# An overview on desert aquaculture in Australia

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**SUMMARY**

The majority of Australia's land is considered to be arid or semi-arid. Deserts occupy 18 percent of Australia's continent, most of which are virtually uninhabited. Within the extension of the large Australian deserts, groundwaters are found in abundance, each with their unique physical-chemical qualities. Several of these water sources may provide service for aquaculture purposes, including: groundwater pumped as part of the Salt Interception Schemes (SIS) to reduce the saline water levels, water pumped as a by-product of the coal seams gas drills, groundwater wells, pit lakes and disused open mine pits. The water quality present within these groundwater sources is a major concern, as they are distinguished by low levels of pH and ionic composition. In fact, potassium ions (crucial for fish physiological processes) are completely deficient within these waters. During the past decade, attention was given to the research and development of aquaculture using saline groundwater, mainly in semi-arid locations. A number of demonstration centres were established in several Australian states showcasing the available technology, in which different systems were developed and tested with several freshwater and marine species. Although several fish species were grown in saline groundwater, only two species were found to have commercial potential: Japanese meagre (mulloway, *Argyrosomus japonicus*) and rainbow trout (*Oncorynchus mykiss*). Currently, only microalgae *Dunaliella salina* and *Artemia* sp. are being reared commercially along Australia's arid coastal areas. Western and Southern Australia are known for their extensive aquaculture of *D. salina,* reared in large shallow lagoons and ponds, as its importance is highly attributed to the natural beta-carotene used in food, cosmetic and pharmaceutical industries, as well as an important source of food for the rearing of *Artemia* sp. During the past several years, Australia's eastern states suffered severe droughts which reduced groundwater availability. As a result, even the efforts of the SIS were reduced significantly due to the low groundwater levels. Therefore, a lack of suitable water sources supplying large volumes is one of the main challenges expanding the development of saline-groundwater desert aquaculture. The emphasis and priorities for the development of this type of aquaculture have shifted towards other aspects. The current funds available for research and development and/or commercial ventures in this area are not sufficient for their protraction. Aside from microalgae and *Artemia*, there are no desert (or semi-arid) aquaculture commercial projects in Australia.

## RÉSUMÉ

La plus grande partie des terres australiennes sont considérées comme étant arides ou semi-arides. Les zones désertiques couvrent 18 pour cent de l'île continent et ne sont pratiquement pas habitées. Dans ce vaste espace, on trouve des eaux souterraines en abondance, qui présentent toutes des caractéristiques physiques et chimiques particulières. Plusieurs d'entre elles peuvent être utilisées à des fins aquacoles, notamment celles qui sont pompées dans le cadre des Plans d'interception du sel visant à réduire leur taux de sel, celles qui sont pompées en tant que sous-produits des forages des gisements houillers ou encore celles qui proviennent des puits, des carrières inondées ou des mines à ciel ouvert qui ne sont plus exploitées. La qualité de l'eau de ces sources souterraines pose problème car celles-ci se caractérisent par un pH bas et une faible composition ionique. Les ions potassium (fondamentaux pour les processus physiologiques des poissons) sont en effet complètement absents de ces eaux. Au cours de la dernière décennie, l'attention s'est notamment concentrée sur la recherche et le développement d'une aquaculture ayant recours aux eaux souterraines salines, principalement dans des zones semi-arides. Des centres de démonstration ont été créés dans plusieurs États australiens pour présenter les technologies disponibles. Différents systèmes d'élevage y ont été mis au point et testés avec diverses espèces marines et d'eau douce. Différentes espèces de poisson ont ainsi été élevées dans des eaux salines d'origine souterraine, mais seules deux d'entre elles se sont avérées avoir un véritable potentiel commercial : le maigre du sud (*Argyrosomus japonicus*) et la truite arc-en-ciel (*Oncorynchus mykiss*). Actuellement, seule *Dunaliella salina* et *Artemia* sp. sont cultivées à des fins commerciales dans les zones arides situées le long des côtes australiennes. L'Australie occidentale et méridionale est connue pour son aquaculture extensive de *D. salina*, réalisée dans de grandes lagunes aux eaux peu profondes et en étang. Cette source naturelle de bêta-carotène est très importante pour les industries agro-alimentaires, cosmétiques et pharmaceutiques. C'est aussi une source importante d'aliments pour la culture d'*Artemia* sp. Au cours des dernières années, de graves sécheresses ont frappé les États de l'est de l'Australie et ont réduit les réserves d'eaux souterraines. En conséquence, même les efforts entrepris dans le cadre des Plans d'interception du sel ont été considérablement réduits du fait des faibles niveaux des eaux souterraines. Le manque de sources d'eau appropriées permettant d'obtenir de grands volumes est par conséquent l'un des principaux défis auxquels est confronté le développement de l'aquaculture en milieu désertique ayant recours aux eaux souterraines salines. L'accent mis sur le développement de ce type d'aquaculture, et son caractère prioritaire, appartiennent au passé. Les fonds actuellement disponibles pour la recherche et le développement et/ou pour les entreprises commerciales présentes en milieu désertique ne sont pas suffisants pour leur maintien. À l'exception de la production de micro-algues et d'*Artemia*, il n'existe pas de projets aquacoles commerciaux dans les déserts ou ans les espaces semi-arides australiens.

