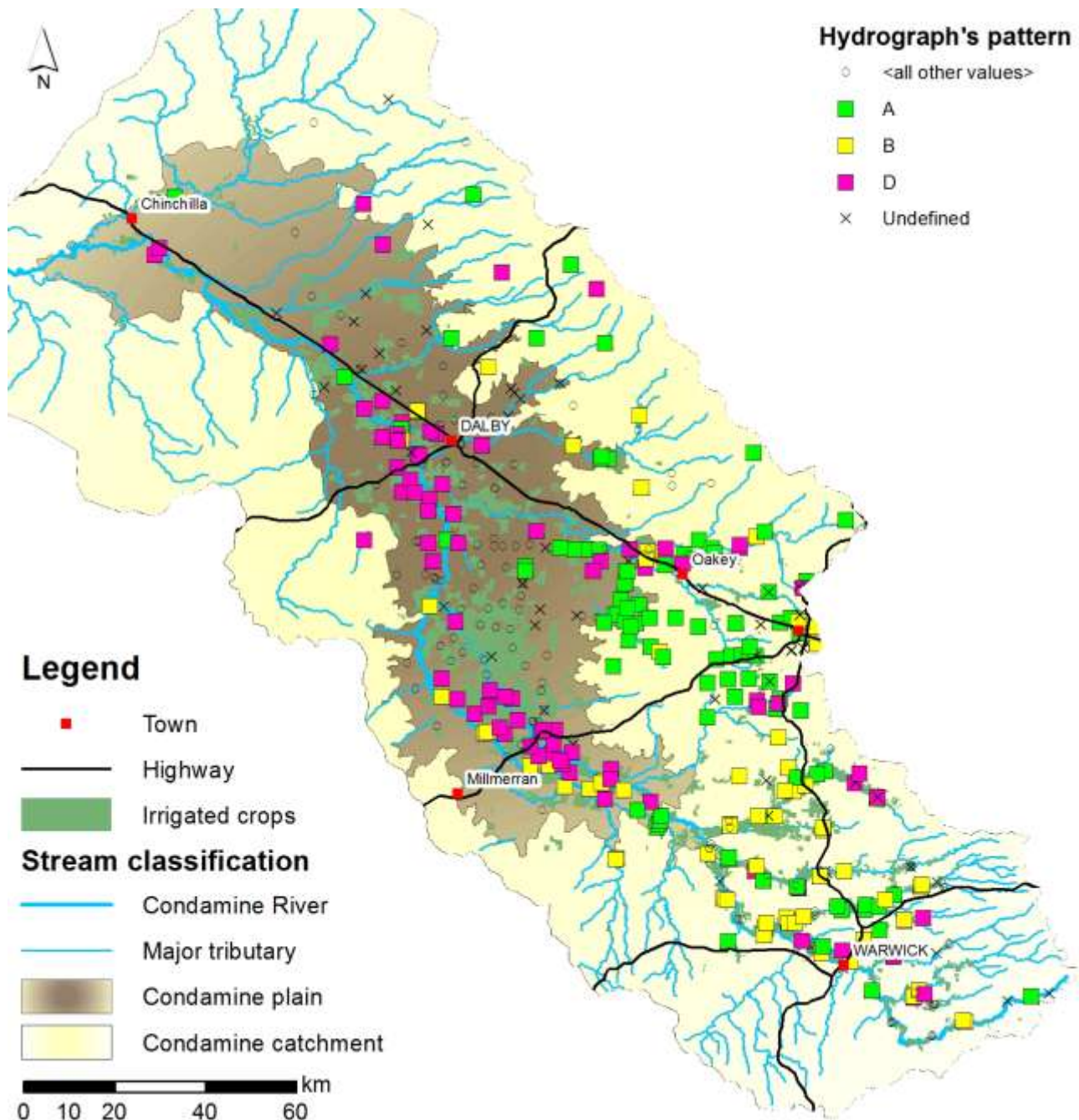


Figure 18: Spatial distribution of hydrograph's patterns A, B and D

The increased water table in the recharge zones induced higher lateral groundwater fluxes from the basalts and GAB aquifers towards the CRAA. In conjunction with the

pumping allocation reduction (made before the summer rains, to 50% in subarea #3 of the CGMA and to 70% in all other parts of the CGMA (White, et al., 2010)) groundwater levels in the Condamine floodplain starts to rise. 96 bores were transformed from stable or declining groundwater level trends to rising conditions (pattern D, Figure 18) and in 59 bores the on-going rise trend (started in 2007) continue (pattern E). In all (patterns D and E) the rise was stable and continuous, and in most cases continued until today. The stable rise is hypothesised to be the result of lateral flow from the recharge areas (including the Condamine River) toward the monitored bores. It is hypothesised that the rise will continue as long as lateral flux exceeds the pumping and other outflow fluxes. However, given the fact that most of the bores in the recharge area show a stabilizing trend, this is expected to reduce again in the next couple of years.

The 2010-2013 groundwater rise map may give an indication to the 'rechargeability', i.e., the tendency to absorb excessive and instantaneous infiltration as recharge to the aquifer; therefore it was compared with Hansen's (1999) 'Net recharge map' (Figure 19). The comparison between 'predicted' (Hansen's map) and 'actual' recharge rates, however, does not supply a clear indication to trends or rates. For example, it is noticeable that the higher rises of groundwater level (+8 to +15) appear in the 'Toowoomba basalt' recharge area; nevertheless, average annual recharge in the same area was estimated to be in a wide range of 25-150 mm/yr. Relatively high recharge rates (125-150 mm/yr) were estimated east of Jandowae and NW of Millmerran; nevertheless, almost all bores in the same areas show no response (+6 m in one instance near Jandowae). Medium recharge rates (50-75 mm/yr) were estimated around Clifton, yet groundwater rise there was around +5 m, which is less than groundwater rises over the 'Toowoomba basalts'.

The discrepancy between the 'Net recharge map' ranks and the actual groundwater rise in 200/11 suggests that sources and processes other than rainfall (diffuse recharge) should be accounted for the recharge; these may be recharge along flooded streams and preferred recharge through cracks and fractures. In addition it supports the idea that recharge is not a linear product of rain, but a more complex process which depends on the initial soil saturation.

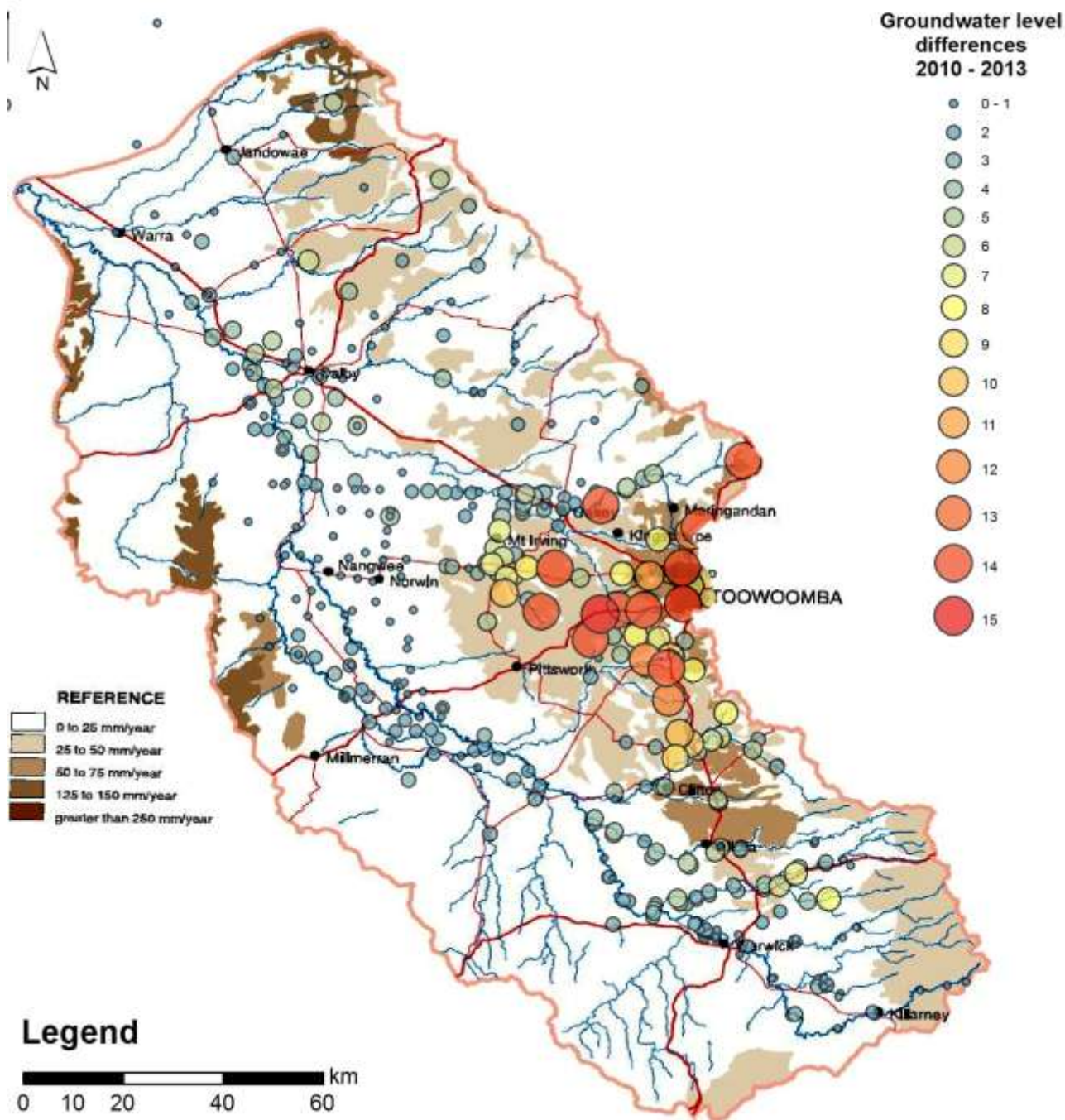


Figure 19: 2010-2013 Groundwater table rise and Hansen (1999) Net Recharge map

5.3 Streams - groundwater connectivity

One of the major recharge sources of the CRAA is the Condamine River; recharge probably occurs also along its major tributaries (Huxley, 1982). To further study the association of surface water and groundwater levels, data from several bores in which automatic monitoring takes place were gathered and hydrographs were plotted along with the stream discharge from the nearby gauging station (Figure 20).

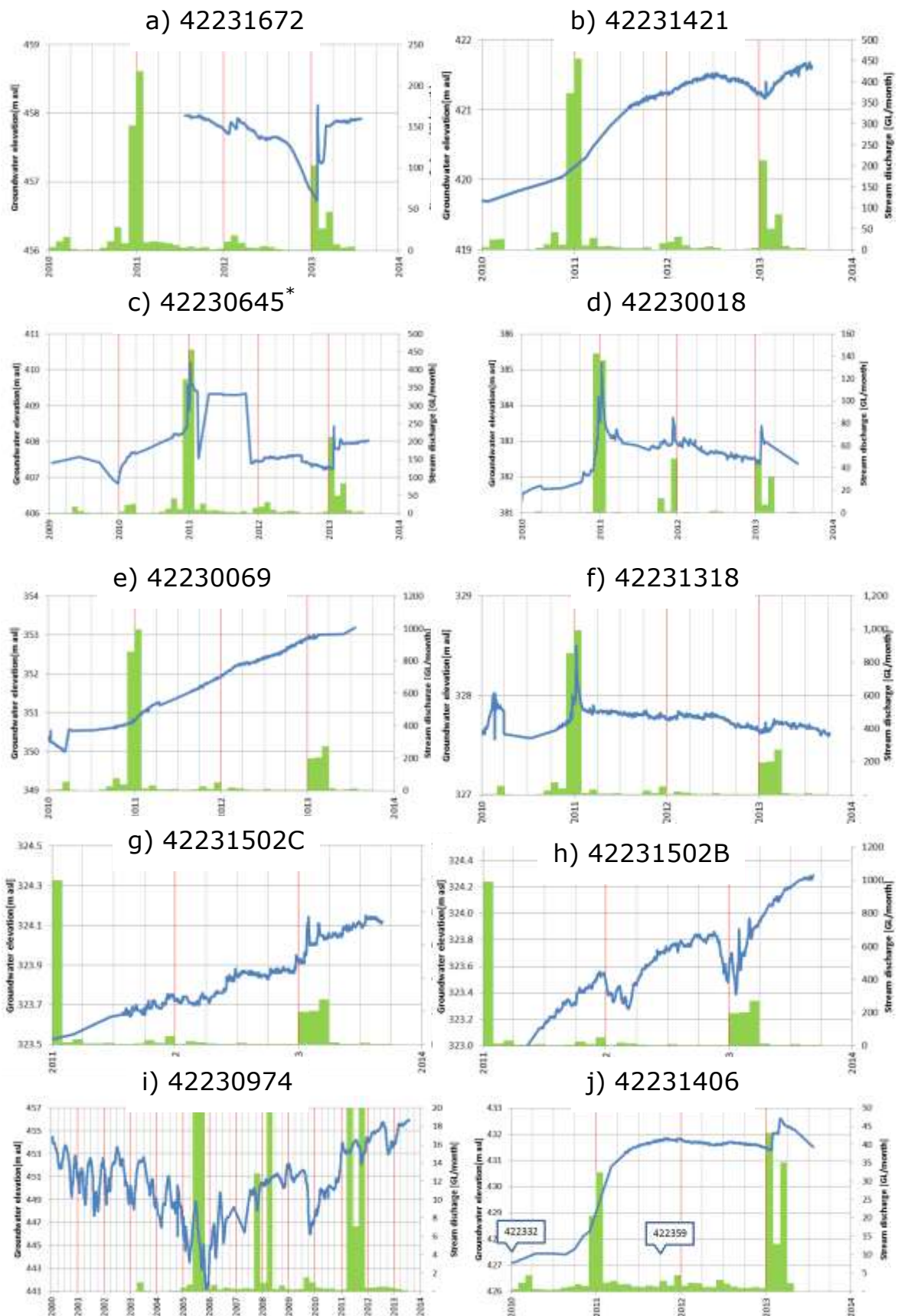


Figure 20: Comparison between groundwater levels in selected bores (blue line) and stream discharge at nearby gauging stations (green bars)

Association between stream discharge and immediate groundwater levels response can be seen in several bores (examples a, c, d, f and g, Figure 20) and excluded in others (b, e, h, i). Generally, the response to recharge is limited to shallow bores which are found close to the Condamine River and some of its tributaries. It is also identified by occurrence of pattern B along the main branch of the Condamine (Figure 18). Deep bores, as well as bores which are found away from these water courses, tend not to show this effect. For example, hydrographs g and h of Figure 20, which are recorded in different horizons within the CRAA.

The short-term recharge events appear as temporary upward spikes and can be visualized as a 'slug-test', i.e. short-term load is introduced along a narrow band (the streams) and is dissipated within a short period of time as it is transmitted further into the aquifer. It is possible to quantify local recharge using analytical methods and to upscale it to the length of the streams, provided that some indication for recharge is collected.

5.4 Rainfall/groundwater relationship

Another source of direct recharge is diffusive recharge, which occurs following rain events. This however should first increase the water content of the soil, to the point where saturation is achieved before recharge (and run-off) occurs (Ravi and Williams, 1998). Under the region's climate conditions, the rainwater is generally evaporated shortly after it percolates to the soil, thus retaining the upper soil horizon in a relatively 'dry' condition. Consequently, recharge events generally, only follow excessive and continuous rain events, whenever soil saturation is achieved. This process is enhanced by fallowing (to accumulate soil water) between crops and irrigation which occur on large areas of the Condamine catchment (Silburn, et al., 2013).

The following graphs (Figure 21) show a comparison between groundwater levels in bore 42231399 (5km NW of Oakey) with local rain series (Jondaryan, Figure 10) and 'excess' rain (above/below long-term monthly average) series. It is apparent that there is no 'straight forward' correlation between the two factors either in the temporal or the extent terms. Other graphs, from which the same conclusion can arise, have been presented in Pearce, et al. (2006). Not all the rain events above a certain threshold will induce recharge, not all the rainfall events above the monthly average will induce recharge, and there is no correlation between the rainfall extent in mm to the

immediate response in groundwater level. That is, recharge does not depend solely on the rainfall extent but on the complex water (moisture) balance of the soil.

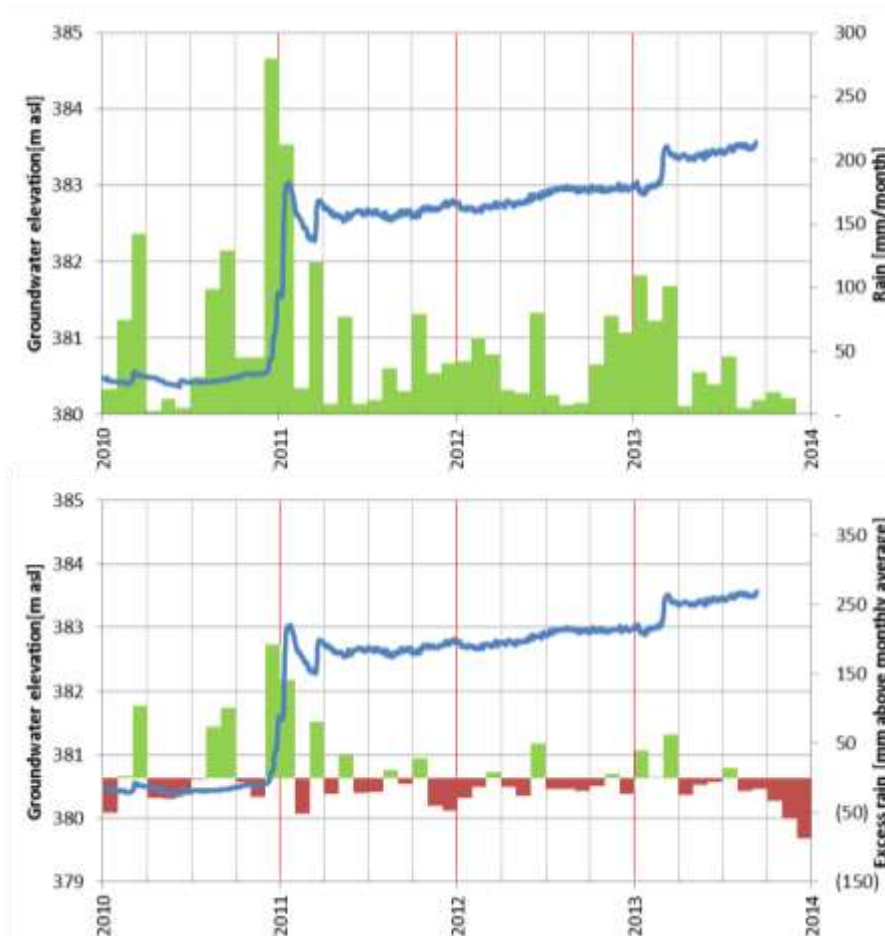


Figure 21: Comparison of bore 42231399 hydrographs with rain in a nearby station (above) and excess (deficit) beyond long-term monthly average (below).

5.5 Pumping effects on hydrographs

Many of the monitoring bores are located in vicinity to irrigation bores (e.g. see Figure 7). Thus, when pumping takes place, an immediate and sharp drawdown occurs in the monitoring bores. Following this, when pumping ceased, the water table recovers to near its previous position due to inflow from the surrounding area.

