Healthy HeadWaters Coal Seam Gas Water Feasibility Study

Assessing the salinity impacts of coal seam gas water on landscapes and surface streams

Final Report

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This document presents outcomes of Activity 3 (Assessing the salinity impacts of coal seam water on landscapes and surface streams) of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study.

The Healthy HeadWaters Coal Seam Gas Water Feasibility Study is analysing the opportunities for, and the risks and practicability of, using coal seam gas water to address water sustainability and adjustment issues in the Queensland section of the Murray-Darling Basin.

The study is being funded with $5 million from the Commonwealth Government, with support from the Queensland Government, as part of the Healthy HeadWaters Program, which is Queensland's priority project funded through the Commonwealth Government's Water for the Future initiative. The study is being managed by the Queensland Department of Natural Resources and Mines (DNRM).

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Summary

Irrigation, irrespective of water source, inherently carries a risk to soils and landscapes. This is due to an unavoidable change in the water and salt balance influencing processes such as deep drainage, runoff, lateral flow and groundwater recharge. The timeframe in which the risk will be expressed is driven by fundamental landscape attributes such as landform, the size of the unsaturated zone and soil properties, as well as management considerations such as the water application rate and crop water use.

This report describes a framework to assess the salinity risk associated with the use of coal seam gas (CSG) water for irrigation in the Queensland Murray-Darling Basin (QMDB) The framework has four components—Biophysical Hazard, Salinity Stage, Current Management Influence and Post-Irrigation Land Use. In addition to these components are Assets—the most difficult component to assess and not a pre-requisite to the risk assessment process. Furthermore, impacts on assets implies that a core objective of the risk assessment process has failed, as the intent is to <u>prevent</u> impacts on assets. The requirement to assess salinity risk out to 100 years meets Queensland's obligations under Schedule B – Basin Salinity Management to Part 12 Schedule 1 of the *Water Act 2007 (Cwlth)* to not permit the undertaking of any action that may have a significant effect on stream salinity in the Murray-Darling Basin.

Irrigation salinity risk can be divided into two parts—soil/water chemistry interactions and landscape salinity risk. The risk assessment framework is applicable to both. It is essential that both aspects of salinity risk are considered for any irrigation development. Different approaches may be applied to defining the components of the salinity risk assessment framework or portions of them, but overall, description and estimation of all components of the water and salt balance is necessary to adequately assess short-term and long-term salinity risk.

Examination of the existing data confirms the findings of previous authors—there is inadequate existing data to assess either site based or cumulative (regional) risk in a quantitative manner without large assumptions, resulting in significant error bounds. Consequently all irrigation developments require site specific investigation and assessment of the salinity risk. Critical data gaps requiring further investment are the collection of regolith/unsaturated zone attributes and land use history. Soil survey, land suitability assessment and unsaturated zone investigations must be a priority for the initial investigation of any irrigation proposal.

If salinity risk is mitigated at the point/paddock scale (through appropriate irrigation management in the context of the risk(s) posed), the overall risk of cumulative impact is reduced significantly. It is possible in a general sense to describe landscape and irrigation management attributes that are likely to lead to a high risk and conversely those that are likely to reduce risk to an acceptable level. To achieve this, however, requires more effective collation and coordination of government and industry based science and research. This should be conducted in the broader context of all irrigation activities, not just CSG related irrigation, as the principles are the same irrespective of water source. At the same time, paradigms used in the regulation of irrigated water need to be re-evaluated and improved to reflect the current science.

Information detailing methods for surveying soils and assessing irrigation suitability are included as appendices to this report (Appendix 2 and 3). This information is designed to aid the CSG industry and regulators in understanding the work required to adequately assess the types of irrigation salinity risk posed in the landscape. Use of this material by both government and industry will establish a better common understanding of the requirements of a science-based salinity risk assessment process.

1. Introduction

Coal seam gas is a natural gas, consisting primarily of methane stored in coal seams. Queensland's abundant coal seam gas reserves are providing the basis for the development of a liquefied natural gas (LNG) industry which is set to become one of the state's major exports. LNG is simply coal seam gas that has been cooled to the point it becomes a liquid and is able to be safely stored and transported.

The rapid growth of the coal seam gas industry in Queensland is resulting in the production of increasing quantities of associated coal seam gas water (CSG water). CSG water contains significant but variable concentrations of salts, with Total Dissolved Solids (TDS) values typically ranging from 1000 to more than 10 000 mg/L. It also has a high Sodium Adsorption Ratio (SAR) and may contain other contaminants (e.g. hydrocarbons and other chemicals such as boron, fluoride and metals and metalloids) in concentrations that may exceed thresholds in the national water quality guideline values (ANZECC and ARMCANZ 2000). The constituents of CSG water therefore have the potential to cause environmental harm if released to land or waters through inappropriate management.

The Coal Seam Gas Water Management Policy was released in December 2012 (DEHP 2012). The objective of this policy is to encourage the beneficial use of CSG water in a way that protects the environment and maximises its productive use as a valuable resource. The objective of the policy is to be achieved by managing CSG water in accordance with the following two priorities: Priority 1—CSG water is used for a purpose that is beneficial to one or more of the following: the environment, existing or new water users, and existing or new water-dependent industries and Priority 2—After feasible beneficial use options have been considered, treating and disposing of CSG water in a way that firstly avoids, and then minimises and mitigates impacts on environmental values. The CSG industry is therefore investigating opportunities for using significant quantities of treated CSG water for agriculture and silviculture in the Queensland section of the Murray-Darling Basin and catchments to the north.

Extraction of CSG in Queensland began in the early to mid-1990s. By the early to mid-2000s, the CSG industry was being encouraged to look for ways to beneficially use the raw water extracted as part of CSG production, rather than simply dispose of it in evaporation ponds or via discharge to streams[1]. A number of studies commissioned by CSG producers (e.g. Raine and Ezlit 2007) showed that the use of raw, untreated CSG water for irrigation was not a sustainable option given the typical quality of this water. Accordingly, CSG producers invested in research, including laboratory trials and field trials studying the use of varying levels of treatment of CSG water for irrigation. Generally, the smaller the mass of dissolved salts that is removed from a unit of water, the lower the cost of treatment, so initial trials focused on uncomplicated forms of treatment such as simply mixing raw CSG water with other better quality water sources. This simple mixing may or may not be supplemented by adding gypsum and/or acid to the raw water to change the water chemistry. Other trials involved using reverse osmosis (RO) permeate for irrigation—either directly or mixed back with raw CSG water. In 2012, trials were underway at a number of sites in the region, using treated CSG water of varying quality (e.g. Electrical Conductivity [EC] 300–4000 μS/cm, TDS 180–2720 mg/L, SAR 4–30). A condition of approval for these trials is the monitoring of groundwater, surface water and soils before, during and after the completion of the trial irrigation.

As with other irrigation practices, the inappropriate use of treated CSG water for irrigation has the potential to mobilise soil and groundwater salt stores, degrade land, and increase saline baseflow

[1] Until mid-2009 most CSG water was disposed of in evaporation ponds ranging from 1 to 100 hectares in area. Some untreated CSG water is/was directly discharged to local streams in the Dawson River catchment and other catchments or used for watering stock and petroleum activities.

to streams. Potential pathways of salt movement include deep drainage under irrigated lands and salt washoff. In some landscapes, deep drainage may move laterally and become baseflow to streams or it may drain to lower unsaturated zones or aquifers. There are also potential issues relating to the elevated sodicity of treated CSG water.

The physio-chemical properties of soils, and as a result soil structure, will also be affected by the application of irrigation water—the nature of these changes depends upon the salinity and sodicity of the applied water. Accordingly, irrespective of the associated salt load, any increase in the amount of water added to the landscape carries with it an inherent salinity risk. The potential impact of applying significant volumes of treated CSG water on landscape salinity therefore needs to be investigated. There is a need to develop a risk assessment framework and guidelines for assessing the risk of secondary salinity associated with the use of CSG water in the catchments of the QMDB.

1.1. Scope of the report

This report brings together the results of Activity 3 of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study. This is a project funded by $5 million from the Commonwealth Government, with support from the Queensland Government, to examine the use of CSG water in addressing water sustainability and adjustment issues in the Queensland section of the Murray-Darling Basin.

The objective of Activity 3 is to provide decision support tools to assess if, where and how CSG water may be used for irrigation in the QMDB without contributing to increases in landscape and stream salinity. Activity 3 will result in improved understanding of the potential risks to stream and landscape salinity associated with using CSG water for irrigation.

This report is divided into seven sections:

1. *Introduction*
   Outlines the extent of the CSG industry in Queensland, defines the area of interest and key terms used in the report, estimates of water and salt production from the CSG industry, and gives an overview of regulation regarding irrigation with coal seam gas water in the Murray-Darling Basin.
2. *Impacts of irrigated CSG water on soils and landscapes*
   Begins by explaining some underlying principles applicable to all irrigation enterprises, summarises known risks to soils and landscapes from irrigation, defines salinity and sodicity interactions in relation to irrigation, describes the impacts of using saline/sodic water for irrigation, and summarises salinity conceptual models.
3. *Methods and principles of salinity risk assessment*
   Outlines principles of salinity risk assessment, explains the concept of thresholds in relation to risk, and summarises previous salinity risk assessments carried out in the QMDB.
4. *Salinity risk assessment framework for irrigation with CSG water*
   Presents the recommended salinity risk assessment framework for irrigation with CSG water, defines the core attributes related to each of the four components of the framework (Biophysical Hazard, Salinity Stage, Current Management Influence and Post-Irrigation Land Use), describes how to assess the four components, discusses how to assess the overall salinity risk, and describes methods used to assess salinity risk including water/salt mass balance assessment.
5. *Landscape salinity hazards in the project area*
   Defines the broad landforms in the project area (focusing on alluvia and hillslopes), describes the broad landscapes found in the project area (alluvia, basalts, quartzose sandstone, unweathered to moderately weathered sedimentary rock, and moderately to strongly weathered sedimentary rock), and discusses landscape salinity risk.

6. *Monitoring requirements*
   Outlines the importance of monitoring irrigation areas, describes some fundamental monitoring principles, discusses the establishment of baseline values, and concludes by considering issues relevant to monitoring soil and groundwater.
7. *Data and knowledge gaps*
   Discusses the suitability of data collected by CSG companies and publicly available data for salinity risk assessment and explains the key knowledge gaps that limit application of the salinity risk assessment framework (expanding on the issue of soils data).

1.1.1. Area of interest

The area of interest for Activity 3 has been defined by considering the extent of the CSG production leases and exploration areas within the QMDB. Figure 1 illustrates the boundary of the project area. The project area includes a portion of the southern Fitzroy catchment, including the towns of Injune, Taroom and Wandoan, because it is contiguous with the QMDB and is an area of CSG production and exploration.

Based on data current to 1 June 2010 when Activity 3 commenced, 18% of the project area was covered by petroleum leases (including petroleum lease applications) while 87% was covered by exploration permits for petroleum (Figure 2). The two forms of lease can and do overlap and so these two coverage areas are not mutually exclusive. A greater percentage of the exploration permits had converted to petroleum leases by the completion of the project.

Petroleum leases (applications and granted leases) coincide with agricultural land class A[2] or B[3] over 8% of the project area, while exploration permits for petroleum (applications and granted leases) coincide with agricultural land class A or B over 48% of the project area.

[2] Class A land = crop land (land suitable for current and potential crops).
[3] Class B land = limited crop land (land marginal for current and potential crops; and suitable for pastures) or a complex of class A and other classes.

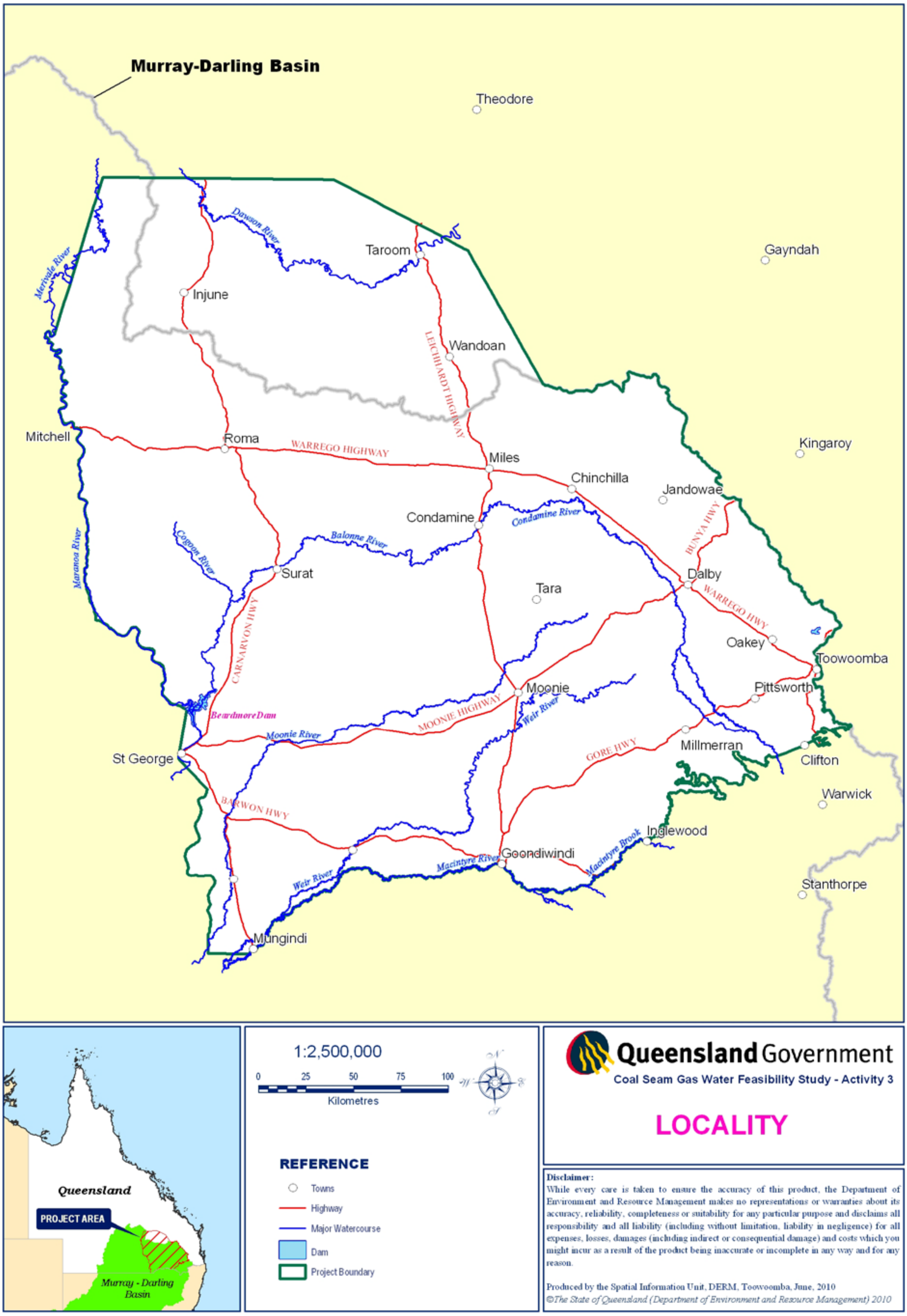


Figure 1 Project area for Activity 3 of the CSG Water Feasibility Study

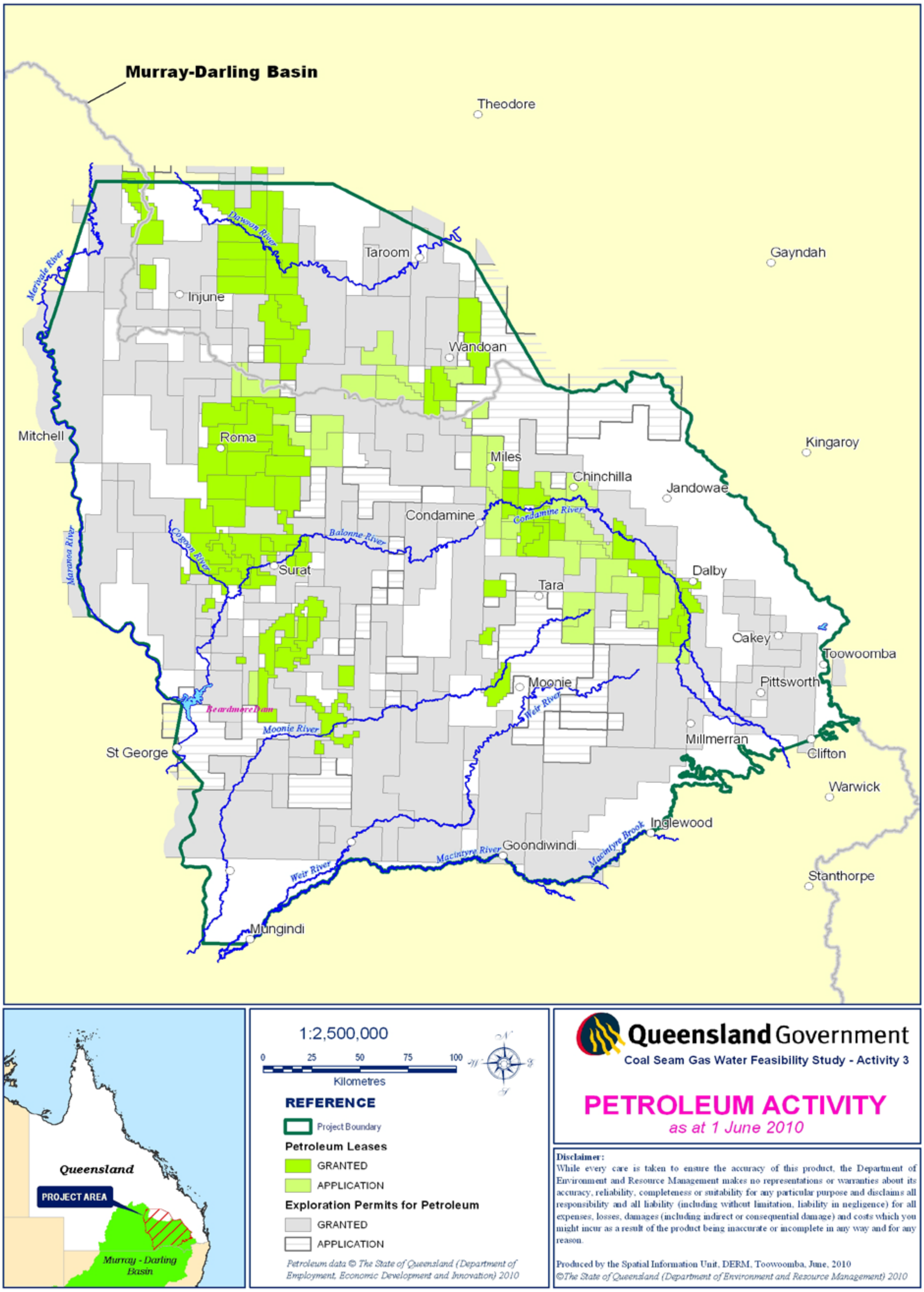


Figure 2 Current and proposed coal seam gas development in the project area (as at 1 June 2010)

1.2. Key definitions

The general processes typically associated with the movement of water and salt through the unsaturated zone are shown in Figure 3.

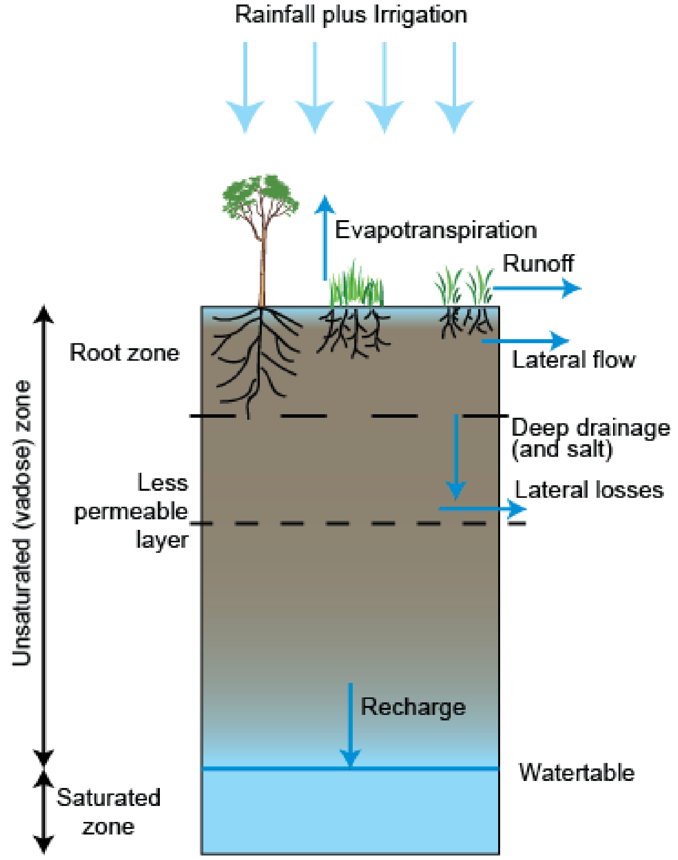


Figure 3 Conceptual diagram of water movement through the unsaturated zone

Note: Not all of these processes occur at every site. Factors such as landscape position, soil properties, climate and land use influence the pathways of water movement.

Explanations of these processes and other terms used in this report are provided in the following definitions.

Deep drainage	Deep drainage is water that moves below the root zone of plants. Deep drainage is affected by climate, soil type, soil properties, landscape position and land use. Deep drainage may become groundwater recharge after some time lag. Deep drainage is a natural and inevitable process which provides the water that recharges groundwater and becomes baseflow in streams. However, problems may arise when deep drainage is excessive as it leads to: - farming systems that are less water-efficient (it represents a loss of water that could be used by crops); - rising watertable levels (if groundwater levels rise to close to, within, or above the root zone, production is adversely affected); - mobilisation of salts previously stored in the soil and regolith, contributing to increased salinity in groundwater and surface water (while leaching of excess salts from the root zone is necessary and beneficial for agricultural production, the fate of these salts, and the water which moves them is of concern); and - increased leaching of nutrients (e.g. nitrogen) which represents a loss to the farming system, an impediment to efficient nutrient cycling, and contributes to poorer off-site water quality (Silburn and Montgomery 2004).
Groundwater	Groundwater refers to water in the subsurface which is beneath the watertable and thus present within the saturated zone. In contrast to water present in the unsaturated zone, which is referred to as soil moisture.
Lateral flow	Lateral flow refers to lateral movement of water within the soil profile, and it is governed by soil characteristics such as texture, permeability, stratification and hydraulic conductivity. The presence of any restricting layers, the permeability of the substrate and the landscape position (e.g. hillslope or alluvial plain) are also important. A highly permeable soil on an impermeable substrate (or lower soil horizon) would generally lead to lateral flow within the soil profile, because the rate of water entry into the soil exceeds the rate of water entry into the substrate.
Leaching fraction	Leaching fraction is the term given to the portion of applied water (rainfall and irrigation) that is required to drain through the root zone to maintain soil salinity at acceptable concentrations (SalCon 1997). The leaching fraction therefore determines the concentration of dissolved salts in the soil. If the leaching fraction fails to remove sufficient dissolved salts, salinity levels in the soil will reach phytotoxic levels. Phytotoxicity thresholds are species and sub-species dependent. If the salinity of irrigation water increases, the leaching fraction can be adjusted to manage soil salt levels by changing the irrigation application. The terms deep drainage and leaching fraction are often used interchangeably. Deep drainage is the <u>quantity</u> of water that leaks below the root zone (whether it is rain or irrigation), whereas leaching fraction is the <u>proportion</u> of water (rainfall and irrigation) that leaks below the root zone.

Raw CSG water	Raw CSG water is water released from CSG wells without any subsequent treatment. Its chemical characteristics may have changed modestly from those in the aquifer due to post-extraction equilibration with atmospheric gases (e.g. CO_2).
Recharge	Recharge is water that arrives at the watertable (Walker *et al*. 2002). The terms recharge and deep drainage have historically been used interchangeably, leading to some confusion. We use these terms as defined by Walker *et al*. (2002) i.e. *deep drainage is the flux of water that moves past the root zone of vegetation*, and *recharge is the amount of infiltrated water that reaches a specific groundwater system*. The relationship between drainage below the root zone and groundwater recharge can be complicated, influenced by factors such as long or uncertain response times, lateral flow in the soil profile, multiple aquifer layers, groundwater pumping and discharge, and multiple land uses contributing to a groundwater system (Silburn and Montgomery 2004).
Regolith	Regolith is the unconsolidated geological material above the base rock and includes the soil profile.
Root zone	The root zone is the depth in which the majority of root activity and water extraction occurs. The effective rooting depth can be at least 3 metres for some common crops, but is highly variable and dependent on plant type.
Salinity	Salinity is the presence of soluble salts in soils or waters. **Primary salinity** is the form of salinity that occurs naturally in soils and waters (SalCon 1997). Primary salinity appears as naturally occurring saline areas and saline soils, e.g. salt lakes, salt pans, salt marshes and salt flats. **Secondary salinity** refers to the forms of salinisation that result from human activities; usually land development and agriculture (SalCon 1997). Secondary salinity can be divided into three groups on the basis of the processes contributing to salting—watertable salting, irrigation water salting and erosion scalding
Salinity hazard	Salinity hazard (also referred to as biophysical hazard) is a function of the inherent attributes of a landscape which predispose a landscape or catchment to the development of either land or water salinity. These attributes include climate, geology, soils and topography. Hazard is independent of human influence (Searle *et al*. 2007).
Salinity risk	Salinity risk is an estimate of the likelihood of secondary salinity expression (in any form) in a spatially defined area within a defined time-span. Risk is a function of human activities, interacting with the inherent biophysical hazard (Searle *et al*. 2007). Risk indicates the probability that certain actions, including land use management, will lead to salinity being expressed (Moss *et al*. 2001).
Saturated zone	The saturated zone is the zone in which the voids in the rocks or soil are filled with water at a pressure head greater than or equal to atmospheric pressure (NWC 2011). The watertable is the top of the saturated zone in an unconfined aquifer.
Sodicity	Sodicity is the presence of a high proportion of sodium ions relative to other cations in water or adsorbed at exchange sites on soil colloids.

Treated CSG water	Treated CSG water is water that has had some form of treatment to improve its quality. Treatment methods may include amendment with additives and/or treatment via reverse osmosis, ion exchange or similar processes. - *Amended CSG water:* this refers to raw CSG water that has been amended with additives to change its ionic composition or other properties. For example, addition of gypsum, 'shandying' (mixing) with other water (e.g. surface water, groundwater), addition of acid or other 'balancing' agents. - *RO treated CSG water:* this refers to water that has been treated by reverse osmosis (RO) to improve its quality. During RO, the input water (raw or amended CSG water) is placed under pressure and passed through a semi-permeable membrane. The treated water that has passed through the membrane is called 'permeate'; the water that is rejected by the membrane (the wastewater) is called 'brine' or 'concentrate'. In this report, RO treated CSG water refers specifically to the permeate. The brine from RO treatment needs to be appropriately managed. As described above, there are varying levels of treatment of CSG water. It is important to realise that after treatment, CSG water may still contain sufficient levels of salt, sodium and/or other contaminants to limit its use. Essential minerals (e.g. calcium) may need to be added to CSG water to improve its ionic balance. The ionic composition of the water is a prime consideration in determining how it may be used.
Unsaturated zone	The unsaturated zone is the zone between the land surface and the watertable (NWC 2011). (Also called the 'vadose' zone.) The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Water still moves through the unsaturated zone, but at much slower rates compared to water movement through the saturated zone.
Watertable	The watertable is the upper surface of a zone of saturation in an unconfined aquifer at which the pore pressure is atmospheric. Below the watertable, the aquifer material is permanently saturated; above the watertable, the rock or soil is unsaturated (SalCon 1997).

1.3. CSG water and salt production

Coal seam gas is a natural gas, consisting primarily of methane stored in coal seams, adsorbed to the coal in tiny pores and cleats (Knights and Hood 2009). The target coal seams are under hydrostatic pressure which restricts the escape of the CSG. CSG is extracted through wells drilled into coal seams. The initial phase of CSG production usually involves the dewatering of the coal seams in order to reduce the hydrostatic pressure and so allow desorption of the methane bound to the coal matrix, and the release of gaseous methane into voids in the dewatered coal seam. The water and the gas are separated in the well, with the water pumped to one reticulation system and the gas to another.

The amount of water brought to the surface is relatively high compared to conventional natural gas production because the coal seams from where the gas is extracted contain many fractures and pores that hold and transmit large volumes of water (US Geological Survey 2000, Draper and Boreham 2006). As coal seams are dewatered, the volume of water pumped typically decreases over time (Figure 4), while the gas production initially increases, before subsiding slowly (US Geological Survey 2000, NRM&E 2004).

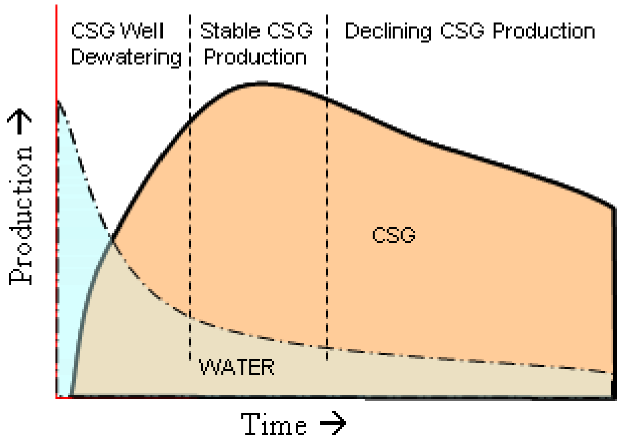


Figure 4 Indicative CSG and associated water production over time

With more proven CSG reserves and expanding LNG markets, the future production of CSG water across the QMDB is likely to increase significantly. Estimates of future water production vary markedly from author to author. The estimates appear dependent upon assumptions regarding physical factors, such as the relative yields of water and gas, aquifer transmissivity, extraction well density and seam thicknesses, as well as economic factors such as readily exploitable reserves, LNG pricing and demand.

Available data indicates that there is significant variability in the volumes and quality of CSG water within the different basins and gas fields. While expansion of the industry can be predicted to some extent, it is much less certain how much water will be produced, what quantities of salt will be produced, and what the actual footprint of the industry will be (particularly in the Condamine Alluvium and in gas fields on the margins of the Surat and Bowen basins). As an example, more associated water per volume of gas is produced in the Surat Basin (in southern Queensland) compared with the Bowen Basin (in central Queensland). This is due to the more complex stratigraphy of the Walloon Coal Measures, which are the principal CSG source in the Surat Basin. At the Fairview Field in the southern Bowen Basin, Santos has reported an initial daily water production of 0.20 ML/day/well declining to 0.02 ML/day/well after 12 years (URS 2009). In the Surat Basin QGC has indicated that initial CSG water production was 0.40 ML/day/well, declining to 0.1 ML/day/well over a period of six months to a few years (ERM 2009).

Many different projections of both water and salt production from the CSG-LNG industry have been published, making it very difficult to precisely predict the impact that this development may have on the environment without more precise spatial and temporal estimations of CSG water production and use for the next 10–30 years and beyond. However, predictions will improve as CSG operators develop their gas fields and report on their annual water production. Table 1 summarises several estimates of CSG water production from the Bowen and Surat basins, ranging from 75 GL per year to 480 GL per year. RPS (2011) commented that Scenarios 1 and 2 are low-development scenarios while Scenario 3 is more likely but future development may exceed this estimate with up to 5290 GL extracted from the Surat basin alone.

Table 1 Estimated CSG water production for the LNG industry in the Surat and Bowen basins

Reference	Estimated CSG water production
RPS (2011)	Scenario 1 = 3150 GL, Scenario 2 = 4900 GL, Scenario 3 = 7065 GL
KPMG (2010)	250–480 GL per year if LNG production reaches 40 Mtpa
APLNG (2011)	Average of 75 GL per year, with a peak of less than 140 GL per year
NWC (2010)	7500 GL over the next 25 years, equivalent to 300 GL per year
Energy Resources (2011)	2540 GL (from 2009–2060); annual flow rates peak at 149 GL in 2021
KCB (2012)	5000 GL (from 2010–2060); annual flow rates peak at 170 GL in 2025

Estimates of salt production from treatment of CSG water are provided in the environmental impact statement reports by Santos, APLNG, QGC and Arrow Energy. These are summarised in Table 2. As most of these estimates appear to be derived from applying typical data for dissolved salt concentrations to the previously described, imprecise associated water yield estimates, the level of imprecision associated with salt yields is commensurately higher. Importantly and largely regardless of the methodological precision, industry predictions of salt production over the life of the CSG-LNG projects are of a similar magnitude to the existing salt inputs from conventional groundwater extraction and rainfall in the Condamine-Balonne catchment over similar timeframes.

Table 2 Industry estimates of salt production by basin

CSG producer	Salt production (tonnes)	
	Surat Basin	Bowen Basin
GLNG[1]	307 000	476 000
APLNG[2]	3 500 000	-
QCLNG[3]	4 600 000	-
Arrow LNG[4]	3 873 450	-

Note: These estimates are based on the following timeframes: GLNG and QCLNG = 20 year timeframe; APLNG = 30 year timeframe; Arrow LNG = 35 year timeframe.
Source: [1]Santos (2010a), Santos (2010b); [2]APLNG (2011); [3]QGC (2010); [4]Arrow Energy (2011).

It is impossible to confidently estimate salt yield due to spatial and temporal variation in water quality in gas fields. Industry predictions are highly variable—it is estimated that the amount of salt produced over a 30 year period could vary from 350 000 tonnes to 1 650 000 tonnes per year. The Interim Report from the Senate Inquiry (The Senate 2011) stated 'conservatively, the industry will be handling some 750 000 tonnes of salt per annum'. If the National Water Commission's estimate of 7500 GL of CSG water production is used with an average TDS content of 3000 mg/L, then the potential salt load brought to the surface over the next 25 years would be 22.5 million tonnes (about 900 000 tonnes of salt produced per year). Since not all of the water will be treated, the amount of brine and solid salt for disposal will be less than this; however, management and disposal options able to deal with significant quantities of brine and solid salt need to be developed.

Given the large volumes of CSG water that will be produced over the next 10–30 years, sustainable and practical options for managing this water (no matter what its volume is) need to be developed. In order to manage the water, more data is required on its reliability of supply, and how its quality and quantity will vary over time and spatially.

It is not possible with currently available information to determine with any certainty the volumes and chemistry of water that will be released as a result of the proposed exponential growth in the Queensland CSG industry. As a result, it is not possible, at this time, to conduct a whole of area salinity risk assessment in the specific context of CSG water irrigation.

1.4. CSG water for irrigation

Water produced during the CSG extraction process is generally of a poorer quality than existing surface water and groundwater used for irrigation. CSG producers are required to ensure any disposal options do not cause environmental harm. The most viable options for 'disposal' of CSG water involve treating raw CSG water (e.g. through addition of amendments, reverse osmosis, or shandying) to reduce the relative concentration of sodium and improve the overall chemical composition of the water.

The variability of water quality, both spatially and temporally is a complex issue in the management of CSG water for irrigation. Predictions of salt balance and salinity risk are by definition relative to specified water/salt balances. Variation in the water/salt balance leads to unpredictable outcomes. There is no *one size fits all* solution to irrigation with CSG water. The choice of crop (annual *vs* perennial) and decadal climate patterns also have a strong influence on water use. Water use and salinity risk in a dry decade can be substantially different from that during a wet decade. While the CSG water supply is effectively continuous, rainfall in the QMDB is highly variable, unreliable, and somewhat episodic in nature. Any irrigation scheme must be able to cope with both extended dry and extended wet periods but also the continual supply of CSG water. This has obvious implications in terms of predicting potential risk/impacts.

The demand for CSG water for irrigation is dictated by:

- quality of water (raw water quality, cost of treatment, price producer/end-user is prepared to pay);
- reliability and stability of supply (to water treatment plants and end-users);
- location (CSG fields *vs* water treatment plants *vs* end-users); and
- commercial factors (e.g. business considerations with the lead time for irrigation enterprise of 3–5 yrs, the viability of CSG/LNG industry developments).

An observation regarding the current CSG development footprint is that a significant proportion of it covers landscapes and soil types that have never been used for irrigation. Furthermore, some areas are unsuited to agriculture other than limited grazing. As a general principle, better irrigation efficiencies and lower salinity risk is obtained when better quality soils are used for irrigation. This poses challenges for how CSG water may be used in relation to irrigation.

1.5. Regulatory context for irrigation with CSG water

Under Queensland law, the CSG industry is regulated by the: *Petroleum and Gas (Production and Safety) Act 2004; Petroleum Act 1923; Environmental Protection Act 1994; Water Act 2000; Water Supply (Safety and Reliability) Act 2008; Waste Reduction and Recycling Act 2011; Sustainable Planning Act 2009*; and *State Development and Public Works Organisation Act 1971*.

A primary objective of Queensland's approach to managing CSG water for irrigation is the prevention of long-term landscape salinity risk, thereby meeting Queensland's obligation under the Basin Salinity Management Strategy (MDBC 2001), the *Water Act 2007 (Cwlth)* and meeting the general duty of environmental care under the *Environmental Protection Act 1994* (Qld) (EP Act). The focus of Queensland's regulation of irrigation using CSG water is to ensure that the resultant increase in groundwater accessions does not result in:

- watertables rising to such an extent that they impact on plant root zones or intercept the soil surface;
- an unacceptable increase in the mass of salt discharged to stream; or
- adverse impacts on any underlying potable aquifers.

The key indicators for evaluating Queensland's success in preventing landscape salinity due to irrigation with CSG water are that:

- the unsaturated zone does not become saturated within 100 years from when irrigation with CSG water starts and irrigation does not lead to any unacceptable discharge of saline waters to stream. This feature is consistent with the definition of a Significant (Salinity) Effect as 'a change in average daily salinity at Morgan which the Murray-Darling Basin Authority estimates will be at least 0.1 EC within 100 years after the estimate is made' (Schedule B – Basin Salinity Management Strategy to Part 12 Schedule 1 of the *Water Act 2007*(*Cwlth*). To achieve this, irrigation using CSG water and the post-CSG water irrigation land use must together leave a sufficient unsaturated buffer so that key assets are not affected by salinity or waterlogging;
- the concentration of salts in the saturated zone (an aquifer) does not increase above initial baseline conditions in the aquifers underlying the irrigation area.

Maintenance of an unsaturated zone buffer at each irrigation site minimises the risk of mobilisation of salinity at the landscape level by either rising watertables or lateral movement of salts and water. Managed this way, the risk of cumulative impact from irrigation at individual sites is substantially reduced, although not entirely negated. Minimisation of salinity risk at the site level is also consistent with two objectives of the Basin Salinity Management Strategy *Water Act 2007*(*Cwlth)* to:

- control the rise in salt loads in all tributary rivers of the Murray-Darling Basin, and through that control, protect their water resources and aquatic ecosystems at agreed levels—meeting the end of valley targets;
- control land degradation and protect important terrestrial ecosystems, productive farm land, cultural heritage, and built infrastructure at agreed levels Basin-wide—expressed as within valley targets.

2. Impacts of irrigated coal seam gas water on soils and landscapes

2.1. Underlying principles related to all irrigation

The principles and processes associated with the different forms of irrigation salinity are well understood at the coarse scale. As indicated earlier, the salinity risk associated with irrigation can be divided into the soil/water interactions and the landscape level. However, even if the best quality water is used for irrigation, there is still a landscape salinity risk in all irrigation schemes, as there is generally enough salt stored naturally in the landscape (primary salinity) that can be mobilised through additional water movement with resultant impacts on the land surface and streams. Thus there are some underlying principles relevant to all irrigation enterprises, regardless of irrigation method, crop type, geographic location, soil type, source of water or irrigation water quality. These include:

1. Irrigation causes a change in water balance
2. Deep drainage is inevitable
3. Salt moves with water
4. The applied water is more saline than rainfall.

These principles are widely accepted, but they are often overlooked in the development and assessment of irrigation proposals. Each of these principles is discussed below.

2.1.1. Irrigation causes a change in water balance

Changing land use from perennial, deep rooted native vegetation to generally shallower rooted and/or annual crops and pasture alters the water balance, causing a decrease in transpiration and an increase in water draining below the root zone (i.e. deep drainage)—unless other factors lead to a greatly increased runoff (the likelihood of the latter occurring is generally low). Changing land use to irrigated farming systems also alters the pattern of soil water use, storage and through flow when compared with that under native vegetation. It therefore leads to greater water balance perturbations, with irrigated systems experiencing increased frequency and magnitude of deep drainage events. Even if the irrigation itself is managed to prevent any deep drainage (e.g. drip irrigation with amounts only just meeting the crop water requirement (McHugh 2003)), some deep drainage will occur due to rainfall and this deep drainage with be greater than that under an equivalent non-irrigated farming system.

Extensive measurement and modelling of deep drainage rates under a variety of land uses has been undertaken in Queensland over the last ten years, e.g. Tolmie *et al*. (2003), Tolmie and Silburn (2003), Yee Yet and Silburn (2003), Silburn and Montgomery (2004), Owens *et al*. (2004), Silburn *et al*. (2007a), Silburn *et al*. (2009), , Robinson *et al*. (2010), Tolmie *et al*. (2011), Silburn *et al*. (2011), Gunawardena *et al*. (2011). This and other research all indicates that deep drainage is generally ordered such that native woodland < native grassland or exotic pasture[4] < opportunity cropping < summer cropping < winter cropping < irrigated summer cropping (see Figure 5). Yee Yet and Silburn (2003) reported that deep drainage significantly increases with irrigation: for example, in the QMDB the average modelled deep drainage for woodland on a grey Vertosol is <1 mm/yr, whereas the average modelled deep drainage rate due to rainfall alone for irrigation is 43 mm/yr (ranging from 8–165 mm/yr). A review of previous deep drainage studies under furrow irrigation in northern NSW and Queensland, mainly on cracking clays, found deep drainage was typically 100 to 200 mm/yr (Silburn and Montgomery 2004).

[4] Native grassland = a developed grassland community cleared of upper storey vegetation dominated by *Dicanthium*, *Bothriochloa* or *Astrebla* spp. An example of exotic pasture is *Cenchrus ciliaris* (buffel grass).

In a dryland woodlot it is possible to effectively replicate the natural deep drainage regime. In the case of irrigated woodlots, this is unlikely as the increased frequency of full soil water profiles increases the likelihood of deep drainage events due to rainfall. It should be noted that changes to the water balance occur irrespective of water source, i.e. in general the fact that the irrigation water is derived from CSG production is largely irrelevant.

The production of CSG relies upon the efficient and economic extraction and disposal of the water in the coal seams. Application of the water to land is fundamentally a disposal mechanism; thus there will always be a tendency towards maximising the application rate in order to use as much water as possible and minimise the cost of CSG water disposal. This can be exacerbated by the mismatch between continuous supply and variable demand. Furthermore, application efficiency may not always be optimised, as in the case of 'forced' irrigation in wet weather due to inefficient equipment or management, or minimal buffering of irrigation water storage capacity. Such situations can lead to supplying water in excess of the crop water demand, therefore increasing the likelihood of deep drainage or it may lead to the use of excessively saline or sodic water resulting in impacts on soil structure and agricultural productivity.

By virtue of the fact that irrigation involves a substantial change to the water balance, the salinity risk is also increased. It is therefore very important when irrigating with CSG water (or any other water source) to have a detailed understanding of the applied water quality and volume and their interaction and potential effects on the receiving environment.

2.1.2. Deep drainage is inevitable

Water that is not used by vegetation, lost to evaporation or flow laterally can 'leak' below the root zone of plants; this component of the water balance is called deep drainage. Deep drainage occurs when the amount of water infiltrating into the soil (rainfall minus runoff) exceeds the soil water deficit (storage space relative to a drained upper limit[5]) created by evapotranspiration (Yee Yet and Silburn 2003). The extent of deep drainage is affected by:

- Climate—key factors are the amount and timing (seasonality) of rainfall and potential evaporation, and the relationship between the two (Tolmie *et al*. 2011);
- Soil properties—major determinants of drainage are plant available water capacity (PAWC) (Radford *et al*. 2009, Tolmie *et al*. 2011) and soil permeability; and
- Vegetation—major factors are perenniality, plant rotation (crop sequence) and effective rooting depth (Tolmie and Silburn 2003, Yee Yet and Silburn 2003).

Deep drainage is a natural process providing water to recharge groundwater and baseflow in streams. Figure 5 illustrates how the amount of deep drainage varies with different land use practices. Even though drainage rates under native vegetation are typically very low in inland Queensland (hence many soils have large salt stores), deep drainage still occurs. Any change in vegetation type or increase in the amount of water applied (e.g. via irrigation) will inevitably lead to increased deep drainage because the plant/soil system is less able to use or store the amount of water it receives over a period of time. The increase in deep drainage can be exacerbated in cropping systems where it is necessary to intercept and store rainfall during fallow periods to sustain a subsequent annual crop—this is a common situation applicable to dryland winter and summer cropping in the QMDB.

[5] Drained upper limit (DUL) is the amount of water the soil is able to hold after drainage. For more information, refer to Dalgliesh and Foale (2005) and Figure 41.

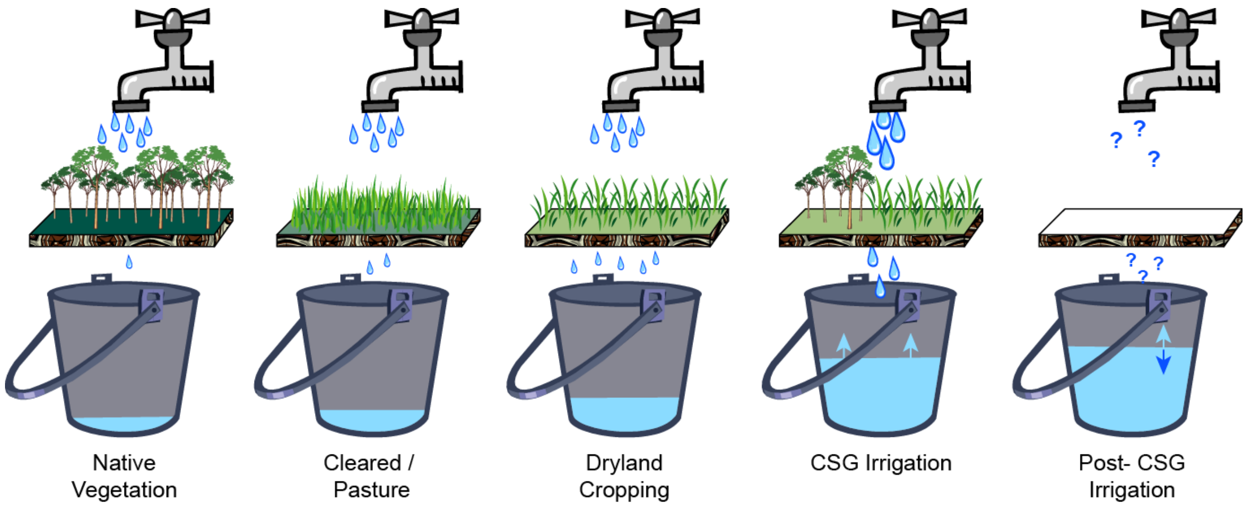


Figure 5 The change in deep drainage with different land use practices

Attempting to create an irrigation system in which deep drainage is zero is neither practical, nor a reflection of the natural system. Some degree of deep drainage is inevitable, with that drainage necessary to help flush salts derived from rainfall past the root zone (see Section 2.2.2 for more discussion on this issue).

Figure 5 also reinforces the need to consider post-irrigation land use, as this influences the overall impact that deep drainage will have on the unsaturated zone, over time (see Section 4.4).

2.1.3. Salt moves with water

All water in the landscape contains some level of soluble salts, as do all soils. Clay soils generally have higher salt stores than sandy soils (this is largely because deep drainage rates are higher in sandy soils and so salts are naturally leached in these soils). Precipitated salts such as gypsum are an example of primary salinity commonly found in clay soils in inland Queensland. Thus the application of water to the landscape will add salt, but more importantly will mobilise the existing salt in the landscape when deep drainage occurs. Surface washoff, lateral flow and deep drainage are the main mechanisms for salt transport in soils. Salt moves through the landscape with water so the movement and distribution of salt is determined by the hydrology of the landscape (Shaw 1997).

2.1.4. The applied water is more saline than rainfall

Rainfall imported salinity in the QMDB is low (EC 13-37 µS/cm), and declines with the distance from the coast (Biggs 2006). Salt concentrations in surface waters (river and creek) is higher than rainfall, due to salt washoff, interflow and baseflow contributions, but it is generally <500 µS/cm which is well under the threshold limits of sensitive crops (Appendix 1), with the exception of some streams in the eastern Darling Downs—largely outside the area currently subject to CSG development. In all cases, the CSG water being applied will be more saline than rainfall and potentially more saline than surface water. Therefore, it is inevitable that there will be an increase in salt accessions to the landscape and that soils reaching equilibrium with the applied irrigation water are likely to have a higher salinity than they naturally possessed. Furthermore, unless treated appropriately, CSG water will have a substantially different ionic composition to surface waters in the region, leading to additional adverse impacts (see Section 2.2).

2.2. Risks to soils and landscapes from irrigation

While irrigation provides a number of important benefits, it is well accepted that there are known risks associated with supplying additional water and associated salts to soil and the wider landscape (see for example, Shaw and Yule 1978, SalCon 1997, ANZECC and ARMCANZ 2000, deHayr and Gordon 2006 and Charman and Murphy 2007).

These risks include:

- Soil structural decline and soil physical instability (leading to surface sealing and crusting, enhanced soil compaction risk, and reduced infiltration, drainage, aeration, macroporosity and permeability);
- Watertable rise, potentially leading to soil waterlogging, shallow watertables, salinisation of soils and/or discharge of saline water to streams;
- Off-site degradation of soil/land and surface and/or groundwater (e.g. erosion, silting, nutrient/pesticide runoff, and salinisation); and
- Poor crop growth and reduced crop yield.

The above list indicates that salinity risk from irrigation can be considered in the context of risk to the soil and risk to the landscape. The former is driven by soil/water chemistry interactions whereas the latter is driven primarily by the volume of water (deep drainage). In both instances, the risk is a result of natural circumstances (soil, geology, landform etc) and a management influence (irrigation). This approach was encapsulated in Figure 4.2.1 in ANZECC (2000), but unfortunately the landscape portion (Step 5 in the Figure) is often ignored and too much focus is paid to Steps 1-4.

Irrigation salinity risk can also be considered from the perspective of direct risk/effects (e.g. change in soil physical/chemical properties) and indirect risk/effects (e.g. groundwater recharge). Direct risks occur in short timeframes or at the point of water application whereas indirect risks occur over long timeframes or off-site. Irrigation salinity risk may also be considered in relation to scale—divided between factors/ processes that function/impact at the paddock scale, versus those that function/impact at the broader scale. This is a somewhat difficult division however as paddock scale impacts often lead to indirect or cumulative impacts at the broader scale. An example is that soil structural decline resulting from the application of poor quality water at a site—can lead to increased runoff, which in turn can carry salt and nutrients to nearby watercourses.

Irrespective of the way in which irrigation salinity risk is viewed, the necessity to understand soil and landscape factors and processes remains the same. The general conceptual salt balance in our landscapes is illustrated in Figure 6.

