The hydrogeology of the Condamine River Alluvial Aquifer (Australia) – a critical review

Prepared by

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April 2013

Citation

Dafny E., Silburn D.M., 2013. The hydrogeology of the Condamine River Alluvial Aquifer (Australia) - critical review. University of Southern Queensland, Toowoomba, Australia.

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Acknowledgement

The authors thank Prof. John Warden (USQ) and Dr. Andrew Biggs (DNRM) for their constructive comments which led to the improvement of this report. Special thanks to Mr. Howard Rother for a first hand introduction to the cotton growing industry in the Condamine.

Executive summary

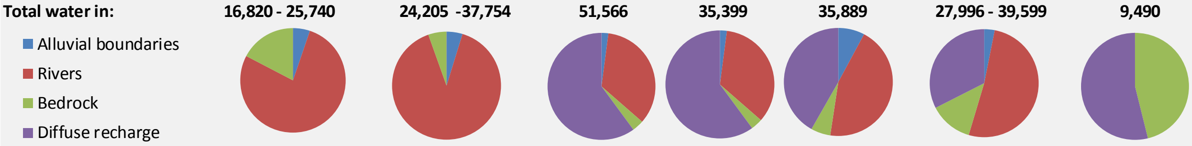
The Condamine plain is an important agricultural zone, with ~118 thousand hectares of irrigated crops. Groundwater pumped from the shallow alluvial aquifer (40-60 GL/yr) accounts for one third of the irrigation water. Sustainable agriculture future implies, among other issues, a reliable supply of groundwater to the farmers, in terms of quality and quantity.

The hydrogeology of the shallow Condamine River Alluvium Aquifer (CRAA) was studied for decades in order to provide a management framework and to determine the 'safe yield', as excessive pumping in the past has led to ongoing decline of the water table, up to ~25 m in places. Notwithstanding the accumulating data and knowledge, the water balance of the aquifer as well as 'safe yield' estimations are still far from been conclusive and has been substantially revised several times during the last decade.

The present report, conducted at the University of Southern Queensland (USQ), collates up-to-date hydrogeological knowledge regarding the CRAA, critically evaluates the accepted hydrogeological conventions, highlights puzzling phenomena and recommends needed work, which can be implemented in a rather expeditious and inexpensive fashion, to overcome the existing knowledge gaps. Refining the hydrogeological knowledge regarding the CCRA is timely, as in the last decade there has been a rapid expansion of the CSG industry in vicinity to the Condamine plain, with the aim to extract methane from the underlying layers. The presumed hydrogeological effects of CSG production upon the shallower CRAA have been delineated but are yet to be adequately quantified. It is our view that the hydrogeological knowledge-gaps should be addressed before (or at least simultaneously with) predictions of CSG activities effects can be made.

Previous water balance estimations of the Condamine River Alluvial Aquifer

	Lane (1979)	Huxley (1982)	SKM (2002) Conceptual	SKM (2002) Numerical	Barnnet & Muller (2008)	KCB (2010)	Coffey (2011)
Total water in:	16,820 - 25,740	24,205 -37,754	51,566	35,399	35,889	27,996 - 39,599	9,490
Total water out:	-67,598	-61,403	-68,116	-56,947	-36,100	-66,645	??



Note: investigated area and period of each study slightly varies.

Major findings

Our review shows:

- There is an emerge interest, both local and international, in understanding and quantifying 'deep-drainage' under irrigated fields through cracking clay soils, including many field studies. This knowledge base should be implemented (and better studied) to the CCRA, in order to establish quantitative and temporal relation between 'deep-drainage' and actual recharge to the groundwater table.

- Percolation of surface water from the Condamine River (i.e., streambed recharge) is regarded one of the most important component of the CCRA water balance. Percolation rates however, are averaged both spatially and temporally, and do not reflect spatial changes in riverbed lithology or temporal changes in river levels (e.g., low during droughts years, high during floods events, etc.). Quantitatively analysis supported by field work and numerical modelling of the unsaturated zone should allow better constrains.
- To date, limited fluxes have been considered between the CRAA and all its bounding hydrogeological units due to adjoining low-permeability alluvial sub-units. However, there is no certainty as to the thickness of this layer, its spatial continuity and its lithology, all of which influence the connectivity of the CCRA and the possible effects (in terms of water balance and water quality) of external stresses such as intense pumping and dewatering. Inter-formation pumping tests at various locations, extensive heads measurements and numerical modelling of solute transport should allow better constrain of these fluxes.
- The hydrogeological conditions at downstream boundary of the CCRA, which presumably drained much of the groundwater flux in the pre-developed period, are poorly understood and constrained. It is possible that at this zone, the CCRA is highly interconnected with the underlying salty formations. Research of this issue involved extensive geological characterization, which is therefore out of the scope of this report. However, the volumetric aspects can be studied in the frame work of a numerical model for the pre-developed period
- The geochemical composition of the CCRA groundwater is very heterogenic and varying from fresh Ca-HCO3 type water to saline Na-Cl type water, generally found in the west and north portions. The fresh water is generally linked to streambed recharge from the Condamine River while the salty water is linked to influx from underlying formations. However, beside this spatial trend, which is related to each bore's location, water composition also varies in the vertical plane (depths and exploited formation), and reflect inputs from different sources. Once again, numerical modelling of solute transport can support and explain the geochemical variability.
- Generally, the recent numerical flow models (SKM, 2003; Barnett and Muller, 2008; KCB, 2010, 2011) are of improved scale and better representation of boundary conditions, including surface-subsurface interactions. This gains current models higher accuracy than field measurements, nevertheless without similar increase in the confidence. It is our understanding that pursuing additional flow modelling, without either (1) acquiring substantial new field data, (2) a better conceptual understanding of hydrogeological processes and (3) use of sophisticated software with superior capabilities (e.g., multiple water tables, integrated surface-sub-surface), which can enhance the reliability of its results, is a secondary priority.

- The current DNRM monitoring-bores net serves different purposes, it is in-frequently measured. A dedicated monitoring net should be establish following a revision of the hydraulic performance of existing bores and of statistical links in-between neighbouring bores. This should be followed by a process of identifying poor-constrained areas/depths and accompanied drilling of new bores in places of interest and need.

Content

Introduction

The Condamine River of south-east Queensland is one of the main tributaries of the Darling River, Australia. Some 70 km downstream from its headwater, it forms a large alluvial plain (Figure 1), which covers a paleo-valley incised into Jurassic aged terrigenous rocks. These two are termed here the Condamine plain and the Condamine paleo-valley.

The alluvium accumulated within the Condamine paleo-valley forms a local aquifer which is exploited mainly for agriculture supply; this is traditionally termed the Condamine River Alluvial Aquifer (CRAA). Aspects of the hydrogeology of the CRAA have been studied since the late 1940's (Gloe, 1949; Morse, 1950; Belcher, 1955; Calvert, 1958,1959,1960; Lumsden, 1966; Lane, 1969,1970 (both references cited by Lane, 1979 but could not be retrieved); Lloyd, 1971; Howe, 1974) but it wasn't until the late 1970's, that an integrated investigation was concluded for the entire CRAA as one water resource (Lane, 1979; Huxley, 1982). These two studies were underpinned with some of the most intensive and extensive data collected for any alluvial aquifer system in Queensland (Kelly and Merrick, 2007). Noticeable efforts in hydrogeological conceptualization and modelling have occurred in the last decade, although this did not include novel data acquisition (SKM, 2003; Barnett and Muller, 2008; KCB, 2010a,b, 2011a,b; Coffey, 2012). Many of the latest studies were internal reports and not all are available or accessible to the public and the scientific community.

Overall, research efforts have three main applications:

1) To assist regulatory agencies in establishing pumping allocations for the local irrigators (e.g., SKM, 2003).
2) To assist farmers with better irrigation practises in order to maximise water use efficiency and minimize water percolation from irrigated fields ('Deep-Drainage', e.g., Silburn and Montgomery 2004; Gunawardena et al. 2011).
3) To establish hydrological and geochemical base-lines. Thereby enabling identification of future changes, especially due to the increased interest in Coal Seam Gas (CSG) extraction, , from the abundant coal measures within the underlying Jurassic rocks, and its possible effects (e.g., KCB, 2010; Coffey, 2012).

Notwithstanding the accumulating data and knowledge, some hydrogeological 'knowledge gaps' remain, leading to various estimations in regards to the aquifer's water budget, including various recharge components (direct recharge, diffuse deep-drainage and streambed recharge) and inter-connectivity with bounding aquifers.

This review critically examines the main hitherto accepted hydrogeological conventions and points out puzzling and contradictory phenomena. The review is timely, as in the last decade there has been a rapid expansion of the CSG industry in the western part of the Condamine catchment. This involves de-pressurization of the target formation (specifically the Walloon Coal Measures, WCM) to liberate methane, i.e., extraction of large volumes of groundwater from the WCM. The presumed effects of CSG production upon the shallower CRAA have been delineated but are yet to be adequately quantified (QWC, 2012). It is our view that the hydrogeological knowledge-gaps should be addressed before a comprehensive understanding can be gained and reliable predictions made.

The review initially describes the physical conditions in the CRAA, including its physiography, geological evolution, alluvial sediments and soils distribution as well as a brief description of regional geology and hydrogeology. This is followed by a description of the existing hydrogeological knowledge, and later the differences between the common conceptions and knowledge gaps which need to be resolved. The last section contains recommendations that can be implemented in a rather expeditious and inexpensive fashion.

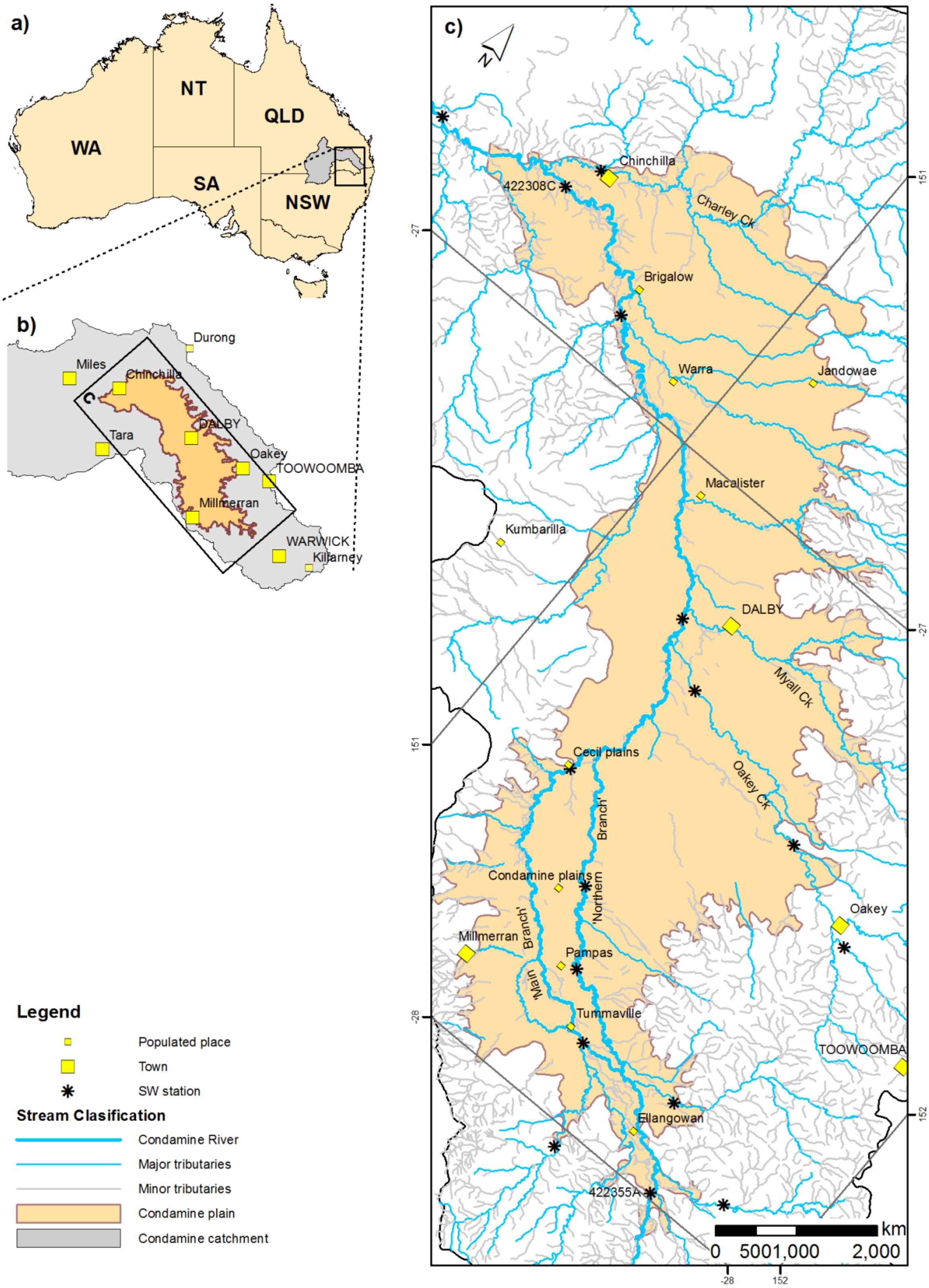


Figure 1: *Location map.*

The Condamine plain

Physiography

The Condamine plain occupies the area between Ellangowan (E151.67°, S27.92°) and Chinchilla (E150.72°, S27.74°), southern inland Queensland (Figure 1). It is stretches over an area of about 7,000 km^2, and is ~190 km long. Its upstream and downstream edges are narrow, but most of floodplain is 15-40 km wide. The topography drops steadily from the south-west to the north-east, from +400 m near Ellangowan to +350 m near Dalby and to +310 m near Chinchilla, with an overall topographic gradient of 0.5 m/km.

Many streams drain the highlands surrounding the alluvial plain, from the east, west and south, to form the Condamine River and the Condamine Catchment Basin. The catchment area of the Condamine River, from its headwater near Killarney down to gauging station 422308C west of Chinchilla, is 19,190 km^2 and comprises varied geological rocks, as outlined below (Figure 2). Alluvium has also accumulated along the Condamine tributaries, to form shallow, narrow, pinch-out units.

The average annual discharge of the Condamine River as it enters and leaves the alluvial plain is 115 GL/yr and 581 GL/yr, respectively (stations 422355A and 422308C, DNRM website), however the Condamine river flow may reduce to a series of drying ponds during severe droughts. In the southern part of the Condamine plain the river splits into two branches- the 'north branch' to the east and the 'main branch' to the west; both merging near Cecil-Plains (Figure 1). Most of the stream flow is routed to the main branch, whereas the northern branch remains inundated at times. Several weirs were erected along the river, including weirs for water supply near Cecil-Plains and Tipton.

Rainfall occurs throughout the year, with 50-100 mm/month during the summer (October to March) and 25-50 mm/month during the winter (Table 1). Evaporation exceeds rainfall, with >200 mm/month and 90-175 mm/month, respectively. The mean maximum monthly temperature ranges from 32.5 degrees Celsius (°C) in summer to 19.7 °C in winter.

Table 1: Mean climate characteristics *(Source: Bureau of Meteorology www.bom.gov.au)*

	← Summer			Winter						Summer →			Annual
	J	F	M	A	M	J	J	A	S	O	N	D	
Precipitation (mm)	77	84	50	21	38	35	23	25	31	61	80	104	629
Evaporation (mm)	280	215	225	175	110	90	95	140	170	235	245	280	2260
Mean max. temperature (°C)	32	31	30	27	23	20	20	22	25	28	30	31	
Mean min. temperature (°C)	19	19	16	13	8	5	4	5	9	13	16	18	

Note: Statistics for Dalby airport (Station number 41522), based on 1992-2012 data.