This effect can be seen in many bores and obscures other effects. The closer the pumping bore to the monitoring bore- the sharper the drawdown will be. A sharp drawdown (~ 1week) occurs when bores are very close; an on-going drawdown (~ 1 month) will occur when distant bores are being pumped. Recovery periods are generally lengthy - up to 7 months - and are demonstrated by negative exponential curves.

5.6 Shallow horizons within the CRAA

The CRAA is generally regarded as one continuous aquifer system. However, in places it does contain two separate horizons (Sub-aquifers ??). This situation is observed in several paired bores, along the eastern rims of the floodplain, as pronounced differences in the water table elevation. This distinction became clear only in the last decades, as levels in the lower horizon decline way below the upper horizon; i.e., it cannot be made based on historical data alone. In the following section, nine cases, accompanied by the 1990-2013 hydrographs, are detailed.

5.6.1 Individual bores

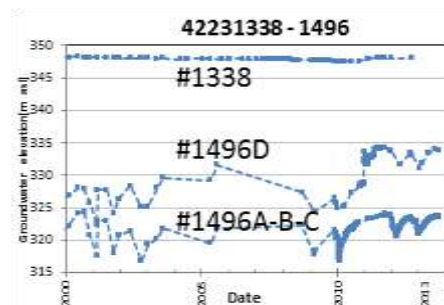
42231317 – 42231318

Bore #1318 penetrates to a depth of 44 m while bore #1317, drilled adjacent to it, penetrates a depth of 124m. Since the 1990s, the first shows relatively stable water table while in the latter a severe drawdown of ~25m appeared. Bore #1318 hydrograph also shows quick response to recharge events (upwards spikes).



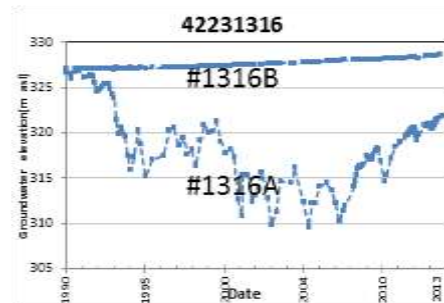
42231338 – 42231496

Bore #1338 penetrates to a depth of 41 m. Bore #1496 adjacent to it is a multi-pipe bore with screens at 50, 71, 91 and 116 m (D, C, B and A respectively). Groundwater level in bore #1338 is shallower by ~17 m than that measured in #1496D and by ~25 m than that measured in #1496A-B-C.



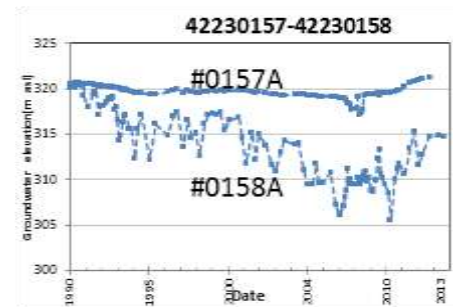
42231316 A-B

Pipe #1316A penetrates to a depth of 105 m, while its paired pipe #1316B penetrated to a depth of 22 m. Since the 1990s, the latter shows continuous increase of water table depth while in the former there has been a severe drawdown of ~25m, followed by a slight recovery since 2007.



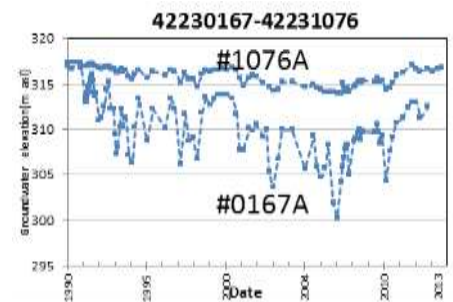
42230157 - 42230158

Pipe #0157A penetrates a depth of 22 m, while its paired pipe #0158A penetrated to a depth of 53 m. Since the 1990s, the former shows relatively a stable water table depth while in the latter a drawdown of ~10 m appeared, followed by a slight recovery since 2010.



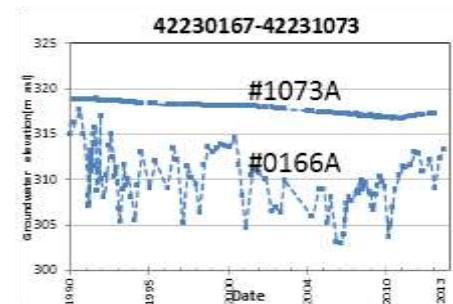
42230167 - 42231076

Pipe #0167A penetrates to a depth of 84 m, while its paired pipe #1076A penetrated to a depth of 28 m. Since the 1990s, the latter shows relatively stable water table depth while in the former a drawdown of ~5 m appeared, followed by a slight recovery since 2007.



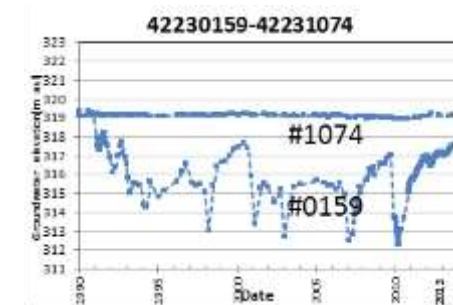
42230166 - 42231073

Pipe #0166A penetrates to a depth of 89 m, while its paired pipe #1073A penetrated to a depth of 18 m. Since the 1990s, both show different water tables, where the latter shows shallower and relatively stable water table depth and the former records a ~7 m drawdown, followed by a slight recovery since 2007.



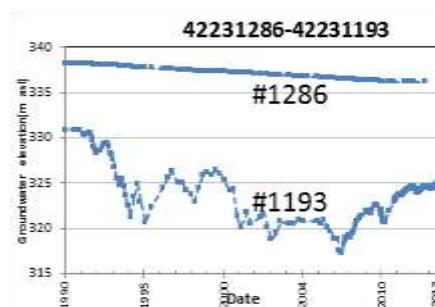
42230159 - 42231074

Pipe #0159A penetrates to a depth of 118 m, while its paired pipe #1074A penetrated to a depth of 28 m. Since the 1990s, both show different water tables. #1074A shows shallower and relatively stable water levels and #0159A records a ~7 m drawdown, followed by a slight recovery since 2007.



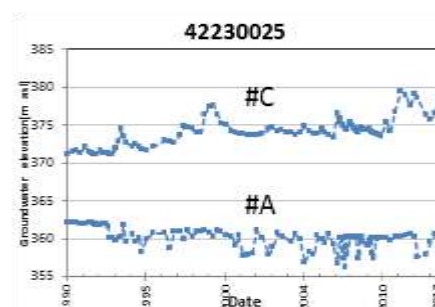
42231286 - 42231193

Bore #1286A penetrates to a depth of 22 m, while its paired pipe #1193B penetrated to a depth of 110 m. In the former, a shallower water table was recorded with mild continuous decrease; in the latter, a drawdown of 12 m occurred since 1990, with a relative recovery since 2007.



42230025

Pipe #0025A penetrates to a depth of 47 m, while its paired pipe #0025C penetrated to a depth of 23 m. Both pipes show different water tables. #0025C shows shallower and relatively increased water levels, while #0025A (as well as pipe #0025B, not shown in the hydrograph) shows relatively stable and deeper water levels. This example may be different to all others, as the upper horizon penetrates CRAA while the lower one probably penetrates the GAB aquifers.



5.6.2 Conclusions

The above examples suggest the existence of two groundwater horizons along the eastern rims and the central part (around and south of Dalby) of the CRAA (Figure 22). It is suggested that an interim semi-pervious layer separates the alluvial section into two sub-aquifers; this zone coincides with the occurrence of the "sheetwash alluvium" described by Lane (1979); and Huxley (1982). The layer is probably continuous in space, spreading from the eastern rims of the CRAA westward; the black dashed line in Figure 22 is suggested as its western boundary. Under these conditions, it is assumed that both sub-aquifers are fed by lateral fluxes from the east. In the last two decades the lateral flux was generally reduced, leading to slightly decreased water table in the upper sub-aquifer; in the several localities where the water table in the upper sub-aquifer are rising, it is reasonable to assume that recharge originate as deep-drainage. The lower sub-aquifer is subject to extensive pumping, as demonstrated by substantial seasonal fluctuation; increasing lateral flux since 2007 along with reduced water allocations has led to partial recovery of the water levels.

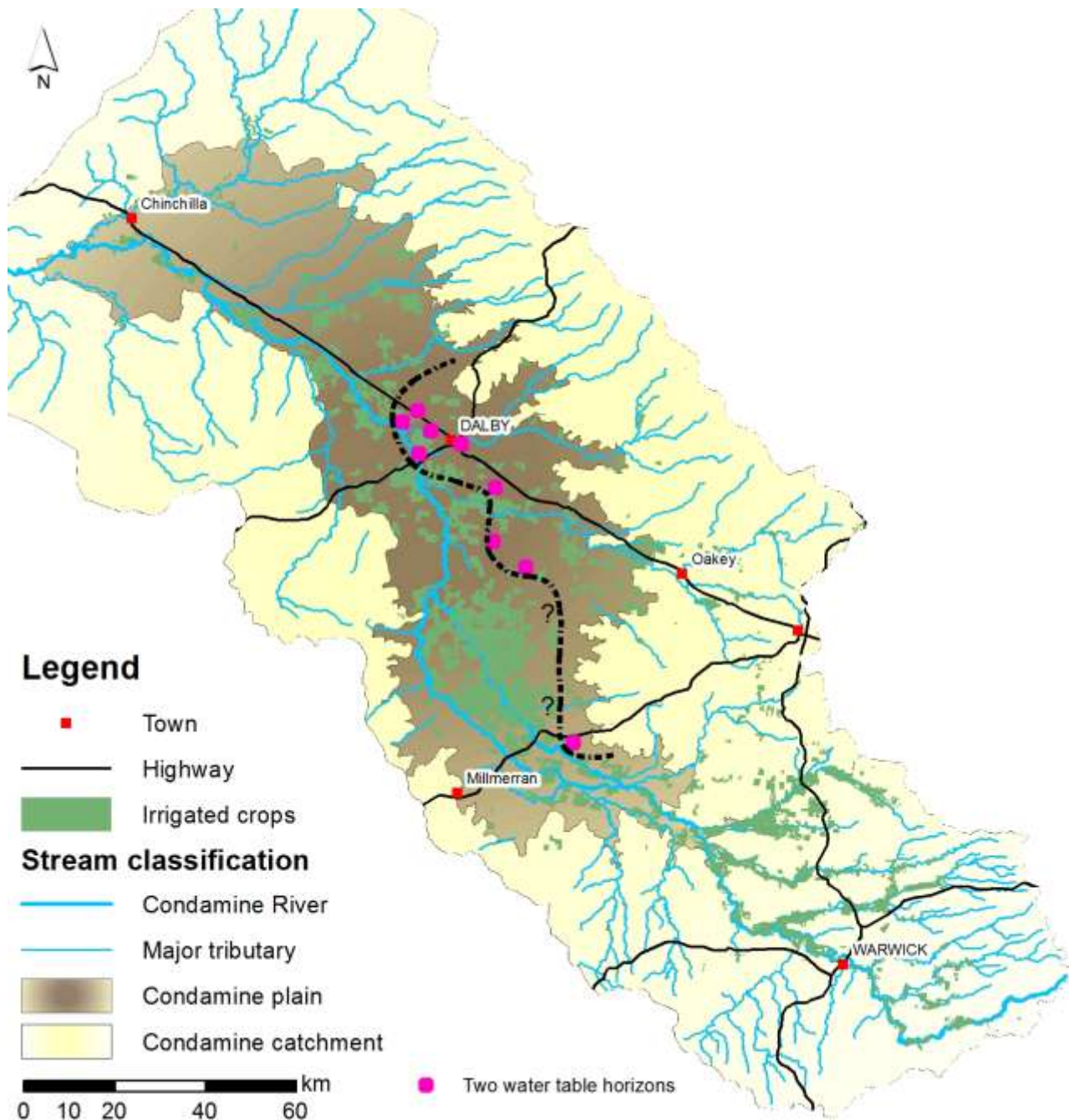


Figure 22: Sites with records of two water table horizons within the CRAA

5.7 Flooded bores

It appears that some bores, which were probably filled with water during major flood events, have not been able to discharge this excessive water and thus currently showing elevated and incorrect water levels. For example, bore #1369 which shows an artificial increase of almost 29 m to a level of +356 m, while bores in its surroundings increase by ~3m to a current levels of +332 m (Figure 23). Another example is bore #0062, which increased since 2010 by ~11m, compared to an

increase of $\sim 2\text{m}$ in the nearby bore #0061. These bores were excluded from this analysis, and should be excluded from future analysis until operations to recover them will take place. This is yet another example of 'expert knowledge' which should be implemented before analysing and interpreting raw data from the GWDB.

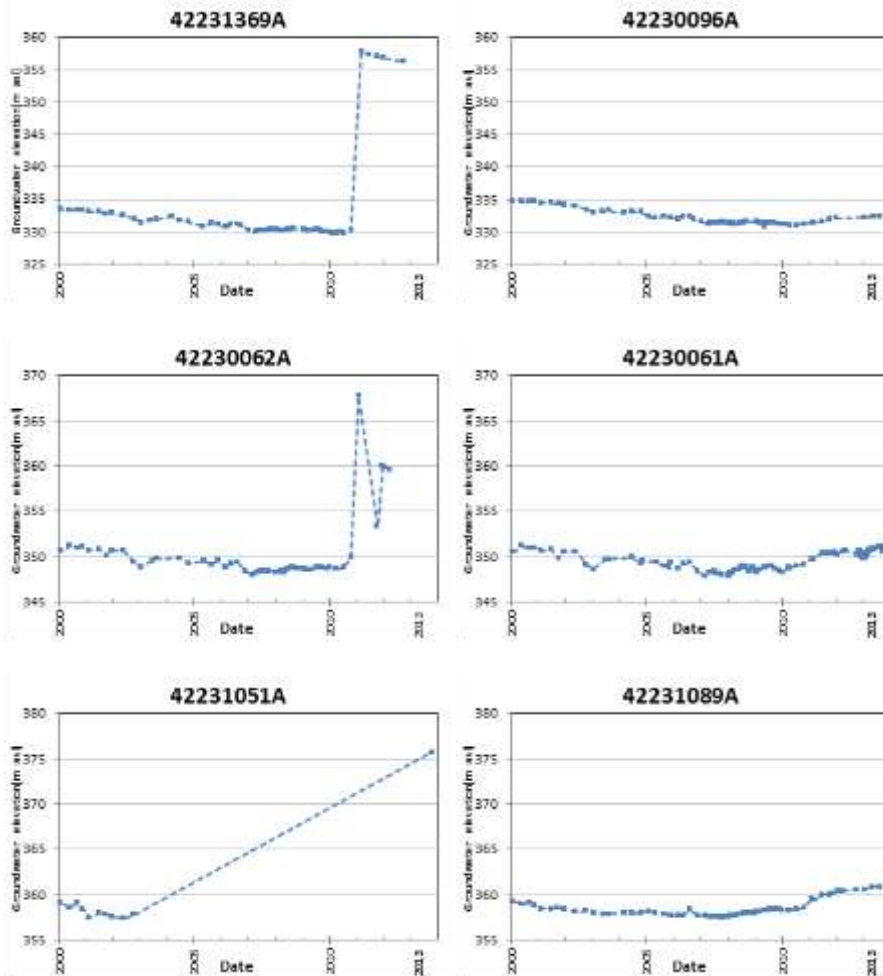


Figure 23: Hydrographs of paired bores- flooded (left) and unaffected (right)

6 Summary

The consistent trend of declining water levels, which occurred for several decades in most parts of the Condamine catchment, ceased in between 2007 and 2010. In most bores in the Condamine catchment, current groundwater levels are higher by 1.5 – 8.5 m than the levels recorded in 2010; higher values of up to 15 m characterize the 'Toowoomba basalts'. In other bores, spread within the main irrigation zones along the Condamine floodplain, groundwater levels were stable for almost 7 years. These are the cumulative result of (1) enhanced recharge during summer 2007/08 and summer 2010/11 flood events, and (2) restriction on water pumping in the CGMA.

The spatial analysis of groundwater level rise and trends helped in identifying an area within the Condamine floodplain, where two sub-aquifers occur in the CRAA. This area is stretched around Dalby as depicted in Figure 22. It also helped in identifying 'outliers' and 'anomalous' bores, in which the water column height is different than the surrounding groundwater levels; the hydraulic connectivity of these bores may be reduced over time due to clogging of the bore's screen.

The analysis of stream flow, rainfall and groundwater level time series revealed that recharge should be studied in the context of soil water-balance rather than a simple cause and effect context. In other words, recharge does not necessarily correspond directly with induced stream flow or rainfall events; its occurrence is dependent to a great extent on the instantaneous soil saturation, and in turn on many spatial (soil type, soil thickness, rock type) and temporal (rain/stream and evapotranspiration time series) factors. For example, a given amount of rain which occurs following drought period and following wet periods will produce different recharge and response of the groundwater levels.

Collecting and analysing reliable groundwater level data, through a widespread bore network is a key issue for this and future recharge studies. In most cases, the existing network and measuring frequency is satisfactory. There are however, some areas where it could be improved or expand, for example: (1) In the SE area, where bores are located only along the streams and alluvial patches but not along the intermittent ridges; (2) in-between Felton, Pittsworth and Kincora, where no monitoring bores exist; and (3) generally along the west rims of the CRAA. Hydrographs of bores which are infrequently monitored, yet show a large seasonal fluctuation (substantial drawdown in the irrigated period), hinder, to a great extent, conclusive remarks to be made and complicated the analysis process; a notation in the GWDB for records which

were collected during the irrigated period will be useful to overcome this complexities. In addition, the use of ALMD should be expanded as a mean to enhance understanding and quantification of the streambed recharge mechanism, preferably in shallow bores which are close (<1.5 km) to the Condamine river or its major tributaries.

7 Reference

- BOM web site, <http://www.bom.gov.au/index.php?ref=hdr>, edited, Australian Bureau of Meteorology.
- Dafny E. and Silburn D. M., 2013. The hydrogeology of the Condamine River Alluvial Aquifer, Australia: a critical assessment. *Hydrogeology Journal*, doi:10.1007/s10040-013-1075-z.
- DNRM web site, 2013. Water Monitoring Data Portal - <http://watermonitoring.dnrm.qld.gov.au/host.htm>, edited, Department of Natural Resources and Mines.
- Hansen A., 1999. Groundwater vulnerability and availability mapping of the upper Condamine River catchment. *Master Thesis*, 76 pp, University of Technology, Sydney.
- Huxley W. J., 1982. Condamine River valley groundwater investigation. The hydrogeology, hydrology & hydrochemistry of the Condamine River valley alluvium. Groundwater branch - Water Resources Commission, Queensland, Brisbane.
- Lane W. B., 1979. Progress report on Condamine underground investigation to December 1978. 262 pp, Queensland's Water Resources Commission, Brisbane.
- National Climate Centre, 2006. *An exceptionally dry decade in parts of southern and eastern Australia: October 1996 - September 2006*, 9 pp., Bureau of Meteorology, Melbourne.
- Pearce B. R., Hansen J. W. L., Stegler J.-C. P., Lee R. B. and Jackson J. A., 2006. Hydrogeological investigation of the northeast Darling Downs Region, Southern Queensland, Australia. Rep. *QNRM06240*, 149 pp, Water Assessment Group, Department of Natural Resources, Mines and Water, Brisbane.
- Ravi V. and Williams J. R., 1998. Estimation of infiltration rate in the vadose zone: Compilation of simple mathematical models Volume I. Rep. *EPA/600/R-97/128a*, EPA.
- Silburn D. M., Foley J. L., Biggs A. J. W., Montgomery J. and Gunawardena T. A., 2013. The Australian cotton industry and four decades of deep drainage research - a review. *Crop & Pasture Science*, 64: 1049-1075.
- White I., Burry K., Baldwin C., Tan P.-L., George D. and Mackenzie J., 2010. Condamine groundwater: from overallocation to sustainable extraction. Rep. *Water Line 37 - PART 3*, National Water Commission, Canberra.