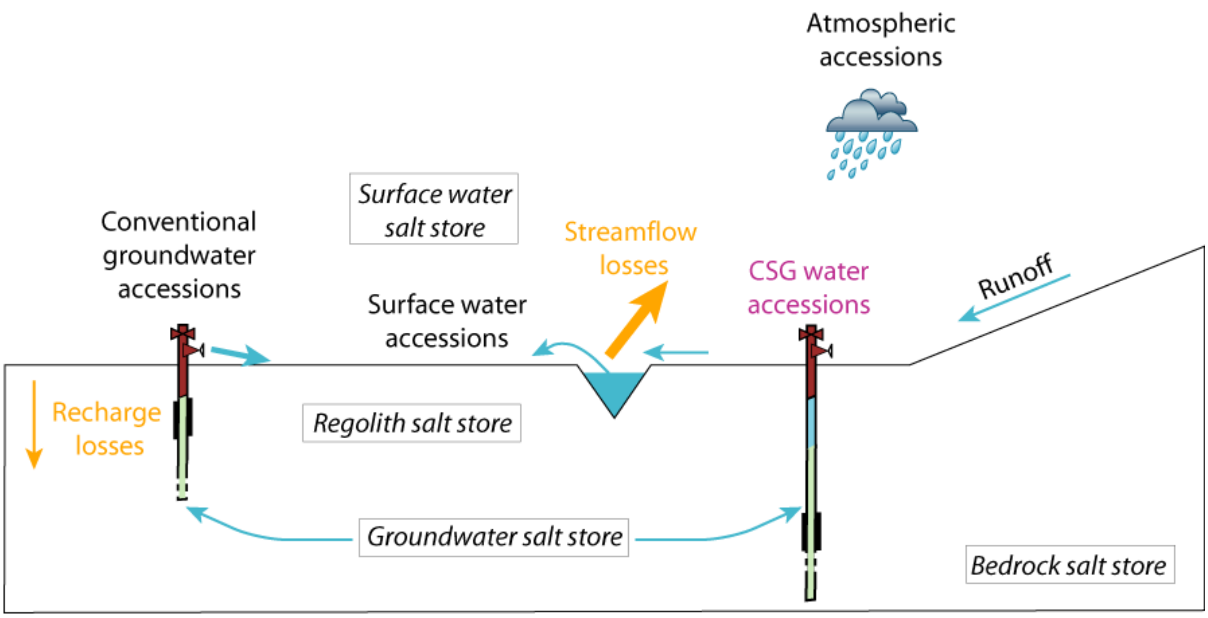


Figure 6 General conceptualisation of salt/water fluxes in the landscape

This broad scale illustration of salt stores and fluxes is further refined in Figure 7 which illustrates that to understand the fate of water and salts in the landscape, and the associated risk of any land use, it is necessary to understand a wide variety of landscape attributes and processes.

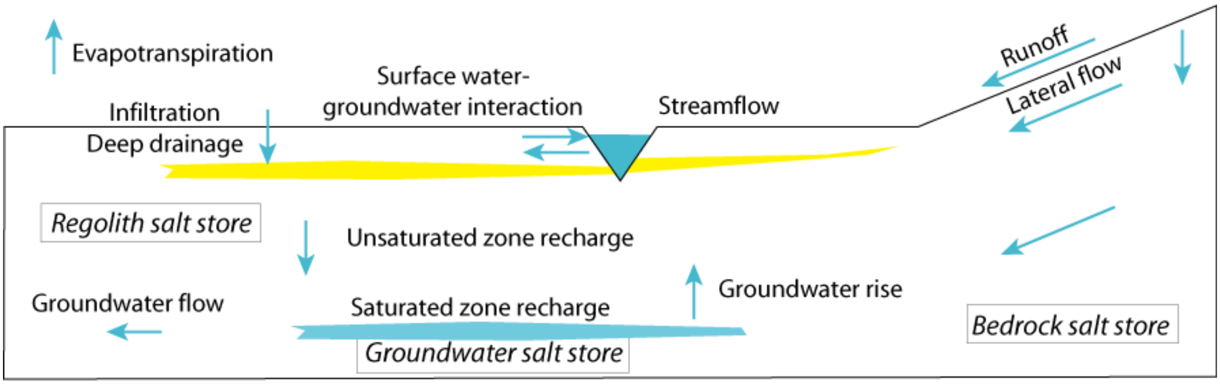


Figure 7 Detailed conceptualisation of salt/water fluxes in the landscape

2.2.1. Soil structural decline

The main mechanisms for soil structural decline under irrigation are the consequence of wetting soils and compaction. Many Queensland soils are susceptible to slaking (the natural collapse of soil aggregates in water) and dispersion on wetting (the soil 'breaks apart' upon wetting as a result of sodium in the soil (see Appendix 1 for more information about sodicity). Dispersion is made worse by regular cultivation—as this reduces organic matter levels—and by rapid wetting of soils as occurs under irrigation. Dispersion leads to sealing and crusting of the soil surface, low permeability, high bulk density and low porosity within the soil. Associated impacts include poor seedling emergence, poor infiltration, increased erodibility, reduced interception of precipitation and reduced water availability. Dispersion of soils is also strongly controlled by interactions between salinity and the proportion of sodium and other ions in soils (see Section 2.3).

Soil surface crusting may also be formed by droplet impact (Sumner 1994). The physical action of water drops hitting the soil surface is enough to 'sort' the soil so that the fine sand, silt and clay particles are re-arranged until they eventually pack together, filling the pore spaces at the surface, causing a surface seal and setting hard like concrete. The surface crust becomes a barrier to

infiltration and therefore less water enters the soil. Drops impacts may increase through irrigation, depending on the water application technique used. There are various methods available to reduce water drop impact, such as low pressure sprays and trailing socks. The presence of a surface crust coupled with reduced permeability and porosity in the soil results in a decreased leaching fraction, meaning there is a higher potential for salt build up in the soil under irrigation, and a potential for increased runoff and associated salt washoff.

Soil compaction also adversely affects infiltration (Silburn and Glanville 2002), soil permeability, bulk density and porosity, therefore reducing the leaching fraction under irrigation. The degree of mechanical compaction is influenced by the soil moisture content. Many soils under irrigation are naturally fine textured (i.e. high clay content), drain poorly and are liable to plastic deformation when worked or driven over in a moist state (thus worsening their poor water transmission and aeration properties).

The method of irrigation also plays a role in structural decline—flood irrigation is generally more harmful than spray or trickle as the latter methods wet the soil more slowly, reducing slaking (Charman and Murphy 2007). The advantages of slow wetting using spray irrigation may however be counteracted by the disruptive effect of droplets hitting the soil. Furrow irrigation affects soil structural stability in the furrows, but not in the slowly wetted rows. Charman and Murphy (2007) state that of flood, furrow, spray and trickle irrigation systems, trickle is likely to be the least damaging to soil structure. In recent years though, advances in spray technology have substantially reduced the issues associated with droplet impact on the soil surface.

Laser levelling is an essential practice on furrow irrigation properties to improve water use efficiency and crop productivity; however it can also lead to soil structural problems because it exposes subsoils with sodic properties (which are less stable and less permeable than surface soils). This can result in irrigation bays with highly variable infiltration properties.

Structural decline of surface soils under irrigation is a major issue requiring management, but an often overlooked issue is degradation of the subsoil structure (Charman and Murphy 2007). This is especially applicable to clayey subsoils. Clayey subsoils often do not drain quickly enough before necessary farm operations are performed. For example, tillage and harvest operations are done when the surface soil is dry, but if the subsoil remains wet, meaning that they are subject to compaction or compression and subsequently losing much of their macroporosity. This makes the subsoil even less well drained, anaerobic and denser, and so roots fail to penetrate the compacted layers. Rotating affected paddocks with dryland cropping techniques can help improve subsoil structure, as it allows more natural drying and shrinking/cracking conditions. However, this can extend over many wetting and drying cycles and thus many years to improve subsoil structure. Pasture leys, controlled traffic and introduction of suitable earthworm species are other possible options (Radford *et al*. 2001).

2.2.2. Watertable rise

As explained in Section 2.1.2, deep drainage refers to water that ‘leaks’ below the root zone of plants. Deep drainage is a natural process, influenced by climate, plant water use and soil/landscape attributes. Figure 8 illustrates how deep drainage changes with rainfall and plant available water capacity (PAWC[6]). In simple terms, the lower the PAWC, the more potential there is for deep drainage. Where PAWC is large, drainage is lower because the soil can store more of the water during wet times until it is used by plants (Yee Yet and Silburn 2003, Radford *et al*. 2009, Tolmie *et al*. 2011). Deep drainage and aquifer recharge rates in irrigation areas are much higher

[6] Plant Available Water Capacity is the amount of soil water that can be extracted by plants—it is calculated as the difference between the upper water storage limit of the soil (‘field capacity’) and the lower extraction limit of a crop over depth of rooting (‘wilting point’). PAWC is determined by soil and plant type, i.e. it is not solely a soil property. Variations between different soil properties will alter the PAWC e.g. a black cracking clay may hold more than 2 mm of water per cm of soil in the top 90 cm of soil depth compared to a sand which might hold 0.4 mm/cm in the same depth.

than in dryland areas due to the extra water being applied (Silburn and Montgomery 2004, Slinger and Tenison 2005). Deep drainage varies considerably depending on soil properties and irrigation management. Soils of low hydraulic conductivity can still give considerable deep drainage under irrigation (Silburn and Montgomery 2004).

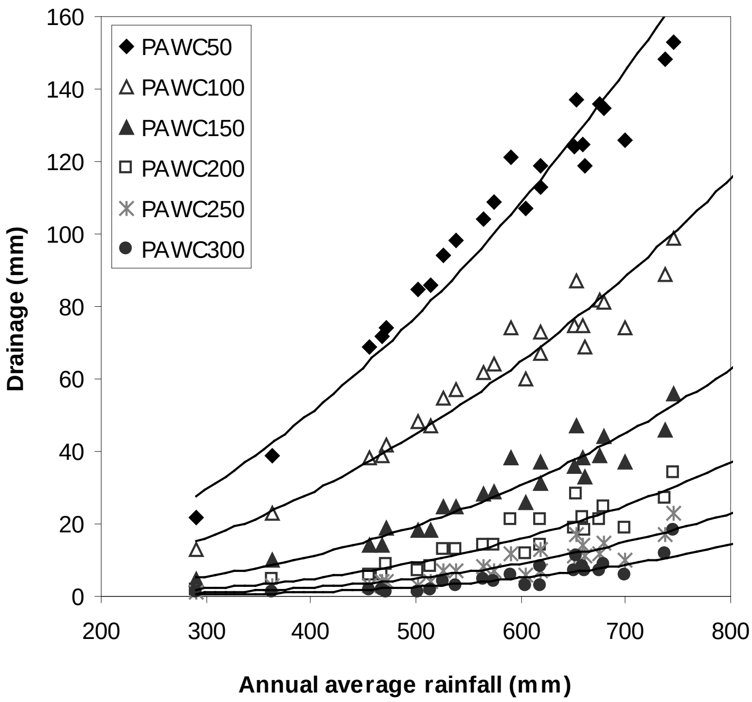


Figure 8 Variation in modelled deep drainage with rainfall and PAWC data

Source: Data from 25 locations across the QMDB under native pasture on free-draining soil (Yee Yet and Silburn 2003).

The following factors contribute to additional deep drainage rates in irrigation areas:

- excessive irrigation of crops (irrigation greater than crop requirements);
- leaking channels and storages due to poor construction methods, or due to poor location of infrastructure, e.g. channels positioned in coarser textured (sandy) soils with higher permeability;
- unsuitable irrigation techniques and methods; and
- irrigation on inappropriate soil types.

Leakage of irrigation water past the plant root zone (deep drainage) will contribute to a rise in watertable levels at some point in the future. Rising watertables can mobilise any salt that is stored deeper in the unsaturated zone, increasing the salinity of the groundwater (see Figure 9). When water levels get within a few metres of the land surface, capillary rise and evaporation can move salts to within the root zone of plants, and even to the soil surface. Associated effects from rising watertable include increased salt washoff.

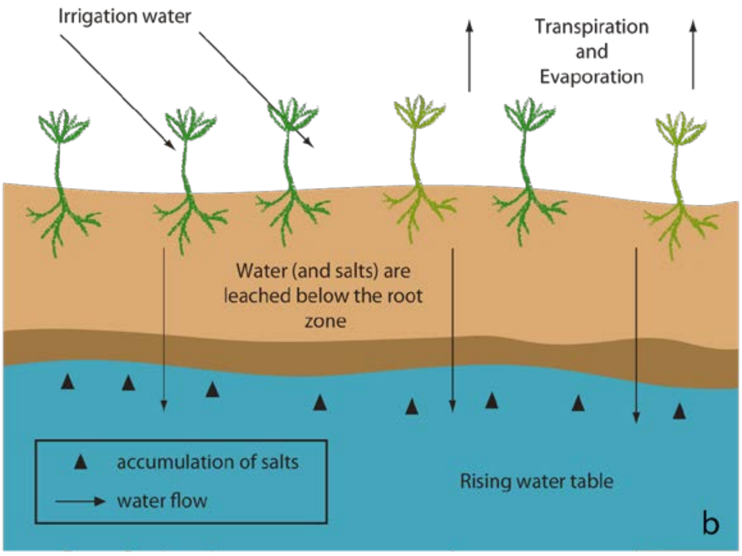


Figure 9 Conceptual interaction between irrigation water and the watertable.
In irrigation areas, water (and salts) can be leached below the root zone and recharge aquifers, leading to rising watertables and salinisation of groundwater.

Watertable rise can also result in discharge of saline water to streams. There is generally minimal connectivity between aquifers and streams in the Queensland Murray-Darling Basin with most aquifers deeper than the incision of streams. However, groundwater discharge to streams can occur in some areas such as the basaltic uplands or close to streams where sandy aquifers occur. Appropriate location of irrigation areas will, however, reduce the risk of saline inflows into streams.

2.2.3. Leaching fraction

A key factor in any sustainable irrigation scheme is to match the water applied with the crop requirement—only applying water that the crop needs. This helps reduce deep drainage rates under irrigation. As discussed in Section 2.1.2, it is important to note however that some level of deep drainage or 'leaching fraction' is needed under irrigation to avoid excess build-up of salts in the soil profile. This is especially true if the irrigation water contains relatively high concentrations of salts. As CSG irrigation water contains salts (though levels vary depending on the nature of treatment or amendment) it is essential that some level of deep drainage occurs to leach the salts out of the root zone. This leads to the questions, 'how much leaching fraction is enough to flush salts, but not contribute to watertable rise in the timeframe of the irrigation scheme?' and 'where does the water and salt ultimately end up?' There are a number of references that detail how to calculate the leaching fraction under irrigation (see for example, Ayers and Westcot 1985, SalCon 1997, deHayr and Gordon 2006 and Salient Solutions 2008).

The required leaching fraction to flush salts out of the root zone is low for good quality irrigation water and increases as the salinity and sodicity of irrigation water increases. For good quality irrigation water, an adequate leaching fraction is provided by deep drainage caused by rainfall and no extra leaching needs to be designed into the irrigation system (Yee Yet and Silburn 2003). The rate of deep drainage/leaching fraction that is acceptable at any site depends on the characteristics of the storage capacity of the unsaturated zone and, in some cases, the receiving groundwater systems, particularly their discharge and pumping rates (if any) (Silburn and Montgomery 2004). Therefore, sustainable irrigation schemes should aim to apply sufficient water to meet the crop water demand plus the leaching requirement without wastage, so as to minimise excess drainage of water below the root zone. If a leaching fraction greater than that afforded by rainfall is needed, it is questionable why such water is being used. In such cases, a greater burden of proof is placed on the proponent to prove that the unsaturated zone and groundwater system can handle the excessive deep drainage and salt load.

The problems of rising watertables and salinisation of soils are endemic in irrigation schemes worldwide (Charman and Murphy 2007). To a very large extent they are inevitable because extra water is applied to soils, which, with the vagaries of climate, frequently coincides with rain to produce a situation where there is more water in the soil than plants can transpire and the atmosphere evaporate. Under such conditions, impacts to the watertable will occur.

2.2.4. Off-site degradation

Rocks and soils in Queensland naturally contain salt, particularly in inland areas where evaporation is higher, and rainfall is lower. Salt bulges in subsoils of vertosols (cracking clay soils) are common and high salt stores in shallow groundwater and weathered to unweathered sedimentary rocks are also encountered. Essentially a supply of salt is rarely a limiting factor in the development of secondary salinity. Irrigation has the potential to mobilise existing soil, regolith and groundwater salt stores leading to salinity issues, even if good quality irrigation water is used.

Over time, surface soils may accumulate salts and become too salty to sustain crop production. Salts may also accumulate in groundwater and coupled with watertable rise under irrigation, may lead to areas being permanently taken out of production. Deep drainage under irrigated lands may move laterally contributing saline baseflow to streams, or drain to lower unsaturated zones or aquifers. The consequences of deep drainage are distinctly different where underlying groundwater can be used for pumping (fresh water, high flow rate) and where it cannot (saline water and/or low flow rate) (Silburn and Montgomery 2004).

In addition to mobilising and moving salt, irrigation can also result in the leaching of nutrients (e.g. nitrogen and potassium), herbicides and pesticides through the soil and into groundwater. This can contribute to poorer off-site water quality, potentially leading to contamination of soils, aquifers and streams, and may also contribute to algal growth and nitrate build-up elsewhere in the catchment (DPI 2008).

Irrigation water travelling over the soil surface can also lead to off-site issues such as:

- erosion and runoff (displacement of the topsoil may clog drainage ditches and streams (silting), harm aquatic habitats, and foul waters used for recreational activities) (Silburn and Glanville 2002, DPI 2008);
- salt washoff (especially if poorer quality irrigation water is used), potentially resulting in overland transport to streams depending on their proximity to irrigation areas; and
- the spread of pathogens and weeds.

2.2.5. Poor crop growth

As described in the sections above, there are a number of ways that crop growth can be adversely impacted under irrigation; for example:

- mobilisation and accumulation of salts in the subsoil and/or at the soil surface (this can have a direct toxicity impact or an osmotic effect, limiting water uptake by the plant);
- watertable rise in shallow saline aquifers;
- erosion of the topsoil affecting soil fertility;
- spreading of pesticides, pathogens and weeds;
- poor infiltration restricting the amount of water available to the crop;
- dense, cloggy subsoils restricting root growth;
- surface sealing/crusting impeding seedling emergence;
- leaching of nutrients (for example, nitrogen), which may be a loss to the farming system; and
- reduced drainage, aeration and permeability of the soil.

2.3. Soil salinity and sodicity interactions

Salinity is the presence of soluble salts in soil or water. The salts commonly found in soils include sodium chloride (NaCl), calcium chloride (CaCl), magnesium sulfate ($MgSO_4$), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), magnesium chloride ($MgCl_2$) and calcium sulphate ($CaSO_4$). Sodicity is the presence of a high proportion of sodium ions relative to other cations in water or adsorbed at exchange sites on soil colloids. Additional information on salinity and sodicity is provided in Appendix 1.

Salinity and sodicity are inter-related in soils and each soil will have a unique response to the ionic composition (salinity and sodicity) of any applied water. For example, an increase in relative sodicity from water increases the risk of dispersion of clay particles in the soil. However, it is not always that clear-cut. The structural stability of soils depends on the interaction between soil sodicity and salt concentration in the soil solution (Loch *et al*. 2005). The adverse effects of sodicity on soil physical properties are evident in soils only when the electrolyte concentration (measured as electrical conductivity) is below a threshold electrolyte concentration (TEC) (Rengasamy and Olsson 1991). That is, upon wetting, clays will swell and disperse spontaneously at a given point when the salt concentration in the soil solution is below the threshold concentration. Quirk and Murray (1991) state '*the threshold concentration concept simply expresses the minimum level of electrolyte [EC] required to maintain the soil in a permeable condition for a given degree of sodium saturation of the soil colloids'*. Quirk and Schofield (1955) defined TEC as the concentration at which a 20% reduction in the soil hydraulic conductivity occurs (i.e. when the TEC is met, the soil will disperse, clay particles will detach and clog pores, and hydraulic conductivity will decrease, meaning that water will not be able to move through the soil as easily).

However, TEC is not simply a unique function of sodium and EC, it also varies with soil type, soil properties and ionic composition of the soil water. The point at which clay swelling and dispersion occurs depends on several soil factors, including:
- texture (clay content);
- clay mineralogy;
- ionic strength (salinity) of the soil;
- amount of sodium in the soil;
- amount and type of organic matter;
- $CaCO_3$ content;
- sesquioxides; and
- pH (Oster and Shainberg 2001).

Additionally, responses to sodicity and salinity differ between surface and subsurface soils. Surface soils are more affected by water drop impact, tillage, animal and vehicular traffic and surface mulches. Subsoils in contrast have slower wetting and drainage rates, and organic matter is generally lower; consequently the criteria of acceptable combinations of salinity and sodicity are different for subsoils as are the methods for their management (Oster and Shainberg 2001).

Published generalised guidelines (e.g. Figure 10 and Figure 11) on soil stability and infiltration in relation to the sodium adsorption rate (SAR) and salinity of irrigation water can only provide approximate guidance—the TEC and soil stability lines should be established for each specific site, taking local soil properties into consideration**.**

Figure 10 also helps to explain the concept that when both salinity and sodicity occur together (high EC and high sodium), the destructive effects of sodicity may not be immediately evident (Rengasamy and Olsson 1991). For example, when EC is ~10 dS/m and SAR >25, the soil is stable. High salt concentrations flocculate the clay and maintain aggregation and hydraulic conductivity. The actual thresholds at which this occurs vary with clay type and ESP. It is only when salts are leached through the profile, making the soil non-saline, that sodicity effects arise

(e.g. when EC drops to say 2, and SAR >25, the soil now becomes unstable). It is important to remember that soil salinity and sodicity levels are dynamic—they change with the amount and quality of infiltrated water, evapotranspiration and rainfall.

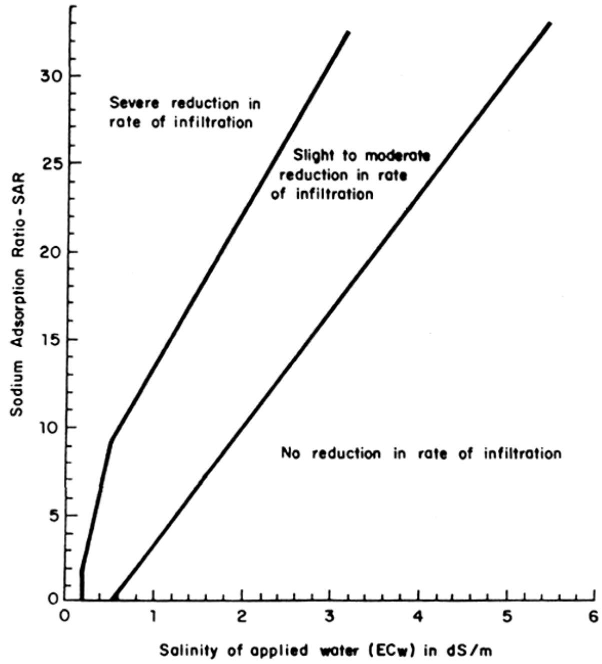


Figure 10 Relative rate of water infiltration as affected by salinity and sodium adsorption rate

This graph shows that both salinity and the SAR of the applied water affect the rate of infiltration of water into surface soil (Source: Ayers and Westcot 1985).

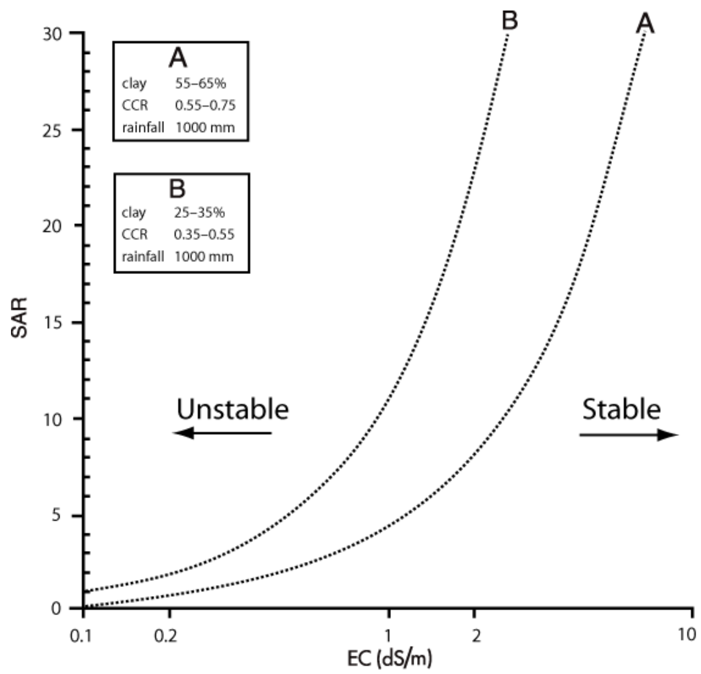


Figure 11 Threshold lines for two soils of different clay content and mineralogy

The soils are unstable in the areas to the left of the lines, and increasingly stable to the right of the lines.

This graph shows the soil EC required to maintain a soil structure for two soils of different texture and various soil ESP levels (Source: Modified from SalCon 1997). Note that the rainfall zone for this graph is 1000 mm, thus it is not transferable to inland areas.

Figure 12 further illustrates the complexity of this concept, showing threshold lines for a number of different American soils.

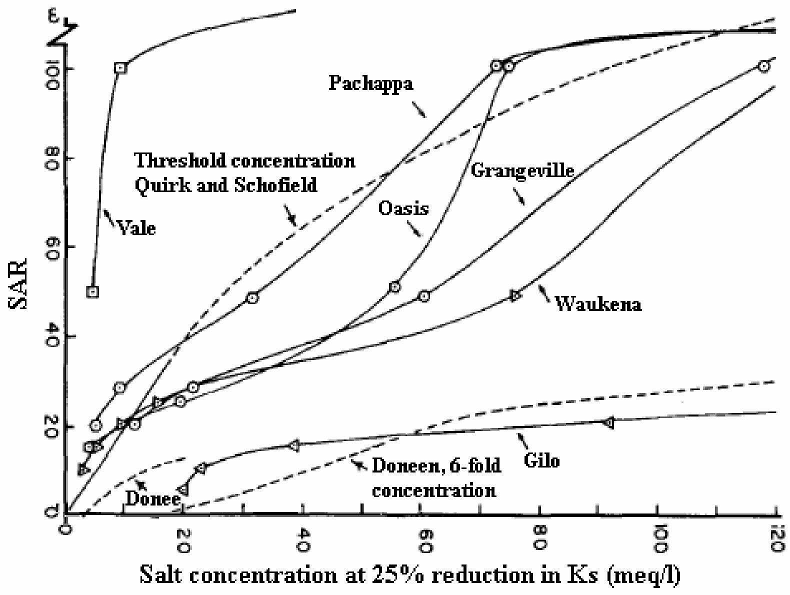


Figure 12 Threshold lines for a number of different American soils

The figure illustrates a range of SAR/EC relationships to maintain soil stability. The Quirk and Schofield (1955) threshold concentration is also shown. The soils are unstable in the areas to the left of the lines, and increasingly stable to the right of the lines. Clay content of soil types: Vale 11%, Pachappa 12.6%, Grangeville 14%, Oasis 22.5%, Waukena 30%, Gilo 60.5%. (Note: Divide the x-axis figures by 10 to get approximate EC values (i.e. the scale goes from 0 to 12 dS/m)) (Source: Modified from McNeal and Coleman 1966).

Research to date has reinforced the need for soil stability lines to be established for a specific site, taking local soil properties into consideration. While many soils may have similar behaviour (Figure 13), some have substantially different behaviour, thus the application of a generalised equation or rule-of-thumb is likely to be erroneous at some sites. If site specific values are not derived, it is necessary to adopt conservative EC/SAR values for irrigation water to ensure that the structure of the majority of soils will remain stable (e.g. EC <1000 μS/cm and SAR <5).

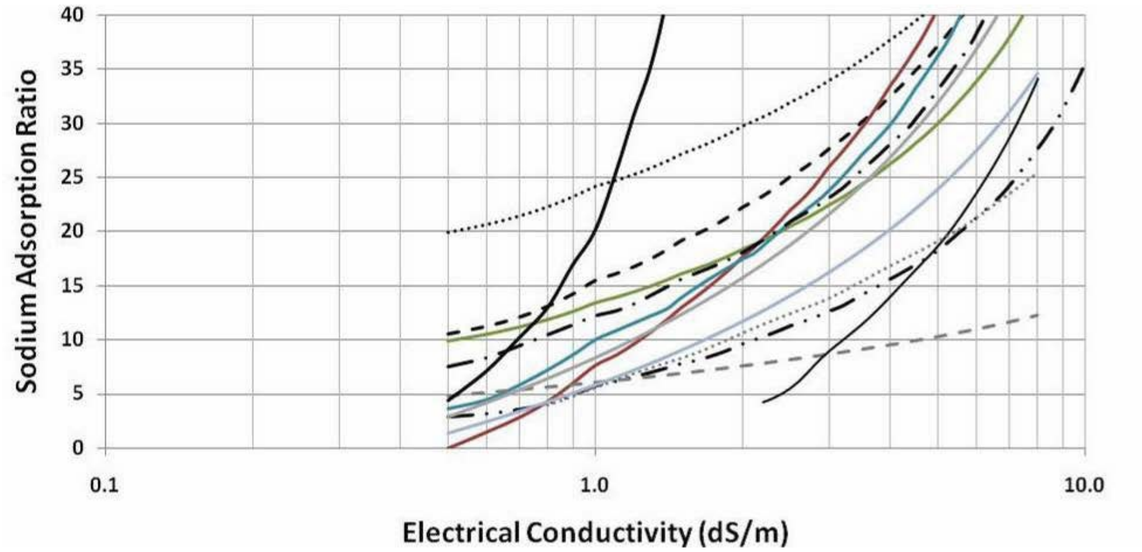


Figure 13 The effect of irrigation water SAR and EC on soil stability

This figure represents a 20% reduction in saturated hydraulic conductivity for common southern Queensland soils. Note: irrigation with water with a SAR and EC above and to the left of each line will result in the degradation of that soil (Source: Raine 2010).

Using elevated SAR water for irrigation will affect soil structure as it increases the sodium content of the soil. High sodium levels affect soil behaviour by increasing soil dispersibility, reducing water entry and reducing hydraulic conductivity, making cultivation and good seed beds more difficult to attain, and reducing soil profile water availability.

Suarez *et al*. (2006) found that even small increases in the SAR of irrigation water (levels only up to SAR 10) had an adverse impact on water infiltration for both cropped and bare soils. They stated that the decreased infiltration rate can be expected to result in increased surface runoff and thus decreased availability of water to the crop. Their laboratory measurements also showed a trend of decreasing hydraulic conductivity with increasing SAR.

Decreased soil hydraulic conductivity under sodic conditions plays an important role in salt movement and accumulation within the root zone. It also strongly influences leaching fraction/deep drainage rates. In many cases, rainfall or good quality irrigation water can leach accumulated salts below the root zone, thus salt accumulation from irrigation can usually be managed. However, using water with high SAR means that leaching rates are reduced.

2.4. Impacts related to CSG water

As discussed in the preceding sections, the principles involved in the application of irrigation water to a soil and the risks associated with irrigation are well understood and documented. While these general principles and risks are widely accepted, they cannot be applied in a generic manner to all soils/landscapes/water types. For instance, the nature of CSG water ($NaHCO_3$ type) is substantially different from "typical" (NaCl type) irrigation water used in Queensland.

As outlined throughout Section 2, there are a number of issues associated with irrigation, regardless of the quality of the water that is being used. However, the situation is exacerbated if poor quality water is used for irrigation. Because CSG water typically has an undesirable relationship between sodicity and salinity, irrigation with raw untreated CSG water would have a major adverse impact on soil stability, dispersibility, permeability and infiltration rates—as confirmed by trials conducted by CSG producers (for example, Raine and Ezlit 2007). Based on CSG water chemistry to date, it is highly unlikely that irrigation with raw CSG water is sustainable and it is therefore not recommended**.**

The use of CSG water for irrigation is no different from the use of other water for irrigation provided the CSG water is suitably treated and amended to suit the conditions where irrigation takes place. However, there are varying levels of water treatment being proposed by CSG operators, ranging from amending the water (e.g. addition of gypsum, mixing with other water, addition of acid) through to treating the water via reverse osmosis. It is important to realise that after treatment, CSG water may still contain sufficient levels of salt, sodium and/or other contaminants to limit its use. Essential minerals (e.g. calcium) may need to be added after treatment to improve the ionic balance of the water.

At present, the actual area of CSG irrigation approved in the QMDB is small; however, this could increase significantly with the move to LNG production from 2014. As at November 2011, seven beneficial use approvals (BUAs) for irrigating with CSG water in the QMDB and southern Bowen Basin had been granted. The BUAs relate to a specific area and type of irrigation for a defined time period. All approvals to date involve trickle or spray irrigation. The current BUAs allow for irrigation of forestry plantations (eucalypt species, other native tree species and pongamia), leucaena, forage crops, and pasture grasses. Under these approvals, at least 3620 ha[7] will be irrigated with approximately 34 100 ML per annum. The water being used has undergone a range of treatment options—accordingly the water chemistry also varies, for example:

- EC ranges from 300–4000 µS/cm
- pH ranges from 5–8.5
- Total Dissolved Solids ranges from 180–2720 mg/L
- Sodium Adsorption Ratio ranges from 4–30.

Given the range in water quality parameters, it is imperative that the following factors be rigorously investigated when considering any irrigation scheme where CSG water will be used:

- soil type (including but not limited to clay mineralogy, clay content, existing salinity and sodicity levels, and soil organic carbon levels);
- the quality of water being applied;
- the relationship between soil and water chemistry;
- irrigation layout and management practices;
- plants/crops to be grown; and
- climate.

Since not all CSG water for irrigation will be treated the same way and to the same quality, it is important to be cognisant of the possible impacts resulting from the use of this water. Higginson *et al*. (1988) reported soils showing signs of physical and chemical degradation resulting mainly from the use of alkaline (pH 8.2) sodic irrigation water that was high in bicarbonate (~450 mg/L) and carbonate, including:

- increased ESP;
- leaching of calcium carbonate;
- leaching of organic matters (especially the fulvic acid fraction);
- clay and silica illuviation;
- crusting and surface cloddiness;
- compaction and reduced macroporosity below 10 cm depth;
- decreased permeability; and
- waterlogging and secondary salinity associated with rising watertables.

The cumulative impacts of irrigating large areas with CSG water must also be considered. Cumulative groundwater recharge by multiple operators is a potential problem that may not be identified in individual development assessments. Another issue is that the development of

[7] One approval involves pumping treated CSG water into Chinchilla Weir; the water is then managed by SunWater and made available to irrigators—they may be existing irrigators or it could go to a new irrigation area.

plantations of trees such as Chinchilla white gum, leucaena and pongamia (currently underway as part of CSG water management regimes) can affect catchment water yields by reducing runoff. Salinity risks and impacts are not easy to quantify because of multiple interactions between surface water and groundwater, soils and regolith, landforms, climate, vegetation and management practices, past, present and future.

2.5. Secondary salinity conceptual models relating to CSG irrigation water

SalCon (1997) provides a list of 12 conceptual models relating to secondary salinity in Queensland. The majority of these are dryland salinity forms, but they are also relevant in irrigated landscapes because the source of extra water (as deep drainage, groundwater recharge or surface water) is not necessarily critical.

The more important conceptual models for different landscapes in the QMDB region have been discussed by Searle *et al*. (2007) and Biggs *et al*. (2010). In the area currently being developed for CSG, the most relevant models are explained below (although all conceptual models may apply). In order for salinity to express in the way described in these and other models, the unsaturated zone usually must be filled.

2.5.1. The bucket model

In addition to these models, there is a simple (and underlying) conceptual model that applies to salinity risk—that of a simple bucket, representing the unsaturated zone. Figure 3 depicts the general water movement through the unsaturated zone. As illustrated in Figure 5, different land uses will contribute differing quantities of water (deep drainage) to the unsaturated zone. Salt will always be transported with the water. The unsaturated zone (the 'bucket') extends from the bottom of the root zone to the first zone of reduced permeability. It is important to note that this zone of reduced permeability is not necessarily where an aquifer/watertable is, but rather it is a layer which impedes vertical water movement and which may develop a watertable if the unsaturated zone above is filled by increased deep drainage. While the use of a bucket type conceptual model is simplistic, it provides a method by which worst-case scenarios can easily be calculated, but also provides the capacity to include further complexity e.g. lateral losses.

The depth of the bucket (unsaturated zone) varies across the QMDB, ranging from <5 m to >100 m, depending on a number of factors including geology, lithology, substrate permeability and porosity, landscape position, slope and landform. Under native, wooded vegetation in semi-arid Queensland, the unsaturated zone has been generally found to be dry[8] (Radford *et al*. 2009, Silburn *et al*. 2011) due to the low deep drainage rates typical of this vegetation. Land management practices also influence the size of the bucket. For example, previous clearing events may have mobilised salt and water, resulting in the bucket already being filled to some extent (Silburn *et al*. 2011).

If there is sufficient capacity within the unsaturated zone, water and salt are effectively stored in a manner that is unlikely to cause detrimental effects on or off-site. However, if the rate of water input exceeds the internal rate of flow, or the total water input exceeds the storage capacity of the unsaturated zone, saturation will occur, and a number of possible consequences will develop—most likely a rising watertable and/or lateral movement of water. If this happens, then off-site effects are more likely to develop.

[8] Note that moisture status (and total capacity) of the unsaturated zone has been measured in only a few locations. Thus it is necessary for each CSG irrigation development to quantify the local status of moisture in the unsaturated zone, to prove that there is adequate capacity.

Thus if the unsaturated zone at the site is managed appropriately, the risk of off-site effects can be reduced significantly. As suggested in Figure 5, the land use after irrigation with CSG water has ceased must also be considered in relation to the 100 year impacts. For example, if irrigation adds 60% of the water capable of being stored in the bucket in ten years, and then stops, the final land use must not add more than 40% of water over the next 90 years. The choice of post-irrigation land use and management for the site can determine if the watertable falls or continues to rise.

2.5.2. Rising groundwater model

Rising groundwater under irrigated lands (Figure 14) is a known problem in certain areas of the QMDB (Brough *et al*. 2008) and in most irrigation areas in Australia. In this region, monitoring of groundwater has historically only occurred in areas in which groundwater is extracted. In general, these areas have experienced water level declines over the years, a good example being the Central Condamine Alluvium. Since about 2000, the monitoring network in other alluvial areas has expanded substantially, and shallow, saline groundwater systems have been found in many alluvial sequences. In general, shallower systems experience trends more closely related to climate/irrigation trends, while deeper alluvial systems are less responsive.

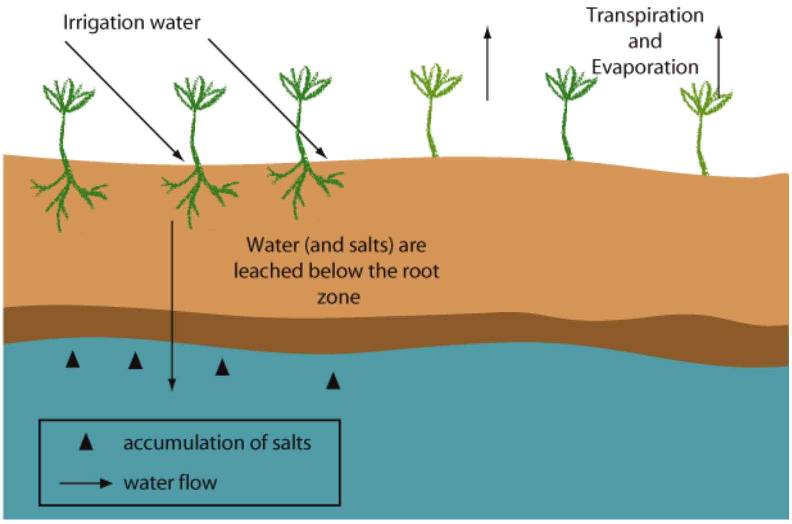


Figure 14 Irrigation salinity—rising groundwater salinity conceptual model

Figure 15 illustrates examples of different water level trends in bores in the lower Balonne alluvia. It illustrates that it is possible to have both rising and falling watertables at the same point in space if multiple aquifers exist which are disconnected. Similar trends may also be found in the Condamine alluvia.

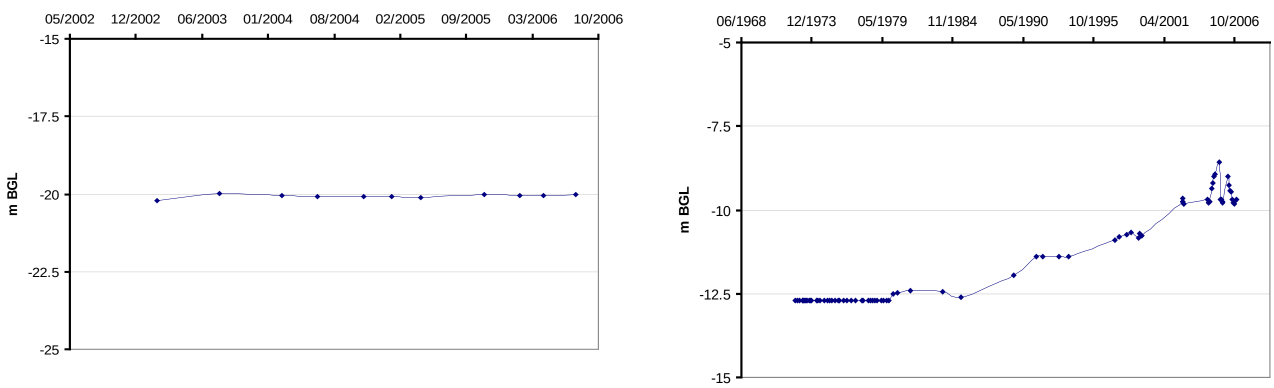


Figure 15 Non-responsive and responsive bores in the lower Balonne alluvia

Most deeper (>10 m) alluvial systems in the region contain stacked aquifers, such that there are multiple potential water bearing zones (Figure 16), mainly consisting of sand and sand/gravel beds. Historically, the uppermost of these may have been episodically wet and were frequently exploited using hand-dug wells in the early part of European settlement. Deeper bores, drilled using modern equipment, generally exploit deeper, thicker, more gravelly materials that yield larger water supplies. The amount of connectivity between waterbeds varies substantially, but it is common for there to be some level of connection. Most aquifers of the types illustrated in Figure 16 behave as semi-confined systems[9]. In areas of thinner alluvia, sequences are often clay dominant, with a very thin (<1 m) or no basal sand/gravel unit.

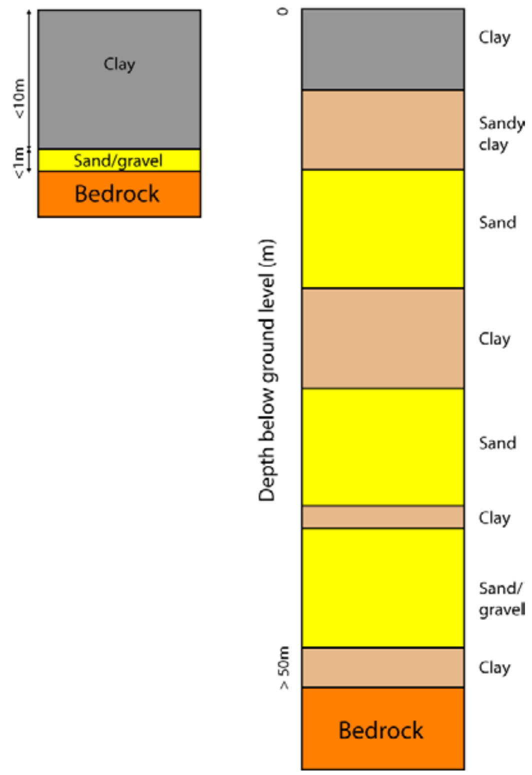


Figure 16 Typical alluvial cross-sections in the region

Water quality in shallow, clay dominant systems is frequently naturally saline (>20 000 µS/cm) due to evapotranspiration and slow, diffuse recharge processes. Aquifers in very sandy areas are generally of low salinity, due to fast recharge processes. In thicker alluvia with disconnected aquifers, quality may also vary vertically (for example, borehole RN 42230025 in the Central Condamine has an EC of 2500 µS/cm at 47 m, 2250 µS/cm at 39 m and 11500 µS/cm at 23 m depth). The two deeper waterbeds are falling due to extraction while the shallowest (23 m) is rising.

Salinisation of aquifers from increased recharge may occur at the same time (or even before) they commence to rise. This can be the result of either salts added (as might be the case with CSG water) or more usually, transport of existing primary salts in the unsaturated zone down to the watertable. Non-basaltic clay materials in inland Queensland usually possess high salt stores.

Many investigations incorrectly focus on the depth to bedrock rather than the depth to the first layer with a reduced permeability. In alluvial systems, the latter is typically a clay zone below the

[9] The span of aquifer types ranges from confined to unconfined with semi-confined being somewhere in-between. An unconfined aquifer has an upper boundary of high permeability material, and the water level in an unconfined aquifer is the water table. A confined aquifer is bounded above and below by confining/low permeability materials like clay or dense rock. Semi-confined systems are likely to have layers of reduced permeability bounding them.

uppermost fining-up sequence. In bedrock this may be more difficult to ascertain but is often at the boundary between the weathered and unweathered zones. This depth has a critical impact on the time lag to fill.

The area in the QMDB with the most significant rising groundwater trends is the lower Border alluvia, where shallow semi-confined saline aquifers have risen substantially in certain areas. This is currently not an area of CSG development. Some areas of rising shallow groundwater do also exist in alluvia in the Condamine-Balonne catchment.

2.5.3. Poor quality/saline water model

Soils are naturally in balance with their salt inputs (usually from rain). Irrigation adds more salt to the soil—especially the case if poor quality/saline water is used. When water is removed by evaporation or transpiration, the salt is left behind (Figure 17). The use of poor quality water for irrigation has occurred in some areas of the region for decades, such as in the Lower Condamine (where groundwater quality declines to the west of Macalister), localities around St George, Chinchilla and parts of the Border Rivers. Typical problems experienced in these areas are surface crusting/sealing, poor infiltration and germination and reduced crop growth/yield. Most of the waters used in irrigation to date are NaCl type waters from alluvial aquifers.

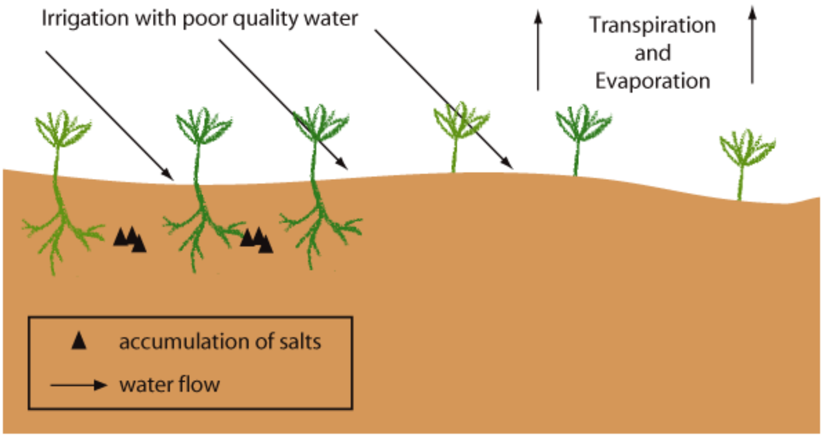


Figure 17 Irrigation salinity—poor quality water salinity conceptual model

Few irrigators in the QMDB use Great Artesian Basin (GAB) or $NaHCO_3$ type waters for broad acre irrigation, although some irrigators in northern NSW do (e.g. in the North Star area). Problems with the use of GAB water for irrigation were documented in research as far back as 1913. Sites of natural or man-assisted flows of GAB water also provide a good example of issues that may occur as a result of disposal of CSG water (particularly untreated CSG water) to land.

The best natural example in the QMDB is the Yelarbon Desert. Lying at the junction of Macintyre Brook and the Dumaresq River, just north of the Queensland-New South Wales border the area around Yelarbon consists of landscapes unique in southern Queensland. Located on the eastern edge of the Great Artesian Basin, this area has been strongly influenced by the upwelling of $NaHCO_3$ rich ground water. The soil while not overly saline is extremely sodic, with exchangeable sodium percentage (ESP) approaching 100%. Normally soils in the region have ESPs <50%. The extreme sodicity (and moderate to high salinity), combined with historical management practices, has led to very substantial degradation in parts of the Desert (Figure 18). Similarly, degradation around GAB bores and bore drains provides an illustration of a worst case scenario of the impacts of bore water with a similar chemical composition to CSG water (Figure 19).

Figure 18 Erosion of an extremely sodic soil in the Yelarbon Desert

Figure 19 Evaporative concentration of salts associated with sodium rich GAB water

2.5.4. Dissolution of salts model

Most clay soils of inland Queensland contain moderate to high levels of subsoil salts, mostly in the form of sodium chloride (NaCl) or gypsum ($CaSO_4.H_2O$). These salts have accumulated naturally because of the low rainfall/high evaporation climate. Construction of irrigation farms exposes these saline subsoils to surface water (Figure 20). Water in irrigation channels, ring tanks and other structures can dissolve these salts and move them—the salts then re-crystalise when the water recedes or evaporates.

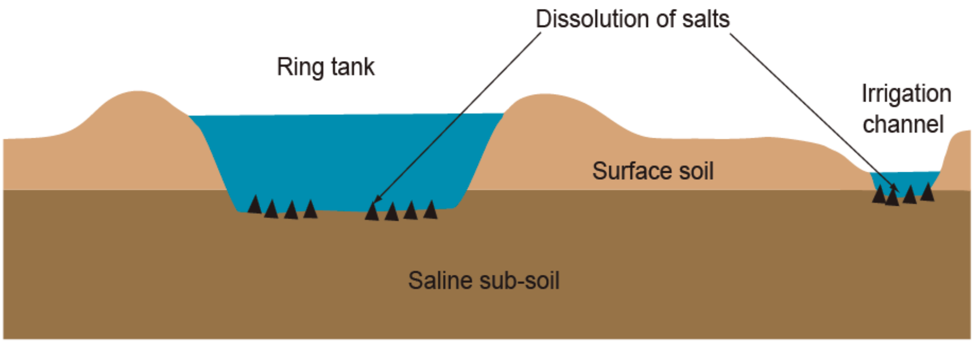


Figure 20 Irrigation salinity—dissolution of salts salinity conceptual model

Irrigation channels can become salinised from dissolution of salts in the soil/regolith/bedrock. This feature has been observed in-field, particularly in soils with high gypsum contents (Figure 21). In extreme cases, it can lead to the formation of iron monosulfides and potential acid sulfate soils.

a) Gypsum crystals naturally present in the soil

b) Re-crystallisation of dissolved subsoil salts

Figure 21 Dissolution of salts in irrigated clays

2.5.5. Dam form model

Leaking dams (Figure 22) are a well known problem in both alluvial and hillslope landscapes of the region. In both instances, water may leak both through the wall (Figure 23), and/or through the base. Leakage is often the result of clay dispersion when wet and cracking when dry. It can cause localised salinity around the dam, and contribute to groundwater recharge. In the case of stock and conventional irrigation dams, construction practices are highly variable, often poor, and leakage is common. Regulations relating to CSG water dams have changed and leakage is less likely to be an issue with new dams constructed by CSG companies. Treated CSG water is however supplied to landholders with existing dams that were not constructed to high standards and there is a potential for increased losses via these dams.