Soils

A fairly homogenous 1-2 m layer of clayey soil covers the major part of the Condamine plain, excluding separate or merged fans, generally on the western part of the valley, where sandy, gravelly and loamy soils formed on sandstone (Huxley, 1982; KCB, 2010). The most common soils are black or grey Vertosols (cracking clays) (Figure 2), renowned for high fertility and moisture holding capacity. They form on a variety of parent materials including basalts, fine-grained sandstone/mudstones and alluvium. Sodosols are largely associated with coarse grained sandstones and derivative alluvia, principally on the western side of the catchment. These soils have low nutrients levels, and various subsoil constraints that generally preclude their development for cropping.

The area's typical Vertosols have a field capacity of 45% and saturation of 55% (volumetric ratios) (Gunawardena et al. 2011). Under native vegetation, the soil is in deficit, i.e. the water content is generally well below these levels to depths greater than 5 m (Foley et al., 2010). The salinity varies between 450-1000 mg Cl/kg, with higher values, up to 2000 mgCl/kg at the downstream parts of the Condamine plain (Harris et al., 1999; Tolmie et al., 2004). In all locations, the upper horizon is less saline. When cropped or irrigate, soils tend to become moister and less saline (Foley et al., 2010). Chloride concentrations decrease at a rate of 0.2-0.3 ton Cl/hectare/yr (Tolmie et al., 2004). These trends are in agreement with worldwide published data (e.g. Scanlon et al. 2010, Kurtzman and Scanlon, 2011) and suggest excessive 'deep-drainage' (Silburn and Montgomery 2004).

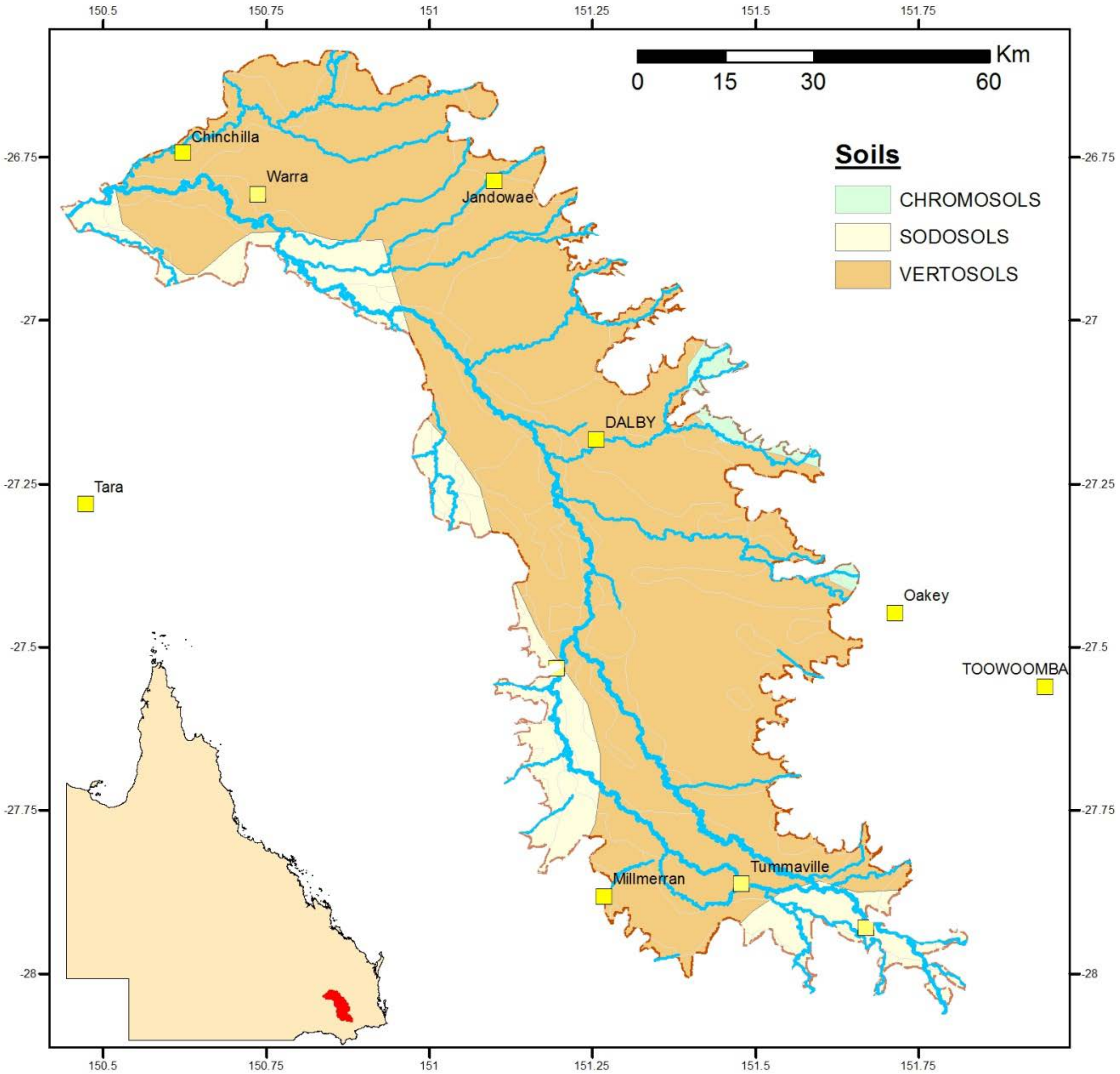


Figure 2: *Dominant soils map (source: DNRM, Queensland).*

Vegetation and land use

The native vegetation (prior to European settlement) on the floodplain consisted of grasslands and open eucalypt woodlands (Vandersee, 1975). Gradually, it was cleared, giving way to the development of cropping agriculture. The clearing however, was very limited prior to WWII, and busted in the following decades when farming machinery (tractors etc.) became available. Until the early 1960's, intensive agriculture expansion was also limited by water availability, as the major source for irrigation was surface water. Rapid growth of irrigated land occurred in the 1960's concurrent with the development of boreholes and pumps to extract groundwater: for example, in Jondaryan shire, total irrigated area increased from 372 hectares in 1960 to 4,259 hectares in 1969 (Lane, 1979). Currently, the area is heavily utilized for agriculture and is one of the largest growing centres of cotton and grains in Australia.

Geological background

The CRAA uncomformably overlies mainly tilting Jurassic rocks, and to lesser extent, in the eastern side of the valley, tertiary volcanics, which have erupted through the Jurassic sediments. (Figures 3, 4). In the southwestern end of the Condamine catchment, the Jurassic sediments lap onto pre-Jurassic granitic and metamorphic rocks of the Texas Block. While the geological setting of the area is reasonable well understood, the geomorphological evolution of the Condamine paleo-valley and the CRAA still remain uncertain.

The Jurassic section

The CRAA straddles the margins of two Jurassic sedimentary basins- the Surat Basin to the west and the Clarence-Moreton Basin to the east (Figure 3). The Jurassic rocks were deposited upon a major peneplain with very subdued topography (Korsch and Totterdell, 2009). They consist primarily of sandstone, silt, mudstones and coal, thus representing a fluvial depositional environment, with alternate spatial and temporal conditions varying between high-energy, meandering channels, to low-energy, oxygen depleted swamps (Exon, 1976; Day et al., 1983). The Jurassic rock section was uplifted and tilted, and currently dips gently to the southwest, with a slope of 5° to 10° (Coffey, 2011).

The spatial relations between the Jurassic geological units include facies changes and inter-fingering. Consequently, geological nomenclature is complex and variations in terminology are common both, within and across the two basins (Scott et al., 2006). A brief description of the Jurassic formations outcrop in the vicinity of the CRAA is given below (from oldest to youngest):

- Hutton Sandstone / Marburg Sandstone

The Marburg Sandstone (AKA Marburg sub-group), of Lower Jurassic age, consists mainly of inter-bedded sandstone and mudstone. Its equivalent unit, the Hutton Sandstone, consists mainly of quartzose to labile sandstones (generally fine- to medium-grained) with interbedded siltstone and minor mudstone and coal (Day et al., 1983). Some geological maps include both in one mapping unit, while in other maps, Hutton Sandstone appears at the north-eastern rims of the CRAA while Marburg Sandstone at the south-eastern rims.

Both units conformably underlie the Walloon Coal Measures, from which it is distinguished by the presence of coarse pebbly sandstones and conglomerates (Day et al., 1983). Its thickness is generally less than 200 m (KCB, 2010b; Coffey, 2012).

- Eurombah Formation

The Eurombah Formation represents a distinct transition between the Hutton/Marburg and Walloon Coal Measures. It consists of inter-bedded siltstones and fine-medium grained sandstones with very low permeability (Day et al., 1983). Though discrete in the rock column, it hasn't been mapped at the regional scale.

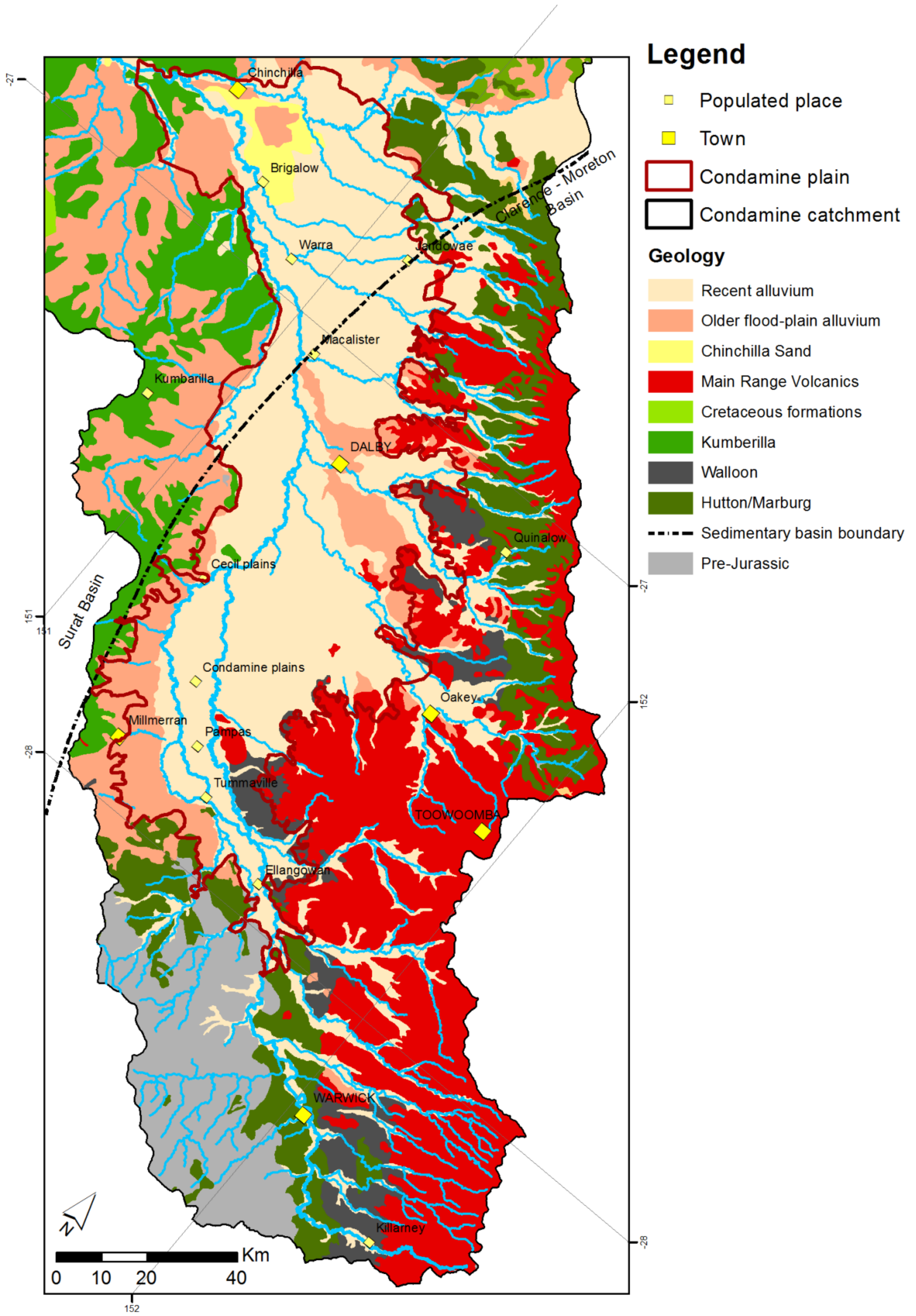


Figure 3: *Geological map (layer source: Worley Parsons, 2012 database). Some of the geological units were originally aggregated into single mapping units; these are represented in the map according to geological age.*

• <u>Walloon Coal Measures (WCM)</u>

The Walloon Coal Measures are of Middle Jurassic age, and consist of very fine to medium grained, labile, argillaceous sandstone, siltstone, mudstone and coal, with minor calcareous sandstone, impure limestone and ironstone (Day et al., 1983). The WCM are subdivided into four sub-units (formations) with varying amounts of coal seams. It is the shallowest target for CSG exploration in the Surat Basin and in the study area. Some geological maps include this unit, along with its equivalent, the Injune Creek Beds, in one mapping unit (Figure 3), whereas in other maps, the WCM appear along the eastern rims of the CRAA, while Injune Creek Beds appear generally further west (Figure 5). The WCM rests conformably over the Hutton/Marburg Sandstones and unconformably overlain by the Springbok Sandstone and Westbourne Formation (Scott et al., 2006).

WCM outcrop in several patches located along a narrow band, east of the Condamine plain; in most places it is covered by the younger volcanic units (Figure 3). White, yellow and mottled clays are a key characteristic of WCM when exposed. Based on regional geological mapping, the WCM is interpreted to underlie major parts of the Condamine Alluvium (KCB, 2011c) (Figure 4). It is also interpreted as 'basement' in many of the drill holes that fully penetrate the CRAA, with logging references such as coal, siltstone, sandstone and shale common. WCM thickness increases from ~50 m at the east to 150-350 m at the west (KCB, 2011c).