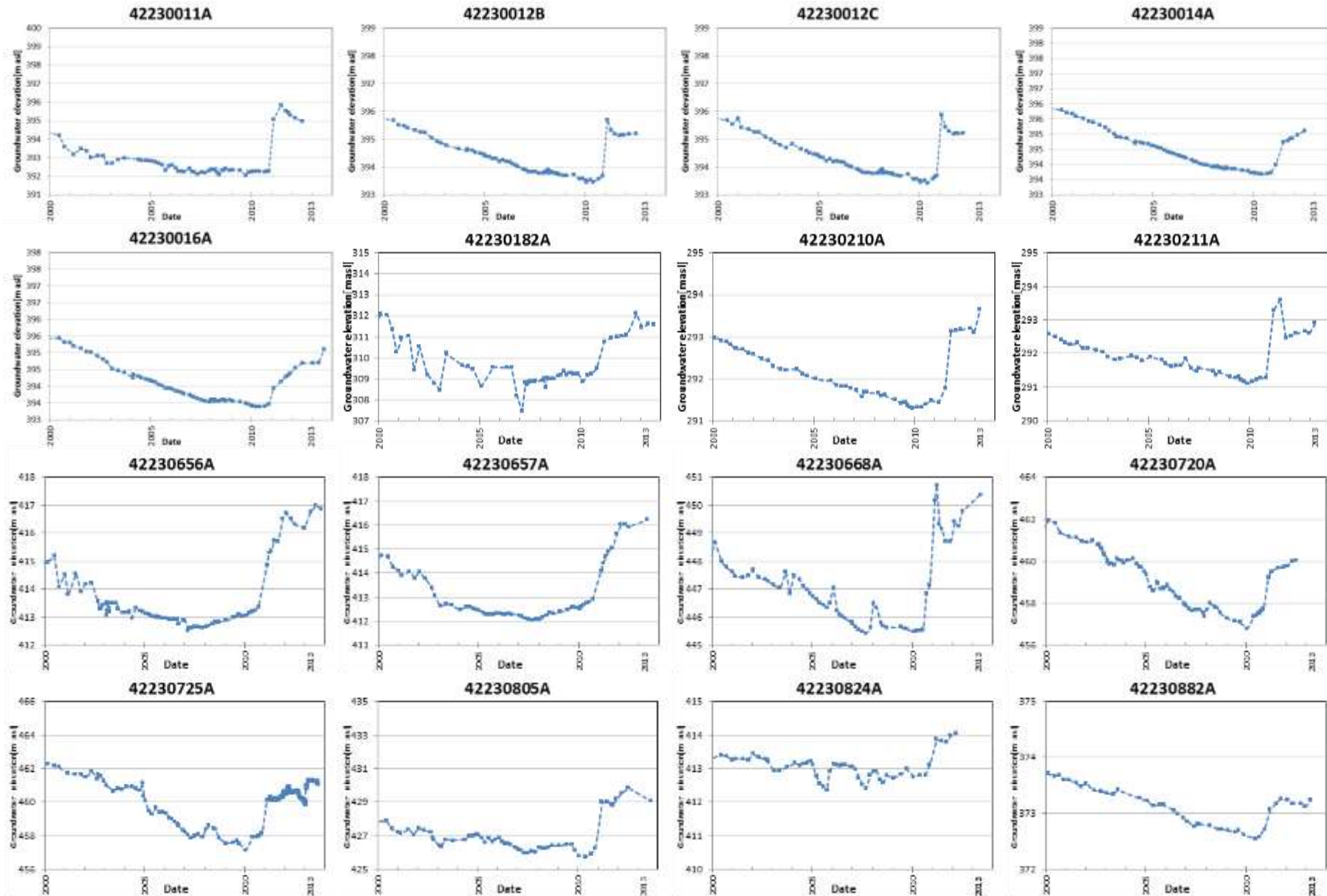
Appendix A - Bore hydrographs

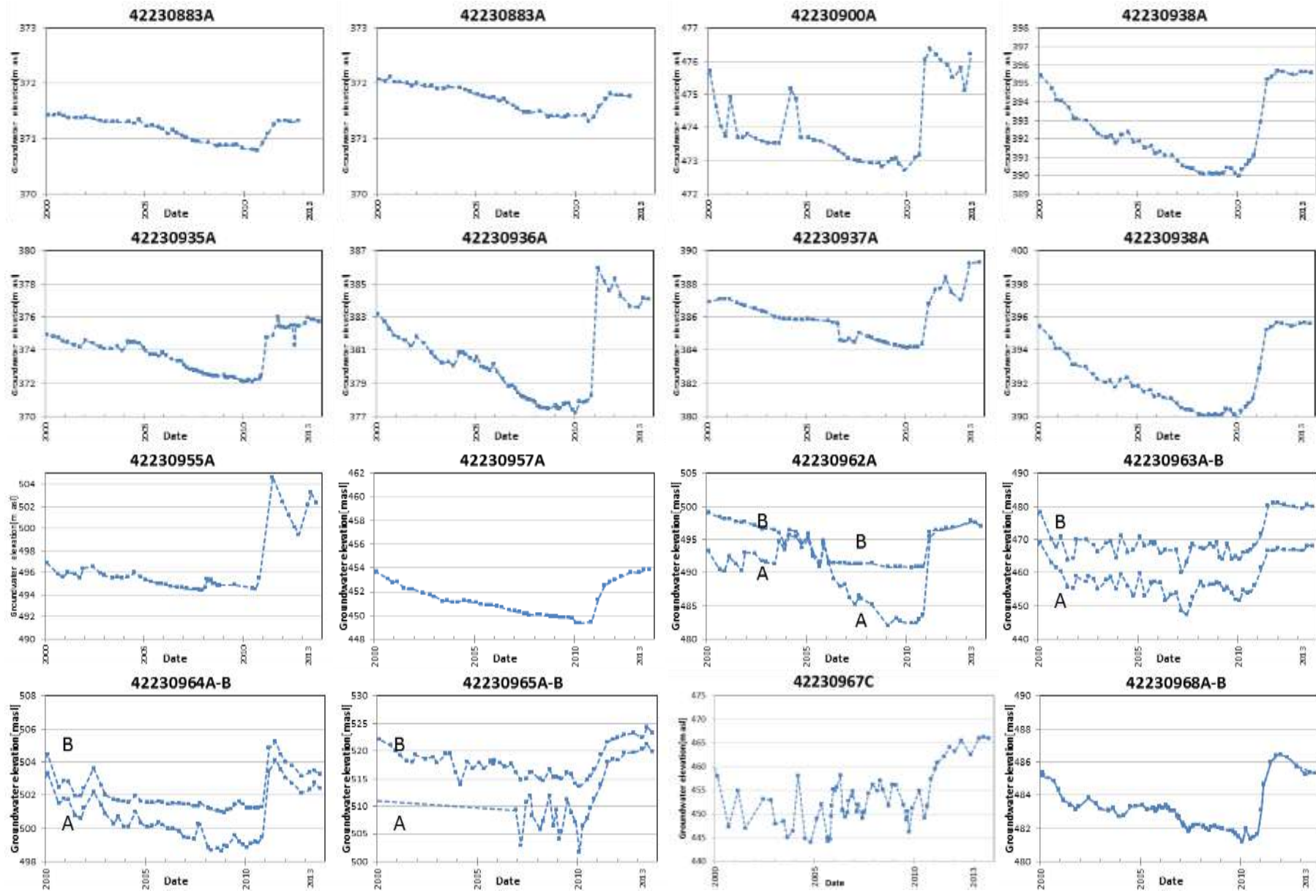
Content	Page
List of bore's hydrographs pattern	A1
Type A	A2
TYPE B	A9
TYPE C	A14
TYPE D	A17
TYPE E	A23
Type F	A27
TYPE G	A28
Type H	A31
Undefined (x)	A32

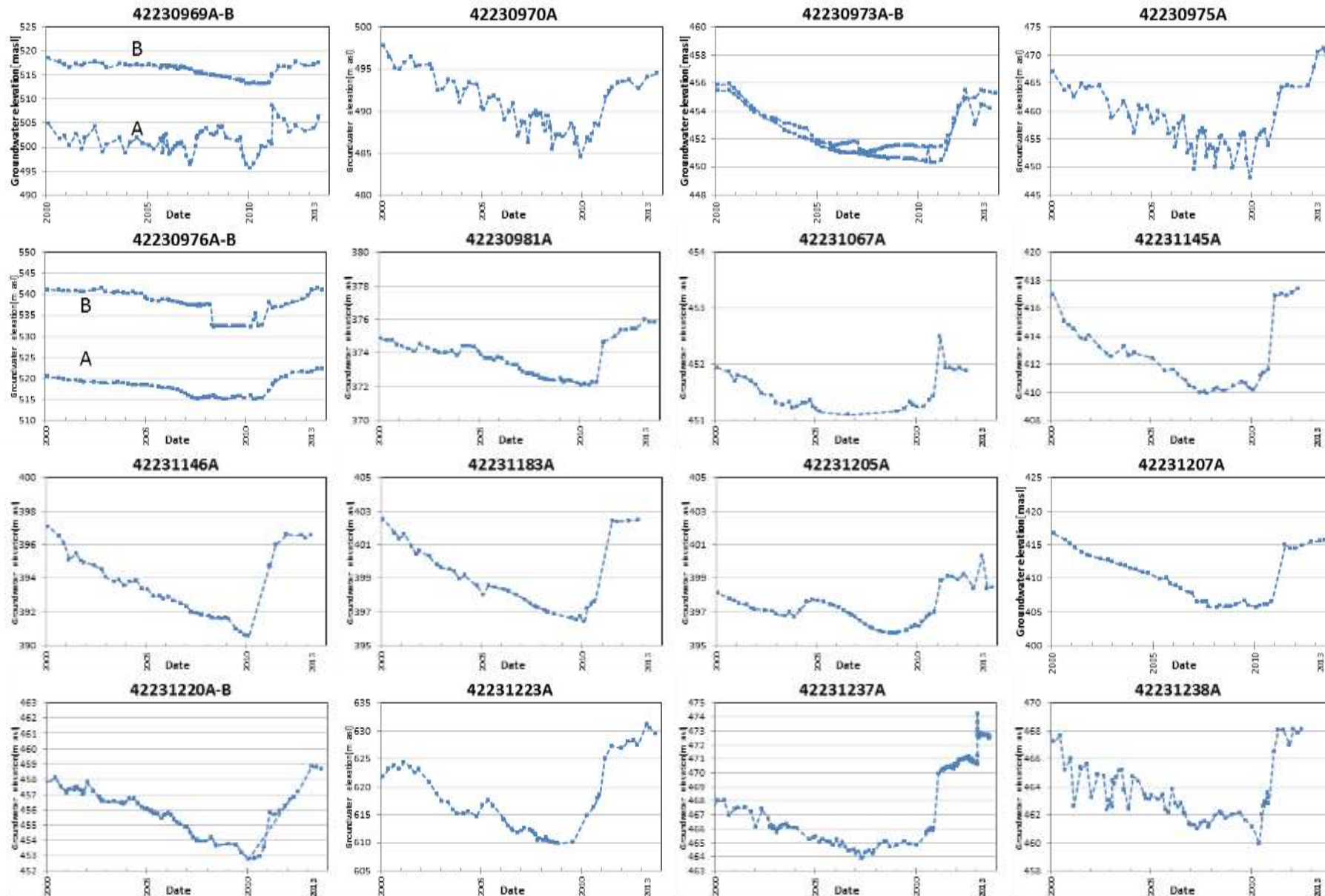
In each category, bores are listed in a sequestering order, according to RN.

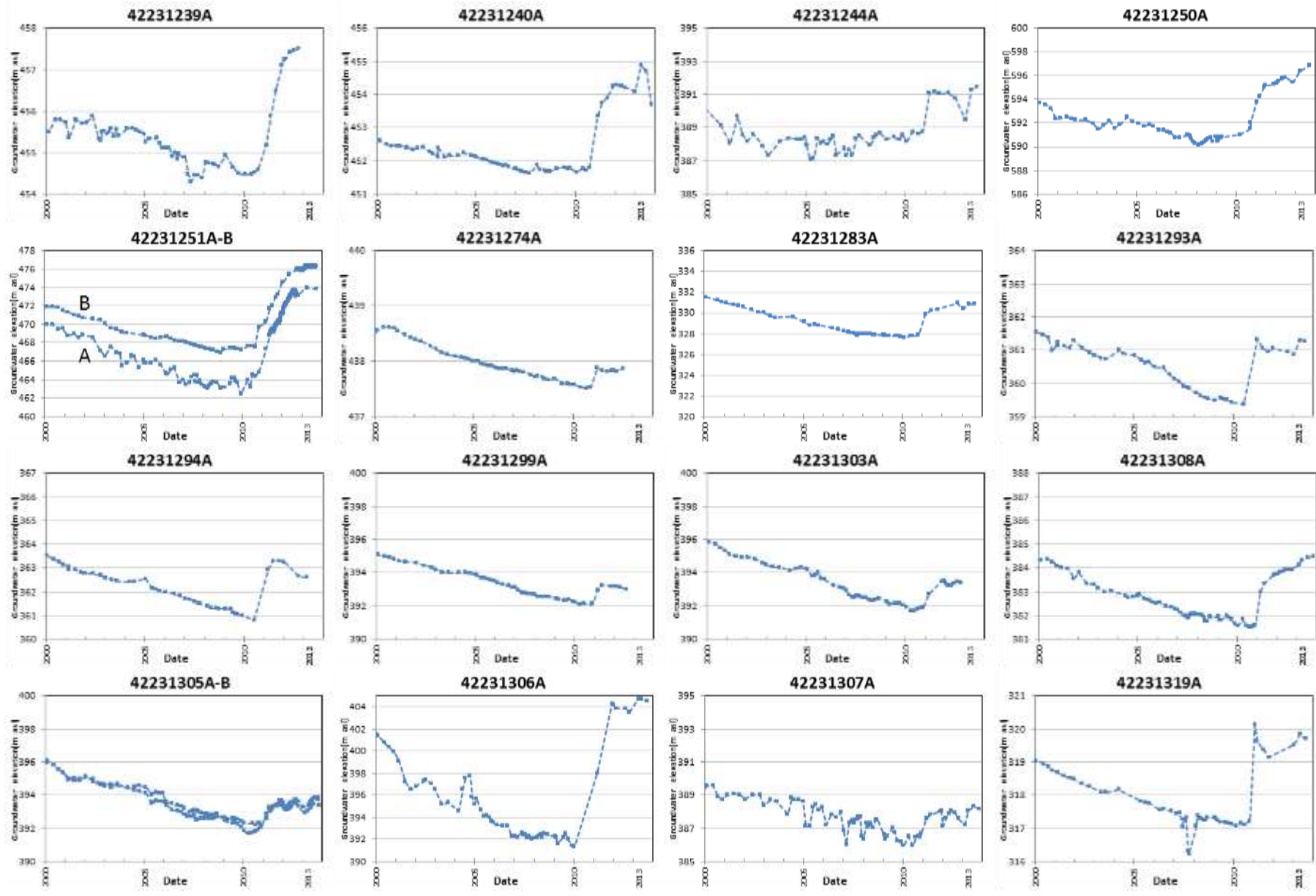
42230001A	E	42230122A	C	42230646A	E	42230848A	G	42230965B	A	42231179A	B	42231280A	C	42231334A	x	42231410A	D	42231496D	A	42231655A	A
42230002A	E	42230148A	D	42230646B	E	42230849A	E	42230965C	x	42231183A	A	42231281A	D	42231335A	A	42231411A	D	42231497A	G	42231656A	B
42230003A	E	42230148B	D	42230647A	E	42230850A	E	42230967B	x	42231193A	E	42231283A	A	42231336A	G	42231412A	D	42231497B	x	42231657A	A
42230004A	E	42230150A	D	42230651A	E	42230852A	B	42230967C	A	42231195A	E	42231286A	G	42231337A	x	42231413A	B	42231497C	x	42231659A	B
42230011A	A	42230151A	D	42230656A	A	42230853A	B	42230968A	A	42231205A	A	42231287A	G	42231338A	A	42231414A	D	42231500A	A	42231660A	x
42230012B	A	42230151C	D	42230657A	A	42230855A	G	42230968B	A	42231207A	A	42231288A	G	42231339A	x	42231415A	D	42231502A	D	42231661A	x
42230012C	A	42230153A	E	42230660A	D	42230856A	E	42230969A	A	42231208A	C	42231290A	x	42231340A	H	42231416A	E	42231502B	D	42231662A	x
42230014A	A	42230153B	D	42230661A	B	42230859A	E	42230969B	A	42231209A	C	42231293A	A	42231342A	G	42231417A	D	42231502C	D	42231663A	x
42230016A	A	42230155A	F	42230668A	A	42230860A	D	42230970A	A	42231210A	C	42231294A	A	42231343A	D	42231419A	E	42231503A	D	42231664A	x
42230018A	B	42230156A	D	42230669A	E	42230861A	D	42230970B	x	42231211A	C	42231295A	G	42231349A	B	42231420A	D	42231504A	E	42231665A	A
42230019A	B	42230156B	D	42230694A	E	42230873A	B	42230971A	D	42231212A	F	42231299A	A	42231350A	D	42231421A	E	42231507A	x	42231668A	A
42230022A	D	42230157A	D	42230695A	E	42230874A	B	42230971B	D	42231213A	F	42231300A	B	42231353A	x	42231422A	E	42231509A	D	42231669A	A
42230025A	x	42230158A	D	42230696A	B	42230876A	B	42230972A	x	42231214A	H	42231301A	D	42231354A	E	42231423A	B	42231523A	H	42231671A	x
42230025B	G	42230159A	x	42230701A	G	42230880A	H	42230972B	x	42231216A	G	42231303A	A	42231358A	A	42231424A	B	42231524A	F		
42230025C	x	42230160A	D	42230702A	G	42230882A	A	42230973A	A	42231219A	B	42231305A	A	42231362A	A	42231425A	B	42231527A	A		
42230031A	E	42230161A	E	42230702B	G	42230883A	A	42230973B	A	42231220A	A	42231305B	A	42231363A	A	42231426A	B	42231529A	A		
42230045A	D	42230162A	H	42230702C	x	42230884A	A	42230974A	E	42231220B	A	42231306A	A	42231364A	B	42231428A	A	42231533A	A		
42230046A	D	42230163B	G	42230704A	E	42230888A	B	42230974B	E	42231221A	x	42231307A	A	42231367A	D	42231429A	B	42231536A	D		
42230047B	C	42230163C	G	42230705A	E	42230895A	C	42230975A	A	42231222A	B	42231308A	A	42231368A	G	42231430A	x	42231537A	A		
42230050A	B	42230164A	x	42230720A	A	42230896A	E	42230975B	A	42231223A	A	42231308B	G	42231370A	C	42231431A	B	42231539A	D		
42230050B	B	42230164B	x	42230725A	A	42230897A	x	42230976A	A	42231224A	D	42231309A	B	42231373A	C	42231432A	D	42231544A	G		
42230050C	G	42230165A	D	42230741A	B	42230900A	A	42230976B	A	42231225A	x	42231310A	B	42231374A	x	42231444A	D	42231545A	A		
42230054A	B	42230166A	x	42230745A	B	42230908A	x	42230981A	A	42231229A	B	42231310B	B	42231375A	A	42231447A	A	42231548A	E		
42230057A	D	42230167A	D	42230749A	E	42230911A	x	42231052A	D	42231230A	B	42231311A	D	42231375B	D	42231450A	B	42231549A	A		
42230058A	C	42230168A	G	42230751A	B	42230912A	x	42231053A	G	42231236A	E	42231312A	H	42231376A	D	42231454A	B	42231553A	F		
42230058B	C	42230169A	D	42230752A	B	42230922A	x	42231054A	D	42231237A	A	42231313A	E	42231376B	D	42231455A	A	42231557A	G		
42230060A	B	42230173A	D	42230752B	B	42230934A	x	42231062A	E	42231238A	A	42231314A	E	42231377A	D	42231456A	B	42231558A	x		
42230060B	B	42230174A	x	42230752C	B	42230934B	x	42231063A	G	42231239A	A	42231315A	E	42231377B	D	42231457A	x	42231560A	G		
42230061A	D	42230178A	F	42230767A	B	42230935A	A	42231065A	E	42231240A	A	42231315B	E	42231378A	D	42231458A	C	42231561A	D		
42230064A	D	42230179A	x	42230768A	D	42230936A	A	42231066A	E	42231241A	D	42231315C	E	42231378B	D	42231462A	G	42231562A	x		
42230068A	C	42230182A	A	42230768B	x	42230937A	A	42231067A	A	42231242A	D	42231316A	E	42231379A	D	42231463A	C	42231563A	D		
42230069A	D	42230184A	C	42230770A	D	42230938A	A	42231068A	E	42231244A	A	42231316B	H	42231379B	D	42231464A	C	42231564A	A		
42230070A	D	42230185A	x	42230771A	x	42230938B	x	42231069A	D	42231245A	E	42231317A	E	42231380A	C	42231465A	G	42231590A	G		
42230071A	D	42230187A	x	42230773A	D	42230953A	x	42231071A	E	42231250A	A	42231317B	E	42231383A	A	42231467A	B	42231591A	A		
42230075A	C	42230188A	G	42230790A	B	42230953B	x	42231072A	D	42231251A	A	42231318A	C	42231390A	D	42231468A	E	42231592A	B		
42230076A	x	42230190A	x	42230792A	B	42230953C	x	42231073A	D	42231251B	A	42231319A	A	42231395A	D	42231469A	B	42231593A	A		
42230079A	C	42230201A	x	42230805A	A	42230955A	A	42231074A	G	42231254A	D	42231320A	A	42231396A	D	42231470A	B	42231594A	A		
42230080A	C	42230203A	C	42230817A	B	42230955B	x	42231076A	B	42231256A	F	42231321A	E	42231397A	B	42231490A	D	42231595A	A		
42230088A	C	42230204A	D	42230819A	B	42230957A	A	42231089A	E	42231259A	D	42231323A	B	42231398A	E	42231491A	A	42231596A	A		
42230089A	C	42230205A	D	42230824A	G	42230960A	x	42231103A	x	42231260A	x	42231323B	B	42231399A	B	42231491B	A	42231597A	A		
42230096A	D	42230210A	A	42230831A	B	42230960B	x	42231128A	C	42231261A	x	42231324A	B	42231400A	D	42231492A	D	42231603A	B		
42230110A	B	42230211A	A	42230832A	B	42230962A	A	42231135A	F	42231266A	B	42231325A	B	42231401A	A	42231493A	D	42231647A	x		
42230111A	x	42230290A	D	42230833A	G	42230962B	A	42231136A	C	42231267A	A	42231326A	B	42231403A	D	42231493B	D	42231648A	C		
42230112A	C	42230291A	D	42230834A	E	42230963A	A	42231137A	C	42231267B	B	42231328A	B	42231404A	E	42231494A	D	42231649A	x		
42230113A	C	42230293A	B	42230836A	E	42230963B	A	42231145A	A	42231271A	E	42231329A	B	42231405A	D	42231494B	D	42231650A	x		
42230114A	C	42230294A	D	42230837A	E	42230963C	A	42231146A	A	42231272A	G	42231330A	x	42231406A	A	42231495A	C	42231651A	B		
42230117A	C	42230295A	C	42230843A	G	42230964A	A	42231169A	E	42231273A	B	42231331A	B	42231407A	B	42231496A	x	42231652A	B		
42230119A	D	42230296A	C	42230846A	G	42230964B	A	42231173A	D	42231274A	A	42231331B	B	42231408A	D	42231496B	G	42231653A	B		
42230121A	C	42230645A	B	42230847A	G	42230965A	A	42231177A	E	42231279A	F	42231333A	B	42231409A	B	42231496C	G	42231654A	B		

