# Salinity and salt load of the Fitzroy River during the water year 2010 - 2011

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# Summary

This report provides the results of a preliminary study into the salinity of the Fitzroy River in north eastern Australia for the reporting water year 2010-11.

The study objectives were to:

- Quantify the coal-mine contribution to the salinity load of surface waters in 2010-11
- Provide a basis for future research into river salinity in the Fitzroy Basin
- Identify data deficiencies relevant to understanding salt transfer in the Fitzroy Basin
- Further calibrate the Fitzroy Salinity Integrated Quantity and Quality Model (IQQM) for the Fitzroy Basin against gauging station data

River salinity is an important subject for Fitzroy Basin resource managers and the community, especially in terms of potential water quality effects from coal-mine releases. Concerns about river salinity due to the effects of mine releases have heightened since the 2008 decline in river water quality that eventuated from large water releases of an open-cut mine that had been inundated during an extraordinarily high rainfall event (DERM 2009b).

Salinity indicates the presence of soluble ions, and in surface waters these are commonly calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate and carbonate. These major ions are useful for tracing water sources and the environmental processes related to the ionic composition (McNeil, Cox & Preda 2005). This present study assessed possible origins of river water in 2010-11 by analysing major ions at sites within the Fitzroy Basin. It found several likely origins of the salinity of water bodies, including rainfall and oceanic spray deposits, weathering of rocks, sodic soils, past gold mining, and the operations of industry and irrigation schemes.

## The setting of the 2010-11 reporting year

Extreme weather affected most of the Fitzroy Basin during 2010-11 with flood warnings beginning early in the wet-season (Bureau of Meteorology 2013). Annual rainfall was more than double the long-term average for most of the basin (Section 1.4). Major flooding occurred around Emerald in the Nogoa catchment in December 2010 (Bureau of Meteorology 2013). In January 2011, flooding affected the Dawson River catchment, particularly around Theodore. More than 38.5 million megalitres (ML) of freshwater flowed from the Fitzroy Basin into Keppel Bay during this year. Hence, regional and local flows were a strong driver of riverine conditions during 2010-11.

There were many consequences of the flooding, including the inundation of coal-mine pits, which saw the release of a large volume of mine-affected water into the Fitzroy River system. This was justified to restore mining operations for the benefit of the Queensland economy. Reportedly, the volume of mine water released comprised 0.09% of the total volume of Fitzroy River flows during the 2010-11 wet season, i.e. 33,500 ML of 38.5 million ML (EHP 2013). However, it was unclear just how much these releases affected the salinity in the Fitzroy River system.

## The IQQM for salinity in the Fitzroy

This study used the IQQM with historic flow and electrical conductivity (EC) data to estimate salinity loads for 2010-11. In addition, calculated salinity loads from actual measurements of EC and stream flow were used to validate the IQQM estimates.

Based on the results of this present study, coal-mine water-releases of water year 2010-11 contributed 7% of the annual salinity load, which was estimated as 4.2 million tonnes at the end-of-valley site, The Gap, for the Fitzroy Basin. This likely varied over the year with variation in coal-mine water-releases and river flow. For instance, when the river flow was nil at The Gap, as in July to August 2010 (Figure 3), the contribution from coal-mine water-releases was likely negligible. Similarly, when there was abundant overland runoff contributing to river flows, as in the following December to January, the contribution from such releases was expected to be well diluted. Then, when stream flow subsided but releases continued, as occurred from February onwards, the contribution from coal-mine water-releases was likely much larger. This is supported by estimates from an analysis of a point-in-time in May 2011 (Section 4.1) and major ion signatures at The Gap (Section 3.2.2).

Interestingly, sources other than the coal-mine water-releases appeared to deliver most of the river salinity load at the end-of-valley, with approximately 93% of the river salinity load for the year being ‘background’. In this context, ‘background’ salinity derives from diffuse sources, which include from natural (climate and geological) and human influences (e.g. mining, irrigated cropping and grazing). Discerning the effect of the different influences requires future study, which would further assist in understanding the salinity issues within the Fitzroy Basin.

The findings of this project provide a basis for future research into river salinity of the Fitzroy Basin. Recommendations include investigating direct methods of incorporating groundwater information into the IQQM, and examining the variability associated with different management practices and climate regimes within the basin. A list of recommendations follows.

## Recommendations

The study findings have led to these recommendations:

- Conduct similar studies for successive wet years, i.e. 2011-12 and 2012-13, to further test and validate the outputs of the Fitzroy IQQM for salinity used in this study.
- Expand model calibration to include dry years and low flow conditions, both in terms of hydrology and salinity.
- Analyse current data and determine and implement appropriate major ion monitoring regime at The Gap gauging station, and higher frequency sampling at end-of-valley sites in sub-catchments to help discern salinity sources. Include community sampling to obtain major ion data for ephemeral streams in upper catchment areas.
- Develop a conceptual model to describe groundwater interactions, hot spots and release points within the Fitzroy Basin to inform a review of the Fitzroy Basin groundwater monitoring network with a view of understanding the contribution of groundwater to river salinity and for use in the IQQM.

- Conduct new research aimed at providing the following: groundwater modules in the Fitzroy Salinity IQQM, a better understanding the variability in salinity from different management practices, and gaining insight into the effects of sulphate accumulation in waters of the Fitzroy.
- Implement a reporting system with a uniform template for the reporting of coal-mine water-release data by industry to expedite the use of these data for future studies, including the development of predictive models. The Wastewater Tracking and Electronic Reporting System (WaTERS) that has been launched in South East Queensland for municipal amenities data is an example of such an approach.

# 1. Introduction

This report describes the salinity load of the Fitzroy River for the reporting water year 2010-11. In this context, a water year involves the 12 month period from July to June to capture the full extent of the summer dominant rainfall period. Results are based on pre-existing data and include the outputs of the Fitzroy Basin Integrated Quantity and Quality Model (IQQM) for salinity, which has been developed by the Queensland Department of Science, Information, Technology, Information and the Arts (DSITIA). The report also informs on the likely sources of salinity in the Fitzroy River system using water chemistry signatures. Additionally, it identifies data deficiencies for realising salinity transfer in the system. The Queensland Department of Natural Resources and Mines (DNRM) was commissioned by the Fitzroy Partnership for River Health to prepare this report for the water year 1 July 2010 – 30 June 2011.

## 1.1. Analysing river salinity loads and sources

River salinity loads are commonly estimated from flow and electrical conductivity (EC) data. A hydrological model, such as the IQQM (DLWC 1995), can be used to estimate salinity loads using these parameters. Gilmore et al. (2001) used an IQQM approach to estimate in-stream salinity within the Hunter Valley, New South Wales. Likewise, the Queensland Government designed an IQQM model to predict the cumulative salinity impact from coal-mine water-releases in the Fitzroy Basin after substantial mine releases in 2008 (Delzoppo 2011).

The subsequent years to 2008 have seen further record-breaking rainfall and flooding of coal mine pits. An IQQM has recently been released that incorporates data from these later years (2008 – 2012). It is proposed that this latest version of the IQQM will provide a good estimate of the salinity load contributions from coal-mine water releases for the reporting water year 2010-11 and that the water chemistry of major ions will identify the salinity origins.

Major ion composition provides a signature that can link water quality of surface water to groundwater, pluvial, lithic or industrial sources (Cañedo-Argüelles et al. 2013). The freshwater suite of major ions include the cations sodium ($Na^{+}$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^{+}$), and the anions chloride ($Cl^{-}$), sulphate ($SO_4^{2-}$), carbonate ($CO_3^{2-}$) and bicarbonate ($HCO_3^{-}$). Accordingly, in this context, ‘salt’ can relate to a variety of ion combinations other than the common sodium chloride (NaCl), which is table salt, the type that normally accounts for ‘salt’ in everyday use.

The sum of major ion concentrations in a freshwater sample is reported as total dissolved ions (TDI) or total dissolved solids (TDS), depending on the author (McNeil & Cox 2000). In this present report, the combined concentration of major ions is referred to as TDS, which is relevant in estimating river salinity loads.

## 1.2. Objectives of this study

This study into the salinity of the Fitzroy River Systems is the first of its kind to validate the IQQM outputs against measured data. It will likely identify gaps in information required for understanding much of the salinity dynamics of the Fitzroy system. Based on these disclaimers, the following are the study objectives:

- Quantify the coal-mine contribution to the salinity load of surface waters in 2010-11
- Provide a basis for future research into river salinity in the Fitzroy Basin
- Identify data deficiencies relevant to understanding salt transfer in the Fitzroy Basin
- Further calibrate the IQQM cumulative salt model for the Fitzroy Basin against gauging station data

## 1.3. Background

Salinity is an important water quality issue for the Fitzroy River. To comprehend why this is so, an overview of the factors at play within the Fitzroy Basin is provided in the following sections.

### 1.3.1. The Fitzroy Basin

The Fitzroy River in Queensland is the largest Australian river basin flowing to the Pacific Ocean. It is a very large and complex system with a catchment size of 142,665 square kilometres, which is twice the size of Tasmania. Numerous rivers, creeks, waterholes and impoundments make up this large system, which has major tributaries of Nogoa, Comet, Mackenzie, Isaac, Connors and Dawson Rivers. Large surface flows of the Fitzroy are sporadic in nature, in line with the intermittent summer rainfall patterns of this region (Kelly 1996; Kennard et al. 2009). Base flows are fed by springs (as in the upper Dawson and Nogoa Rivers, and Carnarvon and Mimosa Creeks) or alluvial aquifers. Flows are also regulated by infrastructure that capture up to 1500 gigalitres of river water for industry, commerce and town use (NR&M 2004); a supply thrice the volume of Sydney Harbour.

The Fitzroy Basin has a sub-tropical climate, which is humid near the coast and semi-arid inland. The climate differs with distance from the ocean and the topography of the basin. To exemplify this, the mean annual rainfall varies from around 1200 mm in the north-east (near the coast) to around 600 mm in the west (300 - 400 km inland). Temporally, climate of the Fitzroy Basin is strongly influenced by the *El Niño* southern oscillation. The strong variation in climate is reflected in surface flows, as evidenced at the end-of-valley site, The Gap, where annual river discharge varies from near zero to just over 35 million megalitres (Figure 1). Furthermore, Figure 2 shows a pattern in the long-term dataset of The Gap that reflects the variation in climate over the 50-year record period, with very wet years interceded by prolonged dry phases. Notably, a 15-year dry phase is shown flanked by the flood years of 1991 and 2008 (Figure 2). Overall, the region experiences a net loss of moisture from the environment in most years with the average monthly evaporation typically exceeding that of rainfall (Kelly 1996).

The effect of climate on salinity of the Fitzroy Basin is likely to be significant. For example, an extended dry period, like 1992 – 2007, would increase the depth of groundwater from the surface and so reduce the salinity surface expression. However, a number of wet years or a large flooding event, as in 2010-11, would again raise the water table and express more salinity at the surface (DERM 2011a; Water and Rivers Commission 2000). Many salinity outbreaks are first noticed after times of above average rainfall (DERM 2011b).

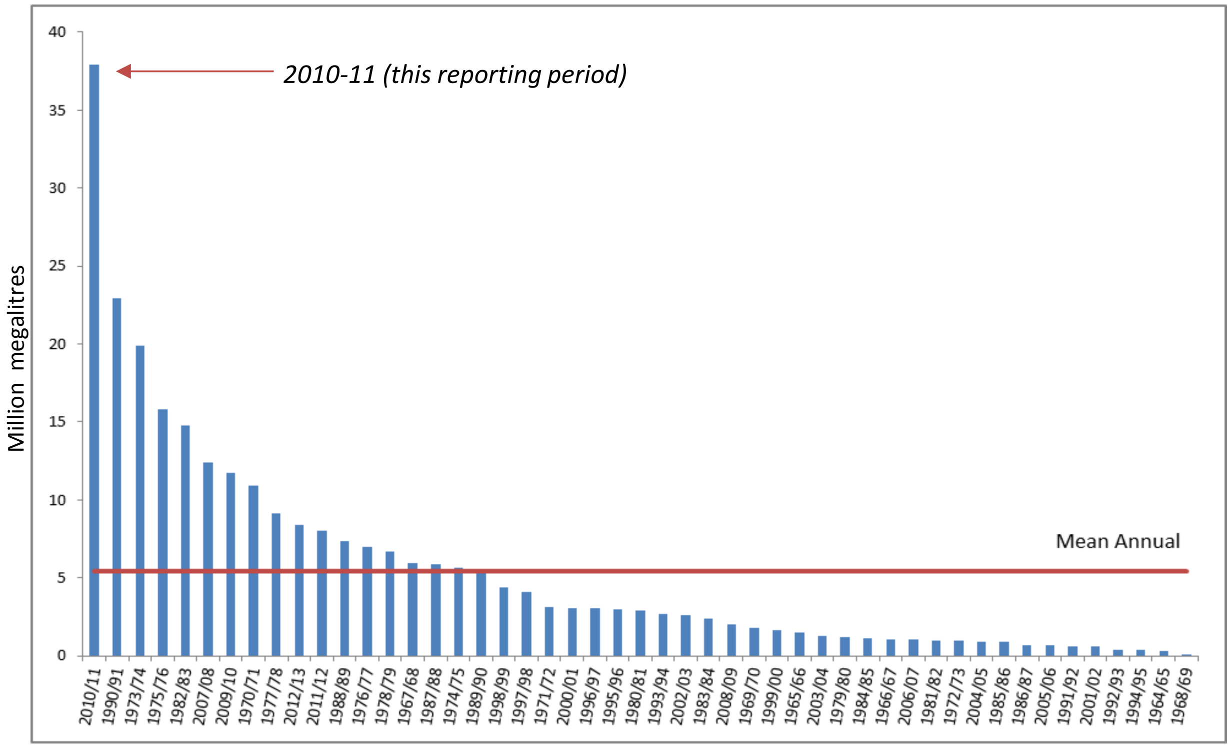



**Figure 1: The ranking of annual discharge (million megalitres) over long-term record (1964-2013) for The Gap**

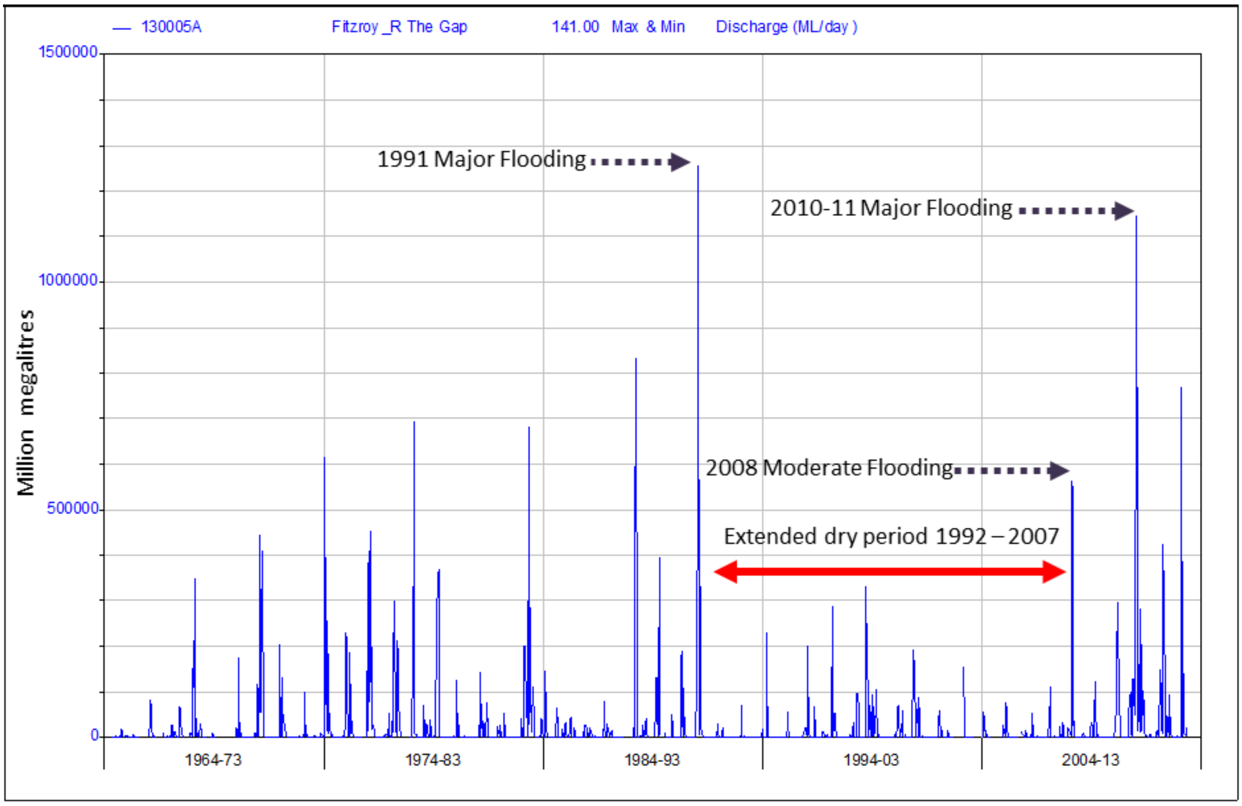



**Figure 2: Plot of the entire flow record as megalitres per day (ML day$^{-1}$) for the end-of-valley location, The Gap, showing the variability in flow that reflects the climate variation between years and decades**