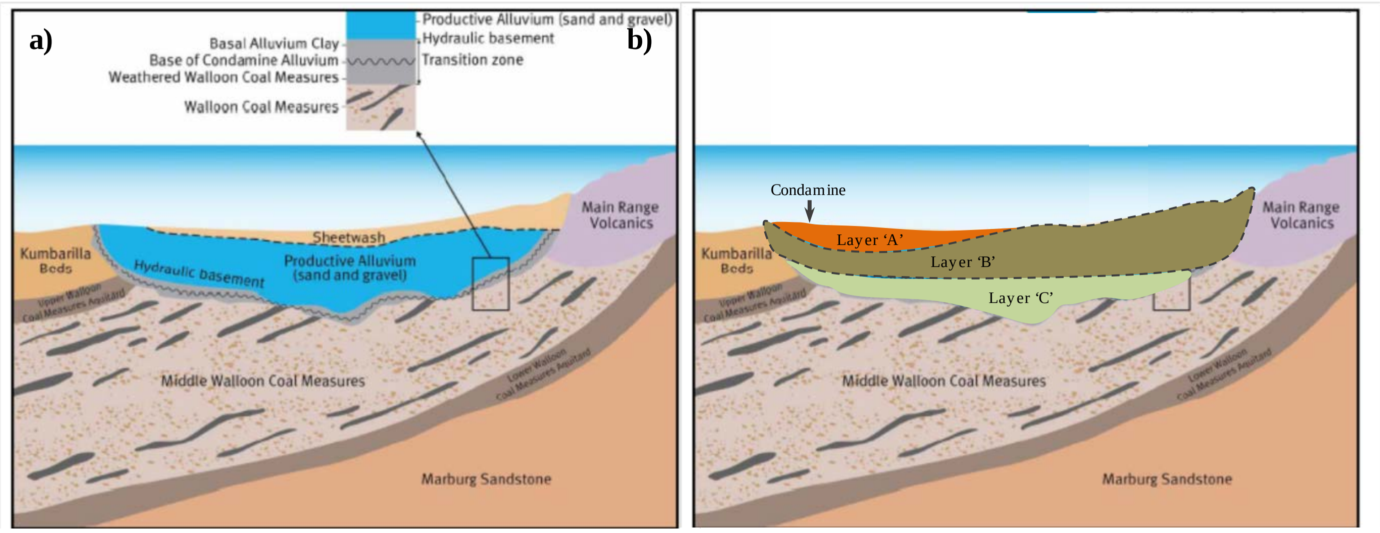


Figure 4: *Schematic geological section across the Condamine Alluvium. (a) After QWC, 2012 (b) the same section adapted to SKM (1999) sub-division of the CRAA.*

• <u>Kumbarilla Beds</u>

Kumbarilla Beds is a generic formation term used to describe the weathered outcrop on the western side of the Condamine catchment. It is equivalent to the Late Jurassic to Early Cretaceous formations, and is exposed in a north-south trending range west of Dalby (Kumbarilla Ridge). Within the study area, the beds are predominantly Jurassic units, comprising (from bottom to top):

- Springbok Sandstone: comprised mainly of medium to thickly bedded sandstone, with some siltstone and mudstone, and thin coal seams.
- Westbourne Formation: comprising fine-grained siltstone and mudstone.
- Gubberamunda Sandstone: consists mainly of medium and coarse-grained, poorly cemented quartzose sandstones. In much of the basin, the Gubberamunda Sandstone conformably overlies the Westbourne Formation.

Some geological maps include these three units in one map unit, while in others, division to Springbok and Gubberamunda units was made (nonetheless, overlooking the Westbourne Formation).

The Kumbarilla Beds outcrops west of the Condamine plain, with some small outcrops protruding through the alluvium around Cecil-Plains. It is thinnest around the margins of the Surat Basin, and in the region of the Condamine Alluvium is probably less than 100 m thick (DME, 1997). Erosion of the Kumbarilla Beds by local creeks and historical flow-paths of the Condamine River has led to some localised sand sheets intermingled with the more clayey alluvium derived from the upstream and eastern side of the catchment.

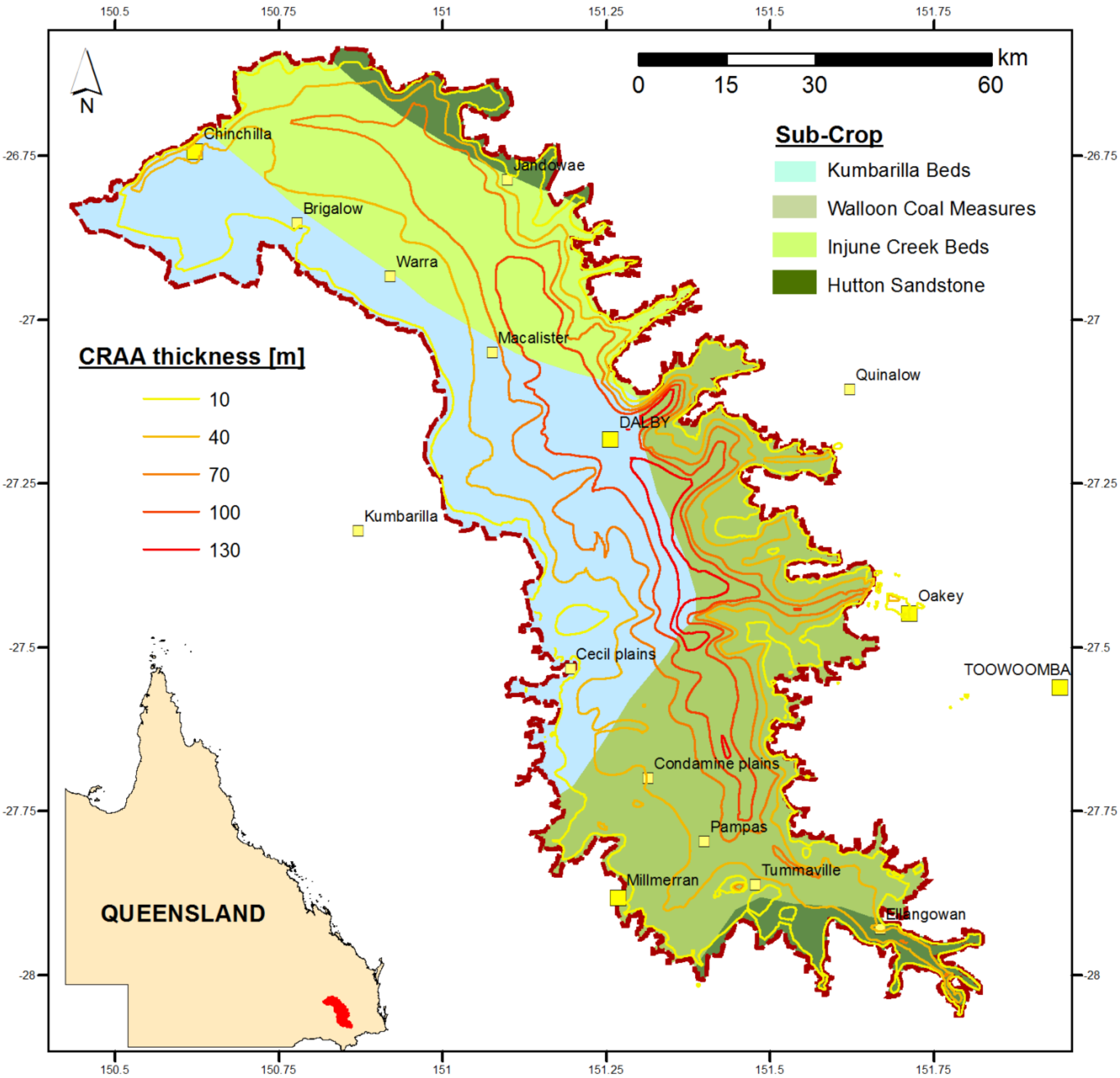


Figure 5: *Sub-crop map of the CRAA (source: GHD, 2012).*

Tertiary Main Range Volcanics (MRV)

The Tertiary Main Range Volcanics (MRV) consists mostly of olivine basalt and some pyroclastics dating from the Late Oligocene to Early Miocene (Day et al., 1983). The MRV outcrops east of the Condamine plain, constructing the Great Dividing Range. Several small isolated outcrops appear within the Condamine plain (Figure 3). The MRV unconformably overlie and cut-through older formations. The basalts are an erosional landscape and have been a primary source of clastic materials for the alluvium since their eruption.

The geological evolution of the Condamine paleo-valley and the Condamine plain

The thickness of the alluvial deposits within the CRAA ranges from less than 10 m in the headwater areas and along the valley margins to apparently 130 m in the central part of the plain, near Dalby (Figure 5). The apparent location of the deepest part of the paleo-valley floor in the middle of the valley, rather than at its downstream end, along with other geological evidence led researchers to postulate the Condamine paleo-valley evolved in two stages (Exon, 1976; Lane, 1979):

1) An incision period during the Cretaceous, during which a southerly flowing river from the north and a northerly flowing river from the south incised into the relatively erodible Jurassic rocks, merging near Oakey and draining eastwards. In its paleo-upstream areas, i.e., in the north and in the south of the valley, a traditional alluvial system with a centrally located channel and moderately symmetrical channel 'walls' developed (KCB, 2010b). As the system progressed downstream and as the alluvial plain broadened, the thalweg was located east of current valley centre, with steep eastern banks and gentler sloping western banks (~20 m/km and 6-7 m/km, respectively). The uppermost weathered Jurassic rocks underlie the alluvial sediments have been described as *"poorly cemented sands with clayey layers... frequently characterised at the upper surface by white or mottled coloured clays"* (Lane, 1979, p.77).
2) A depositional period during the Tertiary, at which time alluvial sediments were accumulated within two sequential environments: a lacustrine environment, in which a large lake filled the valley during the Tertiary-Pliocene, followed by a fluviatile environment, in which a meandering stream gradually developed during the Quaternary, as the valley filled with sediments (Lumsden, 1966; Exon, 1976; Lane, 1979). The Tertiary-Recent alluvial sediments include fine to coarse-grained sediments, gravels and channel sands interbedded with clays deposits, which are derived from the surrounding rocks.

Currently, the Condamine River erodes the Pliocene-Pleistocene terraces (Lumsden, 1966; Lane, 1979). It was assumed that continuous and relatively excessive sediment load from the wetter, more erosive east forced the river to flow at its current location, i.e., in the western rims of the Condamine plain (Lane, 1979).

Lithological sub-division of the alluvium

The Condamine alluvium consists of heterogeneous valley-fill deposits and has been described according to two schemes (Figure 4). The first scheme is based on depositional environments (Lane, 1979; Huxley, 1982) under which the alluvial section is divided into two prominent units:

1) **A 'fluvial alluvium'** ('productive alluvium' in KCB reports) comprised of fine-granular sediments, with a general increase in fine material over granular material in the downstream direction. It formed under varying depositional environment, between riverine high energy to lacustrine low energy. Typical section is comprised of relatively thin (less than 10m) fine, mixed or granular horizons, that are difficult to interpret across section.
2) **A 'sheetwash alluvium'** which presents as a wedge of generally fine and/or mixed material abutting the eastern channel wall and overlying the more varied fluvial alluvium. In many places, individual clay and silt horizons are logged as quite thick (over 20 m), and there is generally an absence of clean granular horizons, except where sediments have been reworked by higher energy streams from the east.

The 'fluvial alluvium' dominates the western part of the valley, and is attributed to flood-plain deposition along both strands of the Condamine River. To the east, and generally east of the 'north branch', it is overlaid by the 'sheetwash alluvium' (Figure 4a), attributed to transport and sedimentation processes from the eastern tributaries, forming outwash fans. The boundary between both does not coincide with the geological mapping units. Several recent studies adopted this scheme while introducing a 'transition layer' at the bottom of the alluvium, as a third layer (Figure 4a) (KCB, 2010b; QWC, 2012). The 'transition layer' (also 'transition zone') refers to a clayey zone in between the granular/mixed alluvium and underlying Jurassic formations, and was encountered in ~200 drill holes (QWC, 2012). This interpretation of the clayey zone is a matter of conjecture, since the same lithology may represent ground-up Jurassic sandy sediments associated with drilling muds (Biggs A., personal communication, 2013).

The second lithological scheme is based solely on borehole lithology (SKM, 1999). Accordingly the alluvial section is divided into three layers marked 'A'-'C' (from top to bottom):

1) **Layer A** characterised by predominance of sand in the uppermost part of the section. Its maximum thickness was limited to 20m, following a statistical analysis of sand distribution in the alluvial profile. It extends from the western margins of the CRAA as far east as the north branch of the Condamine and thickens beneath the main branch of the Condamine.
2) **Layer B** captures all the sediments that are not included in layers A or C. It consists of sands, clays and some gravel. Its thickness ranges from 20 to 80 m, with the greatest thickness along the thalweg of the paleo-valley, thinning westward.
3) **Layer C ('basal layer')** characterised by appearance of white sediments in the lower part of the section. Its upper surface was defined on the basis of the uppermost borehole log records which refer to 'white sands and gravel'; its lower surface is the bedrock. Layer C thickness and extent is therefore determined by the bedrock topography (Figure 5b). Layer C consists of sands and gravel, with clays and fine-grained sediments in places. Its typical thickness varies between 20 m to 60 m, with greater thickness along the thalweg of the paleo-valley floor.

In the geological maps, a different distinction was made between two alluvial units referred to as 'flood-plain alluvium' in the major part of the Condamine plain and 'older flood-plain alluvium', found generally along old fluvial terraces at the valleys rims (Figure 3). A third distinct unit, 'the Chinchilla Sand', crops out near Chinchilla (Figure 3). It contains Cenozoic fossils and comprises conglomerate, sand and sandy clay. No correlation was made between the sub-surface lithological sub-units and the surficial map units. Only limited palynologyical investigations (A common method for dating sediments and correlating lithological units between bores) have been undertaken for the Condamine Catchment (De Jersey, 1973). It is assumed that further work will help with constructing a comprehensive stratigraphy understanding of the colluvium and alluvial sequences (Kelly and Merck, 2007) and the lack of such work is a major deficiency.

Regional Hydrogeology

The Condamine plain lies within the eastern margin of the Great Artesian Basin (GAB); in comparison to the scale of the GAB it is relatively minor both in thickness and extent. The GAB comprises a sequence of alternating layers of permeable sandstone aquifers and lower permeability siltstone and mudstone aquitards (see Table 2), including the Jurassic units which surround the CRAA.

Table 2: Stratigraphy of the Jurassic column

<table>
<tr><th>Age</th><th>Main nomenclature</th><th colspan="2">Alternative nomenclature</th></tr>
<tr><td>Cretaceous</td><td></td><td rowspan="5">Kumbarilla beds</td><td rowspan="3"></td></tr>
<tr><td rowspan="8">Jurassic</td><td>Orallo Formation</td></tr>
<tr><td>Gubberamunda sand stone</td></tr>
<tr><td>Westbourne Formation</td><td rowspan="4">Injune creek Group</td></tr>
<tr><td>Springbok sandstone</td></tr>
<tr><td>Walloon Coal Measures</td><td rowspan="2"></td></tr>
<tr><td>Eurombah Formation</td></tr>
<tr><td>Hutton sandstone</td><td rowspan="2">Marburg sandstone</td><td rowspan="2"></td></tr>
<tr><td>Evergreen Formation</td></tr>
</table>

Notes: reviewed geological units are in bold; prospective aquifers are shade.

Outcrops of the Jurassic units surrounding the CRAA are therefore part of the 'recharge' area of the GAB. The overall recharge rate for sandstone outcrop in the area was estimated to be 1-5 mm/yr (Kellett et al., 2003; QWC, 2012). Groundwater flow in the GAB under the Condamine catchment is generally toward the west-south-west (Welsh, 2006). The major aquifers, including Hutton/Marburg, Springbok and Gubberamunda sandstones are laterally continuous, have significant water storage, and are extensively developed for groundwater use (primarily stock, domestic/town/industrial water supply). Generally, away from the recharge zones, vertical water leakage is induced by pressure differences, and tends to be upwards, with the deeper artesian aquifers feeding shallower artesian aquifers, and shallow artesian aquifers feeding the near surface water table (Welsh, 2006). A general perception is that water levels in the CRAA and the underlying hydrogeological units *"were likely to be similar prior to development of the ground water resources of the alluvium."* (QWC, 2012, p. 29). Water quality in the GAB sub-units is generally good at the recharge areas, with increased salinity along the regional flow paths (Herczeg et al., 1991). Groundwater is typified by Na-Cl and $Na\text{-}HCO_3$ water types (Huxley, 1982).

At its eastern rims, the CRAA bounds several basaltic aquifers, the largest of which lies south to Oakey. Groundwater flow within these aquifers generally resembles the topographic relief. In places several (perched) water tables may arise. Groundwater in the MRV is typically dominated by $Mg\text{-}HCO_3$ water types.