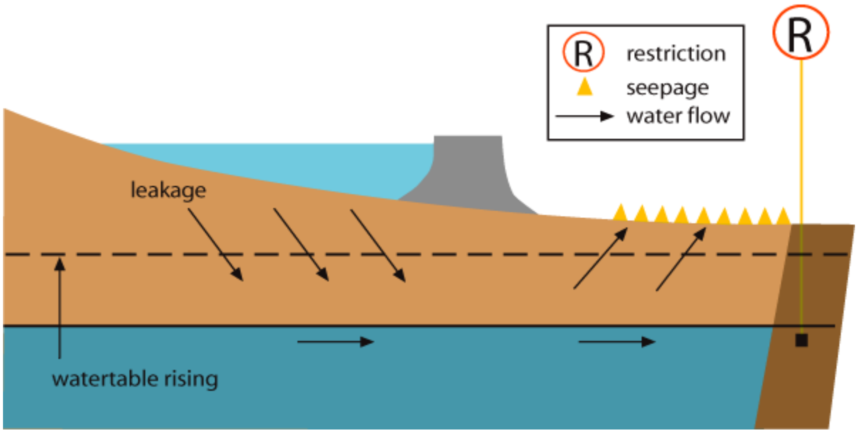


Figure 22 Dam form salinity conceptual model

Figure 23 Seepage through a ring tank wall

2.5.6. Catena form model

This type of salinity is caused by water discharging at the break-of-slope (footslope). Two main types of catena form salinity exist. In the first (Figure 24), shallow, light textured soils occur upslope of deeper and heavier textured (clayey) soils downslope, extending into flat, heavy clay alluvial areas. Water flows easily through the lighter textured soils (and often the substrate), but cannot move as quickly through the heavy soils in the footslope, causing waterlogging and seepage.

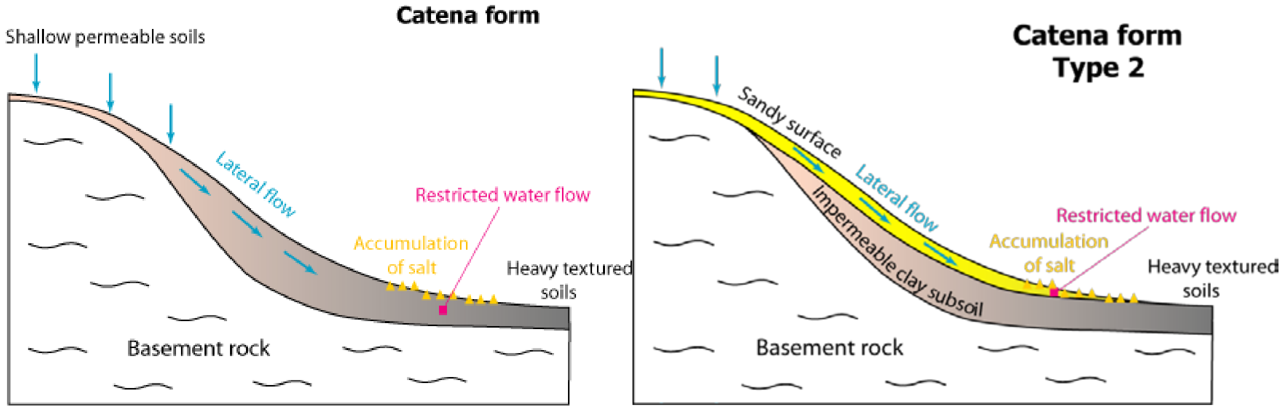


Figure 24 Catena form salinity conceptual models

The second form is similar, Type 2, but is exacerbated by the presence of sandy texture contrast soils on the hillslope. Water moves very easily through the sandy A horizons, which overlie an impermeable subsoil (Figure 24). The thickness of the A horizons often decreases at the contact with the alluvia, and discharge occurs. Evaporative concentration of salts occurs at the soil surface when there is intermittent discharge.

Catena form salinity is very common in southern Queensland, particularly in granite and coarse grained sandstones (e.g. Marburg Sandstones), but it also occurs in the Traprock, and some western landscapes. It is more common in the eastern granite and sandstone landscapes because of higher rainfall and the presence of sandy texture contrast soils on hillslopes.

2.5.7. Stratigraphic form model

Stratigraphic form salinity (Figure 25) can occur in many different landscapes. It is common in horizontally to sub-horizontally bedded sedimentary sequences, but can also occur in basalts and metamorphics. Determination of its presence requires detailed mapping of lithology—regional scale (1:250 000) geology mapping generally does not provide sufficient data.

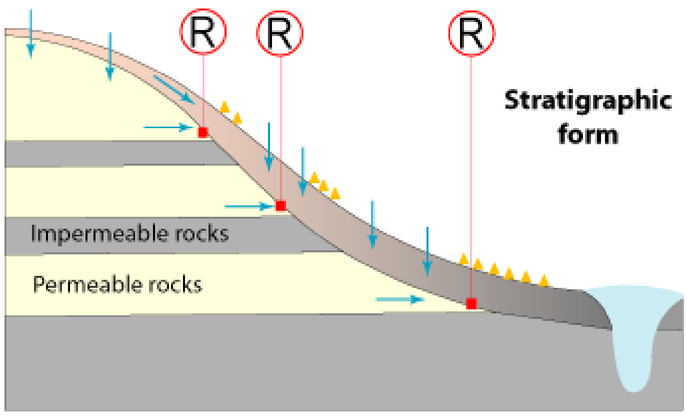


Figure 25 Stratigraphic form salinity conceptual model. (Note: R – restriction)

3. Principles and methods of salinity risk assessment

There is much use (and misuse) of the terms hazard and risk in relation to secondary salinity. In simple terms, hazard is an inherent biophysical property of the landscape, whereas risk is the end-result of the combination of hazard and human activity.

For a salinity risk to exist you need:
1. a salt source—soil, regolith, water (surface, groundwater, CSG water) and
2. a change in hydrology.

The way in which salinity risk is described often depends on whether the enquiry is non-specific or specific—for example, an "overall" risk *vs* a risk to a specific asset. The capacity to describe risk either spatially or non-spatially is of course highly dependent on the quality and scale of available data used to represent the interactions of landscape attributes and processes. The quality of the work will be limited by the weakest data input or process understanding. The following describes some underlying principles of salinity risk assessment, and examples of critical issues that need to underpin appropriate salinity risk assessment.

3.1. Principles of salinity risk assessment

The delineation of salinity risk or hazard can be approached in many different ways including: qualitative, quantitative, spatial, non-spatial, regional and point based methods. Defining the context of the risk assessment is the first step in the process. In the past, this has invariably involved a balance between the nature of the question and the capacity to represent attributes and processes in the landscape, with data availability generally being the most limiting factor. In the case of CSG water re-use, this should not be the case, as an underlying principle is that all relevant data should be collected before commencing irrigation. In some cases, this may require more research to better understand soil/landscape processes.

As discussed above, the expression of a risk leads to impacts on assets. By definition, any expression of secondary salinity will affect an asset—including agricultural land, crop productivity, biodiversity or water quality. Other assets impacted could be built infrastructure and cultural heritage. The degree of impact on an asset will be determined by the severity of the salinity, the resilience and value of the asset and the duration of the exposure. The value of assets and the costs of impacts are determined by a wide variety of factors, including social and economic considerations and the degree of tolerance (vulnerability) of a particular asset to salinity. The availability of asset related data, in particular asset vulnerability is always very limited, and it remains the most significant non-biophysical constraint to assessing potential impacts of salinity.

3.1.1. Precautionary principle

Irrigation occurs within the context of a highly complex natural system where secondary salinity can create severe impacts. Due to the complexity of the natural system and salinity processes and the scarcity of data, scientific knowledge of these issues is still developing. Consequently it is essential that the development of a CSG water irrigation industry should be based around the *precautionary principle* i.e. where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing practical measures to prevent environmental degradation.

3.1.2. Temporal component

Risk contains a temporal component, i.e. the timeframe within which an impact will occur. Defining the timeframe of interest is an essential part of assessing salinity risk and determining appropriate monitoring and management methods. As salinity processes are driven by hydrology, which in term is driven primarily by climate, the time needed to measure changes and conduct associated

research may be decades. The time lags involved in moving salt through natural systems, together with the poor baseline knowledge for the area, means that some decisions based on current knowledge may turn out to be incorrect. In some cases, it may be necessary to "tip the bucket over" in order to discover a threshold value.

3.1.3. Impacts on assets

Assets affected by the development of salinity problems will vary over space and time, but at the bare minimum; soils, groundwater, biodiversity, agricultural production, surface water quality and aquatic ecosystems are assets at risk. Sometimes infrastructure and cultural heritage may also be affected by salinity. The health of these assets is pivotal to the viability of agricultural enterprises and communities in the affected areas and in the broader catchment.

3.1.4. Level of certainty

The level of certainty should always be stipulated for each input/model/output. Historical salinity hazard and risk assessments have been semi-quantitative at best. The current regulatory environment however places a stronger emphasis on "black and white" answers via conditions including monitoring and trigger thresholds. This infers the need for quantitative approaches. However, the level of scientific knowledge in relation to salinity risk in our landscapes is so immature that this may be unrealistic; thus a level of certainty should always be stipulated in relation to a salinity risk assessment. Use of more complex models does not necessarily improve the quality of the "answer" and use of models should not be at the expense of primary data collection. It is also necessary to describe the level of certainty for each model input and underlying assumption.

3.1.5. Use of assumptions

The use of assumptions should be avoided unless they are well founded in proven science. Some historic assumptions have since been found to be wrong, for instance, for many years, most agronomists, crop modellers and soil physicists believed that "cracking clay soils don't drain", which has since been proven to be incorrect (Appendix 1). Any assumptions made in a salinity risk assessment must be clearly stated, and management plans should accommodate the inherent uncertainty.

3.1.6. Holistic approach

Salinity risk assessment involves a holistic approach. It involves many processes and attributes in the landscape, and thus can be a complex exercise. There is no single attribute or process that can be measured to determine the salinity risk of a site, and many attributes and processes interact spatially and temporally.

A related principle is that data sharing should happen as a matter of course. Due to the interwoven nature of the different CSG tenements, and the large geographic area of interest, no single company is likely to invest in all the necessary science. The current knowledge base of salinity risk in Queensland is the result of decades of government investment and knowledge/data exchange. Data and knowledge sharing will be vital for minimisation of research costs and for long-term sustainable use of CSG water for irrigation. This is particularly the case if assessing cumulative risk across multiple tenements.

3.1.7. Changes to water/salt balance

As stated at the beginning of this report, the objective of a salinity risk assessment is to identify the most likely changes to the water and salt balance in the landscape in the context of the imposed management regime, i.e. irrigation. The overall salt and water balance for an agricultural landscape without the presence of CSG water is described in Figure 6. Some of the processes and attributes illustrated are more important than others, and some are more easily assessed than others. When CSG water enters the landscape, there are a number of additional water/salt fluxes,

illustrated in Figure 26. If a salinity risk assessment does not account for all relevant processes and factors, it is inherently deficient. This does not automatically mean a large investment in research or monitoring is required, but rather a holistic approach to understanding the salt/water balance, and an examination of the relative contributions of the different components. Much of this can be understood using first principles and existing research/knowledge.

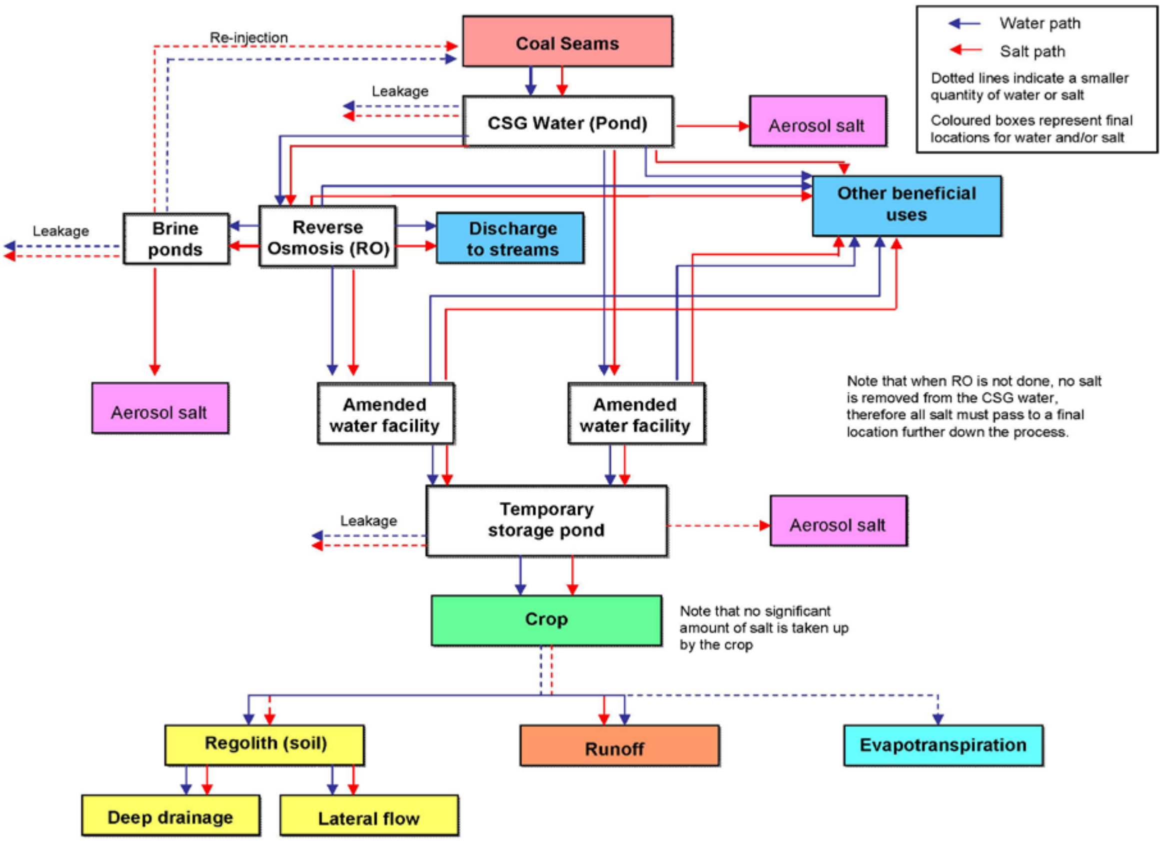


Figure 26 Water and salt fluxes in the landscape due to the extraction of CSG water

Note: This graphic is generic and does not imply that all management options (e.g. discharge to streams, brine dams, beneficial use) apply in all circumstances. Management options and flow paths will vary from site to site. Aerosol salt can be deposited locally with associated impacts on land and vegetation.

3.2. Thresholds and risk

Current regulatory frameworks for applied waters (effluent, wastes etc.) in Queensland have a tendency to rely on critical thresholds for factors such as ‘root zone salinity’ or stipulated leaching fractions. Reference is often made to Table 4.2.5 and 4.2.3 in the ANZECC Guidelines (ANZECC and ARMCANZ 2000). While these provide a clear decision point for operators and regulators, basic principles of salinity risk and demonstrated experience indicate that there is a need for an improved approach.

Thresholds and trigger values are relevant to many aspects of salinity management in the QMDB. At the broadest level are end-of-valley salinity targets (Power *et al*. 2005) and baseline conditions stipulated in the Basin Salinity Management Strategy. Local water quality guidelines currently being developed in the QMDB are another example. With respect to irrigation (of effluent/waste) the two most common regulatory models used are:

- setting a minimum and/or maximum leaching fraction, and
- setting an optimum or maximum root zone salinity.

This approach appears to be derived from Figure 4.2.1 and Table 4.2.3 in the ANZECC Guidelines (ANZECC and ARMCANZ 2000). Careful consideration of Figure 4.2.1 however indicates that this approach is often applied without understanding the broader consequences of leaching or including the last step of the approach, that is to consider the broader landscape issues. In fact this approach overlooks the statement on page 1-1 of the ANZECC guidelines that "*these guidelines should not be used as mandatory standards*". Ensuring an 'acceptable root zone salinity' via maintaining a high leaching fraction can in fact lead to adverse outcomes as it only addresses one half of the salinity risk equation, that being the soil/water chemistry. The use of leaching fractions as the driver in an irrigation system is not a sustainable policy, as it encourages excessive application of water to the landscape, with little recognition of the fate of the leached water and salt. Such an approach propagates the view that salinity risk is only a soil profile issue/impact and that the landscape will look after itself. It is important to note though that while high leaching fractions are not sustainable, minimum leaching fractions are required to prevent build-up of excessive soil salinity (see Section 2.2.2).

The maintenance of appropriate root zone salinity is usually in the context of plant salinity tolerance tables such as in SalCon (1997). Such thresholds (for various levels of yield reduction) are known for many crops, although the degree to which they vary across soil types is less well defined. Tolerance levels are not as well known for native vegetation. While it is essential to ensure that root zone salinity does not impede plant growth and water uptake, determination of appropriate root zone salinity is not as easy as looking up a table. There are many variables in the field that can affect this value, such that setting one based on "textbook values" can be a relatively meaningless exercise. To begin with, the root zone (depth) is very difficult thing to define—it varies with plant species, soil/landscape attributes and other factors such as seasonal rainfall. The depth at which a threshold is set is just as important as the value itself.

The selection of too high an upper threshold may easily impose restrictions on the future land use of an area, as there is generally a tendency to select salt tolerant species in order to maximise the amount of salt disposed of. If this occurs, such a decision needs to be explicitly stated. In some cases though, it may be that the threshold selected is still below the tolerance of native species such as native brigalow-belah communities. Hence the question of upper thresholds is very strongly controlled by the intended long-term use for the landscape. Overall however, where the use of CSG water is to grow irrigated crops, there is an inherent feedback loop. Crop vigour (and water use) will decline as soil salinity levels increase; thus if a core aim of the irrigation scheme is to maximise water use, there is an implicit need to optimise the soil salinity for maximum plant growth.

It could easily be argued that the root zone salinity should not exceed the "natural" level. The natural level can only be determined however if undisturbed native vegetation remains—once land is cleared, salts are leached and the root zone salinity will have decreased (this is the basis of the chloride balance method for estimating deep drainage rates, e.g. Tolmie *et al*. (2011)). If a natural level *can* be described, there are various ways in which it may be used as a threshold. One option is to allow a degree of variation from the natural level, such as an increase/decrease of 10%. The maximum value achieved will however be more likely to have critical impacts in some soils than others.

Another option is to set a maximum profile or paddock salt store. This is simply a variation on setting maximum root zone salinity and implicitly recognises that the landscape is being used as a waste disposal area. The consequence of setting too high a number is that it creates a large salt store for future mobilisation, and potentially restricts future land use. For instance, the store might be created while growing a woodlot. Upon harvest, the water balance will change significantly as demonstrated by Figure 5. If adverse conditions are encountered such as a wet climate phase then a substantial slug of salt may be mobilised.

Clearly there are many ways in which the threshold approaches traditionally used in regulation of applied waters can lead to adverse outcomes. This does not mean however that they are not useful in the correct context, but considerable research is needed to better define critical agronomic and landscape thresholds for landscapes of the region in the context of normal climatic variability.

3.3. Previous salinity risk assessments

There have been a number of salinity hazard/risk assessments undertaken in the QMDB in the last decade. Early on, attempts were made to describe overall hazard or risk, using a semi-quantitative application of a conceptual model. For example, the QMDB salinity hazard map (DNR 2000) used a recharge/discharge conceptual model. This was improved upon by Biggs and Brough (2002) by substituting a more realistic excess water component. Biggs *et al*. (2005) went into greater detail for the Border-Moonie catchments, including some quantitative modelling of deep drainage. Most of these attempts have not explicitly delineated the contributing risk factors in relation to the known salinity conceptual models (described in SalCon 1997, and in Section 2.5). These generalised approaches can lead to poor accuracy in risk assessment. All assessments have noted that a lack of primary data was a significant constraint to the risk assessment process.

The salinity hazard map and other assessments typically used a three component framework—recharge, discharge and salt store. Whether or not these are given equal weighting has varied. While there is uniform agreement regarding the fact that the recharge/discharge model is valid, it is not applicable in all landscapes, as clearly indicated by the conceptual models of SalCon (1997). For instance, the closed depression model does not necessarily involve a recharge/discharge pathway. The focus in historical salinity risk assessments on the salt store has been understandable, and highly relevant to questions such as end-of-valley salinity loads. In general however, it is of low significance to the question of whether secondary salinity will occur, as the primary driver is the change in the water balance, and there is invariably sufficient primary salinity in our landscapes, that can be mobilised.

In recent years, there has been a shift in thinking regarding salinity risk assessment in Queensland, leading to the development of the framework of Grundy *et al*. (2007). The four components in the framework are Biophysical Hazard, Management Influence, Salinity Stage and Assets (Figure 27). This framework was applied in the Condamine catchment by Searle *et al*. (2007), the Burdekin Dry Tropics by SKM (2008) and the Fitzroy by Chamberlain *et al.* (2007). The primary component in the framework is the Biophysical Hazard. It represents the inherent capacity of the landscape to develop secondary salinity, and includes factors such as geology, soils and topography. The Management Influence component enables evaluation of reality as well as scenarios. The Salinity Stage component, for the first time, explicitly acknowledges the cumulative effects of historic land management practices and the time lags involved between a change in land use and/or land management practices and a salinity response. The Assets component allows the identification of assets including environmental, agricultural, infrastructure and amenity assets at risk and the real cost of salinity.

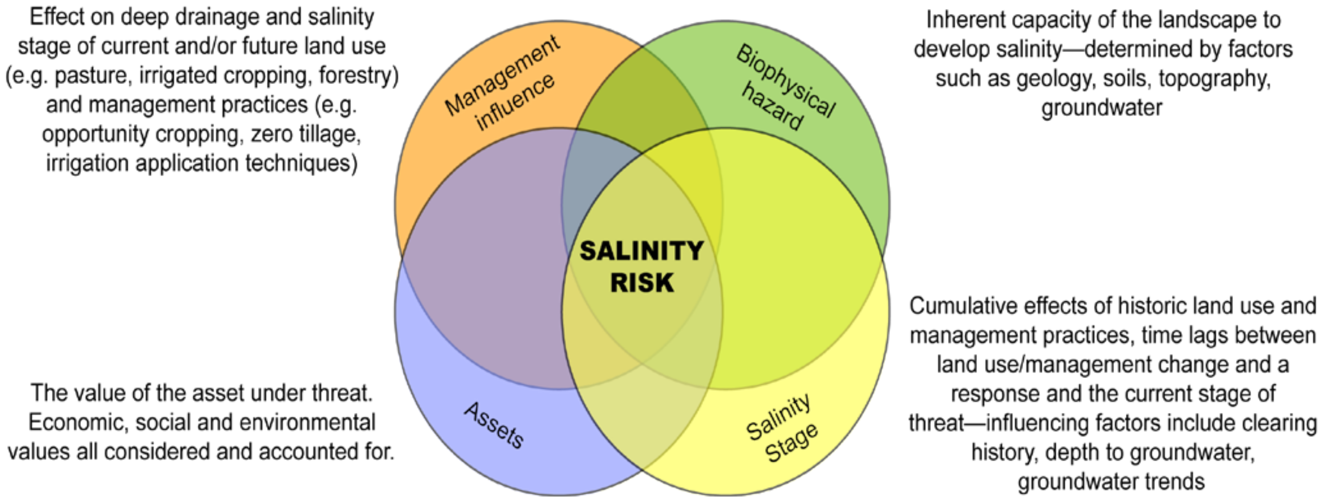


Figure 27 Components of a salinity risk assessment framework
Source: Grundy *et al*. (2007).

While this framework provides a new, and more integrated approach to assessing salinity risk, it is not easily applicable in all areas. Data related to Biophysical Hazard and Management Influence is often readily available, but data relating to historic land use/management, Assets and Salinity Stage is generally limiting.

An advantage of the framework is that it allows flexibility in data used to represent each component. Quantitative work may be fed in at any point, or the framework may be used in an entirely qualitative manner. Its application is also independent of scale. Biggs *et al*. (2010) carried out a salinity risk assessment of the Queensland Murray-Darling Committee management area using a portion of this framework. Once again, they highlighted that lack of primary data was a major constraint, in particular in relation to stage and asset vulnerability.

For example relatively little work has been undertaken historically to assess soil/water sodicity hazard in the QMDB, although it has long been known to be a problem in some irrigation areas. Various unpublished departmental studies occurred in the 70s and 80s in areas such as the lower Condamine alluvia but no comprehensive studies have been undertaken in relation to GAB waters. Studies in NSW in the early 1900s concluded that GAB water was not suited to irrigation due to the sodicity hazard (Pittman *et al*. 1913).

3.4. Salinity risk assessment methods

Given that salinity risk is fundamentally about hydrology, there are many water balance and hydrology models that are useful as part of the salinity risk assessment process. However, there are very few models that are capable of handling all of the elements within salinity risk, thus it is usually necessary to use multiple methods, always ensuring of course that they are fit-for-purpose.

3.4.1. Non-spatial and spatial assessment methods

Both non-spatial and spatial risk assessment methods are available to assess salinity risk. Non-spatial methods are used to assess salinity risk (or more commonly a portion of it) at a point in space (as against a landscape/catchment) and without any linkage to the surrounding hydrology. Examples of these methods are given in Table 3. In reality, all non-spatial methods have a spatial context in that they require a climate file as input (and climate files relate to a geographic location), but from a practical sense they are non-spatial. It is possible, however, to spatialise their results, e.g. Biggs and Brough (2002).

Table 3 Overview of some salinity risk assessment methods[10]

	Method / application / model	Strengths	Limitations
Non-spatial assessment methods	SALF PREDICT, PERFECT, APSIM, HowLeaky, MEDLI	▪ Explore the importance of specific soil attributes, e.g. plant available water capacity (PAWC) and saturated hydraulic conductivity (K_{sat}) on deep drainage and crop water use ▪ Explore relationships to agronomic factors, e.g. irrigation events, crop frequency and yield ▪ Play an important role in understanding the processes within an agricultural landscape	▪ Limited capacity to represent a real landscape and certain processes related to salinity, e.g. lateral flow, salt balance calculations, processes at >2 m depth
	HYDRUS-1D	▪ A numerical model for simulating variably saturated flow and solute transport processes in the vadose zone ▪ Models water movement though the unsaturated zone	▪ Difficult to implement correctly ▪ Properties required are difficult to obtain
	3-PG	▪ Being developed for use in a spatial environment	
Spatial assessment methods	Cumulative index method using grids, e.g. salinity hazard maps	▪ Commonly available	▪ Static, information only applies to one point in time
	Spatial deep drainage and time to fill calculations	▪ Provide insights in to which areas may need to have less irrigation	▪ No groundwater flow or discharge calculations
	2cSalt, BC2C	▪ Integrated catchment models—useful for evaluating land use change scenarios	▪ Require considerable data for calibration and validation ▪ Do not model unsaturated zone storage and lag
	IQQM	▪ Assesses routing of flow and salt in streams	▪ Only assesses one aspect of salinity (i.e. salt additions / extractions in stream)
	RiverManager	▪ Improved capacity to route water and salt in an integrated matter in catchments	▪ Not available yet

Examples of spatial risk assessment methods are also outlined in Table 3. The most common approach used historically in salinity hazard/risk assessment has been a cumulative index method using grids, e.g. salinity hazard mapping (DNR 2000). Similarly, deep drainage modelling and time to fill unsaturated zone calculations can be calculated on various spatial elements (e.g. soils, irrigation management and crop type zones) to obtain a spatial view of salinity risk. This can provide insights into which areas may need to have less irrigation. Recent advances in computing and catchment hydrology modelling (via the Cooperative Research Centre for Catchment Hydrology and subsequently eWater) have led to development of integrated catchment models such as 2cSalt and BC2C. However, neither of these models have an unsaturated zone storage capacity nor time lag. The former has been used in Hodgson Creek catchment on the eastern Darling Downs (Silburn and Owens 2005) and the latter in the Border-Moonie (Biggs *et al*. 2005). A new generation of hydrology tools is currently emerging out of eWater. These include

[10] For more information on these models/methods, refer to Appendix 5.

RiverManager, which is likely to replace IQQM. Once again though, the choice of model/method will be constrained by the specific nature of the enquiry, data availability and process understanding.

Use of more complex models does not necessarily improve the quality of the "answer". With improvements in computing power, there has been a strong focus on building more complex models, often at the expense of primary data collection. The relationship between these two components is illustrated in Figure 28. A more coordinated approach is required to investment in both modelling and measuring to improve understanding of the salinity risk from using CSG water for irrigation. Furthermore, the limitations within models need to be more clearly understood and recognised.

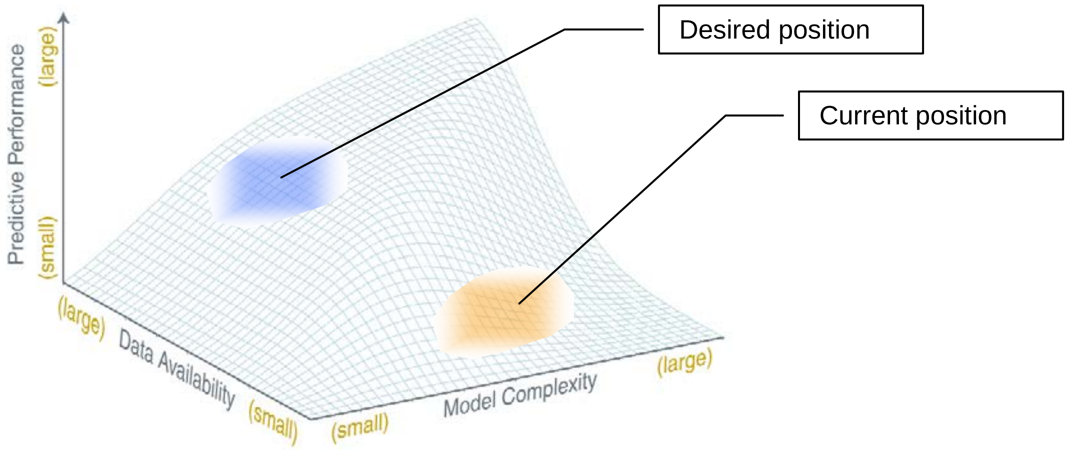


Figure 28 Conceptual relationship—data availability, model complexity and predictive performance
Source: CRC CH (2005).

3.4.2. Water/salt mass balance assessment

Of the many different salinity risk assessment techniques, mass balance assessments of water/salt provide an effective tool for gauging the relativity of parts of the water/salt balance and in appropriate circumstances, loading in systems, e.g. discharge to stream. Understanding the relativity of components of the salt mass balance assists in determining the appropriate level of investigation and concern for each. Mass balance calculations can be conducted at any scale—from the point (a soil profile) through to the catchment and may form part of assessments of the Salinity Stage or Current Management Influence. Many of the models listed in Table 3 contain a salt mass balance component at either the point or catchment scale. In any quantitative exercise – whether it be water or salt balance, it is essential that the law of conservation of mass is implemented.

Salt mass balance calculations in the form of catchment export/import (E/I) ratios have already been derived for many catchments in the QMDB, as part of salinity audit exercises for the Murray-Darling Basin Authority (e.g. Biggs *et al*. (2005), Power *et al*. (2007), Biggs *et al*. (in prep)) and in the Fitzroy Basin (Silburn *et al*. 2007b). A catchment E/I ratio of greater than 1.0 indicates a catchment is exporting stored salt and is expressing hydrologic change after some land use or management changes (a sign of advanced salinity risk stage). Those author's calculations used the two major fluxes—rainfall accessions and streamflow export. With the exception of some smaller eastern catchments, the majority of catchments in the QMDB experience a net accumulation of salt, meaning that the amount entering through rainfall is greater than the amount leaving via streamflow. This is not surprising in a semi-arid, low gradient landscape. Catchments exporting salt tend to be extensively cleared steeper lands with a long history of land use change. Many of these are now in quasi-equilibrium with current climate phases.

At the more detailed level, a variety of processes operate to move water and salt in the landscape (Figure 29). Most of these are significantly affected by land use change, and in particular the development of irrigation. In most areas where CSG water is being produced, there has already been some disturbance of the water/salt balance, generally via land clearing (e.g. removal of upper and mid-storey native vegetation). Thus it is important to consider the relativity of any new water/salt balance (involving CSG water) to both the current water/salt balance as well as the "natural" one.

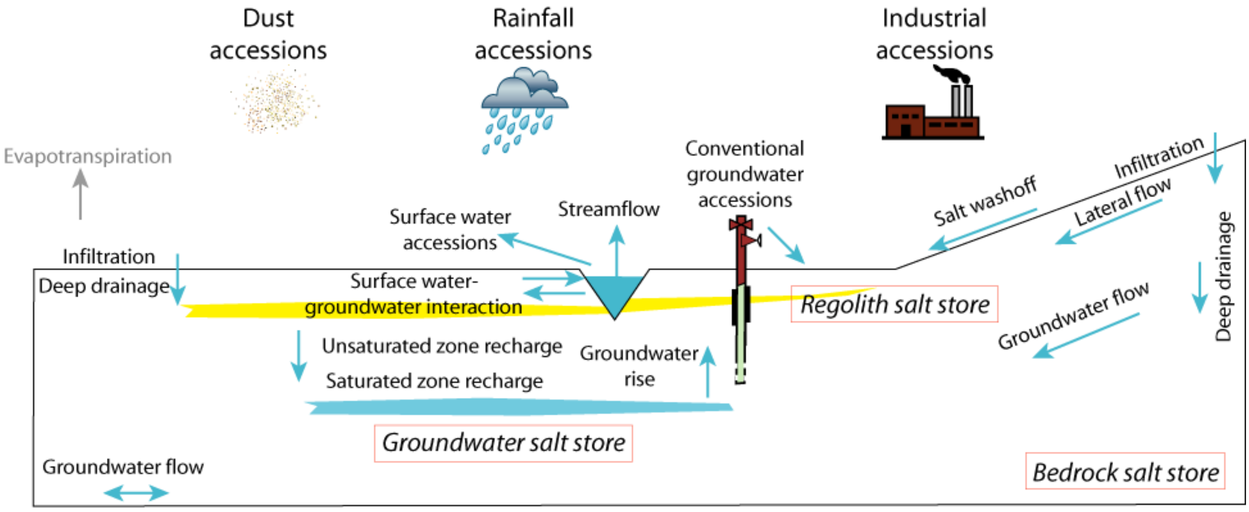


Figure 29 Detailed salt fluxes in the landscape

The paddock level connects to the catchment scale through processes such as runoff/salt washoff, groundwater recharge, surface water/groundwater interaction and groundwater baseflow. These are all natural processes, thus the addition of CSG irrigation water (and associated salt) simply modifies the scale of these processes, particularly given that CSG water, being drawn from GAB aquifers, is essentially "new" water in the landscape.

The flux of salts at the catchment scale is captured under the Basin Salinity Management Strategy (BSMS) requirements, specifically in end-of-valley salinity targets and through annual salt accounting. To date, the data from these activities indicates that for the majority of the QMDB, salt export is driven by rainfall/runoff, rather than groundwater baseflow. The implications of this for the disposal of CSG water by irrigation include:

- Increased catchment cover (wooded area) may lead to decreased catchment runoff (and salt export);
- Potentially increased runoff from irrigated crop areas (due to increased frequency of saturated profiles);
- Greater salt washoff from salinised areas; and
- Increased potential for recharge of shallow aquifers, leading to increased saline groundwater baseflow.

Salt inputs

There are four common natural sources of salts in soils/landscapes—atmospheric, connate (salts trapped in the matrices of sediments since deposition), mineral weathering and groundwater accessions (e.g. artesian springs). Of these, the first is usually regarded as the most significant, but the others may be significant in certain landscapes. A fifth source of salts relevant in some areas is anthropogenic inputs. These include fertiliser, industrial sources, and artificial groundwater accessions such as CSG water. In inland areas of Queensland, the latter is the most significant of the anthropogenic sources.

Rainfall salt accessions
Biggs (2006) has published equations (below) for deriving rainfall inputs of salt for the QMDB (Figure 30). These may be used to calculate rainfall salt inputs across any part of the region as either a total salt mass (TDI) or chloride (Cl) accession. The equations do not separate dryfall from wet accessions; hence they include an element of dust and industrial accessions. Throughout the region, rainfall salinity inputs are <100 kg/ha/yr (<30 kg/ha/yr Cl).

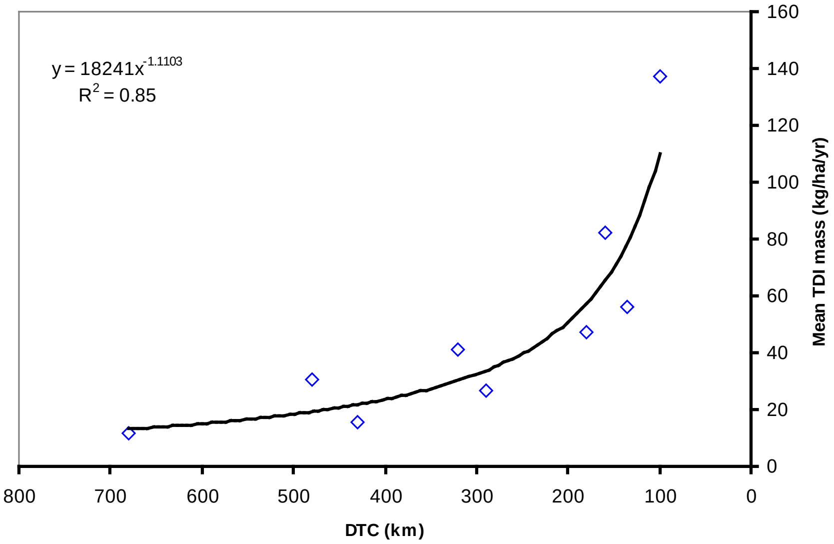


Figure 30 Rainfall salt mass vs distance to coast

While these equations have been available for use for some years, and some rainfall chemistry data collection continues to occur in the region, the presence of numerous climate stations associated with CSG facilities presents an opportunity to collect more site specific data. Such data would eventually lead to an improved regional equation (Biggs *et al*. in prep).

Groundwater salt accessions
Groundwater pumping can add to, subtract from or have no impact on the catchment salt mass balance, depending on the source and fate of the water extracted. In the QMDB, previous catchment salt balances have not quantified groundwater accessions, with the exception of DNR (2000). This report used a rate-of-rise method across very broad hydrogeological units, the output of which was questionable in terms of accuracy. Groundwater discharge to streams (baseflow) is known to be an important contributor of salts, particularly in upland catchments that have undergone significant land use change (NLWRA 2001). It is effectively an input (if it is not cyclic salt), but is only measured in the streamflow output. Unlike the lower Murray-Darling Basin however, baseflow is not a significant component of the major rivers in the QMDB (which frequently experience extended seasonal and longer duration periods of no-flow), although it is known to be an important component in some smaller eastern, upland catchments such as Hodgson Creek, Pike Creek and Oaky Creek (Silburn and Owens 2005, Cresswell *et al*. 2006, Biggs *et al*. 2006). Pumping of saline groundwater and disposal into evaporation basins is used in the lower Murray-Darling Basin to intercept salt before it drains into river systems, but no such activities occur in Queensland.

Until the recent development of the CSG industry, groundwater salt accessions from oil and gas facilities in the region were minor. Salt accessions from conventional groundwater sources (e.g. artesian and sub-artesian, stock and domestic, irrigation, industrial, town water supply) are not easily quantified due to a lack of metering and water quality data. Estimates for all these sources have however been made for the QMDB (Biggs *et al*. in prep). This involved review of available water quality and allocation data, and estimation of probable values using mid-range values. In the case of the CSG industry, a mid-range industry water production number of 196 000 ML/yr (DEEDI

2009) and an upper range number of 560 GL/yr (CG 2010) was used in conjunction with a water quality figure of 3000 mg/L (CG 2010). Figure 31 illustrates the relativity of the different input sources for the Condamine-Balonne catchment (rainfall and conventional groundwater estimates) and the overall CSG water production estimates for the ten years from 2014 when CSG water production is expected to peak, showing a substantial increase in salt inputs from this source.

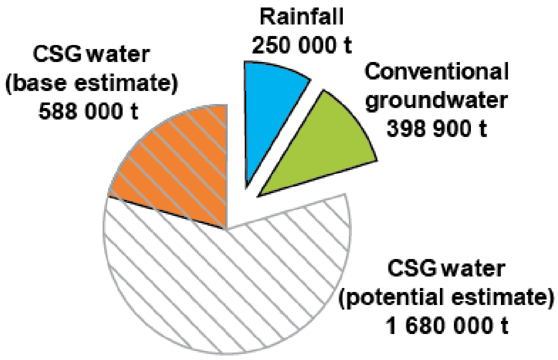


Figure 31 Estimated salt inputs for the Condamine-Balonne and projected CSG salt inputs (t/yr)

It is currently impossible to confidently estimate salt yield due to spatial and temporal variation in water quality in gas fields. Industry predictions are currently highly variable—it is estimated that the amount of salt produced over a 30 year period could vary from 350 000 tonnes to 1 650 000 tonnes per year. The Interim Report from the Senate Inquiry (The Senate 2011) stated '*conservatively, the industry will be handling some 750 000 tonnes of salt per annum*'. If the National Water Commission's estimate of 7500 GL of CSG water production is used with an average TDS content of 3000 mg/L, then the potential salt load brought to the surface over the next 25 years would be 22.5 million tonnes (about 900 000 tonnes of salt produced per year). Since not all of the water will be treated, the amount of brine and solid salt for disposal will be less than this; however, management and disposal options able to deal with significant quantities of brine and solid salt need to be developed. How and where the salt from CSG water is stored and used across the region depends on the location of the gas fields, opportunities for use of CSG water and brine streams, and government policy. Use of treated CSG water for irrigation is part of the mix.

Salt exports

Figure 32 shows the surface water catchments found in the project area. Streamflow is the primary export mechanism of salt from landscapes. In the QMDB, this is measured at end-of-valley gauging stations fitted with time-series electrical conductivity meters, and reported annually as part of BSMS requirements. The data is also used in IQQM modelling to derive the baseline values for end-of-valley salt loads (Table 4) described in Power *et al*. (2005). As the monitoring record for some gauges is relatively short and intermittent, modelling is necessary to synthesise a long-term record. The end-of-valley targets are currently under revision. The most significant difficulty associated with them is measuring and accounting for flood-flows, overland flows and inter-catchment flow on floodplains.

Diffuse recharge to groundwater (e.g. GAB recharge) accounts for a significant sink for catchment water and salt loads. Figures for GAB recharge vary greatly depending on rock type/formation, and can be quite high in quartzose sandstones (GAB recharge beds) and very low in less permeable units such as the Wallumbilla Formation. Given that deep drainage rates under native vegetation are as low as <1 mm/year (Tolmie *et al*. 2003, 2011), a conservative estimate may be derived by using a figure of 0.5 mm and the rainfall salinity.

The extraction of surface water (primarily for irrigation) decreases the salt export from catchments, and re-distributes salt back onto the landscape, where it generally becomes part of the regolith salt store. The decrease in salt export is typically proportional to the water take from streams, mainly for irrigation, because there is little groundwater contribution to streamflow salt loads. Thus conventional irrigation activities using surface water are a key salt transport mechanism in the landscape as they remove salt from streams. For instance, in the Condamine-Balonne catchment, the salt load is decreased by approximately 47% compared to a "non-irrigation" scenario (modelled in IQQM). In simple terms, this means that irrigation activities are adding around 50% more salt to the landscape compared to pre-development levels. Furthermore, this salt has been gathered in whole-of-catchment runoff, but is irrigated onto a much smaller area of land.

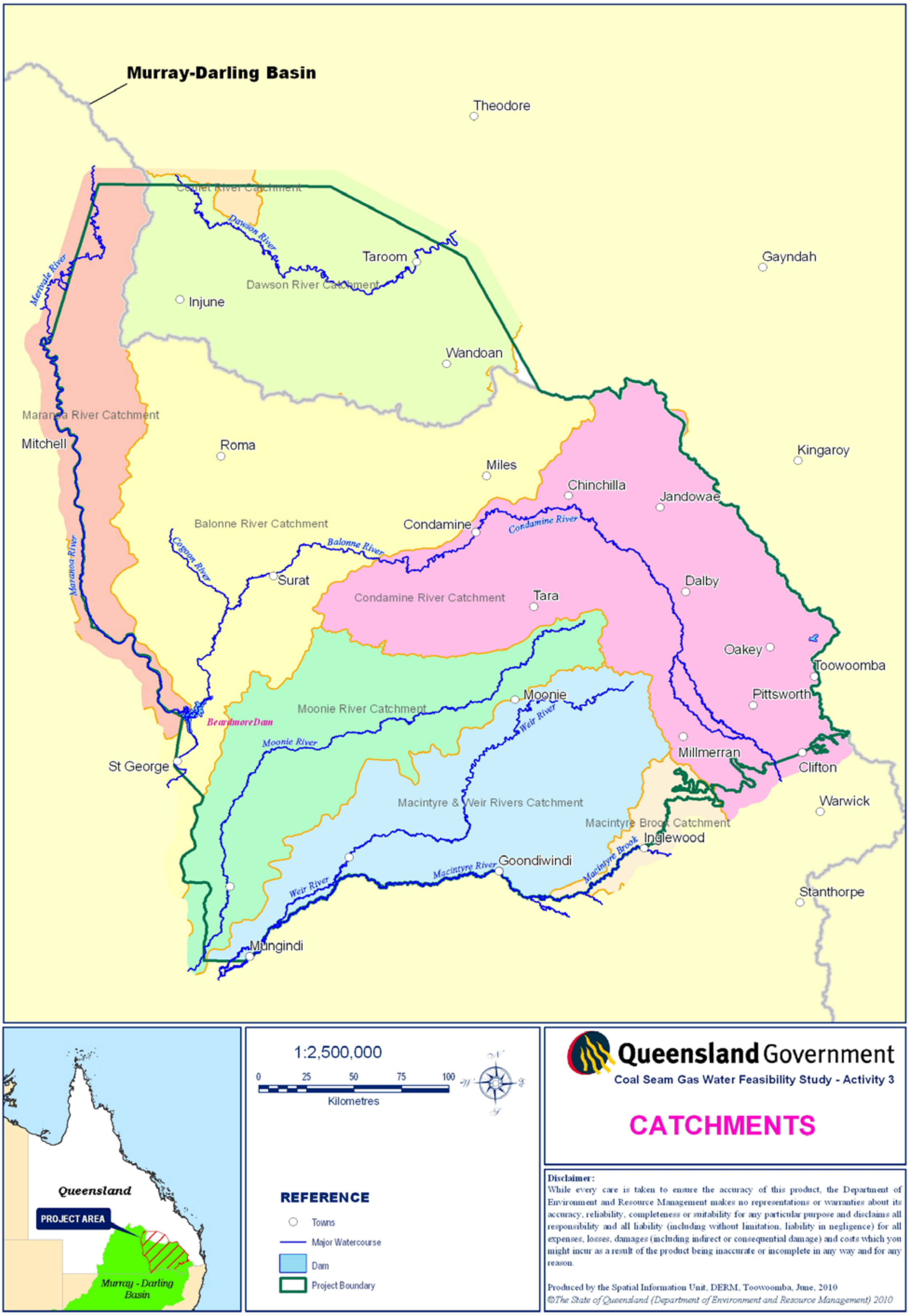


Figure 32 Surface water catchments of the project area

Table 4 End-of-valley salinity targets for the QMDB catchments of the project area

Valley	**Valley Reporting Site** ***(shared target sites shown in italics)***	**Salinity (µS/cm)**		**Salt load (t/yr)**	**Flow (ML/yr)**
		Median (50%ile)	Peak (80%ile)	Average	Average
Qld Border Rivers	*Barwon River @ Mungindi*	250	330	50 000	502 500
Moonie	Moonie River @ Fenton	140	150	8700	131 200
Condamine-Balonne	Ballandool River @ Woolerbilla-Hebel Rd	170	210	4200	49 600
	Bohkara River @ Hebel	170	210	5000	54 200
	Briarie Creek @ Woolerbilla-Hebel Rd	150	280	6500	68 300
	Culgoa River @ Brenda	170	210	29 000	329 700
	Narran River @ New Angeldool No.2	160	210	10 000	120 700

Note there is significant variation particularly in the flow and salt loads from year to year. Assessed baseline conditions are based on the modelled climatic and flow sequence from 1975 to 2000.

For example, a “typical” broadacre irrigation farm applying 6 ML/ha/yr with 150 mg/L salt concentration applies 900 kg salt/ha/yr. This compares with rainfall salinity inputs of <100 kg/ha/yr in the region. By comparison, it is estimated that some CSG water application regimes could add up to 10 000 kg salt/ha/yr (calculations based on applying 5 ML/ha/yr at 2000 mg/L). Accumulation of salts is generally not observed in broadacre irrigation areas in the QMDB, despite some of these being developed on quite saline soils, which suggests that sufficient leaching occurs to prevent evaporative accumulation of salts at the soil surface. However, accumulation of salts has been observed in areas where saline groundwater is used for irrigation, such as the lower Condamine and lower Balonne. Input water quality must therefore be high to ensure detrimental effects do not result from its application.

Table 5 summarises the approved CSG water discharges to streams permitted in the Surat Basin. Some discharges are also permitted in the Dawson catchment. Regardless of whether the water is treated or not, this represents a salt removal mechanism—assuming the salt added is transmitted downstream.

Table 5 Details of approved CSG water discharges to streams in the Surat Basin, as at December 2011

Stream	**Location**	**Amount**	**Water Quality**	**Duration of Environmental Authority**
Arrow Energy discharge into Wilkie Creek	23 km SE of Kogan	Must not exceed: 0.8 m^3/s or 20 ML/day	▪ EC 580 µS/cm (max) ▪ pH 6.5–9.0 ▪ Suspended Solids 180 mg/L (max) ▪ Calcium 34 mg/L ▪ Magnesium 26 mg/L ▪ Sulphate 9.6 mg/L	Subject to a ‘Water Release Reduction Strategy’ No end date
APLNG discharge into Condamine River at Talinga	27.5 km SE of Miles	Must not exceed: 20 ML/day at flow rate consistent with flow velocity in Condamine River	▪ EC 200–500 µS/cm ▪ pH 6.5–8.5 ▪ Suspended Solids 191 mg/L (max) ▪ Calcium >5 mg/L ▪ Magnesium >1 mg/L ▪ Sulphate 3–9 mg/L ▪ Sodium 60–80 mg/L	Maximum period of 18 months and must cease before 20 March 2012

Stream	Location	Amount	Water Quality	Duration of Environmental Authority
QGC discharge into Wieambilla Creek	39 km SE of Miles	12 ML/day Max 3492 ML (until May 2012)	▪ EC 300 µS/cm (max) ▪ pH 6.5–8.5 ▪ Suspended Solids 45 mg/L (max) ▪ Calcium 2–13 mg/L ▪ Magnesium 2–10 mg/L ▪ Sulphate 4.6 mg/L ▪ SAR 4 (max)	July 2010–May 2012 (until Chinchilla Weir pipeline completed by SunWater)
SunWater discharge to Condamine River with off-takes for irrigation and supply to Chinchilla	Chinchilla Weir	Up to 85 ML/day for 20 years But must demonstrate the downstream take balances the volume released. Potential for irrigation off-takes prior to discharge	▪ EC 500 µS/cm (max) ▪ pH 6.5–8.5 ▪ Suspended Solids 175 mg/L (max) ▪ Calcium 6 mg/L (min) ▪ Magnesium 4.5 mg/L (min) ▪ Chloride 135 mg/L (max) ▪ Sulphate 8.8 mg/L (max) ▪ SAR 6 (max)	24 years (20 years resource use, 3 years monitoring, 1 year reporting and assessment) (operation to commence before end of 2011)

Salt mass balance example calculations

Using the input and export data described above, mass balances can be calculated for major catchments in the region (only those for which a daily salt export can be calculated). Figure 33 illustrates the mass balance for the Condamine-Balonne catchment. The spatial variability associated with different inputs and exports is worth noting. Rainfall salt inputs are diffuse across the landscape, whereas most surface water and groundwater accessions (e.g. irrigation) occur on small parcels of land. Losses may be diffuse (deep drainage), but most are constrained as streamflow. It is also difficult to calculate an exact mass balance for one or more CSG tenements, as exports (in the form of streamflow) can only be calculated at gauging stations (or nodes in the IQQM model). As the size of the area assessed decreases, certainty about some fluxes may increase (e.g. irrigation salt inputs), while certainty about other aspects may decrease. In the case of CSG water accessions, the fate of the salt mass brought to the land surface remains the subject of considerable uncertainty.