Stream flow is a driving process of river salinity in the Fitzroy Basin. Jones & Moss (2011) described the common relationship between EC and flow in the Fitzroy, where EC increases as flow subsides. Electrical conductivity in microsiemens per centimetre (µS $cm^{-1}$) is commonly used as the measure for salinity of freshwaters within the Fitzroy region. Figure 3 shows how EC varied with river flow at the end-of-valley site, The Gap, during 2010-11.

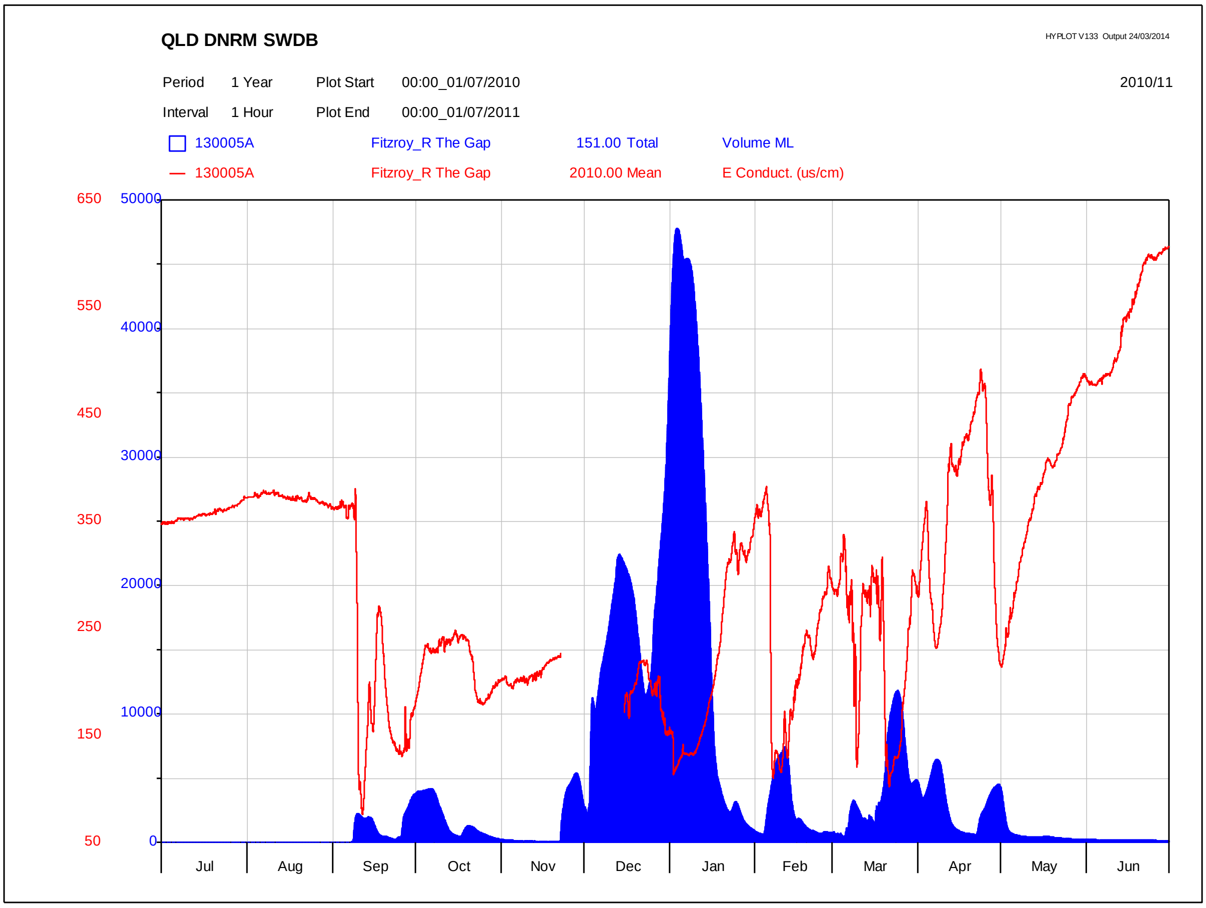



**Figure 3: Plot of hourly salinity measures (as electrical conductivity in µS $cm^{-1}$) and flow (ML) at the end-of-valley site, The Gap, over the reporting year 2010-11**

### 1.3.2. Soil types

The soils within the Fitzroy Basin involve 10 main types, as displayed in Figure 4. These are potential lithic sources of river salinity. Soil type descriptions can be found in Isbell (2002).

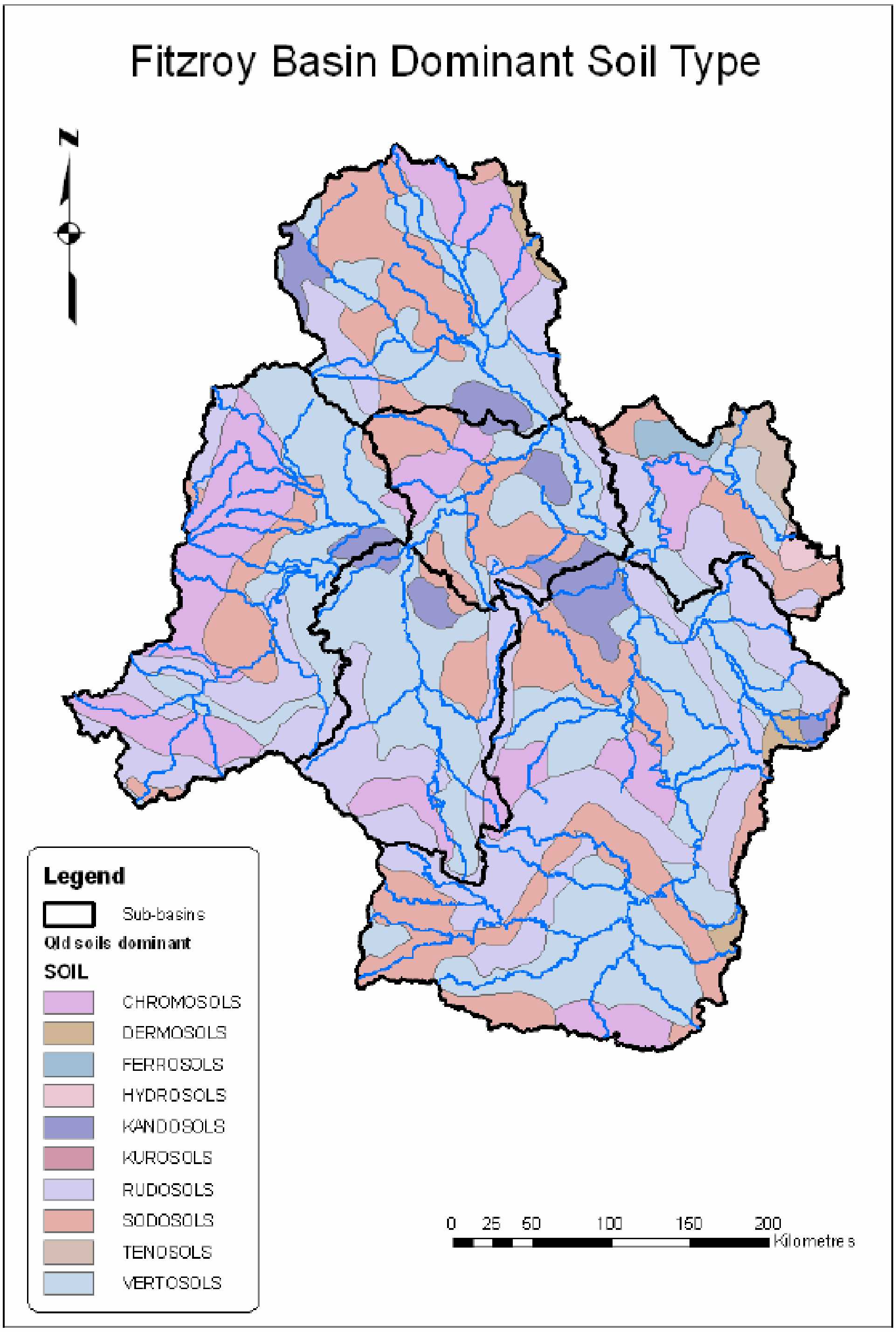



Figure 4: Dominant soil types in the Fitzroy River basin presented in Negus (2007)

## 1.4. The reporting year 2010-11

The major driving force within the Fitzroy Basin during the reporting water year 2010-11 was rainfall, with the Fitzroy Basin one of many areas affected by the extensive Queensland floods of that year. Rainfall was exceptionally high over much of the basin (Figure 5) and annual recordings were 160-180% of the long-term average in most areas, and up to 260% in areas in the north of the Isaac-Connors catchment (Jones, Ukkola & Eberhard 2013). Furthermore, this was the highest-ever annual discharge from the Fitzroy River (period of record: 1 July 1889 to 30 June 2012).

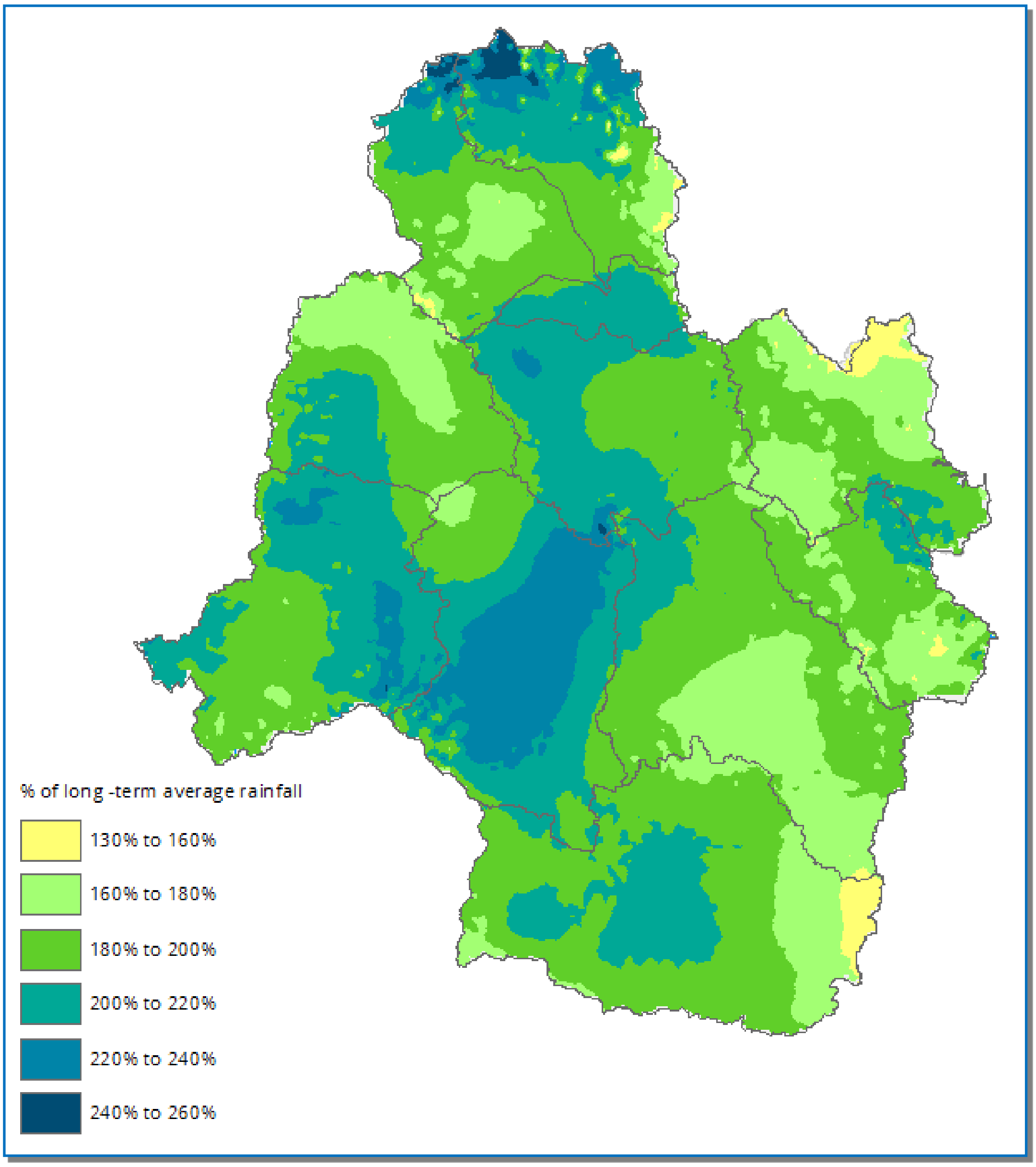



**Figure 5: The rainfall of 2010-11 shown as a percentage of long-term average annual rainfall (30 year record 1961-90) for the spatial extent of the Fitzroy Basin** (*data courtesy of Queensland Government and available from SILO climate data, www.longpaddock.qld.gov.au*)

The first flood warnings began in early September 2010 (Figure 6) and continued through to October 2010, when floodwaters peaked in the Nogoa, Comet, Mackenzie and Dawson Rivers (Bureau of Meteorology 2013). A much larger rainfall event in the week of the 23 to 29 of December 2010 followed, producing record flood heights at Emerald on the Nogoa River, Rolleston on the Comet River and Theodore on the Dawson River (Bureau of Meteorology 2013). Further heavy rain fell in the Dawson catchment in January 2011 and again in the upper Dawson in April 2011 (Bureau of Meteorology 2013). In total, the wide rainfall coverage in this year produced over 38.5 million megalitres (ML) of flood-affected water passing through Rockhampton and discharging into Keppel Bay (Queensland Floods Commission of Inquiry 2012).

