HYDROGEOLOGICAL FRAMEWORK, CONCEPTUAL AND NUMERICAL GROUNDWATER FLOW MODEL OF LAIDLEY CREEK CATCHMENT, QUEENSLAND, AUSTRALIA.

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Statement of original authorship

The work contained in this thesis has not previously been submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signed: QUT Verified Signature ……………………………………………..

Date: 2/7/2013

Abstract

Globally, groundwater is an important resource and is often considered to be reliable and unlimited. However, in many parts of the world groundwater is under threat from excessive use and reduction in quality. The problems associated with unsustainable water use are magnified in small scale alluvial aquifers. An example of a shallow alluvial aquifer system under stress is the irrigated Laidley Creek catchment within the Lockyer Valley, approximately 80 km west of Brisbane in southeast Queensland, the subject of this study.

In order to develop a deeper understanding of the hydrogeological framework of the Laidley Creek catchment, this study comprises five main topics: (1) historical data overview and analysis, (2) design of an up-to-date field collection and analysis program, (3) catchment-wide conceptualization of the hydrogeological structures and processes, (4) development of catchment numerical model to quantify the flows between alluvium and underlying bedrock aquifers, and (5) identification of gaps in the historical and currently acquired datasets with respect to the suitability for the further numerical model development.

After the initial data overview, a field monitoring program was designed to collect and analyse rainfall data (3 gauging stations, daily measurement), stream flow data (single gauging station plus additional observation data), groundwater table data (42 bore hydrographs, measured both manually and automatically) and hydrochemistry data (34 groundwater and 9 surface water samples). The analysis of the current data confirmed the correlation between rainfall, creek flow and alluvium recharge shown by the historical data and provided an insight into both groundwater sources and flow processes within the alluvial aquifer (groundwater mixing).

Based on the catchment conceptualization, a numerical MODFLOW-SURFACT model was developed and calibrated. The model was initially used to quantify flows between alluvial aquifer and bedrock aqufers, however the model performance with regard to flow predictions was not satisfactory. In order to identify the most problematic numerical model parameters, a predictive parameter uncertainty analysis was undertaken. Furthermore, the "data worth" analysis was undertaken in order to identify the

observation dataset that most contributes towards the modeling uncertainty reduction. As a result of the model development process and the analysis of parameter and observation uncertainties, a recommendation for further observations and data collection was made.

Keywords

Lockyer Valley, Laidley Creek catchment, groundwater, alluvium, alluvial aquifer, groundwater monitoring, pressure transducer, major ion chemistry, hydrograph response, conceptual model, numerical model, predictive uncertainty analysis, MODFLOW, SURFACT, PEST

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Abbreviations

AMRR	accumulated monthly residual rainfall
ASUD	Australian Stratigraphic Unit Database
a.g.	elevation [m] above gauge (above set datum)
a.s.l.	elevation [m] above sea level
BOM	Bureau of Meteorology
d	day
DEM	Digital Elevation Model
DERM	Department of Environment and Resource Management – formerly known as DNR (Queensland Department of Natural Resources), DNRM (Queensland Department of Natural Resources and Mines), DNRW (Queensland Department of Natural Resources and Water)
DNR	Queensland Department of Natural Resources (see also DERM)
DNRM	Queensland Department of Natural Resources and Mines (see also DERM)
DNRW	Queensland Department of Natural Resources and Water (see also DERM)
ET	evapotranspiration
GAB	Great Artesian Basin
HC	horizontal hydraulic conductivity
IQQM	integrated quantity and quality model
ML	Mega litre – 1000000 L
LWUF	Lockyer Water Users Forum
MRV	Main Range Volcanics
NSW	New South Wales
QLD	Queensland
QLUMP	Queensland Land Use Mapping Program
RN	Registration Number – ID number used to identify bores
Ss	specified storage coefficient
Sy	specific yield
TDS	total dissolved solids
y	year

Organization of thesis

The following explanations have been included to clarify data formats, settings and conventions used in this thesis:

- For all the spatial references (location of bores and groundwater sampling sites, location of surface water sampling sites, location of rainfall station and stream gauges), refer to the Laidley Creek catchment map presented in Figure 3.
- All objects are referred to by their name or registration numbers (RN). In addition to the map, coordinates of all referred objects are given either directly in the text or in appendices.
- All registration numbers of the Queensland government monitoring bores in the area of Laidley Creek catchment (referenced in this thesis) are in the format **14320xxx** where last three digits of the RN vary. In the text, tables and in maps, bore numbers are most of the time abbreviated for the sake of clarity. In such cases only the last three digits of the RN are used. Example: 332 refers to bore 14320332.
- Date/time notation uses Australian format (dd/mm/yyyy).
- Map references and coordinates use Transverse Mercator projection and MGA (Map Grid of Australia) Zone 56 coordinate system. The datum used is GDA-94.
- Numerical model files, raw field data (groundwater monitoring, rainfall) and the full text of this theses including all the appendices are presented as a digital appendix to the thesis (see attached DVD-ROM). Where relevant, a brief description of files is given in file *readme.txt.*
- See Appendix L for numerical model directory structure.

Digital appendix

For the digital appendix, see attached DVD-ROM at the last page of the thesis.

appendix_data

borelogs - XLS spreadsheet, Strater source file (SDG), all exported borelogs (/export/borelogs_all_export.rar - EMF graphical format).

chemistry - XLS spreadsheet, results of the major ion analysis, maps: sample sites, grouping (PDF).

climatic - EVT and rainfall (daily) data.

creek_flow - Laidley Creek flow and stage dataset.

crossections - simplified crossections through Laidley Creek alluvium (PDF).

hydrographs - manual and automatic (pressure transducer) hydrograph data.

maps - PDF maps - overview map, chemistry maps (water sampling sites, grouping of samples)

thesis - PDF version of this thesis, additional (A3) figures.

model

Numerical model of Laidley Creek catchment - both steady state and transient model files, input and output data, source code for all used utilities. See Appendix L for numerical model directory structure.

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Last but not least, thanks to my family for emotional and financial support and for understanding that certain questions should not be asked. And finally, big thanks to Milli, I would not be here in Australia without your help.

1 Introduction

"When the well's dry, we know the worth of water"
-- Benjamin Franklin, 1746

Groundwater is a globally important and valuable resource (Morris et al., 2003). Although it is often considered a reliable and seemingly unlimited resource in many parts of the world, groundwater is under threat of degradation both by contamination and by inappropriate use. The main threats to groundwater arise from the steady increase in water use demand (Konikow and Kendy, 2005), salinization of available water and pollution due to agricultural, industrial and other human activities (Shah et al., 2000; Jha et al., 2008).

The problems associated with unsustainable water use on a global scale are the same problems that are faced at a national level in Australia. Recently, a severe decade-lasting drought affected most of the Australian coastal and hinterland areas as well as major Australian urban centres (Turner et al., 2009). The so called "Millenium drought" (Whitaker, 2005) has had a substantial impact on agricultural production and water security of most regions in Australia, especially in regions undergoing a rapid population increase such as Queensland (Queensland Government, 2006; Queensland Government, 2009). Due to the recognised decrease of water availability, water resource management in Australia has become a major challenge in recent years (Turner et al., 2009).

Problems associated with poor water management decisions (or the total lack of water management) and excessive water use are magnified in small scale alluvial aquifers. These aquifers are especially vulnerable in terms of depletion or deterioration of water resources. They typically cover a relatively small area (tens or hundreds of square kilometres) and usually are sensitive to local changes in climatic conditions (including the change in recharge), population growth and its associated pressures such as intensification of agricultural production, pollution of shallow groundwater, increase in dryland and groundwater salinity (DNRM, 2003; DNRM, 2005).

The Lockyer Valley in southeast Queensland is an example of a shallow alluvial aquifer system under stress due to a heavy dependance on groundwater (Durick and Bleakley, 2000; Davidson et al., 2002; Kimlin, 2004; Cox and Picarel, 2010). Located approximately 80 km west of Brisbane, the Lockyer Valley is a significant agricultural region growing approximately one third of Queensland's vegetable produce. Similar to many areas of comparable setting around the world, the Lockyer Valley is affected by several related problems:

- decreasing availability of irrigation water compounded by inadequate water management in parts of the Valley and
- water quality degradation caused by overexploitation of available groundwater (KBR, 2002; DNRM, 2003).

A significant part of the answer to the above-mentioned problems is water resources management. With unfavourable changes in local climatic conditions (long lasting drought) and rapid population growth in southeast Queensland (Cox et al., 1996; Queensland Government, 2009) water resources management is an important political issue. Many resource economists believe that in the absence of intervention, groundwater resources are misallocated, therefore there is a pressing need for the development and implementation of management policies for groundwater resources (Kondouri, 2004).

Water resource management policies are currently established for one section of the Lockyer Valley, the Clarendon Subartesian Area. The Clarendon Subartesian Area (Central Lockyer Valley) was declared a protected zone in 1988 to support the sustainable use of groundwater in the valley. It is the only part of the valley where licenses and meters are required for groundwater use for all purposes except stock and/or domestic. Stock and domestic use is currently not licensed, charged or metered in any part of the Lockyer Valley.

Water usage data and other detailed information on the groundwater framework of the declared area provide a much better understanding of the alluvial aquifer behaviour for this area. However, groundwater resources in this part of the valley are dependant on and directly influenced by the condition of groundwater systems surrounding the Central Lockyer area. Unfortunately, the detailed information on either the water use or groundwater systems in these areas have not been available.

This project bridges the information gap in one of the Lockyer Valley subcatchments – Laidley Creek catchment. Although data on water use in Laidley Creek valley are still limited, this report compiles all available data with newly acquired information to describe this important catchment and hydrological processes within it. Importantly, this report also identifies the problems with the lack of particular data, specifically data helping to quantify groundwater flows. This problem needs to be addressed if groundwater resources are to be successfully managed.

2 Aim and research objectives

Australia is a dry continent. To support management decisions regarding water resources, an understanding of Australian groundwater systems is required. Laidley Creek catchment was chosen as an example to explore the application of current data sets appropriate to a representative groundwater system. Currently, detailed understanding of the hydrogeological setting of Laidley Creek catchment is absent. Therefore, this study aims at **understanding the hydrogeology of Laidley Creek catchment** and identifying **gaps in the currently available data** in terms suitability of this data for decision making processes with respect to water (groundwater resources) management support (Figure 1).

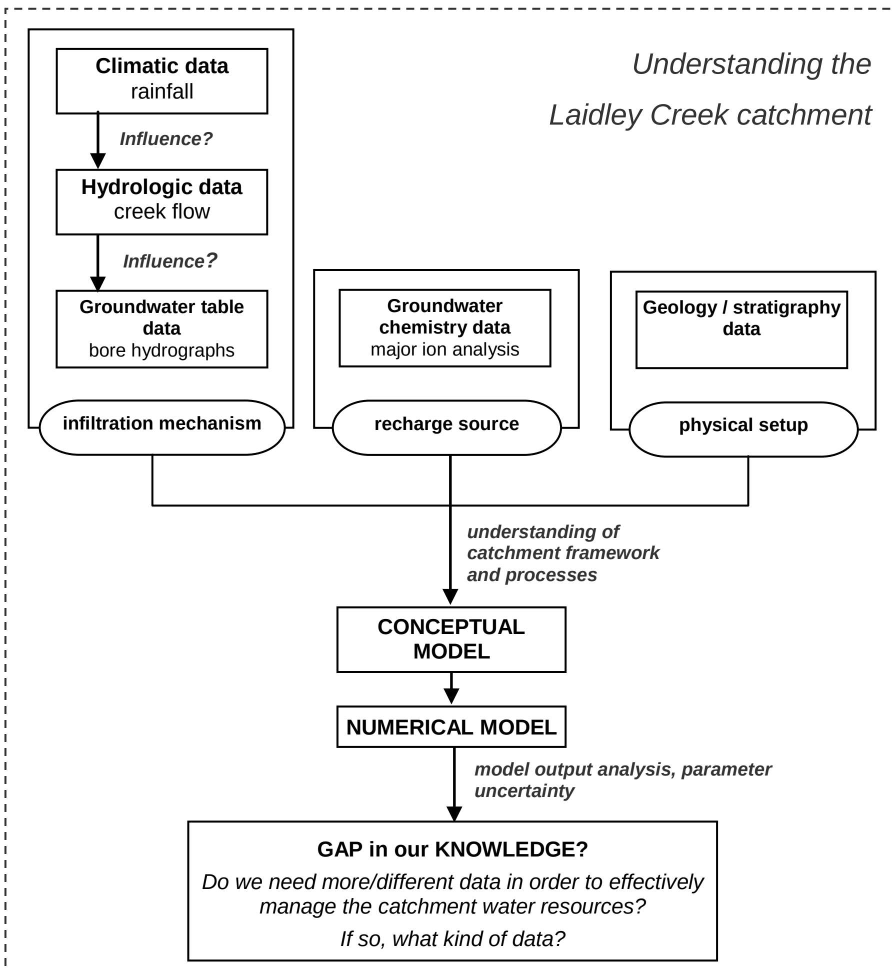


Figure 1. Aims of the Laidley Creek catchment study.

The major focus of this thesis is on the Laidley Creek shallow alluvial aquifer. The alluvium is economically important and widely used because the water quality is adequate for irrigation purposes, the water is also shallow and easily accessible. Other hydrogeological units in the Laidley Creek catchment will be examined only in terms of possible links to the shallow alluvium.

Rainfall intensity and spatial distribution will be examined to assess the influence of precipitation on groundwater levels and flow rate in Laidley Creek. Groundwater and surface water chemistry data will be used to assess the sources of groundwater in the alluvial aquifer as well as mixing of waters from different sources.

The major objectives of the study are:

- To describe the **hydrogeological framework** including the stratigraphical setting of the alluvial aquifer and surrounding units. The description of the stratigraphic units within the catchment is based on existing stratigraphical data;
- To describe **hydrological processes** within the catchment, such as the sources of groundwater (based on major-ion hydrochemistry) and the recharge regimes of the alluvium (based on bore hydrograph analysis);
- To create a **conceptual model** of the Laidley Creek subcatchment: this conceptual model will synthesize all available geological, hydrological and weather data and water chemistry, and will describe the geological system and the processes within it;
- To create a **numerical model** of the Laidley Creek subcatchment. The numerical model will not have predictive capabilities but will be primarily used (by means of the predictive uncertainty analysis) to identify the deficiencies in the data used for model construction. This type of analysis will show what kind of data is needed for better water resources management support and the possible future construction of a numerical model with predictive capabilities.

  The secondary objective of the numerical model is to quantify the catchment processes (inter-aquifer flows, flows between alluvium and bedrock aquifers).

3 Study area

Three broad topics leading towards better understanding of the hydrogeologic framework of the Laidley Creek catchment were defined in the previous chapter: (1) physical setup, geological setup, land and water use, (2) sources of recharge, and (3) mechanisms of recharge (Figure 1).

The knowledge of the physical setup, morphology, geology and stratigraphy is vital for the understanding of hydraulic properties of catchment aquifers. The knowledge of climatic conditions and relations between rainfall, creek flow and the elevation of the groundwater table leads to better understanding of both recharge sources and recharge mechanisms. And finally the information about land and water use leads towards the better understanding of the stresses of the catchment wide hydraulic system. Only with the full understanding of the current level of knowledge, it is possible to suggest its further expansion and refinement.

3.1 Physical setting

The Lockyer Valley (Figure 2) is located in southeast Queensland. The town of Gatton (population 4600) in the centre of the valley, lies about 90 km west of Brisbane, the state capital. The valley covers approximately the area of 2800 km^2. The valley floor consists of a sequence of sedimentary rocks, mostly flat-lying fluvial sandstones and siltstones of Triassic and Jurassic age. Lockyer Valley is bordered in the west and south by Tertiary basalt ridges of the Great Dividing Range which were eroded and weathered by the stream network of the Lockyer Creek and its tributaries.

The Laidley Creek catchment (see Figure 2 for overview and Figure 3 for details) is part of the greater Lockyer Valley, and covers an area of 310 km^2. Laidley Creek flows almost entirely in the north direction for approximately 45 km from the basalt ridges of the Great Dividing Range, and joins Lockyer Creek in the central Lockyer Valley. Lockyer Creek then discharges to the Brisbane River.

The Laidley Creek headwaters are at an elevation of approximately 300 m above sea level. Basalt ridges reaching up to 1070 m above sea level surround the upper third of the

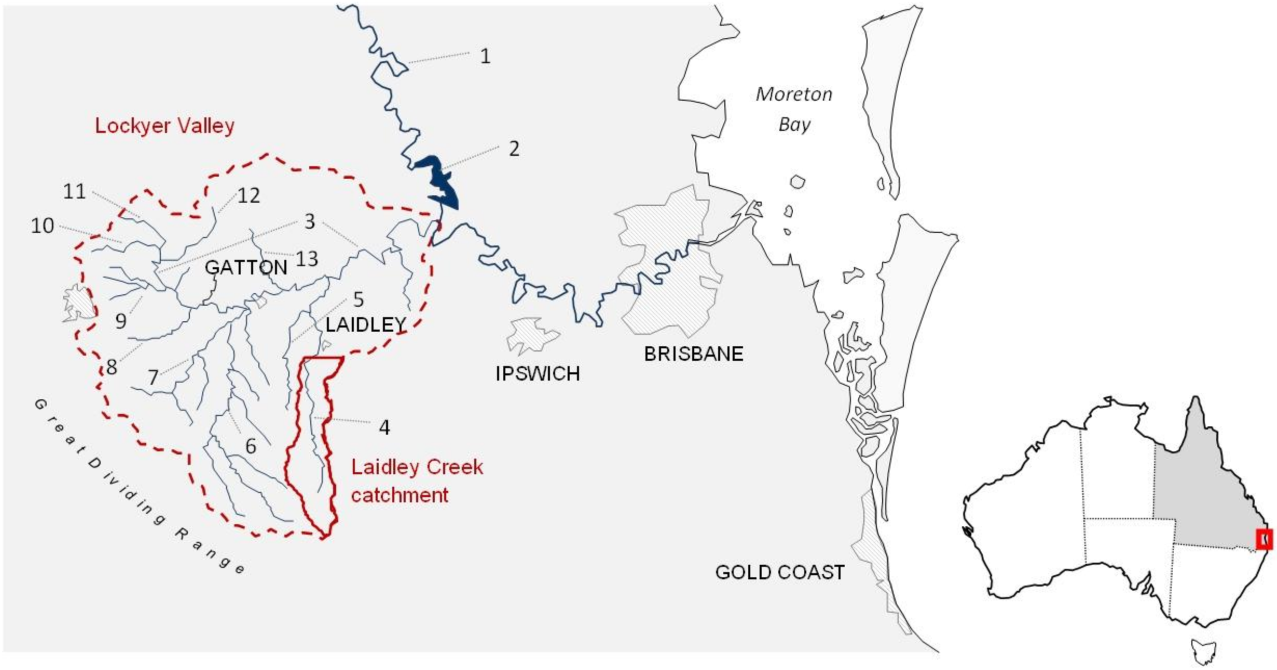


Figure 2. Location of Laidley Creek subcatchment within the Lockyer Valley in southeast Queensland.

1 – Brisbane River, 2 – Lake Wivenhoe, 3 – Lockyer Creek, 4 – Laidley Creek, 5 – Sandy Creek, 6 – Tenthill Creek, 7 – Ma Ma Creek, 8 – Flagstone Creek, 9 – Gatton, Rocky, Six Mile Creeks, 10 – Murphy's Creek, 11 - Fifteen Mile Creek, 12 – Alice Creek, 13 – Redbank Creek

valley, which is covered by colluvial and alluvial sediments. The upper valley alluvial sections are 200 to 600 m wide, and the valley gradually widens to 2000 m in the lower (northern) parts.

The orographic effect of the Great Dividing Range and prevailing southeasterly wind direction over 7 to 8 months per year strongly influences the spatial rainfall distribution. The southern and southwestern subcatchments of Laidley, Tenthill, Ma Ma, Flagstone, Gatton Creek subcatchments thus receive approximately 50-60% more rainfall than the central Lockyer Valley (see Section 3.5).

Laidley Creek is ephemeral in nature. Historically, flow was permanent in the upper part of the catchment and seasonal in the lower catchment. With the onset of the most current drought conditions in the late 1990s however, creek flow became highly irregular even in the upper part of the catchment. Flow in the lower catchment is now rare and typically occurs after intensive rain as a flash flood event.

(external map - see file *figure_03_laidley_overview_map.pdf*)

Figure 3. Map of the Laidley Creek catchment.

The Laidley Creek catchment is geologically and morphologically similar to catchments of other Lockyer Creek tributaries that abut the southern and western basaltic ridges (Tenthill Creek, Ma Ma Creek, Flagstone Creek, Gatton Creek, see Figure 2). Thus the geologic and hydraulic setting of these catchment aquifers described in previous studies (MacLeod, 1998; Wilson, 2005) are similar to the setting and processes in the Laidley Creek subcatchment.

3.2 Geology and stratigraphy

3.2.1 Previous geological investigations within Lockyer Valley

In 1949, the Irrigation and Water Supply Commission of Queensland conducted an extensive drilling program within the alluvium of Lockyer Creek and its tributaries however, results of this process were not summarized until Zahawi's hydrogeological report (Zahawi, 1975). Regional geological survey and mapping was conducted by McTaggart (1963) who classified basic stratigraphic groups in the area. Geology and stratigraphy data were later compiled into the map (scale 1:250000) that served as a basis for further geological mapping of the Lockyer Valley area (Cranfield et al., 1976). Powell (1987), interested in the genesis of alluvial soils, conducted an investigation of Tenthill Creek catchment and part of the central Lockyer Creek alluvial plain. During the reappraisal of the Clarence-Moreton Basin for petroleum availability (Wells et al., 1990; Wells and O'Brien, 1994), the Mesozoic stratigraphic units underlying alluvial aquifers in Lockyer Valley were also redefined. The petroleum prospectivity of Mesozoic formations was further explored by Ingram (1996). Although the emphasis of his report is on the New South Wales section of the Clarence-Moreton Basin, the sediment sequence of Lockyer Valley is also described.

3.2.2 Overview of regional geology

The Lockyer Valley catchment is part of the broader Laidley Sub-basin which lies in the northern part of the greater Clarence-Moreton Basin (Wells and O'Brien, 1994) (Figure 4). The Clarence-Moreton Basin is a wide regional Mesozoic intracratonic basin, overlying mid to late Palaeozoic rocks of the New England Orogen in southeast Queensland and northeast New South Wales (Wells and O'Brien, 1994). It extends from the Kumbarilla Ridge in the west, to the eastern coast of Queensland and New South Wales, covering about 40000 km^2 (Wells and O'Brien, 1994). The basin consists of three sub-basins (from east to west): the Cecil Plains Sub-basin, the Laidley Sub-basin and the Logan Sub-basin (Wells and O'Brien, 1994; Ingram et al., 1996). The Cecil Plains Sub-basin and the Laidley Sub-basin are separated by Gatton Arch (NSW Department of

Primary Industries, 2009), an anticline probably draped over the prominent basement ridge (Cranfield et al., 1976).

Tectonic conditions in the late Triassic led to the deposition of the Bundamba Group (Figure 5, Table 1), a thick sequence of mainly conglomerate and sandstone deposited in a fluvial to lacustrine environment. Paleocurrent measurements in the field indicate that the sediments of the Bundamba Group were derived from the southwestern, southern and southeastern margins of the Clarence-Moreton Basin and were deposited by northward-flowing streams (Ingram et al., 1996). Indication of a humid climate during the deposition of the Bundamba Group is given by findings of fossilised plant fragments and thin coal seams and the absence of red paleosols and carbonate nodules associated with arid and semi-arid floodplain deposits (MacLeod, 1998). Sediments of the Bundamba Group are overlain by the widespread Walloon Coal Measures (Ingram et al., 1996).

Tertiary (Cainozoic) intrusive basalts and associated lavas occur throughout the basin but are concentrated in the north of the basin where they are associated with the Mount Warning Complex, Lamington Volcanics and Main Range Volcanics (Willmott, 1984; Ingram et al., 1996; Willey, 2003).

The structure of the Gatton Arch was mapped in the basement (Bundamba Group) sediments of the upper parts of the Laidley Creek catchment. However, the Laidley Creek catchment does not follow the Gatton Arch. The anticline deviates more towards the northwest and can be followed to the adjoining Sandy Creek catchment. The study area is thus located on the boundary between the Laidley Sub-basin and the Cecil Plains Sub-basin (Figure 4).

3.2.3 Marburg Subgroup

The Marburg Subgroup is widely distributed throughout the Clarence-Moreton Basin. It unconformably overlies the basement of early Jurassic to late Triassic Woogaroo Subgroup sediments (Wells and O'Brien, 1994). The Marburg Subgroup consists of interbedded sandstone, siltstone, mudstone and shale with minor coal seams and ferrugised fossil wood fragments (Willmott, 1984; Wells et al., 1990; ASUD, 2007).

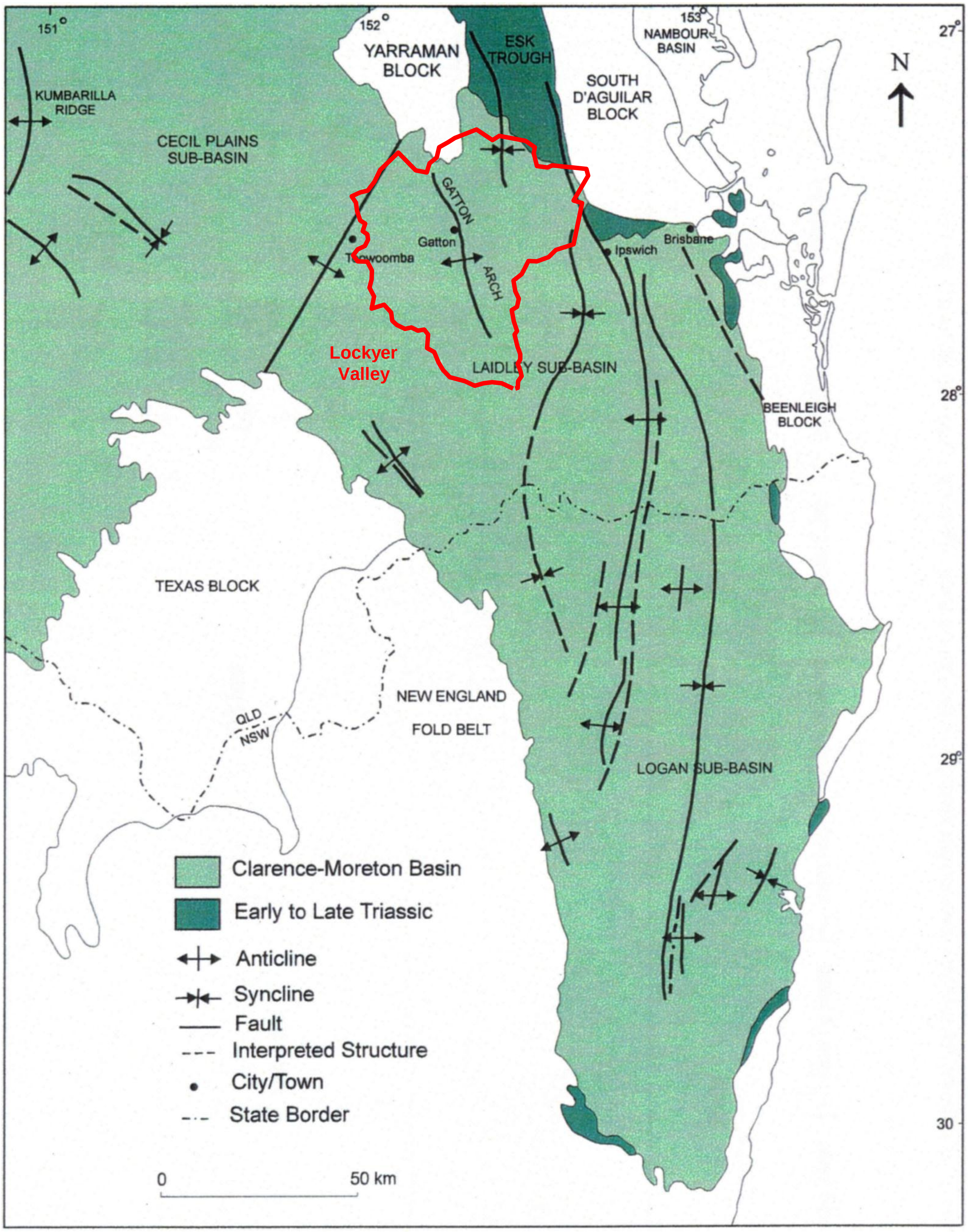
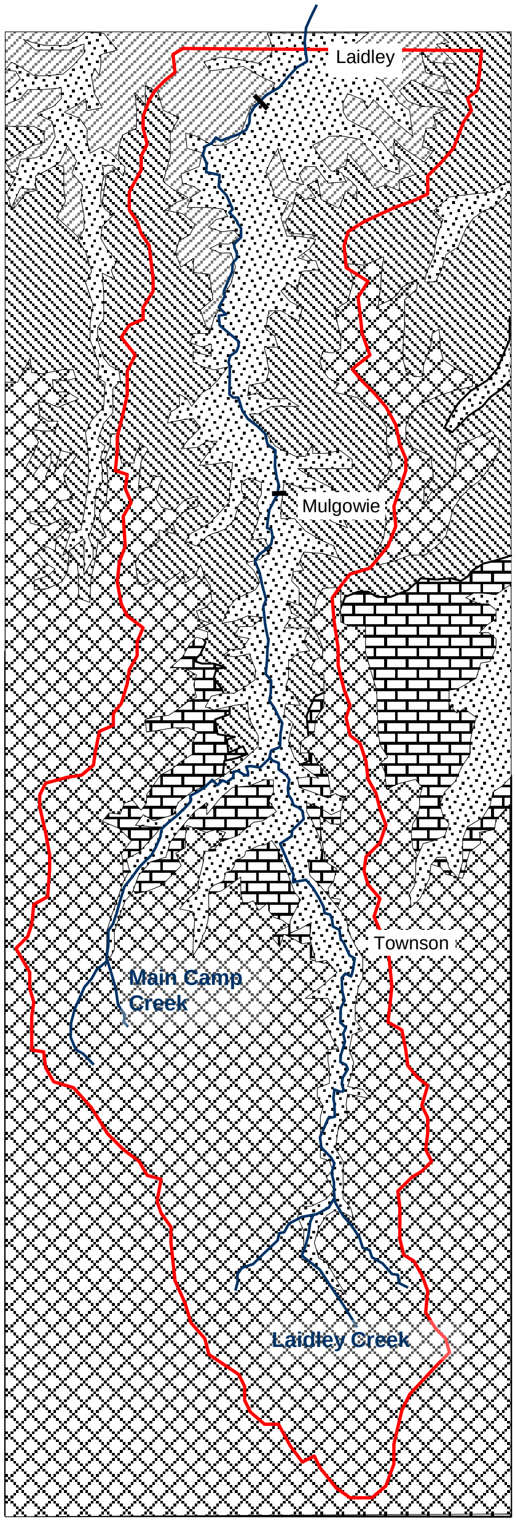


Figure 4. Position of Lockyer Valley (red outline) within the Clarence-Moreton Basin – regional context. Based on (Wells and O'Brien, 1994).



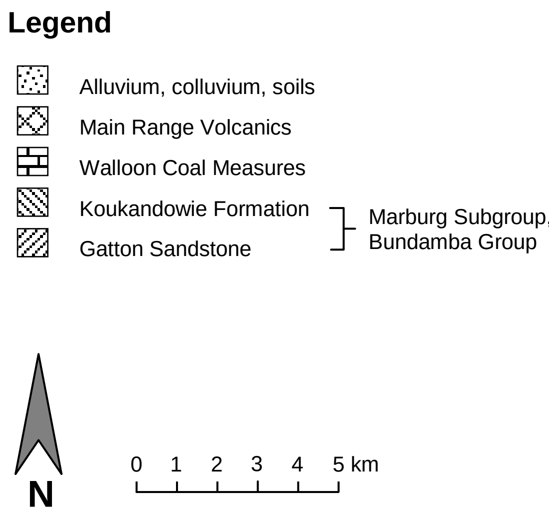


Figure 5. Geological setting of Laidley Creek catchment.

Based on the Helidon (sheet 9342) geological map (DNRM, 2001). Sediments of the Marburg Subgroup as well as Walloon Coal Measures are relatively flat lying. All sedimentary members dip to the south and southwest at an angle about 10° or less (Wilson, 2005).

Table 1. Stratigraphy of the geological formations of the project area.

<table>
<tr><th>Period</th><th colspan="4">Stratigraphical unit</th></tr>
<tr><td>Quaternary</td><td colspan="4">alluvium, colluvium, recent soils</td></tr>
<tr><td>Neogene - Palaeogene</td><td colspan="4">Main Range Volcanics (MRV)</td></tr>
<tr><td colspan="5">Unconformity</td></tr>
<tr><td>mid Jurassic</td><td>Injune Creek Group</td><td colspan="3">Walloon Coal Measures</td></tr>
<tr><td rowspan="4">late Triassic - mid Jurassic</td><td rowspan="4">Bundamba Group</td><td rowspan="4">Marburg Subgroup</td><td rowspan="3">Koukandowie Formation</td><td>Undifferentiated sandstones, siltstones, shales</td></tr>
<tr><td>Ma Ma Creek Member</td></tr>
<tr><td>Heifer Creek Sandstone Member</td></tr>
<tr><td colspan="2">Gatton Sandstone</td></tr>
</table>

Based on Wells et al., 1990; Ingram et al., 1996; Willey, 2003

Two upper members appear in the Laidley Creek catchment area: Gatton Sandstone Member and Koukandowie Formation.

The **Gatton Sandstone Member** is the most widespread unit in the Clarence-Moreton Basin. It consists predominantly of thick-bedded, medium- to coarse-grained quartz-lithic and feldspatic sandstone; pebble conglomerates and shales are common but are subordinate to sandstones. The sandstones were deposited in a stacked channel environment with low sinuosity and high avulsion rates and calcareous cement is common (Ingram et al., 1996). Carbonised wood fragments and pebble beds are abundant in places and are generally characteristic of the formation (Wells and O'Brien, 1994).

The **Koukandowie Formation** is a thick layer sequence formed of fine to coarse grained, quartz to quartz-lithic sandstone. It is cross-bedded and rippled. Thin pebble conglomerates lie at the base of sand channels; shale and siltstone, minor coal and a ferruginous oolite marker are also present (Wells et al., 1990; ASUD, 2007). The base sediments of the Koukandowie Formation suggest deposition in low-energy floodplains or lacustrine conditions (shales and iron-rich clay oolites).

The Koukandowie Formation comprises two members occupying the lower part of the formation and an undifferentiated succession of interbedded argillaceous lithic sandstones, carbonaceous siltstones and shales (Ingram et al., 1996). The two lower members of the Koukandowie Formation are the basal Ma Ma Creek Member and the Heifer Creek Sandstone Member (Ingram et al., 1996).

The *Ma Ma Creek Member* conformably overlies the Gatton Sandstone. It consists of thinly interbedded siltstones, claystones and fine grained sandstones generally 10-20 m thick (Ingram et al., 1996). The *Heifer Creek Sandstone Member* comprises interbedded sandstone, siltstone and shale with minor coal. The sandstones coarsen upwards with less frequent siltstone and shale layers. The sands were deposited mainly as channel fills and commonly have well-developed planar cross-bedding. Some upwards fining units near the top of the member have characteristics of point bar sands. This member commonly forms prominent topographic features with steep slopes and is often exposed in cliffs, benches and cuttings (Wells and O'Brien, 1994). The sandstones are quartzose, fine- to coarse-grained, thin- to very thick-bedded with a variable amount of lithic grains, clay and calcareous cement. The shales and siltstones are typically carbonaceous (Ingram et al., 1996).

The Marburg Subgroup is present along Laidley Creek from the northernmost tip of the valley to the confluence of Camp Creek and Laidley Creek, where sediments of Koukandowie Formation are replaced by beds of Walloon Coal Measures. All sedimentary members dip to the south and southwest at an angle of approximately 10° or less (Wilson, 2005).

3.2.4 Walloon Coal Measures

The Walloon Coal Measures crop out over large areas around the perimeter of the Clarence-Moreton Basin. The Walloon Coal Measures are distinguished by numerous coal seams and by volcanoclastic, lithic and silty sandstones with interbedded claystones and siltstones. The sandstones throughout the Walloon Coal Measures have a high clay content, mainly kaolinite, but commonly also with montmorillonite and chlorite, and are generally calcareous. Carbonaceous material is common in all lithologies (Ingram et al., 1996). The most common arenaceous rock type is massive grey to white sandstone, friable, with numerous dark lithic grains, abundant silt and a montmorillonite matrix (Wells and O'Brien, 1994).

The depositional environment for the Walloon Coal Measures was one of low energy streams meandering across a wide floodplain. A combination of channel/swamp environment deposition (Ingram et al., 1996) produced a combination of channel, overbank and backswamp facies of meandering streams and floodplain environments. Coal and peats are autochtonous, created from plants growing in-situ in a moist, temperate climate (Wells and O'Brien, 1994). The maximum thickness of this stratigraphic unit in the research area is about 60 m (Zahawi, 1975; Wilson, 2005).

3.2.5 Main Range Volcanics (MRV)

Tertiary basalts (of paleogene and Neogene age) of Main Range Volcanics (MRV) originally covered the whole area. Today, most of the material is eroded and the volcanic materials form cliffs of the Great Dividing Range and surround the Lockyer Valley from the south and west. The unit comprises basalt flows, some of which ponded in craters (lava pools) and various interbeds of tuffs (phreatic and magmatic). The basalts typically contain primary olivine, but olivine xenoliths and detritus from xenoliths are common (Willey, 2003).

The Tertiary volcanics consist of a series of basalt plugs and widespread basalt flows with minor interbedded trachyte. Jointing and highly vesicular bands are in evidence throughout the sequence (Zahawi, 1975). Jointing of basalts influences the permeability and storage potential (Fetter, 1994; Hiscock, 2005) of basalt aquifers. These aquifers play an important role as groundwater storage units (e.g. Locsey and Cox, 2003) as well as intermediate (buffer) storage for the recharge of alluvial aquifers. Basalt aquifers are one of the main groundwater sources for communities living atop the Great Dividing Range.

3.2.6 Alluvium

Lockyer Valley alluvium and its genesis was described by Powel (2002). The main source of materials that contributed to the valley alluvium include weathered products of the Main Range Volcanics (MRV) basalts, the Walloon Coal Measures, and the upper beds of the Marburg Subgroup sandstones (Koukandowie Formation). During the early Quaternary period the valley floor was eroded and incised in several stages to depths of 20–30 m. Alluvial sediments were deposited by streams as the valleys filled in the late Quaternary period. Downstream, a wider alluvial plain developed as creeks meandered across the plain. Relict levees of prior streams are still in evidence on the alluvial plain surface (KBR, 2002). Lockyer Creek and its tributary streams in the lower reaches now have a deep meandering channel with a gentle levee extending to an alluvial plain 3–6 km wide.

Modern alluvial deposits consist of gravels, sandy gravels, sands, silts and clays. The aquifers and stream beds in the headwater areas of the southern tributaries consist mostly of cobbles and coarse gravel. In the Laidley Creek catchment, the cobbles are principally of basaltic origin, while in the surrounding catchments, the cobbles are mainly sandstone (Durick and Bleakley, 2000).

Gravels act as good aquifers supporting most of the agriculture in the areas along the axis of the Laidley Creek valley. Finer materials such as silts and clays form a layer of variable extent and thickness on the top of the coarse alluvium, which act as a semiconfining unit (Durick and Bleakley, 2000; Wilson, 2005) especially in the lower Lockyer Valley catchment. Generally, alluvium in the central Lockyer Valley can be up to 40 m thick (Durick and Bleakley, 2000). Alluvial sediments along Laidley Creek are up to 30 m thick and the thickness of the basal, transmissible gravel layer varies from 2 to 10 metres.

The extent and thickness of the alluvial aquifer has been investigated by extensive drilling and analysis of bore logs from private bores. There are records of about 700 existing bores (DERM, 2009) in the Laidley Creek catchment, the majority of these are concentrated in the lower section of the valley, along Laidley Creek and it’s tributary Main Camp Creek. However, the descriptions of borelogs are often incomplete or inaccurate. This is especially problematic when incomplete or inaccurate logs are used to describe the stratigraphic heterogeneity of alluvium, necessary for construction of conceptual and numerical models.

3.3 Land use

The whole Lockyer Valley, sometimes referred to as Queensland’s salad bowl, is a rich agricultural region with farming widely practised on its fertile alluvial soils (Zahawi, 1975). The Lockyer Valley currently grows about one third of Queensland’s total vegetable produce and is also a major lucerne growing area (LWUF, 2006).

Laidley Creek catchment is subject to intense agricultural development, especially along the alluvial plains adjacent to the creek, which are commonly used for cultivation of irrigated crops, including vegetables such as cabbage, beetroot, lettuce, onion, as well as pastures and grain crops such as barley, sorghum and wheat (Jones, 1993). There are also several fruit orchards growing apples, oranges and olives. Depending on the type of crop there are 2-3 cultivation seasons each year. Irrigation of crops became widespread in the mid-1930s with the supply of electricity and increased in the 1950s due to the introduction of the turbine pump (Durick and Bleakley, 2000).

In spite of the intensive cultivation, uncleared remnants of eucalypt open forest communities with a predominantly grassy understory can be found in the catchment (Powell et al., 2002). The most widely distributed tree species are silver-leaved ironbark (*Eucalyptus melanophloia*), Moreton Bay ash (*Corymbia tessellaris*) and blue gum (*Eucalyptus tereticornis*).

Based on data obtained from Queensland Land Use Mapping Program (DNRM, 1999), the alluvial parts of the catchment are described as under "production from irrigated agriculture and plantations/irrigated seasonal horticulture". Land use in the rest of the catchment (slopes of the sandstone and basalt hills surrounding the alluvium) is classified as "production from relatively natural environments/grazing natural vegetations". The entire alluvial plain is intensively cultivated and irrigated (Figure 6).

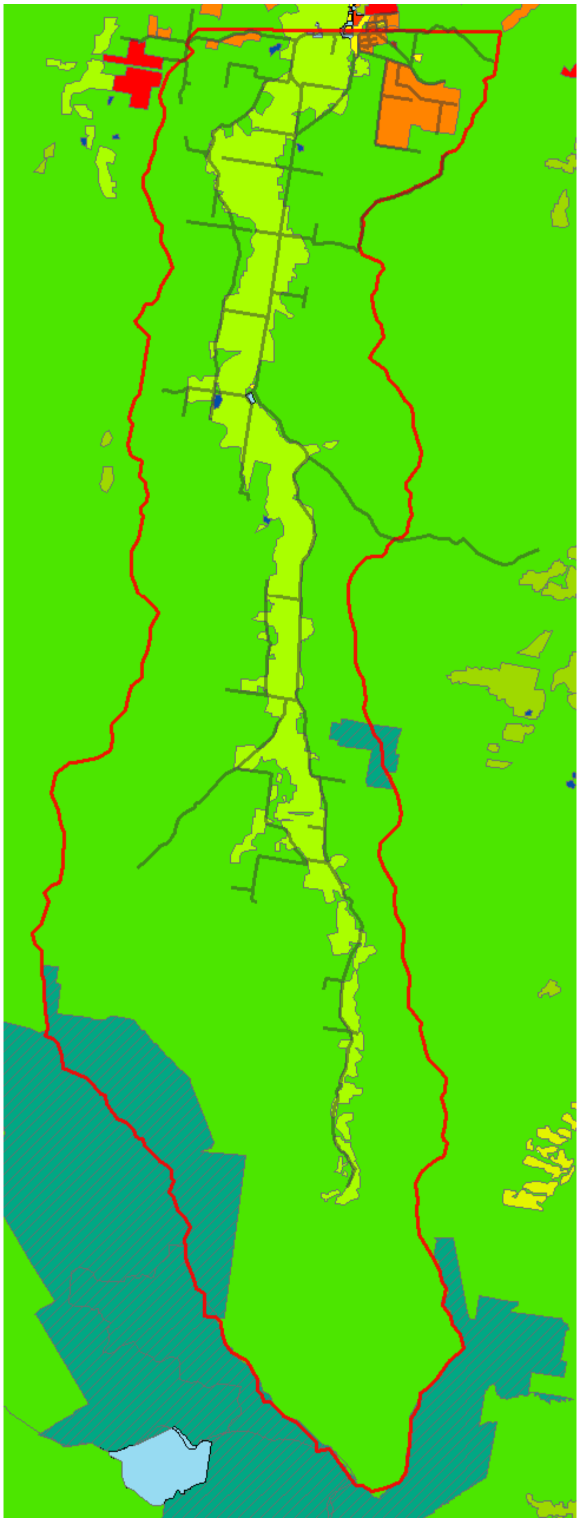


Figure 6. Land use within Laidley Creek catchment.

Based on Queensland Land Use Program (QLUMP) data. Map data provided by Department of Natural Resources and Water (1999).

3.4 Water use

The main irrigation, stock and domestic water supplies in the Lockyer Valley are obtained from groundwater. Surface waters from Laidley and Lockyer Creeks are also used for irrigation. The towns of Gatton and Laidley obtain their town water supply from shallow bores in the alluvium (Zahawi, 1975).

Queensland Department of Environment and Resource Management (DERM) estimated the yield of the alluvial aquifers to be about 25000 ML/y, based on the nine year period of 1918 – 1926, when the alluvial aquifers in the valley were pumped from full to almost dry (DPI, 1994).

KBR (2002) estimated the total yield from both groundwater and surface water sources to be approximately 50000 ML/y. The net deficit for the irrigation users was further estimated to be between 10000 ML/y and 40000 ML/y (KBR, 2002). This deficit leads to either decreased availability of irrigation water or a depletion of the groundwater reserves. Precise values for water consumption are not available for most of the Lockyer Valley subcatchments, the best data are from the Central Lockyer (Clarendon Subartesian Area) where at least the water for irrigation purposes is being metered.

Water consumption in non-declared subcatchments was estimated by DERM and by a sociological survey (information concerning water use were provided by farmers) conducted by Psi-Delta (KBR, 2002; Psi-Delta, 2009).

Table 2. Estimated irrigation water use in selected parts of Lockyer Valley

Catchment	Psi-Delta survey values			DERM estimated values	
	number of respondents	minimum water use rate [ML/ha/y]	maximum water use rate [ML/ha/y]	minimum water use rate [ML/ha/y]	maximum water use rate [ML/ha/y]
Upper Lockyer	11	1.36	10.91	2.00	2.50
Central Lockyer	64	0.80	17.14	1.50	2.00
Lower Lockyer	20	1.07	7.00	3.30	3.50
Flagstone Creek	8	1.36	4.74	2.00	2.25
Ma Ma Creek	13	1.60	15.00	2.00	2.50
Tenthill Creek	23	1.00	11.44	3.00	3.50
Sandy Creek	10	0.63	4.06	1.50	2.00
Laidley Creek	**6**	**1.67**	**9.38**	**3.00**	**3.50**

Adopted from Lockyer Valley hydrological consultancy (KBR, 2002)

3.5 Climate

The Australian climate is in general influenced by the El Niño/La Niña phenomenon. Depending on the difference of Pacific ocean temperatures between the west coast of South America and the northeastern coast of Australia extending all the way to Indonesia, El Niño is usually associated with dry conditions and limited rainfall in eastern and northern Australia while La Niña is associated with wetter-than-usual conditions. The strength and the temporal distribution of this climatic phenomenon is expressed as Southern Oscilation Index (SOI), where the negative values of SOI represent El Niño conditions and positive SOI values represent La Niña conditions (BOM, 2011a).

Observations over the previous decade (years 2000 to 2010) show that the climatic conditions in Australia during the first five years were mostly influenced by El Niño episodes. The drought of 2002-2003 was comparable in severity to the extreme droughts of 1902 and 1982-1983 and the extreme dryness combined with unusually high temperatures resulted in severe bushfires in New South Wales and Victoria (BOM, 2011b). A very similar climatic pattern was observed during years 2006-2007 with the Great Dividing Range fires being the longest burning bushfires in Victoria's history. Although the long lasting drought was broken by weak La Niña events in 2005 and 2008 to 2009, the resulting slightly higher than average rainfall was not sufficient to alleviate the impact of the long lasting drought especially in terms of recharge to shallow aquifers throughout Australia. Current SOI development from the end of 2010 through to the first half of 2011, shows strong La Niña conditions which provided record rainfalls causing devastating floods in central and southeastern Queensland.

Although SOI primarily indicates the climatic condition on a continental scale (Australia wide), the influence of the global phenomenon of El Niño/La Niña can be observed locally as well. A visual comparison of SOI and monthly rainfall from Townson (station 40675 - see Appendix C, Figure 96) shows good correlation between episodes of El Niño and low rainfall (Figure 7). Comparison of SOI and monthly accumulated rainfall (Figure 8) shows localised contribution of La Niña (years 1992, end of 1999, end of 2004, end of 2009, beginning of 2010 and end of 2010) to the generally continuous period of higher than average rainfall.

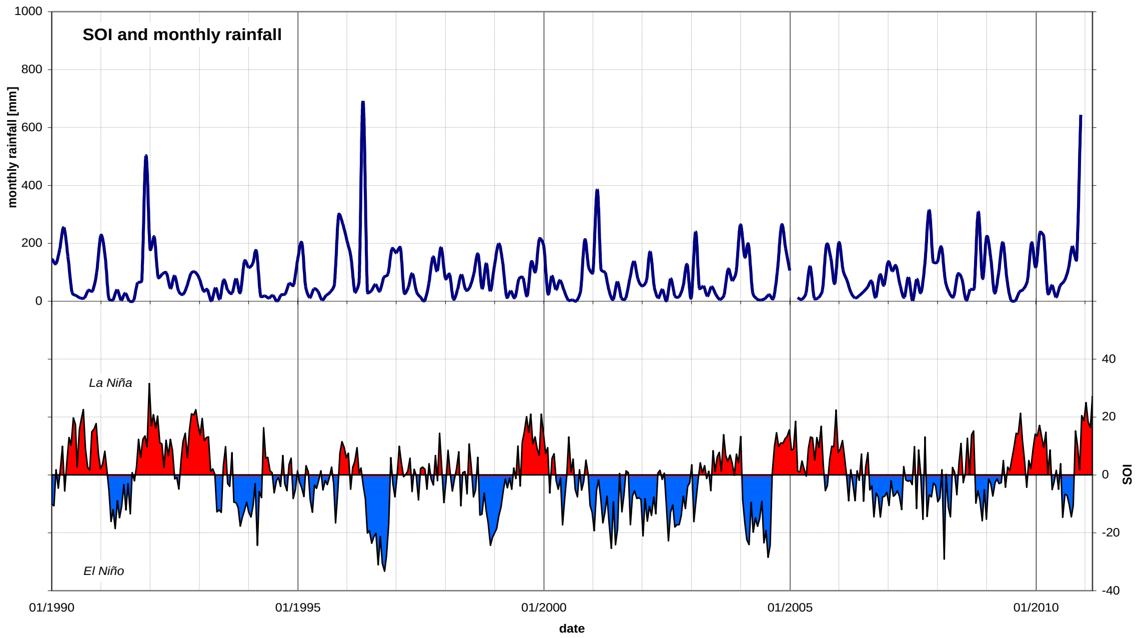


Figure 7. Comparison of monthly rainfall (Townson 40675) and SOI for period of 1990 - 2010.

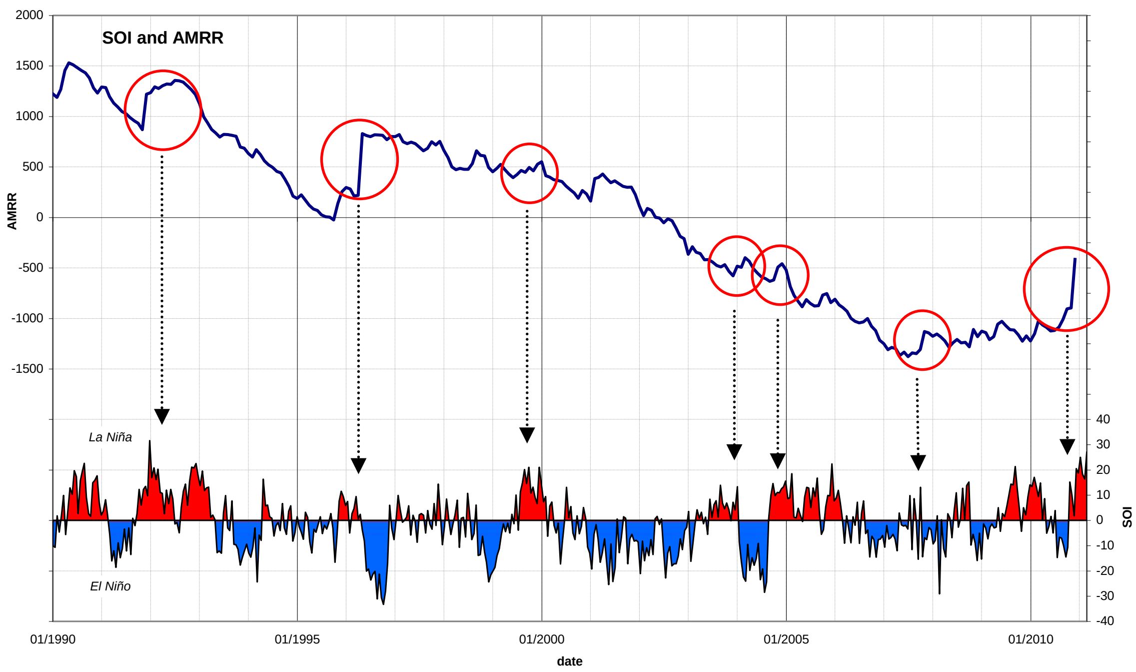


Figure 8. Comparison of AMRR (accumulated monthly residual rainfall - Townson 40675) and SOI for period of 1990 - 2010. Examples of higher than average rainfall during La Niña periods.

Based on the modified Köppen's classification (BOM, 2005) the Laidley Creek catchment experiences a sub-tropical climate, where most of the precipitation falls in the summer months from December to March.

Apart from general climatic trends, the distribution of rainfall within the valley is strongly influenced by the orographic effect of the Great Dividing Range and a southeasterly wind direction for around 7 - 8 months of the year. The upper part of the catchment receives on average about 50 - 60% more rain than the lower parts (Figure 9). In the headwaters the mean annual rainfall is 1100 to 1200 mm, whereas in the lower parts of the catchment the rainfall ranges from 800 to 900 mm per year.

The long term average monthly evapotranspiration (ET, see Table 3) follows the trend of long term average rainfall: the ET cycle is seasonal; maximum ET (80 – 95 mm/month) occurs in summer months (November - January); minimum ET (30 – 40 mm/month) occurs in winter months (May - August). Spatial distribution of evapotranspiration is shown in Figure 11. ET data for the years 2007 and 2008 are not available. The 30 year average yearly ET (720.7 mm/y) is lower than the 30 year average yearly rainfall (775.5 mm/y at Gatton, 1113.8 mm/y at Townson) indicating possible recharge surplus in the water budget.

The long term average rainfall data (Table 3) shows the seasonal annual rainfall cycle with a major peak in summer (November - February). Comparison between the long term average rainfall and the actual rainfall shows that the temporal distribution of the rainfall has changed (Figure 10). Whereas the long term average curve shows consistent rainfall throughout the year with lower rainfall in winter months and higher rainfall in summer, the rainfall in years 2006, 2007 and 2008 (Figure 10) shows the change in annual temporal rainfall pattern and increased seasonal intensity of the rainfall.

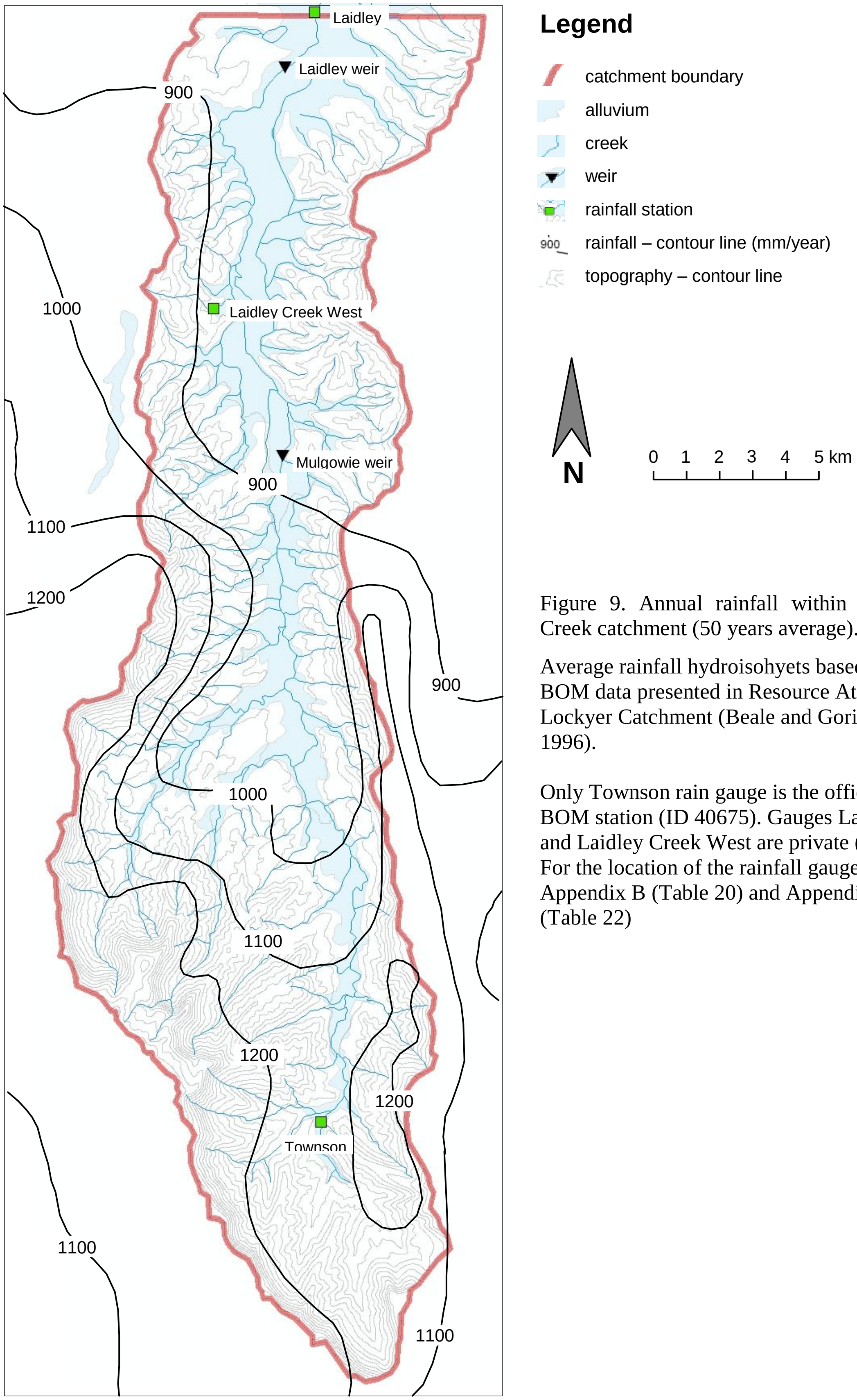


Figure 9. Annual rainfall within Laidley Creek catchment (50 years average).

Average rainfall hydroisohyets based on BOM data presented in Resource Atlas of Lockyer Catchment (Beale and Gorian, 1996).

Only Townson rain gauge is the official BOM station (ID 40675). Gauges Laidley and Laidley Creek West are private (farms). For the location of the rainfall gauges see Appendix B (Table 20) and Appendix C (Table 22)

Table 3. Average monthly rainfall (50 years and 30 years averages) and average monthly ET (30 years average) for Laidley Creek catchment.

month	50 yrs avg rainfall [mm/month]	30 yrs avg rainfall [mm/month]	30 yrs avg effective ET [mm/month]
January	164	136	96
February	167	150	73
March	105	92	73
April	68	77	53
May	75	84	37
June	46	50	32
July	50	49	29
August	41	35	34
September	37	31	49
October	86	79	69
November	134	140	80
December	143	143	96
Σ	1114	1066	721

Data from rainfall monitoring station in Townson. Two different monitoring stations operated in Townson: station number 040392 - Townson East – in operation from 1958 to 1977 and station number 040675 – Townson – in operation from 1978 till today. Unpublished data, available from BOM (2008). For the location of rainfall gauges see Figure 9, Appendix B and Appendix C.

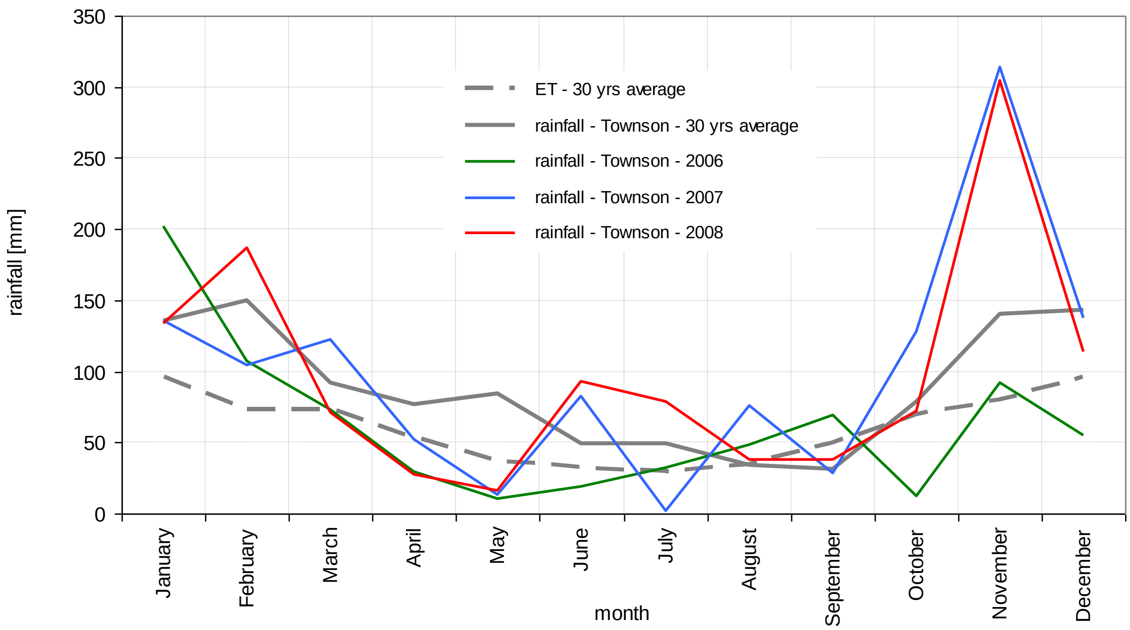


Figure 10. Change in temporal distribution of rainfall and evapotranspiration.

Comparison of total rainfall for 2006, 2007 and 2008 (BOM, unpub. data), 30 years average rainfall (BOM, unpub. data) and 30 years monthly average ET (BOM, 2003)

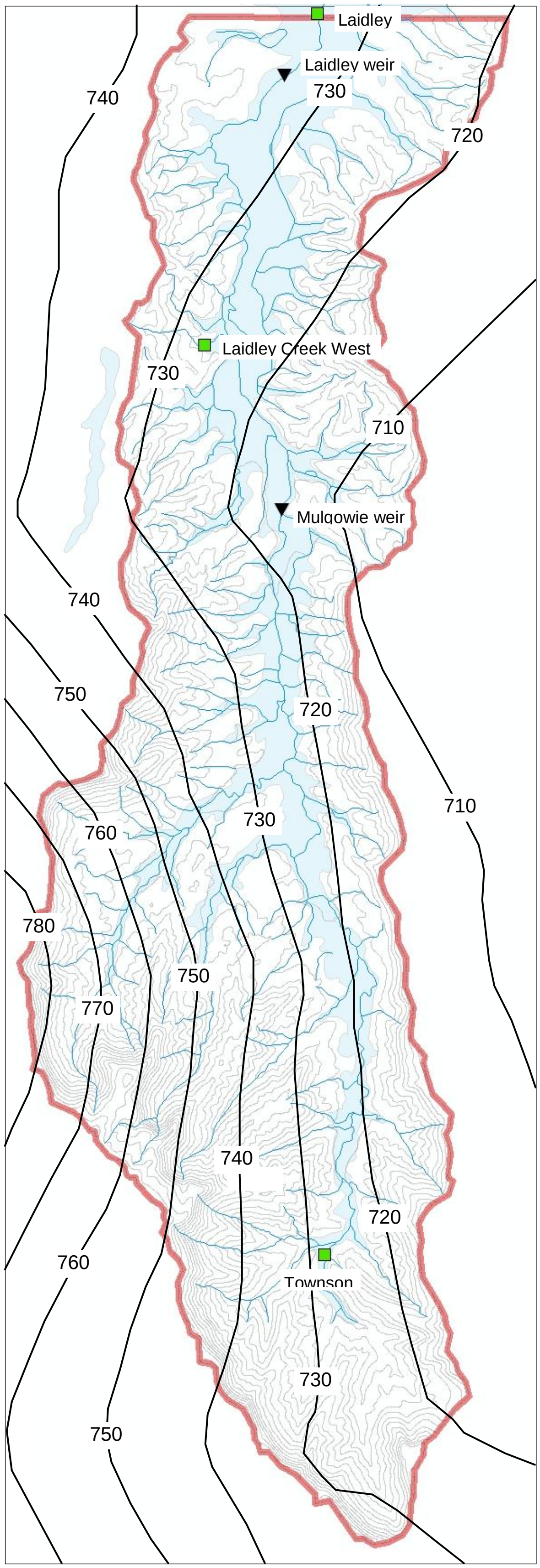


Figure 11. Annual effective evapotranspiration within the Laidley Creek catchment (30 years average)

Interpolation based on Gridded Average ET dataset (BOM, 2003).

During the drier months (April to August) the rain has become very unreliable as can be observed in May and July when the rainfall was below long term average in years 2006 and 2007. Conversely, the rainfall in October and November in years 2007 and 2008 exceeded the average rainfall by more than 100%.

3.6 Creek flow

Mulgowie (1043209B) is the only creek gauging station within the monitored area (Figure 3 – map, Appendix C: Table 20 – coordinates). Flow data from the period 1967 to 2010 show almost continuous creek flow from 1967 – 1980, 1981 – 1985, 1988 – 1992. From 1993 until the present, Laidley Creek at Mulgowie gauging station is shown to have flowed on an irregular basis (Figure 12).

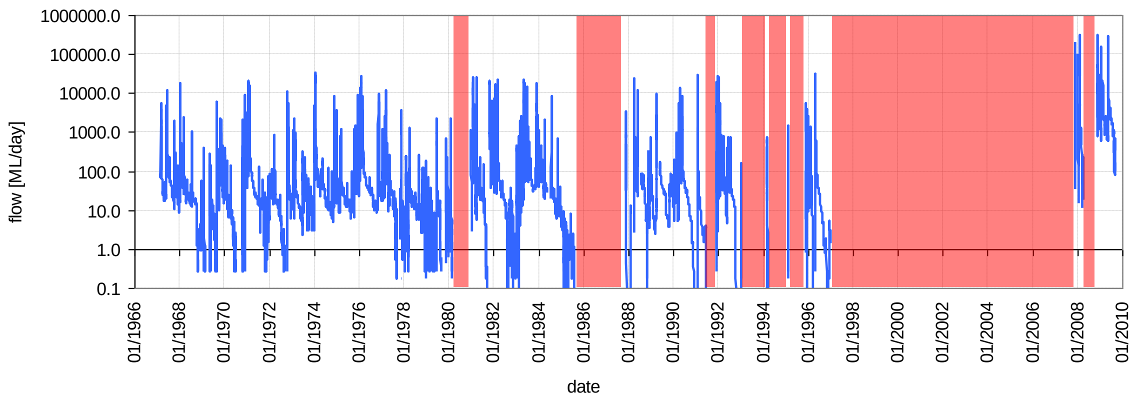


Figure 12. Frequency of the creek flow from 1967 to 2010 - Laidley Creek at Mulgowie (1043209B). No-flow periods marked by red colour. Unpublished DERM data.

Although Mulgowie gauging station is considered to be representative for the part of the catchment upstream from Mulgowie, it does not show the Laidley Creek behaviour upstream from the gauge, especially during the period of lower than average rainfall. During drier periods the creek had often flown in the upper parts of the catchment after the rainfall event in catchment headwaters. Such flows positively impacted the recharge and groundwater levels in the upper catchment alluvium, even if the flow did not reach the gauging station at Mulgowie.

3.7 Groundwater levels monitoring

Although the first groundwater level data from the Laidley Creek catchment come from the year 1945 (bore 14320279), the groundwater level monitoring program became more intensive during 1970s, with the expansion of irrigated farming in the area. At the time of the groundwater level data review (beginning of 2007), the total of 121 bores located within the Laidley Creek catchment, with groundwater level record, were identified in the DERM Groundwater Database (DERM, 2009). The groundwater levels are measured manually, in approximately 2 month intervals (63 days on average, 1st quartile: 18 days, 3rd quartile: 92 days), however in case of expected or observed event that would influence the hydraulic conditions in the catchment such as high rainfall events leading to creek flooding, the groundwater levels are measured in shorter intervals (1 to 2 days).

The relationship between rainfall, creek flow and groundwater table elevation was explored visually, by plotting the data representing historical rainfall trends (AMRR - Accumulated Monthly Residual Rainfall; Ferdowsian et al., 2001) against historical Laidley Creek flow data and historical groundwater table data (Figure 13).

The graphical comparison shows that the increased creek flow correlates with higher than average rainfall (e.g. during years 1974, 1976, 1982, 1988 or 1986) and sustained groundwater levels. The conditions of lower than average rainfall on the other hand translates into low creek flow volumes or dry creek and falling groundwater levels (e.g. periods of 1976 – 1980, 1984 – 1987 or 1992 - 1995). During the last period of “drought” i.e. lower than average rainfall between 1997 and 2007, the Laidley Creek at Mulgowie gauging station was mostly dry, however it is possible to observe the increase (and following decrease) of groundwater levels in some bores. These bores are either located upstream from Mulgowie gauging station, where the creek was flowing more often, or are located in the area of the alluvium recharged directly by rainfall.

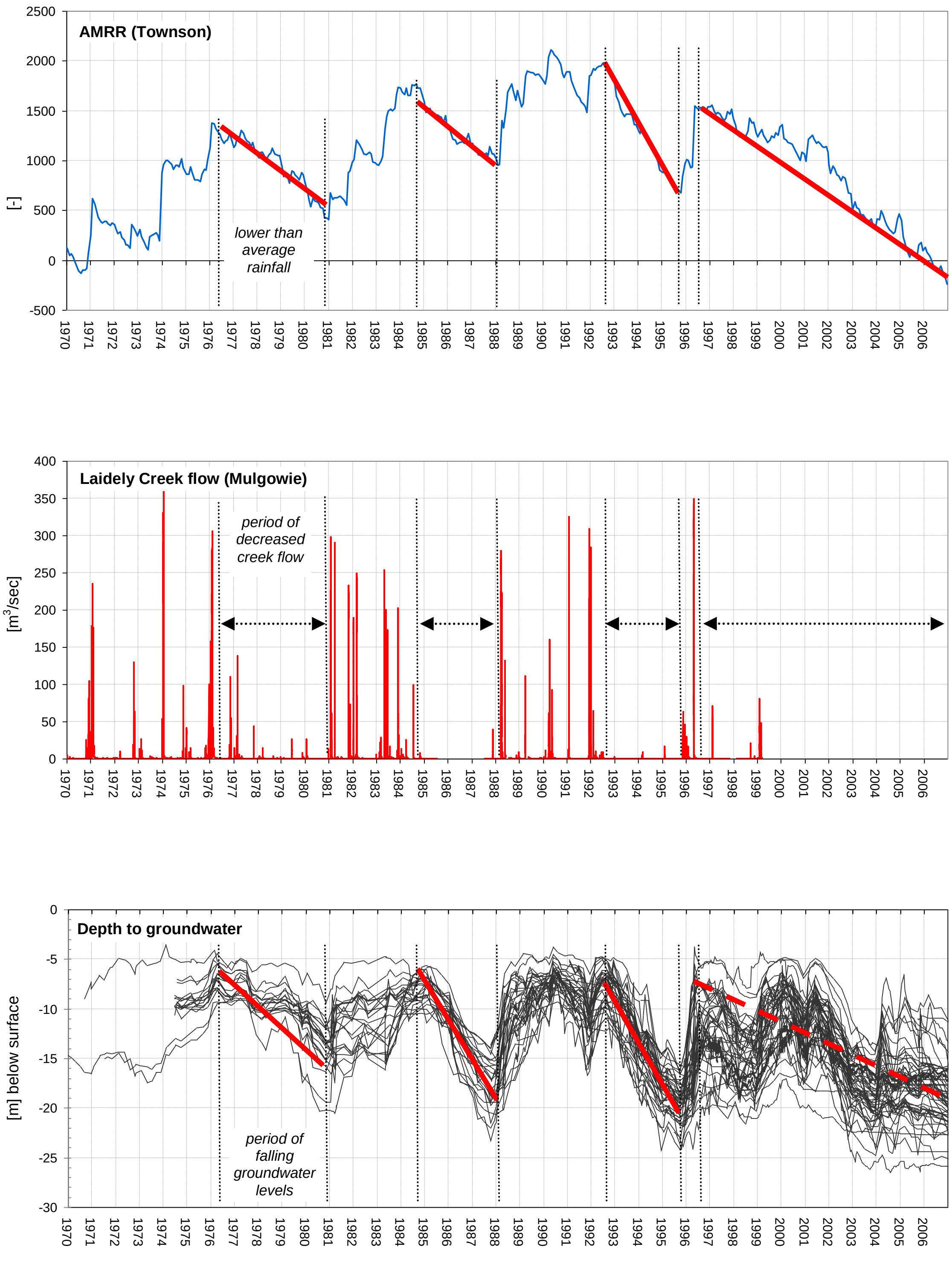


Figure 13. Relationship between rainfall, creek flow and groundwater table elevation (depth to groundwater)

The existing rainfall, creek flow and groundwater table elevation data suggest, that the recharge processes of the alluvium are driven by rainfall, that either directly recharges the alluvial aquifer or triggers the creek flow that recharges the alluvium further downstream.

Although this process appears to be relatively straightforward and fast, the comparison between the rainfall trend (AMRR) and groundwater table elevation in a single bore however shows more complexity then described earlier (Figure 14). Again, drier then average periods can be observed from 1976 – 1981, 1984 – 1988, 1992 – 1995 and from the beginning of 1997 to 2007. However, in the periods of 1976 – 1979 and 1996 – 2001 groundwater level in bore 14320297 was "stable" while the rainfall intensity declined. It means that despite of lower than average rainfall the alluvial aquifer was replenished from another source, most probably from the groundwater stored in higher elevation basalt and sandstone aquifers surrounding the main alluvial aquifer of Laidley Creek.

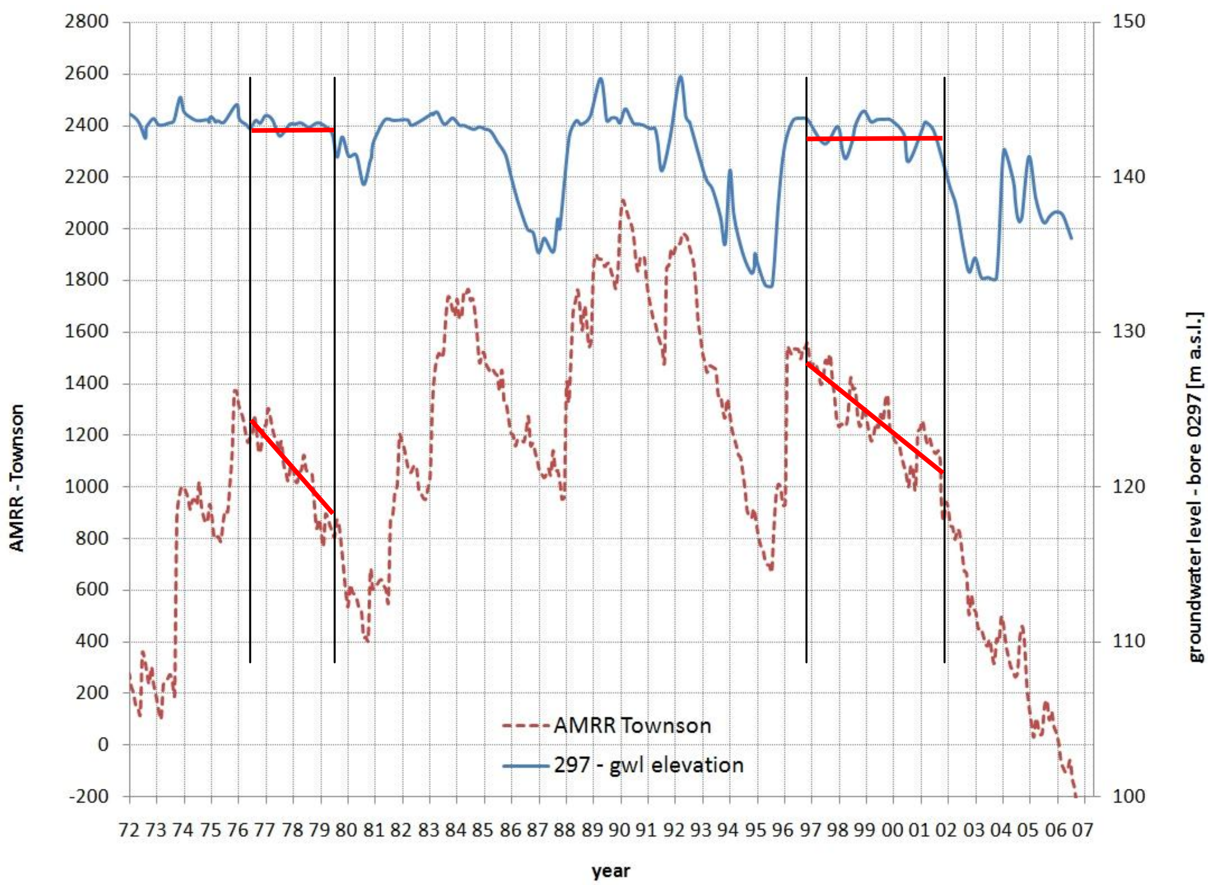


Figure 14. Correlation of groundwater bore hydrograph 14320297 and AMRR (Townson) for the period from 1972 to 2007.

This delayed release theory is supported by previous studies of neighbouring catchments (Cox and Wilson, 2005; Wilson, 2005) in which the non-alluvial aquifers are identified as a source of groundwater by the use of the stable isotope analysis. Sources of the water in the Laidley Creek and in the alluvial aquifer are further discussed in Section 4.4. A tabelated overview of bores with groundwater table elevation data within the Laidley Creek catchment is presented in Appendix E.

3.8 Study area overview: a summary

On a general level of understanding, the existing rainfall, stream flow and groundwater elevation data cover the Laidley Creek catchment relatively comprehensively and provide an insight into the hydrological processes on the catchment level. The data show correlation between rainfall, stream flow and recharge of the alluvium, however due to the groundwater levels' data granularity (a sampling interval of 2 months on average), it is difficult to see effects of short-term, intensive rainfall or stream flow events on the recharge of the alluvium.

When coupled with rainfall, stream flow and hydrochemistry information, higher frequency groundwater elevation data would facilitate a better understanding of recharge processes and sources within the catchment. The data collection process and analysis with respect to more detailed rainfall measurement, higher frequency groundwater table monitoring and major ion hydrochemistry is described in the following chapters.

4 Data collection and analysis

The initial data review undertaken at the beginning stages of this project established the fact that the data collected by various parties (BOM, DERM) during the previous monitoring works were not sufficient for the intended purpose of creating a conceptual and numerical model of the Laidley Creek catchment. A field work program was established with the goal of expanding the understanding of the hydrogeologic framework and the processes within the Laidley Creek catchment. The field monitoring program consisted of:

a) monitoring of rainfall and creek flow;

b) monitoring of groundwater levels and analysis of their behaviour with respect to recharge from rainfall and creek flow, and

c) sampling and hydrochemical analysis of both groundwater and surface water to establish sources of recharge.

4.1 Precipitation

As the understanding of both spatial and temporal rainfall distribution is crucial to the understanding of recharge processes (Srinivasan and Nair, 2005), the first step was to analyze historical rainfall data and examine the relation between precipitation, creek flow and recharge of the alluvial aquifer. The existence of a correlation between the rainfall and creek flow was established in Section 3.7 and further analysis of the link between the rainfall and recharge of the alluvial aquifer follows.

Rainfall in the catchment is regarded as a main source of recharge of both bedrock (basalt, sandstone) and alluvial aquifers (Dharmasiri et al., 1997; DNRM, 2000; DNRM, 2003; Cox and Wilson, 2005; DNRM, 2005; Galletly, 2007; Dvoracek and Cox, 2008). In the case of basalt aquifers and some outcropping sandstone aquifers, the recharge appears to be directly from rainfall. Direct recharge to alluvial aquifers from precipitation is however very slow (Dharmasiri et al., 1997; Cox and Wilson, 2005; Galletly, 2007;

Dvoracek and Cox, 2008) and alluvial aquifers are recharged indirectly through creek bed seepage.

4.1.1 Methodology

Between March 2007 and April 2009 the actual rainfall in the catchment was monitored using data collected from three stations in the catchment (Appendix B, Table 20). The rainfall gauging station at Townson (040675) is the only official BOM station while the stations at Laidley Creek West and Laidley are private gauges on farms. Although unofficial, the data collected by farmers are reliable as gauges are read on a daily basis.

4.1.2 Observed rainfall

Actual monthly rainfall generally conforms to the climatic trend of the drier winters (March - September) and wetter summers (October - February) (Figure 15; Appendix B, Table 21), however the irregularity of actual rainfall in comparison to long term average can be observed (Figure 10). The daily rainfall data are presented graphically in Figure 16 and in tabulated form in Appendix B.

During the period of the weekly groundwater monitoring (approximately 3/2007 – 8/2008) several significant rainfall events were recorded: 23 – 24/11/2007 (1), 4 – 5/1/2008 (2), 3 – 6/2/2008 (3) and 2 – 4/6/2008 (4) (see Figure 16). These rainfall events were later compared with creek flow data to examine the correlation between the rainfall and creek flow (Section 4.2) and also used as time markers during the analysis and grouping of bore hydrographs in Section 4.3.

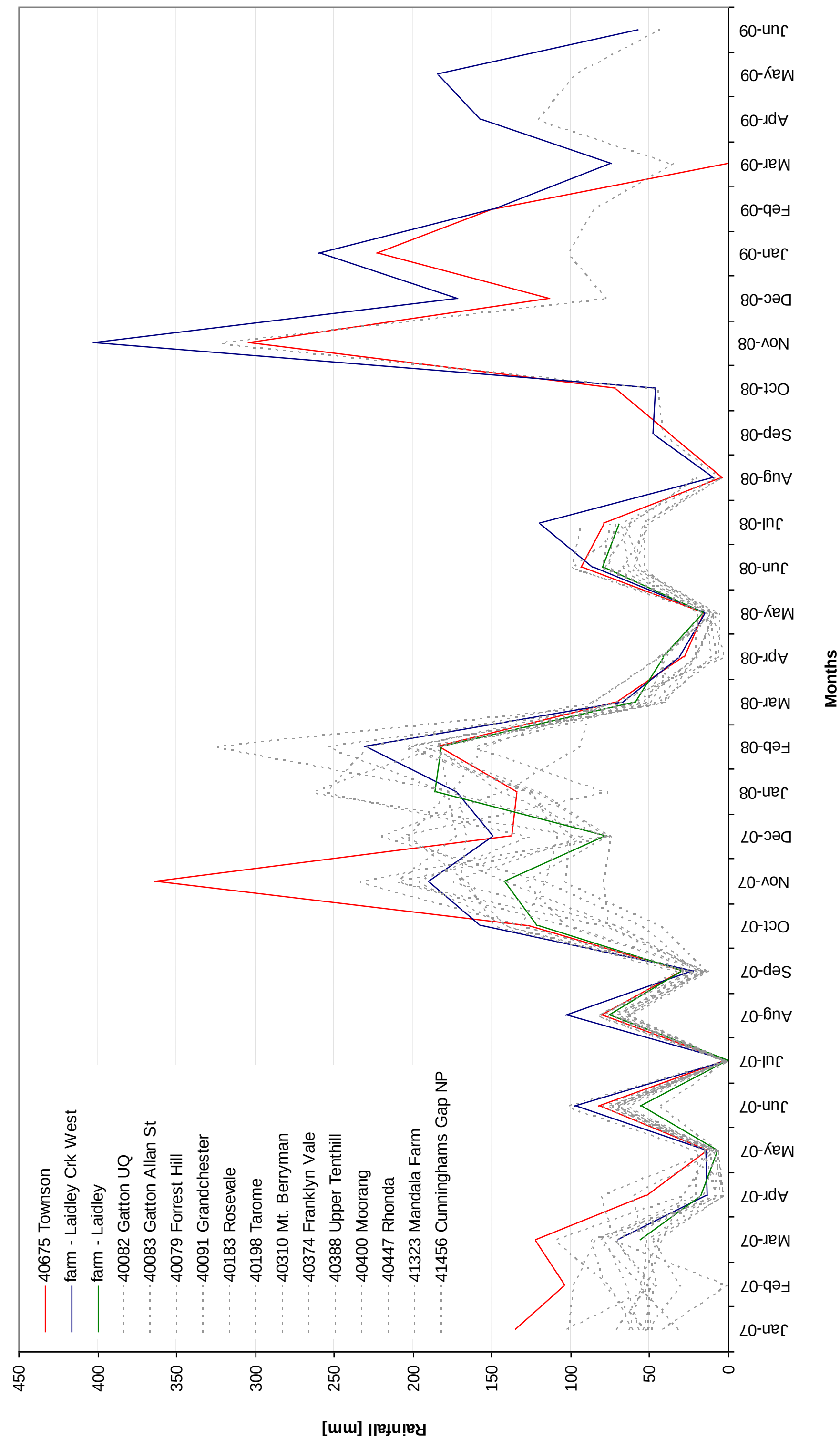


Figure 15. Monthly rainfall in the Laidley Creek catchment (stations Townson, Laidley Creek West, Laidley) compared with monthly rainfall in the surrounding catchments (grey dashed lines).

Stations outside of the Laidley Creek catchment conform to the similar rainfall pattern. All "grey line" stations are located within the greater Lockyer Valley – see Appendix C, Figure 96. Unpublished BOM data.

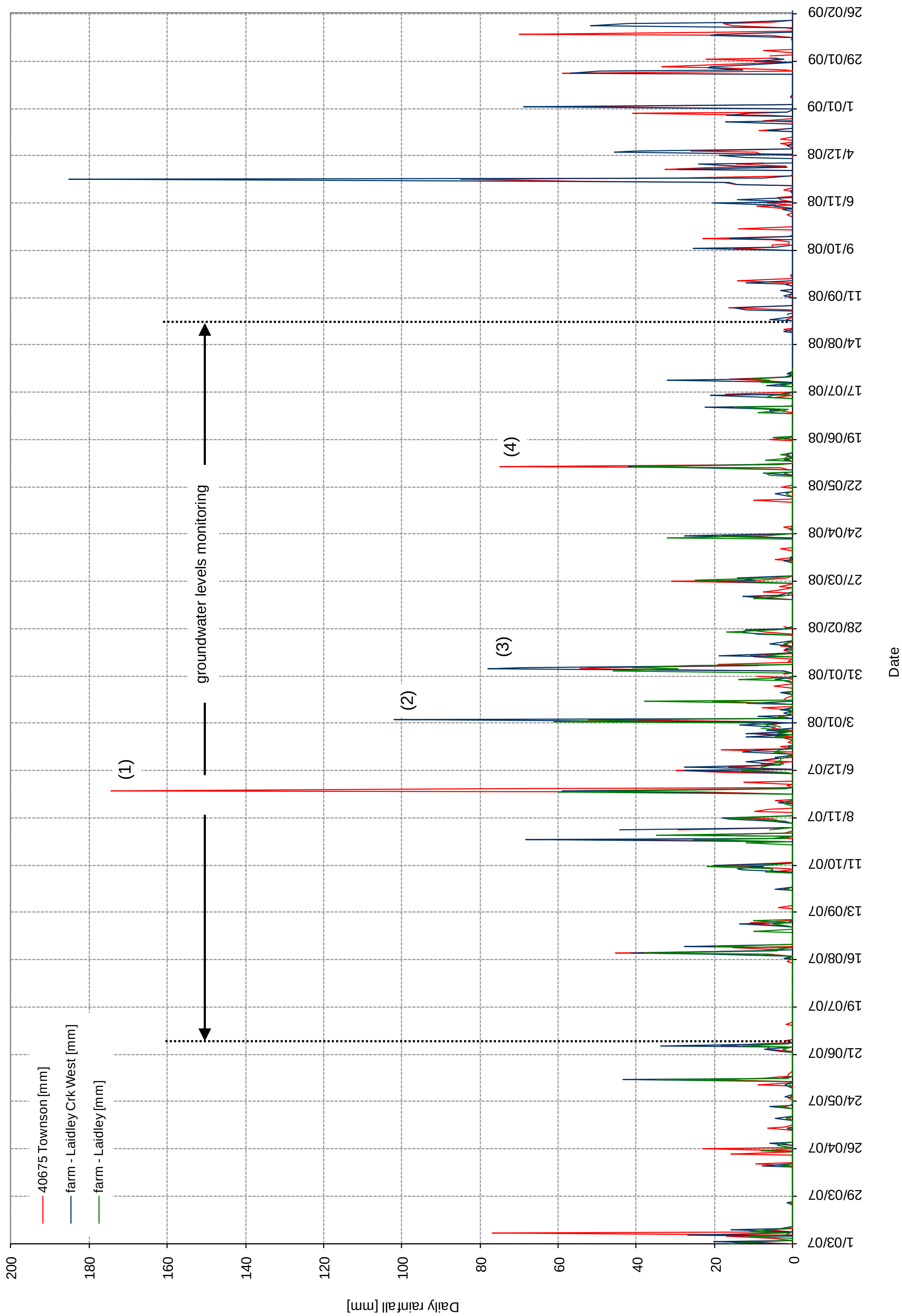


Figure 16. Daily rainfall in Laidley Creek catchment (03/2007 – 02/2009).

From 07/2007 to 08/2008 a weekly manual waterlevel measurement was undertaken and this time period is also used for bore hydrograph analysis. Stations Townson (04675), Laidley (farm), Laidley Creek West (farm). Significant rainfall events marked (1) – (4).

4.2 Laidley Creek flow

4.2.1 Methodology

As discussed in Section 3.6, the only automatic stream gauge on the Laidley Creek (within the project boundaries) is located in Mulgowie (1043209B; see Figure 3 for catchment map and Appendix D for gauge coordinates and actual stream flow data). The gauging station is run by DERM and both current and historical data are available online (DERM, 2012).

The Laidley Creek experienced irregular flow that was triggered only by significant rainfall events (Figure 17) during the monitoring period. Depending on the length of the previous dry period and the intensity of the rainfall, the creek usually ceased to flow downstream of the gauging station (lower catchment) within two days to several weeks after the rainfall event in the valley.

In the upper parts of the catchment (above the gauging station) the creek flow was sustained for up to several months. After the creek stopped flowing, pools of water remained stagnant before the creek dried up entirely. In order to obtain at least some information about the extent of the stream flow during the drier periods (during which there was no record about the stream flow over the gauge), the creek flow was observed visually at selected points such as bridges or road crossings along its course.

4.2.2 Observed creek stage and flows

The daily rainfall was averaged across all three gauging stations in the catchment and compared to the creek flow (creek stage) at Mulgowie gauging station. The comparison of these averaged rainfall and creek stage data (Figure 17) suggests again that rainfall is the main source of water for Laidley Creek as the creek flow episodes directly correlate to the significant rainfall events (as defined in the previous section). Depending on the length of the previous dry period and the actual state of groundwater levels in the catchment the creek flow appears to be triggered by rainfall events of more than 50 - 75 mm/d.

Figure 17 shows that rainfall events (2) and (3) were over 50 mm/day and both of them managed to set off the creek flow events because they followed closely after rainfall event (1). This was however not the case after rainfall event (4) when there was not enough rainfall to support the creek flow event after the relatively longer period of no-flow. Although average values representing the rainfall for the whole catchment were used, the actual amount of rainfall and its spatial distribution play significant roles as creek flow event triggers.

Figure 17 shows that significant rainfall events (as defined in Section 4.1.2) correlate with creek flow episodes as measured at the Mulgowie gauging station. Variable amounts of rainfall in different parts of the catchment (Table 4) and sustained duration of the rainfall influences the intensity of the creek flow episode. Although observation of the dependance of the creek flow on rainfall was carried out over the limited time interval, the correlation between the two processes is apparent and confirms the results of historical rainfall and stream flow data overview presented in Section 3.7.

Table 4. Spatial variability of rainfall with regard to significant rainfall events.

Event	Date	Townson [mm]	Laidley Crk West [mm]	Laidley [mm]	Average [mm]
1	24/11/2007	**174.4**	58.9	42.0	91.8
2	5/01/2008	52.2	**102.0**	38.3	64.2
3	4/02/2008	54.4	**78.0**	29.3	53.9
	5/02/2008	49.8	**69.8**	41.0	53.5
4	3/06/2008	**75.0**	42.0	41.0	52.7

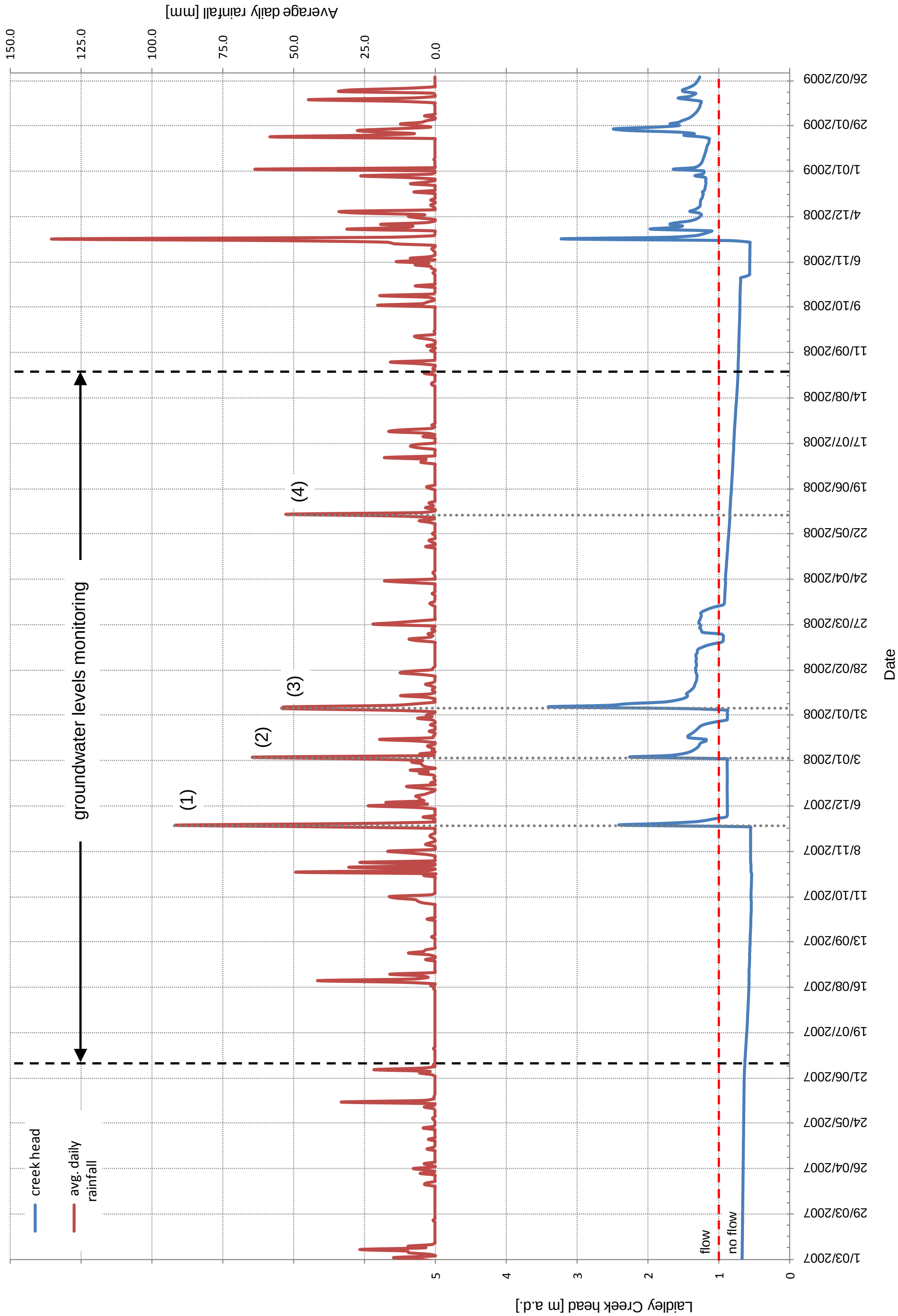


Figure 17. Correlation of average daily rainfall and elevation of Laidley Creek stage (03/2007 – 02/2009).

Daily rainfall average calculated from available data – stations Townson, Laidley Creek West, Laidley. Period of weekly manual groundwater level monitoring (07/2007 to 08/2008) is marked on the chart. Significant rainfall events marked (1) – (4). Creek flow level is 1 m above gauge datum.

4.3 Groundwater level monitoring

4.3.1 Methodology

The analysis of the historical groundwater elevation data (Section 3.7) showed a general correlation between rainfall, the intensity of Laidley Creek flow at Mulgowie gauging station and the change in groundwater table elevations, suggesting the rainfall and the stream flow as a primary recharge mechanisms for the Laidley Creek alluvium. In order to refine the understanding of the recharge process and to recognize zones with different recharge characteristics within the Laidley Creek alluvium, a network of 42 observation points (see Figure 3 for Laidley Creek catchment map and Appendix F for the list of all bores and their coordinates) has been established using both private bores and monitoring bores drilled and maintained by Queensland Department of Environment and Resource Management (DERM).

Groundwater levels were manually measured on a weekly basis. All measurements were undertaken from the top of inner PVC casing and then recalculated to the depth from the ground level. In addition, 10 of these selected monitoring bores were equipped with automatic unvented pressure transducers (HOBO U20 Water Level Logger) to log groundwater level movement at 15-minute intervals (Figure 18). A single pressure transducer located in the upper part of the casing of the bore 14320879 (approximately in the center of the Laidley Creek catchment) was used to record the barometric pressure representative for the valley. The automatic pressure transducers were distributed so that the distance between individual automatically monitored bores would be more or less uniform. The transducers were also located to bores close to Laidley Creek (where possible), so that possible rapid recharge from the creek to the alluvium could be observed.

Monitoring bores are clustered in groups or transects, the distance between individual bores within a transect varies from 50 to 300 m, the distance between transects and groups is from 1 to 5 km. The distance between bores is greater in the upper parts of the catchment, due to the lesser number of bores. Observation bores in the valley are typically screened in their lower section, i.e. within the basal layer of coarse sands and gravels of the alluvial profile (see available borelogs – Appendix P and digital appendix).

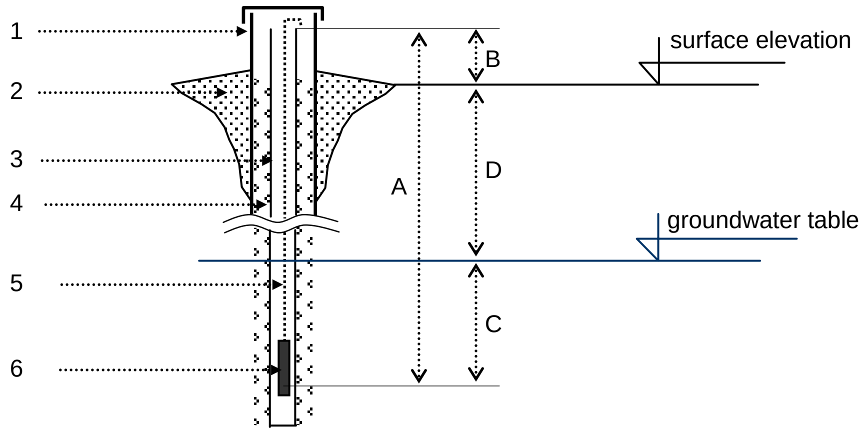


Figure 18. Monitoring bore construction and placement of pressure transducer

1 external steel casing
2 concrete bore collar
3 internal PVC casing – perforated against the aquifer
4 gravel backfill
5 stainless steel cable
6 pressure transducer

A length of the transducer cable (from the datum/measurement point to the pressure sensor
measured before transducer deployment
B "stick-up" – height of the datum/measurement point above surface elevation
measured before transducer deployment
C depth of the pressure sensor below the ground water table
calculated from the pressure of the water column on the pressure sensor
D depth of the groundwater table below the ground surface
calculated as D=A-B-C

4.3.2 Observed variation in groundwater table movement

The beginning of the observation period (from August to November 2007) was dry. There was inadequate rainfall to trigger a stream flow event and consequently the response of the alluvial groundwater table was minimal. With the onset of summer rains in November 2007 and with enough rainfall to initiate and at least temporarily sustain the stream flow, the alluvium started to recharge (Figure 19).

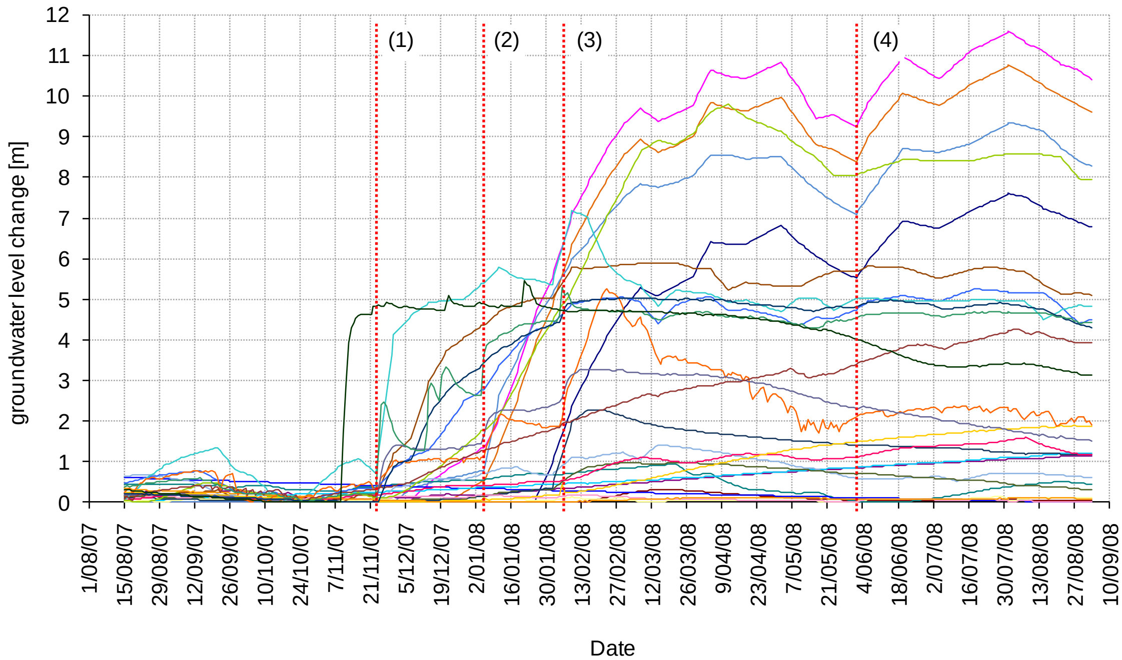


Figure 19. Overview of groundwater hydrographs (08/2007 – 08/2008). Major rainfall events (1 - 4) marked by vertical dashed red lines

In general, the closer the bore is to the headwaters in the basalt ridges of the southern part of the catchment, the faster the groundwater in the bore and surrounding alluvium reacts to the "recharge triggers" like stream flow or rainfall due to higher hydraulic conductivity of the coarse alluvium. Secondly, the alluvium in the upper catchment is bounded by basalt hills and ridges that enable the alluvium to recharge by means of slope runoff from the surrounding basalts. The layer of confining/semiconfining soil layer on top of the coarse alluvial gravels is very thin in the upper catchment and this also contributes to faster aquifer recharge. Bores in the central and lower parts of the catchment recover more slowly.

Because the shape of the bore hydrograph reflects the ability of the alluvium surrounding the bore to recharge, hydrographs were used to classify the areas of alluvium represented by these bores. In order to make the hydrograph data comparable between individual bores, the data were manipulated to represent water level change, rather than actual water table elevation using formula:

$H_{adj} = H_{orig} - H_{min}$

where: H_{adj} ... adjusted value of groundwater head [m]

H_{orig} ... original value of groundwater head [m a.s.l.] - [m above sea level]

H_{min} ... minimum value of groundwater head [m a.s.l.]

Because the groundwater head change in some bores (e.g. 339, 884 and 887) was small, further normalization was applied in order to amplify the trend in groundwater level movement. Plots of the normalized data show groundwater level changes as a percentage of total change within the bore. The data normalization was conducted using the formula:

$H_{adj} = 100 \times (H_{orig} - H_{min}) / (H_{max} - H_{min})$

where: H_{adj} ... percentage of the head change with respect to the maximum amplitude of the groundwater head - [%]

H_{orig} ... original value of groundwater head - [m a.s.l.]

H_{min} , H_{max} minimum and maximum value of the observed water table in the bore - [m a.s.l.]

Simplified schematic diagrams representing the main hydrograph groups are presented in Figure 20, actual non-normalized and normalized hydrographs representing all described groups of bores are presented in Appendix I. Based on visual comparison, hydrographs were clustered into groups of bores with similar head response characteristics:

- (A) *head change related to major rainfall events (and/or creek flow)*: response time and amplitude depend on the distance of the bore from the creek headwaters, distance of the bore from the creek bed and the vertical position of the bottom of the bore with respect to the elevation of the creek bed. The source of recharge is water infiltrating through the creek bed. The hydrographs show:

- (A1) clear "step-like" response of the groundwater levels to first 3 major rainfall events. The response to the fourth significant rainfall event is limited because the alluvium surrounding the bores appears to be saturated. The overall water level change is between 3.5 m and 6.5 m (Figure 21).

  bores: 294, 295, 296, 297, 330, 331, 450, 472, 879, 917, 919, 920, 982, 983, 986

- (A2) minimal or no response to the first two significant rainfall events, followed by a major response to the third significant rainfall event. The overall water level change is between 0.3 m and 2 m (Figure 22).

  bores: 337, 883, 885

- (A3) a small, but consistent response to all significant rainfall events. The overall water level change is between 1 m and 1.5 m (Figure 23).

  bores: 290, 293, 340, 453, 786, 880

- (B) *head change unrelated to the major rainfall events (possible indirect/diffuse recharge)*: bore hydrographs show a slow and gradual head change that started after the first major rainfall event. The hydrograph curve lacks sudden changes in recovery rate (compared with hydrographs of group A).