Existing hydrogeological knowledge

Flow concept

Within the Condamine plain only one regional alluvial aquifer was conceptualised. Localised shallow (perched) aquifers have been identified at some places along the eastern rims of the valley, based on relatively elevated water levels in shallow pipes compared to deeper ones (Silburn M., unpublished information, 2012).

Groundwater flow within the CRAA is essentially from south-east to north-west, parallel to the elongated axis of the valley and the Condamine River (Figure 6a). The common conception is that the CRAA is fed by lateral inflow from the upper Condamine tributaries, with substantial contribution along the flow course of percolated water from the surface (the Condamine River itself and diffuse recharge), as well as lateral flow from the bounding aquifers. Diffuse recharge (rain and irrigation surplus) was only considered as a component in the water budget in the last decades, and its overall significance is under dispute.

The primary flow direction is well demonstrated in historical and current groundwater head maps, showing a gradual decrease of heads from +395 m - +380 m near Ellangowan to +305 m near Warra (Figures 6,7). The 2000-2010 head map (Figure 6b) shows alterations in flow and also demonstrates elevated heads along the Condamine River in several sections between Ellangowan and Tipton. This is in agreement with historical reports that within the same zone, individual property homesteads pumped groundwater for domestic use, as far back as 1946, from depths shallower than 10 m (Morse, 1950; Lane, 1978). Nevertheless, the scarcity of data probably hinders this trend from being mapped and identified for the 1940's map (Figure 6a). A secondary E-W flow direction is superimposed on the regional trend, as seen at the northern-eastern rims of the CRAA, down-gradient Myall creek during the 1940-50's and throughout the eastern rims during 2000-2010 period. It most likely reflects influx from the eastern bounding aquifers (Lane, 1979; Pearce et al. 2006).

Natural groundwater outlets include lateral flows toward the western bounding aquifers and through the limited alluvial section downstream, and probably diffuse discharge via vegetation. Since the 1960's, the CRAA has been heavily exploited mainly for agriculture purposes (irrigation). Estimated abstraction (metred and 'un-metered') varies between 97-70 Gigalitres per year (GL/yr, equivalent to $10e^6$ m^3) to the early 1980's and between 67-46 GL/yr since. The sustainable yield of the aquifer has been estimated, however, to be only 15-30 GL/yr (Kelly and Merrick, 2007). This has produced inevitable, on-going decline in groundwater table elevation at most of the CRAA, interpreted as over-exploitation.

Under the current pumping scheme, several hydraulic sinks exist east of the Condamine River, with groundwater table lower by ~25 m in respect to the un-exploited period (Figure 6b). It is believed that as a consequence, fluxes from the bounding aquifers toward the CRAA have intensified (KCB, 2010b). Furthermore, along the western rims of the CRAA, a reverse gradient was formed between the WCM and the CRAA (Hiller, 2010; KCB, 2011c; QWC, 2012). In addition, vertical gradient was noticed in multiple-pipe boreholes toward the central part of the alluvium, at depths where most pumping is concentrated (SKM, 2003).

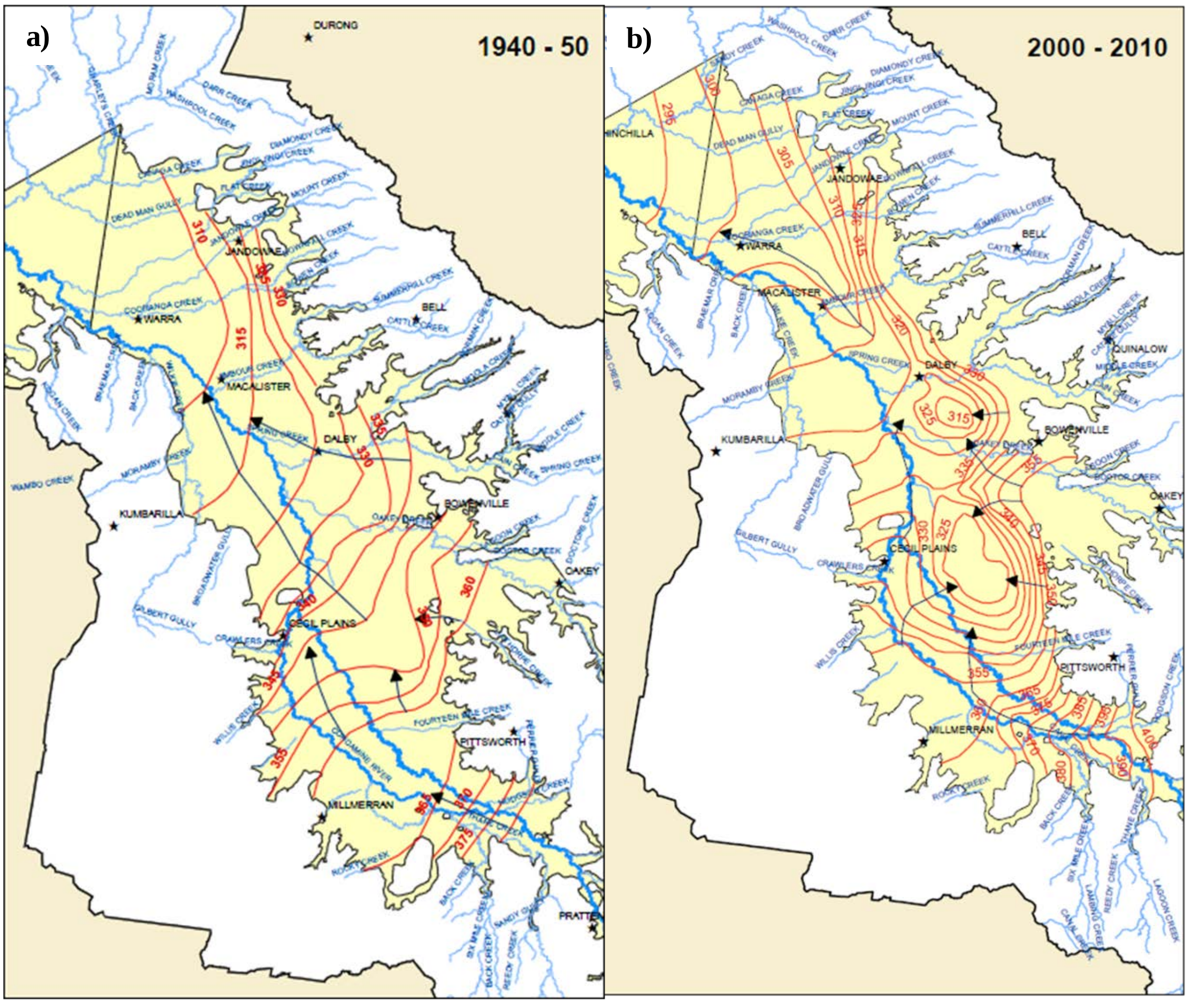


Figure 6: *Groundwater level and flow directions at the CRAA during (a) 1940-1950 and (b) 2000-2010 (adopted from KCB, 2010b).*

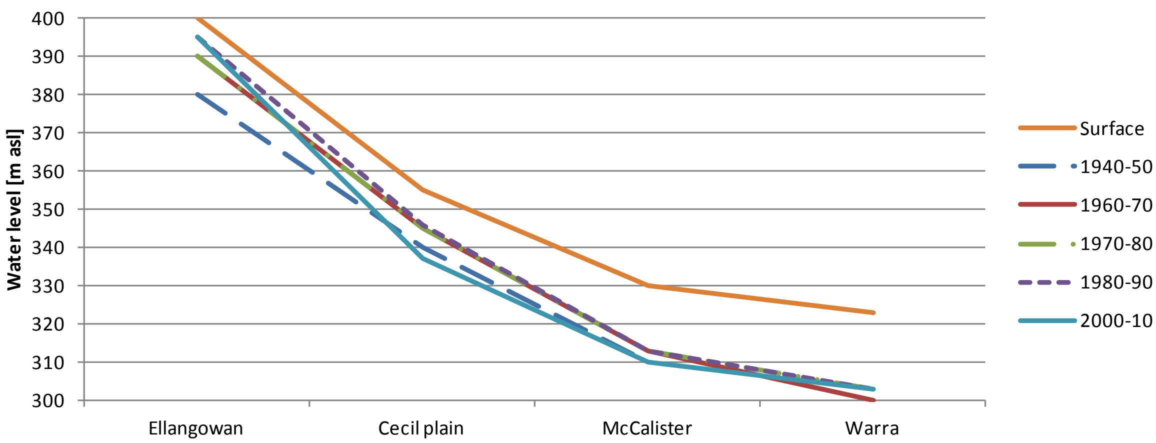


Figure 7: *Groundwater levels of the CRAA, averaged per decades (data adopted from KCB, 2010b maps and presented for locations along the Condamine River).*

Water budget

The overall CRAA water budget estimations, as well as estimations of its component contributions, have varied greatly between several studies (Table 3). For example, the overall influx has been estimated to be between 10 GL/yr to 51 GL/yr. To begin with, each study addressed different geographic areas within the CRAA, but even 'equivalent units', which average areal or linear sources, show large variability (KCB, 2011a). Moreover, different authors have addressed different components while neglecting others and each study covered different periods of time, including relatively wetter or drier periods, which may change some of the water balance components (e.g. more pumping during droughts). For all these reasons, the water budget for the CRAA is far from conclusive. In simple terms, it is comprised of the following components (Table 3):

Rivers contribution

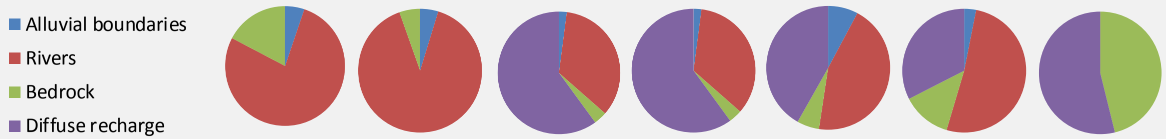
This component relates to percolation of surface-water from major streams, mainly the Condamine River, into the aquifer. Overall, streambed recharge was estimated in previous studies to vary between 11.5 GL/yr to 34.6 GL/yr (Table 3), accounting for the dominant component of the water balance of the CRAA (Lane, 1979; Huxley, 1982; SKM, 2003; Barnett and Muller, 2008; Parsons et al., 2008; KCB, 2010). According to Lane's (1979) observations, the overall conductance (percolation rates) of the Condamine 'main branch' varies between 38.5 to 115 Megalitre (ML, equivalents to $10e^3$ m^3) per year per km, depending on the water depth in the river, i.e. low-flow and flood-flow periods, respectively. In later studies it is considered to be 65-70 ML/yr/km (Huxley, 1982; Barnett and Muller, 2008; KCB, 2011a). Several studies included recharge from abandoned meandering sections along the Condamine River, which are only temporarily inundated, and estimated it to be 2 GL/yr (equivalent to a ~30 km length river section) (Huxley,1982; SKM,1999). Nevertheless, the Condamine's 'north-branch', which is also temporarily inundated, was considered as a detached river, which does not percolate to the groundwater table (Lane, 1979; SKM, 2003; Barnett and Muller, 2008; Parsons et al., 2008).

Lane (1979) concluded that none or negligible recharge occurs under several other streams, namely Hodgson, Oakey, Myall and Jimbour creeks (Figure 1). Yet, he estimated the potential infiltration through the downstream ends of Oakey and Myall creeks (where both traverse the 'fluvial alluvium'), to be 19.4 and 15.6 ML/yr/km, respectively, assuming an infiltration rate of 6 mm/d. Barnett and Muller (2008) included in their assumptions and model, streambed recharge from the Oakey and Linthorpe creeks (Figure 1) at a rate of 19.4 ML/yr/km, as was originally estimated by Lane (1979).

Induced recharge due to higher surface water levels, i.e., during floods and adjacent to weirs, was reported by Lane (1979). He states that "*significant recharge occurred as a result of stream flooding...in the majority of years*" (p. 134). Furthermore, he reports that adjacent to Dalby and Cecil-Plains weirs groundwater levels in shallow bores were slightly elevated (0.98-0.69m) relative to bores immediately downstream. Nevertheless, induced streambed recharge was not considered implicitly in the later studies water balances, primarily because "*there was no discernible or repeated correlation between flood events and hydrographs response*" (KCB, 2010b, p. 75). In their numerical model, KCB (2011b) distinguish a short section upstream to the weirs by using 'ponded' boundary condition as opposed to 'non-ponded' conditions along most sections of the river.

Table 3: Previous estimations of the Condamine River Alluvial Aquifer water balance[*]

			Lane (1979)	Huxley (1982)	SKM(2002) Conceptual	SKM(2002) Numerical	Barnet & Muller (2008)	KCB (2010)	Coffey (2011)
Alluvial boundaries	**Up-stream**	total	760	n/c	810	1163	0	316	n/c
	Eastern tributaries	total	280-410	1,470	250	250	2,800	705	n/c
	Down-stream	total	-645	n/c	-16,467**	-12,568**	-5,100**	-244.5	n/s
		[ML/km width]	129		567.8	433.4	175.9	48.9	
Rivers	**Streambed**	total	12,170 - 20,810	19,085 -32,634	15,750	11,539	16,000	11,158 - 22,761	n/c
		[ML/km stream]	44.6 - 76.2	69.9 - 119.5	102.3	74.9	103.9	40.9 - 83.4	
	Meanders	total	n/c	2,040	2,000	n/c	n/c	n/c	n/c
	Floods	total	n/c	n/c	n/c	n/c	n/c	n/c	n/c
Bedrock	**South-East (MRV***)**	total	380 - 530	1,130	1,410	1,604	1,604***	864	n/c
		[ML/km length]	2.4	5.9	9.4	10.7	8.4	4.5	
	North-East (Marburg)	total	3,230		n/c	n/c	n/c	3742	n/c
	West	total	-8050	520	390	441	485	500	730
		[ML/km length]		2.7	2.6	2.9	2.6	2.6	3.8
	Bottom	total		35	-1649	n/c	n/c	n/c	3,650
		[ML/sqKm]		-	0.4				
Diffuse recharge	**Rainfall**	total	n/c	n/c	23,464	20,402	15,000	10,265	5,110
		[mm/yr]			5.9	5.2	3.8	2.3	0.7
		[% of precipitation]			1%	0.10%	0.10%	0.05%	n/s
	Irrigation (Deep drainage)	total	n/c	n/c	7,492			446	n/c
		[mm/yr]			1.9			0.1	
Abstraction	**Metered**	total	-58,903	-61,403	-50,000	-44,379	-31,000	-46,400	n/c
		[ML/sqKm]	12	8	12.6	11.2	7.8	10.4	
	Un-metered	total	n/c	n/c	n/c	n/c	n/c	-20,000	n/c
		[ML/sqKm]						4.5	
Summary:	**Total in:**		**16,820 - 25,740**	**24,205 -37,754**	**51,566**	**35,399**	**35,889**	**27,996 - 39,599**	**9,490**
	total out:		**-67,598**	**-61,403**	**-68,116**	**-56,947**	**-36,100**	**-66,645**	**??**



Notes:
* Investigated area and period of each study slightly varies.
** Downstrean boundary of this study is located in the middle of the CRAA, see text for explanation.
*** Influx from MRV of 1,304GL/yr and from WCM of 300ML/yr (B. Barnet, personal communication, 2013)

Fluxes through alluvial boundaries

The inflow from the upstream (southern boundary) alluvial tributaries is considered a minor component in the CRAA water budget, yet it controls the general groundwater flow-field since it supports high water tables at this edge of the aquifer. Minor influxes from several other alluvial tributaries located along the eastern boundary of the CRAA are also account for in the water budget. These two were estimated to be 300-1,200 ML/yr and 250-2,800 ML/yr, respectively (Table 3).