Flooding is a natural phenomenon. However, the inundation of coal-mines and runoff over mining and farmed land can increase the minerals and salts entering local waterways and subsequently increase the salinity of adjacent freshwater streams (Cañedo-Argüelles et al. 2013). Figure 7 shows coal stock piles following rainfall events of 2010-11. Product can be seen as having been washed from stockpiles towards natural drainage features.

| JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy rainfall in the western Fitzroy River basin - flood peaks in the Nogoa, Comet, Mackenzie and Dawson Rivers | | | MAJOR FLOODING<br>Emerald<br>Theodore<br>Rockhampton |  | Flooded mines make controlled water releases under environmental authorities and transitional environmental programs | | | | |

Figure 6: Timeline of events for 2010-11

Figure 7: An aerial shot of coal stock piles affected by the rainfall events of 2010-11

The coal-mine water-releases of 2010-11 equated to just 0.09% of the entire wet-season flows passing through Rockhampton, i.e. 33,500 ML of a total 38.5 million ML (EHP 2013). The total contribution of these in terms of salinity loads, however, remained unknown at the time. Officials of the Department of Environment and Resource Management (DERM), now Environment and Heritage Protections (EHP), believed the higher than usual river salinity observed during the later months of 2011 was due to groundwater flows into the river system (Birchley 2011; Brier 2011). Nevertheless, the local community continued to express concerns about the impact of coal-mine water-releases on water quality of the Fitzroy River. At the same time, the effect on the Queensland economy as a result of flooded coal mines, which disrupted coal production, remained an important issue. The Queensland Floods Commission of Inquiry (Ch. 13, Queensland Floods Commission of Inquiry 2012) provides an account of circumstances and activities relating to the coal-mine water-releases that started late 2010 and continued through to the end of the reporting year, i.e. June 2011.

## 1.5. Salinity through human activities (secondary salinity)

Certain landforms in the Fitzroy Basin are more vulnerable to salinity expressions than others (DERM 2011a). Forster (2007) identified 68 dryland salinity occurrences in the Fitzroy Basin: 38 in the lower Fitzroy, 17 in the Dawson, 12 in the Nogoa, one in the Comet and zero in the Isaac/Connors catchments.

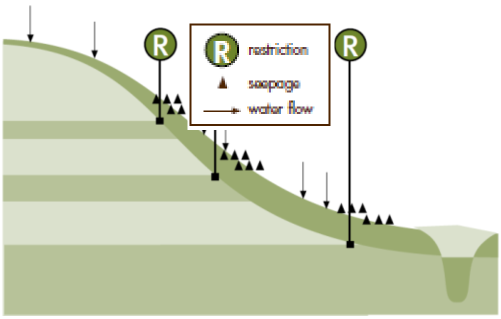
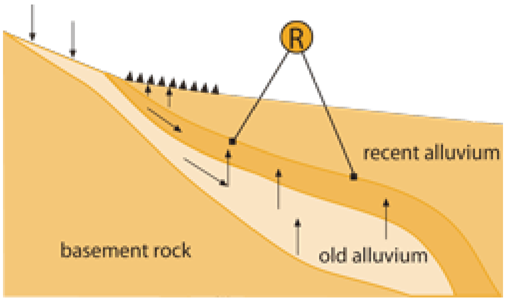
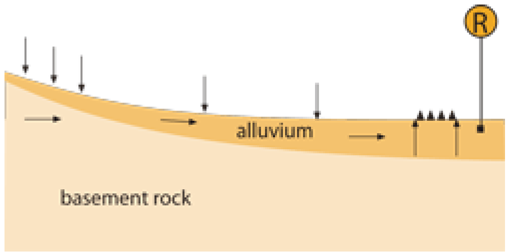



**Figure 8:The salinity model for the stratigraphic form indicated near Clermont, north of Emerald (Nogoa) and at Orion (Comet) as depicted by DERM (2011a)**

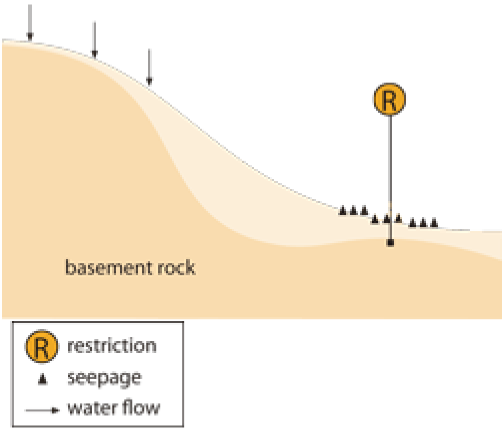
Forster (2007) suggested the salinity outbreaks in the Nogoa (near Clermont and north of Emerald) and the Comet at Orion were associated with a stratigraphic landform (Figure 8), where “small seepages and salted areas appear on hill slopes in response to variation in the permeability of different rock layers”. While climate, geology and landform are natural forces affecting river salinity, land-use activities can lead to greater and more widespread salinity issues than would naturally occur (Cañedo-Argüelles et al. 2013; Chamberlain et al. 2007). Forster (2007) described several landforms with salinity expressions associated with land-use in the Fitzroy Basin (refer to Figure 9 for examples)



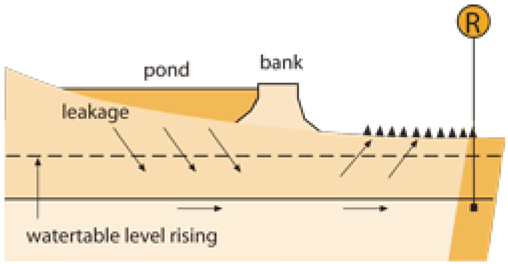

**Alluvial fan**, indicated near Thangool in the Callide Valley



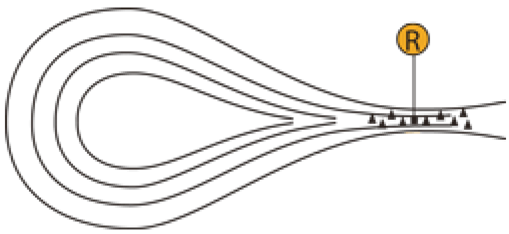

**Alluvial valley** seen south east of Theodore in the Upper Dawson (Wandoan)




**Catena form** seen near Rockhampton and at Marlborough in the lower Fitzroy




**Dams** can contribute to salting both upstream and downstream of the dam itself



**Natural constriction model** at Greenlakes in the lower Fitzroy

**Figure 9: The salinity models by DERM (2011a) that relate to conditions in the Fitzroy Basin**

Native vegetation clearing has greatly modified the Fitzroy Basin, with nearly two-thirds of the entire natural vegetative cover having been either lost or altered by 1999 (Accad et al. 2001). The country dominated by *Acacia harpophylla* was especially affected, since clearing for cropping and grazing was promoted under the auspices of the Brigalow Development Scheme (Cowie, Thornton & Radford 2007; Verwey et al. 2007).

Historically the basin has been cleared for cattle grazing and cropping, which remain major industries within the basin. Livestock grazing comprises 80% of the catchment area above The Gap (Table 1). Production forestry and cropping are the next uppermost land-use types, though covering less than 7% of the basin each. Coal mining and gas extraction activities (Figure 10) involve less than 1% of the total catchment area (Table 1).

Table 1: The land-use activities within the Fitzroy Basin, upstream of The Gap gauging station, as at 2011

| Land-use activity | $km^2$ | % of basin |
|---|---|---|
| Livestock grazing | 108412.5 | 79.81% |
| Production forestry | 8716.8 | 6.42% |
| Cropping | 7851.9 | 5.78% |
| Nature conservation | 6243.0 | 4.60% |
| Irrigated cropping | 1181.1 | 0.87% |
| Mining | 988.3 | 0.73% |
| Managed resource protection | 919.0 | 0.68% |
| Other minimal use | 691.5 | 0.51% |
| Reservoir/dam | 200.6 | 0.15% |
| Lake | 174.8 | 0.13% |
| Residential | 151.8 | 0.11% |
| River | 108.9 | 0.08% |
| Services | 47.5 | 0.03% |
| Grazing modified pastures | 23.6 | 0.02% |
| Irrigated perennial horticulture | 23.6 | 0.02% |
| Channel/aqueduct | 12.7 | 0.01% |
| Intensive animal production | 8.3 | 0.01% |
| Manufacturing and industrial | 18.9 | 0.01% |
| Marsh/wetland | 12.5 | 0.01% |
| Plantation forestry | 9.0 | 0.01% |
| Transport and communication | 18.6 | 0.01% |
| Utilities | 9.0 | 0.01% |

Land use activity covering <0.01% of catchment area not shown

Landscapes cleared of native vegetation are prone to salinity outbreaks because the plant types that replace these natives are shallow-rooted compared to the indigenous types (Cañedo-Argüelles et al. 2013). This is because the Australian native vegetation has adapted to the country's harsh climate and use deep root systems to take advantage of water beneath the surface. This natural adaptation also keeps the water table low and salts at depth. In a scenario where the land has been cleared and replaced with crops or pasture, excess water from rainfall or irrigation seeps through the soil layers into groundwater aquifers, causing a rise in the watertable, and mobilisation of stored salts (DERM 2011a).

The mining and extractive industries can also contribute to river salinisation. A notable example was the effect on salinity caused by the release of mine-affected water in 2008, when heavy rainfall and subsequent floodwaters entered a district coal mine. This mine-affected water was released to restore mining operations and reinstate 200 unemployed mine workers (DERM 2009b).

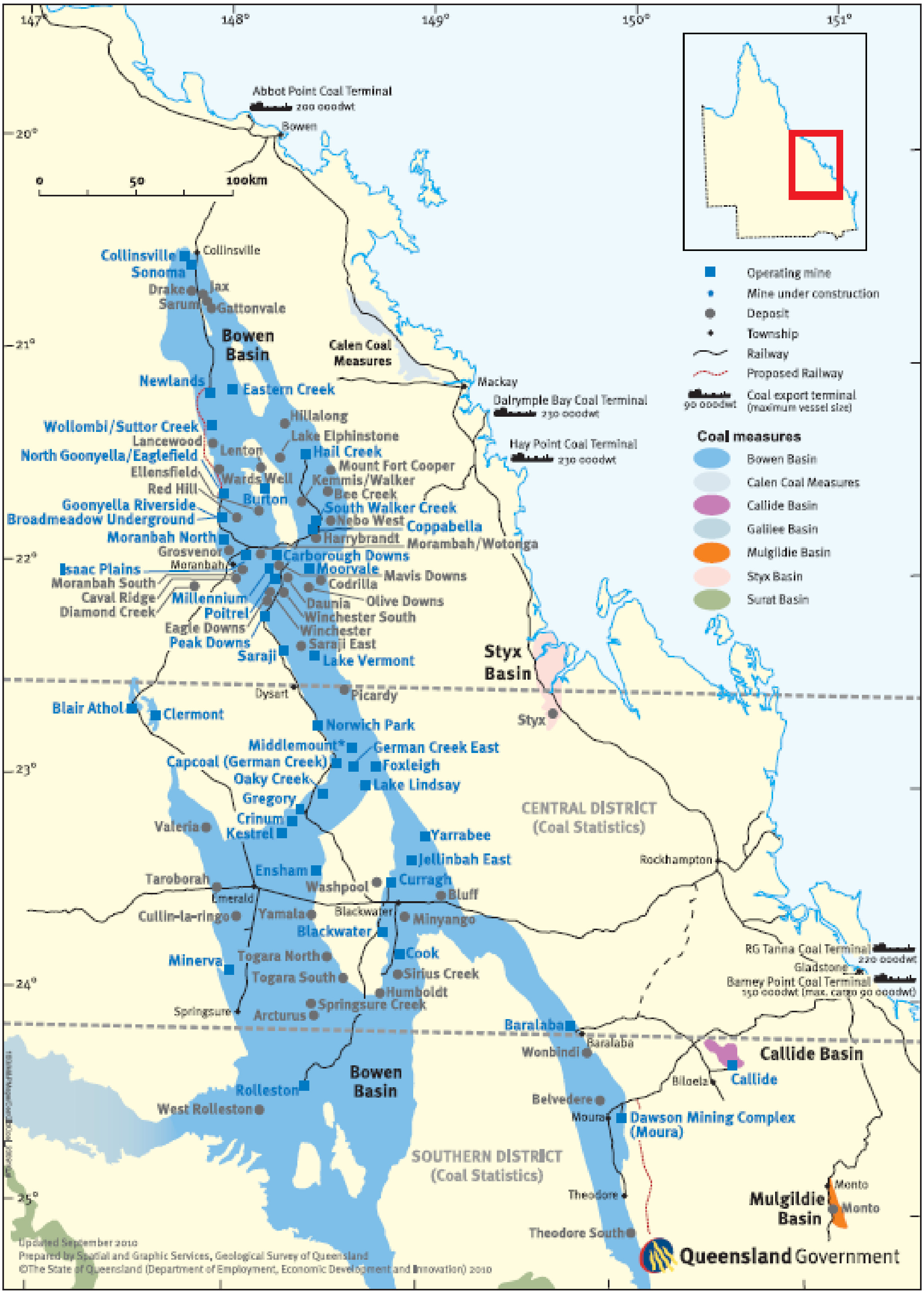



**Figure 10: Bowen Basin coal reserves as at 2010 include the area south of Theodore and Rolleston, west to Blair Athol and north to Hail Creek and North Goonyella in the Fitzroy River Basin** *(courtesy of the then Queensland, Department of Employment, Economic Development and Innovation (now part of DNRM)*

# 2. Methods

## 2.1. Hydrology

The daily flows at the main stream gauges throughout the Fitzroy catchment were estimated for the period from 1889 - 2012 using the IQQM. The calibration of the quantity (flow) module of the IQQM was based on observations of daily stream flows at stream gauges, positioned throughout the catchment. This was performed to ensure a close alignment between predicted and actual flows, so that the flows in the IQQM for the period of interest (2010-11) matched the recorded daily flows to within a few percentages at the stream gauge locations. The calibration method is detailed in full in documents for the Fitzroy Resource Operational Plan (DERM 2011c, 2011d, 2011b) and summarised in a schematic shown in Figure 11. The flow 'calibration' IQQM reflects the actual flows, as opposed to that of the Water Resource Plan (WRP) or Resource Operation Plan (ROP), which mirrors flows that have been modified by take or impoundment of water under the auspices of the WRP (Fitzroy Basin) 2011 (The State of Queensland 2011).