## ملخص

تعتبر غالبية الأراضي الاسترالية قاحلة او شبه قاحلة . وتشكل الصحاري ما نسبته ثمانية عشر في المائة من هذه الأراضي، والتي معظمها في الواقع غير مسكونة. وعلى إمتداد الصحاري الاسترالية الكبيرة، فان المياه الجوفية موجودة بوفرة، وكل منها يتميز بخصائص كيميائية فيزيائية فريدة. والعديد من هذه المصادر للمياه الجوفية يمكن ان توفر خدمات من اجل تربية الأحياء المائية، وتتضمن: ضخ المياه الجوفية كجزء من أنظمة مواجهة الملوحة (SIS) لخفض مستويات المياه المالحة، وضخ المياه كناتج ثانوي من الفحم المنشق من تنقيبات الغاز، وآبار المياه الجوفية، وبحيرات الحفر وحفر المناجم المفتوحة غير المستخدمة. ونظرا لتميزها بالمستويات المنخفضة لمعامل الحموضة والتركيب الأيوني، فإن جودة المياه في هذه المصادر للمياه الجوفية تشكل قلقا رئيسيا. وفي الحقيقة، فان أيونات البوتاسيوم (وهي حاسمة للعمليات الفيزيولوجيه للأسماك) هي ناقصة بشكل كامل في هذه المياه. وخلال العقد الماضي، تم الاهتمام بالبحوث والتنمية في تربية الأحياء المائية باستخدام المياه الجوفية المالحة، وبشكل أساسي في المواقع شبه القاحلة. وتم تأسيس عدد من المراكز الإيضاحية في العديد من الولايات الاسترالية والتي تعرض التقنية المتوفرة التي يتم فيها تطوير وتجربة أنظمة مختلفة للعديد من أنواع الأسماك البحرية وأسماك المياه