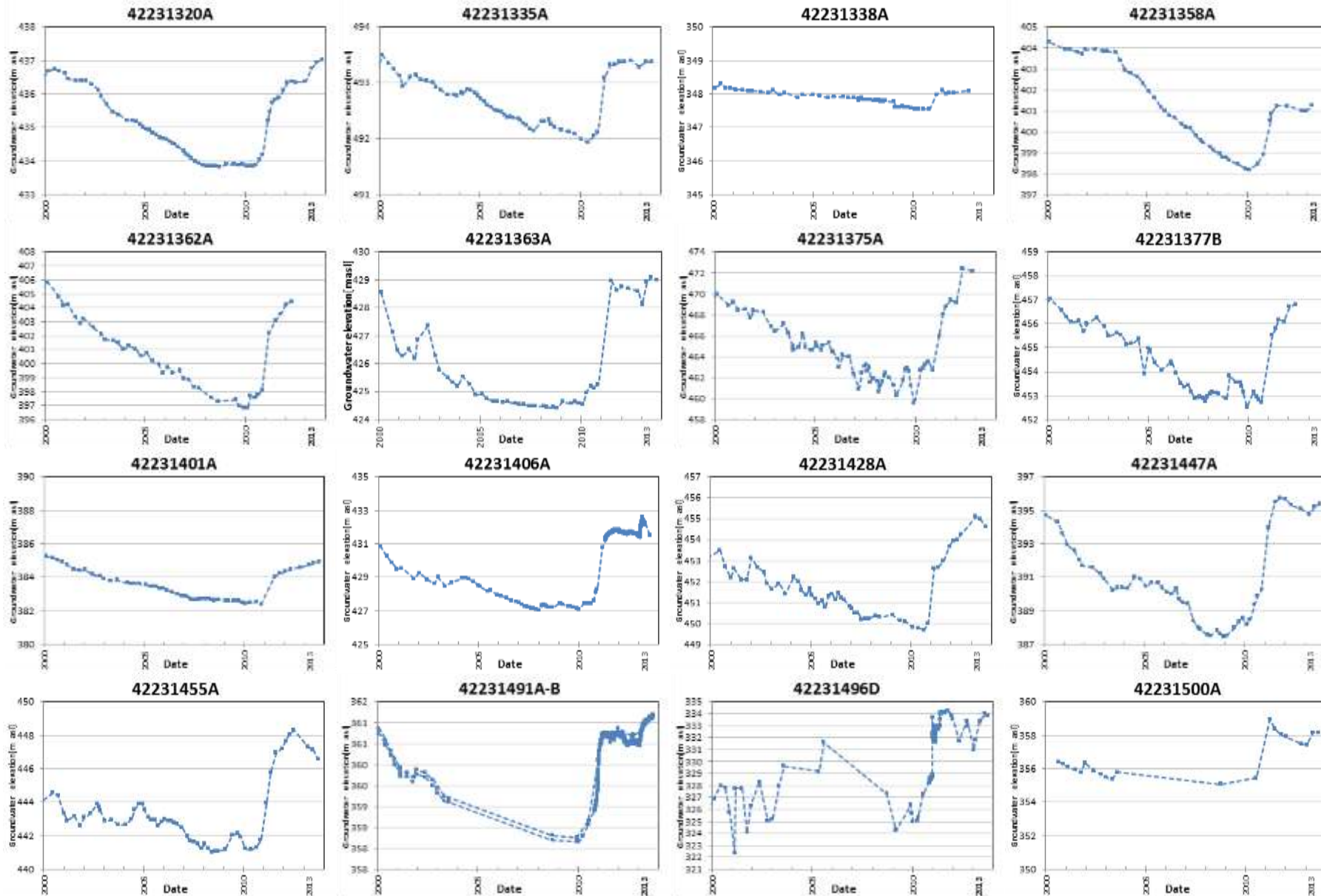
Type A

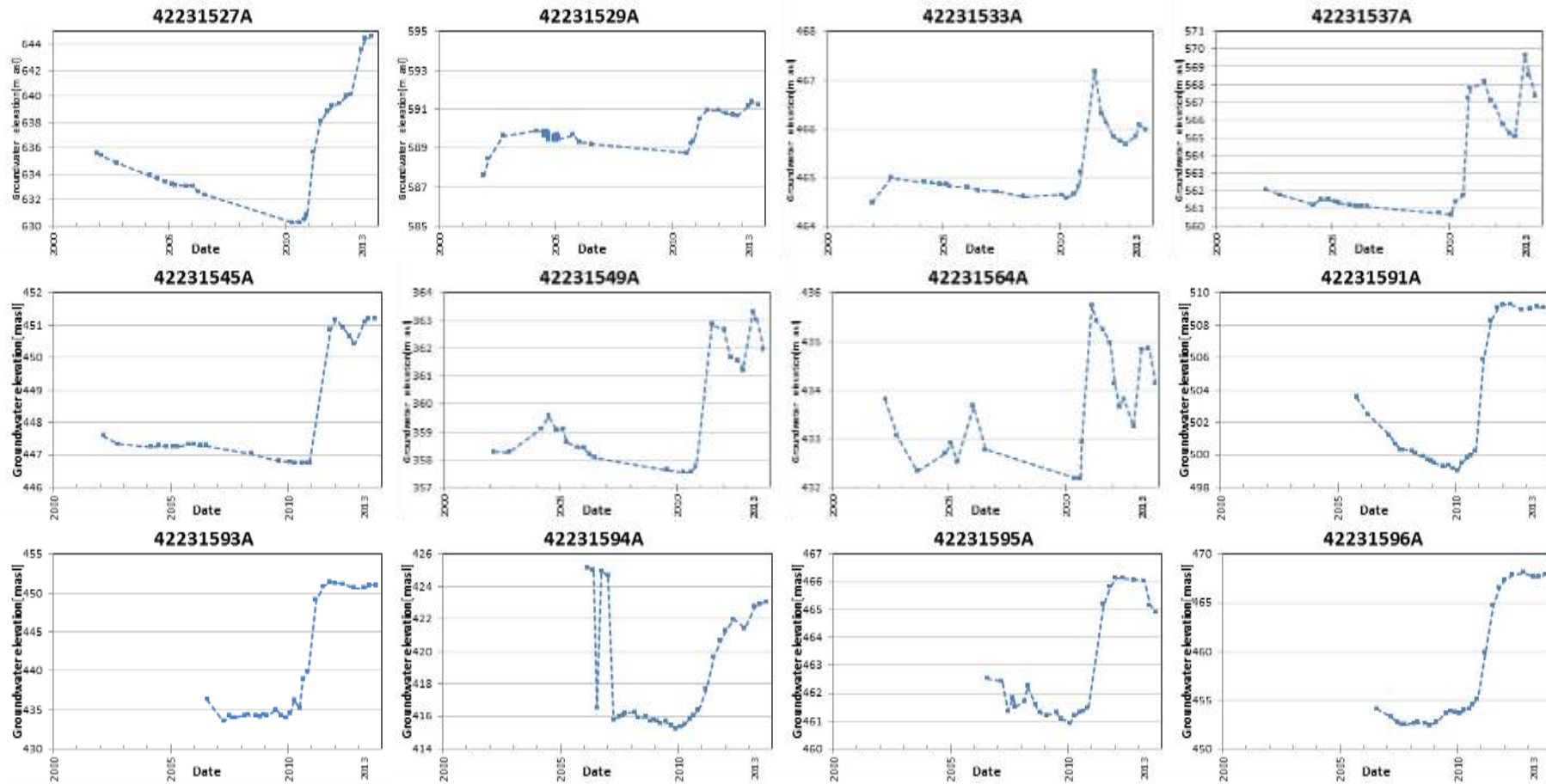


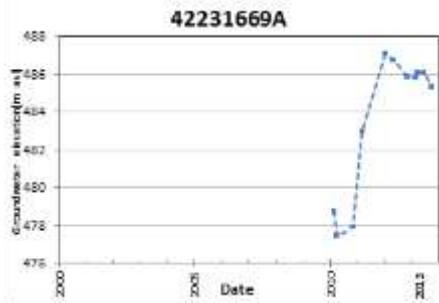
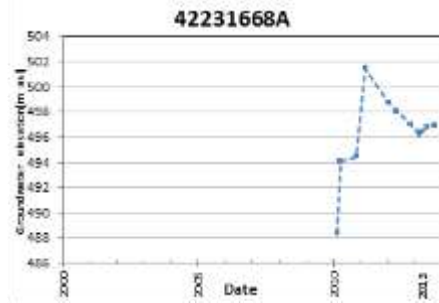
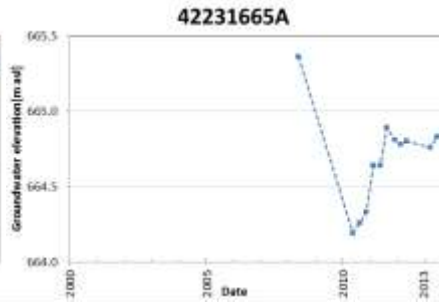
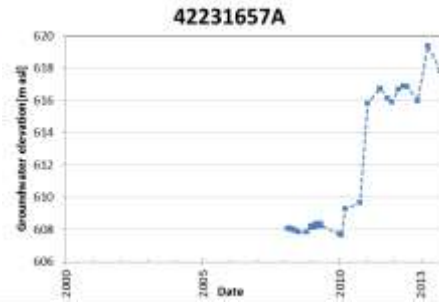
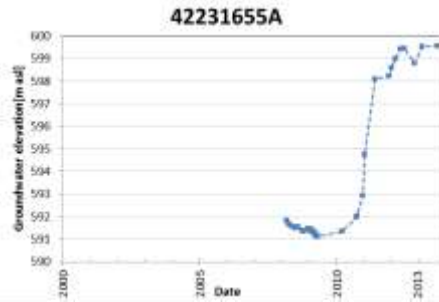
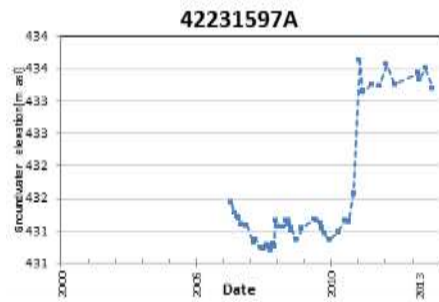