At the down-stream (northern) boundary near Chinchilla, an outflow of 245-645 ML/yr was estimated. The high fluxes in the SKM (2003) and Barnett and Muller (2008) assessments, as appear in Table 3, are the groundwater fluxes crossing the middle part of the Condamine, and are merely due to setting the downstream boundary of their models across the middle part of the Condamine plain and not at its northern edge.

Bedrock contribution

This component refers to sub-surface fluxes from (and to-) bounding aquifers, under the influence of hydraulic gradients; it may represent lateral flow or vertical flow. Inflow to the CRAA occurs where the head in the bounding aquifer is higher than the head at the CRAA – outflow will occur otherwise.

As noted above, the CRAA overlies three aquifers: the MRV and the Marburg/Hutton Sandstones in the east and the Kumbarilla beds in the west. It was inferred that in-between, under most of the CRAA area, it overlies the Walloon Coal Measures Aquitard (KCB, 2010b). A recent sub-crop map, prepared by QWC for the entire Surat basin (Figure 5), exhibits the spatial extend of these units, as well as the Injune Creek Beds equivalent to WCM, beneath the superficial deposits (i.e., the recent alluvium and the MRV) (GHD, 2012).

Previous researchers consider limited-moderate hydraulic connection between the CRAA and the bounding aquifers, primarily due to the existence of the 'transition layer' at the bottom and the 'sheetwash alluvium' at the eastern rims of the CRAA (see section 2.2.4), both acting as low-permeability layers to reduce counter-fluxes. The estimated fluxes through the boundaries are presented in the following sections (Table 3):

• The eastern boundary

Positive gradient between the MRV and the Marburg/Hutton sandstone to the CRAA leads all researchers to consider these two as a permanent source contributing to the CRAA. However, inflow from the MRV was considered much more limited than influx from the Marburg/Hutton sandstone (Table 3). The latter supposition is allegedly supported by three bodies of evidence: (1) existence of E-W hydraulic gradient within the north-eastern rims of the CRAA (Pearce et al. 2006) as opposed to no indication of the existence of a hydraulic gradient within the south-eastern rims of the CRAA (Lane 1979), (2) the appearance of thick 'sheetwash' deposits along the contact line with the MRV as opposed to thinner 'sheetwash' deposits along the contact line with the sandstones, which in turn allow greater flux, and (3) a notable change in the CRAA water type, from Na-HCO3 to Na-Cl type north of Myall creek (Lane, 1979; KCB, 2010b). Barnett and Muller also considered influx from the WCM outcrops, at the south-eastern edge of the CRAA, estimated to be 300 ML/yr (Barnett B, personal communication, 2013).

• The western and bottom boundaries

On the contrary to the general agreement regarding the fluxes from the eastern boundary, the fluxes through the western and lower boundary are far from agreed. This is mainly due to lack of long-term, spatially distributed groundwater level data in these units (Hiller, 2010; KCB, 2010b, 2011c; QWC, 2012). Lane (1979) included in his water balance a leak (loss) of 8,050 ML/yr "*through the base of the alluvium or along the western edge.*" (p. 139) using a transmissivity of 134 m^2/d, hydraulic gradient of 1.16‰ and flow-section of 133 km length. Huxley (1982) estimates a much reduced leak through the western boundary while later studies (SKM, 2003; Barnett and Muller, 2008; KCB, 2010b; Coffey, 2012) conclude an influx of 390-730 ML/yr (Table 3). Flux through the lower boundary was estimated by some (Hiller, 2010; Coffey, 2012) to be positive (influx) while others estimated a leak from the

CRAA (Lane, 1979; SKM, 2003), based on controversial data showing a positive and negative hydraulic gradient, respectively. For example, SKM (2003) uses a vertical hydraulic conductivity of 1x10E^{-5} m/d and vertical gradient of 228^{o}/$_{oo}$ (8 m head difference / 35 m thick) to calculate a leak from the CRAA to the WCM of at least 1,649 ML/yr through an area of ~1970 km^2. Others (Huxley, 1982; Barnett and Muller, 2008; KCB, 2010b) did not account for vertical fluxes at all. At several localities, a dynamic transition from positive to negative gradient was observed over time due to decreasing heads in the CRAA (Hiller, 2010; QWC, 2012).

Diffuse recharge

This component relates to the percolation of water through the soils and vadose zone and into the aquifer following rainfall events and irrigation.

For decades, the common perception regarding diffuse recharge was that it is absent or negligible (Lane, 1979; Huxley, 1982; SKM, 1999; Hillier, 2010). To start with, the evaporation (monthly and annually) exceeds rainfall data (see Table 1), and leads researchers to concluded "*that most of the rainfall will be intercepted in the soil moisture store where it can be readily transpired before it can percolate to the aquifers located at depth.*" (Lane, 1979, p.15). Moreover, due to their low saturated hydraulic conductivities (on the order of 10 mm/day or less), montmorillonite clay soils were viewed as "*effectively preventing deep percolation*" *(*Huxley, 1982, p.13) and increasing runoff. Consequently, it was hypothesised that although cracking/swelling clays characterize these soils, and are permeable when dry due to cracking, the clay soils quickly becomes relatively impermeable after wetting due to swelling of the clays and sealing of the cracks (Huxley, 1982; SKM, 1999; Hillier, 2010).

Since the 1990's, a series of investigations, using deep soil coring, lysimeters, resistivity imaging, solute and water mass balances and modelling conclude that water does percolate, at different rates, through clay soils (Thorburn et al. 1990; Shaw, 1995; Willis and Black 1996; Willis et al. 1997; Moss et al., 2001; Yee Yet and Silburn, 2003; Tolmie et al., 2004, 2011; Smith et al., 2005; Scanlon et al., 2007; Radford et al. 2009; Hulugalle et al., 2010; Silburn et al., 2011; Kurtzman and Scanlon, 2011; Gunawardena et al., 2011; Baram et al., 2012). Deep drainage may be as low as 0.3 mm/yr under native vegetation (Tolmie et al., 2004), 2-18 mm/yr under dryland cropping (Tolmie et al. 2011) and as much as 50-200 mm/y under furrow irrigation (Silburn and Montgomery, 2004; Ringrose-Voase and Nadelko, 2012). The latter values are typical for furrow irrigation and can be significantly reduced with modern irrigation management (Silburn et al. 2013). The rationale was that for short-term periods, the cumulative effective infiltration (rainfall and irrigation minus evapotranspiration) exceeds the soil water deficit in the root-zone, and hence deep drainage can and will occur, negating the 'evaporation exceeds rainfall' argument. As the Condamine plain is an area with highly variable and seasonable rainfall, deep-drainage may occur several times each year, but is highly variable (Yee Yet and Silburn, 2003). One study (Foley et al., 2010) reported that the soil was dry under native vegetation but was wet (near saturated) to some 10 m under irrigated fields.

The researchers in the preceding paragraph suggested two co-existing mechanism for deep-drainage - the first is through the soil matrix, as the wetting front progress downward slowly and uniformly (Tolmie et al., 2004), while the other is a preferential flow ('*crack flow*', '*macro-pore flow*', '*bypass flow*'), when water infiltrates downward rapidly through discrete flow paths along the soil cracks (Kurtzman and Scanlon. 2011; Greve et al., 2012; Ringrose-Voase and Nadelko, 2012). Detailed description of these mechanisms is beyond the scope of this paper.

Following the growing evidence of the feasibility of percolation through cracking clays, several recent researchers (Hansen, 1999; SKM, 2003; Kelly and Merrick, 2007; Barnett and Muller, 2008; KCB, 2010b) have included a component of diffuse recharge in their assumptions or models. For most, it was determined to be a small fraction of the rainfall, express either as percentage (1% - 0.05%) or constant value (1 mm/yr, Schlumberger, 2011)(Table 3). Several studies used unsaturated-zone soil moisture water balance models, into which soil type, depth to GW and irrigation intensity was incorporated (SKM, 2003; Barnett and Muller, 2008). Hansen (1999) estimated recharge from rainfall and irrigation processes to vary between 0 to 25 mm/year and QWC (2012) mentioned that *"recharge rates through preferred pathway flow during high intensity rainfall events... can be up to 30 mm per year"* (p. 23), but are averaged to 2.8 mm/yr. Overall estimation of deep drainage under the entire irrigated cotton area at the Condamine plain is ~13 GL per irrigation season (30,000 hectare x 4.3 ML/hectare x 10%), equal to ~43 mm per season (Kelly and Merrick, 2007). One should note that the irrigated croplands in the CRAA cover approximately 109,000 hectares.

Abstraction

Throughout the 'Central Condamine Alluvium Groundwater Management Area' (CCA GMA), there are 315 water licenses held by 235 licensees, with a total entitlement of 94,000 ML/yr. The average estimated usage after mandatory and voluntary reductions is 67,000 ML/yr (Tan et al., 2010). Ninety per cent of groundwater extraction is by irrigators. Stock intensive uses and urban demand in regional centres account for about 5 per cent each.

Up until the 1960's, groundwater production from the CRAA was relatively small, and was not monitored or licensed. It was only in the 1960's that parts of Condamine plain were declared a 'district of sub artesian supply'- requiring new and existing irrigation bores to be licensed. Following on-going groundwater table depletion, a 'Condamine Restricted License Area' was declared in 1970 over the central irrigation area, resulting in an embargo, which restricted new irrigation licenses in this area. In 1978-9 The 'Condamine GMA' was declared, replacing the Condamine Restricted License Area. Meters were installed in this area to collect data and reduce demand; in the upper, lower and eastern rims of the Condamine plain pumping remained 'un-metered', with annually authorised allocation (cap) per end-user. Charges for use of groundwater and for 'excess water use' were introduced, in 1980 and 1982, respectively. As a result of these steps, water use dropped from ~75 GL/yr to 42.5 GL (Tan et al., 2010). Further mandatory reduction between 90%-70% of allocations was enforced over the central parts of the Condamine plain since 1994. Concurrently, total allocation for unmetered abstraction significantly increased between 1980 to 2009 (KCB, 2011a). In 2010, the CCA-GMA was reconfigured to match the geographical boundaries of the Condamine plain, and meters were installed through the entire area (Tan et al., 2010).

As a result of the former administrative divisions and existence of 'metered' pumping vs. 'un-metered' or 'un-registered' pumping for stock, domestic and coal and gas prospects, the historical pumping can be only roughly estimated. Lately KCB (2010b) estimated average metered abstraction for the years 1980-2010 of 46 GL/yr, aligned with official estimations (CSIRO, 2008), and un-metered abstraction (which was not accounted for in the numerical model) of 20 GL/yr (KCB, 2010b). As discussed previously, actual abstraction exceeds available yield estimations (13.2-30 GL/yr, Kelly and Merrick, 2007), and led to pronounced decline in groundwater levels within the CRAA. It should be noted that less than one-third of the water in-use for irrigation is based on groundwater pumping. The rest is from releases from major storages, harvesting stream-water and capturing of overland flow (SKM, 2003).

Water quality

Geochemistry

The geochemical composition of the groundwater is measured infrequently in all bores, especially in irrigation wells, for which most have only one record. Nevertheless, over time a substantial water chemistry dataset of thousands of records, dated back as far as the 1940's, has been accumulated. Some of the data was collected through several "designed" campaigns by different researchers (Lane, 1979; Huxley, 1982). A statistical summary of major ions chemistry from two of the recent studies is presented in Table 4.

Groundwater chemistry within the CRAA varies considerably (Table 4). For example, TDS ranges over three orders of magnitude, from fresh (103 mg/L) to saline (24,473 mg/L). Even when considering the 25th to 75th Quartile values, TDS still ranges over two orders of magnitude (440 - 1,640 mg/L). However, low concentrations of NO_3 (0.5-2.2 mg/l) and K (1.4 – 3.2 mg/l), as well as consistent mildly alkaline pH (7.6-8.2) are reported in most samples (Table 4).

The Condamine River water is characterized by TDS <300 mg/l (Lane, 1979). It is of Mg-HCO_3 composition along the tributaries, with gradual change to Na-HCO_3 composition downstream (Huxley, 1982).

***Table 4:** Summary statistics for water chemistry of the Condamine River Alluvial Aquifer*

a) KCB, 2010b

Parameter	Unit	Maximum	Minimum	Average	Quartile 25	Quartile 50	Quartile 75	Standard deviation	Number of Samples
Ca	mg/l	1150	1.7	67.2	28	40	60	111.4	2533
Cl	mg/l	13200	5	632.7	70	152	642.5	1297.8	2532
CO3	mg/L	3040	0.1	9	1.6	3.4	6.8	76.9	1680
Cond	uS/cm	30000	187	2384.6	730	1100	2845	3329.7	2534
Fe	mg/L	80	0.01	0.6	0.01	0.02	0.05	5.14	891
HCO3	mg/l	7950.8	2.4	397.4	310	388	458	207.7	2520
K	mg/L	82	0.1	2.83	1.4	2	3.2	3.83	1685
Mg	mg/l	1020	0.1	61.4	20	30	56	105.1	2526
Na	mg/l	7464.6	13	396.3	91.7	160	486.5	632.4	2531
NO3	mg/L	220	0.1	2.98	0.5	0.7	2.2	11.7	1391
pH		11.6	3.6	7.9	7.6	7.9	8.2	0.465	2534
SO4	mg/l	1300	0.1	65.1	7	22	81	110.8	2277
TDS	mg/L	24473.4	103.2	1437.3	440	640	1640.1	2174.4	2534

b) Coffey, 2012

Parameter	Unit	Maximum	Minimum	Average	Quartile 25	Quartile 50	Quartile 75	Standard deviation	Number of Samples
pH		9.7	5.6	7.9	Statistics not supplied				534
Conductivity	µS/cm	32,790	225	2,095					531
TDS	mg/L	21,313	146	1,361					531
Ca	mg/L	1,426	0.2	56					574
Mg	mg/L	1,020	0.1	49					565
Na	mg/L	5,775	7.1	353					572
Cl	mg/L	12,642	7	526					575
HCO_3	mg/L	1,179	0.4	372					546
SO_4	mg/L	826	0.3	56					513

Note: Ca= Calcium, Cl = Chloride, CO3= Carbonate, Cond= Conductivity, Fe= Ferrous, HCO3=Bicarbonate, K = Potassium, Mg= Magnesium, Na= Sodium, NO3= Nitrate, SO4= Sulphate, TDS= Total dissolve solids.

Maps of concentrations of specific ions, TDS and other geochemical properties (temperature, pH, conductivity etc.) were produced by different authors for different periods based on the collective data (Lane, 1979; Huxley, 1982; KCB, 2010b). A correlation between geochemical properties and concentrations to physical aspects of the aquifer, and to proximity to different water sources was identified from their compilation. Overall, low TDS, EC, Cl and Na concentration were correlated with a proximity to 'fresh' recharge sources; these were identified as mainly the Condamine River but also along several zones at the south-eastern rims of the CRAA (Lane, 1979; Huxley, 1982) (Figure 8). Increased sodium and chloride concentrations were thought to be the result of mixing/interaction with saltier bedrock water along zones of lower transmissivity, with the tacit assumption that water from these zones has a longer residence time in the aquifer (Huxley, 1982). Increased influence of groundwater from 'older sediments' was used to explain the trend of increased TDS with depth in several boreholes (Lane, 1979); to explain the increase in the conductivity downstream, toward the northern edge of the CRAA (Huxley, 1982) and; to explain several 'anomalous' geochemical compositions which appear in deep wells, perforated close to the basement rocks (KCB, 2010b).