The Fitzroy Basin flow 'calibration' IQQM contains four sub-systems. These consist of a sub-system for each of three sub-catchments (Callide, Comet and Dawson) and one for the remainder of the basin. This separation was necessary for ease of modelling. Each subsystem is broken into sub-models before incorporating flow changes subsequent to construction of infrastructure (e.g. dam construction). This then provides for 'planning' IQQMs, which account for extraction and impoundment of water under the auspices of the Fitzroy WRP for each sub-system. The models of the four sub-systems are linked together to form one entire Fitzroy Planning IQQM.

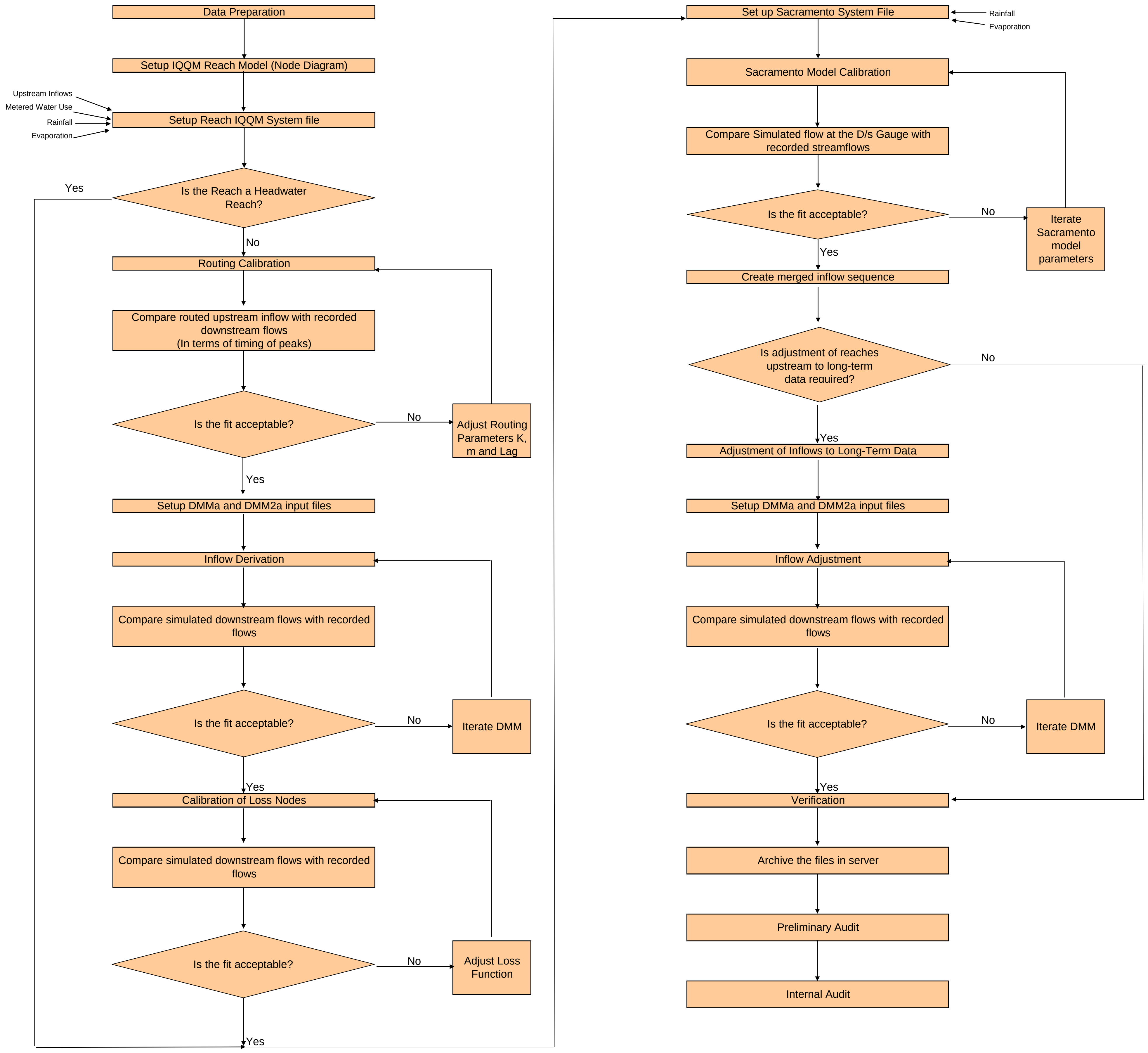



**Figure 11: Schematic showing steps in calibrating the IQQM for catchment hydrology including data collection and preparation, derivation of calibration inflow sequences, Sacramento model calibration, and adjustment of flow sequences**

*DMM: Data Modification Module consists of a number of programs that can be used to adjust subarea inflows on a daily basis to give good agreement between the IQQM predicted flow and the flow recorded at a stream gauge*

## 2.2. Salinity load estimates

The salinity load estimations involved two approaches. The main one was the Fitzroy Salinity IQQM. The second method involved actual measurements of site EC and flow data.

The second method was incorporated as a way of validating outputs of the IQQM. Ten sites were initially selected for the validation. These were gauges that continuously logged EC and flow data, and were closest to the end-of-valley for their respective catchments (Figure 12). Of these, only five were used in the validation process, as it was deemed the others had too many missing data points, i.e. > 40% incomplete (Table 2). The five sites chosen had limitations as listed (Table 2). These included missing EC data and use of substitutes for the second method (Table 2). In addition, deficiencies in the reporting of mine data (one mine in the Comet and five in the Isaac; Section 2.2.1) meant the data for these releases were not included in the IQQM (Table 2).

**Table 2: Sites used for estimating catchment salinity loads**

| End of catchment gauges (Sites) | Catchment | Comments |
|---|---|---|
| Nogoa River at Duck Ponds | Nogoa | 32% substitution required |
| Isaac River at Yatton | Isaac/Connors | 0% substitution required; lacking data from 5 mines |
| Don River at Rannes | Callide | 19% substitution required |
| Dawson River at Beckers | Dawson | 0% substitution required |
| Comet River at Comet Weir | Comet | <1% substitution required, lacking data from 1 mine |

Additional information pertaining to the calibration of the Fitzroy Basin Salinity Model can be found in Appendix A.

### 2.2.1. The mine release data

The data reported by coal mining companies for releases in 2010-11 provided the EC and flow information for estimating the contribution from coal-mine water-releases. The data were assessed and incorporated into the Fitzroy Salinity IQQM. This information was sourced from 32 of the 42 operating coal-mines within the Fitzroy Basin. Four of the 42 had no releases and six had insufficient information for inclusion in the modelling. Table 3 provides a summary of the reported coal-mine water-release data that were used in the estimation of salinity loads for 2010-11 by the IQQM.

**Table 3: Summary of mine data included into the IQQM – mining releases in the Fitzroy Basin 2010-11**

| Catchment | Mines (*n*) | Flow (ML $yr^{-1}$) | Load (tonnes $yr^{-1}$) | % of total load | Conc* (mg $L^{-1}$) |
|---|---|---|---|---|---|
| Callide | 1 | 8,726 | 4,142 | 1 | 475 |
| Comet** | 1 | 7,786 | 5,021 | 1 | 645 |
| Dawson | 2 | 111,299 | 62,996 | 16 | 566 |
| Isaac/Connors*** | 15 | 167,192 | 189,092 | 47 | 1131 |
| Mackenzie | 6 | 54,367 | 51,800 | 13 | 953 |
| Nogoa | 2 | 93,913 | 85,128 | 21 | 906 |
| **TOTAL** | 27 | 443,283 | 398,179 | 100 | 898 |

** Annual concentration is calculated as (annual load)/ (annual flow); ** one mine has been excluded because of deficiencies in reporting of data. *** five mines have been excluded because of deficiencies in reporting of data. Abbreviations: n - number, ML – megalitres, yr - year.*

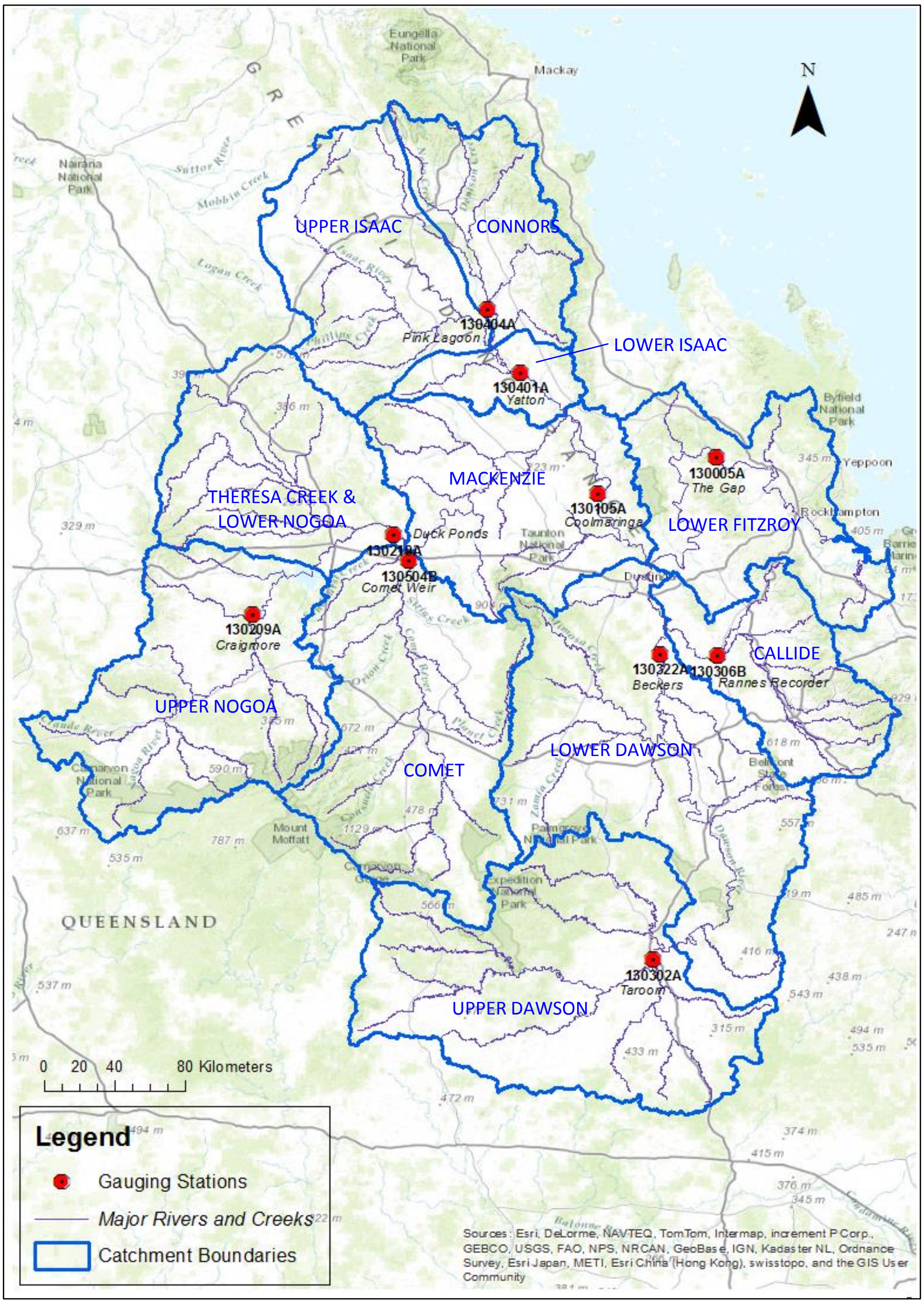



**Figure 12: Map showing the ten sites with continuously logged EC and flow data that were initially selected for estimation of catchment salinity loads in the validation method**

### 2.2.2. Modelling salinity mass using IQQM

The Fitzroy Salinity IQQM of this project was an expansion of an earlier salinity model that ran data from January 1889 to December 2007 (Delzoppo 2011). This new salinity IQQM extended the build out to December 2012. The below schematic outlines the steps in developing the salinity model, including data preparation and calibration (Figure 13).

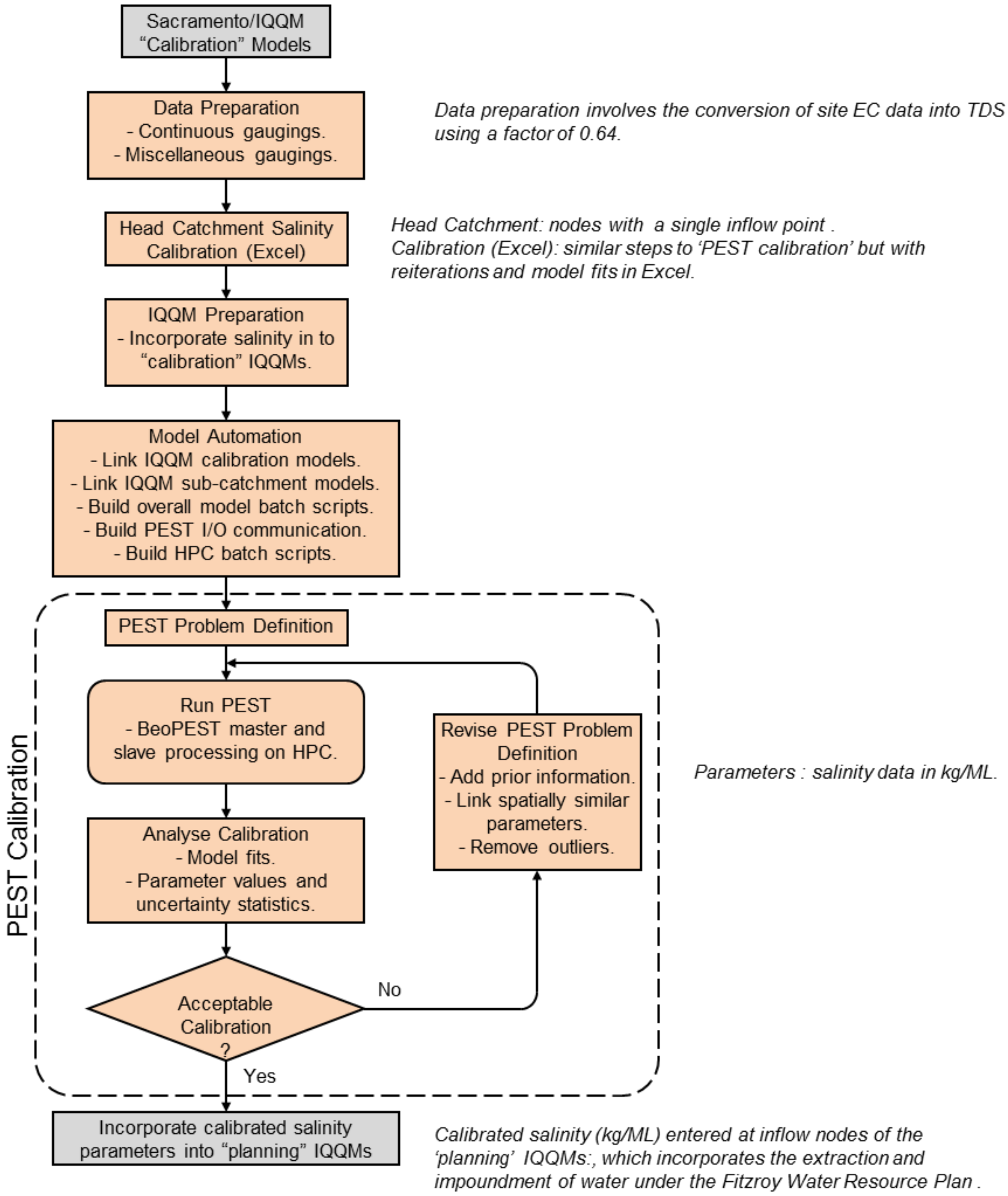



**Figure 13: Schematic showing steps in the preparation and calibration of the Fitzroy Salinity IQQM**

*PEST: Model-Independent Parameter Estimation & Uncertainty Analysis; I/O: input/output; BeoPEST: version of PEST that undertakes parallel processing to utilise the power of additional computers developed by Willem Schreuder using Beowulph Clusters; HPC: High performance computing.*

Electrical conductivity data for the whole period (1 January 1960 to 30 June 2012) were extracted from the DNRM *Hydstra* database and assessed for input into the IQQM. These data were mostly time series EC readings, collected and managed by DNRM. Extreme outliers and data that were flagged as poor quality were left out of the computations. In total, 64,090 EC observations across 48 gauges were initially used. However, the salinity model was eventually calibrated using data from the period 01 January 2010 to 30 June 2012 only, as these covered a very wet period not unlike that of 2010-11 and involved a better fit than the entire dataset. While this meant fewer salinity observations (i.e. 16,414 cf. 64,090), a better account of more recent saline conditions resulted.