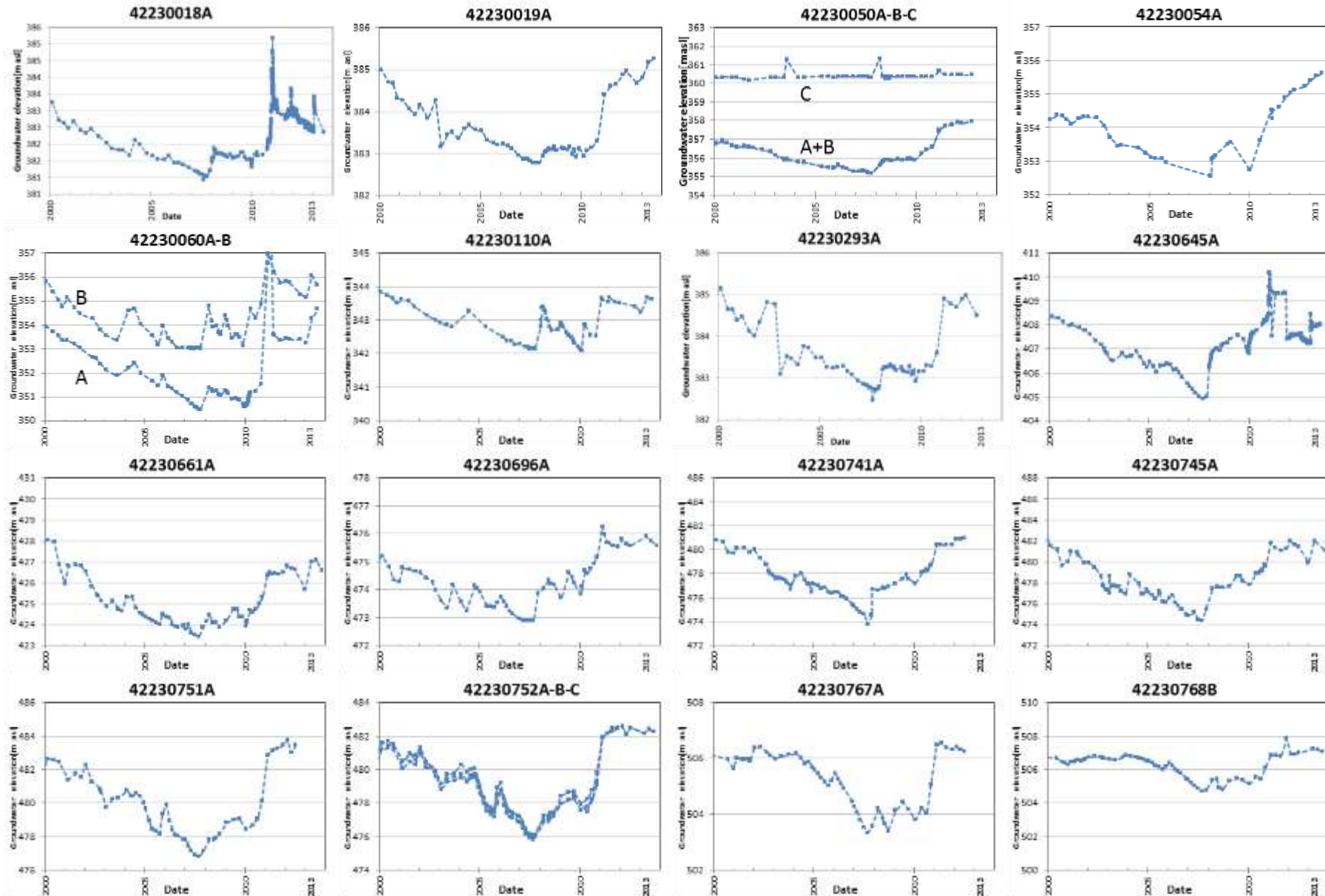


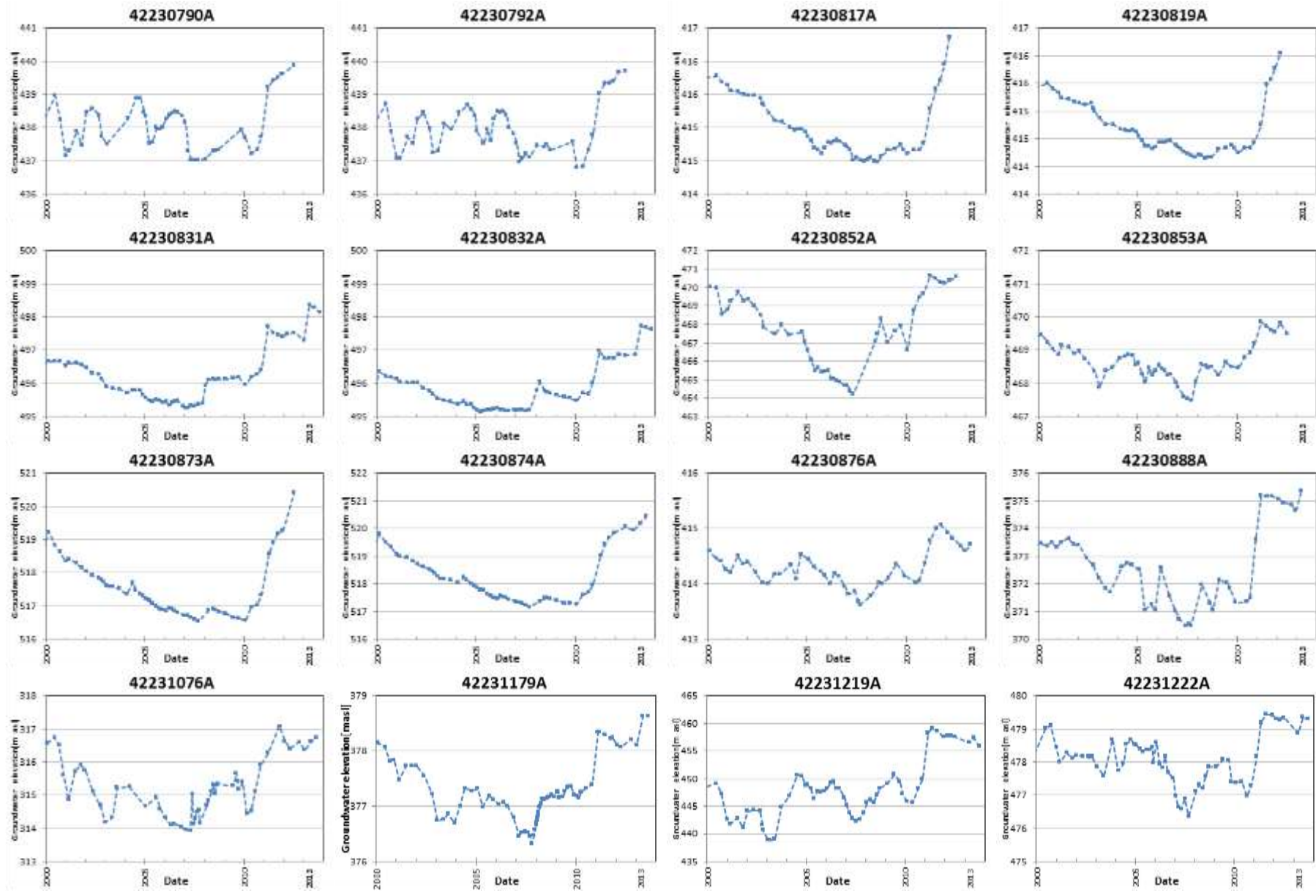


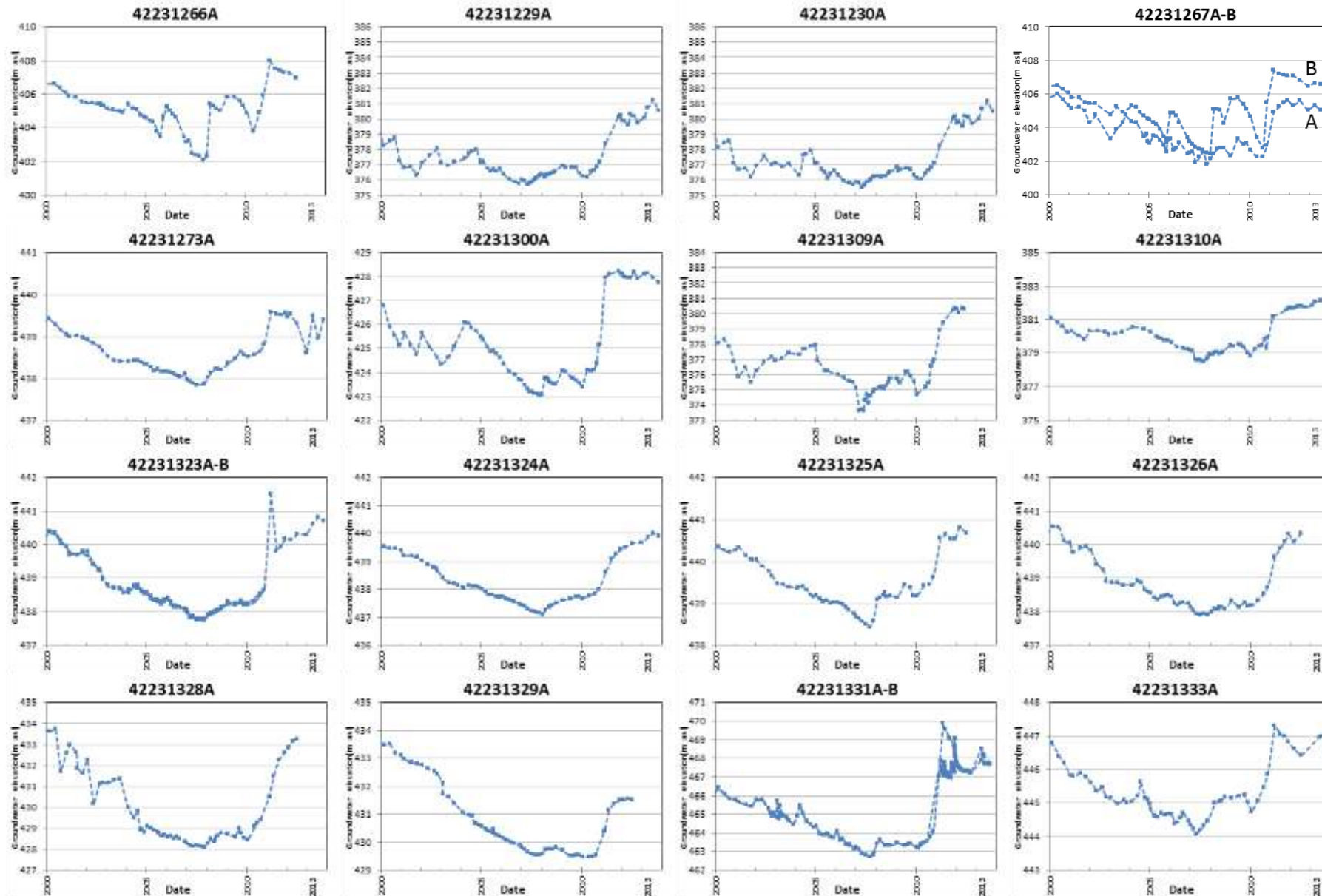


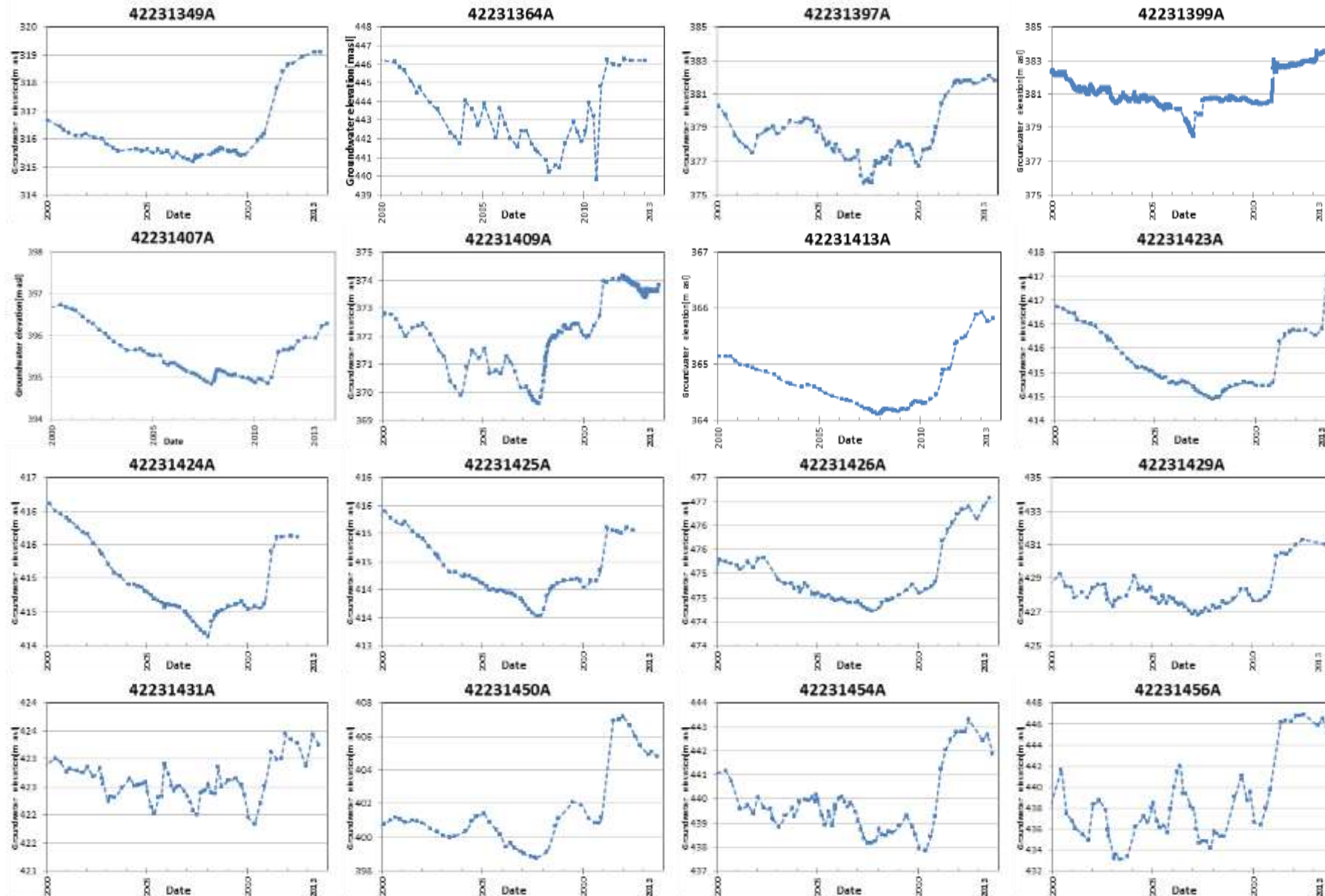


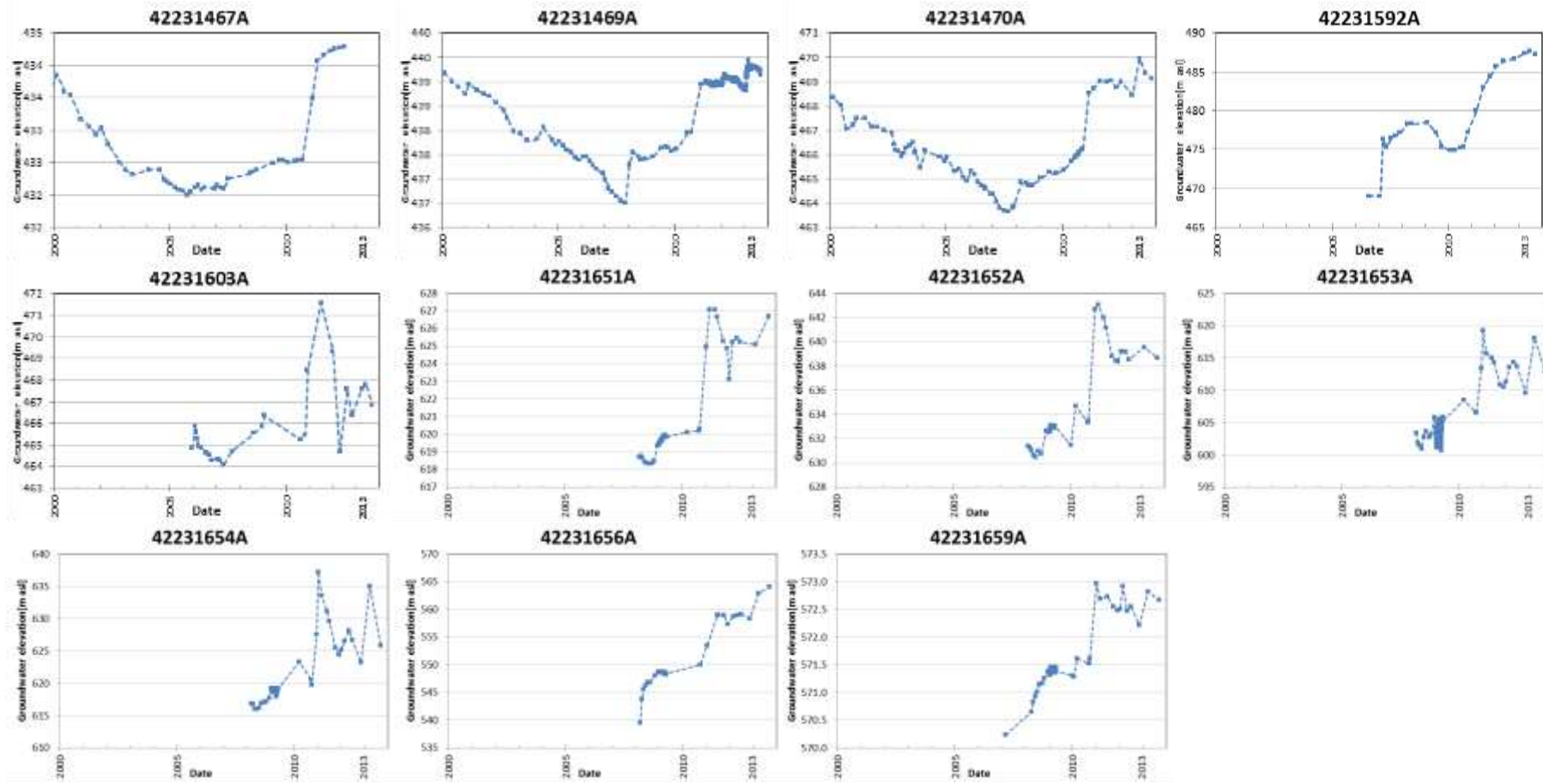
TYPE B



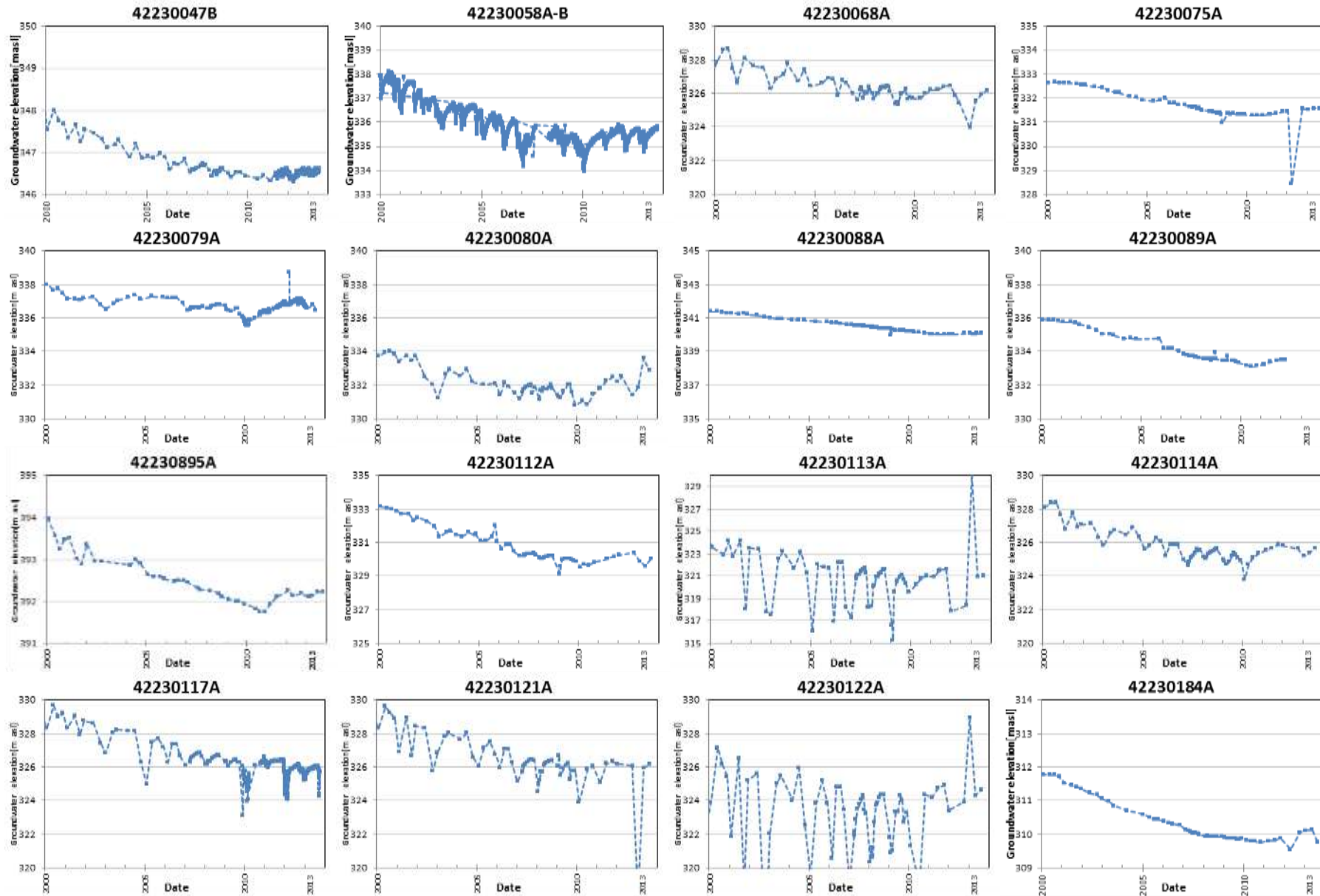


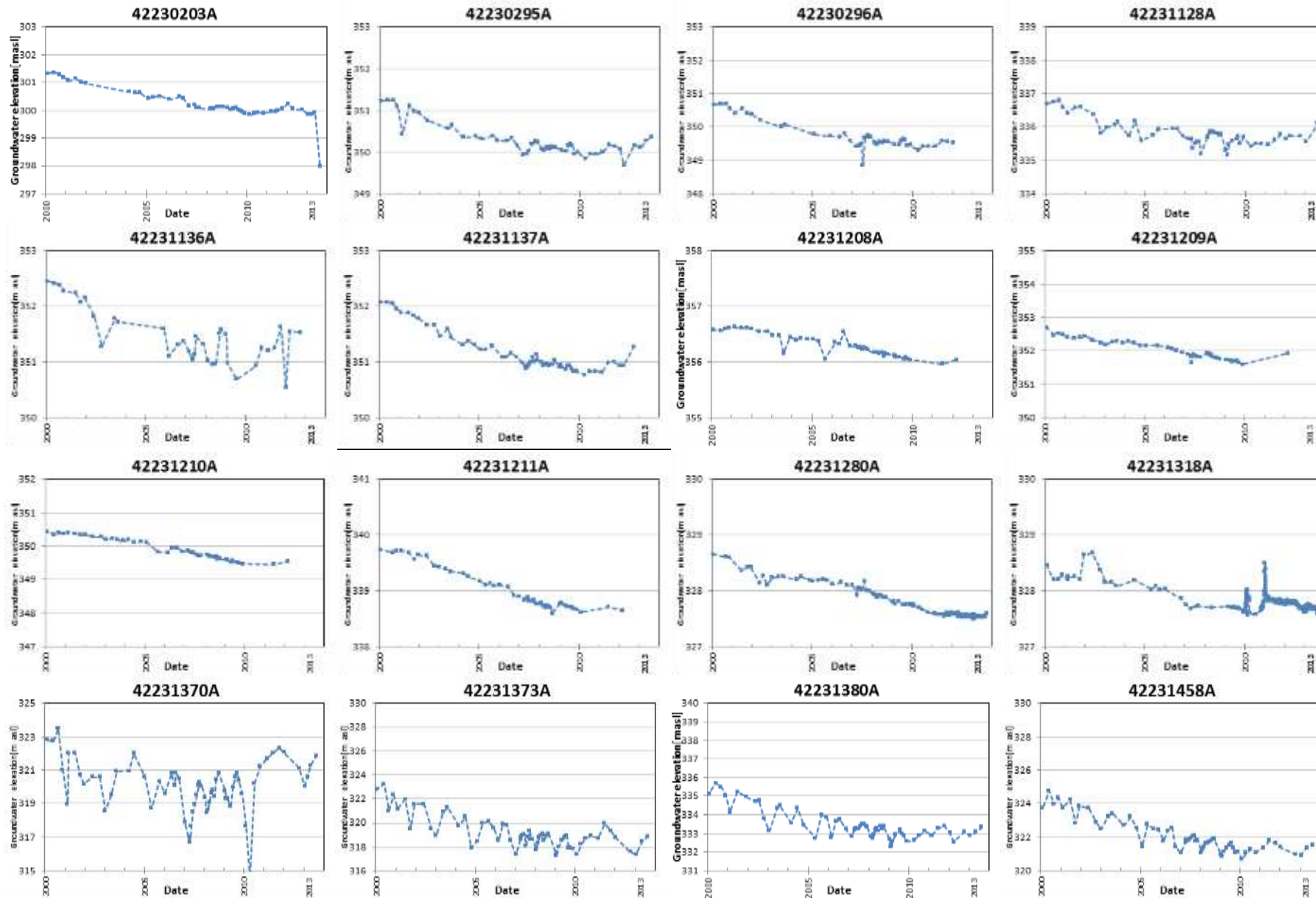


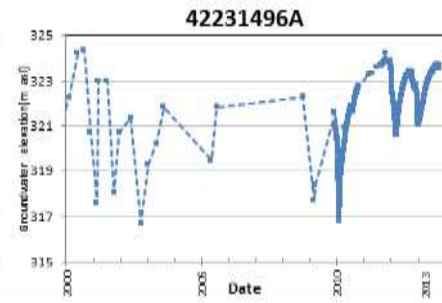
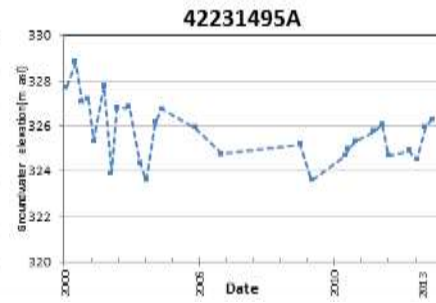
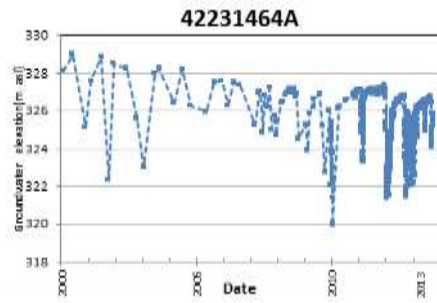
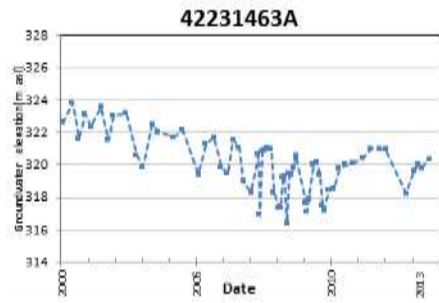