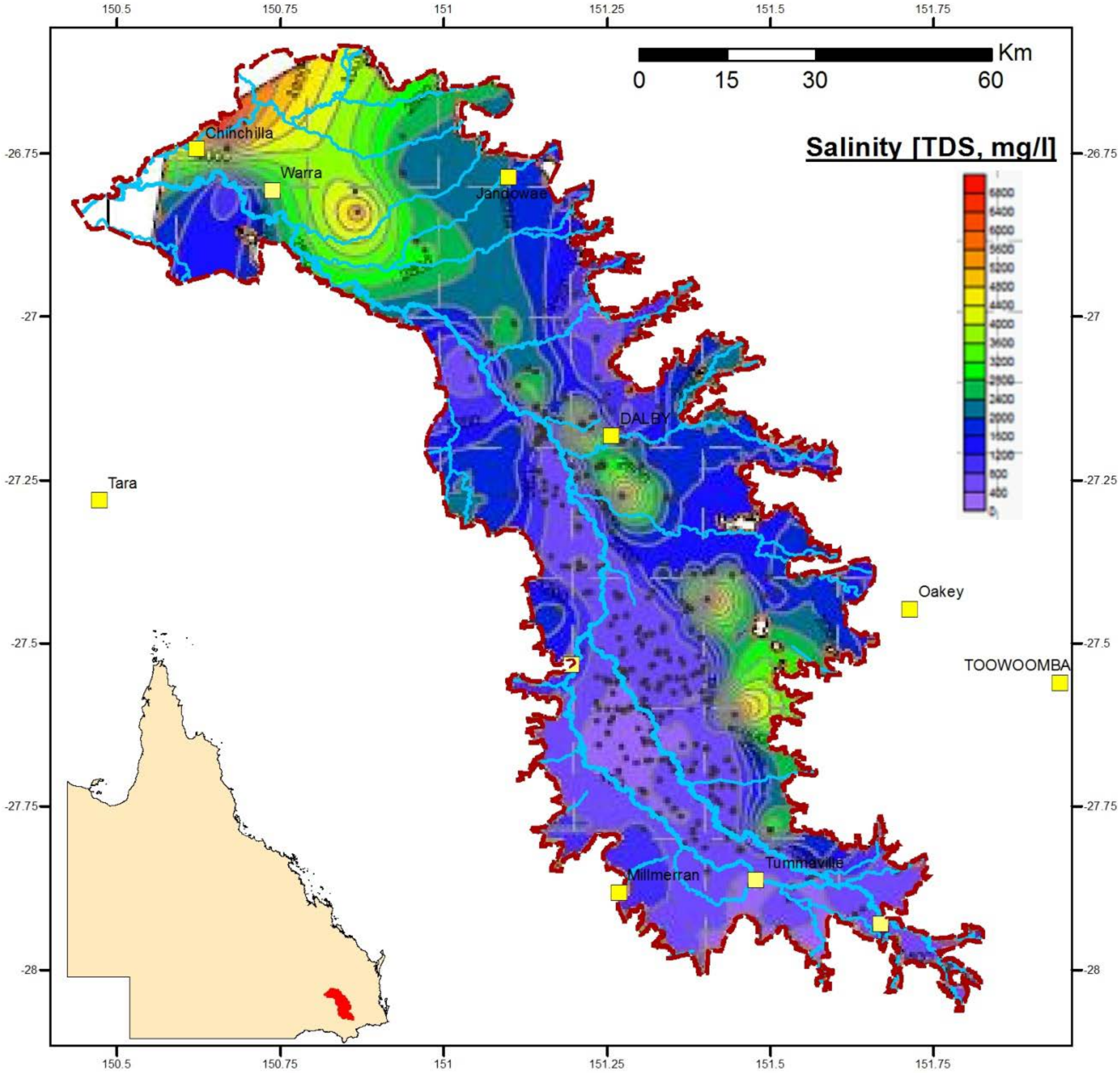


Figure 8: *Distribution of TDS content (mg/l) in the CRAA for the period 1985-1989 (source: KCB, 2010b).*

A northeast-southwest 'band' or 'belt' of high conductivity, TDS and other solutes was identified east of the Condamine (see Figure 8) (Lane, 1979; Huxley, 1982; KCB, 2010b). Lane (1979) correlates this feature to changes in the alluvium transmissivity; Huxley (1982) ascribes the increased values to the effects of the saltier fluxes from bedrock formations and KCB (2010b) notes that this belt corresponds with boreholes screened within deeper sediments which may have different (saltier) parent-rock.

Temporal variations of salinity of groundwater along the Condamine River, studied by McNeil and Horn (1997), show non-uniform trends. At that time, indication of decreased salinity appeared in the up-stream area of the Condamine (Pampas to the Condamine's branches convergence point near Cecil Plains, Figure 1c) and non-indicative rising salinity appeared further down-stream, to Dalby. KCB (2010b) presumed that McNeil and Horn observations were biased by a short-term temporary trend, and that over a long-term, the bulk geochemical concentrations of specific ions remain relatively constant; they reported minor temporal variations of concentrations only in several boreholes, with evidently very limited local effects.

It was also shown that the upstream part of the CRAA is dominated by $Mg\text{-}HCO_3$ water type, the central part by a $Na\text{-}HCO_3$ water type, and through the northern part a significant increase in the frequency of Na-Cl water-type occurs (Huxley, 1982; KCB, 2010b). The low salinity magnesium bicarbonate type water in the upstream areas was associated with influence of the Main Range Volcanics and the high salinity sodium-chloride type water in the downstream areas with influence of the Walloon Coal Measures. Different mechanisms, namely, water-rock interaction (rock weathering), mixing and dilution with surface water and between different water bodies, and halite dissolution, were suggested to explain the groundwater chemistry and the spatial variability by different authors (Gunn and Richardson, 1979; Huxley, 1982; KCB, 2010b).

Most trace-elements metals were below detection limits (Huxley, 1982; Silburn, unpublished data, 2009). Measurable amounts of iron, copper and zinc were linked to the borehole's (galvanised) steel casings, and thus samples were considered 'contaminated' (Huxley, 1982).

Pesticides

The Condamine plain is an area of intense agriculture where pesticides are frequently used. Nevertheless, the presence of pesticides in the groundwater has only been tested sporadically, both in time and place. In 1998 and 1999 several bores were sampled at Millmerran, Dalby, Chinchilla and St. George areas every 6 months (Waters, 2004); in 2001, another bore was sampled at Dalby (Waters, 2004); and in March 2009 three bores in the central part of the CRAA were sampled by Silburn (Shaw et al., 2012). The first and only positive detection of pesticides in the groundwater was reported in 2001, close to Dalby; bore water contained traces of several chemicals including endosulfan, metolachlor, trifluralin, atrazine, chlorpyrifos and prometryn in two occasions (Waters, 2004).

It should be noted that in the Condamine River itself, atrazine, endosulfan, prometryn and metolachlor have at times been detected (Waters, 2004; Kelly and Merrick, 2007). Thus, detection of pesticides in groundwater does not necessarily indicate leaching through soils, but may be due to river recharge.

Hydraulic properties

It is well acknowledged that due to the heterogeneous nature of the alluvium (recall section 2.2.4), the hydraulic properties of the CRAA are spatially and vertically variable. This was reflected in pumping tests analysis, where hydraulic conductivity ranges between 1-781 m/day and storativity ranges between 1.7×10^{-6} – 4.8×10^{-2} (Lane, 1979). In this matter, Huxley (1982) found that pumping tests are of *"very little use for determining hydraulic parameters"*, mainly for the considerable variation of the water-bearing horizons within the alluvial section. However, as a first estimation, the accepted perception was that moderate conductivities (30 m/d > K > 3 m/d) occurs in most of the CRAA, relatively high conductivity (K>30 m/day) occurs in the area where the Condamine River splits to two branches and in several other small patches, and low conductivity (K<3 m/d) occurs north of Warra- Jandowae line and along the south-western and south-eastern rims of the CRAA (Figure 9) (Huxley, 1982; Hansen, 1999; Schlumberger, 2011).

Nevertheless, it was speculated that different lithological units (i.e., layers 'a', 'b' and 'c' or 'sheetwash alluvium' vs. 'fluvial alluvium', see Table 5) have different hydraulic properties. For example, the 'sheetwash alluvium' was considered less permeable due to its increased clay content (Lane, 1979; Huxley, 1982; KCB, 2010b). In its model, KCB (2010b) assigned this unit conductivity of 0.2-2 m/d in compared with 10-40 m/d to the laterally fluvial unit. In contrast, the uppermost sandy layer along the Condamine River was considered relatively permeable. Laboratory testing of sand samples from the CRAA indicates hydraulic conductivities in the range 10-30 m/d (Lane, 1979, p. 190). This relatively high permeability made these units a subject for induced recharge studies (Lane, 1979; Donhue, 1989; KCB, 2011d). Barnett and Muller (2008) assigned their sandy 'layer A' a conductivity of 10 m/d compared with generally lower values to other units.

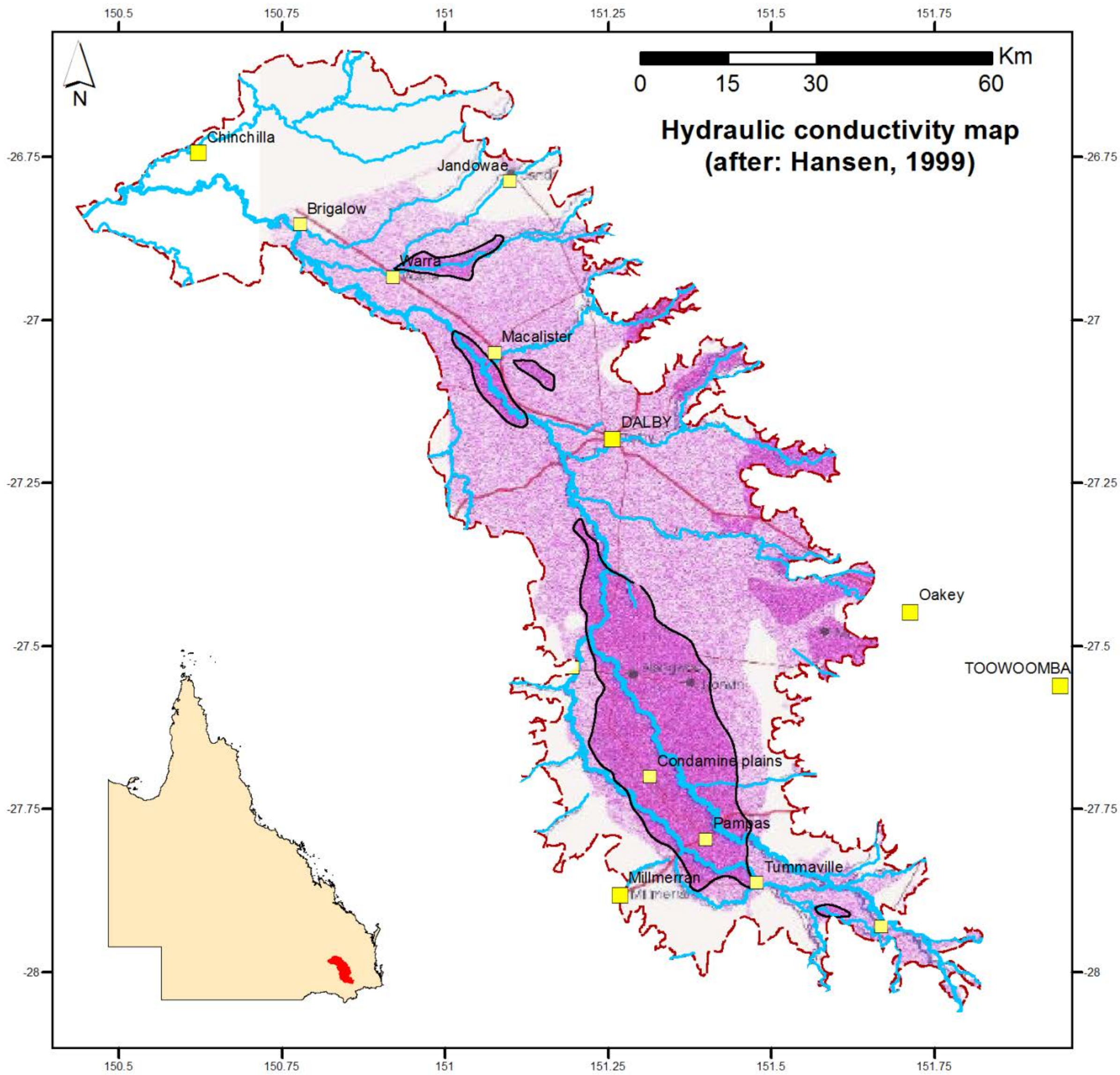


Figure 9: *Hydraulic conductivity (m/d) in the CRAA (source: Hansen, 1999).Colours represents hydraulic conductivity (K): dark purple K>30m/d; light purple 30m/d>K>3m/d; off-white K<3 m/d.*

As Table 5 suggests, a vertical distinction between sub-units within the CRAA has been adopted in most recent studies (SKM, 2003; Barnett and Muller, 2008; KCB, 2011b). Still, the adopted horizontal hydraulic conductivities values (0.2 m/d – 40 m/d) are generally lower than the values measured in pump tests, and this is rationalized as applying the bulk of the aquifer, which also contains clayey horizons, rather than being extrapolated for prospective sandy horizons (KCB, 2010b). Storativity however, is rather homogenous through the entire CRAA in all studies (Table 5).

The vertical hydraulic conductivity of the 'transition layer' is estimated to be in the range of $1x10e^{-2}$ - $1x10e^{-1}$ m/d (Huxley, 1982; SKM, 2003), though some (QWC, 2012) state a much wider range, spread over five orders of magnitude, from $8x10e^{-6}$ m/d to $1.5x10e^{-1}$ m/d. In the sole model to quantify the CRAA – WCM interconnectivity, vertical hydraulic conductivity was set to be 0.5 m/d through most of the model domain, with a value of $1x10e^{-3}$ m/d in the southern zone of the CRAA (Schlumberger, 2011). It should be noted that this exercise resulted in the highest vertical influx to the CRAA, of 3.6 GL/yr.

Table 5: *Hydraulic properties assessments of the CRAA*

Study	Hydraulic Horizontal Conductivity (m/day)	Kv:Kh Ratio	Specific Storage (m_{-1})	Specific yield [%]
Hansen, 1999	1 - 30			
SKM, 2002 Layer A (3 zones) Layer B (5 zones) Layer C (5 zones)	5 – 30 0.5 – 10 5 - 10	1:10 – 1:50 1:2.5 – 1:700[1] 1:10 – 1:50[1]	5 x $10e^{-6}$	4% - 6%
B&M, 2008 Layer A (4 zones) Layer B (6 zones) Layer C (6 zones)	4 – 12 0.5 – 12 1 - 12	1:10 – 1:50[1] 1:5 – 1:50[1] 1:10 – 1:50[1]	5 x $10e^{-6}$	4% - 6%
KCB, 2011b Fluvial Al. Upper (L1) Fluvial Al. Lower (L2) Sheetwash Al. (L1) Chinchilla sands (L1,2)	10 – 40 0.7 – 40 0.2 – 2 0.5 - 30	1:1[2]	6 x $10e^{-5}$ – 2 x $10e^{-2}$	1% - 10%
Schlumberger, 2011	5	1:10[1]	n/s[3]	5%
GHD, 2012	1.9 – 40 (Avg. 16)	1:1	Extracted from KCB, 2011b.	

Notes:
1 Anisotropy of 1:4000 - 1:5000 was set at the south-east part, where Kv was lowered to 0.001 m/d.
2 based on visual estimation.
3 not specified in the relevant report.