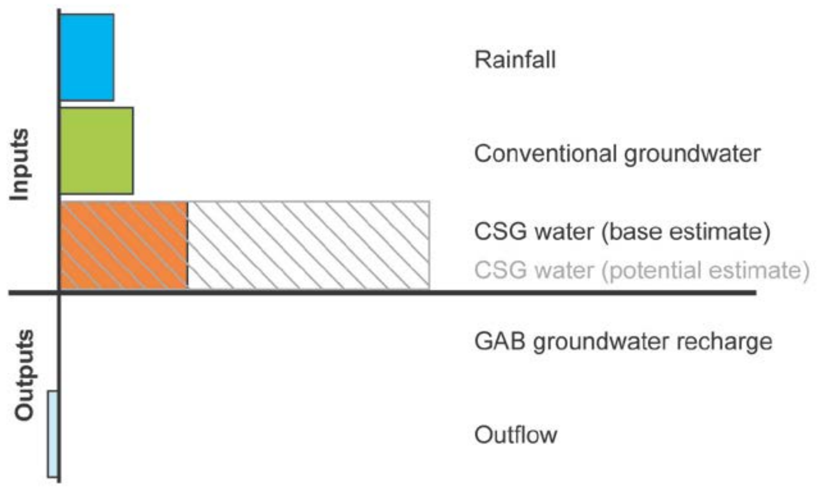


Figure 33 Estimated salt mass balance (t/yr) for the Condamine-Balonne catchment

Salt mass balance calculations are also useful at the point scale, an example being the chloride balance method for estimating deep drainage. In simplest terms, they involve an estimate of salt store, additions and leaching. Tools such as SALF PREDICT can facilitate such calculations. At the more complex end, they may also involve estimates of surface washoff, lateral flow, groundwater discharge/recharge and other such calculations.

An example of a simple calculation is shown in Figure 34 and Table 6. This uses typical salinity values for hillslope soils and CSG water application rates. In a shallow profile (1 m depth), the salt store may be increased by up to 17% if there are no loss mechanisms[11]. The deeper the profile, the smaller the proportional increase, partly because deeper soils generally have higher EC and therefore a high salt store per cubic metre.

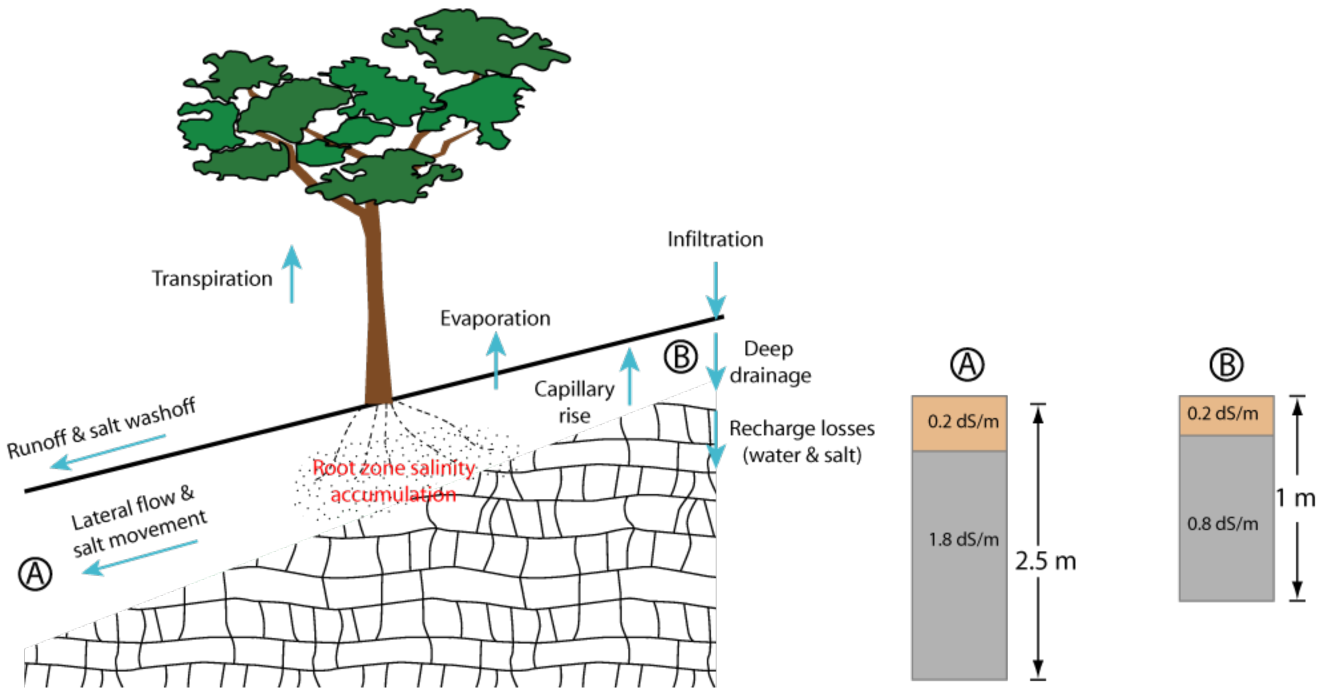


Figure 34 Example scenarios for salt mass calculations of two hillslope soils

While these are only example calculations, they illustrate a number of important points, in particular that the potential to proportionally increase the soil salt store is greater on shallow soils, and that application of CSG water (whether amended raw water or RO water) generally adds a greater quantity of salt than the use of conventional surface water sources.

Similar calculations to these may be carried out to investigate the importance of other soil attributes such as clay content and permeability. Correctly identifying the critical factors in a landscape is essential to optimising irrigation management and monitoring.

Table 6 Example salt mass calculations for irrigation scenarios on two hillslope soils

	Shallow soil	**Deep soil**
Starting salt store (t/ha)	28.76	193.74
Irrigation with amended CSG water (2.5 ML/yr @ 2500 mg/L = 5 t/ha/yr)	17.4% of soil salt store	2.6% of soil salt store
Irrigation with RO treated CSG water (7 ML/yr @ 300 mg/L = 2.1 t/ha/yr)	7.3% of soil salt store	1.1% of soil salt store
Conventional irrigation (6 ML/yr @ 200 mg/L = 1.2 t/ha/yr)	4.2% of soil salt store	0.6% of soil salt store

[11] Calculation is based on 1 m^2 of soil.

4. Salinity risk assessment framework for irrigation with CSG water

The preceding sections describe the principles of salinity risk assessment and some of the historical work in the project area. The task for a water user is to choose one or more risk assessment methods and the task for the regulator is to determine if the risk assessment answers the questions posed in relation to beneficial use of CSG water, in particular that there will be no harm caused as a result of the water use. It is important to note that there is no "perfect" or "one size fits all" salinity risk assessment method, as the method chosen will be influenced by the specific nature of the enquiry and the landscape of interest. In general, it will be appropriate to apply multiple approaches in order to consider all aspects of irrigation salinity risk.

The recommended salinity risk assessment framework for irrigation with CSG water is an adaption of the framework described in Figure 27, and is illustrated in Figure 35. The framework is equally applicable to the question of soil/water chemistry risk as it is to landscape salinity risk. Assets have not been included in the framework as the framework is designed to understand and assess salinity risk so that the risk can be avoided, and therefore there is no impact on assets to consider. In the case of CSG water irrigation, the management component is constrained to a defined time-span (typically less than 25 years), determined by the duration of availability of the CSG water. Due to this, the land use after cessation of irrigation plays an important role in determining salinity risk over the longer timeframe (100 years from commencement of irrigation, as required in the Murray-Darling Basin). Post-Irrigation Land Use has therefore been explicitly introduced to the framework and is an integral part of the risk assessment process.

The framework has the flexibility to incorporate both quantitative and qualitative data. Its application is independent of scale and not wedded to any specific modelling environment. The framework also provides the opportunity to assess risk from completely different approaches. Applications of the Grundy *et al*. (2007) method and other methods to date generally adopt an implicit assumption that saturation will be reached, e.g. spatial prediction of catena form or leaking dam form salinity. This remains an important approach, as it can be used to investigate worst-case scenarios and potential impacts on assets. Another approach is to back-calculate the capacity of the landscape to absorb excess water, thus aiming to prevent the unsaturated zone from becoming saturated within a given timeframe.

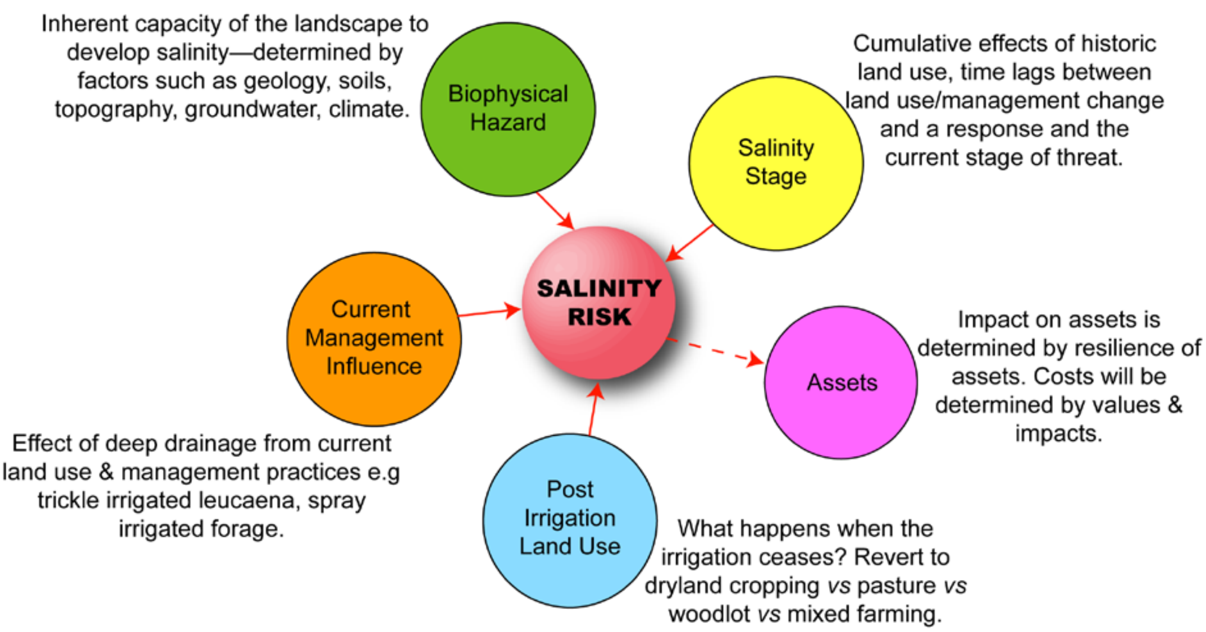


Figure 35 Salinity risk assessment framework for irrigation with CSG water

As discussed above, the timeframe for assessment of impacts in the Murray Darling Basin is 100 years from commencement of irrigation. The timeframe of 100 years can also be used when investigating a proposal for a CSG water irrigation activity outside the QMDB. Thus if the size of the unsaturated zone is determined (Biophysical Hazard), taking into account "new water" since original clearing (Salinity Stage) and then the requirement to have 100 years of "freeboard" in the unsaturated zone (consideration of the Post-Irrigation Land Use), the amount of water that may be added via CSG water irrigation (Current Management Influence) can be calculated (Figure 36). Such a calculation would of course need to be modified if off-site processes also impact at that location, for example rising groundwater due to recharge from other land management activities off-site.

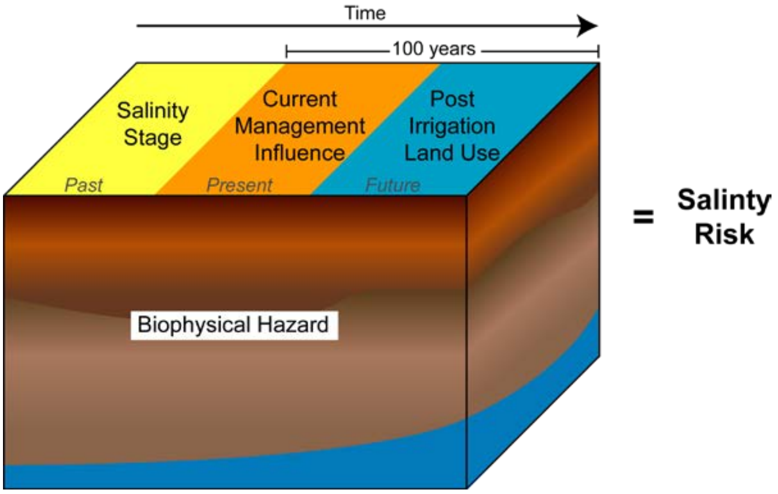


Figure 36 Temporal relationship between the salinity risk components

The exact approach adopted will in part determine the attributes needed for the assessment process, but in general there is a core set of attributes needed for any assessment (Table 7).

Table 7 Core attributes related to salinity risk assessment components

Biophysical Hazard	**Salinity Stage**	**Current Management Influence**	**Post-Irrigation Land Use**
Landform	Climate since clearing	Climate	Climate
Soil and regolith properties	Time since clearing	Water application rate	Land use
Salt store	Land use since clearing	Water quality	Crop management
Available unsaturated zone storage	"New" water added since clearing	Crop type/water use	
Hydrogeology			

A more extensive (but not exhaustive) list of core attributes is given in Figure 37, framed in the context of hillslope versus alluvial landforms. These landforms have a number of specific management considerations and factors, such as flooding, fluvial architecture, stratigraphic variability and lateral flow in texture contrast soils, as well as many in common. The broad distribution of alluvial and hillslope landscapes in the region is shown in Figure 38. This is only one of a number of different ways in which to conceptualise the landscape and proponents should use whichever is most appropriate to the landscape in question.

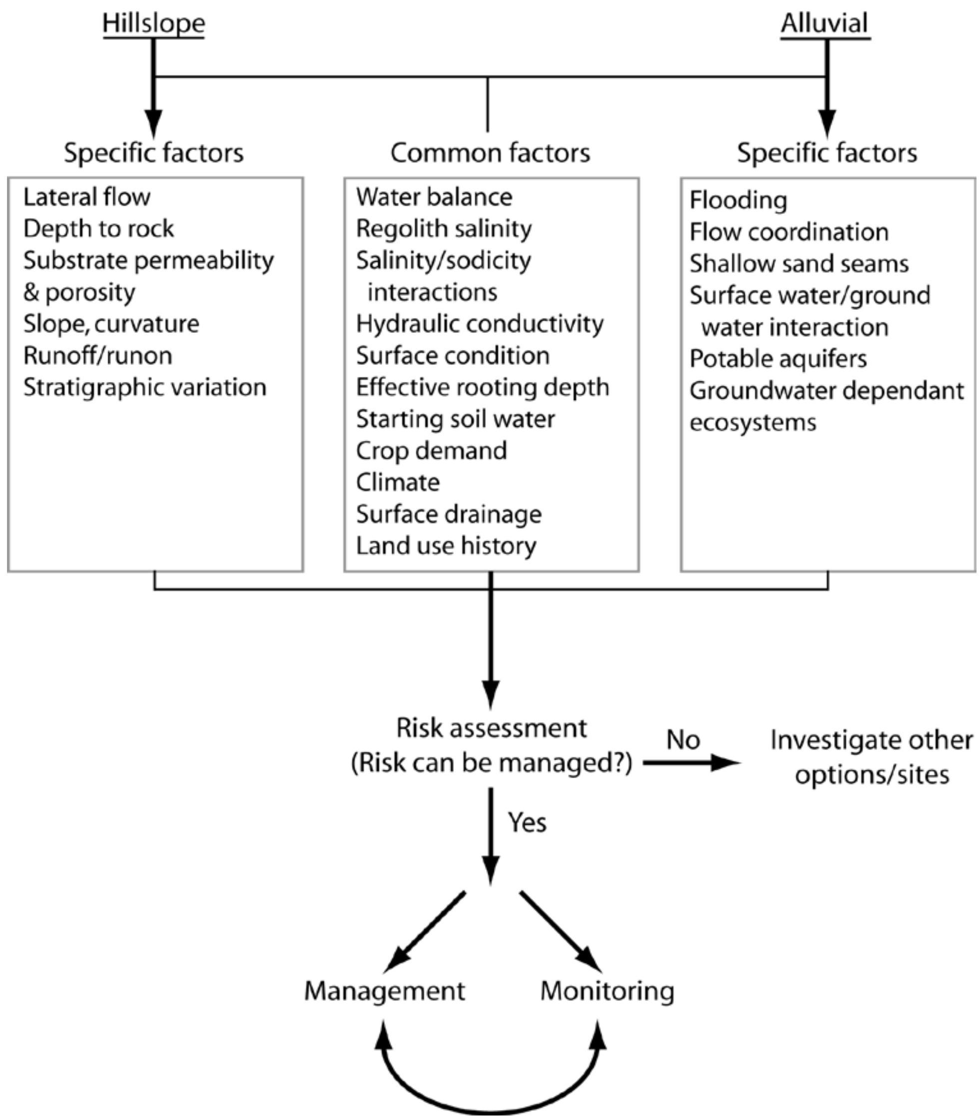


Figure 37 Salinity risk factors in the context of hillslope and alluvia

Identifying all necessary attributes is the first step in any salinity risk assessment. Table 8 outlines typical data sources for many of these attributes.

Some of these factors are very sensitive to land use change (and thus relate to the management component), while others are not. Some may be manipulated, while others may not. Some are relatively static over time, and some are not. Understanding the respective role and nature of all factors as far as is reasonably possible is critical to a comprehensive salinity risk assessment. A good understanding of the areas of weakness in terms of data/knowledge is also essential to framing the monitoring program for a development.

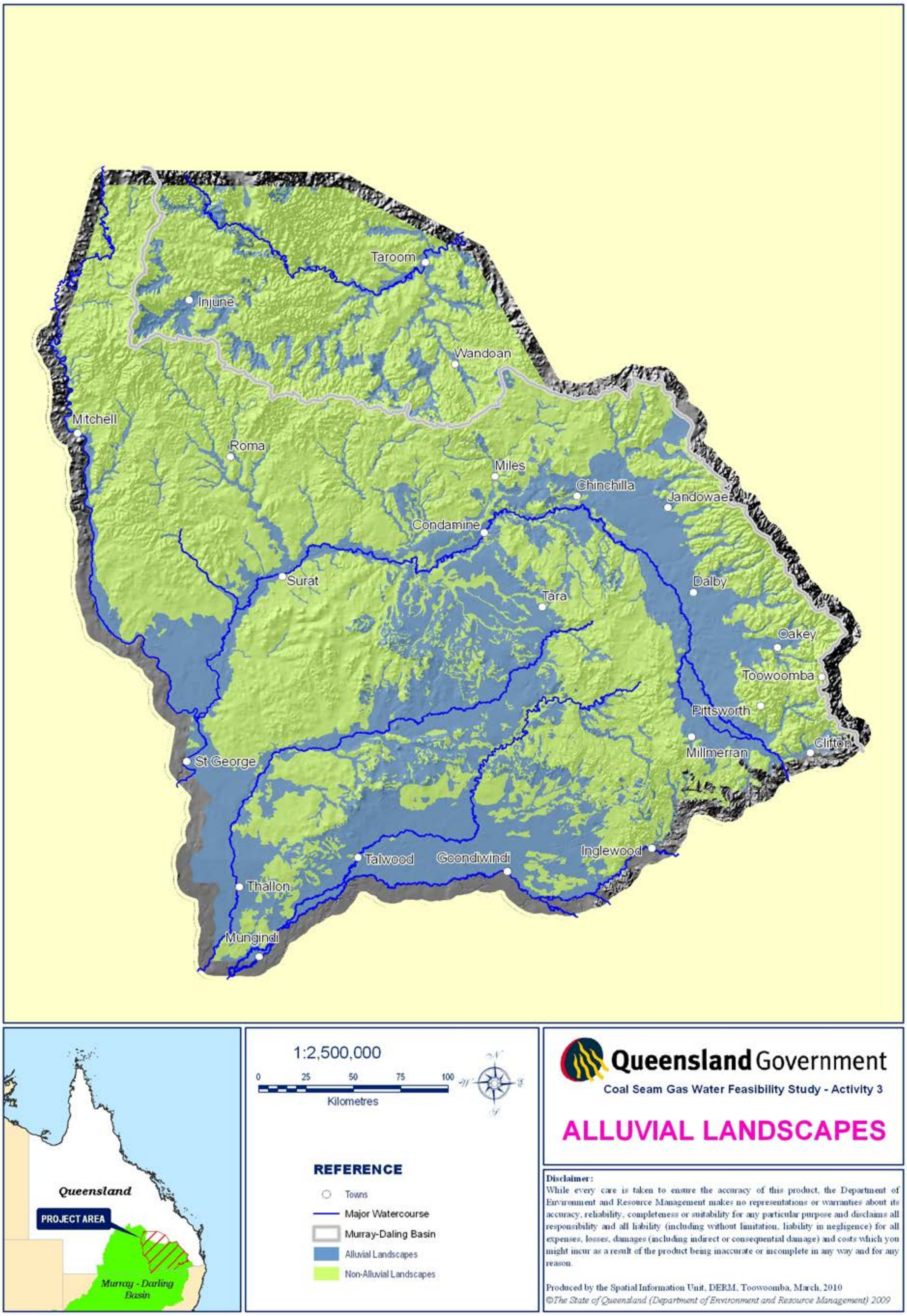


Figure 38 Alluvial and non-alluvial landscapes of the project area

Table 8 Typical data sources for salinity risk assessment attributes

Attribute	Data sources
Biophysical Hazard	
Depth to substrate or other reduced permeability zone	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey
Regolith architecture in alluvial sequences	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey
Regolith salt store, porosity, hydraulic conductivity	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey
Landform, slope, curvature	25 m DEM from DNRM, shuttle radar from GA, company data
Lateral flow, runoff/runon	Existing land resource data, modelling, field measurements
Infiltration rate	Published data, field measurements
Soil EC, ESP	Land resource studies and technical reports, SALI database
Surface drainage (proximity to watercourses)	Existing topographic data/survey (validated during site surveys)
Results from soil survey	Land resource surveys (DNRM, CSIRO), company data
Salinity Stage	
Historic land use	DNRM land use mapping, landholder records, historical imagery, historical reports e.g. land surveys
Time since clearing	DNRM land use mapping, landholder records, historical imagery, historical reports e.g. land surveys
Land use since clearing	DNRM land use mapping, landholder records, historical imagery, historical reports e.g. land surveys
Climate since clearing	BoM, landholder records
Groundwater trends	DNRM groundwater database, DNRM publications, landholder and company records, hydrogeological investigations
Existing salt expressions	Soil survey, DNRM salinity site database, publications, landholder knowledge, field survey, imagery
Salt export/import ratio (E/I)	DNRM data/reports
Current Management Influence	
Irrigation water quantity	CSG companies and irrigators
Irrigation water quality	CSG companies
Irrigation method/regime	Irrigators, consultants
Soil properties	Existing land resource data
Effective rooting depth	Soil survey, agronomic data and crop models, DNRM groundwater database, GSQ, company geological data, hydrogeological investigations
Crop type	Irrigators, consultants
Crop lower limit	APSoil database (APSRU website)
Climate	BoM, companies, landholders
Flooding	Gauging stations, old flood maps, landholders

Acronyms: APSRU - Agricultural Production Systems Research Unit, BoM - Bureau of Meteorology, DEM - Digital Elevation Model, DNRM - Department of Natural Resources and Mines, GA - Geoscience Australia, GSQ - Geological Survey of Queensland , SALI - Soil and Land Information database (DNRM)

Investigation techniques that will facilitate the compilation and analysis of key data relevant to the salinity risk components are outlined in:

- Appendix 2: Soil surveys and agricultural land suitability assessments for coal seam gas water irrigation development,
- Appendix 3: Irrigation suitability requirements, and
- Appendix 4: Investigating the unsaturated zone.

4.1. Assessing Biophysical Hazard

The biophysical hazard represents the inherent capacity of the landscape to develop secondary salinity, and includes factors such as geology, soils, topography and climate. The attributes that make up biophysical hazard vary substantially with the relevant salinity conceptual model, but the most common attributes used are soil type (or more specifically soil attributes) and topographic derivatives (Table 9).

Searle *et al*. (2007) have undertaken the most comprehensive assessment of hazard in relation to specific conceptual models to date for the Condamine catchment. The principles they used may be applied elsewhere, e.g. Biggs *et al*. (2010). No single attribute can be used in isolation to determine biophysical hazard. Soil/regolith salt store is certainly relevant, although as previously stated, it appears to be the least important of the factors. Topographic derivatives such as curvatures and wetness index are frequently useful due to the simple fact that water/salt moves downhill. Thus they can provide an indication of where water and salt may accumulate.

Table 9 Attributes relevant to Biophysical Hazard

Attribute	Comment	Measurements
Depth to substrate or other reduced permeability zone	Determines potential thickness of unsaturated zone. Critical to determination of landscape salinity risk.	Depth, hydraulic conductivity, pore space relations, water characteristic, bulk density, particle size
Regolith architecture in alluvial sequences	Affects vertical and horizontal water movement (e.g. porosity, hydraulic conductivity and connectivity).	Particle size
Salt store	Knowledge of potential mobilisation of primary salt stores.	EC, chloride, total soluble salts, solid phase salts
Landform	Affects surface and subsurface drainage.	Slope, slope shape, landscape position
Lateral flow, runoff/runon	Determined by nature of the soil profile (e.g. texture contrast soil) and topography.	Presence/thickness of A horizons in relation to B horizon, soil texture
Infiltration rate	Determined by texture, clay type, surface soil salinity/sodicity, surface cover, slope gradient, microrelief (i.e. surface detention time).	K_{sat}
Soil salinity/sodicity	Affects soil water movement; indicator of natural water/salt fluxes; affects plant vigour (and resultant evapotranspiration). Critical to determination of soil/water salinity risk.	EC, Cl, ESP, exchangeable ions, soluble ions, solid phase salts
Surface drainage (proximity to watercourses)	Influences likelihood of salt washoff, lateral flow or shallow groundwater movement moving salt to streams; influences transport times for solutes discharging to stream.	Distance to watercourse, stream incision
Results from soil survey	Base data for many purposes, especially water balance modelling.	Nature and distribution of soil types with associated attributes that influence agronomic use

In many cases, the disposal of CSG water via irrigation will be in greenfield developments, areas which have not been previously used for irrigation. As outlined in Section 7.3.1 and Appendix 2, a minimum scale of 1:25 000 over the irrigated footprint is required for soil surveys related to the use

of CSG water for irrigation. Apart from validating that the area is capable of growing the crop, the data collected will be vital in determining both biophysical hazard and management implications, as well as providing baseline data against which future monitoring data will be compared.

Point scale assessments may be undertaken to investigate detailed aspects of the proposed irrigation water quality and soil types, in particular addressing sodicity issues. This may involve field and laboratory experimental work, as well as modelling. The results of this may further refine the assessment of land suitability. The attributes relevant to determine the biophysical hazard of a site are outlined in Table 9.

Unsaturated zone properties that influence water storage, transmission and loss include mineralogy, texture, structure, surface condition, bulk density, porosity and antecedent water content. A failure of previous evaluations of salinity risk has been the lack of consideration of attributes at depths deeper than the conventional cropping root zone. Considerable investigation is needed to improve this knowledge gap. While considerable soil site data exists in Queensland (available from DNRM), data below 1.8 metres is limited. Maps of soil profile (or regolith) thickness are not common. Mapping of the unsaturated zone thickness and associated properties (e.g. stratigraphy) should be undertaken at all proposed irrigation sites. As a general principle, soil depth increases with distance downslope and slope length. In reality, this can be significantly affected by erosion, substrate lithology and weathering rates. On alluvial plains, the depth to and thickness of the first coarse-textured seam (potential aquifer material) is of significance, as is the overall alluvial thickness. This data is essential for understanding the likelihood of perched watertables and connectivity to streams (surface water/groundwater interaction).

The importance of understanding the properties of the unsaturated zone cannot be understated. In hillslope lands, the effective unsaturated zone thickness may be as shallow as the thickness of the soil profile. In alluvial areas it can be highly variable. An example of the importance of the unsaturated zone attributes is given in Table 10. Assuming no losses, the size of the unsaturated zone (available storage) for a unit area is determined by its thickness multiplied by the unfilled porosity. The unfilled porosity is of course less than the air-filled porosity, which is less than the total porosity (Details for investigating the unsaturated zones can be found in Appendix 4). In the context of biophysical hazard, this parameter is established under native vegetation, preferably by sampling and measurement. Once it is established, a simple calculation can be made of the time it will take to fill the unsaturated zone, assuming a given deep drainage rate and the assumption that there are no lateral inflows or outflows. This of course simulates the worst-case scenario. In reality there are loss mechanisms such as groundwater outflow, but in the majority of landscapes in the QMDB, the rate of losses is much less than the rate of input.

Table 10 Time to fill example calculations for Biophysical Hazard[12]

Unsaturated zone thickness (m)	**SC_I (%)**	**P_S (mm)**	**AW_n (mm)**	**Avail. Storage (mm)**		**Native veg. deep drainage (mm/yr)**	**Time to fill (years)**	**Irrigation deep drainage (mm/yr)**	**Time to fill (years)**
2	10	200	100	100		0.5	**200**	30	**3.3**
20	10	2000	100	1900		0.5	**3800**	30	**63**
Biophysical Hazard			*Stage*					*Management*	*RISK*

Initial storage capacity (SCI) = Drained upper limit (DUL) – starting water content for native vegetation (SWnv)

Available storage = (D x SCI%) – AWn

where D = unsaturated zone thickness in mm and AWn = water added (mm) in n years since clearing

[12] For more information on the terms used in this table, refer to Dalgliesh and Foale (2005), Yee Yet and Silburn (2003) and Figure 41.

While the unsaturated zone thickness can be established from either historical or new soil survey and drilling data, its moisture content is less well understood. Very little work has been done on this topic in Queensland. Given that anecdotal data suggests roots of native vegetation may penetrate as deep as 30 metres on the alluvial plains, it is possible that there is a large unsaturated zone in such areas. Porosity of the unsaturated zone material may be measured or estimated. In some instances, it may also be relevant to measure or estimate the *in situ* hydraulic conductivity of both the regolith and the underlying substrate (generally sandstone, mudstone or siltstone in the CSG development area).

The salinity of a soil/regolith profile is important for a number of reasons. In relation to management, it may influence the amount of salt that can be applied in irrigation water. From a risk perspective, it indicates the potential future risk if salt mobilisation occurs. Salinity in profiles may be represented in several ways. A standard method is a vertical profile from analytical data represented using either EC or chloride concentrations as surrogate measures of salinity. In some instances, the maximum value within the profile, along with the depth at which that maximum value is reached, may be of significance—for example, where chloride levels may restrict root growth in sensitive crops such as chickpea. In other instances, calculation of a profile weighted mean value is useful. In salt mass balance calculations and catchment scale modelling, the total salt store (as tonnes per unit area to a specified depth) is required. In general, the way in which soil/regolith salinity is represented is driven by the end use of the data.

Example calculations of soil salt store (based on EC) for profiles in the region give figures of 0.1–7 kg/m^3. In general, EC and chloride increase with depth, often dramatically so at the long-term wetting front. Below the long-term wetting front, salinity often remains constant unless a lithological change is encountered. In some soils, a second salt store exists in the form of solid phase salts—generally gypsum and lime. These are typically not measured quantitatively, but can be substantial in some soil types, e.g. up to 50% in the subsoil of *Dulacca* soils.

Landscape salt stores may also include salts in the bedrock and groundwater. Whether these are considered in a risk assessment depends on the landscape and hydrologic processes of relevance. In much of inland Queensland, particularly in the brigalow lands, the geology consists of Jurassic to Cretaceous argillaceous sediments (e.g. mudstone, siltstone) with varying degrees of weathering. In general, these materials appear to be relatively impermeable and thus may be considered as the hydrogeological basement in a worst case scenario. Limited data for these materials suggests there can be substantial variations in salt content both between weathered and unweathered materials and within weathered zones (Wilkinson and Chamberlain 2004, Biggs *et al*. 2005, Power *et al*. 2007, Biggs and Silburn 2008). Figure 39 illustrates variation in chloride content for gilgaied alluvial clay materials in the Border-Moonie and shows the importance of “digging deep”, as the maximum chloride value is not reached until about 2 m in the mound, and 3.7 m in the depression.

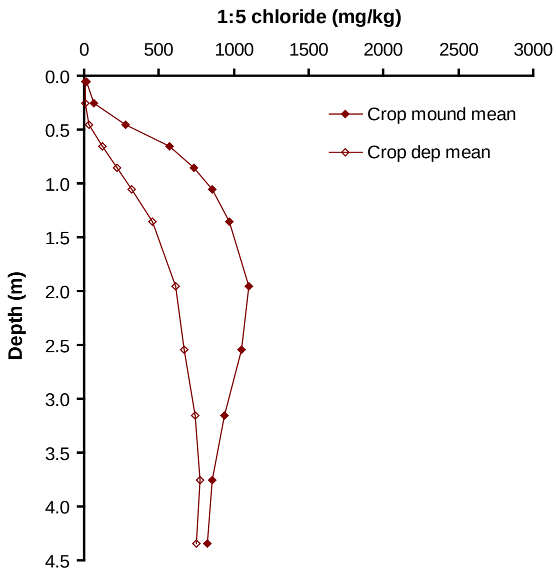


Figure 39 Example chloride data for a deep soil core, Moonie
Source: Silburn *et al*. (2011).

Figure 40 illustrates variations in salt store in a Cretaceous mudstone in the region. Generally there is greater variability within rock materials than soils.

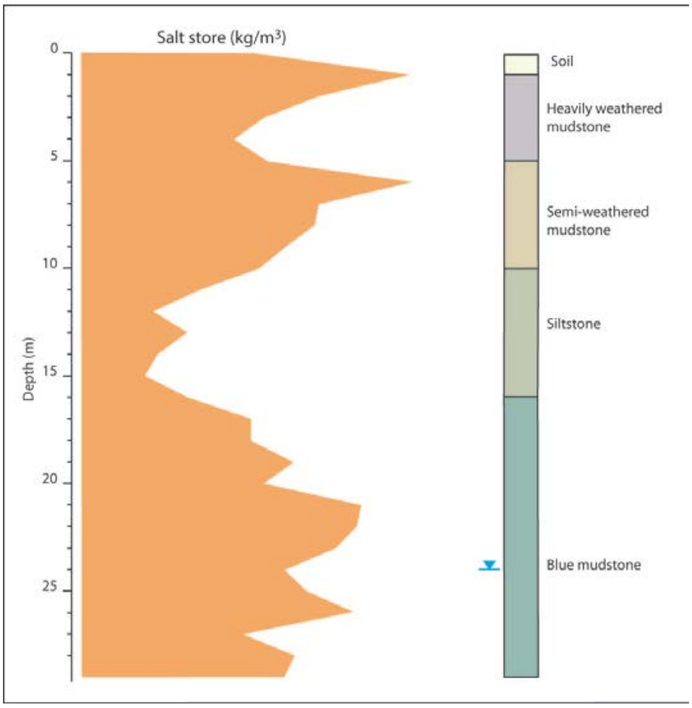


Figure 40 Salt store with depth for a Cretaceous mudstone
Source: Power *et al*. (2007).

4.2. Assessing Salinity Stage

The Salinity Stage component identifies the current expression of salinity which has resulted from all the historic land use and management practices. The key attributes relevant to Salinity Stage are in Table 11.

Table 11 Attributes relevant to Salinity Stage

Attribute	Comment	Measurements
Historic land use	Affects historic deep drainage/recharge.	When cleared, cropped, crop types
Time since clearing	In absence of more detailed land use records, this gives an estimate of the time over which increased deep drainage has been occurring.	When cleared
Water added since clearing	Reduces the available unsaturated zone; calculated or measured; need information on land use and climate since clearing to calculate this attribute.	Unsaturated zone moisture content of native veg; modelled deep drainage
Groundwater trends	Indicator of saturated zone dynamics in relation to historic land use.	Water level
Existing salt expressions	Indicator of historical recharge/discharge—their presence indicates the “bucket is full”.	Location, extent, trend of salt sites
Catchment salt export/import ratio (E/I)	Change over time reflects complex landscape processes in a simple manner (most inland catchments are accumulating salt so E/I <1).	Catchment salt input and losses
Soil salinity	Can be used to infer deep drainage e.g. chloride balance method	Soil chloride

The history of a site is reflected most significantly in the available porosity or starting water content of the unsaturated zone—or to use the bucket model introduced in Section 2.5, how full is the bucket as a result of previous land management activities? Traditionally, little effort has been invested in answering this question. Whether undertaking simple calculations or using a conceptual mass balance model (e.g. BC2C) it is imperative to have an understanding of this factor. The direct way of establishing the starting water content (and associated attributes such as porosity) is via investigation of the regolith, either coupled with soil survey activities or specific, targeted investigations. The minimum depth of investigation should be the depth to bedrock in hillslope lands and alluvia <30 m deep, noting the presence of any zones of reduced permeability. Depending on the properties of the bedrock or alluvia, for example, if it is highly porous, investigations may need to extend beyond 30 m.

Salinity stage may be inferred via a number of methods. Statistics such as catchment salt export/import ratios (E/I) are useful, but are an after-the-fact or lag indicator, as is the presence of salt expression sites (investigated by Biggs and Power 2003), groundwater trends and other such indicators (Searle *et al*. 2007). These indicators tell you that an area is at an advanced stage, i.e. the bucket is full or nearly full. An earlier indicator of hydrologic change is a decrease in soil profile chloride content in areas cleared for pasture or cropping (Silburn *et al*. 2011, Tolmie *et al*. 2011). A more accurate method involves derivation of land use history—when did initial land use change (clearing) occur? Deep drainage calculations from various sources (e.g. chloride balance and crop growth/water balance models) can then be applied to knowledge of the unsaturated zone to produce a more predictive estimate of the Salinity Stage. This method still has a degree of uncertainty and should be validated against field measurements.

It is worth noting that soil/water chemistry interactions are not included in the concept of Stage due to the assumption of this irrigation is occurring in greenfield developments. While soil chemistry does change over time, there is an implicit assumption that the relevant properties for assessing soil/water interactions will be determined from new soil sampling undertaken in assessing the irrigation suitability.

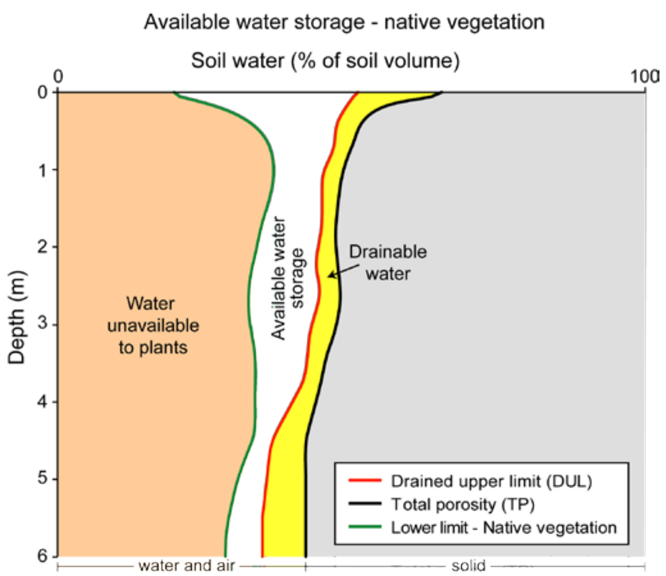
Using the example from the previous Section, the importance of salinity stage (water added since clearing) can be illustrated Table 12 by considering the impact of different quantities of added water (AW_n) .

Table 12 Time to fill example calculations for Salinity Stage

Unsaturated zone thickness (m)	**SC_I (%)**	**P_S (mm)**	**AW_n (mm)**	**Avail. Storage (mm)**		**Native veg. deep drainage (mm/yr)**	**Time to fill (years)**	**Irrigation deep drainage (mm/yr)**	**Time to fill (years)**
20	10	2000	50	1950		0.5	**3900**	30	**65**
20	10	2000	500	1500		0.5	**3000**	30	**50**
Biophysical Hazard			*Stage*					*Management*	*RISK*

Initial storage capacity (SC_I) = Drained upper limit (DUL) – starting water content for native vegetation (SW_{nv})
Available storage = (D x SC_I%) – AW_n
where D = unsaturated zone thickness in mm and AW_n = water added (mm) in *n* years since clearing

Figure 41 provides an example of how the addition of “new” water in the unsaturated zone fills the available water storage in the soil.



Definitions

DUL: the amount of water the soil is able to hold after drainage

TP: space in soil able to be filled with water and air

CLL: extent to which plant can extract water from a soil

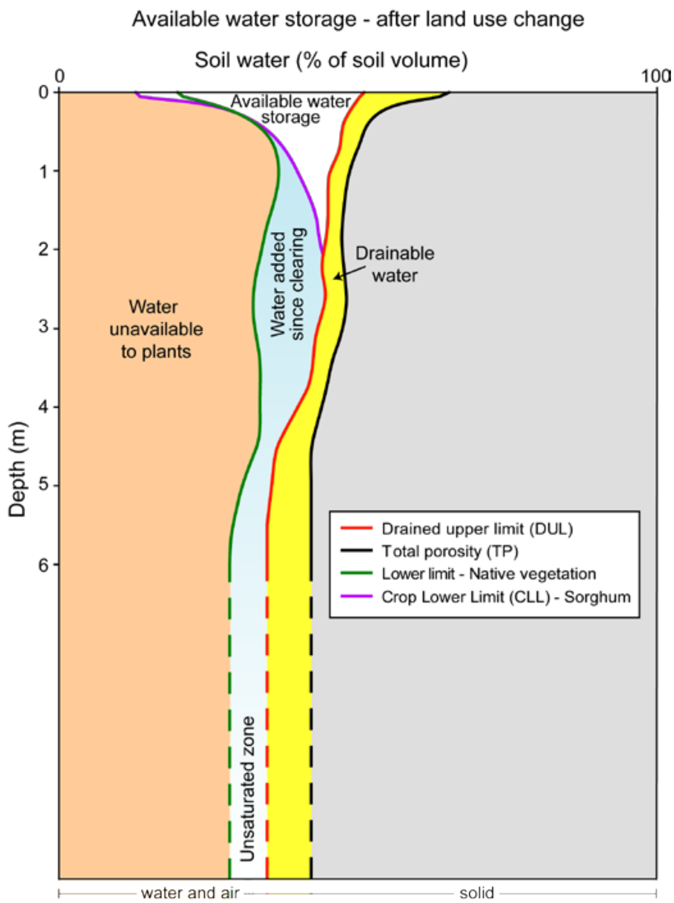


Figure 41 Soil water content under native vegetation and after land use change
Note: Based on data from an irrigated site at Dalby.

4.3. Assessing Current Management Influence

In any catchment there are many different land uses, which in combination with soil, landform and climate factors drive the water balance (and therefore deep drainage). In the case of paddock scale assessment, there is usually only a single land use—in this case irrigation. Deep drainage associated with irrigation is determined as much by application method/frequency as biophysical factors.

In any irrigation system, achieving an appropriate water balance (regardless of the salt issues) is important in order to avoid waterlogging and optimise irrigation efficiency. Much research and development has occurred in the last ten years in the technical aspects of irrigation methods and how best to maximise efficiency. In the case of CSG water for irrigation, drip and spray application methods are more likely to be used than conventional furrow irrigation. This is primarily because these methods are more adaptable to different landscapes and crop types, and allow for easier monitoring and control of water supply.

The key attributes required for designing and maintaining efficient irrigation practices are:

- climatic variables;
- water quality;
- soil (regolith) properties;
- crop water use; and
- irrigation management (e.g. irrigation scheduling, application efficiency and rate).

The key attributes relevant to Current Management Influence are given in Table 13. These attributes assist in determination of crop demand in time scales ranging from daily to annual. They are also essential for determining likelihood and magnitude of deep drainage events. The data can be used for both operational and strategic purposes. Relevant soil and water chemistry data is essential for determining salinity risk from CSG water irrigation.

Table 13 Attributes relevant to Current Management Influence

Attribute	Comment	Measurements
Irrigation water quantity	Directly influences frequency and magnitude of deep drainage events and thus the time to fill.	Application rate
Irrigation water quality	Affects sodicity/salinity relations and associated attributes (e.g. infiltration, permeability, frequency and magnitude of deep drainage events).	Ionic composition of water
Irrigation method/regime	Interacts with climate and soil to influence frequency of saturation and deep drainage events.	Application method, timing, rate
Soil properties	Influences crop growth, irrigation method, sodicity/salinity relations, hydraulic properties.	EC, ESP, PSA, moisture characteristic
Effective rooting depth	Affects water storage capacity and water uptake profile.	Soil EC, pH, ESP, depth, plant tolerance
Crop type and crop lower limit	Affects consumptive water use.	Species, variety, water uptake pattern
Climate	Interacts with irrigation method/regime, relationship between rainfall and evaporation.	Rainfall, evapotranspiration
Flooding	Affects land use options and water balance.	Inundation period

Climate data such as evaporation and temperature can easily be collected on a daily basis using “off-the-shelf” climate stations. The data provides input to water balance/crop models and

calculations. The recommended method for calculation of potential evapotranspiration is the Penman-Monteith equation (Allen *et al*. 1998). Alternatively, soil water balance models calculate potential and actual evapotranspiration. Climate files for models are available from tools such as the Data Drill[13]. Collection of rainfall samples on an event and/or monthly basis can also provide real data for salt balance calculations. However it is more important to measure the irrigation water salinity regularly as it is likely to be higher than rainfall salinity.

An example of the way in which current management (expressed as deep drainage) affects the time to fill the unsaturated zone is given in Table 14.

Table 14 Time to fill example calculations for Current Management Influence

Unsaturated zone thickness (m)	SC_I (%)	P_S (mm)	AW_n (mm)	Avail. Storage (mm)		'Efficient' irrigation deep drainage (mm/yr)	Time to fill (years)	'Inefficient' irrigation deep drainage (mm/yr)	Time to fill (years)
20	10	2000	100	1900		30	**63**	100	**19**
Biophysical Hazard			*Stage*			*Management*	*RISK*	*Management*	*RISK*

Initial storage capacity (SC_I) = Drained upper limit (DUL) – starting water content for native vegetation (SW_{nv})
Available storage = (D x SC_I%) – AW_n
where D = unsaturated zone thickness in mm and AW_n = water added (mm) in *n* years since clearing

Understanding the water use pattern (e.g. daily, weekly, seasonally) of the irrigated plants is critical to ensuring that neither too much, nor too little water is applied. Various approaches to irrigation scheduling exist, e.g. water on demand. Crop water use factors for many commonly grown crops are widely published and incorporated in many crop models (e.g. PERFECT, HowLeaky, APSIM[14]). While the theoretical water use pattern of a crop may be known, the actual daily use will be driven by local climatic, management, system design and other factors. Measurement of the necessary attributes is therefore essential to calculating or modelling the plant water use. Use of soil moisture induction probes provides a means to continuously monitor soil moisture status in real time, and any variation in soil moisture status with depth. It is important to recognise that soil moisture probes only provide information at a point source. Lateral heterogeneity in soil type, slope, etc., may produce significant variation in soil moisture statues, even within the same irrigation management unit. In paddocks with significant soil variability, careful consideration must be given to the likelihood of over-watering or under-watering certain soil types. Ensuring the profile is never irrigated to saturation is a simple way of decreasing the likelihood of excessive deep drainage.

Water balance modelling and field research by Yee Yet and Silburn (2003), Tolmie *et al*. (2003) and others tells us that deep drainage generally increases depending on the plant cover from woodland, native or buffel pasture, opportunity cropping, summer cropping, winter cropping then irrigated summer cropping (Figure 5).

Water use and deep drainage for a dry decade can be substantially different from that during a wet decade, showing the importance of climatic data. Figure 42 illustrates this, showing large time periods for which no deep drainage occurs. The implication of this is that while the water supply of CSG water may be engineered to be continuous the rate of rainfall is not. Any irrigation scheme must be able to cope with both extended dry and extended wet periods.

[13] http://www.longpaddock.qld.gov.au/silo/datadrill/index.php
[14] Refer to Appendix 5 for more information on crop models.

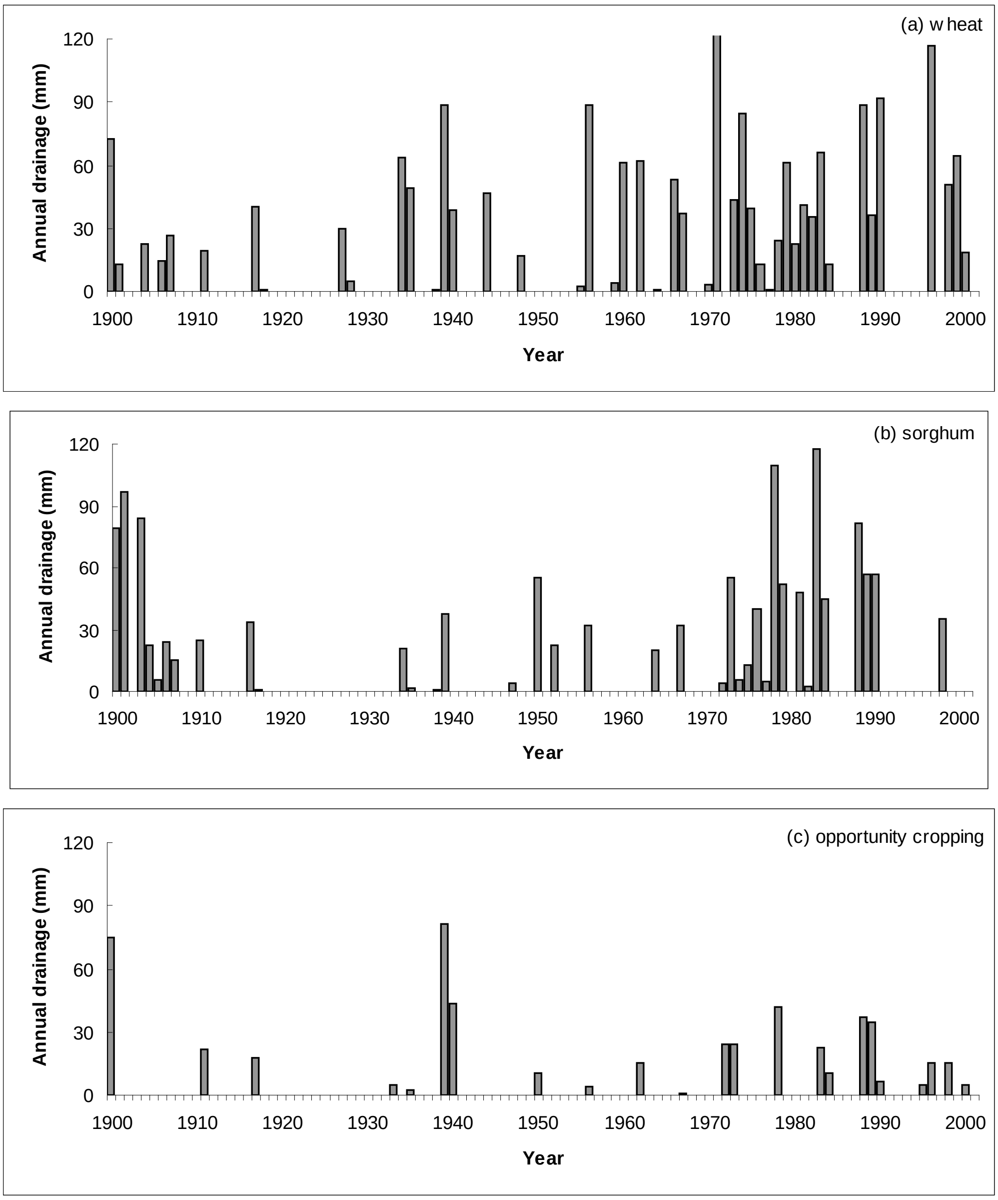


Figure 42 Modelled annual deep drainage at Dalby for three land uses
Source: Yee Yet and Silburn (2003).