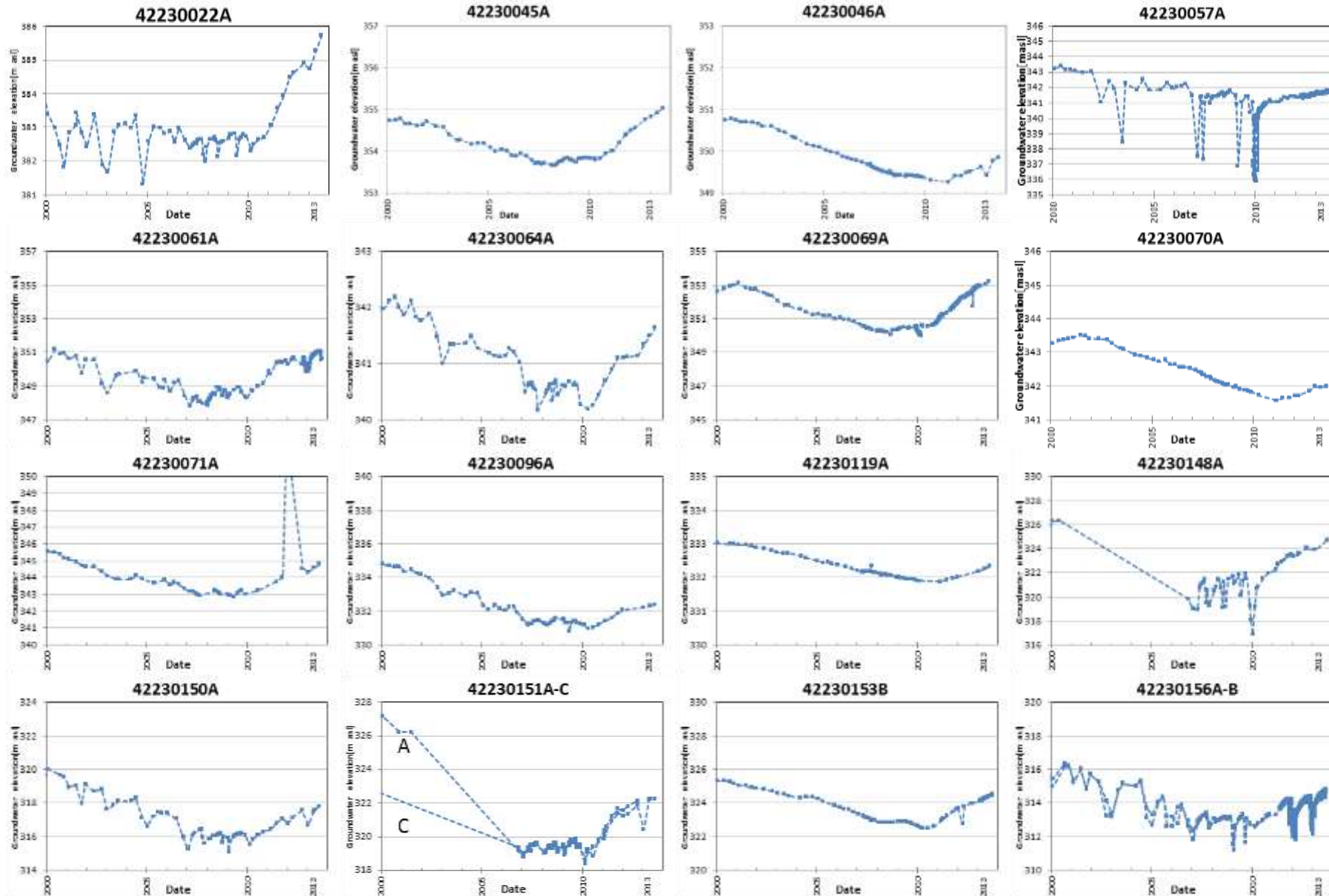
TYPE C

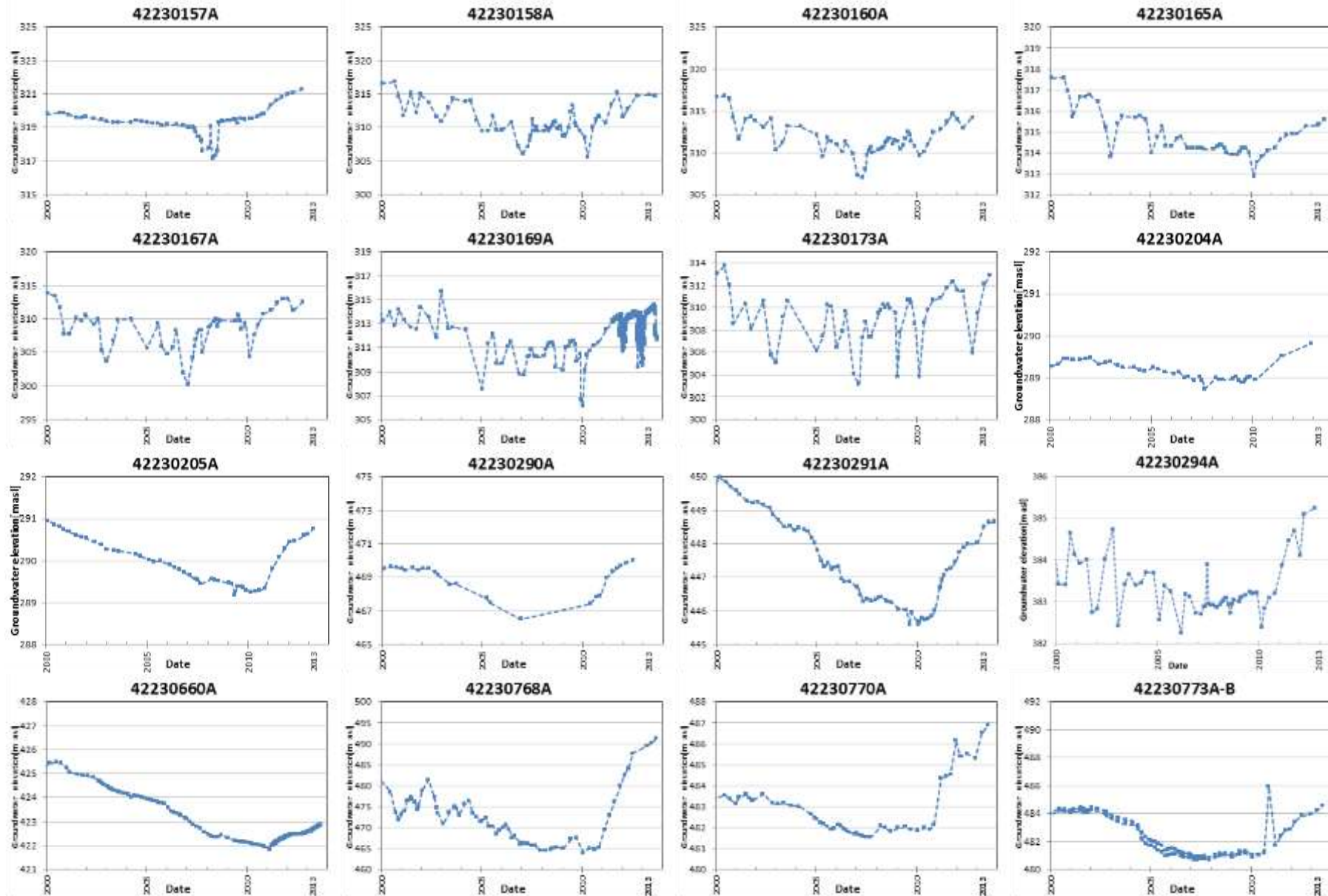


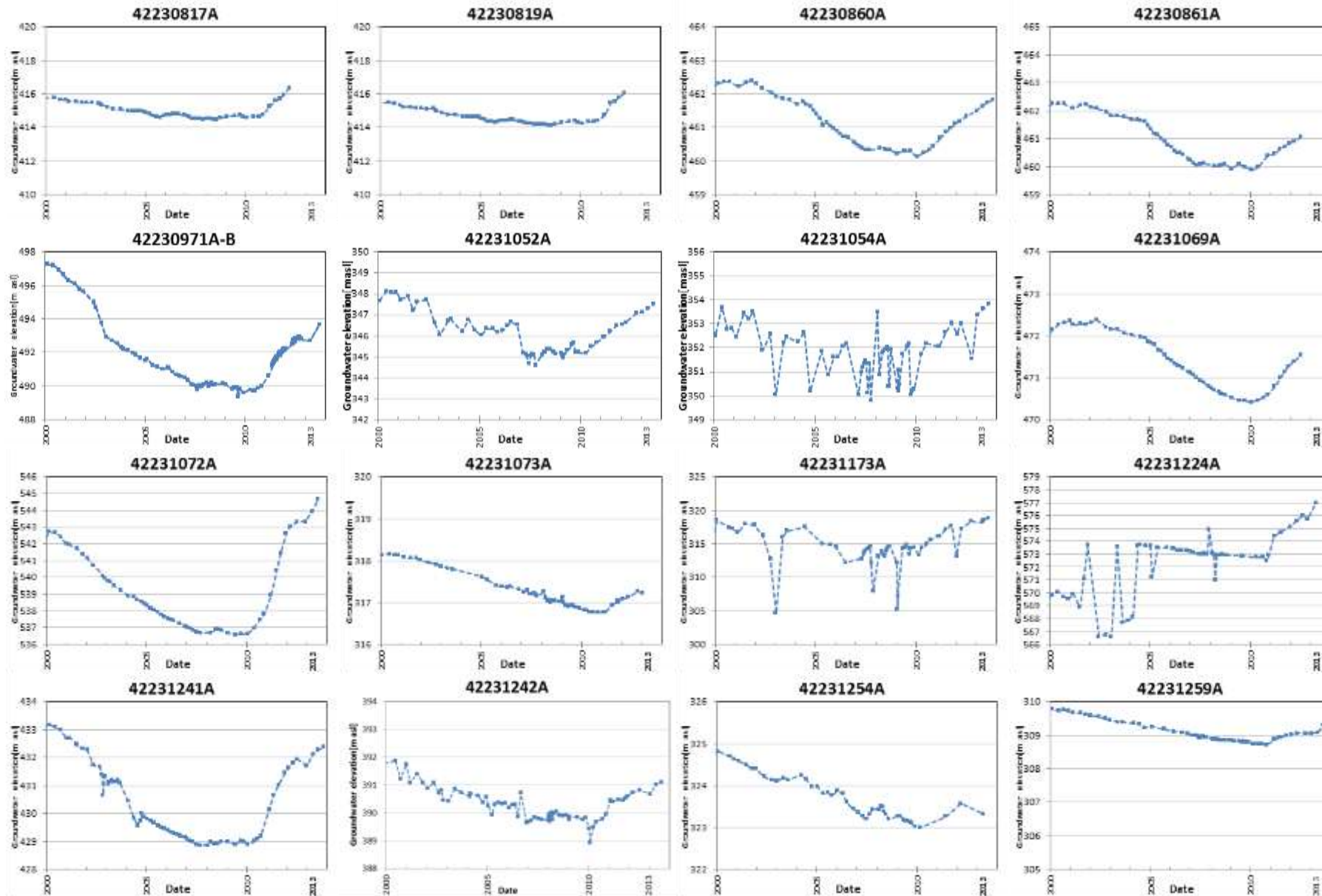


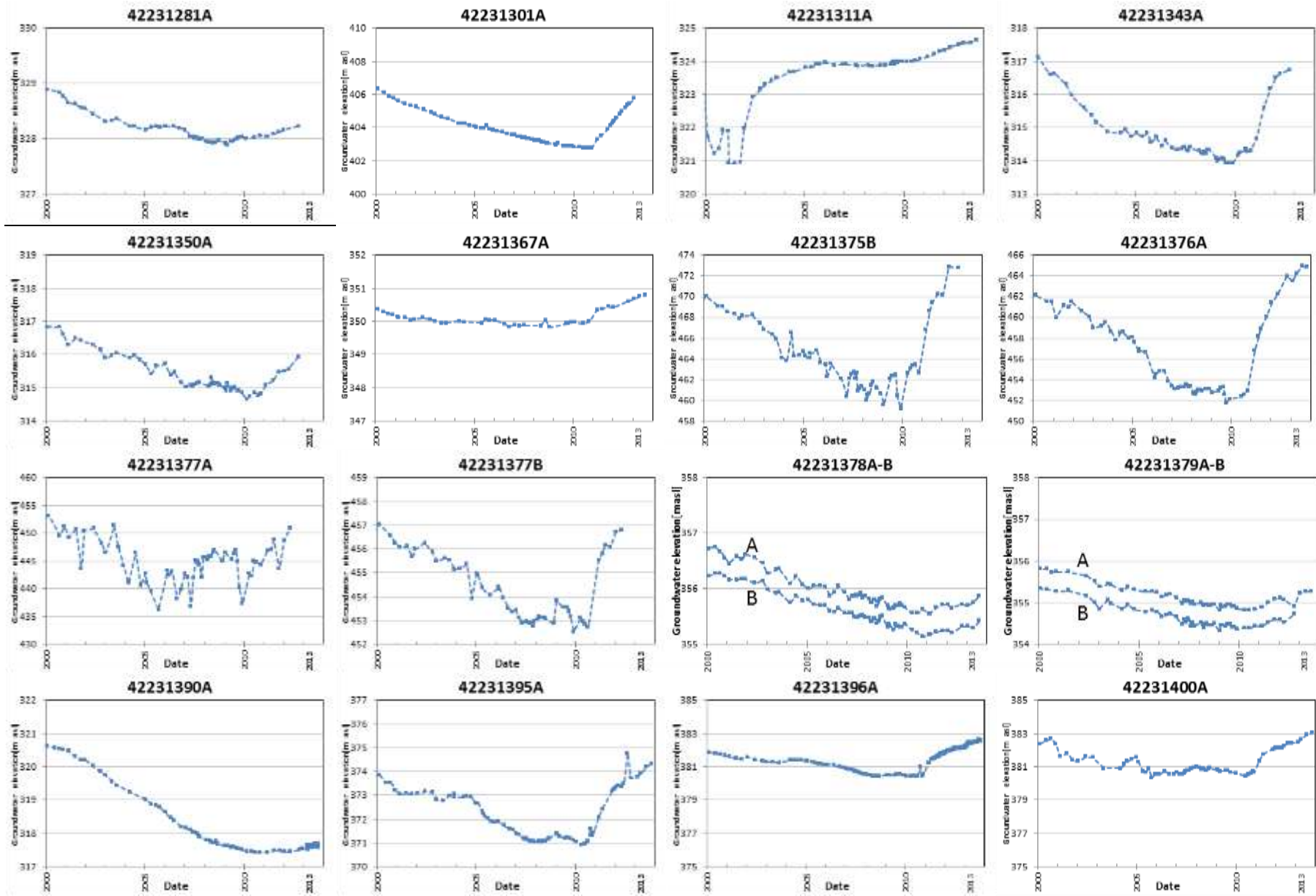


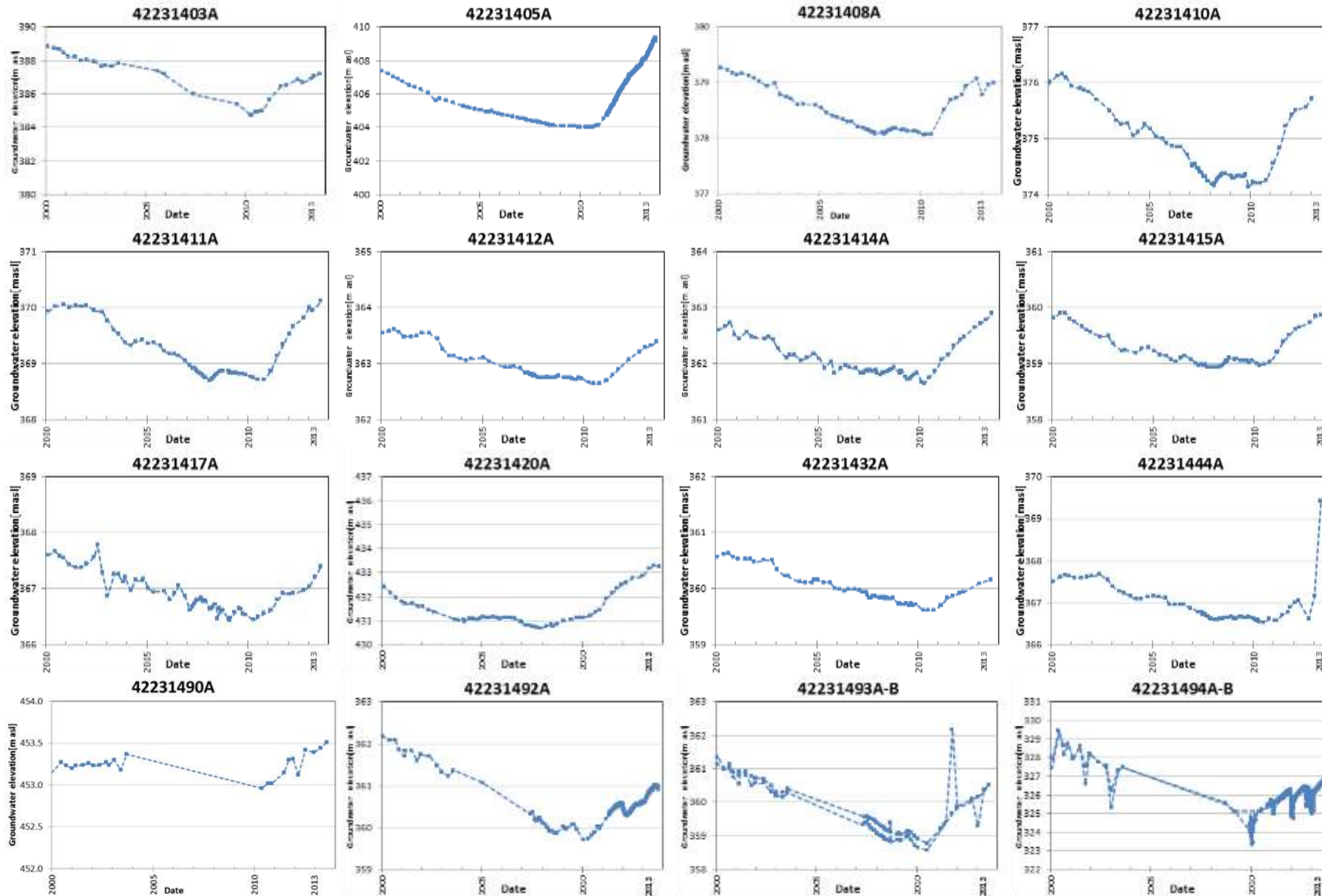
TYPE D

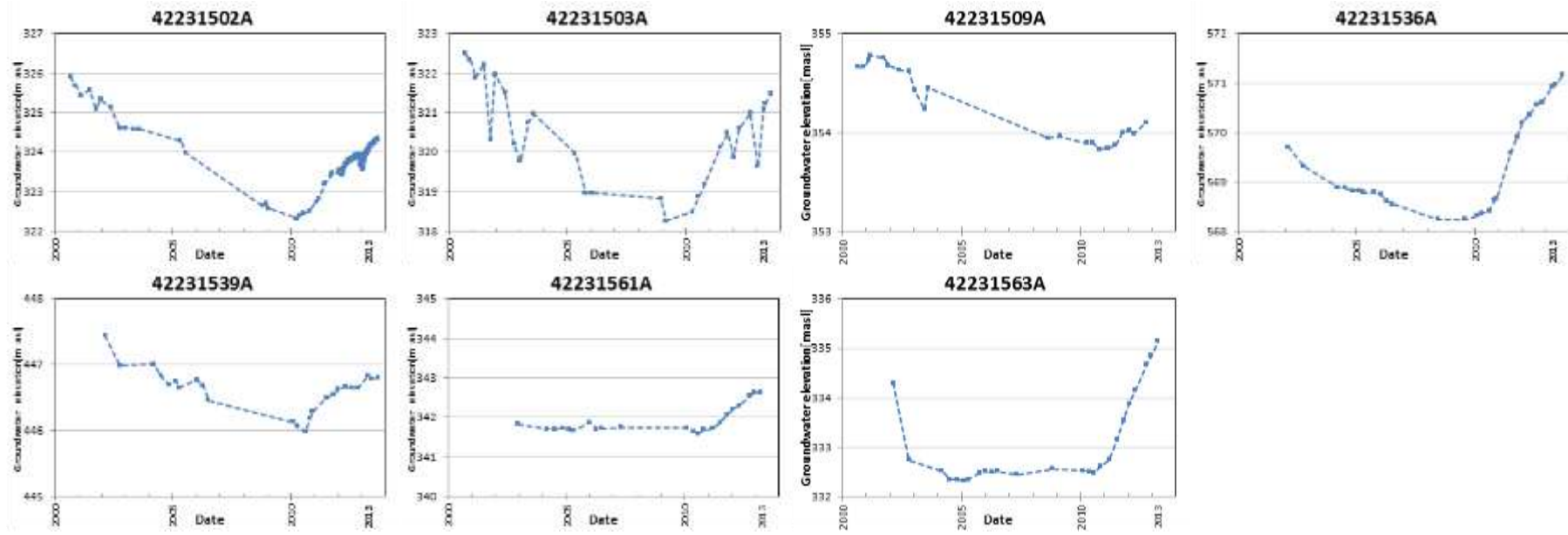