To obtain concentrations for the model, site EC data in µS $cm^{-1}$ were converted to TDS in kilograms per megalitre (kg $ML^{-1}$) using the multiplier 0.64, which is based on previous interpretations (DERM 2011a, p159).

Head catchment nodes were those with single entry flows. The data for these nodes were calibrated using best model fits in Microsoft Excel (Figure 13).

The remainder was calibrated using Model-Independent Parameter Estimation & Uncertainty Analysis (PEST), a model-independent non-linear parameter optimiser (Doherty 2002), which uses a modified Gauss-Marquardt-Levenberg algorithm to calibrate parameters. High performance computing (HPC) dealt with the complex algorithms and potentially long run-times. Ultimately, this provided a final set of calibrated salinity data.

The calibrated salinity data were then integrated into the Planning IQQM (Section 2.1). This involved adding a salinity concentration (kg $ML^{-1}$) at each point of flow entry (called a node) before routing the resulting saline flows through the model. It included an algorithm that related flow (*Q*) to concentration (*C*), as has been described elsewhere (Thorburn, Shaw & Gordon 1992). Various Queensland studies have used this approach (e.g. McGloin 2001; McNeil & Cox 2004; QDPI 1994), which involves the following equation:

$$EC = \frac{K1 - K2}{1 + K3Q^{K4}} + K2$$

where *K1* is the assumed EC of base flow, *K2* is the lowest EC expected in runoff, and *K3* and *K4* are constants relating to curvature.

With the availability and right choice of data, the above function can reproduce the incremental salinity increases that are often seen where stream flow becomes increasingly dominated by the more saline baseflows.

Finally, the parameters of EC and flow from the 2010-11 coal-mine water-release data supplied by the mining companies (Section 2.2.1) were prepared and added to the calibrated salinity IQQM. This allowed computation of salinity loads that included the contribution from coal-mine water-releases.

### 2.2.3. Measuring salinity mass using actual data

Salinity loads were estimated from actual measurements of EC and stream flow using in-built features of Microsoft® *Excel*® 2010 (MS Excel). Records of EC (as daily averages) and river-flow (as daily volumes) were extracted from the DNRM *Hydstra* database. Again, these were time-series data for the period 1 July 2010 to 30 June 2011. Like that of the IQQM, the EC data (µS $cm^{-1}$) were converted to concentrations (TDS in kg $ML^{-1}$) using a multiplier of 0.64. The result was then multiplied by the coinciding flow (ML $day^{-1}$) to provide the salinity mass in tonnes (t).

If a gauging station had an incomplete daily series of EC data, the missing values were replaced with substitutes. It is not unusual to find missing observations in time-series data (Kondrashov & Ghil 2006; Sheung Chi Fung 2006). Rather than rejecting valuable data, a suitable imputation method was sought to deduce viable substitutes and provide concentrations from which salinity loads could be estimated.

There were four methods tested to estimate missing values:

Method 1: The mean daily EC reading for 2010-11 for that gauging station

Method 2: The period-weighted method, described by Linkens et al. (1977, cited in Dann, Lynch & Corbett 1986), where the average of the concentration at the beginning and end of an interval is multiplied by the volume of water flowing by, during that time interval, to compute the salinity load

Method 3: The values from a growth trend series formula in MS Excel 2010 starting with the last non-blank cell and ending with next non-blank (i.e. Fill > Series> Growth> Trend in cells between the last non-blank cell and the next non-blank cell)

Method 4: The expectation–maximization (EM) algorithm of PRIMER 6, version 6.1.11 © 2008 Primer-E Ltd, based on all the observed EC and corresponding flow values for that gauging station

Six gauging stations had complete EC datasets (i.e. 365 observations in total) and these were used to test the four methods of imputation (the process of replacing missing data with substituted values). All six gauging stations were modified so that 10, 20, 30 and 40 per cent of the daily EC readings (numbering 365 cells) were substituted with values from every imputation method.

All imputation methods for every gauging station in each substitution test (i.e. 10 – 40 per cent) were treated equal in that the same row reference (numbering 1 - 365) was selected and the contents deleted. An online random number generator provided the random numbers between 1 and 365 to select the row references in each test case. The longest spell of missing data that resulted from this approach involved 17 consecutive cells.

The empty cells were filled with substitute values using each of the four imputation methods, for every gauging station in each substitution case. The similarities between the results of every method (Methods 1 to 4) and the actual observations for each of the six stations were examined in a non-metric multidimensional analysis of similarities (nMDS), based on Euclidean distances of the data (Clarke 1993). An nMDS requires few assumptions (e.g. as compared to ANOVA) and although it has a complex algorithm, the output is simple to interpret. It produces a plot that shows distances between sample points to indicate dissimilarity or similarity between them. In this case it was used to assess the similarity between the imputation methods and the actual sample points.

Of all the methods, Method 1 (m1) was the most dissimilar to the actual observations (Figure 14 a). When looking at a subset of this first plot for a closer examination, Method 3 (m3) displayed the greatest likeness to the actual observations, with the 10% substitution exhibiting the greatest likeness, i.e. least distance between the 'm3' and 'A' data points on the plot (Figure 14 b). Thus, Method 3 was chosen to complete datasets with missing data in this study.

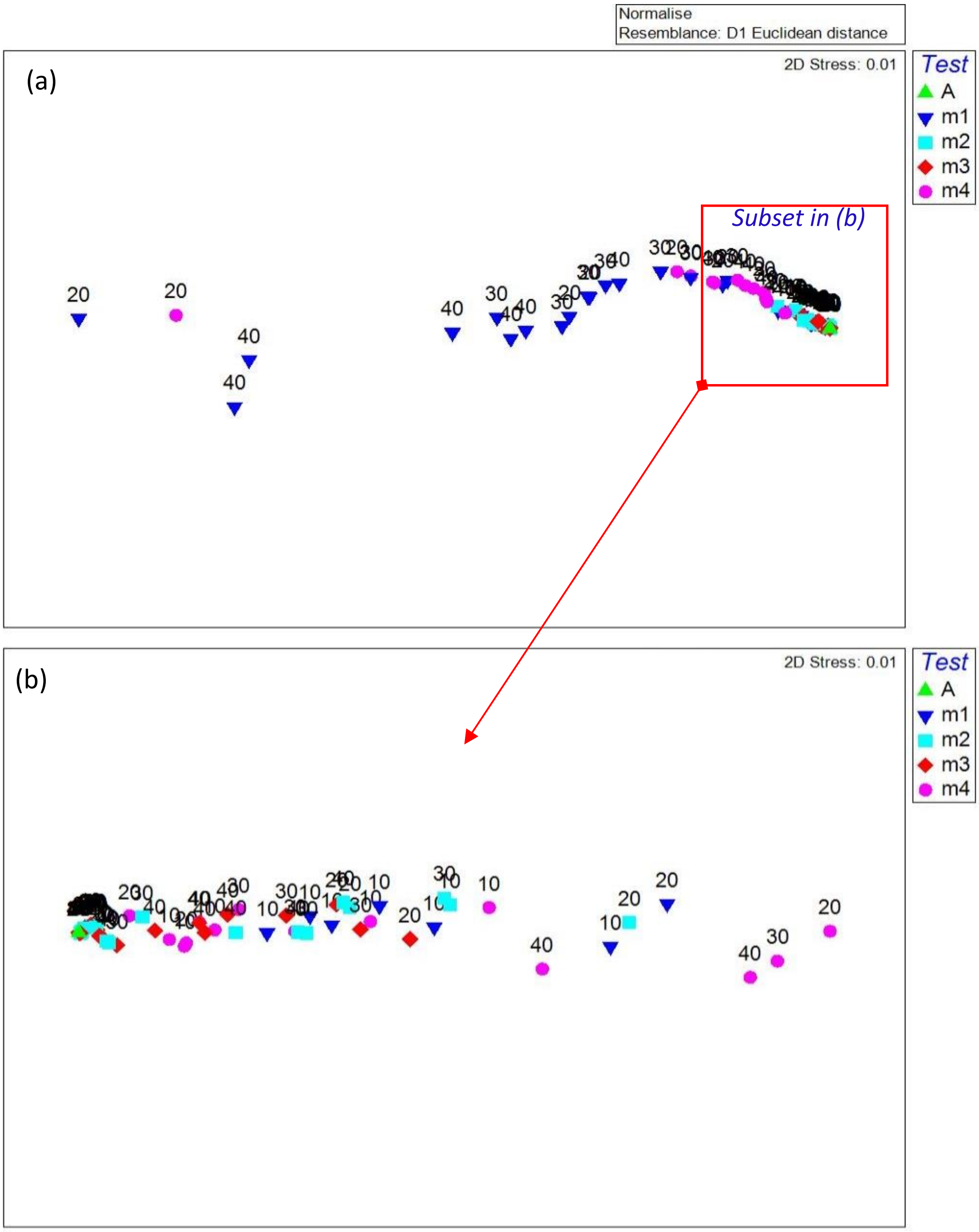



Figure 14: nMDS plots show (dis)similarities between test cases of imputation methods 1 – 4 [m1 – m4] and the actual observations [A] for six gauging stations (a) with a subset of these (b) providing a close-up view of the test cases close to the actual observations [A: green triangles] (labels 10, 20, 30 and 40 indicate the percentage of substitution in the methods)

## 2.3. Major ions for identifying sources of in-stream salinity

Major ion data of stream and groundwater sites were examined to identify possible sources of in-stream salinity in the Fitzroy River system between 1 July 2010 and 30 June 2011. Data were extracted from the DNRM *Hydstra* database.

Apart from The Gap, which was monitored monthly, recordings from gauging stations within the Surface Water Ambient Network (SWAN) of DNRM provided quarterly major ion data. The exception was when access conditions due to flooding had restricted sampling of the site. In addition, major ion data were available from the monitoring of stream sites downstream of coal-mine water-releases within the Isaac/Connors and an August 2010 field survey, both by the previous Department of Environment and Resource Management (DERM).

The Gap is the most downstream SWAN site with continuous logging of EC data in the Fitzroy Basin and therefore serves as the end-of-valley location for the purposes of this study. This site is located approximately 50 km north west of Rockhampton.

### 2.3.1. Groundwater

Major ion data of groundwater samples were extracted from the DNRM groundwater database (GWDB). This resulted in seven groundwater samples for the reporting year 2010-11. These were from the Connors, Upper Dawson and Lower Fitzroy catchments. Annually, DNRM monitor approximately 34 bores within Fitzroy Basin for water chemistry (Figure 15). The small number in the reporting year was because of widespread, prolonged flooding and the resulting logistical problems in accessing sites. The main areas, where the Queensland Government monitors the water quality of groundwater in the Fitzroy Basin, involve The Emerald Irrigation Area, the Callide Valley Water Supply Scheme and the Nebo district (DERM 2009a).

### 2.3.2. Data analyses

In total, 282 water samples (groundwater: 7 and surface water: 275) provided major ion data for this assessment, with the data processed by *AquaChem*® 2012.1 (SCHLUMBERGER CANADA Ltd) to yield water types, ionic balances and piper plots of the data.

To standardise the data prior to multivariate analyses, the data in mg $L^{-1}$ were converted to percentage equivalents (% eq). A two-stage cluster analysis, similar to that used by McNeil, Cox & Preda (2005), was then performed on the data using *PRIMER 6* software to examine similarities among the data and identify the main water groups. The stages were as follows:

1. A cluster analysis on Pearson's correlations of the data using a group-average mode (Clarke 1993). This produced six clusters of water types with 85% correlation between samples.

2. A principal component analysis (PCA) on these data to indicate whether the groups that had been identified in the cluster analysis, were based on associations between specific major ions. Whereas a cluster analysis identifies groups of samples based on the similarity among variables, a PCA indicates the correlations between variables (indicated by vectors) and samples (Clarke 1993; Clarke & Warwick 2001).

An nMDS of monthly major ion data at The Gap (Lower Fitzroy) was also performed to identify the temporal differences in water chemistry at the end-of-valley location for the Fitzroy Basin.