العذبة. وعلى الرغم من نمو عدد من الأنواع السمكية في المياه الجوفية المالحة، الا ان هناك نوعين فقط لديهما الإمكانية التجارية: سمك النعاق الياباني (ملواي، *Argyrosomus japonicus*) وتراوت قوس قزح (*Oncorynchus mykiss*). وفي الوقت الحالي، فإن الطحالب المجهرية *Dunaliella salina* والارتيميا *Artemia* sp. هما فقط الذين يتم تربيتهما بشكل تجاري في المناطق الاسترالية الساحلية الجافة. ان المناطق الاسترالية الغربية والجنوبية معروفة باستزراعها الواسع للطحالب من نوع *D. Salina* والتي يتم تربيتها في بحيرات وأحواض ضحلة كبيرة وأهميتها تعزى بشكل كبير الى البيتا كاروتين الطبيعية المستخدمة في الصناعات الغذائية، والتجميلية والدوائية، بالإضافة الى كونها تشكل مصدرا مهما كغذاء في تربية الارتيميا. وخلال عدد من السنوات الأخيرة، عانت الولايات الشرقية الاسترالية من جفاف حاد والذي ساهم في تخفيض وفرة المياه الجوفية. وكنتيجة لذلك، حتى جهود أنظمة مواجهة الملوحة (SIS) قد انخفضت بشكل كبير بسبب المستويات المنخفضة للمياه الجوفية. وبالتالي، فان النقص في مصادر المياه التي توفر كميات كبيرة هو أحد التحديات الرئيسية أمام توسيع تنمية تربية الأحياء المائية الصحراوية التي تستخدم المياه الجوفية المالحة. ان التركيز والأولويات نحو تنمية هذا النوع من تربية الأحياء المائية قد تتغير نحو جوانب أخرى. والتمويلات الحالية المتوفرة للبحوث والتنمية و/أو المشاريع التجارية في هذا المجال هي غير كافية تماما لإطالتها. وفيما عدا الطحالب المجهرية والارتيميا، لايوجد هناك مشاريع تجارية للاستزراع الصحراوي (او شبه القاحلة).

## INTRODUCTION

Australia is a large continent characterized by a relatively small population concentrated along the coastal areas, with low seafood consumption per capita. When compared to other countries, the Australian aquaculture industry is composed entirely of small-scale operations, with no history of large-scale aquaculture ever present. The majority of species production found throughout Australia is composed of yellowtail amberjack (*Seriola lalandi*), giant tiger prawn (*Penaeus monodon*), barramundi (*Lates calcarifer*), edible oysters (*Saccostrea glomerata* and *Crassostrea gigas*), and silverlip pearl oyster (*Pinctada maxima*), as well as reatively large-scale production of salmon.

Diversification from traditional agriculture products was thought to benefit rural Australia. In fact, large semi-arid and arid areas with large reservoirs of groundwater were considered to have potential interest for inland aquaculture. As a result, Australia, both at federal and state government level, has invested in research and development focusing on aquaculture opportunities utilizing this untapped resource.