Modelling effort

The groundwater flow field within the CRAA was modelled in the framework of either an independent aquifer or as a small part of the Surat Basin or the GAB (Table 6). The areal spread, initial and boundaries conditions, water balance, 3D grid, number of layers, calibration period and calibration methods vary between models, according to each conceptual and numerical approach and thus will not be discussed here in detail. For example, some models included several layers, allowing a vertical gradient to occur within the CRAA (SKM, 2003; Barnett and Muller, 2008; KCB, 2011b), while others included only one layer.

The last decade's models have higher spatial resolution and are usually calibrated for transient conditions over long periods. Most of these models were carried out as part of the increasing interest in CSG exploration, either by commercial companies (Golder, 2009; URS, 2009; Worley Parsons, 2010; Schlumberger, 2011) or on-behalf of the regulatory agencies (KCB, 2011b; GHD, 2012).

A sole attempt to model transport processes in the CRAA was made by SKM (2003). Their model was based on the finite-differences method and accounts for advection and dispersion. Boundary conditions included inputs from effluent irrigation lands, the Condamine River and Oakey and Linthorpe creeks. The model was not calibrated and serves to test changes in water quality in several predictive irrigation scenarios (effluent irrigation), with respect to homogenous initial values.

Table 6: *Previous numerical models for the Condamine Aquifer*

Model	**Frame** C - CRAA S - Surat	**Software**	**No. Of layer for CRAA**	**Spatial Resolution (cell dimension) [m]**	**Remarks**
Lane, 1979	C	IFD[1]	1	(5,000-10,000)^2	
Young, 1990 Richards, 1991 Bengtson, 1996	C	MODFLOW	1	(5,000-10,000)^2	All three have same structure.
SKM , 2002	C	MODFLOW	3	1,000x1,000	Upper CRAA part, down to Dalby
Barnett and Muller, 2008	C	MODFLOW	3	1,000x1,000	Upper CRAA part, down to Dalby
Golder, 2009	S	MODFLOW	1	250x250	3 sub-regional models
URS, 2010 [2]	S	FEFLOW	n/a	n/a	
Worley Parsons, 2010 [2]	S	FEFLOW	1	n/a	
Schlumberger, 2011	S	MODFLOW	1	1,000x1,000	
KCB, 2011b	C	MODFLOW	2	500x500	
GHD, 2012	S	MODFLOW	1	1,500x1,500	

Notes:

1) Self script which solves the continuity equation with Integral Finite Difference method.

2) Original reports are confidential and were not available, however findings are discussed in USQ, 2011.

Critical review

The previous sections present a detailed description of the existing knowledge about the main hydrogeological features of the CRAA. From this, the authors conclude that the state of the art is far from being complete, perfect and clear. It obviously includes numerous 'gray areas' of significant uncertainty as to the basic elements essential to formulation of numerical models and understanding mechanisms of recharge, flow processes within the aquifer, and interrelations with neighbouring aquifers. These issues will be discussed in detail below. Water management and water allocations issues are excluded from this discussion as are their legislative-social-political context; the reader is referred to the recent paper by Tan et al. (2012) regarding these topics.

Hydrogeological processes

Identifying and quantifying the hydrogeological processes are of fundamental importance to any aquifer study. It accounts for the various components of groundwater entering and leaving a system for a given period, which may be in steady-state or a snapshot of time in dynamic states. Whether all the components are given, a balance between influx and outflux should exist. However, usually this is not the case, and many components are estimated.

The groundwater budget of the CRAA suffers from large uncertainty in all its inflow and outflow components (KCB, 2011a). To begin with, the pumping component, which can be easily and precisely captured and calculated, is only estimated, since until now there was a substantial fraction of unmonitored pumping in the CRAA. In addition, the downstream outflux through the northern edge of the CRAA is only roughly constrained, due to the lack of monitoring data in that area. Furthermore, lack of thorough understanding of the recharge processes from the upper surface (streams and lands) hamper better recharge estimations (Kelly and Merrick, 2007). These three components (pumping, downstream flux and recharge) were identified to have the highest likelihood of affecting the overall accuracy of the water balance (KCB, 2010b). Likewise, sub-surface fluxes are only rough estimates since all factors, the contact area, the vertical hydraulic conductivity at the contact, and the hydraulic gradient across the contact, are unknown or merely speculated. The following sections detail the knowledge gaps for the major water-budget components:

Streambed recharge

There is no doubt that the Condamine River was, and still is, the major source of low salinity water to the aquifer. Streambed recharge was estimated in previous quantitative studies between 11.5 GL/yr to 34.6 GL/yr, which is equivalent, when averaged over the length of the Condamine River, to 41 - 120 ML/yr/km. The remaining questions are: do the percolation rates vary in space and time, and if so, what are the geological, lithological, and hydrological conditions which control the percolation rates?

The answer to the first question is forthright. Lane (1979) himself (whose field work is the prime reference to streambed recharge estimation), testifies that recharge rates are spatially and temporally variable, in the range of 38.5 - 115 ML/yr/km, depend on the water depth in the river. Thus, a direct correlation to meteorological and hydrological conditions was established. However, researchers disagree where exactly the ‘yielding’ sections are. McNeil and Horn (1997) concluded that ‘good’ hydraulic connection appears down to the Condamine’s convergence point (5km north of Cecil Plains), ‘poor’ connectivity appears further down to Warra, and ‘weak’ connectivity appears from Warra to Chinchilla. Barnett and Muller (2008) noted that no percolation occurs along the downstream reach of the Condamine River, northern to its convergence with Linthorpe Creek. Parsons et al. (2008) rated most of the Condamine River in the studied area as a ‘medium’ losing stream, with the exception of a ‘high’ rank in the Ellangowan-Pampas section (Figure 1). None of these studies contains a quantitatively analysis of the percolation rates.

Two independent pieces of evidence may be used to solve this surface-groundwater connectivity uncertainty. The first is the lithology along the river and its vicinity. It is well recognized that the streambed recharge rates depend on the streambed lithology; higher recharge rates appear along sandy river banks than along clayey ones. Occurrence of sandy sediments near the surface is generally attributed to 'Layer A'. In accordance, SKM (1999) correlate the high connectivity river sections with the occurrence of this layer. The second is groundwater geochemistry: As the Condamine's surface water is apparently the 'freshest' water source of the CRAA, and groundwater tends to become saltier away from the Condamine River (Lane, 1979; Huxley, 1982; KCB, 2010b), maps of solute concentration may serve to detect streambed recharge areas. Previous studies (Lane, 1979; Huxley, 1982) already noted this trend, having correlated low TDS, EC, and chloride and sodium concentration with the proximity to the Condamine River, but nevertheless didn't indicate spatial distributions. Merely by looking at the TDS distribution map (Figure 8) one can detect such spatial variance. It seems therefore appropriate to combine groundwater salinity maps with the thickness map of 'layer A' to identify those sections in which streambed recharge occurs.

In addition, with the exception of the Condamine main branch, there is no agreement between researchers regarding other contributing streams. For example, recharge from Oakey Creek was considered as negligible by Lane (1979), but significant in Barnett and Muller (2008). From the text itself, it can be deduced that only major and continuous-flow streams are included in the water balances, however only Lane (1979) provides explanation to the inclusion and exclusion of tributary streams.

Furthermore, there is no consideration of the temporal changes in the stream-flow. This may include (1) the on-going trend of declining stream-flow (and hence declining water depth at the streams) occurring since the 1970's or 1980's (Kelly and Merrick, 2007), (2) land use changes over the catchment basin, which in-turn affect run-off fraction and (3) increasing effluent discharge to streams that previously were dry or intermittent.

To conclude, it seems that there is a great need to conduct field-work in order to establish and verify recharge rates through both, the perennial stream sections and the seasonal streams, including flooded meanders and weirs. Modelling the hydraulic processes in the unsaturated zone under and around the streams can also shed light on recharge rates and the time gap between a flood-event and the recharge; this includes flow and transport processes. Integrated models (surface – groundwater) can then be used on a regional scale to quantify streambed recharge with different scenarios such as climate changes effects. Numerical transport models can help to quantify recharge rates on a regional scale; such attempt has yet to be carried out.

Sub-surface fluxes

Overall, net inflow fluxes from bounding aquifers were found in previous studies to vary between 6% (Schlumberger, 2011) to 3% (SKM, 2003) of the total water balance. This reflects the complexity of estimating sub-surface fluxes through irregular surfaces (with unknown hydraulic permeability), but to a greater extent, the uncertainty in evaluating the hydraulic gradient between the CRAA and most of its bounding aquifers.

To date, limited fluxes have been considered between the CRAA and all its bounding hydrogeological units due to adjoining low-permeability alluvial sub-units. However, there is no certainty as to the thickness of this layer, its spatial continuity and its sediments, all of which influence the overall connectivity and conductivity. Firstly, it should be clarified whether the transition layer constitutes the uppermost, weathered part of the Walloon Coal Measures, following the originally definition of Lane (1979) or the broader definition of QWC (2012) which includes also "*low permeability basal alluvium clays of the Condamine Alluvium*" (p. 28) which "*may represent ... periodically deposited lacustrine sediments at the lake margins during filling of the system*" (KCB, 2010 p. 23). While the difference between the two may seem semantic, variation of over 40 m in thickness occur in places (QWC, 2012). Geophysical methods can be used to help identifying the 'true contact' in respect to the 'hydraulic base' horizons (both are KCB terminology). Furthermore, the thickness varies considerably between <5m to >40m, in some areas, such as near Dalby, over very short distances, and *"at some location the productive alluvial sands and gravels* (i.e. the CRAA) *seats directly on coal seams"* (QWC, 2012; p.28). So far no systematic analysis was done to correlate paleo-physical conditions, such as proximity to paleo-channels or paleo surface slope to the thickness of this layer. Likewise, no direct measurements of the permeability of the 'transition layer' are available, and estimates range over five orders of magnitude, from 8x10e^{-6} m/d to 1.5x10e^{-1} m/d (QWC, 2012). It should be noted that in the flow equations there is a trade-off between the thickness of a layer and its hydraulic conductivity; thus inaccuracy in either may reflect on the calculated inter-formational fluxes.

In addition, a lack of long-term, spatially distributed monitoring well network for the different hydrogeological units clearly hinders better estimations, as has been flagged in several previous publications (SKM, 2003; KCB, 2010b; QWC, 2012). Moreover, even existing boreholes penetrating the Jurassic section, are sometimes considered as 'un-representative', i.e., affected by or connected to the CRAA (KCB, 2010b). Establishing a regional dedicated monitoring network, with multiple pipes ('bore clusters') at selected locations, as recommended by QWC (2012), seems to be the best practise. Head maps of all bounding aquifers surrounding the CRAA should then combine with a sub-crop map (see previous section) and CRAA head maps to outline connectivity zones and to identify areas of positive/negative gradients (i.e., areas of inflow and outflow, respectively). Pumping tests performed by pumping from the lower aquifer while monitoring the head changes in the CRAA will help to constrain the vertical hydraulic conductivity. Altogether, this will enable better quantification of the sub-surface cross-formational fluxes. Spatially varied hydraulic gradient and hydraulic conductivity between the CRAA and the bounding aquifer should be considered also in numerical models.

The existing fluxes merely represent the current conditions, following long-term drawdown at the CRAA, and care should be taken when considering the fluxes at other (past or future) periods. For example, KCB (2010b) fluxes through the eastern boundary are slightly higher than Lane's (1979) estimations and are explained by steepening of the cross-formational gradient. A transport model may also assist with constraining the sub-surface fluxes, as it includes salt mass-balance as well as water mass-balance.

Diffuse Recharge

In contrast to other components of the water balance, there is no consensus among researchers regarding diffuse recharge. Previous estimations of diffuse recharge (rain + irrigation) for the CRAA can be divided into two schools: the earliest (Lane, 1982; Huxley, 1982) advocates that diffuse recharge could be neglected, while the current school, postulates that it should be accounted for in the overall water balance, with estimations varying between 5 GL/yr to 30.8 GL/yr (Table 3). The literature (e.g., Kelly and Merrick, 2007) treats the transition from the 'older' school to the current perception, as an 'evolutionary' process, deriving support from mounting evidence-base studies which testify to the existence of deep-drainage under clayey soils (Tolmie et al., 2004, 2011; Silburn and Montgomery, 2004; Silburn et al., 2008, 2011; Gunawardena et al. 2011; Kurtzman and Scanlon, 2011; Baram et al., 2012). However, it is now apparent both schools should be studied in the context of two land-use regimes - pre-cultivated and cultivated – as there is evidence of changes in the hydraulic conditions of the soil and infiltration rates due to the massive clearance of the native vegetation and its replacement by shallow-rooted annual crops and pastures (e.g., Foley et al., 2010). These include:

- Annual crops and pastures have shallower roots than the original native vegetation. This effectively reduces the amount of soil water available to plants and the buffer against deep drainage (Zhang et al., 1999).
- Annual crops and pastures have generally lower advection rates, less interception loss through canopy and overall lower evapotranspiration rates than the original native trees. This effectively increases the initial water reaching the surface per rain event, and thus increases the susceptibility to temporary deep-drainage (Zhang et al., 1999).
- Annual crops involve fallow (non-cropping) periods intended to increase soil moisture storage, resulting in soils

likely to reach saturation capacity more frequently (Yee Yet and Silburn 2003).

- As irrigation usually involves near-saturation of the soil, it increases the chance that following rainfall event will exceed saturation and result in deep drainage (Gunawardena et al. 2011).

Diffuse recharge in the pre-cultivated period can be neglected throughout the entire CRAA (KCB, 2011a), as suggested by the first school, as any possible infiltration would have been balanced by evapotranspiration. This concept is further supported by geochemical evidence: pore water in the un-saturated zone under native vegetation (leachate) is much saltier than groundwater, indicating that the accumulation of salts occurred over a long period of time. If extensive leaching had occurred, soil salinity would be predicted to be in steady-state with groundwater salinity (Foley et al., 2010; Tolmie et al., 2011). Similar soil-groundwater salinity dis-equilibrium is also known from other parts of the world with Vertosols soil types (Scanlon et al. 2010; Kurtzman and Scanlon, 2011). To date, no novel model has been built and calibrated for the pre-cultivated period, though such a model can constrain the hydraulic properties and other components of the CRAA water balance. In contrast, during the later cultivated period, diffuse recharge should not be ignored; however it should be distinct from the 'deep-drainage', for the following reasons. Thanks to the contribution of contemporary soils studies, there is almost no doubt that deep-drainage occurs under cultivated fields. It can be as high as 100-200 mm/yr under un-managed furrow irrigation (Silburn and Montgomery, 2004; Smith et al. 2005; Gunawardena et al. 2011) and up to 18 mm/yr under dryland cropping (Tolmie et al. 2011). In the upper part of the soil profile (1-3m), Cl concentrations are decreasing due to leaching (Foley et al., 2010; Gunawardena et al. 2011;Tolmie et al., 2011) (except where poorer quality groundwater is used for irrigation). The leachate is much saltier than irrigation water: up to 3 fold where irrigation water is salty (4ds/m) and up to 13 fold where irrigation water is fresh (0.3ds/cm) (Silburn et al., 2009; Gunawardena et al. 2011). Nevertheless, soil studies suggest that the deep-drainage is currently "filling" the unsaturated zone left dry by the previous native vegetation, rather than directly enriching the groundwater (Foley et al., 2010). In other words, the unsaturated zone serves as "moisture buffer", with a distinct time lag between the occurrences (initiation) of the deep drainage to the occurrence of the recharge. It is also hypothesised that the unsaturated zone serves as a "geochemical buffer" with a new equilibrium expected to be established over a time scale of 30 to >200 years (depending on drainage rate) from the time of land clearance, with a modified soil salinity concentration only a fraction of the original (Silburn et al., 2009; Gunawardena et al. 2011). These two concepts are supported by geochemical evidence as well: where ever the saltier leachate which percolates through the soil matrix has reached the groundwater, vertical salinity variance in the saturated groundwater column would occur, with the saltiest water-bearing horizons at the top. Though these settings were identified in a few multi-pipe monitoring boreholes, it is certainly not the general settings throughout the CRAA, with few other multi-pipe monitoring boreholes tracking the reverse situation. Thus, given that the moisture status and moisture capacity of the unsaturated zone remains poorly defined, inclusion of deep-drainage rates directly in the water balance as 'recharge' may be misleading.