4.4. Assessing Post-Irrigation Land Use

In practice, CSG water for irrigation will only be available for a relatively short time. Therefore, the risk associated with the change back to a non-irrigated regime must be investigated. For instance, if a salinity/sodicity equilibrium is achieved in the soil after 10–20 years of irrigation with coal seam gas water, what impacts will occur when the system reverts to a rainfall only regime, or to irrigation use with better quality water?

The Post-Irrigation Land Use may be considered as a "future stage". It plays a very important role in determining the irrigation management regime and strategy for using the unsaturated zone to dispose of water and salt. Given the relative scarcity of alternative water sources, the most probable land uses following CSG water irrigation will be dryland forestry, dryland cropping or grazing. Under *good* management these result in less deep drainage than irrigation. More capacity will be available in the unsaturated zone if the post-irrigation land use is specified (e.g. by

covenant or regulation) to be a long-term deep rooted crop such as a tree crop that will use some of the added water, and effectively start to reduce or reverse the rate of recharge.

Where the land use following cessation of irrigation with CSG water is mixed farming, the land use with the highest deep drainage should be used to model salinity risk. Where the future land use is uncertain, the highest deep drainage land use (most likely irrigated grain cropping) should be used to model salinity risk. Table 15 illustrates the influence that Post-Irrigation Land Use has on the time to fill the unsaturated zone.

Table 15 Example calculations for Post-Irrigation Land Use

Unsaturated zone thickness (m)	**Avail. Storage (mm)**	**Post-irrigation avail. storage (mm)**		**Dryland trees deep drainage (mm/yr)**	**Time to fill (years)**	**Long-fallow wheat deep drainage (mm/yr)**	**Time to fill (years)**
20	1900	800		0.5	**1600**	15	**53**
Hazard	*Stage*	*Post-Irrigation Stage*		*Post-Irrigation*	*RISK*	*Post-Irrigation*	*RISK*

Initial storage capacity (SC_I) = Drained upper limit (DUL) – starting water content for native vegetation (SW_{nv})
Available storage = (D x SC_I%) – AW_n
where D = unsaturated zone thickness in mm and AW_n = water added (mm) in *n* years since clearing

4.5. Assessing Overall Salinity Risk

Assuming all necessary components and attributes have been assessed and necessary ones quantified, the data may be integrated to assess overall salinity risk. This may occur in a spatial or non-spatial manner and should be adjusted according to the specific salinity risk being investigated, i.e. site-specific soil/water risk versus landscape risk. Both types of risk must be clearly documented during the process of assessing the overall risk. Traditional approaches such as cumulative index in spatial assessments (e.g. salinity hazard map) are not always necessary to assess the irrigation salinity risk. First and foremost is the assessment of the capacity of the unsaturated zone to accept the proposed deep drainage. This, in conjunction with considerations of soil/water chemistry, is the core of assessing risk, and is carried out most effectively at the point scale. Only after this is done should consideration be given to spatial assessment of risk. Once an overall risk has been determined (within associated error bounds), this, or earlier attribute data, can be used in an iterative feedback process to adjust the management regime to reduce the risk (Figure 43).

Section 1.5 of this report outlines some regulatory context for CSG water irrigation, in particular the requirement to assess the irrigation water impact and land use over a 100 year timeframe from commencement of irrigation. As discussed in Section 4.4, it is essential to incorporate an assessment of post-irrigation land use. Given these requirements, it is possible to back-calculate the “freeboard” required in the unsaturated zone, and therefore the available water storage capacity, and thus how much deep drainage may be added as a result of CSG irrigation.

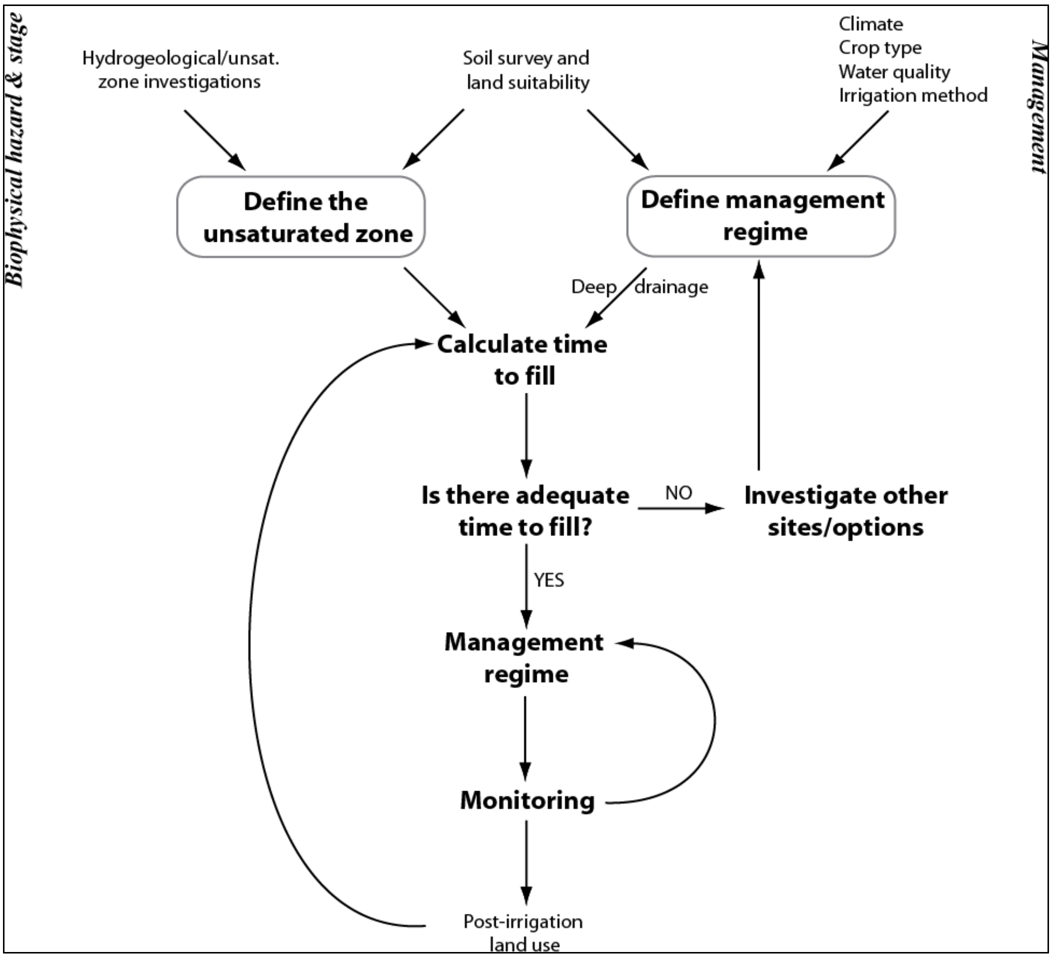


Figure 43 Salinity risk assessment process

Using the analogy of the unsaturated zone as a bucket (see Figure 5 and Section 2.5.1), this back-calculation process starts with a small amount of water in the bucket (under native vegetation). The post-clearing/pre-irrigation added water content is subtracted from the available storage capacity. The amount of unsaturated zone equivalent to 100 years of deep drainage (for a specified land use/climate) may be calculated, and is also subtracted from the available storage, leaving the volume of water that may be added to the system[15]. The rate at which water can be added may also then be calculated (based on many variables such as water supply projections, crop water use and soil properties).

This method of back-calculation is the preferred method for assessing salinity risk from CSG water application as it takes into account long-term risk and applies a precautionary approach. It also meets the objectives of the Basin Salinity Management Strategy and satisfies the requirement the *Water Act 2007* (*Cwlth*) not to cause a significant change in salinity.

[15] This simulates the worst-case scenario. While these calculations are an over-simplification of the complex processes that may occur in the unsaturated zone (for example drainage out of the regolith [leakage from the bottom of the bucket], and post-irrigation crop water use in excess of rainfall [extractions out of the bucket]), in reality, in the majority of landscapes in the QMDB, the rate of such losses is much less than the rate of input. Therefore these calculations give a good idea of the volume of water that may be added to the system.

5. Landscape salinity hazards in the project area

Salinity risk is usually assessed at one of two scales: landscape level or site specific. It is at the landscape level that salinity impacts on catchment assets such as stream water quality, biodiversity and aquatic ecosystem health are assessed. At the site specific scale, salinity impact assessment is mainly focused on loss of agricultural production, soil salinisation, waterlogging and deterioration of groundwater quality. Broad landscape issues are often assessed independently of site specific impacts, but there is a connection between the two. Effectively managing salinity risk at the site specific scale of individual irrigation developments—by applying the salinity risk assessment framework described in Section 4—is a key mechanism for managing landscape level salinity risk.

As discussed earlier, the biophysical characteristics of an area are a major contributor to salinity risk. There are a number of ways to represent the biophysical hazard of an area—one is to consider landforms, while another is to consider landscapes or hydrogeological units (there are many ways in which these can be spatially represented). Sections 5.1 and 5.2 discuss the dominant landforms and geomorphic units of the project area. In the context of this report, landforms are broader units consisting simply of alluvial (flat) areas and hillslope areas, while geomorphic units provide a better representation of biophysical hazard as more attributes (e.g. geology) are involved. Both of these however are regional scale simplifications and not of sufficient detail to be used in a comprehensive risk assessment.

5.1. Broad landforms of the project area

A simplistic view of landforms is presented in Section 4, with Figure 38 showing the location of alluvial and non-alluvial areas in the project area. However, to only view the project area in terms of these two broad landforms is over-simplifying a very complex natural system. Dividing the alluvial landform into “thick” and “thin” alluvia and isolating areas of texture contrast soils can assist in illustrating the broad scale variability in the region, and gives an improved representation of some aspects of biophysical hazard.

Water and salt movement processes within landform elements are summarised in Figure 44. In alluvial landforms, the primary irrigation water/salt paths are evapotranspiration (water only) and deep drainage. In hillslope landforms, runoff and lateral flow become important. Thus an understanding of broad landform attributes improves understanding of water/salt movement processes occurring at the landform level.

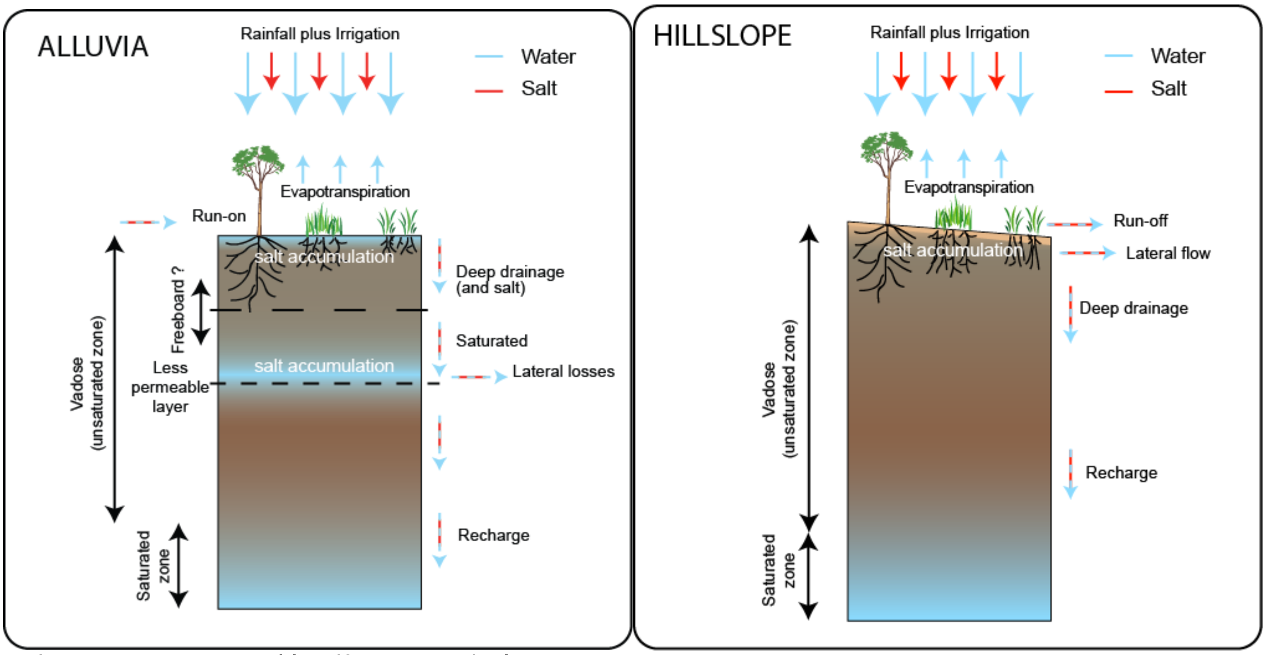


Figure 44 Conceptual landform water/salt movement

Within the project area there is insufficient detailed soil/regolith data to determine with certainty which units occur in some landforms, and nearly all map units are heterogeneous. As such, Figure 45 is an *indicative* map only of the broad landforms of the project area which are described as follows:

- Thin alluvia – alluvia where there is a zone of less permeable material at less than 10 metres below the surface. This characteristic broadly creates a limited unsaturated zone for irrigation deep drainage and salt storage to occupy.
- Thick alluvia – alluvia where less permeable material is not found in the top 10 metres of the soil profile. Thus there are fewer restrictions in the unsaturated zone to water and salt storage and drainage under irrigation.
- Texture-contrast – map units dominated by texture contrast soils on hillslopes.
- Hillslope – map units that are not dominated by texture contrast soils on hillslopes.

Due to the variability within landforms and land resource mapping units, the data cannot be interpreted down to the paddock scale.

5.2. Broad geomorphic units of the project area

An alternative way to represent biophysical hazard is via functional hydrogeological units or similar. Previous approaches have used groundwater flow systems (GFS) (Coram 1998) and hydrogeological units (DNR 2000). These were based on broad scale (and limited) data with many assumptions. The original GFS layer for the QMDB was derived using 1:250 000 scale geological mapping. This may be simplified even further into five units (termed geomorphic units in this report) within the project area. As with the use of 'landforms' in Section 5.1, these are not definitive map units to be used in a risk assessment but rather a way in which to illustrate the variation in geology/landscapes within the region. Recent work (Biggs *et al*. in prep) has highlighted that historical approaches of using either land resource mapping or geological mapping as the basis for hydrogeological units in the region can be flawed and it is essential that more detailed assessment is undertaken at the local scale when conducting a salinity risk assessment.

There are more than 130 different land systems/land resource area (LRA) units mapped within the project area. These units have been amalgamated to produce the following five broad simplified geomorphic units:

- Alluvia;
- Basalts;
- Quartzose sandstones;
- Unweathered to moderately weathered non-quartzose sedimentary rock; and
- Moderately to strongly weathered non-quartzose sedimentary rock.

These geomorphic units were assigned because of their inherent characteristics that cause them to behave differently and therefore predispose them to varying levels of salinity risk. The nature of the landscape will affect the way the salinity risk assessment framework is applied at a specific location. For example, the focus of an assessment will differ when examining alluvia as opposed to quartzose sandstones.

Figure 46 illustrates the distribution of these five broad units over the project area. Due to the variability within geomorphic units and their constituent land resource mapping units, the characteristics of specific sites should be assessed *locally* to determine their suitability for proposed land uses rather than relying on broad scale mapping and descriptions.

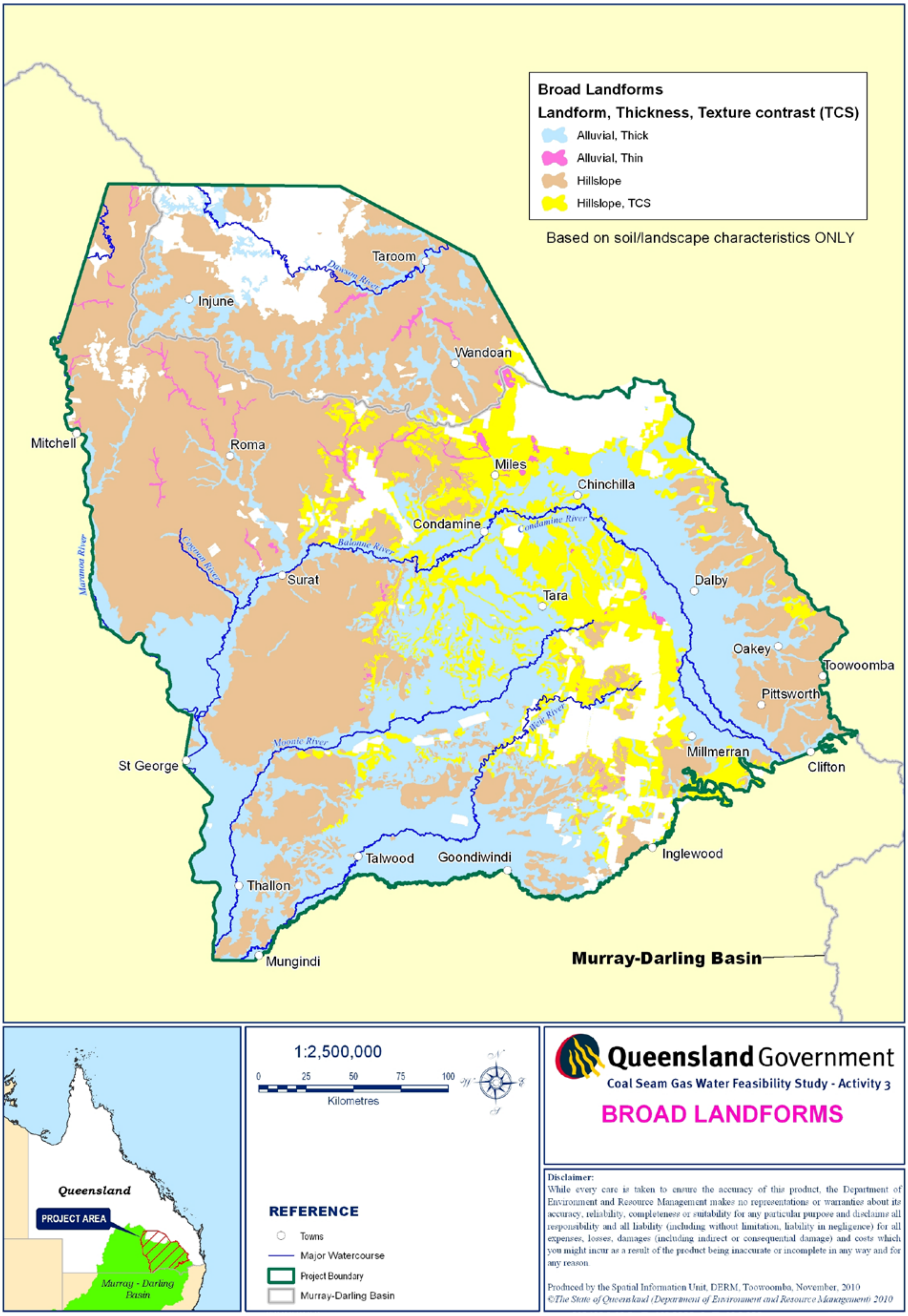


Figure 45 Indicative broad landforms of the project area

Note: White areas are state land or areas not suitable for agricultural uses.

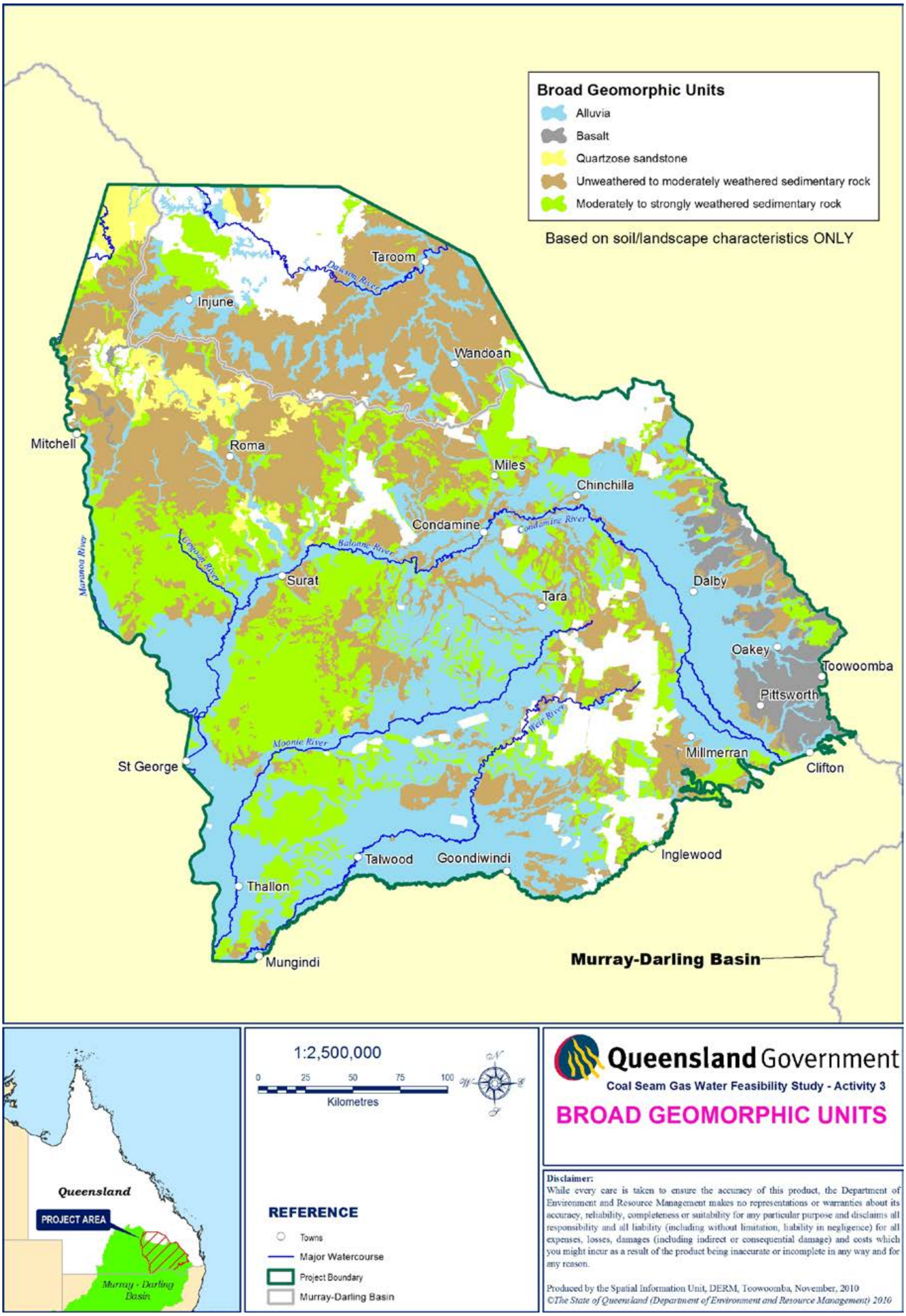


Figure 46 Broad geomorphic units of the project area

Note: White areas are state land or areas not suitable for agricultural uses.

5.2.1. Alluvia

The alluvial landscapes of the project area are diverse. They include the clay soil floodplains in the Condamine, Border Rivers, Moonie and Balonne catchments which have been extensively developed for both dryland and irrigation cropping as well as older alluvial plains where grazing is more common. CSG exploration activities are now extending out into alluvial landscapes. Many of the alluvial plains are characterised by clay dominant soils such as black and grey Vertosols, although hardsetting/surface crusting soils such as Sodosols and sandy soils such as Tenosols are found on some river levees, terraces and channels.

The Condamine floodplains extend over approximately 850 000 ha, the Border Rivers floodplains cover approximately 180 000 ha, and the Balonne-Culgoa floodplain covers approximately 357 000 ha. In areas such as the Condamine floodplains east of Macalister, groundwater tables have been depleted by extraction of groundwater for irrigation since the 1960s. West of Dalby, the groundwater becomes increasingly saline. Irrigation in this area of the Condamine floodplain also needs to take into account the shallower nature of the alluvium compared to areas upstream. In the lower Macintyre and Weir River catchments west of Goondiwindi, the alluvial groundwater is relatively shallow and saline. In some irrigated areas in the Border Rivers there has been a general rising trend in groundwater (up to 0.5 m/yr) over the last 30 years.

While landscape salinity hazard in the alluvia is lower than for hillslope lands due to the lack of slope, other factors are relevant, such as high salt stores and shallow saline groundwater in older alluvia. The complex lithology and stratigraphy of the alluvium means that perched watertables may occur at shallow depths, despite the large overall thickness of the alluvium. On the lower Balonne floodplain, groundwater is often deeper and salinity hazard is generally less than in the lower Macintyre and Weir River catchments because of the greater depth to bedrock.

Local hydrogeological investigations are necessary to determine the lithology and stratigraphy of alluvium where irrigation is proposed. The transition from deeper to shallow alluvium may occur over short distances so once again hydrogeological investigations are needed to determine the nature of the alluvium, its depth and groundwater quality and disposition in the alluvium.

Waterlogging is a potential risk in years of higher rainfall, particularly during extended wet phases when rainfall exceeds evapotranspiration. Flooding is of course an issue on alluvial areas and in some landscapes it can lead to substantial and rapid groundwater recharge. In addition to salinity risk, soil erosion is a major risk where infrastructure such as roads, pipelines and drains divert and concentrate overland flow or where exposed lighter, sandy soils are prone to wind erosion. While most of the alluvia are suitable for irrigation, there are areas with severe limitations to irrigation due to factors such as the thin unsaturated zone, erosion potential and flooding.

5.2.2. Basalts

The basalt landscapes are diverse, ranging from the high rainfall basaltic plateaus and ranges in the east to isolated ridges in the north-west. Deeper clay soils (Vertosols and Ferrosols) are common in the east, while shallow, stony Dermosols are more common in the isolated western units. Both dryland and irrigated cropping are common land uses on basalt landscapes in the Condamine catchment. Significant basalt areas are conserved in the Bunya Mountains and Main Range National Parks. In western areas the land use is grazing, forestry and nature conservation. Due primarily to the depth of basalt overlying coal bearing sedimentary material, economic considerations have meant that to date there has been little CSG activity in this landscape, although potentially exploitable coal deposits do underlie much of this material.

Most recorded salinity sites in the Condamine catchment are associated with basalt/sandstone interfaces (Searle *et al.* 2007) where recharge through permeable basalt discharges at the interface with underlying lower permeability sandstones (Walloon Coal Measure and Marburg Sandstones). Experience from investigating salinity occurrences in the basaltic uplands of the

Condamine catchment indicates that salinity outbreaks take 30–60 years to develop after land use change (clearing and conversion to cropping); therefore any proposals for irrigation and post-irrigation land use in basalt landscapes may trigger surface salinity occurrences within 100 years.

Any assessment of proposals for irrigation in basaltic landscapes must consider the likelihood of drainage below the root zone causing salinity downslope, including the investigation of salinity occurrences in the vicinity of the proposed irrigation. Existing salinity expressions downslope of a proposed irrigation site would be an indication that the site may not be suitable for irrigation and that the unsaturated zone is already "full". Any proposal for irrigation with CSG water in this landscape will require a detailed assessment because of salinity and other environmental risks such as erosion.

5.2.3. Quartzose sandstones

Dissected sandstone plateaux, hills with rocky crests and steep to vertical upper slopes, and deep incised valleys with narrow alluvial drainage floor areas opening out to rolling and undulating terrain are features of the quartzose sandstone landscapes. Good examples of these features are evident in the Carnarvon Range to the north of Injune and in the Lynd and Expedition Ranges north of Taroom. Soils are mainly sandy, with deep sands or sandy-surfaced texture contrast soils on lower sloping areas. Mixed layered eucalypt forests and woodlands are the dominant vegetation in upland areas while cypress pine forests are widespread on lower slopes and rolling terrain. The quartzose sandstones are important intake beds for the Great Artesian Basin.

Land use is predominantly grazing, forestry and conservation estate so that a high percent of native forests and woodlands remain intact. There is very little cropping in this area because of the various limitations of the soils and landforms. Santos and Origin Energy have domestic gas fields in the quartzose sandstone landscape unit.

Texture contrast soils often have limited deep drainage through the subsoil matrix, but bypass flow and lateral flow are common. Due to the sandy nature and low plant available water capacity of the soils in this unit, more frequent irrigation is required than on cracking clay soils. This in turn increases the risk of deep drainage and lateral flow. Stratigraphic and catena forms of salinity may also occur in quartzose sandstone landscapes.

Previous land uses in the quartzose sandstones have not increased salinity significantly because over 80% of the deep rooted vegetation cover has been retained (DERM 2009). There is limited potential for the development of irrigation in this landscape due to the severe soil limitations.

5.2.4. Unweathered to moderately weathered non-quartzose sedimentary rock

The topography of the brigalow uplands and open downs grasslands varies from rolling downs through undulating rises to steep low hills with some lateritic scarps. These areas are mainly used for grazing and dryland cropping with some forestry. Presently Santos, Origin Energy, Queensland Gas Company and Arrow Energy are exploring for gas and producing CSG for the domestic market in these areas.

The soils in this landscape have formed from the weathering and erosion of less resistant sediments such as siltstones, mudstones and fine-grained sandstones. The soils are highly variable and include clay dominated soils (Vertosols), texture contrast soils (Sodosols) and loamy soils (Kandosols). Salt levels are generally high in the subsoils.

Common limitations of soils in these landscapes are surface crusting, impaired drainage, waterlogging, saline/acidic subsoils and erosion potential. Skeletal soils often occur on scarps and outcrops. Potential landscape forms of salinity include catena and stratigraphic forms. Waterlogging and soil salinisation due to rising shallow watertables and impaired drainage may result in lateral drainage and accelerated runoff.

The salinity risk assessment for the Queensland Murray-Darling Committee region (Biggs *et al*. 2010) shows that salinity risk has increased in this landscape following clearing. Development of small bare, scalded areas is common in footslopes and depressions. While there are more opportunities for irrigation with CSG water in this landscape unit due to the proximity to CSG water supplies and the location of some areas with good agricultural soil, detailed site investigations are required for each proposal to irrigate using CSG water.

5.2.5. Moderately to strongly weathered non-quartzose sedimentary rock

This landscape features sandstone plateaux and lateritic scarps, low hills and jump ups, and undulating plains. Eucalypt forests dominated by ironbarks, spotted gum and bloodwoods occur on the uplands with poplar box and cypress pine woodlands on the undulating plains. Dominant soils include skeletal gravelly soils and texture contrast soils (Sodosols) on the plateaus, with sandy loams (Rudosols), loamy to sandy surfaced soils overlying clay subsoils (Chromosols) and siliceous sands (Tenosols) on the undulating plains. The Herries and Thomby Ranges and the Barakula area north of Chinchilla show representative features of this landscape. Red Kandosols supporting mulga communities mainly occur to the west and south of Surat.

The main land uses are grazing, dryland cropping and forestry. The four major CSG companies are involved in CSG production and exploration in this landscape. On-ground investigation and monitoring of salinity occurrences and shallow groundwater tables in the Goondoola Basin in the Moonie Catchment and in the lower Macintyre and Weir River catchments (Biggs *et al*. 2010) together with airborne geophysical investigations in the lower Balonne catchment (Wilkinson and Chamberlain 2004) give a good understanding of salinity processes and risk in these landscapes. Rising shallow saline groundwater tables, which can be acidic, pose a major risk. This risk is increased by irrigation and dryland cropping.

An example of dryland salinity in this landscape is Goondoola Basin. Significant investment in site investigations, groundwater monitoring and salinity management strategies (e.g. converting cropping land to pasture and planting salt bush) has led to a decline in the extent of the salt affected area which had resulted from earlier clearing and winter cropping. This illustrates the need for detailed investigations when considering where to use CSG water for irrigation.

6. Salinity risk assessment implementation

At the broad level, salinity risk exists in all landscapes, and particularly with respect to irrigation. Given the lack of existing data in the majority of the CSG development areas, it can be safely said that for CSG water irrigation developments, site specific investigations recommended in this report should be undertaken**.**

The outcome of site specific assessment will determine if:
1. The risk of salinity expression as a result of the proposed CSG water irrigation development is minimal and can be managed to not cause significant on-site or off-site impacts; or
2. The risk of salinity expression is significant and the site is therefore not suitable for irrigation.

Figure 47.summarises the generalised decision making process for irrigation projects using CSG water. If site specific assessment are conducted correctly and irrigation development is managed appropriately, ensuring maintenance of an acceptable degree of unsaturation in the unsaturated zone from the start of irrigation to 100 years in the future, then the likelihood of cumulative landscape impact in relation to saline groundwater discharge to stream is generally small.

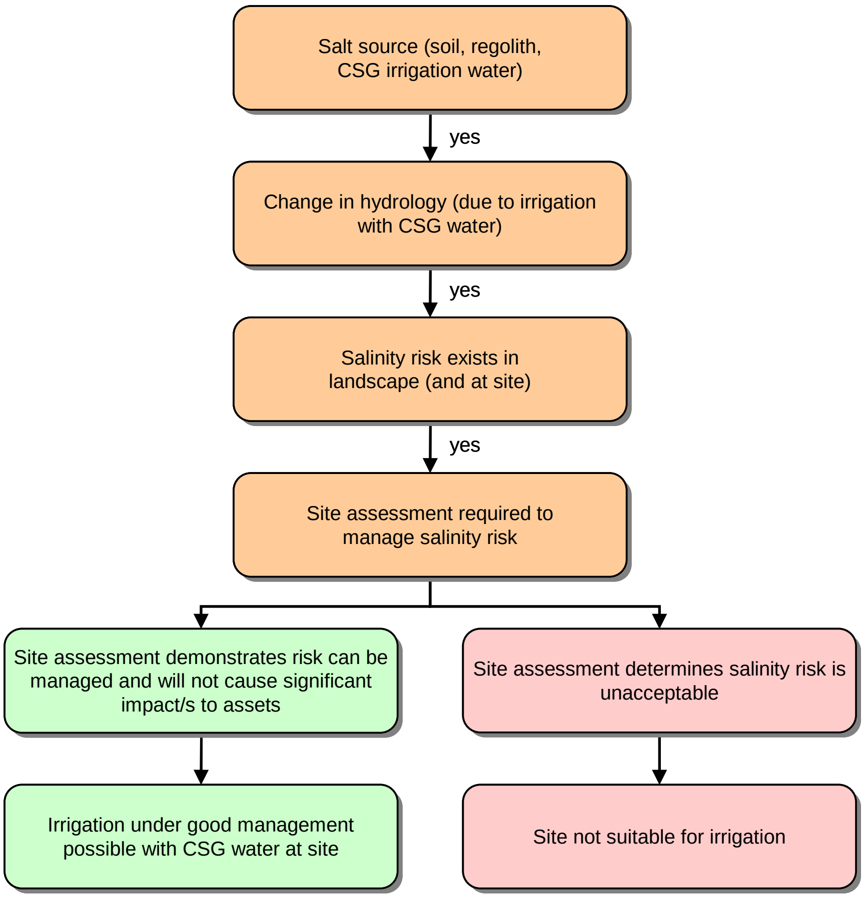


Figure 47 Generalised decision-making process for irrigation projects using CSG water

It is worth noting that even if all site-based assessments lead to 'perfect' irrigation systems with minimal site soil/water and landscape salinity risk, this does not fully negate some catchment scale salinity issues. For instance, broad-scale reforestation or afforestation in catchments can reduce runoff, which in certain catchments could lead to an increase in stream salinity.

The salinity risk assessment framework described in the preceding sections was developed using a significant amount of expert knowledge. It is essential that expert knowledge is applied throughout a salinity risk assessment as there is a high level of expertise required to produce valid results. The application of expert knowledge and interpretations at every stage of the process is necessary to ensure that the most appropriate data and tools are selected and applied effectively to produce the best quality assessment. This expert knowledge is also critical in the final review of the outputs to ensure that the results are valid and can be used as a basis for further interpretation, analysis and benchmarking.

Establishing ‘safe’ conditions for irrigation

The need for a site-specific assessment does not automatically mean that large hydrogeological, soil and water data collection programs with associated intensive modelling are required to assess salinity risk for all sites. Both theoretical models and real data indicate that under certain circumstances, various combinations of soil and water chemistry can be deemed to have very low risk of adverse impacts. Similarly, a certain combination of unsaturated zone properties and management practices can lead to a low and acceptable level of risk. The challenge is to more clearly define these circumstances, both non-spatially and spatially. The level of data required to do so does not currently exist, but given the current level of investment in science by the industry, it may be possible to do so in the near future.

For example, in the case of soil/water salinity/sodicity interactions, there is considerable industry-funded research underway. Some value may also be gained though from analysis of existing data. For instance, Figure 48 illustrates the relationship between EC and SAR in groundwater used for irrigation in the St George and Condamine alluvial areas. The Condamine ‘poor’ water and some of the St George water are known to cause soil sodicity/salinity problems. Further analysis of such data in the context of soil types could assist in more clearly defining water and soil types that are ‘safe’ from the perspective of soil degradation.

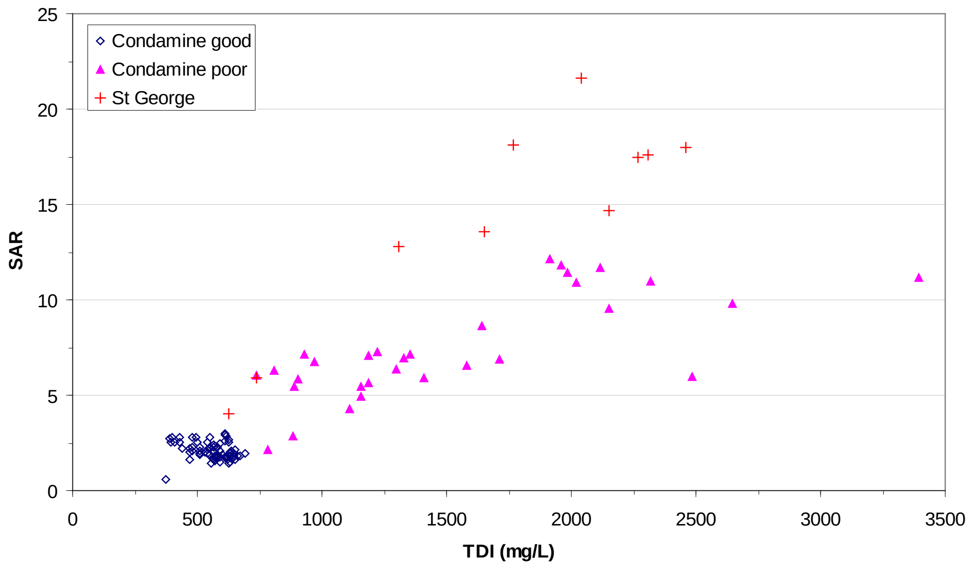


Figure 48 Relationship between salinity and sodicity of groundwater used for irrigation in the St George and Condamine alluvial areas

A similar approach may be applied to the question of maximum irrigation water salinity. CSG water irrigation will be transient— this irrigation water supply will be in the landscape for a defined period of time and then there is a post-irrigation land use. Two main scenarios exist—either conversion of pasture land to irrigation (greenfield sites) or conversion of existing dryland cropping land to

irrigation. In both instances, it is implicit that post-irrigation, the land will continue to be used to grow plants. In the case of dryland cropping land, it should be possible post-irrigation to continue to grow the same suite of dryland crops that were grown prior to irrigation. If this approach is taken, then the agronomic salinity thresholds for the least tolerant of those crops may be used as a starting point for defining a maximum soil salinity threshold for the irrigation area. In the case of pastures a similar approach may be taken, but the salinity tolerances of many pasture species are not as well defined, as yet.

The required size of the unsaturated zone in relation to deep drainage may also be calculated in a general sense with a number of assumptions (10% porosity in the case of Figure 49). While only a crude estimate, it illustrates the ease with which an approximation of risk may be generated using water balance model outputs and first principles. A combination of such methods with the approaches described above for soil/water salinity/sodicity interactions could lead to the development of a more robust definition of 'safe' conditions for irrigation.

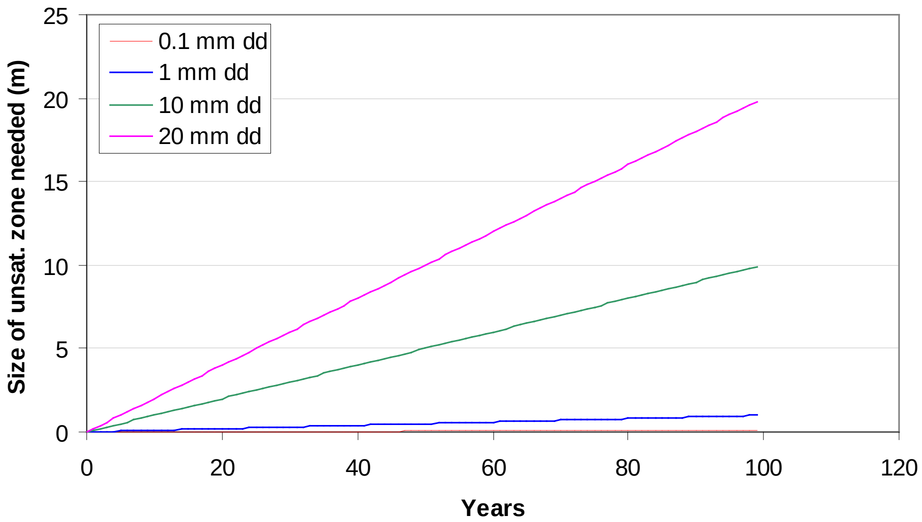


Figure 49 Required size of the unsaturated zone in relation to varying rates of deep drainage

6.1. Monitoring requirements

The establishment of new irrigation areas involves many assumptions and estimates regarding the water and salt balance as part of the initial design and planning phase. Effective monitoring is critical to adaptive management and fine tuning of irrigation systems and cropping practices. A well designed monitoring regime allows for an evaluation of the underlying risk assessment and management regime, as well as early identification of any escalation in risk. It should account for both the spatial and temporal scales of processes.

The data gathering process associated with the salinity risk assessment provides a comprehensive range of information that can be used as the foundation of a customised monitoring regime and for informing adaptive management.

A detailed monitoring regime and appropriate baseline data collection is essential to determining if an irrigation system is functioning as planned. If the monitoring regime provides evidence that the irrigation project is producing unexpected impacts, the irrigator is responsible for amending the management of the irrigation project to deal with these impacts. Monitoring results that would require adjustment of management practices may include, but are not limited to:

- results indicating that higher than expected levels of deep drainage are occurring;
- soil salinity or pH levels outside an expected range;

- waterlogging and perched watertables occurring/saline seeps occurring on footslopes; or
- crops showing signs of stress, retarded growth or less than expected yields.

Monitoring should not focus solely on symptoms, such as the identification of salinity scalds. The intent of a well managed monitoring system is to avoid impacts (expression of risk). Effort should therefore be focussed on indicators that identify an increase in risk before an impact occurs, rather than those that only measure an impact after the risk has been expressed. This will allow management practices to be amended to prevent the impact occurring. Indicators can be divided into two categories—current stage and forward looking (Grundy *et al*. 2007). Current stage indicators include extent of salinised land, groundwater depth and stream salinity. Forward looking indicators include chloride profiles and unsaturated zone moisture content.

When designing a monitoring program, it is important to define the intent. For example, monitoring to understand a landscape process may be very different to that required for regulatory reports. Distinction should be made between monitoring an indicator or surrogate versus a monitoring a primary attribute, and the implications for interpretation. In essence, every monitoring point should have an associated statement of purpose and rationale.

An optimum monitoring frequency is difficult to define. As a general rule of thumb, the more responsive the system is perceived to be, the more frequent the monitoring should be. Thus initial monitoring should always err on the side of higher frequency. This is easily achieved with tools such as data loggers. An example is groundwater monitoring. If a watertable fluctuates on a weekly or seasonal basis, but is only measured annually, then the monitoring regime is unlikely to identify significant changes or the time lag between recharge events and groundwater table responses. The first few years of monitoring can inform an assessment of the responsiveness of a system—if it is deemed to be non-responsive, then monitoring frequency can be reduced.

6.1.1. Establishing baseline values

The determination of baseline values is essential to the identification of change. In some instances, baseline values may be obtained from historic data, but given the sparseness of most natural resource data in the region, it is unlikely that sufficient data will exist for all proposed irrigation areas. Baseline data may be essential to the calculation or interpretation of other descriptive values, or it may be the value of interest in relation to establishing thresholds or trigger values. It is important to determine if a baseline value is likely to change or not. For instance, particle size of a soil is unlikely to change, thus ongoing monitoring of it is not necessary. By contrast, soil chloride is very dynamic, thus regular monitoring of it is necessary.

The establishment of natural variation within baseline values is also important. Many variables, in particular hydrologic ones, are driven by climate events. For instance, stream EC typically decreases as flow increases during rainfall events. Capturing the way in which variables naturally change with such drivers is critical to both the determination of appropriate trigger values and the correct design of monitoring programs.

6.1.2. Soils

Soil monitoring may be conducted in a time-series manner with *in situ* sensors or via sampling. Many advances have been made in recent years in the technical aspects of *in situ* monitoring of variables such as soil water content, soil water potential and electrical conductivity and the ability to extract soil solution samples. In the case of soil water variables, most instruments infer the parameter of interest by measurement of a surrogate such as a dielectric constant. It is essential therefore that an instrument be calibrated to the soil type it in which it is installed. This requires physical sampling and laboratory analysis.

In situ soil solution samplers are used extensively for assessing the movement of solutes through the unsaturated zone. However, the quality of the data can be suspect, for example due to the

impact of the applied suction on natural flow fields and variability in soil pore sizes from where the soil water solution was extracted. It is also difficult to determine solute flux rates. The use of these samplers can be costly and time-intensive but if installed and used appropriately, they can provide useful data. This data needs to be used in conjunction with knowledge of drainage and soil conductivity variables and estimated mass balance of water flux and volumes collected by the samplers.

Some soil variables, such as soil chloride, cannot as yet be measured reliably *in situ* and soil sampling remains the only way to measure them. Sample sites must be adequately characterised, replicated and located to be representative of a certain soil type. This can only be achieved if an appropriate scale soil survey has been undertaken.

Soil parameters to be monitored include: pH, EC, chloride, sodicity and moisture content down the profile at least as far as the defined root zone, but preferably beyond. Changes in these parameters may indicate either salt build up or excessive leaching. Moisture (content and/or matric potential) in the upper unsaturated zone (1.5-6m) should be monitored to document the progress of water filling the unsaturated zone. Geophysical methods such as resistivity/EM (electromagnetic) imaging may also be used to 'join the dots' between sample points.

6.1.3. Groundwater

Groundwater monitoring is performed for a variety of purposes. In areas of extraction, it is usually to detect aquifer drawdown and any associated change in quality. In areas of irrigation, the intention will be to detect accumulation of deep drainage above impermeable zones. Groundwater monitoring is the most frequently misunderstood component of a monitoring program. Monitoring groundwater is not a surrogate for measuring deep drainage, as the two are only linked if the profile between the root zone and the groundwater table is saturated. This is rarely the case, and if it is, then it is likely that more serious environmental problems will ensue.

The depth of groundwater monitoring should take into account flow processes. For instance, a watertable in Cretaceous mudstone bedrock at 50 m depth is highly unlikely to be influenced by surface management, due to the low permeability of the bedrock and the relatively large depth of the regolith above the watertable. Theoretical flow times from the land surface to the aquifer may be in the hundreds to thousands of years, depending on the land use.

Shallow groundwater monitoring bores should be constructed in potential aquifer materials as often as in actual aquifers. The best example is sand seams found in the upper 10 m of the major alluvial sequences in the region. These sand seams are often dry, but by virtue of overlying thick clay sequences or bedrock, they are likely to accumulate water if sufficient recharge occurs. Construction of monitoring bores can be coupled with regolith investigation activities. Existing strata logs and drilling coupled with shallow geophysical methods should be used to define and map the shallower potential aquifers and zones of reduced permeability (where deep drainage may accumulate) under the site.

A consistent problem with groundwater monitoring in greenfield areas is that the monitoring commences at the same time as, or just prior to, the implementation of the new land use. Thus there is no temporal baseline. In most circumstances, this is not a critical issue as lag times in the landscape are such that groundwater will not be affected by land use for many years. However, groundwater monitoring should also take into account the land use history at a site. For example, watertable changes measured now may be the result of accumulated effects from the last 50 years—this is the Salinity Stage component in salinity risk assessment.

6.1.4. Surface water/streams

Monitoring of surface water in irrigation areas provides an important complement to on-site soil monitoring activities. While surface-water monitoring generally uses late-stage indicators, these can identify system behaviours and issues not identified in on-site monitoring. Salinity processes affecting surface water (such as salt washoff) may be more or less important depending on landscape type and irrigation method, but where these are deemed relevant, local surface water monitoring should be strengthened accordingly. Increased monitoring is also appropriate if natural connectivity between shallow groundwater and surface water is known or highly probable, such as in incised quartzose sandstone landscapes or in certain alluvial landscapes. Methods and instrumentation for construction of time-series water quality (EC in particular) and flow monitoring are widely available.

Accurate monitoring of the on-site water balance is a key component of determining if a system is functioning as planned and if salinity risk has changed. Relevant data includes paddock application rates and on-site climatic data.

7. Data and knowledge gaps

This section examines the quantity and quality of data available from both the CSG industry and from public records for use in salinity risk assessment. Knowledge gaps are then highlighted. The issue of soils data is specifically discussed as this is a key area where more detailed information is required to ensure effective assessment of irrigation suitability and salinity risk.

The quantity and quality of data available for use in salinity risk assessment is variable. When applying the salinity risk assessment framework, it is important to keep in mind that each component has different requirements in terms of the type and quality of data needed to represent the process being described.

It is important to choose and apply appropriate reporting units before implementing the salinity risk assessment framework. As with any data-dependent framework/model, the use of data and the collective result are constrained by the lowest resolution/accuracy inputs. One such example is the spatial grouping and averaging of results to report on larger geographic areas such as catchments or sub-catchments. These areas are unlikely to have consistent properties for many of the salinity risk assessment attributes such as groundwater levels and trends. Thus the results obtained by averaging or interpolating sparse or clustered data are unlikely to provide an accurate representation of risk at the catchment scale.