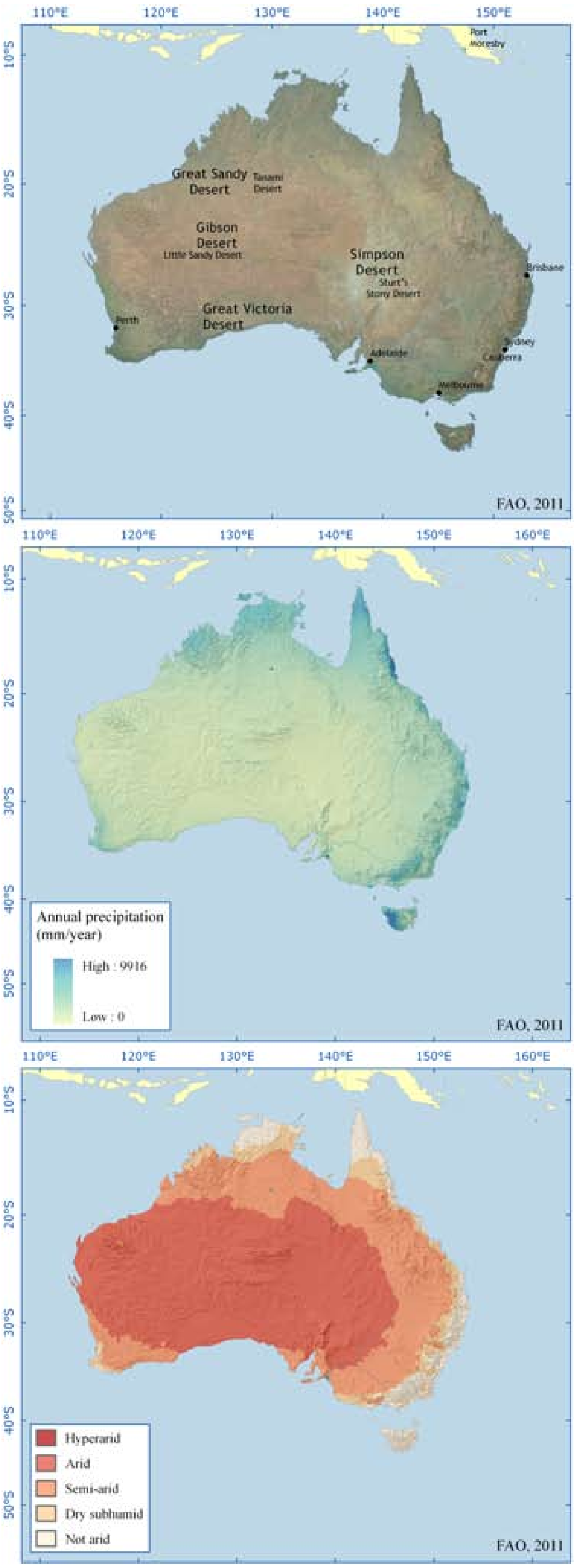
## GEOGRAPHY

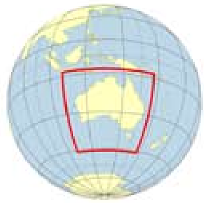
Australia comprises a land area of almost 7.7 million km$^2$. The bulk of the Australian land mass lies between latitudes 10° 41′ south (Cape York, Queensland) and 43° 38′ south (South East Cape, Tasmania) and between longitudes 113° 09′ east (Steep Point, Western Australia) and 153° 38′ east (Cape Byron, New South Wales). The most southerly point on the mainland is South Point (Wilson's Promontory, Victoria) 39° 08′ south. The latitudinal distance between Cape York and South Point is about 3 180 km, while the latitudinal distance between Cape York and South East Cape is 3 680 km. The longitudinal distance between Steep Point and Cape Byron is about 4 000 km (Figure 1).

The land area of Australia is almost as great as that of the United States of America (excluding Alaska) and about 50 percent greater than Europe (excluding the former Union of Soviet Socialist Republics [USSR]). Apart from Antarctica, Australia is the lowest, flattest and driest of the continents. Australia's population in 2010 is just over 22 million, of which the majority of the population concentrates around the coastal areas (Australian Bureau of Statistics – www.abs.gov.au).

The largest part of Australia is considered to be desert or semi-arid land (Figure 1). Most of the deserts lie in the central and northwestern reaches of the country (Figures 2a and 2b). The combined desert area in Australia is 1 371 000 km$^2$ and occupies 18 percent of the continent (Table 1). Most of the deserts in Australia are uninhabited, or are inhabited by small towns, large farms and/or small aboriginal communities.

FIGURE 1
**Maps of Australia**



## Australia

Country area: 774122 (1000 Ha)
Source: FAOSTAT. Estimated, 2007

Land area: 768230 (1000 Ha)
Source: FAOSTAT. Estimated, 2007

Agricultural area: 425449 (1000 Ha)
Source: FAOSTAT. Official data, 2007

Aquaculture Production Average 2004-2008: 29700 tonnes
Source: FISHSTAT. Official data

Aridity:
Approx. areas of hyperarid regime: 0 (1000 Ha)
Approx. areas of arid regime: 427564 (1000 Ha)

A typical landscape of an arid region in Australia.

COURTESY OF I. TOBI

## WATER SOURCE

Groundwaters abound in Australia, even within the expanse of the significantly large deserts. Water chemistry, quality and quantities vary significantly from place to place. The hydrogeological map of Australia (Commander, Jacobson and Lau, 1987) indicates the major aquifers' location, volume and yield. There are several major groundwater areas in Australia with salinity in the range of 20–40 g/litre including:

1. The lower Murray Hydrogeological Basin (Victoria);
2. Eyre Peninsula (South Australia);
3. Central Australia and Northern Territory;
4. Southwest of Western Australia.