Combining all the evidence we can conclude that even today, under cultivated conditions, broad-scale diffuse recharge remains doubtful (KCB, 2011a); groundwater quality in most places has not changed over several decades (KCB, 2010b) and there are no confirmatory evidence of vertical variations. This conclusion should have a large impact on the CRAA water budget. Diffuse-recharge through cultivated soils and the unsaturated zone should be addressed in future studies, including its dependency on land use (crops demand) and on soil type, precipitation rates, irrigation intensity (water/moisture availability), and the thickness and properties of the unsaturated zone (water retention and time-lag). At the same time, it is recommended that monitoring of the upper part of the alluvium, at and near the groundwater depth should be undertaken, to detect salination.

Downstream boundary (north)

Estimates of the flux through the CRAA down-stream (northern) boundary are relatively low, comprising only 1-3% of the overall water-budget. While this may represent the current conditions, where most groundwater is pumped and utilized, it is more than reasonable that in the pre-developed period, this flux volume have been much higher. The head map (Figure 6b) suggests that currently only the area north of Warra-Jandowae line drains toward this boundary; the reminder draining towards several 'hydraulic lows' created by over-exploitation. To date, no attempt has been made to characterize the hydrological conditions along this boundary during the pre-developed period, including a possible condition of a 'gaining stream' along segments of the Condamine River. Indeed the sediments and their properties are also poorly defined in this large downstream segment of the CRAA.

Temporal and spatial analysis of geochemical database

There are several obstacles hindering a thorough analysis, both in space and in time, of the substantial water chemistry data set available. To begin with, about 50% of the CRAA wells were sampled only once, and just 1% of the wells were sampled more than 5 times. For this reason, no attempt to characterise salination trends in specific boreholes, which can lead to better understanding of the recharge processes, has been ever published. More frequent measurements would allow analysis of time-trends, such as multi-annual salination, seasonal changes and even saline water migration in response to pumping in specific boreholes (as suggested for the 'anomalies samples', KCB, 2010).

Furthermore, so far the geochemical data has been presented on a two-dimensional plane view (i.e., maps) and not filtered or sorted by depth or geological material. Thus heterogeneity of the groundwater quality in the vertical plane was generally ignored, despite the earlier observation by Lane (1979). Displaying ion concentrations over geological cross-sections can be one practical way to demonstrate heterogeneity, layering and trends. Nonetheless, many of the borehole descriptions lack data regarding their total depth, perforation depth and feeding aquifer unit (information that is extremely important for deep wells and wells at the rims of the CRAA), impeding any such attempt. It is worth noting that the sole intent to identify hydro-geochemical processes by aggregating water samples from vertical slices of the aquifer proved inconclusive and did not highlight end-members or dominate processes (KCB, 2010b).

Inconsistent sampling strategies and drivers make the task of sorting 'representative' samples/sites for the entire CRAA yet another obstacle for regional analysis of geochemical data. For example, some data may be relevant merely to a well's immediate vicinity, as its monitoring purpose is to collating local information (e.g., leaks from dams (ring tanks) which in turn characterise the water composition in the dams). Some samples may contain drilling fluids, if taken during drilling, without proper purging. These data may be interpreted as 'anomalous' when extrapolated for the entire region. Any attempt to identify and exclude these 'artificial influenced' boreholes, must be done manually; a process which is time costly and therefore is not attempted. This is yet another step beyond a systematic quality control process which filters and removes invalid samples (e.g., with extremely poor ion balance). It should be noted that 'sorting' effort has been conducted several times so far, creating duplicated and wasted work; these were never implemented or stored as a separated corporate database.

Any future analysis should attempt to identify 'end-members' from which the aquifer water evolved. Such end-members may include 'fresh' Condamine water, 'fresh' basaltic water, brackish deep-drainage and 'saline' bedrock water types. Likewise, future studies should quantify the 'diffuse-recharge' and the relationship between soils and deep-drainage to the groundwater, including the hydro-chemical processes and travel time in the unsaturated zone. It should be noted that the high salinity water in the upper soils and the unsaturated zone endanger the aquifer, by the risk of salination. The failure to quantify these processes creates a high degree of uncertainty in the management policy of the basin.

Model formulation

Generally, the recent models (SKM, 2003; Barnett and Muller, 2008; KCB, 2010, 2011) are of improved scale and better representation of boundary conditions, including surface-subsurface interactions. Nevertheless, none of the models incorporate all hydrogeological processes and water budget components; for example, influx from the eastern WCM outcrops was only incorporated in Barnett and Muller (2008) model, and influx from Marburg-Hutton sandstones was only incorporated in KCB (2011) model. None of the models include fluxes from, and to, the underlying WCM, though several include this component in their conceptual model. Furthermore, there is still disagreement regarding the internal lithological schemes which reflects on the values and distribution of the hydraulic properties of the alluvium. Specifically, several issues need to be addressed:

• Model domain:

This should be based on (hydro) geological rather than administrative constraints. It should include all the prospective zones of the Condamine Valley, i.e. zones of perceptible alluvial thickness. Since at its rims, the alluvium section is usually thin (<5m) it is often overlooked, and considered un-prospective. Where ever these zones are not included in the model domain, a sub-surface inflow should be considered through these boundary sections, as the thin alluvium zones are often saturated. This methodology was demonstrated in KCB (2011b) model only for sections where thick alluvial fans are governing the CRAA from the east.

• The north-western boundary:

Recent models do not consider the large quantity of water which, in pre-developed times, may have discharged through natural outlets, in particularly through the down-gradient, north-western boundary. Presumably, if the groundwater discharged through the western boundary, an E-W gradient would have occurred. Since this was not the case (see Figure 6a), it is assumed that the northern boundary served as the major natural outlet. However, the alluvial section along this boundary is shallow and narrow. Therefore it is possible that the outflow was to the surface water 'gaining streams' or through the underlying aquifers. Assigning and testing this hypothesis can be conducted by setting-up a model for the pre-developed period.

• The lower boundary:

The lower boundary of the CRAA should be clearly defined and mapped. It should allow influx and outflux between the CRAA and the bounding formations, either aquifers or aquitards, according to the sub-crop map, the prevailing head differences and characterized hydraulic conductivities. Such a method was demonstrated in the settings of KCB (2011b) model, assuming limited conductivity ($5x10e^{-3}$ m^2/d) and bounding head equal to the CRAA pre-developed head, though it is not clear whether it was actually implemented since water fluxes through this boundary were not presented or discussed.

• Boundary conditions:

As mentioned above, all the CRAA spatial and vertical boundaries should allow hydraulic inter-connection with the neighbouring aquifers and alluvial tributaries. One way of doing so is by setting-up third type boundary conditions with (1) limited conductivity and (2) reasonable bounding head. The main advantage of this methodology is allowing water to enter or leave the model according to the dynamic hydraulic gradients, while at the same time constraining the fluxes from being infinite. This methodology was best demonstrated in Barnett and Muller (2008) and the KCB (2011) model, for most of the spatial boundaries.

• Parameterization:

The CRAA alluvial deposits are highly heterogenic and efforts to enforce internal geological-lithological schemes are hindered in many cases by poor description of wells logs. Use of a stochastic approach to characterize the hydraulic conductivity, would be a possible solution to overcome this difficulty. Accordingly the available well logs lithology's should be categorized, clustered into 2-3 groups and interpolated in space. An example of such an approach in other Australian alluvial aquifer (Maules creek) was demonstrated lately by Giambastiani et al. (2012).

Nevertheless, despite the use of cutting-edge modelling technology and software, a lack of basic data still hinders decisive conclusions. Kelly and Merrick (2007) hypothesise in the matter of the CRAA models that *"...all groundwater modelling will contain some level of uncertainty in the available yield estimates and quantifying recharge locations and rates."* (p.14). Therefore, it seems that pursuing additional flow modelling effort, without acquiring substantial new data which can enhance the reliability of its results, is a secondary priority.

For the same reasons, care should be taken when using the current models for simulating past and future scenarios, such as climate changes. For example, it is highly unlikely that the severe changes in precipitation that occurred during merely the last 120 years (Kelly and Merrick, 2007) will be better acknowledged without a more refined understanding of diffuse-recharge mechanism.

Using the current models for predicting possible CSG effects should be of concern as well. As CSG extraction involves dewatering and depressurizing of the Jurassic WCM underling the CRAA, two separate groundwater tables might be formulated, one in the CRAA and the other in the underlying formations. Present models cannot handle these physical conditions due to software limitations. Thus any future modelling should be carried out using software which is capable of modelling multiple water tables such as FEFLOW.

Summary and Recommendations

The Condamine River Aquifer represents a commonly encountered hydrological situation- a rather shallow aquifer having several major distributed water sources, all unconstrained, with most of its hydrological data acquired during and following an intensive exploitation period. Lack of historical measurements with definite "closed" boundaries complicates the conceptualization of the aquifer, especially its water balance and hydrogeological processes.

Despite these complexities, the hydrogeology of the Condamine River Aquifer, including various hydrological, hydrochemical, and geological aspects has been studied for more than three decades. Better input approximations have been used to model the groundwater flow in the CRAA thereby increasing precision over time, however, with only minor increases in the confidence of the outcome. This is a direct result of the lack of well-focused field work to support and refine conceptualizations and modelling.

In order to enhance our level of understanding of the CRAA, the above mentioned knowledge gaps should be addressed. This includes conducting field work, desk-studies, modelling and monitoring. Field work outcome are invaluable and have no substitutes, yet it often involves extensive budget, time and work load. For this reason, we have facilitated a list of tasks which does not involve new drillings or excessive field work. It comprises monitoring and data acquisition at the current facilities, improving the database in terms of QC, and formulating several models for flow and transport, and presented below:

• Monitoring

The CRAA monitoring network includes 225 monitoring sites, some with multiple pipes ('bore-cluster'). Its extent and spread is generally satisfactory. However, monitoring frequency is far from been sufficient- most boreholes are monitored only 1-4 times a year and include only groundwater depth readings. More frequent measurements of levels, as well as Temperature and EC (herein, L-T-C), would allow identification of temporal trends, including seasonal fluctuations, multi-annual salination, and even saline water migration in response to pumping in specific boreholes (as suggested for the 'anomalies samples', KCB, 2010).

The authors recommend a more detailed monitoring scheme which includes frequent monitoring (10-12 times a year) in some boreholes, and less frequent monitoring in others (once every 6 month - 2 years). Measurements should be carried using standard L-T-C meters, which nowadays are routinely available. Automatic L-T or L-T-C recorders should be installed in key boreholes, to support identification of recharge mechanisms by recording the possible instantaneous responses to precipitation events.

• Quality Control (QC) of the geochemical dataset

The existing geochemical dataset contain thousands of records. Many of these however, are not valid and cause further confusion when analyses. A thorough QC process should be carried out to sort invalid records, such as samples with poor ionic balance, or samples which represent drilling fluids rather than aquifer water. This process can benefit from accompanied process to correct the aquifer which is attributed to each borehole. The refined dataset should be publicly available, unlike several previously similar efforts.

• Acquisition of geochemical and isotopic data

At the present, there is a lack of groundwater isotopic composition data, pesticides presence and other new-evolving geochemical compounds (e.g., CFC's, PPCB's.). These can assist in detecting hydrogeological processes in the CRAA, including detecting fast flow diffuse recharge through soils cracks and constraining ‘groundwater age’. For example, if river water (which presumable contains pesticides year round) is a major source of recharge as theorised elsewhere, and half-lives are long in the Condamine River (Waters, DNRM, pers. Comm. 2011), then pesticides may be seen as a tracer of river recharge. In turn, it can also assist in determining the vulnerability of the aquifer (to leaks of agriculture compounds and fertilizers). Therefore we recommend a systematic sampling campaign for stable and radioactive isotopes, pesticides and other compounds as a high priority. The campaign can also benefit from borehole imagining (i.e. lowering a camera into the bore) to check/describe the screened sections – this data is often absent from bore logs data base.

• Reproduction of sub-crop map

Though the conceptual realization of the Jurassic section underlying the CRAA is well understood, a detailed sub-crop map for the CRAA is yet to be published. Such a map will enable better quantification of the inter-formational fluxes by better constraining the contact area. The “solid geology” map of GHD (2012) (Figure 5), is a subtle version of such a map; however it does not include the underlying MRV and does not distinguish between lower sub-units within the Kumbarilla Beds, namely the Springbok Sandstone and the Westbourne Formation, which act as an aquifer and confining unit, respectively. Furthermore, it is seems desirable to divide the Injune Creek Beds west of Dalby into sub-units which may be equivalent to the nomenclature units of the Clarence-Moreton Basin. The sub-crop map may be reproduced based on the existing well-logs data, but can only benefit from new borehole data, in particular in the area between Dalby and Chinchilla, where there is a lack of clarity as to the true thickness of the CRAA.

• Formulation of a flow model for the pre-developed period

So far, no attempt has been made to capture the initial water-balance of the CRAA for the pre-cultivated period. Such a model will minimize the inherent uncertainty regarding several components of the water balance equation (mainly pumping, and as suggested earlier also diffuse recharge) and by doing so, achieve better calibration of the hydraulic conductivity of the CRAA, the ‘natural’ components of the water balance and the inter-connectivity with the bounding aquifers. These volumes should then be inputted into the (existing) dynamic models for the current period.

• Formulation of dynamic models for the current period

As mentioned above, sophistication of most current models is far ahead of the data reliability. It is therefore not of a priority to construct a new dynamic flow model prior to either (1) acquisition of superior field data, (2) a better conceptual understanding of hydrogeological processes and (3) use of sophisticated software with superior capabilities (e.g., multiple water tables, integrated surface-sub-surface). This however is not the case regarding transport models. So far, no attempt has been made to calibrate a transport model for the CRAA. Transport modelling should be pursued despite the mentioned uncertainty in water budget, since its calibration process possibly will enhance the understanding of hydrogeological processes and quantification of incoming and outgoing fluxes.

• Better coordination and collaboration

In the current environment of strong interest in the Condamine alluvium, and in particular with respect to its interaction with the WCM, it is essential that there is a more co-ordinated approach to investigations, research and modelling in the area. Multiple energy companies (coal and CSG), government agencies and universities are all ‘playing in the same field’ with little overall coordination. There is no strategic data capture plan and multiple organisations all attempting to achieve similar outcomes. A clearly defined research and data sharing plan would lead to more efficient and cost-effective data capture and less disparity in related modelling efforts.

Abbreviations

CRAA - Condamine River Alluvial Aquifer

CSG - Coal Seam Gas

DNRM - Queensland Department of Natural Resources and Mines

GAB - Great Artesian Basin

GL - Giga-litre (10e^{6} litre)

ML - Mega-litre (10e^{3} litre)

MRV - Main Range Volcanics (geological unit)

WCM- Walloon Coal Measures (geological unit)

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