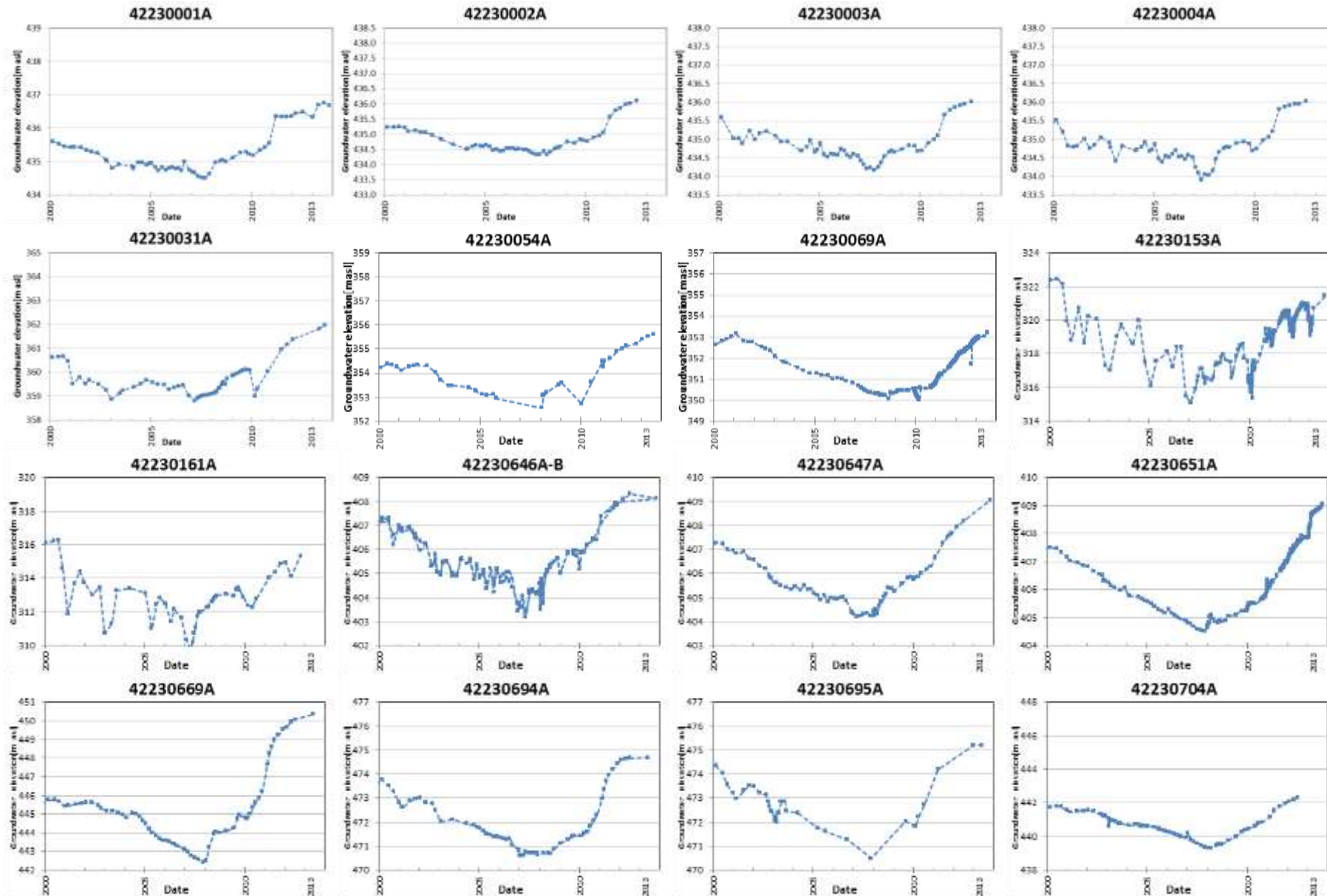


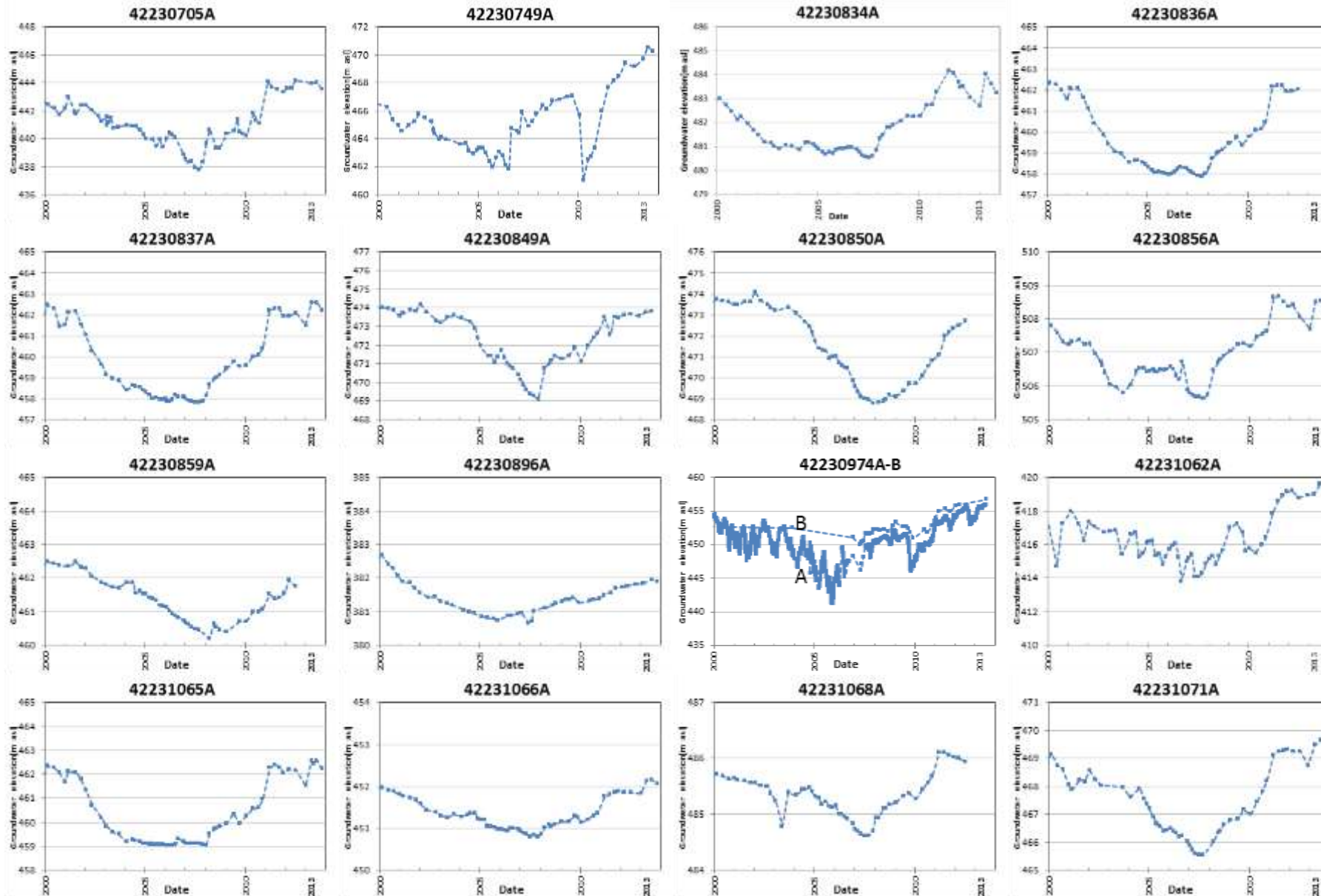


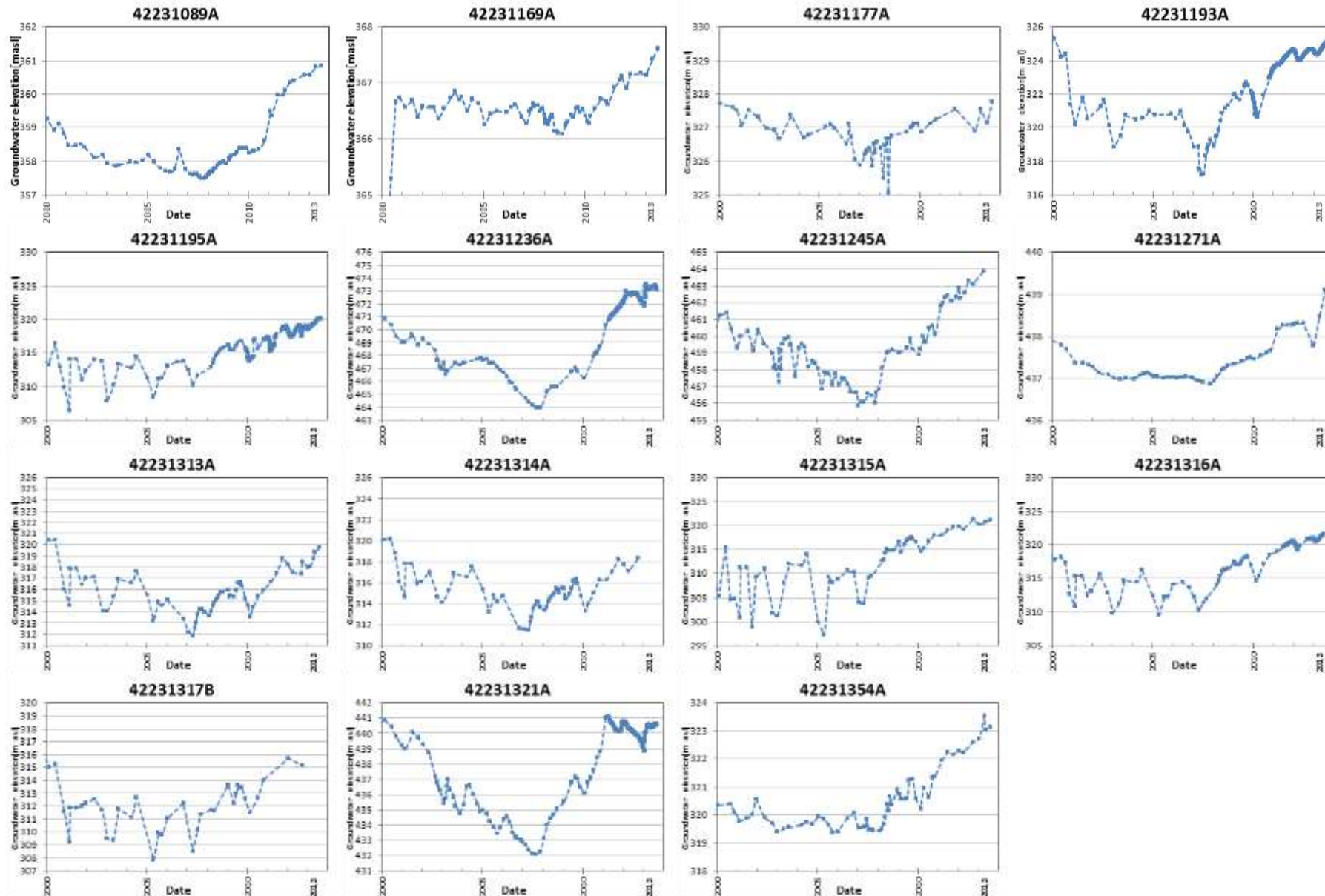


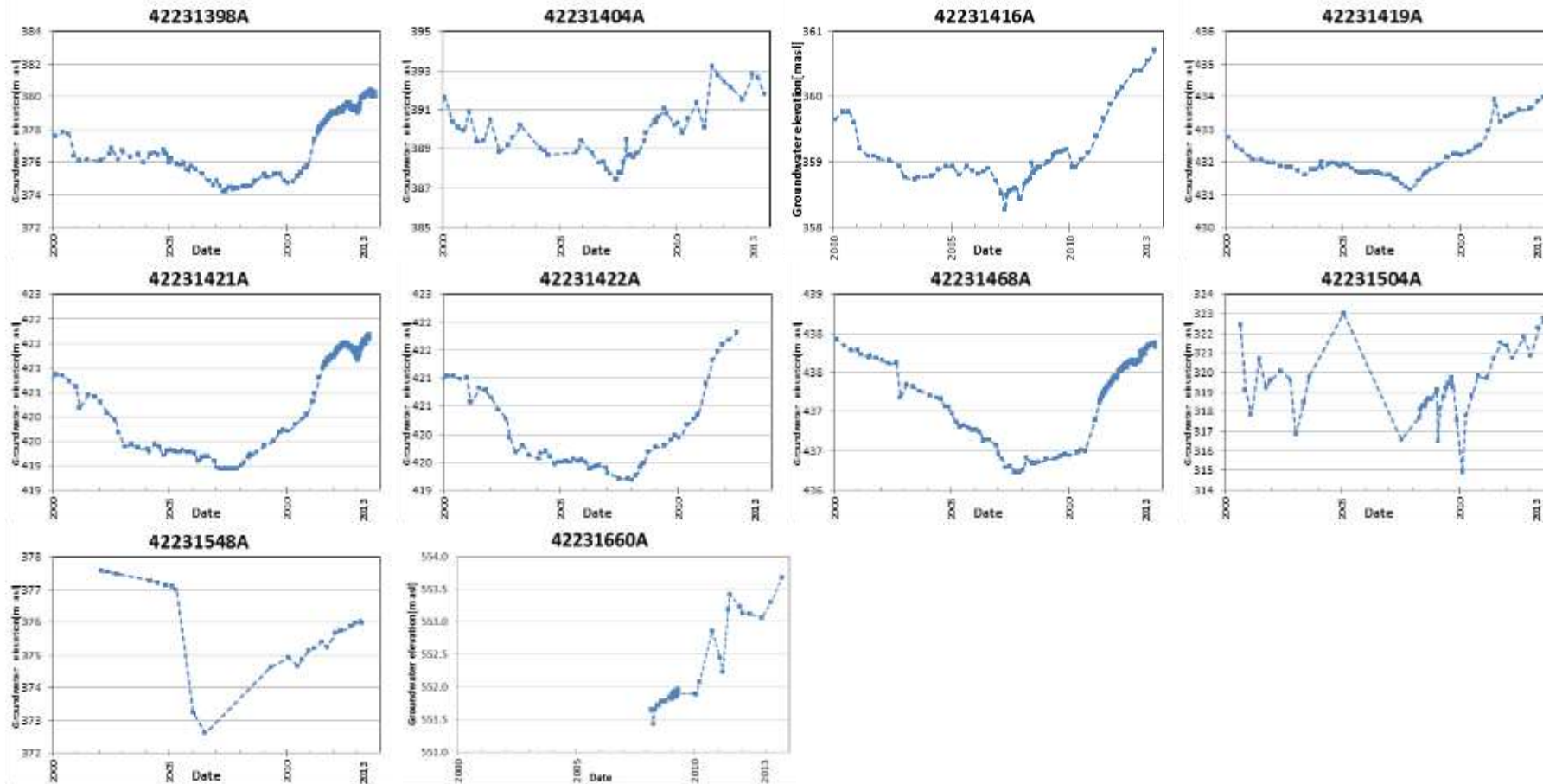


TYPE E

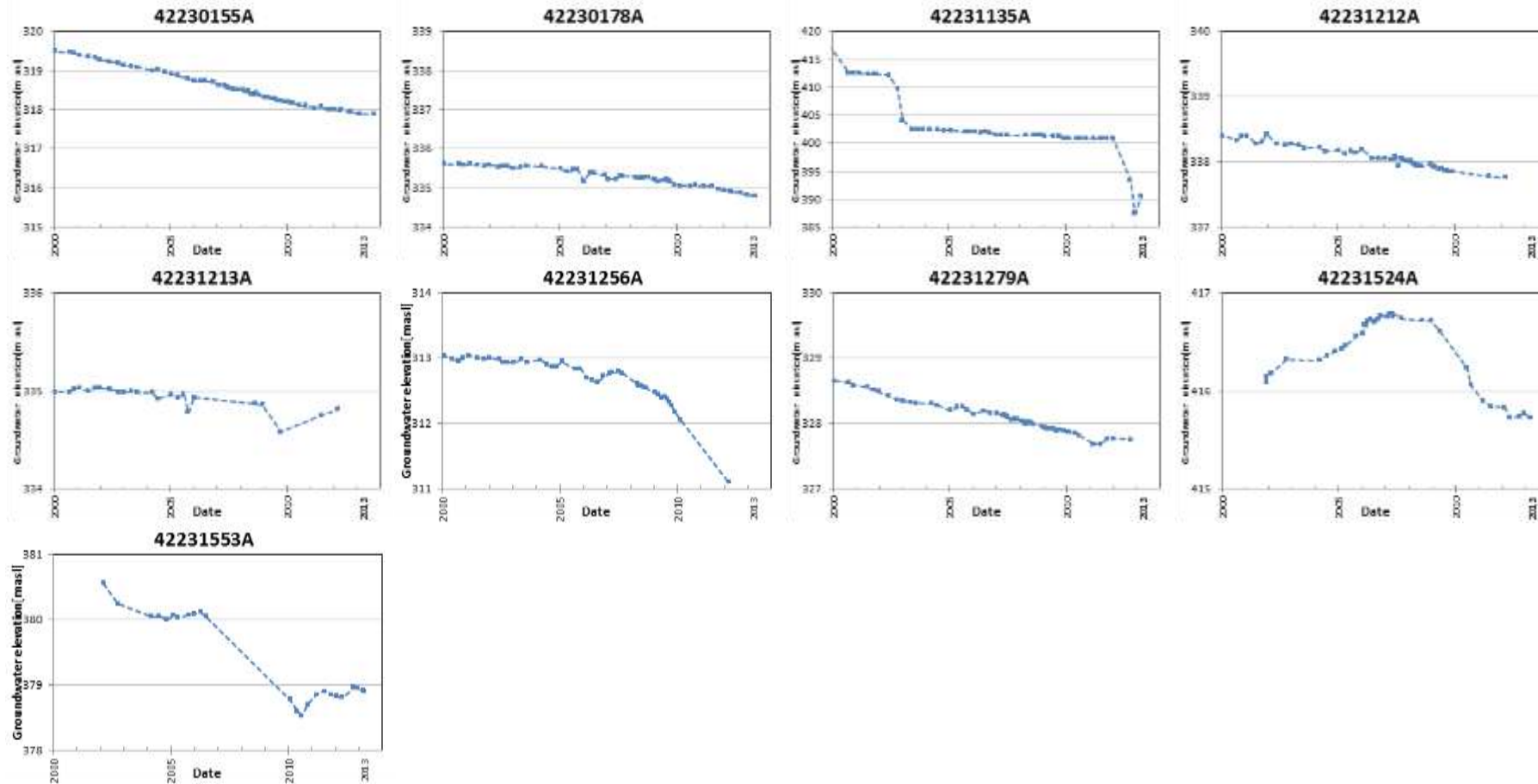




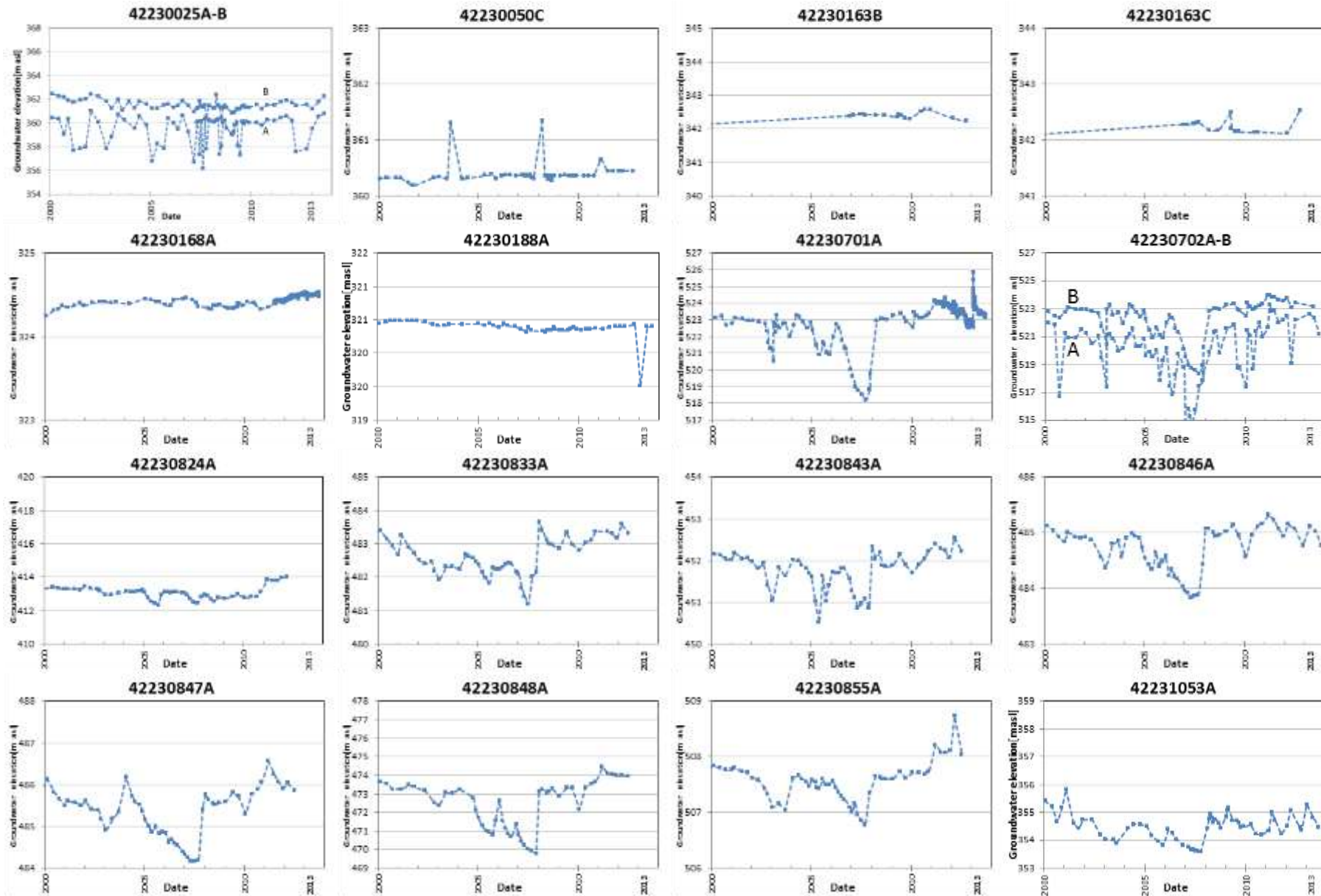