Areas of brackish groundwater (1.5–5 g/litre) usually surround the higher salinity regions and include most of South Australia, Western Australia and areas of New South Wales, Victoria and Northern Territory and some areas in southwest and eastern Queensland (Allan, Banens and Fielder 2001; Allan, Heasman and Bennison, 2008).

Salination of both land and water resources is a critical problem in Australia that has rendered large areas of agriculture unproductive and is deteriorating the surface water quality in many areas (Figures 2a and 2b).

FIGURES 2a and 2b
**Effect of salination on land**

COURTESY OF MURRAY-DARLING BASIN AUTHORITY

TABLE 1
**Australian deserts**

| Desert | State/Territory | Size | | Proportion of Australian landmass % |
|---|---|---|---|---|
| | | km$^2$ | Mi$^2$ | |
| Great Victoria Desert | Western Australia, South Australia | 348 750 | 134 650 | 4 |
| Great Sandy Desert | Western Australia | 267 250 | 103 190 | 3.5 |
| Tanami Desert | Western Australia, Northern Territory | 184 500 | 71 200 | 2.4 |
| Simpson Desert | Northern Territory, Queensland, South Australia | 176 500 | 68 100 | 2.3 |
| Gibson Desert | Western Australia | 156 000 | 60 000 | 2.0 |
| Little Sandy Desert | Western Australia | 111 500 | 43 100 | 1.5 |
| Strzelecki Desert | South Australia, Queensland, New South Wales | 80 250 | 30 980 | 1.0 |
| Sturt Stony Desert | South Australia, Queensland, New South Wales | 29 750 | 11 490 | 0.3 |
| Tirari Desert | South Australia | 15 250 | 5 890 | 0.2 |
| Pedirka Desert | South Australia | 1 250 | 480 | 0.1 |

FIGURE 3
**SIS pumping site**

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The cause of the rising saline groundwater is due to the impacts of land-use by people. This form of salination occurs within irrigation systems (irrigation salinity) and/or dryland farming management (clearing trees, etc.) systems (dryland salinity). This anthropogenic salination mobilizes salt in the soil profile that reaches the groundwater and is transported to the surface as the water table rises (Gavine and Bretherton, 2007).

In 2000, it was estimated that at least 2.5 million hectares (less than 5 percent) of cultivated land in Australia were affected by salinity (AFFA, 2000) and 5.7 million hectares are under high risk (Allan, Heasman and Bennison, 2008), with a predicted increase to 12 million hectares (22 percent) and up to 17 million hectares by 2050 (ANRA, 2001). The land and water degradation in Australia is considered to be one of the biggest challenges faced by the agriculture sector, costing more than AUD3.5 billion annually (AFFA, 2000).

To combat the rising salinity, Salt Interception Schemes (SIS) were developed in many areas (mainly in Victoria and New South Wales [NSW]). The SIS are engineered work solutions which intercept saline water flows and dispose of them, usually by evaporation (Figure 3). The use of evaporation basins for this purpose is not new (first recorded by Jutson in 1917). The scale and size of these projects vary between areas and states. A thorough survey of saline water resources around Australia was published by Allan, Banens and Fielder (2001). More recent reviews were published by Partridge, Lymbery and George (2008) and Allan *et al.* (2009). These studies looked at the potential aquaculture use of saline groundwater and evaporation basins.

The majority of the SIS occur in the Murray-Darling Basin (MDB), the biggest irrigated agriculture zone in Australia, accounting for 60 percent of the country's irrigated agriculture.

The MDB SIS, considered being the biggest in the world, discharge saline water to around 190 evaporation basins (Allan, Banens and Fielder, 2001; MDBC, 2008, 2010). These evaporative basins represent an opportunity for aquaculture projects. Allan, Banens and Fielder (2001) identify 11 evaporation basins in the MDB, covering an area of 6 250 ha, which may be suitable for aquaculture in terms of water quality and quantities, logistics and other criteria. However, in recent years, due to the effectiveness of the scheme and long-term drought, the pumping rates from the SIS have decreased, highlighting the risks for long-term commercial viability for potential aquaculture projects (MDBC, 2010). The saline groundwater level significantly subsided and many of the evaporation basins are, in fact, dry.