7.1. Suitability of CSG company data for salinity risk assessment

The CSG industry and the regulatory environment in which it functions are continually changing. As a result, the data required to be collected to support the industries' operation and development is changing. The scale and accuracy of data collected varies across the CSG development area, with some data meeting current assessment requirements while other data does not. Where the irrigation activity is developed by a third party, it should be noted that a large amount of data required for the salinity risk assessment will be the responsibility of the third party and not the CSG company. Thus an assessment of the data available should not just focus on data from companies but must also cover data from third parties.

A review was undertaken of relevant data from a selection of early beneficial use approvals for the use of CSG water for irrigation. This review found:

- A notable range in the quality and quantity of data supplied from poor to good;
- Soils related data was generally limited to ≤1.5 metres depth;
- Very limited data was provided on the unsaturated zone and the depth to the first zone of reduced permeability;
- Climate data was generally based on the nearest climate station only, which in some cases was a considerable distance away;
- Limited data was provided on land use history and in particular clearing and management history of the development area;
- Implications of climate and land use history were not explored;
- Data covering groundwater levels/trends was limited and analysis tended to inappropriately focus on deep groundwater with insufficient focus on (potential) shallow systems;
- Crop attributes (e.g. water demand and use patterns, rooting depth, climate conditions) were not always discussed in sufficient detail;
- Limited discussion was provided on the fate of the additional salt being disposed of by the irrigation activity;
- Some discussion was provided on the build-up of salt in the root zone of the crop; and
- Limited data was provided on post-irrigation land use and management.

It is apparent that while some companies invest strongly in research and development in relation to management of new irrigation areas, there are obvious weaknesses in the nature and quality of some work. There is a need to improve the quality of work conducted and for a more strategic approach to data collection in order to minimise long-term risk.

7.2. Suitability of publicly available data for salinity risk assessment

While CSG company data is specific to the company's development area, publicly available data in the regions tends to be broad-scale. The main public data sources relevant to salinity risk assessment include:

- DNRM/CSIRO land resource data/publications;
- DNRM groundwater database;
- DNRM Hydstra surface water data;
- Bureau of Meteorology (BoM/SILO) climate data;
- DNRM/National Action Plan for Salinity and Water Quality (NAPSWQ) salinity publications;
- Historical aerial photography;
- Geological Survey of Queensland (GSQ) geology and petroleum data;
- Geosciences Australia (GA) topographic data;
- CSIRO/Agricultural Production Systems Research Unit (APSRU) soil and plant trial data;
- Queensland Land Use Mapping Program (QLUMP) land use mapping; and
- Australian Bureau of Statistics (ABS) land use data including crop and water use statistics.

Appendix 6 evaluates the suitability of publicly available data to describe and inform the individual components of the salinity risk assessment framework. This evaluation highlights that the majority of source data required for a salinity risk assessment is not available at a scale suitable for site-specific salinity risk assessment. Given the inherent variability in the landscapes of the project area, this data is also insufficient for modelling landscape salinity risk.

In general, publicly available land resource, geology and topographic mapping in the CSG areas is limited to a scale of 1:250 000 or larger. Such data is limited in its use at a property level and therefore limited in its use for salinity risk assessment. This broad-scale data is best suited to reconnaissance investigations, broad scale study planning and cross-referencing the results of detailed investigations. Appropriate data cleansing, validation and accuracy assessments should be applied to most government raw data sets (hydrology, groundwater, soils) prior to use.

7.3. Knowledge gaps and limitations

As highlighted throughout this report, limitations in available data and resources pose major obstacles to salinity risk assessment. The limitations within a salinity risk assessment process are generally divided into two groups:

- the interpretation method(s) ; and
- the quantity/quality of data available.

Limitations regarding the interpretation methods should be addressed by employing appropriately qualified experts who bring expert knowledge to the application of modelling tools, interpreting data and applying the salinity risk assessment framework.

The key limitations and knowledge gaps that have been identified in terms of data required for salinity risk assessment by previous works and the current project include;

- Soil and regolith (unsaturated zone) properties;
- Rainfall salinity;
- Catchment hydrology;

- Critical thresholds for agronomic and degradation issues;
- Process understanding (e.g. lateral flow, salt washoff);
- Location and extent of salt expressions;
- Shallow groundwater monitoring data at appropriate spatial and temporal resolutions;
- Spatial delineation of current and past land management practices; and
- Calculation of deep drainage for all land use and management scenarios.

Soil and regolith (unsaturated zone) properties
While all companies are now required to undertake soil surveys as part of their irrigation development, the quality and scale of data and information used is still variable. The majority of CSG development is in areas where only regional scale data is publicly available, hence detailed surveys are essential. This is further discussed in Section 7.3.1. Better quality surveys and improved collation/correlation of the data will improve all stakeholders' capacity to assess salinity risk.

Associated with this is a need to dig deeper. Studying soil/regolith properties to only 1.5 m depth is no longer acceptable. Studies must be undertaken to depths below the "root zone" as this is where deep drainage ends up. Furthermore, the root zone for different crops must be more effectively defined. Critical attributes that need attention are porosity, starting soil water content, substrate permeability/conductivity and lateral flow processes.

Rainfall salinity
Rainfall salinity data is required for salt mass balance calculations. While the equations of Biggs (2006) provide a starting point for the region, they have limitations. The widespread presence of weather stations on CSG tenements for environmental monitoring purposes and their use to calculate daily water balances for irrigation provides a clear opportunity to substantially improve the input side of the salt balance equation for relatively low cost. Such data could also feed into the national rainfall salinity monitoring network. While this is not a critical data gap, it is one that could be improved with ease and relatively low investment.

Catchment hydrology
The development of irrigation areas changes catchment hydrology, just as clearing of the catchments has over the last 150 years. In many instances, companies are currently being conditioned to install gauging stations for various monitoring purposes. A more strategic approach to locating these stations and collation of the data, e.g. provision to BoM, is needed that takes into account the objectives for collecting the data and the way in which the data is collected and used. Such an approach across the industry is also likely to lead to cost savings and will provide broader long-term benefits by contributing to the assessment of cumulative risk in catchments.

Critical thresholds
The use of critical thresholds in regulatory frameworks remains an issue. While these provide a clear decision point for operators and regulators, experience indicates that there is a need for an improved approach. The best example of this is "an acceptable root zone salinity". There are so many variables in the field that can affect this number that setting one based on "textbook values" can be a relatively meaningless exercise. Considerable research is needed to better define critical thresholds for agronomic and degradation purposes across the landscapes of the region.

Process understanding
Surface wash off, lateral flow and deep drainage are the main mechanisms for water (and therefore salt) transport in soils. An understanding of the fate of excess water (e.g. whether it become lateral flow or deep drainage) in soils plays a major role in determining salinity risk. Understanding deeper soil/regolith processes and properties is therefore essential to calculating salinity risk. Unfortunately, our knowledge of these factors is very poor. More detailed soil survey and research of lateral flow process is required.

Salt expressions
Significant salt expressions have been mapped through the project area. Biggs and Power (2003) conducted a comprehensive review of salinity in the eastern half of the QMDB, identifying 194 salt affected areas totalling 2 444 ha; including 145 (2212 ha) in the Condamine, 13 (31 ha) in the Balonne and two in the Nebine-Mungallala catchment (201 ha).

Salt expressions are an indicator of historical recharge/discharge—their presence indicates that "the bucket is full". The hectares of salt-affected land reported are undoubtedly an under-estimate and fluctuate with seasonal conditions. Most salinised areas in the region are strongly controlled by climate, with salinity outbreaks increasing during wetter years and receding during drier periods. Most expressions are small (<25 ha) and are a result of local scale flow systems involving surface and near-surface flow processes. Further detailed assessment is required to capture emerging salt expressions and to investigate existing salt expressions.

Shallow groundwater monitoring
Groundwater monitoring is the most frequently misunderstood component of a monitoring program. The depth of monitoring should take into account flow processes. For instance, shallow (i.e. <30 m) groundwater monitoring bores need to be established in order to detect excessive drainage resulting from irrigation practices. Shallow groundwater monitoring bores should be constructed in potential aquifer materials as often as in actual aquifers. The best example is sand seams found in the upper 10 m of the major alluvial sequences in the region. These sand seams are often dry, but by virtue of overlying thick clay sequences, they are likely to accumulate water if sufficient recharge occurs.

A detailed shallow groundwater monitoring network throughout the project area needs to be put in place, and be adequately maintained and monitored.

Current and past land management practices
Historic land use and management practices affect historic deep drainage/recharge rates. Data capture from historic aerial photos and reports over time is required. Current land use records need to be updated regularly (at least five yearly) to ensure land use changes are adequately captured.

Deep drainage calculations
Yee Yet and Silburn (2003) modelled deep drainage for a range of soil, land use and climate combinations in the QMDB. They reported that drainage generally increases in the order: woodland < native or buffel pasture < opportunity cropping < summer cropping < winter cropping < irrigated summer cropping. Drainage rates from modelling need to be further tested against measured deep drainage data to provide reliable long-term estimates of deep drainage. All land use and management scenarios need to be investigated.

7.3.1. Current gaps in land resource assessment data for irrigation development

A thorough land resource assessment (soil survey) contributes a substantial volume of data to the salinity risk assessment process, outlined in Section 4, and provides baseline data for monitoring activities (see Appendix 2 for further detail). Given the importance of this assessment, a detailed review of currently available information has been undertaken.

A soil survey must describe the distribution of soils and landscapes at the property level and the way in which they affect land use/management and associated risks. Land resource information feeds into the assessment of biophysical hazard and management components in the salinity risk assessment framework. The scale of land resource assessment required (and how many profile descriptions form part of it) is driven by both the complexity of the landscape, and the skill of the soil surveyor. Appendix 2 provides further detail on recommended land resource assessment and agricultural land evaluation methods.

Land resource information has been collected at a broad scale (1:250 000–1:1 000 000) across all of Queensland (primarily by DNRM or its predecessors and CSIRO). However, the application of this regional scale information to detailed planning, design, construction and property level management is not appropriate. Broad scale land resource information is limited by its level of detail, a reflection of the purpose(s) for which it was originally collected. A key aspect of such regional scale mapping is that the map units represent landscapes (usually land systems, which are comprised of many landforms and soils). Therefore the map units are heterogeneous. Most importantly, they are not soil maps. It is not acceptable for maps published at a broad scale to be used for detailed assessments. Further information on mapping scale and land and soil surveys is provided in the *Guidelines for Surveying Soil and Land Resources* (McKenzie *et al*. 2008).

The limitations of scale at a property level are illustrated in Table 16. The analysis is based upon existing soils and land resource area mapping for an area of 1000 ha near Pittsworth.

Table 16 Summary of mapping units over 1000 ha at different mapping scales

Mapping scale	Mapping unit	Purpose
1:25 000	Soils	Moderately intensive uses at field level, detailed project planning
1:100 000	Soils	Extensive land uses, project feasibility, regional land inventory, district-level planning
1:250 000	Land Resource Areas, Land Systems	Very extensive land use, regional planning, national land inventory
1:1 000 000	Geomorphic unit	Generalised from land resource mapping
1:2 000 000	Atlas map unit	Very general information, not suitable for project planning

It is evident from the table above that mapping beyond 1:100 000 should not be used as the primary source of information for property planning. Within the project area, there is very limited mapping available at 1:100 000 or finer detail (e.g. 1:25 000). A minimum mapping scale of 1:25 000 is required to provide the data that will allow differentiation of soil types and other land attributes that in turn affect land use suitability. Consequently, proposals to use CSG water for irrigation will require proponents to prepare new mapping products to inform the planning design and monitoring of the project. Appropriate survey methods, applied at a sufficiently detailed scale will yield not only baseline data, which may also be used for monitoring purposes, but data that supports different aspects of land use and land management—not just agricultural uses.

Different approaches to collecting and interpreting land and soils mapping affect how the information may be used. Land resource and land systems mapping generally delineate recurring combinations of geology, landform, vegetation and soils. They consider surface features (relief, slope, drainage), climate, lithology, vegetation (structure and type), and soil associations. Soil mapping on the other hand is primarily based on soil characteristics but mapping scale still limits the degree to which intricate soil patterns can be differentiated. Even with finer scale mapping of soils it is important to understand which soil properties have been described as the basis for soil mapping. Older soil surveys such as Beckmann and Thompson (1960) have limited data associated with them (generally only a description of the soil type). There is generally an assumption that each instance of a given map unit has the same range of properties.

As discussed above, land resource data over the project area is generally limited to a scale of 1:250 000 or larger. Such data should not be used at a property level as is required for the application of the salinity risk assessment framework presented in this report. This broad scale data is best suited to reconnaissance investigations, detailed study planning and quality checking the results of detailed investigations. Significant investment is required to gain more detailed scale land resource coverage over the CSG development area.

7.4. Conclusions

A salinity risk assessment framework for (CSG water) irrigation that is consistent with Murray Darling Basin and local needs and goals has been described. This framework is both flexible and robust and allows for consideration of all necessary factors and processes that contribute to both soil salinity/sodicity and landscape salinity risk. The findings of previous authors remains unchanged—despite the presence of this improved risk assessment framework, it is not possible to assess salinity risk at a broad scale with the currently available data. The key data gap remains description of the unsaturated zone. A more coordinated approach to investment and research and formal adoption of key methods within the industry and government would lead to more robust science and greater certainty that risks posed at the site scale will not lead to inappropriate impacts at the landscape/catchment scale.

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Appendix 1: Additional information on key soil concepts

Deep drainage

Deep drainage is water that moves below the root zone of plants. Deep drainage occurs when the amount of water infiltrating into the soil (rainfall minus runoff) exceeds the soil water deficit (storage space relative to drained upper limit) created by evapotranspiration (Yee Yet and Silburn 2003).

The extent of deep drainage is affected by (Tolmie and Silburn 2003, Yee Yet and Silburn 2003, Tolmie *et al*. 2011):

- Climate—key factors are the amount and timing (seasonality) of rainfall and evaporation, and the relationship between the two:
  - Rainfall in the QMDB is summer dominant which coincides with high rates of potential evaporation; thus the risk of deep drainage is theoretically lower than in regions with winter dominant rainfall, because of the increased likelihood of summer-growing vegetation making use of this water. However, if cumulative rainfall over any period exceeds the amount the soil can hold in the root zone (soil storage capacity), drainage will occur.
  - For a given land use, modelling and measurements show that average annual drainage increases with average annual rainfall.
  - Walker *et al*. (1999) report that while drainage is often lower in summer dominated rainfall areas, it is also more episodic and depends on the rainfall sequence, i.e. drainage is highly variable from year to year and from decade to decade, and in many years no drainage occurs (for example, more than 50% of total drainage may occur in only 10% if years).
  - Annual drainage is poorly related to annual rainfall, as it relates more to coincidences of larger rainfall events on near-full soil profiles.

- Soil properties—major determinants of drainage are plant available water capacity (PAWC) and soil permeability:
  - PAWC determines the 'buffer' between rainfall inputs and evapotranspiration outputs, i.e. it defines the maximum potential soil water deficit that can store rainfall and prevent drainage.
  - Drainage is much higher from soils with lower PAWC because they cannot hold much water (e.g. sandy or shallow soils).
  - Soils with a higher clay content and PAWC can store larger amounts of water, and hence have lower drainage rates.
  - The more permeable the soil is, the higher the deep drainage is likely to be, as the amount of drainage depends on how easily water can move through the soil and subsoil.
  - Soils such as sands and Red Ferrosols have a high permeability and have higher rates of drainage, compared to soils with higher clay content such as Vertosols (which have lower permeability and lower drainage rates).
  - Drainage is lower for soils with low subsoil hydraulic conductivity and/or high runoff.

- Vegetation—major factors are perenniality, plant rotation (crop sequence) and effective rooting depth:
  - The greater the amount of water used by vegetation, the less potential deep drainage.
  - Perennial plants generally use more water than annuals because they transpire over longer periods, and they also develop more extensive and deeper root systems.
  - Drainage is more likely for land uses with periods of zero (e.g. fallows) or low (e.g. frosted pastures) plant water use than for perennial evergreen vegetation.
  - Changing cropping sequences to plant more crops when soil water is available can reduce drainage.
  - Deep rooted plants generally have lower rates of drainage, as deeper roots allow plants to draw water from deeper into the soil.
  - Trees generally have a much larger rooting depth and PAWC than crops and pastures.

- Rooting depth depends on the depth of soil or depth to parent material, and properties of the soil (e.g. salt content, pH, ESP and physical limitations such as bulk density).
- Actual hydrologic behaviour (how much water the root extracts) is more closely related to the soil water capacity (PAWC), how it is exploited by different species, and the water use pattern of vegetation through the year.

Deep drainage rates under native vegetation are typically very low in inland Queensland. This is due to lower summer dominant rainfall, high evapotranspiration and high plant water use. Prior to European settlement, trees were dominant in the majority of landscapes, with the exception of the Mitchell grass and bluegrass grasslands. Furthermore, rainfall is highly variable, and distinct wet and dry phases occur. The end result is virtually nil deep drainage for lengthy periods. The presence of naturally saline shallow groundwaters with the chemical profile of evaporated rainfall in inland Queensland is evidence of this. During wet phases (e.g. La Nina events), deep drainage may occur, even under native vegetation.

Yee Yet and Silburn (2003) modelled deep drainage for a range of soil, land use and climate combinations. They reported that drainage generally increases in the order: woodland < native or buffel pasture < opportunity cropping < summer cropping < winter cropping < irrigated summer cropping. They state:

- "Drainage is very low under woodland for most soils and locations, because of year round water use and greater root depths which can access water that has drained into the deep subsoil below the effective rooting depth of annual crops.
- Drainage is slightly higher for perennial pastures (compared with woodland) due to low water use during cooler months. Overgrazing of pastures causes a decrease in cover and hence a decrease in transpiration and an increase in runoff and deep drainage.
- Annual fallowing accumulates soil water and reduces the riskiness of cropping, but is inefficient and increases drainage (and runoff). Farming systems that reduce the duration of fallows and match crop water use with rainfall (opportunity cropping) reduce deep drainage.
- Summer crops are not using water from April to October when 40% of average annual rainfall occurs and when soil evaporation is low.
- Winter crops are only using water from May to October, and are not transpiring in summer during the fallow, when rainfall is highest and most drainage occurred.
- The modelled irrigated system assumes no drainage during irrigation (i.e. some form of 'perfect' irrigation that refills the soil water deficit to field capacity). Drainage results from rainfall only, but is greater than for non-irrigated systems because lower soil moisture deficits are maintained during the crops. The results therefore represent an estimate of the lower limit of drainage for a deficit-irrigated scenario."

Deep drainage is often only a relatively small component of the overall water balance, can vary greatly between seasons, and is quite episodic in the Australian environment—these factors confound measurement of deep drainage (Tolmie and Silburn 2003). Deep drainage can be significant (e.g. 100–200 mm/yr) with furrow irrigation on cracking clay soils—"clay soils do drain" (Silburn and Montgomery 2004, Smith *et al*. 2005).

Salinity and sodicity

Salinity

Salinity is the presence of soluble salts in soils or waters. Salinity processes are natural processes closely linked with landscape and soil formation processes. However, human activities can accelerate salinity processes, contributing to long-term land and water degradation. Salinity in soils usually becomes an issue when the concentration of salts adversely affects plant growth or degrades the soil. Salinity in water is an issue when the potential use of water is limited by its salt content (SalCon 1997) or there are adverse effects on values such as biodiversity.

Primary salinity is salinity that occurs naturally in soils and waters (SalCon 1997). Primary salinity appears as naturally occurring saline areas and saline soils, e.g. salt lakes, salt pans, salt marshes and salt flats.

Secondary salinity refers to salting that results from human activities; usually land development and agriculture (SalCon 1997). SalCon (1997) states:

> *The division between primary and secondary salinity is useful for separating areas where human activities do not appear to be affecting salinity processes (primary salinity) from areas where salinity is clearly influenced by human activities (secondary salinity), frequently associated with quite rapid changes in the environment. However, it is often difficult to categorise salting outbreaks as one or the other type because secondary salinity is often primary salinity accelerated by human activity. Many areas that now exhibit secondary salinity show considerable evidence of having been affected by primary salinity in the past.*

There are a range of soluble salts[16] that contribute to a soil or water becoming saline. The dominant sources of salt are rainfall and rock weathering. Rainfall patterns and soil properties determine the extent to which salt remains in the soil profile. Where rainfall is the dominant source of salt, sodium chloride (NaCl) is the most common salt. Where weathering dominates, bicarbonate salts are more common (SalCon 1997).

The interaction of processes contributing salt (rainfall and weathering), combined with the influence of other climatic processes (e.g. evaporation), landscape features (e.g. landform, soil type) and the effects of human activities, determine where salt is likely to accumulate in the landscape. Salt moves through the landscape with water—the movement and distribution of salt is determined by the hydrology of the landscape (Shaw 1997).

Measurement

There are a range of methods for measuring salinity. Two common ways are by using an electrical conductivity (EC) meter or by measuring how much salt is in a solution of soil or water (for more information see SalCon 1997), as follows:

- An EC meter measures how much electricity moves through a solution—the saltier the solution, the more electricity moves through it, hence the higher the conductivity reading. Electrical conductivity is expressed in different units—for soil, EC is measured in deciSiemens/metre (dS/m), while water is measured in microSiemens/centimetre (µS/cm). (Note that 1000 µS/cm = 1 dS/m) (see Table 17 for a list of typical salinity limits for water). The EC of soil and water can be measured easily in the field, or in the laboratory.
- Another way to detect salinity is by measuring how much salt is in a solution—this is done in the laboratory by measuring all the major ions and adding them up. These measurements are called total dissolved ions (TDI) (equivalent to total soluble salts (TSS)) or total dissolved solids (TDS). Results are reported in units of milligrams/litre (mg/L) or parts per million (ppm). Higher readings mean more salt is present in the solution.

Impacts

Impacts of salinity include:

- increasing the osmotic pressure of the soil solution, which increases the difficulty with which plants can extract water from the soil (Epstein 1972);
- increasing the soil's content of specific ions which may be toxic to some plants—this is especially of concern in irrigation areas where chloride, sodium and bicarbonate ions may be increased to concentrations toxic for some crops (Charman and Murphy 2007). Different ions will have various effects on different plants. Slatyer (1967) suggests that the ionic effects may

[16] Salts are the product of acid/base or metal/acid reactions. A solid consisting of oppositely charged ions is called an ionic solid or a salt (Zumdahl 1986). The salts commonly found in soils include sodium chloride (NaCl), calcium chloride (CaCl), magnesium sulfate ($MgSO_4$), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), magnesium chloride ($MgCl_2$) and calcium sulphate ($CaSO_4$) (Slinger and Tenison 2005).

be more significant than the osmotic effect because plants are able to adjust the osmotic effect to some degree;
- increasing exchangeable sodium on the soil's exchange complex—this is the main effect on soils, and may lead to breakdown of soil structure due to the dispersing effect of sodium ions on clay particles;
- poor germination, plant establishment and plant growth;
- waterlogging leading to low levels of oxygen in soil;
- increased erosion due to lack of vegetative cover, potentially resulting in high sediment loads to local watercourses. Water flowing off such areas is likely to be saline also;
- change in vegetation species; and
- damage to infrastructure (due to waterlogging, concentration of salts on metals, and/or growth of salt crystals in porous material like bricks).

Crop tolerance to salt levels needs to be considered. Not all plants respond to salinity in a similar manner; some crops can produce acceptable yields at much greater soil salinity than others. This is because some are better able to make the needed osmotic adjustments enabling them to extract more water from a saline soil. In areas where a build-up of soil salinity cannot be controlled at an acceptable concentration for the crop being grown, an alternative crop can be selected that is both more tolerant of the expected soil salinity and can produce economical yields, depending on the soil salt levels. Specific ion toxicity (e.g. sodium) to plants also needs to be considered.

Table 17 Typical salinity limits for water

		Electrical Conductivity (EC)		***TDS***
		(μS/cm)	***(dS/m)***	***(mg/L or ppm)***
Distilled water		1	0.001	0.67
Rainfall		30	0.03	20
Sewage effluent		840	0.84	565
Freshwater		0–1500	0–1.5	0–1000
Great Artesian Basin water		700–1000	0.7–1.0	470–670
Brackish water		1500–15 000	1.5–15	1000–10 050
Upper limit recommended for drinking		1600	1.6	1070
Tolerances of livestock to salinity in drinking water (at these values, animals may have an initial reluctance to drink, but stock should adapt without loss of production)	Poultry	2985–4475	2.9–4.4	2000–3000
	Dairy cattle	3730–5970	3.7–5.9	2500–4000
	Beef cattle	5970–7460	5.9–7.5	4000–5000
	Horses	5970–8955	5.9–8.9	4000–6000
	Pigs	5970–8955	5.9–8.9	4000–6000
	Sheep	7460–14 925	7.5–14.9	5000–10 000
General limits for irrigation	Salt sensitive crops	650	0.65	435
	Moderately salt sensitive crops	1300	1.3	870
	Salt tolerant crops	5200	5.2	3485
	Generally too saline for crops	8100	8.1	5430
Salt water swimming pool		5970–8955	5.9–8.9	4000–6000
Seawater		55 000	55	36 850
Dead Sea		110 000	110	73 700

Note: It is important to also check other water quality parameters (e.g. chemical composition, sodium adsorption ratio, metals etc) before use (Source: Table 1 from Watling 2007).
Note: To convert from μS/cm to dS/m, divide by 1000. To approximately convert from μS/cm to mg/l, multiply by 0.67.

Impacts

Impacts of salinity include:

- increasing the osmotic pressure of the soil solution, which increases the difficulty with which plants can extract water from the soil (Epstein 1972);
- increasing the soil's content of specific ions which may be toxic to some plants—this is especially of concern in irrigation areas where chloride, sodium and bicarbonate ions may be increased to concentrations toxic for some crops (Charman and Murphy 2007). Different ions will have various effects on different plants. Slatyer (1967) suggests that the ionic effects may be more significant than the osmotic effect because plants are able to adjust the osmotic effect to some degree;
- increasing exchangeable sodium on the soil's exchange complex—this is the main effect on soils, and may lead to breakdown of soil structure due to the dispersing effect of sodium ions on clay particles;
- poor germination, plant establishment and plant growth;
- waterlogging leading to low levels of oxygen in soil;
- increased erosion due to lack of vegetative cover, potentially resulting in high sediment loads to local watercourses. Water flowing off such areas is likely to be saline also;
- change in vegetation species; and
- damage to infrastructure (due to waterlogging, concentration of salts on metals, and/or growth of salt crystals in porous material like bricks).

Crop tolerance to salt levels needs to be considered. Not all plants respond to salinity in a similar manner; some crops can produce acceptable yields at much greater soil salinity than others. This is because some are better able to make the needed osmotic adjustments enabling them to extract more water from a saline soil. In areas where a build-up of soil salinity cannot be controlled at an acceptable concentration for the crop being grown, an alternative crop can be selected that is both more tolerant of the expected soil salinity and can produce economical yields, depending on the soil salt levels. Specific ion toxicity (e.g. sodium) to plants also needs to be considered.

Sodicity

Sodicity is the presence of a high proportion of sodium ions (Na^+) in a soil or water, relative to other cations (in exchangeable and/or soluble form). As sodium salts (e.g. sodium chloride NaCl) are leached through the soil, some sodium remains in the soil bound to clay particles, displacing other cations such as calcium. Soil structure is sensitive to sodium. A high proportion of exchangeable sodium attached to clay mineral exchange sites weakens the bonds between soil particles when the soil is wetted. As a result, the clay particles swell and often become detached and disperse. Small clay particles move through the soil, clogging pore spaces (SalCon 1997).

Sodic soils are widespread in Australia (Rengasamy and Olsson 1991). Sodic soils are commonly associated with the weathering of sedimentary parent materials of marine origin; sodium accessions to soils can also occur via rainfall, groundwater rise or from aeolian sources[17]. The accumulation of soluble salts in soils also depends on the age of sediments and topographic location.

Measurement

The two most common measures of sodicity are:

- Exchangeable Sodium Percentage (ESP) which is the proportion of sodium adsorbed onto clay mineral surfaces as a proportion of the total cation exchange capacity (CEC). ESP is calculated as:

  $$ESP = 100 * \frac{Na^+}{CEC}$$

  where CEC is the amount of cations on the surface layers of clay minerals which can exchange with other cations when they are available in solution.

[17] In geologic terms, aeolian is defined as carried, deposited or eroded by wind.

- Sodium Adsorption Ratio (SAR) which is the relative concentration of sodium to calcium and magnesium in the soil solution or in water. SAR is calculated from the following equation:

  $$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

  where Na, Ca and Mg are expressed in milliequivalents per litre (meq/L).

Impacts

The impacts of sodicity include:

- adverse effects from raindrop impact and wetting on the structural stability of the soil;
- severe surface crusting—the dispersed clay at the soil surface can act as a cement, forming crusts that are relatively dense and hard but typically thin (up to 10 mm thick). The crust impedes seedling emergence and can tear seedling roots as it dries and shrinks. The degree of crusting depends on soil textural composition, clay mineralogy, exchangeable sodium content, raindrop impact and rate of drying (SalCon 1997);
- very low infiltration rates restricting water entry—due to dispersed small clay particles that clog pore spaces;
- severe cloddiness (formation of soil aggregates greater than 100 mm), resulting in reduced soil porosity and commonly formed under cultivation;
- reduced hydraulic conductivity (the ability of the soil to conduct water);
- salt accumulation over time, giving rise to saline subsoils—low infiltration and reduced hydraulic conductivity limits leaching, allowing salts to accumulate rather than be leached from the soil profile;
- increased susceptibility to erosion by wind and water, including tunnel, rill, gully and sheet erosion;
- poor aeration due to clogging of soil pores; and
- limiting the ability of plants to uptake water and nutrients from the soil.

Irrigation issues

Because the relative proportions of exchangeable cations in a given soil are determined by the relative concentration of cations in the soil solution, the composition of irrigation water can influence soil sodicity (Rengasamy and Olsson 1991). When irrigation waters with a high proportion of sodium ions compared with other cations are added to soil, sodium displaces other cations on the clay mineral exchange sites, resulting in a sodic soil.

Decreased soil hydraulic conductivity under sodic conditions plays an important role in salt movement and accumulation within the root zone. It also strongly influences leaching fraction/deep drainage rates. In many cases, rainfall or good quality irrigation water can leach accumulated salts below the root zone, thus salt accumulation from irrigation can usually be managed. However, using water with an elevated SAR means that leaching rates are reduced.

Appendix 2: Conducting soil surveys and agricultural land suitability assessments for coal seam gas water irrigation development

Various national and state standards/guidelines for land resource and land suitability assessment exist. These include the Australian Soil and Land Survey Handbooks—in particular the "yellow book" (NCST 2009) and the "blue book" (McKenzie *et al*. 2008). Local guidelines to assist the development of land and water management plans have also been developed (DERM 2002) as have some industry guidelines such as Cotton BMP[18]. Agricultural land suitability and capability assessment guidelines for Queensland are described in LRB (1990)[19]. These and other documents provide a mixture of general and specific information in relation to soil survey and agricultural land evaluation, but do not provide enough specific detail in the context of CSG water irrigation development.

The purpose of this appendix is to provide clear and consistent technical and practical procedures for soil survey and agricultural land suitability assessment in relation to approvals required under the *Environmental Protection Act 1994* and the *Waste Reduction and Recycling Act 2011*, particularly in relation to CSG water irrigation development.

Objective of soil survey and agricultural land evaluation

The aim of soil survey and agricultural land evaluation is to describe the distribution of soils and landscapes at the property level and the way in which they affect land use/management and associated risks. While written specifically for CSG water irrigation development, the principles outlined in this technical note are applicable to any similar development.

The data required for soil survey and agricultural land evaluation includes basic soil and landscape attributes. Such data may serve multiple purposes, such as salinity risk assessment, informing pipeline planning and setting environmental benchmarks. Time and money spent conducting high quality surveys at the beginning of developments will provide long-term beneficial outcomes for both the proponent and the regulator.

Given the considerable amount of existing work on methods and practices for soil surveys, this document does not repeat all aspects, but highlights the key issues that need to be addressed (in the context of irrigation development in inland southern central Queensland), methods and practices and provides key references for further information.

1. Introduction

Prior to the development of any irrigated land, appropriate investigations are necessary to ensure that both short-term and long-term risk of land degradation and the agronomic viability of the enterprise are assessed. This is particularly the case for greenfield[20] development areas, although pre-existing irrigation use does not reduce the need for such investigations.

Soil and land survey data plays a critical role in determining the agronomic suitability of an intended land use, salinity risk, erosion potential, and baseline soil and water quality values for future monitoring assessment. It also provides useful data for other activities that may be undertaken at a site, for example, pipe laying/trenching and road construction.

[18] For further information see <http://www.bmpcotton.com.au/>
[19] These are currently under review due to policy changes related to conservation of cropping land.
[20] Greenfield areas (for irrigation development) are areas which have not been previously developed for irrigation.

1.1 Common issues

The most common issues encountered in the development of a CSG water irrigation area concern the scope and conduct of the soil survey required, appropriate methods for analysis and preferred interpretation techniques. Key questions include the following:

- How to access existing soil data?
- What scale of soil survey is required?
- How many soil sites should be described?
- How deep should soils be described/samples be collected?
- How should soils be classified?
- Which analytical methods are required?
- How should regolith be investigated?
- How should agricultural land suitability be determined?

2. Existing data

Broad scale land resource information exists for all parts of the state. Prior to any detailed assessment, a review should be undertaken of all existing data. This, combined with pedological principles should be used to formulate a hypothesis regarding soils and landscapes likely to be encountered in the study area. Desktop assessment also includes tasks such as analysis of terrain (using derivatives of DEMs[21]), analysis of surficial features using geophysical data such as airborne radiometrics, analysis of satellite imagery and aerial photograph interpretation. While analysis of remotely sensed data can provide a quick interpretation of landscapes and be useful for the derivation of key attributes such as slope and weathering, stereo-interpretation of aerial photographs remains the most effective method for detailed soil survey. Aerial photos are available from the Department of Natural Resources and Mines (DNRM).

Many different types and scales of land resource mapping data exist in Queensland. At the broadest scale is the Atlas of Australian Soils[22] (Northcote *et al.* 1960–1968). This data, like any broad scale data, is not appropriate for detailed investigations related to CSG development. Regional scale mapping (1:250 000 to 1:500 000 land systems or land resource area data) exists for nearly all parts of Queensland. Land systems represent recurring combinations of geology, soils, landform and vegetation. In the current areas of CSG development in inland southern and central Queensland, land systems or land resource area (LRA) data is often the only polygonal data layer available. LRA mapping is similar to land systems mapping in terms of concept. It is generally at 1:250 000 scale, maps broad land types and is the mapping used in Land Management Manuals (e.g. Harris *et al*. 1999). Despite the coarse scale, the value of land systems and LRA data should not be under-estimated and considerable information is held in the descriptions of the map units (component land units and soils). LRA and land systems mapping can be used to determine if certain soil types of interest are likely to be present in a particular area. Many land systems reports have associated land capability assessments. Land capability (Rosser *et al*. 1974) is an assessment of broad agricultural land use potential e.g. cropping, pasture.

In some areas, detailed land resource assessment has been undertaken (1:100 000 scale or better). Older assessments (pre-1985) are typically only soil surveys, with a limited set of attribute data associated with each polygon (often just the soil type). These surveys are often referred to as mapcode-based mapping. Modern surveys use the concept of Unique Mapping Areas (UMAs) where each mapped area or polygon has a unique identifier. In such mapping, for each UMA (or individual polygon), one or more soil types are described, along with detailed attributes or features of the soil or landscape. This data is the basis for agricultural land suitability assessment. The assessment of agricultural land suitability in Queensland is described in LRB (1990)[23]. The

[21] DEM (Digital Elevation Model) – DEM data is available from DNRM and Geoscience Australia.
[22] For further information see <www.asris.csiro.au/themes/Atlas.html>
[23] Currently under review due to policy changes related to conservation of cropping land.

process utilises the concept of limitations and five suitability classes. Some limitations are generic across all land uses (e.g. soil depth), while others may only affect certain land uses (e.g. certain nutrient limitations). The distribution of the various scale studies for the main CSG production area in Queensland is shown in Figure 50 and Figure 51.

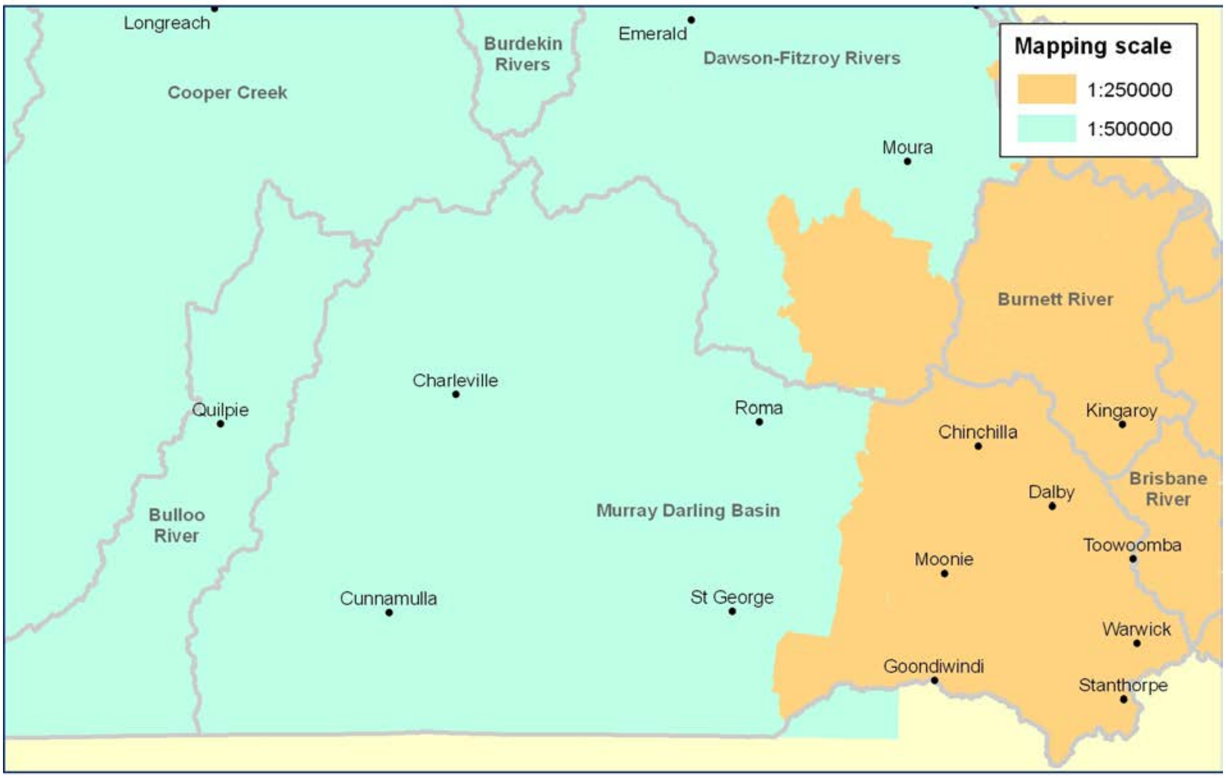


Figure 50 Extent of broad scale land resource mapping for inland southern and central Queensland

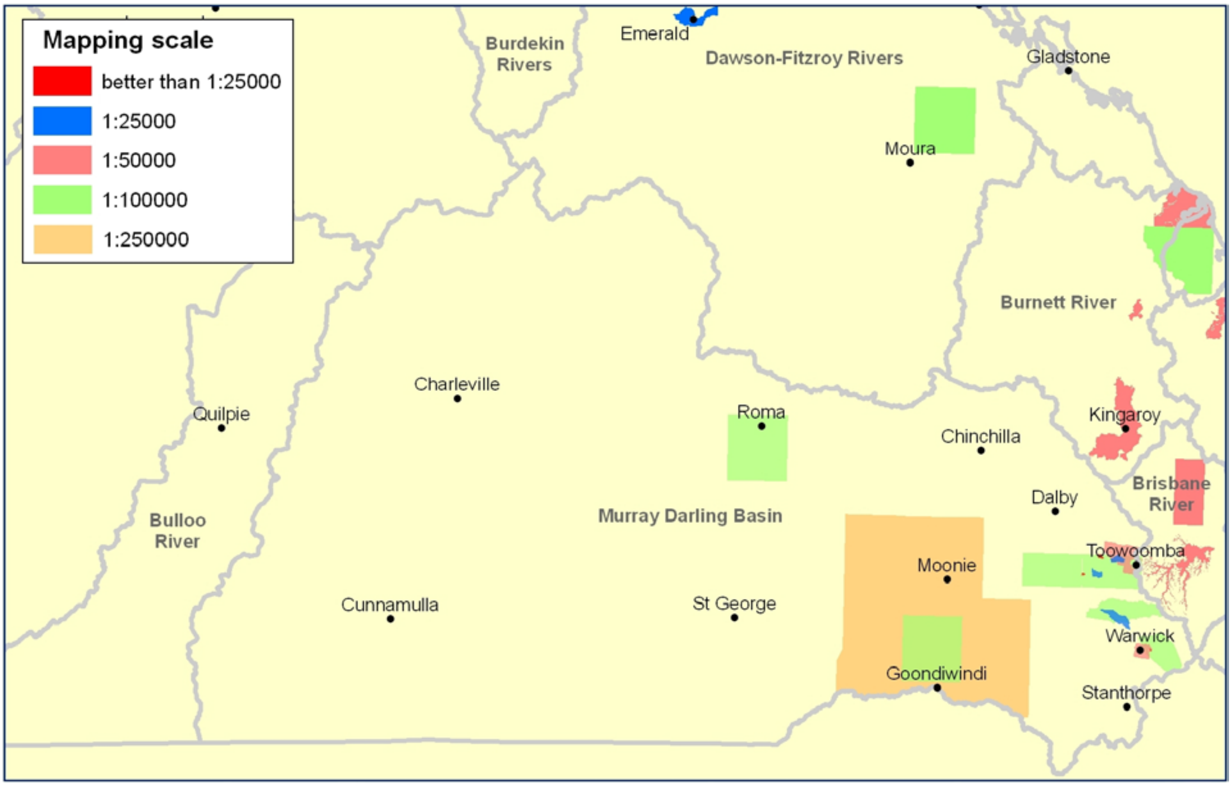


Figure 51 Extent of detailed soil surveys in inland southern and central Queensland

Site data collected by various organisations (primarily DNRM and its predecessors and CSIRO) is scattered across the state. In excess of 90 000 profile descriptions exist in Queensland, about 14% of which include analytical data (Figure 52). This data is stored in the DNRM soil and land information database (SALI).

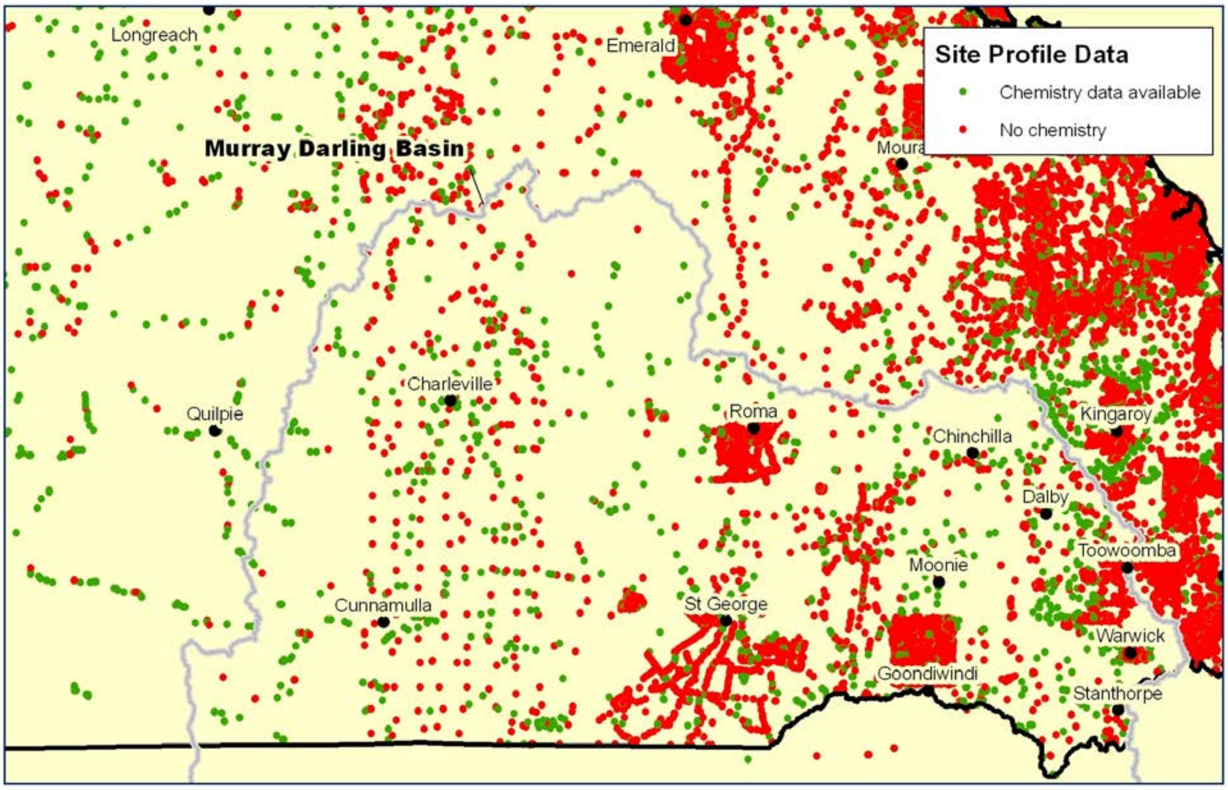


Figure 52 Existing DNRM site data in inland southern central Queensland

A considerable amount of research data also exists in published and unpublished formats for many cropping soils in inland southern central Queensland. The value of this data to CSG developments is substantial but it can generally only be used after sufficient correlation with and between soil types has occurred.

DNRM and CSIRO data is currently available digitally as shapefiles, database output and pdf scans of original published documents from DNRM. Some interpreted data is also available via ASRIS (Australian Soil Resource Information System), although this has significant limitations and should only be used at the reconnaissance scale. Data access avenues include:

- *DNRM library catalogue* <http://dermqld.softlinkhosting.com.au/liberty/libraryHome.do>
  Allows users to search the DNRM library catalogue and download pdf scans of reports and maps.
- *Interactive resource and tenure maps (IRTM)* <webgis.dme.qld.gov.au/webgis/webqmin>
  Allows users to zoom, pan, search and display land resource data and geological data with mining and exploration tenure information for the whole of Queensland. Data can also be downloaded.
- *DNRM website* <http://www.derm.qld.gov.au/science/slr/index.html>
  Lists land resource publications available by region (under the 'Publications' tab). Provides links to purchase digital data.
- *Queensland Government Information Service (QGIS)* <http://dds.information.qld.gov.au/DDS/>
  Allows users to search a catalogue of Queensland Government information and associated data for the purposes of downloading and using appropriate software to view the data.

3. Mapping

General guidelines for soil surveys are well established in Queensland and Australia. The "blue book" (McKenzie *et al*. 2008) provides substantial information on survey design, techniques and practice. The "yellow book" (NCST 2009) provides the soil and land survey codes for use in the field. A national database framework also exists (ASRIS 2006).

Within Queensland, further information is available in documents such as the *Guidelines for Agricultural Land Evaluation*[24] (LRB 1990) and *State Planning Policy 1/92: Development and the Conservation of Agricultural Land* (DPI/DHLGP 1993). With enhanced computerisation, remote sensing and access to accurate GPS, land resource assessment techniques have evolved considerably in the last decade, as evidenced by the difference between Gunn *et al*. (1988), the first "blue book", and McKenzie *et al*. (2008), the second "blue book". Despite this, the general procedure remains the same. For CSG developments, it can be defined as:

1. Desktop assessment using existing data (various scales, typically 1:250 000)
2. Reconnaissance scale investigations (1:100 000)
3. Prioritisation
4. Detailed investigations (1:25 000 or better) in the irrigation footprint

A variety of methods exist for designing surveys—these are discussed in detail in McKenzie *et al*. (2008). The most common decisions to be made are site selection method and mapping method. Common site selection methods include grid and free survey (purposive or random). Considerable time can be devoted to analysis of site selection, but the gains achieved via detailed geostatistical or similar approaches must be clearly identified. Conventional survey methods (hybrid, free, random/purposive site selection) remain acceptable and efficient. In general, sites should be distributed in a manner proportional to the areal distribution of soil/land type and be guided by the landscape—for example, standard survey methodology is to describe sites in a transect down a catena. Sites located on UMA/polygon boundaries should be avoided unless their purpose is to specifically characterise transition zones or the UMA/polygon boundary. At least one site should be described in each map unit. The variation within a map unit should be less than the variation between map units.

Digital soils mapping, or elements thereof, is common-place today and can provide a rapid way in which to derive certain soil or land attributes. The best example is the use of high resolution digital elevation models to derive slope or related attributes such as aspect or wetness index. Other examples are geophysics (e.g. gamma radiometrics, electromagnetic induction (EM), resistivity). The use of these is well established in soil surveys, but as with all remotely sensed data, care must be taken to establish sufficient calibration and estimates of uncertainty and error. Such techniques are easily misused and the value of the data over-stated, or as is often the case with EM, conducted with low return on investment due to poor understanding of potential causes of variability. The conventional mapping method of stereo-pair aerial photo interpretation remains a highly efficient and effective method for detailed land resource mapping and the preferred method for deriving linework (UMA/polygon boundaries). Linework should be captured digitally and geo-rectified. Polygons (UMAs) should either contain all necessary attributes and limitations or be linked to a database/spreadsheet containing such. The national database structure (ASRIS 2006) is recommended as a template for designing survey data structure.

3.1 The question of scale

Scale is generally the most problematic part of soil surveys. It consists of two components—site density and polygonal/raster scale. The two are not independent. The minimum scale required for irrigation developments related to use of CSG water is 1:25 000 for the irrigation footprint. Outside of the irrigation footprint, survey scale should be 1:50 000 to 1:100 000. No mapping of this scale

[24] Currently under review due to policy changes related to conservation of cropping land.

currently exists in the CSG development area. Consequently, proposals to use CSG water for irrigation will require proponents to prepare new mapping at 1:25 000 scale to inform the planning, design and management of the project. Appropriate survey methods, applied at the proper scale will yield not only baseline data, which will be used for monitoring purposes, but data that supports different aspects of land use and land management—not just agricultural uses.

3.1.1 Site density

Historical standards (Gunn *et al*. 1988) and the SPP 1/92 guidelines (DPI/DHLGP 1993) suggest a rule of thumb of one site per square centimetre of map area (e.g. one site per 6.25 ha) for a scale of 1:25 000. Figure 18 summarises the required site densities for different survey scales and different site sizes for the purpose of irrigating land with CSG water. It is important to note that site density in detailed surveys is also influenced by the complexity of the landscape, which cannot be determined without sufficient reconnaissance work. If the site intensity differs from Table 18 methodology and justification should be documented to enable scale and accuracy assessment.