  - (B1) The recovery generally starts with the first significant rainfall event, however the water level rise is slow and "smooth". The response to later individual rainfall events is not clear, but the water level generally rises. The overall water level change is between 1 m and 4 m (Figure 24).

    bores: 332, 849, 916

  - (B2) The head change is minimal and the hydrograph response to the rainfall is gradual with no obvious steps. There appears to be about 2 months delay between the first rainfall event and the change in hydrograph trend (Figure 25).

    bore: 339

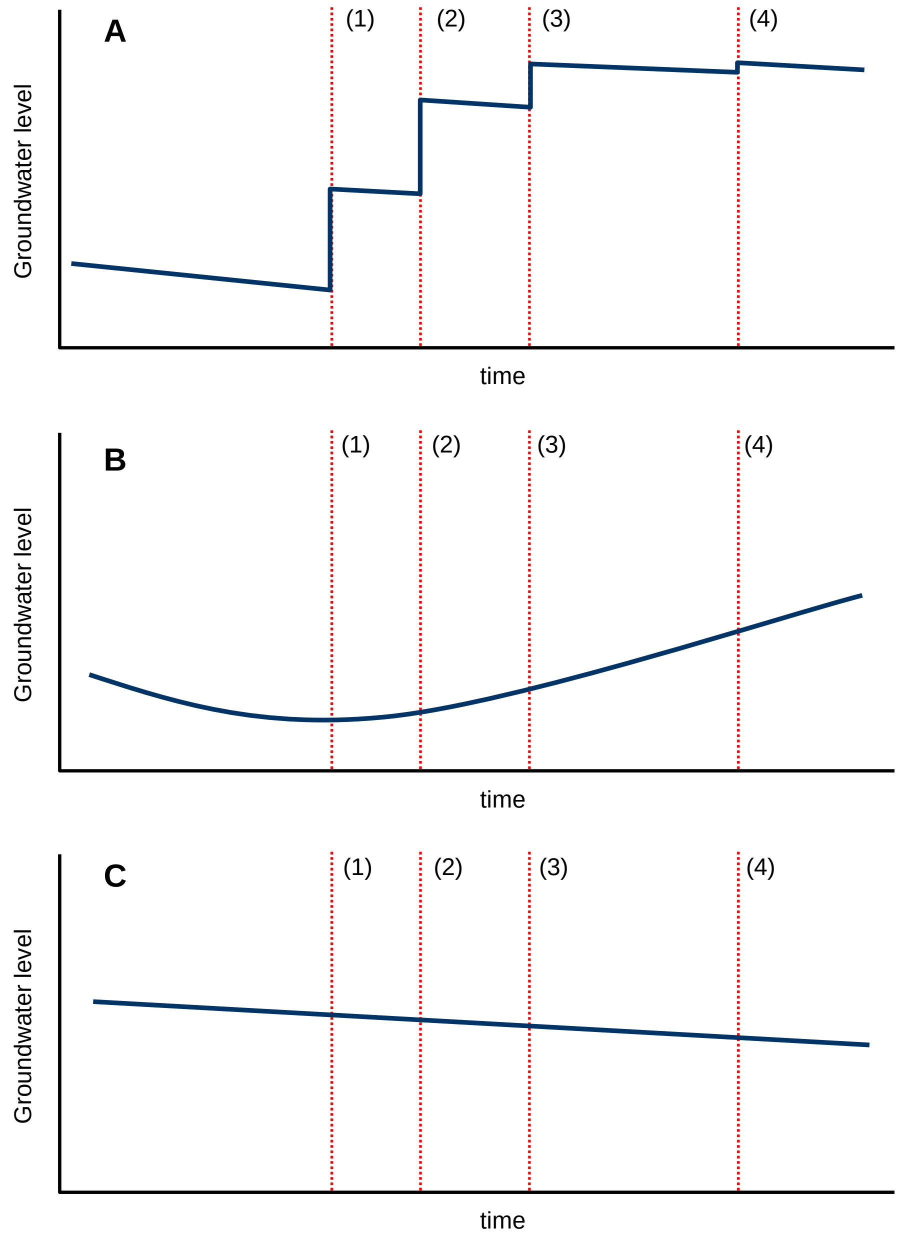


Figure 20. Simplified representation of major hydrograph groups. Major rainfall events (1 - 4) marked by vertical dashed red lines.

group A – clear recharge related to major rainfall events and/or creek flow
group B – recharge unrelated to major rainfall events and/or creek flow
group C – minimum or no recharge

Actual hydrographs representing all described groups of bores are all presented in Appendix I.

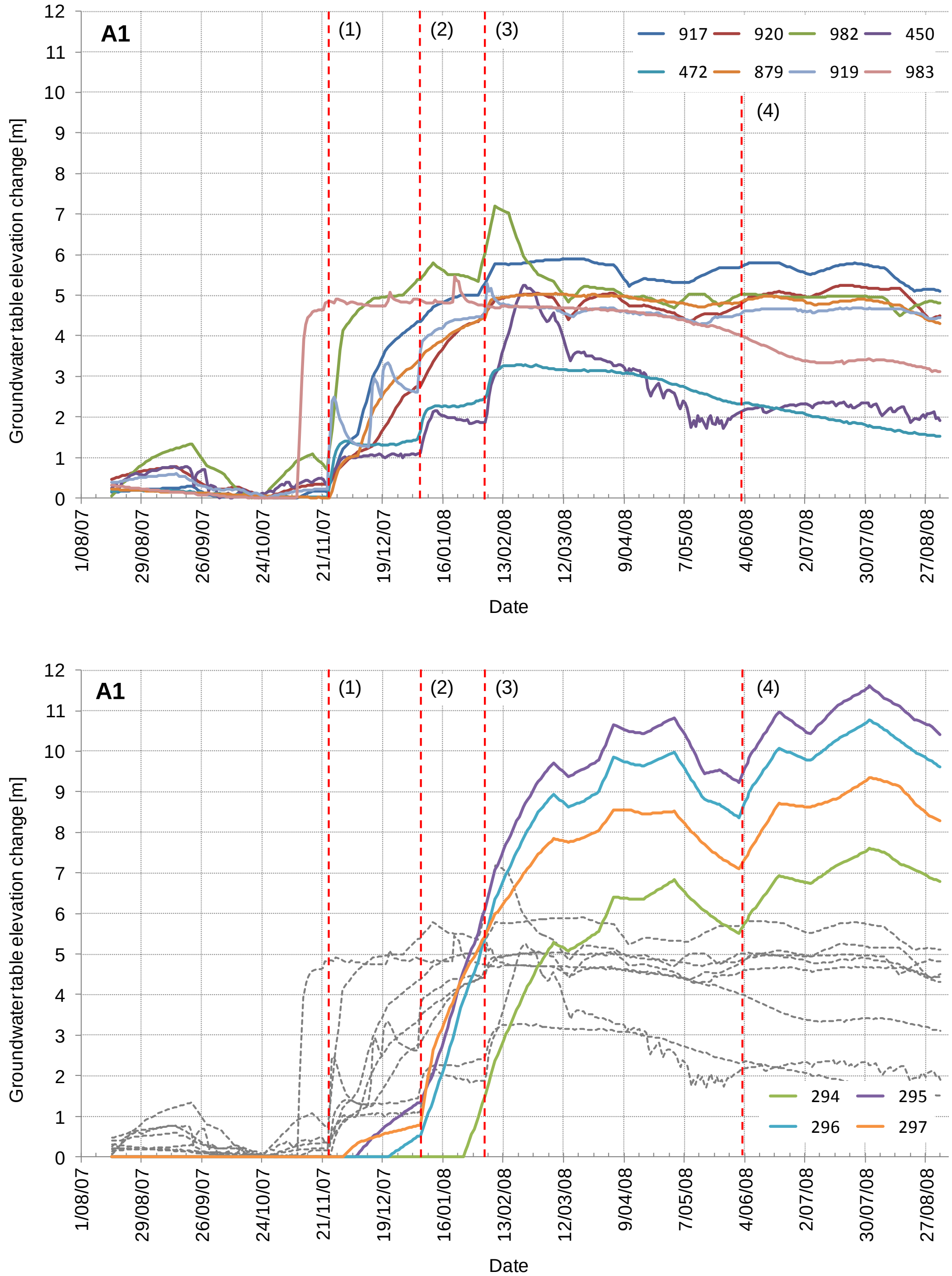


Figure 21. Bore hydrographs – group A1 – recharge related to major rainfall events and/or creek flow. Clear "step-like" response of the bore hydrograph to first 3 major rainfall events. Response to fourth significant rainfall event is limited. Major rainfall events are indicated using thick vertical dashed line in the chart.

Bores 14320294, 14320295, 14320296 and 14320297 are drilled in a profile perpendicular to Laidley Creek, very close to Mulgowie recharge weir. Bores (and weir) were dry untill the first significant rainfall, only after this rainfall event the head in the aquifer started to recover. Other hydrographs belonging to group A1 shown for comparison (grey dashed lines).

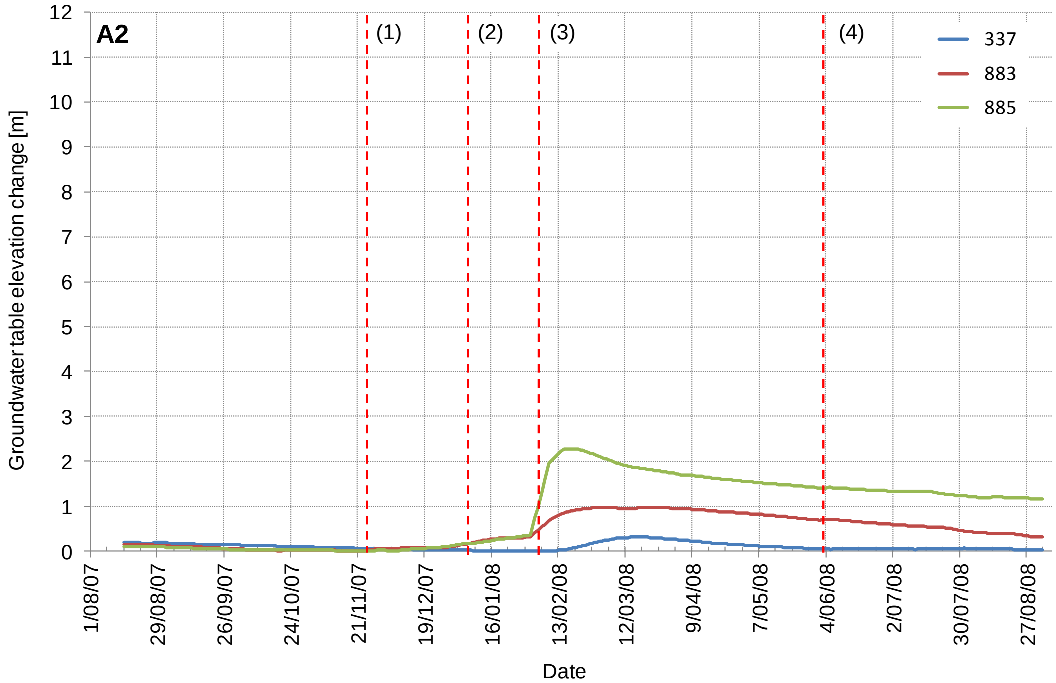


Figure 22. Bore hydrographs – group A2 – recharge related to major rainfall events and/or creek flow. Minimal or no response to first two significant rainfall events, major response to third significant rainfall event

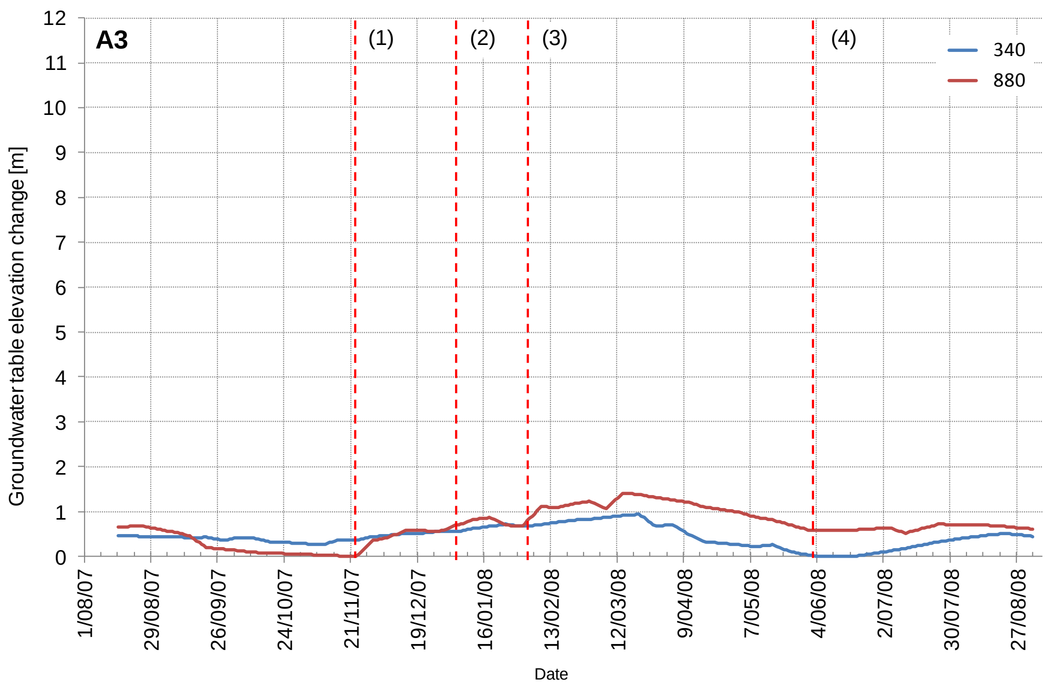


Figure 23. Bore hydrographs – group A3 – recharge related to major rainfall events and/or creek flow. Small, but consistent response to all significant rainfall events.

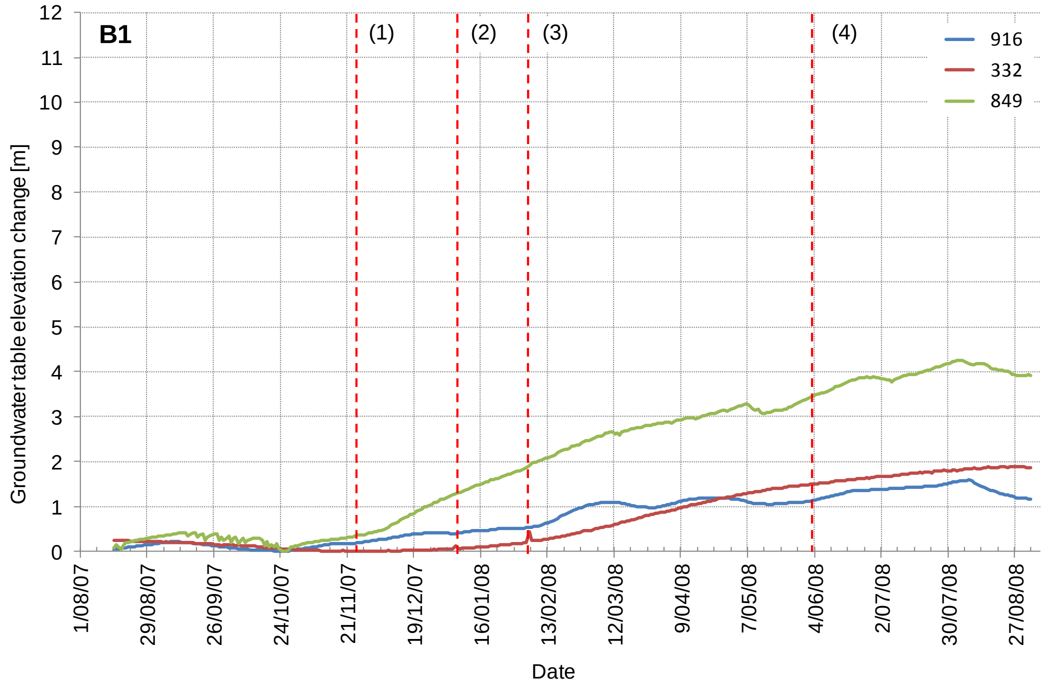


Figure 24. Bore hydrographs – group B1 – recharge unrelated to the major rainfall events (indirect recharge). Smooth and steady rise of groundwater table.

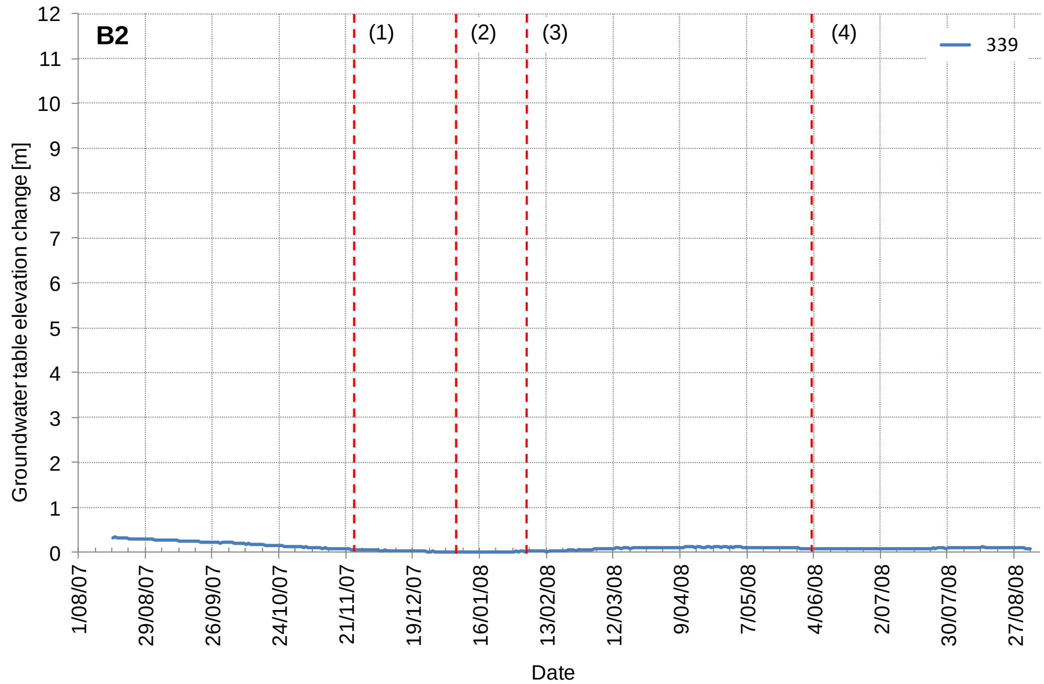


Figure 25. Bore hydrographs – group B2 – recharge unrelated to the major rainfall events (indirect recharge). Minimal, delayed recharge.

- (C) *minimal or no recharge*: bore hydrographs show:
    - (C1) erratic behaviour not visibly correlated to any rainfall and/or creek flow event (Figure 26).
      bores: 884, 887
    - (C2) steady recharge or discharge of the alluvial aquifer during which the alluvium surrounding the bore is gaining or losing the water regardless of the rainfall or any creek flow event throughout the entire monitoring period. The amplitude of the water level movement is small, up to 0.5 m througout the monitoring period (Figure 27).
      bores: 547, 553

The grouping of groundwater hydrographs represents different recharge regimes of the alluvial bores located in the different parts of the catchment. Apart from bores belonging to group C, the bores recharged after either rainfall or rainfall induced creek flow event (hydrograph groups A and B) which support the "rainfall → alluvium recharge" and "rainfall → creek flow → alluvium recharge" scenario that was proposed previously (Section 3.7). What drives the groundwater head change in bores belonging to group C is not clear. These bores are located mostly in the lower part of the catchment and at a significant distance from Laidley Creek. It was observed (Ashley Bleakley, personal communication, 2008) that under more favourable conditions of continuous creek flow those bores recharge quite readily however such conditions were not experienced during the course of the field monitoring program.

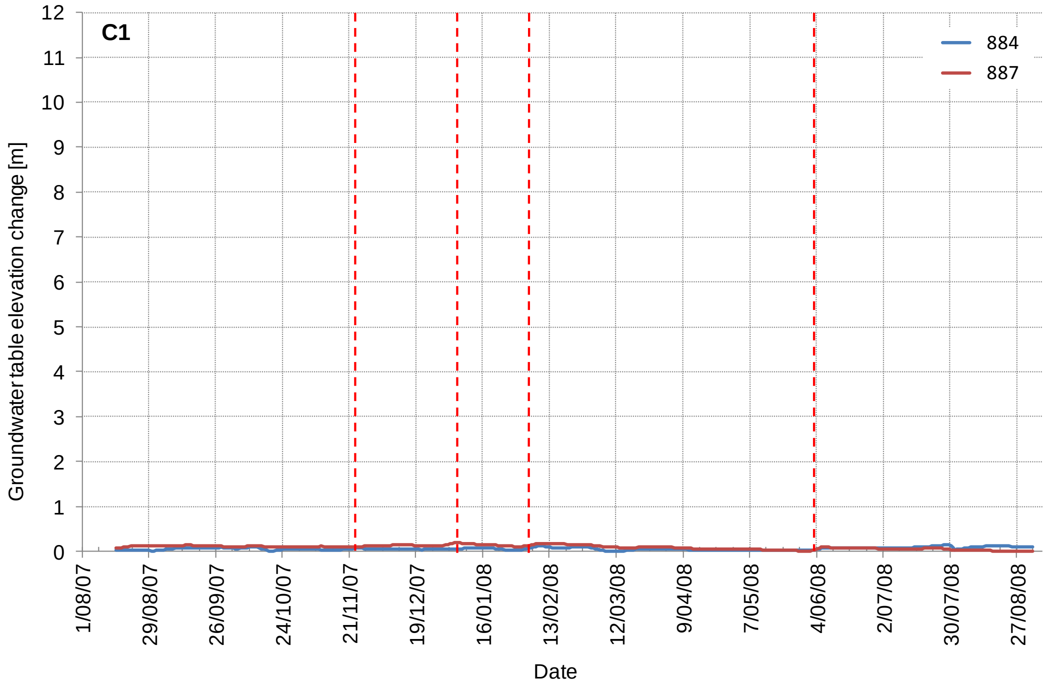


Figure 26. Bore hydrographs – group C1 – minimal or no recharge. Erratic behavior not visibly correlated to any rainfall and/or creek flow event.

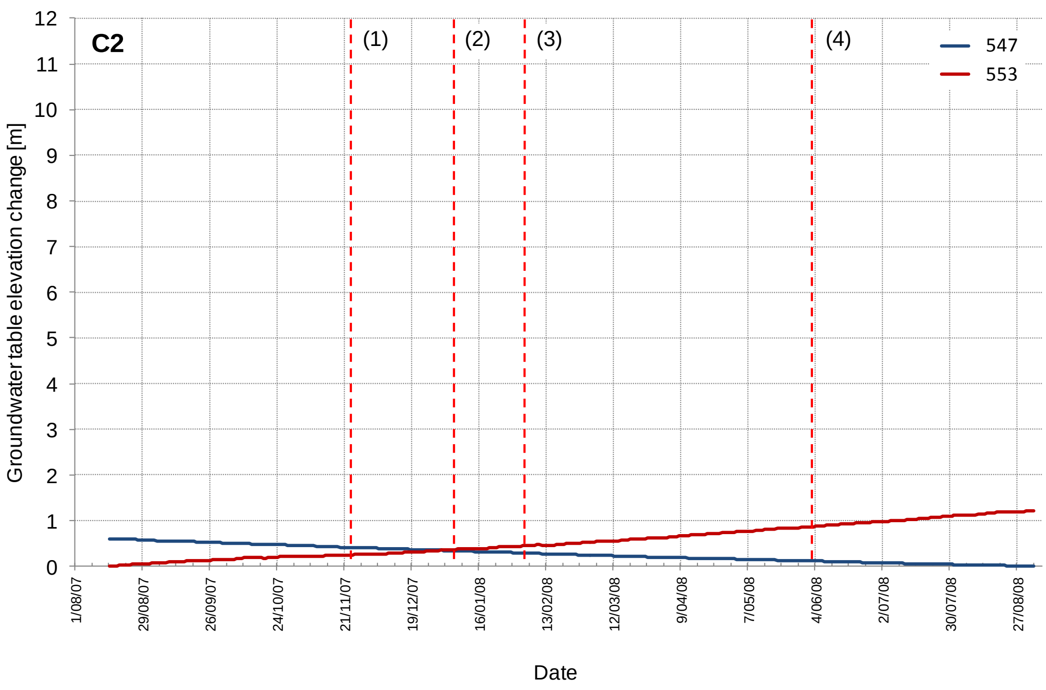


Figure 27. Bore hydrographs – group C2 – minimal or no recharge. Steady recharge or discharge regardless of the rainfall and/or creek flow event.

4.4 Hydrochemistry

In general terms, hydrochemistry is indicative of processes in groundwater and of processes between groundwater and the aquifer. It is a useful tool, helpful with description and analysis of general groundwater processes, such as mixing of waters from different sources or geochemical interaction between groundwaters and aquifers.

In order to conduct hydrochemical characterization of the Laidley Creek groundwaters and surface waters, the following steps were taken:

- an overview of previous hydrochemical investigations within the wider Lockyer Valley area and overview of existing hydrochemical data with respect to stratigraphy of the sampled aquifers were carried out;
- to obtain current hydrochemical data, 34 groundwater samples and 9 surface water samples were taken and analysed;
- the results of the major ion analysis were then characterized using graphical (Stiff and Piper diagrams) and statistical (HCA) methods.

4.4.1 Previous hydrochemical investigations within the wider Lockyer Valley

Hydrochemical investigations in the greater Lockyer Creek catchment have been previously conducted in order to address two types of issues: (1) to describe the recharge processes of both alluvial and non-alluvial aquifers and (2) to address the issues of water quality (mainly increased salinity and pollution by agricultural fertilizers) throughout the catchment.

4.4.1.1 Recharge processes

During the period from 1984 to 1987, Dixon and Chiswell (1992) used major ion analysis of groundwater samples from locations in Ma Ma and Tenthill creek catchments to localize areas of saline groundwater intrusions into the alluvial aquifer.

Dharmasiri et al (1997) proposed that the main sources of groundwater recharge in the Lockyer Valley were the creeks and rainfall infiltration through sandstone outcrops. Using tritium as a natural tracer, Dharmasiri (1997) showed that the direct recharge of the silty alluvium within the central Lockyer Valley is very slow. This conclusion was also accepted by Ellis and Dharmasiri (1998) and Ellis (1999). The projected rate of advance of movement of water fronts through the soils averaged approximately 20 mm/year (about 3% of average annual rainfall). In a catchment wide study, Cox and Wilson (2005) used isotopes and hydrochemistry to confirm that the major recharge mechanism is direct recharge from streams and indirect recharge from basalts and sandstone bedrock. Some water samples also confirmed the presence of deep GAB (Great Artesian Basin) water.

Apart from the description of recharge processes, hydrochemical investigations have been conducted in order to address the issues of water quality such as increased salinity and pollution by agricultural fertilizers throughout the Lockyer Creek catchment.

4.4.1.2 Salinity and water quality

Water quality issues of the whole Lockyer Valley were described by McNeil et al. (1993). The report described the existing water quality monitoring network and concluded that it is not sufficient. Revision of the monitoring network was suggested to address the problem of groundwater pollution by chemical fertilizers (nitrates and pesticides) and to improve the sampling techniques so that a larger area is effectively covered at more frequent intervals. The report also acknowledges the economic and social importance of the Lockyer Valley and community concerns about soil erosion, water quality and land management issues.

Talbot et al. (1981) and Wills et al. (1996) focused on the quality of irrigation water throughout the Lockyer Valley. Wills also compared his results (data from 1984 - 1994) with previous monitoring and analysis (Talbot et al., 1981). The report concluded that the water quality (in terms of salinity and nitrate concentrations) had dropped during the period 1980 – 1994 and that there was a high correlation between water quality and the amount of water in the aquifer (groundwater level above the sandstone bedrock).

McMahon (1995) and McMahon and Cox (1996) investigated groundwater chemistry of saline water in the Sandy Creek catchment. This thesis describes six different hydrochemical groups that are related to the four members of the Marburg Sub-group. McMahon concluded that the seepage from underlying sandstone units is a significant form of recharge to the alluvium during periods of low groundwater levels in the alluvium.

Li and Cox (1996) analyzed groundwater sampled from the Walloon Coal Measures and commented on groundwater evolution and salinity. Based on the results of their research, they suggested that the source of the salinity are cyclic salts and the transfer mechanism of the salts from the ocean into the soil is precipitation. Current groundwater chemistry is also influenced by processes derived from lithology of Walloon Coal Measures (e.g. ion exchange).

Groundwater quality in the alluvium of Sandy Creek was examined by McMahon and Cox (1996) who concluded that the chemical composition of the alluvial groundwater closely reflects the hydrochemistry of groundwaters discharging from the bedrock aquifers, especially during low stream flow periods.

MacLeod (1998) examined the hydrochemistry and geology of Ma Ma Creek catchment and delineated areas of recharge from different sources such as the sandstones of Ma Ma Creek member and basalts of Main Range Volcanics and pointed out that the increased salinity of groundwater originated from the sandstones.

Kunde (2001) summarized the current knowledge of dryland, surface water and groundwater salinity in the Laidley and Sandy Creek catchments. Water quality has been assessed from the point of agricultural land use and correlation between land use, water use, climatic conditions and salinity was shown.

Picarel (2004) examined groundwater chemistry and salinity of the Lower Lockyer valley. Based on hydrochemical and isotopic data Picarel was able to determine the recharge processes and degree of groundwater mixing in the project area. She also pointed out several bores in which the very high water salinity was a result of stagnation of groundwater in basement depressions.

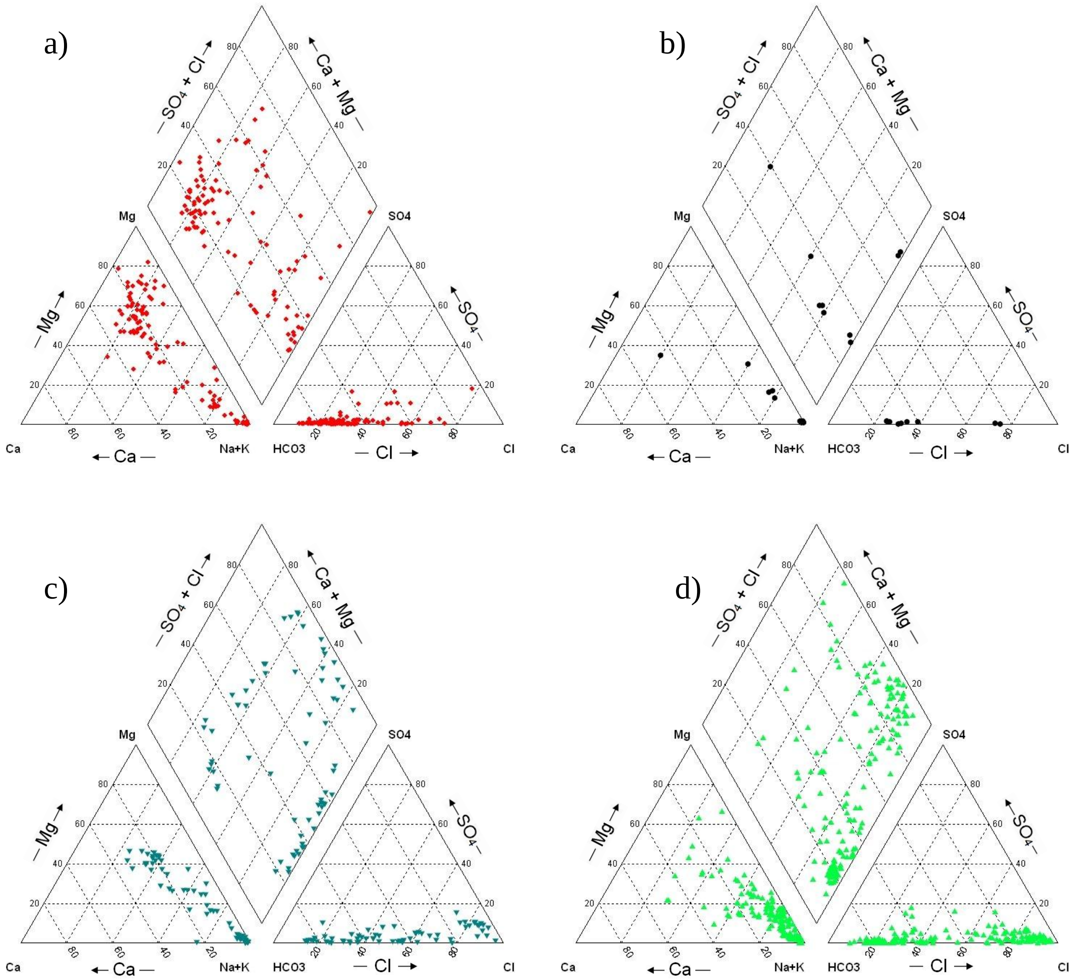
An extensive report compiled by Pearce et al. (2007) describes the hydrogeological framework and processes within the greater Lockyer Creek catchment and addresses issues of regional groundwater flow, connectivity of alluvial and non-alluvial aquifers and water quality. The authors also discuss the recharge of both types of aquifers and mixing of different water types and increased groundwater salinity in non-alluvial tertiary Clarence-Moreton Basin aquifers. The report also looks at groundwater level trends and causality between climatic conditions such as rainfall and drought and groundwater extraction.

4.4.2 Existing hydrochemical data

In terms of the stratigraphic setup, climatic conditions and land/water use patterns, the previously examined neighbouring catchments are similar to the Laidley Creek catchment. Because of this similarity, the findings of previous investigations are highly relevant to the situation in the Laidley Creek subcatchment.

Historical hydrochemical data from several sources (McMahon, 1995; MacLeod, 1998; Pearce et al., 2007; DERM, 2009) were compiled and examined in order to analyze possible correlation between groundwater chemistry and individual stratigraphic units in Laidley Creek catchment and thus infer the sources of groundwater in different parts of the catchment. The samples were divided into groups based on their source aquifer stratigraphy and each group was plotted separately onto the Piper diagram so that differences between individual groups can be visualized (Figure 28). The sources of data with regard to groundwater chemistry were:

- McMahon (1995) – 3 samples;
- MacLeod (1998) – 6 samples;
- DERM Groundwater Database (DERM, 2009) – 577 samples;
- Pearce et al. (2007) – 114 samples, after removing duplicate records that were acquired from DERM Groundwater Database.



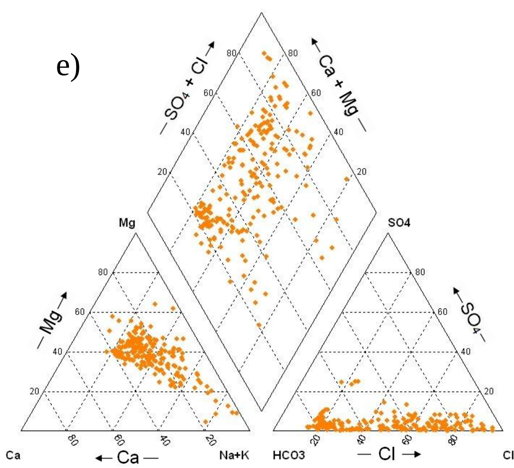


Figure 28. Piper diagrams - groundwater hydrochemistry (major ions) - historical data (McMahon, 1995; MacLeod, 1998; Pearce et al., 2007; DERM, 2009)

a) MRV basalts
b) Walloon Coal Measures
c) Koukandowie Formation
d) Gatton Sandstone
e) Laidley Creek Alluvium

The samples were spatially selected from the whole Lockyer Valley area, however only samples representing stratigraphical units existing in the Laidley Creek catchment were used.

Water samples from the basalts of the Main Range Volcanics have typically elevated concentrations of magnesium and bicarbonates, with very low sulfide and calcium concentration. Some basaltic samples also have high concentrations of Na^{+}+K^{+} and Cl^{-} (Figure 28). Although diverse, the composition of basalt groundwaters is within the expected ranges of ionic concentrations as described from other localities with dominant volcanic material related groundwaters in Australia (Locsey and Cox, 2000; Locsey and Cox, 2003; Locsey et al., 2012) and in other parts of the world (Dewandel et al., 2005; Demlie et al., 2007; Pradhan and Pirasteh, 2011). The Mg-HCO_3 type water samples tend to have low concentration of TDS and their chemical composition is usually representative for "shallow circulation" water (groundwater with short resident time in basaltic aquifer). On the other side of the spectrum are "deep circulation" (long residence time) water samples which are typically depleted in magnesium and have increased concentrations of chloride and potassium/sodium (Dewandel et al., 2005).

Compared to basalt groundwater samples, groundwaters from Clarence-Moreton Basin sedimentary aquifers (Walloon Coal Measures, Koukandowie Formation and Gatton Sandstone) have elevated concentrations of sodium, calcium and chloride ions and a lower concentration of magnesium ion. Sedimentary aquifer groundwaters are also on average highly mineralized. The concentration of total dissolved solids (TDS) in sedimentary aquifers is generally higher than those of basalt samples, in some cases reaching over 20000 mg/L (Table 5).

Groundwater samples from the Laidley Creek alluvium do not have distinct groundwater composition, however with an average TDS of 1375 mg/L, their TDS is generally somewhere between that of basalt groundwaters and sedimentary aquifer groundwaters.

Although collected over a period of almost 50 years (the earliest samples were collected in February 1962) in different conditions with regard to the groundwater elevation in aquifers, the chemical composition of groundwater from different stratigraphical units appears to be distinctive enough to indicate the origin of the groundwater.

Table 5. Statistical overview: mineralization of water samples associated with individual stratigraphical units.

	sample count	TDS min [mg/L]	TDS max [mg/L]	TDS avg [mg/L]
MRV Basalts	94	174	8249	775
Walloon Coal Measures	12	500	6500	2217
Koukandowie Formation	73	223	24294	2623
Gatton Sandstone	202	139	18969	3150
Laidley Creek Alluvium	212	146	8494	1375

In conclusion to the overview of previous studies and examination of existing data:

- rainfall is the dominant **source** of recharge (Dixon and Chiswell, 1992; Li and Cox, 1996; Dharmasiri, 1997; Dharmasiri et al., 1997; Ellis and Dharmasiri, 1998; Ellis, 1999; Cox and Wilson, 2005);
- chemical composition of the groundwater reflects the lithology of the aquifer through which it infiltrates, mineral dissolution processes within the aquifer and length of the flowpath (residence time);
- depending on the position within the catchment, direct rainfall infiltration in the headwaters and indirect infiltration through the creek bed in downstream areas are the two main **recharge mechanisms** (Dharmasiri, 1997; Dharmasiri et al., 1997);
- direct rainfall infiltration into the alluvium in downstream areas is very slow due to a thick clayey and silty layer covering coarse alluvial sediments (Dharmasiri et al., 1997; Ellis and Dharmasiri, 1998; Ellis, 1999);
- lowered groundwater levels in alluvial aquifers are causing inflow from surrounding and underlying non-alluvial aquifers thus reducing the water quality of the alluvial groundwater due to groundwater mixing (Dixon and Chiswell, 1992; McMahon, 1995; McMahon and Cox, 1996; MacLeod, 1998).

4.4.3 Sampling and analysis methodology

In order to obtain current data and assess the validity of the above assumptions, major ions analysis was undertaken with the goal of characterizing the waters in both alluvial and non-alluvial aquifers of the Laidley Creek subcatchment. This characterization, together with the analysis of water mixing, can indicate possible sources of recharge in different parts of the subcatchment and leads to the better understanding of the hydrological processes and groundwater/surface water interaction within the subcatchment.

A total of 34 groundwater samples and 9 surface water samples were collected and analysed (see Figure 29). Surface water samples were taken from Laidley Creek at easily accessible locations such as bridges and fords (paved creek crossings). The northernmost creek sampling site location was at Mulgowie weir as Laidley Creek was dry from this point downstream (see Figure 3). Sampling was undertaken over a span of 4 weeks during the relatively dry period in September and October 2008.

Groundwater physico-chemical parameters (EC, pH, Eh and temperature) were measured in the field with a TPS90FL field meter as water passed through a flow cell connected to a submersible pump. The field meter was calibrated once a day, before the sampling and measurements begun. Three bore volumes of groundwater were purged in order to obtain representative groundwater samples.

Unfiltered anion samples were collected using 1 L plastic bottles and cation samples were filtered in-situ and collected using 125 mL plastic bottles acidified with HNO_3 in order to prevent metal precipitations from the sample. All samples were then put on ice for the duration of the field work and stored in the refrigerator upon returning to the lab. All the analytical work was done within 36 hours after the collection of the samples. Field blanks were used to ensure that sampling bottles were not contaminated while duplicate samples were used to check the precision of analytical instruments. All the sampling was done in accordance with internal QUT sampling methodology recommendations based on internationally used standard APHA sampling methods (Clesceri et al., 1998).

Cation concentrations (Na^+, K^+, Mg^{2+}, Ca^{2+}, Sr^{2+}, Mn^{2+}, Fe^{2+}, Zn^{2+}, Cu^{2+}, Al^{3+}) were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES – Varian Liberty 200); anions (F^-, Cl^-, Br^-, SO_4^{2-}, NO_3^{2-}, HCO_3^-, PO_4^{3-}) were analyzed by ion chromatography (IC – Dionex DX300). Total alkalinity was determined by titration. Laboratory blanks were used to verify that contamination of the instruments did not occur and the instruments were recalibrated with a set of standards after every 10 analyses. All analyses were carried out at the Analytical chemistry laboratory, Queensland University of Technology, Brisbane using APHA methodology guidelines (Clesceri et al., 1998).

4.4.4 Major ion analysis precision

Major ion charge balance errors were less than 5% for 36 samples, less than 10% for 5 samples and 2 samples reached a 10% charge balance error limit (-10.4% and 10.3% respectively). These were all considered acceptable for the purposes of the study.

Sample site locations, physical properties (pH, electric conductivity), total dissolved solids (TDS), water type, ionic balance error and actual analysis results for both groundwater and surface water samples are listed in Appendix J.

4.4.5 Graphical interpretation of major ion analysis results

Principles of the graphical methods are based on the visualisation of the relationship between individual ions or groups of ions (Zaporozec, 1972), showing the relative proportions of certain major ionic species (Hem, 1985). Graphical methods can be used to aid the visual grouping of different water types or explore the possibilities of mixing of waters from different sources.

Two types of graphical plots were used to analyse the results of major ion analysis: Stiff diagrams (Stiff, 1951) and Piper diagrams (Piper, 1953). Both types of diagrams were used to visualize similarities (or differences) between individual water samples. The water samples analysis results were also correlated with the geology of underlying stratigraphic units using the geological map. Firstly, Stiff diagrams of all analysis results were created; secondly, results of the analyses were plotted on Piper diagrams. As the samples were examined with respect to their sources (stratigraphy of the aquifer), the

(external file - *figure_29_map_chemistry_sampling_sites.pdf*)

Figure 29. Map: location of both groundwater and surface water sampling sites.

studied group of samples was plotted on the Piper diagram as red dots so that their relation to the samples from other stratigraphies (plotted as gray dots) can be observed and described. See Appendix K for Stiff diagrams representing all analysed groundwater and surface water samples.

4.4.5.1 Groundwater – Main Range Volcanics (MRV) – Tertiary basalts

Samples: Crosby M1, Crosby M2, 983, 982

Bores 982 and 983 are drilled in coarse basaltic alluvium with contact to underlying basalts, while bores Crosby M1 and Crosby M2 are drilled through a thin layer of coarse alluvium into basaltic bedrock. The groundwater is fresh, mostly of Mg-Ca-HCO_3 or Mg-Ca-Na-HCO_3 types with TDS values ranging from 168 mg/L (sample 983) to 244 mg/L (sample 982) (Figure 30). The dominating Mg^{2+} and Ca^{2+} cations are both expected to be found in waters influenced by igneous or metamorphic rocks. Mg^{2+} is typically contained in dark colored ferromagnesian minerals such as olivine, amphibole or mica while Ca^{2+} can be found in a number of silicates or feldspars. The concentration of both cations is generally low because the rate of decomposition of most igneous rock and metamorphic minerals is slow (Hem, 1985).

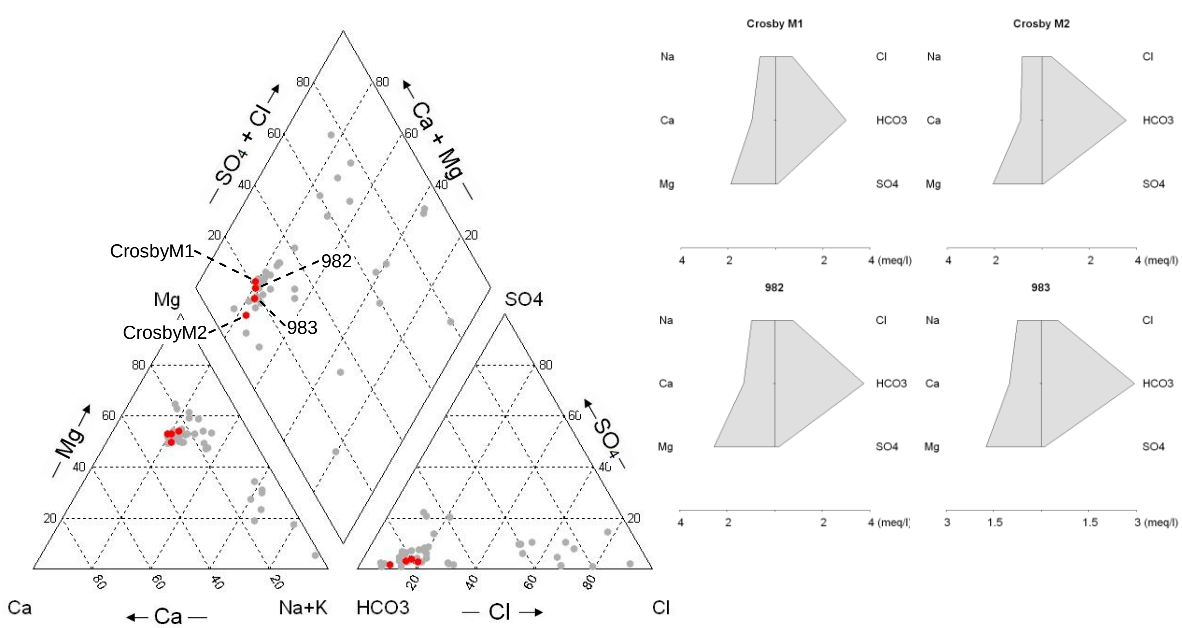


Figure 30. Piper and Stiff diagrams: Tertiary basalts groundwater samples.

The meteoric origin of the water is indicated by the fact, that the Na^+ and Cl^- ions are close to equilibrium together with an elevated concentration of HCO_3 anion. The elevated content of bicarbonate can be explained by the dissolution of carbonaceous minerals by the infiltrating rainwater.

Compared to historical MRV groundwater samples described previously (Chapter 4.4.2), the composition of samples representing basalt aquifer in the headwaters of the Laidley Creek subcatchment is at the lower end of the range of expected values (170 – 8250 mg/L; see Table 5) for this type of groundwater. Very low TDS also indicates short residential time and suggests that all basaltic groundwater samples from the Laidley Creek subcatchment fall into "shallow circulation groundwaters" category.

4.4.5.2 Groundwater – Walloon Coal Measures (WCM) and Koukandowie Formation

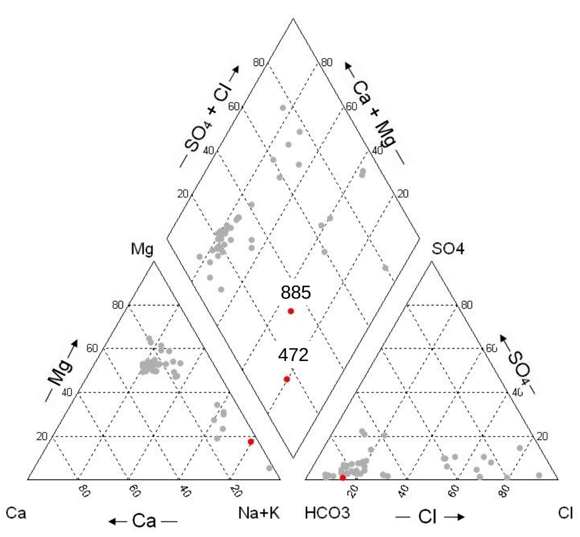
Samples: 472, 885

Bore 472 is the only bore representing Walloon Coal Measures. The observation bore was drilled approximately 50 m south from the Main Camp Creek in the valley slope. Although the DERM records (DERM, 2009) state that the stratigraphic localisation of the bore is unsure, it was suggested that the bore penetrates both alluvial sediments of the Main Camp Creek as well as underlying mudstone of Walloon Coal Measures (Bleakley 2008, pers. communication). The connection of the bore with the alluvium of Main Camp Creek can be also observed on the bore hydrograph as the groundwater head clearly reacts to first three significant rainfall events (see Appendix H for hydrograph; hydrograph group A1). Bore 885 was drilled in shallow Lockyer Creek alluvium and penetrates the underlying sandstone of Koukandowie Formation. The bore belongs to hydrograph group A2 and the groundwater head recovery in the bore 885 was not as pronounced as in bore 472.

The water type in both cases is $Na\text{-}HCO_3$ and the TDS is 248 mg/L for sample 885 and 552 mg/L for sample 472 (Figure 31). The concentration of Na^+ cations exceeds the concentration of Cl^- anions indicating some other source of Na^+ (*sample 472:* 310 mg/L Na^+ vs. 85 mg/L Cl^-; *sample 885*: 91 mg/L Na^+ vs. 37 mg/L Cl^-). Together with low Ca^+, the elevated concentration of Na^+ is most likely a product of cation exchange (natural softening) between groundwater and Na rich minerals (e.g. feldspars) associated with Walloon Coal Measure and Koukandowie formations as described by Hounslow (1995) using the formula:

$$2 \times [Na - clay] + Ca^{2+} \rightarrow [Ca - clay] + Na^{+}$$

In general, the higher content of HCO_3^- anion can be caused by three main processes within the coal seams and coal containing strata: (a) dissolution of carbonates by recharging rainwater (Freeze and Cherry, 1979; Fetter, 1994), (b) bicarbonate enhancement due to biogenic and thermogenic processes within the coal seam (Taulis and Milke, 2007) and (c) sulfate reduction (Hounslow, 1995). Both of the samples were acquired from shallow bores, both samples had a distinctive H_2S odour, and the coal seam in this particular part of the strata is absent. Therefore, the source of the HCO_3^- anion is most likely the combination of carbonate dissolution, sulfate reduction and mixing with meteoric (alluvial) water. Sulfate reduction (H_2S odour) is also implied by low SO_4^{2-} content, especially in sample 472 (8.3 mg/L). The relatively high concentration of HCO_3^- anion can also lead to the decrease of Ca^{2+} and Mg^{2+} concentrations (van Voast, 2003) as the precipitation of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) causes the decrease of Ca^{2+} and Mg^{2+} solulibity.



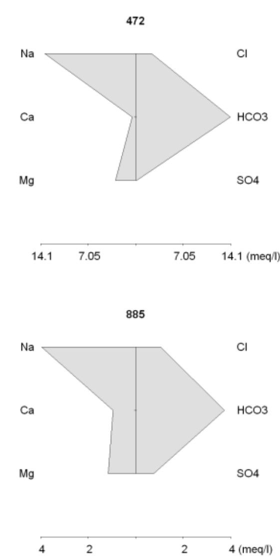


Figure 31. Piper and Stiff diagrams: Walloon Coal Measures (472) and Koukandowie Formation (885) groundwater samples.

Both samples can be placed on the very low end of the range of concentrations representing their respective lithologies (compare to Table 5). Given the samples relatively low TDS and the shallow depth from which the samples were taken, both samples represent groundwaters with relatively short residence time as well as mixing with fresh alluvial groundwaters.

4.4.5.3 Groundwater – Gatton Sandstone

Samples: 883, 884, 887

Gatton Sandstone is represented by three samples (Figure 32). Groundwater is of Na-Mg-Cl (883, 884) and Na-Cl-HCO_3 (887) types, TDS ranges from 5049 to 12814 mg/L (brackish to saline; after Freeze and Cherry, 1979). Increased concentrations of NaCl are generally associated with sedimentary aquifers of the Clarence-Moreton Basin, which include the Gatton Sandstone as described in previous studies (Jones, 1993; McNeil et al., 1993; McMahon, 1995; MacLeod, 1998; Ezzy, 2000; Davidson et al., 2002; Picarel, 2004; Cox and Wilson, 2005).

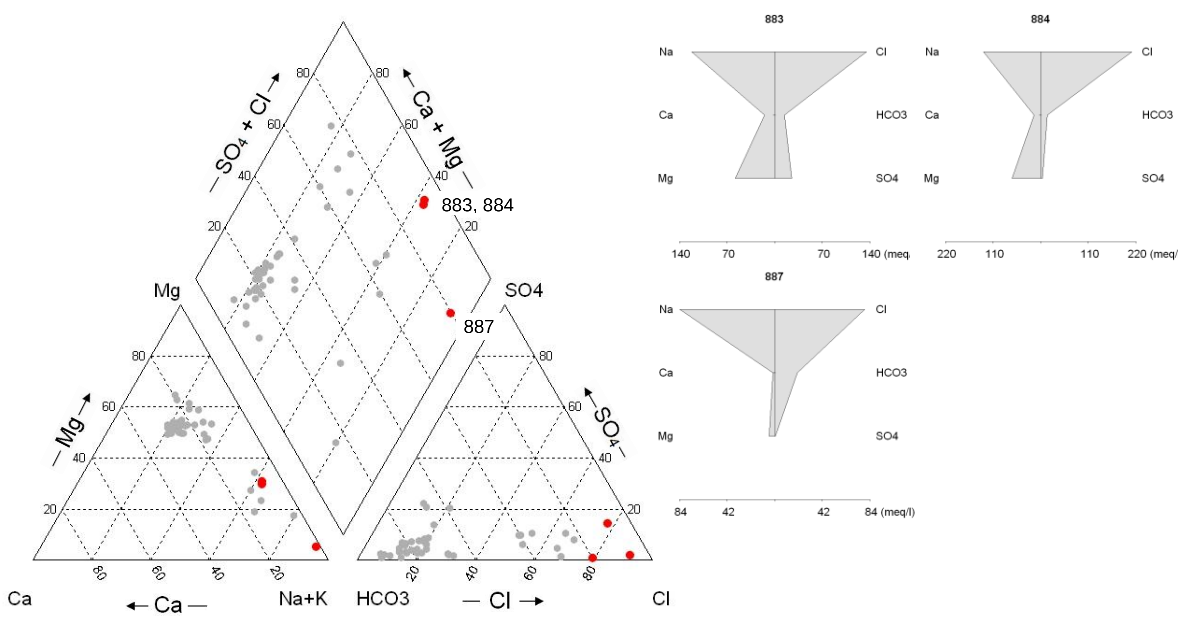


Figure 32. Piper and Stiff diagrams: Gatton Sandstone groundwater samples.

The origin of salts in both sedimentary and alluvial aquifers was studied by Zahawi (1975) who suggested the Mesosoic sea transgression might have been the reason of the saline waters inundating the sediments, however further studies (Li and Cox, 1996; MacLeod, 1998; Cox and Wilson, 2005) disagree with the connate origin of the NaCl and points to the meteoric origin (aerosol fallout) of the (cyclic) salts as suggested by Hem (1985). Another indication of the meteoric origin of the salinity are the relatively low Cl/Br ratios (265 – 617, average 412; Drever, 1997).

The composition of the Gatton Sandstone groundwater within Laidley Creek subcatchment is consistent with both historical samples from the same area as well as Gatton Sandstone samples from other parts of the Lockyer Valley (Table 5).

4.4.5.4 Groundwater – alluvium

Samples: 290, 293, 294, 295, 296, 297, 330, 331, 332, 337, 339, 340, 450, 453, 547, 553, 786, 849, 879, 880, 916, 917, 919, 920, 986

Groundwater from shallow alluvial aquifers is represented by 25 samples (Figure 33). The major ion analysis shows variability in groundwater hydrochemistry. Alluvial groundwater ranges from fresh to brackish (TDS ranges from 224 mg/L to 2472 mg/L) and water types that are dominated by Mg-Ca-Na-HCO_3 (fresh groundwaters), Na-Mg-Cl-HCO_3 and Mg-Na-Cl-HCO_3 (brackish groundwaters).

Based on the groundwater type, the samples can be divided into two groups. The first group consists of mostly fresh groundwater samples with prominent concentrations of Mg^{2+} and HCO_3. All of these samples are similar to waters originating in the basalt formation of the Main Range Volcanics. These samples were obtained from bores in the upper part of the catchment where the alluvium is composed of coarse gravels and basaltic pebbles, or from bores close to Laidley Creek.

The second group consists of samples collected mostly from bores distant from the creek and in lower parts of the alluvium. The groundwater samples are fresh to brackish and, in general terms, the further from the creek the higher TDS of the sample. The variability of the groundwater composition and quality is usually attributed to mixing of groundwaters originating from basalt aquifers and groundwaters originating from sedimentary Clarence-Moreton Basin aquifers and will be discussed later in chapter 4.4.8.

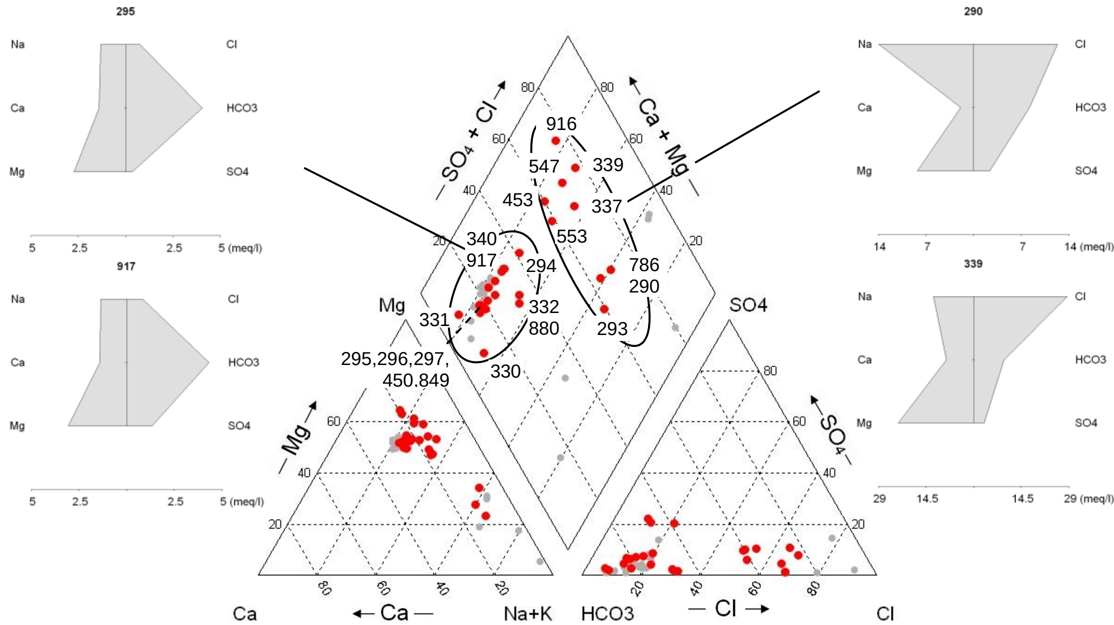


Figure 33. Piper and Stiff diagrams: grouping of alluvium groundwater samples.

4.4.5.5 Surface water – Laidley creek

Samples: Crosby M1 Creek, Crosby M2 Creek, Crosby House, Crosby Park, Peacock Bridge, Bonnel Road, Clarke Bridge, Peters Road, Mulgowie weir

In total, 9 samples were collected from Laidley Creek (Figure 34). At the time of the sampling the water in Laidley Creek was flowing only up to Mulgowie weir, the creek bed downstream from Mulgowie weir was mostly dry with only a few patches of stagnated water.

The surface water is fresh, mostly of Mg-Ca-HCO_3 or Mg-Ca-Na-HCO_3 types with TDS values ranging from 137 mg/L (sample Crosby M2 Creek) to 402 mg/L (sample Clarke Bridge). Higher TDS values were generally measured in downstream samples (e.g. Clarke Bridge - TDS of 402 mg/L, Peters Road - TDS of 393 mg/L) while upstream samples (e.g. Crosby M1, M2, Crosby House, Peacock Bridge) had low TDS values (137 - 240 mg/L). The water characteristics (low TDS, dominating Mg^{2+} cation and HCO_3^-

anion) suggests that the source of the water are Tertiary basalts and coarse basaltic alluvium from which the creek is fed.

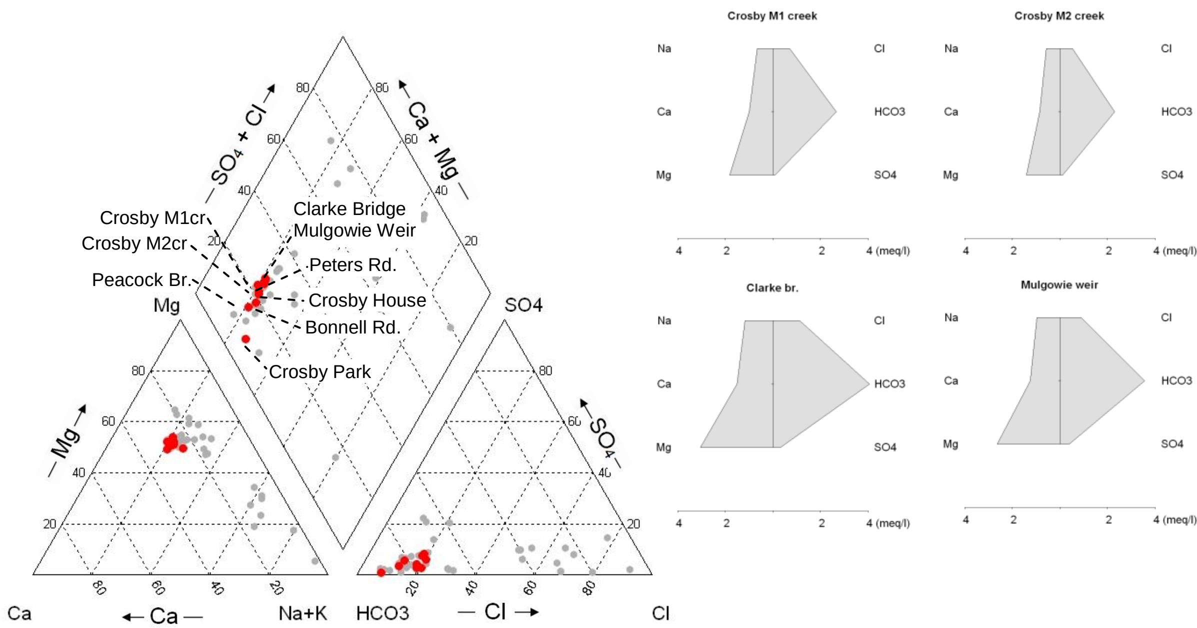


Figure 34. Piper and Stiff diagrams: Laidley Creek (surface water) samples.

4.4.6 Grouping of water types

The overview of the existing historical data together with the graphical analysis of new groundwater and surface water samples established that within Laidley Creek catchment the character of the water is significantly correlated to geology. Based on this correlation, the samples were divided into the following four groups:

- **Group 1** represents both surface water and groundwater of good quality (fresh water, TDS in the interval of 173 to 826 mg/L). This water type was sampled in the creek and in the alluvium close to the creek. The water composition with dominant Mg^{2+} and HCO_3^- ions suggests that the water comes from the MRV basalts that underlie as well as surround the upper parts (headwaters) of the Laidley Creek alluvium. The presence of the Group 1 water in some parts of the alluvium in the lower catchment indicates recharge of these parts of the alluvium by infiltration from Laidley Creek.

Group 1 samples: 294, 295, 296, 297, 330, 331, 332, 450, 849, 879, 880, 917, 919, 920, 982, 983, 986, Crosby M1, Crosby M2 and all surface water samples - Crosby M1 Creek, Crosby M2 Creek, Crosby House, Crosby Park, Peacock Bridge, Bonnell Road, Clarke Bridge, Peters Road, Mulgowie weir.

- **Group 2** represents two samples from Walloon Coal Measures and Koukandowie Formation. The water is characterized by dominance of HCO_3^- anion and dominance of Na^+ over Mg^{2+} cation.

  Group 2 samples: 472, 885

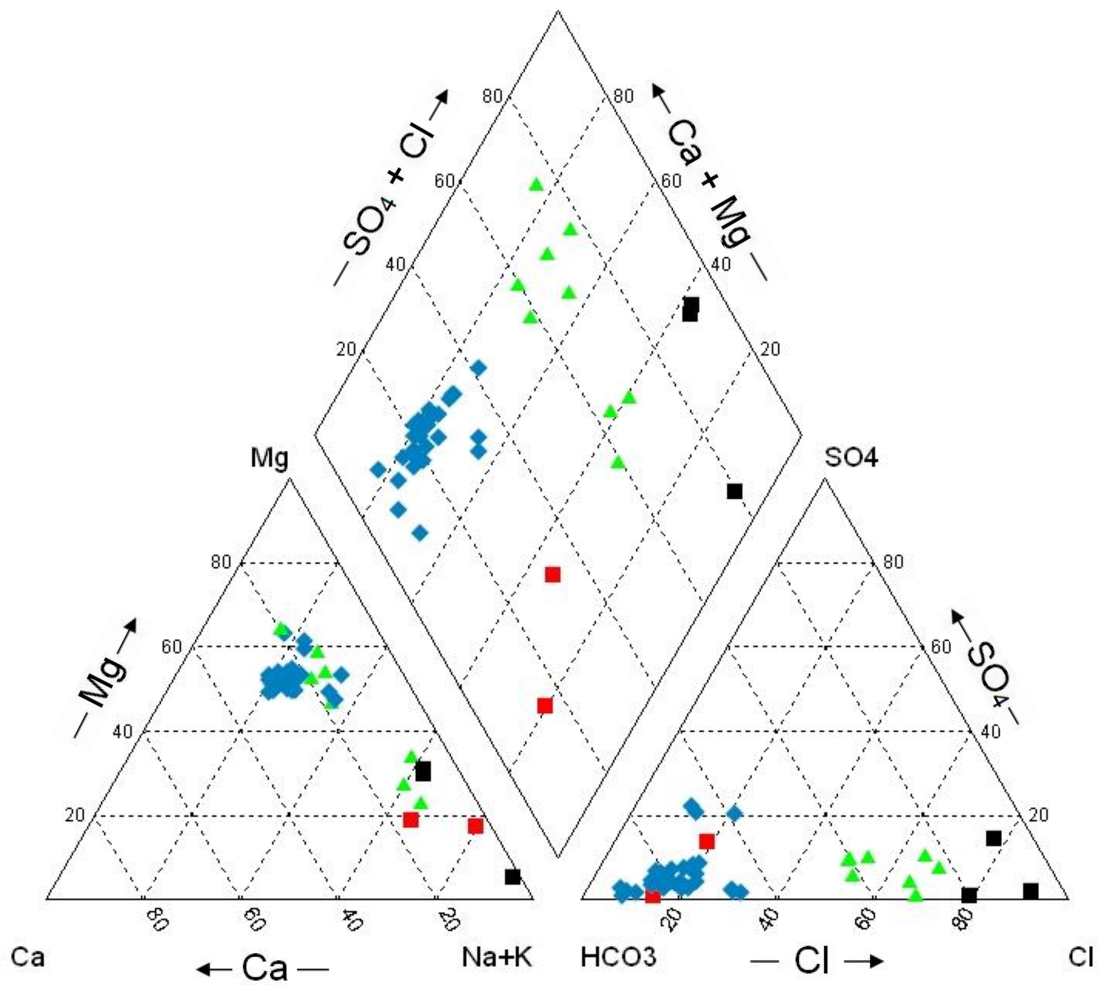
- **Group 3** water samples were taken from Gatton Sandstone bores. Water samples are brackish to saline (TDS between 5050 and 12800 mg/L), and Na^+ and Cl^- ions (with low SO_4^{2-}) are the major components defining the water type.

  Group 3 samples: 883, 884, 887

- **Group 4** water was sampled in the lower part of Laidley Creek alluvium in bores with limited recharge from the creek. Water composition and quality is variable, indicating the mixing of Group 1 and 2 water types.

  Group 4 samples: 290, 293, 337, 339, 340, 453, 547, 553, 786, 916

The results of major ion analysis are presented in Appendix J and Stiff diagrams of all samples and final grouping of samples are presented in Appendix K. The visual representation of the hydrochemistry groups is presented in the form of Piper diagram in Figure 35. The summary of all groundwater samples, their grouping and correlation to underlying bedrock is presented in Table 6. The summary of all surface water samples is presented in Table 7.



Legend

Group	Water type	TDS [mg/L]	Source
1 ◆	Mg-Ca-Na-HCO_3 Mg-Ca-HCO_3	173 - 826	MRV basalts, coarse upstream alluvium of Laidley Creek, Laidley Creek water
2 ■	Na-HCO_3	248 - 553	Walloon Coal Measures, alluvium along Main Camp Creek, Koukandowie Formation
3 ■	Na-Mg-Cl Na-Cl-HCO_3	5050 - 12800	Gatton Sandstone members
4 ▲	Ca-Mg-Cl-HCO_3, Mg-Na-Cl-HCO_3	660 - 2472	Downstream Laidley Creek alluvium, further from Laidley Creek

Figure 35. Grouping of water samples based on major ion chemistry - overview.

(external file - *figure_36_map_chemistry_groups.pdf*)

Figure 36. Map: grouping of water samples based on major ion chemistry.

Table 6. Groundwater samples and their classification based on water type and bedrock formation.

sample	chem. gr.	bedrock formation	water type	TDS [mg/L]
14320290	4	Alluvium / Gatton SSN	Ca-Mg-Cl-HCO_3	1336
14320293	4	Alluvium / Gatton SSN / Koukandowie Fmtn SSN	Ca-Mg-Cl-HCO_3	660
14320294	1	Alluvium / Koukandowie Fmtn SSN	Mg-Na-Ca-HCO_3-NO_3	826
14320295	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3	253
14320296	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3	224
14320297	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3	258
14320330	1	Alluvium / Gatton SSN	Mg-Na-HCO_3	470
14320331	1	Alluvium / Gatton SSN	Mg-HCO_3	409
14320332	1	Alluvium / Gatton SSN	Mg-Na-HCO_3-Cl	755
14320337	4	Alluvium / Gatton SSN	Mg-Na-Cl-HCO_3	1930
14320339	4	Alluvium / Gatton SSN	Mg-Na-Cl-HCO_3	2472
14320340	4	Alluvium / Gatton SSN	Mg-Na-HCO_3-Cl	1192
14320450	1	Alluvium / Gatton SSN	Mg-Na-HCO_3	328
14320453	4	Alluvium / Gatton SSN / Koukandowie Fmtn SSN	Mg-Na-Ca-Cl-HCO_3	1188
14320472	2	Walloon CM	Na-HCO_3	553
14320547	4	Alluvium / Gatton SSN	Na-Mg-Cl-HCO_3	1660
14320553	4	Alluvium / Gatton SSN	Mg-Na-Cl-HCO_3	1557
14320786	4	Alluvium / Gatton SSN	Na-Mg-Cl-HCO_3	1930
14320849	1	Alluvium / Walloon CM	Mg-Na-Ca-HCO_3	304
14320879	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3	246
14320880	1	Alluvium / Koukandowie Fmtn SSN	Mg-Na-HCO_3-Cl	589
14320883	3	Koukandowie Fmtn SSN / Gatton SSN	Na-Mg-Cl	10737
14320884	3	Gatton SSN	Na-Mg-Cl	12814
14320885	2	Alluvium / Koukandowie Fmtn SSN	Na-HCO_3	248
14320887	3	Gatton SSN / Koukandowie Fmtn SSN	Na-Cl-HCO_3	5049
14320916	4	Alluvium / Gatton SSN	Mg-Ca-Cl-HCO_3	1799
14320917	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3-SO_4	286
14320919	1	Alluvium / Koukandowie Fmtn SSN	Mg-Ca-Na-HCO_3-SO_4	414
14320920	1	Alluvium / Koukandowie Fmtn SSN	Mg-Na-Ca-HCO_3-Cl	477
14320982	1	Alluvium / MRV Basalts	Mg-Ca-HCO_3	244
14320983	1	Alluvium / MRV Basalts	Mg-Ca-Na-HCO_3	168
14320986	1	Alluvium / Koukandowie Fmtn SSN	Mg-Na-Ca-HCO_3	687
Crosby M1	1	MRV Basalts	Mg-Ca-HCO_3	174
Crosby M2	1	MRV Basalts	Mg-Ca-Na-HCO_3	168

Comment: Gatton SSN = Gatton Sandstone member; Koukandowie Fmtn SSN = Koukandowie Formation Sandstone member; Walloon CM = Walloon Coal Measures; MRV Basalts = Main Range Volcanics Basalts

Table 7. Surface water samples and their classification based on water type

sample	chem. gr.	bedrock formation	water type	TDS [mg/L]
Crosby M1 creek	1	--	Mg-Ca-HCO_3-Cl	252
Crosby M2 creek	1	--	Mg-Ca-HCO_3	137
Crosby house	1	--	Mg-Ca-HCO_3	165
Crosby park	1	--	Mg-Na-Ca-HCO_3	303
Peacock br.	1	--	Mg-Ca-HCO_3	180
Bonnel rd.	1	--	Mg-Ca-Na-HCO_3	215
Clarke br.	1	--	Mg-Ca-Na-HCO_3	403
Peters rd.	1	--	Mg-Ca-Na-HCO_3	394
Mulgowie weir	1	--	Mg-Ca-HCO_3	238

4.4.7 Hierarchical cluster analysis

Hierarchical cluster analysis (HCA) is a multivariate statistical technqiue that has become more frequently used in recent hydrogeochemical investigations than traditional graphic (visual comparison) methods (e.g. Güler et al., 2002). HCA is a semi-objective tool that allows scientists to group similar objects in various scientific fields (e.g. physical sciences, social sciences, finance; Drever, 1997). In hydrological/hydrochemical application, HCA is beneficial for two reasons: (a) it can incoporate any number of user-defined variables including pH or electric conductivity which makes it easier to distinguish between samples or find similarities that allow to group samples into distinct hydrochemical facies, and (b) the weighting process of variables ensures that all parameters regardless of their magnitude, contribute to the clustering process (Güler et al., 2002).

For the Laidley Creek hydrochemistry investigation, the statistical software package SPSS (IBM, 2012) was used to conduct the hierarchical cluster analysis based on Ward's algorithm (Ward, 1963) using Euclidean distance as a measure of similarity. The algorithm was applied only to the dataset representing groundwater samples collected during the study of Laidley Creek catchment (43 samples), and no historical data from the DERM database were used in this analysis. Parameters used for the analysis included ion concentrations, pH, conductivity and TDS. Censored data where no value was determined (i.e. where the measured concentrations of ions are below the detection limit) are not appropriate for multivariate statistical techniques as HCA only considers complete cases.

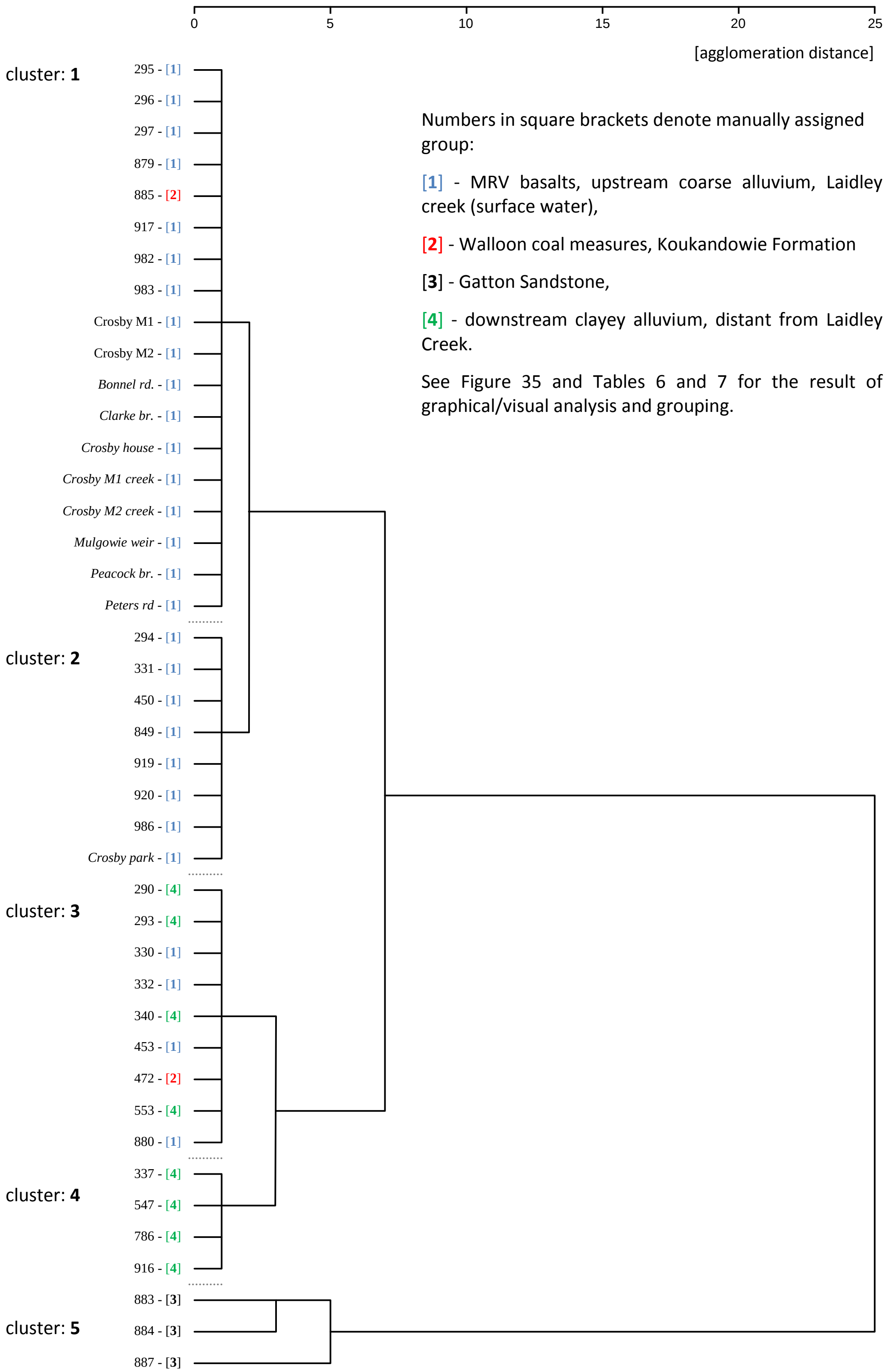


Figure 37. Result of the hierarchical cluster analysis (dendrogram).

These censored values need to be replaced with unqualified values (e.g. Güler et al., 2002), as for example with zero, ½ the detection limit (DL) or a value equal to DL (e.g. Farnham et al., 2002; Templ et al., 2008). In the present study, values reported as being below the detection limit were replaced with a value equal to zero.

The result of the automatic cluster analysis is presented in the form of a dendrogram (Figure 37) where the closeness of the samples is expressed by the fact they fall into the same cluster. The closeness (or lack of thereof) between the clusters is then shown as a "agglomeration distance" (see the horizontal distance scale at the top of the dendrogram).

The automatic clustering process created 5 individual clusters. Clusters 1 and 2 could be mostly identified with Group 1 representing the MRV groundwaters and the surface water of Laidley Creek. Cluster 3 contains groundwater samples from both Group 1 (basalt waters) and Group 4 (downstream Laidley Creek alluvium with slow recharge from the creek), thus representing the mixing process in the Laidley Creek alluvium. Cluster 4 represents the lower Laidley alluvium samples with higher TDS, where the recharge from the creek was very slow or not observed. Finally, cluster 5 exclusively contains all three Gatton Sandstone samples and correlates with Group 3.

The only samples assigned by the clustering algorithm to different groups than the graphical analysis appear to be samples 885 and 472, manually assigned to group 2 (Walloon Coal Measures and Koukandowie Formation), and automatically assigned to clusters 1 and 3 respectively. There are two main reasons for their classification: (a) the chemistry of the samples resembles that of samples within clusters 1 and 3, and (b) the information about surrounding geology was not part of the dataset used to group the samples.

"Manual" grouping of the samples based on graphical methods will always be subjective. Both graphical and statistical methods should be used with conjunction of the local knowledge and understanding of the system in order to properly investigate the hydrochemical processes within the system. Although, in case of the Laidley Creek catchment study, the automatic cluster analysis did not produce a perfect agreement with the manual classification, it showed the same *patterns* in grouping of the samples as the graphical analysis.

4.4.8 Analysis of groundwater mixing

A two-sample mixing analysis was undertaken using AquaChem (Waterloo Hydrogeologic, 2010) in order to estimate the relative contributions of individual water types to groundwater in the alluvial aquifer. The mixing analysis was run in "optimization" mode which enables the determination of the optimal mixing ratio of two selected samples so that the mixing result is as close to the third sample as possible. The two "endpoint" samples were selected to represent individual water types and source geological formations (Walloon Coal Measures, Koukandowie Formation, Gatton Sandstone, MRV basalts), whereas the third "target" sample represents the product of mixing (groundwater in alluvium).

The result of the mixing analysis is presented as the volume contribution (in %) of both endpoint samples towards the mixing product. In order to assess how well the ideal mixing product resembles the real-world sample, the compositions of all three samples (both mixing endpoints and mixing product) are presented in tabular form and composition of the field (measured) sample is compared to the ideal, modelled (optimised) sample.

It is necessary to realize that in a real-world system, groundwater is involved in more complex processes than can be represented by a simple two-samples mixing, e.g. mixing of multiple watertypes, ion exchange, evaporation and combination of some or all above. In spite of this fact, the results of the two-samples mixing analysis are sufficient for the purpose of this study as they show the mixing trends, thus indicating the dominant water sources, and quantify the mixing constituents with sufficient accuracy (order of magnitude).

The Piper diagram was used to guide the selection of suitable samples for the mixing analysis as the mixing product of two water samples should lie on the straight line between two "endpoint" samples (Hounslow, 1995) or as close to the straight line as possible. Please refer to the catchment map (Figure 3 or Figure 29) for endpoint sample locations.

4.4.8.1 Mixing example 1: Gatton Sandstone and Koukandowie Formation

The two endpoint samples for this analysis represent Koukandowie Formation (885) and Gatton Sandstone (883). The target sample, representing groundwater in alluvium, is 293. Monitoring bore 293 is located in the lower part of the catchment about 330 m from Laidley Creek and because of difficulties with access to the bore the groundwater levels in the surrounding alluvium were not monitored. However, personal communication with landowners indicated that there is very little (or no) infiltration of Laidley Creek water into the alluvium at this particular reach of the stream. The water composition in bore 293 thus reflected only the water compositions of the underlying Gatton Sandstone and the overlying Koukandowie Formation. In the case of the prolonged period of the Laidley Creek flow and consequential recharge of the alluvium and recovery of the groundwater table in bore 293, the currently observed mixing process would probably have been overshadowed by the fresh groundwater with its "basalt" signature.

The idealised crossection of the alluvium and surrounding non-alluvial aquifers (Gatton Sandstone and Koukandowie Formation) is presented in Figure 38. The actual mixing process and results of AquaChem mixing analysis are presented in Figure 40.

4.4.8.2 Mixing example 2: Gatton Sandstone and Laidley Creek

Two mixing endpoints are represented by samples 884 (Gatton Sandstone) and 331 (representing creek water that seeped to the alluvium surrounding the stream through the creek bed and banks infiltration process). The target sample is 332. Bore sample 331 was selected as a representative of "creek" water because the bore is located right at the Laidley Creek bank, approximately 5 metres from the creek, and about 50 metres downsteram from Laidley weir. Although the creek was not flowing at the time of sampling, the creek had flowed in the weeks before the sampling date so that the composition of sample 331 is very similar to the composition of creek water as observed upstream. Bore 332 is located on the Laidley Creek alluvial plain, about 400 m from the creek. The alluvium overlies the Gatton Sandstone.

When groundwater sample 332 was taken, the groundwater table in the alluvium was low. The bore hydrograph shows that the groundwater table in this part of the alluvium was recovering slowly and did not indicate direct influence on the rainfall and/or creek

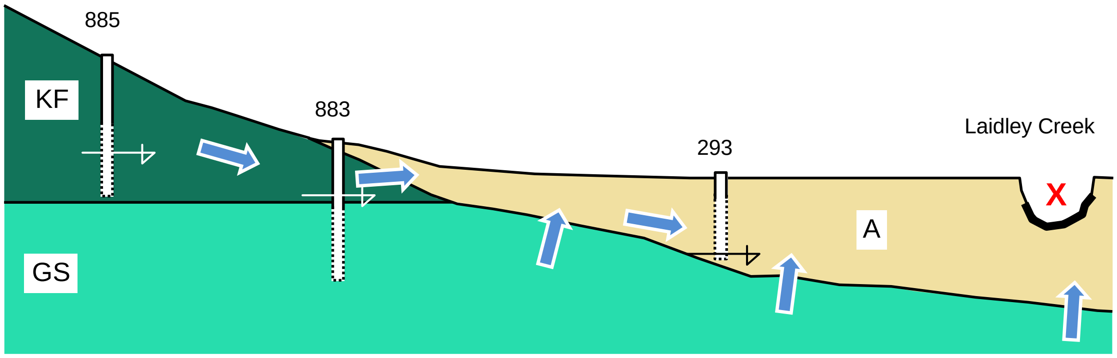


Figure 38. Water mixing in alluvium; idealised crossection (Gatton Sandstone groundwater and Koukandowie Formation groundwater).

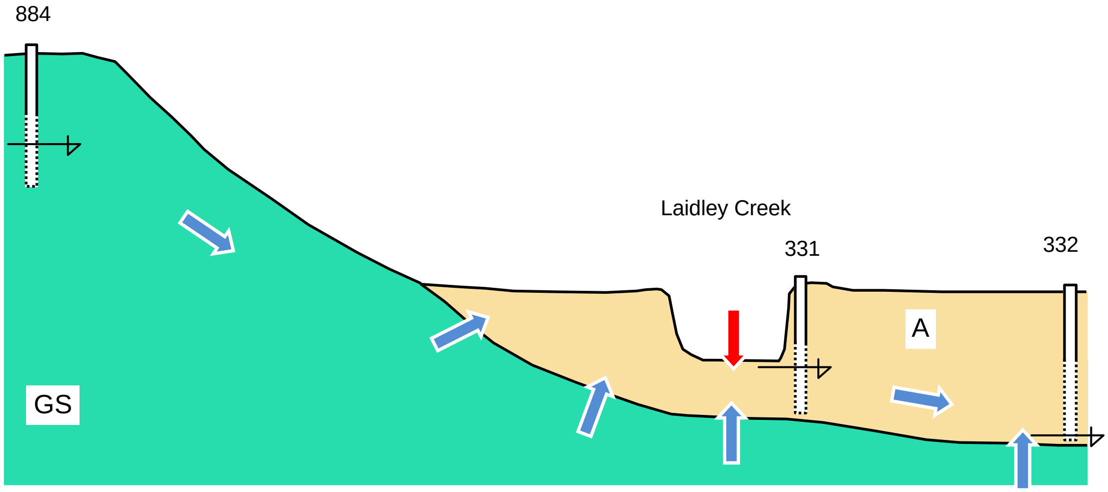
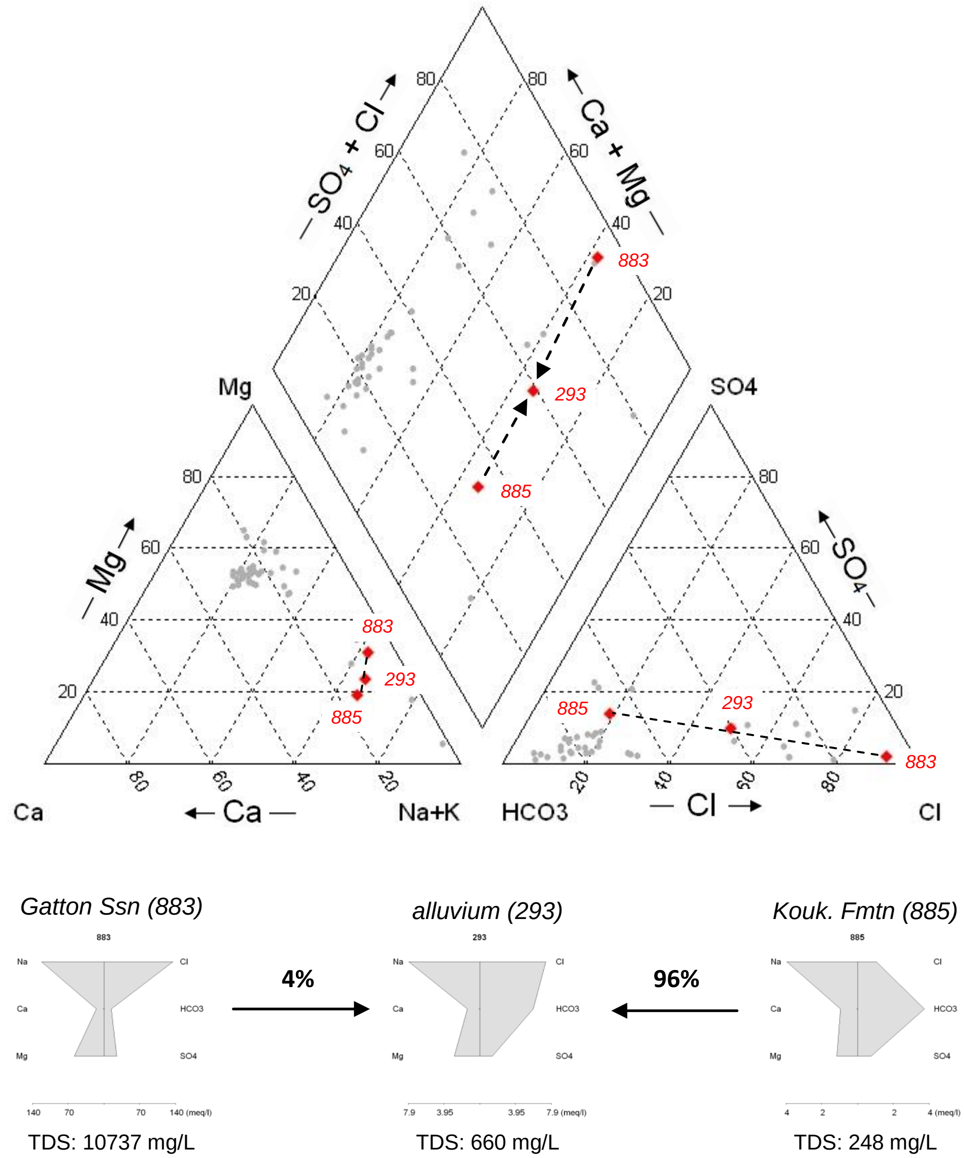


Figure 39. Water mixing in alluvium; idealised crossection (Gatton Sandstone groundwater and fresh infiltration from Laidley Creek).

Legend:

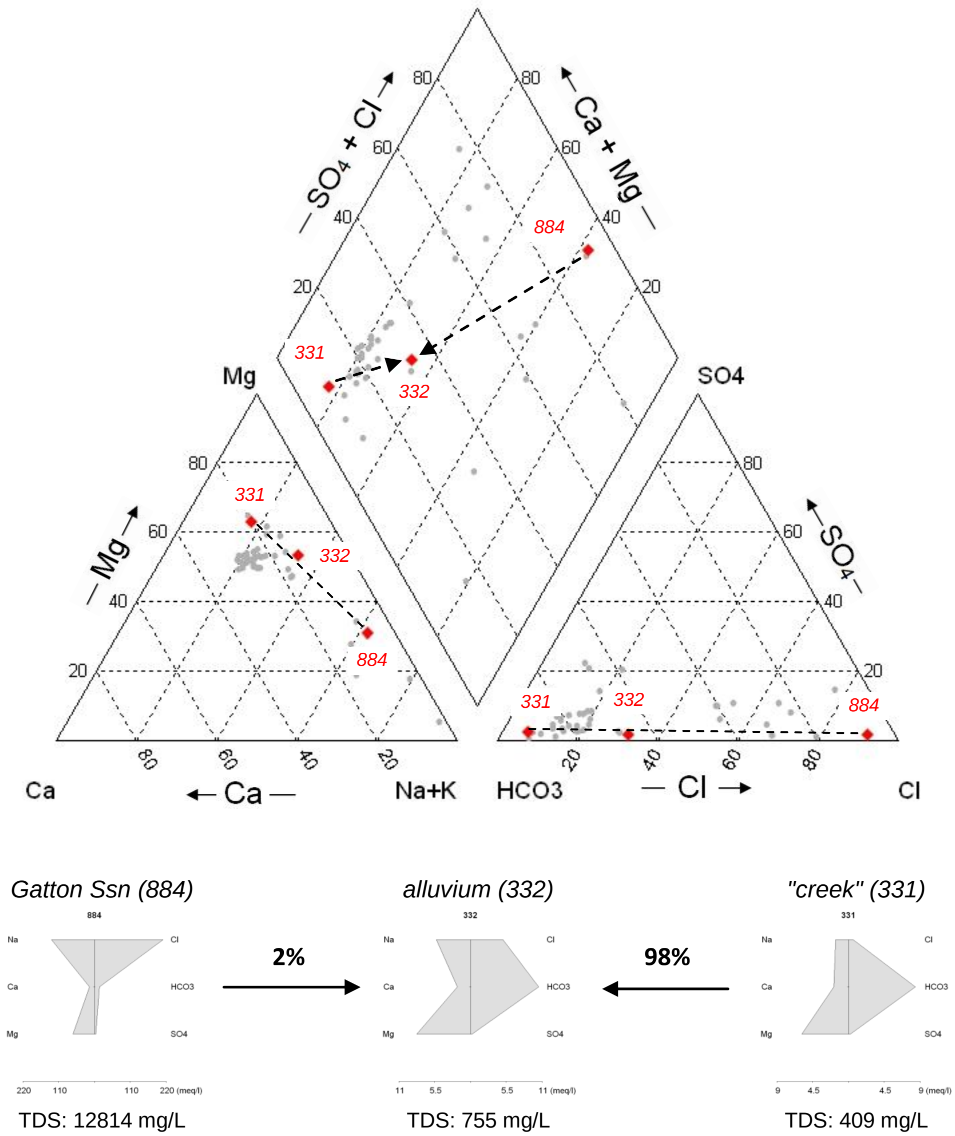
A - alluvium
KF - Koukandowie Formation
GS - Gatton Sandstone

- probable groundwater movement (blue arrow)
- infiltration through the creek bed (red arrow)
- measured groundwater table in bore



	concentration [mg/l]			
	Gatton Ssn. (883)	alluvium (293)		Kouk. Fmtn (885)
	measured	measured	optimized	measured
Na	2800.00	180.00	199.36	91.00
K	36.00	3.19	4.61	3.30
Ca	296.00	27.00	30.08	19.00
Mg	704.00	34.00	41.60	14.00
Cl	4785.50	258.48	227.31	37.38
HCO_3	871.40	360.90	253.55	227.80
SO_4	1215.00	67.30	84.06	36.94

Figure 40. Water mixing: Gatton Sandstone and Koukandowie Formation.



	concentration [mg/L]			
	884	332		331
	measured	measured	optimized	measured
Na	3040.00	120.00	97.06	37.00
K	28.00	1.30	0.70	0.14
Ca	296.00	40.00	42.18	37.00
Mg	800.00	100.00	85.58	71.00
Cl	7469.40	177.38	170.36	21.40
HCO_3	995.10	639.10	521.45	512.60
SO_4	205.00	12.84	14.92	11.04

Figure 41. Water mixing: Gatton Sandstone and rainfall/creek water.

flow. The idealised crossection of the alluvium and underlying Gatton Sandstone aquifer is presented in Figure 39. The actual mixing process and results of AquaChem mixing analysis are presented in Figure 41.

Both mixing examples show that recharge of the alluvium from underlying non-alluvial aquifers (sandstones) occurs. However, the volume of infiltrating saline water is small (4% and 2% respectively). Although small in terms of volume, the salinity of Gatton Sandstone groundwaters (the concentration of TDS in bore *883* is 10737 mg/L; in *884* is 12814 mg/L) can potentially have a detrimental effect on groundwater quality in the alluvial aquifer, especially at times when the groundwater table elevation in alluvium is low.

4.4.9 Hydrochemistry – conclusions

Based on the assessment of the water chemistry using both graphical and statistical methods, as well as comparison with existing historical data (Section 4.4.2), Laidley Creek catchment waters are contained within three major hydrogeological units: (1) Main Range Volcanics basalts, (2) consolidated sediments of Clarence-Moreton Basin bedrock aquifers (Walloon Coal Measures, Koukandowie Formation and Gatton Sandstone) and (3) alluvium. The 2008 dataset used in this study contains groundwater samples from the alluvium as well as surface water samples taken from Laidley Creek. The analysis of the dataset confirmed the assumption inferred from previous investigations and illustrates the major recharge processes of both alluvial and non-alluvial aquifers.

Two main pathways of recharge (direct and indirect recharge) can be inferred from the combination of groundwater table behaviour (Sections 3.7 and 4.3), observation of Laidley Creek flow (Section 4.2) and analysis of the hydrochemical data (this chapter). The rainfall directly recharges all aquifers present in the catchment (MRV basalts, Clarence-Moreton Basin sedimentary aquifers and alluvium). However, in case of the alluvial aquifer, the intensity of the direct (diffuse) rainfall recharge depends on the location of the rainfall event and is effectively constrained to the upper part of the catchment. Indirect recharge can be described as a process during which rainfall that recharges the alluvium travels down the catchment in the form of creek flow and recharges the alluvial aquifer in the form of seepage through the creek bed.

Both types of recharge can be inferred from the hydrochemical data and mixing analysis. All bores in the upper catchment, i.e. bores in basalt or coarse basaltic alluvium, contain fresh water (low TDS) with prominent HCO_3^- concentrations. Additionally, the Mg^{2+} concentration indicates that the rainwater was in contact with igneous rock rich in Mg minerals, although the residence time of the water in the basalts appears to be short. Further downstream and with increasing distance away from Laidley Creek, the mixing analysis indicates that the alluvial groundwater is a product of the mixing of fresh rainwater transported to those parts of the alluvium by Laidley Creek and groundwaters from bedrock sedimentary aquifers (Section 4.4.8.2, example 2). In the absence of stream flow-induced recharge of alluvium, mixing of groundwaters originating from different bedrock aquifers was also observed (Section 4.4.8.1, example 1). Because of the layer of silty and clayey material that overlies the basal gravel and sands (Section 5.3.2.1), very little or no influence of direct recharge from rainfall was observed in bores in the lower part of the catchment on groundwater hydrographs further away from the Laidley Creek.

5 Model of the Laidley Creek catchment

5.1 Purpose of the model construction

Depending on the purpose for which a model is constructed, models are usually divided into several broad categories (Anderson and Woessner, 1992; Middlemis, 2001; Reilly and Harbaugh, 2004) including:

- hydrologic investigation (data synthesis),
- water management (aquifer behaviour prediction),
- education and communication of the scientific information to public, and
- legal determination of responsibility (Reilly and Harbaugh, 2004).

The model of the Laidley Creek alluvial aquifer falls mostly into the "hydrologic investigation" category. It can be described as an **interpretative model**: it will be primarily used as a tool to synthetise and organize the field data (conceptual model) and to identify the gaps in the existing hydrological data (numerical model). The analysis of model run outcome will show what kind of data is needed for water resources management support and for the future construction of a numerical model with predictive capabilities.

Construction of the Laidley Creek catchment model follows established modeling protocols (Anderson and Woessner, 1992; Hill, 1998; Middlemis, 2001; Reilly and Harbaugh, 2004; Hill and Tiedeman, 2007):

a) conceptual model development,
b) numerical model development,
c) numerical model calibration and
d) analysis of model parameter uncertainties and observation data worth.

5.2 Previous modeling projects within the Lockyer Valley

A numerical modeling exercise has been conducted by Doherty and NRM at the lower part of Laidley Creek catchment (Doherty, 1999). The goal of the project was to build a composite IQQM (Simons et al., 1996) and MODFLOW (Harbaugh et al., 2000; McDonald and Harbaugh, 2003) model of the selected area.

Durick and Bleakley (2000) built the first MODFLOW model covering the Central Lockyer area to run different water allocation and recharge scenarios for the declared area. A transient setup (23 stress periods) was used with a timespan of 5.8 years (1/7/1987 – 15/12/1992).

Consultants KBR (2002) developed a set of predictive tools based on hydrogeological and hydrological modeling techniques to assess the sustainability of water resources and examine groundwater flow, recharge, nutrient balance, salinity and groundwater/surface water interaction in the Central Lockyer area based on different scenarios of groundwater recharge. A number of different software packages were used in the course of the examination: SPLASH was used to model the soil moisture, MODFLOW was used to model groundwater flow, MT3DMS was used to model solute transport, MODHMS was used to estimate flow rate through the unsaturated zone and as a nutrient transport model. The KBR model covers Central Lockyer (declared) area.

The area of Lower Tenthill and Ma Ma creeks and their confluence with Lockyer Creek was examined by Wilson (2005) who conducted several pumping tests to establish the ranges of hydraulic properties of the alluvial aquifer and developed a conceptual model of the area based on the acquired knowledge of groundwater chemistry (both major ion and stable isotope analysis) and behaviour of groundwater hydrographs. This conceptual model was then used as a base for the transient numerical model covering the time interval between March 1993 and May 1996.

5.3 Conceptual model

The purpose of the conceptual model is to simplify the field problem and to synthetize and organize all available data so that the system can be easily analysed and described (Anderson and Woessner, 1992; Spitz and Moreno, 1996; Middlemis, 2001; Reilly, 2001). However, groundwater systems are complicated and difficult to evaluate comprehensively. There is usually insufficient data, which leads to a lack of understanding and inadequate characterization of the system.

The conceptual model provides a simplified description of the hydrogeological system. It describes the physical structure of the model (stratigraphy), groundwater levels and flow direction (flow processes), recharge mechanisms, groundwater quality and groundwater use. The conceptual model often takes a form of diagramatic representation of the system (Anderson and Woessner, 1992; Spitz and Moreno, 1996) such as crossections, diagrams and maps. There are three basic steps in building the conceptual model: (a) definition of hydrostratigraphic units and definition of boundaries, (b) definition of the flow system and (c) estimation of catchment inflows and outflows. As an idealised representation of the physical setup, flow processes and system stresses, a conceptual model is a key component of the general modeling process and a necessary prerequisite step for construction of the numerical model.

The conceptual model of the Laidley Creek catchment is based on the data analysed and interpreted in the previous parts of this study. Information on the physical setting (Section 3.1) and geology and stratigraphy of the area (Section 3.2) are used to define the hydrostratigraphic units of the conceptual model and set up the model boundaries. Information on the chemical composition of the groundwater and surface water (Section 4.4) together with the analysis of the groundwater hydrographs (Section 4.3) were used to describe the sources of groundwater and recharge processes to the alluvial aquifer along Laidley Creek and thus define the flow system within the catchment. And finally the rainfall (Sections 3.5 and 4.1) and creek flow observations (Sections 3.6 and 4.2) were used to prepare a catchment wide water budget.

5.3.1 Model boundaries

The correct setting of model boundaries is a critical step in model design (Anderson and Woessner, 1992; Reilly, 2001) because the boundary conditions largely determine the flow pattern. Two basic types of boundaries are widely recognised: **physical boundaries** formed by the presence and shape of impermeable rock or a large water body, and **hydraulic boundaries** based on hydrologic conditions such as groundwater divides or dividing streamlines.

Due to the lack of suitable physical boundaries in the Laidley Creek catchment, hydraulic boundaries were used. The eastern, southern and western boundaries run along the Laidley Creek catchment divide line and are defined as *specified flow* (no-flow) boundaries. The northern boundary was created artificially along the straight line (east-west), north of bore 14320450 (map: Figure 3) and is of combined *specified flow* / *specified head* type. The specified head boundary is defined accross the alluvium in order to physically enable the drainage of the alluvium (Anderson and Woessner, 1992). The *specified-flow* (no-flow) boundary was also applied to the bottom of the lowermost model layer (Gatton Sandstone) suggesting that there is no hydraulic communication between Gatton Sandstone and underlying stratigraphic unit (Woogaroo subgroup). Although this is certainly not correct in the strict physical sense, the vertical flows between Gatton Sandstone (the bottom-most model layer) and underlying Woogaroo Subgroup have negligible impact on the processes in the Laidley Creek alluvium, which is the focal point of this study.

5.3.2 Geological framework and definition of hydrostratigraphic units

Based on the knowledge of the main stratigraphic units of the catchment (Section 4.3), the geological framework consist of five units, each of these units is represented by a single model layer (Figure 42):

- L1: alluvium / weathered regolith;
- L2: basalts of Main Range Volcanics;
- L3: Walloon Coal Measures;

- L4: Koukandowie Formation and
- L5: Gatton Sandstone

Although the alluvium is stratigraphically divided into layers of variable permeability (coarse gravels or sands vs. clays and silts) as observed in existing bore logs (Appendix P), there are no existing data that would enable the calibration of multiple layers in the alluvium. Thus the alluvial aquifer was modelled as a single layer.

As observation data with this level of detail (i.e. separate head measurement for different hydraulic facies) are not available throughout the wider Lockyer area, a sinlge-layer alluvium approach similar to previous modeling projects within the Lockyer Valley area (Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005) was adopted.

Because the focus of the previous hydrogeological investigations was mostly on the alluvial aquifer, there is a significant lack of detailed hydrogeological knowledge pertaining to the non-alluvial geological units (basalts and Clarence-Moreton Basin units). As detailed information on both distribution of hydraulic properties and groundwater heads is not available, the modeling of non-alluvial stratigraphic units will be simplified, using a single value for each of the individual hydraulic parameters: horizontal and vertical hydraulic conductivity, specific yield and specific storage. Sensitivity and uncertainty analysis of all model parameters will be undertaken as part of the model calibration in order to quantify the contribution of those parameters towards the modeling error.

As the calibration data relate mostly to model layer 1, it might seem desirable to simplify the model structure by combining layers with (presumably) similar hydraulic properties (Gatton Sandstone, Koukandowie Formation and Walloon Coal Measures) into single layer. Although this approach would decrease the model uncertainties associated with definition of separate model layers, it would also make it impossible to analyze flows between the individual bedrock stratigraphic units and alluvium and between individual bedrock aquifer layers and reach one of the goals of the study.

5.3.2.1 Zonation of the Laidley Creek alluvium

As discussed previously, the alluvium can be further divided into zones based on a combination of different hydraulic properties of the alluvium, characteristic recharge regimes and controls on the flow. These zones reflect the morphology of the alluvium-filled valley channel incised into the bedrock, and the relationship between Laidley Creek and the alluvium as well as recharge regimes in different parts of the alluvium. It is however necessary to understand that the defined alluvial zones reflect our current state of understanding of the complex processes within alluvium. The zonation is used to conceptually represent the spatial heterogeneity of the alluvial aquifer without the exact knowledge of the distribution of all hydraulic parameters.

Zones within the alluvium are labeled from the catchment headwaters in the south, northward. A simplified map of alluvium zonation is shown in Figure 43, and the following description of individual zones also refers to the grouping of groundwater samples based on their hydrochemistry (Section 4.4) as well as the grouping of monitoring bores based on the rates of groundwater head fluctuations reflecting the rate of recharge in the alluvium aquifer (Section 4.3.2). For exact locations of various geographic features (e.g. roads, bridges and creek crossings) refer to the catchment map (Figure 3). Both automatic and manual hydrographs can be found in the digital appendix (appendix_data/hydrographs), the manual bore hydographs are also presented in the Appendix H. Simplified crossections of the Laidley Creek alluvium (appendix_data/crossections) are presented in digital form.

Zone I – headwaters

Morphology and surface hydrology: The valley fill of coarse alluvial sediment comprises basaltic boulders, pebbles and coarse gravel covered by a thin layer of topsoil. The width of alluvial infill ranges from 200 m to about 1 km. The thickness of the alluvial layer is 10 to 15 m. The upper creek channel is wide, shallow and braided, narrowing and incising deeper into the alluvium in the lower reaches.

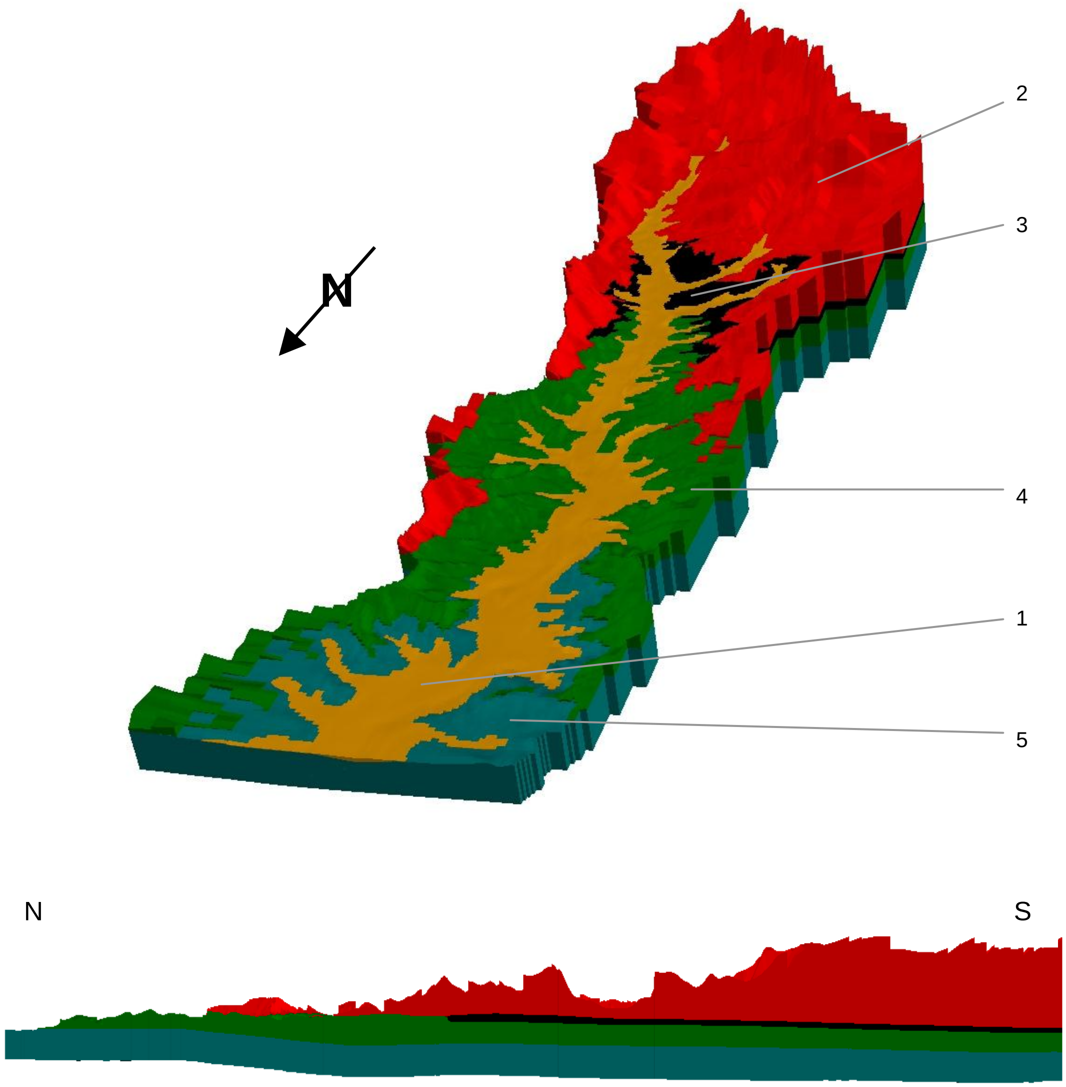


Figure 42. Structural setup of model layers (stratigraphy): a 3D view and north-south crosssection.