A slightly different approach to deal with salination is used in the Wheatbelt region of Western Australia (WA). This region accounts for more than 70 percent of the state's salinized land (Doupe', Lymbery and Starcevich, 2003). Western Australia does not have centralized management of SIS and in most cases is struggling to combat salination resulting from earthwork and open drains on farms or in townships (Trewin, 2002). Partridge, Lymbery and George (2008) suggested that, with already 38 towns in rural Western Australia under threat from rising salinity (George *et al.*, 2005), groundwater pumped from beneath these towns might become a source for aquaculture ventures. However, in most cases, due to overlying rock or granite aquifers, the pumping yield is relatively small (George, 1990).

Another potential source of water could lie in the extraction of liquified natural gas from coal-seams for energy use. This relatively new industry (expanded from ten gas well drills in the 1990s to 600 in 2007/2008, Queensland Mines and Energy, Department of Employment, Economic Development and Innovation), based mainly in Queensland, produces, as a by-product, large volumes of water during the extraction of gas from drilled wells, usually with low salinity. Brinckerhoff (2004) reported that 65 percent of the 393 registered wells (in 2004) in Queensland have salinity of 3 g/litre or lower and only 1 percent have salinity over 18 ppt. Volumes vary significantly; however, total water yield (Vink *et al.*, 2008) for 2007 was 34 000 $m^3$/day with a predicted increase to 1 370 000 $m^3$/day by 2020. Currently, some of the water is piped back into the aquifers, but the majority of the water is diverted into evaporation basins without any secondary use. In 2009, the Queensland Government changed the regulations in relation to the discharge water, forcing the mining companies to find a solution for the disposal of the water. Currently, there are still no solutions for treating the water. Irrigation and aquaculture are currently being looked at, however, the waste water from any potential aquaculture project will still need to be disposed of, by pumping it back into the aquifer or by other methods.

FIGURE 4
**Disused open-cut mine**

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One of the limitations of using groundwater from active mining operations is the dependence on the mine activity. Cheap (or at no cost) access to water can only be secured while the mine is operating. If the mine or the pumping activity stops for any reason, the cost of pumping will have financial and logistical implications for the aquaculture operation.

Disused open-cut mines may present an opportunity for small-scale aquaculture ventures. Once pumping and de-watering stops, and surface and groundwater equilibrate, the open voids may form pit lakes (Castro and Moore, 1997; McCullough and Lund, 2006). There are an estimated 1 800 disused open-cut pits in Western Australia alone ranging in size and volumes from a few hectares and a few meters deep to several $km^2$ and hundreds of meter deep (Johnson and Wright, 2003) (Figure 4).

## WATER QUALITY

Groundwater sources in Australia vary significantly (Allan *et al.*, 2009; Kumar, McCullough and Lund, 2009) in quality and quantity between areas, regions and even between similar close-by resources. Salinity, pH, ionic composition, temperature, contaminants (heavy metals, herbicides, etc.) vary between aquifer types, SIS drainage basins, evaporation basins, open-cut pits, and need to be tested at every location for their intended use (Table 2).