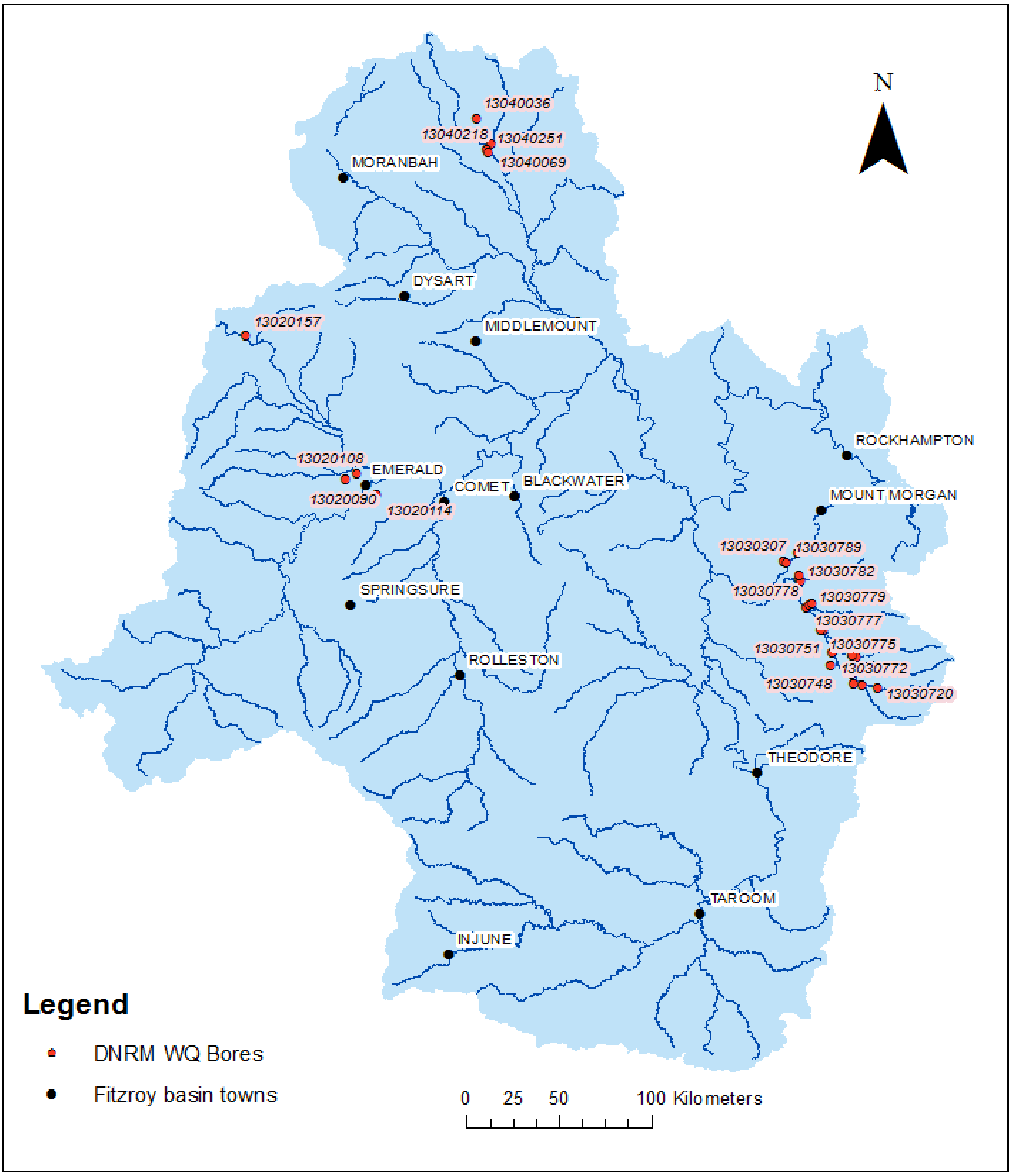



**Figure 15: The map showing where water chemistry is currently tested in the DNRM bores (*n* = 35*) of the Groundwater Monitoring Network as of 2013** (**not all bore labels are shown due to crowding of sites*)

### 2.3.3. Quality assurance and quality control

The ionic balance of every major ion record helped verify the adequacy of the data. A tolerance up to 5% is generally permissible (Lambrakis 2006; Raymond & McNeil 2011). Two samples that were slightly above the 5% threshold were included. Another two records were found to be well outside the threshold because of previous transcription errors. These were corrected before inclusion in analyses.

At each stage of analyses, records were cross-checked by another person. This was later followed by random checks, where if any errors were found, all manipulations within the data range were re-examined. As a final check, all equations (including calculations and conversions) and manipulated fields were re-examined for accuracy and the correct cell referencing.

# 3. Results

## 3.1. Salinity load estimates

The salinity load estimates for the water year 2010-11 were as follows:

- The IQQM end-of-valley total: 4.2 million tonnes
- The actual measurements method end-of-valley total: 4.5 million tonnes
- The contribution from reported coal-mine releases at end-of-valley: 0.4 million tonnes

The percentage of salinity load contributed by mine releases for the year was approximately 9% of the total for the Fitzroy (both methods gave a value within 0.53% of this result). The model output involved a loss of approximately 0.1 million tonnes or 25% of the mine-water salinity load between the release point and the end-of-valley.

### 3.1.1. Comparing IQQM to actual measurements

The salinity load contributions (%) for individual catchments were similar between the two methods: IQQM and actual measurements (Figure 16). They computed the same salinity load contribution (%) for the Dawson catchment and close resemblances for others (Figure 16). The Isaac/Connors, Nogoa and Dawson contributed the most in terms of overall salinity load of the catchments represented in Figure 16, with the Isaac/Connors contributing about a third, and Nogoa and Dawson about a quarter each.

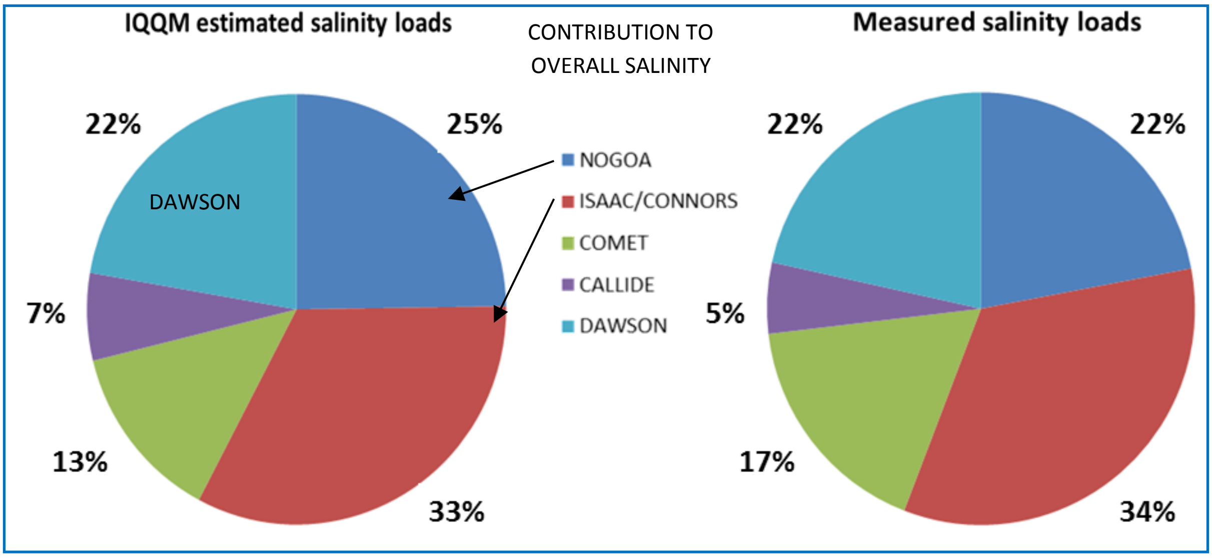



**Figure 16: Comparison of estimated salinity loads between modelled (IQQM) and actual measurements method (measured salinity) for major Fitzroy Basin sub-catchments showing the Isaac/Connors, Nogoa and Dawson as contributing the most in terms of overall salinity load, followed by Comet and then Callide for year 2010-2011**

## 3.2. Major ions

### 3.2.1. Surface water

The cluster analysis followed by the PCA revealed six main water types based on dominant ions. These were classed from A to F (Table 4).

**Table 4: The six main chemistry water types of the Fitzroy Basin 2010-11, grouped into classes A to F**

| Class | Main chemistry | Description |
|---|---|---|
| A | Ca, Mg, $SO_4$ | High sulphate type |
| B | Mg | Magnesium dominant |
| C | Na, Mg, Ca, Cl, $HCO_3$ | No particular defining cation |
| D | Ca, Mg, Na, $HCO_3$ | Alkaline – $HCO_3$ dominant ion |
| E | Na, Cl | Chloride dominant water |
| F | Na, Cl, $HCO_3$ | Sodium dominant water (Cl and $HCO_3$ roughly equal) |

Almost 95% of the variation in major ion data among the sites was explained by the first three principal components. That is, PC1 accounted for nearly 55%, and PC2 and PC3 explained about 20% each (Table 5). Overlaid vectors showed a strong gradient of bicarbonate (HCO3), as the main variant along the PC1 axis, whereas along the PC2 axis sodium (Na) was the main variant, and sulphate ($SO_4$) the major ion along PC3 (Figure 17 a & b; Table 5). Vectors showed that Group A was defined by $SO_4$, Group B by Mg, Group C by no particular cation but Cl as the prominent anion; Group D by no particular cation but $HCO_3$ and Cl equally prominent anions, Group E by Cl, and Group F by Na (Figure 17).

**Table 5: The results of the PCA of major ion data in samples of the Fitzroy Basin, June 2010 to July 2011**

Eigenvalues

| PC | Eigenvalues | % Variation | Cumulative % Variation |
|---|---|---|---|
| 1 | 575 | 54.6 | 54.6 |
| 2 | 221 | 21.0 | 75.5 |
| 3 | 199 | 18.9 | 94.4 |

Eigenvectors

(Coefficients in the linear combinations of variables making up PC's)

| Variable | PC1 | PC2 | PC3 |
|---|---|---|---|
| Ca | -0.231 | 0.264 | 0.076 |
| Mg | -0.210 | 0.426 | -0.203 |
| Na | 0.471 | **-0.639** | 0.114 |
| K | -0.030 | -0.051 | 0.014 |
| Cl | 0.461 | 0.426 | 0.519 |
| $HCO_3$ | **-0.655** | -0.394 | 0.254 |
| $CO_3$ | -0.002 | -0.009 | 0.005 |
| $SO_4$ | 0.195 | -0.024 | **-0.778** |

*Bolded values relate to the most prominent variable in explaining the variation along the specific axis*

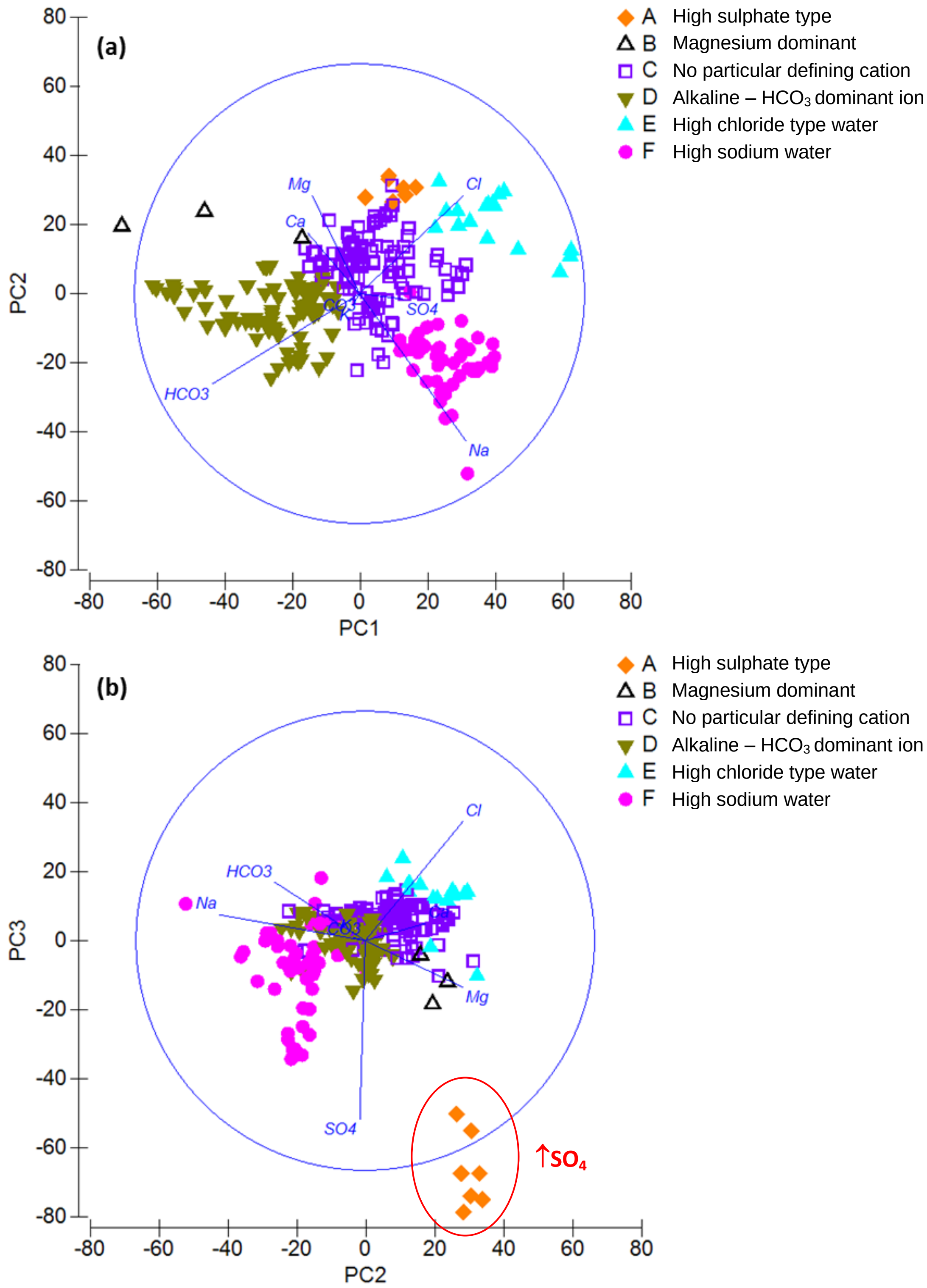



**Figure 17: A PCA of major ion data (percentage equivalents) for the Fitzroy Basin for June 2010 to July 2011 supported the grouping of samples with 0.85 resemblance (A – F) based on a cluster analysis run on a Pearson's correlation matrix of the data (Plots show axes of PC1 and PC2 (a) and PC2 and PC3 (b) that explain the variation in the major ion data and vectors that indicate variable associations)**

*Abbreviations: HCO3 – bicarbonate, Cl – chloride, Mg – magnesium, SO4 – sulphate, Na - Sodium*

Appendix B provides the 2010-11 piper plots and tables of water types for sites within catchments. It also contains the spatial representations of the dominant water types within five sub-regions of the Fitzroy Basin, and of the sites in relation to land-use.

*Class A* type water chemistry appeared in surface waters of the Callide Valley at Rannes on the Don River, the pump station on south Kariboe Creek (130334A) and Wura on the Dee River (130335A). The highest sulphate concentration of the entire dataset was 644 mg $L^{-1}$ (Appendix B) at the pump station on south Kariboe Creek in October 2010. This was prior to the heavy rains of the wet season. With the high flows of the wet season the sulphate concentrations declined to 120 mg $L^{-1}$ (Figure 18). A plot of historic data shows that prior to 1992-93 sulphate concentrations at this site were consistently low. Higher sulphate concentrations were recorded past this time, along with a reduced frequency of sampling (Figure 18).