1 - Laidley Creek alluvium - recharge zone 100
2 - Main Range Volcanics (basalts) - recharge zone 200
3 - Walloon Coal Measures (sandstone, shale, claystone/mudstone) - recharge zone 300
4 - Koukandowie Formation (sandstone) - recharge zone 400
5 - Gatton Sandstone - recharge zone 500

Assigned recharge zone numbers are used later in budget (inter-aquifer groundwater connectivity) calculations (Section 5.6.3)

Hydrogeology: The coarse alluvial sediments are highly permeable (K estimated to be up to 100 m/d) and movement of water levels in the bores (982 and 983; hydrograph Group A1) correlates well with water levels in the stream. The creek appears to be fed from the surrounding basaltic alluvium (see *Chemistry* below) and the underlying and surrounding bedrock basalts. As the gradient of the valley, as well as the gradient of the bedrock, is steep, the combination of this downvalley flow and irrigation use from bores can result in groundwater levels dropping rapidly. Local advice is that within 9 months of the creek ceasing to flow, groundwater levels are low enough for farmers to experience supply problems (Ashley Bleakley - pers. communication, 2008).

Chemistry: Both surface and ground waters were classified into Group 1. Mineralization is low, with average concentration of TDS of 227 mg/L. Waters are of $Mg\text{-}Ca\text{-}Na\text{-}HCO_3$ type (groundwater) or $Mg\text{-}Ca\text{-}HCO_3$ types (creek water). Water chemistry suggests that the basalts of the Main Range Volcanics unit are the primary source.

Zone II – low permeability zone

Morphology and surface hydrology: (see digital appendix, section M) A short zone reflecting a possible bedrock restraint or low-permeability sediments in the course of the flow of Laidley Creek, diverting it sharply towards the western border of the alluvium. The layer of coarse alluvial sediments is approximately 10 m thick and covered by 6 to 10 m of less permeable material (loams, clays and topsoil). However, the gravels are very clayey which was demonstrated by drilling of irrigation bores on the flat within 100 m upstream of bore 849 (Ashley Bleakley - pers. communication, 2008). The downstream boundary of this zone is not clearly defined as there are no monitored bores downstream of Bonnell Road crossing (map: Figure 3).

Hydrogeology: The aquifer does not appear to be connected to the creek, as the groundwater level rise in the observation bore 849 is very slow and shows no distinct relationship to a particular rainfall event (hydrograph Group B1). This suggests that underflow along the valley axis is the main recharge mechanism for Zone II. Zone II allows the stream to flow through without significant interaction with the alluvium.

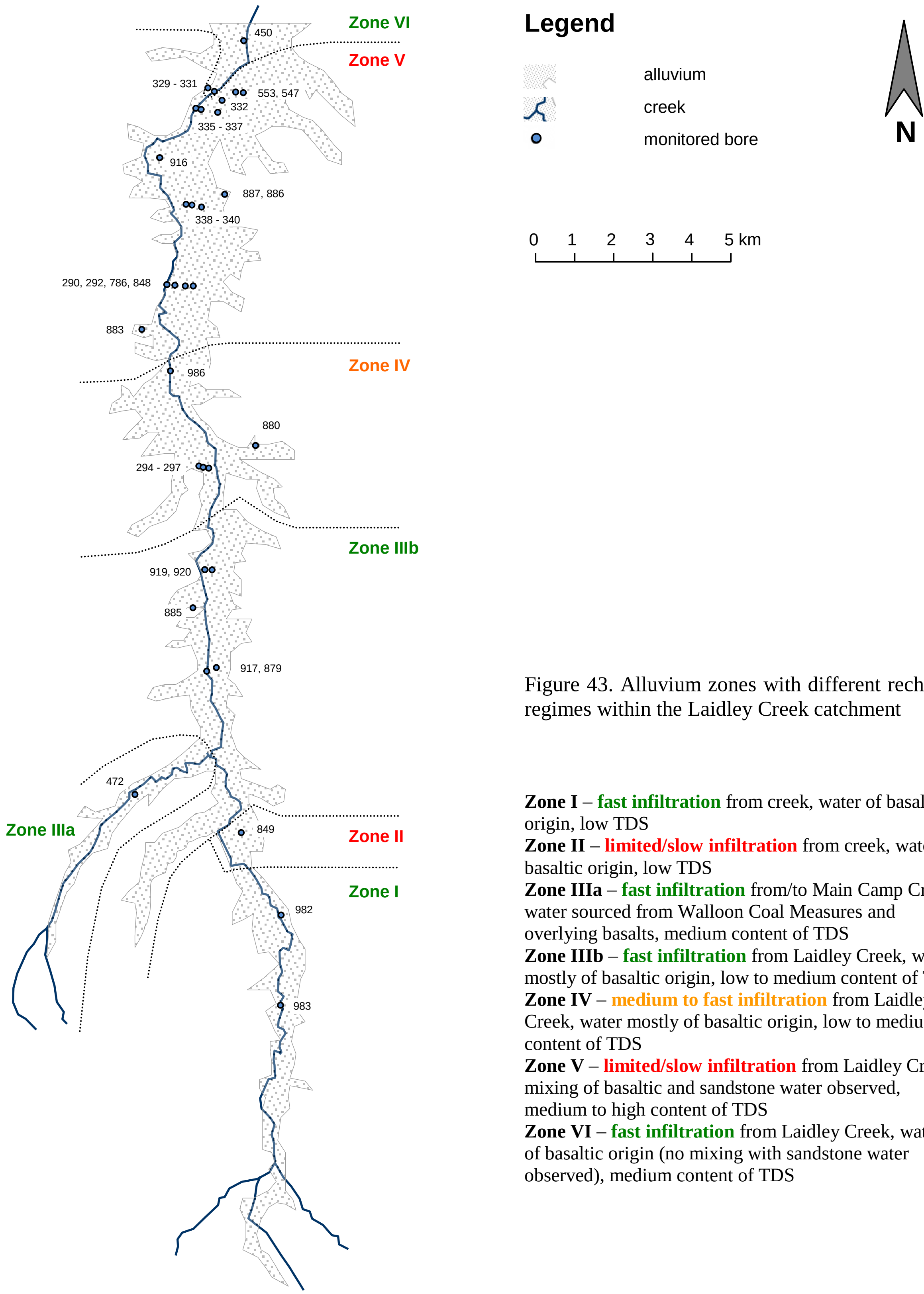


Figure 43. Alluvium zones with different recharge regimes within the Laidley Creek catchment

Zone I – **fast infiltration** from creek, water of basaltic origin, low TDS
Zone II – **limited/slow infiltration** from creek, water of basaltic origin, low TDS
Zone IIIa – **fast infiltration** from/to Main Camp Creek, water sourced from Walloon Coal Measures and overlying basalts, medium content of TDS
Zone IIIb – **fast infiltration** from Laidley Creek, water mostly of basaltic origin, low to medium content of TDS
Zone IV – **medium to fast infiltration** from Laidley Creek, water mostly of basaltic origin, low to medium content of TDS
Zone V – **limited/slow infiltration** from Laidley Creek, mixing of basaltic and sandstone water observed, medium to high content of TDS
Zone VI – **fast infiltration** from Laidley Creek, water of basaltic origin (no mixing with sandstone water observed), medium content of TDS

Chemistry: Both surface water (Bonnell Rd. crossing) and groundwater (bore 849) samples fall into Group 1. Creek water is of Mg-Ca-Na-HCO_3 type with a TDS concentration of 215 mg/L and bore water is of Mg-Na-Ca-HCO_3 type with a TDS concentration of 303 mg/L. Water chemistry analysis did not confirm any hydraulic connection with the underlying mudstone and sandstone of Walloon Coal Measures.

Zone IIIa – alluvium of Main Camp Creek

Morphology and surface hydrology: Zone IIIa covers the alluvium of Main Camp Creek, the western tributary of Laidley Creek. The alluvium of Main Camp Creek is highly permeable, 5 - 8 m thick and forms an uppermost layer that lies on sandstones of the Walloon Coal Measures. The bed of Main Camp Creek is cut directly into the alluvium, and the communication between the creek and surrounding alluvium is good. The creek flows for only very short periods after a major rainfall event.

Hydrogeology: The alluvium also communicates hydraulically with the underlying sandstones (see *Chemistry* of Zone IIIa). The alluvium is shallow and during the monitoring period practically empty, although the groundwater table reacts well to the major rainfall events and periods of Main Camp Creek flow as demonstrated by the hydrograph of bore 472 (Group A1).

Chemistry: Water is of Na-HCO_3 type, the samples fall into hydrochemistry Group 2 (WCM and Koukandowie Formation groundwater). Concentration of TDS is approximately 550 mg/L.

Zone IIIb

Morphology and surface hydrology: Coarse, highly permeable sediments are 5 to 8 m thick along the central axis of the alluvium. These sediments are covered by a layer of less permeable sediments with an average thickness of 10 m. Laidley Creek cuts through less permeable loamy and clay rich layers and intersects coarse gravels, enabling direct and rapid recharge from (or to) the creek. See the digital appendix for alluvial crossections (sections K and L).

Hydrogeology: The high recharge rate is demonstrated by bore hydrographs in both profiles (Appendix H). All of the hydrographs show alluvial response to rainfall and subsequently flow in the creek: bores 917, 879, 919 and 920 belong to hydrograph Group A1, bore 885 (representing mixing of meteoric waters and Koukandowie Formation waters) belongs to Group A2.

Chemistry: Water samples fall into the Groups 1 (fresh alluvial groundwater), prevailing types of water are Mg-Ca-Na-HCO_3 and Mg-Ca-Na-HCO_3-SO_4. Concentration of TDS varies from 250 mg/L in the upstream part of the zone (bores 879 and 917) to approximately 450 mg/L (bores 919, 920)

Zone IV

Morphology and surface hydrology: The thickness of the coarse, highly permeable basal layer is variable, with bore logs showing thicknesses of 3 to 10 m. Although the creek does not completely cut though the 15 – 18 m thick upper low permeability layers, the rate of infiltration from the creek into the alluvial gravels is high, especially in the alluvial zones along the creek (Mulgowie farm profile - bores 294, 295, 296, 297, see digital appendix, sections I and J).

Hydrogeology: A recharge weir on Laidley Creek increases infiltration through the creek bed. During the first half of the monitoring periods, some of the bores were completely dry (294, 295, 296). However, they filled up fast as a response to the first and second major rainfall events. The bore hydrographs fall into the Groups A1 (Mulgowie Farm profile - bores 294-297, 986) and A3 (880).

Chemistry: Groundwater samples fall into Group 1. Water in this area is of Mg-Ca-Na-HCO_3 type (bores 295, 296, 297) or Mg-Na-Ca-HCO_3 type (bore 294). Elevated concentrations of NO_3 (~90 mg/L) were measured in bore 14320294. This bore is the most distant one from the creek and located in the middle of a field. Because the whole area is highly cultivated (Mulgowie farm) the NO_3 concentration is probably elevated due to fertilizer use. The fact that NO_3 was not "flushed out" during the water table rise (recharge of the alluvium around the bores) as well as the much higher TDS (825 mg/L in the bore 14320294 in comparison to about 250 mg/L in bores 14320295 – 14320297) points to a slower recharge rate and less mixing in this bore than in bores closer to the creek. It also confirms the influence of diffuse rainfall and irrigation return recharge/infiltration process in the areas more distant from the Laidley Creek.

Zone V – bedrock restraint / low permeability zone

Morphology and surface hydrology: The flow of the creek is influenced by the rising bedrock on the western part of the valley. Stream flow is diverted along the western border of the alluvium, as in Zone II. The thickness of the highly permeable coarse layer at the base of the alluvium is 1 to 5 m, and the thickness of the semipermeable layer of clays, loams and topsoil is about 15 to 25 m. As the valley widens in down-stream direction, the width of the deep channel alluvium becomes much greater in this zone than in upstream zones, hence the creek has a much larger area of alluvium to recharge. See digital appendix, sections B to H.

Hydrogeology: Relationship between rainfall (and creek flow) and recharge in this zone is variable. Current observation suggests that although there is a general trend of rising groundwater as a response to rainfall upstream of Zone V, the rise is gradual and relatively small. This applies to the narrower southern part of the zone in particular; the north-eastern part of this zone displayed dropping groundwater levels throughout the monitoring period, regardless of upstream rainfall. In terms of recharge, observed behaviour of Zone V can be compared to behaviour of Zone II, and under current climatic conditions (2006 to 2008) the recharge can be attributed mostly to a combination of underflow along the catchment axis and irrigation return.

Historical records, however, show a different picture (Ashley Bleakley - pers. communication, 2008): during the periods of long-term creek flow (and high creek water levels) through this zone, the bores in the southeastern part of the zone (453, 293 and 290) showed relatively rapid responses to creek flows indicating recharge from the creek. In addition, bores in transect 338 –340 appear to be recharged from the creek if the water level is high enough. The historical high flows (e.g. 1973 or 1996 flood) showed very rapid recharge to all bores of this transect.

Chemistry: Water samples in the area defined as Zone V fall into Group 1 and Group 4. The water has high concentration of TDS (1000 – 2500 mg/L), mostly of Na-Cl-HCO_3 type currently indicating hydraulic connection with the underlying sandstone (see Section 4.4.8.2). This hydraulic connection could be highly problematic, especially when the groundwater levels in the alluvium are low because salts in the irrigation water can cause an increase in soil salinity.

Zone VI

Morphology and surface hydrology: Alluvial aquifer thickness varies from 4 to 7 m, covered by a surface layer which is 15 to 25 m thick. The bedrock control on the channel (as seen in Zone V) or low permeability sediments (as seen in Zone II) are not present and the stream returns to the axis of the valley. For the alluvial crossections see digital appendix, sections A and B.

Hydrogeology: Although the stream is not incised into the highly permeable basal layer, recharge to the alluvium is inferred from the monitoring bore hydrograph (bore 450, Group A1). The groundwater level is influenced by upstream rainfall and creek flow, and is similar to the recharge regimes of Zones III and IV. Bores in the southern part of the Zone VI (330 on the eastern bank of Laidley Creek and 331 on the western bank of the creek) were monitored only towards the end of the monitoring period, but the hydrographs indicate a very good hydraulic connection of alluvium and Laidley Creek (when the creek was flowing towards the very end of the monitoring period).

Chemistry: Water samples from Zone VI fall into Group 1. The water mineralization is relatively low (concentration of TDS is 330 – 470 mg/L), mostly of Na-HCO_3-Cl or Mg-HCO_3 types. Water chemistry and bore hydrographs indicate groundwater recharge from the creek. Hydraulic connection with the underlying sandstone appears to be minimal or is overshadowed by combined recharge from creek and underflow.

5.3.3 Topographic surface - DEM

A digital elevation model (DEM) of the catchment with a grid cell size of 25×25 m was used to define the topographic surface. Created as a 25 m drainage enforced digital terrain model produced from scanned 1:100000 scale data (Geoscience Australia, 2007), the DEM cannot be relied upon in terms of high elevation accuracy. No other usable elevation data were available during the work on the project. The DEM error (Table 8; see DEM01 point error) was identified at bore locations where surveyed elevations (DERM, 2009) and DEM values were mismatched.

Table 8. Topographic surface (DEM) elevation error.

RN	Topo elevation (survey) [m a.s.l]	Topo elevation (DEM01) [m a.s.l.]	DEM01 point error [m]	Topo elevation (DEM02) [m a.s.l.]	DEM02 point error [m]
14320290	134.260	126.583	7.677	133.742	0.518
14320293	135.790	135.279	0.511	136.490	-0.700
14320294	147.950	146.636	1.314	148.412	-0.462
14320295	148.390	142.374	6.016	147.930	0.460
14320296	149.210	141.458	7.752	148.969	0.241
14320297	149.430	141.458	7.972	148.969	0.461
14320329	114.000	116.777	-2.777	114.683	-0.683
14320330	114.500	110.775	3.725	113.819	0.681
14320331	114.600	110.775	3.825	113.819	0.781
14320332	112.200	112.400	-0.200	112.148	0.053
14320333	113.200	114.457	-1.257	113.421	-0.221
14320335	118.700	112.234	6.466	118.409	0.291
14320336	117.100	110.272	6.828	116.696	0.404
14320337	115.900	112.792	3.108	115.896	0.004
14320338	127.400	120.094	7.306	126.637	0.764
14320339	125.700	123.198	2.502	125.829	-0.129
14320450	109.480	108.651	0.829	109.381	0.099
14320453	137.310	127.495	9.815	136.790	0.520
14320547	109.540	114.559	-5.019	109.976	-0.436
14320553	110.350	113.284	-2.934	110.276	0.074
14320785	133.680	124.347	9.333	133.095	0.585
14320786	133.740	124.347	9.393	133.095	0.645
14320848	132.040	130.186	1.854	132.509	-0.469
14320849	190.600	193.018	-2.418	190.663	-0.063
14320879	171.100	169.362	1.738	170.897	0.203
14320917	170.280	170.137	0.143	170.441	-0.161
14320919	160.490	154.385	6.106	160.035	0.455
14320920	159.380	160.096	-0.716	159.743	-0.363
14320982	203.130	211.434	-8.304	203.758	-0.628
14320983	219.820	227.081	-7.261	220.973	-1.153
14320986	139.150	131.449	7.701	138.801	0.350
Cummulative absolute error [m]:			**142.799**		**13.054**

The calculated error (DEM01 point error) was interpolated across the whole catchment in order to create the "error matrix" (Figure 44a). After the subtraction of the error matrix from the original DEM, a new and more accurate topographic surface was created and used for the numerical model setup. Based on calculated cummulative absolute error of the new DEM, the precision of the new DEM (Table 8, column DEM02 point error and Figure 44b) increased approximately ten times.

5.3.4 Time discretization

The Laidley Creek catchment model was run in both steady state and transient modes. The steady state run was used to establish the initial modeling conditions for the transient run. Transient stresses such as rainfall and pumping were then applied to the model to predict the impact on processes within the alluvium such as head distributions and flows between alluvium and bedrock aquifer.

The model was run for a period of 630 days (90 weeks, approximately 1.7 years) between 20/7/2007 and 10/4/2009. The beginning and the end of the transient simulation run coincides with the start and the end of the author’s weekly manual bore monitoring. The transient simulation was divided into 90 stress periods, with each of the stress periods being 7 days long. The length of the stress period was selected on the basis of the manual groundwater monitoring interval, which was usually 1 week. The stress period is also short enough to capture most of the details in the alluvium groundwater head change as well as the Laidley Creek stage change.

5.3.5 Water budget

The water budget of the catchment quantifies flows into the catchment or out of the catchment and the amount of water stored in the catchment aquifers. In the case of numerical models, the water budget is one of the most important measures of the model convergence.

This conceptual water budget summary is looking at the catchment inflows and outflows in the most general terms possible. Some of the values presented are relatively precise

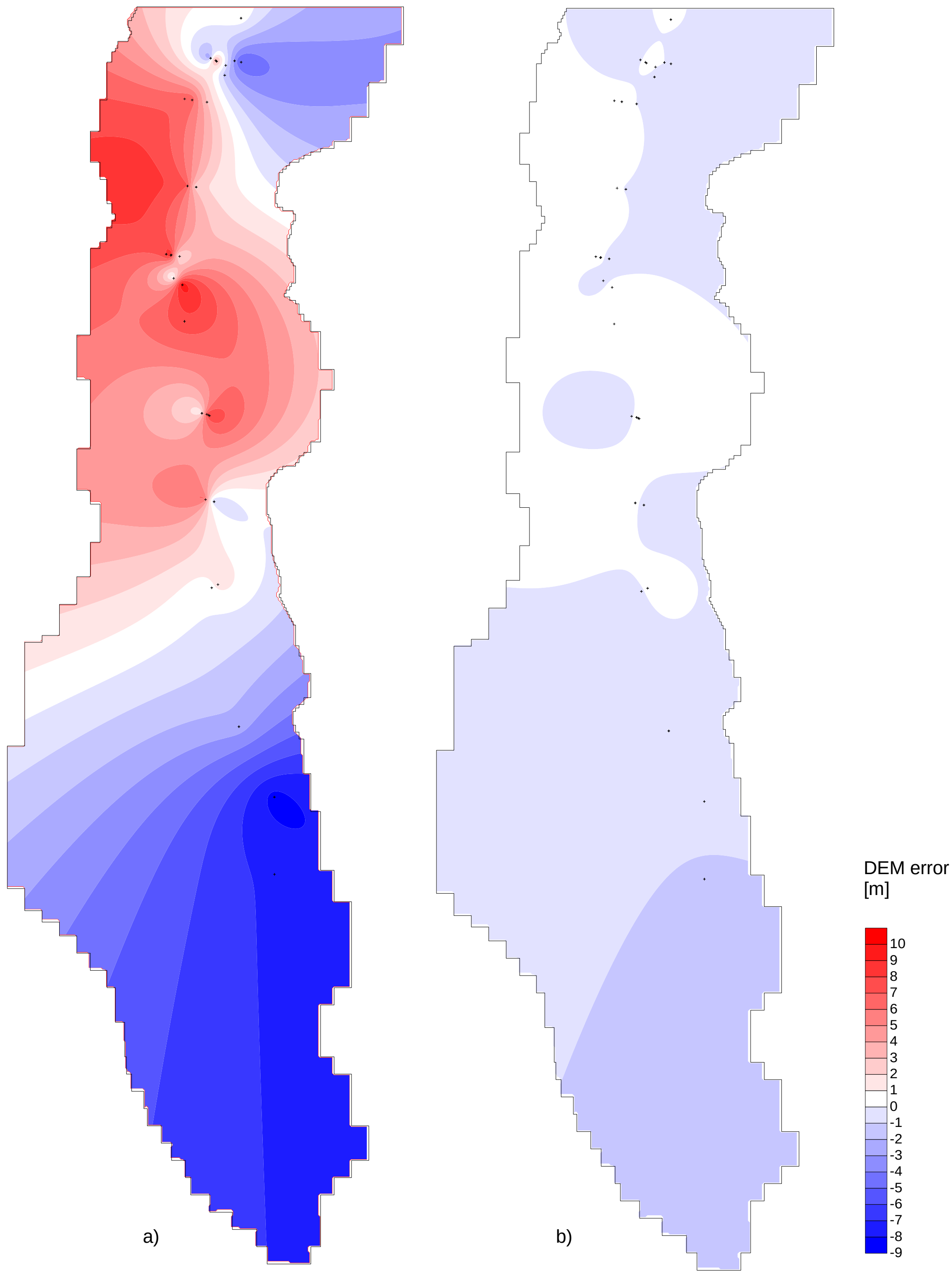


Figure 44. DEM error prior (a) and post (b) rectification.

(e.g. rainfall, evapotranspiration), other components of the water budgets are known, or estimated, only approximately. Regardless of this variability of precision, the catchment scale budget provides one of the opportunities to constrain future numerical model calibration by providing bounds on probable inflows/outflows.

For the purpose of the conceptualization of the catchment budget, the most significant component of the inflow is the rainfall, while the main components of the outflow are the evapotranspiration, creek flow, cross boundary groundwater outflow and pumping. All the inflows/outflows presented were calculated with regard to the expected timeframe of the transient model run (i.e. 630 days, from 20/7/2007 to 10/4/2009).

Rainfall (inflow)

The rainfall information was acquired from 3 rainfall gauges. Data for all three rainfall gauges were available on a daily basis. The volume of rainfall (for the period of 630 days) was calculated using the value of average daily rainfall applied over the area of the catchment (239.1 km^2). The calculated rainfall inflow volume is 555294.6 ML (for the period of 630 days).

Evapotranspiration (outflow)

Evaporation and evapotranspiration data were not available from the on-site measurements, the data provided by Queensland Bureau of Meteorology (BOM) were used instead. BOM provides a dataset of 50 years average actual areal evapotranspiration as an annual or monthly ET. The calculated loss by evapotranspiration is 316059.2 ML (for the period of 630 days).

Creek discharge (outflow)

Creek discharge is the volume of water exiting the catchment via the surface stream flow. The only flow volume data available are from the Mulgowie (143209B) gauging station with daily stream gauge head and flow data provided by DERM. There are also historic data available from Laidley Showgrounds gauging station (143225A). Because the Laidley Showgrounds gauge was situated very close to the northern boundary of the conceptual model area, it would be a very convenient measurement point to estimate Laidley Creek discharge. Historical comparison of stream flow data between Mulgowie and Laidley Showgrounds shows that the discharge at Laidley Showgrounds was 1.5 to 4 times higher than the flow at Mulgowie.

The value of Laidley Creek discharge at Mulgowie was calculated as 28269.2 ML (for the period of 630 days). Based on the historic data comparison between Mulgowie and Laidley Showgrounds gauges (Appendix D), the creek discharge at the northern model boundary is estimated to be between 42404 ML (1.5 times the flow at Mulgowie) and 113077 ML (4 times the flow at Mulgowie).

Cross boundary groundwater discharge (outflow)

Cross boundary groundwater discharge is relevant only for the northern model boundary, all other boundaries were defined as "no-flow". The volume of cross boundary outflow cannot be directly derived from the pre-modeling data, however it can be at least roughly estimated. The estimate of the cross boundary flow is based on Darcy's flow equation:

$$Q = K \times A \times (H_y - H_x)/L$$

The elevation of the groundwater table at the northern boundary (H_x) was set to the average groundwater table elevation at bore 450 (topographic surface: 109.5 m a.s.l.; average depth to groundwater: 20.2 m; average groundwater table elevation: 80.3 m a.s.l.). The elevation of the groundwater table at the southern boundary (H_y) of the theoretical catchment alluvial aquifer was estimated using the known elevation of topographic surface (230 m a.s.l.) and average depth to groundwater table in bores in the upper catchment (982: 6.7 m; 983: 6.8 m) to be approximately 223.3 m a.s.l.

Other dimensions of the theoretical catchment aquifer were set to:

- average width: 1.5 km;
- length: 30.0 km and
- average depth: 10 m.

Based on general knowledge of the hydraulic properties of alluvial sediments (de Marsily, 1986; Kruseman and de Ridder, 1991; Fetter, 1994), the value of horizontal hydraulic conductivity was set to be within the interval of 0.1 to 50 m/day. Based on the presented assumptions and with an acceptance of the unreliability of this estimate, the cross boundary outflow for the duration of the modeling period (630 days) was calculated to vary between 4.5 ML to 2252.3 ML.

Pumping (outflow)

Based on the Psi-Delta sociological survey data (KBR, 2002), the extraction volumes due to pumping from the alluvium were estimated to be between 1.67 ML/ha/year and 9.38 ML/ha/year (Table 2). This is problematic because (a) the minimum and maximum values differ almost by an order of magnitude, (b) the extraction volumes depend on water availability, so in a period of on-going drought pumping will be most likely lower because the groundwater levels in the alluvium are very low, and (c) the single value interval is given “per year” and does not reflect any temporal changes of extraction volumes depending on the season and type of crop. The absence of hard pumping data in the form of measured volumes across different parts of the catchment presents a significant challenge for the model setup.

Based on the known extent of the irrigated cropland (19.32 km^2 - see Figure 6), the volume extracted from the aquifer for irrigation purposes is between 5573 ML and 31302 ML.

Irrigation return (inflow)

Irrigation return refers to a water that was pumped out of the aquifer, applied to soil as irrigation but was not used up by the crops or lost to evaporation and contributes to the groundwater recharge process. The amount of irrigation return depends on (a) the amount of pumping and (b) the type of crop. While some types of crops such as corn, sunflowers and legumes prefer drier soil, others (such as leafy vegetables like lettuce) require a saturated soil profile. Based on the research conducted by CSIRO in other parts of the Lockyer Valley (Wolf, 2011), the amount of possible irrigation return was quantified to be from 100 to 600 mm/year which translates to an extra recharge of 4920 to 29500 ML.

Although defined as "inflow", from the catchment point of reference, the irrigation is not an extra inflow, it is "recycled" water. If there was no rainfall to the catchment, there would be no pumping and no irrigation return. The estimated volume of irrigation return is enumerated here for completness sake, it is also necessary for the numerical model parameter definition process.

Table 9. Initial quantification of the water budget for the period between 20/7/2007 and 10/4/2009 – 630 days (period of transient numerical model run).

Inflows		
	min [m³]	*max [m³]*
rainfall	555294568	
irrigation return	4918366	29510193
∑ (max)	584804761	
Outflows		
	min [m³]	*max [m³]*
EVT	316059191	
river	42403824	113076864
pumping	5572931	31301853
cross boundary flow	4505	2252250
∑ (max)	462690158	

Table 9 shows that the sum of possible maximum outflow is lower than the sum of possible inflows. Based on the presented numbers alone, aquifer recharge (water inflow into storage), as well as increase in water extraction is theoretically possible.

5.3.6 Description of the flow system

The processes within the framework are presented on a set of simplified vertical profiles (Figure 45) through the catchment to explain the links between individual stratigraphic units and the relation between alluvium, groundwater and surface stream water.

The major form of recharge to the catchment is rainfall (1). Water that is not lost to evapotranspiration (13) infiltrates to the ground through basalts (B) or is collected (via the slope runoff) in the surface waters of Laidley Creek (E). If rainfall and surrounding aquifers are able to sustain the creek flow (4) long enough to reach the catchment boundary the water leaves the catchment in the form of channel runoff (5).

Water that infiltrates into the bedrock aquifers surrounding the Laidley Creek alluvium (Main Range Volcanics basalts or sandstones of Koukandowie Formation, Walloon Coal

Measures or Gatton Sandstone) after a lag time, discharges into the alluvium (A) where, in its upper reaches, it contributes to Laidley Creek flow (3). Within the alluvium, the water folows the hydraulic gradient and moves as underflow (8) to be discharged from the catchment (9) at its lowest point.

Depending on the elevation of the groundwater table (F), its relative position with respect to stream water level, and other controls such as morphology of bedrock or conductivity of stream bed, the creek is either gaining water from the alluvium (3), in equilibrium with groundwater in alluvium (6) or losing water to alluvium (7).

Groundwater pressure gradients can influence the hydrological connection with the underlying aquifers. Major ion chemistry analysis showed the mixing between alluvial and sandstone (10) water (Section 4.4.8). In the case of higher groundwater levels in the alluvium, the water from the alluvium would be probably slowly recharging the bedrock sandstone. In the period of ongoing drought, the groundwater head in the alluvium is low and the sandstone groundwater is seeping into the alluvial aquifer, possibly causing degradation of water quality because of the increased concentration of salts in sandstone water. Hydraulic connection between overlaying basalts and underlying stratigraphic units (12) depends on the hydraulic gradient between basalts and sandstones or individual sandstone units.

Although the non-alluvial aquifers (basalts in the headwaters, sandstone outcrops on both sides of the alluvium in the lower parts of the catchment) are recharged directly by rainfall, the direct rainfall recharge to the alluvium is quite small compared to the stream recharge through the bed of Laidley Creek (4). As shown by the observation of groundwater levels in bores adjacent to the creek, and the groundwater and surface water chemistry, the surface water then seeps through the creek bed into the alluvium (7), making the creek bed recharge the most important recharge mechanism of the alluvial aquifer.

Pumping bores are located along the axis of the valley, mainly in the alluvium. The volume of groundwater extraction (11) for irrigation purposes is poorly quantified. Based on the measured extraction in the Central Lockyer area (KBR, 2002; Psi-Delta, 2009) as well as the survey among the farmers (Psi-Delta, 2009), the extraction volumes were estimated for the whole Laidley Creek catchment without any regard for type of crops and/or seasonality. Dependant on the pumped volume as well as crop type is the volume of the irrigation return (14). Irrigation return appears to be a significant contributor to direct alluvial recharge in irrigated sections of alluvium.

Figure 45. Conceptual model – model domain boundaries and processes within the catchment (overleaf).

Legend for Figure 45

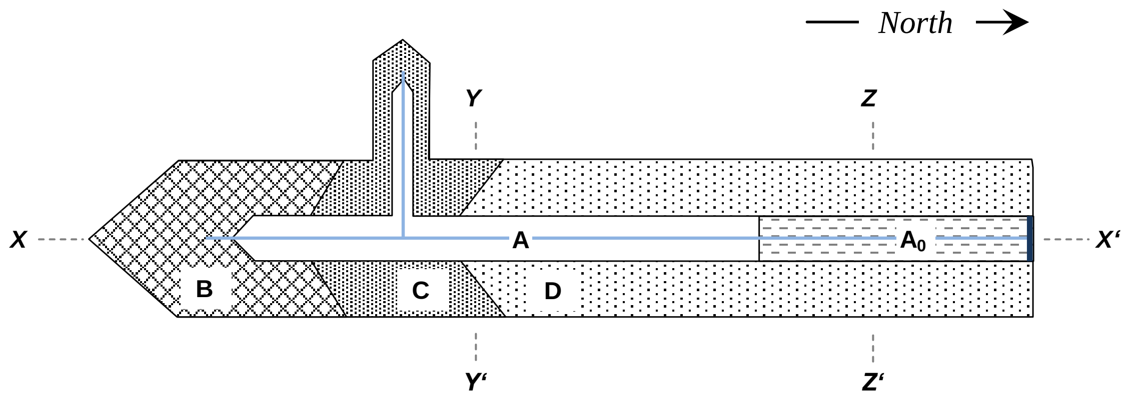
For the overview of stratigraphy, see Section 3.2 and Table 1.

Geological units and features:

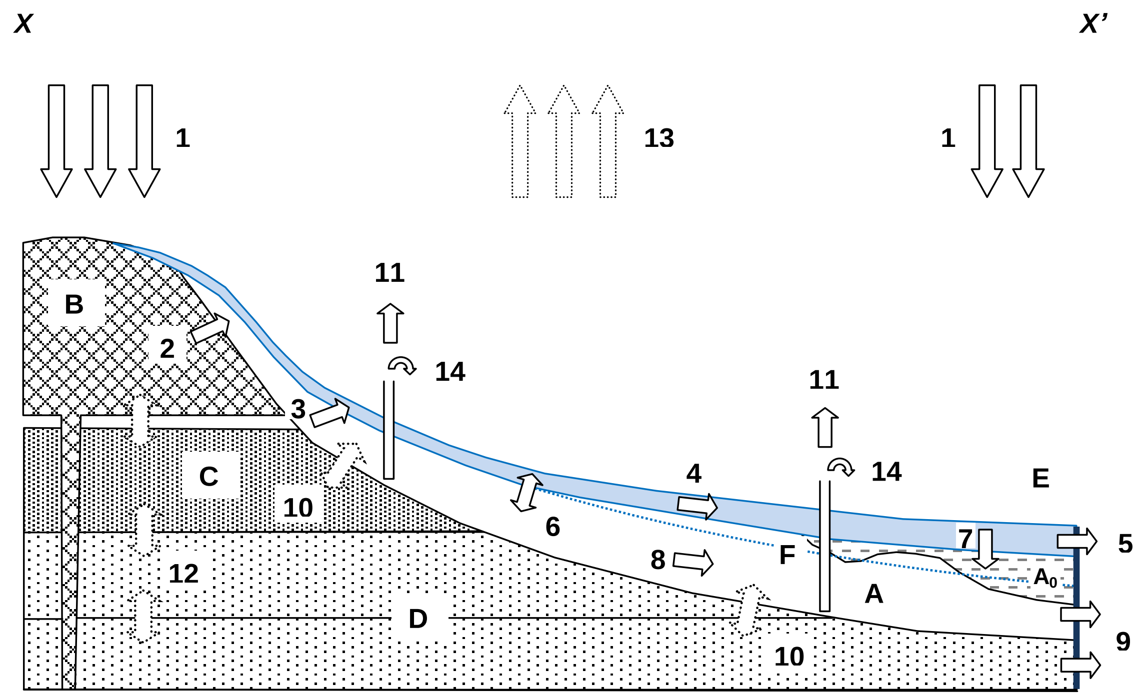
A	coarse alluvium
A_0	less permeable silt and clay surface layer covering the coarse alluvial sediments
B	basalts - Main Range Volcanics (MRV)
C	shales / sandstones - Walloon Coal Measures
D	sandstones of Bundamba Group members (Koukandowie Formation, Gatton Sandstone)
E	Laidley Creek
F	groundwater table in alluvium

Processes:

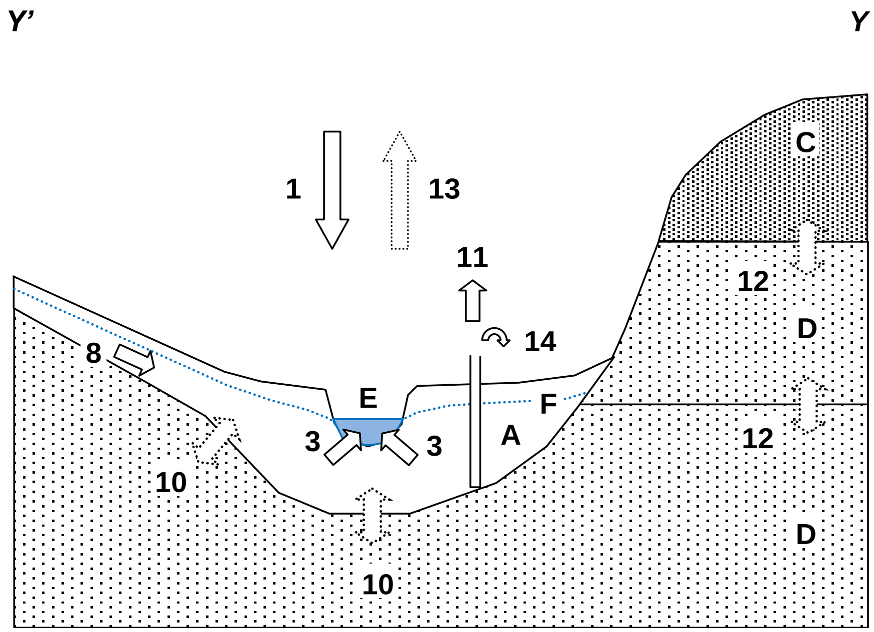
1	rainfall
2	groundwater seeping from basalts to alluvium
3	groundwater seeping from alluvium to Laidley Creek
4	surface flow of Laidley Creek
5	water lost to catchment through surface flow of Laidley Creek
6	depending on the elevation of groundwater table with respect to elevation of creek bed, the creek can be both losing water to alluvium or gaining water to alluvium
7	the creek is main source of recharge to the alluvium in lower parts of the catchment
8	groundwater within the alluvium is generally moving along the axis of the catchment
9	groundwater discharging from the catchment in its lowest point
10	the hydraulic interaction between alluvium and underlying sandstones is not specified in terms of volume, however chemistry of the groundwater suggests water flows from shales and sandstones to alluvium, especially when the groundwater table elevation in alluvium is low
11	volume of water extraction for domestic and irrigation purposes (pumping) is not known
12	hydraulic interaction between different sandstone members is probable, but not known and is outside the scope of this study
13	evaporation, evapotranspiration
14	irrigation return



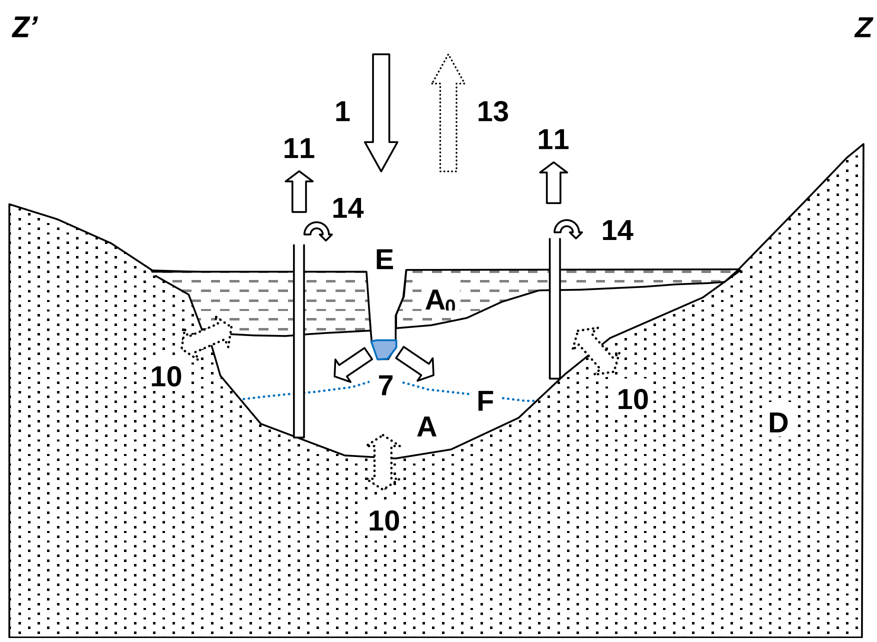
Conceptual model – simplified plan of the lateral extent of conceptual model domain.



Conceptual model – X-X‘ crossection – parallel to the axis of the Laidley Creek catchment



Conceptual model – Y'–Y crossection – perpendicular to the axis of the catchment, located in the upper part of the Laidley Creek catchment. Creek is gaining, water from the alluvium recharges into the creek.



Conceptual model – Z'–Z crossection – perpendicular to the axis of the catchment, located in the lower part of the Laidley Creek catchment. Creek is losing water to alluvium (creek water recharges the alluvium).

5.4 Numerical model construction

A numerical model is a set of equations (usually computer based), which, subject to certain assumptions, quantifies the physical processes active in the aquifer system being modelled. Groundwater models are used to integrate our hydrogeological understanding with the available data and to develop either an interpretative or predictive tool for evaluating groundwater systems. The conceptual model (previous Section 5.3) is the first necessary step towards the development of the numerical flow model.

5.4.1 Purpose of the numerical model construction

The model of the Laidley Creek alluvial aquifer can be described as an interpretative model: it is primarily used as a tool enabling the users to synthetise and organize field data and can be utilized as a framework for study of the system dynamics. The conceptual model of the Laidley Creek catchment was constructed to represent the catchment hydrogeological framework: its geological setting, groundwater flow proceses and groundwater/surface water interactions. The numerical model will quantify some of the catchment processes, namely the flows between the individual bedrock layers and the alluvial aquifer. The existence of the hydraulic connection between alluvium and bedrock sandstones was discussed previously (Section 4.4.8). Although the salinization of alluvium via the inflow from bedrock sandstones might represent an environmental (and potentially economic) threat, it has not been examined by other groundwater studies in the wider Lockyer area so far (Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005). In order to draw some conclusion with regard to reliability of modelled flows (flow predictions), parameter sensitivity and predictive uncertainty analysis will be undertaken.

5.4.2 Computer code selection

There are many different groundwater flow modeling codes available and each has its limits, characteristics and capabilities. Selection of the computer code is however not based only on the modeling code itself, the requirements and goals of the groundwater project where modeling process is used are also very important. It is therefore important to select the appropriate code for a particular project (ASTM, 2006).

The main selection criteria are (a) objective criteria, (b) technical criteria and (b) implementation criteria (Bond and Hwang, 1988; Back et al., 1994; Hill, 1998; van Waveren et al., 1999; McMahon et al., 2001; Middlemis, 2001; ASTM, 2006; Hill and Tiedeman, 2007). Objective criteria refer to the suitability of the code to the goals and objectives of the study. Technical criteria relate to the mathematical suitability of the code to cope with the physical and conceptual conditions of the modelled area. Implementation criteria are dependant on the modeling code availability, accessibility and ease of use (Bond and Hwang, 1988; Spitz and Moreno, 1996).

Based on the current knowledge of the described system, availability of suitable software, and familiarity with modeling code, the following programs were selected:

- ArcGIS, MapInfo, PMWIN for initial data visualization and pre-processing;
- MODFLOW derived code for numerical modeling of groundwater flow, and
- PEST and programs from Groundwater utilities suite for model calibration, parameter estimation and analysis of parameter uncertainties.

ArcGIS was used mainly for initial data management and mapping, MapInfo was used for modeling data pre-processing (operations with model grid such as calculation of lengths of the Laidley Creek within individual grid cells or assigning grid coordinates to pumping bores). PMWIN (Chiang and Kinzelbach, 2000) was used to build the model structure (model layers) and generate model grid file (see Section 5.4.2.2). Additionally, Fortran95 was used to write "service" code (called *model.exe*) which is (1) responsible for the assembly of MODFLOW packages from primary input data, (2) MODFLOW code launch for both steady state and transient models and (3) model results (heads, flows, budgets) extraction. See the digital appendix for the source code and binary files.

5.4.2.1 MODFLOW

Since the early development of MODFLOW in the 1980s (McDonald and Harbaugh, 2003), the program went through several major releases (MODFLOW-88, MODFLOW-96, MODFLOW-2000 and MODFLOW-2005) and is currently accepted as the de-facto standard aquifer simulator (Domenico and Schwartz, 1997). However, it has been widely acknowledged that the original USGS MODFLOW code has difficulties handling the rewetting of dry cells (Goode and Appel, 1992; Harbaugh et al., 2000; Doherty, 2001; Barthel et al., 2005). When the model cell "dries up", it is effectively removed from further calculations and it becomes impervious from the model point of view. This is especially problematic for transient models, where dry periods are followed by wet periods during which the model is supposed to recharge. Several ways to circumvent the dry cell problem exist.

The most obvious one is to use the in-built rewetting capability of standard USGS MODFLOW. Previous versions of the BCF package (BCF2) used heads at the neighbouring cells to determine whether to switch a dry (no flow) cell into a variable-head cell. This method often leads to numerical instability in the form of numerical oscillation (Goode and Appel, 1992; Doherty, 2001; Barthel et al., 2005) where cells go cyclically dry and then are being rewetted. In such cases the MODFLOW solver will often not converge. Also, when nonlinear parameter estimation software (PEST, UCODE) is used to calibrate the model, the process of drying and rewetting interferes with the operation of the Gauss-Marquardt-Levenberg method on which the functionality of such software is built (Harbaugh et al., 2000; Doherty, 2001). Cell rewetting problems of the BCF2 package were documented by Goode and Appel (1992) who also implemented more advanced schemes and introduced the BCF3 package that provides alternative procedures for calculation of the transmissivity of dewatered cells. The re-wetting problem was also addressed by Doherty (2009) who circumvented the problem by changing the calculations of intercell conductances and cell storage, resulting in grid cells that effectively never dry up. The latest USGS code (MODFLOW-NWT) introduced the upstream weighting (UPW) process (Painter et al., 2008) and two asymmetric matrix solvers (GMRES and CGSTAB). MODFLOW-NWT uses the Newton method to solve the non-linear groundwater flow equation, thus extending the applicability of MODFLOW to problems of unconfined flow, surface water/groundwater interaction (Niswonger et al., 2011) and flow under unsaturated conditions.

Another change of solution algorithm was introduced by HydroGeoLogic (1998; 2009). HydroGeoLogic (HGL) achieved the numerical stability of the flow simulation (with dry cells) by using the pseudo-soil water retention function and thus enabling flow calculations in a variably saturated zone. Updated HGL code, originally based on

MODFLOW-96 but extended with MODFLOW-2000 functionality, became available as MODFLOW-SURFACT and as well as the unsaturated flow capabilities, it also introduced new modules (e.g. ATO - advanced timestepping package) and solvers (e.g. MATIS matrix solver).

As a part of the code selection process, three MODFLOW variants were tested. The preference was to use freely available code i.e. MODFLOW-ASP or MODFLOW-NWT, however problems such as numerical instabilities in the case of MODFLOW-ASP, and prohibitively long runtime (in the case of MODFLOW-NWT) prevented the use of the free codes.

Structural properties of the Laidley Creek catchment model i.e. steep hydraulic gradients combined with conditions of variable saturated/unsaturated flow caused the numerical non-convergence of MODFLOW-ASP. Although numerical convergence was achieved with the use of MODFLOW-NWT, the approximately 40 minutes necessary to solve the steady state model run imposed a time constraint that would make the steady state and transient model calibration impracticable. In the end, because of its adaptive timestepping capabilities as well as an extremely fast matrix solver, MODFLOW-SURFACT was selected as the modeling code of choice and necessity. Any reference to MODFLOW in further text thus relates to MODFLOW-SURFACT.

5.4.2.2 PMWIN (Processing MODFLOW for Windows)

PMWIN (Chiang and Kinzelbach, 2000) was used as one of the data preprocessors to generate templates for MODFLOW input files. It was also used to check the structural integrity of the model layers and extract head data form MODFLOW generated files. The MODFLOW simulation itself, however, was not run from within PMWIN. MODFLOW was run with a use of aforementioned "service" *model.exe* application, that reads all input data, generates MODFLOW packages on the fly and then runs the numerical model itself.

5.4.2.3 PEST (Parameter ESTimation tool) and groundwater utilities

PEST (Doherty, 2006; Doherty, 2009) and its parallel run enabling variant BeoPEST (Schreuder, 2009; Doherty, 2010; Hunt et al., 2010) was used during the automatic calibration process to estimate unknown hydraulic parameters. Calibration is the process of adjusting boundary conditions, distribution of hydraulic properties and external stresses until the calculated values (e.g. modelled heads) fit the observed values (field data such as measured heads).

PEST is basically a model independent parameter estimation tool. It runs in conjunction with any model that uses input and creates output in plaintext ASCII files. In the case of the Laidley Creek model, PEST was used in conjunction with MODFLOW. With every MODFLOW run, PEST changes one of the parameters and then compares the calculated results with calibration data set. One PEST iteration takes as many model runs as the number of parameters which are to be estimated. Depending on the number of parameters, one PEST iteration can take up to several hundreds of MODFLOW runs. This process continues until PEST reaches previously defined level of model fit by dropping the value of the objective function (sum of squared residuals) below the calibration target.

As the hydraulic parameter values are not uniform across the model domain, the model requires different parameter values to be assigned to different grid cells. To achieve this, the zonal approach or pilot point approach can be applied (Doherty, 2003).

First proposed by de Marsily (1984), the pilot points are defined as locations at which the values of particular model parameter (e.g. horizontal hydraulic conductivity, vertical hydraulic conductivity, recharge, evapotranspiration) are known. The values of this particular parameter are then interpolated (usually using kriging) between individual pilot points in order to create a *parameter field* that represents the spatial distribution of particular parameter. The pilot point values are usually considered as unknown parameters that can be adjusted as part of the calibration process (Christensen and Doherty, 2008).

Although zones with uniform hydraulic properties are easy to set up and use, the use of zones is often impractical because it can introduce additional uncertainties into the modeling process. Even when based on intimate knowledge of the modelled area, the setting of zone boundaries is usually quite arbitrary. In such cases the use of pilot points is preferable. The parameter values are then interpolated from pilot point locations across the model grid. PEST uses kriging as the selected interpolation algorithm because it is numerically efficient, smooth and respects values assigned to pilot points.

Pilot points supported interpolation was the method of choice for the Laidley Creek model. Different sets of pilot points were used during different calibration runs. See the Appendix L for an overview of all pilot points files (ppts_*.txt) and their locations within the model directory structure.

5.4.3 Spatial discretization

In terms of the vertical discretization of the model, the decision had to be made between a single and a multi-layer model setup. Although similar modeling projects throughout the Lockyer catchment area (Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005) use a single layer model setup, a multi-layer approach was chosen for the Laidley Creek catchment model. The discussion on stratigraphic units and model layers was previously presented in Section 5.3.2.

In the horizontal plane, a rectangular grid of 280 rows and 124 columns was created to cover the area of the catchment (Figure 46, Figure 47). As the physical orientation of the catchment is north-south, no grid rotation was necessary. The grid cell size is variable (Figure 46, Table 10), smaller cells cover the alluvial aquifer where most of the observations are concentrated, areas with lower density of observations are covered by larger cells. The maximum size of the cells is 500×500 m, the size of the grid cells covering the alluvium is 50×100 m.

In order to prevent the numerical convergence instabilities, the grid construction followed two basic rules: (1) the step-up ratio of the dimensions of any two adjacent cells will not exceed a factor of 1.5, and (2) the ratio of the minimum to the maximum dimension of the grid row or column should not exceed 1:10. The so called *telescopic* grid minimizes the total number of model cells while enabling the use of smaller cells in the area of interest (Laidley Creek alluvial aquifer - see Figure 46). The model domain size is 12910 m along its east-west border and 36900 m along its north-south border, extending over an area of 476.38 km^2. The total active model area is 239.11 km^2. The number of active cells

(29 558) is the same for each model layer. The total amount of active cells in the whole model is 147 790. The chosen length unit for the model is metres [m].

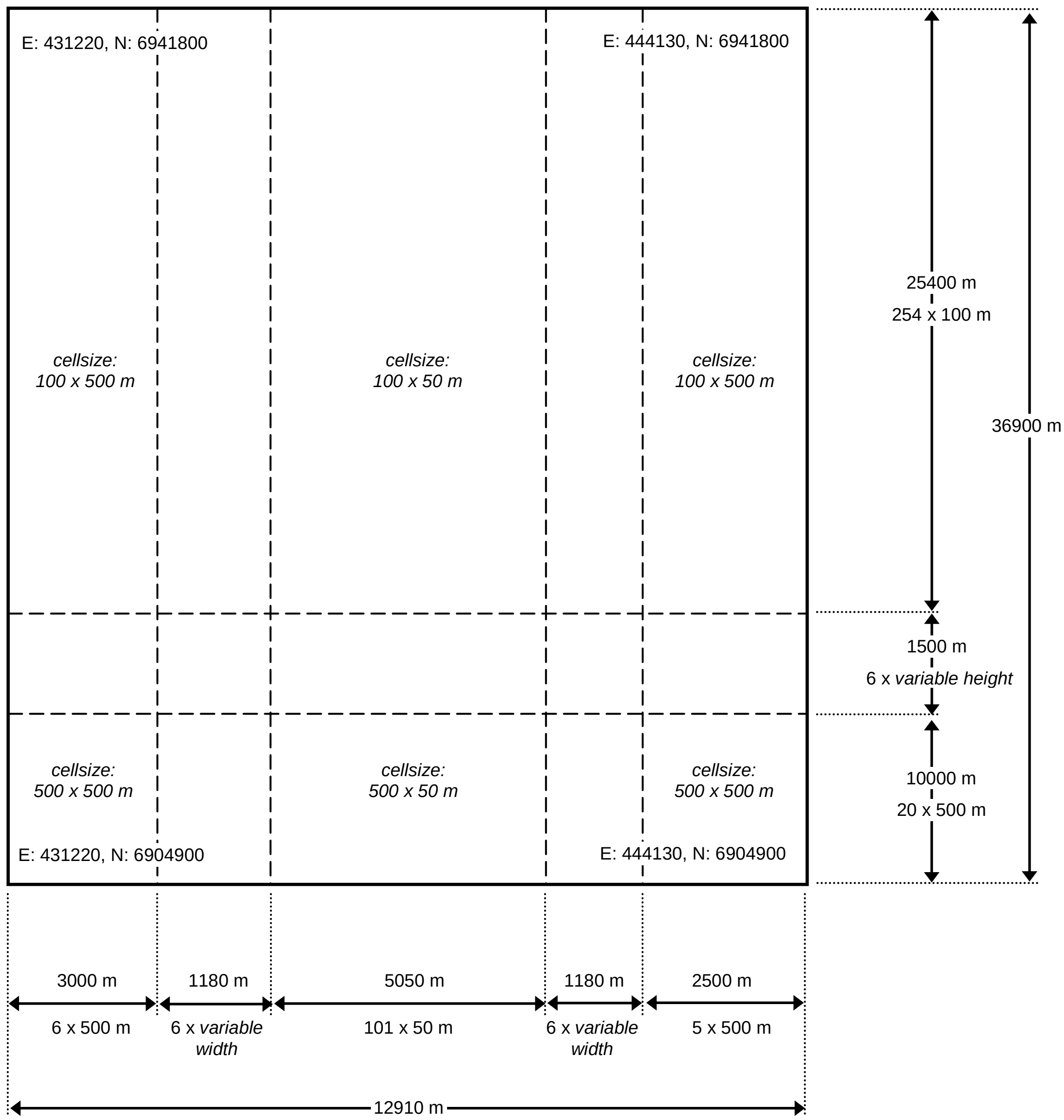


Figure 46. Grid setup with description of variable grid cells. Cell dimensions presented as [*row height x column width*].

Table 10. Grid setup and variable dimensions of grid cells.

columns				rows			
easting	col width [m]	col count	block distance [m]	northing	row width [m]	row count	block distance [m]
431220	500	6	3000	--	--	--	--
434220	390	1	1180	--	--	--	--
434610	280	1		--	--	--	
434890	200	1		--	--	--	
435090	140	1		--	--	--	
435230	100	1		--	--	--	
435330	70	1		--	--	--	
435400	50	101	5050	6941800	100	254	25400
440450				6916400			
440520	70	1	1180	6916270	130	1	1500
440620	100	1		6916100	170	1	
440760	140	1		6915890	210	1	
440960	200	1		6915630	260	1	
441240	280	1		6915300	330	1	
441630	390	1		6914900	400	1	
444130	500	5	2500	6904900	500	20	10000
∑		124	12910	∑		280	36900

5.4.4 Boundary conditions

Boundary conditions define locations and volumes of flow into the model and out of the model. The choice of correct boundaries is a crucial step in any modeling effort (McKee and Clark, 2003). The boundary conditions to be imposed were briefly discussed during the conceptualization phase (Section 5.3.1), particulars of the boundaries definitions with respect to the numerical model setup are discussed in the following paragraphs. The model grid and boundary conditions are presented in Figure 47.

5.4.4.1 Specified flow and head dependant boundaries

Assuming that the topographic catchment boundary and the groundwater divide align, a *no-flow* boundary (a special type of *specified-flow* boundary) was used along the whole eastern, southern and western side of the catchment. This type of boundary suggests that the catchment behaves as closed unit, where there are no cross boundary inflows.

In order to enable the drainage of the alluvial aquifer, a head dependant hydraulic boundary (*specified head*) was used for the northern catchment border (Anderson and

Woessner, 1992). Head dependant boundaries are able to represent either a potentially infinite source or sink of groundwater. The inflow into alluvium and outflow from alluvium between the boundaries then depends on the hydraulic gradient between the boundaries and hydraulic properties of the alluvium. Because of the simplicity of the use of this boundary condition, specified head boundaries are sometimes used incorrectly and can be a source of significant errors in flow calculations. The flows through the boundary need to be checked with respect to the physical groundwater availability and conceptual catchment budget. The specified head boundary was set along 19 cells of the northern catchment border, the groundwater head elevation for all cells was derived from the groundwater head in bore 14320450 (Figure 3).

5.4.4.2 River

Although technically also a head dependant boundary, the river or creek boundary is described separately in this section. The flow between the river (creek) and the underlying cell depends on the groundwater head in the cell, surface water head in the creek, the length (L) and width (W) of the stream within the cell, vertical hydraulic conductivity (Kv) of the stream bed and thickness (T) of the stream bed. The information concerning the creek geometry and hydraulic properties is combined into a single parameter of **stream bed conductance (**L×W×Kv/T**)** that is used in the flow calculations. Depending on the relative positions of the groundwater head and stream head, the creek is either gaining, when the creek stage is below the groundwater head in the surrounding alluvium, or losing, when the creek stage is above the groundwater head.

The courses of the two main streams, Laidley Creek and Main Camp Creek, as well as the courses of all other minor streams were adopted from the digital topographic map dataset (Geoscience Australia, 2008). The data was analysed using GIS (MapInfo, see Section 5.4.2) and the lengths of stream sections in individual grid cells were calculated. The stream dataset was then separated into three sections:

(external file - *figure_47_model_grid.pdf*)

Figure 47. The Laidley Creek catchment model grid and boundary conditions

(1) Laidley Creek: elevation of the creek bed for individual river cells was estimated using surveyed data obtained from DERM Groundwater Database (DERM, 2009). Because of the limitations of available DEM (see Section 5.3.3), elevations of several points in the creek bed were obtained by surveying elevation profiles across the creek bed by the author. Survey profiles were created from points with known elevations (DERM bores). Elevations of the creek bed along the course of the creek were then calculated using linear interpolation between surveyed creek bed points. Depth of the water in the creek was observed during the course of the field data collection period and using this observation, in conjunction with stream gauge data from Mulgowie, creek stage elevations along the creek course were interpreted. The width of the stream was set to be 10 to 12 m along the whole stream course. The course of Laidley Creek was divided into 16 zones of variable vertical creek bed conductivity in order to simulate different rates of seepage through the creek bed into the alluvium. For the flow matrix defining head for individual creek cells during all stress periods see digital appendix (/model/input/river/ see _readme.txt).

(2) Main Camp Creek: based on the field observations undertaken during the course of the study, the elevations of the creek bed were derived directly from the DEM by lowering the topographic surface by 5 m. The width of the stream was set to be between 5 to 7 m along the course of the stream. When the creek was flowing, the depth of the water was measured at certain locations and used to calculate the creek stage elevations. A single value of vertical creek bed conductivity was used for all Main Camp Creek cells.

(3) All remaining streams were set to a *drain mode* by setting the head in the river cells to the same elevation as the creek bed bottom (not to be confused with the use of MODFLOW *drain package*, the cells in the drain mode are still river cells). In the *drain mode*, the river cells interact with the groundwater head only when the groundwater head is higher than the bottom of the river cells. The width of *drain mode* cells was set to be 1.5 m and the elevation of the bed for those river cells was set to 1.5 m below topographic surface. A single value of vertical creek bed conductivity was used for all *drain mode* cells.

The distribution of various types of river cells as well as the distribution of 16 zones of variable vertical hydraulic conductivity (Laidley Creek only) across the model domain is presented in Figure 48.

5.4.4.3 Groundwater pumping

No detailed information about groundwater extraction from alluvium, such as pumping rates or pumping volumes over time, was available. The data concerning location and type of existing irrigation pumps were extracted from the DERM groundwater database (DERM, 2009). In total, 216 bores with installed pumps are registered in the Laidley Creek catchment. Based on the estimated water use (Section 3.4, Table 2), the extraction rate was calculated to be 36.6 to 205.8 m^3/day/pump. An average value of 100 m^3/day/pump was used as a representative value for the transient model run.

In order to set more realistic pumping conditions for the Laidley Creek model, the starting head in every pump location was checked against the elevation of the floor of the alluvial aquifer. If the starting groundwater head was less than 0.75 m above the floor of the alluvium, the pump was not "turned on" to avoid a dewatering of the area surrounding the pump. After the model files were generated, only 115 pumps were active. The map of the irrigation pumps is presented in Figure 49.

5.4.4.4 Recharge

The non-alluvial consolidated basalt and sandstone aquifers are recharged by infiltration of rainfall, while the alluvial aquifers are recharged by a combination of two processes: direct rainfall recharge and infiltration through the creek bed. Additional recharge in the alluvium occurs in the form of irrigation return. While the direct rainfall recharge is directly dependant on the rainfall distribution, the volume of the irrigation return depends on the pumped volume and type of crops, soil type and evapotranspiration.

In order to approximate the spatial distribution of rainfall in time, the rainfall data from three rainfall gauges had to be interpolated across the whole catchment. To be able to approximate the known rainfall distribution (more rainfall in the upper parts of the

(external file *figure_48_river.pdf*)

Figure 48. River package (RIV) cells and vertical conductance zones of the Laidley Creek bed.

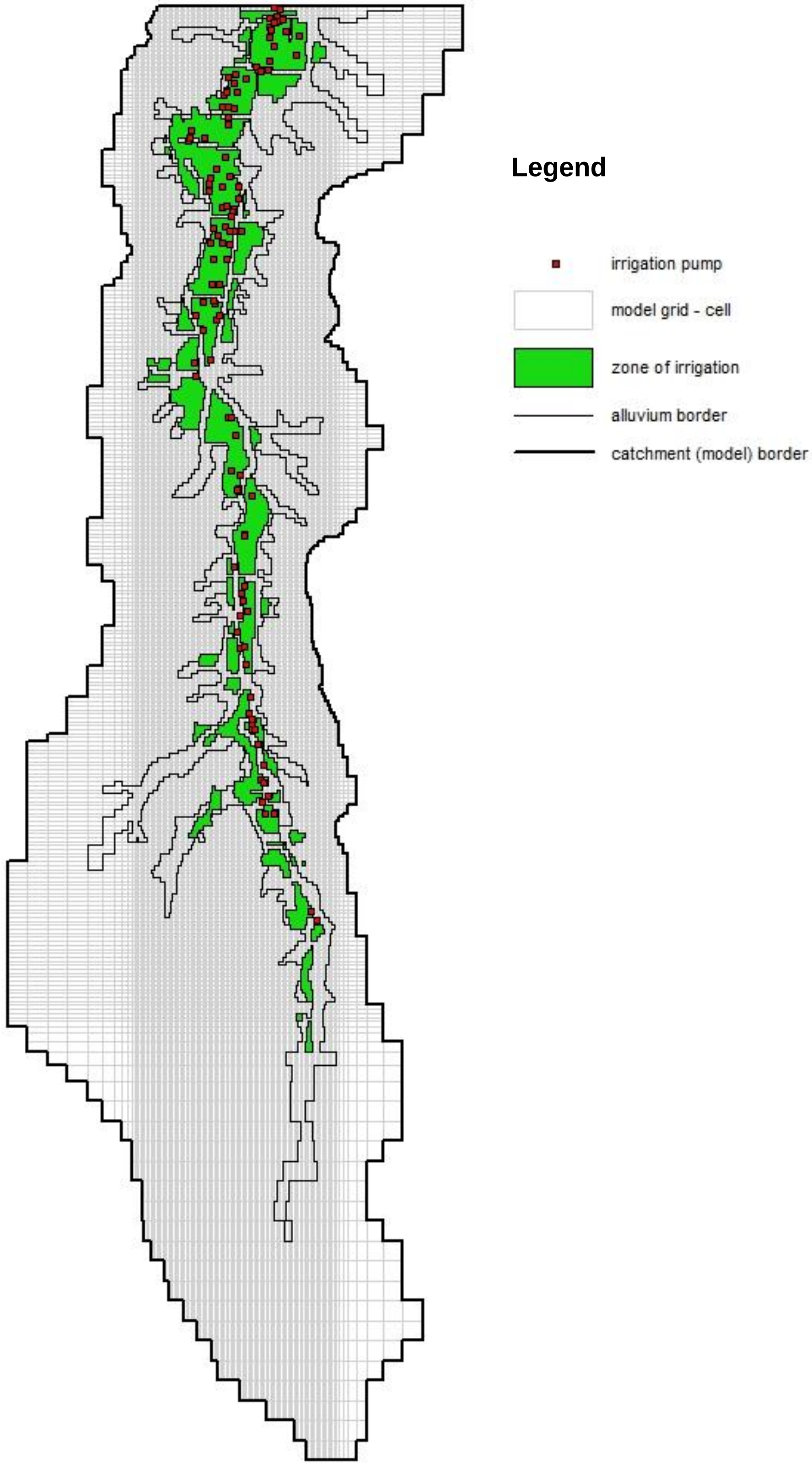


Figure 49. Distribution of irrigation pumps.

catchment and on the ridges, less rainfall in the lower catchment), the interpolation was carried out in several steps:

Firstly, average rainfall values were obtained by digitizing the existing rainfall distribution map (Figure 9, after Beale and Gorian, 1996) and interpolated across the model grid. Rainfall values were then transformed to rainfall factors (percentages) representing the rainfall *trend*.

In the next step three sets of pilot points were created, each set representing individual rainfall station. Rainfall factors (F_B) associated with individual base stations (rainfall gauges, see Table 11) and all pilot point factors (F_{PPT}) were obtained from the rainfall factor grid. Rainfall factors (F_B and F_{PPT}) together with rainfall data measured in the location of the rainfall gauges (R_B) were then used to calculate the rainfall values for individual pilot points using formula:

$$R_{PPT} = R_B \times F_{PPT} / F_B$$

where: R_{PPT} - calculated rainfall (pilot point value)
R_B - measured rainfall (base station / rain gauge value)
F_{PPT} - pilot point conversion factor
F_B - base station conversion factor

Interpolation of the pilot point values was then used to calculate the rainfall for individual model grid cells. The calculated rainfall distribution for selected stress periods is presented in Figure 50. See the digital appendix (/model/input/rainfall/rainfall_distribution_factors.txt) for pilot point factors (F_{PPT}).

Table 11. Base factors for rainfall stations within the Laidley Creek catchment.

	easting	northing	base station factor
Townson	439874	6912617	0.9575853
Laidley Creek West (farm)	436375	6933689	0.7178467
Laidley (farm)	438949	6941472	0.6822737

Water budget estimates (Section 5.3.5, Table 9) show that depending on the chosen options of minimal and maximal volumes of various types of outflow, up to 22% of rainfall is theoretically available for rainfall recharge. This value is however unrealistically high for southeast Queensland. Goverment studies indicate possible recharge

(external file: *figure_50_rainfall.pdf*)

Figure 50. Examples of spatial distribution of rainfall for selected stress periods (derived from actual rainfall data).

up to 5% of rainfall under conditions similar to those in the Lockyer Valley (Kellett et al., 2003; Baker, 2007; Crosbie et al., 2008; Crosbie et al., 2009; Crosbie et al., 2010). The final recharge values were estimated during the calibration process, however recharge parameter bounds were set to 5% of the rainfall for the weathered regolith and 15% for the Laidley Creek alluvium. The increased recharge to the alluvium should allow for both direct rainfall recharge and potential slope runoff recharge along the edges of the alluvium. Spatial variability of the recharge within the alluvium was determined with the use of 42 pilot points. Interval boundaries for irrigation return value have been set to 0 - 600 mm/year (Wolf, 2011).

5.4.5 Ranges of hydraulic properties

As suggested by the conceptual model (Section 5.3.2.1) the hydraulic properties of the Laidley Creek alluvium are spatially heterogeneous throughout the model domain. The heterogeneity of the model parameters in the **conceptual model** is described using the zonal approach. The heterogeneity of hydraulic properties within **numerical model** layer 1 (alluvium/weathered regolith) was interpolated using the pilot points approach (Doherty, 2003). The spatial distribution of pilot points in alluvium was driven mostly by the conceptual understanding of zones of hydraulic properties within the Laidley Creek alluvium (Section 5.3.2.1, Figure 43). The density of pilot points is higher in the areas where it was expected that the heterogeneity (change of hydraulic properties) of the alluvium would be high (zone boundaries, areas with decreased K possibly acting as recharge barriers, e.g. zone II, zone V).

Separate sets of pilot points were created for each of the estimated properties such as horizontal hydraulic conductivity, specific yield and specific storage. The ranges used to define the hydraulic property values were adopted from previous studies (Table 12) and specific values in pilot point locations were estimated using PEST and then interpolated throughout the model grid using kriging. See Figure 51 for the pilot point distributions.

(external file: *figure_51_pilot_pts.pdf*)

Figure 51. Distribution of pilot points used for definition of heterogeneity of hydraulic properties.

Table 12. Ranges of hydraulic properties of various alluvial units within Lockyer Valley.

Reference	horiz. hydraulic cond. [m/d]		specific yield [-]		specific storage [-]	
	min	max	min	max	min	max
Wilson	--	70	--	0.24	--	4×10^{-4}
KBR	1	250	0.01	0.05	--	--
MacLeod	4.5	--	--	--	--	--
Durick	0.1	250	0.01	0.20	--	1×10^{-5}

Adopted from MacLeod (1998), Durick (2000), Wilson (2005) and Kellog, Brown and Root (2002).

Because there is a little in-situ data pertaining to hydraulic properties of consolidated non-alluvial (basalt and sandstone) aquifers, these aquifers were modelled using a single zone approach. Single values representing average value of particular parameter (horizontal or vertical hydraulic conductivity, specific yield, specific storage) was assigned to individual model layers. In a similar way to the alluvial aquifer properties, properties of non-alluvial model layers were defined in terms of possible data range, and an inverse modeling process (using PEST) was employed to find the most appropriate parameter values within defined data ranges. The upper and lower data intervals were based on the generally accepted value ranges as defined in the reference literature (Freeze and Cherry, 1979; Fetter, 1994; Hiscock, 2005) as well as on data used in modeling projects of consolidated aquifer units in a similar stratigraphical setup of the Surat Basin (USQ, 2011).

The final ranges of hydraulic parameters of non-alluvial aquifers (parameter boundaries in PEST) were set to: 1×10^{-5} m/d (minimum) and 1 m/d (maximum). See Section 5.5.3 for calibrated values of hydraulic properties.

5.5 Numerical model calibration

A steady state model run is traditionally used to obtain the input parameters and starting heads for the transient model run; however, under the highly variable conditions of the Laidley Creek catchment, this approach can be problematic. Given the combination of hydraulic properties, unfavourable initial conditions such as extremely low starting heads, and stresses of the alluvial system, the system **cannot** be considered to be in a steady state.

At the beginning of the transient simulation the alluvial aquifer is almost empty; groundwater levels are very low throughout the catchment which makes the 'steady state' scenario numerically unstable. However, the major issue is that creek bed conductance could not be realistically estimated since the creek has very little water in the upper catchment and is dry in the lower catchment.

To avoid this problem the steady state model was not calibrated independently. Instead, both steady state and transient models were run in tandem and shared the same parameters (hydraulic properties of aquifers, creek bed conductivities, recharge). During the tandem run, the steady state model was run first to create the starting conditions for the transient model run. The PEST calibration was then undertaken only against the transient observations dataset.

5.5.1 Model parametrization

The parameter estimation and calibration process uses both estimable and non-estimable parameters. The estimable parameters were listed so that their values can be estimated during the calibration process. The non-estimable parameters, on the other hand, were used for convenience sake. These parameters' values were never meant to be "calibrated", they were listed only for the purpose of the parameter uncertainty analysis. Listing the non-estimable parameters in the PEST control file also provides the modeller with a convenient way to change those parameters manually, when the model is run in predictive mode.

The nature of the modeling process forces the modeller to make assumptions (usually based on the perception of expert local knowledge) in order to simplify the existing data and make the modeling process possible. These assumptions, such as the thickness of the creek bed, depth of the creek bed, or the width of the creek and many others, are usually adopted for the whole model domain without a full understanding of their influence on the modeling predictions. Making such parameters a part of the calibration/parameter estimation process enables the modeller to analyze the impact of these parameters on the model predictions by means of a predictive uncertainty analysis. An overview of all the parameters used including relevant parameter files is presented in Appendix L.

The model parameters were divided into four sets of basic parameter groups: (1) hydraulic parameters, (2) recharge parameters, (3) pumping parameters and (4) parameters relating to river induced recharge/discharge.

(1) Hydraulic properties parameters include horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield and specific storage. These parameters vary for individual model layers. In order to describe the known heterogeneity of Layer 1 (Laidley Creek alluvium and weathered regolith), the hydraulic properties were also made variable by the use of pilot points. In total, 1099 pilot points were used for Laidley Creek alluvium, 335 pilot points for weathered regolith and 343 pilot points for both specific yield and specific storage. The pilot points themselves were not assigned the actual parameter value, all pilot points were used as "factors" in conjunction with the "base" property value. For example, in the case of the horizontal hydraulic conductivity (HC) of the alluvium, a parameter `hc-l1z1` (hydraulic conductivity of model layer 1, zone 1, see Appendix L) was used to carry the base value, while the pilot points were able to vary between 0.0001 and 1.0. If the base value for the horizontal hydraulic conductivity equals 50 m/d, the "factor" pilot points enable the parameter value to change in the interval between 0.005 m/d and 50 m/d across the model domain.

Vertical hydraulic conductivities (VHC) are also defined as factors with respect to the value of horizontal hydraulic conductivity for a particular layer. The values of VHC are usually 0.001 - 0.15 times lower than value of horizontal hydraulic conductivity.

(2) Recharge is applied to the highest active model layer i.e. on top of the alluvium and weathered regolith. Recharge to both weathered regolith and alluvium was calculated as a percentage of rainfall, and while the recharge to the non-alluvial zone was based on a single base value, recharge to the alluvium was calculated using 42 pilot points, allowing for variable recharge into the alluvium. The variability of recharge into the alluvium should encompass the variable thickness of the low-conductivity clayey layer (or lack of it) as well as variability of slope runoff contributing to the recharge of alluvium.

(3) Pumping parameters such as pumping volume per bore, minimal required head of ground-water in alluvium, are examples of unestimable model parameters. The definition of pumping volumes is based only on the self-reported sociological study and DERM estimates. The inclusion of pumping volume as a model parameter makes it easy to model the influence of this parameter with respect to the model predictions of calculated heads and flows.

(4) River related parameters are both estimable and non-estimable. The estimable parameters are vertical hydraulic conductivities for different zones of Laidley Creek and creek bed conductivities for Main Camp Creek and other drains. The non-estimable parameters define the physical features of the streams: their width, depth from the topographic surface to the creek bed bottom and thickness of creek bed.

5.5.2 Observations: calibration data set

Model parameters were calibrated against two datasets: (1) groundwater level data and (2) groundwater level differences. Groundwater levels were measured manually in roughly weekly intervals. Additionally, automatically measured groundwater level data from 8 pressure transducers were used. Groundwater level differences (head gradients) were derived directly from the groundwater heads dataset by subtracting the value at any given time from the previous head measurement. The use of groundwater head gradients effectively doubles the amount of observations, making the calibration and parameter estimation process more effective (Kim et al., 1999; Guo and Zhang, 2000; Welsh, 2006).

Individual observations (observation = single head measurement or single difference between two head measurements) were classified into observation groups, where all the observations pertaining to a single bore were grouped together. Observation groups make possible a so called *data worth* analysis (Dausman et al., 2010) showing the scale of influence of individual observations towards predictive uncertainty. A special head gradient observation group named *dfot* was created as the result of the head differences calculations. Values in the *dfot* observation group represent a difference between the last head value of one head observation group and the first head value of the next head observation group. This observation group does not have a meaning in the physical sense, it is an artifact of the calculation of head gradients.

In order to increase the effectiveness of the parameter estimation process, the observation weights were adjusted so that their contribution to objective function was the same for all observation groups (Doherty, 2006; Hill and Tiedeman, 2007). Weights were increased for observation groups with less observations (bores with manually measured heads) and decreased for observation groups with more observations (pressure transducers measurements). The observation weights were restored to 1.0 for all observations towards the end of parameter estimation process in order to obtain unbiased calibration performance measures (Middlemis, 2001).

5.5.3 Calibration results

The groundwater flow model was calibrated as an inverse problem where model parameters (hydraulic properties of aquifer, direct diffuse recharge, creek bed infiltration, pumping) were adjusted in order to achieve the best possible fit between measured and calculated observations. PEST and BeoPEST (Doherty, 2006; Doherty, 2010) were used to aid the calibration process. For the calibration protocol and exact values of estimated parameters see the pertinent PEST run and record files (/model/calibration/*.pst; *.rec).

Estimated values of base hydraulic parameters are presented in Table 13. Pilot point parameter fields are presented in Figure 52 (HC, SS, SY of Laidley Creek alluvium - model Layer 1), and Figure 53 (HC, SS, SY of non-alluvial aqifers of model Layer 1 - weathered regolith). Initial calibrated heads for layer 1 are presented in Figure 54.

(external file: *figure_52_hydr_params_alluvium.pdf*)

Figure 52. Layer 1: hydraulic properties of the alluvium.

(external file: *figure_53_hydr_params_regolith.pdf*)

Figure 53. Layer 1: hydraulic properties of the regolith zone (non-alluvium).

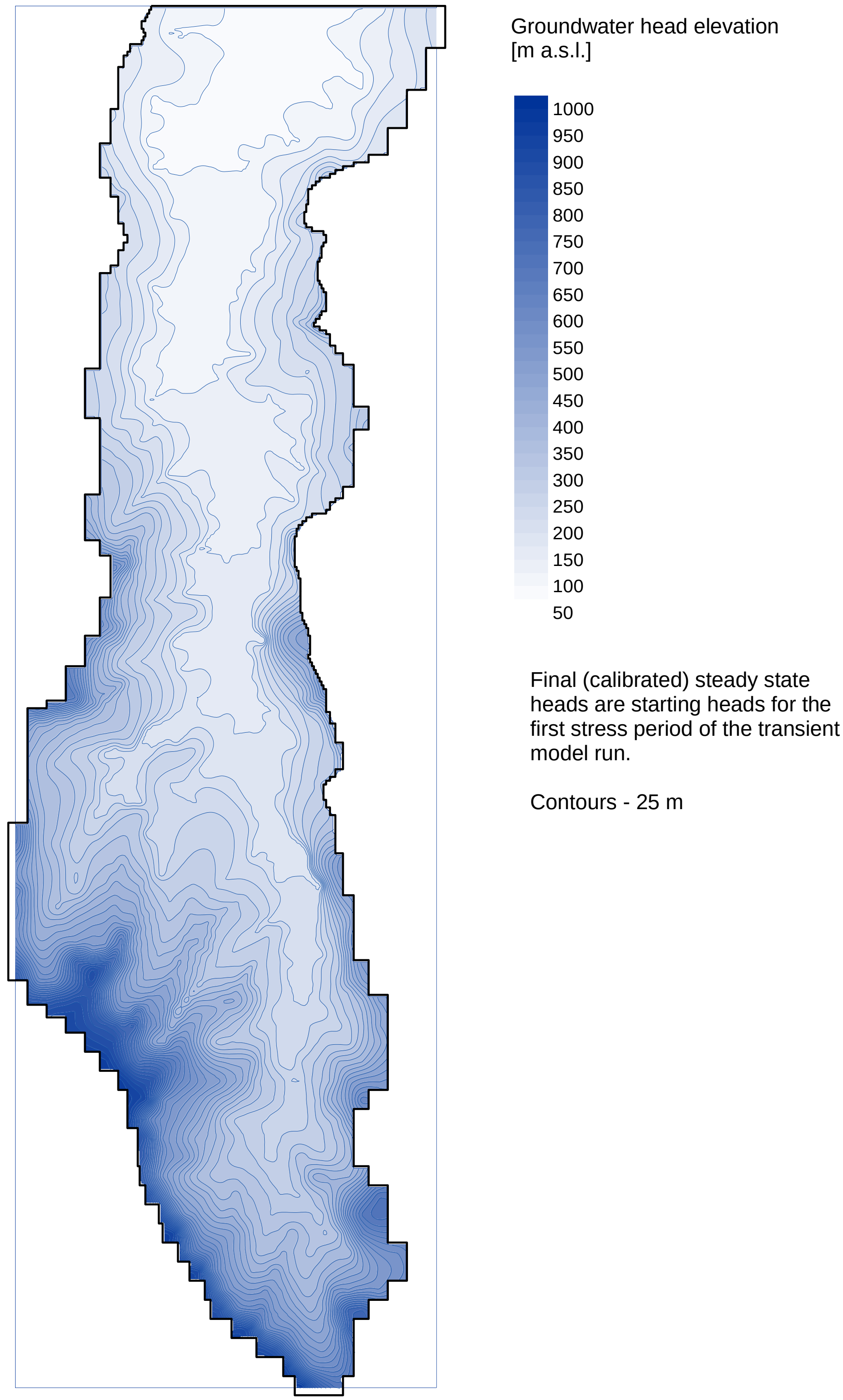


Figure 54. Layer 1: calibrated heads (steady state) at the beginning of the transient model run.

Table 13. Calibrated hydraulic properties.

		HC [m/d]		VHC [m/d]	
		alluvium	regolith	alluvium	regolith
Layer 1	min	0.045356	0.008127	0.002503	0.000449
	1st quartile	48.596620	0.134140	2.682145	0.007403
	median	81.791825	0.179941	4.514254	0.009931
	average	72.470896	0.150019	3.999814	0.008280
	3rd quartile	102.080725	0.179941	5.634039	0.009931
	max	111.615600	0.197935	6.160288	0.010924
	values	8566	20992	8566	20992
Layer 2			0.000727		0.000030
Layer 3			0.000044		0.000004
Layer 4			0.000453		0.000045
Layer 5			0.000299		0.000039
		unconfined storage SY [-]		confined strorage SS [-]	
		alluvium	regolith	alluvium	regolith
Layer 1	min	0.000022	0.000023	0.000079	0.000068
	1st quartile	0.099117	0.043413	0.003999	0.000072
	median	0.100422	0.065180	0.006370	0.000073
	average	0.099596	0.073777	0.005449	0.000073
	3rd quartile	0.101295	0.094874	0.007276	0.000074
	max	0.197586	0.200000	0.007276	0.000076
	values	8566	20992	8566	20992
Layer 2			0.002151		0.000156
Layer 3			0.002073		0.000066
Layer 4			0.001083		0.000044
Layer 5			0.002754		0.000088

The values of Sy (average of 0.0995 or 9.95% for alluvium, 0.0737 or 7.37% for regolith) and Ss (average of 0.00545 or 0.545% for alluvium, 0.000073 or 0. 0073% for regolith) reflect the fact that the groundwater heads within alluvium/regolith (model layer 1) are mostly under confined conditions. Because the conditions in regolith zone rarely revert to unconfined (head is mostly below the base of layer 1), the Ss value was quite insensitive to model calibration and was estimated with higher degree of uncertainty.

5.5.4 The quality of calibration

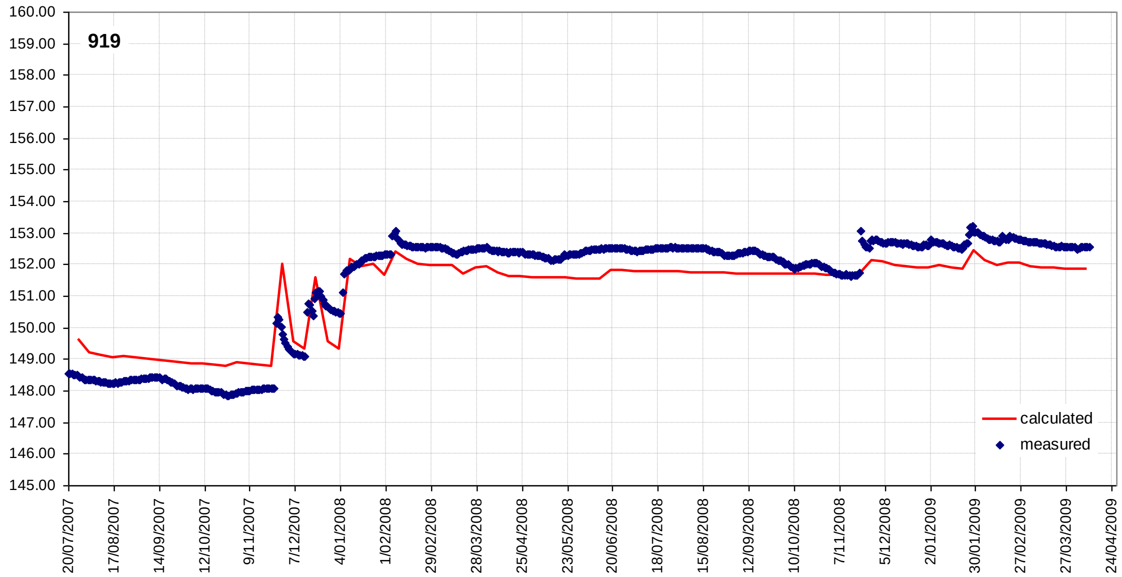
The quality of model calibration can be assessed by checking the performance measures against the specific calibration criteria. For the calibration of the Laidley Creek model calibration acceptance measures based on the Groundwater Flow Modeling Guideline

(Middlemis, 2001) were used. The calibration performance measures include: water balance error, iteration residual error, qualitative and quantitative calibration measures.

The **iteration residual error** was set to be 0.001 m and the model converged in every timestep of the model run. The average absolute **water balance error** for the model run is 0.05%, however, there is one stress periods where the model exceeds desirable error of the 1% of the budget (-1.3%). Although this model behaviour is not ideal, the scale of water balance error is acceptable with respect to the numerical model purpose (Section 5.4.1). For the more detailed discussion on the water balance error see Section 5.6.1.

The **qualitative measures** comprise an assessment of the goodness of fit between calculated (modelled) and measured groundwater heads. This assessment was undertaken by comparing the hydrographs of measured and calculated heads (see Appendix O for comparison of modelled and measured transient heads). It is not possible to simply specify the area with the highest value of residual, because the distribution of residuals is different for each timestep of the simulation. On the other hand, it is possible to quantify the contribution of individual observation groups (measurements of heads or head gradients for individual bore) to the value of the objective function (Doherty, 2006).

There are two conditions of using the contribution of individual observation groups towards the objective function as a calibration measure: (1) all the measurements should have the same weight and (2) there must be a roughly similar count of observations for each of the observation groups. For example, bores equipped with pressure transducers produced a head measurement every 15 minutes. Even thinned out to 1 representative measurement per day, the dataset from the pressure transducer represents 630 measurements, compared to 90 measurements (or less) from manual weekly measurements. If the average residual in both cases is the same, the contribution to the objective function will be 7× higher for the observation group with 630 measurements than for the observation group with 90 measurements. In order to use this measure in a meaningful manner, the contribution of individual observation groups towards the objective function needs to be weighted with respect to the number of observations within



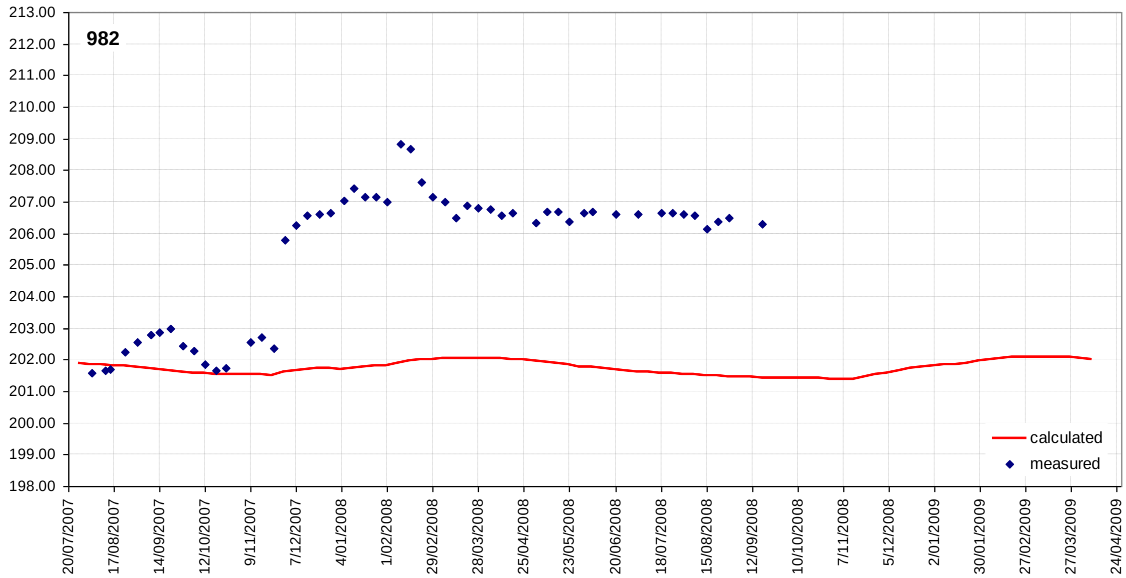


Figure 55. Comparison of predicted and measured heads: an example of a good fit (bore 919) and bad fit (bore 982).

Table 14. Contribution of individual observation groups towards the objective function, weighted with respect to number of observations within a group.

	contribution [m^2]	obs. count	wtd contribution [m^2]		contribution [m^2]	obs. count	wtd contribution [m^2]
h290	9.246	23	0.402	**d290**	1.635	22	0.074
h294	558.280	31	18.009	**d294**	10.170	30	0.339
h295	595.560	38	15.673	**d295**	20.522	37	0.555
h296	567.660	34	16.696	**d296**	10.626	33	0.322
h331	304.430	20	15.222	**d331**	4.610	19	0.243
h332	1989.700	631	3.153	**d332**	2.426	630	0.004
h336	688.600	49	14.053	**d336**	0.747	48	0.016
h337	116.630	49	2.380	**d337**	0.697	48	0.015
h340	29.124	53	0.550	**d340**	0.469	52	0.009
h450	340.870	631	0.540	**d450**	5.372	630	0.009
h472	242.190	392	0.618	**d472**	0.381	391	0.001
h547	113.340	50	2.267	**d547**	1.624	49	0.033
h553	543.760	51	10.662	**d553**	2.330	50	0.047
h786	88.435	22	4.020	**d786**	0.824	21	0.039
h849	460.930	631	0.730	**d849**	0.517	630	0.001
h879	2656.500	631	4.210	**d879**	0.806	630	0.001
h880	4734.800	45	105.218	**d880**	0.734	44	0.017
h883	22606.000	51	443.255	**d883**	0.470	50	0.009
h884	11.595	53	0.219	**d884**	0.343	52	0.007
h885	3004.100	54	55.631	**d885**	2.370	53	0.045
h887	5.588	52	0.107	**d887**	0.269	51	0.005
h916	2192.000	51	42.980	**d916**	0.307	50	0.006
h917	300.780	55	5.469	**d917**	4.983	54	0.092
h919	320.620	631	0.508	**d919**	11.048	630	0.018
h920	142.670	55	2.594	**d920**	3.900	54	0.072
h982	947.640	53	17.880	**d982**	19.209	52	0.369
h983	3558.700	617	5.768	**d983**	9.006	616	0.015
h986	804.600	52	15.473	**d986**	7.157	51	0.140
∑	47934.348			∑	123.553		

Group prefix **h** signifies grouping with respect to head mesurement, prefix **d** signifies grouping with respect to head diffecernces (gradient) mesurement. Observation group *dfot* was removed from the assesment process by weighting.

the observation group (Table 14). The weighted contribution can be then mapped in order to visualise the spatial distribution of calibration error (Figure 58).

With respect to head observations, the highest contributors to model calibration error are bores outside or on the edge of the alluvium (880, 883, 885) and some of the bores in the lower alluvium, in the area of low permeability (916, 986, 982). The error of bores outside of the alluvium can be explained by the model conceptualization of alluvium and weathered regolith zone. While the alluvium is structurally quite well defined, the weathered regolith zone is defined only as "non-alluvium" with thickness arbitrarily set to 20 m. The second, probably more significant contributor to error for non-alluvium fringe bores is the DEM (see Section 5.3.3).

If the calibration process tries to match the calculated heads against "wrong" observation data, it will most likely have to compensate for the error by pushing the hydraulic parameters and/or recharge out of realistic bounds, just in order to achieve better (but structurally wrong) data fit.

With respect to the head gradients observations, the highest contributors to model error are bores 331, 295 and 982. As the head gradients really represent the recharge trend, a better fit might be achieved by a possibly denser grid and detailed information about spatial variability of hydraulic properties, especially about specific yield and specific storage.

The most important of the **quantitative measures** is the sum of squared weighted residuals (SSQ) used by PEST as the optimization target (objective function). The value of objective function for transient run is 48058 [m^2] where head observation groups contributed 47934 [m^2] and head gradients observations contributed 123 [m^2] (without *dfot* contribution). Other calibration performance measures (with respect to heads) are listed in Table 15. See also Appendix N for calibration measures definition and overview (Middlemis, 2001)

Table 15. Transient model run - calibration performance measures for head observations

Abbreviation	Calibration performance measure	Unit	Value
SR	weighted sum of residuals	[m]	8804.600
MSR	mean sum of residuals	[m]	1.725
SMSR	scaled mean sum of residuals	[%]	1.357
SSQ	sum of squared residuals	[m^2]	47934.290
MSSQ	mean sum of squared residuals	[m^2]	9.390
RMS	root mean square	[m]	3.064
RMFS	root mean fraction square	[%]	2.301
SRMFS	scaled root mean fraction square	[%]	2.683
SRMS	scaled root mean square	[%]	2.412

The scatterplot of modelled and measured heads (Figure 56) does not show any clear trend in the distribution of residuals. The only clear outlier is the observation group associated with bore 883. The reason for the difference between the observed and calculated heads in bore 883 is most likely the incorrect DEM, because although the comparison of calculated and measured heads show a bad fit, the head gradients representing the flow regime show a good fit (see Table 14).

The scatterplot of modelled and measured head gradients (Figure 57) is strongly influenced by the magnitude of the *dfot* observation group. The full scale plot (Figure 57a) does not offer any interesting information, the detailed view at the unobfuscated head gradients distribution (Figure 57b) however presents two interesting trends: (1) clustering of points along both axes and (2) an irregular spread of the datapoints in the area of 4th quadrant of the scatterplot (Q IV).

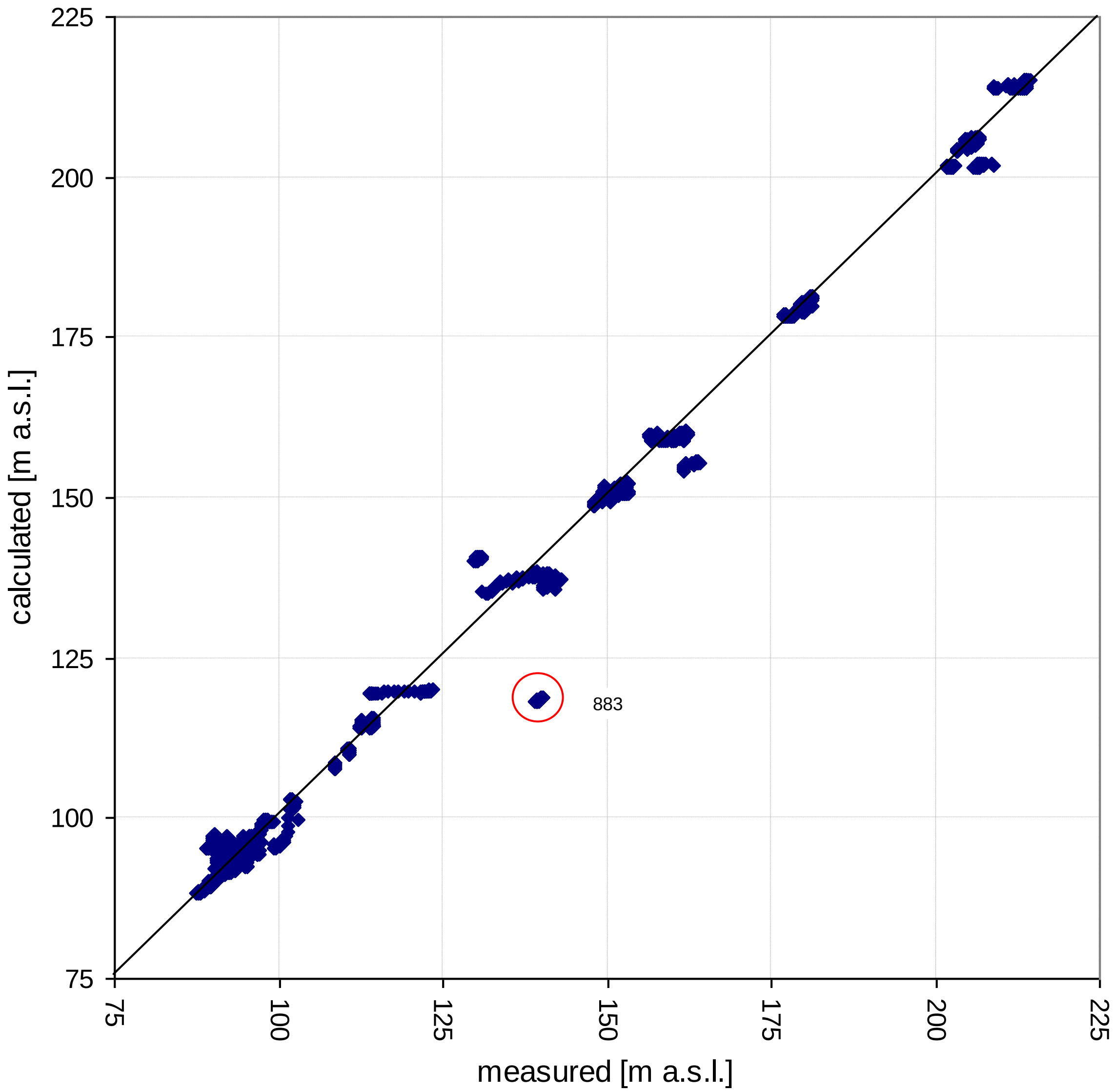


Figure 56. Scatterplot of calculated vs. measured heads showing the transient model fit.

The head gradients were calculated using formula:

$$\Delta H = H_{(i)} - H_{(i+1)}$$

Based on the above presented formula, the positive value of ΔH means that the heads are falling and negative ΔH represents recharging aquifer (rising heads).

With respect to the Figure 57b the clustering of the data points along both vertical and horizontal axis of the scatterplot represents the lack of fit between measured and calculated change in the groundwater head. If the datapoints are clustered along the horizontal axis, the observed data (measurements) are changing, but the calculated (modelled) hydrograph is very flat with almost no change (e.g. bore 982). If the datapoints are clustered along the vertical axes, the observed hydrograph shows a smaller degree of head change then the calculated (modelled) hydrograph (e.g. bores 332, 337, 547 or 553).

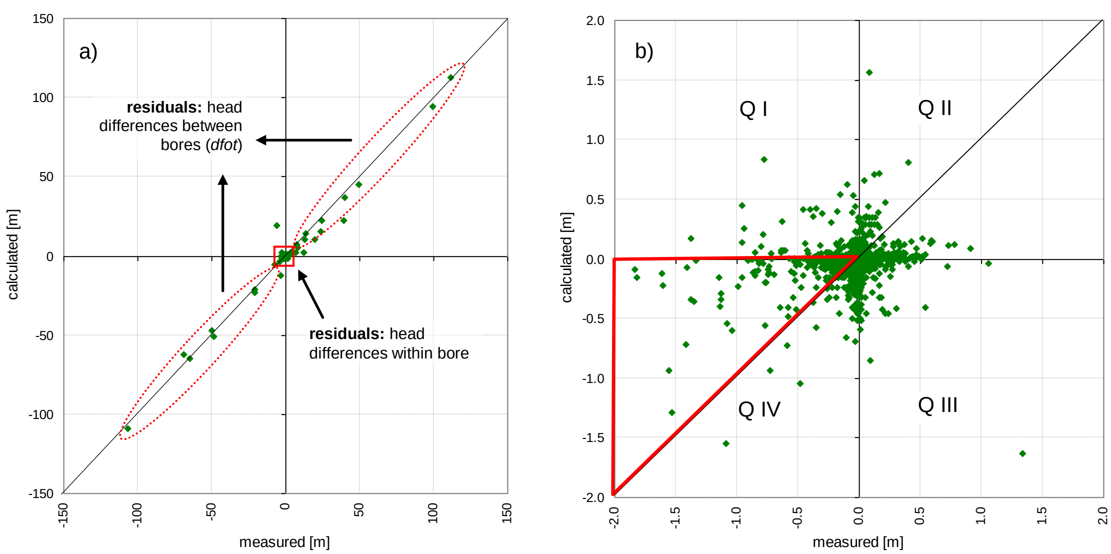
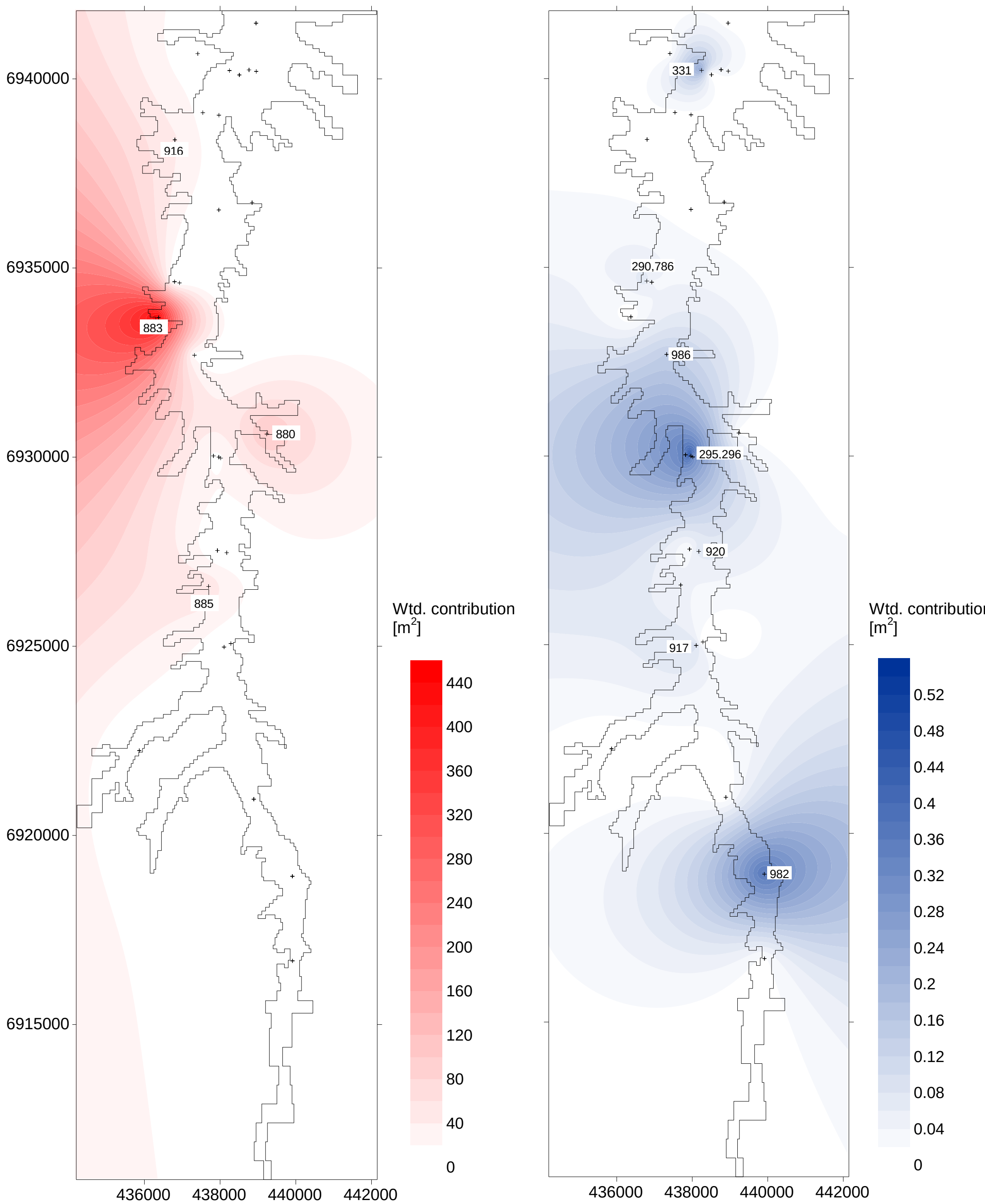


Figure 57. Scatterplot of calculated vs. measured head gradients. Plot a) shows the whole dataset (large head differences due to *dfot* observation group), plot b) shows only subset within the range of -2 m to 2 m.

The datapoints in the fourth quadrant (Q IV) of the scatterplot are located mostly above the "perfect fit" line, but below the horizontal axis. The position in the Q IV signifies recharge for both modelled and measured hydrographs, position above the "perfect fit" line (red triangle, Figure 57b) signifies that the modelled aquifer was reacting more slowly than the physical aquifer. In other words, the modelled alluvium is recharged at a



a) heads

b) head gradients

Figure 58. Spatial distribution of the weighted contribution of individual observation groups towards the objective function.

lower rate than the real alluvial aquifer. The model however behaves this way only during recharge events, the discharge rate (quadrant Q II) seems to be more proportionate for both model and real alluvial aquifer.