TABLE 2
**Water chemistry for different water sources around Australia**

| | Salinity ppt | pH | Alkalinity | $Cl^-$ mg/l | % ion relative to seawater | $Ca^{2+}$ mg/l | % ion relative to seawater | $Mg^{2+}$ mg/l | % ion relative to seawater | $K^+$ mg/l | % ion relative to seawater | $Na^+$ mg/l | % ion relative to seawater | $SO^{2-}_4$ mg/l | % ion relative to seawater | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coastal seawater | 35 | 8.02 | 114 | 20 000 | 100 | 375 | 100 | 1 150 | 100 | 370 | 100 | 9 800 | 100 | 1 050 | 100 | Kolkovski, 2010, personal comm. |
| Wakool (New South Wales) | 19.6 | 7.9 | 195 | 11 000 | 55 | 504 | 134.4 | 820 | 71.3 | 9.2 | 2.5 | 4 210 | 43 | | – | [1]Fielders *et al.* 2001 |
| Pyramid Salt groundwater (Victoria) | Vary (salt works) | – | – | 21 000 | 105 | 590 | 157.3 | 1 400 | 121.7 | 90 | 24.3 | – | – | – | – | [1]Gavin and Bretherton, 2007 |
| Undrea (Victoria) | 10 | nr | Nr | 4 130 | 20.7 | 350 | 93.3 | 470 | 41 | 25 | 6.8 | 2 700 | 27.5 | 1 280 | 122 | [1]Ingram *et al.* 1990 |
| Waikerie SIS (South Australia) | 16.5 | 7.2 | – | 9 374 | 46.9 | 260 | 69.3 | 407 | 35.4 | 87 | 23.5 | 5 966 | 60.8 | 1 430 | 136 | Hutchinson and Flowers, 2008 |
| Stockyard Plains Disposal Basin discharge (South Australia) | 17.2 | 7.1 | – | 9 861 | 49.3 | 431 | 115 | 506 | 44 | 88 | 23.8 | 5 161 | 52.6 | 1 644 | 156.6 | Hutchinson and Flowers, 2008 |
| Wannamal (Western Australia) | 32 | Nr | – | 15 800 | 79 | 592 | 158 | 1 537 | 133.7 | 80 | 21.6 | 8 026 | 83.6 | 1 614 | 153.7 | [1]Prangnell and Fotedar, 2006 |
| Quirindi CSG[2] | 5 | 7.5–8 | Nr | 700 | 3.5 | 10 | 2.7 | 30 | 2.6 | Nr | – | 3 000 | 31.2 | nr | – | [1]Dutney, pers comm |
| Stuart basin CSG[2] | 1.2–4.3 | 8–9 | nr | 590–1 900 | 2.9–9.5 | 3–9 | 0.8–2.4 | 1–3 | 0.08–0.26 | Nr | – | 300–1 700 | 3.1–7.2 | 5–10 | 0.47–0.95 | [1]Anon, 2004 |
| Collie basin (coal mine, Western Australia) | Nr | 3.8–5 | – | – | – | 2.3–6 | 0.6–1.6 | 0.077–16.3 | 0–1.4 | – | – | – | – | – | – | Kumar *et al.* 2009 |

[1] from Allan *et al.* 2009.
[2] CSG – Coal-seams gas.

*Salinity* – The salinity in groundwater vastly depends on the source of the water. In evaporation SIS basins, the salinity tends to be higher and depends on the rate of evaporation/recharge (Mazor and George, 1992). The authors reported that 66 percent of 88 wells tested in Western Australia's Wheatbelt (southeast region) had a salinity of 5–45 g/litre, suitable for euryhaline fish, while the salinity range between the walls was 0.28–320 ppt. These figures might be higher due to the increase in salination in the past decades.

Mine lakes and flooded open-cut pits are also prone to increase salinity, especially in arid and semi-arid areas with high evaporation and low (or no) recharge. For example, Johnson and Wright (2003) reported that the salinity in the Mount Goldsworthy pit increased from 14 to 55 g/litre over 14 years with an even more extreme increase from 15 to 79 g/litre over three years evident in the Keringal mine lake.

Pit water quality is influenced by many factors including climate, groundwater, depth (some of the pits are a few hundred metres deep), wind (or lack of it in sheltered mine pits) and local mineralogy (Boland and Padovan, 2002; Jones *et al*., 2008; McCullough, 2008).

*Ionic composition* – Ionic composition of groundwater (of any source) represents a major challenge in terms of suitability of water (at any salinity) for growing any aquatic organism. Partridge, Lymbery and George (2008) noted that, although the main source of salt in the Australian landscape is oceanic (Mazor and George, 1992; Zalizniak, Kefford and Nugegoda, 2006), the ionic composition of saline groundwater varies considerably from seawater. Both Partridge, Lymbery and George (2008) and Allan *et al*. (2009) compared several elements that consisted of the majority of seawater ions (by dry weight; Spotte, 1992) seawater to several saline groundwater sources (Table 3). They noted that, aside from potassium, deficiencies or excesses vary between locations and sources.