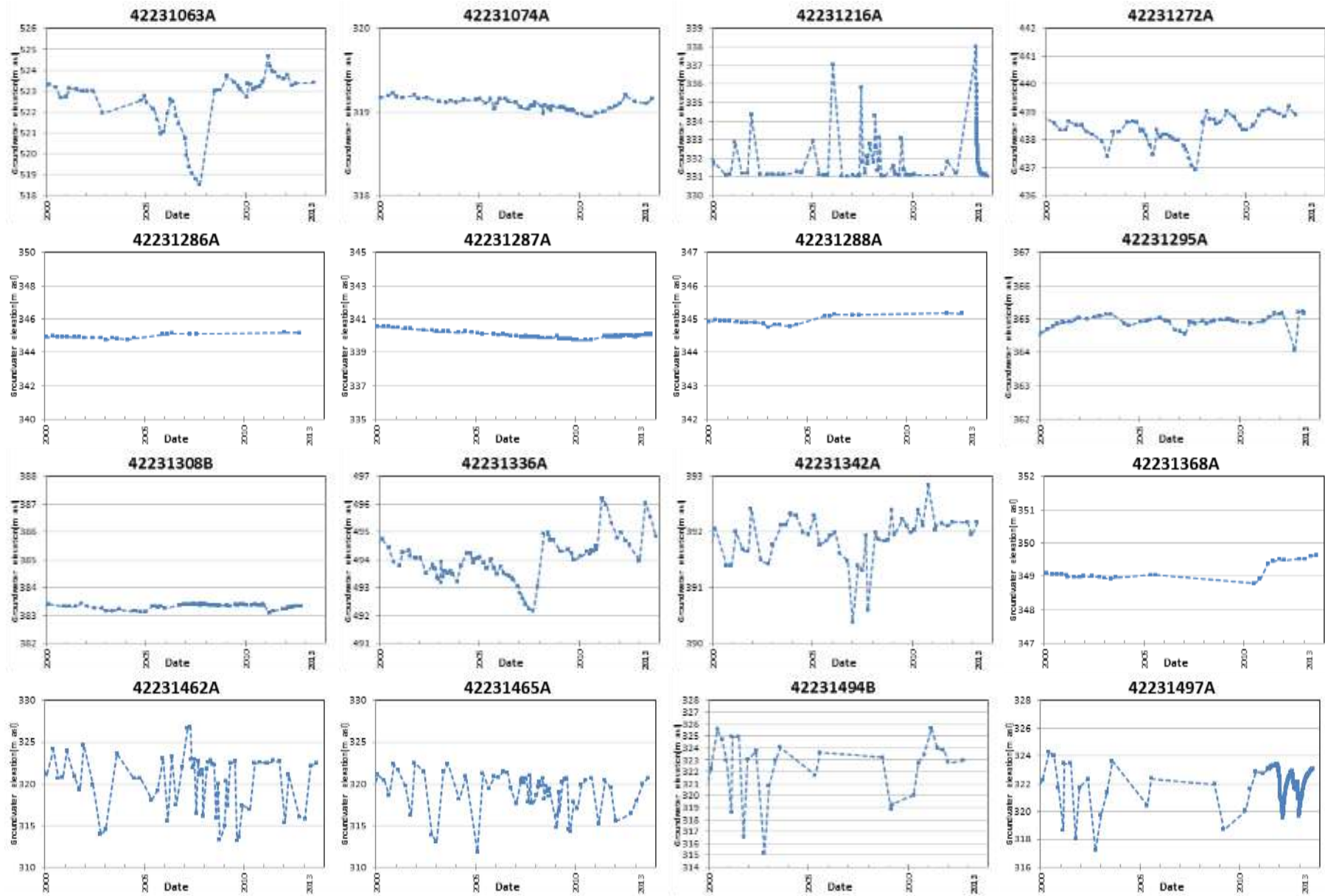


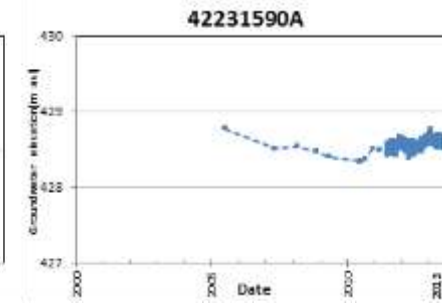
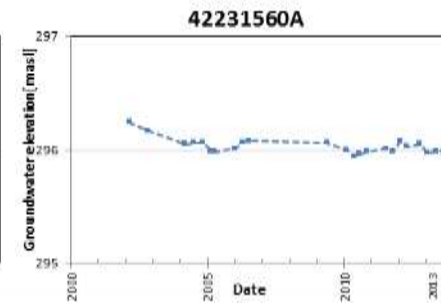
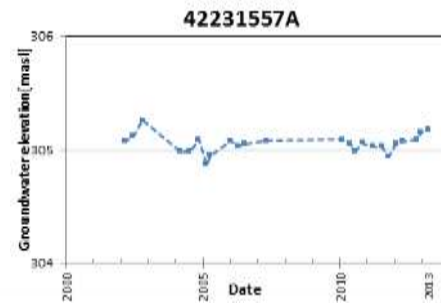
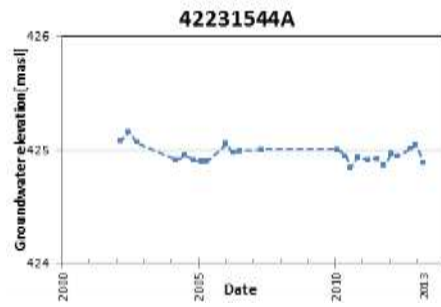
Type F



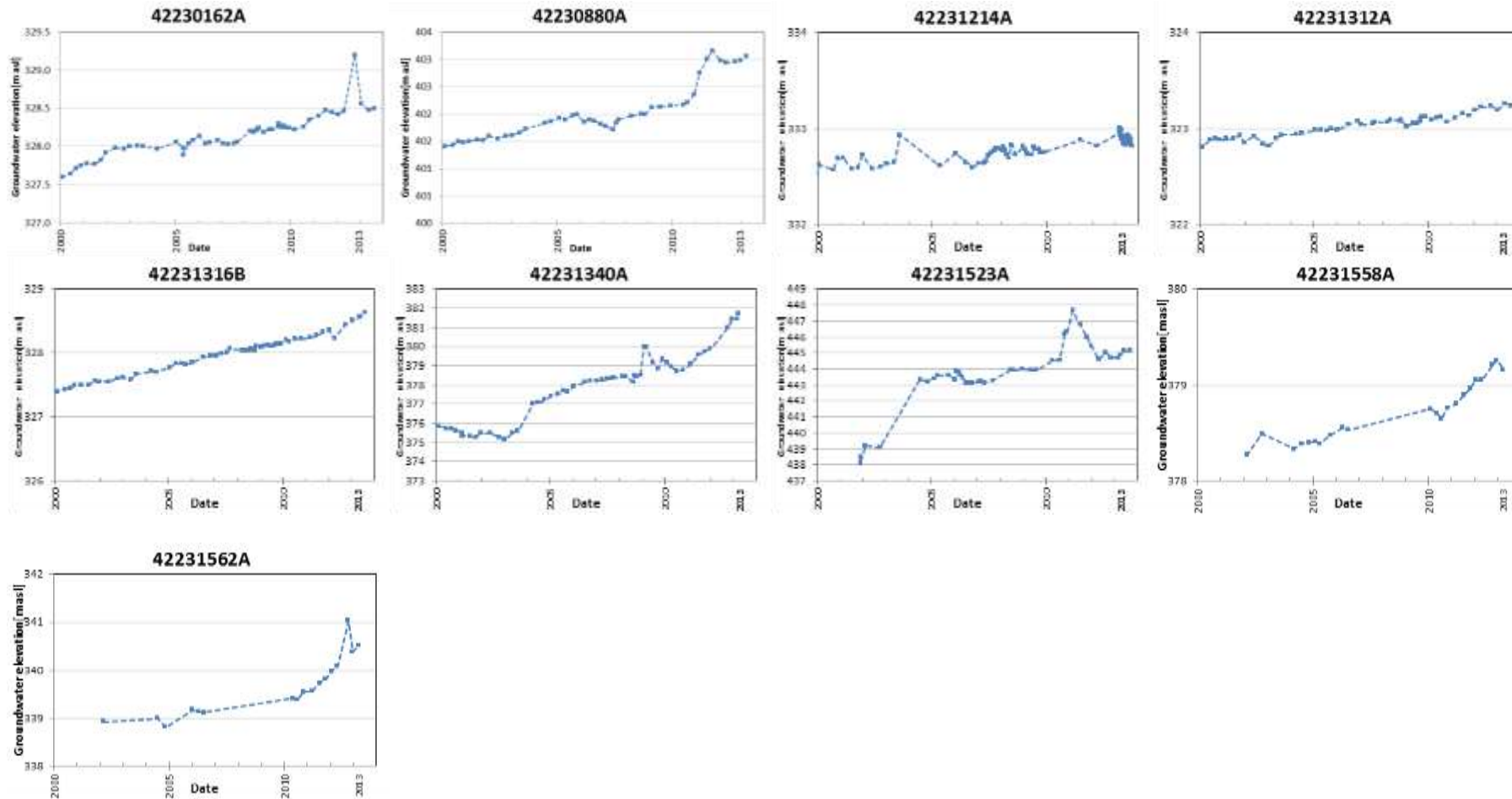
TYPE G







Type H



Undefined