The reason behind the slower recharge of the modelled aquifer probably lies in the comparison of the real alluvium and modelled alluvium. The real alluvial aquifer is highly heterogeneous and its hydraulic properties vary within a couple of meters and due to this heterogeneity and granularity, the existence of preferential flowpaths can lead to really fast recharge, especially if the aquifer was previously dry. In spite of the use of pilot points to approximate the variability of hydraulic parameters, the interpolated parameter field is always *smooth* and lacks the heterogeneity of the real alluvial aquifer.

5.6 Water budget and inter-aquifer flows

Quantifying flow processes within the groundwater model, the water budget is often used as an important measure of model quality. The budget is by default calculated for the whole model domain and presented in a regular model output file, however the calculated and recorded cell-by-cell flows can be used to quantify intra- and inter-aquifer flows within the modeling domain.

In terms of the water budget for the whole model domain, the inflow terms are: specified heads, river and recharge. Correspondingly, the outflow terms are: specified heads, river and wells (pumping). In terms of the inter-aquifer processes, the flows were calculated between alluvium and individual bedrock aquifers (MRV basalts, Walloon Coal Measures, Koukandowie Formation and Gatton Sandstone) as well as between the consolidated aquifer units themselves.

All previous modeling studies undertaken in the wider Lockyer Valley area focused on the processes within the alluvium (Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005), making the boundary between the alluvium and bedrock a no-flow boundary. Although this approach makes the models simpler and faster (and thus easier and more practical to use as a predictive tool with respect to distribution of the groundwater head in alluvium), it also makes it impossible for the modeller to examine the hydraulic connectivity between the alluvium and the bedrock.

In case of Laidley Creek catchment model, the calculated values of flows between alluvium and bedrock are in fact model *predictions*. In the later parameter uncertainty overview, the analysis is related to those flow predictions. The uncertainty analysis shows how large an influence each model parameter can carry with respect to flow predictions and how the uncertainties related to individual parameters changed as a result of model calibration process.

5.6.1 Water budget error

The budget error (water balance error) is one of the measures of the quality of model setup. The average absolute water balance error for the model run was 0.05%, however, the budget error exceeded 1% at the beginning of the stress period 69 (Figure 59). The increased budget errors can be generally associated with the sudden change in the flow regime. This is exactly the case of stress period 69, during which the catchment experienced a strong recharge event driven by the rainfall and creek flow events at 20/11/2008. See Figure 17 for rainfall and creek flow visualisation, see Appendix B for rainfall data and Appendix D for Laidley Creek flow data.

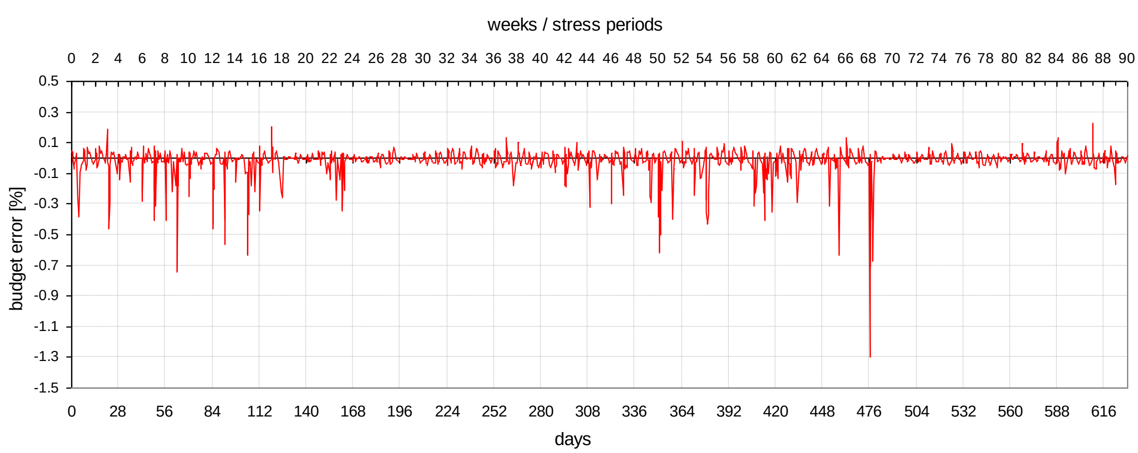


Figure 59. Budget error during the transient model run.

It would be possible to decrease the budget error further below 1% by decreasing the timestepping. This setup would make the model run significantly slower. It might be prudent to strive for the minimal balance error under the conditions of predictive numerical model run. However, under the circumstances of interpretative model use, an occasional increase over 1% of water budget error is deemed acceptable.

5.6.2 Model domain water budget

The model budget summary is presented in digital form (MS Excel spreadsheet) in the file /model/output/budget/budget_transient_summary.xls.

5.6.2.1 Specified heads flows

Specified (time variant) heads are located across the alluvium, along the length of the northern model boundary. A specified head boundary allows the water to be removed from the model via cross-boundary outflow. Specified heads elevations are bound to the observed elevations in bore 450 and are on average 0.6 m lower than the observed head in this bore. Although conceptually the boundary should facilitate the cross boundary outflows, the model generates both inflows and outflows (Figure 60).

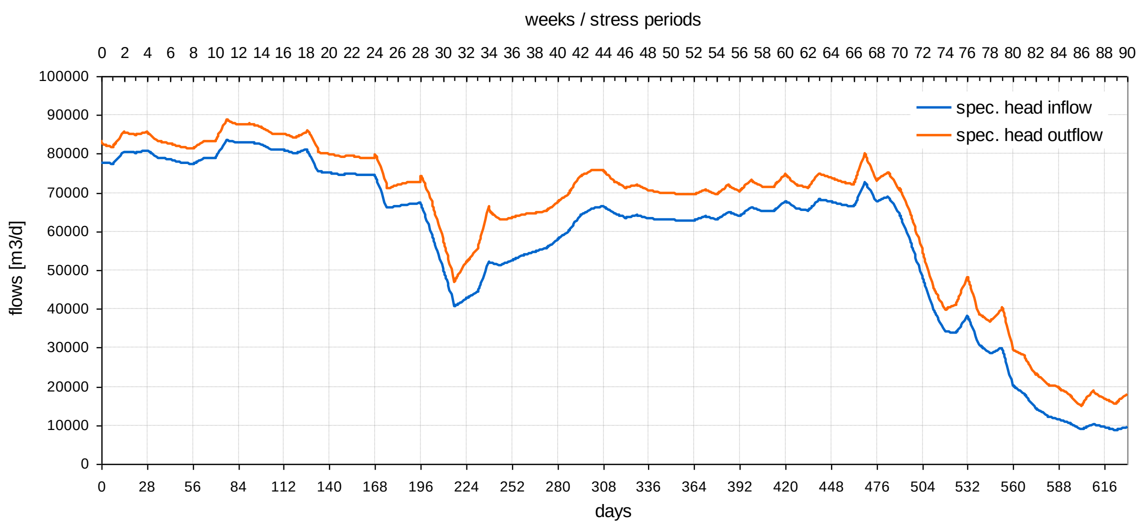


Figure 60. Flows in and out of specified head boundary.

The generation of both model inflows and outflows is predicted by the model boundary setup (Figure 61). The position and count of specified head cells cannot change during the model run. Also, by definition, the groundwater head elevation in the specified head cell is not allowed to drop below the bottom of this cell.

In order to simulate the situation during which the head in the alluvium is dropping and the extent of the boundary is decreasing, the specified head can be set at an elevation just above the bottom of the cell. This adjustment however leads to the creation of an artifical hydraulic gradient between neighbouring cells (Figure 61b) and hence generates flows between neighbouring cells. In other words, the inflows through the model boundary under the described conditions are an artefact of the solution of the transient problem.

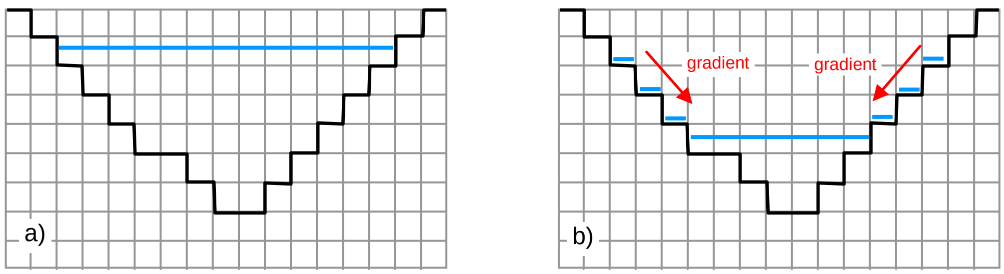


Figure 61. Idealized crossections demonstrating the specified heads setup in case of high (a) and low (b) groundwater levels in alluvium.

The actual outflow across the model boundary can be calculated as the difference between model inflows and outflows. This value varies between 3914 m^3/day and 14318 m^3/day (6886 m^3/day on average), which would translate to approximately 4342 ML for the duration of the model run (630 days). This value is slightly higher then the upper limit of the cross-boundary flow 2252 ML estimated for the conceptual model budget overview (Section 5.3.5).

5.6.2.2 Rainfall, irrigation return and recharge

Diffuse recharge of the uppermost model layer depends on two parameters: rainfall and irrigation return. The total recharge into the model domain is presented in Figure 62.

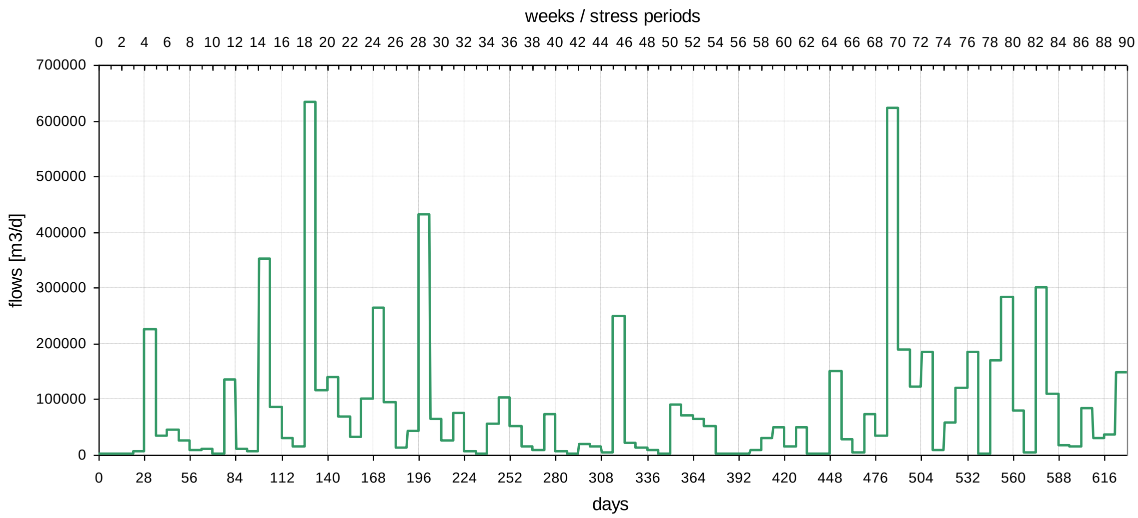


Figure 62. Combined recharge into the model domain.

The total recharge into the model for the period of the model run is 50880 ML, out of this approximately 1627 ML (approximately 23% of the water pumped for irrigation, see Section 5.6.2.4) comes from the irrigation return and 49253 ML comes from the rainfall. On average, the recharge from rainfall constitutes about 8.8% of rainfall across the catchment.

5.6.2.3 River recharge and discharge

Recharge of the alluvial aquifer from Laidley Creek, as well as discharge of the alluvium into Laidley Creek is highly variable with time and depends on the amount of water in Laidley Creek (creek stage) and the creek bed conductance term (discussed in Section 5.3.5). Depending on the creek stage and aquifer head elevation, Laidley Creek becomes either a losing stream which recharges the alluvium, or a gaining stream where the creek is recharged from the alluvium.

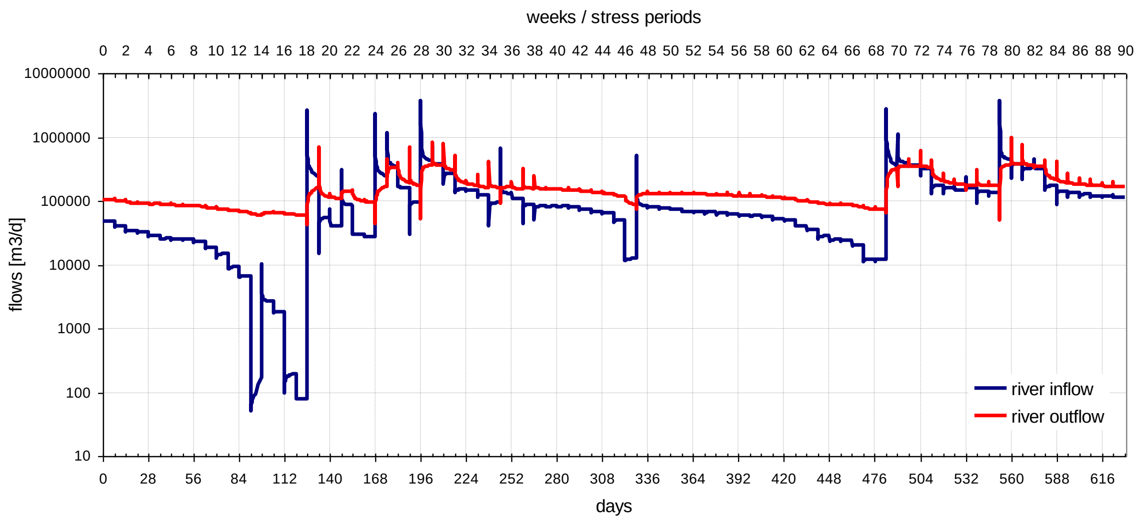


Figure 63. Seepage through the Laidley Creek bed: inflows and outflows.

In total, recharge from alluvium (gaining creek; river outflow) is approximately 99447 ML, recharge to alluvium (losing creek; river inflow) is 74850 ML, resulting in a net creek recharge (and aquifer discharge) of 24597 ML during the 630 days of the transient model run.

5.6.2.4 Pumping

From a conceptual point of view, the groundwater extraction for irrigation purposes was discussed in Section 5.4.4.3. Because of the self-imposed limiting condition of a minimum starting head of 0.75 m above the base of alluvium, 101 pumps become inactive.

As no data concerning pumping rates were available, the rate was constant during the model run. In total, 115 pumps were active, extracting 100 m^3/day/pump (11.5 ML/day or 7245 ML during the interval of model run; 2.17 ML/year per hectare of irrigated land).

5.6.2.5 Numerical model budget overview

An overview of the calculated flows during the period of the numerical model run (20/7/2007 to 10/4/2009, 630 days) is presented in Table 16. The inflow into the model domain is driven by rainfall (with added recharge from irrigation return) and was quantified as 50880 ML. The outflow comprises Laidley Creek flow (24597 ML; the alluvium recharges the creek), pumping (115 pumps, extracting 7245 ML) and cross-boundary flow (4342 ML). The difference between inflows and outflows represents the change in groundwater storage. During the 630 days of the model run, the aquifers of Laidley Creek catchment were recharged by 14696 ML.

Table 16. Post calibration quantification of the water budget for the period between 20/7/2007 and 10/4/2009 – 630 days (period of transient numerical model run).

Inflows [ML]		Outflows [ML]	
rainfall recharge	49207	cross boundary flow	4342
irrigation return	1627	river	24597
		pumping	7245
∑ in:	50880	∑ out:	36184

5.6.3 Inter-aquifer flows: model predictions

The hydraulic connection between the bedrock aquifers and alluvium has been shown to influence the water quality in the alluvium, especially during the drier periods when groundwater heads in the alluvium are low (Section 4.4.8). Although the rate of the inflow into the alluvium might be very low, the increased salinity of the bedrock sandstone groundwaters poses a potential environmental risk for groundwater users.

As previous groundwater models within Lockyer Valley (Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005) regarded the boundary between bedrock and alluvium as impermeable, the existence of inflows from sandstones was discussed on a qualitative level but was never quantified.

During the process of the groundwater model run, flows between every cell in the model and any of its neighbouring cells are calculated. If different flow zones for every model layer can be defined, the cell-by-cell flows can be then summarized for each of the defined zones. The zone's definition is completely at the discretion of the modeller and depends on the modeling goals. For example, in management applications, zones can be defined as pumping entitlement areas, whereas in mining applications, the mine dewatering zones can be defined as the pit outlines. In the Laidley Creek model, zones were defined as the geological (stratigraphic) units.

In order to explore the flows between individual aquifers, five zones corresponding to the model layers (aquifers) were defined (see Figure 42):

- flow zone 100 - Laidley Creek alluvium
- flow zone 200 - Main Range Volcanics
- flow zone 300 - Walloon Coal Measures
- flow zone 400 - Koukandowie Formation
- flow zone 500 - Gatton Sandstone

Because of the way the flow zones were set up, the flows could be calculated not only between alluvium and bedrock aquifers, but also between individual sedimentary aquifers.

5.6.3.1 Flows between alluvium and bedrock aquifers

The calculated flows between the alluvium and the bedrock aquifers are presented in Figure 64. The chart shows that the recharge from bedrock aquifers (both basalts and sandstones) is relatively stable. The direction of the recharge process is from bedrock to alluvium during the entire model run, no reversal of flow (from alluvium to bedrock aquifer) was observed. Also contrary to the model conceptualization, the overall flows between the alluvium and bedrock were calculated to be higher than expected. While the average recharge volumes from rainfall and the river for alluvium (zone 100) are 5896 and 10046 ML respectively, the average inflows from the bedrock aquifers into the alluvium were calculated to be 4433 ML (from MRV basalts), 3377 ML (from Walloon Coal Measures), 7801 ML (from Koukandowie Formation) and 4064 ML (from Gatton Sandstone).

When summarized, the inflow of saline groundwaters from bedrock sandstone aquifers represents approximately 43% of all inflows into the alluvium (see Table 17). The mixing analysis based on major ion chemistry (see Section 4.4.8) suggests the volumetric contribution of 2-4% of Gatton Sandstone groundwater into the alluvial groundwater. This value of modelled flow between bedrock aquifers and alluvium is unrealistically high and the topic of reliability of those flows will be discussed in the next chapter (Section 5.7).

Table 17. Modelled groundwater mixing in alluvium.

inflows from Clarence-Moreton Basin aquifers (increased salinity)		
Walloon Coal Measures	3376.8 ML	9.5%
Koukandowie Formation	7800.8 ML	21.9%
Gatton Sandstone	4064.4 ML	11.4%
∑	**15242.0 ML**	**42.8%**
inflows/recharge from other sources		
Laidley Creek	10045.7 ML	28.2%
rainfall (diffuse recharge)	5896.2 ML	16.6%
Main Range Volcanics basalts	4432.5 ML	12.4%
∑	**20374.4 ML**	**57.2%**
total inflows	**35616.4**	**100.0%**

Inflow volumes are calculated for the period of model run (630 days).

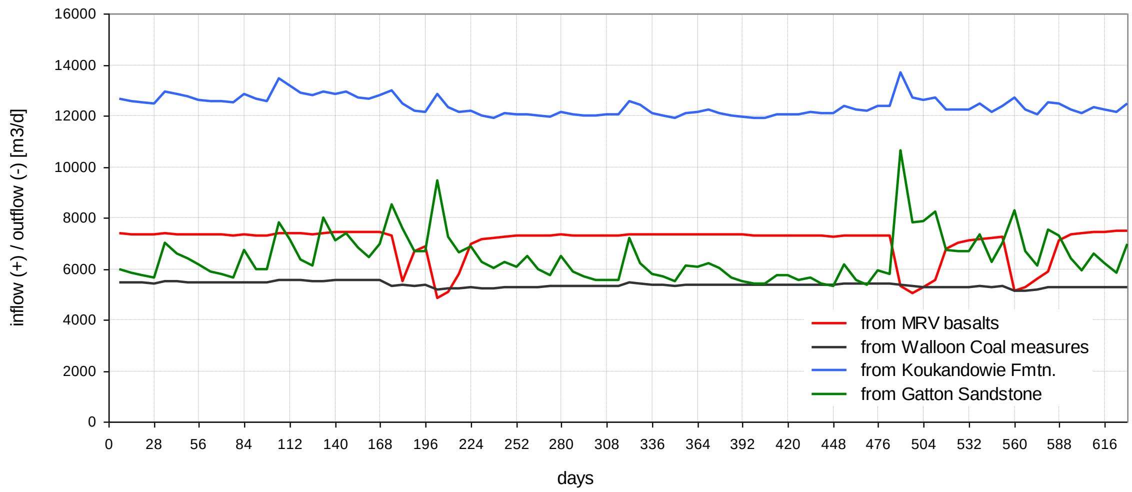


Figure 64. Inflows from MRV basalts and Clarence-Moreton Basin sedimentary aquifers into the Laidley Creek alluvium (zone 100).

5.6.3.2 Flow between non-alluvial aquifers

Compared to the flows from and into the alluvium, the flows between non-alluvial aquifers are smaller. Given the low hydraulic conductivities compared to the alluvium, the discharge rates are also more stable and do not change rapidly as a result of diffuse recharge from rainfall (Figure 65).

In all cases, the stratigraphically higher aquifer recharges the stratigraphically lower one. The rate of recharge of the "lower" aquifer depends on the extent and volume of the "upper" aquifer, as well as on the hydraulic properties of both.

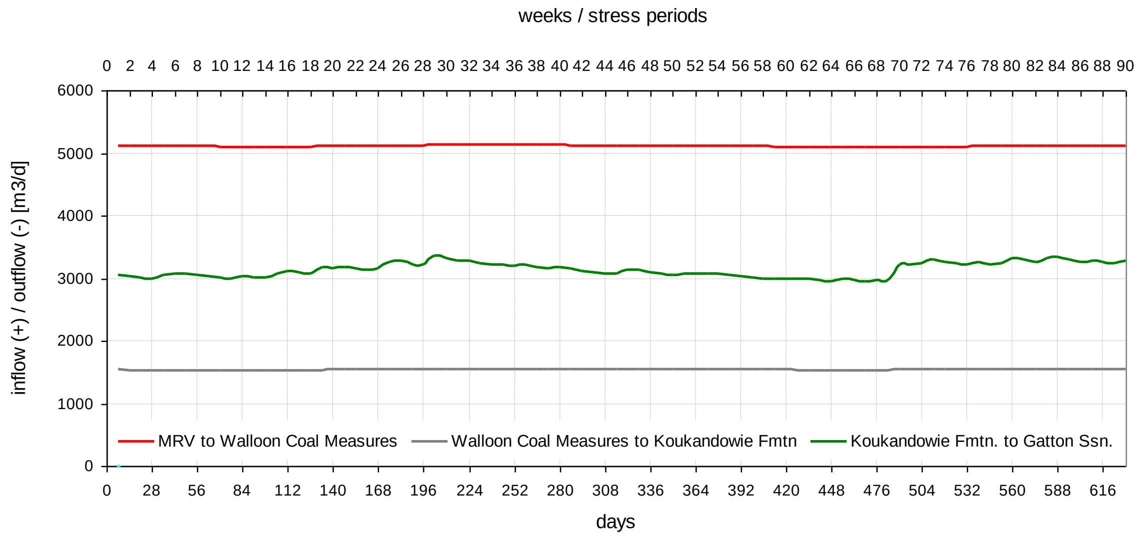


Figure 65. Flows between non-alluvial aquifers (absolute values of discharge).

The average flow from Main Range Volcanics basalts to Walloon Coal Measures (Figure 65) is about 5.1 ML/d resulting in a total discharge of 3219 ML from basalts over the period of the model run (630 days). The average flow from the Walloon Coal Measures to Koukandowie Formation is approximately 1.5 ML/d, resulting in 968.5 ML of discharge from Walloon Coal Measures. The average flow from Koukandowie Formation into Gatton Sandstone is 3.1 ML/d which results in 1974.5 ML of discharge.

The rainfall recharge of non-alluvial aquifers (Figure 66) depends on the surface area of the aquifer as well as on the rainfall intensity in the particular recharge zone. Predictably, the most diffuse direct recharge is received by MRV basalts (zone 200) as they have the largest area among all the non-alluvial recharge zones and are located in the area with the highest average rainfall. Given the relatively small area of Walloon Coal Measure outcrops (zone 300), the direct recharge into WCM is small. Comparably, a small recharge rate is applied to the Gatton Sandstone, however the limiting factor is the very low hydraulic conductivity of this stratigraphic unit.

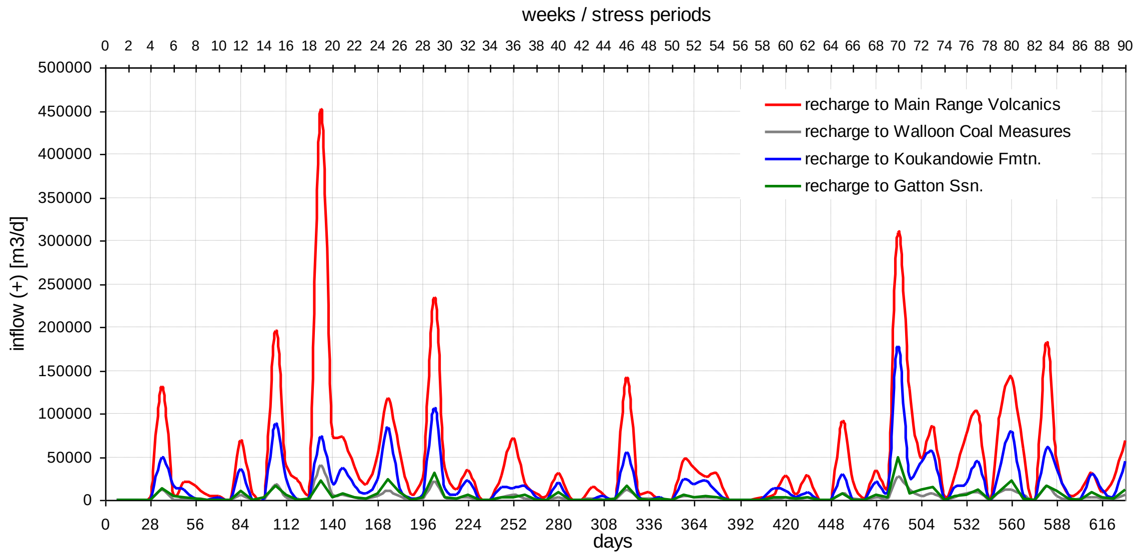


Figure 66. Diffuse (rainfall) recharge into individual flow zones.

5.7 Data worth and predictive uncertainty

5.7.1 Background and methodology

The purpose of the majority of models is to be used as a management support tools. In this role, models are deployed to make predictions of the behaviour of groundwater systems. Some examples of model predictions are: the nature of change of groundwater heads as a response of increased pumping, the calculation of speed of travel of contaminants, or the calculation of flows within the aquifer or between different aquifers.

Models are often calibrated against a single type of observation, usually groundwater heads. Heads are reasonably easy to obtain as head monitoring is an integral part of almost every hydrogeological study and, also, historical records often exist. Model parameters are then calibrated against measured heads and when the model is able to replicate the observed head distribution (given the appropriate model excitation), it is usually considered to be calibrated and suitable to be used for predictive analysis. It is, however, necessary to understand that model predictions of processes that did not contribute to the calibration, can be considerably in error, although they match the historical data perfectly (Moore and Doherty, 2005).

Although this approach (i.e. calibrate against heads first, then try to predict flow rates, concentrations, temperatures etc.) is common, the implications of this approach with respect to the predictive uncertainty of groundwater models are not well understood. The Laidley Creek model is a perfect example of such a "traditional" approach, where the model was calibrated against groundwater head and head gradients datasets and is in part used to examine flows within different aquifers. Using different types of datasets for calibration (heads) and prediction (flows) provides an opportunity to examine model parameters and their influence over model predictions, enabling the most (or least) important ones to be determined.

If the uncertainty derived from the implementation of the numerical solution to the groundwater equation is ignored, the most important sources of model predictive uncertainty are the model parameters. Information defining model parameters can be either direct information describing physical model properties such as hydraulic properties and their distribution or indirect information describing model state such as groundwater heads, groundwater flows, contaminant concentrations etc. (Moore and Doherty, 2005).

As model predictions depend on a set of hydraulic parameters of unknown complexity, the scale of this complexity is determined by predictive uncertainty (the propensity of the model for error). Assuming the linearity of the model where the relationship between model outputs and model parameters can be represented by a matrix whose coefficients are independent of the parameter values, the predictive uncertainty can then be calculated as a byproduct of the model calibration through regularized inversion. Because the uncertainty of the model prediction can always be reduced by the acquisition of additional data, the worth of this data can be assessed in terms of its ability to decrease the uncertainty of the model prediction (Dausman et al., 2010).

Predictive uncertainty variance of a prediction ***s*** can be expressed using the formula (Dausman et al., 2010):

$$\sigma_s^2 = y^t C(p) y - y^t C(p) X^t [X C(p) X^t + C(\varepsilon)]^{-1} X C(p) y \qquad (1)$$

where:

- p — is a set of parameters used by the model; C(p) is a covariance matrix of innate parameter variability;
- $C(\varepsilon)$ — is the covariance matrix of measurement noise;
- X — is the observation sensitivity matrix; it represents the means by which the model outputs are calculated from model parameters;
- y — is the prediction sensitivity vector.

The precalibration uncertainty is represented by the first term on the right side of the equation, the second term represents the reduction of precalibration uncertainty through the observations.

In the course of the model uncertainty analysis, the sensitivity matrix *X* can be calculated by varying each model parameter incrementally and computing the change in observation values. Then, the excitation in the form of the change of the pumping rate is introduced into the model and the predictive sensitivity vector *y* is calculated. The predictive uncertainty variance and predictive uncertainty for a specific prediction can then be obtained using formula (1).

In order to assess the worth of an individual observation or observation group towards the prediction, this observation (or observation group) is removed from the model and then the variance is recalculated. The difference between "before the observation was removed" and "after the observation was removed" variances then represents the worth of this particular observation (Dausman et al., 2010).

The data worth of observation (or observation groups) together with parameter uncertainty contribution towards the uncertainty of model predictions for the Laidley Creek model was calculated using the PREDUNC set of groundwater utilities (following the methodology described above) from John Doherty (Doherty, 2006; Doherty, 2007; Doherty, 2011). Three utilities were used: PREDUNC1 to analyse so called "notional predictive uncertainty reduction", PREDUNC4 to calculate the contribution of individual parameters towards the predictive uncertainties and PREDUNC5 to calculate the data worth by observation addition and reduction.

The predictions used to undertake the analysis were the inter-aquifer flows i.e. groundwater flows between alluvium and bedrock aquifers. Because the flows were computed for all flow zones and all stress periods, it would not be practical to analyse the uncertainties with respect to all 360 flow predictions. Instead, 4 representative flow event predictions were selected for every flow zone: flows in stress period 1 which represent the beginning of the model run, stress periods 29 and 70 representing significant recharge events, and the last stress period 90 representing the end of the model run.

5.7.2 Overall pre- and post-calibration uncertainties

The overall uncertainty reduction achieved during the calibration process was calculated using the PREDUNC1 utility. The result of this analysis shows pre- and post-calibration uncertainties associated with individual predictions representing the flows between alluvium and bedrock aquifers. There are four predictions (four selected stress periods: 1, 29, 70 and 90) for the flow between the alluvium each of the other stratigraphic units (zone 200: MRV basalts; zone 300: WCM; zone 400: Koukandowie Fmtn; zone 500: Gatton Ssn.).

The analysis shows that the overall uncertainty towards all of the predictions have been greatly reduced by the calibration process, the biggest relative reduction was for the flow predictions in zone 500 (flows between the alluvium and Gatton Sandstone).

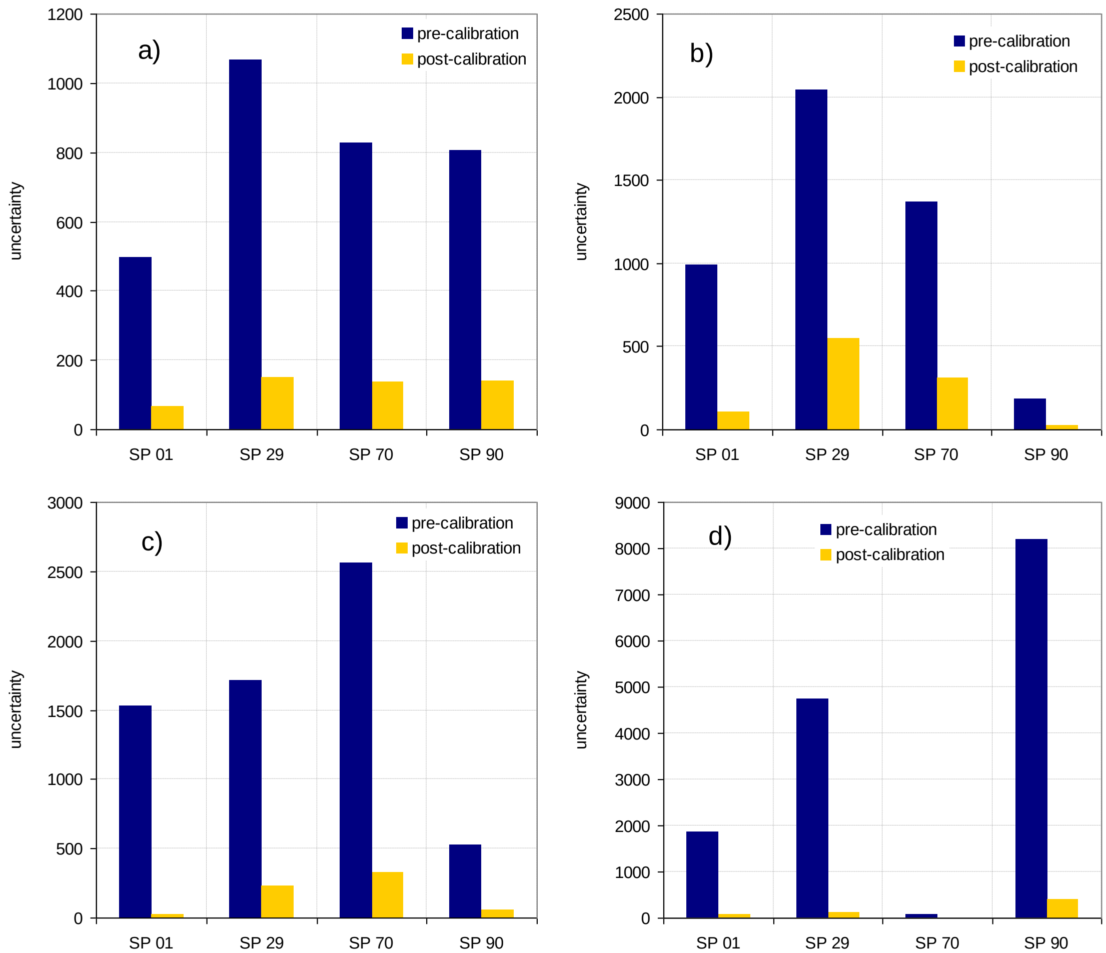


Figure 67. Notional predictive uncertainty reduction; pre- and post calibration uncertainties of flows for particular stress periods between:

a) Laidley Creek alluvium and Main Range Volcanics basalts

b) Laidley Creek alluvium and Walloon Coal Measures

c) Laidley Creek alluvium and Koukandowie Formation

d) Laidley Creek alluvium and Gatton Sandstone

5.7.3 Parameter contributions to uncertainty

Similarly to PREDUNC1, the PREDUNC4 utility was used to compute the reduction of the uncertainty of a specific prediction. The reduction is however calculated for an individual parameter or parameter group, identifiying the parameters in terms of their importance for the calibration/predictive process. Both pre- and post-calibration uncertainties for individual parameters were calculated.

In terms of the hydraulic parameters, the level of parameter uncertainty depends on a particular prediction. If the prediction is related to zone 200, than the most uncertainty will be carried by some of the parameters pertinent to model layer 2 (MRV basalts), e.g. horizontal hydraulic conductivity (`hc-l2`) and specific storage coefficient (`ss-l2`). If the prediction is related to zone 300, the most uncertain parameters are vertical hydraulic conductivity (`vhc-l3`) and specific storage coefficient (`ss-l3`). The full results of the parameter uncertainty analysis of hydraulic properties are presented in full in the digital appendix (/model/output/param_uncertainty.xls, tab PREDUNC4) and visualized as charts in Figure 68 to 72.

Similarly to the uncertainty of hydraulic parameters, the uncertainty of recharge depends on the prediction. However, as the recharge in the alluvium was applied with the use of pilot points, the recharge uncertainty can be related to individual pilot points and thus expressed spatially (Figure 72). With respect to the observations of flows between alluvium and both the MRV basalts (zone 200) and the Walloon Coal Measures (zone 300), the highest uncertainty was observed for point 36 (Figure 72a, b and c). The highest uncertainty for predictions of flows between alluvium and Koukandowie Formation (zone 400) was calculated at point 26 (Figure 72a and d), while the highest uncertainty for the predictions of flows between the alluvium and Gatton Sandstone (zone 500) was calculated at recharge point 2 (Figure 72a and e).

Uncertainty of the vertical hydraulic conductivities of the creek bed (Figure 73 to 77) was calculated for Main Camp Creek (`r2cnd` - single parameter), minor drainage cells (`r3cnd` - single parameter) and all zones of Laidley Creek (16 parameters - `r1z`*XX*, where *XX* represents the zone number; for the location of individual creek bed conductivity zones see Figure 48). The highest uncertainties were calculated for Laidley

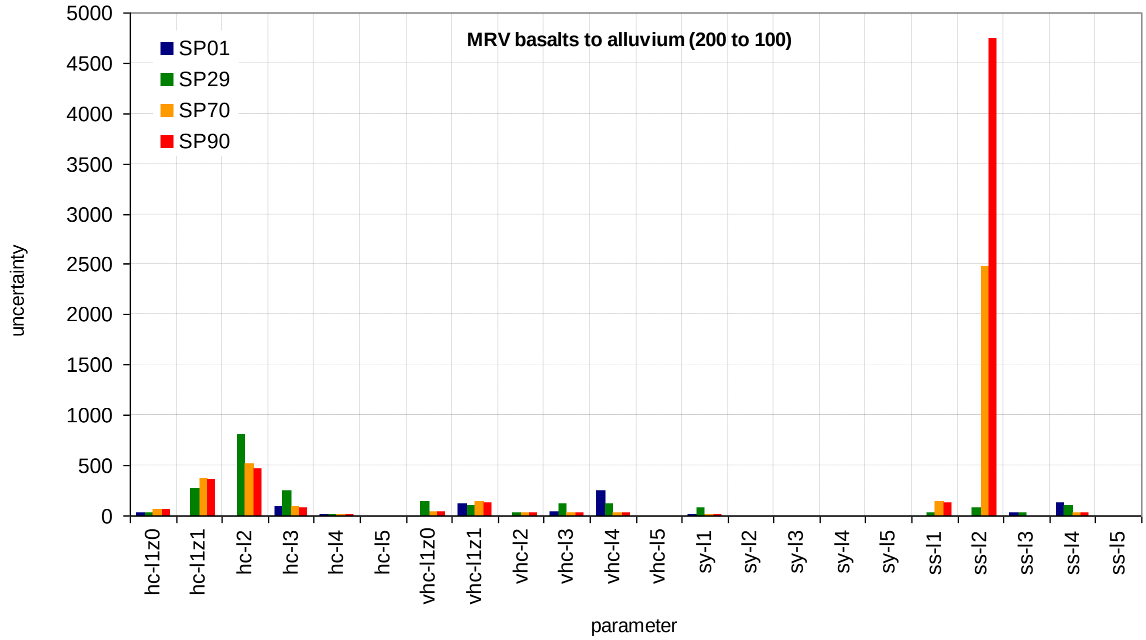


Figure 68. Uncertainties of estimated hydraulic properties with respect to the flows between alluvium (zone 100) and Main Range Volcanics (zone 200).

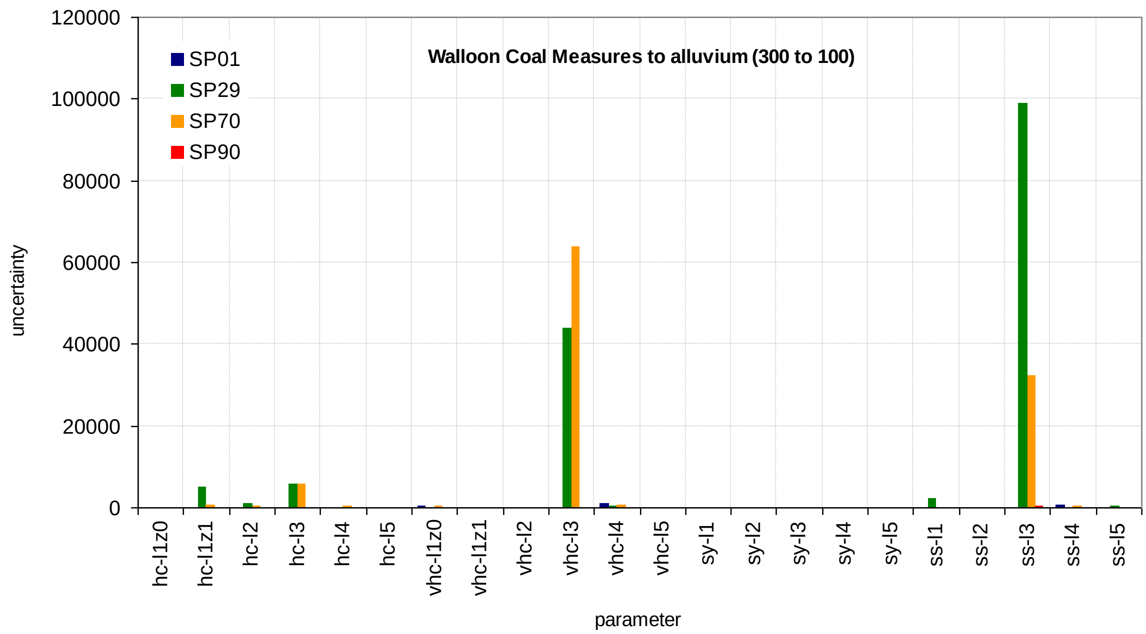


Figure 69. Uncertainties of estimated hydraulic properties with respect to the flows between alluvium (zone 100) and Walloon Coal Measures (zone 300).

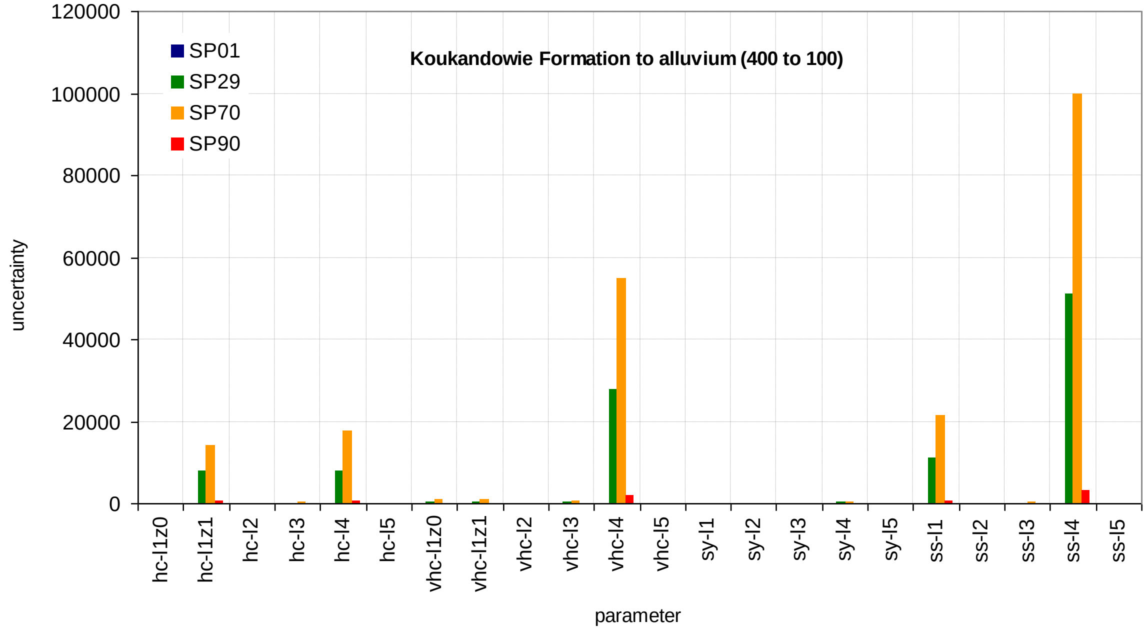


Figure 70. Uncertainties of estimated hydraulic properties with respect to the flows between alluvium (zone 100) and Koukandowie Formation (zone 400).

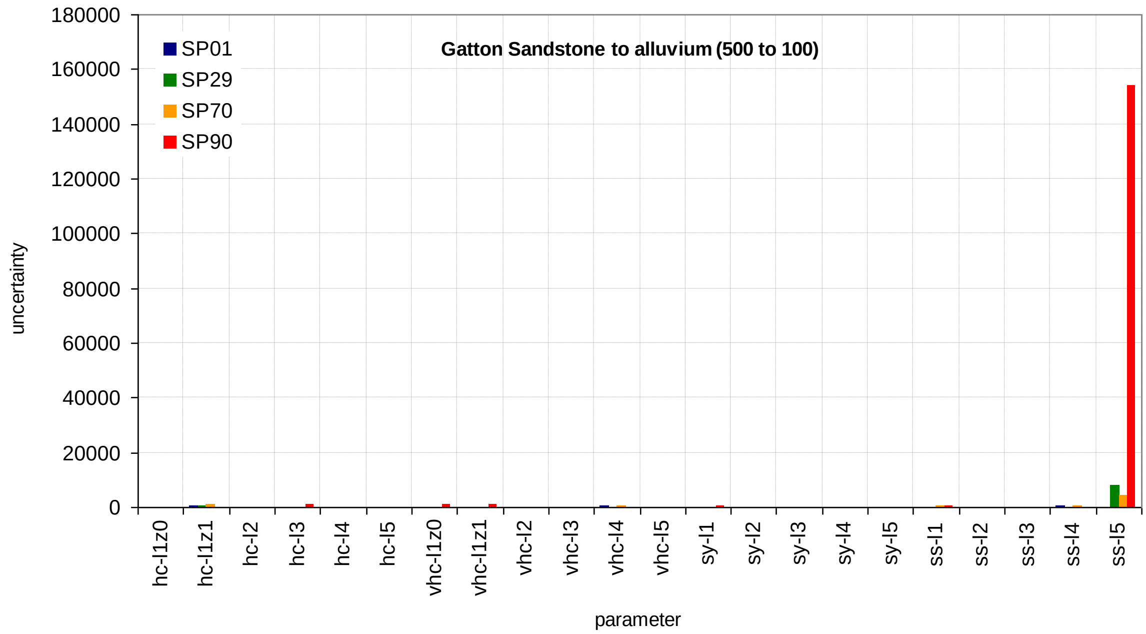


Figure 71. Uncertainties of estimated hydraulic properties with respect to the flows between alluvium (zone 100) and Gatton Sandstone (zone 500).

(external file: *figure_72_uncertainty_recharge_alluvium.pdf*)

Figure 72. Recharge distribution pilot points and spatial distribution of alluvial recharge uncertainty.

a) Spatial distribution of pilot points used to interpolate recharge into the alluvium
b) Recharge uncertainty with respect to the flows between alluvium and Main Range Volcanics (200)
c) Recharge uncertainty with respect to the flows between alluvium and Walloon Coal Measures (300)
d) Recharge uncertainty with respect to the flows between alluvium and Koukandowie Formation (400)
e) Recharge uncertainty with respect to the flows between alluvium and Gatton Sandstone (500)

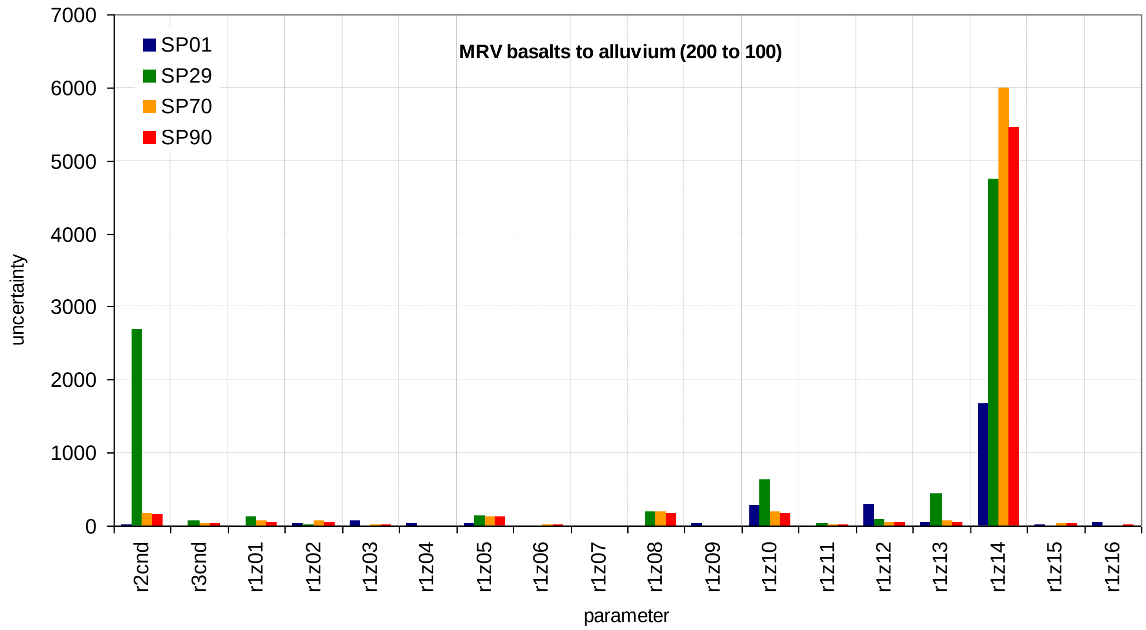


Figure 73. Uncertainties of estimated vertical hydraulic conductivities for Main Camp Creek (r2cnd), individual zones of Laidley Creek (r1z*xx*) and all other model river cells (r3cnd), with respect to the flows between alluvium and MRV basalts (zone 200).

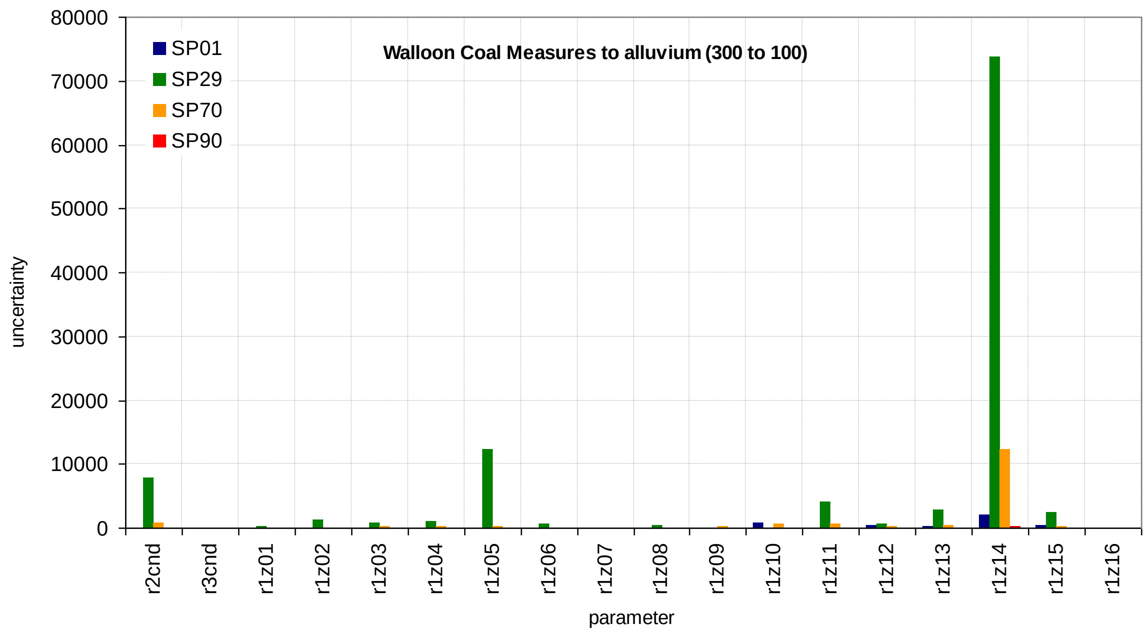


Figure 74. Uncertainties of estimated vertical hydraulic conductivities for Main Camp Creek (r2cnd), individual zones of Laidley Creek (r1z*xx*) and all other model river cells (r3cnd), with respect to the flows between alluvium and Walloon Coal Measures (zone 300).

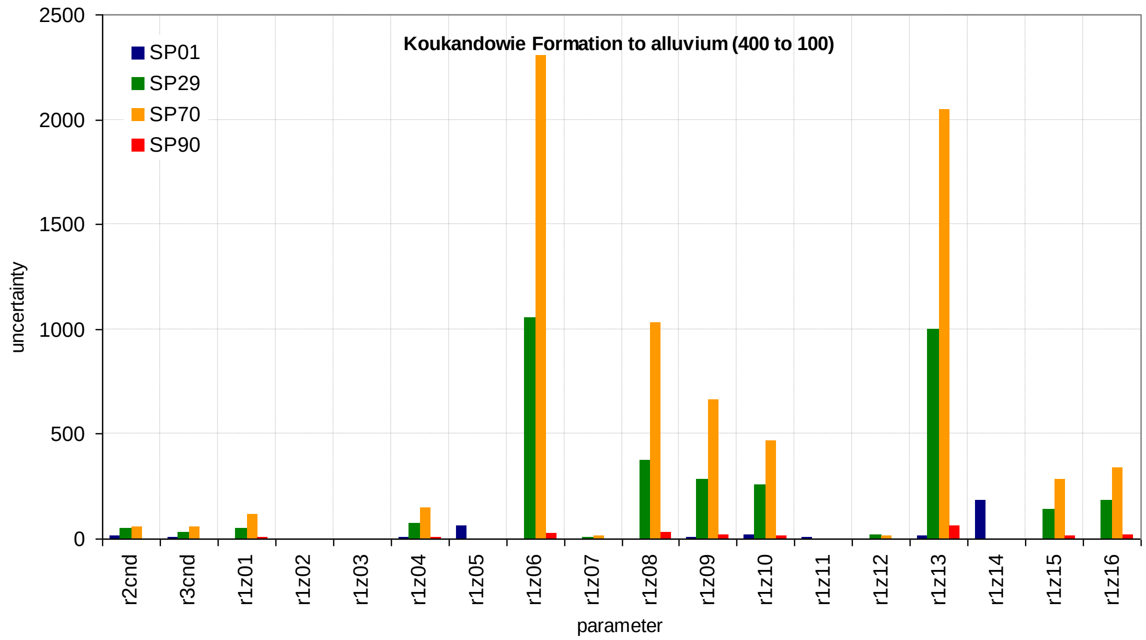


Figure 75. Uncertainties of estimated vertical hydraulic conductivities for Main Camp Creek (r2cnd), individual zones of Laidley Creek (r1z*xx*) and all other model river cells (r3cnd), with respect to the flows between alluvium and Koukandowie Formation (zone 400).

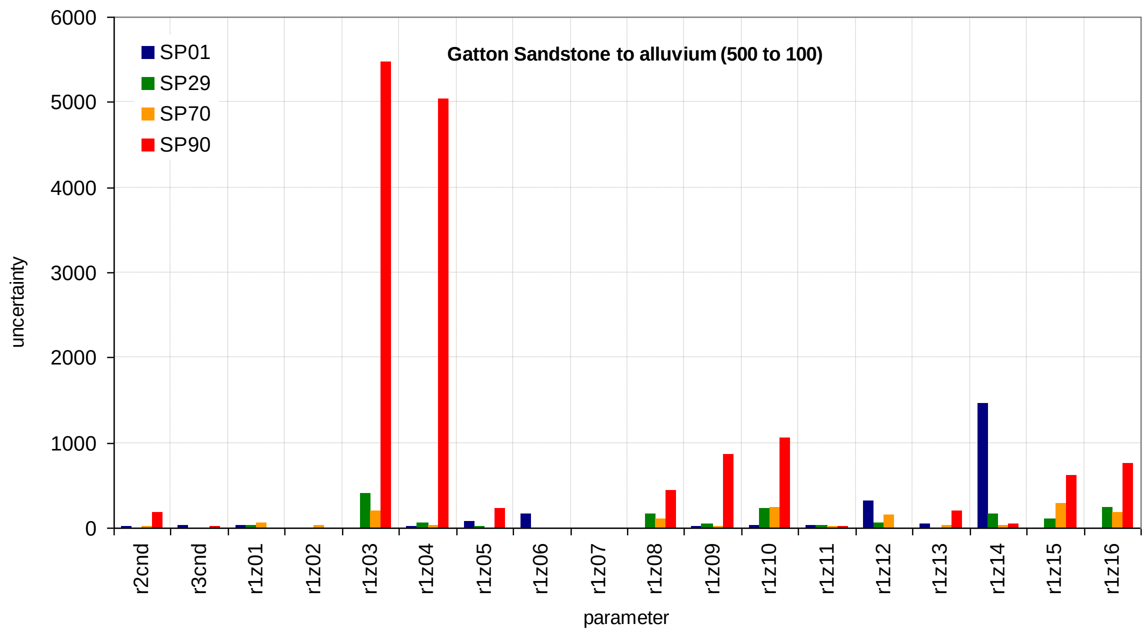


Figure 76. Uncertainties of estimated vertical hydraulic conductivities for Main Camp Creek (r2cnd), individual zones of Laidley Creek (r1z*xx*) and all other model river cells (r3cnd), with respect to the flows between alluvium and Gatton Sandstone (zone 500).

Creek zone 14 (for flow zones 200 and 300), 6 and 13 (flow zone 400) and 3 and 4 (flow zone 500). Increased uncertainty of Main Camp Creek bed vertical conductivity (parameter `r2cnd`) for flow zones 200 and 300 signifies the importance of this parameter to the recharge of the alluvium via Main Camp Creek and further recharge of the bedrock Walloon Coal Measures and MRV basalts. The uncertainty of the parameters associated with the minor drainage (`r3cnd`) is relatively low, however those drainage cells did not really engage in the model run, because the groundwater head in the alluvium did not rise above the bottom of the drainage cells.

5.7.4 Observation contributions to uncertainty

To calculate the effect of individual observation groups on model predictions and hence evaluate the worth of the observation data, the utility PREDUNC5 was used. PREDUNC5 calculates the data worth by the means of removal of the observation or the addition of the observation.

In the case of the observation removal, observations are taken away from the dataset one by one, and for each of the removed observations, the uncertainty of the model prediction is calculated. By means of comparison of the newly calculated uncertainties with the original predictive uncertainty, the worth of the observation is calculated either as an uncertainty increase or decrease. The analysis performed by adding of observations starts with the calculation of predictive uncertainty for the theoretical modeling scenario during which no observations exist. Observations are then added one by one and the decrease of the predictive uncertainty is then calculated for each observation or observation group. This analysis can be used to calculate the worth of non-existent observations (observations that are purely modelled) and thus be applied as a basis for optimization of any future data acquisition.

The most important observation with respect to predictions of flows between alluvium and bedrock aquifers in the upper catchment (Main Range Volcanics and Walloon Coal Measures) are those of head gradients of bores in the lower central alluvium (336, 337, 547 and 553). A high reduction of predictive uncertainty of flow in zone 300 (Walloon Coal Measures) was also achieved by monitoring of bore 472 (effectively located in

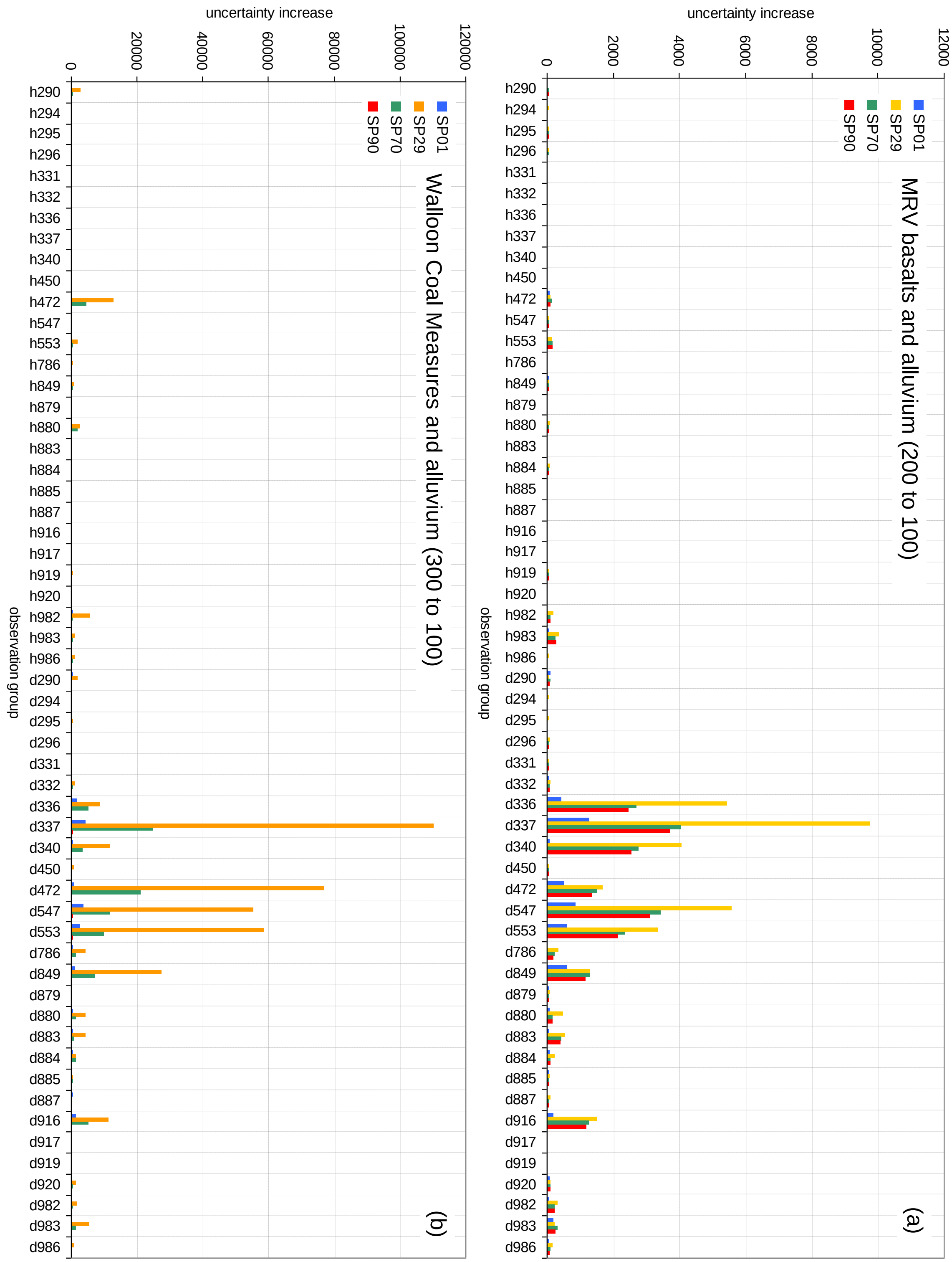


Figure 77. Data worth: reduction of the predictive uncertaity of calculated flow between alluvium and Main Range Volcanics (a) and alluvium and Walloon Coal Measures (b). Data worth calculated by omitting the observation.

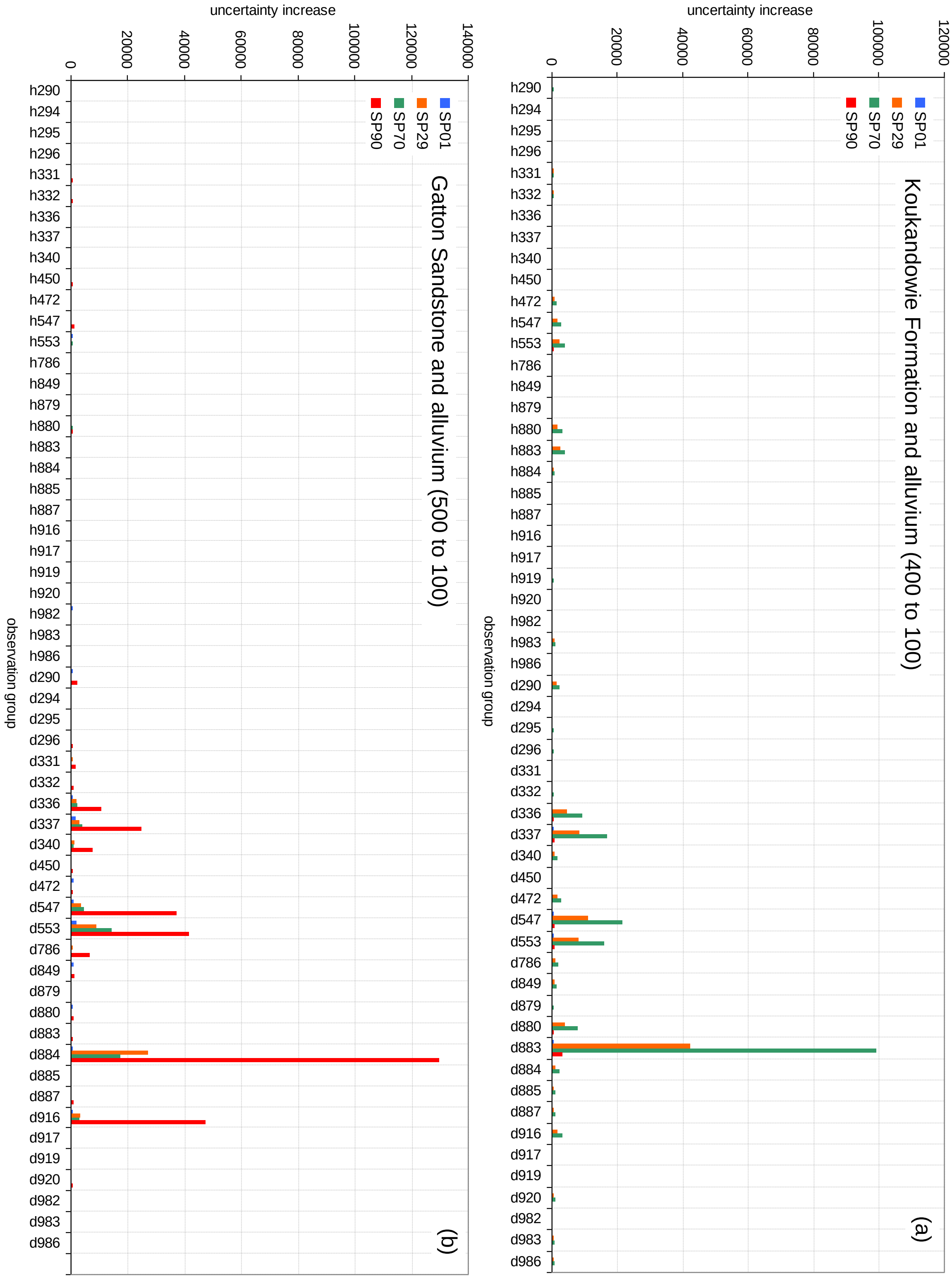


Figure 78. Data worth: reduction of the predictive uncertaity of calculated flow between alluvium and Koukandowie Formation (a) and alluvium and Gatton Sandstone (b). Data worth calculated by omitting the observation.

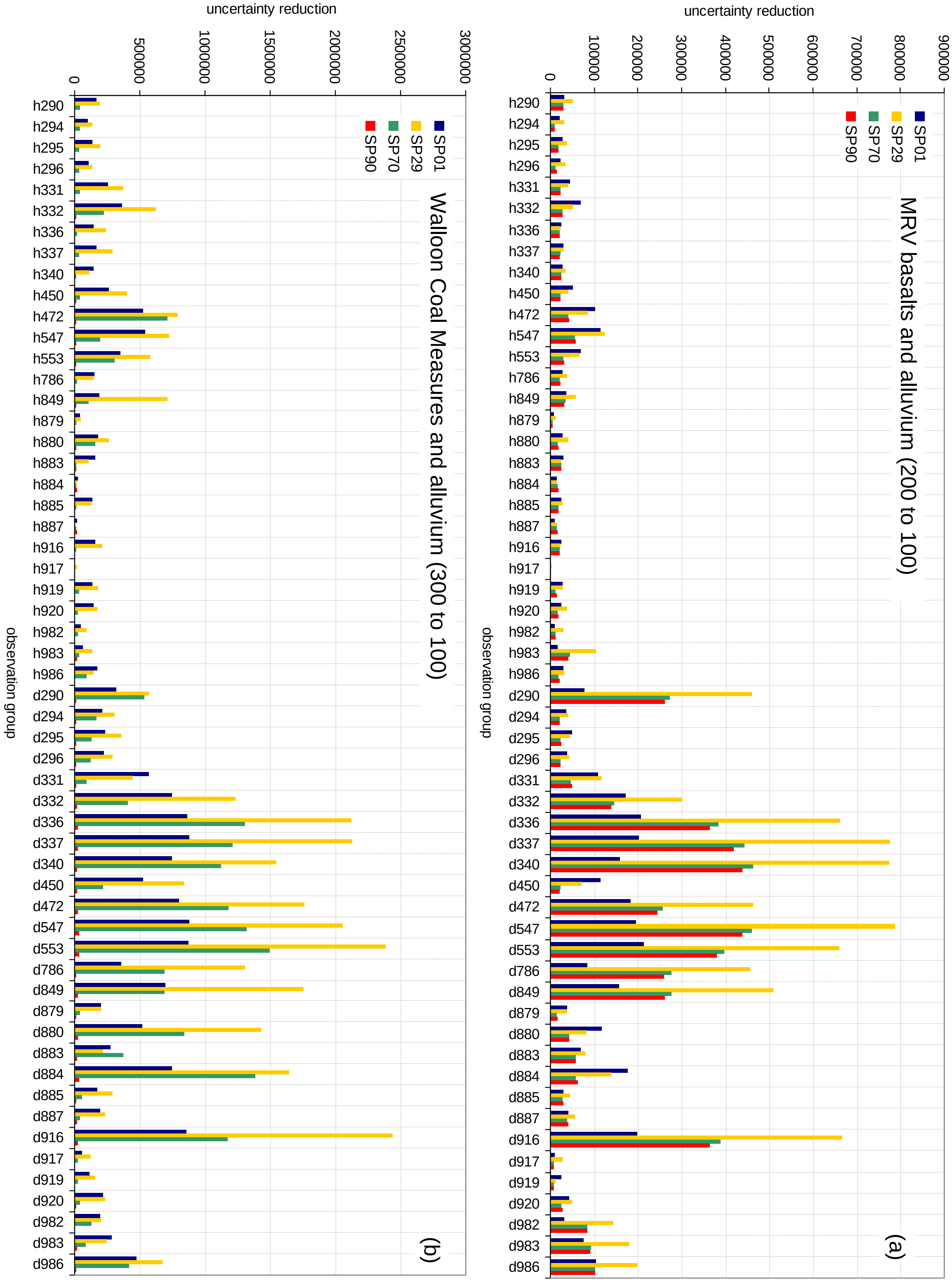


Figure 79. Data worth: reduction of the predictive uncertaity of calculated flow between alluvium and Main Range Volcanics (a) and alluvium and Walloon Coal Measures (b) by adding single observation group.

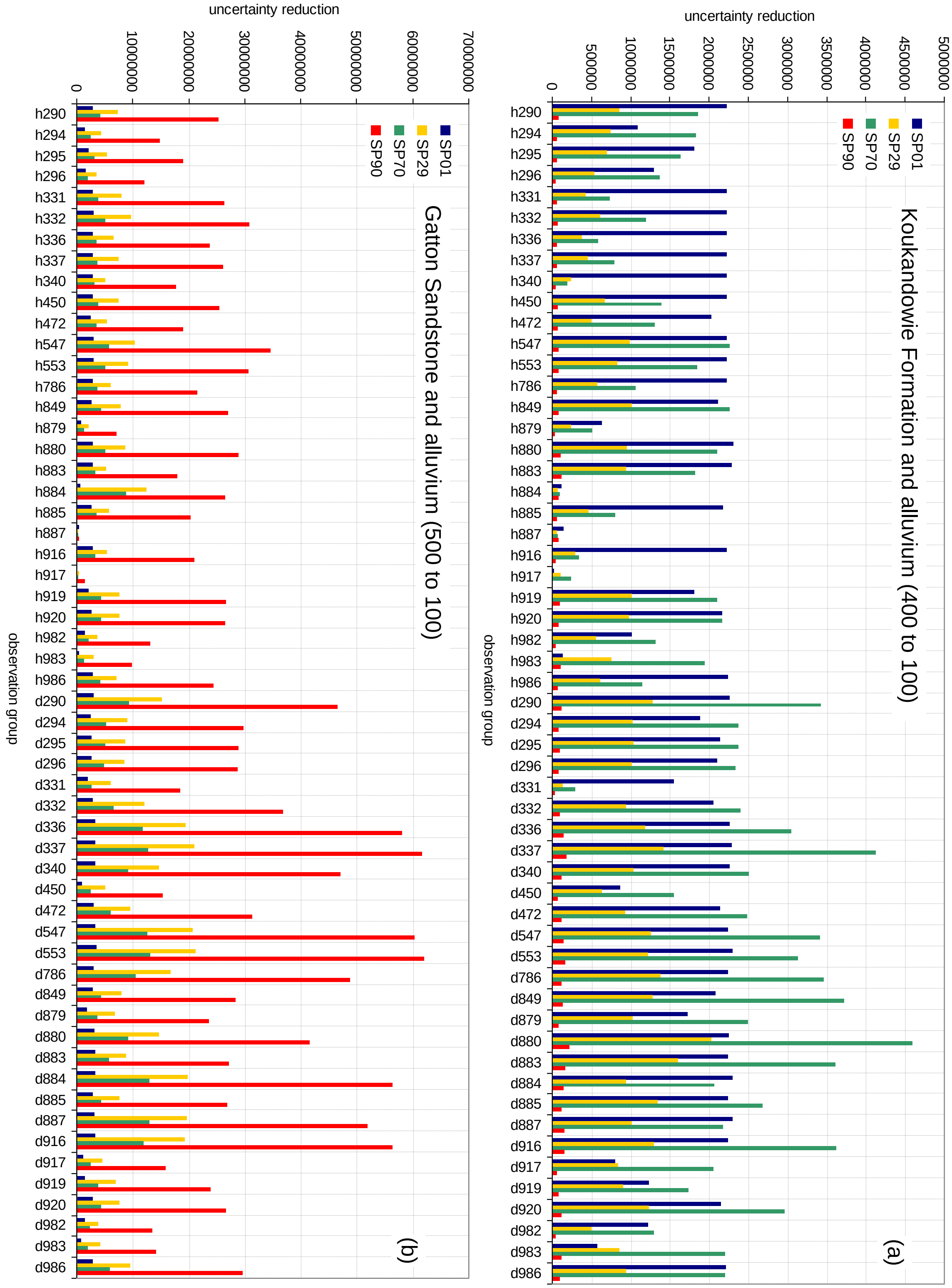


Figure 80. Data worth: reduction of the predictive uncertaity of calculated flow between alluvium and Koukandowie Formation (a) and alluvium and Gatton Sandstone (b) by adding single observation group.

Walloon Coal Measures) (Figure 77a and b). The highest impact on the uncertainty of flow predictions in the lower parts of the catchment (Koukandowie Formation and Gatton Sandstone) showed head gradients observations of bores 883 and 884, drilled in the Gatton Sandstone (bore 884) and on the contact of alluvium and sandstone of Koukandowie Formation (bore 883). See Figure 78a and Figure 78b for the visualisation of the decrease of predictive uncertainties with respect to flows in zones 400 and 500.

Athough the data worth analysis by observation addition does not provide such a clear picture as the analysis by observation subtraction, the trend is very similar and the highest data worth is carried by the observations of head gradients (Figure 79 and Figure 80).

The overview of the results shows that the observation of head gradients carries most of the "information" necessary to decrease the uncertainty of model predictions, compared to observation of heads. This trend was demonstrated for both types of analysis (by omission of observations or by addition of observations). As the head gradients dataset is direcly derived from head observation dataset, it constitutes "bonus" observation data and yet its contribution to the reduction of predictive uncertainty outweighs the contribution of the original dataset (observation of heads).

6 Summary and discussion

Recognised as an important and valuable resource on a global scale (Morris et al., 2003), groundwater is being threatened by aquifer overexploitation (Konikow and Kendy, 2005), water and soil salinisation and other industrial and agricultural activities (Shah et al., 2000; Jha et al., 2008) in Australia and worldwide. As rainfall is recognised to be the main recharge source, especially of the shallow, small-scale aquifers, unfavourable climatic conditions can lead to a decrease of water availability and present a major challenge for water resources management (Turner et al., 2009). The problem of water resources management in times of water scarcity became pronounced in recent years, when Australia was affected by a long-term drought (Whitaker, 2005; BOM, 2011a). If water resources are not properly managed, the conditions of drought may lead to overuse of the groundwater resources (water mining), especially in agriculture areas, where groundwater is used for irrigation.

Because of its dependence on alluvial groundwater, the Lockyer Valley has been recognised as an example of a shallow alluvial aquifer system under stress (Durick and Bleakley, 2000; Davidson et al., 2002; Kimlin, 2004; Cox and Picarel, 2010). A detailed understanding of the hydrogeological framework of the catchment is required to facilitate the efficient management of its resources.

This study aims to provide an understanding of the hydrogeology and hydrological processes in Laidley Creek catchment, one of the subcatchments of greater Lockyer Valley. The integrated approach to this project involved a field survey of climatic, hydrogeological and hydrochemical conditions, data analyses and interpretation, as well as the development of conceptual and numerical models.

The main objectives of the study were:

- To use both existing and newly acquired data (information about rainfall, creek flow and groundwater table movement) to describe the flow and recharge processes and establish the **hydrogeological framework** of the Laidley Creek catchment;

- To develop a **conceptual model** of the Laidley Creek subcatchment to synthesize all available data;
- To develop a **numerical model** of the Laidley Creek catchment in order to confirm the validity of the catchment conceptualization, and explore the flow and recharge processes established during the conceptualisation phase;
- To use the numerical model to undertake an **uncertainty analysis** and identify the model parameters and observation data with the highest impact on the reliability of the numerical model results (primary modeling objective);
- To **quantify the flows** between alluvium and non-alluvial aquifers to address the potentially problematic mixing of fresh alluvial groundwater and the saline groundwater from sedimentary bedrock of the Clarence-Moreton Basin (secondary modeling objective).

6.1 Establishing the hydrogeological framework

The understanding of the geologic (stratigraphic) setting and the major groundwater and surface water processes was built in two steps: existing data concerning the catchment were collected and after identifying the gaps in the data; an additional data collection program was designed to address the deficits discovered during literature review and historical data collection phase. The field program was designed mainly to collect higher frequency groundwater data to aid the objective of developing a conceptual and numerical groundwater flow model of the Laidley Creek catchment.

6.1.1 Overview of the existing information

The literature review undertaken during the initial phase of the study focused on the information regarding the description of the (1) catchment setting and (2) processes within the catchment, such as recharge of different aquifers within the Lockyer Valley or changes in groundwater quality.

The catchment setting (1) was described in terms of the physical setting (Section 3.1), geology and stratigraphy (Section 3.2), land use (Section 3.3), groundwater use

(Section 3.4) and climatic conditions (Section 3.5). The processes within the catchment (2) were described mainly in terms of previous recharge investigations of both alluvial and non-alluvial aquifers and the water quality investigations, with focus on increased salinity and pollution by agricultural fertilizers (Section 4.4.1). An overview of the previous groundwater modeling efforts within the greater Lockyer Valley was undertaken (Section 5.2) with respect to the modeling part of the Laidley Creek catchment study.

As a part of the literature review process, available databases were queried to obtain historical data for the Lockyer Valley and the Laidley Creek catchment: BOM datasets for rainfall and evapotranspiration (BOM, 2003; BOM, 2008), DERM Groundwater Database for locations of irrigation pumps and monitoring bores, groundwater elevation data and bore construction (DERM, 2009), and DERM Water Monitoring Data Portal (DERM, 2012) for information concerning flow rates and groundwater levels for Laidley Creek.

The literature review summarized the extent of our understanding of the recharge processes within Lockyer Valley:

- Rainfall is the dominant **source** of alluvial aquifer recharge (Li and Cox, 1996; Dharmasiri, 1997; Dharmasiri et al., 1997; Ellis and Dharmasiri, 1998; Ellis, 1999; Cox and Wilson, 2005), while a direct rainfall infiltration and infiltration through the creek bed are the two main **recharge mechanisms** (Dharmasiri, 1997; Dharmasiri et al., 1997);

- The lowering of groundwater table in the alluvium can lead to an inflow of groundwaters from the underlying bedrock (Clarence-Moreton Basin sandstone) aquifers. Because of the increased salinity of bedrock groundwaters, groundwater mixing can potentially lead to the decrease of groundwater quality in the alluvium (Dixon and Chiswell, 1992; McMahon, 1995; McMahon and Cox, 1996; MacLeod, 1998).

- Direct rainfall infiltration is relatively fast at the edges of the Lockyer Valley, where the alluvium is shallow, surrounded by steep slopes and covered only with a thin layer of topsoil. Direct rainfall infiltration in the central Lockyer Valley is slow due to a thick silty and clayey layer, covering the basal alluvium (Dharmasiri et al., 1997; Ellis and Dharmasiri, 1998; Ellis, 1999).

The overview of the available hydrogeological and climatic data (BOM Climate Data Online, DERM Groundwater Database, DERM Water Monitoring Data Portal) moved the focus from the broader Lockyer Valley to the Laidley Creek sub-catchment. The graphical comparison of the rainfall trend, creek flow and the alluvial groundwater table elevations (Section 3.7, Figure 13) demonstrated that in the Laidley Creek catchment (as with other areas of the Lockyer Valley), a correlation between rainfall (as a recharge source), stream flow (as a recharge mechanism) and alluvium recharge exists.

Although the recharge processes were generally understood at the catchment level, detailed description of recharge for particular sections of the Laidley Creek alluvium did not exist. In order to address this problem, a field program consisting of rainfall monitoring, groundwater table monitoring, creek stage monitoring, and groundwater sampling and analysis was developed.

6.1.2 Collection and analysis of up-to-date hydrogeological data

A field monitoring and sampling program was established in order to gather detailed data relevant to recharge of the Laidley Creek alluvium. The field campaign consisted of (a) the collection of rainfall data, (b) monitoring of the creek stage, (c) monitoring of groundwater table in alluvium and (c) sampling and analysis of both groundwater and surface water.

6.1.2.1 Rainfall monitoring

The rainfall data were collected from three gauges: Townson (official BOM station 040675), Laidley Creek West and Laidley (Figure 3). Based on the knowledge of the long-term spatial rainfall distribution (Figure 9) and actual data from three monitoring gauges, the rainfall data were interpolated across the whole Laidley Creek catchment (5.4.4.4) to serve as one of the inputs of the numerical model. Four significant rainfall events (Section 4.1.2, Figure 16) were recognised and used as time markers to correlate the rainfall events with creek flow (Section 4.2.2, Figure 17 and Table 4) and groundwater recharge (using groundwater hydrographs, see Section 4.3.2).

6.1.2.2 Laidley Creek flow monitoring

The Laidley Creek flow was monitored at the automatic gauging station at Mulgowie (1043209B; see Section 4.2). Based on the gauging data and visual documentation of the creek flows along the course of the stream, the regime of the Laidley Creek flow was extrapolated from the gauge data to cover the whole length of the creek (Section 5.4.4.2). The stream heads along the Laidley Creek were also used as one of the data inputs of the numerical model.

The comparison of the creek stage data from Mulgowie and rainfall shows strong correlation between the two observations (Section 4.2.2, Figure 17), suggesting the dependence of the stream flow on the rainfall.

6.1.2.3 Groundwater head monitoring and hydrograph analysis

The historical groundwater elevation data (Section 3.7) together with rainfall and Laidley Creek flow data (Figure 13) showed a correlation between all three processes and illustrated that in a general sense, both stream flow and groundwater elevations depend on the rainfall throughout the catchment. Using only the historical data, the relation between the stream flow and groundwater levels in the alluvium was however not quite visible, most likely due to insufficient frequency of the groundwater monitoring data, as DERM monitored the bores on average in 2 month intervals (Section 3.7).

In order to observe the influence of creek flow on the infiltration of creek water into the alluvium, the groundwater level data were collected on a weekly basis. A network of 42 groundwater bores was monitored manually from 07/2007 to 08/2008. In addition, 10 of the monitored bores were equipped with automatic pressure transducers (HOBO U20 Water Level Logger) to record the groundwater level data at 15-minute intervals and this measurement continued till 06/2009.

The results of the groundwater monitoring process were visualised in the form of hydrographs, charts showing the change of the groundwater head with time (Section 4.3.2). Based on the scale and speed of the recharge process (represented by bore hydrograph), the hydrographs were divided into 3 main groups (Figure 20): bores that recovered fast as a result of rainfall or creek flow event (group A), bores that recovered slowly (group B) and bores that did not recover at all (group C). Hydrograph groups represent different recharge regimes in various parts of the alluvium. The groups were later used as one of the criteria for the delineation of different recharge zones in the Laidley Creek alluvium (Section 5.3.2.1).

6.1.2.4 Hydrochemistry and groundwater mixing

The hydrochemical analysis of both groundwater and surface water samples has been undertaken in order to identify the sources of waters in the Laidley Creek catchment as well as to quantify the mixing processes. The initial review of hydrochemical investigations in other areas of the Lockyer Valley demonstrated that (1) the hydrochemical characterization of the water sample is determined by the lithology of the source aquifer (Dixon and Chiswell, 1992; McMahon, 1995; McMahon and Cox, 1996; MacLeod, 1998; Picarel, 2004; Cox and Wilson, 2005; Pearce et al., 2007; Cox and Picarel, 2010) and thus the source of water can be established, and (2) the groundwaters in alluvium are the product of mixing processes between surface waters (stream bed infiltration, direct rainfall infiltration) and groundwaters in the underlying bedrock (mostly sandstone) aquifers (Dixon and Chiswell, 1992; McMahon, 1995; Li and Cox, 1996; McMahon and Cox, 1996; Dharmasiri et al., 1997; Ellis and Dharmasiri, 1998; MacLeod, 1998; Ellis, 1999; Picarel, 2004; Cox and Picarel, 2010).

In order to establish the groundwater sources and mixing processes within the Laidley Creek alluvium, major ion analysis of water samples collected in the Laidley Creek catchment was undertaken. A total of 34 groundwater and 9 surface water (Laidley Creek) samples were collected and analysed (Section 4.4.3, Figure 29) at the Analytical chemistry laboratory at QUT using AHPA methodology guidelines (Clesceri et al., 1998).

The results of the hydrochemical analysis were interpreted using graphical methods, including Stiff and Piper diagrams (Section 4.4.5). The analysis compared the current (Laidley Creek catchment) samples with samples from other Lockyer Valley subcatchments (Section 4.4.2; Pearce et al., 2007). The analysis of all available data was directed to aquifer type and lithology, and location within the catchment. Based on the hydrochemical (major ions) signature, the Laidley Creek catchment water samples were grouped into 4 groups representing the main aquifer lithologies (Section 4.4.6, Figure 35 and Figure 36): Main Range Volcanics basalts (Group 1; mostly Mg- Na-HCO_3 or Mg-Ca-HCO_3 waters, TDS from 173 to 862 mg/L), Walloon Coal Measures and Koukandowie Formation (Group 2; Na-HCO_3 type, TDS from 248 to 553 mg/L), Gatton Sandstone (Group 3; Na-Mg-Cl type, TDS from 5050 to 12800 mg/L) and central alluvium (Group 4; Ca-Mg-Cl-HCO_3 and Mg-Na-Cl-HCO_3 types, TDS from 660 to 2472 mg/L).

The hierarchical cluster analysis (HCA; see Section 4.4.7) was employed to support the results of the sample clustering based on the graphical comparison method. The result of the HCA is presented in the form of a dendrogram (Figure 37). The similarity (or the lack of similarity) of the samples is expressed in the form of *agglomeration distance.* The automatic clustering process created 5 clusters, which could be identified with the hydrochemistry groups created by graphical analysis of the water samples. Although the results of the graphical analysis and the HCA do not conform entirely, the HCA shows the same trends as the more subjective graphical analysis, thus provides strong supporting evidence for the results of the grouping.

In order to quantify the inflow of the brackish sandstone bedrock groundwater into the alluvium, a two-sample groundwater mixing analysis (Section 4.4.8) was undertaken using AquaChem (Waterloo Hydrogeologic, 2010). Two couples of samples were identified as possible candidates of the mixing analysis:

- Samples 885 and 883 to demonstrate the mixing of Koukandowie Formation (885) and Gatton Sandstone (883) groundwaters in the alluvium (Section 4.4.8.1), and
- Samples 331 and 884 to demonstrate the infiltration of Gatton Sandstone (884) waters into the lower Laidley Creek alluvium and mixing with fresh Laidley Creek water (bore 331; Section 4.4.8.2).

The two-sample mixing analysis showed, that the mixing process between groundwaters sourced from aquifers with different lithologies (as described in other Lockyer Valley subcatchments), occurs in the alluvium of the Laidley Creek. The contribution of the Gatton Sandstone groundwaters to the groundwaters of the Laidley Creek alluvium was calculated to be approximately 2%, while the alluvial groundwater in the area with very limited creek infiltration comprised 96% of Koukandowie Formation waters and 4% of Gatton Sandstone waters.

The results of the water sampling, major ion analysis and graphical and statistical examination confirmed the occurrence of the hydrogeological processes similar to processes within Ma Ma catchment, Tenthill catchment and Central Lockyer Valley and expanded the insights gained from the assessment of the rainfall, creek flow and groundwater head data. Specifically:

- Rainfall (in the form of diffuse infiltration or creek bed infiltration) is the main **source** of the alluvial recharge, while the creek bed infiltration is the main **recharge mechanism**. The major ion signature of groundwaters in the bores close to the creek is very similar to the surface water in the creek (Figure 36).
- Second source of groundwater in the alluvium are the underlying bedrock (sandstone) aquifers. Although the infiltration rate from sandstones to alluvium is small (2-4%) in terms of volume, the salinity of sandstone groundwaters (TDS over 10000 mg/L) can potentially lead to a decrease in the groundwater quality.

6.2 Conceptual model development

A conceptual model (Section 5.3) provides a simplified description of the hydrogeological system and allows a synthesis of all available data (Anderson and Woessner, 1992; Spitz and Moreno, 1996; Middlemis, 2001; Reilly, 2001). The conceptual model of the Laidley Creek catchment summarizes the knowledge concerning the physical and geological structure (stratigraphy), groundwater levels and directions of flow (flow processes), recharge mechanisms and groundwater use. The conceptual model is presented in the form of a simplified map, idealised crossections (Figure 45), detailed description of the processes on a catchment wide scale (Section 5.3.6) and description of the settings and groundwater processes within the Laidley Creek alluvium (Section 5.3.2.1). Stratigraphy (Section 5.3.2), catchment boundaries (Section 5.3.1) and groundwater use (Section 5.3.5) are also discussed as a part of the catchment conceptualisation.

The Laidley Creek catchment conceptual model is based on the data collected, analysed and interpreted during previous stages of the study and used as the foundation for development of the numerical model.

6.3 Numerical model development

The Laidley Creek catchment numerical model was built as an interpretative model (Section 5.4.1). The steady state and transient simulations were created and run in sequence (steady state simulation followed by transient simulation). The steady state simulation was run to set the starting conditions (starting heads) for the transient model run. The transient simulation was then run for the period representing 630 days, in the interval between 20/7/2007 and 10/4/2009 with weekly stress periods. The modeling code used was MODFLOW-SURFACT (HydroGeoLogic, 1998); Section 5.4.2.1).

The main reasons for the numerical model development (Section 5.4.1) were:

- Quantification of the catchment processes such as the inter-aquifer flows, specifically flows between the sandstone bedrock aquifers and overlying alluvium (Section 5.6.3), and
- To use the model as a mean of the parameter uncertainty analysis (Section 5.7) with the aim to identify the observations and model parameters contributing to the uncertainty of potential modeling predictions.

6.3.1 Model calibration process and performance measures

The numerical model was calibrated using the inverse modeling approach, automated by employing PEST/BeoPEST (Parameter EStimation Tool; see Section 5.4.2.3). The calibrated (*estimable*) parameters were: hydraulic properties (horizontal and vertical hydraulic conductivities, specific yield, specific storage), diffuse recharge (based on rainfall) and parameters related to river induced recharge/discharge (vertical hydraulic conductivity of the creek bed). The parameters in model layer 1 (alluvium and regolith zones) were spatially distributed using the pilot point approach (de Marsily, 1984; Doherty, 2003; Doherty, 2006)

Two observation datasets were used during the inverse modeling process: groundwater heads and groundwater head gradients (Section 5.5.2). Groundwater heads were obtained from both automatic and manual field measurements while the groundwater head gradient dataset was derived directly from the head measurement dataset. The goodness of fit between calculated and measured datasets (qualitative calibration measures) was assessed using the scatterplot of corresponding predicted and measured heads (Figure 56) and scatterplot of corresponding measured head gradients and predicted head gradients (Figure 57). The spatial distribution of the calibration error was demonstrated by mapping the contribution of individual observation groups towards the value of the calibration objective function (the sum of squared residuals; see Figure 58). With regard to observed heads, the biggest calibration error is associated with bores 883 and 880. With regard to head gradients, the biggest error is associated with bores 294, 295, 296 and 982.

The quality of the numerical model calibration was assessed using the standard calibration performance measures (Middlemis, 2001): iteration residual error, water balance error, goodness of fit between predicted (modeled) and measured datasets and quantitative statistical measures.

The iteration error (head change convergence criterion) was set to be 0.001 m and using this criterion, the numerical solution converged for every timestep of the transient modeling run. The absolute water balance error was very low throughout the whole modeling run (0.05% on average). The model, however, exceeds 1% error for one timestep which was associated with a sudden change in flow regime (stress period 69, Figure 59). In spite of this single occurrence of the increased error, the water budget calculations are acceptable.

The aim of the automated calibration process undertaken with the use of PEST was to minimize the calibration objective function. The value of the objective function was defined as the sum of squared residuals (SSQ). The final value of the objective function was 47934 [m^2] for the heads dataset and 123 [m^2] for the head gradient dataset. The full list of used quantitative measures is presented in Section 5.5.4, Table 15 (see Appendix N for the definitions of individual quantitative calibration performance measures).

Based on recommended values of calibration performance measures (Middlemis, 2001; Welsh, 2006), the calibration process for the Laidley Creek catchment groundwater flow model was shown to be successful.

6.3.2 Quantification of catchment processes

The quantification of catchment processes (i.e. calculating the flows across the catchment boundary and calculating the flows between individual aquifers) was a secondary objective of the Laidley Creek catchment model (see Section 2).

In terms of the summary model-wide budget, the components are: rainfall recharge and irrigation return (inflows), and cross-boundary flows, river seepage and pumping (outflows). All flow rates and volumes were compiled from the standard MODFLOW output file and are presented as volumes (in ML) per duration of the model run (630 days; see Section 5.6.2, Table 16).

The model domain flows were quantified as follows: summary inflows: 50880 ML (rainfall recharge: 49207 ML; irrigation return: 1627 ML), summary outflows: 36184 ML (cross-boundary flows: 4342 ML, river outflows: 24597 ML, pumping: 7245 ML). This summary suggests that in the period of the transient model run, the Laidley Creek aquifers were recharged by 14696 ML. In relative terms, the recharge from rainfall represents on average about 8.8% of rainfall and the irrigation return represents approximately 23% of the pumped groundwater.

The inter-aquifer flows (Section 5.6.3) were quantified by defining flow zones (in case of the Laidley Creek numerical model the flow zones were defined as catchment aquifers; Figure 42) and then by summarizing the cell-by-cell flows for individual zones. Using the cell-by-cell flow calculations, the flows between the alluvium and non-alluvial aquifers (MRV basalts, Walloon Coal Measures, Koukandowie Formation and Gatton Sandstone) were calculated to be approximately 19 675 ML of inflows into alluvium (4432 ML from MRV basalts, 15 242 ML from sedimentary Clarence-Moreton Basin aquifers). Compared to total inflows into the alluvium (35 616 ML of combined inflows from non-alluvial aquifers, rainfall recharge and recharge from Laidley Creek), the calculated inflow from Clarence-Moreton Basin aquifers represents approximately 43%.

While the model performance with respect to heads (matching predicted and observed heads, see Section 6.3.2) is good, the model performance with respect to modeling flows is poor. As the possible volumetric inflow of the bedrock groundwaters into the alluvium was quantified to be 2-4% using the hydrochemistry data (Section 4.4.8), the inflow from the non-alluvial aquifers calculated by the numerical model (43%) is unrealistically high.

6.4 Predictive uncertainty analysis

The predictive uncertainty analysis enables the modeler to understand the importance of individual model parameters (or parameter groups) and their contribution to the overall uncertainty of the model results. Two types of analysis were performed: (1) analysis of model parameters and (2) analysis of model observations. Because the Laidley Creek catchment numerical model was defined as an interpretative model (Section 5.1), the predictive uncertainty analysis was the primary objective of the modeling exercise.

The calculated flows between non-alluvial aquifers and the Laidley Creek alluvium were chosen as the analysed predictions. Because the model performance with respect to flow calculations was shown to be inadequate (Section 6.3.2), the uncertainty analysis is a suitable tool to suggest the most effective way to improve the numerical model performance.

There are four non-alluvial aquifers (zones: 200 - MRV basalts, 300 - WCM, 400 - Koukandowie Formation, 500 - Gatton Sandstone); from these four flow conditions (for stress periods 1, 27, 70 and 90) were selected as representative flows between each of the non-alluvial aquifers and the Laidley Creek alluvium (zone 100). In total, 16 flows became a subject of the uncertainty analysis.

6.4.1 Parameter contributions to uncertainty

The results of parameter uncertainty analysis are presented in Section 5.7.3 and summarized in Table 18. In terms of aquifer properties, the most problematic parameters are specific storage and vertical hydraulic conductivities. In terms of the vertical hydraulic conductivities of the Laidley Creek bed, the most problematic zones are upper catchment Zone 14 (with respect to flows between alluvium, MRV basalts and Walloon

Coal Measures) and lower catchment Zones 3, 4 and 6 (with respect to the flows between alluvium and Koukandowie Formation aquifer and alluvium and Gatton Sandstone aquifer).

The contribution of rainfall recharge to the predictive uncertainty is strongly predicated on the location of the outcrop of the particular aquifer and is presented in the form of a prediction-specific map (Figure 72). For the full list of model parameters, see Appendix L.

Table 18. The highest contributing parameters towards model uncertainty.

Prediction	Parameter
Aquifer hydraulic properties	
Flows between MRV basalts and alluvium (200 to 100)	ss-l2
Flows between Walloon Coal Measures and alluvium (300 to 100)	ss-l3, vhc-l3
Flows between Koukandowie Formation and alluvium (400 to 100)	ss-l4, vhc-l4
Flows between Gatton Sandstone and alluvium (500 to 100)	ss-l5
Vertical hydraulic conductivities of Laidley Creek bed	
Flows between MRV basalts and alluvium (200 to 100)	r1z14
Flows between Walloon Coal Measures and alluvium (300 to 100)	r1z14
Flows between Koukandowie Formation and alluvium (400 to 100)	r1z06, r1z13
Flows between Gatton Sandstone and alluvium (500 to 100)	r1z03, r1z04
Recharge to alluvium	
Flows between MRV basalts and alluvium (200 to 100)	rch36, rch28, rch24
Flows between Walloon Coal Measures and alluvium (300 to 100)	rch36, rch16, rch23
Flows between Koukandowie Formation and alluvium (400 to 100)	rch26, rch04, rch15, rch12
Flows between Gatton Sandstone and alluvium (500 to 100)	rch42, rch41, rch40

The Laidley Creek transient model was calibrated primarily against groundwater head data. The predictive uncertainty analysis showed that the parameters with lowest sensitivities with respect to the calibration target (groundwater heads) such as specific yield and storage of non-alluvial aquifers, introduce the highest uncertainty with respect to model predictions (groundwater flows). If in the future water quality predictions based on modeled groundwater flows, and modeled mixing of different groundwater types are required, then additional flow related observation such as measured salinity or water temperature, should be considered as a calibration targets.

6.4.2 Observation contributions to uncertainty (data worth)

The influence of observations (observation groups) towards the prediction uncertainties is discussed in Section 5.7.4 and summarized in Table 19. All observation groups were analysed using both "observation loss" and "observation addition" methodology. Although the "observation addition" method produced results that were not so clear when compared to the "observation loss" method, both approaches selected the same bores.

Table 19. The highest contributing observations towards model uncertainty.

Prediction	Observation
Loss of observation	
Flows between MRV basalts and alluvium (200 to 100)	d336, d337, d340, d547, d553
Flows between Walloon Coal Measures and alluvium (300 to 100)	d337, d472, d547, d553, d849
Flows between Koukandowie Formation and alluvium (400 to 100)	d336, d337, d547, d553, d883
Flows between Gatton Sandstone and alluvium (500 to 100)	d337, d547, d553, d884, d916
Addition of observation	
Flows between MRV basalts and alluvium (200 to 100)	d337, d340, d547, d553, d916
Flows between Walloon Coal Measures and alluvium (300 to 100)	d336, d337, d547, d553, d916
Flows between Koukandowie Formation and alluvium (400 to 100)	d337, d849, d880, d883, d916
Flows between Gatton Sandstone and alluvium (500 to 100)	d336, d337, d547, d553, d884

Although both observation datasets (heads and head gradients) were included in the *data worth* analysis, the most influential observations are the observations of head gradients. The data worth analysis shows, that the most important observations (with respect to flow predictions) are the observations of the head gradients in the bores located in the downstream central Laidley Creek alluvium (336, 337, 547, 553, 916) and bores either on the fringe of alluvium or outside (880, 883, 884).

6.5 Identified data inadequacies

The inadequate data were identified throughout various stages of the study. While some challenges appeared during the initial data review (DEM vertical error, information about groundwater pumping), others were encountered in the numerical model development phase (distribution of surface water head along the whole course of the Laidley Creek).

6.5.1 Data describing the model structure

The imprecision of the data describing the model structure can play a role in the uncertainty of the model prediction. This applies to the DEM data defining the ground surface, but also to the geological data used to define the bottom of the alluvial aquifer and other model layers.

The DEM vertical error (described in Section 5.3.3) was noticed by comparing the surveyed elevations of selected bore casings (from DERM Groundwater Database) with the elevation values obtained from DEM. Based on this comparison, there was a mismatch between DEM and data acquired by the elevation survey. The error was up to 9.8 m (approximately 30% of the maximum thickness of the alluvial aquifer) both positive and negative. The use of this unrectified DEM would translate into reversal of hydraulic gradients in some parts of the catchment, producing unrealistic flows. The DEM was rectified using calculated "error matrix" and the absolute cumulative DEM error was reduced from 143 m to 13 m, however, this operation might have created a different DEM discrepancy in the area without surveyed elevation data (vicinity of bore 883, see the discussion in Section 5.5.4).

The definition of the bedrock surface (bottom of the alluvial aquifer) was a process that depended on the precision of the surface (DEM) data (elevation of bedrock is derived from known surface elevation and known depth to bedrock) as well as the spatial density of bores with known depth to bedrock. The distance between the bores in the north-south direction was on average 5 km (compared to the minimum 100×50 m cellsize of the model grid) which together with the fact, that the bedrock was defined by interpolation from known bore data would introduce another structural uncertainty into the numerical model.

The vertical heterogeneity of the alluvium is referred to in the Section 5.3.2. The drill logs show the stratification of the alluvium into the less permeable upper layer and highly permeable basal layer. Despite this conceptualization, the alluvium of the Laidley Creek catchment model was created as a single layer. The hydraulic properties in this "combined" layer represent the average hydraulic properties of the particular cell. The reason for modeling the alluvium as a single layer was mainly from the lack of discrete observation data of groundwater heads in the separate alluvial units.

The impact of the vertical heterogeneity of alluvium on the yield of the alluvium might be significant, especially if predictions within a smaller area of the catchment are considered. In order to explore the interaction between low permeable topsoil and high permeable gravel and sand layers, the observation piezometers should be screened separately at the upper, low conductivity layer and at the bottom of the alluvium.

As a part of the numerical modeling exercise, the alluvial aquifer was examined in relation to other non-alluvial aquifers (MRV basalts, Walloon Coal Measures, Koukandowie Formation and Gatton Sandstone) in terms of the calculations of inter-aquifer flows. Although relations between alluvium and bedrock aquifers within the Lockyer Valley were intensively studied in the past as a part of recharge studies and water quality studies (Dixon and Chiswell, 1992; McMahon, 1995; McMahon and Cox, 1996; Dharmasiri et al., 1997; MacLeod, 1998; Picarel, 2004), they were not built into numerical models. Given the potential impact of groundwater flows between alluvium and bedrock sandstones on the quality of the groundwater in the alluvium, the alluvium should not be modelled as a standalone hydrogeological unit. The no-flow boundaries between alluvium and bedrock aquifers as employed by previous modellers (Doherty, 1999; Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005) are not suitable for the analysis of inter-aquifer flows and possible water quality degradation.

6.5.2 Temporal distribution of data

The "coarseness" of data sampling is partially determined by the purpose of the modeling exercise and should be on a similar scale to the required model predictions. Another consideration for selection of the frequency of the data collection is the frequency and amplitude of various system stresses such as pumping.

Some parameters were measured multiple times, such as groundwater heads, creek head and rainfall. However, the groundwater and surface water chemistry was analyzed onlz once and the pumping rates of irrigation bores were not known with good precision and were estimated from the data provided by Psi-Delta (2009) and DERM (see Section 3.4, Table 2; after (KBR, 2002). The availability of the seasonal pumping rate data would improve the numerical model calibration as well as contribute towards reducing the modeling predictive uncertainty.

6.6 Considerations for future data collection

Based on the results of the uncertainty analysis of model parameters (Sections 5.7 and 6.4) and other observations of existing data gaps (Section 6.5), the following data have been shown to be insufficient to calibrate the numerical model with respect to flow predictions:

- **Structural data**: The structural precision of the model can be improved by either better DEM (e.g. LIDAR derived) or by DEM rectification process using more bore elevation survey data. The more precise DEM can ideally improve not only the topographic data but can also help to define the width and depth of the creeks. Additional information concerning the contact of the alluvium and bedrock should be obtained either through drilling or by the means of geophysical survey. The issue of the vertical heterogeneity of the alluvium should be addressed by constructing and monitoring piezometers targeting individual units of the alluvium.

- **Aquifer properties**: The hydraulic properties of all aquifers were estimated using the inverse modeling approach. Besides the inverse modeling process, the values of hydraulic parameters were influenced by parameters adopted from previous studies in the Lockyer Valley (for alluvium, see Durick and Bleakley, 2000; KBR, 2002; Wilson, 2005) and from the geological reference literature (for non-alluvial aquifers, see Freeze and Cherry, 1979; Fetter, 1994; Hiscock, 2005; USQ, 2011). The parameters associated with highest levels of uncertainty with respect to Laidley Creek catchment model predictions were the parameters defining or limiting transient flow within non-alluvial aquifers: specific storage of layers 2 to 5 (MRV basalts to Gatton Sandstone) and vertical hydraulic conductivities of layers 3 and 4 (Walloon Coal Measures and Koukandowie Formation; see Sections 5.7.3 and 6.4.1).

- **Groundwater heads**: Manual measurement of the groundwater heads in approximately weekly intervals proved to be sufficient for the construction of the Laidley Creek catchment groundwater flow model, however, shorter time intervals (one day) would be more useful. The frequency of the groundwater head data collection depends on the time discretization of the model for which the data are collected. Given the area of interest and time constraints, the undertaking of the daily head measurements will not be possible without measurement automation.

The future efforts should focus on collecting the observations that have the biggest impact on decreasing model uncertainties (Sections 5.7.4 and 6.4.2) such as the bores on the fringes of alluvium or outside of the alluvium (883, 884), bores in the side subcatchments (472) and bores in the low permeability sediments of lower alluvium with limited recharge from Laidley Creek (336, 337, 547, 553, 916).

- **Surface water heads**: The daily head and flow data obtained from DERM for the Mulgowie gauging station were not suitable to define the flow along the entire Laidley Creek (headwaters to Laidley). The DERM data (DERM, 2012) were complemented by weekly observation of head (stream water elevation) along the creek. There were also no official head and flow observation data for Main Camp Creek (a tributary to Laidley Creek). Compared to the diffuse rainfall recharge, the infiltration through the Laidley Creek bed plays a major role with respect to the recharge into the alluvium. Realistic determination of head along the Laidley and Main Camp Creeks is crucial for creek recharge calculations.