Table 18 Site density for different survey scales

Area (ha)	Survey scale	Sampling intensity (sites/ha)
<5	1:2500	1 site per 0.06 ha
5–10	1:5000	1 site per 0.25 ha
10–50	1:10 000	1 site per 1 ha (1 site per 0.8–4 ha)
50–100	1:25 000	1 site per 6.25 ha (1 site per 5–25 ha)
>100	1:25 000	1 site per 6.25 ha (1 site per 5–25 ha)
>100	1:50 000	1 site per 25 ha (1 site per 20–100 ha)
>100	1:100 000	1 site per 100 ha (1 site per 80–150 ha)

Note: Table data developed from Section G, Appendix 3 (DERM 2002), and Table 3.1 and Table 14.4 (McKenzie *et al.* 2008).

From an operational perspective, every mapped UMA/polygon should contain at least one detailed site description, and overall site density should approximate the theoretical requirement of one site per 6.25 ha unless clear evidence can be provided for deviation from this—for example, a highly uniform landscape and well established surrogate indicators. Not all sites need to be described in detail (see Section 4), as check-sites in uniform landscapes or to define mapping boundaries are acceptable, providing the minimum data such as location, landform, soil surface features and some notes are recorded.

3.1.2 Polygonal/raster scale

There is no strict rule with regards to minimum or maximum size of a polygon for a given survey. Polygonal scale has historically been determined by scale of available aerial photos and digitisation method (e.g. artiscope, scanning, direct digitising). Substantial improvements in GIS software and computing have removed some of these limitations but others, such as scale of stereo-pair aerial photos, remain. Polygon size is also determined by landscape complexity and the intended map scale. Resolution of a polygon at the printed scale of a map remains the best guide for minimum size of polygons.

Raster based methods are commonly used to support modern land resource assessment exercises. The scale of these is a function of pixel size, but an accuracy element also exists, as the algorithm used to interpret contours into a DEM has a definable error. Effective scale can also vary within a grid—for example, a 25 m cell size DEM may resolve hillslope hydrology at sufficient resolution, but be inadequate for a floodplain. Raster scale should be approximated to a conventional scale. For instance, a 250 m cell size is inappropriate for paddock scale

determinations of attributes. Raster data is often transformed into polygonal data for presentation or other purposes (similarly polygonal data is sometimes rasterised). Care should be taken to not overstate the accuracy of polygonal data via rasterising to a very small cell size.

4. Site data

There are five types of sites that may be described during a soil survey:

- Full profile morphology with complete analytical data down the profile;
- Full profile morphology with selected analytical data (at selected points in the profile);
- Full profile morphology with no analytes (but may have field measurements such as pH, EC);
- Quick observation of soil type and landscape at a point (using a soil core or similar); and
- Quick observation of soil type and landscape at a point (surface inspection only).

Data for full sites includes (but is not limited to):

- geo-location;
- geology and lithology;
- land use and management;
- landscape attributes (landform, vegetation, land degradation);
- microrelief;
- soil profile morphology;
- soil profile chemical and physical attributes;
- soil classification;
- correlation within the survey; and
- correlation to existing mapping/soil types (where available).

At quick observation sites, the minimum data recorded should include geo-location, land use and management, landscape attributes and correlated soil type (either correlated internally or externally within the survey). Approximate proportions of site types are listed in Table 19.

Table 19 Site density for different survey scales

Site type	Approx. proportion of total sites
Full profile morphology with complete analytical data down the profile	~10%
Full profile morphology with selected analytical data (at selected points in the profile)	any number
Full profile morphology with no analytes (but may have field measurements such as pH, EC)	~50%
Quick observation of soil type and landscape at a point (using a soil core or similar)	<50%
Quick observation of soil type and landscape at a point (surface inspection only)	<25%

All descriptions should be made on a standard field sheet (see next pages for an example) using terminology provided in NCST (2009) or other appropriate texts e.g. Neldner *et al*. (2005).

It is recommended that all sites are clearly marked on maps provided as part of applications (such as beneficial use approvals) or other submissions and all data is provided in appendices or other parts of reports. Digital copies of data in spatial formats compatible with ArcGIS are recommended.

Climate information should be recorded for each soil survey, including available historic climatic data and current data. Ideally, on-site weather stations should be installed to collect location-specific climatic data. This data should include but not be limited to: temperature (extremes and averages), flooding, frosts, rainfall patterns and drought. Climate data should be able to be correlated to land use and management for the subject location. Climate stations are normally installed to meet other licensing requirements and should need little, if any, adaptation to meet these data collection requirements.

Geology	Slope					Landform Element					Landform Pattern				Land Use			Described By	Date (ddmmyy)	Project	Site
	Eval	Percent	Class	MT	Incl	Type	Loc	Height	Width	Length	Pattern	Class	Modal	RMS	LU1	Mgt1	Mgt2				
	A																	B I G A	1 0		

TSO	M Type	L Meas	Obs Reas	Runoff	Perm	Drainage	M Samp	Aggredn	Depth R Horiz	Tax Unit		Map Unit		Air Photos			Substrate														
										Type	Code	Type	Code	Film No	Run No	Frame No	OT	Distance	Conf	Depth	Gr S	Str	Por	Sp F	Alt	Str	Lith	Gen T	Text	Mass Str	MDS
C	M	4																													

Location			Australian Soil Classification										PPF	GSG	Disturb	Surface Condition	Microrelief						Surface Coarse Fragments						Outcrop		Profile D
Datum	Zone	Easting / Latitude	Northing / Longitude	Conf	Ord	Sub Ord	GG/ Or2	SG/ SO2	F1	F2	F3	F4	F5		aff			Type	Agent	Cmpt	Prop	VI	HI	Abun	Size	Shape	Lith	Str	Alt	Abun	Lith	
3																																

Erosion				Community			Community 1 Details											
Type	State	Deg	GD	No	Ref No	Name	Strata	Form	Ht Cl	Cov Cl	Height	Cover	Species 1	Prop	Species 2	Prop	Species 3	Prop
				1			T											
				2			M											
				3			L											

Number	Horizon	Depth		Confid	Bound		Field Texture		Facies	SWS	Colour (M Book)				Mottles					Coarse Fragments						Structure				Segregations					Cracks	Strgth		Pans				
		Upper	Lower		Dsct	Shape	Field Texture	Qual			Hue	V	C	Moist	Type	Abun	Size	Contr	Col	Abun	Size	Shape	Lith	Str	Alt	Dist	Grade	Size	Type	Cmpd	Abun	Nat	Form	Size	Eff		SWS	Cons	Type	Cmnt	Cont	Str
1																																										
2																																										
3																																										
4																																										
5																																										
6																																										
7																																										

Test	Meth	
pH - RP		
EC		
Disp		

NOTES:

SITE DESCRIPTION SHEET - NOTES

Project	Site	Obs

Type	Site Notes

Type	Observation Notes

Type	Horizon Notes

Other Notes

4.1 Geo-location

All sites must be geo-located using a GPS with an accuracy of five metres or better. Co-ordinates must be expressed in Map Grid of Australia (MGA), stating the zone and using the Geodetic Datum of Australia (GDA94)[25]. Long-term monitoring sites must be physically marked or pegged, or located to an accuracy of less than 1 m.

4.2 Geology and lithology

Correlation to the best available geology mapping and the lithology of the soil parent material must be recorded. The source of this data must be included in the project report and stated on any maps produced with these attributes.

4.3 Land use and management

An outline should be provided of current land use and management practices[26] at the site. Information should also be provided on land use history and management (e.g. provide a synopsis of major historical changes in land use intensity) from the time of clearing the native vegetation to the present day. This data is vital to setting the scene of the site, understanding historical agricultural limitations, and establishing irrigation salinity risk. It also provides valuable information for comparison to other areas with similar history and management regimes.

4.4 Landscape attributes

The standard landscape attributes described at a site include landform (e.g. slope (%), element, pattern) and the relationship of the site to these. Surface drainage (proximity to watercourses, channel occurrence and patterns, etc), vegetation (original and current) and current land use should be recorded, along with presence of erosion, rock outcrop, surface coarse fragments, soil surface condition, microrelief and presence of any degradation (e.g. erosion, salt expressions).

4.5 Microrelief

Gilgai microrelief is a natural soil feature frequently associated with non-rigid soils (i.e. cracking clays or Vertosols). Gilgai consist of mounds and depressions, sometimes separated by an almost planar ground surface (NCST 2009). There can be significant variation in soil properties between the mound and depression and this should be considered in site selection and sampling. The key attributes of gilgai microrelief are the depth (vertical interval) of the gilgai depressions and the areal extent of depressions within a particular area of gilgai.

4.6 Soil profile inspection

Site descriptions may be made from either augered holes, undisturbed cores or excavated pits. The latter are the most expensive and limited in depth for safe access (typically <1.5 m). Pits or cores are preferred to manually or mechanically augered holes, as a more accurate representation of horizon depths is obtained and soil features such as structure, soil horizon transitions and slickensides are better preserved for inspection.

4.6.1 Sampling depth

Traditionally, soil profile descriptions were to depths of 1.2–1.8 m. This was particularly the case for hand-augered holes in hard soils. For modern surveys, soil descriptions often need to be deeper. The importance of characterising the unsaturated zone (of which the soil profile is the upper part) is described in Appendix 4.

In the case of hillslope soils, all sites should be described to bedrock (C or R horizon) where soil depth is <1.8 m. In hillslope areas where soil depth is >1.8 m, a minimum of half the holes should be to bedrock[27]. For alluvial areas, where depth to bedrock may be up to 100 m, there is an overlap with regolith/groundwater/unsaturated zone investigations. All soil profiles should be

[25] Some GPS lack this datum. WGS84 may be substituted.
[26] Codes and descriptions of land use and management practices can be found in ABARES (2011).
[27] It is uncommon for hillslope soils to exceed 3 m depth in inland Queensland.

described to a minimum of 1.8 m, and a subset (~25%) to a depth of at least 5 m. Integration with regolith/groundwater studies is essential to provide sufficient characterisation of the unsaturated zone. Basic soil properties are easily described for such materials using soil description standards such as NCST (2009). For deeper profile inspections and sampling, regolith standards (e.g. Pain *et al*. 2007) can also be used. Where earthworks for water storages are planned, samples should be taken to at least 2 m below the expected excavation depth, to assess the likelihood of permeable layers that may lead to leakage from the storage. Such sampling may overlap with geotechnical investigations.

4.7 Soil profile morphology

Soil profile morphology descriptions should follow the national standard (NCST 2009), with all appropriate attributes recorded. The minimum data set is:

- horizon depths;
- horizon designation;
- boundary distinctness;
- field texture;
- colour;
- mottles;
- coarse fragments;
- structure;
- segregations; and
- field tests (e.g. pH and EC).

Description of features such as cutans, fabric, etc. are not essential. Field texture should be calibrated against sufficient particle size laboratory data to indicate correlation with % clay and sand.

4.8 Soil profile chemical and physical attributes

Methods for soil chemical and physical attributes are described in many texts, including *Soil Chemical Methods – Australasia*[28] (Rayment and Lyons 2010) and *Soil Physical Measurement and Interpretation for Land Evaluation* McKenzie *et al.* (2002). The casual observer will note that there are many different methods for measuring some attributes such as phosphorous and hydraulic conductivity. There are many reasons for this, including the evolution of methods and apparatus, fundamental changes in understanding and operational efficiency in laboratories.

In many instances, the specific method chosen (e.g. exchangeable cations) is determined by one or more other attributes of the soil (e.g. pH), which must be determined prior to selecting the method. There are also instances where no single method is perfect and the level of uncertainty associated with any method is high. For all methods, estimates of error and uncertainty must be included in reports. See Section 5.2 for more information on soil analysis.

4.9 Grouping site data

Site data should be grouped or organised into similar soil types, preferably based on similar landform and/or parent material, as displayed on most Queensland Government soil maps. This allows correlation with other mapping, as described below. Where appropriate, soil types may be grouped and mapped into soil management units, but the basis of such grouping must be clearly demonstrated.

4.10 Soil classification

Soil classification serves many purposes, the primary of which is a communication tool. The national soil classification for Australia is the *Australian Soil Classification* (Isbell 2002) and all

[28] This replaces Rayment and Higginson (1992).

profiles should be classified using this scheme to at least the Great Group level. Use of other schemes is acceptable but they should not be used in place of the ASC.

4.11 Soil correlation to existing mapping (where available)

Correlation of both sites and UMA/polygon data to existing soil data should always be undertaken. The correlation process is part of demonstrating a critical understanding of the attributes of a soil or map unit, and the way in which it relates to others. Where close correlation exists, it may be possible to use data from previous assessments in that locality or on similar soil types/landscapes, for example, plant available water capacity (PAWC) and crop model parameter files in water balance modelling. Correlation cannot occur, however, without appropriate profile descriptions.

5. Sampling and laboratory analysis

The number of soil profiles that are sampled for physical or chemical analysis in the laboratory will vary depending on the scale of the survey and the size of the area being investigated (Figure 18). As a minimum, 10% of sites should be sampled, providing at least one representative site for each soil type to be irrigated, and preferably more for the major soil types, or soils where their suitability for irrigation is questionable. For small survey areas (<50 ha) the number of sites sampled should be 25–50%. The value of archived samples for baseline measurements cannot be understated—just because a sample is collected, doesn't mean it needs to be analysed straight away. The figures given above, however, are the minimum number of samples that should be analysed and reported at the time of survey.

Any laboratory used must be NATA[29] accredited (for each method) and preferably ASPAC[30] accredited. Most laboratories offer standard suites of analytes, related to method preferences suited to available equipment and operational efficiency.

5.1 Sample collection

The aim of soil sampling should be to characterise the variability in soil physio-chemical properties with depth. Many guidelines are available regarding general methods of sample collection, often from companies providing an analytical service. Publications such as Baker and Eldershaw (1993) also provide some useful advice. DNRM uses standard sample depths of 0–10, 20–30, 50–60, 80–90, 110–120, 140–150, 170–180 cm etc, particularly for uniform or gradational soils, and this is the recommended sampling intensity for soil surveys in areas using CSG water for irrigation. However, these depths must be modified to ensure that significant horizon boundaries (e.g. an A2e/B2 boundary) are not crossed in the sample. This is particularly the case for texture contrast soils. Field tests for pH and EC may be necessary to determine the exact location of critical horizon boundaries in some soils, in particular pH inversion Vertosols[31].

In some circumstances, the sampling intensity can be altered, but the basis for doing so must be clearly demonstrated. For example, sampling intensity may be reduced if existing data is available which shows little variation in soil physio-chemical properties with depth. Altering the sampling intensity to suit specific test requirements (e.g. keeping sample increments contiguous and narrow—such as every 10 cm—when undertaking chloride balance analysis) may also be appropriate. However, there are some aspects of sampling intensity which must always be adhered to:

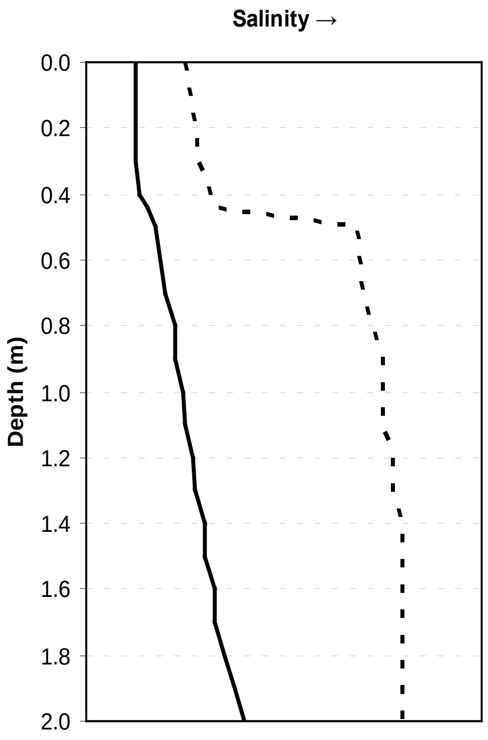
- In the top one metre of the soil profile
    - the maximum sample thickness should not exceed 20 cm

[29] National Association of Testing Authorities, Australia <http://www.nata.asn.au/>
[30] Australasian Soil and Plant Analysis Council Inc <http://www.aspac-australasia.com/>
[31] pH inversion Vertosols have an alkaline upper profile and a strongly acidic lower profile. The horizons are difficult to discern visually therefore field pH testing ensures horizon boundaries are not crossed in a sample.

    - the maximum sampling interval should not exceed 30 cm;
- Below one metre
    - the maximum sample thickness should not exceed 30 cm
    - the maximum sampling interval should not exceed 50 cm;
- Samples should not span significant horizon boundaries;
- Samples should not be bulked between sites[32]; and
- Samples must be from a described site (essential landscape and soil profile attributes).

Figure 53 illustrates the standard sampling intensity and an adjusted sampling intensity. If the standard sampling intensity approach is followed, a total of eight samples are collected from the surface to two metres depth. If an adjusted sampling intensity is used (for example, if existing data is available indicating little change in soil chemical properties with depth, like the solid line in the graph), then a total of six samples are collected. Regardless of the sampling intensity approach, four samples must always be collected in the top one metre of the profile.

The top one metre of the soil profile is sampled more intensely for several reasons:
- The most rapid changes in soil morphological and chemical characteristics usually occur in the top one metre;
- The majority of nutrients and water for plant uptake are found in the top one metre (the top 10 cm is the most critical zone—surface fertility samples (0–10 cm) are traditionally taken from a bulk sample (6–9 points) around the sample site); and
- The effective rooting depth for many annual species is about one metre.



Profile depth (cm)	Standard sampling intensity	Low sampling intensity
0	]	]
10	]	]
20	]	
30	]	
40		]
50	]	]
60	]	]
70		]
80	]	
90	]	
100		]
110	]	]
120	]	]
130		]
140	]	
150	]	
160		
170	]	]
180	]	]
190		]
200	]	]
210	]	

Figure 53 Approaches to sampling intensity

In the example given above it is clear that a reduced sampling intensity in the top one metre could miss establishing where the change in salinity occurs for the dashed line profile, whereas it would be less significant for the profile illustrated by the solid line.

[32] Multiple cores at a site are acceptable, but should span as short a horizontal distance as possible.

Soil samples should constitute at least 0.3 kg each to allow sufficient sample for physical and chemical analysis. As stated earlier, just because a soil sample is collected, does not mean it needs to be analysed. However, it is much more cost effective and efficient to collect as many samples as possible when a site is initially investigated and described, rather than spend time re-visiting a site to collect additional samples.

5.1.1 Soil sample care

It is important that soil samples are handled appropriately, for example:

- Samples may be collected using plastic or paper bags (or other containers)—the choice of which is not critical unless moisture sampling is being undertaken;
- Where soil moisture is being measured, either sealable tins or zip lock bags are suitable for sample transportation
- Cross-contamination between samples should be prevented;
- Steps should be taken to ensure the integrity of sample identification, e.g. use waterproof labels/ensure all samples from the one site are stored together in one large bag;
- Where necessary, appropriate chain of custody procedures should be followed;
- Samples should not be taken from atypical areas (e.g. stock camps, dam sites), within 10 to 20 m from current/old fence lines, headlands, paddock corners, dung/urine patches or other significantly disturbed areas (unless information about these specific areas is needed);
- Do not allow bagged samples to “cook” in the sun—this is particularly relevant for attributes such as nitrate and moisture content;
- Avoid field contamination of samples—in particular ensuring that oil lubricants are not used with hydraulic tube samplers when sampling for carbon; and
- Samples should be stored and transported appropriately and analysed as soon as possible after collection.

5.2 Sample analysis

All analyses should be undertaken with a specific function in mind, e.g. to assess fertility, to characterise historical drainage, to parameterise a model, or to characterise a soil type. As discussed above, all analysis should be undertaken by accredited laboratories following the methods outlined in Rayment and Lyons (2010) and McKenzie *et al.* (2002). Standard analytes include:

- pH, EC, Cl (all on 1:5 soil water ratio);
- exchangeable cations, (E)CEC[33], ESP (calculated);
- particle size analysis;
- air dry moisture content (ADMC), moisture characteristic (1/3, 15 bar);
- fertility suite (macro and micronutrients);
- organic carbon, total nitrogen, available P;
- sulphate; and
- total P, K, S.

Other analyses might include:

- threshold electrolyte concentration (TEC) curves;
- hydraulic conductivity;
- bulk density and plant available water capacity (PAWC);
- carbonate content; and
- gypsum content.

[33] Effective Cation Exchange Capacity (ECEC) is the sum of exchangeable calcium, magnesium, potassium, sodium and aluminium ion equivalent concentrations.

Some of these analyses (such as available P) are primarily required for agronomic assessment, while others (such as Cl) are necessary for both salinity and agronomic purposes. Many of these analyses are conducted only in a laboratory, while others involve measurements from both the field and the laboratory. In instances where good profile descriptions and correlation to other relevant research and assessments have been proven, or there is existing site/analytical data from other sources (e.g. DNRM), the number of analyses undertaken may be reduced.

Threshold electrolyte concentration (TEC) curves
TEC curves illustrate the relationship between salinity and sodicity for a soil sample. They are used to determine the point at which a given reduction in hydraulic conductivity occurs. The generic curve (Figure 54) is only semi-quantitative. For high Na waters (such as CSG water), they are a useful tool for determining whether problems with reduced infiltration are likely to occur.

The TEC and soil stability lines should be established for each specific site, taking local soil properties into consideration. Samples of soils to be irrigated should be analysed using the water specific for the proposed CSG irrigation area. The soils used should have other attributes (morphology, chemistry) characterised to enable correlation with other analysed sites. Additional sampling will usually be required to develop site-specific TEC curves e.g. 0–20, 20–50 and 50–80 cm.

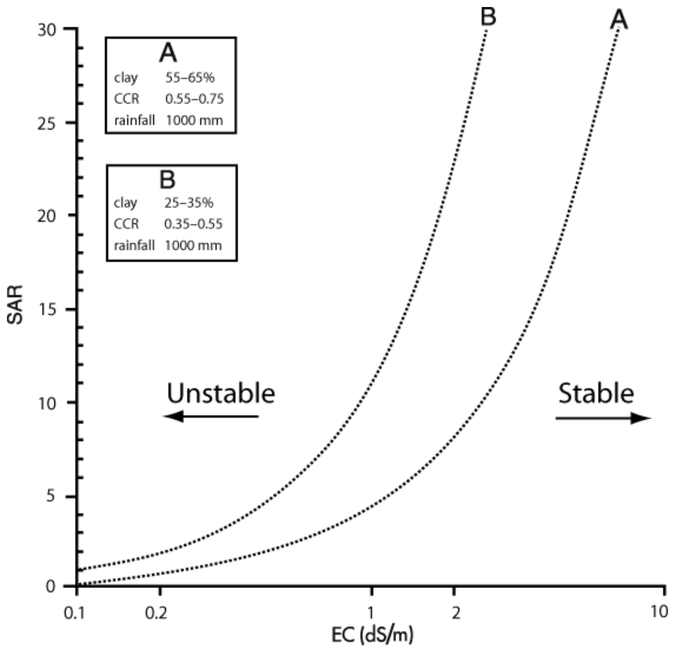


Figure 54 Threshold lines for two soils of different clay content and mineralogy for a 25% reduction in hydraulic conductivity.

This graph shows the soil EC required to maintain a soil structure for two soils of different texture and various soil ESP levels, with an annual rainfall of 1000 mm. The soils are unstable in the areas to the left of the lines, and increasingly stable to the right of the lines. (Source: Modified from SalCon 1997).

Sample collection should account for changes in soil chemistry down the profile. For example, most cracking clay soils in the region have a large increase in sodicity with depth, thus generating a TEC curve for only the soil surface does not represent the full scenario for that soil.

Bulk density and PAWC
Plant available water capacity (PAWC) and bulk density measurements[34] are required for many calculations and models. In the short-term (for instance for initial crop/water balance modelling) they may be estimated, particularly if there is existing data for correlated soil types of the area. In the longer term, appropriate measurements should be made at the site of interest. If using estimates, examination of error bounds should occur e.g. ± 25%.

PAWC should be measured in the field using the method described by Dalgliesh and Foale (2005). For greenfield areas, pasture can be used in place of crops for initial measurements, but subsequent measurements should be made to confirm the value for the crop(s) grown. Bulk

[34] Instructions for calculating bulk density are provided in Appendix 4: Investigating the unsaturated zone

density for shrink/swell soils should be derived at drained upper limit (DUL). The dimension of a core (2", 3" or 4") is less critical than the moisture content at which the bulk density samples are obtained. DUL and bulk density measurements can be derived from the same wet-up site.

6. Agricultural land suitability assessment

Agricultural land suitability assessment is a defined process for determining whether a given land use can be conducted sustainably on a specified soil type/landscape. The methods for agricultural land suitability assessment in Queensland are described in LRB (1990) and must be applied to the assessment of proposals involving irrigation with CSG water. The soil survey described in Section 5 is the principal source of data for the assessment. Data is described for each polygon/unique mapping area (UMA) within the survey, and compared to crop growth requirements (to create suitability rules). The attributes described for each UMA are those required across the range of land uses being assessed. Some are a feature of the landscape (e.g. slope, flooding, climate), while others are a feature of the soil profile (e.g. fertility, moisture holding capacity). These attributes are expressed in terms of land use limitations. The limitations typically described are given in Table 20.

Table 20 Land use limitations identified for agricultural land uses in Queensland

Code	Limitation	Land use requirement
A	Wind erosion	Minimum soil loss from wind erosion
C	Climate	Favourable climate (may be a combination of other climatic limitations)
Cf	Frost	Frost free
Cr	Solar radiation	Adequate solar radiation
Ct	Temperature	Favourable temperature conditions
Ch	Humidity	Favourable humidity
Cp	Precipitation	Favourable rainfall
Cw	Wind	Favourable wind conditions
D	Drainage water hazard	Low level of off-site effects from drainage water
Da	Drainage water hazard (from acid sulfate/pyritic soils)	Low level of off-site effects specifically from toxic quantities of acid, aluminium, iron and heavy metals associated with acid sulfate soil leachate
E	Water erosion hazard	Minimum soil loss from water erosion
Es	Subsoil erosion hazard	Minimum soil loss from subsoil (from water erosion)
F	Flooding	Absence of damaging floods
I	Furrow infiltration	Efficient furrow irrigation
M	Water availability	Adequate soil water supply
N	Nutrient supply	Favourable nutrient conditions
Nd	Nutrient deficiency	Adequate nutrient supply
Nf	Nutrient fixation	Nutrient fixing conditions
Nl	Nutrient leaching	Adequate retention of added nutrients against leaching
Nr	Nutrient-soil reaction trend	Satisfactory soil reaction in root zone
Nt	Nutrient toxicity	Low level of toxic elements
P	Soil physical factors	Favourable soil physical conditions
Pa	Soil adhesiveness	Ability to harvest underground crops
Pc	Susceptibility to compaction	Minimum soil compaction
Pd	Soil depth	Adequate soil depth for plant physical support

Code	Limitation	Land use requirement
Pm	Narrow moisture range	Suitable timing for cultivation
Pp	Excessive permeability	Ability to pond water
Ps	Surface condition	Ease of seedbed preparation, no restriction to germination
Pv	Vertic properties	Avoid vertic properties that affect engineering and some plants
R	Rockiness	Rock free
S	Soil salinity	Favourable salinity conditions in general
Sa	Salinity	Favourable levels of soluble salts
Si	Intake potential	Minimum potential to cause secondary salting
Ss	Outflow potential	Minimum susceptibility to secondary salting
T	Topography	Slope influences water management, ease of development and erosion control
Tg	Gullies	Land surface free of gullies
Tm	Microrelief	Level land surface
Ts	Slope	Safe and efficient use of machinery
V	Vegetation	Free of a general vegetation restriction to use (density, species etc)
Vr	Vegetation regrowth	Free of vegetation regrowth problems (rate, density)
W	Wetness	Adequate soil aeration
X	Landscape complexity	Adequate production areas, uniform production areas
Xs	Soil complexity	Complex distribution of managerially different soils
Xt	Topographic complexity	Complex distribution of managerially different slopes etc
Z	Pests and diseases	Absence of soil borne diseases and pathogens

The purpose of agricultural land suitability assessment in the context of CSG water irrigation development is to:

1. Demonstrate that the intended land use is sustainable and agronomically viable, given the existing technological and economic conditions;
2. Identify crops that would be suitable;
3. Define irrigation measures/methods required for sustainable development; and
4. Ensure proposed activities will not result in degradation of the soil and surrounding landscape.

These assessments should occur for irrigation development regardless of specific issues to do with CSG water. This is particularly important where crops new to the district (e.g. Pongamia) are being grown or greenfield development is occurring. In instances where existing dryland cropping land is being converted to irrigated land, a suitability assessment is still required because the quality and quantity of water applied needs to be considered. Land suitability rules exist for most agricultural zones of Queensland, for many different crop types.

The way in which limitations are evaluated varies. Some limitations are an expression of a single attribute or attributes that are clearly and explicitly defined, such as slope. Other limitations are described using a number of attributes, and the methods for describing those attributes can vary. Examples of the attributes and methods related to each limitation are given in Table 4.2 in the *Guidelines for agricultural land evaluation in Queensland* (LRB 1990) and reproduced/refined in Table 21.

Table 21 Summary of diagnostic attributes used to evaluate limitations

Code and Limitation	Diagnostic Attributes
A – Wind Erosion	• Soil surface texture • % dry aggregates less than 0.84 mm
C[$] – Climate	• General climatic conditions
Cf – Frost	• Frequency of damaging frosts • Landform, landscape position
Cr – Solar Radiation	• Cloud cover • Sunshine hours • Nett radiation
Ct – Temperature	• Mean monthly temperature during growing period • Mean monthly maximum and minimum temperatures during growing period • Number of days outside a critical range during growing period
Ch – Humidity	• Relative humidity • Average rain days
Cp – Precipitation	• Annual average rainfall, drought periods • Seasonality and episodicity of rainfall
Cw – Wind	• Slope, aspect • Wind run
D – Drainage Water Hazard	• Depth to watertable • Texture, structure, permeability • Substrate properties
Da – Drainage Water Hazard (from acid sulfate / pyritic soils)	• Depth to watertable • Texture, structure, permeability • Substrate properties • Presence of acid sulfate soil conditions
E – Water Erosion Hazard	• Slope/soil type combinations • Slope length • Amount, intensity and distribution of rainfall
Es – Subsoil Erosion Hazard	• Depth to B horizon • Exchangeable sodium percentage (ESP), electrical conductivity (EC) • Cation exchange capacity and Ca/Mg ratio
F – Flooding	• Frequency of flooding, period of inundation • Landform • Rainfall intensity/duration
I – Furrow Infiltration	• Infiltration rate/slope combinations • Surface horizon thickness, texture and structure • Slope • Depth to slowly permeable B horizon • Surface stability with irrigation • Degree of mottling
M – Water Availability	• Amount and distribution of rainfall, evaporation • Plant available water capacity, unavailable water capacity • Texture, structure, effective rooting depth • Gravimetric moisture contents at –10, -33 and -1500Kpa • Depth of water able • Height of capillary rise
N[$] – Nutrient Supply	• General nutrient conditions
Nd – Nutrient Deficiency	• Chemical analysis of elements availability
Nf –Nutrient Fixation	• Al or Fe oxide content, organic matter content • Nutrient sorption measurements • Soil colour
Nl – Nutrient Leaching	• Soil type, soil colour • CEC, soil texture • Soil base saturation • Soil organic matter content

Code and Limitation	Diagnostic Attributes
Nr – Nutrient-soil Reaction Trend	• Soil pH
Nt – Nutrient Toxicity	• Chemical analysis of element levels • Soil pH
$P^{\$}$ – Soil Physical Factors	• General soil physical conditions
Pa – Soil Adhesiveness	• Consistence • Clay percentage, clay mineralogy • Soil type
Pc – Susceptibility to Compaction	• Soil type, clay mineralogy • Compaction tests (e.g. liquid limit, plastic limit)
Pd – Soil Depth	• ESP profile, salinity profile, pH profile • Depth to watertable, presence of roots • Soil texture, structure and consistence • Depth to impermeable horizon, depth to hardpan or rock
Pm – Narrow Moisture Range	• Soil type • Surface soil texture, clay mineralogy • Liquid limit, plastic limit, linear shrinkage
Pp – Excessive Permeability	• Field permeability measurements • Depth and texture of A horizon and B horizon • Shape of salinity profile • Soil colour • Depth to and degree of mottling
Ps – Surface Condition	• Structure / texture / consistence and condition of soil surface
Pv – Vertic Properties	• Evidence of cracking, linear shrinkage • Texture • Clay type (measured or estimated via clay activity ratio (CAR)) • Liquid limit, plastic limit
R – Rockiness	• Size and content of coarse fragments • Distribution of coarse fragments in the plough zone • % rock outcrop
$S^{\$}$ – Salinity	• General salinity conditions
Sa – Salinity	• Mean root zone salinity EC_{se} or $EC_{1:5}$ • Leaching fraction • Indicators of restricted drainage (refer permeability limitation) • Depth to saline watertable
Si – Intake Potential	• Landscape position • Soil colour, texture and structure • Soil pH profile, salinity profile • Field permeability measurement • Substrate • Vegetation type
Ss – Outflow Potential	• Landscape position • Soil colour, texture and structure • Soil pH profile, salinity profile, ESP profile • Substrate • Depth to watertable • Vegetation type
$T^{\$}$ – Topography	• General topographic conditions
Tg – Gullies	• Size and frequency of small gullies
Tm– Microrelief	• Size and frequency of microrelief • Land levels
Ts – Slope	• Slope %
$V^{\$}$ – Vegetation	• Vegetation type • Presence of specific species
Vr – Vegetation Regrowth	• Vegetation type • Presence of specific species • Propensity to sucker • Growth rates
W – Wetness	• Depth to and degree of soil mottling

Code and Limitation	Diagnostic Attributes
	• Soil colour, soil drainage class • Field permeability measurements • ESP • Native vegetation • Time period with a redox potential (Eh) below 400mV • Time period of water saturation • Soil structure and texture
X$ – Landscape Complexity	• Size and shape of areas between large gullies • Size and shape of areas of suitable land types • Suitability of contiguous UMAs
Xs – Soil Complexity	• Variability of soil types
Xt – Topographic Complexity	• Variability of managerially different slopes
Z – Pests and Diseases	• Presence of pest or disease organisms

Source: Modified from Table 4.2, LRB (1990)
$ may be a combination of individual limitations

7. Data interpretation and presentation

Data should be presented in a clear, concise manner with an appropriate level of interpretation. As software has evolved, the capacity to display data in innovative ways on maps or in reports has also improved. No standards exist but some examples are given below. Recent publications (e.g. Harris *et al.* 1999, Harms and Main 2006 and others such as McKenzie *et al* 2004) provide good examples of presentation layout for many different types of data.

7.1 Mapping

All maps should follow cartographic conventions, and include the following:

- Scale for polygonal data, cell size and scale for rasters;
- North arrow;
- MGA grid;
- Appropriate locality data e.g. towns, administrative boundaries;
- Legend;
- Due reference to data sources and currency of data;
- Date of preparation; and
- Statement of any limitations of the data/map e.g. related to scale, accuracy, reliability.

Location of soil profile descriptions and sampling sites must always be provided on a suitable map such as a soil/landscape map (Figure 55). Analytical or morphological data may benefit from being displayed graphically on maps.

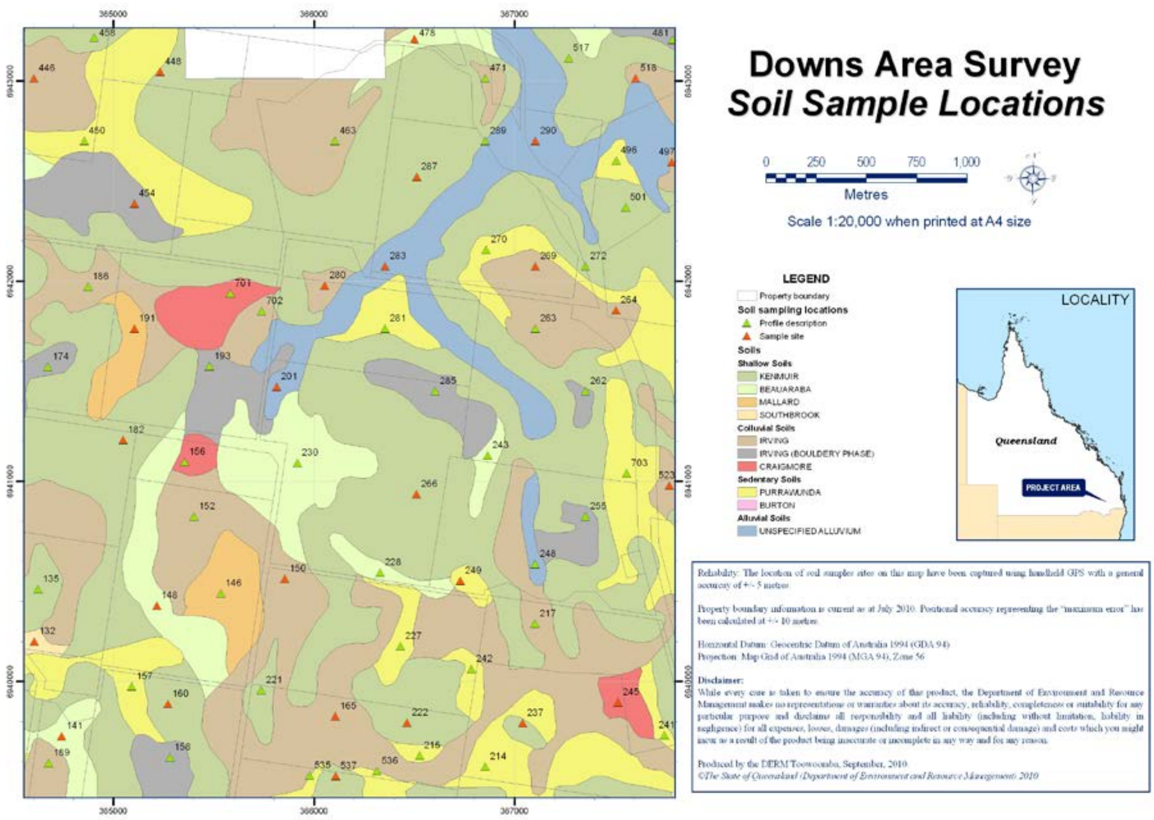


Figure 55 Example soil map with site locations shown

7.2 Site data

All site descriptions should be provided in submitted reports. Site descriptions may be provided in either coded or decoded format. Descriptions should include soil classifications and correlations and where relevant, analytical or related data.

7.3 Analytical data

Description of analytical method, quantification limits and correlation to method codes from Rayment and Lyons (2011) or other appropriate references should be given for all reported data. Where conversions have been applied (e.g. $EC_{1:5}$ to EC_{se}), the conversion algorithm should be provided. If ratings are used (e.g. low, medium, high), then the rating categories should be explicitly defined. Data should be presented in the appropriate units (see Table 22).

Inference between sample intervals is often required. There are many methods for doing so (e.g. cubic splines), but any method used should be statistically appropriate for the data and must be clearly stated.

Table 22 Guidelines for reporting analytical data

	Result Code	Analysis Description	Method Code[A]	Uncertainty %	Limit of Quantitation	Unit	Method Used	Reporting Basis
1:5 soil/water (aqueous) analysis	pH	pH (H_2O)	4A1	5	0.1	–	Aqueous 1:5, electrode	Air dry (48 hrs at 40°C)
	EC	Electrical conductivity	3A1	10	0.01	dS/m	Aqueous 1:5, electrode	Air dry (48 hrs at 40°C)
	Cl	Chloride	5A2	10	20	mg/kg	Aqueous, 1:5 soil:water	Air dry (48 hrs at 40°C)
	NO_3-N	Nitrate nitrogen	7B1	15	1	mg/kg	Aqueous 1:5, colorimetry	Air dry (48 hrs at 40°C)
Moisture	ADMC	Air dry moisture content	2A1	8	1.5	%	Air dry moisture content	Air dry (48 hrs at 40°C)
	Moist WP	~ permanent wilting point	2E1	15	1.5	%	15 Bar, pressure plate	Air dry (48 hrs at 40°C)
Particle size analysis	CS	Coarse sand fraction	–	10	1	%	Reciprocating shaker dispersion (in solution of sodium hexa metaphosphate) – gravimetric determination for sand fractions, hydrometer for silt and clay[B]	Oven dry (48 hrs at 105°C)
	FS	Fine sand fraction	–	8	1	%		
	SIL	Silt fraction	–	8	1	%		
	CLA	Clay fraction	–	5	1	%		
Dispersion	R1	Dispersion ratio	–	8	0.1	–	Aqu. Silt+Clay/Total Silt+Clay	Air dry (48 hrs at 40°C)
Exchangeable cations ('aqueous')	ECEC	Effective cation exchange capacity	15J1	0	0.03	cmol(+)/kg	Sum of exch. bases (Ca+Mg+Na+K) plus exchange acidity (exch. Al+H)	Oven dry (48 hrs at 105°C)
	Ca	Calcium	15A1_Ca	10	0.14	cmol(+)/kg	Aqueous 1M NH_4Cl at pH 7.0	Oven dry (48 hrs at 105°C)
	Mg	Magnesium	15A1_Mg	10	0.3	cmol(+)/kg	Aqueous 1M NH_4Cl at pH 7.0	Oven dry (48 hrs at 105°C)
	Na	Sodium (± correction)[C]	15A1_Na	10	0.08	cmol(+)/kg	Aqueous 1M NH_4Cl at pH 7.0	Oven dry (48 hrs at 105°C)
	K	Potassium	15A1_K	10	0.03	cmol(+)/kg	Aqueous 1M NH_4Cl at pH 7.0	Oven dry (48 hrs at 105°C)
Exchange acidity	Al	Exch. aluminium	15G1_Al	10	0.03	cmol(+)/kg	Exchangeable Al^{3+} by 1M KCl	Oven dry (48 hrs at 105°C)

	Result Code	Analysis Description	Method Code[A]	Uncertainty %	Limit of Quantitation	Unit	Method Used	Reporting Basis
	H+	Exch. H^+	15G1_H	10	0.03	cmol(+)/kg	Exchangeable H^+ by 1M KCl	Oven dry (48 hrs at 105°C)
Exchangeable cations (‘alcoholic’)[D]	CEC	Cation exchange capacity	15C1_CEC	10	3	cmol(+)/kg	Cation exch. capacity pH 8.5 – measured after displacing NH_4^+ (and Cl^-)	Oven dry (48 hrs at 105°C)
	Ca	Calcium	15C1_Ca	10	0.18	cmol(+)/kg	Ethanolic 1M NH_4Cl at pH 8.5	Oven dry (48 hrs at 105°C)
	Mg	Magnesium	15C1_Mg	8	0.31	cmol(+)/kg	Ethanolic 1M NH_4Cl at pH 8.5	Oven dry (48 hrs at 105°C)
	Na	Sodium	15C1_Na	10	0.091	cmol(+)/kg	Ethanolic 1M NH_4Cl at pH 8.5	Oven dry (48 hrs at 105°C)
	K	Potassium	15C1_K	12	0.015	cmol(+)/kg	Ethanolic 1M NH_4Cl at pH 8.5	Oven dry (48 hrs at 105°C)
Total elements (XRF)	P	Phosphorus	9A1	5	0.015	%	Total P pressed powder, XRF	Oven dry (48 hrs at 65°C)
	K	Potassium	17A1	5	0.015	%	Total K pressed powder, XRF	Oven dry (48 hrs at 65°C)
	S	Sulfur	10A1	5	0.01	%	Total S pressed powder, XRF	Oven dry (48 hrs at 65°C)
Total Elements (dry furnace)	TC	Total carbon	6B4	5	0.05	%	High frequency induction furnace – Dumas	Oven dry (48 hrs at 105°C)
	TN	Total nitrogen (dry furnace)	7A7	5	0.03	%	High frequency induction furnace – Dumas	Oven dry (48 hrs at 105°C)
Extractable iron	Fe-cit	‘Free’ Fe	13C1	10	1.2	%	22% Na-citrate soln. and Na-dithionite	Oven dry (48 hrs at 105°C)
	Fe-oxa	‘Active’ Fe	13A1	10	0.1	%	Acid ammonium oxalate (pH 3.0)	Oven dry (48 hrs at 105°C)
Trace elements	Fe	Iron	12A1_Fe	10	0.1	mg/kg	0.005M DTPA extractable, ICP	Air dry (48 hrs at 40°C)
	Mn	Manganese	12A1_Mn	10	0.1	mg/kg	0.005M DTPA extractable, ICP	Air dry (48 hrs at 40°C)

	Result Code	Analysis Description	Method Code[A]	Uncertainty %	Limit of Quantitation	Unit	Method Used	Reporting Basis
	Cu	Copper	12A1_Cu	10	0.1	mg/kg	0.005M DTPA extractable, ICP	Air dry (48 hrs at 40°C)
	Zn	Zinc	12A1_Zn	10	0.1	mg/kg	0.005M DTPA extractable, ICP	Air dry (48 hrs at 40°C)
Other analyses (mainly surface soil fertility)	OC (WB)	Organic carbon	6A1	10	0.03	%	Org. Carbon, colorimetry (Walkley & Black)	Oven dry (48 hrs at 105°C)
	TKN	Total nitrogen (Kjeldahl)	7A2	10	0.01	%	Total N, Kjeldahl, colorimetry	Oven dry (48 hrs at 105°C)
	Extr. P(bic)	Phosphorus ('Colwell')	9B2	10	1	mg/kg	0.5M $NaHCO_3$ extr. colorimetry automated colour	Air dry (48 hrs at 40°C)
	Extr. P(acid)	Phosphorus ('BSES')	9G2	12	2	mg/kg	0.005M H_2SO_4 automated colour	Air dry (48 hrs at 40°C)
	Extr. K[D]	Extractable potassium	18B1	8	0.1	cmol(+)/kg	0.05M HCl extractable, flame	Air dry (48 hrs at 40°C)
	SO_4-S	Extr. sulfur ('sulfate sulfur')	10B3	10	1	mg/kg	0.01M $Ca(H_2PO_4)_2$ extr. ICP	Air dry (48 hrs at 40°C)

Notes:

[A] Rayment GE and Lyons DJ (2010). *Soil Chemical Methods – Australasia*. CSIRO Publishing, Collingwood, Victoria.

[B] Thorburn PJ and Shaw RJ (1987). Effects of different dispersion and fine fraction determination methods on the results of routine particle size analysis. *Australian Journal of Soil Research*. **25(4):** 347–360.

[C] Where the soil $EC_{1:5}$ exceeds 0.3 dS/m, a correction based on the concentration of Cl^- is used to adjust the apparent level of exch. Na^+ present in the soil (i.e. method 15A3_Na).

[D] Extr. K measures exch. K plus some non-exch. K. To convert to mg/kg, multiply the cmol(+)/kg value by 390.

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Appendix 3: Irrigation suitability requirements

1. Irrigation suitability framework

The process for assessing agricultural land suitability in Queensland is described in LRB (1990). The process aligns with the Food and Agriculture Organization of the United Nations (FAO) guidelines, and utilises the concept of limitations and five suitability classes (see Table 23). Some limitations are generic across all land uses (e.g. soil depth), while others may only affect certain land uses (e.g. certain nutrient limitations).

Table 23 Agricultural suitability class definitions

Class	Description
Class 1	Suitable land with negligible limitations. This is highly productive land requiring only simple management practices to maintain economic production.
Class 2	Suitable land with minor limitations which either reduce production or require more than the simple management practices of Class 1 land to maintain economic production.
Class 3	Suitable land with moderate limitations which either further lower production or require more than those management practices of Class 2 land to maintain economic production.
Class 4 `	Marginal land which is presently considered unsuitable due to severe limitations. The long term significance of these limitations on the proposed land use is unknown. The use of this land is dependent upon undertaking additional studies to determine whether the effects of the limitation(s) can be reduced to achieve sustained economic production.
Class 5	Unsuitable land with extreme limitations that preclude its use.

Source: LRB (1990)

The agricultural land suitability assessment process includes three distinct steps, outlined below, and expressed diagrammatically in
Figure 56.

Step 1
The primary step occurs as an integral part of modern soil/land resource mapping. It involves establishing the degree to which the various limitations are expressed within each unique mapping area (UMA). The possibility exists of more than one soil type within a UMA. This is catered for by recording the limitation levels for each soil. The result is data for each limitation, for each soil, within each UMA. Limitations identified for agricultural land uses are shown in Table 24, and described in more detail in Section 3.

Step 2
For each land use assessed, it is necessary to express the requirements for that land use in terms of the same soil and land limitations listed above. The development of these land use "rules" is achieved by canvassing experienced technical and extension staff, landholders and scientific literature. They are developed using certain assumptions and qualifications. The nature of the framework is such that it is possible to easily modify any of the rules, and regenerate the suitability assessment.

Step 3
Interpolation between the requirements for a specific land use, and the specific limitations of each UMA, will result in a ranking for each limitation within each UMA (for each land use). The ranking system uses a scale of one to five, as described in Table 23.

The limitation expressed to the greatest degree (i.e. the highest number) with regards to effect on land use, will be the most limiting factor within a UMA and is assigned to a UMA for the land use being considered. A map of land suitability may then easily be developed. For example, a UMA may contain all limitations favourable to the cropping of wheat (classes 1-3), except for excessive rock levels (class 5). The rockiness is therefore the most limiting factor and the UMA would be suitability class 5 for wheat.

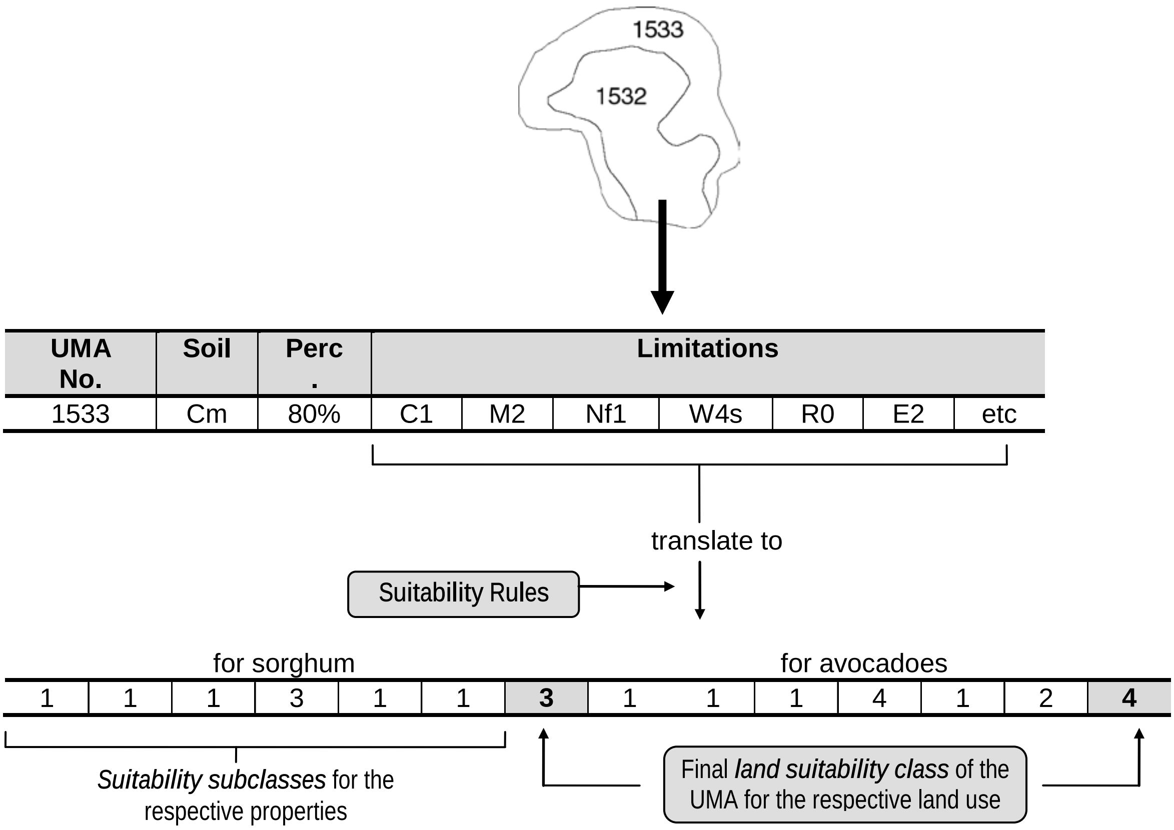

Figure 56 The agricultural land suitability assessment process
Source: Adapted from Biggs and Philip (1995).