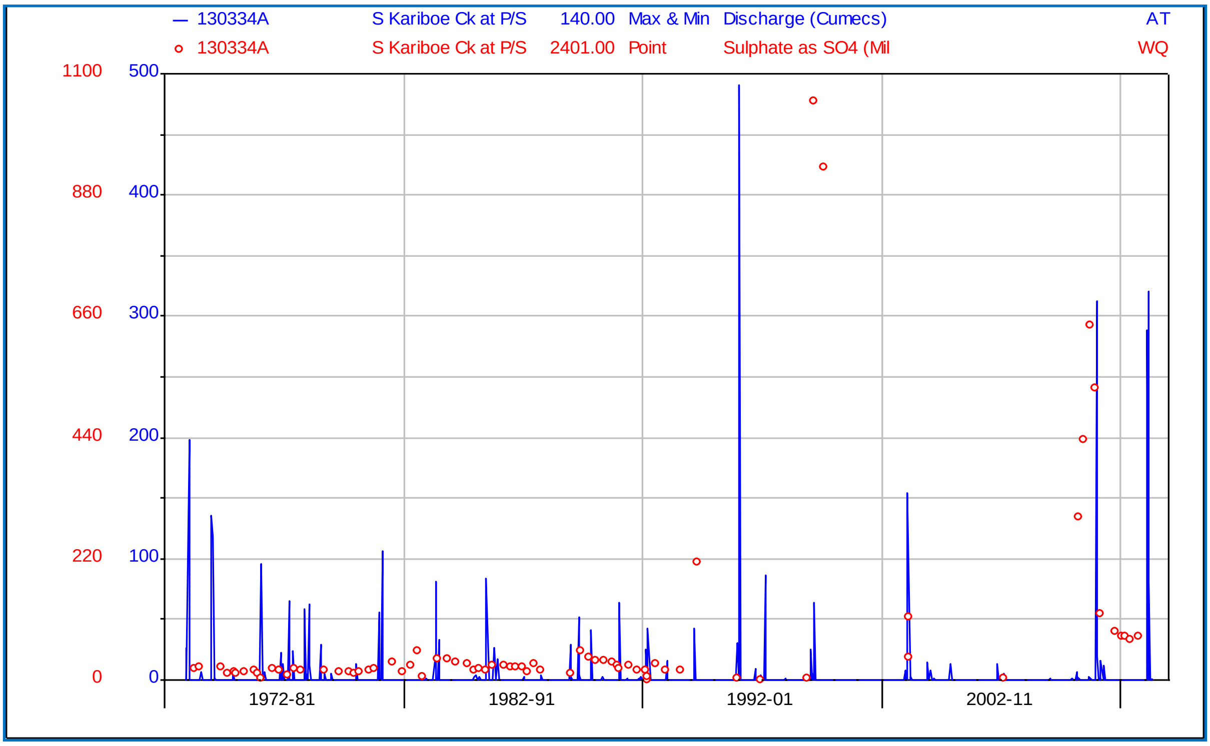



**Figure 18: A plot of sulphate and surface flows at the south Kariboe Creek site (130334A) in the Callide Valley (for the entire record; 1972 – 2013)**

*Class B* was solely observed at Marlborough Creek and its tributary Spring Creek in the Lower Fitzroy. *Class C* was common across the basin, including surface waters of the Callide, Connors, Dawson, Isaac, Lower Fitzroy, Mackenzie, lower Nogoa and Theresa Creek. *Class D* was similarly common, although it also included the Comet and Upper Nogoa. *Class E* type water was observed in catchment waters of the Upper Isaac, Lower Fitzroy (e.g. Alligator Creek) and the lower section of the Dawson (Appendix B). *Class F* type water was identified at sites 1304026, 1304029, 1304031, 1304033, 1304069 and 130414A in the Upper Isaac where TDS was recorded as high as 1436 mg $L^{-1}$ (Appendix B). *Class F* type water was also observed at Gwambegwine Creek to the north west of Taroom in the Upper Dawson, though with a TDS reading of 90 mg $L^{-1}$.

Table 6 provides summary statistics of the major ions at surface water sites within catchments of the Fitzroy Basin. This summary reveals a study limitation in the sampling effort with inequality among catchments. The Isaac/Connors catchment was most sampled (*n* = 149 cf. 11 - 44) because of additional monitoring by DERM in relation to coal-mine water-releases. Appendix B provides sample details for individual sites.

**Table 6: Summary statistics of the available major ion data for surface waters within Fitzroy catchments**

| | Fitzroy | | | Nogoa | | | Callide | | |
|---|---|---|---|---|---|---|---|---|---|
| | Range | Mean | *n* | Range | Mean | *n* | Range | Mean | *n* |
| Ca | (1.9 - 95) | 24 | *33* | (9.2 - 69) | 30 | *15* | (9.2 - 166) | 48 | *44* |
| Mg | (3.6 - 170) | 30 | *33* | (6.1 - 53) | 20 | *15* | (6.1 - 87) | 32 | *44* |
| Na | (10 - 160) | 41 | *33* | (13 - 95) | 40 | *15* | (13 - 143) | 57 | *44* |
| K | (0.2 - 5.9) | 3 | *33* | (1.7 - 7.6) | 5 | *15* | (1.2 - 15) | 4 | *44* |
| Cl | (7.4 - 385) | 76 | *33* | (8.8 - 190) | 52 | *15* | (8.8 - 290) | 91 | *44* |
| $HCO_3$ | (16 - 751) | 174 | *33* | (65 - 438) | 187 | *15* | (15 - 438) | 188 | *44* |
| $CO_3$ | (0 - 2.2) | 0 | *33* | (0 - 11) | 1 | *15* | (0 - 15) | 1 | *44* |
| $SO_4$ | (1.1 - 178) | 17 | *33* | (3 - 103) | 18 | *15* | (3 - 644) | 90 | *44* |
| | **Comet** | | | **Dawson** | | | **Isaac/Connors** | | |
| | Range | Mean | *n* | Range | Mean | *n* | Range | Mean | *n* |
| Ca | (21 - 47) | 31 | *11* | (2.3 - 42) | 20 | *27* | (4.8 - 192) | 41 | *149* |
| Mg | (12 - 45) | 23 | *11* | (2.2 - 13) | 7 | *27* | (2.7 - 115) | 23 | *149* |
| Na | (14 - 29.3) | 20 | *11* | (9.1 - 70) | 33 | *27* | (13 - 415) | 116 | *149* |
| K | (1.8 - 6.4) | 3 | *11* | (2.1 - 7.1) | 5 | *27* | (0.8 - 8.7) | 5 | *149* |
| Cl | (9 - 25) | 15 | *11* | (8.4 - 91) | 35 | *27* | (15 - 1000) | 155 | *149* |
| $HCO_3$ | (135 - 387) | 224 | *11* | (15 - 257) | 122 | *27* | (39 - 586) | 224 | *149* |
| $CO_3$ | (0 - 5.1) | 2 | *11* | (0 - 3.8) | 0 | *27* | (0 - 11) | 3 | *149* |
| $SO_4$ | (2.2 - 13.3) | 8 | *11* | (0.5 - 13.5) | 5 | *27* | (1.1 - 222) | 46 | *149* |

### 3.2.2. Temporal differences in major ions at The Gap

An nMDS of monthly major ion data at The Gap (Lower Fitzroy) clearly grouped the monthly samples of this site into three. Vectors showed how these groups were related to ionic signatures. The relationships were July – September 2010 with Mg and $CO_3$, October 2010 – January 2011 with Na, Cl and $SO_4$, and February – June 2011 with Ca, K and $HCO_3$ (Figure 19).

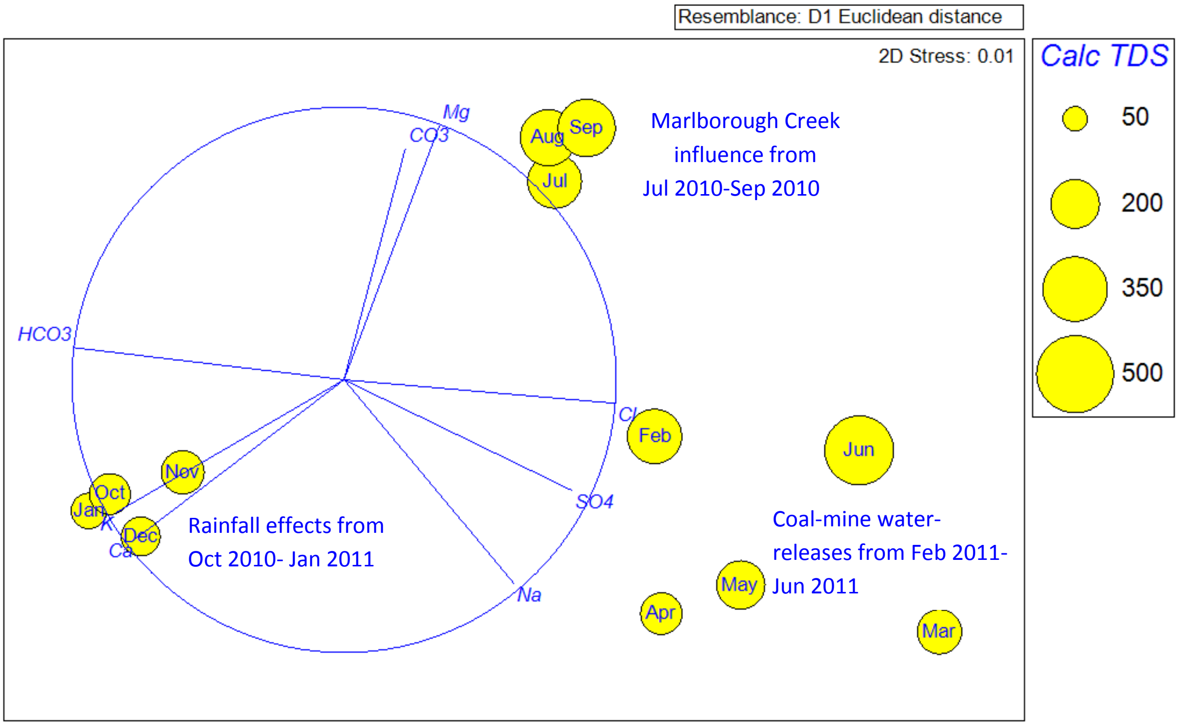



**Figure 19: An nMDS plot shows (dis)similarities between months in the major ion data at The Gap gauging station in the Lower Fitzroy, with three groups, each relating to associations of different ions (the symbol size corresponds to the calculated total of ion concentrations (calc TDS) where the size of the circle represents the level of salinity of the sample)**

### 3.2.3. Groundwater

Groundwater samples from individual bores within the Connors comprised *Classes C*, *D* and *E* (*n* = 2, 2, 1). The single groundwater sample from the Lower Fitzroy was *Class E* (sodium/chloride type) and that from the Upper Dawson was *Class F* (high sodium type with roughly equal chloride and bicarbonate). Table 7 provides the bore ID, catchment, month of sampling and water type for the groundwater samples. The amount of data was limited this year because of access reasons, as explained in Section 2.3.1

**Table 7: Details of groundwater samples collected by DNRM during the study year July 2010 - June 2011**

| Bore ID | Month | Catchment | Class | Main water chemistry |
|---|---|---|---|---|
| 13040218GW | July 2010 | Connors | D | Na-Mg-Ca-HCO3-Cl |
| 13040254GW | July 2010 | Connors | D | Na-Ca-Mg-HCO3-Cl |
| 13040055GW | July 2010 | Connors | E | Na-Mg-Cl-HCO3 |
| 13000288GW | Aug 2010 | Fitzroy | E | Na-Cl |
| 13030808GW | June 2011 | Upper Dawson | F | Na-HCO3-Cl |

## 3.3. Limitations and assumptions

The study limitations and assumptions include the following:

- It was assumed that the data submitted by mining companies were correct.
- The coal-mine water-release data were reported with various formats and reporting styles. This protracted the task at hand because of the need for tedious reconfiguration and follow-up of suitable data. Improvements are suggested to expedite future modelling projects (Appendix D).
- An assessment of major ion data in coal-mine water-releases was not possible due to lack of suitable data at the time.
- The groundwater salinity inputs for the IQQM were incorporated by increasing salinity with diminishing flows.
- The DNRM groundwater dataset contained only seven samples in total for 2010-11. Hence, a measured assessment of groundwater interaction with surface waters could not be done.

# 4. Discussion

## 4.1. Salinity load estimate

The Fitzroy Salinity IQQM estimated an annual salinity load of 4.2 million tonnes for the water year 2010-11 at the Fitzroy Basin end-of-valley. The same model computed a salinity load of approximately 0.4 million at this location as a consequence of coal-mine water-releases in this year. This result was based on mining company data supplied to EHP (formerly DERM). It excludes releases from six coal mines that were not assessed because of shortfalls in their data reporting. In summation, coal-mine water-releases of 2010-11 yielded about 9% of the total salinity load delivered to the end-of-valley of the Fitzroy Basin for the water year 2010-11.

There was likely temporal variation in this contribution from the coal-mine water-releases. It is proposed that when the river flow was nil at The Gap, as in July to August 2010 (Figure 3), the contribution from coal-mine water-releases was likely negligible. Similarly, when there was abundant overland runoff contributing to river flows, as in December 2010 to January 2011, the contribution from such releases was expected to be well diluted. Then, when stream flow subsided but releases continued, as occurred from February onwards, the contribution from coal-mine water-releases was likely much larger.

A sulphate signature at The Gap (Figure 17) supports the theory of a higher contribution from coal-mine water-releases in the months from February onwards. It is noted that sulphate is an accepted indicator of coal-mining influence (Merovich Jr et al. 2007; Rikard & Kunkle 1990). In addition, a point-in-time analysis for May 2011 implied a higher contribution from coal-mine water-releases during this time. An estimate of up to 18 - 25% of the total salinity load at the Gap was attributed to coal-mine water-releases for this point-in-time (Appendix C). It was a period when only four mines were releasing, and flow and EC were reasonably steady. Appendix C provides details of the calculations, including caveats in deriving and citing these figures. It is noted that although the contribution was seemingly high at this time, the corresponding daily EC was 350 - 400 µS/cm (Figure 3) and fell within the 450 µS/cm threshold for protection of freshwater aquatic ecosystems of the lower Fitzroy catchment.

## 4.2. The background salinity

The model calibration for the water year 2010-11 involved data of 1 January 2010 to 10 June 2012, which were from a very wet period. Being able to perform separate dry-wet year scenarios is important for the Fitzroy Basin, which sees prolonged droughts interceded by years of exceptional ‘wet’ in this region (Rustomji, Bennett & Chiew 2009). Separate scenarios can be performed in the Fitzroy Salinity IQQM by choosing different historic data to allow model simulations for either ‘dry’ or ‘wet’ year ‘background’ salinity.

In this context, ‘background’ salinity refers to salinity from diffuse sources within the Fitzroy Basin in contrast to that from coal-mine water-releases, which are point sources. The point source data provided by coal mining companies were entered into the ‘background’ salinity model at relevant nodes and then routed through the model to provide the final modelled estimates of salinity load for the water year 2010-11.

The total salinity load at the end-of-valley for the Fitzroy comprised about 9% contribution from coal-mine water-releases (point sources). Hence, about 91% of this total salinity load for the water year 2010-11 was from diffuse sources, which derive from natural and human activities. As mentioned earlier, some Fitzroy Basin landforms are more vulnerable to salinity outbreaks than others and various studies have identified probable causes of salinity outbreaks due to human activities (Section 1.5). These can include land-use that facilitates the movement of salts through soil layers into aquifers and sub-soils, and from there into adjacent waterways with subsurface flows of very wet seasons (Cañedo-Argüelles et al. 2013).