  The creek heads can be measured by pressure transducers placed into shallow piezometers constructed directly into the creek bed (e.g. using star picket). The piezometers should be ideally placed at the northern catchment boundary (in the vicinity of the bore 450), in front and behind the Laidley and Mulgowie weirs, and at the creek crossings. Based on the possibility of the rapid change in creek head during the flooding events as observed in summer months of late 2008 and early 2009, the data sampling frequency should be at least one hour.

- **Groundwater and surface water chemistry**: For the Laidley Creek catchment study, the water chemistry was examined only once, in order to establish the hydrogeochemical background and describe some of the recharge processes and groundwater mixing. The data were not sufficient to use in the construction of the numerical model beyond a conceptual sense, because (1) the selected modeling code (MODFLOW-SURFACT) could not model chemical reaction (licence limitation) and transport and (2) the temporal component of the data (defined change in time) was missing. If the analysis of groundwater and surface water is undertaken repeatedly, the results can be used as the calibration data for the numerical model. This approach might require the use of a different numerical code such as MODHMS or SUTRA or coupling a MODFLOW code with specialized contaminant/energy transport code.

Recommendations here are made with respect to the specific numerical and conceptual model of Laidley Creek catchment, it's stated purpose and it's predictions. Although the suggestions can be generalized and used as a guide for any hydrogeological survey in the area, the specific need for further data evaluation and collection prior to any new modeling effort will always depend on the extent of the modeling domain, the type of expected modeling predictions and the modeling timeframe.

7 Conclusions

Lockyer Valley in southeast Queensland is an example of a catchment-hosted shallow alluvial aquifer system. Because of the pressures associated with the increase of agricultural production and previously prolonged drought conditions, the entire catchment is under stress. The study presented here focuses on the Laidley Creek subcatchment, one of the southern subcatchments of the wider Lockyer Valley. The Laidley Creek subcatchment is geomorphically representative of multiple areas along the eastern slopes of the Great Dividing Range in Australia and small alluvial catchments in subtropical settings elsewhere.

This study was developed around five main topics: (1) historical data overview and analysis, (2) design of up-to-date field monitoring/collection (precipitation, creek flow, hydrochemical data) and analysis program (graphical hydrograph analysis, major ion analysis and it's graphical and statistical interpretation), (3) catchment-wide conceptualization of the aquifer system and hydrological processes (recharge and inter-aquifer flows), (4) development of catchment numerical model to quantify the flows between alluvium and underlying bedrock aquifers, and (5) identification of gaps in the historical and currently acquired datasets with respect to the suitability for the further numerical model development.

(1) The review of data established that a correlation between rainfall, stream flow and recharge of the alluvium (groundwater level elevations) exists, similarly as described in the studies of other subcatchments of the Lockyer Valley. Specifically:

- Increased creek flow correlates with higher than average rainfall (e.g. during years 1974, 1976, 1982, 1988 and 1986) and sustained groundwater levels;
- Lower than average rainfall translates into low creek flow volumes (or creek drying out) and falling groundwater levels (e.g. periods of 1976 – 1980, 1984 – 1987 and 1992 - 1995), and
- During the initial phases of the dry period, a delayed recharge of the alluvium from basalt aquifers takes place in the upper parts of the catchment.

(2) In order to narrow down the general findings of the literature and historical data overview, a field campaign to collect and analyse the current and more detailed data was planned and carried out. The data collected were:

- *Rainfall:* daily measurements, gauges expanded from single BOM station to three stations across the Laidley Creek catchment. See the catchment conceptualization section (below) for the rainfall quantification.
- *Stream flow:* stream head and flow rate; DERM gauging station data were complemented by weekly observations along the course of the Laidley and Main Camp Creeks. See the catchment conceptualization section (below) for the creek flow quantification.
- *Groundwater table elevations:* monitoring of 42 bores in approximately weekly intervals for the period between 13/3/2007 and 10/12/2008. Additionally, 10 of the monitored bores were equipped by automatic pressure transducers, logging the groundwater elevation data at 15-minute intervals. The groundwater head data varied (amplitude: maximum elevation - minimum elevation) between 0.1 m (Gatton Sandstone bores 884 and 887) and 11.5 m (alluvium bore 295);
- *Groundwater and surface water hydrochemistry:* 34 groundwater and 9 surface water samples were collected and analysed (major ions).

The data analysis process comprised:

- *Graphical correlation of rainfall and creek flow data:* with regard to rainfall, four significant rainfall events were recognised (24/11/2007, 5/1/2008, 4-5/2/2008 and 3/6/2008) and used as the markers for the further correlation with creek flow and groundwater level data;
- *Graphical analysis of groundwater hydrograph data:* hydrographs were grouped according to the hydrograph response to either rainfall or creek bed infiltration. Three basic groups were: Group A (groundwater head reacts clearly and rapidly to major rainfall events and/or creek flow: bores 290, 293, 294-297, 330, 331, 337, 340, 450, 453, 472, 786, 879, 880, 883, 885, 917, 919, 920, 982, 983, 986), Group B (groundwater heads react slowly to rainfall and/or creek flow, bores:

332, 339, 849, 916) and Group C (minimum or no groundwater table movement, bores: 547, 553, 884, 887);

- *Analysis of groundwater and surface water chemistry:* Three types of analyses were carried out: (a) graphical analysis of major ion concentrations using Piper and Stiff diagrams. Four groups were defined: fresh, MRV basaltic waters (Group 1: Mg-Ca-HCO_3 and Mg-Na-HCO_3 type, TDS from 173 mg/L to 826 mg/L), Walloon Coal Measures and Koukandowie Formation waters (Group 2: Na-HCO_3 type, TDS from 248 to 553 mg/L), saline Gatton Sandstone waters (Group 3: Na-Mg-Cl type, TDS from 5050 to 12800 mg/L) and mixed central Laidley Creek alluvium waters (Group 4: Ca-Mg-Cl-HCO_3 and Mg-Na-Cl-HCO_3 types, TDS from 660 to 2472 mg/L).

  The second type of analysis was (b) hierarchical clustering analysis (HCA). Although not matching the graphical grouping entirely, the HCA showed very similar clustering trends, confirming the correlation between major ion composition and the lithology of the source of groundwater.

  In order to establish the volumetric ratios of groundwaters mixing in the central Laidley Creek alluvium, the two-sample mixing analysis (c) was undertaken using AquaChem software. The result of the analysis showed that the Gatton Sandstone waters seep into the Laidley Creek alluvium and constitute approximately 2-4% of the groundwater mix. The hydrochemistry analyses also established that the water in the Laidley Creek is sourced from rainfall and from MRV basalts and it is the main source for the alluvium recharge process.

(3) The conceptualization presented the catchment as a 5-layer system where 3 layers of Clarence-Moreton Basin aquifers (Gatton Sandstone, Koukandowie Formation and Walloon Coal Measures) are capped by remnants of Tertiary basalt flows (1 layer). A relatively thin and narrow alluvium (1 layer) is incised into both basalts and sandstones. The Laidley Creek alluvium is also the main source of irrigation water in the catchment. Based on the different recharge rates (represented by different hydrograph groups), the Laidley Creek alluvium was divided into 6 zones.

The conceptual catchment-wide water budget (over the period of 630 days, between 20/7/2007 and 10/4/2009) quantified the catchment wide fluxes as follows:

- catchment inflows: approximately 584865 ML (rainfall: 555295 ML, irrigation return: 29570 ML);
- catchment outflows: 462690 ML (EVT: 316059 ML, river: up to 113077 ML, pumping: up to 31302 ML, cross-boundary outflow: up to 2252 ML)

(4) A catchment-wide, 5-layer numerical transient model was developed. The model was calibrated against groundwater head and groundwater head gradient datasets. Based on the generally used calibration performance measures (SSQ: 48058 m^2, $RMFS_{(heads)}$: 2.31%), the calibration process was successful. The calibration analysis identified that the most problematic areas of the catchment to calibrate were along the edges of the alluvium (bores 880 and 883; with respect to heads dataset) and in some parts of the alluvium (bores 294, 295, 296 and 982; with respect to head gradients dataset).

The model was further used to calculate flows between alluvium and bedrock aquifers and the calculated volumes were compared to the numbers obtained during the analysis of groundwater mixing in the alluvial aquifer. The flows between the alluvium and non-alluvial bedrock aquifers were calculated to be approximately 15242 ML (inflows into alluvium), which represents approximately 43% of calculated total inflows into alluvium (35616 ML). This result is unrealistically high as the analysis of hydrochemistry suggests that the contribution of bedrock sandstone aquifers towards the groundwater mix in the alluvium is approximately 2-4%. Although reasonably well calibrated against head data, the model performance with respect to flow predictions is poor and the numerical model overpredicts the flows between alluvium and bedrock aquifers.

(5) The numerical model was investigated using the predictive uncertainty analysis methodology which identified that specific storage and vertical hydraulic conductivities of bedrock aquifers represent the highest contribution towards the uncertainty of modeling predictions (calculated flows). The "data worth" analysis further showed that the most important observations that lead to the maximum decrease of model predictive uncertainty are observations of groundwater head gradients (not groundwater heads) for bores in the lower central alluvium (bores 336, 337, 547, 553, 916), bores drilled in the

Gatton Sandstone and bores on the contact of alluvium and bedrock sandstone (bores 880, 883, 884).

The study integrated data and analyses of hydrogeology, hydrological processes, climate and hydrochemistry to improve the understanding of Laidley Creek catchment hydrogeological framework. The study presented a MODFLOW-SURFACT based numerical model of the catchment. In spite of the performance issues with respect to modeling inter-aquifer flows, the numerical model analysis identified hydraulic parameters that are contributing the most to the predictive uncertainty. The model analysis also identified a set of observations that have the highest positive impact onto the model calibration process.

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9 Appendices

Appendix A. Project photo documentation

Figure 81. Central Lockyer Valley geomorphology – intensively cultivated and irrigated alluvial plain.

Figure 82. Lower Laidley Creek catchment geomorphology – relatively narrow alluvial plain surrounded by low sandstone hills.

Figure 83. Upper Laidley Creek catchment geomorphology – narrow alluvial plain surrounded by steep basalt ridges.

Figure 84. Sandstone (Koukandowie formation) outcrop at the road cut south of Laidley.

Figure 85. Sandstone (Koukandowie formation) outcroping at the bottom of Laidley Creek during the no-flow period. About 200 m north of McGarrigal road bridge.

Figure 86. Fractured basalt outrop at the side of the road near Townson.

Figure 87. Basaltic lava flow remnant – Crosby Park, upper Laidley Creek catchment.

Figure 88. Coarse alluvium – Laidley Creek north of Crosby Park (upper catchment) during the no-flow period.

Figure 89. Monitoring bore with automatic pressure transducer. Bore is locked so that the automatic pressure transducer is not accessible during the measurement.

Figure 90. Laidley diversion weir in 04/2008. Dry creek, no-flow period.

Figure 91. Laidley diversion weir in 11/2008. Flattened grass indicates the maximum height of the flood.

Figure 92. Mulgowie recharging weir in 7/2007. Laidley Creek completly dry along its whole course.

Figure 93. Mulgowie recharging weir in 11/2007. 24 hours after minor flood event, the water disappeared from the creek into the alluvial aquifer.

Figure 94. Mulgowie recharging weir in 1/2008.

Figure 95. Irrigation waterhole in alluvium; alluvial groundwater table visible. Upper Laidley Creek, south of Crosby Park, 8/2007.

Appendix B. Actual rainfall measurement – monthly totals and daily measurements

See the digital appendices for data in digital form: /data/climatic/rainfall.xls

On-line rainfall data available from the BOM website:

http://www.bom.gov.au/climate/data/weather-data.shtml

Table 20. Position of monitored rainfall stations and stream gauging station

station	station type	easting	northing	monitoring period
Townson (040675)	rainfall	439874	6912617	03/2007 – 02/2009
Laidley Creek West	rainfall	436375	6933689	03/2007 – 06/2009
Laidley	rainfall	438949	6941472	03/2007 – 07/2008
Mulgowie (143209B)	creek flow	437246	6932380	01/2007 – 12/2008

Table 21. Actual monthly rainfall data for stations within the catchment collected during the course of the project.

year / month	Townson [mm]	Laidley Crk West [mm]	Laidley [mm]
2007 / 03	122.0	70.5	55.9
2007 / 04	51.8	13.9	17.2
2007 / 05	13.6	14.6	7.2
2007 / 06	82.4	97.1	56.1
2007 / 07	1.6	0.0	0.0
2007 / 08	81.0	103.5	75.9
2007 / 09	28.8	22.5	28.4
2007 / 10	127.8	157.1	121.4
2007 / 11	363.7	190.5	142.2
2007 / 12	137.2	149.6	77.3
2008 / 01	134.2	172.9	186.0
2008 / 02	184.8	230.6	182.3
2008 / 03	71.0	67.5	59.3
2008 / 04	27.6	31.5	41.4
2008 / 05	16.0	15.0	15.8
2008 / 06	93.4	86.3	80.2
2008 / 07	79.2	120.0	69.8
2008 / 08	4.0	9.8	n/a
2008 / 09	37.5	48.0	n/a
2008 / 10	71.8	46.1	n/a
2008 / 11	304.9	402.8	n/a
2008 / 12	113.8	171.8	n/a
2009 / 01	223.0	259.5	n/a

Stations "Laidley Creek West" and "Laidley" are unofficial rainfall gauges on farms. Data from station "Laidley" are available only till the end of July 2008.

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day	month/y																							
	01/07	02/07	03/07	04/07	05/07	06/07	07/07	08/07	09/07	10/07	11/07	12/07	01/08	02/08	03/08	04/08	05/08	06/08	07/08	08/08	09/08	10/08	11/08	12/08
1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	7.4	12.8	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	2.8	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	1.8	0.0	0.0	0.0	0.0	8.4	0.0	0.0	0.0	0.0	3.4	0.0
3	0.4	0.2	0.0	0.0	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	45.4	0.0	0.0	0.0	0.0	0.2	0.0
4	10.8	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	6.6	41.0	0.0	0.0	0.0	5.4	0.0	0.0	0.2	0.0	2.2	4.6
5	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.8	0.0	0.0	4.6	40.4	74.0	0.0	0.0	0.0	0.0	0.0	0.0	20.4	0.0	0.0	9.8
6	0.4	0.0	11.0	0.0	0.0	27.8	0.0	0.0	7.0	0.0	5.4	32.4	0.0	6.6	0.0	0.0	0.0	0.0	7.2	0.0	0.2	0.0	26.2	21.4
7	0.0	0.0	0.4	0.0	0.0	3.4	0.0	0.0	1.8	0.0	7.8	0.0	20.4	11.4	0.0	0.0	0.0	2.2	1.8	0.0	0.0	0.0	0.2	13.2
8	0.0	0.0	0.0	0.0	0.4	0.6	0.0	0.0	0.0	0.6	15.2	15.4	0.0	1.2	0.0	4.2	0.0	0.0	13.2	0.0	0.0	0.0	3.6	0.0
9	0.0	0.0	15.0	0.0	0.6	0.2	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.6	0.0	0.0	0.4	0.0	0.0	0.0	8.2	0.2
10	0.2	0.0	19.6	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.2	1.6	0.0	0.0	0.0	0.2	0.0	1.2	0.0	0.0	0.0	10.0	0.0	0.2
11	0.0	10.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	1.0	0.8	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	16.2	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	9.4	0.4	5.6	0.0	0.2	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0
13	0.0	9.2	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	6.6	0.0	7.6	0.4	0.0	0.0	0.2	0.0	0.0	1.6	0.0	3.6	0.0
14	0.0	0.8	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	26.8	0.0	0.0	0.0	0.0	2.4	0.0	0.0	0.2	0.0	0.0
15	0.0	0.6	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.4	0.0	0.0	0.0	0.0	0.0	0.2	0.0	2.2	0.0	0.0	0.0
16	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.2	1.4	0.0	0.0	0.0	3.4	0.4	0.0	0.0	0.0	0.0	10.0	0.0	0.0	8.4	0.0	0.0
17	0.0	5.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	1.4	0.8	0.0	0.0	0.0	0.2	0.0	0.0	3.4	3.8	0.0
18	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	7.8	0.0	0.0	5.0	0.0	7.4	0.0	0.0	0.0	0.0	0.2	25.6	0.0
19	0.0	0.2	0.0	0.0	0.0	0.4	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.2	0.8	0.0	0.0	0.8	0.0	0.0	0.0	0.0	33.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	170.6	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	2.6	0.0	0.0	0.0	0.0	0.4	0.0	16.4	0.0	10.0	0.0
22	0.0	0.0	0.0	0.0	3.8	0.0	0.0	8.0	0.0	0.0	0.0	0.0	7.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.4	0.0
23	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	2.0	0.2	0.0	0.0	0.4	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0
24	0.0	0.0	0.2	0.0	0.0	3.8	0.4	18.6	0.0	0.0	58.8	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.8	0.0	0.0	5.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	10.4	0.0	0.0	0.0	0.0	15.6
26	31.8	0.0	0.4	0.0	0.2	16.4	0.0	0.6	0.0	12.4	0.0	0.0	0.0	12.8	0.0	0.0	0.2	0.0	0.8	0.0	0.0	0.0	0.8	0.0
27	0.2	0.0	0.0	0.0	0.0	9.6	0.0	0.0	1.6	0.0	0.0	1.2	0.0	12.8	25.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	16.4	0.0
28	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.4	2.4	0.0	0.2	7.6	0.6	0.0	0.0	2.2	0.0	0.0	0.0	0.0	5.6
29	0.0	--	0.0	2.6	0.2	0.0	0.0	0.0	0.2	11.2	0.0	3.6	0.0	0.0	3.6	0.0	0.4	0.0	0.0	1.6	0.0	0.0	10.0	2.6
30	0.0	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.6	--	0.2	0.0	2.0	0.0	0.0	0.2	0.0	0.0	3.0	2.8
31	0.0	--	0.0	--	0.4	--	0.0	0.0	--	0.0	--	0.0	6.2	--	0.0	--	0.8	--	0.0	0.0	--	0.0	--	0.0
Σ	50.6	29.8	47.0	2.6	6.6	65.2	0.8	71.6	12.8	41.8	103.2	99.4	125.4	205.0	43.8	6.2	10.8	66.0	49.4	4.0	41.0	43.6	321.2	76.0

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day	month/year																							
	01/07	02/07	03/07	04/07	05/07	06/07	07/07	08/07	09/07	10/07	11/07	12/07	01/08	02/08	03/08	04/08	05/08	06/08	07/08	08/08	09/08	10/08	11/08	12/08
1	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.4	0.0	7.2	2.2	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4.4	0.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0
3	23.6	0.0	0.0	0.0	0.0	8.8	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.8	0.0	0.0	0.0	75.0	0.0	0.0	0.0	0.0	2.9	0.0
4	36.4	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	54.4	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	9.2	0.0
5	0.0	0.0	17.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	16.6	52.2	49.8	0.0	0.0	0.0	0.0	0.0	0.0	16.4	0.0	0.0	8.2
6	16.4	0.0	0.0	0.0	0.0	21.0	0.0	0.0	9.6	0.0	3.0	30.0	0.0	9.0	0.0	0.0	0.0	0.0	4.0	0.0	0.4	0.0	6.8	9.4
7	0.0	0.0	77.0	0.0	0.0	8.2	0.0	0.0	10.8	5.4	5.0	0.0	3.8	19.0	0.0	0.0	0.0	0.8	5.4	0.0	0.0	0.0	0.0	26.0
8	0.0	0.0	0.0	0.0	6.4	1.2	0.0	0.0	0.0	0.0	14.2	16.4	0.0	0.0	0.0	0.0	0.0	2.0	16.2	0.0	0.0	0.0	3.2	0.0
9	5.4	0.0	7.0	0.0	2.0	1.2	1.6	0.0	0.0	1.0	0.0	4.0	0.0	1.2	0.0	4.4	0.0	1.0	0.4	0.0	0.0	0.0	4.0	0.0
10	0.6	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	12.4	0.0	8.0	0.8	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	15.0	0.0	0.0
11	0.0	34.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.8	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	3.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	9.8	9.0	7.8	10.8	0.0	0.0	0.0	0.0	0.0	0.0	0.8	5.4	0.0	0.0
13	0.0	36.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.6	0.0
14	0.0	6.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	4.6	0.0	0.0	0.8	2.2	3.0
15	0.0	6.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	1.0	4.6	2.4	0.0	3.0	0.0	0.0	0.0	0.0	2.8	5.2	0.0	0.0
16	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.6	3.6	0.0	0.0	0.0	20.6	0.0	0.0	0.0	0.0	0.0	17.2	0.0	0.0	23.0	0.0	0.0
17	0.0	6.0	0.0	9.6	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	2.4	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	14.4	0.0
18	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	18.4	1.8	3.0	11.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.8	0.0
19	0.0	3.0	0.0	0.0	0.2	0.0	0.0	6.2	0.0	0.0	0.0	0.0	0.0	1.8	0.4	0.0	0.0	5.8	0.0	0.0	1.6	0.0	53.6	8.6
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.4	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	85.0	0.0
21	0.0	5.4	0.0	0.0	2.6	0.0	0.0	8.6	0.0	0.0	0.0	0.0	2.0	0.0	7.4	0.0	0.0	0.0	3.0	0.0	14.2	0.0	29.8	0.0
22	0.0	1.8	0.0	0.0	0.4	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	2.8	0.0	0.0	0.0	0.5	14.0	0.0	0.0
23	0.0	0.0	0.0	15.8	0.0	0.0	0.0	15.2	0.0	0.0	23.2	1.2	0.0	0.0	0.0	18.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.2	0.0	6.6	0.0	0.0	0.0	0.0	174.4	0.0	0.0	0.0	3.4	0.0	0.0	0.0	10.0	0.0	0.6	0.0	0.0	0.0
25	8.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	80.0	2.2	4.8	0.0	0.6	0.0	0.0	0.0	16.0	0.0	0.0	0.0	0.0	7.6
26	17.2	0.0	0.0	23.0	1.2	18.4	0.0	0.0	0.0	54.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	32.8	0.0
27	19.0	0.0	0.0	0.0	0.0	8.6	0.0	0.0	2.2	0.0	1.4	7.2	0.0	11.6	31.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.0	0.2
28	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.2	0.0	0.0	8.4	2.2	0.0	0.0	1.2	0.0	0.0	0.0	1.8	5.4
29	0.0	--	0.0	3.2	0.0	1.8	0.0	0.0	0.0	28.0	12.6	0.0	0.0	2.2	1.4	0.0	0.0	0.0	0.0	1.6	0.0	0.0	14.4	41.0
30	0.0	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	2.2	--	0.0	0.0	2.2	0.0	0.0	0.2	0.0	1.4	7.4	1.4
31	0.0	--	0.0	--	0.0	--	0.0	0.0	--	0.0	--	5.4	9.2	--	0.0	--	1.0	--	0.0	0.0	--	0.0	--	0.0
Σ	135.2	104.2	122.0	51.8	13.6	82.4	1.6	81.0	28.8	127.8	363.7	137.2	134.2	187.0	71.0	27.6	16.0	93.4	79.2	4.0	37.5	71.8	304.9	113.8

Laidley Creek West - farm

day	month/year																						
	01/07	02/07	03/07	04/07	05/07	06/07	07/07	08/07	09/07	10/07	11/07	12/07	01/08	02/08	03/08	04/08	05/08	06/08	07/08	08/08	09/08	10/08	11/08	12/08
1			1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.3	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0
2			20.3	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	13.5	0.0	0.0	0.0	0.0	25.5	0.0	0.0	0.0	0.0	2.6	0.0
3			0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	42.0	0.0	0.0	0.0	0.0	0.0	12.0
4			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.3	78.0	0.0	0.0	0.0	9.8	0.0	0.0	12.0	0.0	4.9	18.8
5			0.0	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	3.8	102.0	69.8	0.0	0.0	0.0	0.0	5.6	0.0	15.0	0.0	4.5	0.0
6			27.0	0.0	0.0	43.5	0.0	0.0	13.5	0.0	5.6	27.8	0.0	10.9	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	20.6	45.8
7			1.9	0.0	0.0	3.0	0.0	0.0	1.1	0.0	16.5	0.0	9.0	0.0	0.0	0.0	0.0	2.3	3.0	0.0	0.0	0.0	0.0	40.5
8			0.0	0.0	1.5	0.0	0.0	0.0	0.0	13.1	18.0	27.8	0.0	0.0	0.0	2.3	0.0	0.0	22.5	0.0	0.0	0.0	14.3	0.0
9			15.8	0.0	0.0	0.0	0.0	0.0	0.0	14.3	0.0	3.0	2.3	0.0	0.0	0.8	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0
10			3.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	0.0	6.0	0.0	0.0	0.0	0.8	0.0	1.5	0.0	0.0	0.0	25.5	0.0	1.5
11			0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.3	0.0	12.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0
12			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	18.8	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0
13			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0
14			0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0
15			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6	0.0	0.0	0.0	0.0	0.0	21.0	0.0	3.0	0.0	0.0	0.0
16			0.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	3.0	0.0	0.0	16.1	0.0	0.0
17			0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	3.8	12.8	0.0	0.0	6.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	14.3	0.0
18			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	0.8	12.8	0.0	4.5	0.0	0.0	0.0	0.0	0.0	16.5	0.0
19			0.0	0.0	0.0	0.0	0.0	21.8	0.0	0.0	0.0	0.0	0.0	6.0	3.8	0.0	0.0	0.0	0.0	0.0	2.3	0.0	62.3	6.4
20			0.0	0.0	0.0	0.0	0.0	41.3	0.0	0.0	0.0	1.1	0.0	1.9	1.5	0.0	0.0	3.8	0.0	0.0	12.0	0.0	185.3	0.0
21			0.0	0.0	6.0	0.0	0.0	10.5	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	6.8	0.0	0.0	0.0	7.5	0.0
22			0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.8	0.0
23			0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	39.0	0.0	0.0	0.0	0.0	27.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24			0.0	0.0	0.0	7.1	0.0	27.8	0.0	0.0	58.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.3	0.0	0.0	0.0	0.0	17.3
25			1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	9.0	0.0	0.0	0.0	0.0	10.9	0.0	0.0	0.0	0.0	0.0
26			0.0	0.0	0.0	33.8	0.0	0.0	0.0	68.3	0.0	12.0	0.0	12.8	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	29.3	0.0
27			0.0	0.0	1.9	3.4	0.0	0.0	4.5	5.3	0.0	0.0	0.0	12.0	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0
28			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	2.3	2.3	9.8	0.0	0.0	0.0	1.5	0.0	0.0	0.0	13.9	16.9
29			0.0	6.0	0.0	0.0	0.0	0.0	0.0	28.5	0.0	0.0	4.5	0.0	14.3	0.0	0.0	0.0	0.0	6.0	0.0	0.0	24.0	11.3
30			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.8	0.0	--	0.0	0.0	7.5	0.0	0.0	1.5	0.0	0.0	0.0	1.5
31			0.0	--	0.0	--	0.0	0.0	--	0.0	--	0.0	0.0	--	0.0	--	0.0	--	0.0	0.0	--	0.0	--	0.0
Σ	n/a	n/a	70.5	13.9	14.6	97.1	0.0	103.5	22.5	157.1	190.5	149.6	172.9	230.6	67.5	31.5	15.0	86.3	120.0	9.8	48.0	46.1	402.8	171.8

Laidley - farm

day	month/year																							
	01/07	02/07	03/07	04/07	05/07	06/07	07/07	08/07	09/07	10/07	11/07	12/07	01/08	02/08	03/08	04/08	05/08	06/08	07/08	08/08	09/08	10/08	11/08	12/08
1			16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0					
2			7.6	0.0	0.0	0.6	0.0	0.0	10.0	0.0	0.0	0.0	5.1	0.0	0.0	0.0	0.0	20.0	0.0					
3			0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	12.0	46.0	0.0	0.0	0.0	41.0	0.0					
4			0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	61.0	29.3	0.0	0.0	0.0	3.7	0.0					
5			11.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	1.4	38.3	41.0	0.0	0.0	0.0	0.0	9.0					
6			2.0	0.0	0.0	35.0	0.0	0.0	5.1	0.0	2.1	13.0	2.0	26.0	0.0	0.0	0.0	0.0	2.3					
7			0.7	0.0	0.0	1.1	0.0	0.0	0.4	7.0	10.0	8.0	3.4	0.0	0.0	0.0	0.0	7.0	1.1					
8			11.0	0.0	0.6	0.0	0.0	0.0	10.0	4.9	17.0	8.0	0.0	0.0	0.0	0.8	0.0	0.0	15.0					
9			5.9	0.0	0.0	0.0	0.0	0.0	0.0	5.3	0.0	5.0	0.8	0.0	0.0	0.3	0.0	0.6	0.0					
10			1.1	0.0	0.0	0.0	0.0	0.0	0.0	22.0	0.0	2.3	0.0	0.0	0.0	0.3	0.0	3.0	0.0					
11			0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.6	0.0	4.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0					
12			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	7.0	0.0	0.0	0.0	0.0	0.0					
13			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0					
14			0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	7.0					
15			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	5.0					
16			0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	38.0	0.7	0.0	0.0	0.0	0.0	1.1					
17			0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	1.4	4.8	0.0	0.0	10.0	0.0	1.1	0.0	0.0					
18			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.3	3.0	0.0	1.7	0.0	0.0					
19			0.0	0.0	0.0	0.0	0.0	8.2	0.0	0.0	0.0	0.0	0.0	2.3	1.4	0.0	0.0	0.0	0.0					
20			0.0	0.0	0.0	0.0	0.0	38.0	0.0	0.0	0.0	0.4	0.0	0.7	0.6	0.0	0.0	5.0	0.0					
21			0.0	0.0	4.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	3.0					
22			0.0	0.0	0.3	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.0	0.0	0.0	0.0					
23			0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	60.0	0.0	0.0	0.0	0.0	7.0	0.0	0.0	8.0					
24			0.0	0.0	0.0	2.7	0.0	20.0	0.0	12.0	42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0					
25			0.6	8.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	5.0	0.0	0.0	0.0	0.0	11.0					
26			0.0	0.0	0.0	12.7	0.0	0.0	0.0	25.6	0.0	4.5	0.0	17.0	0.0	0.0	0.0	0.0	0.7					
27			0.0	0.0	0.7	1.3	0.0	0.0	1.7	2.0	0.0	0.0	0.0	4.5	14.0	1.0	0.0	0.0	0.0					
28			0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.8	0.8	25.0	0.0	0.0	0.0	0.6					
29			0.0	2.3	0.0	0.0	0.0	0.0	0.0	35.0	0.0	0.0	14.0	0.0	5.3	0.0	6.0	0.0	0.0					
30			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	1.0	--	0.0	0.0	7.0	0.0	0.0					
31			0.0	--	0.0	--	0.0	0.0	--	0.0	--	8.0	0.0	--	0.0	--	0.0	--	0.0		--		--	
Σ	n/a	n/a	55.9	17.2	7.2	56.1	0.0	75.9	28.4	121.4	142.2	77.3	186.0	182.3	59.3	41.4	15.8	80.2	69.8					

Appendix C. Historical rainfall in wider area

See the digital appendices for original data: /data/climatic/rainfall.xls

On-line rainfall data available from the BOM website:

http://www.bom.gov.au/climate/data/weather-data.shtml

Table 22. Data availability for BOM stations surrounding Laidley Creek catchment.

	station number	easting	northing	elevation	data availability
Gatton UQ	40082	434638	6953135	94.0	1899 - 2008
Gatton Allan St	40083	430688	6953224	70.0	1895 - 2008
Forrest Hill	40079	436540	6948049	92.0	1894 - 2008
Townson	40675	439874	6912617	280.0	1978 - 2008
Grandchester	40091	447529	6940347	76.0	1894 - 2008
Rosevale	40183	448802	6919084	100	1909 - 2008
Tarome	40198	452008	6905360	134.0	1912 - 2008
Mt. Berryman	40310	432083	6933181	434.0	1962 - 2008
Franklyn Vale	40374	446394	6929375	100.0	1886 - 2007
Upper Tenthill	40388	423050	6943097	137.0	1959 - 2007
Moorang	40400	448237	6913099	137.0	1919 - 2007
Rhonda	40447	446999	6903678	168.0	1953 - 2007
Mandala Farm	41323	429809	6900487	548.6	1959 - 1969, 1983 - 2008
Cunningham's Gap NP	41456	438774	6896770	732.0	1977 - 2008

Table 23. Rainfall monitoring stations in Laidley Creek and surrounding catchments.

Date	40675 Townson	Laidley Crk West	Laidley	40082 Gatton UQ	40083 Gatton Allan St	40079 Forrest Hill	40091 Grandchester	40183 Rosevale
Jan-07	135.2			50.6	31.2	53.4	55.6	41.2
Feb-07	104.2			29.8	55.8	46.6	63.6	0.0
Mar-07	122.0	70.5	55.9	47.0	44.2	71.4	77.2	71.6
Apr-07	51.8	13.9	17.2	2.6	2.6	8.2	6.8	80.2
May-07	13.6	14.6	7.2	6.6	5.6	5.5	11.0	8.8
Jun-07	82.4	97.1	56.1	65.2	69.6	69.4	68.7	71.8
Jul-07	1.6	0.0	0.0	0.8	0.8	1.0	0.6	0.0
Aug-07	81.0	103.5	75.9	71.6	82.4	67.9	65.2	60.4
Sep-07	28.8	22.5	28.4	12.8	18.8	13.5	16.9	11.0
Oct-07	127.8	157.1	121.4	41.8	53.2	74.8	67.8	98.8
Nov-07	363.7	190.5	142.2	103.2	114.8	78.3	174.2	209.6
Dec-07	137.2	149.6	77.3	99.4	108.2	73.5	91.5	171.8
Jan-08	134.2	172.9	186.0	125.4	124.0	174.6	263.1	177.8
Feb-08	184.8	230.6	182.3	205.0	201.0	154.4	183.8	182.2
Mar-08	71.0	67.5	59.3	43.8	68.2	71.8	41.4	39.2
Apr-08	27.6	31.5	41.4	6.2	5.8	1.4	10.1	20.6
May-08	16.0	15.0	15.8	10.8	4.6	9.8	12.4	6.6
Jun-08	93.4	86.3	80.2	66.0	59.2	77.9	98.2	58.0
Jul-08	79.2	120.0	69.8	49.4	53.2	60.9	61.5	50.2
Aug-08	4.0	9.8		4.0	3.6	19.1	20.2	

Date	40198 Tarome	40310 Mt. Berryman	40374 Franklyn Vale	40388 Upper Tenthill	40400 Moorang	40447 Rhonda	41323 Mandala Farm	41456 Cunninghams Gap
Jan-07	59.6	102.2	62.0	50.4	47.6	51.4	70.4	101.0
Feb-07	74.4	44.6	54.0	49.2	52.6	77.6	50.0	97.4
Mar-07	109.2	51.2	81.0	70.6	51.6	86.4	41.6	84.0
Apr-07	28.0	6.8	15.5	4.0	61.0	2.0	27.8	20.3
May-07	11.2	14.2	6.5	6.8	5.2	8.4	8.8	19.2
Jun-07	74.8	69.8	75.0	73.4	42.2	79.2	63.0	101.3
Jul-07	0.6	0.4	0.0	0.2	0.0	0.0	0.0	0.4
Aug-07	69.8	62.6	62.5	74.2	71.0	82.0	63.4	78.3
Sep-07	22.6	15.0	15.5	14.6	19.0	21.8	26.4	31.9
Oct-07	140.2	101.2	77.0	70.4	131.4	147.8	128.6	139.2
Nov-07	169.6	128.2	208.5	139.2	115.2	164.8	233.0	195.8
Dec-07	165.6	75.6	74.0	207.2	219.6	202.6	77.6	125.3
Jan-08	170.6	120.8	118.5	76.0	143.4	176.6	141.2	254.3
Feb-08	324.0	202.0	192.0	160.6	185.2	253.6	93.6	228.0
Mar-08	57.4	54.4	39.5	45.6	50.8	49.1	85.6	85.0
Apr-08	19.6	20.2	41.5	19.0	39.0	33.6	42.4	43.3
May-08	19.0	9.0	6.5	8.4	14.2		9.2	8.1
Jun-08	52.6	62.0	72.5	54.8	74.8		78.8	98.0
Jul-08	52.4	67.0		65.0	71.4		74.2	92.9
Aug-08	7.6	7.0						

Figure 96. Rainfall monitoring stations in Laidley Creek and surrounding catchments.

Appendix D. Laidley Creek flow data

Site ID:	143209B
Site Name:	Laidley Creek at Mulgowie
Grid reference:	Zone – 56; easting: 437246.0; northing 6932380.0
Latitude:	27:43:53S
Longitude:	152:21:48E
Map Datum:	MGA94
Gauge elevation:	132.926 m a.s.l.
Cease to flow level:	1.024 m

See the digital appendices for original data: /appendix_data/creek_flow/laidley_creek_flows.xls

Online creek flow data available from: http://watermonitoring.derm.qld.gov.au/host.htm

Table 24. Creek gauging station Mulgowie (143209B) – Laidley Creek flow data – Jan 2007 – Jun 2007

day	Jan 2007		Feb 2007		Mar 2007		Apr 2007		May 2007		Jun 2007	
	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]
1	0.689	0	0.681	0	0.674	0	0.666	0	0.658	0	0.65	0
2	0.689	0	0.681	0	0.674	0	0.666	0	0.658	0	0.65	0
3	0.689	0	0.681	0	0.674	0	0.666	0	0.658	0	0.65	0
4	0.689	0	0.681	0	0.673	0	0.665	0	0.658	0	0.65	0
5	0.688	0	0.68	0	0.673	0	0.665	0	0.657	0	0.649	0
6	0.688	0	0.68	0	0.673	0	0.665	0	0.657	0	0.649	0
7	0.688	0	0.68	0	0.673	0	0.665	0	0.657	0	0.649	0
8	0.688	0	0.68	0	0.672	0	0.664	0	0.657	0	0.649	0
9	0.687	0	0.679	0	0.672	0	0.664	0	0.656	0	0.648	0
10	0.687	0	0.679	0	0.672	0	0.664	0	0.656	0	0.648	0
11	0.687	0	0.679	0	0.672	0	0.664	0	0.656	0	0.648	0
12	0.686	0	0.678	0	0.671	0	0.663	0	0.656	0	0.648	0
13	0.686	0	0.678	0	0.671	0	0.663	0	0.655	0	0.647	0
14	0.686	0	0.678	0	0.671	0	0.663	0	0.655	0	0.647	0
15	0.686	0	0.678	0	0.67	0	0.662	0	0.655	0	0.647	0
16	0.685	0	0.677	0	0.67	0	0.662	0	0.654	0	0.646	0
17	0.685	0	0.677	0	0.67	0	0.662	0	0.654	0	0.646	0
18	0.685	0	0.677	0	0.67	0	0.662	0	0.654	0	0.646	0
19	0.685	0	0.677	0	0.669	0	0.661	0	0.654	0	0.646	0
20	0.684	0	0.676	0	0.669	0	0.661	0	0.653	0	0.645	0
21	0.684	0	0.676	0	0.669	0	0.661	0	0.653	0	0.645	0
22	0.684	0	0.676	0	0.669	0	0.661	0	0.653	0	0.644	0
23	0.684	0	0.676	0	0.668	0	0.66	0	0.653	0	0.643	0
24	0.683	0	0.675	0	0.668	0	0.66	0	0.652	0	0.642	0
25	0.683	0	0.675	0	0.668	0	0.66	0	0.652	0	0.641	0
26	0.683	0	0.675	0	0.668	0	0.66	0	0.652	0	0.642	0
27	0.683	0	0.675	0	0.667	0	0.659	0	0.652	0	0.639	0
28	0.682	0	0.674	0	0.667	0	0.659	0	0.651	0	0.638	0
29	0.682	0	--	--	0.667	0	0.659	0	0.651	0	0.636	0
30	0.682	0	--	--	0.667	0	0.659	0	0.651	0	0.635	0
31	0.682	0	--	--	0.666	0	--	--	0.651	0	--	--

Table 25. Creek gauging station Mulgowie (143209B) – Laidley Creek flow data – Jul 2007 – Dec 2007

day	Jul 2007		Aug 2007		Sep 2007		Oct 2007		Nov 2007		Dec 2007	
	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]
1	0.634	0	0.594	0	0.57	0	0.548	0	0.555	0	0.883	0
2	0.633	0	0.592	0	0.569	0	0.546	0	0.555	0	0.882	0
3	0.632	0	0.591	0	0.568	0	0.545	0	0.555	0	0.882	0
4	0.630	0	0.591	0	0.568	0	0.545	0	0.555	0	0.882	0
5	0.629	0	0.589	0	0.569	0	0.545	0	0.555	0	0.882	0
6	0.628	0	0.588	0	0.568	0	0.545	0	0.555	0	0.882	0
7	0.627	0	0.587	0	0.566	0	0.544	0	0.555	0	0.883	0
8	0.625	0	0.586	0	0.565	0	0.546	0	0.555	0	0.883	0
9	0.623	0	0.585	0	0.566	0	0.548	0	0.555	0	0.883	0
10	0.622	0	0.584	0	0.565	0	0.549	0	0.555	0	0.883	0
11	0.620	0	0.583	0	0.562	0	0.549	0	0.555	0	0.883	0
12	0.619	0	0.582	0	0.562	0	0.549	0	0.555	0	0.884	0
13	0.618	0	0.582	0	0.561	0	0.549	0	0.555	0	0.884	0
14	0.616	0	0.58	0	0.561	0	0.548	0	0.555	0	0.884	0
15	0.615	0	0.579	0	0.561	0	0.547	0	0.555	0	0.885	0
16	0.614	0	0.579	0	0.560	0	0.545	0	0.555	0	0.885	0
17	0.612	0	0.578	0	0.560	0	0.544	0	0.555	0	0.885	0
18	0.611	0	0.576	0	0.558	0	0.544	0	0.555	0	0.885	0
19	0.609	0	0.577	0	0.556	0	0.544	0	0.555	0	0.884	0
20	0.607	0	0.578	0	0.556	0	0.542	0	0.555	0	0.884	0
21	0.606	0	0.578	0	0.555	0	0.542	0	0.555	0	0.884	0
22	0.604	0	0.577	0	0.554	0	0.541	0	0.555	0	0.884	0
23	0.603	0	0.575	0	0.553	0	0.541	0	0.555	0	0.883	0
24	0.602	0	0.577	0	0.552	0	0.539	0	2.363	27.837	0.883	0
25	0.601	0	0.577	0	0.552	0	0.540	0	1.845	4.014	0.883	0
26	0.600	0	0.576	0	0.552	0	0.548	0	1.371	0.385	0.884	0
27	0.598	0	0.576	0	0.552	0	0.549	0	1.179	0.018	0.884	0
28	0.598	0	0.573	0	0.551	0	0.549	0	1.061	0.005	0.884	0
29	0.597	0	0.572	0	0.549	0	0.549	0	0.903	0	0.885	0
30	0.596	0	0.571	0	0.548	0	0.55	0	0.883	0	0.885	0
31	0.595	0	0.570	0	--	--	0.55	0	--	--	0.885	0

Table 26. Creek gauging station Mulgowie (143209B) – Laidley Creek flow data – Jan 2008 – Jun 2008

day	Jan 2008		Feb 2008		Mar 2008		Apr 2008		May 2008		Jun 2008	
	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]
1	0.885	0	0.883	0	1.320	0.105	1.249	0.028	0.897	0	0.847	0
2	0.885	0	0.882	0	1.316	0.091	1.251	0.028	0.896	0	0.846	0
3	0.885	0	0.882	0	1.320	0.108	1.258	0.029	0.895	0	0.847	0
4	0.884	0	1.484	3.497	1.326	0.141	1.228	0.025	0.893	0	0.847	0
5	2.240	13.233	3.382	41.517	1.322	0.118	1.176	0.017	0.892	0	0.846	0
6	1.710	2.433	2.561	18.317	1.317	0.093	1.120	0.010	0.890	0	0.844	0
7	1.526	1.023	2.286	11.123	1.324	0.128	1.039	0.002	0.888	0	0.843	0
8	1.428	0.567	1.789	3.180	1.327	0.146	0.942	0	0.886	0	0.842	0
9	1.372	0.376	1.620	1.632	1.312	0.076	0.925	0	0.885	0	0.840	0
10	1.335	0.210	1.519	0.980	1.304	0.055	0.923	0	0.883	0	0.839	0
11	1.303	0.052	1.459	0.686	1.304	0.056	0.921	0	0.881	0	0.838	0
12	1.283	0.033	1.442	0.616	1.282	0.033	0.92	0	0.879	0	0.837	0
13	1.272	0.031	1.459	0.686	1.228	0.025	0.919	0	0.878	0	0.835	0
14	1.246	0.027	1.436	0.592	1.168	0.016	0.918	0	0.876	0	0.833	0
15	1.181	0.018	1.404	0.478	1.080	0.006	0.917	0	0.875	0	0.831	0
16	1.183	0.098	1.378	0.394	0.962	0	0.915	0	0.874	0	0.829	0
17	1.428	0.566	1.358	0.337	0.940	0	0.914	0	0.873	0	0.827	0
18	1.440	0.608	1.346	0.300	0.939	0	0.913	0	0.870	0	0.825	0
19	1.407	0.486	1.339	0.250	0.939	0	0.911	0	0.868	0	0.824	0
20	1.371	0.373	1.329	0.160	0.938	0	0.910	0	0.866	0	0.824	0
21	1.342	0.258	1.320	0.107	0.969	0.001	0.908	0	0.864	0	0.823	0
22	1.314	0.088	1.313	0.077	1.227	0.025	0.907	0	0.863	0	0.821	0
23	1.289	0.034	1.313	0.078	1.247	0.027	0.911	0	0.861	0	0.820	0
24	1.267	0.030	1.308	0.063	1.255	0.029	0.909	0	0.860	0	0.818	0
25	1.218	0.023	1.313	0.080	1.273	0.031	0.908	0	0.858	0	0.817	0
26	1.135	0.012	1.323	0.126	1.256	0.029	0.907	0	0.856	0	0.815	0
27	1.017	0.002	1.326	0.141	1.266	0.03	0.906	0	0.854	0	0.813	0
28	0.887	0	1.327	0.144	1.286	0.033	0.904	0	0.853	0	0.813	0
29	0.882	0	1.33	0.166	1.279	0.032	0.902	0	0.851	0	0.811	0
30	0.882	0	--	--	1.266	0.03	0.900	0	0.850	0	0.810	0
31	0.882	0	--	--	1.261	0.029	--	--	0.849	0	--	--

Table 27. Creek gauging station Mulgowie (143209B) – Laidley Creek flow data – Jul 2008 – Dec 2008

day	Jul 2008		Aug 2008		Sep 2008		Oct 2008		Nov 2008		Dec 2008	
	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]	level [m]	discharge [m3/s]
1	0.808	0	0.771	0	0.731	0	0.710	0	0.567	0	1.425	0.851
2	0.807	0	0.77	0	0.730	0	0.709	0	0.567	0	1.337	0.523
3	0.806	0	0.769	0	0.730	0	0.708	0	0.567	0	1.291	0.383
4	0.805	0	0.767	0	0.730	0	0.708	0	0.567	0	1.262	0.309
5	0.804	0	0.766	0	0.729	0	0.707	0	0.567	0	1.247	0.274
6	0.803	0	0.765	0	0.728	0	0.707	0	0.566	0	1.282	0.363
7	0.802	0	0.763	0	0.727	0	0.706	0	0.566	0	1.411	0.882
8	0.802	0	0.762	0	0.726	0	0.706	0	0.566	0	1.345	0.546
9	0.800	0	0.760	0	0.725	0	0.705	0	0.566	0	1.304	0.422
10	0.799	0	0.758	0	0.724	0	0.706	0	0.565	0	1.271	0.330
11	0.797	0	0.756	0	0.723	0	0.705	0	0.565	0	1.264	0.384
12	0.795	0	0.754	0	0.722	0	0.704	0	0.565	0	1.262	0.428
13	0.794	0	0.753	0	0.722	0	0.704	0	0.565	0	1.262	0.428
14	0.793	0	0.751	0	0.721	0	0.704	0	0.564	0	1.257	0.406
15	0.793	0	0.750	0	0.721	0	0.704	0	0.564	0	1.242	0.345
16	0.793	0	0.748	0	0.721	0	0.703	0	0.564	0	1.231	0.305
17	0.792	0	0.747	0	0.720	0	0.703	0	0.565	0	1.229	0.299
18	0.790	0	0.746	0	0.720	0	0.702	0	0.565	0	1.220	0.268
19	0.789	0	0.744	0	0.719	0	0.701	0	0.876	6.022	1.235	0.321
20	0.787	0	0.742	0	0.718	0	0.700	0	3.214	40.095	1.206	0.225
21	0.786	0	0.741	0	0.717	0	0.700	0	1.735	3.198	1.197	0.198
22	0.785	0	0.740	0	0.717	0	0.699	0	1.342	0.549	1.195	0.194
23	0.784	0	0.739	0	0.716	0	0.698	0	1.229	0.235	1.189	0.178
24	0.783	0	0.737	0	0.716	0	0.696	0	1.154	0.103	1.185	0.167
25	0.782	0	0.736	0	0.715	0	0.695	0	1.105	0.128	1.183	0.161
26	0.781	0	0.735	0	0.714	0	0.694	0	1.954	7.087	1.190	0.178
27	0.779	0	0.734	0	0.713	0	0.694	0	1.671	2.248	1.183	0.161
28	0.778	0	0.733	0	0.712	0	0.614	0	1.513	1.304	1.196	0.206
29	0.776	0	0.732	0	0.711	0	0.568	0	1.691	2.391	1.340	0.833
30	0.775	0	0.732	0	0.711	0	0.568	0	1.605	1.797	1.234	0.317
31	0.773	0	0.732	0	--	--	0.568	0	--	--	1.210	0.236

Appendix E. Historical groundwater table observations (overview)

An overview of the historical groundwater table measurement data from DERM Groundwater database. Available upon request from DERM.

RN	easting	northing	date from	date to	max depth [m]	min depth [m]	min/max head diff. [m]	measure-ments
61350	439331	6942525	31/10/1980	20/06/2007	-24.97	-4.33	20.64	825
66443	439483	6941004	19/09/1988	20/06/2007	-19.30	-6.77	12.53	115
73562	437086	6947437	03/11/1998	12/12/2006	-21.01	-17.12	3.89	29
73644	436366	6948941	15/06/1995	12/12/2006	-22.38	-18.87	3.51	44
98240	439752	6945373	04/06/2001	20/06/2007	-16.90	-7.78	9.12	24
98246	438988	6946135	14/10/1996	20/06/2007	-23.09	-14.37	8.72	22
98252	439120	6945806	16/03/1998	22/01/2007	-20.99	-8.55	12.44	35
98267	437392	6948742	31/07/1995	06/07/2007	-21.64	-8.12	13.52	131
98276	437020	6948178	14/08/1996	20/06/2007	-22.37	-16.45	5.92	39
98290	439475	6942157	22/07/1998	20/06/2007	-15.00	-4.78	10.22	32
98291	439406	6942392	03/09/1998	20/06/2007	-21.91	-6.23	15.68	42
98316	438570	6940294	13/04/1988	06/07/2007	-21.84	-5.64	16.20	155
99612	437092	6923525	22/03/2007	15/06/2007	-9.31	-9.28	0.03	2
99676	435580	6947059	15/06/1995	18/06/2007	-24.23	-18.83	5.40	50
106878	434524	6944623	29/11/2004	15/06/2007	-21.75	-19.43	2.32	11
129055	438999	6942371	15/03/2005	22/03/2007	-20.09	-13.15	6.94	8
14320277	438510	6947061	27/03/1974	06/07/2007	-20.63	-2.78	17.85	326
14320279	439061	6947697	05/08/1945	23/03/2007	-8.15	-1.37	6.78	225
14320284	439651	6943025	27/03/1968	14/06/2007	-20.84	-6.09	14.75	101
14320286A	440256	6942923	12/09/1973	14/06/2007	-6.13	-2.88	3.25	144
14320286B	440256	6942923	12/09/1973	14/06/2007	-6.67	-2.41	4.26	142
14320287	440728	6942858	31/07/1974	14/06/2007	-5.63	-2.02	3.61	136
14320290	436796	6934637	05/02/1974	15/06/2007	-20.01	-5.04	14.97	180
14320292	436719	6934649	27/02/1975	15/06/2007	-8.45	-5.22	3.23	116
14320293	437010	6933940	29/06/1971	19/07/2007	-25.14	-6.25	18.89	87
14320294	437822	6930032	29/06/1971	15/06/2007	-15.79	-2.54	13.25	218
14320295	437965	6930000	10/09/1970	19/07/2007	-19.20	-3.52	15.68	287
14320296	438015	6929975	20/08/1971	15/06/2007	-19.95	-4.62	15.33	727
14320297	438045	6929962	10/09/1970	15/06/2007	-16.54	-2.97	13.57	173
14320310	434085	6942827	02/10/1969	15/06/2007	-18.31	-6.66	11.65	167
14320311	434351	6942791	09/09/1970	15/06/2007	-13.00	-4.23	8.77	186
14320312	434607	6942749	09/09/1970	15/06/2007	-19.46	-4.95	14.51	169
14320313	435502	6946259	09/06/1971	14/06/2007	-20.72	-9.53	11.19	171
14320314	433962	6945917	19/07/1971	15/06/2007	-8.53	-4.17	4.36	139
14320315	433898	6943850	19/07/1971	06/07/2007	-22.70	-6.57	16.13	346
14320321	439165	6944092	31/07/1974	14/06/2007	-21.93	-5.47	16.46	183
14320322	439290	6944286	31/07/1974	20/06/2007	-21.36	-6.76	14.60	164
14320325	439560	6944051	31/07/1974	06/07/2007	-19.43	-5.05	14.38	373
14320326	439708	6944026	31/07/1974	14/06/2007	-13.85	-6.30	7.55	168

RN	easting	northing	date from	date to	max depth [m]	min depth [m]	min/max head diff. [m]	measure-ments
14320327	439506	6943376	28/02/1975	20/06/2007	-21.88	-7.04	14.84	187
14320329	438074	6940312	31/07/1974	20/06/2007	-12.91	-4.58	8.33	151
14320330	438221	6940242	19/06/1974	20/06/2007	-20.40	-6.15	14.25	154
14320331	438247	6940220	19/06/1974	12/12/2006	-17.62	-5.93	11.69	138
14320332	438508	6940103	19/06/1974	31/07/2007	-17.42	-5.25	12.17	164
14320333	438479	6939817	19/06/1974	20/06/2007	-9.83	-3.70	6.13	142
14320335	437325	6939133	27/06/1974	20/06/2007	-10.52	-7.40	3.12	135
14320336	437542	6939104	27/06/1974	06/07/2007	-26.47	-6.42	20.05	330
14320337	437968	6939041	27/06/1974	20/06/2007	-21.55	-6.80	14.75	155
14320338	437407	6936611	31/07/1974	15/06/2007	-17.14	-6.81	10.33	144
14320339	437658	6936580	26/06/1974	31/07/2007	-22.30	-5.43	16.87	167
14320340	437966	6936534	26/06/1974	19/07/2007	-22.54	-4.42	18.12	172
14320341A	437295	6936191	26/06/1974	15/06/2007	-16.83	-7.10	9.73	109
14320341B	437295	6936191	31/07/1974	15/06/2007	-13.60	-7.40	6.20	106
14320372	437808	6939880	31/07/1974	22/03/2007	-19.15	-5.97	13.18	129
14320413	434002	6942590	06/11/1979	13/09/2006	-19.30	-6.36	12.94	68
14320414	433954	6942425	06/11/1979	13/09/2006	-12.21	-4.78	7.43	330
14320439	437569	6939576	06/11/1979	20/06/2007	-26.06	-5.58	20.48	362
14320450	438949	6941472	07/09/1979	31/07/2007	-23.30	-7.34	15.96	169
14320451	439101	6942009	07/09/1979	20/06/2007	-21.91	-6.67	15.24	151
14320452	439356	6942903	07/09/1979	20/06/2007	-19.44	-6.02	13.42	141
14320453	437262	6933749	07/09/1979	19/07/2007	-26.42	-7.89	18.53	109
14320454	437020	6933261	15/01/1980	15/06/2007	-14.46	-6.90	7.56	282
14320472	435762	6922267	11/07/1983	15/06/2007	-8.67	-4.56	4.11	91
14320473A	439752	6942534	01/02/1984	20/06/2007	-22.00	-3.71	18.29	121
14320473B	439752	6942534	01/02/1984	20/06/2007	-10.68	-4.45	6.23	118
14320474	440288	6942490	11/10/1983	20/06/2007	-9.58	-5.49	4.09	110
14320510	438990	6944116	12/04/1988	25/06/2007	-21.38	-6.26	15.12	90
14320511	438885	6944103	12/04/1988	14/06/2007	-21.39	-6.95	14.44	61
14320512	438939	6944038	19/09/1988	13/06/2007	-21.16	-6.06	15.10	80
14320525	437124	6948947	07/01/1988	06/07/2007	-21.77	-7.05	14.72	229
14320527	439254	6945667	13/10/1987	20/06/2007	-20.29	-6.75	13.54	102
14320528	437140	6947756	07/01/1988	18/06/2007	-21.66	-11.75	9.91	107
14320532	437507	6948953	12/04/1988	08/06/2007	-15.38	-1.18	14.20	113
14320537	439576	6945988	13/10/1987	20/06/2007	-14.23	-3.85	10.38	117
14320538	439392	6946237	13/10/1987	20/06/2007	-19.80	-4.84	14.96	126
14320541	439130	6943441	19/09/1988	20/06/2007	-21.75	-6.33	15.42	81
14320542	436320	6947186	14/02/1989	14/06/2007	-24.69	-17.92	6.77	100
14320544	439926	6943503	07/08/1990	14/06/2007	-9.01	-3.74	5.27	73
14320546	438528	6941902	14/02/1989	20/06/2007	-10.20	-5.27	4.93	82

RN	easting	northing	date from	date to	max depth [m]	min depth [m]	min/max head diff. [m]	measure-ments
14320547	438954	6940198	19/04/1989	20/06/2007	-16.43	-5.88	10.55	80
14320553	438764	6940236	15/02/1989	20/06/2007	-24.70	-5.79	18.91	86
14320555	435634	6947306	14/02/1989	20/06/2007	-17.17	-11.87	5.30	85
14320658	437524	6947448	01/11/1990	18/06/2007	-17.30	-6.93	10.37	84
14320659	436465	6947762	01/11/1990	14/06/2007	-23.00	-15.09	7.91	85
14320660	436240	6946131	01/11/1990	18/06/2007	-19.07	-11.42	7.65	85
14320661	437305	6947626	01/11/1990	18/06/2007	-19.61	-9.52	10.09	85
14320662	440082	6945336	01/11/1990	20/06/2007	-18.53	-5.03	13.50	99
14320665	438750	6947386	05/02/1991	31/07/2007	-18.39	-4.84	13.55	3797
14320666	438593	6947189	05/02/1991	31/07/2007	-19.77	-4.79	14.98	3840
14320667	438781	6947625	30/04/1991	20/06/2007	-15.52	-3.85	11.67	74
14320668	438835	6947890	30/04/1991	20/06/2007	-10.29	-2.99	7.30	77
14320771	439118	6945995	03/08/1995	20/06/2007	-22.98	-11.01	11.97	62
14320772	436722	6947859	15/06/1995	20/06/2007	-23.81	-19.36	4.45	48
14320785	436940	6934616	21/05/1996	06/07/2007	-21.88	-10.60	11.28	112
14320786	436927	6934606	29/03/1996	15/06/2007	-21.30	-11.90	9.40	43
14320805	435555	6946690	07/01/1998	14/06/2007	-20.44	-18.05	2.39	49
14320806	435555	6946659	07/01/1998	14/06/2007	-22.48	-18.80	3.68	37
14320816	438244	6947455	06/12/1998	06/07/2007	-18.73	-7.09	11.64	103
14320819	440103	6947191	31/03/1999	20/06/2007	-1.86	-0.48	1.38	33
14320820	440884	6945188	14/04/1999	20/06/2007	-2.85	-1.45	1.40	33
14320821	440907	6947331	01/05/1999	20/06/2007	-4.60	-2.90	1.70	33
14320848	437179	6934573	15/04/2002	15/06/2007	-18.78	-14.03	4.75	22
14320849	438890	6920957	15/04/2002	31/07/2007	-14.01	-10.70	3.31	79
14320878	434940	6942539	12/03/2004	25/06/2007	-21.53	-20.55	0.98	12
14320879	438283	6925072	22/10/2004	31/07/2007	-14.86	-9.98	4.88	24
14320880	439334	6930793	22/10/2004	25/06/2007	-9.31	-6.34	2.97	11
14320883	436375	6933689	25/03/2004	15/06/2007	-5.82	-2.88	2.94	12
14320884	437410	6940665	01/04/2004	15/06/2007	-16.77	-16.01	0.76	12
14320885	437694	6926581	31/03/2004	19/07/2007	-14.63	-11.92	2.71	13
14320886	438847	6936728	02/03/2004	15/06/2007	-16.67	-15.84	0.83	11
14320887	438845	6936720	02/03/2004	15/06/2007	-16.38	-15.80	0.58	12
14320888	433527	6946084	22/10/2004	15/06/2007	-7.80	-7.13	0.67	11
14320915	437909	6931255	11/11/2005	15/06/2007	-17.12	-10.39	6.73	7
14320916	436804	6938388	08/06/2005	25/06/2007	-26.42	-23.84	2.58	10
14320917	438105	6924979	27/04/2005	19/07/2007	-14.10	-8.67	5.43	14
14320918	438045	6926055	08/06/2005	22/03/2007	-12.50	-8.75	3.75	8
14320919	437928	6927532	15/04/2005	31/07/2007	-12.48	-8.57	3.91	25
14320920	438175	6927472	16/04/2005	19/07/2007	-11.02	-7.42	3.60	14
14320922	434822	6945307	03/03/2005	15/06/2007	-16.89	-14.16	2.73	14

RN	easting	northing	date from	date to	max depth [m]	min depth [m]	min/max head diff. [m]	measure-ments
14320936	436746	6944327	12/10/2005	15/06/2007	-48.98	-47.07	1.91	9
14320937	433163	6943546	30/09/2005	15/06/2007	-4.94	-3.99	0.95	8

Appendix F. Monitored bores – position, elevation, depth

Table 28. List of monitored bores, their position, elevation and depth.

RN	easting	northing	depth	elev. DEM	elev. NRW DB	elev. precision
99984	436431	6922940	11.41	195.8	-	-
14320290	439796	6934637	27.57	125.09	134.26	SVY
14320292	436719	6934649	7.37	127.42	133.91	SVY
14320293	437010	6933940	25.01	135.70	135.79	SVY
14320294	437822	6930032	15.45	146.90	147.95	SVY
14320295	437965	6930000	18.91	142.60	148.39	SVY
14320296	438015	6929975	15.38	141.50	149.21	SVY
14320297	438045	6929962	15.82	141.00	149.43	SVY
14320329	438074	6940312	12.06	115.50	114.00	SVY
14320330	438221	6940242	30.91	110.39	114.50	SVY
14320331	438247	6940220	30.88	109.89	114.60	SVY
14320332	438508	6940103	16.58	112.70	112.20	SVY
14320333	438479	6939817	8.87	114.43	112.20	SVY
14320335	437325	6939133	9.96	110.90	118.70	SVY
14320336	437542	6939104	30.18	111.20	117.10	SVY
14320337	437968	6939041	27.91	113.30	115.90	SVY
14320338	437407	6936611	16.78	120.20	127.40	SVY
14320339	437658	6936580	28.35	123.20	125.70	SVY
14320340	437966	6936534	22.98	127.70	124.20	SVY
14320450	438949	6941472	31.29	108.00	109.48	SVY
14320453	437262	6933749	32.61	127.50	137.31	SVY
14320472	435864	6922242	31.22	211.03	212.21	SVY
14320547	438954	6940198	18.73	114.50	109.54	SVY
14320553	438764	6940236	29.12	113.45	110.35	SVY
14320785	436940	6934616	31.52	124.70	133.68	SVY
14320786	436927	6934606	34+	124.50	133.74	SVY
14320848	437179	6934573	17.53	130.70	132.04	SVY
14320849	438890	6920957	15.73	192.90	190.60	SVY
14320879	438283	6925072	16.79	170.30	171.10	SVY
14320880	439232	6930610	36.89	176.80	196.00	GPS
14320883	436375	6933689	23.24	133.90	152.20	GPS
14320884	437410	6940665	50+	124.25	146.20	GPS
14320885	437694	6926581	21.13	173.00	182.00	GPS
14320886	438847	6936728	37.80	126.30	143.00	GPS
14320887	438845	6936728	50+	126.30	143.00	GPS
14320916	436804	6938388	26.99	112.62	-	-

RN	easting	northing	depth	elev. DEM	elev. NRW DB	elev. precision
14320917	438105	6924979	18.18	169.90	170.28	SVY
14320919	437928	6927532	21.04	153.70	160.49	SVY
14320920	438175	6927472	17.54	160.20	159.38	SVY
14320982	439909	6918919	15.08	212.15	203.13	SVY
14320983	439912	6916683	15.02	226.70	219.82	SVY
14320986	437322	6932694	26.07	134.00	139.15	SVY

Appendix G. Manual water level measurements

RN	easting	northing	elevation [m a.s.l.]	e. precision	m.pt. [m]	depth [m b.s.]
99984	436431	6922940	195.8	DEM	0.39	11.41
14320290	439796	6934637	134.3	SVY	0.44	27.57
14320292	436719	6934649	133.9	SVY	0.20	7.37
14320293	437010	6933940	135.8	SVY	0.29	25.01
14320294	437822	6930032	148.0	SVY	0.15	15.45
14320295	437965	6930000	148.4	SVY	0.23	18.91
14320296	438015	6929975	149.2	SVY	0.90	15.38
14320297	438045	6929962	149.4	SVY	0.38	15.82
14320329	438074	6940312	114.0	SVY	0.32	12.06
14320330	438221	6940242	114.5	SVY	0.35	30.91
14320331	438247	6940220	114.6	SVY	0.32	30.88
14320332	438508	6940103	112.2	SVY	0.35	16.58
14320333	438479	6939817	112.2	SVY	0.23	8.87
14320335	437325	6939133	118.7	SVY	0.38	9.96
14320336	437542	6939104	117.1	SVY	0.35	30.18
14320337	437968	6939041	115.9	SVY	0.29	27.91
14320338	437407	6936611	127.4	SVY	0.15	16.78
14320339	437658	6936580	125.7	SVY	0.25	28.35
14320340	437966	6936534	124.2	SVY	0.07	22.98
14320450	438949	6941472	109.5	SVY	0.33	31.29
14320453	437262	6933749	137.3	SVY	0.17	32.61
14320472	435864	6922242	212.2	SVY	-0.10	31.22
14320547	438954	6940198	109.5	SVY	0.14	18.73
14320553	438764	6940236	110.4	SVY	0.14	29.12
14320785	436940	6934616	133.7	SVY	0.48	31.52
14320786	436927	6934606	133.7	SVY	0.21	34+
14320848	437179	6934573	132.0	SVY	0.26	17.53
14320849	438890	6920957	190.6	SVY	0.37	15.73
14320879	438283	6925072	171.1	SVY	0.66	16.79
14320880	439232	6930610	196.0	GPS	0.27	36.89
14320883	436375	6933689	152.2	GPS	0.29	23.24
14320884	437410	6940665	146.2	GPS	0.30	50+
14320885	437694	6926581	182.0	GPS	0.27	21.13
14320886	438847	6936728	143.0	GPS	0.28	37.80
14320887	438845	6936728	143.0	GPS	0.31	50+
14320916	436804	6938388	112.6	DEM	0.23	26.99
14320917	438105	6924979	170.3	SVY	0.12	18.18
14320919	437928	6927532	160.5	SVY	0.22	21.04
14320920	438175	6927472	159.4	SVY	0.12	17.54
14320982	439909	6918919	212.2	DEM	0.36	15.08
14320983	439912	6916683	226.7	DEM	0.37	15.02
14320986	437322	6932694	134.0	DEM	0.53	26.07

RN	13.3.07	19.7.07	3.8.07	12.8.07	15.8.07	24.8.07	31.8.07	9.9.07	14.9.07
99984	8.22	8.05	n/a	n/a	n/a	n/a	8.51	8.51	8.54
14320290	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320292	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320293	23.60	24.46	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320294	14.90	dry	dry	dry	dry	dry	dry	dry	dry
14320295	15.90	18.62		18.27	18.62	18.62	18.72	18.69	18.68
14320296	16.20	dry	dry	dry	dry	dry	dry	dry	dry
14320297	14.90	dry	dry	dry	15.50	15.51	15.51	15.52	15.52
14320329	n/a	n/a	n/a	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320332	16.50	16.94	16.72	16.05	17.06	16.91	17.09	17.11	17.12
14320333	n/a	n/a	n/a	n/a	dry	dry	dry	dry	dry
14320335	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320336	n/a	n/a	n/a	n/a	25.91	25.82	25.94	25.84	25.83
14320337	n/a	n/a	n/a	n/a	21.26	21.28	21.27	21.29	21.30
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	21.30	21.82	21.63	21.88	21.90	21.91	21.93	21.97	21.97
14320340	21.79	22.25	22.12	22.23	22.18	22.19	22.19	22.19	22.23
14320450	20.60	21.22	21.48	21.61	21.71	21.38	21.37	21.19	21.19
14320453	25.50	26.08	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320472	n/a	n/a	n/a	n/a	8.76	10.97	8.76	8.76	8.77
14320547	n/a	n/a	n/a	n/a	16.10	16.11	16.13	16.16	16.15
14320553	n/a	n/a	n/a	20.18	20.16	20.12	20.10	20.07	20.05
14320785	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320786	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320848	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320849	13.00	13.33	13.23	13.68	13.71	13.56	13.48	13.41	13.37
14320879	13.80	14.20	14.08	14.25	15.26	16.40	14.29	14.31	14.33
14320880	n/a	n/a	n/a	n/a	9.06	9.02	9.09	9.18	9.25
14320883	n/a	n/a	n/a	5.51	5.51	5.51	5.54	5.56	5.56
14320884	n/a	n/a	n/a	15.73	16.50	15.76	15.79	15.73	15.72
14320885	n/a	14.13	14.15	14.26	14.16	19.45	14.18	14.19	14.21
14320886	n/a	n/a	n/a	15.76	15.77	15.72	15.72	15.71	15.70
14320887	n/a	n/a	n/a	15.69	15.69	15.63	15.63	15.64	15.62
14320916	n/a	n/a	26.07	26.07	26.10	n/a	25.99	25.93	25.95
14320917	12.38	13.76	13.76	13.78	13.82	13.77	13.75	13.72	13.71
14320919	10.90	11.99	12.09	12.25	12.23	12.16	12.11	12.05	12.04
14320920	9.50	10.73	10.92	11.02	10.96	10.82	10.75	10.68	10.66
14320982	n/a	n/a	10.55	10.48	10.44	9.91	9.60	9.35	9.27
14320983	n/a	n/a	9.32	9.48	9.58	9.59	9.64	9.72	9.72
14320986	n/a	19.80	n/a	20.16	20.19	20.23	20.10	19.90	19.77

RN	21.9.07	28.9.07	5.10.07	12.10.07	19.10.07	25.10.07	9.11.07	16.11.07	23.11.07
99984	11.08	9.17	8.57	8.57	8.59	8.56	n/a	n/a	n/a
14320290	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320292	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320293	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	24.62
14320294	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320295	18.69	18.68	18.69	18.69	18.69	18.69	18.69	18.69	18.69
14320296	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320297	15.55	15.54	15.55	15.55	15.55	15.55	15.55	15.56	15.55
14320329	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320332	17.13	17.00	17.01	17.20	17.05	17.08	17.12	17.13	17.32
14320333	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320336	25.84	25.78	25.83	25.95	25.86	26.00	26.09	26.02	26.04
14320337	21.31	21.31	21.33	22.34	21.35	21.36	21.38	21.39	21.40
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	21.99	22.00	22.02	22.06	22.06	22.07	22.12	22.14	22.18
14320340	22.21	22.28	22.22	22.24	22.33	22.33	22.38	22.27	22.28
14320450	21.36	21.44	21.89	21.88	21.82	21.82	21.56	21.53	21.65
14320453	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	25.82
14320472	8.80	8.82	8.85	8.89	8.91	8.93	8.92	8.92	8.97
14320547	16.17	16.18	16.20	16.21	16.23	16.23	16.26	16.28	16.29
14320553	20.04	20.02	20.01	19.96	19.98	19.95	19.94	19.92	19.91
14320785	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320786	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320848	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320849	13.42	13.55	13.49	13.51	13.70	13.81	13.59	13.56	13.50
14320879	14.34	14.35	14.37	14.40	14.4	14.43	14.45	14.46	14.49
14320880	9.51	n/a	n/a	9.62	n/a	n/a	n/a	n/a	9.71
14320883	5.59	5.60	5.62	5.62	5.65	5.62	5.64	5.65	5.66
14320884	15.72	15.71	15.74	15.69	15.80	15.74	15.76	15.77	15.73
14320885	14.21	14.23	14.23	14.24	14.25	14.23	14.25	14.27	14.27
14320886	15.73	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320887	15.65	15.65	15.67	15.63	15.67	15.67	15.65	15.67	15.67
14320916	25.99	26.04	26.08	26.12	26.13	26.15	26.03	25.97	25.98
14320917	13.66	13.88	13.92	13.93	13.88	13.93	13.96	13.79	13.80
14320919	12.18	12.37	12.43	12.42	12.5	12.59	12.45	12.42	12.41
14320920	10.90	11.16	11.22	11.15	11.29	11.43	11.16	11.10	11.08
14320982	9.16	9.70	9.86	10.28	10.50	10.40	9.58	9.42	9.79
14320983	9.77	9.80	9.83	9.88	9.9	9.94	9.96	9.96	9.95
14320986	19.76	19.91	19.98	20.10	20.07	20.18	20.07	20.00	20.13

RN	30.11.07	7.12.07	14.12.07	20.12.07	28.12.07	5.1.08	11.1.08	18.1.08	25.1.08
99984	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320290	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320292	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320293	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320294	dry	dry	dry	dry	dry	dry	dry	dry	13.20
14320295	18.70	17.43	17.01	16.70	16.42	16.16	15.43	14.29	12.91
14320296	dry	dry	dry	17.83	16.68	16.42	15.55	14.42	13.07
14320297	15.55	15.20	n/a	14.96	14.88	14.77	12.91	12.02	11.08
14320329	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320332	17.30	17.30	17.29	17.28	17.26	17.08	17.23	17.20	17.16
14320333	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320336	25.96	25.99	25.93	25.89	25.91	25.94	25.88	25.84	25.80
14320337	21.40	21.41	21.42	21.43	21.43	21.44	21.45	21.45	21.45
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	22.17	22.18	22.19	22.20	22.20	22.20	22.20	22.21	22.20
14320340	22.20	22.17	22.12	22.12	22.08	22.08	22.02	21.97	21.92
14320450	20.94	20.92	20.86	20.89	20.83	20.82	19.77	19.91	20.02
14320453	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320472	7.55	7.61	7.61	7.63	7.55	7.28	6.65	6.64	6.61
14320547	16.30	16.31	16.32	16.34	16.35	16.36	16.37	16.39	16.39
14320553	19.89	19.89	19.86	19.85	19.82	19.79	19.78	19.77	19.73
14320785	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320786	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320848	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320849	13.40	13.28	13.07	12.87	12.68	12.49	12.37	12.22	12.09
14320879	13.60	13.42	11.33	11.72	11.34	10.99	10.65	10.38	10.17
14320880	11.44	11.36	11.22	11.22	11.24	11.10	10.97	10.93	11.10
14320883	5.60	5.60	5.58	5.58	5.58	5.51	5.43	5.38	5.36
14320884	15.74	15.75	15.74	15.76	15.75	n/a	15.73	15.72	15.76
14320885	14.25	14.26	14.22	14.20	14.17	14.10	14.08	14.01	13.97
14320886	n/a	n/a	n/a	16.01	15.75	15.68	15.70	15.71	15.74
14320887	15.63	15.63	15.61	15.64	15.65	15.57	15.60	15.61	15.64
14320916	25.92	25.87	25.80	25.75	25.74	25.75	25.70	25.69	25.63
14320917	12.76	12.38	11.00	10.23	9.91	9.61	9.26	9.07	8.95
14320919	10.82	11.29	9.85	9.24	9.83	9.01	8.55	8.28	8.20
14320920	10.60	10.30	10.15	9.57	8.94	8.67	8.08	7.56	7.19
14320982	6.37	5.89	5.59	5.53	5.50	5.12	4.71	4.98	5.01
14320983	5.38	5.11	5.06	4.88	5.19	4.77	5.09	5.02	5.13
14320986	20.08	19.85	19.56	19.22	18.87	18.47	18.11	17.31	16.47

RN	1.2.08	9.2.08	15.2.08	22.2.08	29.2.08	7.3.08	14.3.08	21.3.08	28.3.08
99984	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320290	n/a	n/a	20.12	20.01	19.97	19.99	19.98	19.88	n/a
14320292	n/a	n/a	7.36	7.04	7.22	dry	dry	dry	dry
14320293	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320294	12.24	10.82	10.06	9.21	8.49	7.92	8.12	7.89	7.64
14320295	11.97	10.41	9.67	8.87	8.23	7.77	8.11	7.93	7.71
14320296	12.11	10.58	9.86	9.07	8.43	7.99	8.31	8.16	7.93
14320297	10.43	9.57	9.15	8.58	8.08	7.71	7.80	7.68	7.52
14320329	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320332	17.12	17.07	17.03	16.95	16.86	16.79	16.70	16.59	16.50
14320333	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320336	25.77	n/a	25.71	25.67	25.64	25.61	25.58	25.54	25.52
14320337	21.46	n/a	21.44	21.35	21.26	21.18	21.15	21.15	21.18
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	22.20	22.19	22.19	22.17	22.17	22.14	22.14	22.12	22.12
14320340	21.97	21.93	21.88	21.83	21.81	21.77	21.73	21.70	21.97
14320450	20.03	18.87	17.86	16.63	17.02	17.32	18.43	18.30	18.46
14320453	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320472	6.50	5.73	5.42	5.61	5.62	5.70	5.73	5.73	5.74
14320547	16.41	16.42	16.44	16.44	16.46	16.46	16.48	16.49	16.50
14320553	19.72	19.69	19.70	19.66	19.64	19.61	19.60	19.56	19.55
14320785	n/a	n/a	21.71	21.65	21.63	21.58	21.56	21.52	21.52
14320786	n/a	n/a	21.25	21.23	21.23	21.18	21.15	21.10	21.07
14320848	n/a	n/a	dry	dry	dry	dry	dry	dry	dry
14320849	11.97	11.74	11.62	11.44	11.30	11.16	11.14	11.01	10.93
14320879	10.01	9.44	9.40	9.37	9.34	9.33	9.36	9.36	9.38
14320880	11.11	10.68	10.71	10.62	10.57	10.74	8.30	8.33	8.40
14320883	5.35	4.97	4.80	4.73	4.69	4.70	4.71	4.69	4.69
14320884	15.76	15.67	15.73	-0.30	15.70	15.79	15.79	15.75	15.74
14320885	13.91	12.30	11.99	12.01	12.14	12.29	12.39	12.45	12.51
14320886	15.76	15.68	15.70	15.72	15.73	15.77	15.78	15.78	15.77
14320887	15.66	15.58	15.59	15.61	15.62	15.66	15.68	15.68	15.67
14320916	25.65	25.58	25.47	25.27	25.13	25.05	25.07	25.15	25.18
14320917	8.95	8.18	8.20	8.17	8.11	8.08	8.08	8.06	8.19
14320919	8.15	7.71	7.86	7.90	7.90	7.93	8.10	7.98	7.94
14320920	7.07	6.55	6.47	6.41	6.38	6.50	7.02	6.58	6.43
14320982	5.15	3.31	3.48	4.54	4.99	5.15	5.66	5.28	5.33
14320983	5.12	5.00	5.16	5.23	5.21	5.22	5.23	5.23	5.25
14320986	15.76	15.01	14.22	13.31	12.49	11.61	11.31	11.44	11.15

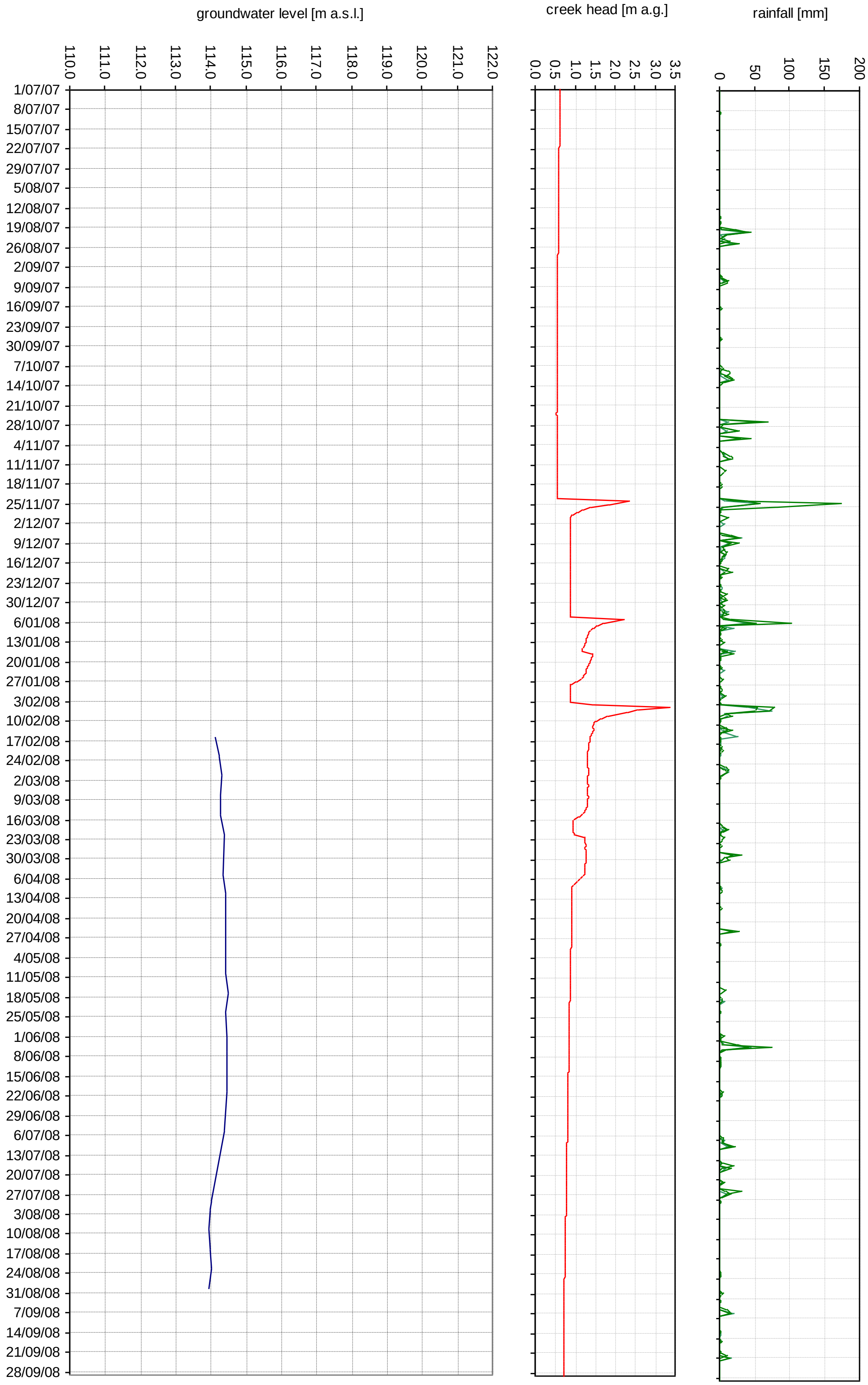
RN	4.4.08	11.4.08	18.4.08	9.5.08	16.5.08	23.5.08	1.6.08	6.6.08	20.6.08
99984	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320290	19.90	19.85	-0.44	19.85	19.78	19.86	19.81	19.80	19.80
14320292	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320293	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320294	6.79	6.84	6.84	6.80	7.13	7.41	7.69	7.27	6.27
14320295	6.84	7.00	7.06	7.26	8.04	7.95	8.26	7.65	6.52
14320296	7.08	7.23	7.30	7.54	8.12	8.25	8.57	7.54	6.86
14320297	7.01	6.99	7.10	7.47	7.85	8.16	8.45	7.87	6.84
14320329	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320331	13.12	13.21	13.33	n/a	13.70	13.81	13.90	13.89	14.00
14320332	16.41	16.32	16.24	16.00	15.93	15.88	15.82	15.79	15.69
14320333	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320336	25.47	25.44	25.41	25.33	25.28	25.28	25.24	25.23	25.17
14320337	21.21	21.25	21.28	21.36	21.37	21.39	21.41	21.42	21.41
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	22.11	22.11	22.11	22.12	22.11	22.13	22.14	22.14	22.15
14320340	21.93	22.15	22.31	22.42	22.38	22.52	22.62	22.63	22.64
14320450	19.61	18.71	18.81	19.91	20.14	20.12	19.81	19.72	19.67
14320453	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320472	5.77	5.80	5.89	6.21	6.32	6.46	6.52	6.55	6.68
14320547	16.51	16.52	16.53	16.56	16.56	16.58	16.59	16.59	16.61
14320553	19.53	19.49	19.46	19.39	19.34	19.33	19.30	19.28	19.22
14320785	21.50	21.46	-0.48	21.49	21.50	21.55	21.57	21.58	21.59
14320786	21.06	21.04	-0.21	21.01	21.03	21.05	21.34	21.35	21.36
14320848	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320849	10.88	10.80	10.75	10.59	10.65	10.58	10.40	10.24	9.92
14320879	9.38	9.42	9.49	9.61	19.65	9.58	9.55	9.47	9.41
14320880	8.45	8.51	8.62	8.84	8.89	9.00	9.13	9.12	9.12
14320883	4.72	4.73	4.77	4.85	4.88	4.93	4.97	4.95	5.02
14320884	15.75	15.76	15.77	15.77	15.77	15.78	-0.30	15.74	15.73
14320885	12.57	12.60	12.65	12.76	12.79	12.82	12.86	12.85	12.90
14320886	15.77	15.80	15.80	15.82	15.83	15.84	15.86	15.78	15.78
14320887	15.68	15.70	15.71	15.72	15.73	15.74	15.76	15.67	15.69
14320916	25.10	25.01	24.96	25.08	25.10	25.08	25.04	24.98	24.81
14320917	8.22	8.73	8.55	8.65	8.44	8.28	8.28	8.15	8.17
14320919	7.93	8.04	8.06	8.25	8.31	8.15	8.07	7.99	7.94
14320920	6.37	6.71	6.68	7.08	6.88	6.90	6.69	6.49	6.34
14320982	5.37	5.58	5.52	5.48	5.48	5.76	5.49	5.47	5.54
14320983	5.26	5.28	5.30	5.44	5.50	5.58	5.71	5.74	6.02
14320986	10.62	10.43	10.75	11.46	11.74	12.18	12.17	12.07	11.80

RN	4.7.08	10.7.08	17.7.08	26.7.08	29.7.08	1.8.08	8.8.08	15.8.08	22.8.08
99984	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320290	19.88	n/a	n/a	n/a	20.26	20.29	20.33	20.30	20.25
14320292	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320293	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320294	6.46	n/a	6.01	5.78	n/a	5.60	5.69	5.97	6.12
14320295	7.06	n/a	6.36	6.09	n/a	5.88	6.18	6.39	6.71
14320296	7.16	n/a	6.63	6.36	n/a	6.16	6.39	6.67	6.94
14320297	6.93	n/a	6.71	6.41	n/a	6.20	6.29	6.42	6.83
14320329	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320330	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
14320331	n/a	14.26	n/a	14.30	n/a	14.33	14.38	14.46	14.64
14320332	n/a	15.60	n/a	15.51	n/a	15.49	15.47	15.43	15.40
14320333	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320336	n/a	25.11	n/a	25.06	n/a	25.03	25.01	25.00	24.97
14320337	n/a	21.42	n/a	21.40	n/a	21.40	21.40	21.41	21.42
14320338	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320339	n/a	22.15	n/a	22.13	n/a	22.12	22.12	22.11	22.11
14320340	n/a	22.46	n/a	22.31	n/a	22.26	22.21	22.17	22.13
14320450	n/a	19.57	n/a	21.81	19.59	19.68	19.83	19.70	22.13
14320453	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
14320472	6.85	n/a	6.97	7.06	n/a	7.11	7.18	7.24	7.29
14320547	n/a	16.64	n/a	16.65	n/a	16.67	16.68	16.68	16.69
14320553	n/a	19.15	n/a	19.08	n/a	19.05	19.05	19.34	18.96
14320785	21.62	n/a	n/a	n/a	n/a	21.54	21.57	21.54	21.53
14320786	21.12	n/a	n/a	n/a	21.13	21.31	22.34	22.31	21.16
14320848	dry	dry	dry	dry	dry	dry	dry	dry	dry
14320849	9.92	n/a	9.77	9.60	n/a	9.50	9.55	9.57	9.67
14320879	n/a	n/a	9.53	9.47	n/a	9.49	9.56	9.62	9.80
14320880	9.07	9.19	n/a	8.99	n/a	9.00	9.01	9.02	9.04
14320883	n/a	5.10	n/a	5.14	n/a	5.23	5.25	5.27	5.28
14320884	n/a	15.73	n/a	15.68	15.64	15.76	15.71	15.68	15.68
14320885	12.94	n/a	12.95	13.02	n/a	13.04	13.08	13.07	13.08
14320886	n/a	15.80	n/a	15.77	n/a	15.82	15.81	15.82	15.84
14320887	n/a	15.71	n/a	15.69	n/a	15.74	15.73	15.75	15.76
14320916	n/a	24.75	n/a	24.69	n/a	24.61	24.56	24.75	24.88
14320917	8.45	n/a	8.21	8.17	n/a	8.23	8.29	8.61	8.85
14320919	8.01	n/a	7.94	7.92	n/a	7.92	7.94	7.94	8.05
14320920	6.48	n/a	6.18	6.20	n/a	6.26	6.28	6.26	6.62
14320982	5.55	n/a	5.52	5.52	n/a	5.54	5.56	6.02	5.77
14320983	6.36	n/a	6.59	6.62	n/a	6.60	6.57	6.62	6.55
14320986	n/a	11.80	11.81	11.71	n/a	11.64	11.65	11.67	11.73

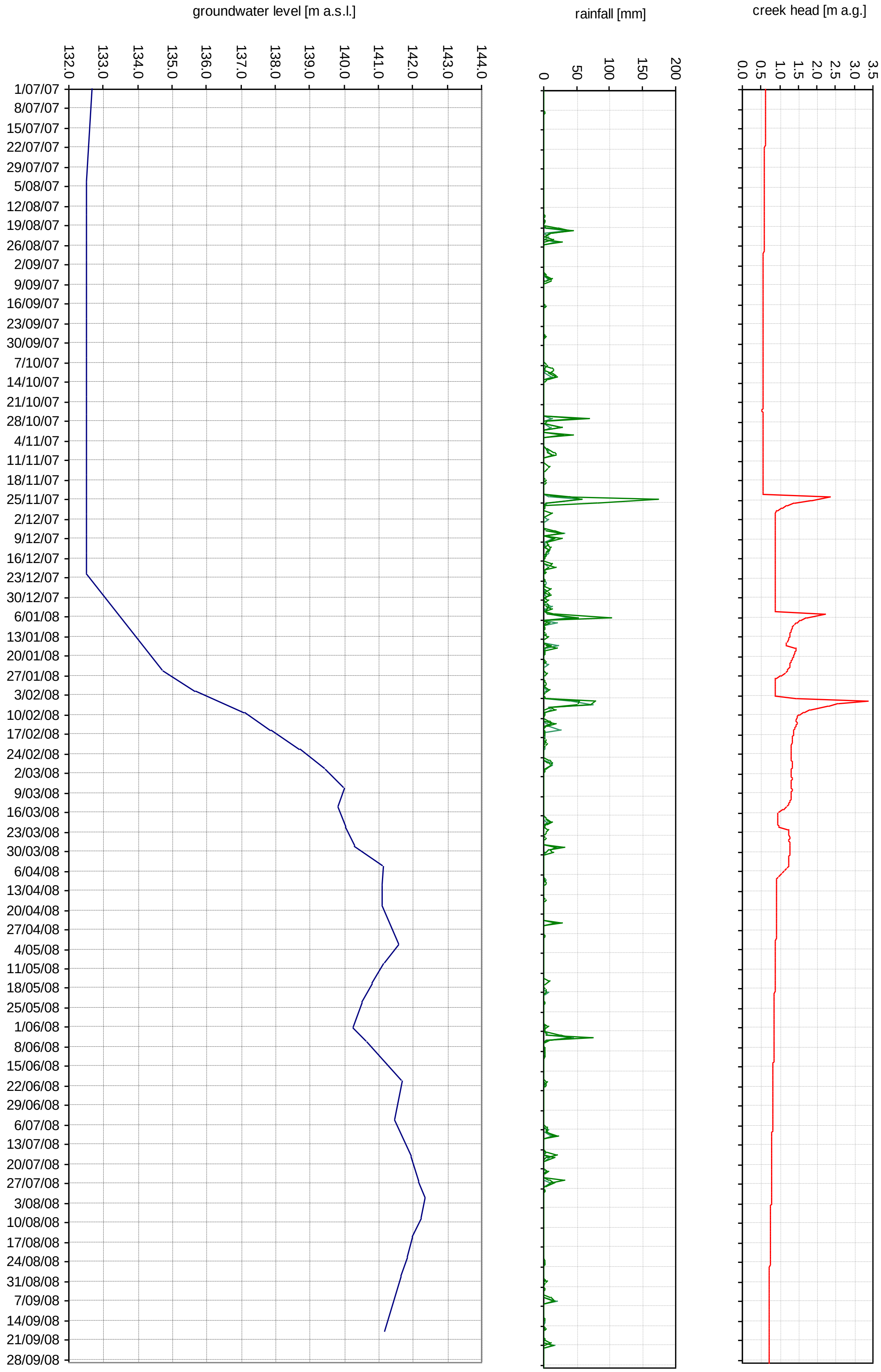
RN	29.8.08	18.9.08	6.10.08	20.11.08	10.12.08
99984	n/a	n/a	n/a	n/a	n/a
14320290	20.33	20.37	n/a	n/a	n/a
14320292	dry	dry	dry	dry	dry
14320293	n/a	n/a	22.97	22.97	n/a
14320294	6.31	6.78	n/a	7.56	5.69
14320295	6.85	7.76	n/a	8.17	6.02
14320296	7.15	7.88	n/a	8.48	6.29
14320297	7.15	7.65	n/a	8.27	6.29
14320329	dry	dry	dry	dry	dry
14320330		14.86	15.27	15.49	11.71
14320331	14.80	14.97	15.34	15.43	11.64
14320332	15.41	15.41	n/a	n/a	15.56
14320333	dry	dry	dry	dry	dry
14320335	dry	dry	dry	dry	dry
14320336	24.96	24.91	24.84	n/a	24.75
14320337	21.43	21.43	21.43	n/a	21.19
14320338	dry	dry	dry	dry	dry
14320339	22.13	22.15	n/a	22.26	22.29
14320340	22.16	22.29	22.37	22.43	22.30
14320450	19.83	19.94	n/a	19.82	16.77
14320453	n/a	n/a	23.17	n/a	n/a
14320472	7.37	7.45	n/a	7.14	5.82
14320547	16.70	16.72	16.73	n/a	16.81
14320553	18.96	18.91	18.84	18.83	18.83
14320785	21.57	21.56	n/a	n/a	n/a
14320786	21.18	21.20	n/a	n/a	n/a
14320848	dry	dry	dry	dry	dry
14320849	9.82	9.83	n/a	11.17	10.85
14320879	10.01	10.18	n/a	n/a	9.43
14320880	9.08	9.15	n/a	n/a	8.83
14320883	5.33	5.41	n/a	n/a	3.78
14320884	15.70	15.68	n/a	15.64	15.66
14320885	13.10	13.13	n/a	13.28	12.71
14320886	15.86	15.87	n/a	n/a	15.81
14320887	15.76	15.78	n/a	n/a	15.28
14320916	24.97	25.03	n/a	n/a	24.81
14320917	8.81	9.01	n/a	9.82	8.10
14320919	8.19	8.11	n/a	7.55	7.77
14320920	7.03	6.62	n/a	6.99	6.14
14320982	5.64	5.84	n/a	n/a	5.01
14320983	6.62	6.86	n/a	5.51	5.22
14320986	12.27	12.29	n/a	14.26	11.75

Appendix H. Hydrographs – manual measurement

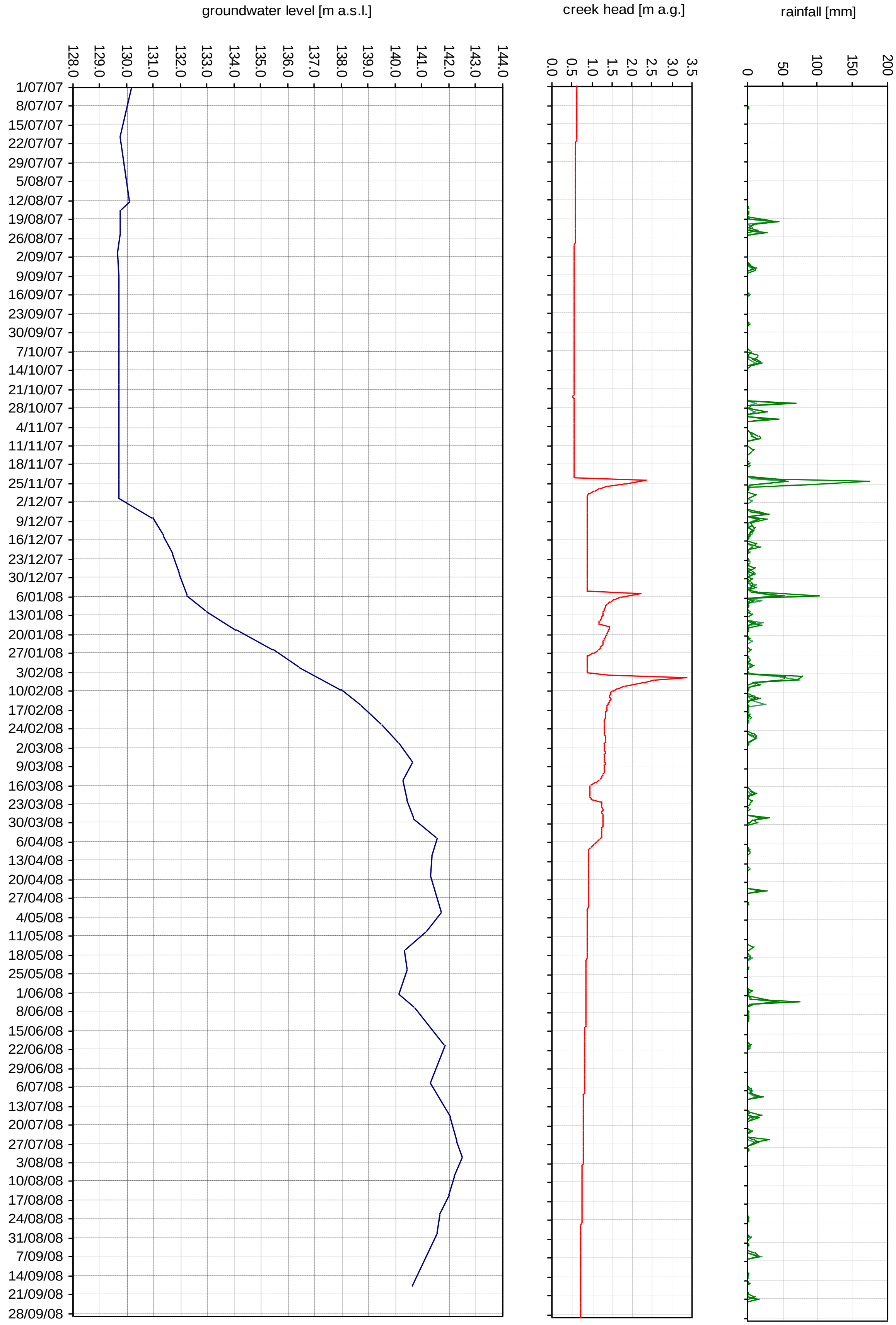
14320290


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
110.0
111.0
112.0
113.0
114.0
115.0
116.0
117.0
118.0
119.0
120.0
121.0
122.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

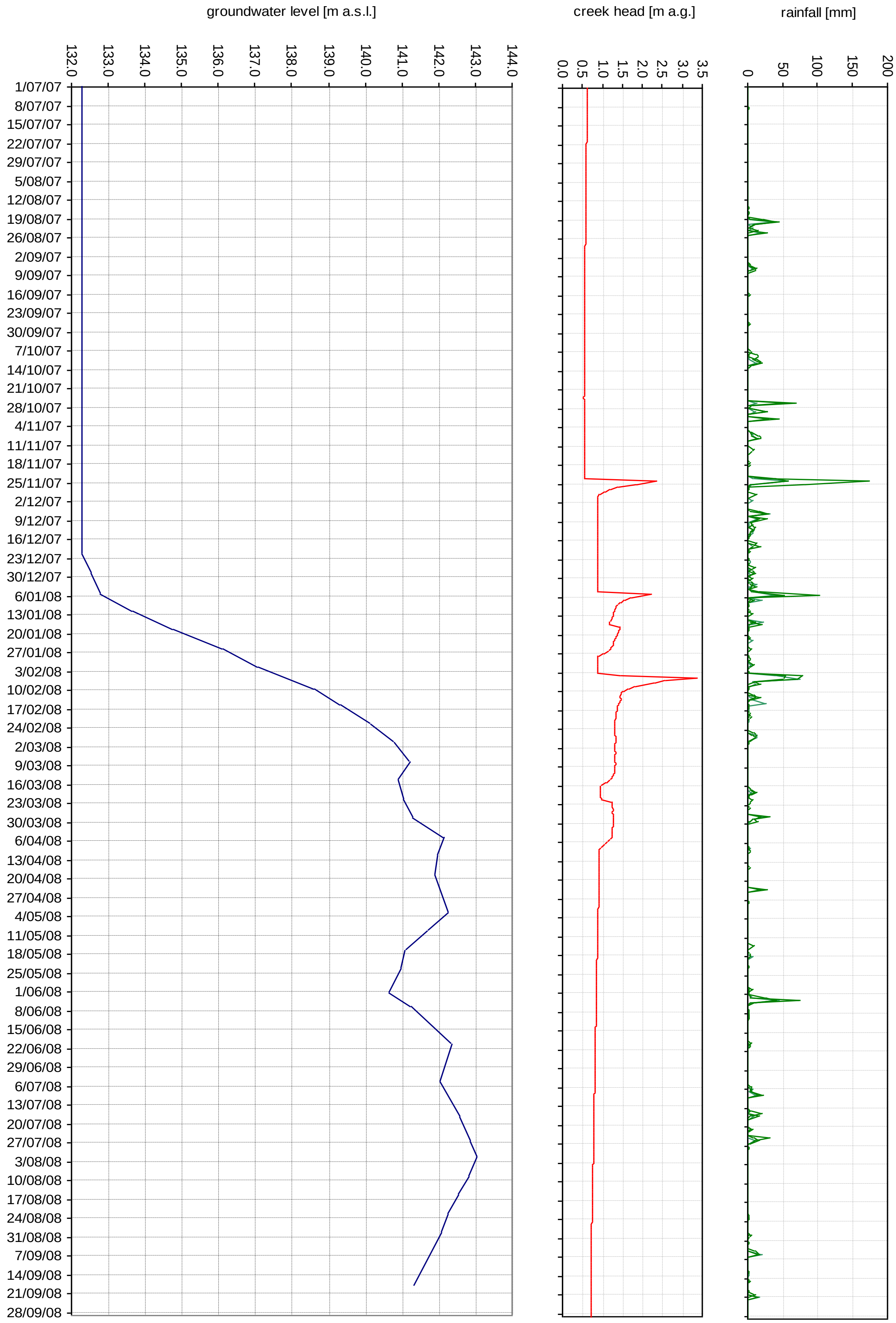
14320294


groundwater level [m a.s.l.]
rainfall [mm]
creek head [m a.g.]
132.0 133.0 134.0 135.0 136.0 137.0 138.0 139.0 140.0 141.0 142.0 143.0 144.0
0 50 100 150 200
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320295


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
128.0 129.0 130.0 131.0 132.0 133.0 134.0 135.0 136.0 137.0 138.0 139.0 140.0 141.0 142.0 143.0 144.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 50 100 150 200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320296


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
132.0 133.0 134.0 135.0 136.0 137.0 138.0 139.0 140.0 141.0 142.0 143.0 144.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 50 100 150 200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
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2/03/08
9/03/08
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6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
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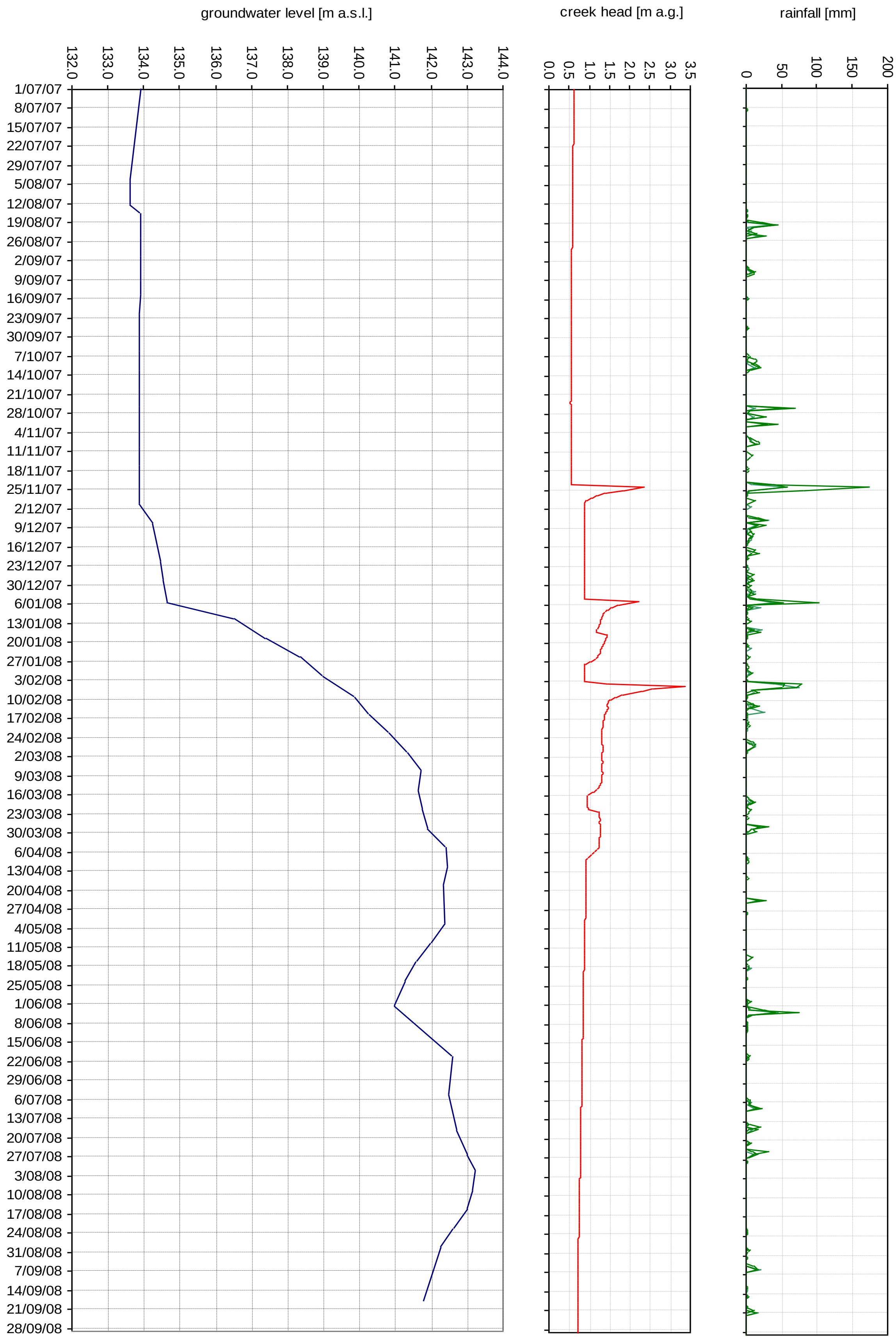
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320297