The resultant data is usually expressed visually as a map of land suitability class for each land use. In some instances, a number of land uses may have similar requirements, and therefore may be grouped together.

A simplistic preliminary assessment of irrigation suitability of land systems (Step 2 of the process described above—the development of 'suitability rules') was undertaken as part of Activity 3 and the results are presented in Section 3 of this appendix. The assessed land use requirements and corresponding limitations identified for agricultural land uses are shown in Table 24.

Land use requirements are those requirements applicable to all agricultural land uses within the project area. Land use requirements are those which can be expressed as those affecting plant growth, machinery use, grazing or land degradation control. *Limitations* are those which restrict the fulfilment of the requirements in the project area.

The land uses chosen for assessment in this project were:

- Drip irrigated spotted gum
- Drip irrigated Chinchilla white gum
- Spray (pivot) irrigated leucaena
- Spray (pivot or lateral move) irrigated winter and summer cereal crops
- Spray (pivot or lateral move) irrigated grass and legume improved pastures.

All spray irrigation was assumed to be low to medium pressure emitters at a height appropriate for the inter-row pasture or crop.

The crop codes used in the assessment are shown in Table 25.

Attributes of the land which measure or estimate the degree to which the defined land uses are limited are given in Table 26.

Table 24 Land use requirements and corresponding limitations identified for agricultural land uses in the project area

Land Use Requirements	Limitations
Requirements affecting plant growth	
Frost free	Frost (Cf)
Rock free	Rockiness (R)
Absence from flooding	Flooding (F)
Adequate nutrient supply	Nutrients (N)
Adequate water supply	Moisture Supply (M)
Favourable level of soluble salts	Salinity (S)
Favourable wind conditions	Wind erosion (A)
Absence (or close thereof) of erosion	Water Erosion (E)
Absence of hardsetting or crusting conditions during germination	Physical condition (P)
Requirements for machinery use	
Free of large rocks	Rockiness (R)
Level land surface or surface of acceptable slope	Slope (A)
Adequate trafficability	Wetness (W)
Ease of seedbed preparation	Physical Condition (P)
Land surface free of washouts and gullies	Topography (T)
Land surface free from large melon hole gilgai	Topography (T)
Requirements affecting control of land degradation	
Minimum soil loss from water erosion	Water erosion hazard (E)
Minimum soil loss from wind erosion	Wind erosion hazard (A)
Minimum land damaged from floods	Flooding (F)
Minimum potential to cause secondary salting	Secondary salting hazard (S)

Table 25 Crop code descriptions used for limitations

Crop Code	Description
CWG	Chinchilla White Gum
SG	Spotted Gum
L	Leucaena
WC	Winter crops
SC	Summer crops
GP	Grass pastures
LP	Legumes pastures

Table 26 Summary of land/diagnostic attributes used to evaluate limitations

Limitation	Land Attributes	Limitation	Land Attributes
Wind Erosion Hazard (A)	• Erodibility (texture, structure, surface condition, mineralogy) • Moisture • Groundcover • Roughness	Soil Physical Condition (P)	• Crusting • Hardsetting • Narrow moisture range for working • Pans, compaction layers
Climate – Frost (Cf)	• Landscape position • Frequency of frosts • Severity of frosts • First and last date of frosts	Rockiness (R)	• Size • Shape • % of surface and plough layer affected
Water Erosion Hazard (E)	• Amount and intensity of rainfall • Slope/soil type • Erodibility (texture, structure, surface condition, mineralogy)	Secondary Salting Hazard (S)	• Outflow/discharge potential (Ss) • Intake recharge potential (Si) • Primary salinity in soils and rocks • Groundwater tables
Flooding (F)	• Frequency and duration	Soil Salinity (Sa)	• Root zone salinity • Chloride • Depth to saline watertable • Leaf burn in plants
Moisture Supply (M)	• Plant available water capacity • Evaporation • Amount and distribution of rainfall • Effective soil depth • Depth of rooting • Texture profile • Structure	Topography (T)	• Gilgai • Size (horizontal and vertical interval) • Shape, type, configuration • Complexity, variability in morphology • Broken topography, erosion • Size of production areas
Soil Nutrition (N)	• Deficiencies (N, P, K, Zn, Cu, Mo) • Decline with utilisation • pH	Wetness (W)	• Runoff, permeability, drainage • Soil structure • Soil colour

2. Water quality required for irrigation

As outlined in the main report, irrigation with raw untreated CSG water would have a major adverse impact on soil stability, permeability and infiltration rates—as confirmed by trials conducted by CSG producers (for example, Raine and Ezlit 2007). Based on CSG water chemistry to date, it is highly unlikely that irrigation with raw CSG water is sustainable and it is therefore not recommended.

The use of CSG water for irrigation is no different from the use of other water for irrigation provided the CSG water is suitably treated and amended to suit the soil conditions where irrigation takes place. It is imperative that the specific relationships between soil and water chemistry are investigated for any site being used for irrigation with CSG water.

3. Irrigation suitability land use limitations

This section provides an irrigation suitability framework based on the land use requirements and limitations (Table 24), proposed crops (Table 25) and land diagnostic attributes (Table 26) outlined in Section 2 of this appendix.

3.1.1. Limitation: Wind erosion hazard (A)

Effects

- Loss of productive surface soil
- Sandblasting and burial of plants
- Off-site effects (dust)

Diagnostic land attributes

- Surface condition
- Particle size distribution
- Moisture relations
- Organic matter
- Water repellence
- Calcium carbonate

Assessment

- Soil erodibility from wind is closely linked to aggregate and particle size; finer aggregates (<1 mm) are usually the most vulnerable to wind erosion
- Fine sand and silt are both wind mobile fractions in soils
- Annual crops are more susceptible to wind erosion than permanent crops

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
A1	Fine textured soils >25% clay (clay loam or heavier) except where strong self-mulching surface structure with <50% of aggregates <1 mm. *Barely perceptible erosion levels*	1	1	1	1	1	1	1
A2	Hardsetting, crusting or cloddy light textured soils 15–25% clay (sandy loam or heavier) or heavier soils where >50% of aggregates are <1 mm or where fine sand >30%. *Control of erosion requires conservation land management practices such as stubble retention and conservative stocking rates*	1	1	1	2	2	1	1
A3	Light textured soils, sandy loam or coarser with firm or soft consistence and/or fine sand <50% of sand fraction. *Control of erosion requires conservation land management practices such as stubble retention and conservative stocking rates and soil conservation structures*	2	2	2	3	3	2	2
A4	Loose soils, sandy loam or coarser with fine sand and/or silt >50%. *Control of erosion requires high levels of management inputs and specialised conservation land management practices such as windbreaks, permanent pastures and reduced stocking pressure*	2	2	2	3	3	3	3

3.1.2. Limitation: Climate – frost (Cf)

Effects

Frost causes yield reduction when coinciding with susceptible growth stages of most plants (e.g. germination, flowering). Frost occurrence influences planting date decisions and hence is a determinant of yield potential. Summer and winter crops are affected by frosts in different ways, with winter crops being tolerant of all but the heaviest of frosts during the majority of their life cycle.

Diagnostic land attributes

- First and last frost dates
- Frost incidence (frequency of frosts)
- Probability of frost coincident with susceptible growth stages

Assessment

The incidence and severity of frosts are used to distinguish frost susceptible areas. Upper slopes and ridges are more likely to be frost free, while footslopes, drainage depressions and alluvial plains are more likely to experience frosts. Depressions and channels along the floodplains experience the most severe frosts. Frost records are very limited or non-existent in most areas, so landholder knowledge is used. A light frost is defined as a crop temperature between approximately -4.5ºC (at which ice begins to form) to a minimum temperature of -5.5ºC. A heavy frost is any in-crop temperature below -5.5ºC. Temperatures below -5.5ºC have been found to cause significant plant damage.

Choice of planting time can be used to avoid frost impacts in annual crops, while perennial crops must be frost hardy, otherwise productivity (and water use) will decline during winter.

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
Cf0	Frost free	1	1	1	1	1	1	1
Cf1	Light frost (-4.5ºC to -5.5ºC)	1	3	3	1	1	2	2
Cf2	Heavy frost (below -5.5ºC)	2	4	4	2	2	3	3

3.1.3. Limitation: Water erosion hazard (E)

Effects

- Loss of productive topsoil (high levels of nutrients, organic matter, best conditions for emergence and moisture relations)
- Exposure of poor quality subsoils
- Reduction in moisture storage capacity
- Gullies restricting machinery use
- Off-site effects

Diagnostic land attributes

- Slope
- Erodibility (soil texture and aggregate stability)

Assessment

Tree crops (gums, leucaena) are most susceptible to erosion during the establishment phase. Stubble retention should be practiced as a matter of course in annual crops, regardless of slope. Floodplains with flow velocities exceeding 1 m/s require specific management actions to avoid concentrated flow.

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
E1	All soils with slope <1%, except floodplains with flow velocity >1 m/s. *Little erosion is likely*	1	1	1	1	1	1	1
E2	All soils with 1–3% slope, except Sodosols. *Control can be obtained with soil conservation practices, and by phasing development*	1	1	1	2	2	1	1
E3	All soils with 3–8% slope, and Sodosols (A horizon >0.5 m) up to 3% slope. *Control will require the adoption of soil conservation practices and structures*	2	2	2	3	3	2	2
E4	Sodosols (A horizon >0.5 m) 3–8% slope	3	3	3	4	4	3	3
E5	Sodosols (A horizon <0.5 m) >3% slope and all other soils with 8–15% slope. *Even with intensive soil conservation works, significant erosion and soil loss will occur from this class of land. Not recommended for cultivation*	4	4	4	4	4	4	4
E6	Floodplains with flow velocity >1 m/s	4	4	4	2	2	2	2

3.1.4. Limitation: Flooding (F)

Effects

Yield reduction or plant death can be caused by high water temperatures and/or silt deposition and/or anaerobic conditions induced during inundation. Physical removal or significant damage of plants and soil erosion can be caused by flowing water.

Assessment

Assessing the effects of flooding on an individual unique mapping area (UMA) is difficult. Flooding frequency has been used to distinguish between suitable and unsuitable land only in extreme frequency situations or for intolerant crops. Flooding records, local experience, landscape position and flood debris are used to distinguish affected areas.

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
F0	No flooding	1	1	1	1	1	1	1
F1	Flooding frequency of approximately less than 1 in 10 years	1	2	1	1	1	1	2
F2	Flooding frequency of approximately 1 in 5–10 years and/or has gilgai >0.30 m in depth	2	3	3	3	2	2	3
F3	Flooding frequency approaching 1 in <5 years	4	4	4	4	4	3	4
F4	Flooding frequency exceeding 1 in 2 years	5	5	5	5	5	4	5

3.1.5. Limitation: Moisture supply (M)

Effects

The availability of moisture to the plant is a major determinant of yield and production. In irrigated crops, moisture supply is much less of a limitation than dryland crops. Limited soil moisture storage capacity (via low plant available water capacity (PAWC)) can however increase the frequency (and therefore cost) of irrigation and the likelihood of the profile filling to saturation from a combination of irrigation and rainfall. Moisture availability is a complex factor that depends on the interaction between rainfall, infiltration, evaporation, drainage and the capacity of the soil to store water and supply it to plants.

Diagnostic land attributes

- Plant available water capacity (PAWC)
- Gravimetric moisture content at specified tensions
- Unavailable water

Assessment

PAWC may be estimated using:

- Traditional gravimetric moisture contents at specified tensions
- Application of regression models relating PAWC to soil attributes such as cation exchange capacity (CEC), exchangeable sodium percentage (ESP), electrical conductivity (EC), profile texture, and gravimetric moisture content at a specified tension, together with an estimate of effective rooting depth. Effective rooting depth may be assessed by observation of roots in the field, or by inference from Cl, EC, ESP, pH, carbonate, gypsum or other profile indicators.
- Field measurement of moisture contents associated with significant plant growth stages and seasonal conditions, such as after fallow pre-planting, just prior to harvest after heavy rainfall and during prolonged drought.
- Plant growth models can be used to predict yield probabilities commensurate with various levels of PAWC and other moisture characteristics.

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
M1	>150 mm PAWC to 1.2 m	1	1	1	1	1	1	1
M2	100–150 mm PAWC to 1.2 m	2	2	2	2	2	2	2
M3	50–100 mm PAWC to 1.2 m	3	3	3	3	3	3	3
M4	<50 mm PAWC to 1.2 m	4	4	4	4	4	4	4

3.1.6. Limitation: Soil nutrition (N)

Effects

Shortage of plant nutrients causes a reduction in plant growth and consequent reduction in yield and product quality. While many soils in southern inland Queensland have limiting levels of some plant nutrients, only a small proportion of crops, and very few pastures are fertilised. Under irrigated scenarios, nutrients generally become the most limiting factor to maximum yield/productivity. Deficiencies of P, N, K, S, Zn, Cu and Mo occur in some soils. Addition of N in broadacre farming systems is assumed to occur as a matter of course. A decline in levels of plant nutrients occurs over time with most land use types in the district, and the rate of decline is partially dependent on soil type. P fixation in some soils can significantly impact on the availability of applied P. The ability of soils to retain applied nutrients is also an important factor. In general, sandy soils are more prone to nutrient leaching than clay soils. Soil pH can affect availability of certain nutrients and lead to deficiencies or toxicities—in particular, Al toxicity when the pH is <5.5.

Diagnostic land attributes

- Concentration of nutrient in soil
- Rate of nutrient loss—related to clay content and type

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
Nd0	No nutrient deficiencies	1	1	1	1	1	1	1
Nd1	Low to moderate nutrient deficiency with moderate rates[35] of nutrient decline	2	2	2	2	2	2	2
Nd2	Moderate to high nutrient deficiency with high rates[36] of nutrient decline	3	3	3	3	3	3	3
Nd3	Very high nutrient deficiency—very low levels of macronutrients and/or multiple deficiencies[37]	4	4	3	4	4	4	4
Nf1	Low P fixation	1	1	1	1	1	1	1
Nf2	Mod to high P fixation (e.g. Red Ferrosols)	2	2	3	2	2	2	3
Nr1	pH <5.5 and texture >sandy clay loam	4	4	4	4	4	4	4
Nr2	pH 5.5–8.5	1	1	1	1	1	1	1
Nr3	pH >8.5	2	2	2	2	2	2	2

[35] Moderate rates of decline defined as >10 years of cultivation before change in management practices are required to increase mineralisation in the soil.
[36] High rates of decline defined as 5–10 years of cultivation before change in management practices are required to increase mineralisation in the soil.
[37] Low levels of macronutrients defined as <5 years of cultivation before change in management practices are required to increase mineralisation in the soil.

3.1.7. Limitation: Soil physical condition (P)

Effects

Soil physical properties affect many agronomic aspects of cropping systems, from germination through to harvest.

Effects of 'Moisture range for cultivation (Pm)'

- Important factor in determining the ability to cultivate a soil successfully
- Some soils can be cultivated at any moisture content; others can only be cultivated successfully over a very narrow moisture range
- Restricts timeliness of operations and hence limits yield potential
- Soils may be prone to structural damage if cultivated or driven on outside the desirable moisture range

Effects of 'Surface condition (Ps)'

- Physical barrier to emergence and water entry
- Difficulty in achieving required seedbed conditions
- Can be influenced by management practices (irrigation application, stubble)

Diagnostic land attributes

- Structure, consistence (strength of cohesion and adhesion in the soil)
- Particle size distribution
- Clay type (CEC/clay ratios)
- Organic matter content, dispersion
- Soil surface condition

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
Pm1	Wide moisture range	1	1	1	1	1	1	1
Pm2	Moderate moisture range	1	1	2	2	2	2	2
Pm3	Narrow moisture range	3	3	3	3	3	3	3
Ps1	Soils with soft or loose sandy surface horizons (S–SL); very coherent seed soil contact and not prone to slaking or sealing; fine self-mulching clays (<2 mm)	1	1	1	1	1	1	1
Ps2	Soils with soft, firm or only weakly hardsetting, sandy to loamy surface horizons (S–SCL); prone to moderate slaking and sealing; or self-mulching clays with a variable, fine to coarse (<2–5 mm) surface condition	2	2	2	2	2	2	2
Ps3	Coarse self-mulching clays (>2–5 mm); poor seed soil contact due to separation of large peds with drying; prone to slaking and weak sealing	2	2	2	3	3	3	2
Ps4	Clay soils with hardsetting, firm pedal or weakly self-mulching surface horizons; prone to significant slaking, sealing and coarse, cloddy structure	3	3	3	4	4	3	3
Ps5	Loamy or clayey surface soils (CL–LC, FS or Z) that are hardsetting, massive or only weakly structured; powdery, pulverescent and crusting	4	4	4	4	4	4	4

3.1.8. Rockiness (R)

Effects

Coarse fragments and rock in the plough zone will interfere with the efficient use of, and may cause damage to, agricultural machinery. Surface rock in particular interferes with harvester machinery for subsurface and ground crops such as peanuts and potatoes. Coarse fragments are particles greater than 2 mm not continuous with underlying bedrock (McDonald *et al.* 1990) and include rock fragments and segregations. Rock outcrop is defined as being continuous with bedrock.

Assessment

Visual assessment of the size, abundance (McDonald *et al.* 1990) and distribution of coarse fragments and rocks in the plough layer.

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
R0	No rock	1	1	1	1	1	1	1
Rf1	2–6 mm, 0–2%	1	1	1	1	1	1	1
Rf2	2–6 mm, 2–10%	1	1	1	1	1	1	1
Rf3	2–6 mm, 10–20%	1	1	1	1	1	1	1
Rf4	2–6 mm, 20–50%	1	1	1	2	2	2	2
Rf5	2–6 mm, >50%	1	1	1	3	3	3	3
Rm1	6–20 mm, 0–2%	1	1	1	1	1	1	1
Rm2	6–20 mm, 2–10%	1	1	1	1	1	1	1
Rm3	6–20 mm, 10–20%	1	1	1	2	2	2	2
Rm4	6–20 mm, 20–50%	1	1	1	2	2	2	2
Rm5	6–20 mm, >50%	2	2	2	3	3	3	3
Rg1	20–60 mm, 0–2%	1	1	1	1	1	1	1
Rg2	20–60 mm, 2–10%	1	1	1	1	1	1	1
Rg3	20–60 mm, 10–20%	1	1	1	2	2	2	2
Rg4	20–60 mm, 20–50%	2	2	2	3	3	3	3
Rg5	20–60 mm, >50%	3	3	3	4	4	4	4
Rc1	60–200 mm, 0–2%	1	1	1	1	1	1	1
Rc2	60–200 mm, 2–10%	1	1	1	2	2	2	2
Rc3	60–200 mm, 10–20%	2	2	2	3	3	3	3
Rc4	60–200 mm, 20–50%	3	3	3	4	4	4	4
Rc5	60–200 mm, >50%	4	4	4	5	5	5	5
Rs1	200–600 mm, 0–2%	1	1	1	1	1	1	1
Rs2	200–600 mm, 2–10%	2	2	2	3	3	3	3
Rs3	200–600 mm, 10–20%	3	3	3	4	4	4	4
Rs4	200–600 mm, 20–50%	4	4	4	5	5	5	5
Rs5	200–600 mm, >50%	5	5	5	5	5	5	5
Ro1	>600 mm or rock outcrop, 0–2%	1	1	1	2	2	2	2
Ro2	>600 mm or rock outcrop, 2–10%	2	2	2	3	3	3	3
Ro3	>600 mm or rock outcrop, 10–20%	3	3	3	4	4	4	4
Ro4	>600 mm or rock outcrop, 20–50%	4	4	4	5	5	5	5
Ro5	>600 mm or rock outcrop, >50%	5	5	5	5	5	5	5

3.1.9. Limitation: Secondary salinity risk (S)

Effects

The potential for secondary salinity to occur in a landscape is of significance in many agricultural uses, particularly where vegetation is removed and/or the hydrology of the landscape is altered in some way. Salinity risk is assessed using the methodology defined in Section 4 of the report. The predilection for a landscape to develop secondary salinity is a function of climate, geology, soil, vegetation, topography and hydrology.

If landscape salinity risk is assessed as per the framework outlined in this report, the resultant information may then be used to delineate areas of land unsuited to irrigation. This may be applied in a yes/no manner, or in a graduated manner as per other land suitability limitations.

3.1.10. Limitation: Soil salinity (Sa)

Effects

High levels of soluble salts in the soil have a number of effects, including:

- Reduced ability of plant to access moisture due to high osmotic potential
- May cause specific ion toxicity (e.g. Cl, Na)
- Adverse affect on structure and structurally related attributes (e.g. drainage, permeability, erodibility, surface condition)

Chloride toxicity is the most easily determined soil salinity attribute that impacts on crop production. Accurate correlation of soil EC to crop productivity is currently not possible in the region. Saline irrigation water may also cause direct impacts on plants e.g. leaf burn, when used in spray irrigation systems. This can be managed via choice of application method, but there is an inherent assumption that irrigation water applied is agronomically appropriate and will not cause a reduction in yield >10%. If appropriate, a limitation rule set should be created for the salinity of the irrigation water in order to assess the direct application impacts.

In the case of irrigation with saline and/or sodic water, the soil salinity may interact with the salinity of the applied water leading to detrimental effects. The many possible permutations of this cannot be currently dealt with via a suitability framework and an assumption is made that the relationship between soil and water chemistry is investigated appropriately and the irrigation scheme is designed to avoid soil chemical/physical problems created via the application of the water.

Diagnostic land attributes

- EC and chloride measurement of soil profiles
- Ionic composition of applied water

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
Sa1	Cl <400 mg/kg	1	1	1	1	1	1	1
Sa2	Cl 400–600 mg/kg	1	2	1	1	1	1	1
Sa3	Cl 600–1000 mg/kg	2	3	2	2	2	2	2
Sa4	Cl 1000–1500 mg/kg	3	4	3	3	3	3	3
Sa5	Cl >1500 mg/kg	4	5	5	4	4	4	4

3.1.11. Limitation: Topography (T)

Effects

Effects of 'Slope (Ts)'

- Restricts machinery use and irrigation layout
- Lateral move irrigators do not function efficiently at slopes >3%
- Pivot irrigators may be used up to 15% slope
- Drip irrigation functions less efficiently at slopes >7%

Effects of 'Gilgai (Tm)'

- Restricts operation of machinery, ponds water, causes difficulty in design and operation of some irrigation methods (travelling, pivot)

Diagnostic land attributes

- Slope
- Type of gilgai
- Vertical (VI) and horizontal intervals (HI)
- Difference in soil attributes between mound and depression
- Difficulty of levelling
- Depth to phytotoxic material on mound

Limitation level	Description	CWG	SG	L	WC	SC	GP	LP
Ts1	<3% slope	1	1	1	1	1	1	1
Ts2	3–8% slope	2	2	2	3	3	2	2
Ts3	8–15% slope	3	3	3	5	5	3	3
Ts4	>15% slope	5	5	5	5	5	5	5
Tm1	No gilgai or small gilgai (VI <15 cm). *No restrictions to machinery or irrigation*	1	1	1	1	1	1	1
Tm2	Gilgai VI 15–50 cm. *Minor restrictions to machinery use and minor restrictions to irrigation*	2	2	2	2	2	2	2
Tm3	Gilgai VI >0.5 m, HI >5 m. *Considerable restrictions to machinery use and minor restrictions to irrigation*	3	3	4	4	4	3	3
Tm4	Gilgai VI >0.5 m, HI <5 m. *Severe restrictions to machinery use and moderate restrictions to irrigation*	4	4	4	5	5	3	3

3.1.12. Limitation: Wetness (W)

Effect
Waterlogging of soils will reduce plant growth and hamper effective machinery operation. Prolonged waterlogging can modify soil physical and chemical characteristics (e.g. N, S). In irrigated forage systems, waterlogging can cause loss of production due to animal bogging, and poaching of soils.
Assessment
Internal and external drainage are assessed by examining soil morphology (such as landform, microrelief, texture, grade and type of structure, colour, mottles, segregations, bleaches, roots, voids, consistence, soil water status (especially following rain), segregations (Ca, CO_3, $CaSO_4$), pH profile and impermeable layers) and position in the landscape. Vegetation is often an indicator of soil wetness. Limitation classes are determined by relating drainage class and soil permeability (McDonald *et al.* 1990) to crop tolerance information, local experience and the effect on machinery operations.

'Soil Permeability'
- Movement of water into and through the soil profile (encompasses infiltration)
- Independent of climate and drainage
- Controlled by the potential to transmit water of the least permeable layer in the soil
- Inferred from attributes of the soil such as structure, texture, porosity, cracks and shrink-swell properties
- Saturated hydraulic conductivity (K_S)

'Drainage'
- Water exiting the profile either through the lower profile or the soil surface
- Local soil wetness conditions
- Provides a statement about soil and site drainage likely to occur in most years
- Internal attributes include soil structure, texture, porosity, hydraulic conductivity and water holding capacity
- External attributes include source and quality of water, evapotranspiration, gradient and length of slope, and position in the landscape.

Limitation level	Drainage Class	Description
W1	Rapidly drained	Water exits the soil rapidly in relation to supply. Excess water flows downwards rapidly if underlying material is highly permeable. No horizon is normally wet for more than several hours after water addition
W2	Well drained	Some horizons may remain wet for several days after water addition. Typically medium in texture
W3	Moderately well drained	Some horizons may remain wet for as long as a week after water addition. Typically medium to fine in texture
W4	Imperfectly drained	Some horizons remain wet for weeks. Some horizons gleyed, mottled or possess orange or rusty root channels
W5	Poorly drained	All horizons remain wet for periods of several months. Some horizons gleyed, mottled or possess orange or rusty root channels
W6	Very poorly drained	Water is removed from the soil so slowly that the watertable remains at or near the surface for most of the year

Permeability limitation level	Description
W1v	Rapidly drained, very slowly permeable
W1s	Rapidly drained, slowly permeable
W1m	Rapidly drained, moderately permeable
W1h	Rapidly drained, highly permeable
W2v	Well drained, very slowly permeable
W2s	Well drained, slowly permeable
W2m	Well drained, moderately permeable
W2h	Well drained, highly permeable
W3v	Moderately well drained, very slowly permeable
W3s	Moderately well drained, slowly permeable
W3m	Moderately well drained, moderately permeable
W3h	Moderately well drained, highly permeable
W4v	Imperfectly drained, very slowly permeable
W4s	Imperfectly drained, slowly permeable
W4m	Imperfectly drained, moderately permeable
W4h	Imperfectly drained, highly permeable
W5v	Poorly drained, very slowly permeable
W5s	Poorly drained, slowly permeable
W5m	Poorly drained, moderately permeable
W5h	Poorly drained, highly permeable
W6v	Very poorly drained, very slowly permeable
W6s	Very poorly drained, slowly permeable
W6m	Very poorly drained, moderately permeable
W6h	Very poorly drained, highly permeable

Permeability codes	K_S range	Drainage time
h – High permeability	>500 mm/day	Hours
m – Medium permeability	50–500 mm/day	Days
s – Slow permeability	5–50 mm/day	Weeks
v – Very slow permeability	<5 mm/day	Months

3.1.13. Landscape complexity (X)

Effects
An area of suitable land may be too small or too isolated to justify its development as a production area for a particular land use. Additionally, small areas of suitable land surrounded by unsuitable lands occur in some map units due to dissected topography or soil complexity.
Assessment
Map units that have complex soil patterns or dissected topography are downgraded if the contiguous area of suitable land is smaller than an acceptable minimum production area for the land use in question.

No limitations are set in relation to crop type and size of contiguous area, but the following may be used as a guide.

Irrigation Method	Most common crop use (for smallest setup)
Hand shift/fixed sprinklers, drip irrigation and micro sprinklers	Horticultural tree crops Horticultural vegetable crops Silviculture
Travelling sprinklers (gun) and boom travelling sprinklers	Hay production Pastures Summer forage crops Winter forage crops
Centre pivot and lateral move irrigation	Summer grain crops Winter grain crops

Limitation level	Description
X1	<15 ha. *Minimum commercially viable area for hand shift/fixed sprinklers, drip irrigation and micro sprinklers*
X2	15–50 ha. *Minimum commercially viable area for travelling sprinklers (gun) and boom travelling sprinklers*
X3	>50 ha. *Minimum commercially viable area for centre pivot and lateral move irrigation*

Appendix 4: Investigating the unsaturated zone

The following information provides details on investigating the unsaturated zone. The work described below can be undertaken as part of soil survey, geotechnical or hydrogeological investigations. In an ideal scenario, the three activities would be linked.

The aim of the unsaturated zone investigation is to identify the storage capacity for deep drainage resulting from the irrigation activity. This includes identifying the shallowest layer(s) of reduced permeability where a water table has or may occur; estimating the moisture holding capacity and current moisture status of the unsaturated zone, and therefore estimate the available non-drainable water storage depth in the unsaturated zone between the root zone and the shallowest potential aquifer.

The discussion below concerns measuring various attributes of the unsaturated zone. The nature of the unsaturated zone could range from essentially soil materials through to rock. Most of the methods described have evolved in the soil science discipline and there are some challenges to the application of them to consolidated materials.

Site intensity

Sufficient sites should be sampled to characterise the key land types in a proposed irrigation area. The site distribution may not always be directly proportional to the areal proportion of land types. For example, a small area of a sandy soil may be specifically targeted as it may be the greatest potential zone of leakage. Geophysical methods (e.g. electromagnetic induction, resistivity, shallow seismic) may be used to interpolate between points and to assist in choosing sites.

Depth of sampling

All sampling should be to a minimum depth of 15 m for cropping areas. In a subset of sites, especially in alluvial areas, investigations will need to continue to depths up to 30 m. This is particularly the case if shallow aquifers are known/suspected to exist or for developments involving a long time span of irrigation (>10 years).

Given the majority of the cost in deep coring is incurred on site (i.e. digging the hole), maximum use should be made of samples. With large diameter cores (4”), it is possible to obtain both chemical and physical measures from the one point in the core. Processing of samples for moisture content is relatively cheap compared to wet chemistry, hence more of these may be undertaken.

When drilling deeper holes (>5 m), investigators should be cognisant of regulations regarding interception of water tables and the requirement to appropriately backfill holes, particularly in the case of large diameter holes[38]. In most cases, backfilling with bentonite chips is appropriate.

Method of sampling

Ideally, the sampling method should produce an undisturbed core, with minimal compression or expansion or change in temperature. Core holes enable more accurate description of the soil/regolith and allow for bulk density and moisture sampling. Real depth of the hole should be compared with core length as each core is taken, to establish if compression or expansion occurs and this should be accounted for where necessary. Larger diameter cores (75–100 mm) are preferable to small diameter cores (<50 mm). The sampling method should avoid use of water injection or high pressure air injection (e.g. rotary air drilling or rotary mud drilling), particularly if there is a risk of the core being contaminated (wet) or dried out.

[38] see http://www.derm.qld.gov.au/water/management/pdf/minimum-const-req.pdf

Measuring bulk density

The bulk density of sections of cores should be calculated for the different material types present e.g. clay versus sand. Obviously this can be more difficult in sandy zones and illustrates the importance of good coring technique and the advantage of sleeved cores. Core sections used for bulk density measurement should not span major lithological changes.

Bulk density sections of core should be cut in lengths of approximately 10–20 cm. The exact length of the section should be measured in a minimum of three positions around the core and the average length calculated. The diameter of the core should similarly be measured at both ends and the mean diameter calculated. If it does not match the diameter of the cutting tip, it indicates core expansion has occurred. The diameter of the cutting tip should be used to calculate the volume of the core. The core section may then be split in two (preferably lengthways) and one half used for determining the moisture content. It should be stored in a moisture tight container, out of direct heat sources. Measure the weight of the core. After the water content (described below) is determined, the weight of the whole core can be corrected to oven dry weight. The bulk density (B.D) is the whole core oven dry weight divided by the core volume (e.g. in kg/m^3 or gm/cm^3).

Estimating the water content

The core section should be weighed to at least one decimal point accuracy, accounting for the weight of the sample container. It can then be oven dried (105°C). The period of time required to dry the core will vary with material type and core dimensions. Periodic weights may be taken to establish that the core is dry. For further information on moisture content measurement methods, refer to Rayment and Lyons (2010) and McKenzie *et al*. (2002). Once dry, the sample should be re-weighed and the moisture content calculated. This is the gravimetric moisture content (θ_g) which is expressed in g/g. It can be converted to a volumetric moisture content (θ_v) by the following equation:

$$\theta v = \frac{\theta g * B.D}{\rho H_2 0}$$

The density of water is normally taken as 1 g/cm^3, hence only the top part of this equation is used.

The total porosity (*f*) can also be determined:

$$f = 1 - \frac{B.D}{2.65}$$

Once the total porosity is known, the air filled porosity (ε) can be calculated as it equals the total porosity minus the water filled porosity i.e. $\varepsilon = f - \theta_v$. The total porosity (whether water or air filled) is critical in determining the quantity of deep drainage that can be stored in the unsaturated zone because it is within this porosity that the water is stored. For deep drainage to be “stored” and not continue to move downwards to eventually become diffuse recharge to groundwater, the moisture content must be below the drained upper limit (DUL) i.e. not draining.

The total volume of storage can be calculated as the difference between the current soil moisture (volumetric) and the materials DUL, for each of the textural layers down the profile. While this appears straightforward, determining the DUL for deeper layers in the regolith is difficult. This volume represents a theoretical maximum. In practice it may be considerably less, particularly in heterogeneous, layered profiles. As water moves between layers, sandier layers positioned between more clay rich layers are physically unable to fill to DUL (due to flow dynamics created by surface tension, pore size class boundaries, ink bottle effect etc.) reducing the overall storage capacity.

Calculating storage capacity and drainable porosity

To calculate the total volume of storage, three measurements are required. The first is the total porosity (*f*) of each layer in the profile. This can be simply calculated from B.D measures using the equation above. The second and third measurements required are the DUL and the drainable porosity of each layer. The drainable porosity is the percentage of air-filled pores present when the soil has drained to DUL and is calculated as total porosity minus soil moisture content at DUL. Drainable porosity is influenced by soil texture and structure, with sands or coarser-textured soils having large drainable porosities and clays or fine-textured soils having smaller drainable porosities. The drainable porosity may range from ~5-7 % for heavy clay Vertosols (70-80% clay) up to 20-25% for sandy soils such as Kandosols. For most of Queensland's southern clay soils (Black, Brown and Grey Vertosols) it will be ~5-11%.

DUL is calculated from total porosity in the following way:
Total Porosity (*f*) = DUL + drainable porosity + entrapped air (~3%)

Calculation example:
For the purposes of demonstrating the calculation, assume a Black Vertosol soil is cored and we want to know the storage capacity between 2-3 m depth. If the measured volumetric moisture is 0.42 and soil B.D is 1.3, to calculate the available storage capacity-

Total porosity (*f*) = 1-(1.3/2.65) = 0.51

Assuming 0.03 of the volume contains entrapped air and the drainable porosity is 0.03,

DUL = 0.51 – 0.03 – 0.03 = 0.45

As the soil moisture is already at 0.42, the available storage is 0.03 (0.45 minus 0.42) or 3% of the soil profile between 2-3 m. This is equivalent to 30 mm of available storage.

This calculation can be performed for every layer in the profile. The difficulty however lies with determining the drainable porosity of each layer. There is currently no all encompassing (across soils and textures) relationship between drainable porosity and other soil attributes (such as clay content). Existing methods of deriving drainable porosity involve its determination, as part of overall moisture characterisation studies, using both field and laboratory approaches. Field measurements include i) wetting up soil plots and coring to measure volumetric soil moisture content when the soil is at (approximately) DUL to determine plant available water content (PAWC), however this is not practical for deeper regolith studies, or ii) deriving drainable porosity by measuring soil water potential using tensiometers and moisture sampling when the soil is at between -10 – 25 kPa (-10 kPa for sandier soils and -25 kPa for heavy clays) to determine DUL. Drainable porosity can also be determined from water retention curves measured in the laboratory using small intact samples taken at depths down the profile. A water retention curve describes the relationship between a water content and water potential. The drainable porosity is the portion/percentage of the curve between saturation (0 kPal) and DUL (-10-25 kPa). These curves are highly sensitive to B.D and textural changes, so each discrete layer requires a separate curve. A correction for overburden pressure is also required for swelling clay soils otherwise the drainable porosity will be considerably under-estimated. Modelling approaches using pedotransfer functions may also be used to estimate the water retention function.

Other measurements

Cores taken from the unsaturated zone should also be utilised for conventional chemistry. Pore fluids may be obtained for analysis or conventional soil analytical methods may be applied. Key analytes include particle size analysis, pH, EC and Cl. Particle size, in conjunction with bulk density and porosity can assist in estimating hydraulic parameters. In certain circumstances, samples may also be analysed for attributes such as mineralogy and hydraulic parameters. Cores may also be analysed by passive sensing tools such as HyLogger (located at GSQ, Zillmere). Similar measurements e.g. EM39, gamma, may be undertaken down-hole at the time of sampling.

Appendix 5: Models/methods used in salinity risk assessment

Models used in salinity risk assessment

Models	Comment	Reference
2cSalt	2cSalt is a water and salt balance model that can be used to assess the impacts of land use change on stream flow and stream salinity in catchments up to 2000 km^2 in area. Only applicable to upland catchments that are already expressing hydrologic change and with gaining not losing streams.	Stenson *et al*. (2005, 2011)
3-PG	3-PG is a well-established forest growth model, which is used commercially and non-commercially around the world. It is capable of producing accurate growth results across a number of parameterised species, with minimal input data requirements.	<http://www.csiro.au/products/3PGProductivity.html>
APSIM	APSIM (Agricultural Production Systems Simulator) is a farming systems model that simulates the effects of environmental variables and management decisions on crop yield, profits and ecological outcomes.	<http://www.apsim.info/Wiki/>
BC2C	BC2C is a conceptual mass balance model designed to simulate the long-term average salt and water yield of whole catchments. BC2C is aimed at a catchment or sub-catchment scale, not at an enterprise/farm scale. Only applicable to catchments that are already expressing hydrologic change and with gaining not losing streams.	<http://www.toolkit.net.au/Tools/BC2C>
HowLeaky	HowLeaky represents a rebuilding of the PERFECT V3 model, with an enhanced interface designed to be useful to a range of non-modellers to explore the implications of alternative land-uses on water balance, runoff, erosion, and drainage. Has enhanced irrigation management functionality.	<http://www.apsim.info/How/HowLeaky/howleaky.htm> Rattray *et al*. (2004), Robinson *et al*. (2010)
IQQM	The IQQM (Integrated Quantity Quality Model) is a generalised hydrological simulation model that is capable of operating on a daily basis. IQQM was developed for use in planning and evaluating water resource systems and their management policies. IQQM has been widely applied in Queensland and New South Wales over the 1990s and 2000s for the development of water sharing and water resources plans.	DLWC (1997)
MEDLI	MEDLI (Model for effluent disposal using land irrigation) is a user-friendly program for designing effluent re-use schemes.	<http://www2.dpi.qld.gov.au/environment/5721.html>
PERFECT	PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) is a biophysical model that simulates the plant soil water management dynamics in an agricultural system. It was developed to simulate the major effects of management and environment and to predict runoff, soil loss, soil water, drainage, crop growth and yield. Similar emphasis is given to land degradation and crop production aspects.	Littleboy *et al*. (1989), Littleboy *et al*. (1993)
RiverManager	RiverManager is an eWater product. It is a software product that supports planning and management of river systems.	<http://www.ewater.com.au/products/ewater-source/for-rivers/river-manager/>
SALF	The SALF (Salt and Leaching Fraction) PREDICT model is	SalCon (1997)

Models	Comment	Reference
PREDICT	based on the assumption that soil leaching or deep drainage is related to soil hydraulic conductivity, which in turn is influenced by the amount of clay (%), mineralogy (defined by CEC/Clay %) and exchangeable sodium percentage (ESP). Once these properties and water quality and quantity parameters have been determined the SALF PREDICT model can be used to estimate the rate of deep drainage or salt build-up at steady-state using various amounts or qualities of irrigation water.	

Deep drainage methods

Method	Comment	Reference
Lysimetry (D)	A device to measure the volume flow of water with or without application of tension, or to obtain water samples from the soil.	Titus and Mahendrappa (1996)
Zero flux plane method (D)	Measures drainage by soil water change over short time intervals, above (evapotranspiration) and below (drainage) the zero flux plane.	Bond (1998)
Darcy's Law methods (I)	Hydraulic conductivity and hydraulic gradient measured to give flow rate.	Bond (1998)
Measured water balance (I)	All other components of water balance measured and drainage determined by difference.	Zhang *et al.* (2002), Ward *et al*. (2001)
Modelled soil water balance (I)	Rainfall is distributed into runoff, soil evaporation, transpiration, drainage and soil storage, stepping through time.	Zhang *et al.* (2002)
Groundwater response (I)	Simplistically, drainage rate equals increases in water height multiplied by aquifer porosity, however, aquifers have other losses (discharge) and gains, and cover large areas (e.g. >5 km^2). A groundwater model is usually needed.	Cook and Herczeg (1998), Allison *et al*. (1983)
Artificial tracers e.g. bromide (I)	Drainage inferred by monitoring tracer movement; useful when drainage rates are high.	Petheram *et al.* (2000)
Steady-state chloride mass-balance (I)	Summary of all salt inputs and outputs for a defined volume or depth of soil during a specified period of time; uses equilibrium chloride concentration profiles.	USSL (1954), Hillel (1980), Walker (1998)
Transient chloride mass balance (I)	Compares time series or paired site chloride concentration profiles to infer rate of water movement (SODICS).	Rose *et al*. (1979), Thorburn *et al.* (1987, 1990)
Chloride front (or peak) displacement (transient) (I)	Traces movement of the chloride front with depth during the drainage process; used to infer rate of water movement.	Allison and Hughes (1983), Walker *et al*. (1991)

Deep drainage methods sourced from Tolmie and Silburn (2003).
D = direct methods, I = indirect methods.

Appendix 6: Evaluation of publicly available data for salinity risk assessment

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Biophysical Hazard								
Depth to substrate or other reduced permeability zone	Determines potential thickness of unsaturated zone	Biggs *et al*. (2005), Wilkinson and Chamberlain (2004), Chamberlain *et al*. (2007)	Calculation of size of unsaturated zone	Low (broad scale mapping not specific to landscape)	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey	Not adequate	Field investigations	Limited
Regolith architecture in alluvial sequences	Affects vertical and horizontal water movement	Biggs *et al*. (2005), Wilkinson and Chamberlain (2004)	Determines likelihood of connectivity, size of unsaturated zone	Low	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey	Not adequate	Field investigations	Not known
Regolith salt store, porosity, hydraulic conductivity	Affects rate of water movement and mobilisation of primary salt stores	Biggs *et al*. (2005), Wilkinson and Chamberlain (2004), Chamberlain *et al*. (2007)	Determination of salt stores, likelihood of connectivity, size of unsaturated zone	Low	DNRM groundwater database, DNRM publications, GSQ, company geological data, hydrogeological investigations, soil survey	Not adequate	Field investigations	Not known
Landform, slope, curvature	Affects surface and subsurface drainage	Summerell *et al*. (2004), Biggs *et al*. (2005)	Characteristics effect waters path through the system and provide initial assessment of salinity risk potential	Medium	25 m DEM from DNRM, shuttle radar DEM from GA, company data	Not adequate	More detailed topographic data	Yes – variable scale and quality

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Lateral flow, runoff / runon	Determined by nature of the soil profile, e.g. texture contrast and topography		Determination of water/salt movement risk in hillslope areas	Low-medium	Existing land resource data, modelling, field measurements	Needs to be assessed on a site by site basis	More detailed soil survey and research of lateral flow process	No
Infiltration rate	Determined by texture, clay type, sodicity, surface cover		Affects choice of irrigation method and water application rate	Medium	Published data, field measurements	Needs to be assessed on a site by site basis	Field measurements	Variable
Soil EC, ESP	Affects soil water movement; indicator of natural water/salt fluxes	SalCon (1997), Raine and Elzit (2007)	Determination of salt stores, accumulation / leaching, hydraulic conductivity	Low-medium	Land resource studies and technical reports, SALI database	Not adequate	Current knowledge is generally confined to top 2 m of soil profile. Further investigation is required to capture the soil properties to bedrock	Limited
Surface drainage (proximity to water courses)	Influences transport times for solutes discharging to stream		Likelihood of salt washoff, lateral flow or shallow groundwater movement moving salt to streams	Medium	Existing topographic data/survey; validated during site surveys	Needs to be assessed on a site by site basis	Ensuring all stream data has flow direction attributes to enable modelling, better detail required in areas where scale is limited (1:100 000 or greater) and floodplains	Yes – variable scale and quality

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Results from soil survey	Base data for many purposes, especially water balance modelling	Ross and Crane (1994)	Collection of many soil attributes that influence water storage and movement	Low	Land resource surveys (DNRM, CSIRO)	Not adequate	More detailed soil survey	Yes – variable scale and quality
Salinity Stage								
Historic land use	Affects historic deep drainage / recharge	Biggs *et al*. (2010)	Determination of water balance stage	Low-medium	DNRM land use mapping, landholder records, historical imagery, historical reports, e.g. land surveys	Needs to be assessed on a site by site basis	Data capture from historic aerial photos and reports over time is required. Current land use records need to be updated regularly (at least five yearly) to ensure land use changes are adequately captured	No
Time since clearing	In absence of more detailed land use records, this gives an estimate of the time over which increased deep drainage has been occurring	Chamberlain *et al*. (2007), Searle *et al*. 2007), Biggs *et al*. (2010)	Determination of water balance stage	Low-medium	DNRM land use mapping, landholder records, historical imagery, historical reports, e.g. land surveys	Needs to be assessed on a site by site basis	Data capture from historic aerial photos and reports over time is required	No

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Land use since clearing	Required to calculate water added since clearing which reduces the available unsaturated zone	Biggs *et al*. (2010)	Determination of water balance stage	Low-medium	DNRM land use mapping, landholder records, historical imagery, historical reports, e.g. land surveys	Needs to be assessed on a site by site basis	Data capture from historic aerial photos and reports over time is required	No
Climate since clearing	Required to calculate water added since clearing which reduces the available unsaturated zone	Biggs *et al*. (2010)	Determination of water balance stage	Medium	BoM, landholder records	Variable, often adequate	Increase number of stations collecting data and data collected, e.g. include frost measurements at all stations	No, but is available from BoM
Groundwater trends	Indicator of saturated zone dynamics in relation to historic land use	Wilkinson and Chamberlain (2004), Biggs *et al*. (2005), Searle *et al*. (2007)	Surrogate for/indicator of stage	Low-medium	DNRM groundwater database, DNRM publications, landholder and company records, hydrogeological investigations	Not adequate	Limited groundwater monitoring networks have recently been put in place. There is limited historical groundwater level information to base trends off. A detailed groundwater monitoring network throughout the CSG area needs to be put in place, and be adequately maintained and monitored	Limited

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Existing salt expressions	Indicator of historical recharge / discharge—their presence indicates the "bucket is full"	Biggs *et al*. (2005), Searle *et al*. (2007), Chamberlain *et al*. (2007)	Surrogate for/indicator of stage	Medium	Soil survey, DNRM salinity site database, publications, landholder knowledge, field survey, imagery	Needs to be assessed on a site by site basis	Significant salt expressions have been mapped through the project area. Further detailed assessment is required to capture emerging salt expressions	No
Salt export/import ratio (E/I)	Change over time reflects complex landscape processes in a simple manner (most inland catchments are accumulating salt so E/I <1).	Biggs *et al*. (2005), Searle *et al*. (2007), Chamberlain *et al*. (2007), Power *et al*. (2007), Silburn *et al*. (2007)	Surrogate for stage across whole catchment	Medium	DNRM data/reports	Needs to be assessed on a site by site basis	Localised salt balance calculations	No
Current Management Influence and Post-Irrigation Land Use								
Irrigation water quantity	Directly influences time to fill		Directly influences time to fill	Medium-high	CSG companies and irrigators	Needs to be assessed on a site by site basis		Yes
Irrigation water quality	Affects sodicity / salinity relations and associated attributes (e.g. infiltration, permeability)	SalCon (1997)	Affects sodicity / salinity relations and associated attributes (e.g. infiltration, permeability).	High	CSG companies	Needs to be assessed on a site by site basis	Data sharing	Yes

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Irrigation method / regime	Interacts with climate to influence frequency of saturation events		Interacts with climate to influence frequency of saturation events	Medium-high	Irrigators, consultants	Needs to be assessed on a site by site basis		Yes
Soil properties	Influence crop growth, irrigation method, sodicity / salinity relations	SalCon (1997), Raine and Elzit (2007)	Influence crop growth, irrigation method, sodicity / salinity relations	Low	Existing land resource data	Needs to be assessed on a site by site basis	Field measurements	Variable
Effective rooting depth	Affects water uptake profile	Dang *et al*. (2010)	Effective rooting depth in the soil/s of the irrigation development area—determined by crop tolerance and subsoil constraints	Low-medium	Soil survey, agronomic data and crop models, DNRM groundwater database, GSQ, company geological data, hydrogeological investigations	Needs to be assessed on a site by site basis	Field measurements	Limited
Crop type	Affects water use		Directly influences water balance and time to fill the unsaturated zone		Irrigators, consultants	Needs to be assessed on a site by site basis		Yes
Crop lower limit	Affects water use		Directly influences water balance and time to fill the unsaturated zone		APSoil database (ASPRU website)	Needs to be assessed on a site by site basis	Field measurements	Limited

Factor	Comment	Example assessment / study	Purpose/use of factor in risk assessment	Current level of knowledge	Example available data sources	Adequacy of available data for site specific salinity risk assessment	Action required to increase knowledge	Data collected by CSG company previously
Climate	Interacts with irrigation method / regime		Understand the variation and impact of variations in climate (rainfall, temperature, frosts) on landscapes and crops	Medium	BoM, companies, land holders	Needs to be assessed on a site by site basis	Increase number of stations collecting data and data collected, e.g. include frost measurements at all stations. Install weather stations at irrigation development sites, log historic data	Limited
Flooding	Affects land use options and water balance		Influences design criteria for irrigation water storages and other farm management methods, e.g. catch drains	Low-medium	Gauging stations, old flood maps, landholders	Not adequate	Data collation, modelling	Limited

Acronyms:
APSRU Agricultural Production Systems Research Unit
BoM Bureau of Meteorology
CSIRO Commonwealth Scientific and Industrial Research Organisation
DAFF Department of Agriculture, Fisheries and Forestry
DEM Digital Elevation Model
DNRM Department of Natural Resources and Mines
GA Geoscience Australia
GSQ Geological Survey of Queensland
SALI Soil and Land Information database (DNRM)