## 4.3. Validating the IQQM results

Measuring the uncertainty in the modelled outputs of the Fitzroy Salinity IQQM was deemed to be unworkable because of the numerous factors and complex interactions involved. As a way of providing confidence in the IQQM outputs, salinity load estimations were calculated from actual data for the water year 2010-11 and then compared to the estimates computed by the IQQM.

In relative terms, the outputs from the Fitzroy Salinity IQQM were similar to those of the actual measurements method and this provides confidence in the further use of the Fitzroy Salinity IQQM to predict effects of modified industry releases, e.g. with proposed amendments to mine water release rules.

Figure 16 shows the basis of this surmise with the outputs from the two methods comparing well on a catchment by catchment basis. Small anomalies in salinity load contribution (%) between the two methods can be expected. For example, the Nogoa salinity load (%) for the actual measurements method was lower than that of the IQQM by 3% (Figure 16). However, the actual measurements method relied heavily on substitution (32%; Table 2; Section 2.2) and with a higher degree of imputation comes a greater likelihood of departure from certainty. Callide had a similar scenario of a lower contribution from the actual measurements than from the IQQM; a difference of 2% (Figure 16). This could also be due to the actual measurements method relying on substitution of 20% of the values in calculations (Table 2; Section 2.2). Conversely, the Isaac/Connors had a higher salinity contribution from the actual measurements method compared to the IQQM. This was a difference of 1%, which possibly related to the omission of data from five mines in the Isaac catchment (Section 2.2.1). Similarly, the omission of data from one mine in the Comet because of data reporting reasons may have influenced the higher salinity contribution seen in the actual measurements method compared to the IQQM; a difference of 4% (Figure 16).

In absolute terms, the IQQM gave a total salinity load estimate at the end-of-valley that was 0.3 million tonnes less that the estimate from the actual measurements method. The latter involved a high number of observations (*n* = 341) at The Gap and fewer than 7% substitutes. This indicates a high degree of certainty in terms of the total salinity load estimate from the actual measurements method, and possible shortfalls in the modelling. Nevertheless, both methods estimated a contribution from coal-mine water-releases of approximately 7% (± 0.3%) of the total.

Factors affecting the Fitzroy Salinity IQQM estimate at The Gap for the water year 2010-11 included the absence of suitable groundwater information for entering and routing through the model, as mentioned below. Another was the incomplete coal-mine water-release dataset for the year, with issues in the reporting of appropriate data from six mines (Section 2.2.1). One more was the absence of inflow data from Marlborough Creek, which would be relevant, considering the August 2010 sampling that revealed elevated TDS at this location (1134 mg $L^{-1}$ at MCCR, Appendix B). Marlborough Creek flows into the Fitzroy River upstream of The Gap. It appears a prime source of salinity at this site, as suggested by the Mg signature at The Gap in early 2010-11 (Figure 19 and Section 4.5.6).

Since this time, DNRM has reinstated the gauging station on Marlborough Creek to record continuous EC and stream flow, which will assist with future model simulations.

## 4.4. Groundwater

The Fitzroy Salinity IQQM for the water year 2010-11 used an indirect means of incorporating groundwater into the model. Specifically, it dealt with groundwater contribution by increasing salinity concentrations as stream flow subsided, to mimic that in nature where groundwater inflows (base flow) increase as surface runoff abates. It is acknowledged that explicit groundwater data would improve salinity load computations for the Fitzroy Basin. Raymond and McNeil (2011) reasoned the need for additional groundwater data to improve knowledge of groundwater influence on surface waters of the Fitzroy Basin. The present arrangement of groundwater monitoring by DNRM is spatially constrained in terms of providing this information (Figure 15). Groundwater data from industry monitoring might complement the DNRM dataset in this regard and should be investigated for suitability in the future.

## 4.5. Major ion investigation

Six main water types were identified for the Fitzroy Basin in the water year 2010-11. The following describes the possible sources and effects of water masses with these water types.

### 4.5.1. High sulphate

Surface waters of the Callide catchment displayed a high sulphate type (*Class A*). This type of sulphate enriched water had previously been described for the Dee River, which is impacted by historic gold mining at Mount Morgan (Jones 2000). The source of high sulphate water at the Kariboe Creek pump station site (130334A) is distinct from that of the Dee River, since past gold mining does not appear important in terms of this site. Kariboe Creek is associated with the Callide Irrigation Scheme. Over a long period of time, it has received water from the Callide Dam to recharge groundwater within the scheme (McNeil 1998). The maximum sulphate concentration of 644 mg $L^{-1}$ was observed at the pumping station site during the dry conditions of October 2010 (Figure 18). In March 2011, sulphate concentrations declined to 120 mg $L^{-1}$ with high surface flows from a wet-season rain event (Figure 18). This suggests the sulphate elevation is related to base flows. From 1992 onwards there is evidence of elevated sulphate in base flows at this site (Figure 18). It appears the groundwater in this area has been enriched with sulphate and impacts the Kariboe site, as seen in the high sulphate water of 2010-11.

Sulphate concentrations are typically less than 20 mg $L^{-1}$ in streams of the Fitzroy Basin and Queensland overall (Jones & Moss 2011; McNeil, Cox & Preda 2005). In the water year 2010-11, sulphate concentrations were several times above this benchmark at times within the Isaac, Lower Fitzroy and Nogoa catchments, with recordings up to 222 mg $L^{-1}$, 178 mg $L^{-1}$ and 103 mg $L^{-1}$, respectively (Table 6; Appendix B).

Sulphate accumulation in watercourses often occurs downstream of coal mining (Sams & Beer 1999; WVDEP 2008). Moreover, US authorities use the percentage of stream length with sulphate above 50 mg $L^{-1}$ to indicate coal mining impact on stream condition (WVDEP 2008, 2010, 2012). Notably, the sites with elevated sulphate in the Nogoa and Isaac are downstream of Bowen Basin coal mines. The site in the Lower Fitzroy (Limestone Creek), however, is downstream of historic abandoned mine sites and a World War 2 US military base, and not associated with coal mines.

A potential implication of elevated sulphate in freshwater environments (whether from mining or other human activity) is increased eutrophication, i.e. undesirable algal and aquatic plant growth through over-enrichment of waters. This especially affects waters with low oxygen levels, such as wetlands, waterholes and impoundment during ‘no flow’ periods. Microbial communities in these environments use sulphate in place of oxygen to metabolise organic matter. In the process, they convert sulphate to sulphide, a more toxic substance than the former, particularly for aquatic flora (Bernhardt & Palmer 2011; Lamers et al. 2002; Lamers, Tomassen & Roelofs 1998).

The extra available sulphide can also increase concentrations of dissolved phosphorus (P) in the water column. In freshwater environments P is mostly bound to iron (Fe) minerals. Sulphide similarly binds to Fe and, when high enough, can interfere with P binding to Fe, resulting in greater availability of P in the water column (Lamers, Tomassen & Roelofs 1998).

Theoretically, the accumulation of sulphate in waterways can lead to elevated sulphide, which potentially heightens bioavailable P concentrations and increases the risk of eutrophication (Cañedo-Argüelles et al. 2013). This conceivably amplifies the threat from nutrients that enter waterways because of cropping activities and cattle grazing. The Fitzroy River has a number of adjacent areas of cropping and supports extensive cattle grazing. Furthermore, the Fitzroy has several impoundments for town and supplemented water supply that could be adversely affected by augmented eutrophication, especially with the Fitzroy River system having a number of potentially toxic species of blue-green algae (Fabbro 1999; Fabbro & Duivenvoorden 1996).

### 4.5.2. Magnesium dominant

The magnesium dominant water type (*Class B*) was observed in the Marlborough Creek system. It most likely derives from the serpentinite soils of the area, which contain high levels of magnesium (Forster 2007). In addition, magnesium is a dominant anion of the groundwater of the Marlborough Creek district (Raymond & McNeil 2011).

### 4.5.3. Transitional type waters

The water types with balanced cations (*Classes C* and *D*) were common across the basin. McNeil, Cox & Preda (2005) characterised these as transitional waters that are of mixed origins, including rainfall and weathered rock. Correspondingly, The Gap, where waters flow from mixed origins, displayed transitional types (*Classes C* and *D*) over the year. In general, the major trunks in the Fitzroy Basin presented transitional type waters.

### 4.5.4. Chloride dominant

*Class E* type water with the Na/Cl characteristic appeared in three areas: the Lower Fitzroy near the coast, the steep areas of the Upper Isaac, and Mimosa Creek at the foothills of the Blackdown Tableland (Appendix B). This type is reportedly derived from oceanic spray. It normally associates with steep, eastern areas of the basin that receive high rainfall (Douglas 1968; McNeil, Cox & Preda 2005). This description fits the sites displaying this water type in this present study.

### 4.5.5. High sodium type water

In contrast to the above, the *Class F* type water with about equal amounts of bicarbonate and chloride and a dominance of sodium, was confined to a few locations: sites 1304026, 1304029, 1304031, 1304033, 1304069 and 130414A, in the Upper Isaacs (with TDS up to 1436 mg $L^{-1}$) and a site on the Gwambegwine Creek, north-west of Taroom in the Upper Dawson, which involved one low TDS reading of 90 mg $L^{-1}$. Interestingly, 'Sodosols' was the dominant soil type in these areas (Figure 4). Sodosols are texture contrast soils that contain high sodium levels in the upper subsoil (Forster 2007). Forster (2007) noted that soluble salts can accumulate in the upper subsoils of these 'sodic' soils, which display lateral flow through "the sandy and loamy surface horizons, across the relatively impermeable clay subsoil". This is supported by the high TDS (up to 2179 mg $L^{-1}$) at Upper Isaac sites, especially in May and June 2011 (Appendix B). Land clearing and other surface disturbances might be the reason for these high TDS values.

### 4.5.6. Signatures expressed at The Gap site

An nMDS of the major ion data at The Gap revealed signatures in the water mass that were temporally distinct. Figure 19 displays three clusters that differed in signatures of dissolved ions. These likely involved three different sources: 1) the adjoining Marlborough Creek catchment, 2) rainfall interaction with soil mineralogy and 3) releases from the flooded coal-mines. The following explains these categories in more detail.

First, the July, August and September 2010 group related to a magnesium signature, which points to Marlborough Creek as the main influence at this time (Figure 19). In support of this, the August 2010 sampling of surface waters in Marlborough Creek displayed high magnesium concentrations relative to other anions (MCCR, Appendix B), as mentioned in Section 4.5.2.

Second, the cluster of November and December 2010, and January 2011 saw the main expression involving calcium, potassium and bicarbonate ions (Figure 19). This signature was most likely the effect of rainfall on soil mineralogy and the release of these ions in runoff, as has been described elsewhere (Lakshmanan, Kannan & Senthil Kumar 2003; Singh, Meetei & Meetei 2013).

The sulphate, sodium and chloride expression for the remaining cluster involved February to June 2011 and coincided with water releases from the flooded coal-mines (Queensland Floods Commission of Inquiry 2012). As mentioned previously, sulphate is an indicator of coal mining impact (Merovich Jr et al. 2007; Rikard & Kunkle 1990) and, apart from observations in areas affected by industry, sulphate is typically low in Queensland waters. Historic sulphate records show sulphate concentrations below 20 mg $L^{-1}$ in streams of the Fitzroy Basin (Jones & Moss 2011; McNeil, Cox & Preda 2005).

# 5. Conclusions

The Fitzroy Salinity IQQM computed an annual contribution of 0.4 million tonnes in salinity load from coal-mine water-releases for the water year 2010-11. This equated to 9% of the total end-of-valley salinity load for the Fitzroy for this year.

The Fitzroy Salinity IQQM has value in predicting changes in salinity loads in relative terms. Particularly, it would be useful for understanding the degree of effects from changes to industry release rules.

However, in terms of understanding the absolute transfer of salinity load through the Fitzroy River system, it requires additional support, e.g. a greater understanding of groundwater quality, inflows and interactions with surface flows.

Overall, the monthly monitoring of major ions at The Gap helped identify possible sources of river salinity within the Fitzroy Basin. The results exemplify the value of major ion monitoring and analyses at strategic locations within the Fitzroy Basin. Moreover, the continuous logging of EC and flow is extremely important for this type of study. Additional locations to consider for more frequent monitoring of major ions are sites that flow most of the year and represent end-of-valley locations for the sub-catchments. Where there is ambiguity regarding salinity sources, it is advantageous to have major ion data collected from upper catchment streams. These waterways are generally ephemeral by nature. The flashy nature of their flows requires a readiness and proximity of sample collectors or otherwise installation of automatic samplers. For the former, a community monitoring program would be ideal for obtaining these samples, which do not require special collection techniques. In terms of groundwater data, much more water chemistry data is needed to assist in attributing groundwater sources to stream salinity

With reference to the original objectives, this report accomplished the following:

- It determined that the coal-mine water-releases of 2010-11 contributed 9% of the total salinity load at the Fitzroy Basin end-of-valley.
- It provided a basis for future research into river salinity of the Fitzroy Basin. Recommendations include investigating implicit ways of incorporating groundwater into the IQQM and examining the variability in salinity associated with different management practices and climate regimes of the basin.
- It identified data deficiencies that are relevant to the understanding of salinity transfer and sources within the Fitzroy Basin. These included inconsistencies in the formatting and reporting of data supplied by mining companies, and the need for more groundwater major ion data, especially for areas where groundwater may interact with surface water of the Fitzroy.
- The study further calibrated the annual outputs of the Fitzroy Salinity IQQM by comparing modelled outputs with manual calculations of observed site data for the same timeframe.

# 6. Recommendations

The study findings have led to these recommendations:

- Conduct similar studies for successive wet years, i.e. 2011-12 and 2012-13, to further test and validate the outputs of the Fitzroy IQQM for salinity used in this study.
- Expand model calibration to include dry years and low flow conditions, both in terms of hydrology and salinity
- Analyse current data and determine and implement appropriate major ion monitoring regime at The Gap gauging station, and higher frequency sampling at end-of-valley sites in sub-catchments to help discern salinity sources. Include community sampling to obtain major ion data for ephemeral streams in upper catchment areas.
- Develop a conceptual model to describe groundwater interactions, hot spots and release points within the Fitzroy Basin to inform a review of the Fitzroy Basin groundwater monitoring network with a view of understanding the contribution of groundwater to river salinity and for use in the IQQM.
- Conduct new research aimed at providing the following: groundwater modules in the Fitzroy Salinity IQQM, a better understanding the variability in salinity from different management practices, and gaining insight into the effects of sulphate accumulation in waters of the Fitzroy.
- Implement a reporting system with a uniform template for the reporting of coal-mine water-release data by industry to expedite the use of these data for future studies, including the development of predictive models. The Wastewater Tracking and Electronic Reporting System (WaTERS) that has been launched in South East Queensland for municipal amenities data is an example of such an approach.

Further to the above recommendations provided, additional comments and figures are provided in Appendix E with future improvements, and value add comments, should a similar task be undertaken again in future. Many of the changes suggested were beyond the scope of any additional changes to this report, but provide a means to maximize value for future calibrations of IQQM salt models within the Fitzroy River Basin under different conditions.

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