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
132.0
133.0
134.0
135.0
136.0
137.0
138.0
139.0
140.0
141.0
142.0
143.0
144.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
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3/02/08
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2/03/08
9/03/08
16/03/08
23/03/08
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20/04/08
27/04/08
4/05/08
11/05/08
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20/07/08
27/07/08
3/08/08
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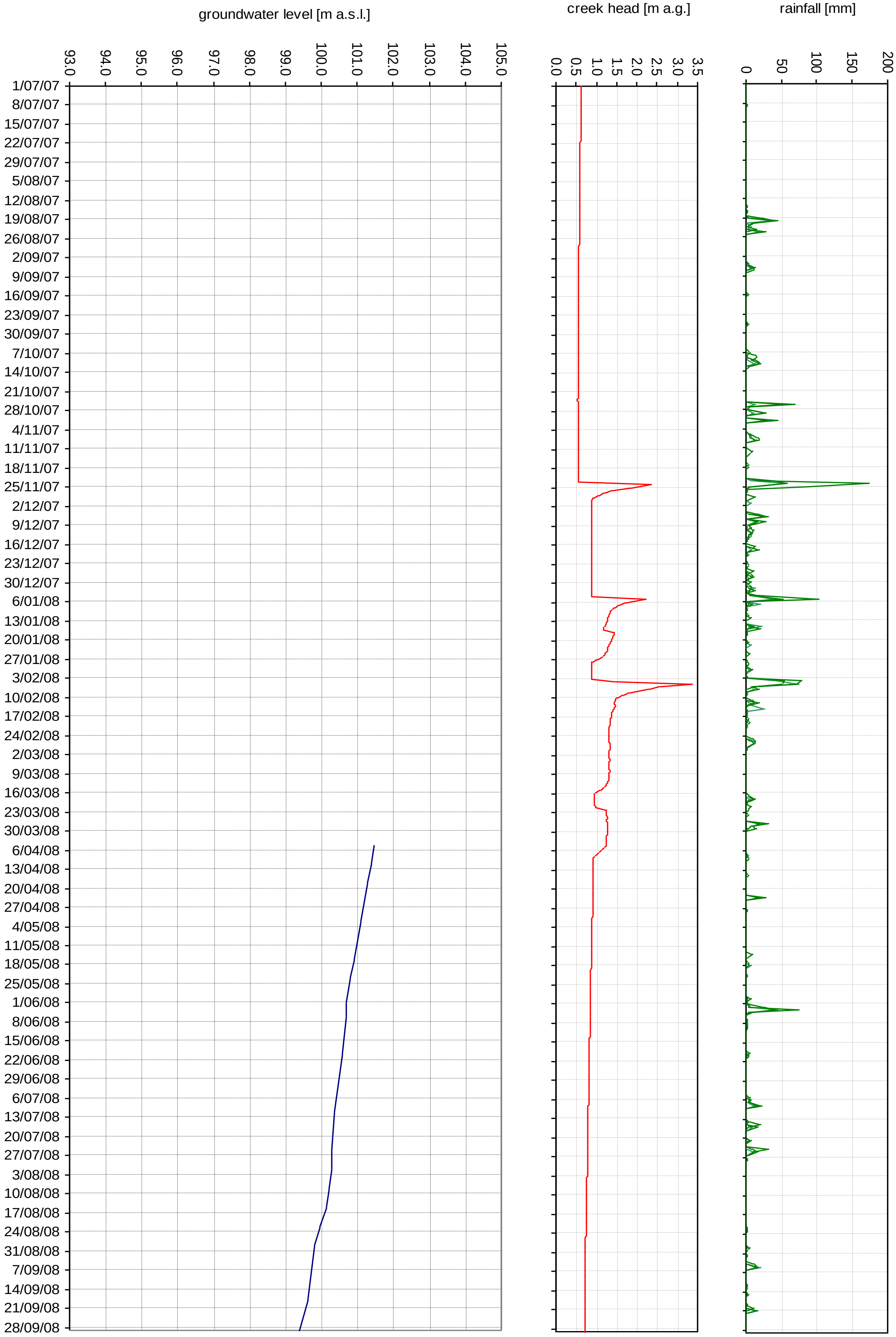
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320331


groundwater level [m a.s.l.]
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0
101.0
102.0
103.0
104.0
105.0
creek head [m a.g.]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
rainfall [mm]
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
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9/03/08
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23/03/08
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4/05/08
11/05/08
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27/07/08
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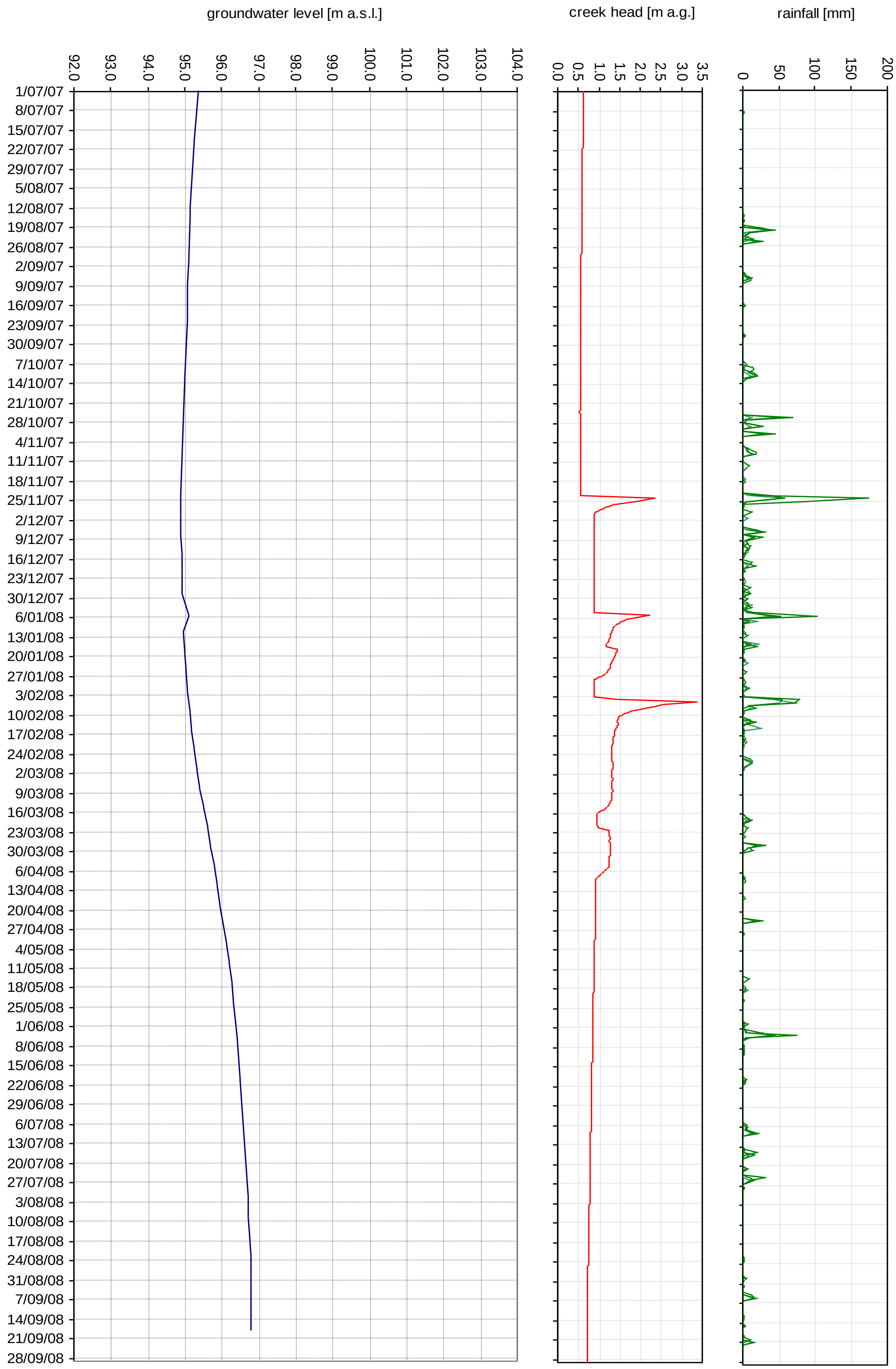
7/09/08
14/09/08
21/09/08
28/09/08

14320332



groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
92.0
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0
101.0
102.0
103.0
104.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
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4/05/08
11/05/08
18/05/08
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27/07/08
3/08/08
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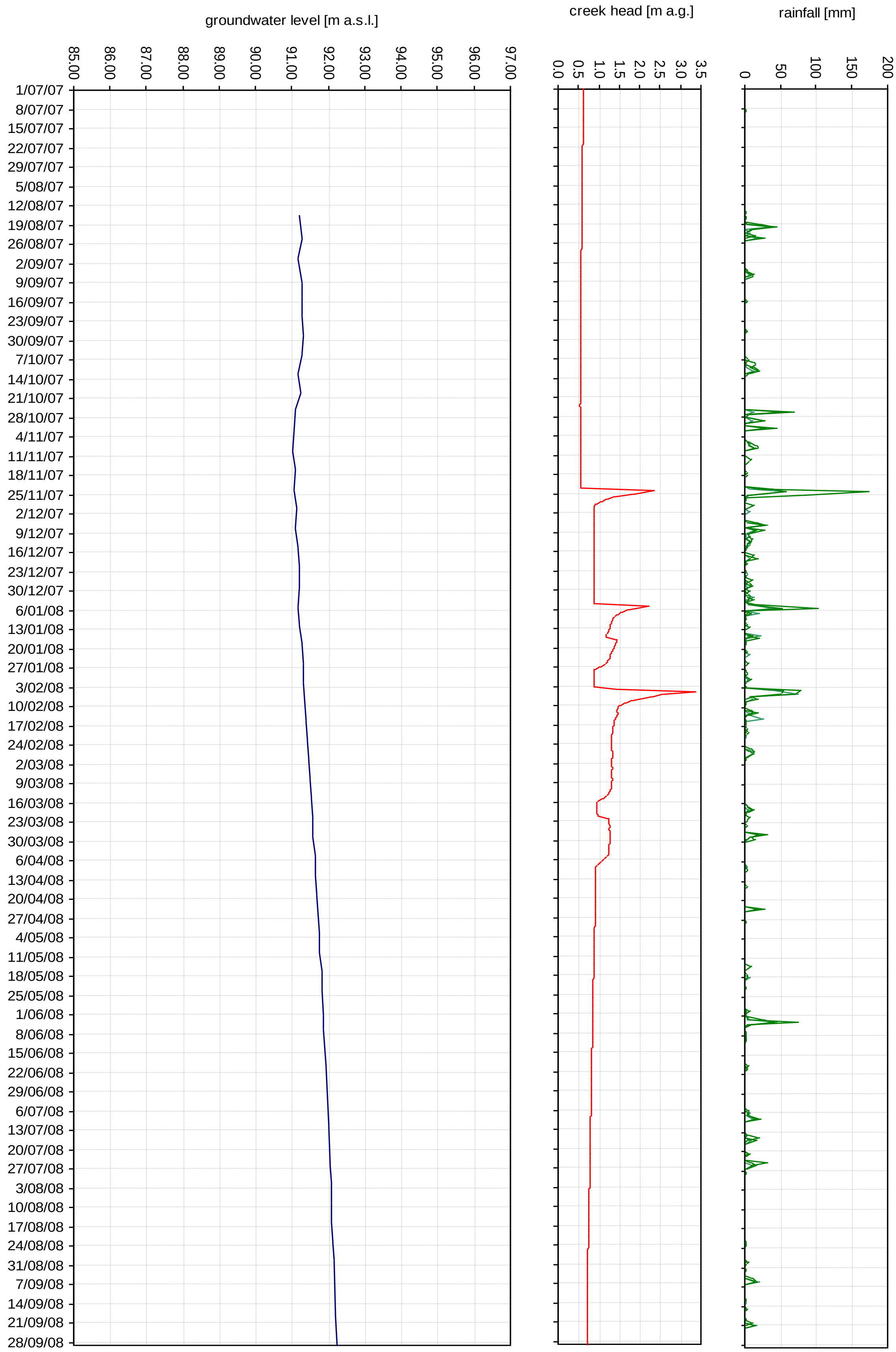
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320336


groundwater level [m a.s.l.]
85.00
86.00
87.00
88.00
89.00
90.00
91.00
92.00
93.00
94.00
95.00
96.00
97.00
creek head [m a.g.]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
rainfall [mm]
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
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9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
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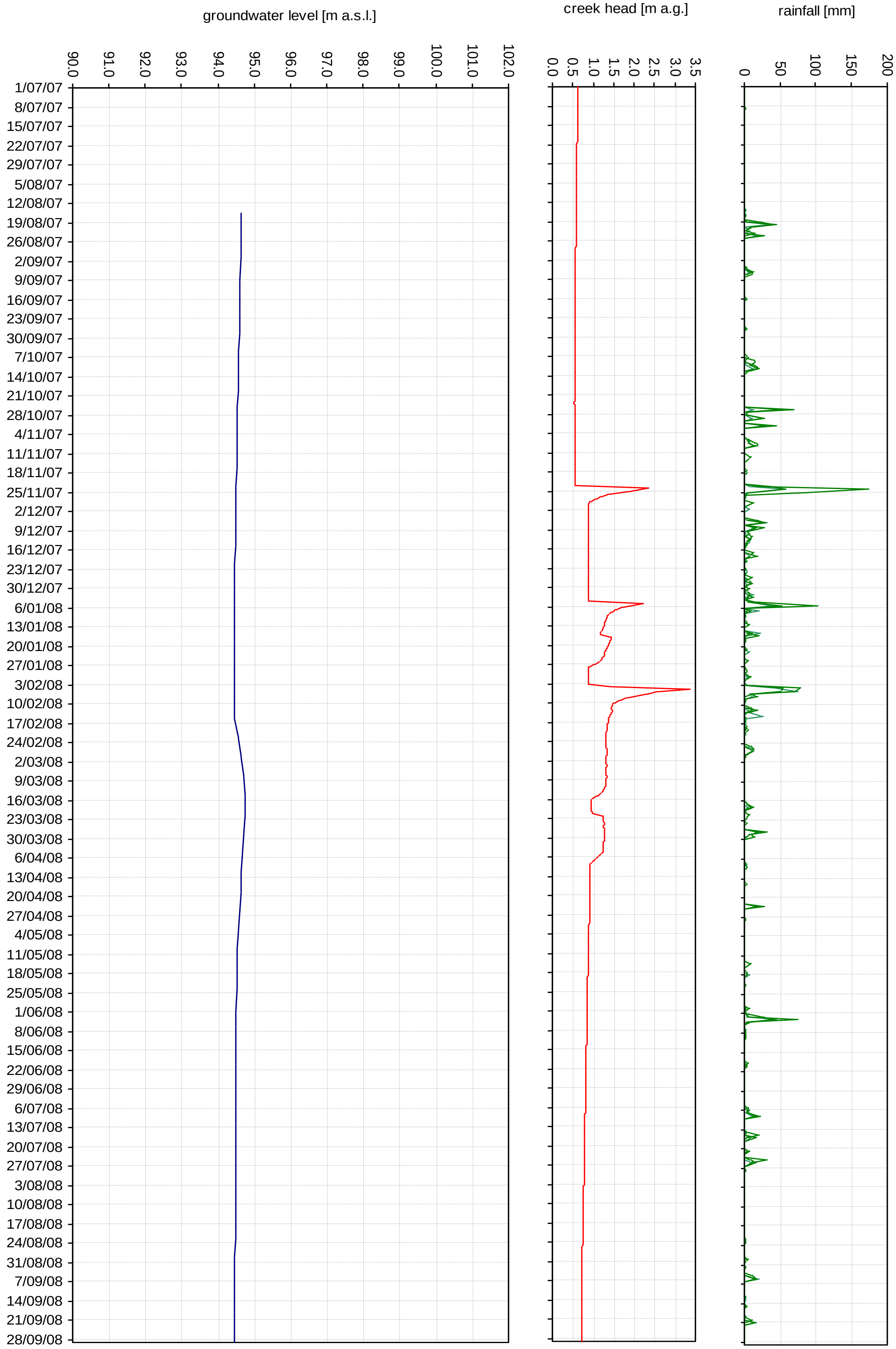
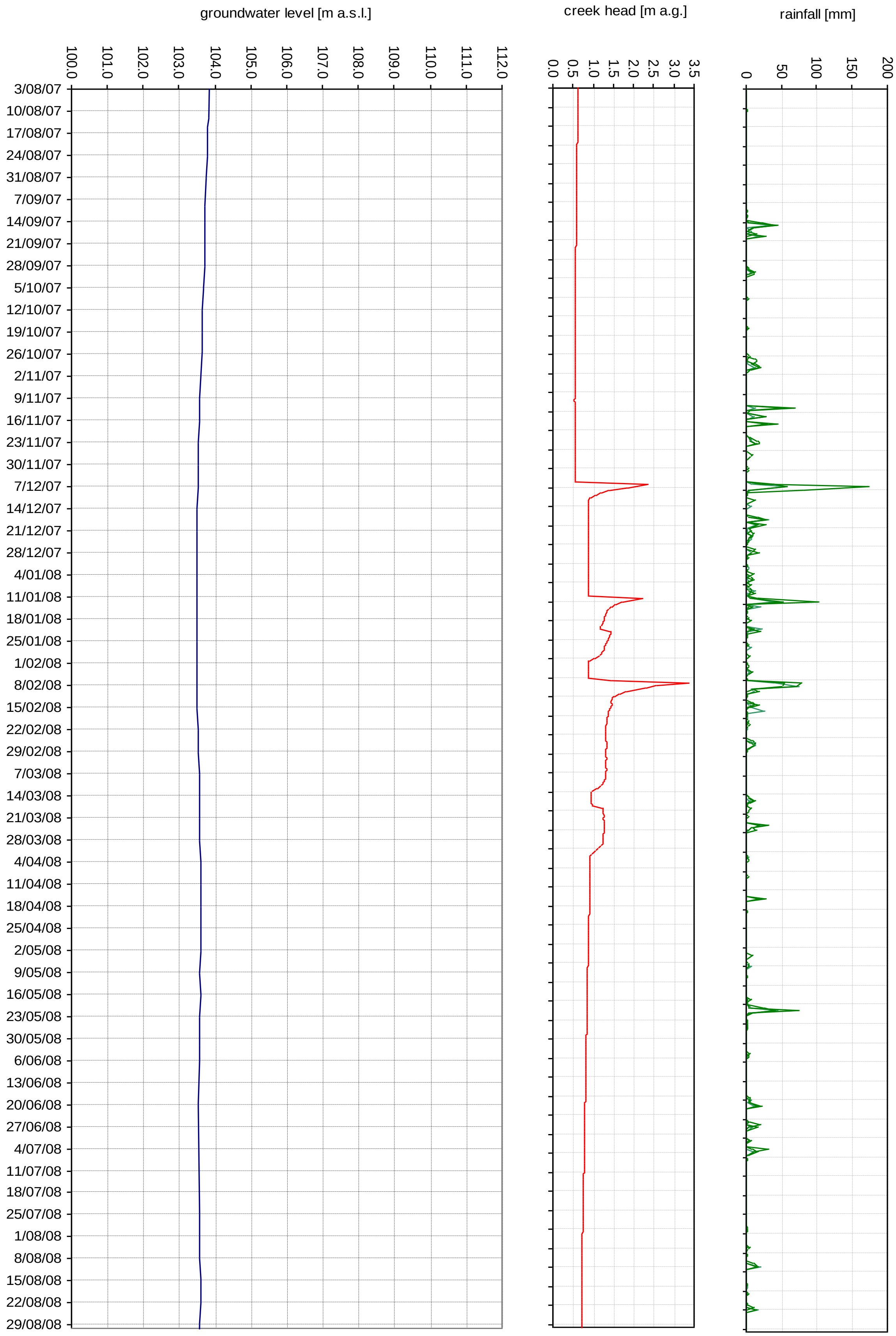
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320337

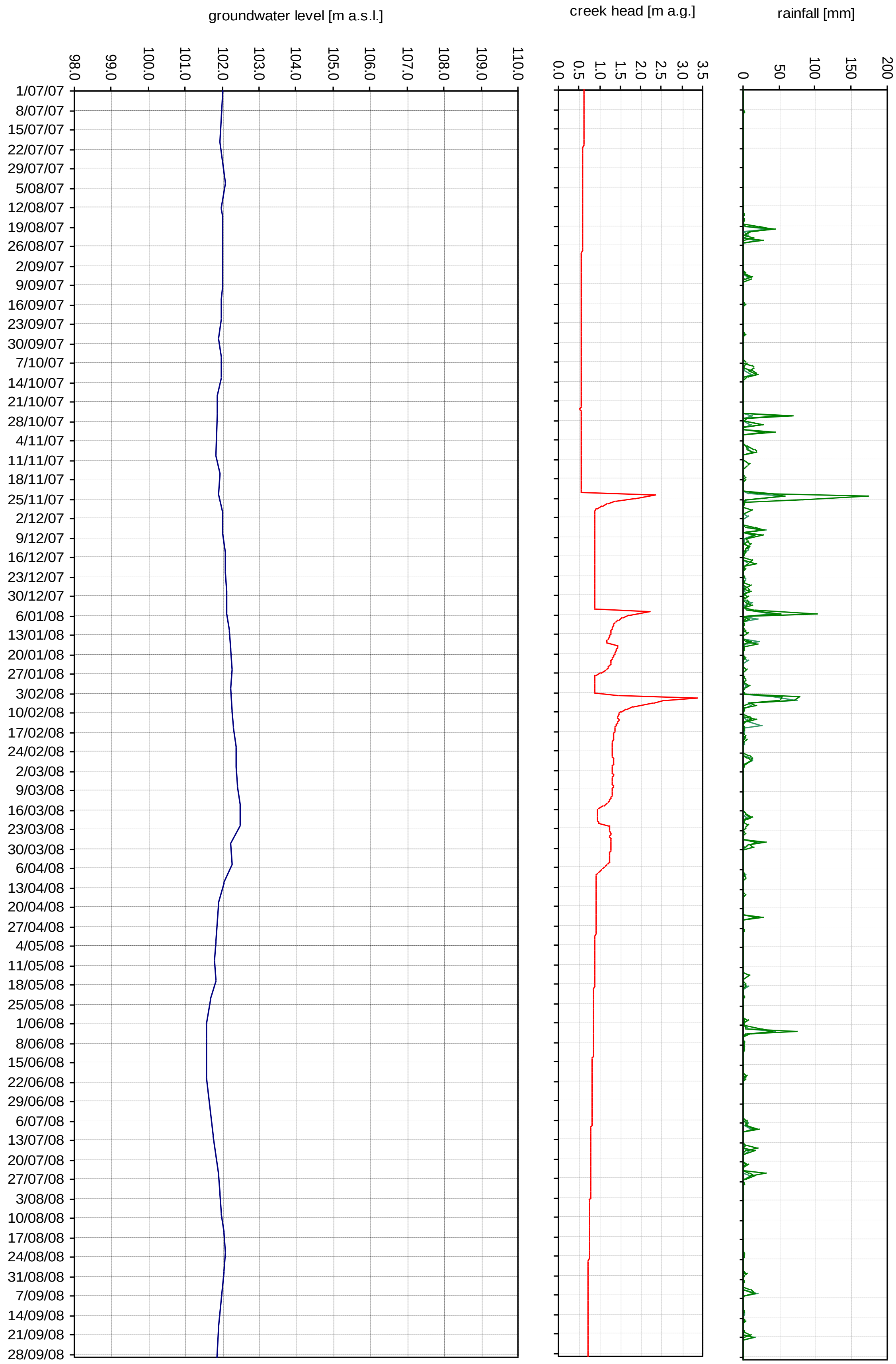


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0
101.0
102.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320339

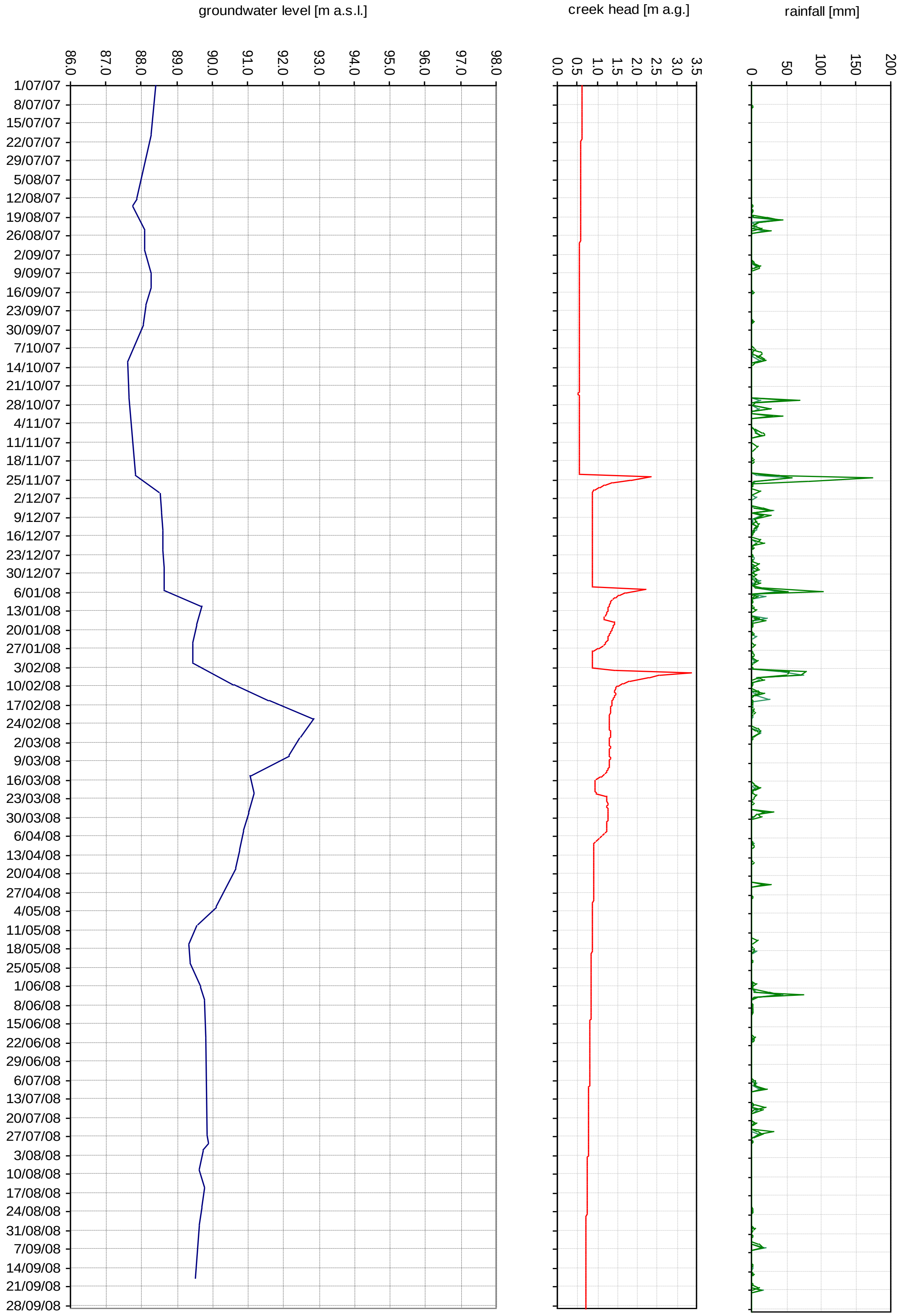

groundwater level [m a.s.l.]
100.0 101.0 102.0 103.0 104.0 105.0 106.0 107.0 108.0 109.0 110.0 111.0 112.0
creek head [m a.g.]
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
rainfall [mm]
0 50 100 150 200
3/08/07
10/08/07
17/08/07
24/08/07
31/08/07
7/09/07
14/09/07
21/09/07
28/09/07
5/10/07
12/10/07
19/10/07
26/10/07
2/11/07
9/11/07
16/11/07
23/11/07
30/11/07
7/12/07
14/12/07
21/12/07
28/12/07
4/01/08
11/01/08
18/01/08
25/01/08
1/02/08
8/02/08
15/02/08
22/02/08
29/02/08
7/03/08
14/03/08
21/03/08
28/03/08
4/04/08
11/04/08
18/04/08
25/04/08
2/05/08
9/05/08
16/05/08
23/05/08
30/05/08
6/06/08
13/06/08
20/06/08
27/06/08
4/07/08
11/07/08
18/07/08
25/07/08
1/08/08
8/08/08
15/08/08
22/08/08
29/08/08

14320340

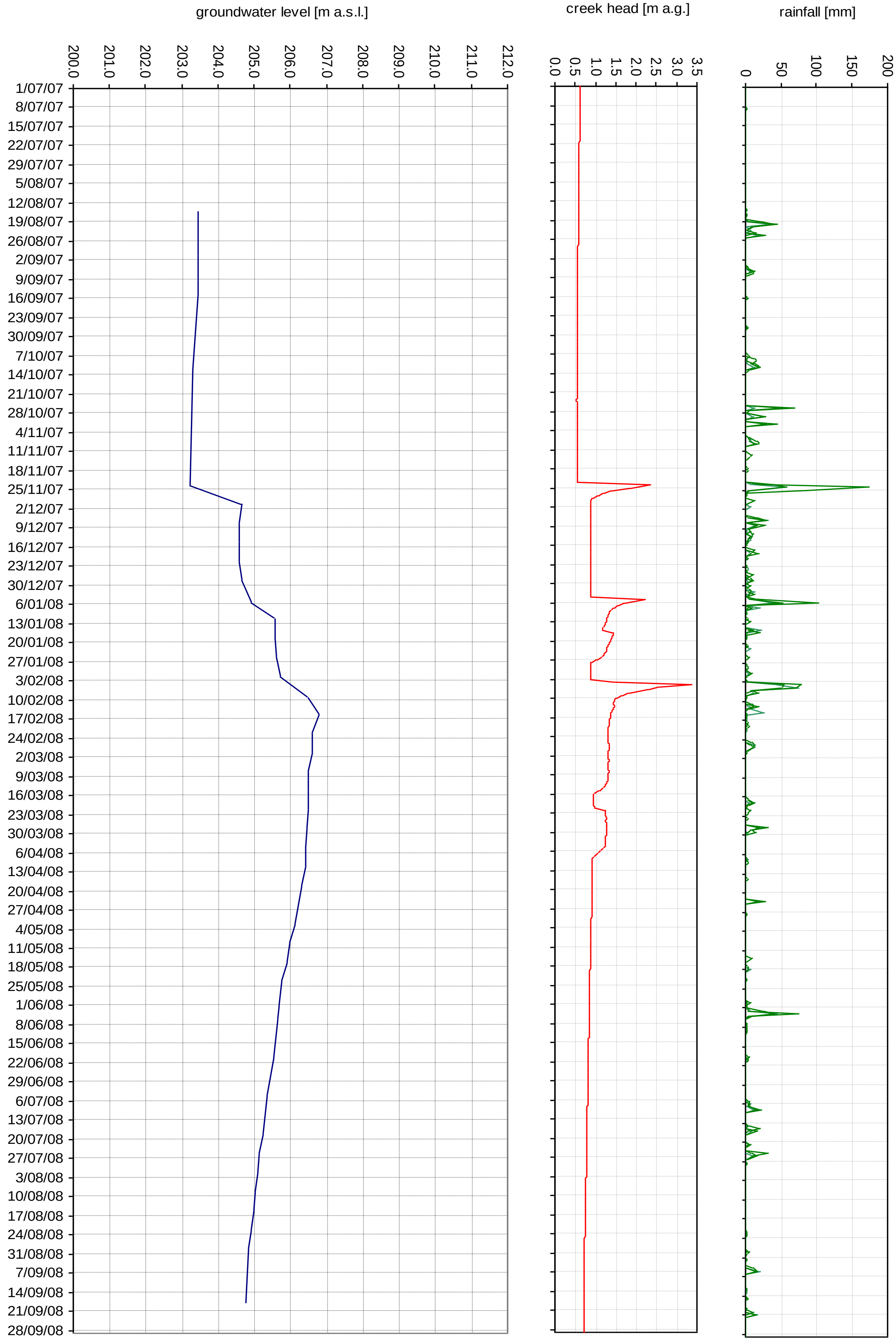


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
98.0
99.0
100.0
101.0
102.0
103.0
104.0
105.0
106.0
107.0
108.0
109.0
110.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320450

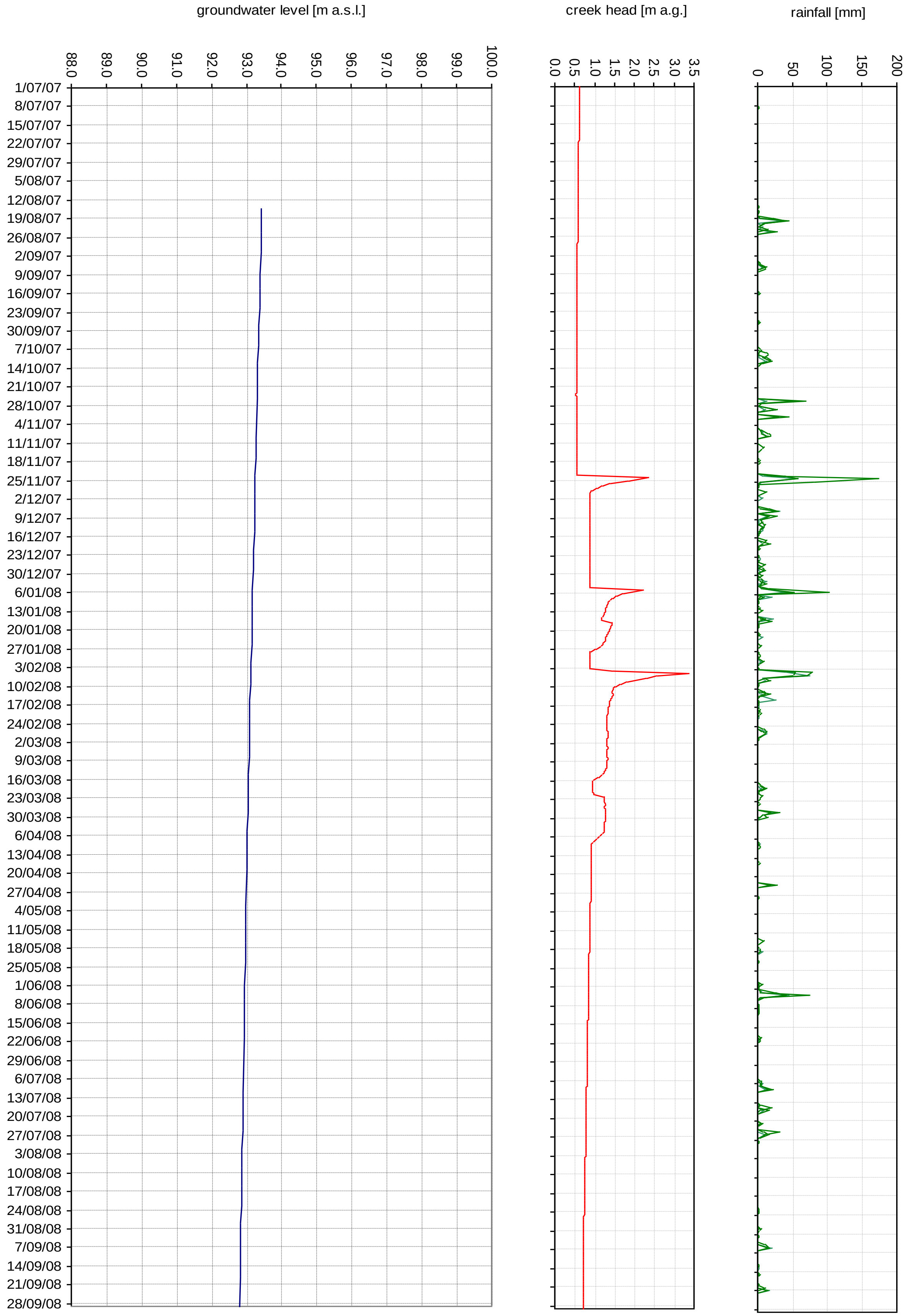

groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
86.0
87.0
88.0
89.0
90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
98.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320472

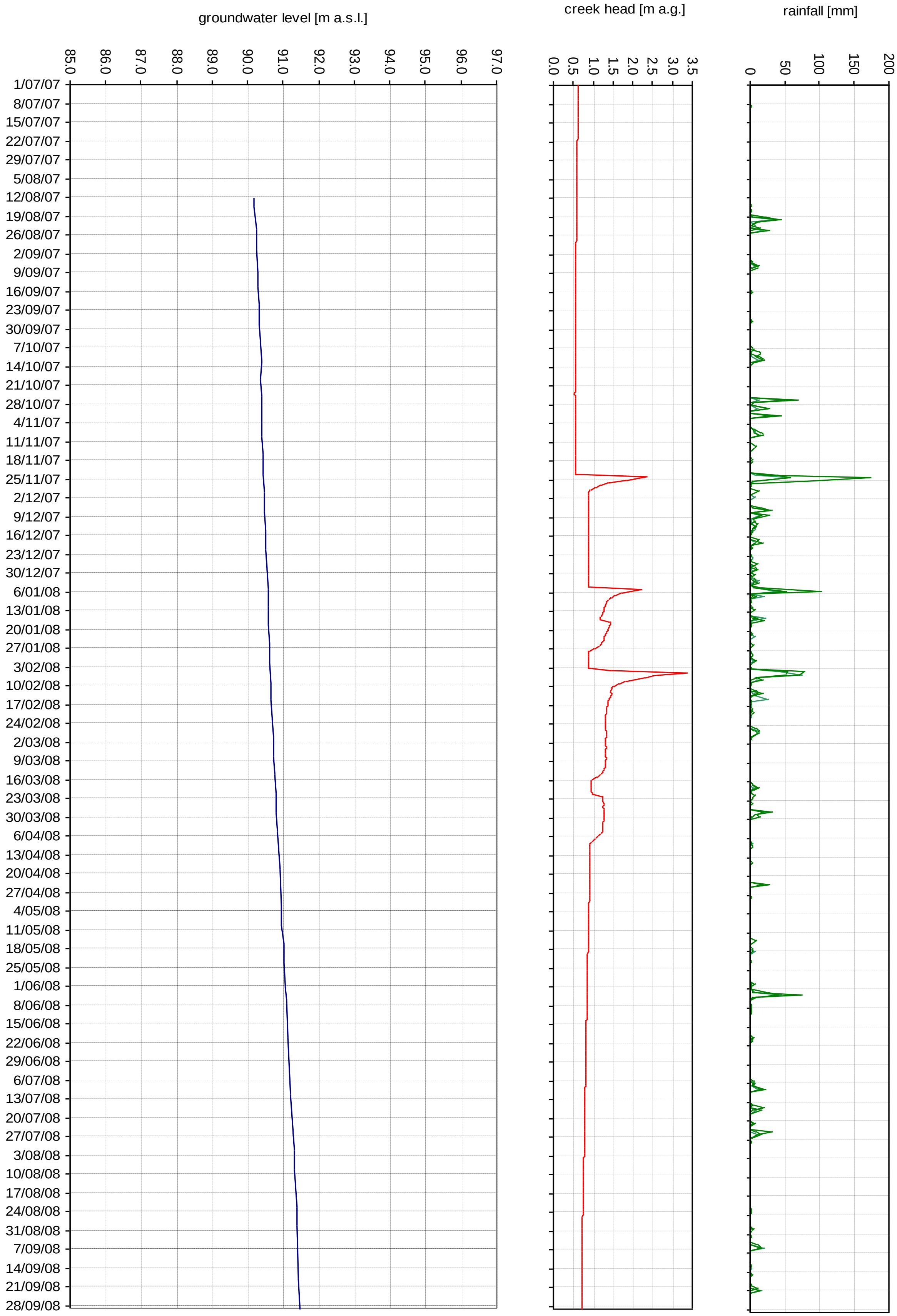


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
200.0
201.0
202.0
203.0
204.0
205.0
206.0
207.0
208.0
209.0
210.0
211.0
212.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320547

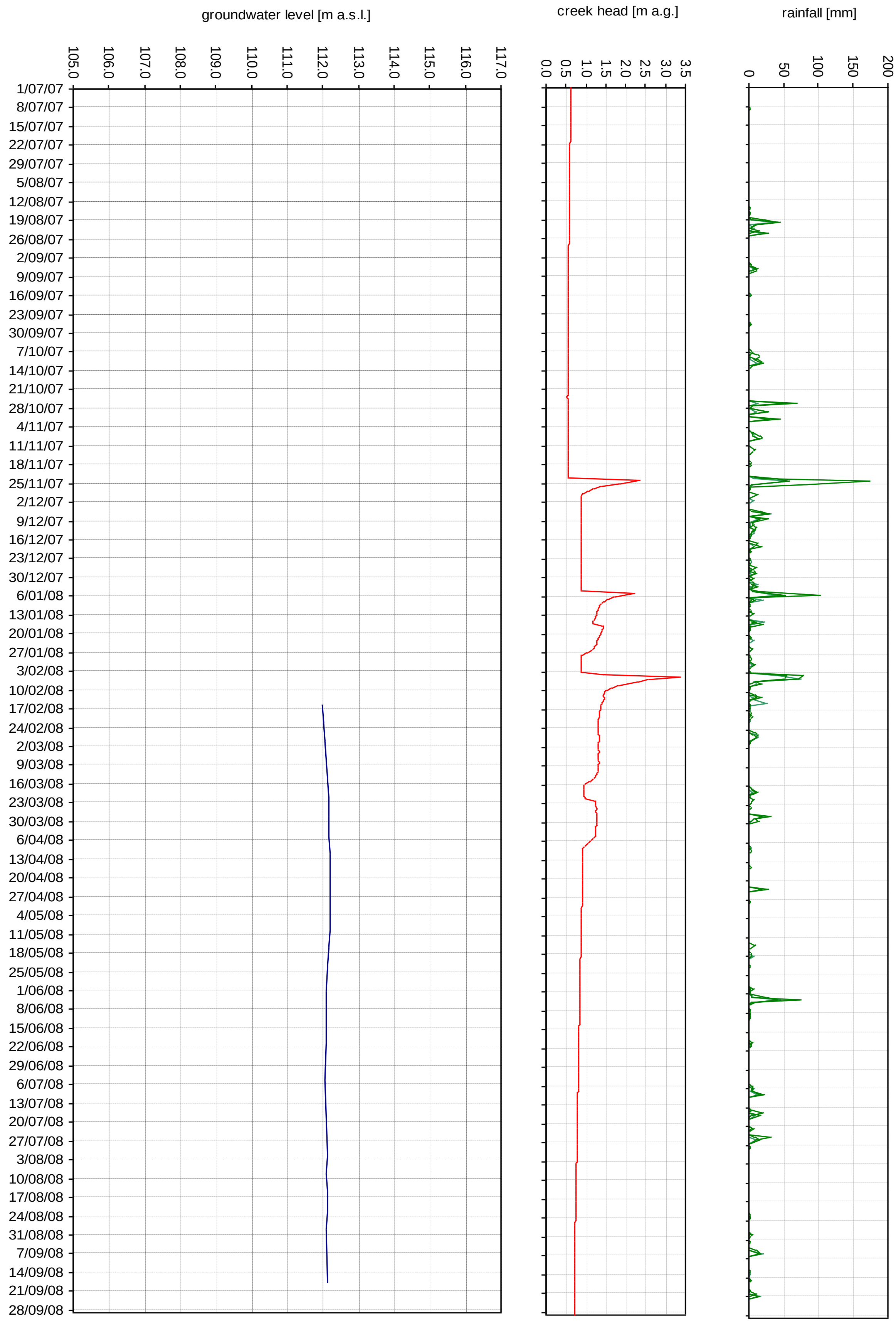

groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
88.0
89.0
90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320553



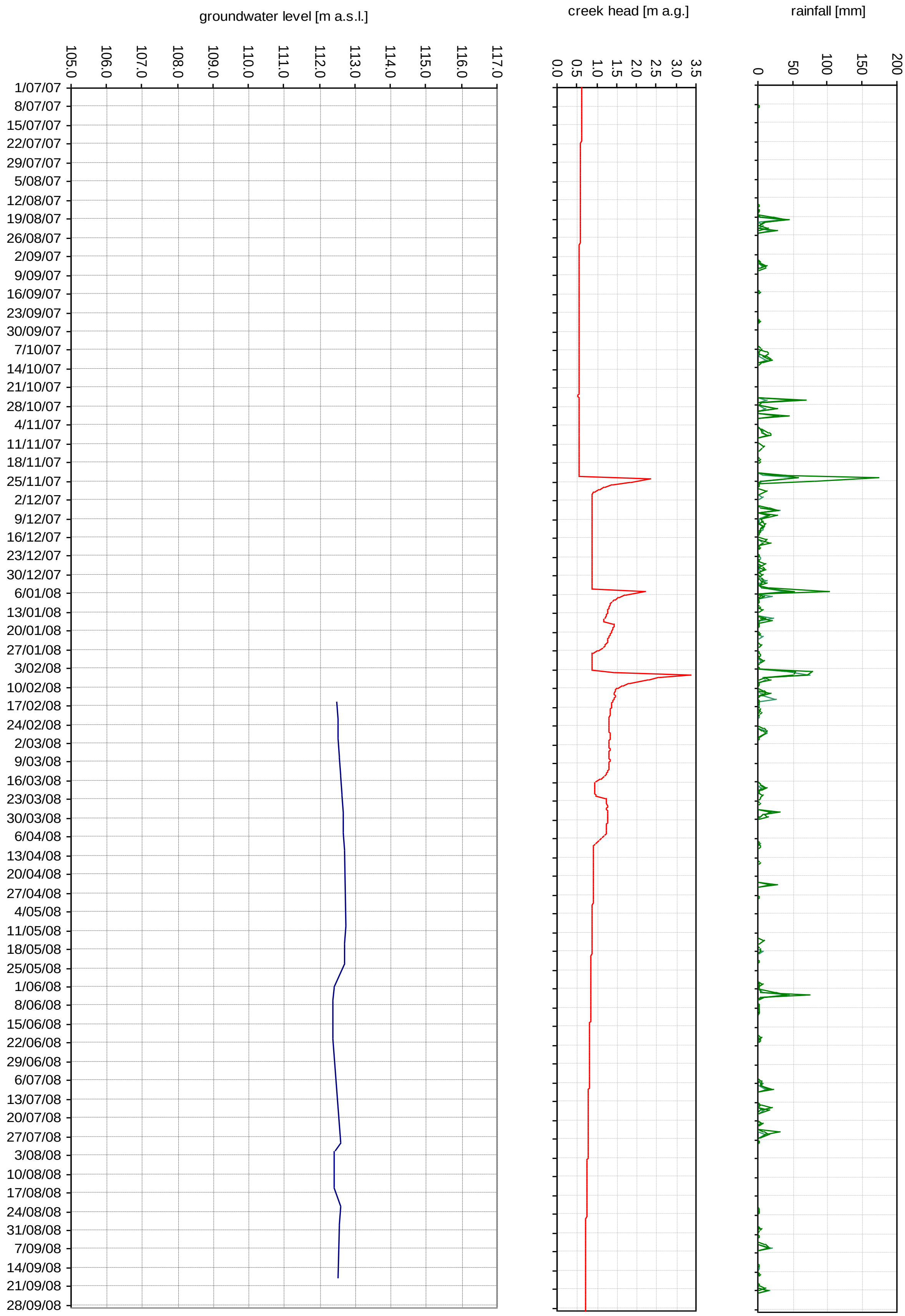
groundwater level [m a.s.l.]
85.0
86.0
87.0
88.0
89.0
90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
creek head [m a.g.]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
rainfall [mm]
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320785



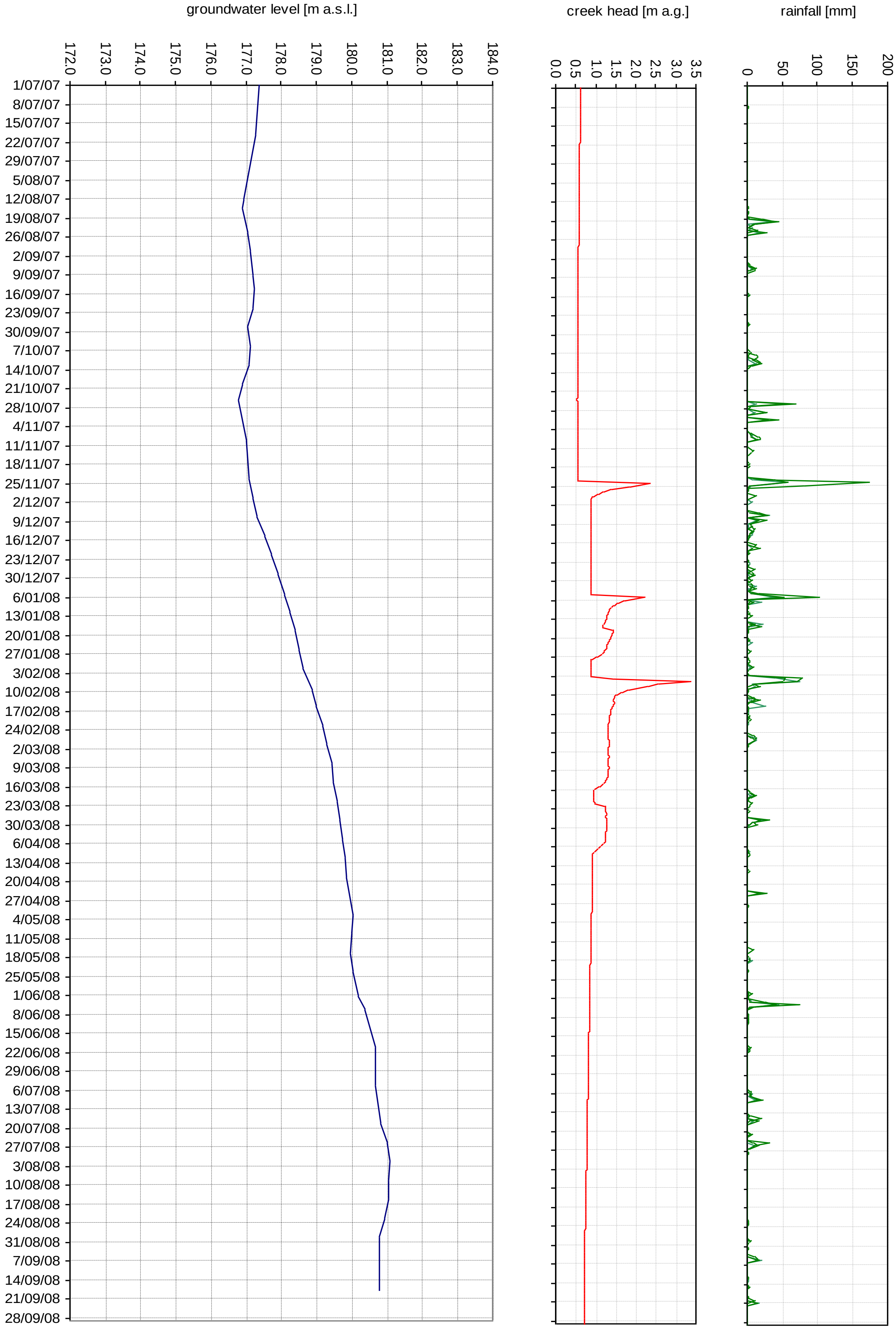
groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
105.0
106.0
107.0
108.0
109.0
110.0
111.0
112.0
113.0
114.0
115.0
116.0
117.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320786

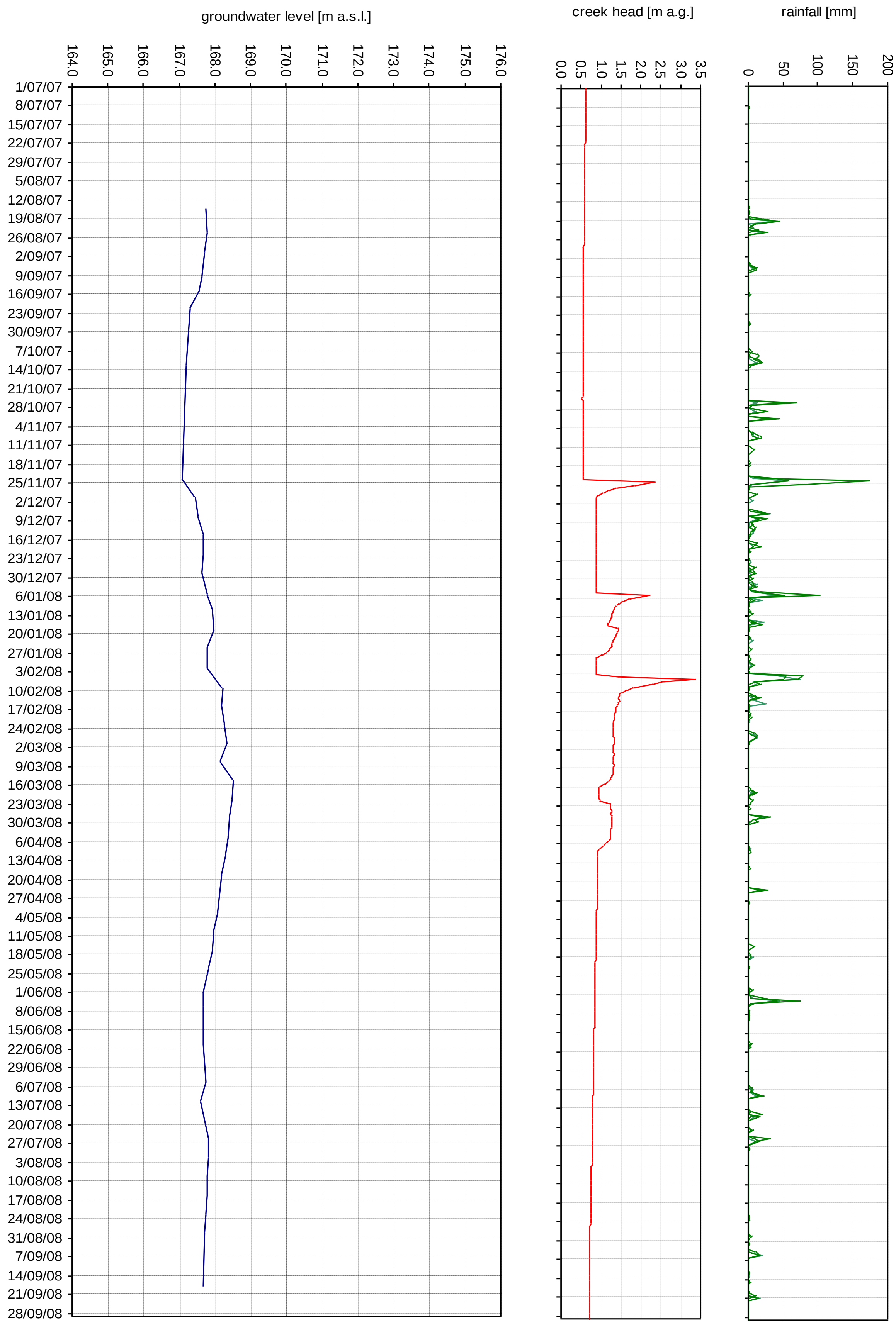


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
105.0
106.0
107.0
108.0
109.0
110.0
111.0
112.0
113.0
114.0
115.0
116.0
117.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

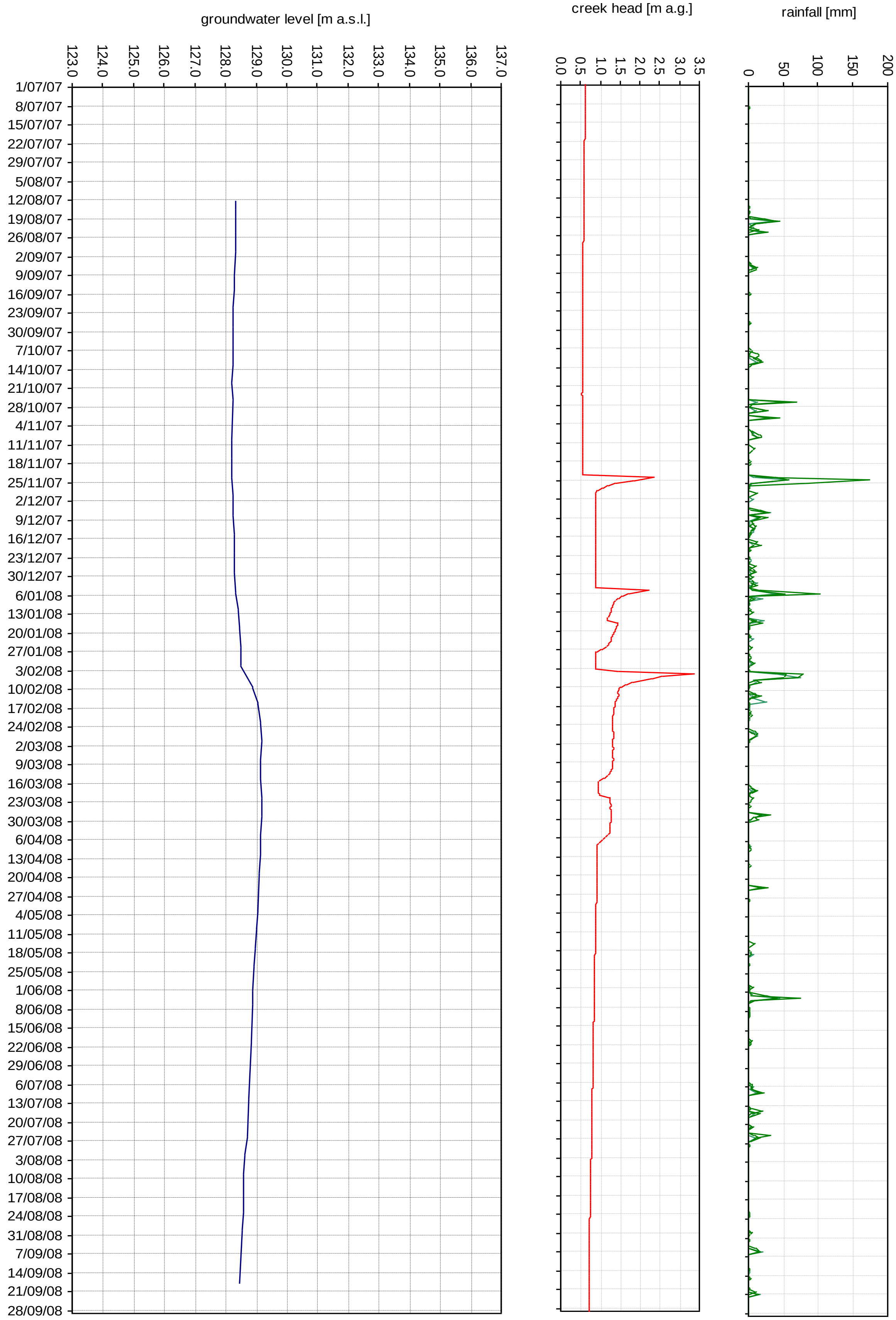
14320849


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
172.0
173.0
174.0
175.0
176.0
177.0
178.0
179.0
180.0
181.0
182.0
183.0
184.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320880


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
164.0
165.0
166.0
167.0
168.0
169.0
170.0
171.0
172.0
173.0
174.0
175.0
176.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320883



groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
123.0
124.0
125.0
126.0
127.0
128.0
129.0
130.0
131.0
132.0
133.0
134.0
135.0
136.0
137.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
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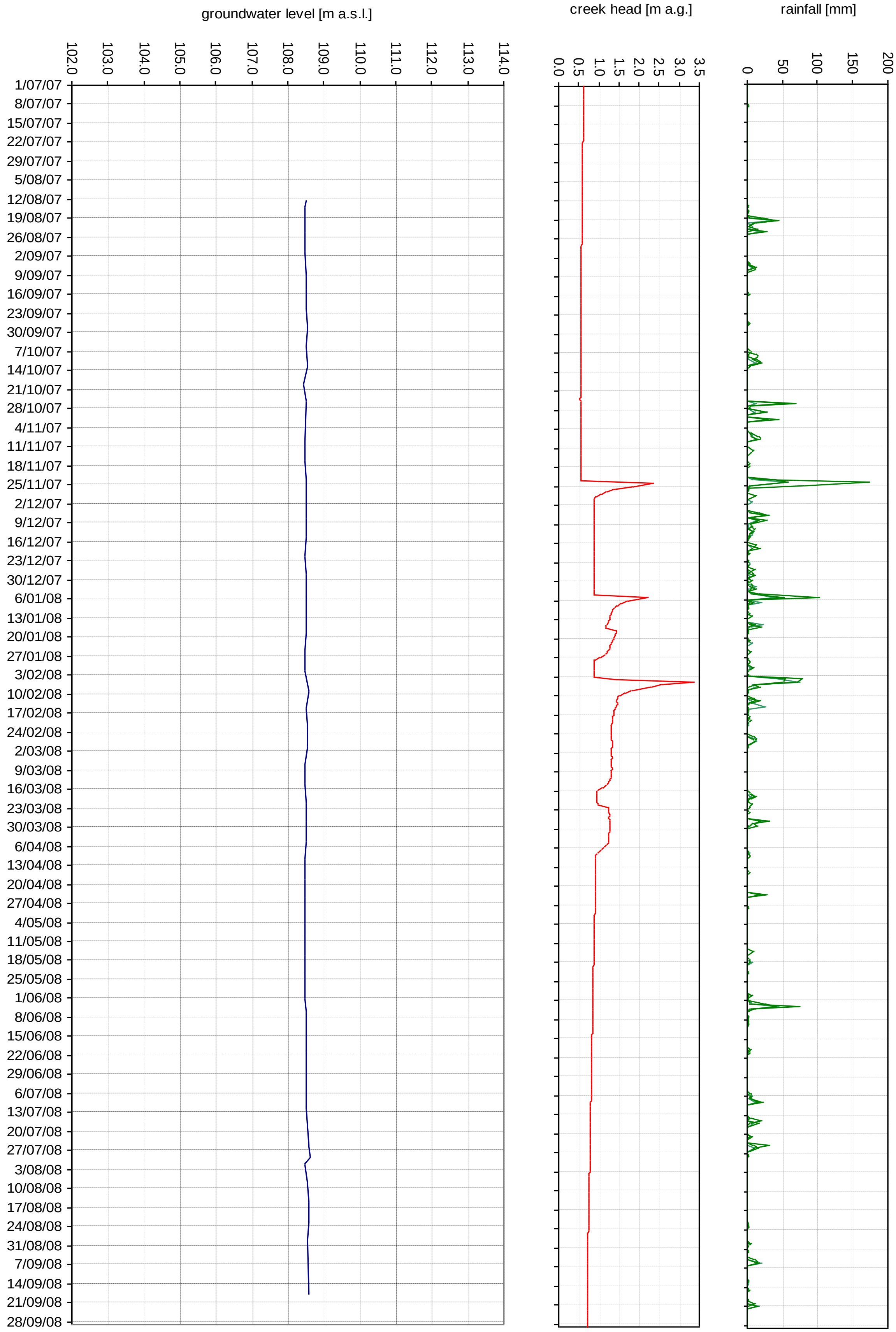
14/09/08
21/09/08
28/09/08

14320884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creek head [m a.g.]
rainfall [mm]
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103.0
104.0
105.0
106.0
107.0
108.0
109.0
110.0
111.0
112.0
113.0
114.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
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27/01/08
3/02/08
10/02/08
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24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
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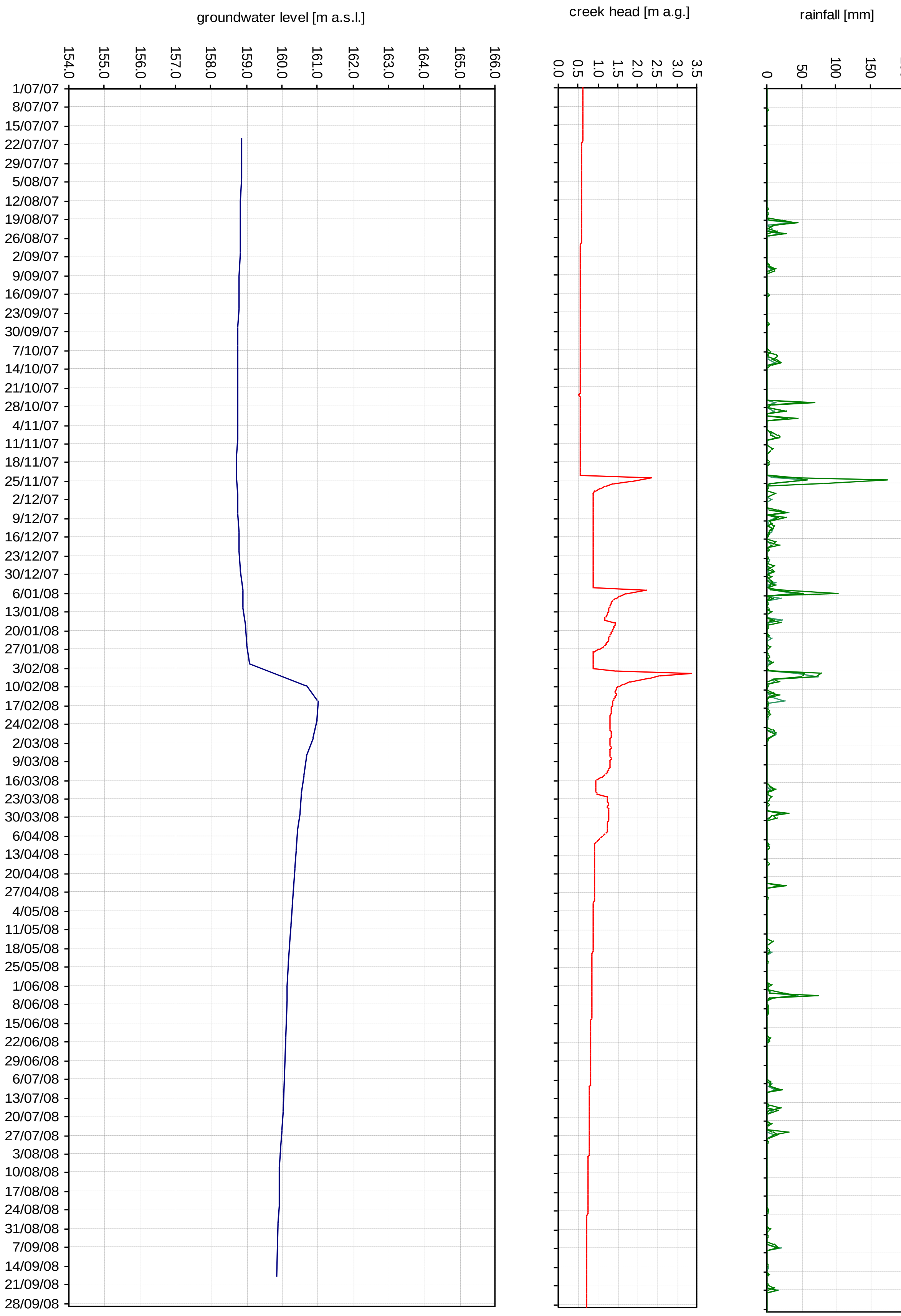
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320885


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
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155.0
156.0
157.0
158.0
159.0
160.0
161.0
162.0
163.0
164.0
165.0
166.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
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27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
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27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
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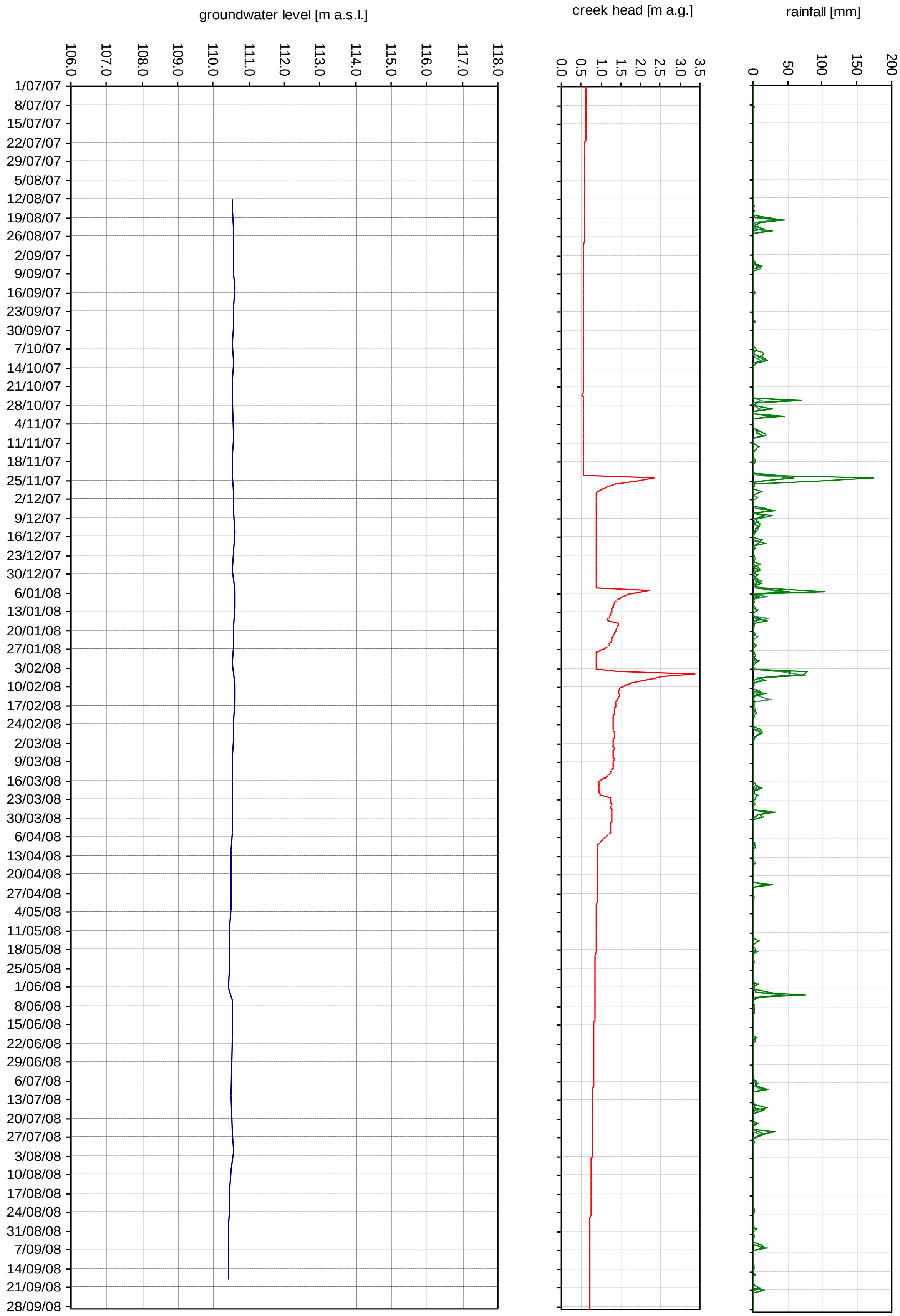
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320886


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
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107.0
108.0
109.0
110.0
111.0
112.0
113.0
114.0
115.0
116.0
117.0
118.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
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8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
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27/07/08
3/08/08
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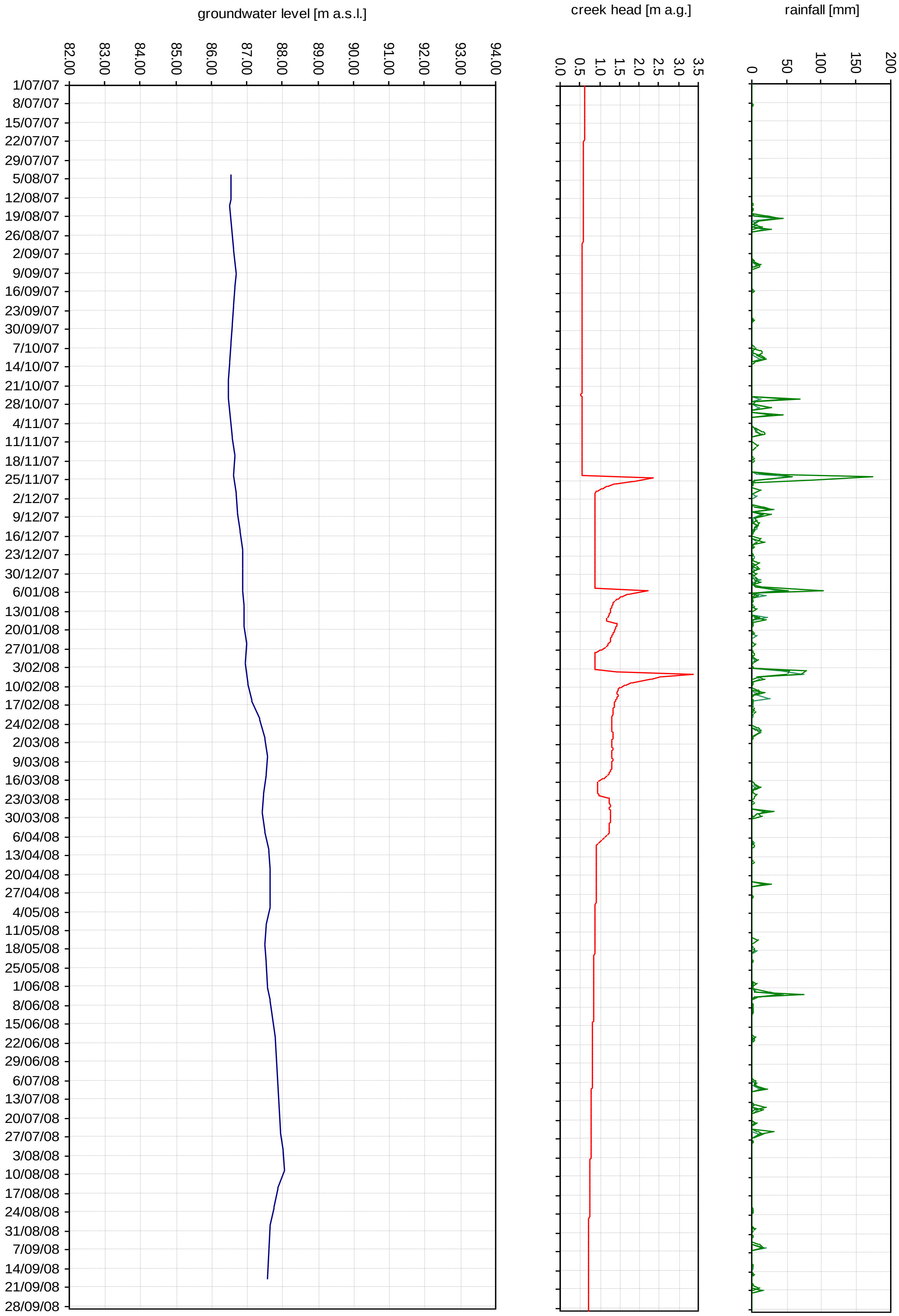
7/09/08
14/09/08
21/09/08
28/09/08

14320887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82.00
83.00
84.00
85.00
86.00
87.00
88.00
89.00
90.00
91.00
92.00
93.00
94.00
creek head [m a.g.]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
rainfall [mm]
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
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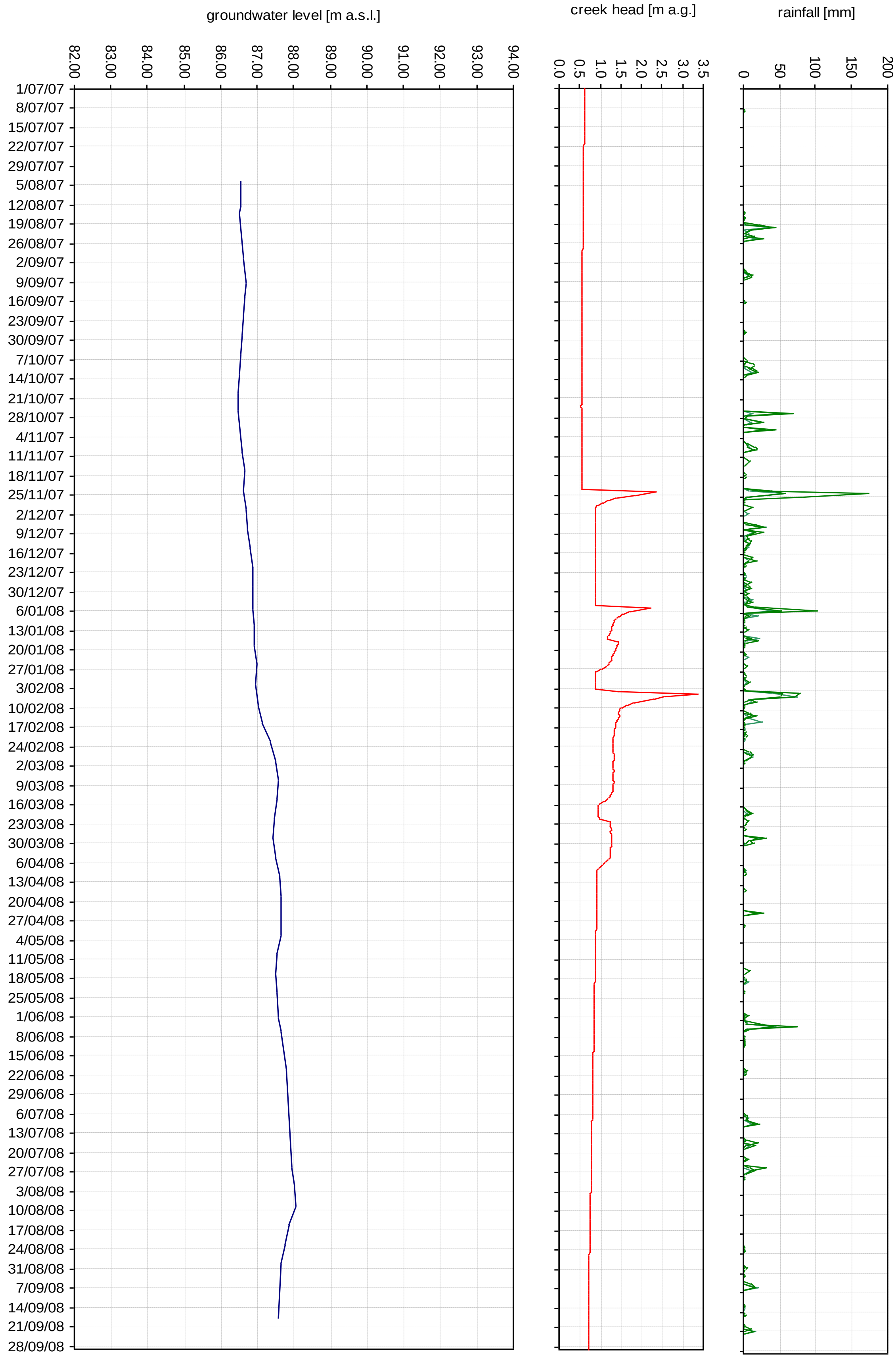
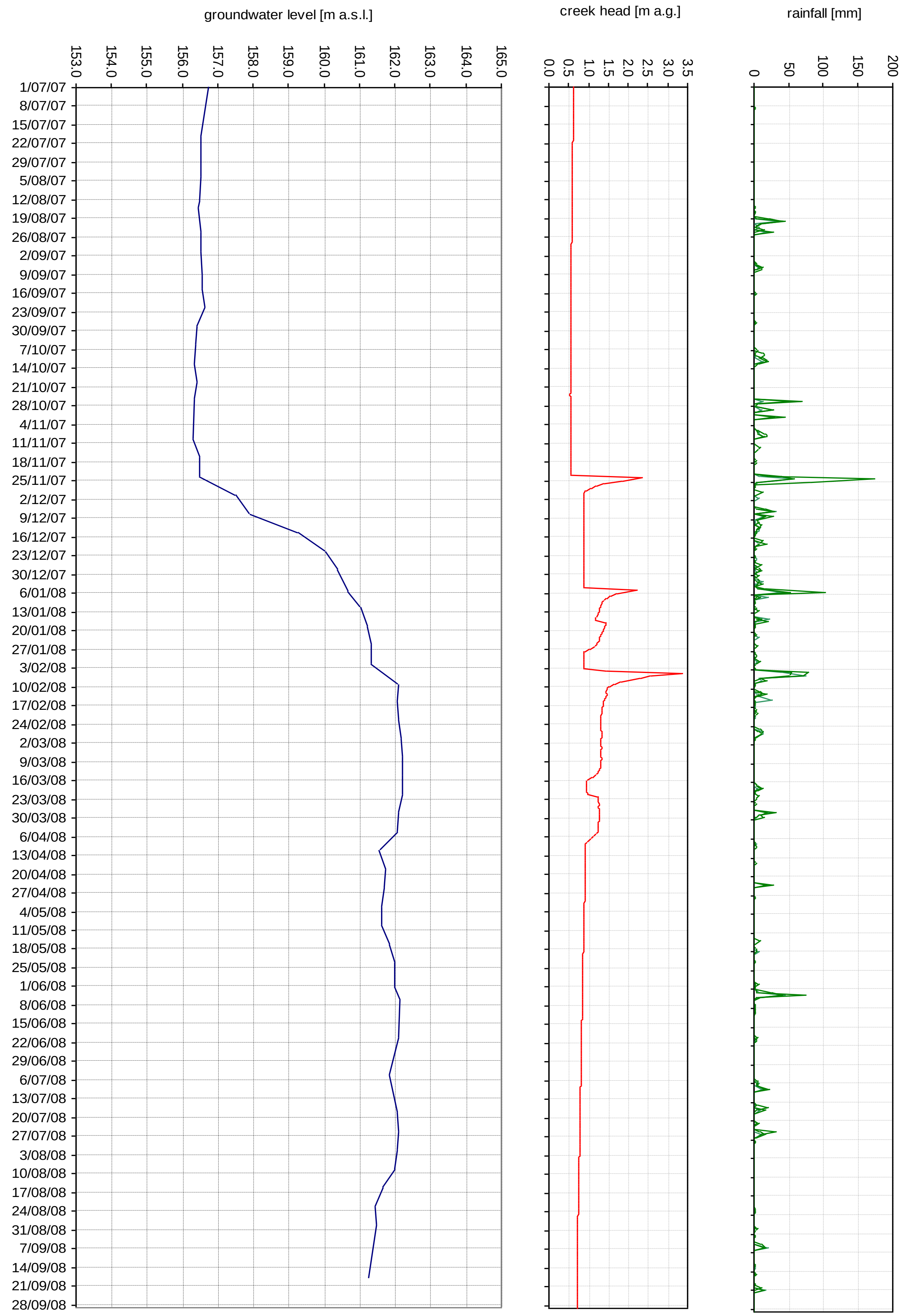
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

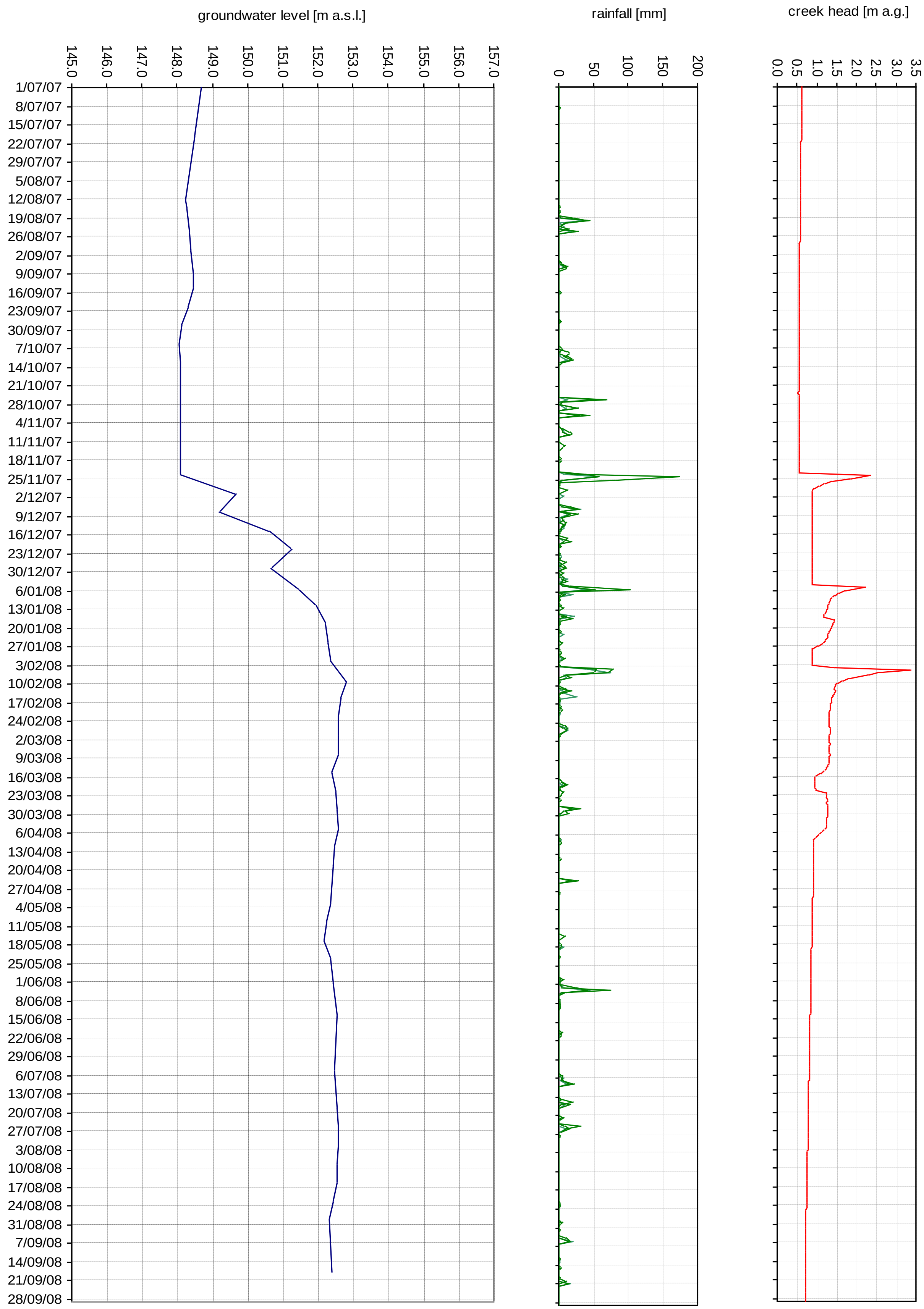
14320916



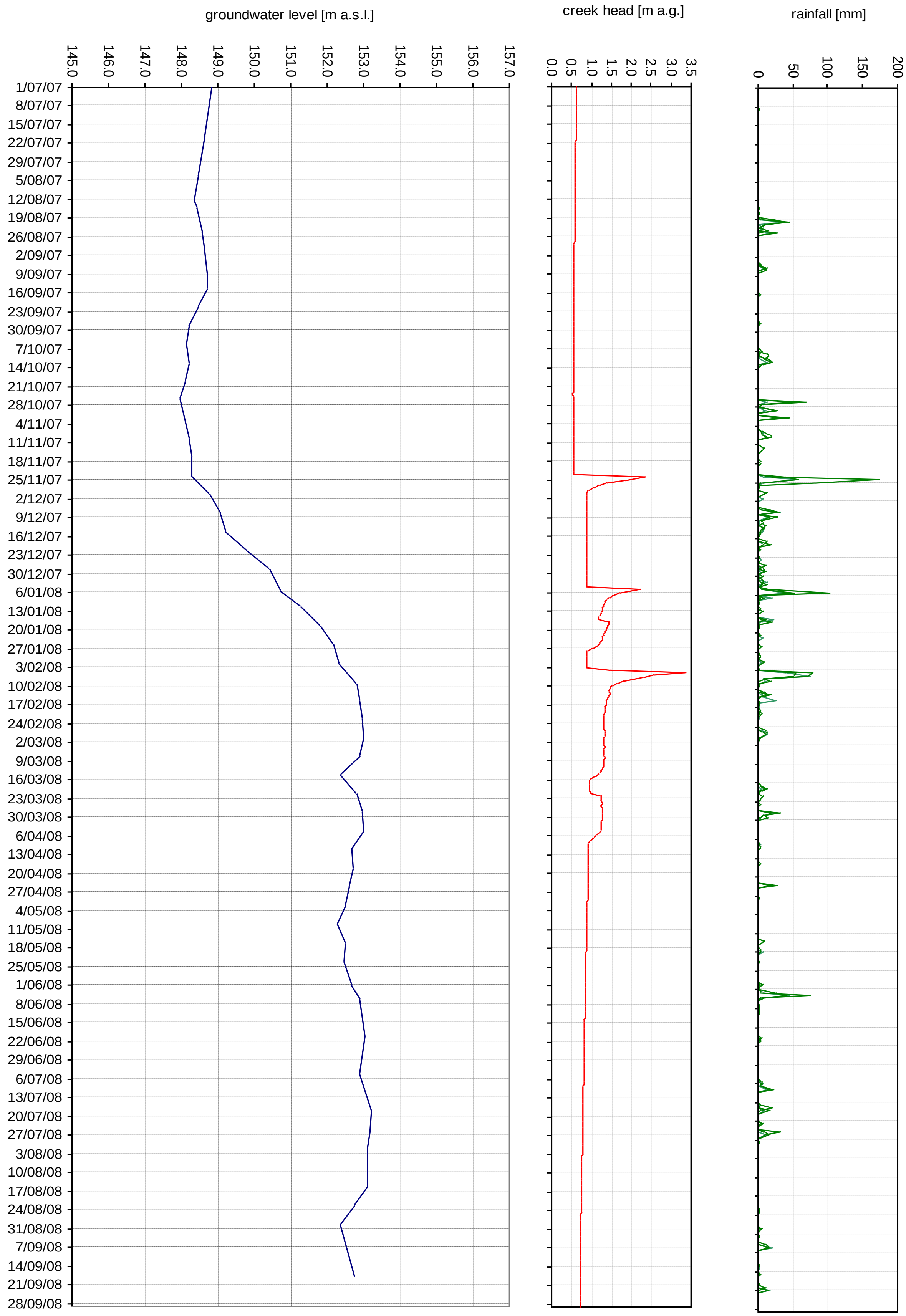
14320917


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
153.0 154.0 155.0 156.0 157.0 158.0 159.0 160.0 161.0 162.0 163.0 164.0 165.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 50 100 150 200
1/07/07 8/07/07 15/07/07 22/07/07 29/07/07 5/08/07 12/08/07 19/08/07 26/08/07 2/09/07 9/09/07 16/09/07 23/09/07 30/09/07 7/10/07 14/10/07 21/10/07 28/10/07 4/11/07 11/11/07 18/11/07 25/11/07 2/12/07 9/12/07 16/12/07 23/12/07 30/12/07 6/01/08 13/01/08 20/01/08 27/01/08 3/02/08 10/02/08 17/02/08 24/02/08 2/03/08 9/03/08 16/03/08 23/03/08 30/03/08 6/04/08 13/04/08 20/04/08 27/04/08 4/05/08 11/05/08 18/05/08 25/05/08 1/06/08 8/06/08 15/06/08 22/06/08 29/06/08 6/07/08 13/07/08 20/07/08 27/07/08 3/08/08 10/08/08 17/08/08 24/08/08 31/08/08 7/09/08 14/09/08 21/09/08 28/09/08

14320919


groundwater level [m a.s.l.]
145.0
146.0
147.0
148.0
149.0
150.0
151.0
152.0
153.0
154.0
155.0
156.0
157.0
rainfall [mm]
0
50
100
150
200
creek head [m a.g.]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
17/02/08
24/02/08
2/03/08
9/03/08
16/03/08
23/03/08
30/03/08
6/04/08
13/04/08
20/04/08
27/04/08
4/05/08
11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
20/07/08
27/07/08
3/08/08
10/08/08
17/08/08
24/08/08
31/08/08
7/09/08
14/09/08
21/09/08
28/09/08

14320920



groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
145.0
146.0
147.0
148.0
149.0
150.0
151.0
152.0
153.0
154.0
155.0
156.0
157.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
20/01/08
27/01/08
3/02/08
10/02/08
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4/05/08
11/05/08
18/05/08
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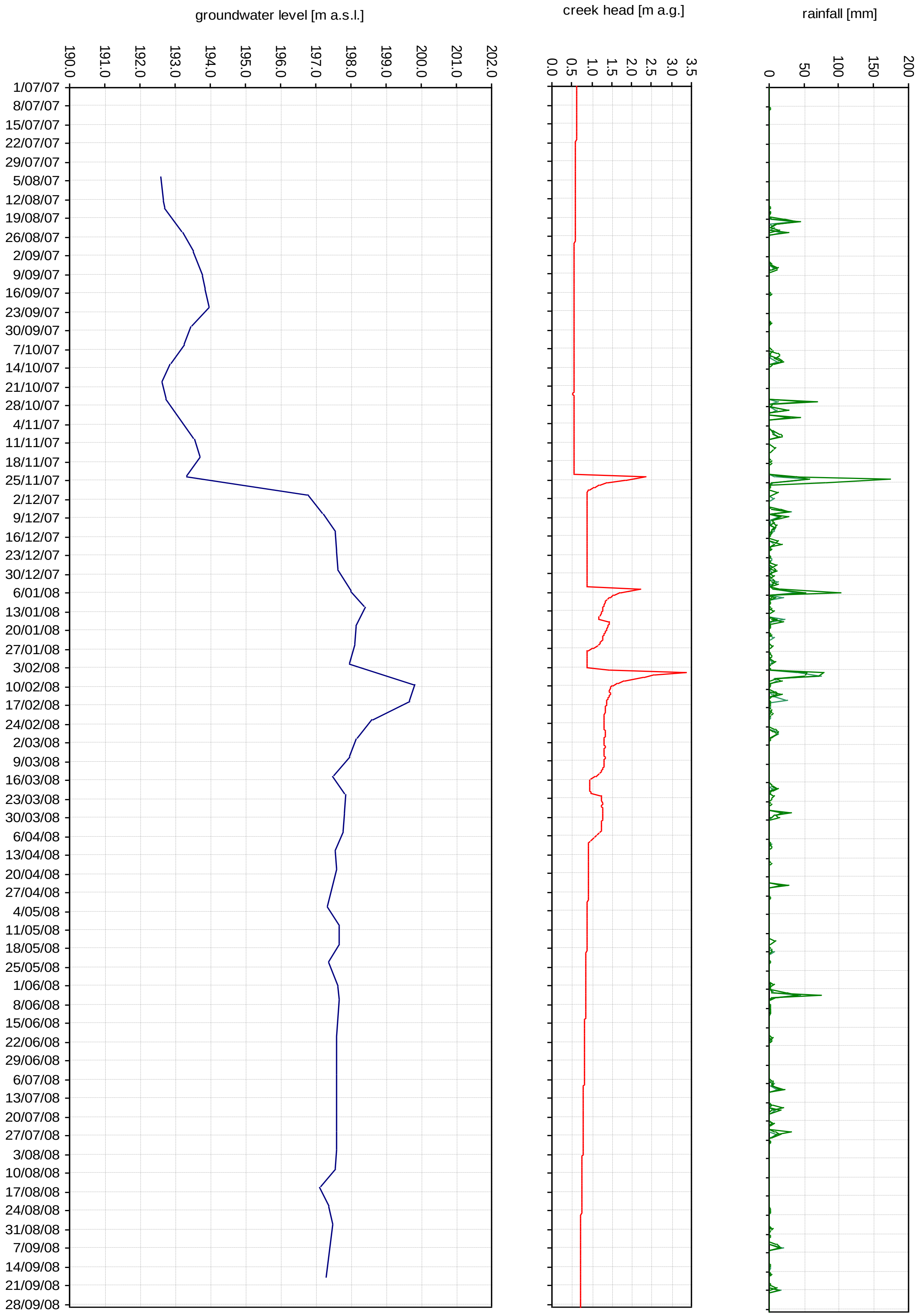
21/09/08
28/09/08

14320982


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
190.0
191.0
192.0
193.0
194.0
195.0
196.0
197.0
198.0
199.0
200.0
201.0
202.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
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7/10/07
14/10/07
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28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
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27/01/08
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27/04/08
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11/05/08
18/05/08
25/05/08
1/06/08
8/06/08
15/06/08
22/06/08
29/06/08
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27/07/08
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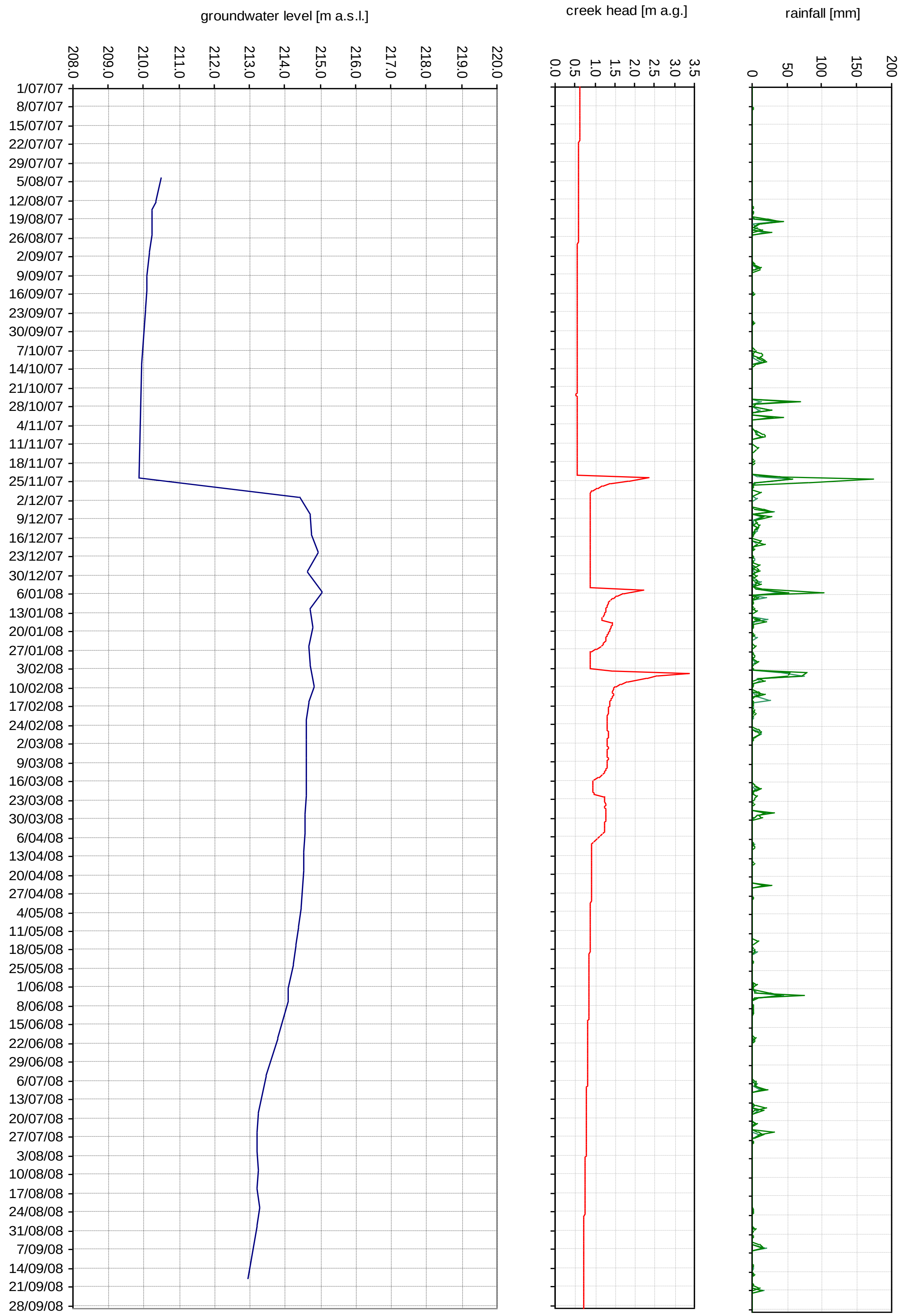
21/09/08
28/09/08

14320983



groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
208.0
209.0
210.0
211.0
212.0
213.0
214.0
215.0
216.0
217.0
218.0
219.0
220.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
1/07/07
8/07/07
15/07/07
22/07/07
29/07/07
5/08/07
12/08/07
19/08/07
26/08/07
2/09/07
9/09/07
16/09/07
23/09/07
30/09/07
7/10/07
14/10/07
21/10/07
28/10/07
4/11/07
11/11/07
18/11/07
25/11/07
2/12/07
9/12/07
16/12/07
23/12/07
30/12/07
6/01/08
13/01/08
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3/02/08
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15/06/08
22/06/08
29/06/08
6/07/08
13/07/08
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27/07/08
3/08/08
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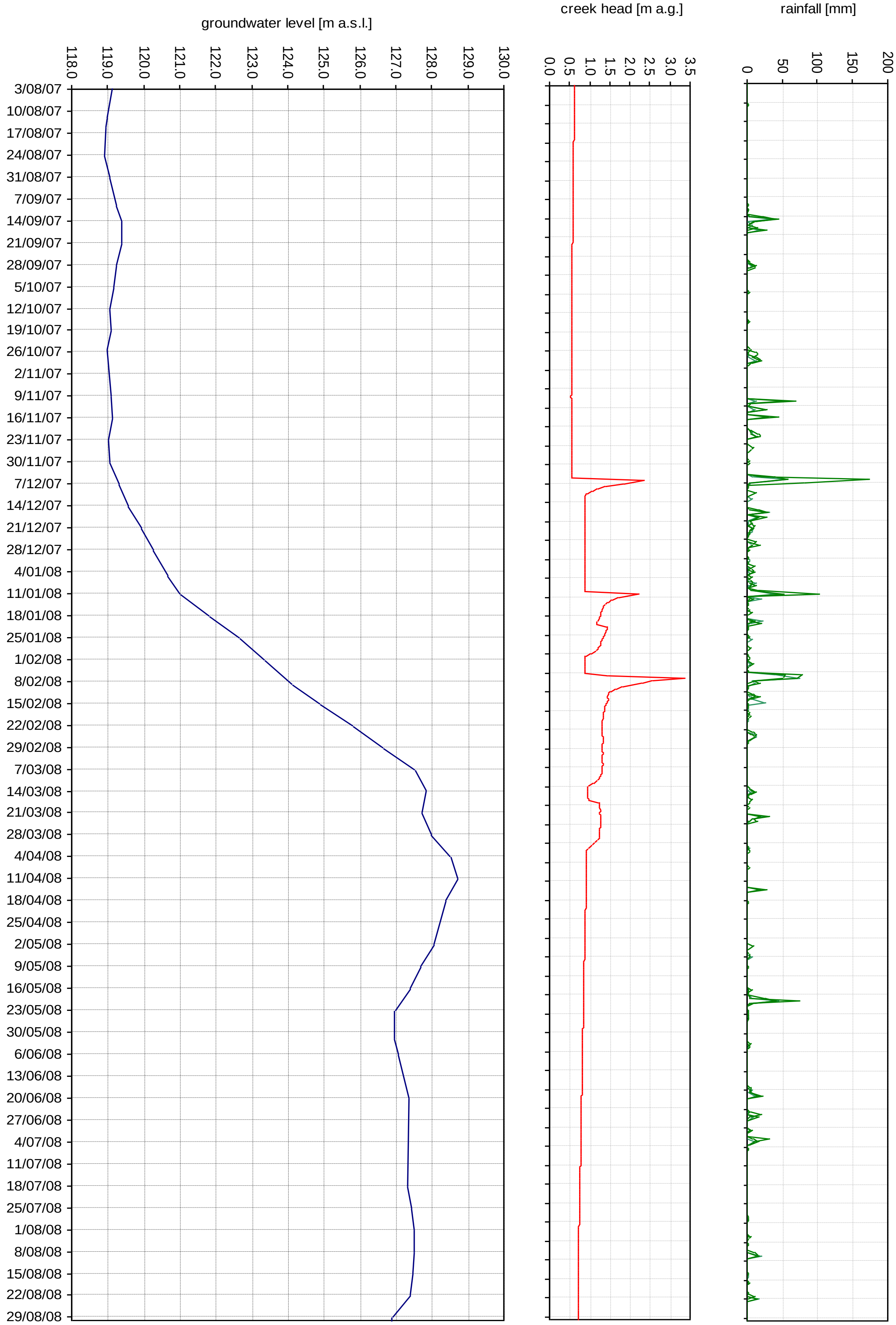
14/09/08
21/09/08
28/09/08

14320986


groundwater level [m a.s.l.]
creek head [m a.g.]
rainfall [mm]
118.0 119.0 120.0 121.0 122.0 123.0 124.0 125.0 126.0 127.0 128.0 129.0 130.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
0 50 100 150 200
3/08/07
10/08/07
17/08/07
24/08/07
31/08/07
7/09/07
14/09/07
21/09/07
28/09/07
5/10/07
12/10/07
19/10/07
26/10/07
2/11/07
9/11/07
16/11/07
23/11/07
30/11/07
7/12/07
14/12/07
21/12/07
28/12/07
4/01/08
11/01/08
18/01/08
25/01/08
1/02/08
8/02/08
15/02/08
22/02/08
29/02/08
7/03/08
14/03/08
21/03/08
28/03/08
4/04/08
11/04/08
18/04/08
25/04/08
2/05/08
9/05/08
16/05/08
23/05/08
30/05/08
6/06/08
13/06/08
20/06/08
27/06/08
4/07/08
11/07/08
18/07/08
25/07/08
1/08/08
8/08/08
15/08/08
22/08/08
29/08/08

Appendix I. Grouping of bore hydrographs

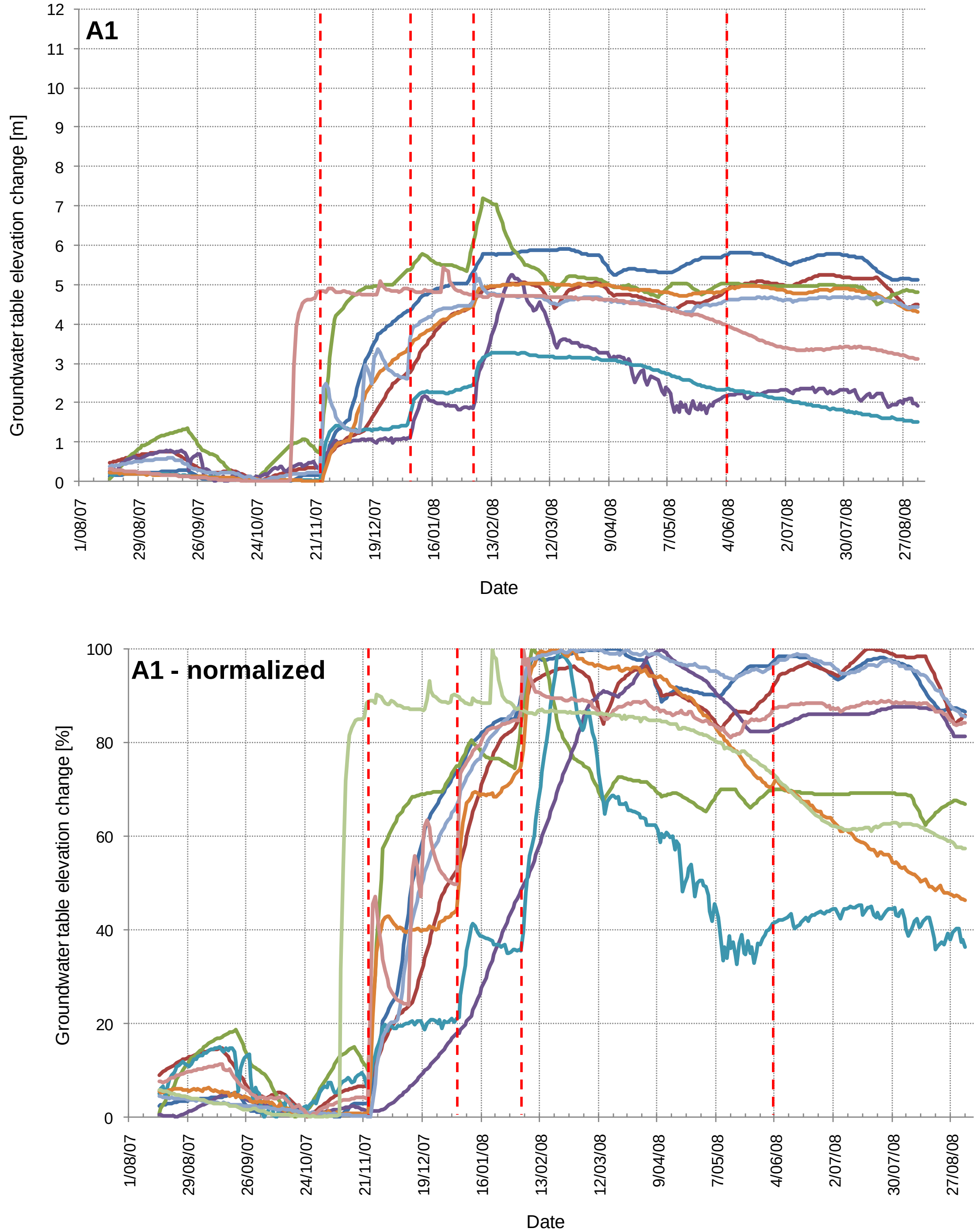


Figure 97. Bore hydrographs – group A1 – recharge related to major rainfall events and/or creek flow. Clear "step-like" response of the bore hydrograph to first 3 major rainfall events. Response to fourth significant rainfall event is limited. Major rainfall events are indicated using thick vertical dashed line in the chart.

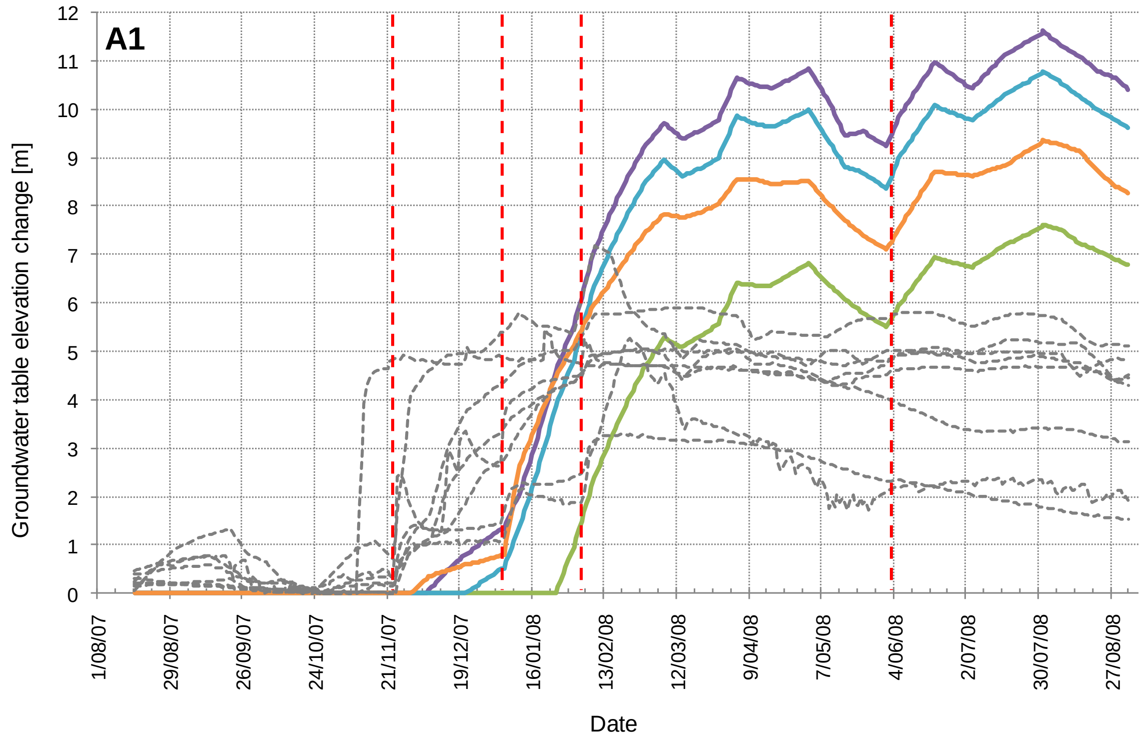


Figure 98. Bore hydrographs – group A1 – recharge related to major rainfall events and/or creek flow. Mulgowie Farm profile.

Bores 14320294, 14320295, 14320296 and 14320297 are drilled in a profile perpendicular to Laidley Creek, very close to Mulgowie recharge weir. Bores (and weir) were dry untill the first significant rainfall, only after they started to recharge. Major rainfall events are indicated using thick vertical dashed line in the chart. Other hydrographs belonging to group A1 shown for comparison (grey dashed lines).

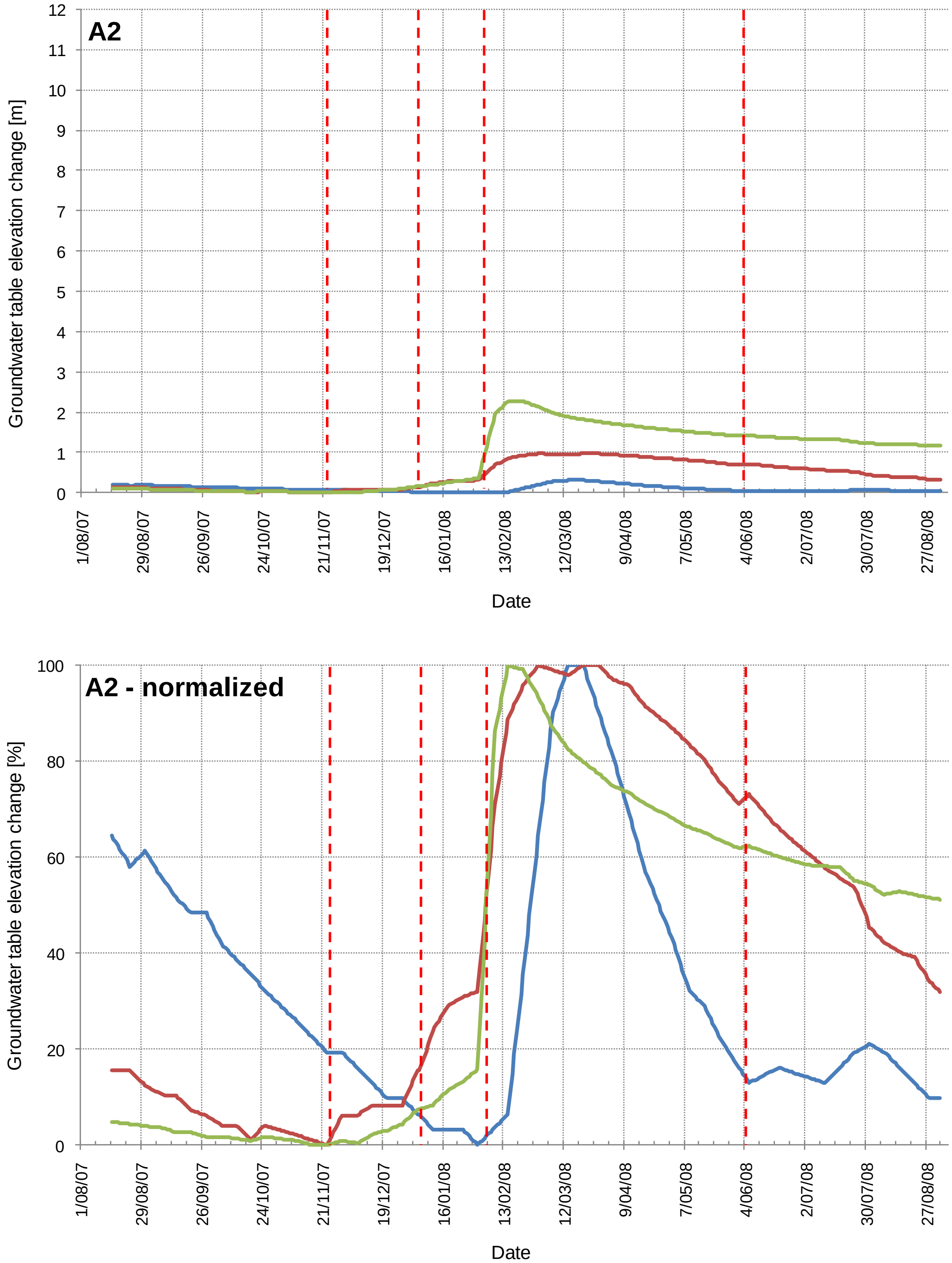
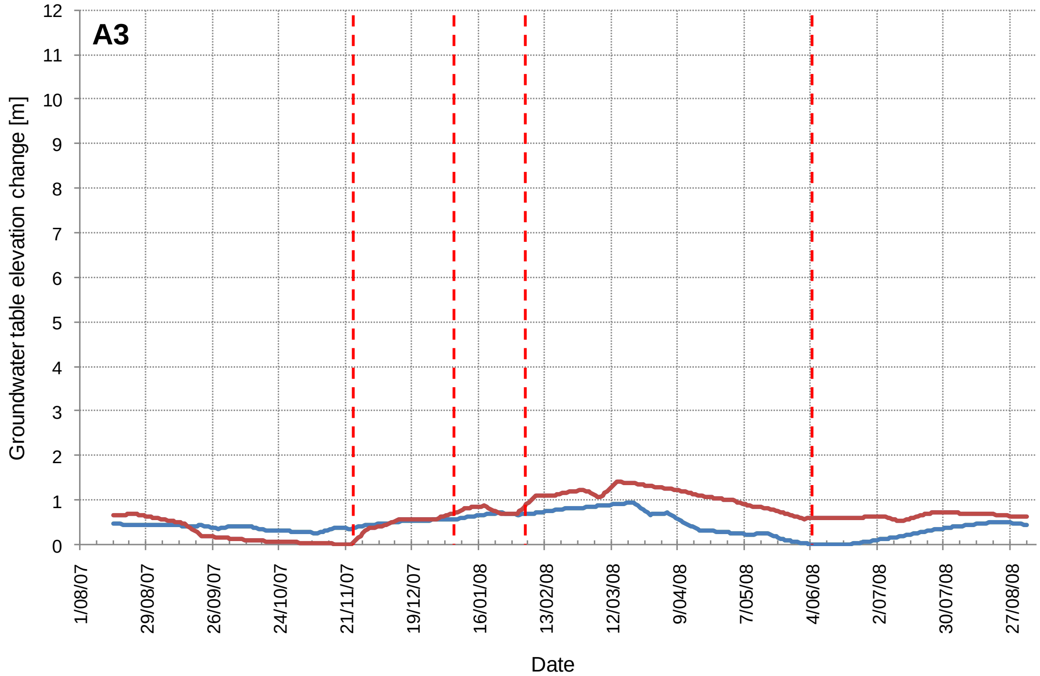


Figure 99. Bore hydrographs – group A2 – recharge related to major rainfall events and/or creek flow. Minimal or no response to first two significant rainfall events, major response to third significant rainfall event

Major rainfall events are indicated using thick vertical dashed line in the chart.



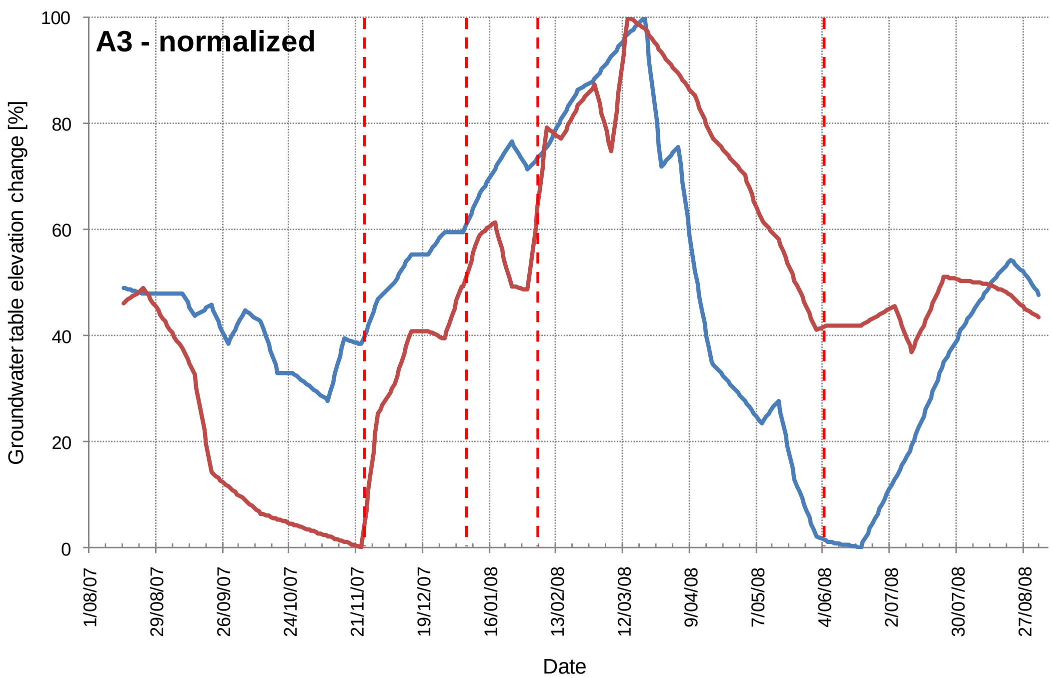
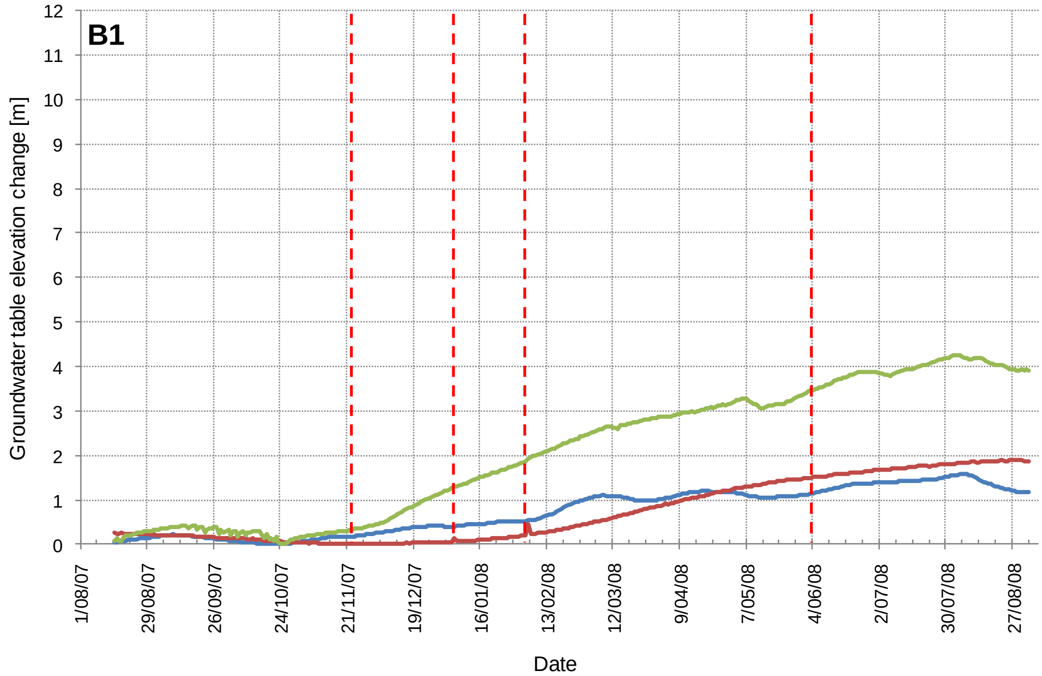


Figure 100. Bore hydrographs – group A3 – recharge related to major rainfall events and/or creek flow. Small, but consistent response to all significant rainfall events.

Major rainfall events are indicated using thick vertical dashed line in the chart.



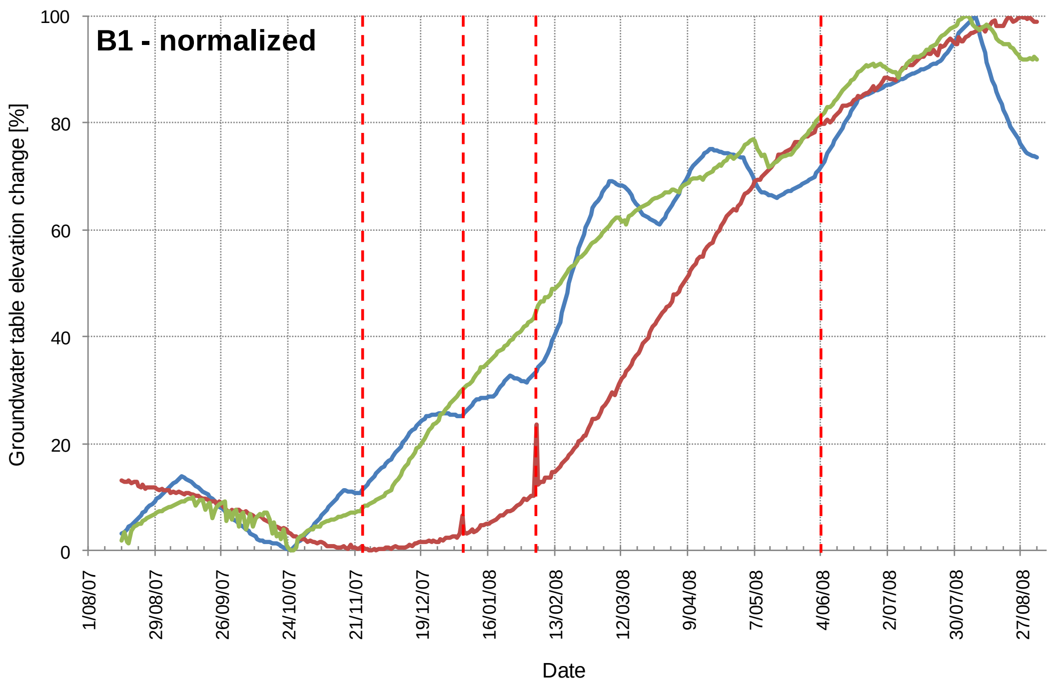
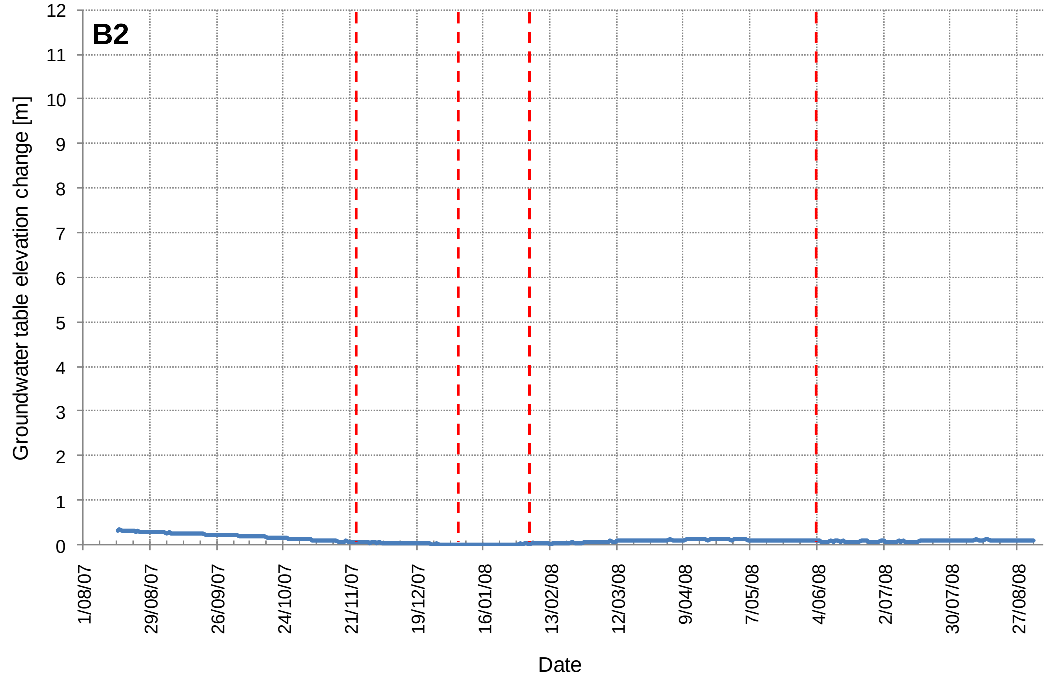


Figure 101. Bore hydrographs – group B1 – recharge unrelated to the major rainfall events (indirect recharge). Smooth and steady rise of groundwater table.

Major rainfall events are indicated using thick vertical dashed line in the chart.



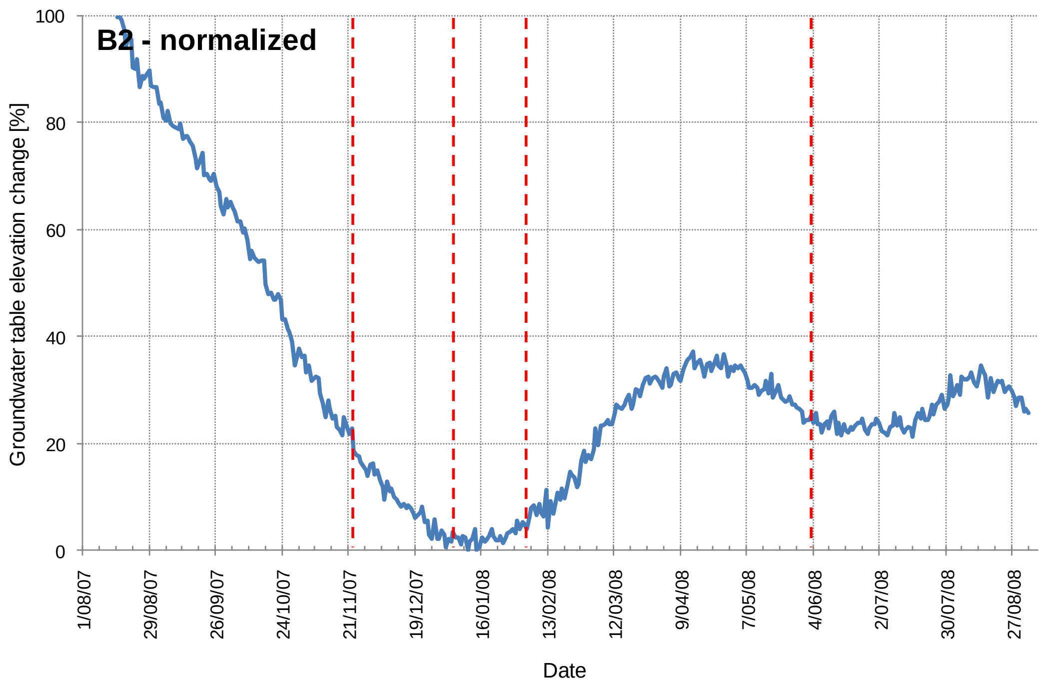
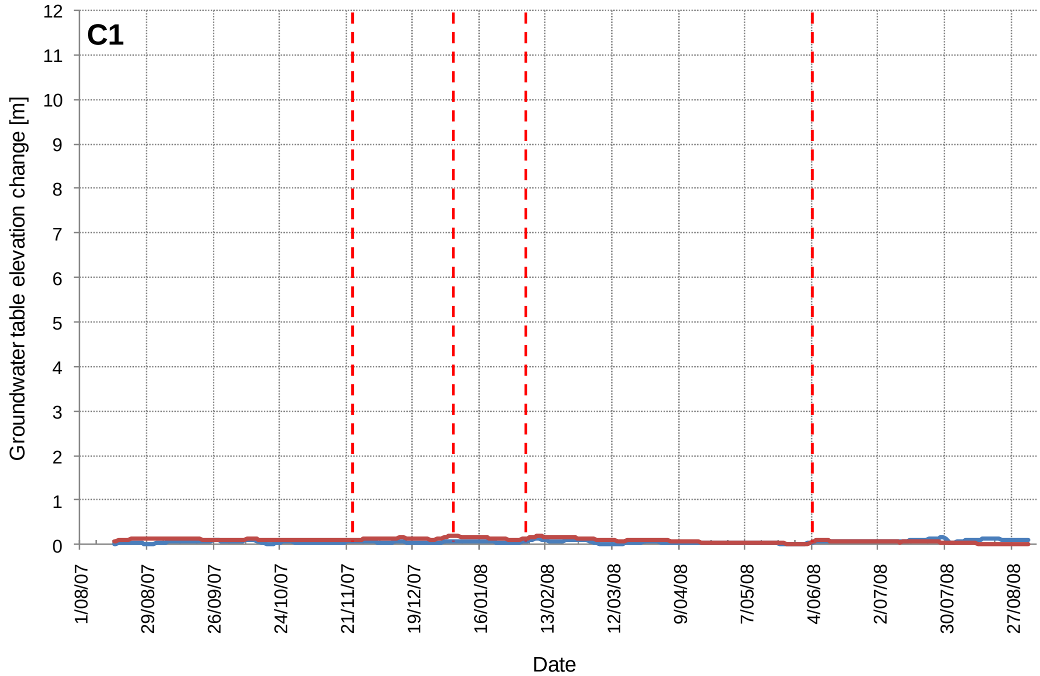


Figure 102. Bore hydrographs – group B2 – recharge unrelated to the major rainfall events (indirect recharge). Minimal, delayed recharge.

Major rainfall events are indicated using thick vertical dashed line in the chart.



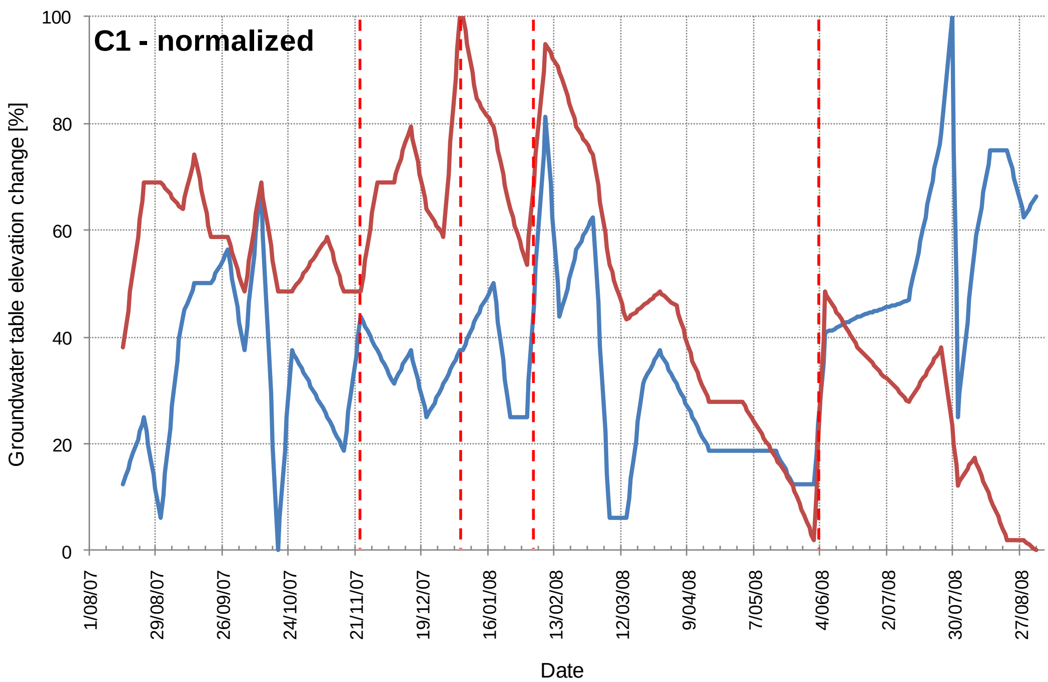
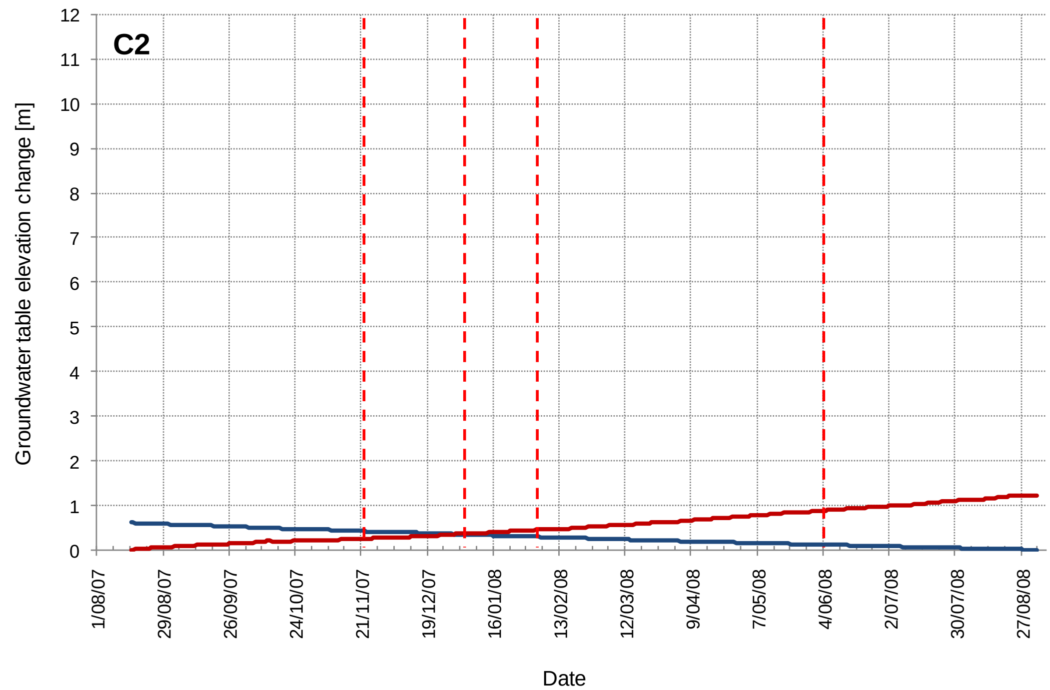


Figure 103. Bore hydrographs – group C1 – minimal or no recharge. Erratic behavior not visibly correlated to any rainfall and/or creek flow event.

Major rainfall events are indicated using thick vertical dashed line in the chart.



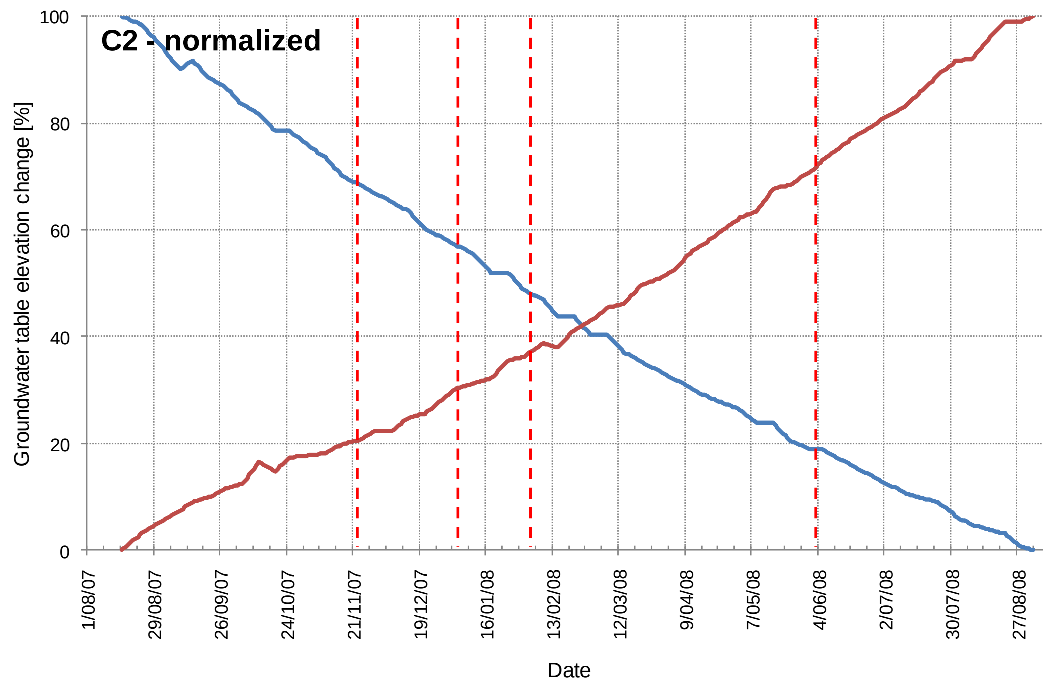


Figure 104. Bore hydrographs – group C2 – minimal or no recharge. Steady recharge or discharge regardless of the rainfall and/or creek flow event.

Major rainfall events are indicated using thick vertical dashed line in the chart.

Appendix J. Major ions analysis – results

Table 29. Sample site location, physical properties, TDS, water type and ionic balance error – groundwater samples

RN	easting	northing	pH	cond [uS]	TDS [mg/l]	water type	bal. err. [%]
14320290	439796	6934637	6.12	2570	1336.4	Na-Mg-Cl-HCO_3	-3.4
14320293	437010	6933940	7.3	1671	660.5	Na-Mg-Cl-HCO_3	-10.4
14320294	437822	6930032	7.29	916	825.6	Mg-Na-Ca-HCO_3-NO_3	-7.2
14320295	437965	6930000	7.39	n/a	252.6	Mg-Ca-Na-HCO_3	0.6
14320296	438015	6929975	8.21	n/a	224.3	Mg-Ca-Na-HCO_3	-2.0
14320297	438045	6929962	7.32	495	258.4	Mg-Ca-Na-HCO_3	-0.5
14320330	438221	6940242	7.21	977	470.2	Mg-Na-HCO_3	-0.9
14320331	438247	6940220	6.89	775	409.2	Mg-HCO_3	-1.4
14320332	438508	6940103	6.91	1422	755.1	Mg-Ca-HCO_3-Cl	-1.3
14320337	437968	6939041	7.29	2650	1929.9	Mg-Na-Cl-HCO_3	1.4
14320339	437658	6936580	6.93	3220	2472.0	Mg-Na-Cl-HCO_3	2.5
14320340	437966	6936534	7.12	n/a	1192.0	Mg-Na-HCO3-Cl	-1.7
14320450	438949	6941472	7.03	567	327.5	Mg-Na-HCO_3	2.1
14320453	437262	6933749	7.04	1882	1187.6	Mg-Na-Ca-Cl-HCO_3	10.3
14320472	435864	6922242	7.84	1435	552.5	Na-HCO_3	0.9
14320547	438954	6940198	7.21	2230	1659.8	Mg-Na-Cl-HCO_3	0.9
14320553	438764	6940236	7.48	2180	1556.9	Mg-Na-Cl-HCO_3	-0.6
14320786	436940	6934616	5.79	3090	1929.6	Na-Mg-Cl-HCO_3	-5.0
14320849	438890	6920957	6.97	622	303.7	Mg-Na-Ca-HCO_3	0.5
14320879	438283	6925072	7.21	n/a	246.3	Mg-Ca-Na-HCO_3	-3.9
14320880	439232	6930610	6.52	1163	588.9	Mg-Na-HCO3-Cl	-2.7
14320883	436375	6933689	6.27	14840	10736.7	Na-Mg-Cl	5.6
14320884	437410	6940665	6.45	15970	12813.6	Na-Mg-Cl	-3.8
14320885	437694	6926581	7.71	n/a	247.9	Na-HCO_3	3.1
14320887	438845	6936728	7.17	8450	5048.9	Na-Cl-HCO_3	-5.6
14320916	436804	6938388	6.08	2730	1798.7	Mg-Ca-Cl-HCO_3	5.2
14320917	438105	6924979	7.03	317	286.2	Mg-Ca-Na-HCO_3-SO_4	-6.1
14320919	437928	6927532	7.20	717	414.3	Mg-Ca-Na-HCO_3-SO_4	-2.9
14320920	438175	6927472	7.24	886	477.5	Mg-Na-Ca-HCO3-Cl	0.8
14320982	439909	6918919	6.78	472	243.8	Mg-Ca-HCO_3	-4.5
14320983	439912	6916683	7.23	336	167.5	Mg-Ca-Na-HCO_3	-4.2
14320986	437322	6932694	6.95	885	687.2	Mg-Na-Ca-HCO_3	3.2
Crosby M1	439009	6910109	7.15	n/a	174.2	Mg-Ca-HCO_3	-4.0
Crosby M2	440469	6911781	6.88	n/a	168.1	Mg-Ca-Na-HCO_3	-2.9

Table 30. Sample site location, physical properties, TDS, water type and ionic balance error – surface water samples

RN	easting	northing	pH	cond [uS]	TDS [mg/l]	water type	bal. err. [%]
Crosby M1 creek	439032	6910125	7.74	n/a	251.5	Mg-Ca-HCO_3-Cl	-0.5
Crosby M2 creek	440519	6911776	7.71	n/a	137.2	Mg-Ca-HCO_3	-2.5
Crosby house	439727	6912978	7.14	n/a	165.4	Mg-Ca-HCO_3	-4.9
Crosby park	439658	6913601	7.73	644	302.7	Mg-Na-Ca-HCO_3	-0.1
Peacock bridge	440001	6919222	7.30	380	179.7	Mg-Ca-HCO_3	-4.5
Bonnel road	438628	6920891	7.80	404	215.1	Mg-Ca-Na-HCO_3	0.6
Clarke bridge	438242	6924968	7.41	516	402.7	Mg-Ca-Na-HCO_3	1.3
Peters road	437964	6927513	7.42	497	393.7	Mg-Ca-Na-HCO_3	2.5
Mulgowie weir	438106	6929949	7.10	436	238.2	Mg-Ca-HCO_3	-0.4

Table 31. Major ion analysis results - groundwater samples

RN	Na^{+}	K^{+}	Mg^{2+}	Ca^{2+}	Sr^{2+}	Mn^{2+}	Fe^{2+}	Zn^{2+}	Cu^{2+}	Al^{3+}	F^{-}	Cl^{-}	Br^{-}	SO_4^{2-}	NO_3^{2-}	HCO_3^{-}	PO_4^{3-}
14320290	320.00	2.60	100.00	38.00	0.55	0.08	--	0.02	--	--	--	437.55	3.20	115.23	87.41	501.40	--
14320293	180.00	3.19	34.00	27.00	0.22	0.20	--	0.01	0.00	--	0.35	258.48	--	67.30	7.44	360.90	--
14320294	67.00	0.95	69.00	57.00	0.16	0.01	0.06	0.01	--	--	0.15	76.37	0.47	98.92	90.49	363.40	1.65
14320295	30.00	0.80	33.00	28.00	0.06	0.01	--	0.01	--	--	0.26	26.92	--	17.29	2.39	247.10	1.33
14320296	25.00	1.40	31.00	25.00	0.06	0.34	0.12	--	0.00	--	0.07	21.21	--	16.31		256.20	--
14320297	31.00	0.86	35.00	29.00	0.07	0.00	--	0.01	--	--	0.17	23.29	--	11.86	2.74	280.00	2.03
14320330	87.00	0.82	68.00	40.00	0.30	0.26	--	0.00	--	--	0.11	32.72	--	11.06	9.13	619.50	--
14320331	37.00	0.14	71.00	37.00	0.20	0.01	--	--	--	--	0.23	21.40	0.38	11.04	5.53	512.60	1.55
14320332	120.00	1.30	100.00	40.00	0.55	0.29	--	--	--	--	0.25	177.38	1.00	12.84	2.16	639.10	0.62
14320337	260.00	4.80	184.00	116.00	0.68	1.02	0.02	0.06	--	0.07	0.30	753.30	3.30	19.75	3.55	581.60	1.50
14320339	279.00	6.00	279.00	165.00	1.08	0.21	0.10	0.10	0.02	--	0.30	1009.16	3.18	154.38	6.89	566.00	1.60
14320340	88.00	1.92	120.00	59.00	0.43	0.51	1.20	--	--	--	0.24	182.84	0.74	16.58	0.84	719.80	--
14320450	37.00	0.49	54.00	24.00	0.16	0.04	--	0.01	0.02	--	0.27	37.21	--	8.55	0.99	343.20	0.88
14320453	120.00	1.72	140.00	100.00	0.44	0.24	--	0.01	0.01	--	1.76	310.88	1.44	82.28	5.48	423.40	--
14320472	310.00	3.00	36.00	10.00	0.21	0.02	0.09	--	--	--	0.78	84.76	0.39	8.28	--	859.20	0.30
14320547	170.00	1.91	200.00	82.00	1.00	0.60	1.40	0.00	0.00	--	0.60	633.15	2.60	58.85	3.55	503.60	0.57
14320553	170.00	1.77	160.00	75.00	0.47	0.32	0.00	0.04	0.00	--	0.65	457.77	1.65	70.80	2.77	615.10	0.61
14320786	390.00	9.40	95.00	72.00	1.40	0.23	0.93	0.01	--	--	0.38	751.04	3.48	19.26	2.46	578.30	5.76
14320849	38.00	1.90	43.00	30.00	0.13	0.30	--	--	--	--	0.13	30.43	0.23	19.93	--	324.20	1.08
14320879	25.00	1.10	32.00	27.00	0.11	0.00	--	--	0.02	--	0.12	32.45	0.25	19.51	0.80	249.40	0.77
14320880	99.00	1.30	70.00	42.00	0.92	0.11	--	--	--	--	0.34	133.45	0.61	14.74	--	537.10	0.04
14320883	2800.00	36.00	704.00	296.00	8.80	0.78	0.10	0.13	0.08	0.06	0.15	4785.50	18.00	1215.00	0.50	871.40	0.28
14320884	3040.00	28.00	800.00	296.00	6.80	0.16	0.18	0.14	0.01	0.02	0.79	7469.40	12.09	205.00	--	955.10	--
14320885	91.00	3.30	14.00	19.00	0.10	--	--	--	--	--	0.24	37.38	0.28	36.94	5.32	227.80	0.39
14320887	1920.00	10.20	57.00	29.10	2.85	0.33	--	0.02	--	--	0.35	2822.68	8.00	37.57	--	1226.50	--
14320916	120.00	1.90	260.00	130.00	0.75	1.70	0.03	0.05	--	--	0.66	688.60	3.48	150.14	2.16	439.00	0.30
14320917	31.00	1.30	37.00	28.00	0.11	0.06	--	--	--	--	0.14	29.81	--	64.66	0.82	264.10	0.41
14320919	46.00	0.67	55.00	41.00	0.13	--	--	--	--	--	0.21	35.21	--	94.75	2.03	362.70	1.37
14320920	59.00	1.60	65.00	43.00	0.16	0.81	--	--	0.00	--	0.17	73.95	0.65	19.99	--	450.60	0.87

RN	Na^+	K^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Mn^{2+}	Fe^{2+}	Zn^{2+}	Cu^{2+}	Al^{3+}	F^-	Cl^-	Br^-	SO_4^{2-}	NO_3^{2-}	HCO_3^-	PO_4^{3-}
14320982	22.00	1.20	31.00	26.00	0.10	--	--	--	0.00	--	0.08	27.05	--	8.88	17.30	229.00	0.31
14320983	17.00	1.20	21.00	20.00	0.08	--	--	--	--	--	0.09	18.95	--	5.28	4.97	180.20	0.45
14320986	53.00	1.10	67.00	45.00	0.23	0.56	--	--	--		0.29	65.74	0.44	38.21	--	415.70	--
Crosby M1	15.00	1.20	23.00	20.00	0.07	0.00	--	--	--		0.07	25.80	--	4.73	--	183.00	0.56
Crosby M2	19.00	1.20	25.00	18.00	0.06	0.01	0.09	0.15	0.02		0.12	14.66	--	2.98	--	217.60	--

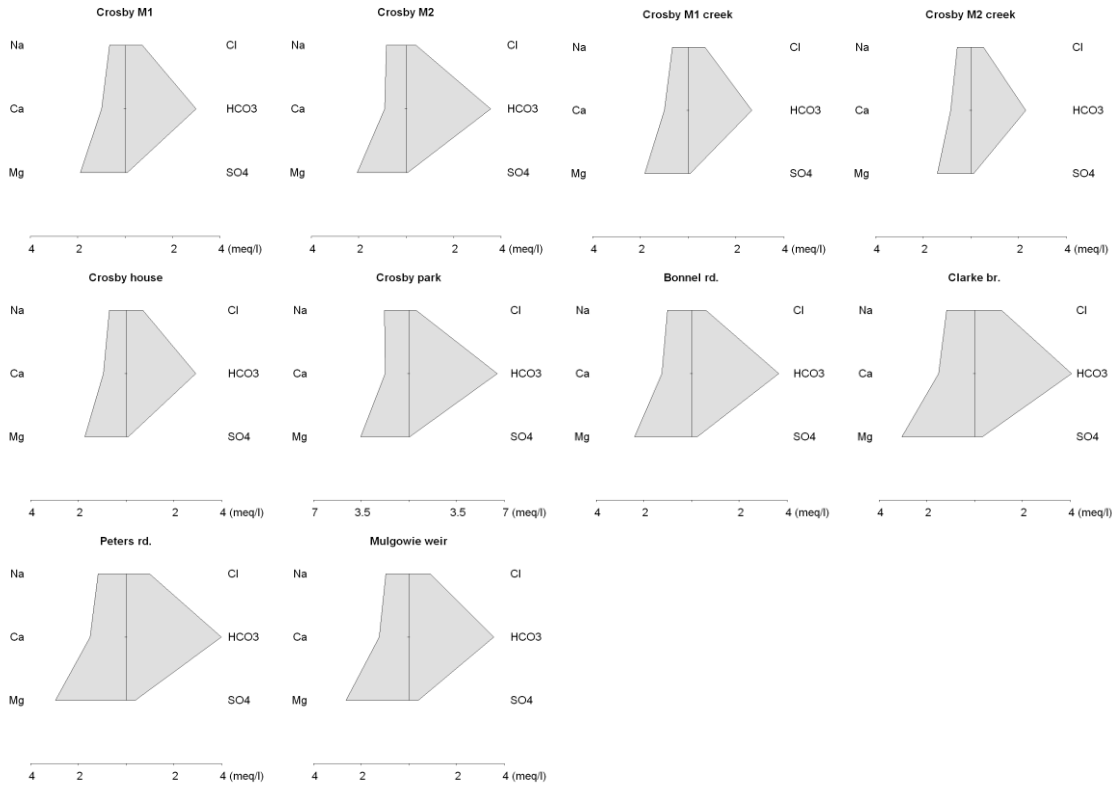
Table 32. Major ion analysis results - surface water samples

RN	Na^+	K^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Mn^{2+}	Fe^{2+}	Zn^{2+}	Cu^{2+}	Al^{3+}	F^-	Cl^-	Br^-	SO_4^{2-}	NO_3^{2-}	HCO_3^-	PO_4^{3-}
Bonnel road.	23.00	1.50	29.00	25.00	0.09	0.01	--	--	--	--	0.10	21.38	--	11.82	0.63	223.30	0.97
Clarke bridge.	27.00	2.10	37.00	30.00	0.11	0.01	--	0.01	--	--	0.14	40.08	0.29	15.85	1.47	248.20	0.44
Crosby house	16.00	1.70	21.00	19.00	0.07	0.00	--	0.01	--	--	0.09	24.89	--	4.72	0.13	178.00	0.49
Crosby M1 creek	15.00	1.20	22.00	20.00	0.06	--	--	--	--	--	0.07	24.97	--	4.64	0.30	162.70	0.53
Crosby M2 creek	13.00	1.30	17.00	17.00	0.06	--	--	--	--	--	0.05	18.89	--	5.71	--	140.60	0.40
Crosby park	41.00	3.70	43.00	35.00	0.14	0.13	--	--	--	--	0.10	19.35	--	2.43	--	396.70	0.89
Mulgowie weir	22.00	2.30	32.00	25.00	0.09	0.01	--	--	--	--	0.10	31.98	--	19.02	0.77	217.60	0.45
Peacock bridge.	18.00	1.20	24.00	22.00	0.08	0.01	--	--	--	--	0.09	18.40	--	6.47	0.86	215.40	0.49
Peters road.	27.00	2.40	36.00	30.00	0.10	--	--	0.01	--	--	0.11	34.73	--	18.84	0.39	243.70	0.43

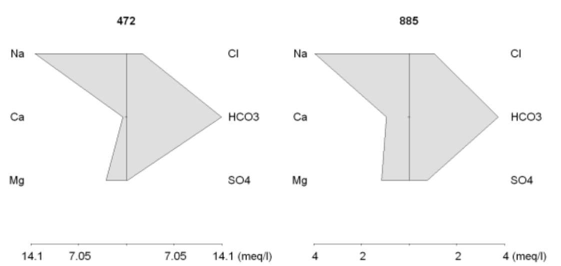
Appendix K. Major ions analysis – Stiff diagrams – grouping of samples

Group 1 – "basalt" groundwater

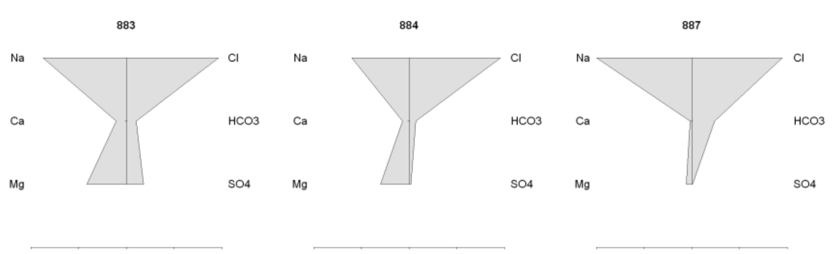
Group 1 – "basalt" surface water (Laidley Creek)



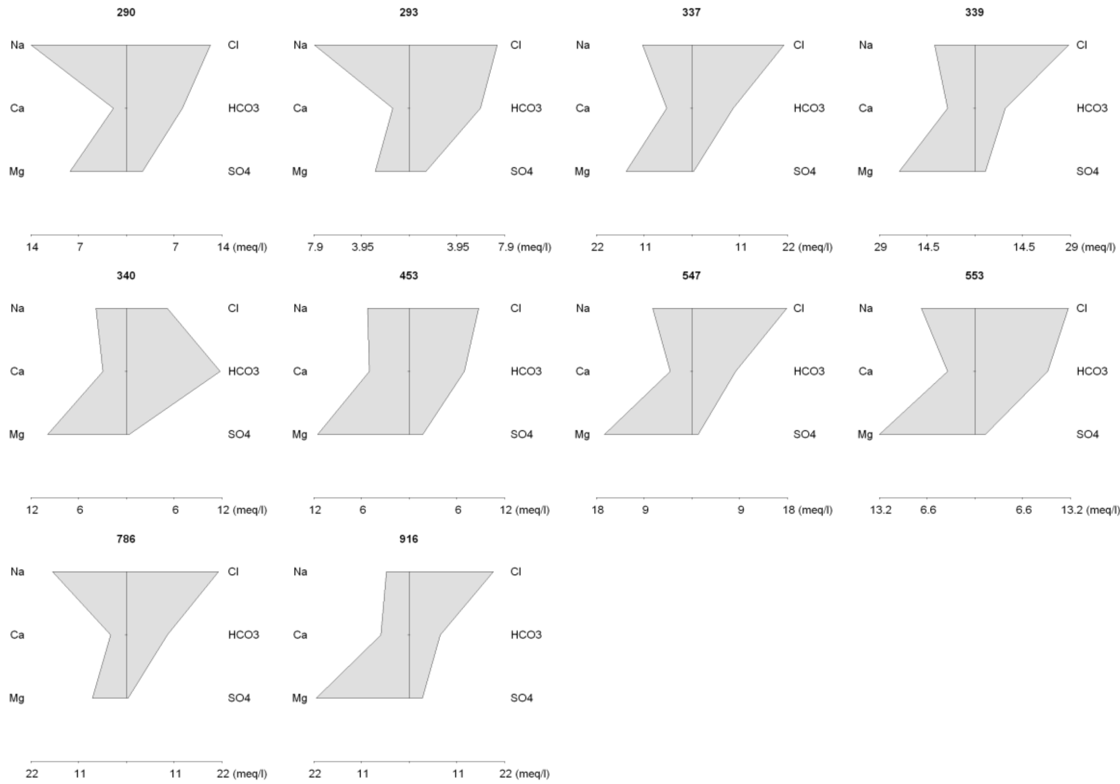
Group 2 – "Walloon Coal Measures / Koukandowie Formation water"



Group 3 – "Gatton Sandstone water"



Group 4 – "central alluvium water"



Appendix L. Numerical model directory structure

dir: model - model "home" directory, contains files and directories necessary for the model run and generated MODFLOW-SURFACT files (laidley_ss.* for the steady state model, laidley_tr.* for the transient model). To run the full simulation, run `model.exe`. Optionally, run steady state or transient models separately:

```
msft -2 laidley_ss
msft -2 laidley_tr
```

Any model run requires MODFLOW-SURFACT licence.

All model output files are available without model re-run: *.hds (heads), *.obw (calculated "observations" in bores), *.out (model output), *.cbb (cell-by-cell flows)

dir: model/calibration - input (*.pst) and output (everything else) PEST files for the ultimate (calibrated) run.

dir: model/input - contains all input data:

dir: budget - budget zonation files.

dir: heads - array files - starting heads for individual layers (heads_ss_*.ref), bore coordinates file (bores_coords*.txt), specified head boundary definitions (chd_definition.txt, time_specified_heads.xls).

dir: hydraulic_properties - array files (*.ref), pilot point files (usually *.txt), pilot point template files (used by PEST, usually *.tpl).

dir: irrigation - pump coordinates, irrigation return definition files, irrigation zonation file.

dir: observation - coordinate files (measured heads) for both steady state and transient runs (bores_coords_*.txt).

dir: rainfall - daily rainfall data (three stations: Townson, Laidley Crk. West, Laidley), rainfall distribution factor file.

dir: recharge - recharge pilot points (alluvium).

dir: river - definition of different types of river/creek cells (cells_*.csv), definition of flows/heads (flow_*.xls) along the courses of Laidley and Main Camp Creeks (flow arrays).

dir: structure - model grid definition file (*.grd), boundary conditions for individual layers (ibound.inf), definitions of layers tops and floors (l*_bot.ref).

dir: time - model time (stress periods) setup.

dir: model/output - contains all output data:

contrib_to_phi.xls - calibration analysis, contribution of individual observation groups towards the value of objective function.

param_uncertainty.xls - results and graphs of the parameter and observation uncertainty analysis.

scatter.xls - calibration results - comparison of measured and modelled heads and head gradients, calibration performance measures.

dir: budget - generated budgets - model wide budget (budget_transient_summary.txt) and cell-by-cell-flow derived budgets for individual zones: 100 - alluvium, 200 - MRV basalts, 300 - Walloon Coal Measures, 400 - Koukandowie Formation, 500 - Gatton Sandstone.

dir: heads - final heads of the steady state run.

dir: hydraulic_properties - arrays of horizontal hydraulic conductivity (hc), vertical hydraulic conductivity (vhc), vertical conductance term (vcont), specific storage (ss) and specific yield (sy) for individual layers.

dir: maps - files used to generate maps and diagrams, Surfer and MapInfo based.

dir: observation - model generated heads and head gradient files, used in the calibration process, R script to generate quick hydrographs (gen_hydrographs.r), PEST instruction files (*.ins).

dir: rainfall - model generated rainfall pilot point files (for each stress period), model generated rainfall arrays (*.ref).

dir: recharge - steady state recharge array.

dir: river - transient (flow) river difinition arrays (riv_definition_tr_*.inf), overview definition files.

dir: structure - model structure files - tops and bottoms of layers, layer thickness arrays, for overview purposes.

dir: model/source_code - Fortran source code for binaries used during model run. If any changes are made, needs to be re-compiled. Binaries located in parent (model/) directory.

model.f90 - master modeling code - reads appropriate input files, builds MODFLOW packages (for both steady state and transient runs), runs models and extracts some results.

modelout-sf.f90 - extracts heads and budgets from the MODFLOW output file. Uses modelout.in as an input file.

obw2smp.f90 - reads MODFLOW generated observation file (*.obw) and re-orders the values so that they can be easily plotted. Uses 3 input files (obw2smp_*.txt).

Appendix M. Model parameters and parameter files

Description of parameters listed in PEST control file (*.pst)

Hydraulic properties

hc-l1z0	Base value of horizontal hydraulic conductivity for layer 1, zone 0 (regolith).
hc-l1z1	Base value of horizontal hydraulic conductivity for layer 1, zone 1 (alluvium).
hc-l2 - hc-l5	Base values of horizontal hydraulic conductivity for layers 2 - 5
hcr-001 - hcr-284	Pilot point values representing change of horizontal hydraulic conductivity. Pilot points used to create factor matrix to adjust base value of HC for zone 0 (regolith).
Hc0001 - hc1099	Pilot point values representing change of horizontal hydraulic conductivity. Pilot points used to create factor matrix to adjust base value of HC for zone 1 (alluvium).
vhc-l1z0	Factor (multiplier) used to calculate vertical hydraulic conductivity in layer 1, zone 0 (regolith). Vertical hydraulic conductivity calculated from horizontal hydraulic conductivity - factor applied uniformly to the whole zone 0.
vhc-l1z1	Factor (multiplier) used to calculate vertical hydraulic conductivity in layer 1, zone 1 (alluvium).
vhc-l2 - vhc-l5	Factor (multiplier) used to calculate vertical hydraulic conductivity for layers 2 - 5
sy-l1 - syl5	Base value of specific yield for layers 1 to 5.
sy001 - sy343	Pilot point values representing change of base value of SY in layer 1. Points 001 - 089 define SY values for zone 0 (regolith), points 090 - 343 define SY values for alluvium of Laidley Creek (zone 1).
ss-l1 - ssl5	Base value of specific storage coefficient for layers 1 to 5.
ss001 - ss343	Pilot point values representing change of base value of SS in layer 1. Points 001 - 089 define SS values for zone 0 (regolith), points 090 - 343 define SS values for alluvium of Laidley Creek (zone 1).

Relevant parameter files:

```
params_bcf.txt
.\input\hydraulic_properties\ppts_hc_alluvium.txt
.\input\hydraulic_properties\ppts_hc_regolith.txt
.\input\hydraulic_properties\ppts_ss.txt
.\input\hydraulic_properties\ppts_sy.txt
```

Recharge

`rbz0`	Base value of recharge (as percentage of rainfall) for zone 0 (regolith).
`rch01 - rch42`	Pilot point values for recharge (as percentage of rainfall) into zone 1 (alluvium).

Relevant parameter files:

```
params_rech.txt
.\input\recharge\ppts_rch_zone1.txt
```

Pumping

`pumpv`	Extracted volume (per bore) in [m3/day]. Pumping is distributed evenly between known irrigation wells.
`pumph`	Minimum amount of water in aquifer in [m] that allows the pump to be active. If there (location of well) is less water than `pumph` at the beginning of the model run, the pump becomes inactive.
`irr`	Irrigation return - percentage of pumping volume that returns back into the aquifer - value added to recharge from rainfall.

Relevant parameter files:

```
params_wel.txt
params_rch.txt
```

River

`r1w, r2w, r3w`	"Width" of the river - 1 - Laidley Creek, 2 - Main Camp Creek, 3 - all other river cells in the model domain. Width of the river is constant for individual river cell groups (1, 2 and 3).
`r2d, r3d`	"Depth" of the river - how deep is the elevation of the river cell with respect to topographic surface. Values are constant for river cell groups 2 (Main Camp Creek) and 3 (other river cells). Values of river depth for Laidley Creek are defined on the per-cell basis.
`r1bt, r2bt, r3bt`	River bed thickness - constant for individual river cell groups.
`r3wd`	Water depth - head of water above the river cell. Defined only for group 3, depth of water for Laidley and Main Camp Creek is defined on per-cell basis.
`r1z01 - r1z16`	Vertical conductivity of the river bed - values for zones 1-16 of Laidley Creek.
`r2cnd, r3cnd`	Vertical conductivity of the river bed for cells of groups 2 (Main Camp Creek) and 3 (other river cells).

Relevant parameter files:

```
params_riv.txt
```

Appendix N. Calibration quality measures

Acquired from Middlemis (2001): Murray-Darling basin comission: Groundwater flow modeling guideline; p. 45

Table 3.3.1
Calibration Performance Measures

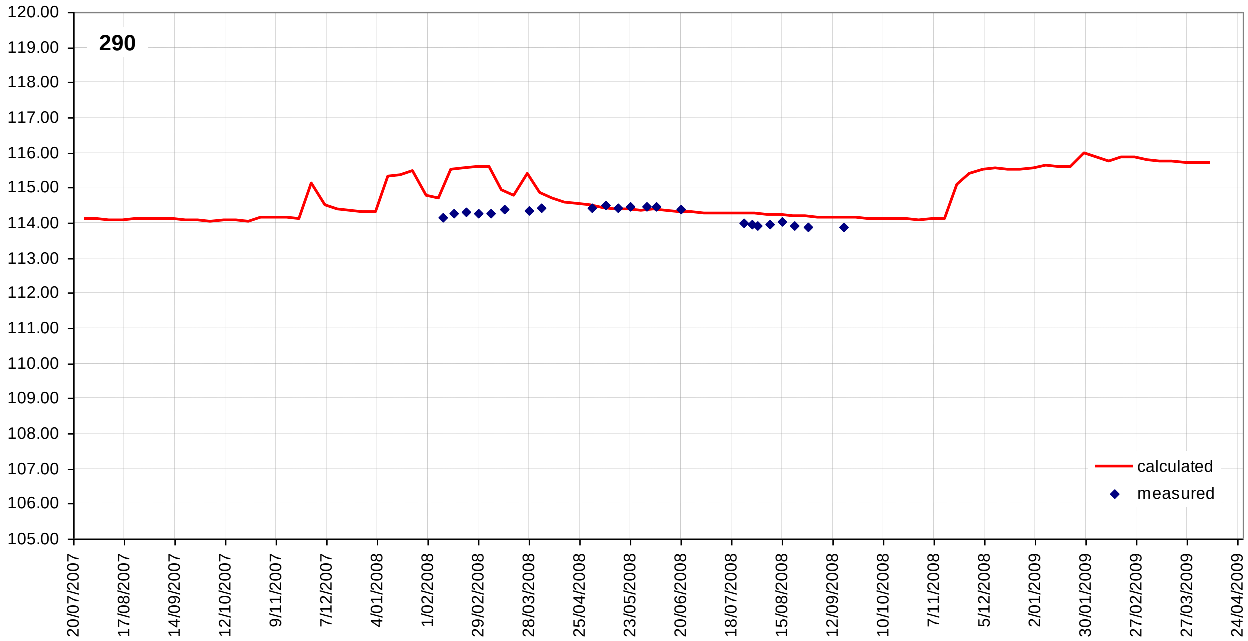
No	Description	Equation	Comment
1	Residual	$R_i = h_i - H_i$ [m] Ri = residual; Hi = measured head at point i; hi = modelled head at approximate location where H_i was measured.	Use the maximum as a criterion, or display a histogram of residuals; this should be normally distributed around zero.
2	Sum of Residuals (SR)	$\sum_{i=1}^{n} Wi\left\|hi - Hi\right\|$ [m] Wi = weighting (range 0 to 1)	Weighting can be (subjectively) applied at selected points to help account for confidence in the data quality. SR is not intuitive, as it varies with sample size.
3	Mean Sum of Residuals MSR = $\frac{SR}{n}$	$\frac{1}{n}\sum_{i=1}^{n} Wi\left\|hi - Hi\right\|$ [m]	Independent of sample size, but depends on the range in the measured values.
4	Scaled Mean Sum of Residuals (SMSR)	$\frac{100.MSR}{\Delta H} = \frac{100.SR}{n.\Delta H}$ [%] ΔH =range of measured heads across model domain.	SMSR is an intuitive relative measure which is independent of sample size and independent of the measurement range.
5	Sum of Squares (SSQ)	$\sum_{i=1}^{n}\left[Wi(hi - Hi)\right]^2$ [m^2]	The units [m^2] indicate that this is not an intuitive measure of performance. Depends on the sample size
6	Mean Sum of Squares MSSQ = $\frac{SSQ}{n}$	$\frac{1}{n}\sum_{i=1}^{n}\left[Wi(hi - Hi)\right]^2$ [m^2]	Not an intuitive measure of performance, but it is independent of the sample size
7	Root Mean Square RMS = $\sqrt{MSSQ} = \sqrt{\frac{SSQ}{n}}$	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[Wi(hi - Hi)\right]^2}$ [m]	An absolute measure that is problem-dependent (ie. its value is affected by the range in the measured values). It is usually thought to be the best error measure if errors are normally distributed.
8	Root Mean Fraction Square (RMFS)	100x $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[Wi\left(\frac{hi - Hi}{Hi}\right)\right]^2}$ [%] Weight Wi applies to fraction, not the residual.	This measure is affected by magnitude of Hi, which is determined by the datum. Model boundary conditions may constrain hi. An improved performance can be contrived by changing the datum to increase Hi.
9	Scaled RMFS (SRMFS)	SRMFS = RMFS $\frac{\overline{H}}{\Delta H}$ [%]	$\overline{H}$ = mean of measured head values, which have a range of ΔH.
10	Scaled RMS (SRMS)	SRMS = $\frac{100.RMS}{\Delta H}$ [%]	SRMS and SRMFS should both be both low (say less than 5% or some other agreed value), indicating that the ratio of error to total head differential is small, and hence errors are only a small part of the overall model response.
11	Coefficient of Determination (CD)	$\frac{\sum_{i=1}^{n}\left[Wi(Hi - \overline{H})\right]^2}{\sum_{i=1}^{n}\left[Wi(hi - \overline{H})\right]^2}$ [-]	CD tends to one for perfect calibrations.

Appendix O. Transient calibration – comparison of measuerd and calculated heads

source files:

/model/output/observation/heads_tr_calculated.smp

/model/output/observation/heads_tr_observed.smp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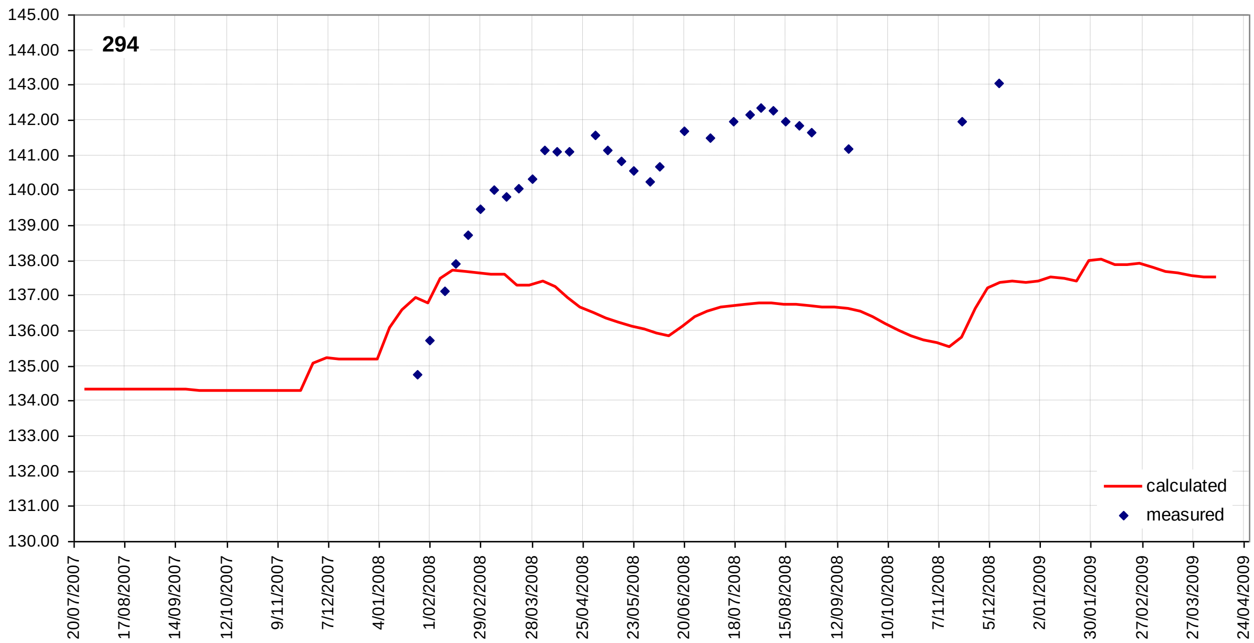
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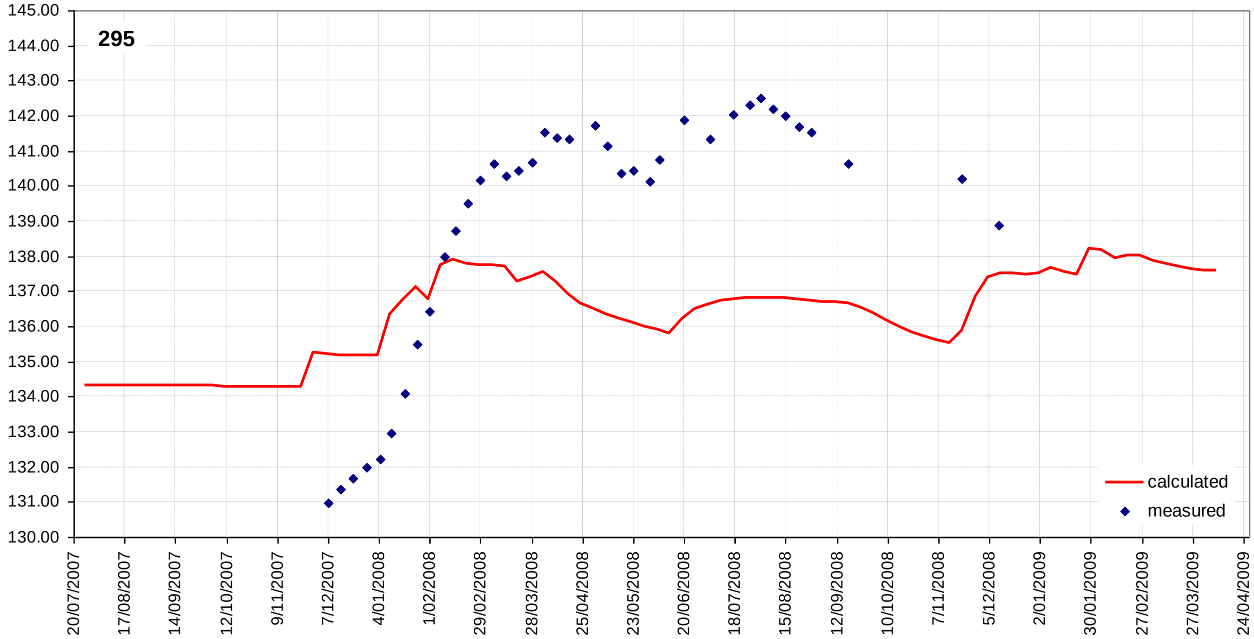
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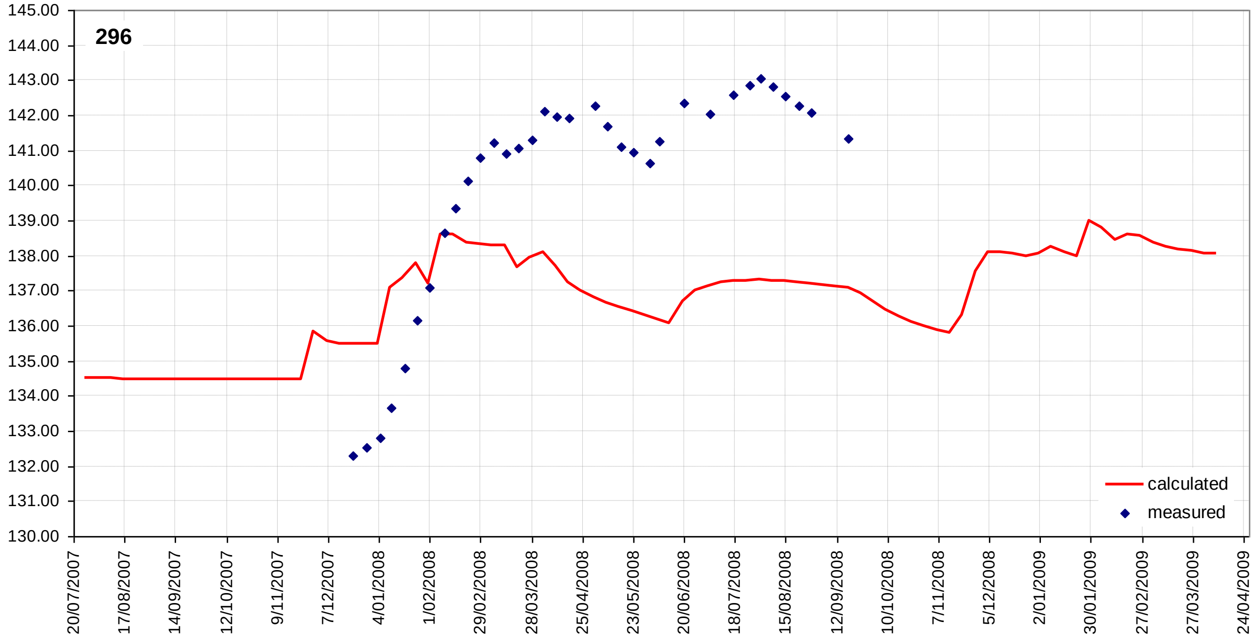
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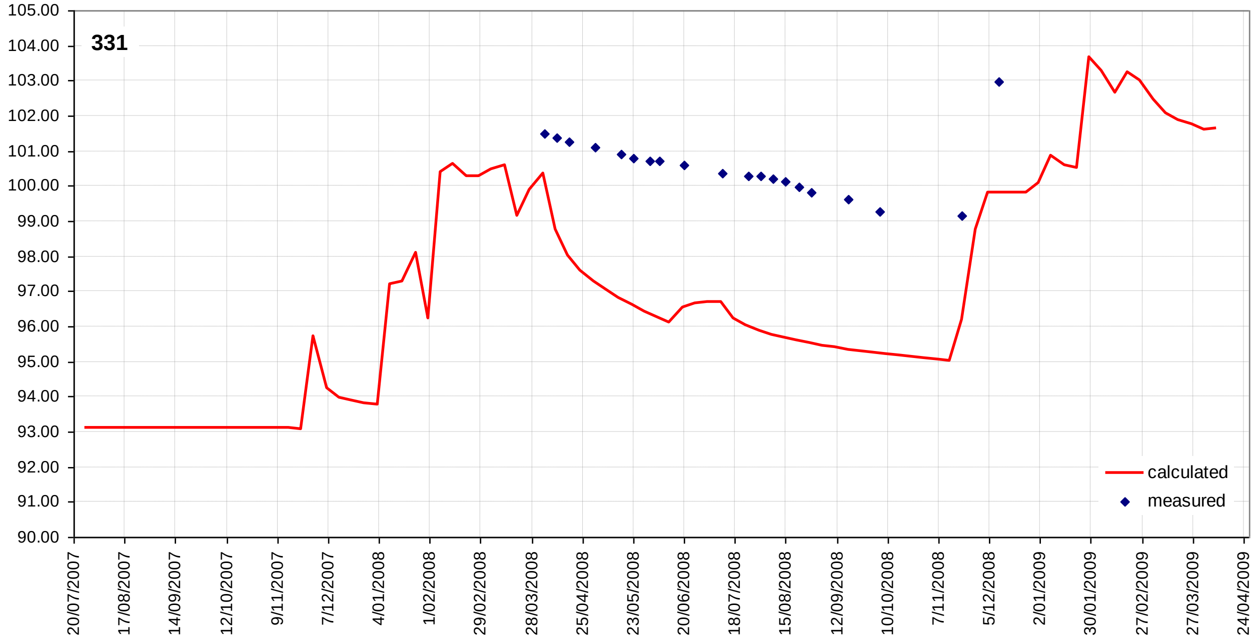

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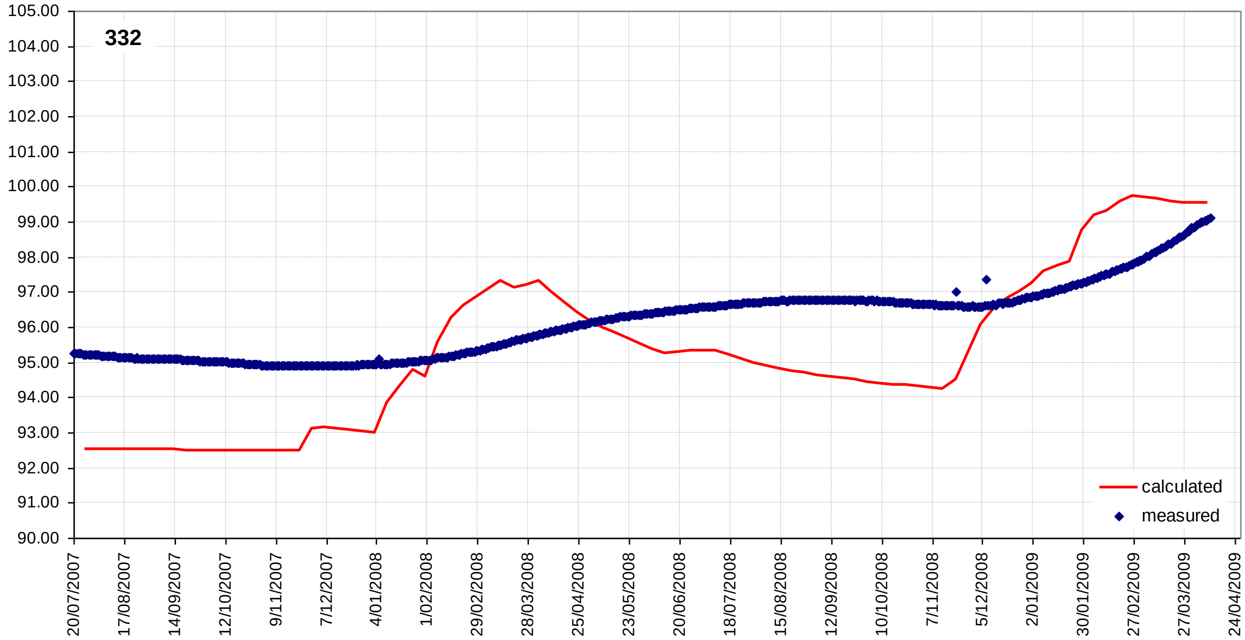

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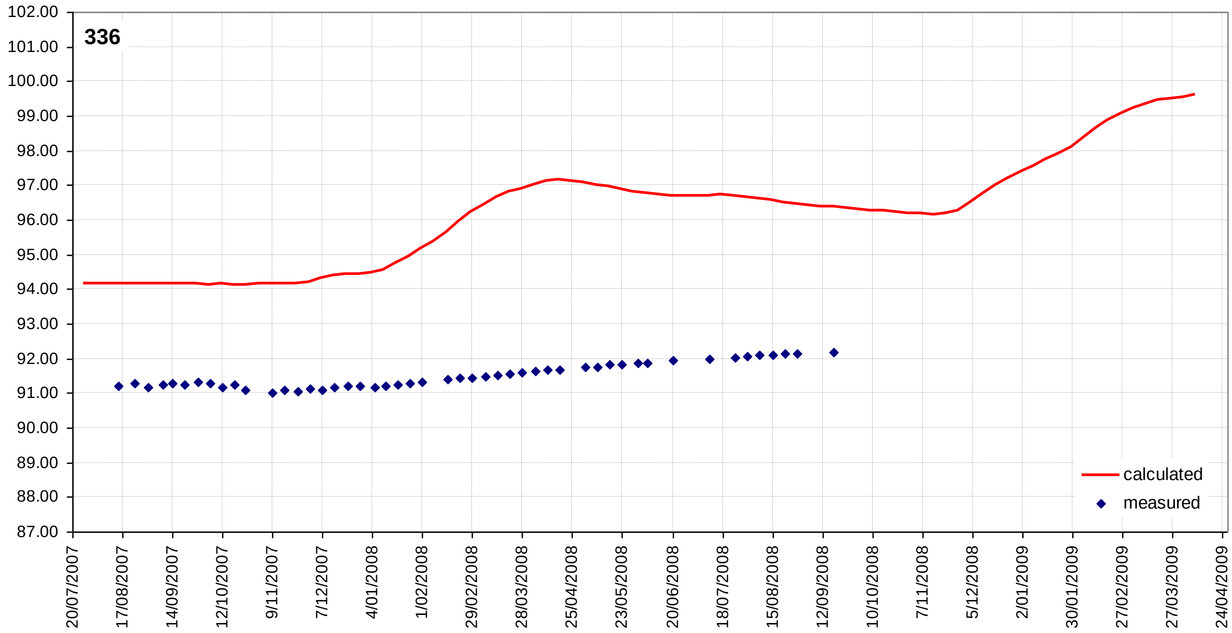
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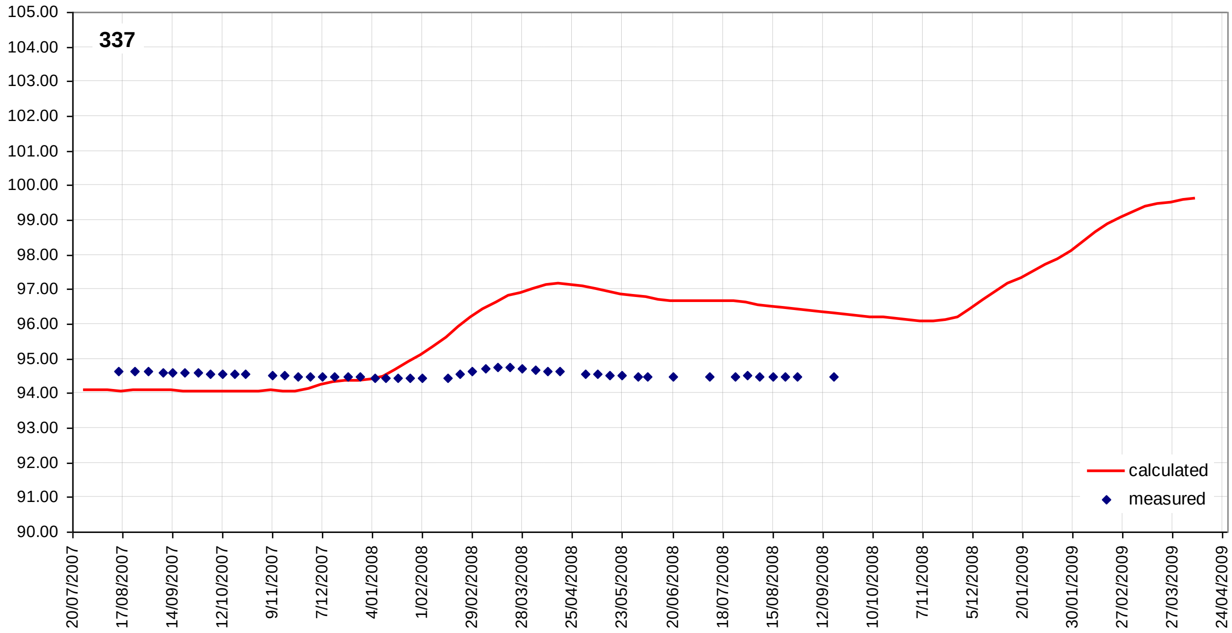
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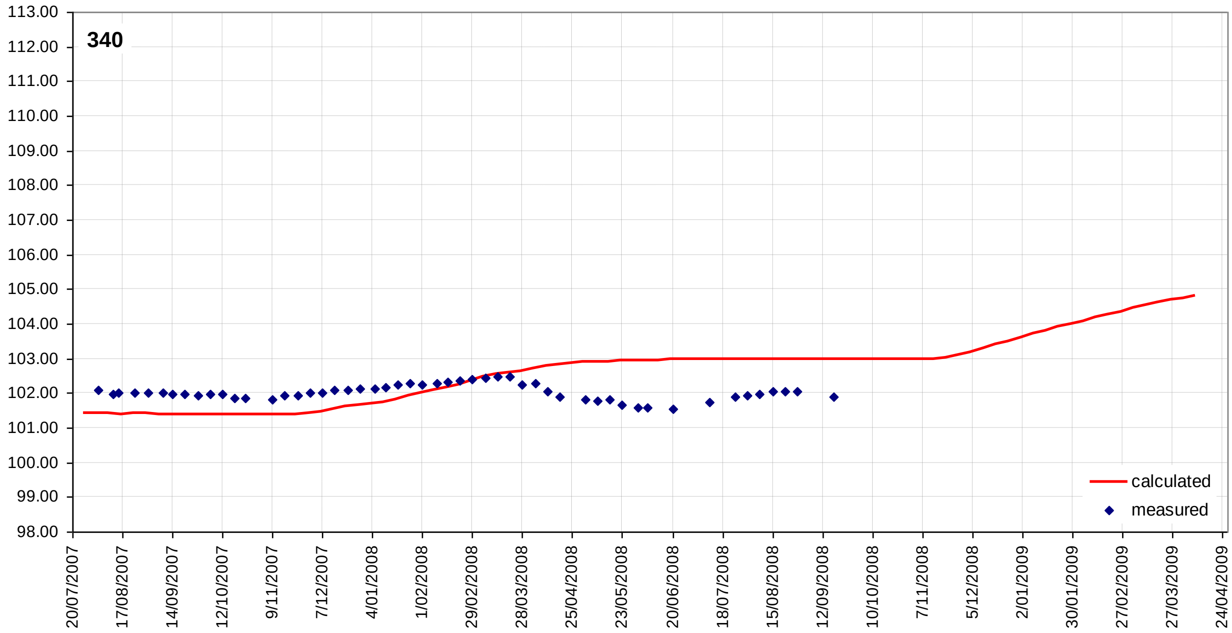
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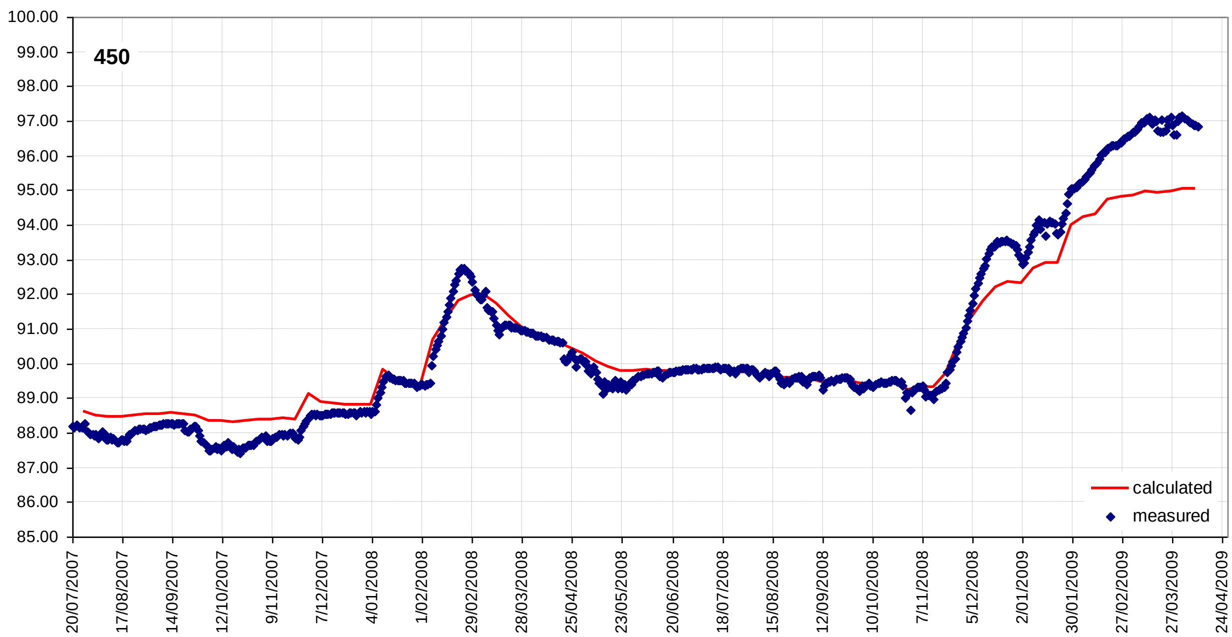
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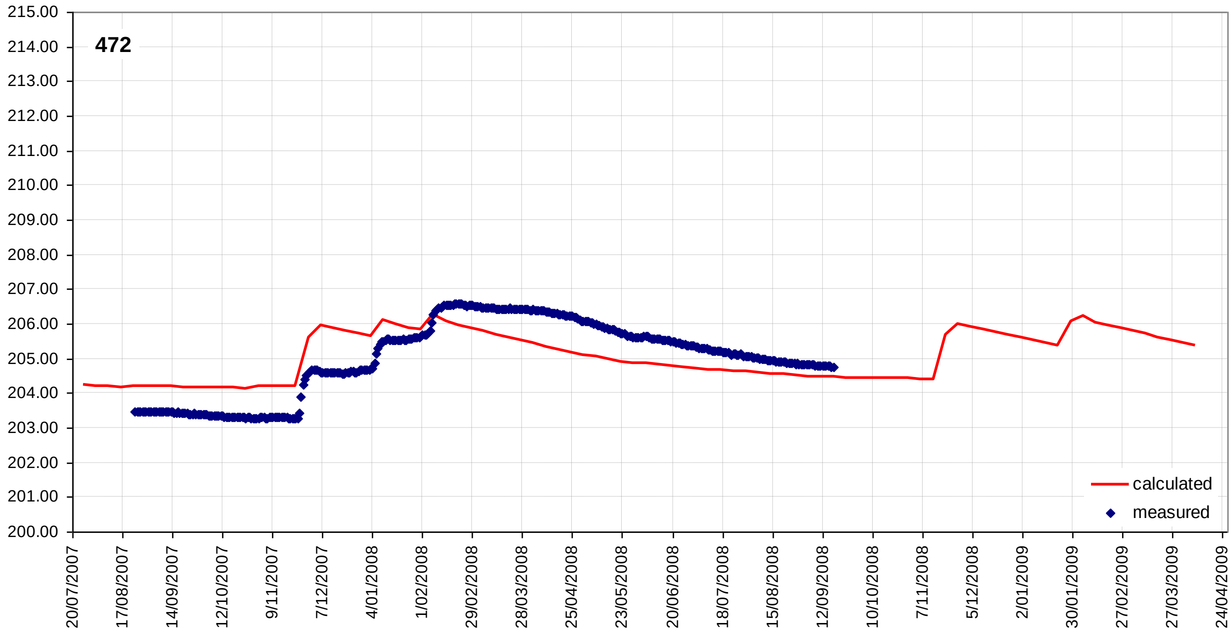
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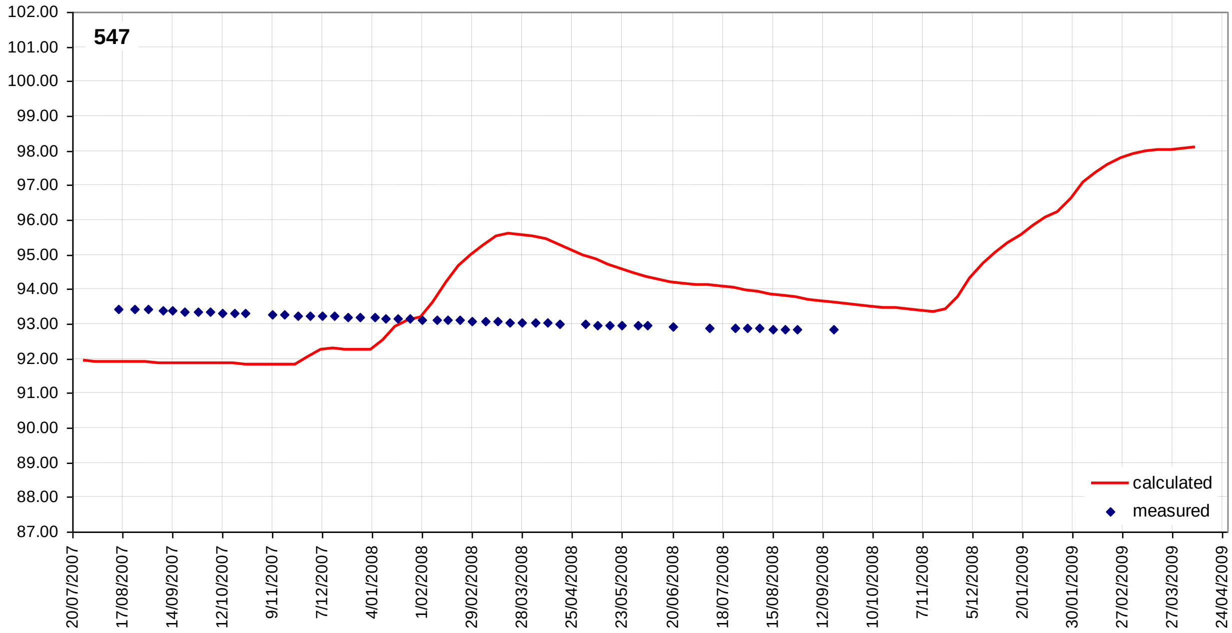
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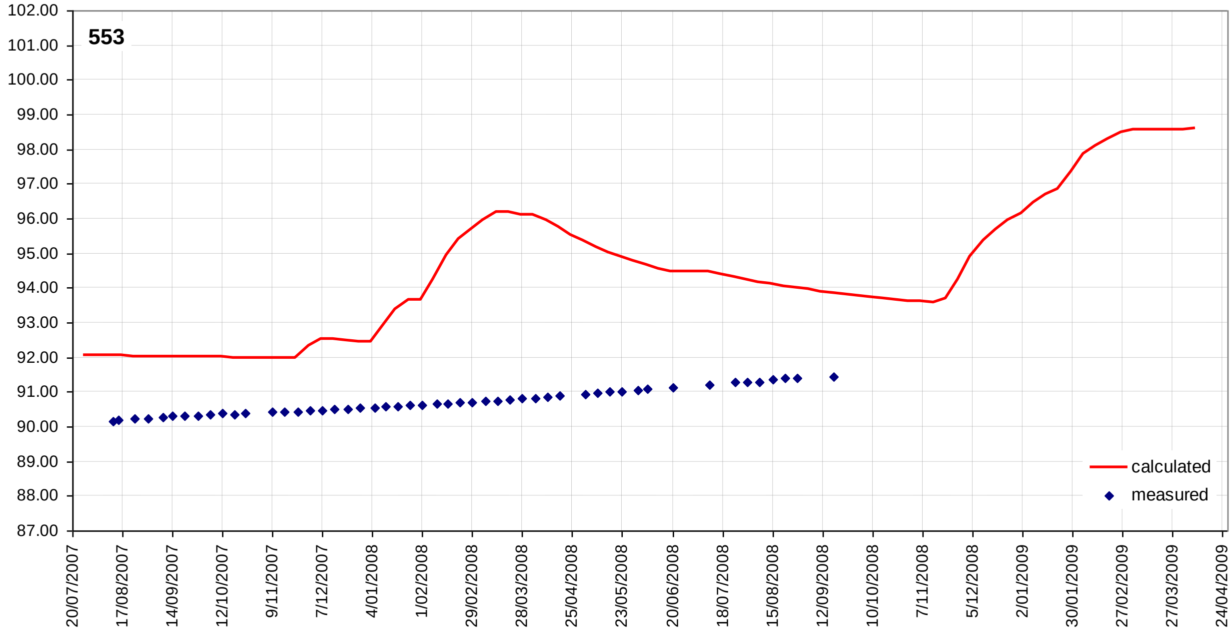
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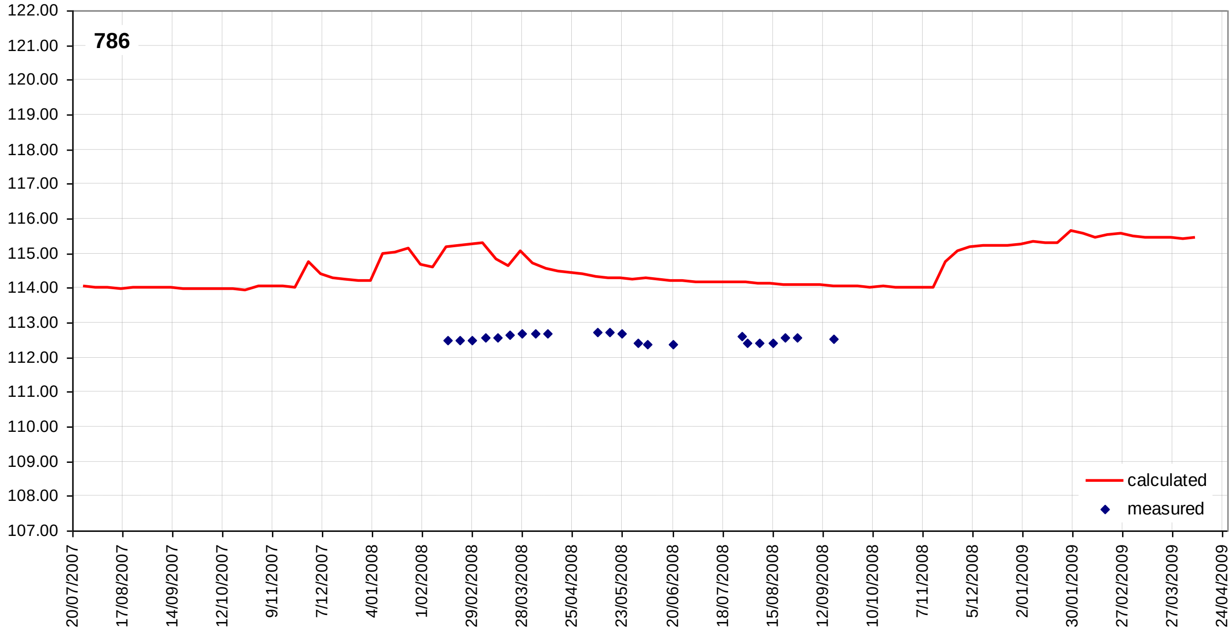
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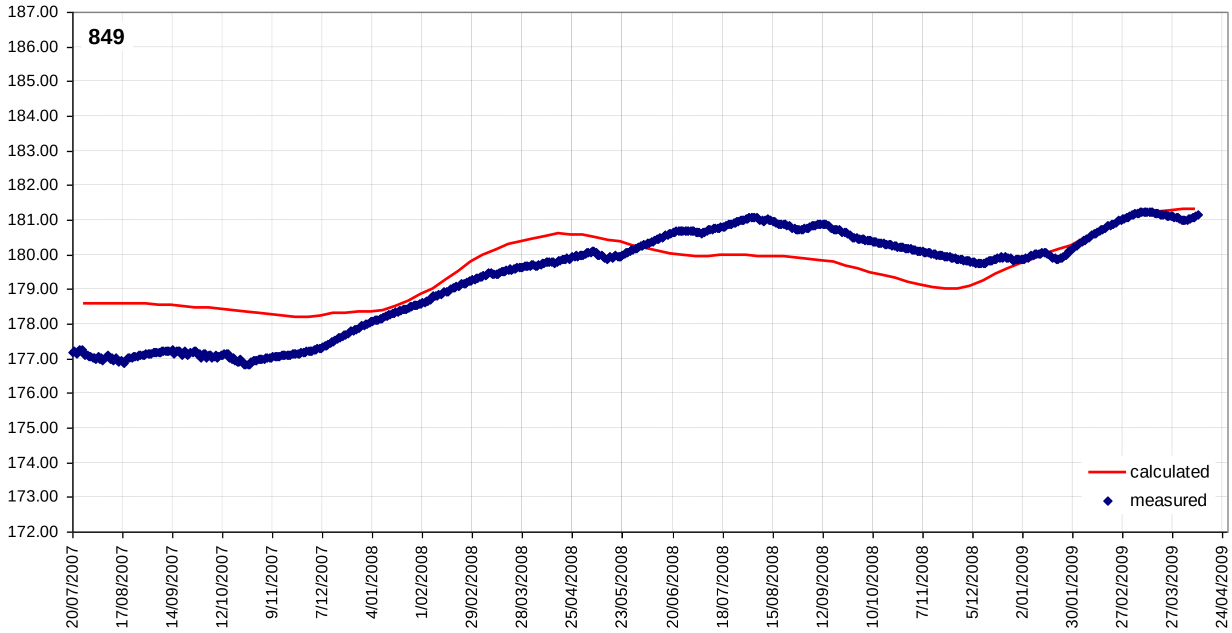
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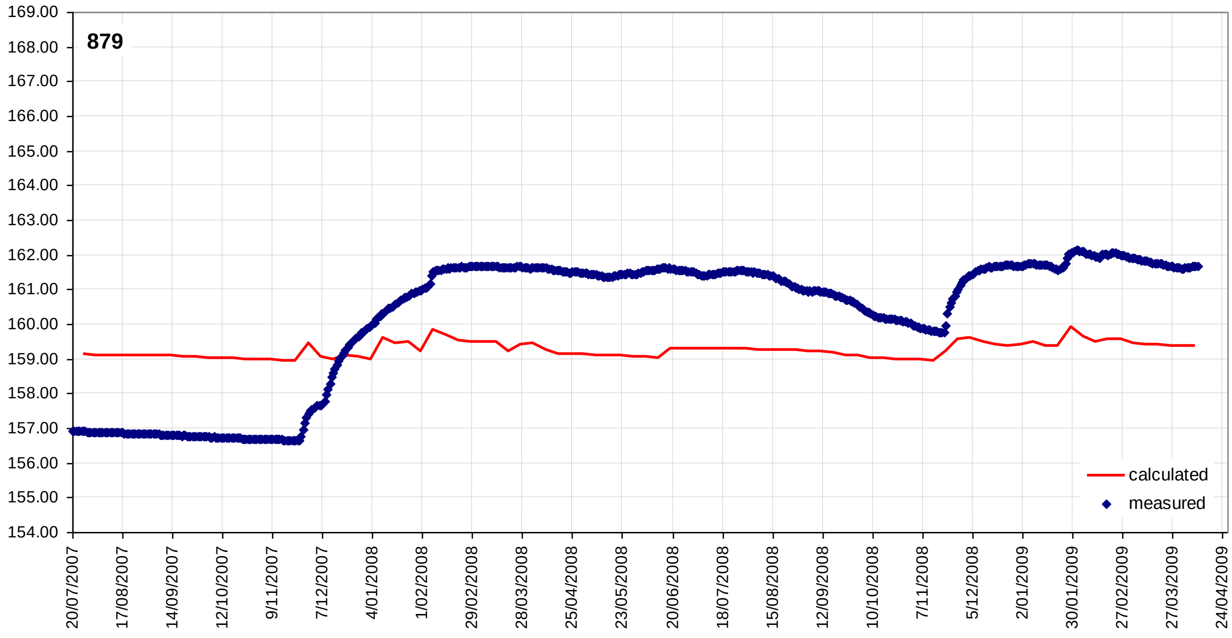
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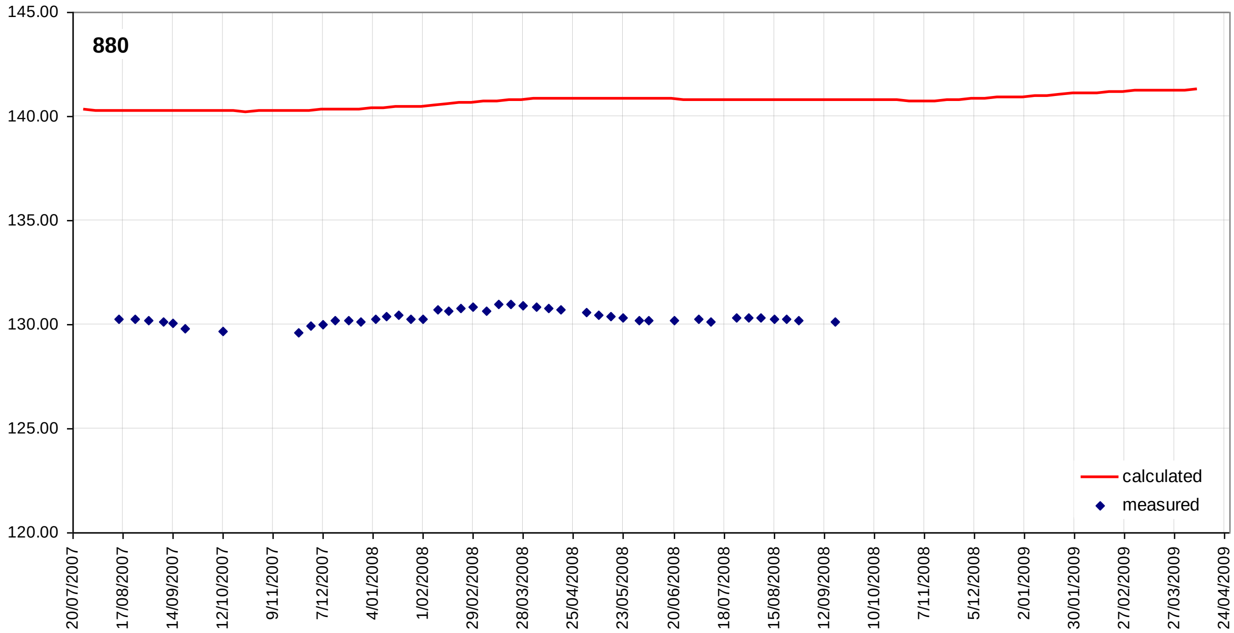
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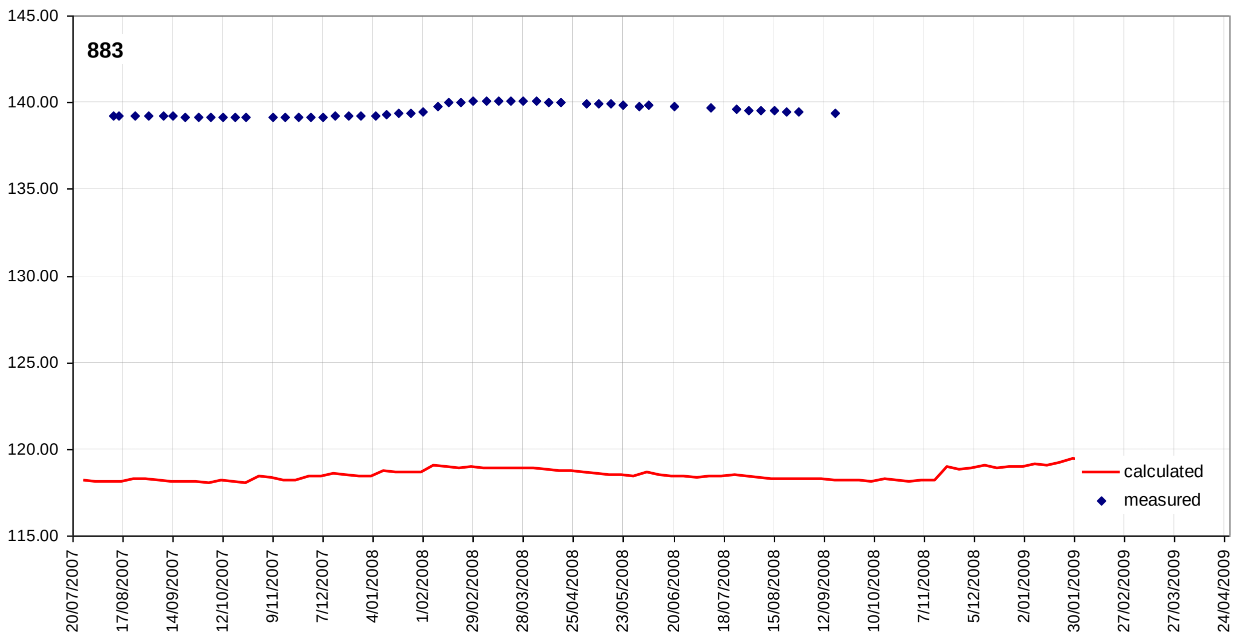
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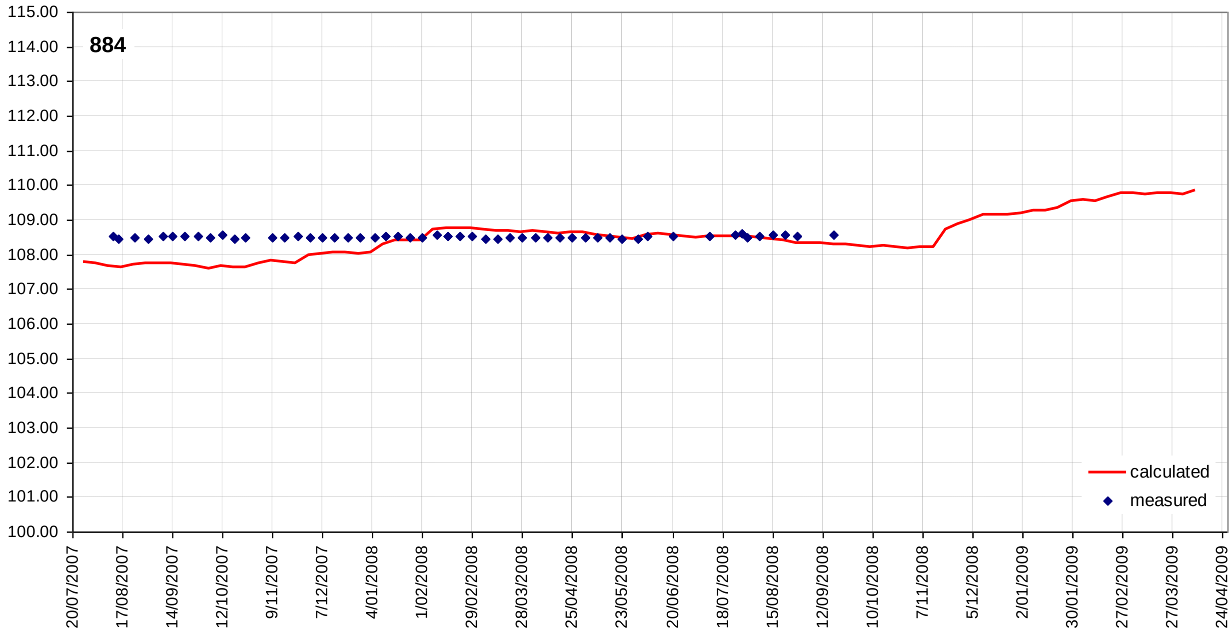
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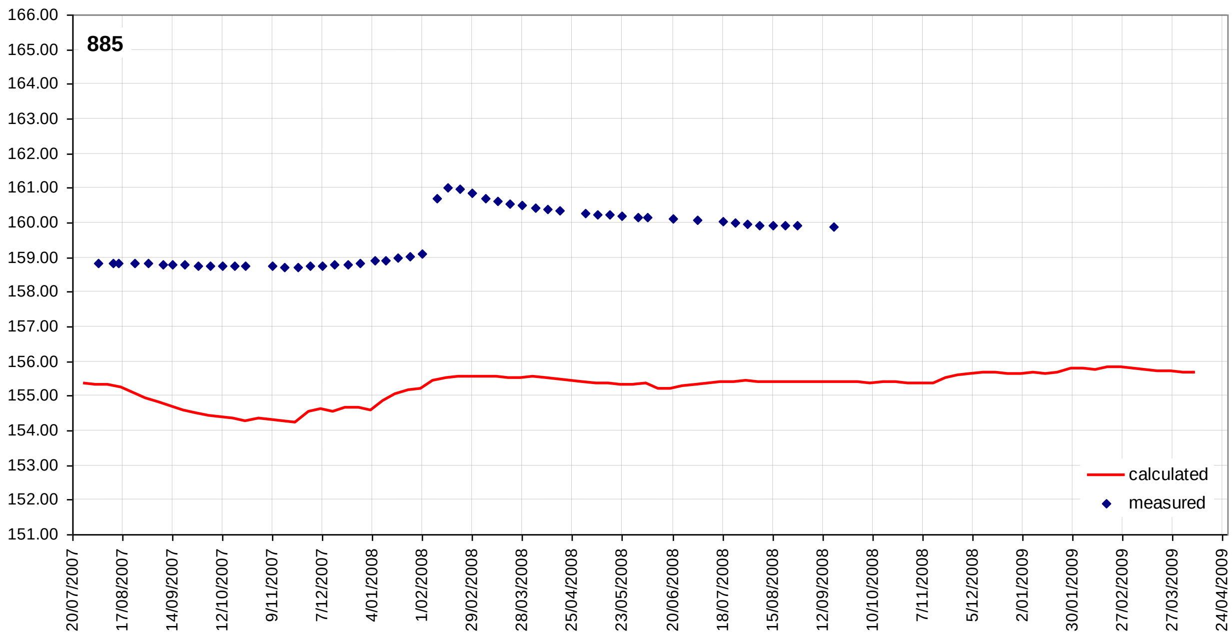
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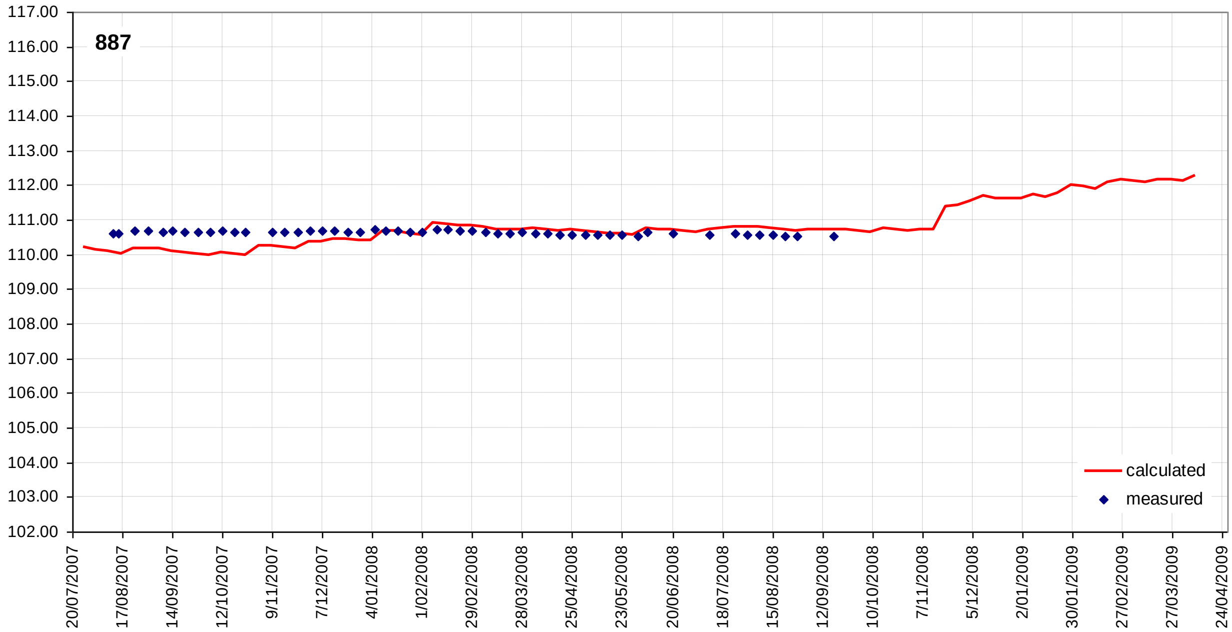
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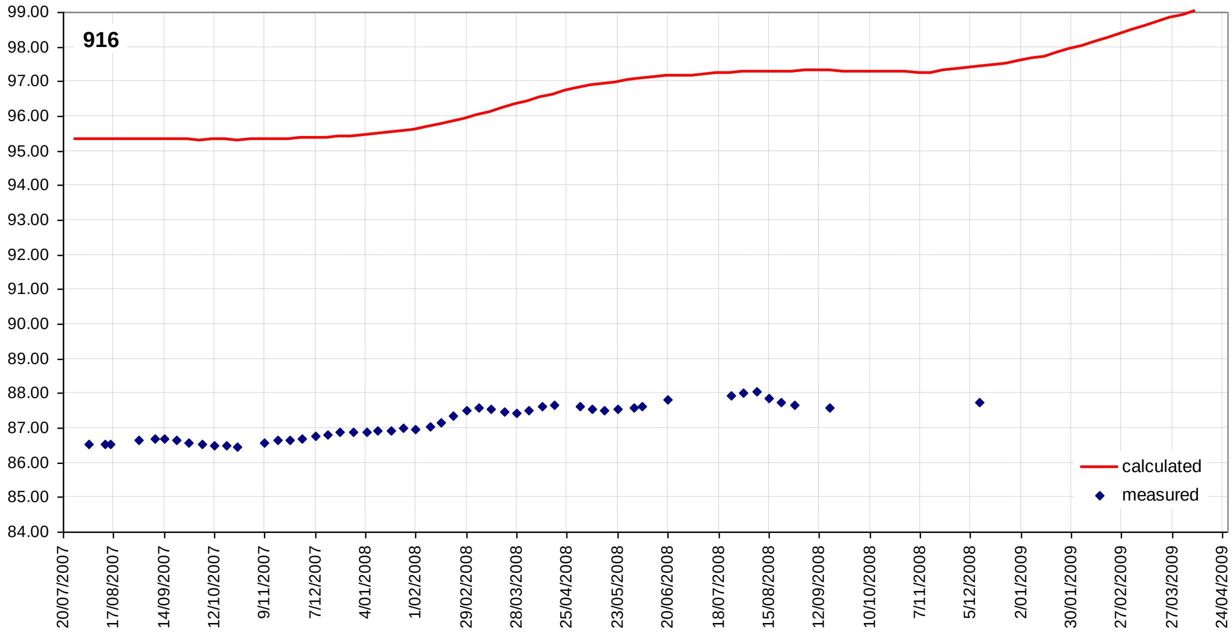
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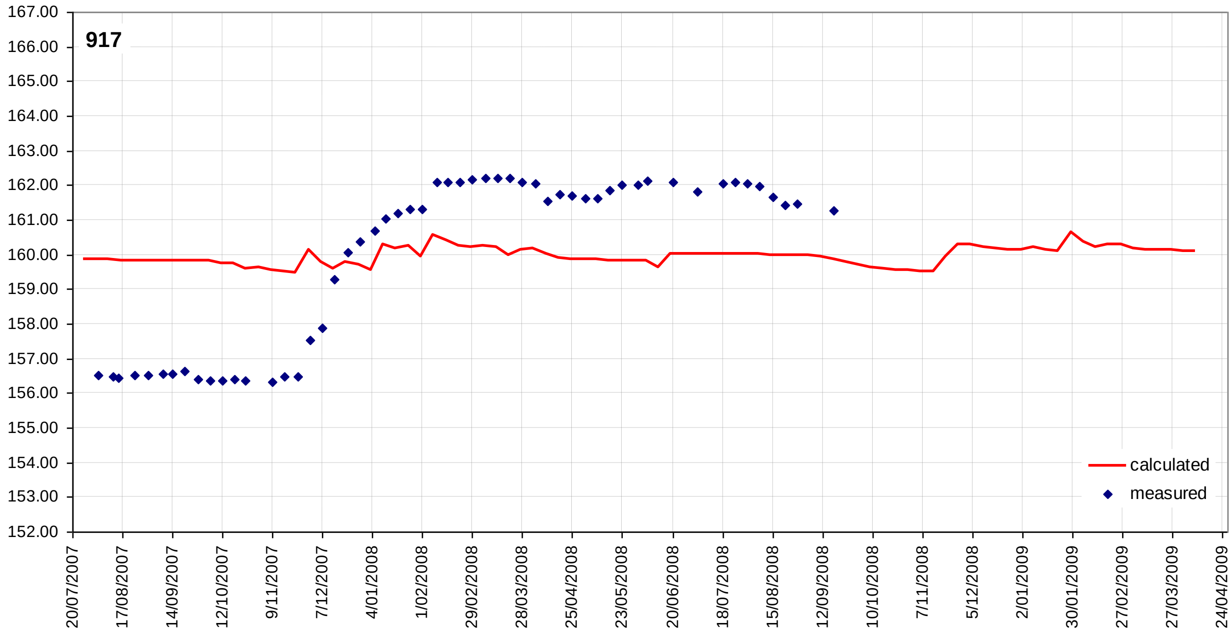
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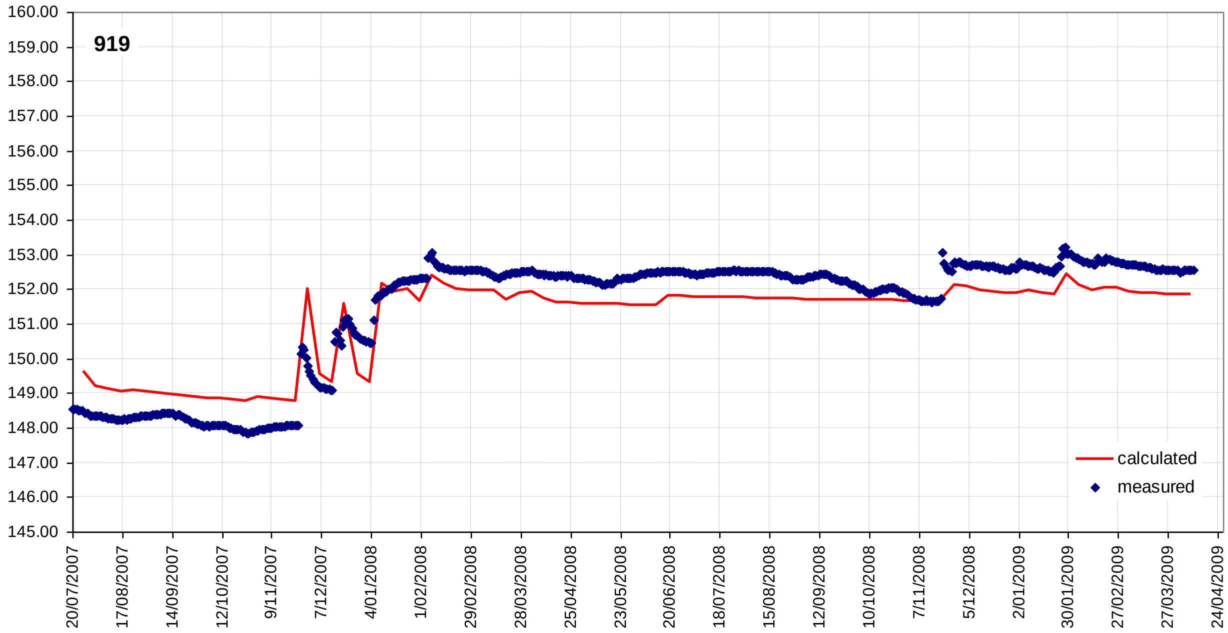
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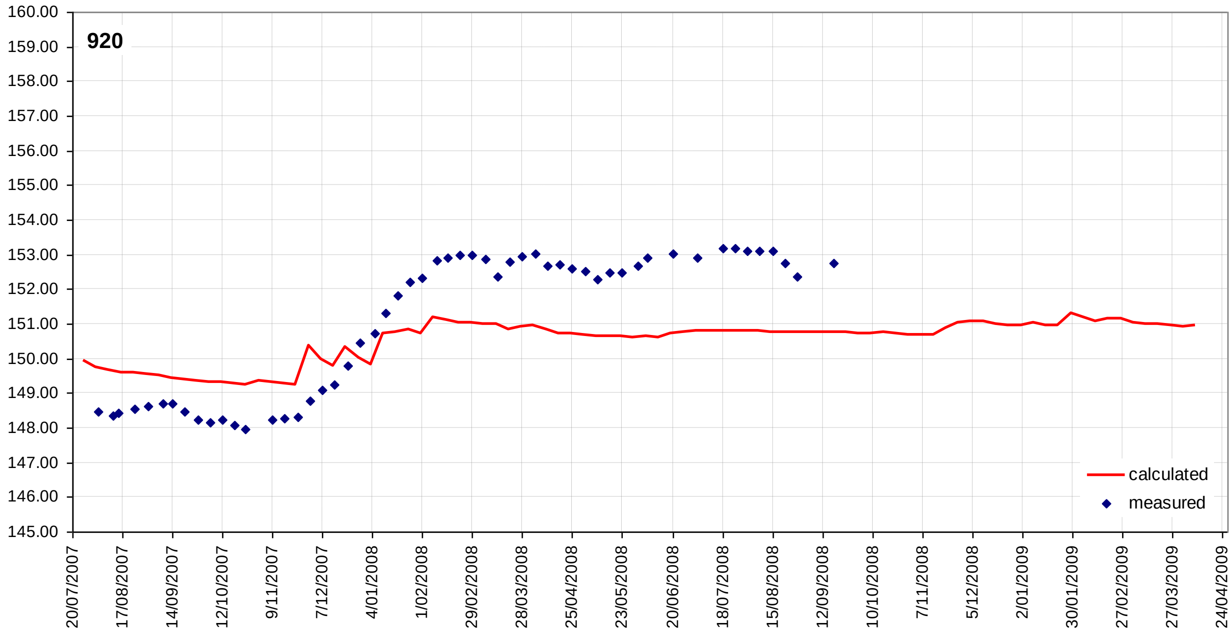

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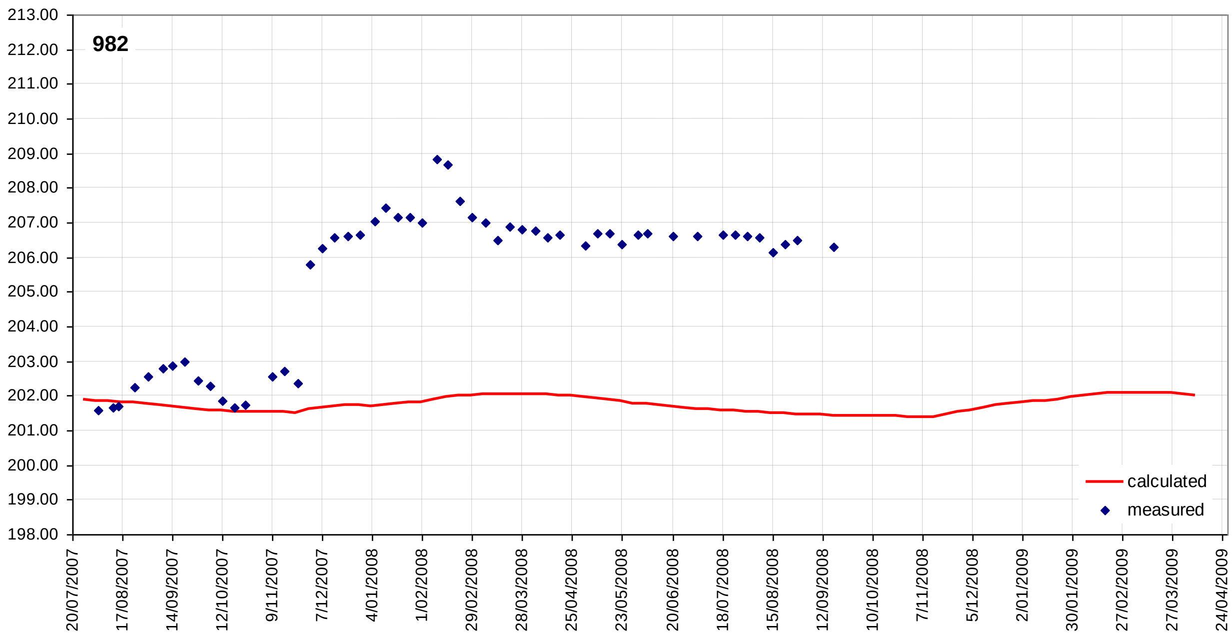

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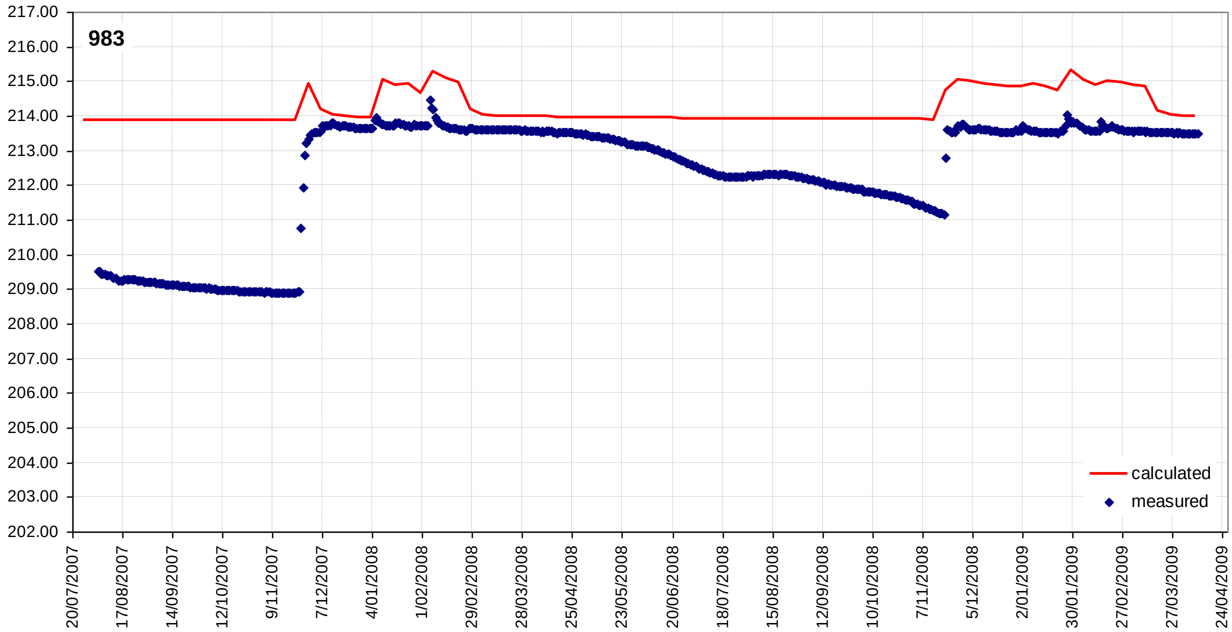
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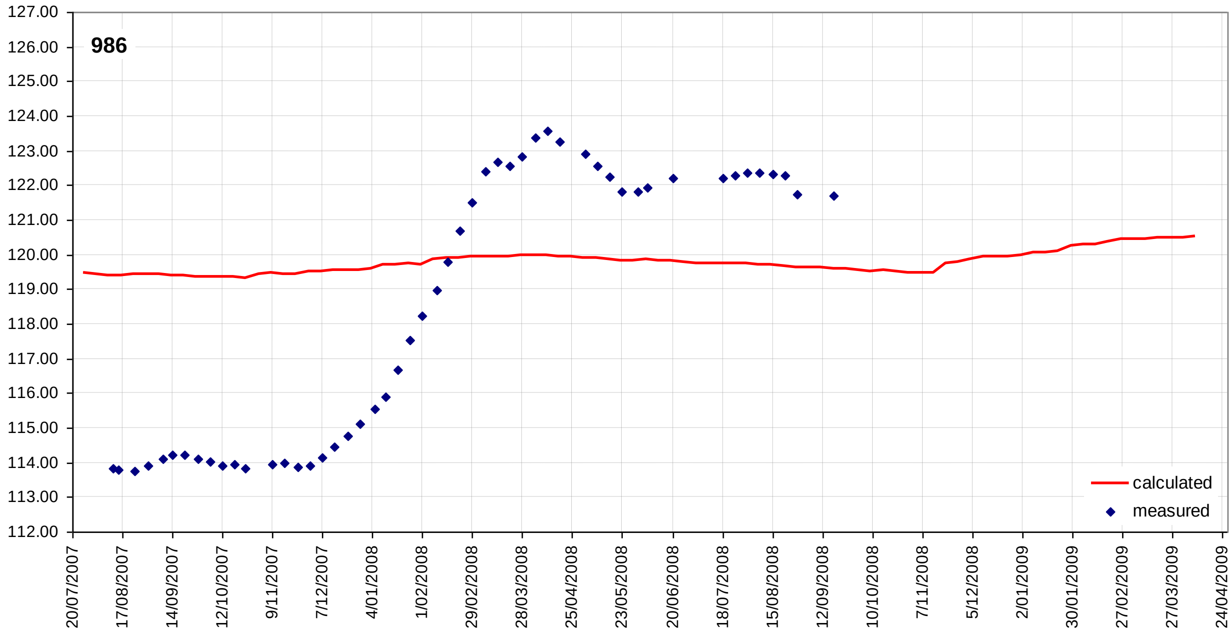
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Appendix P. Bore logs

All bore logs were generated from data provided by Queensland Department of Natural Resources and Water (DERM, 2009). For the purpose of this study, total of 214 bore logs were generated. Only logs of monitored bores are attached in physical form, the rest of the logs are attached in digital form.

See the digital appendices for original data:

/data/borelogs/borelogs.sdg
/data/borelogs/export/borelogs_all_export.rar

Location precision:

- SURV – **survey** - the location of the facility has been determined by a proper survey.
- SKET – **sketch** - the property owner or driller or other person has provided a sketch or plan of the property with the bore location indicated on it.
- PHOT – **aerial photo** - the bore has been located by using aerial photographs.
- INSP – **government inspection** - the bore has been inspected by a Government Officer, and approximately located using methods such as car mileage etc.
- UNKN – **unknown** - it is unknown how the bore's position has been determined.
- GPS – **global positioning system** - the bores location has been determined by a global positioning system (GPS).

Elevation precision:

- SVY – **surveyed**
- BAR – **aneroid barometer**
- EST – **estimate** using contours
- GPS – **global positioning system**
- DEM – elevation obtained from 25m Digital Elevation Model of southeast Queensland (can be off by up to 20 meters)

Aquifer description:

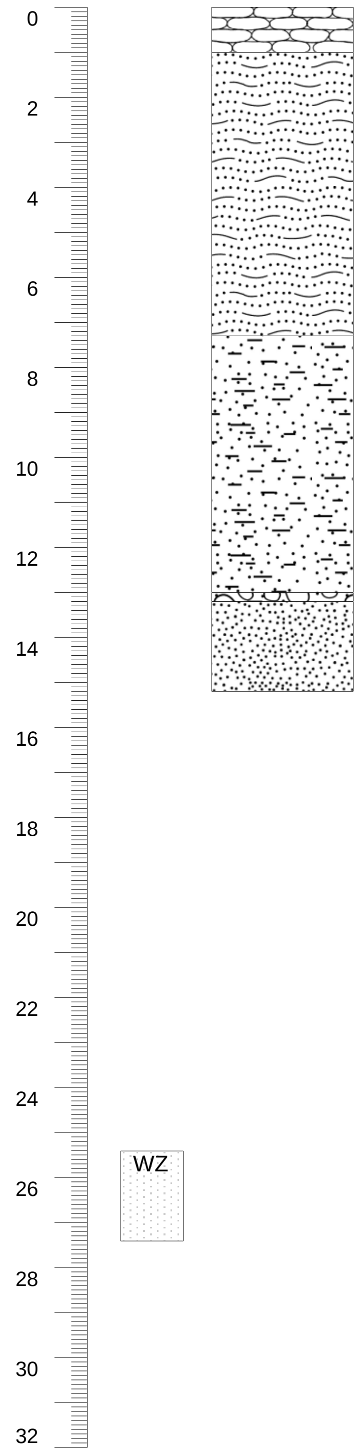
- Porous Rocks
    - **UC** - unconsolidated
    - **PS** - consolidated
    - **SC** - semi-consolidated
- Fractured Rocks
    - **FR** - fractured
    - **VS** - vesicular
    - **CV** - cavernous
    - **WZ** - weathered zone

RN:	14320290		pos. accuracy:	GPS
easting:	436796		elev. accuracy:	SVY
northing:	6934637			
elevation:	134.26	m a.s.l.	**monitored**	

depth | aquifer | lithology | description

RN:	14320292	pos. accuracy:	GPS
easting:	436719	elev. accuracy:	SVY
northing:	6934649		
elevation:	133.91 m a.s.l.	**monitored**	

depth aquifer lithology description



topsoil

loam sandy

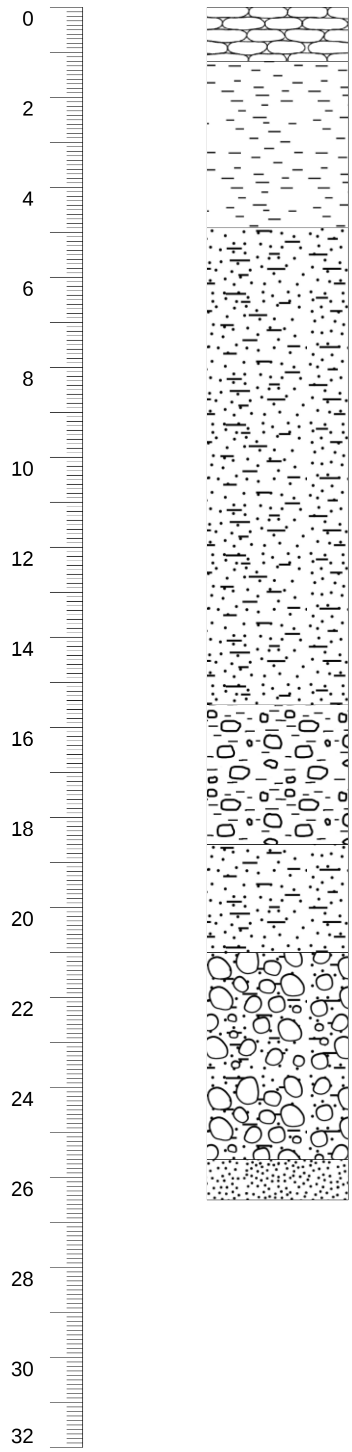
clay sandy

hard band

sandstone

RN:	14320294	pos. accuracy:	GPS
easting:	437822	elev. accuracy:	SVY
northing:	6930032		
elevation:	147.95 m a.s.l.	**monitored**	

depth aquifer lithology description



topsoil

clay

clay sandy

clay & gravel

claybound gravel

clay sandy

gravel & clay sandy

claybound gravel sandy

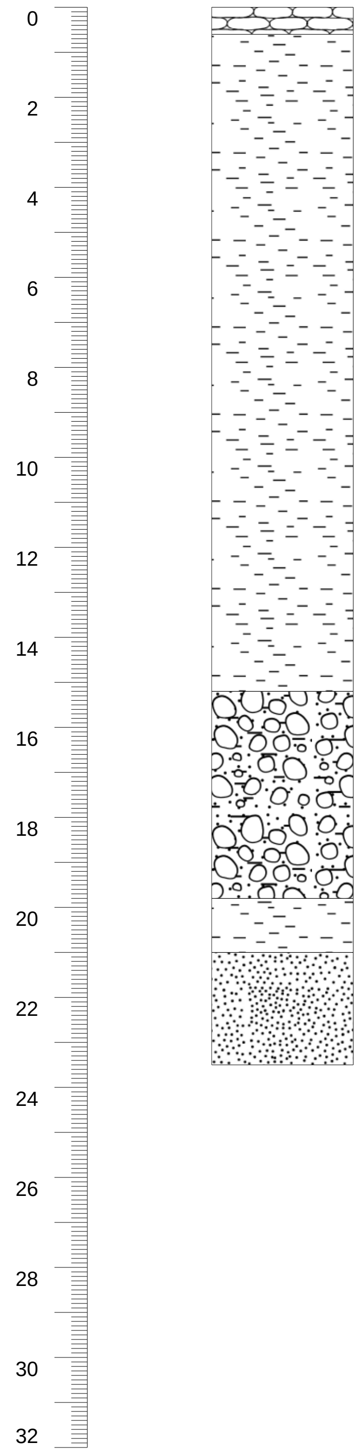
white sandstone

RN: 14320295
easting: 437965
northing: 6930000
elevation: 148.39 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY

monitored

depth	aquifer	lithology	description



topsoil

clay

clay silty

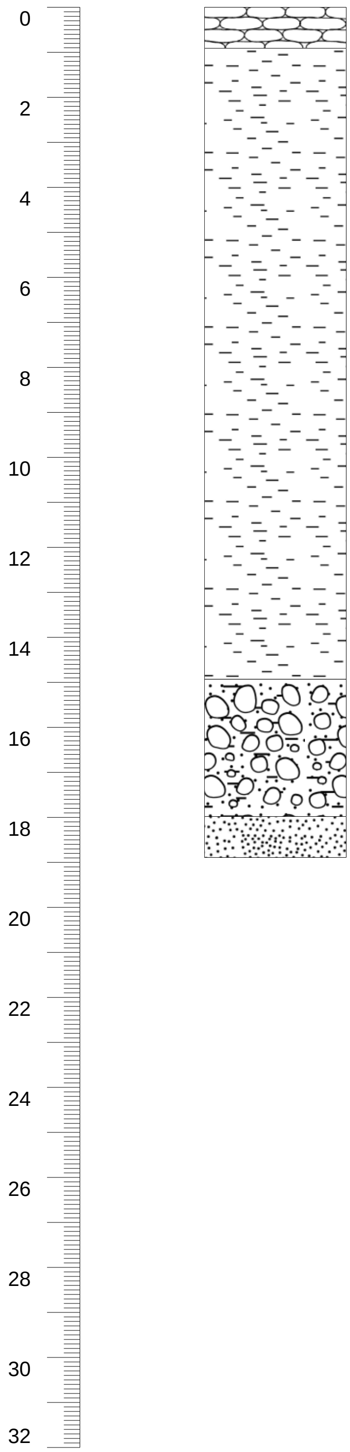
sand gravel & clay

clay

sandstone

RN:	14320297	pos. accuracy:	GPS
easting:	438045	elev. accuracy:	SVY
northing:	6929962		
elevation:	149.43 m a.s.l.	**monitored**	

depth | aquifer | lithology | description



topsoil

silty clay

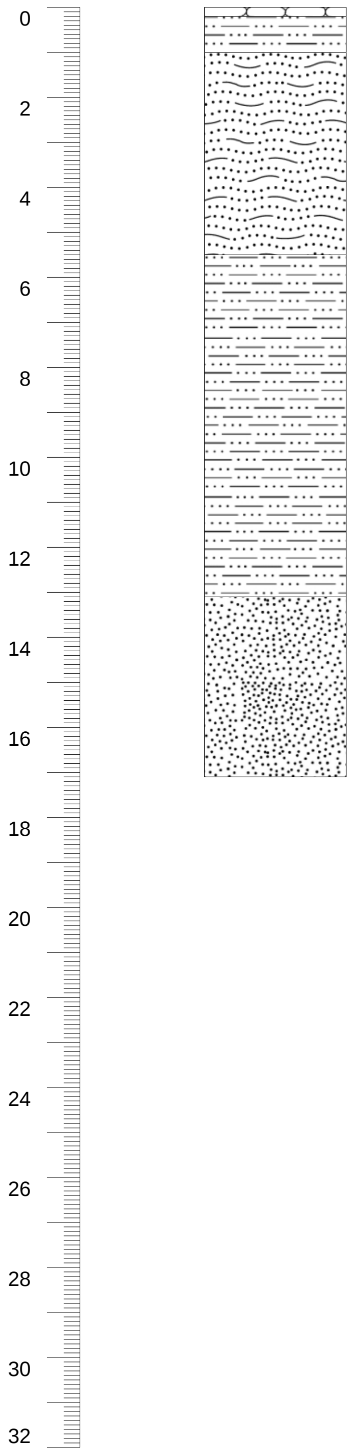
clay & wood

sand gravel & clay

sandstone

RN:	14320329	pos. accuracy:	GPS
easting:	438074	elev. accuracy:	SVY
northing:	6940312		
elevation:	114 m a.s.l.	**monitored**	

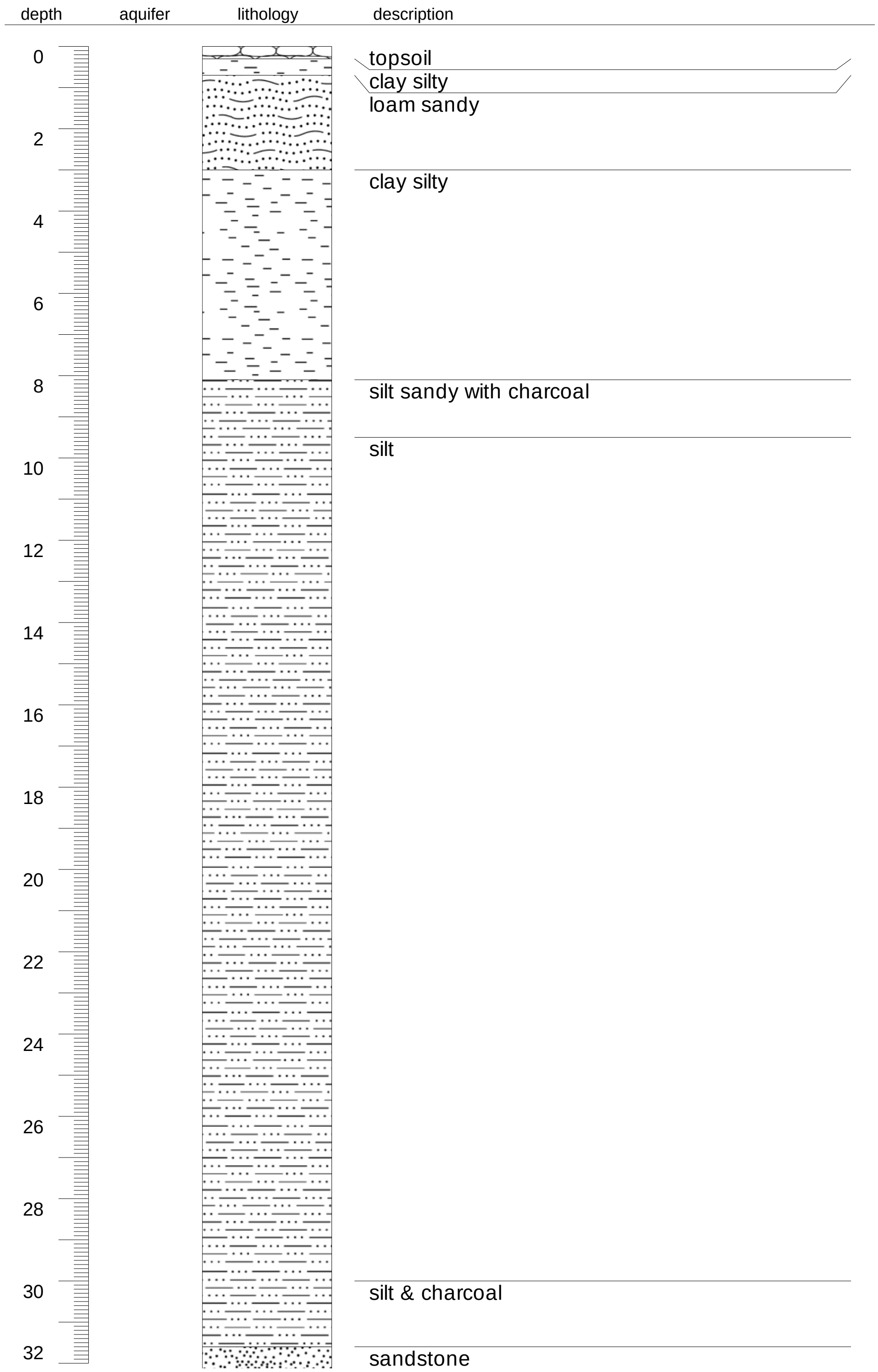
depth aquifer lithology description



topsoil
loam silty
loam sandy
loam silty
silt & cemented sand bands
sandstone

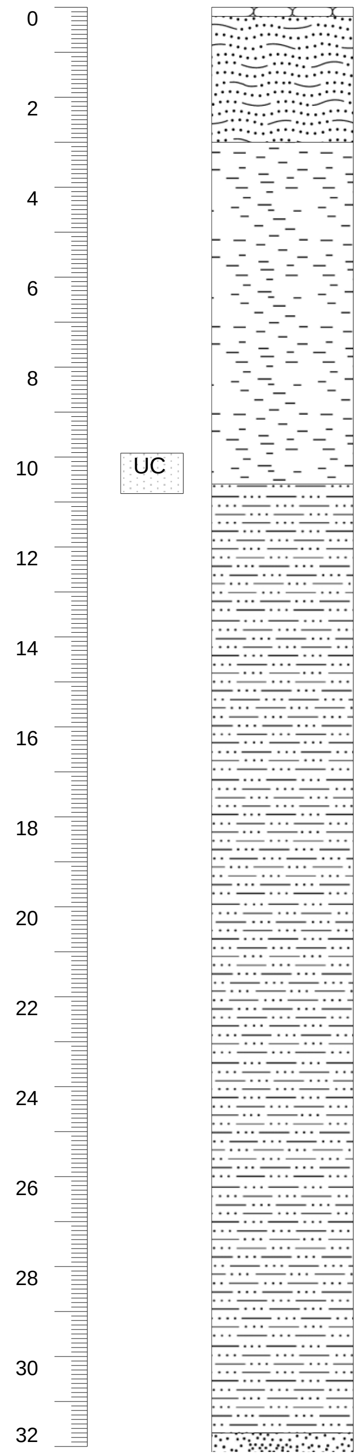
RN: 14320330
easting: 438221
northing: 6940242
elevation: 114.5 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY
max. depth 33.50 m
monitored



RN:	14320331		pos. accuracy:	UNKN
easting:	438247		elev. accuracy:	SVY
northing:	6940220		max. depth 33.50 m	
elevation:	114.6	m a.s.l.	**monitored**	

depth | aquifer | lithology | description



topsoil

loam sandy

clay silty with charcoal

clay silty

silt

silt & charcoal

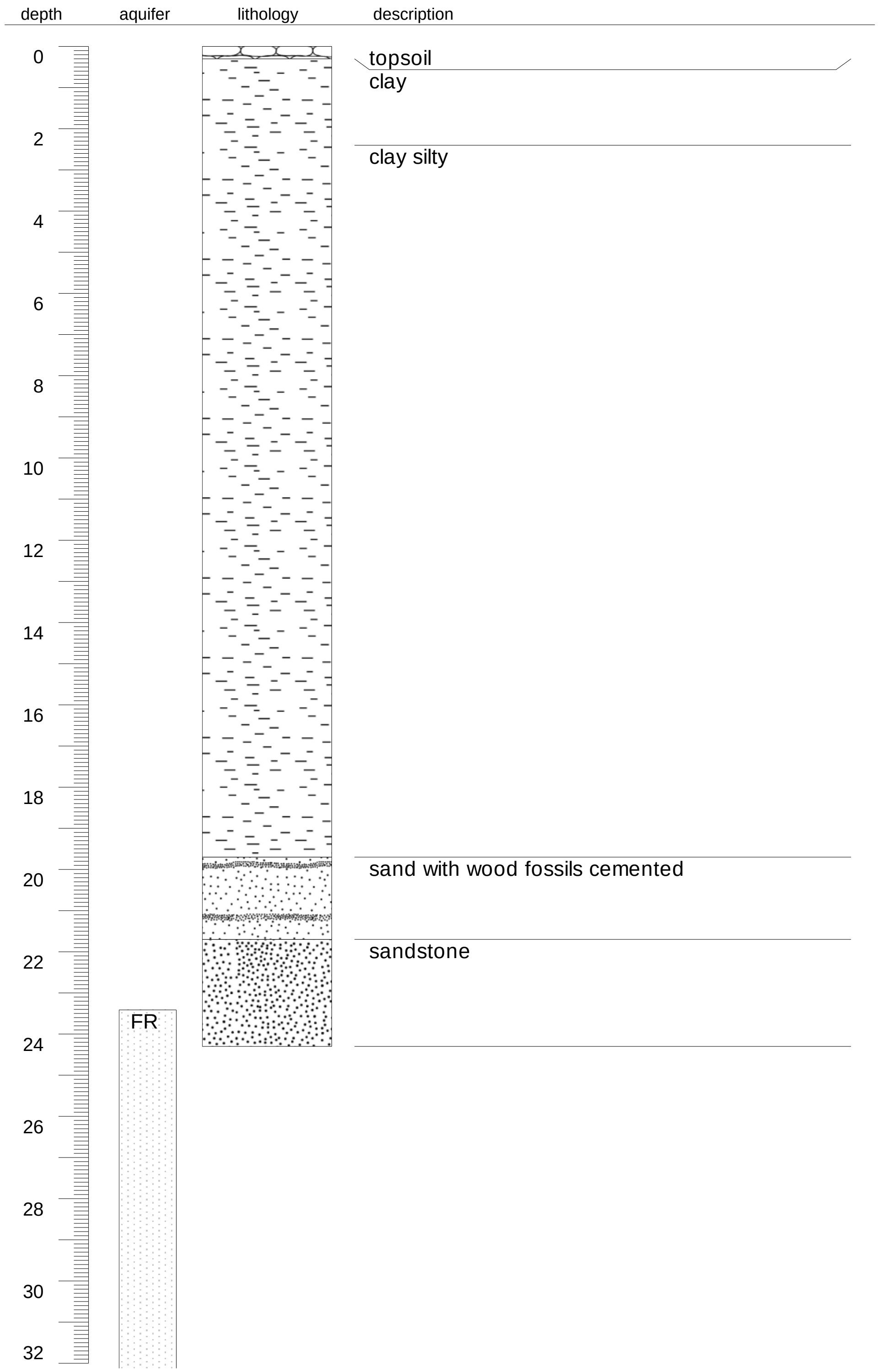
sandstone

RN: 14320332 | pos. accuracy: GPS

easting: 438508 | elev. accuracy: SVY

northing: 6940103

elevation: 112.2 m a.s.l. | **monitored**

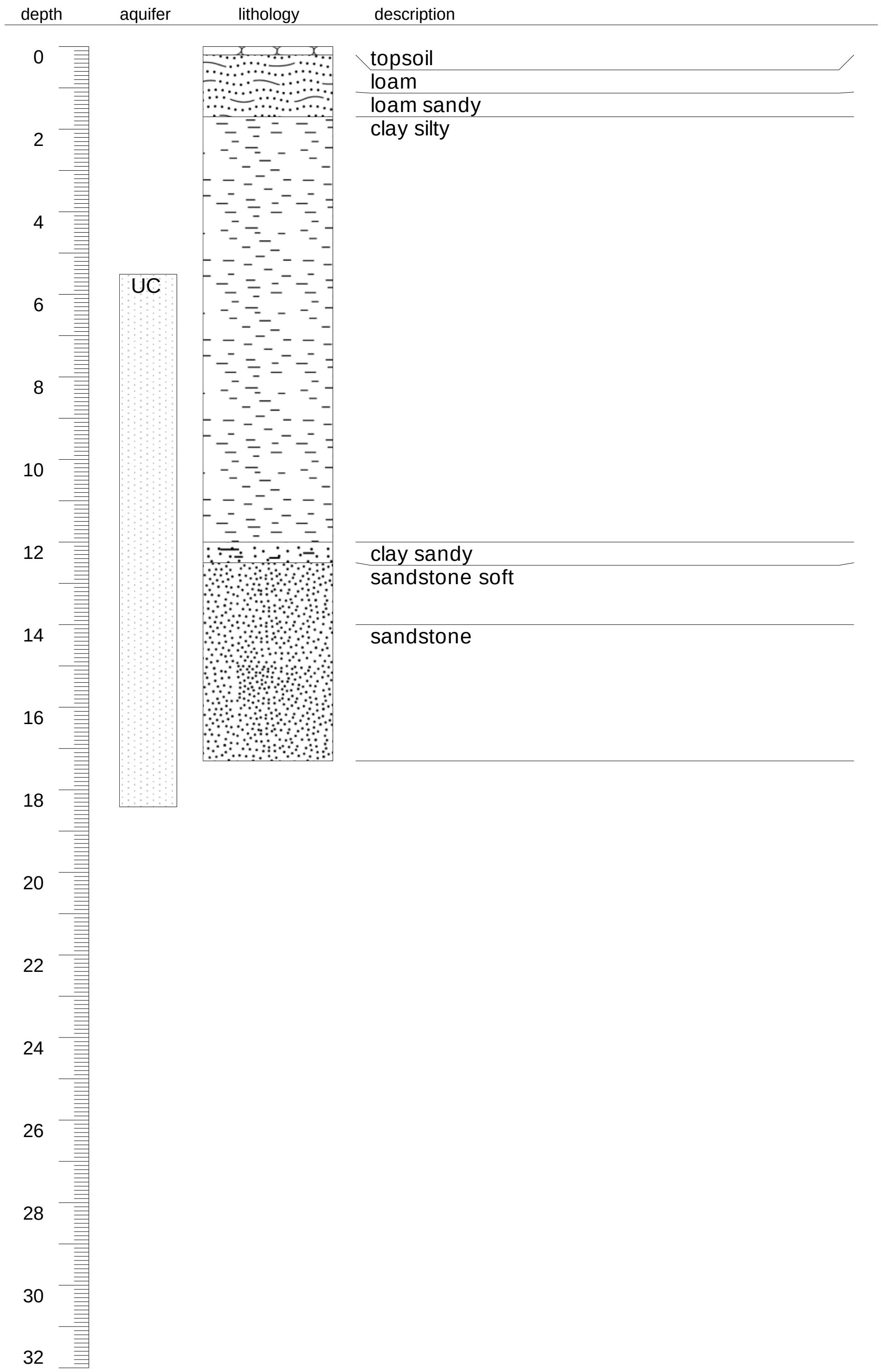


RN: 14320333 | pos. accuracy: GPS

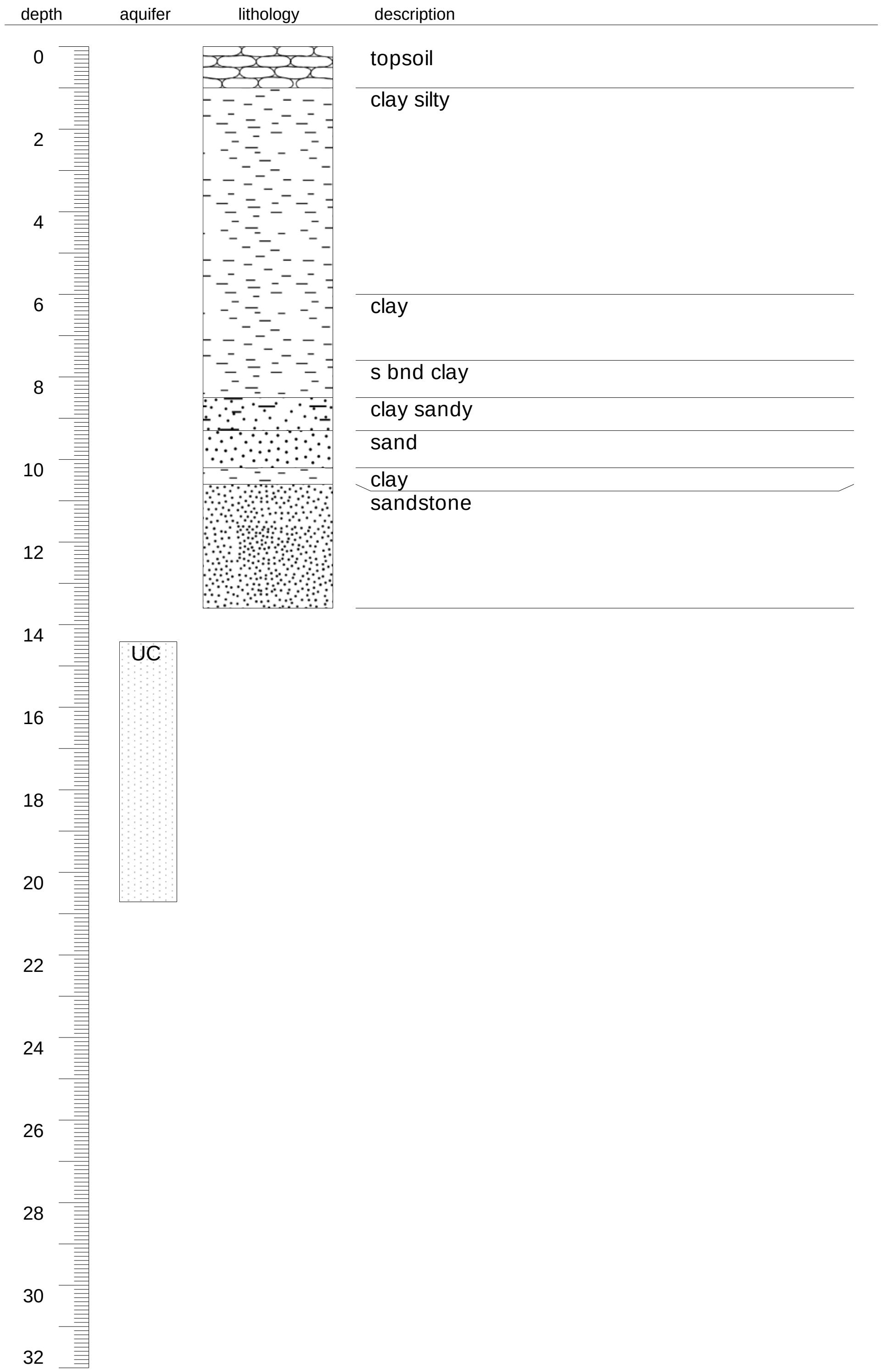
easting: 438479 | elev. accuracy: SVY

northing: 6939817

elevation: 112.2 m a.s.l. **monitored**

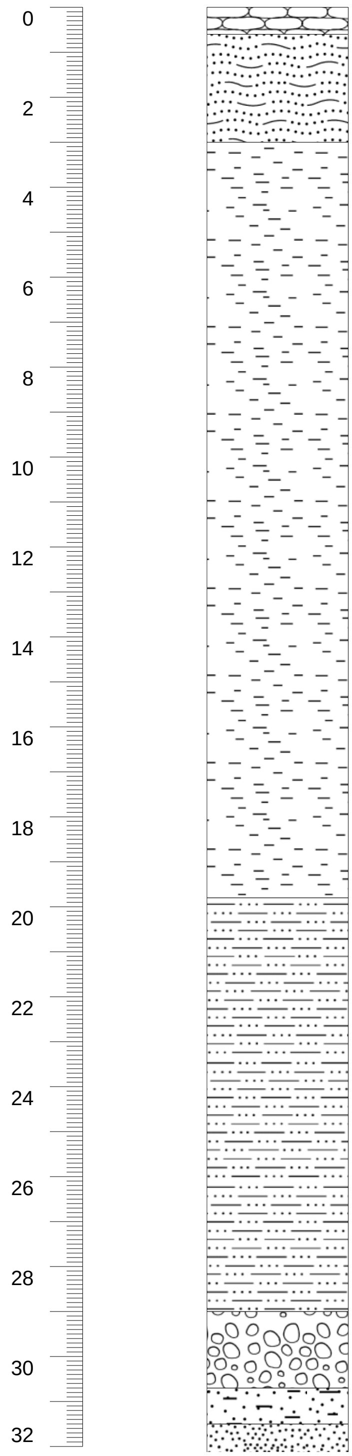


RN: 14320335 pos. accuracy: GPS
easting: 437325 elev. accuracy: SVY
northing: 6939133
elevation: 118.7 m a.s.l. **monitored**



RN:	14320336	pos. accuracy:	GPS
easting:	437542	elev. accuracy:	SVY
northing:	6939104	max. depth 33.70 m	
elevation:	117.1 m a.s.l.	**monitored**	

depth | aquifer | lithology | description



topsoil

loam sandy

clay silty

clay silty with charcoal

silt & charcoal

gravel

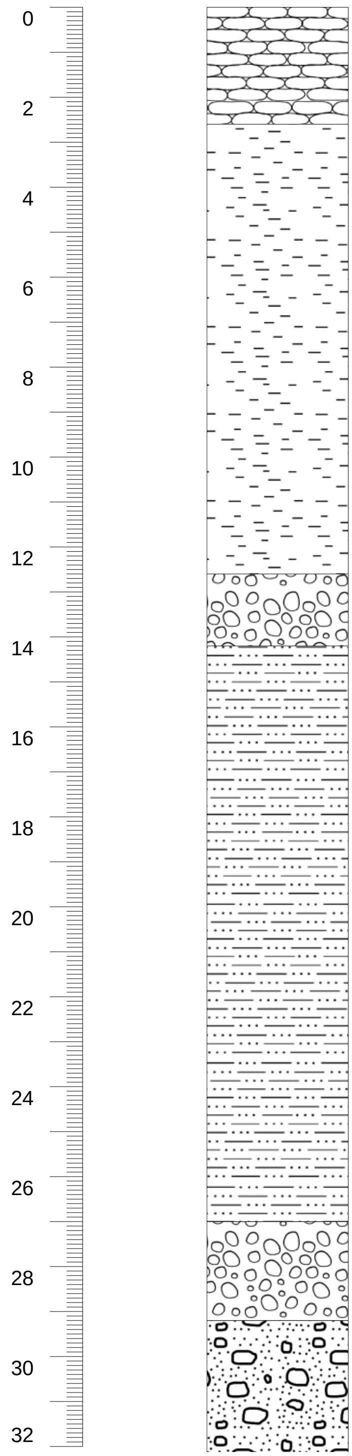
boulder

clay sandy

sandstone

RN:	14320337		pos. accuracy:	GPS
easting:	437968		elev. accuracy:	SVY
northing:	6939041		max. depth 33.20 m	
elevation:	115.9	m a.s.l.	**monitored**	

depth aquifer lithology description



topsoil

clay

clay sandy silty

clay silty

gravel

silt

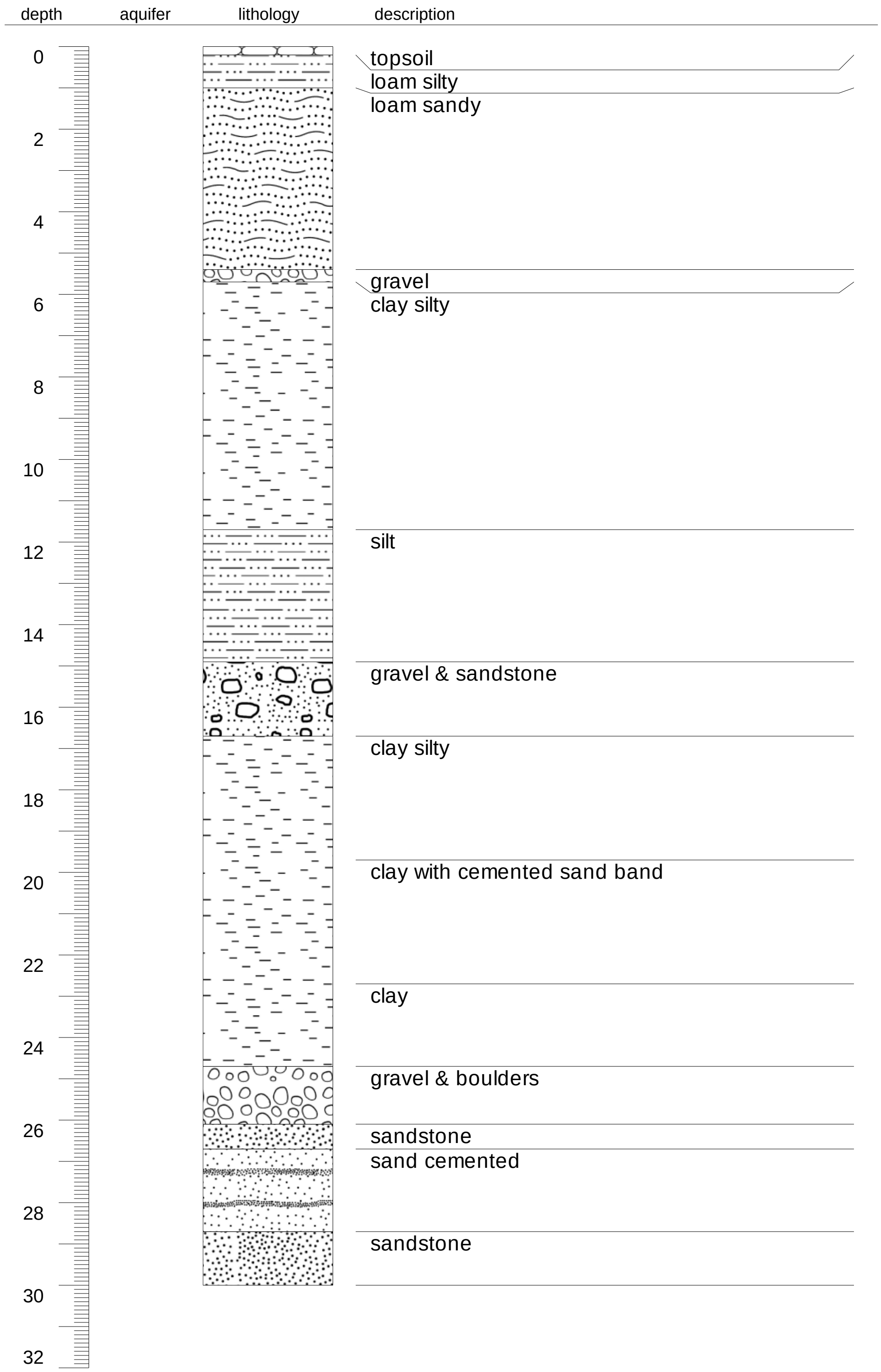
gravel

boulders

sand & stones

RN:	14320338	pos. accuracy:	GPS
easting:	437407	elev. accuracy:	SVY
northing:	6936611		
elevation:	127.4 m a.s.l.	**monitored**	

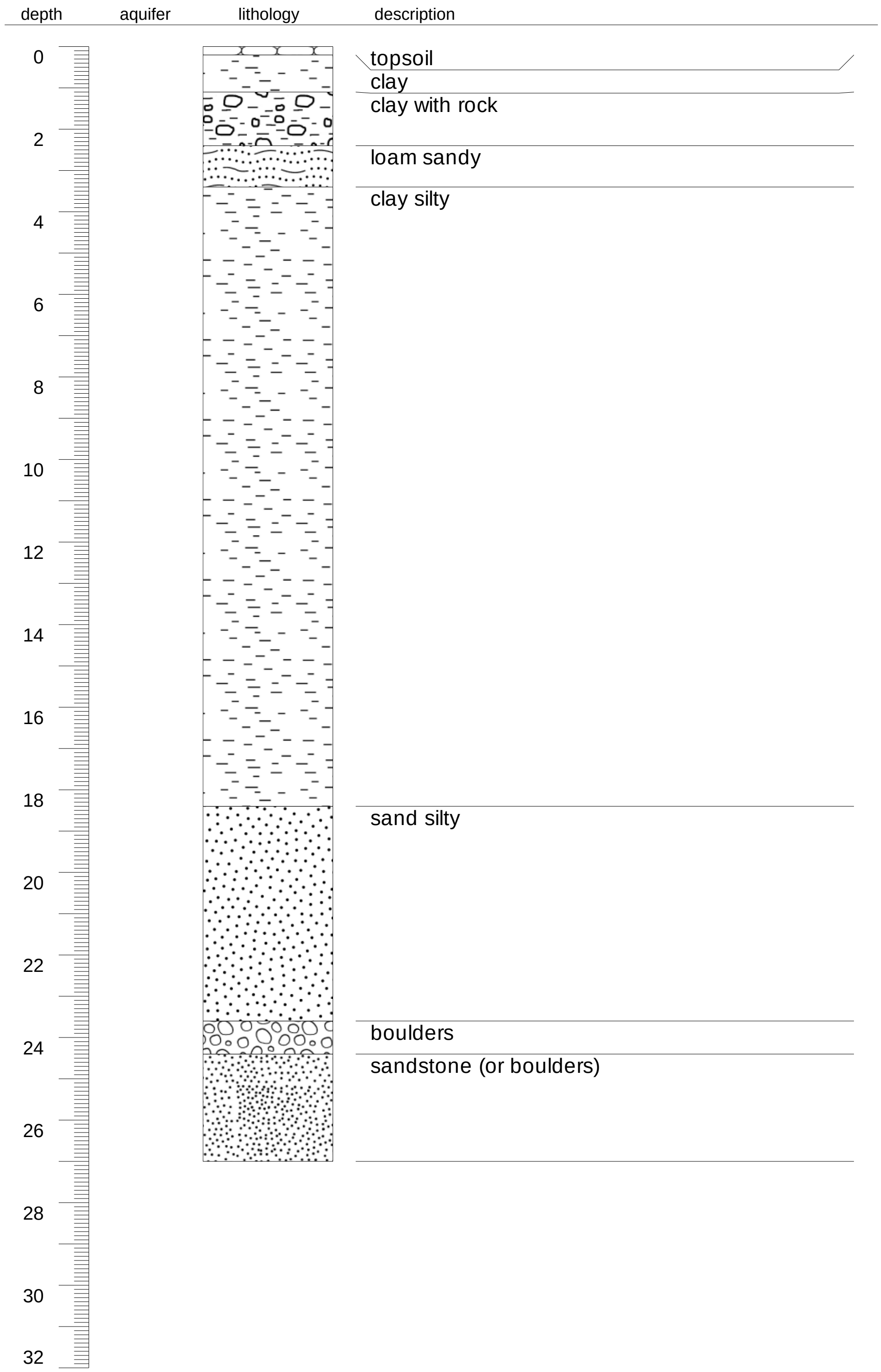
RN:	14320339	pos. accuracy:	GPS
easting:	437658	elev. accuracy:	SVY
northing:	6936580		
elevation:	125.7 m a.s.l.	**monitored**	



RN: 14320340
easting: 437966
northing: 6936534
elevation: 124.2 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY

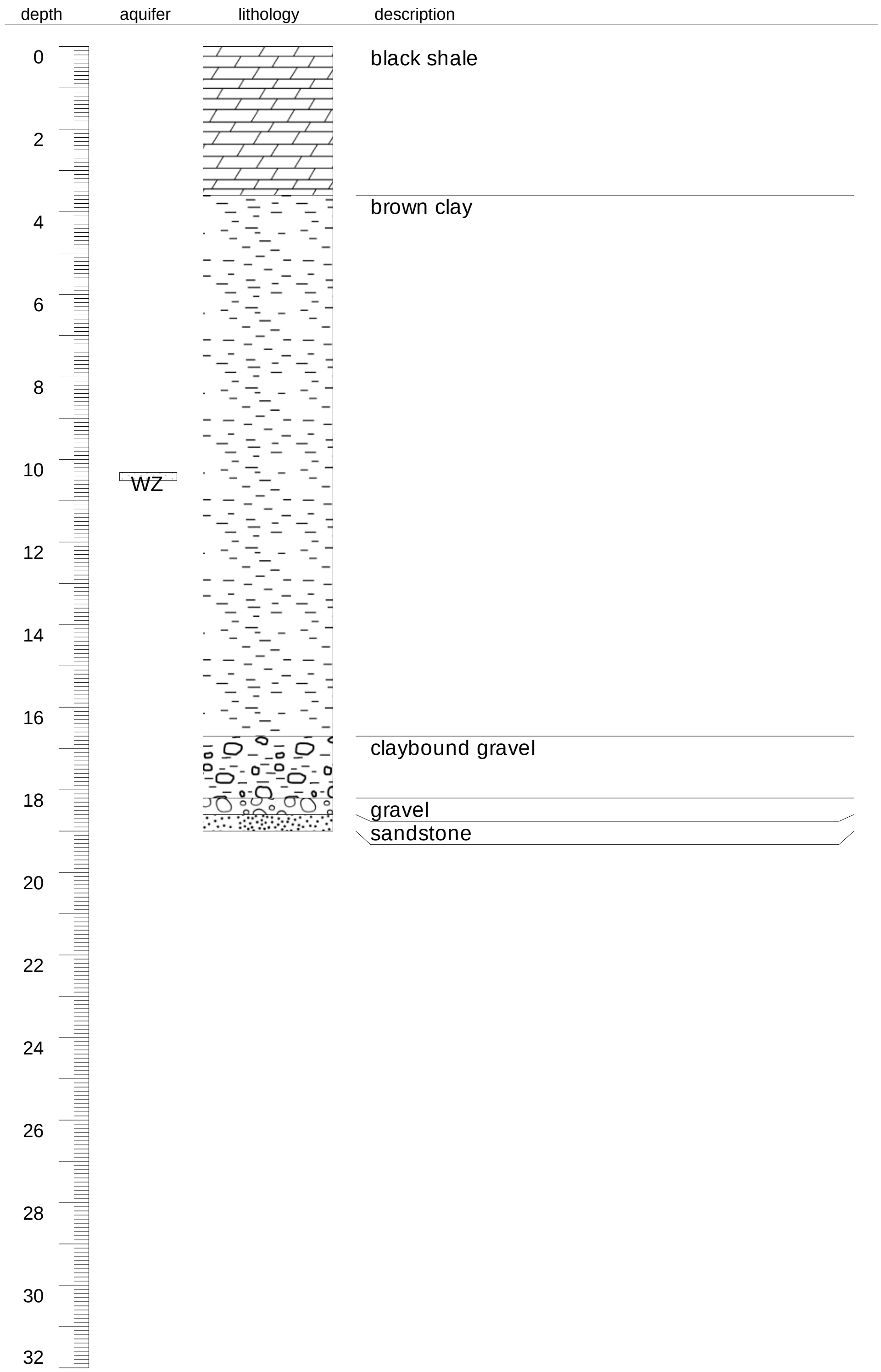
monitored



RN: 14320547
easting: 438954
northing: 6940198
elevation: 109.54 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY

monitored



RN: 14320553

easting: 438764

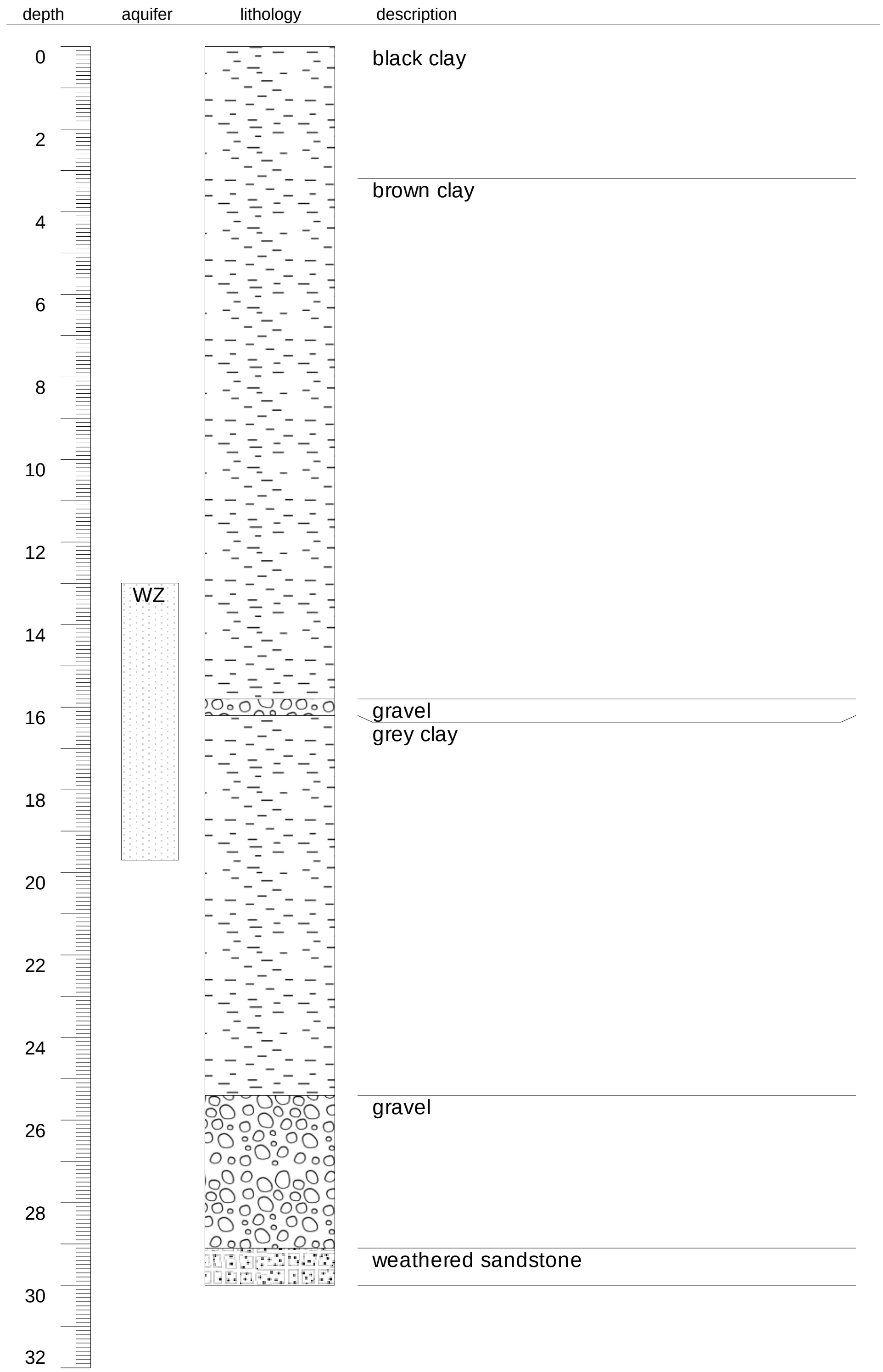
northing: 6940236

elevation: 110.35 m a.s.l.

pos. accuracy: GPS

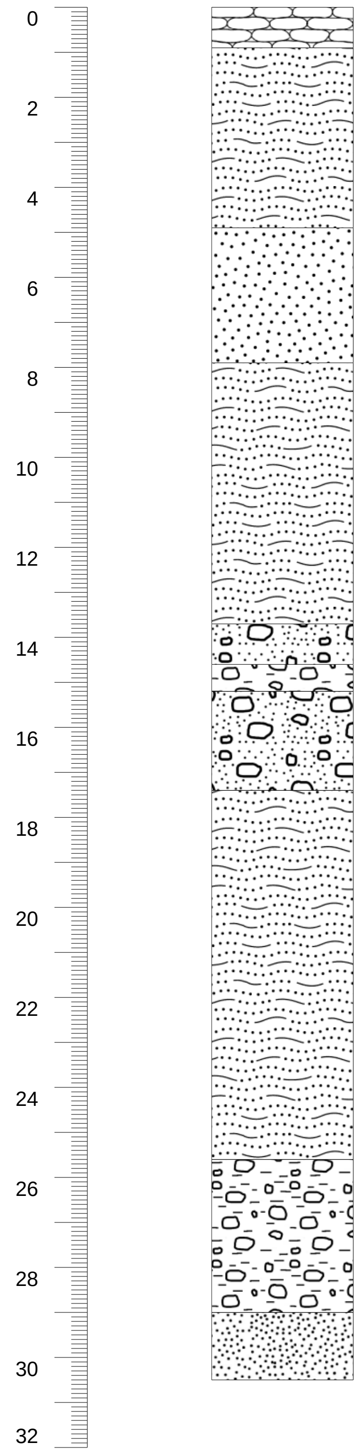
elev. accuracy: SVY

monitored



RN:	14320848	pos. accuracy:	GPS
easting:	437179	elev. accuracy:	SVY
northing:	6934573		
elevation:	131.51 m a.s.l.	**monitored**	

depth | aquifer | lithology | description



top soil

loam

sandy loam

loam

sand-gravel

claybound gravel

sand-gravel

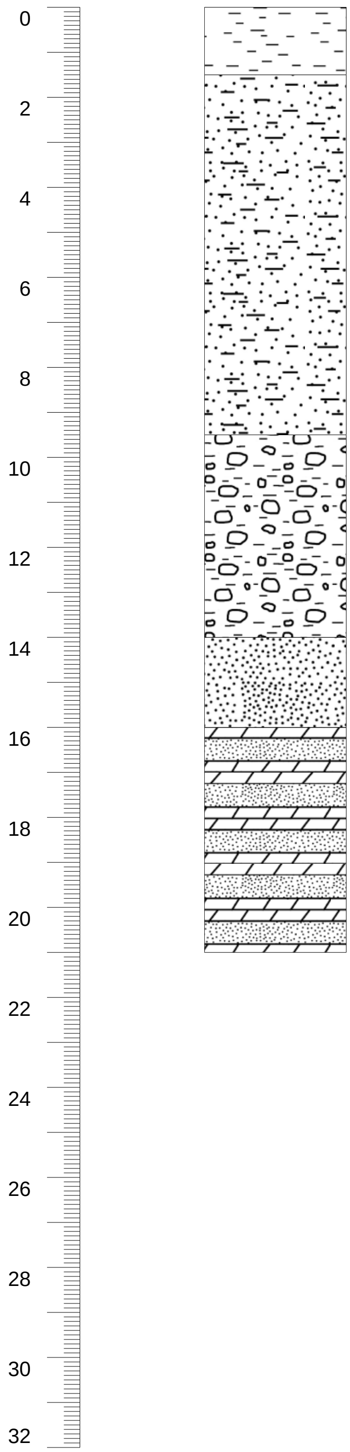
loam

clay bound gravel

sandstone

RN:	14320879		pos. accuracy:	GPS
easting:	438283		elev. accuracy:	SVY
northing:	6925072			
elevation:	171.1	m a.s.l.	**monitored**	

depth aquifer lithology description



dark brown clay soil

brown sandy clay

brown clay-bound lithic gravel, abundant basalt fragments

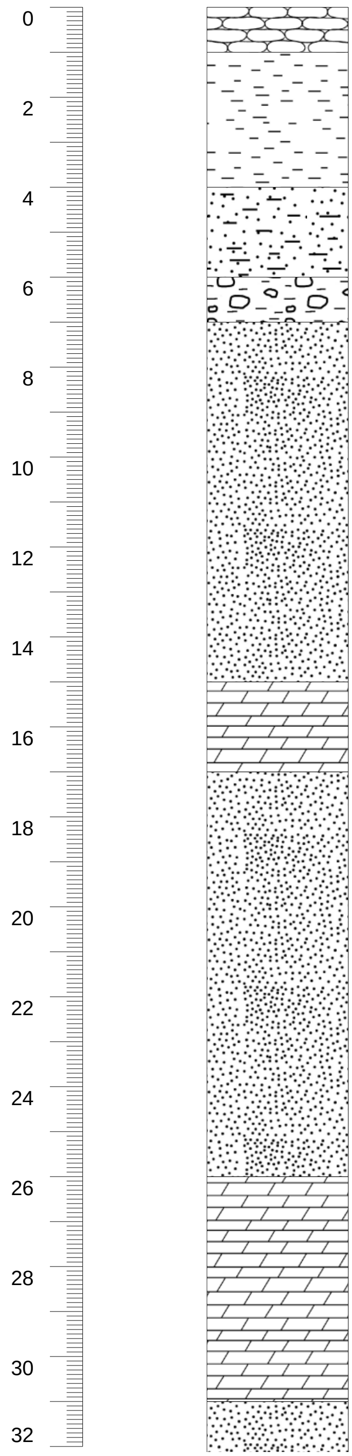
light brown f-m lithic sandstone

light brown f-m lithic sandstone;

light grey siltstone & vf-f sandstone

RN:	14320880		pos. accuracy:	GPS
easting:	439334		elev. accuracy:	GPS
northing:	6930793		max. depth 38.00 m	
elevation:	196	m a.s.l.	**monitored**	

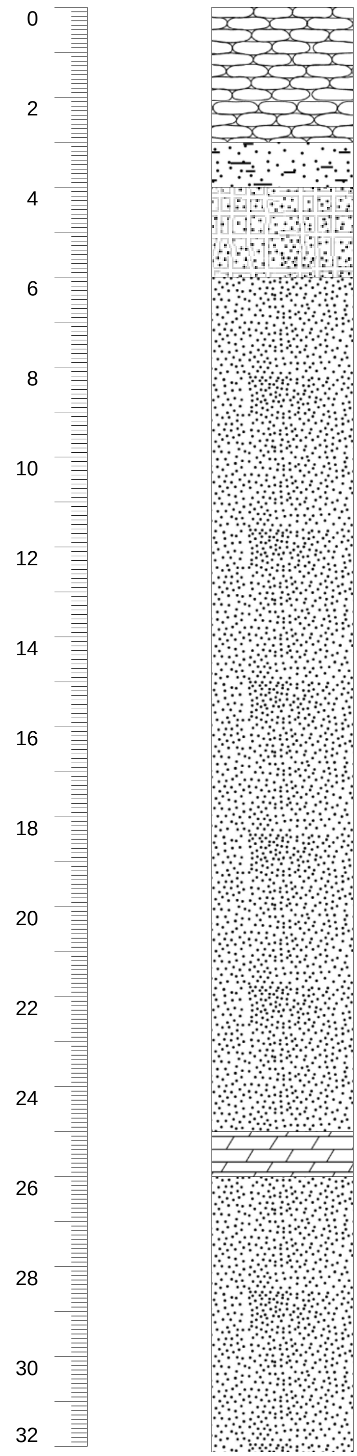
depth | aquifer | lithology | description



- black brown clay soil
- dark grey brown sandy clay, fe mottle
- grey sandy clay, red brown fe mottle
- brown clay-bound lithic gravel
- pale brown m-vc sandstone, weathered
- pale brown f sandstone, weathered, fe staining & cementing
- grey f-m lithic sandstone
- dark grey shale, plant fossils (xylopteris? fragments)
- dark grey carbonaceous shale & siltstone, plant fossil fragments
- grey vf lithic sandstone, plant fossil fragments
- grey vf-f lithic sandstone
- brownish grey f-m lithic sandstone
- dark grey siltstone
- grey siltstone
- grey vf lithic sandstone; water

RN:	14320884	pos. accuracy:	INSP
easting:	437410	elev. accuracy:	SVY
northing:	6940665	max. depth 70.00 m	
elevation:	128.32 m a.s.l.	**monitored**	

depth | aquifer | lithology | description



dark grey brown sandy clay soil

brown sandy clay soil

pale brown vf-med sandstone, weathered

beige med-vc sandstone, clay matrix, weathered

light brown vf-fn sandstone, weathered

light brown fn-crs sandstone

light brown vf-fn sandstone, weathered

off white fn-med lithic sandstone

off white fn-crs lithic sandstone

off white fn-vc lithic sandstone, clay matrix

off white fn-med lithic sandstone, rust brown fe mottling

light grey vf-fn lithic sandstone

light grey fn-med lithic sandstone

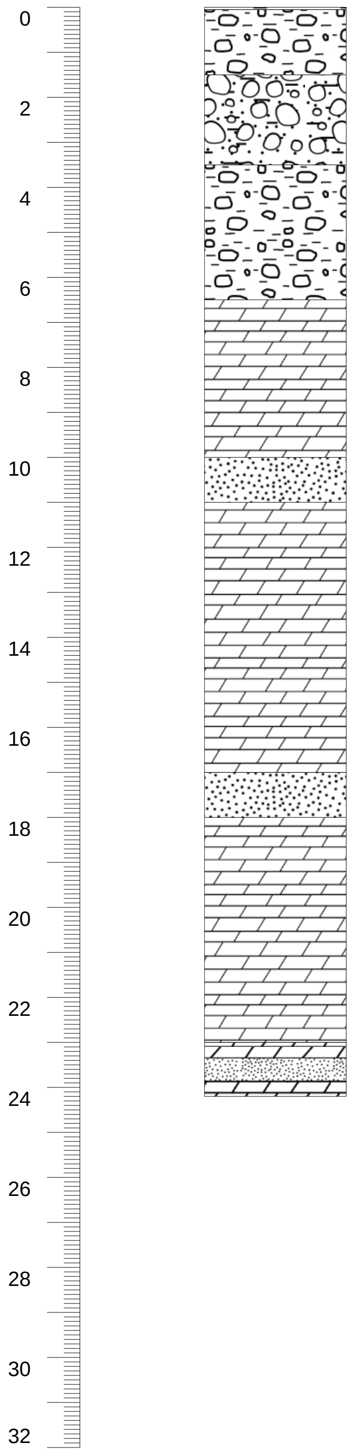
grey siltstone

light grey vf-fn lithic sandstone

light grey fn-med lithic sandstone

RN:	14320885	pos. accuracy:	GPS
easting:	437694	elev. accuracy:	GPS
northing:	6926581		
elevation:	182 m a.s.l.	**monitored**	

depth | aquifer | lithology | description



dark brown clayey soil

dark brown clayey soil with angular basalt gravel 20mm

red brown sandy soil with sub rounded basalt gravel 20mm

light brown clayey soil with sub rounded basalt gravel to 20mm

cream grey shale, weathered

cream grey weathered siltstone

grey brown clayeyy vf sandstone

grey shale & weathered siltstone, limonite staining; water bed at 12m?

grey carbonaceous siltstone

grey f-m sandstone, limonite staining

grey carbonaceous mudstone & weathered siltstone

grey siltstone

grey siltstone & vf sandstone

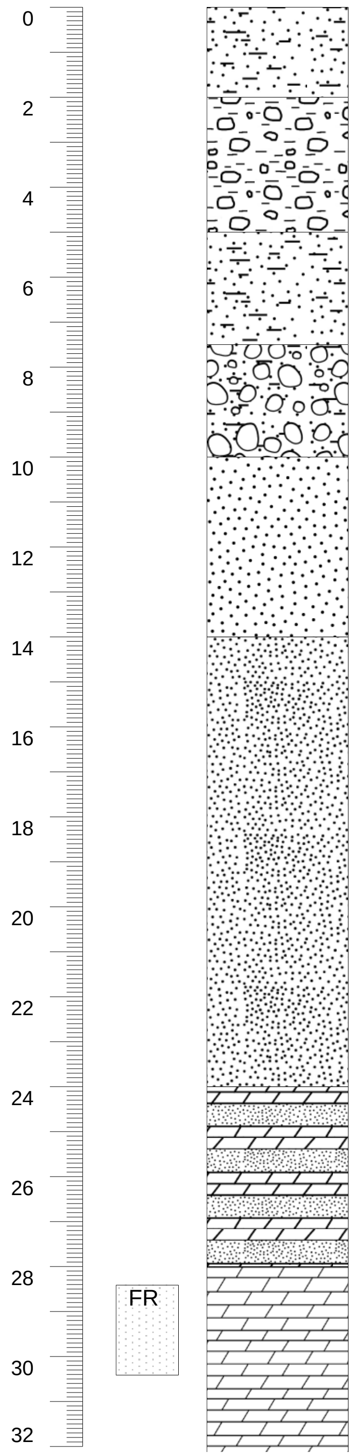
RN: 14320886 pos. accuracy: GPS

easting: 438847 elev. accuracy: SVY

northing: 6936728 max. depth 65.50 m

elevation: 143 m a.s.l. **monitored**

depth aquifer lithology description



brown sandy clay soil

greybrown sandy clay & gravel5mm

brown sandy clay

brown clayey sand & gravel 5mm

grey clayey f-vc sand

pale brown vf-f sandstone, weathered, limonite staining

light grey vf-m lithic sandstone

grey vf lithic sandstone & siltstone

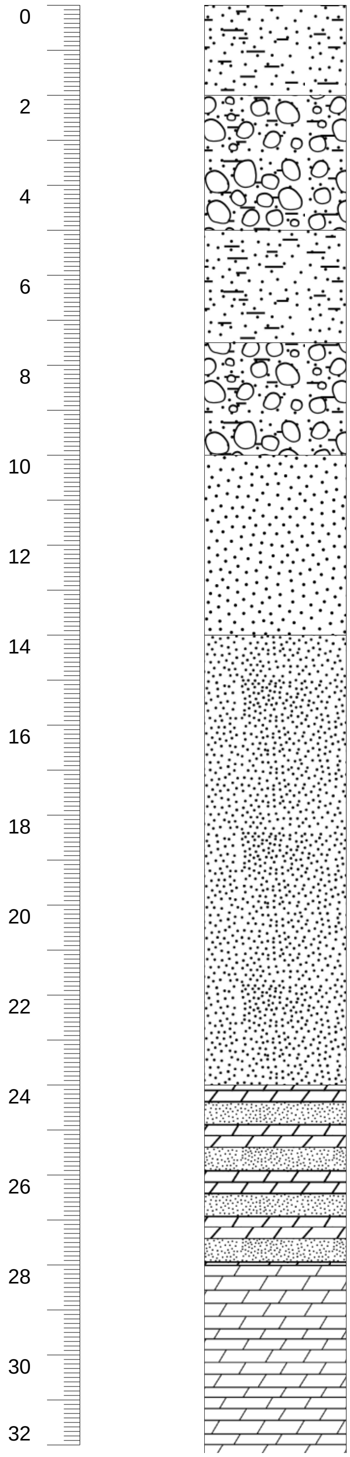
grey laminated shale & siltstone

dark grey carbonaceous shale, plant fossils

RN: 14320887
easting: 438845
northing: 6936720
elevation: 132.8 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY
max. depth 38.00 m
monitored

depth	aquifer	lithology	description



brown sandy clay soil

grey brown sandy clay & gravel 5mm

brown sandy clay

brown clayey sand & gravel 5mm

grey clayey f-vc sand

pale brown vf-f sandstone, weathered, limonite staining

light grey vf-m lithic sandstone

grey vf lithic sandstone & siltstone

grey laminated shale & siltstone

dark grey carbonaceous shale, plant foosils; minor water at 34m

RN: 14320916

easting: 436746

northing: 6938390

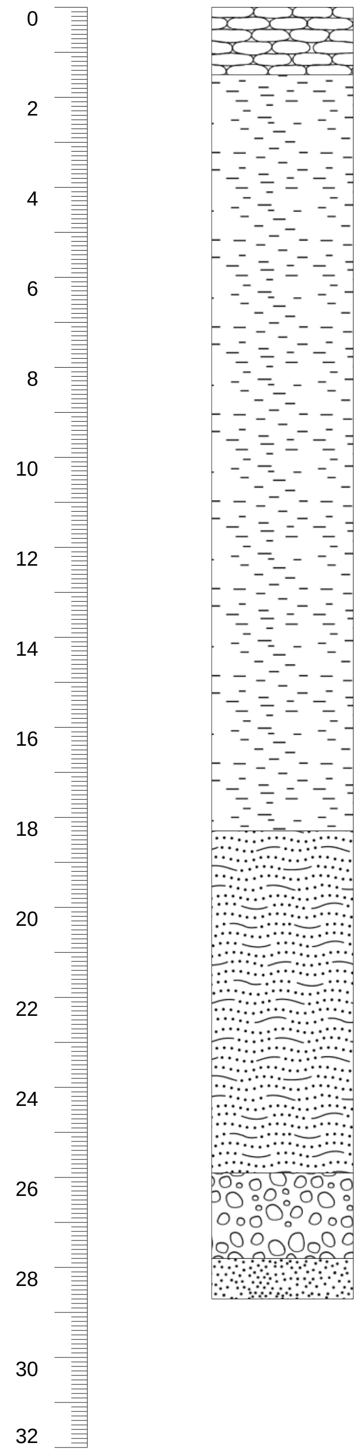
elevation: 119.5 m a.s.l.

pos. accuracy: INSP

elev. accuracy: EST

monitored

depth | aquifer | lithology | description



soil

clay

loam

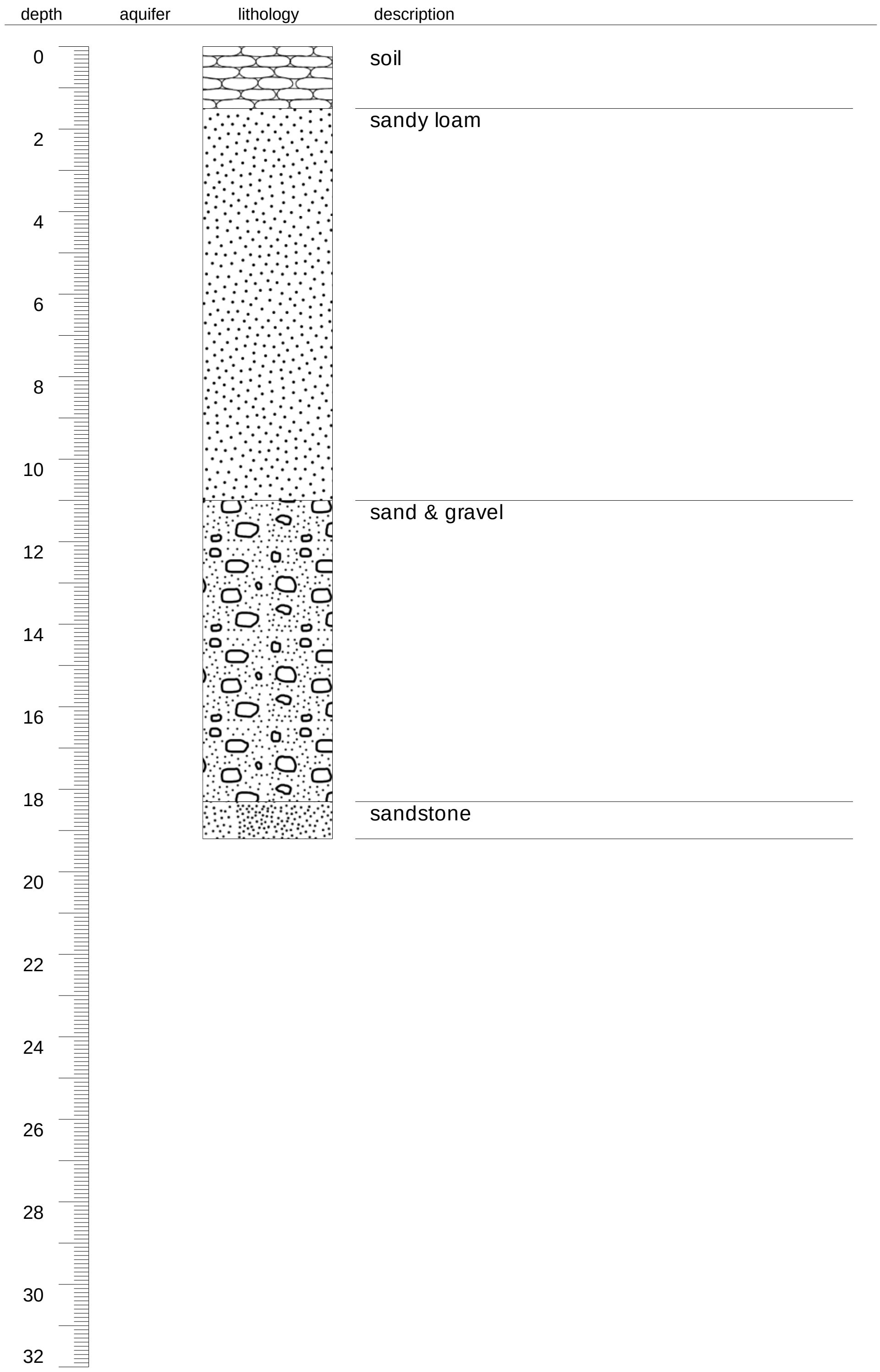
gravel

sandstone

RN: 14320917
easting: 438105
northing: 6924979
elevation: 170.28 m a.s.l.

pos. accuracy: INSP
elev. accuracy: SVY

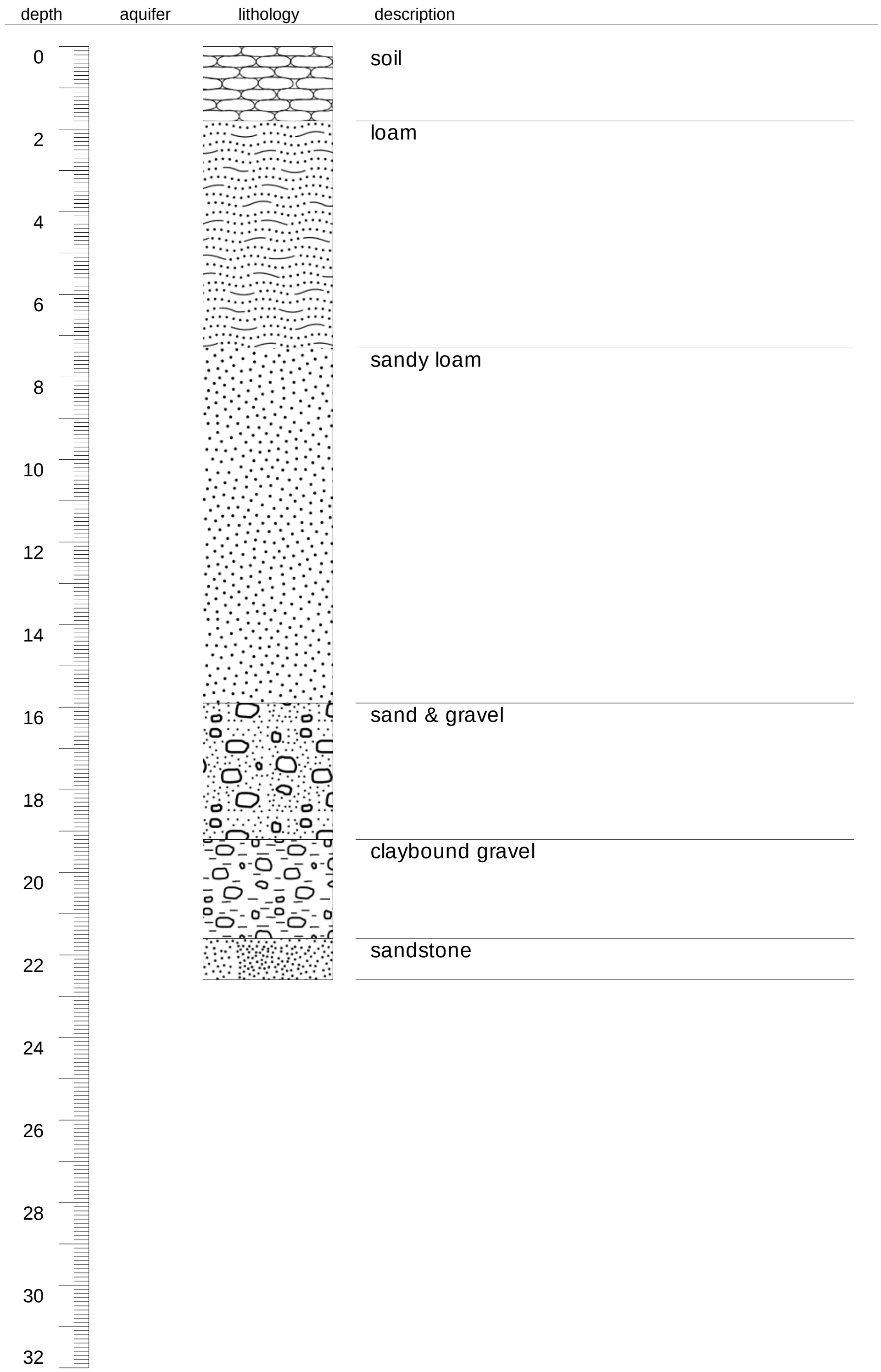
monitored



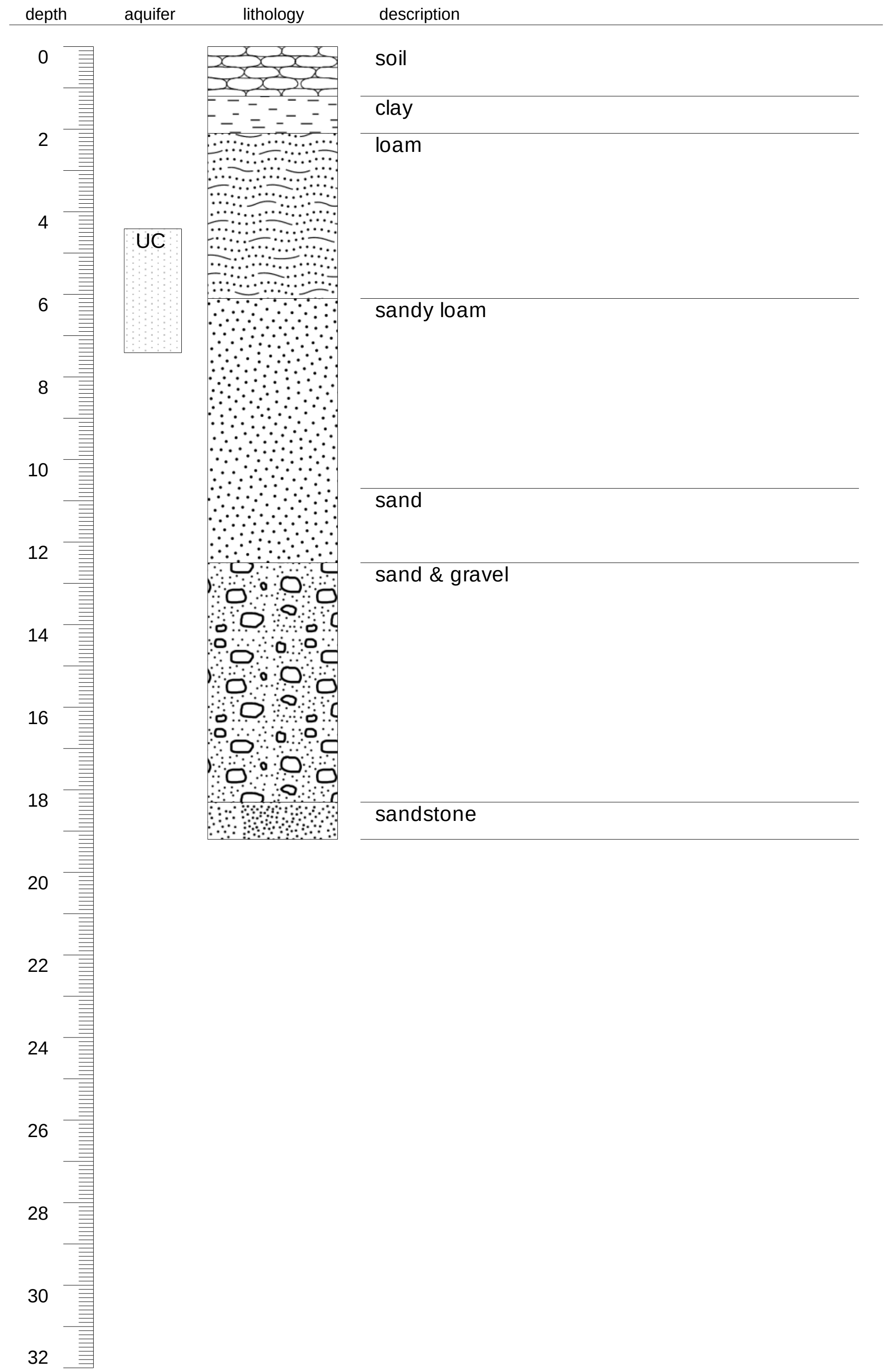
RN: 14320919
easting: 437928
northing: 6927532
elevation: 160.49 m a.s.l.

pos. accuracy: INSP
elev. accuracy: SVY

monitored



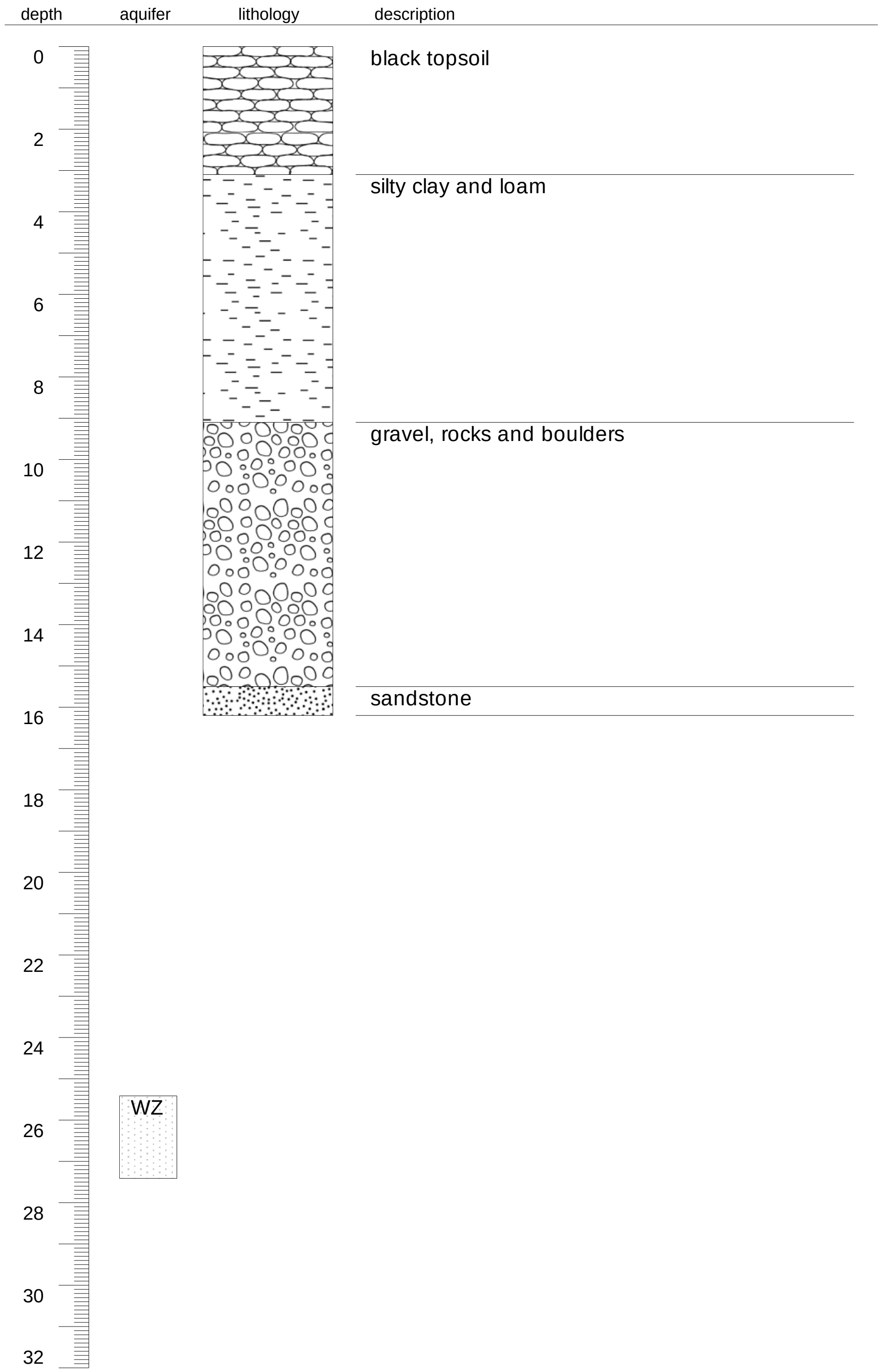
RN:	14320920	pos. accuracy:	INSP
easting:	438175	elev. accuracy:	SVY
northing:	6927472		
elevation:	159.38 m a.s.l.	**monitored**	



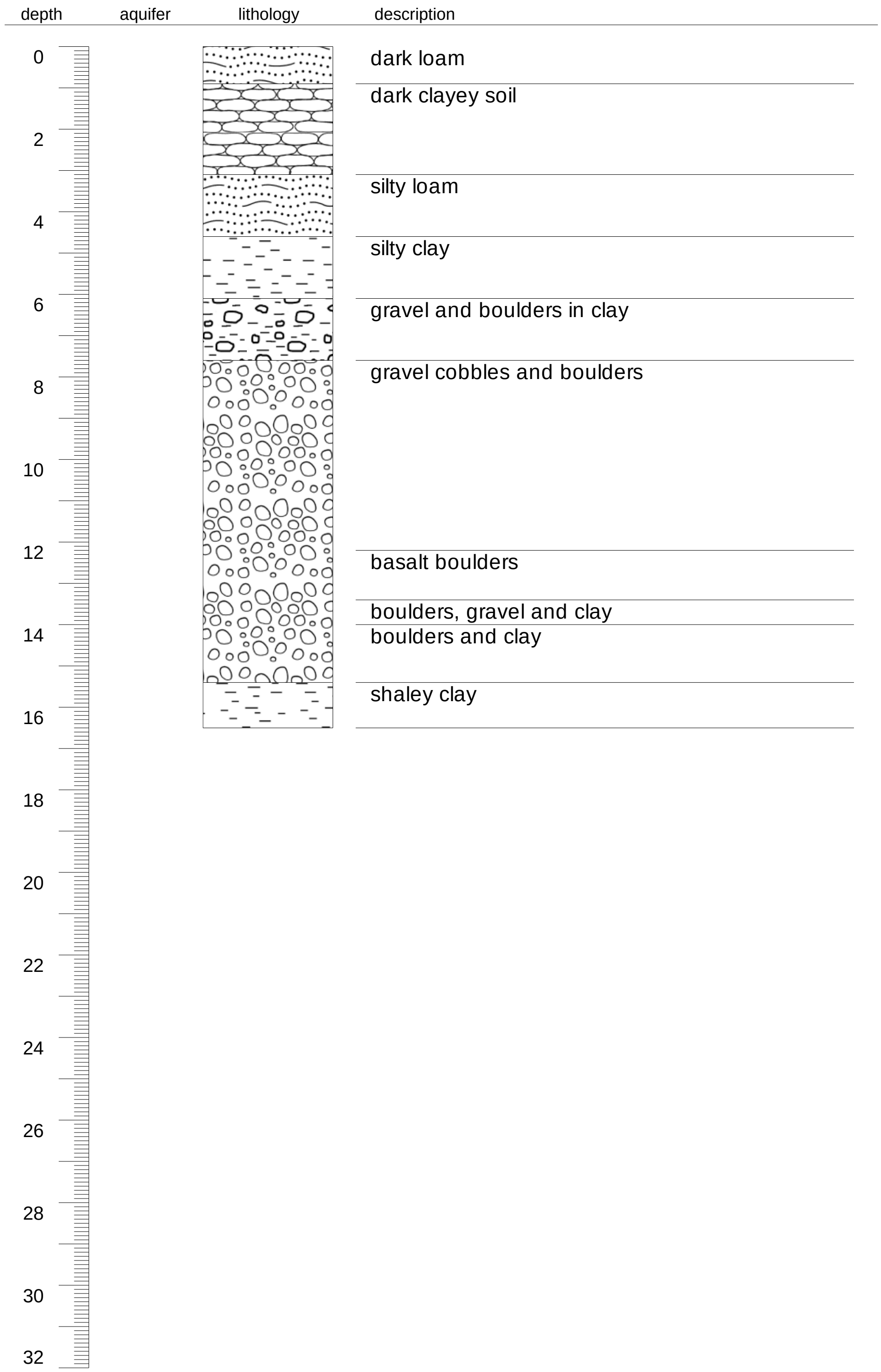
RN: 14320982
easting: 439909
northing: 6918919
elevation: 203.13 m a.s.l.

pos. accuracy: GPS
elev. accuracy: SVY

monitored



RN:	14320983	pos. accuracy:	GPS
easting:	439912	elev. accuracy:	SVY
northing:	6916683		
elevation:	219.82 m a.s.l.	**monitored**	



RN: 14320986

easting: 437163

northing: 6932482

elevation: 139.15 m a.s.l.

pos. accuracy: GPS

elev. accuracy: SVY

monitored