Potassium, however, was deficient in all the water sources. Usually, the deficiency is caused by the uptake of potassium by clay soils over sodium (Stumm and Morgan, 1996).

Potassium has a pivotal role in many physiological cycles of cultured species and specifically in fish involved in osmo-regulation, as well as acid-base balance (Marshall and Bryson, 1998; Evans, Piermarini and Choe, 2005) and, therefore, its deficiency from groundwater is most significant. Potassium deficiency in groundwater was reported to cause mortality in several fish species. Fielder, Bardsley and Allan (2001) reported mortality of silver seabream (*Pagrus auratus*) reared in 19 g/litre groundwater with 5 percent K-equivalence to seawater (100 percent seawater). The mortality was reduced when the potassium content adjusted to 40 percent of seawater, but with significantly lower growth compared to fish reared in 60 percent K-equivalence. The same results were evident with Japanese meagre (mulloway, *Argyrosomus japonicas* – Doroudi *et al*., 2006; Hutchinson and Flowers, 2008), barramundi (*Lates calcarifer* – Partridge and Creeper, 2004), and silver perch (*Bidyanus bidyanus* – Ingram, Mc Kinnon and Gooley, 2002; Fielder, Bardsley and Allan, 2001; Doroudi *et al*., 2007). These authors found that the susceptibility to potassium deficiency is related to salinity, i.e. the lower the salinity, the higher the survival in potassium-deficient water.

*pH* – The pH range for fish culture is between 6.5–8.5, with 7.5–8 considered to be optimal. In many cases, groundwater is acidic with pH lower than 6 (Partridge, Lymbery and George, 2008; Hutchinson and Flowers, 2008; Allan, Banens and Fielder, 2001; Allan *et al.,* 2009). In many cases, the low pH is associated with high levels of metals such as iron and copper that are also toxic to fish (Lee, 2001; Gooley and Gavine, 2003). Buffering and removing or binding the metals is possible (Hunt and Patterson, 2004), however, not in a way that would be commercially feasible for large volume of waters.

TABLE 3
**Open-cuts and disused mines characteristics**

| Parameter | Collie Basin, Western Australia | Collinsville, North Bowen Basin, Queensland | Mount Morgan, Queensland | Mary Kathleen, Queensland | Ranger Mine, Northern Territory | Kemerton, Western Australia | St Barbara Mines, Western Australia | Thalanga Mine, Queensland |
|---|---|---|---|---|---|---|---|---|
| Ore type | Coal | Coal | Au, Cu | U | U | Silica sand | Au | Cu-Pb-Zn |
| Depth (m) | 8–70 | 4–14 | – | – | – | 6 | – | 70 |
| Area (km$^2$) | 0.06–1.03 | 0.01–0.06 | – | – | – | – | 0.006–0.95 | – |
| pH | 3.8–5.0 | 1.5–4.9 | 2.8 | 6.1 | 7.6 | 8.5 | 8.0–8.6 | 7.7 |
| Total P | <0.005–0.009 | <0.005 | – | – | 0.01 | 0.02 | - | – |
| Total N | <0.05–1.5 | 0.51 | – | – | 1.96 | 0.573 | 7.3–22.8 | – |
| Dissolved Organic Carbon | 3.1–7.3 | 1–59 | – | – | – | 22 | – | – |
| Salinity (gr litre$^{-1}$) | <3 | 5-15 | 6.9 | 3 | 0 | 1 | – | 0.5 |
| Sulphate | 31–107 | 300–25 000 | 12 100 | 1 840 | 782 | 296 | 2 570–7 190 | 7 950 |
| Aluminium (mg litre$^{-1}$) | 0.001–0.006 | 23–1 300 | 740 | 0.032 | 0.026 | 0.1 | 0.02–0.06 | <1 |
| Calcium | 2.3–6.0 | 124–519 | 520 | 464 | 0.02 | 67 | 334–1 120 | 718 |
| Cadmium | <0.002 | <0.01–0.023 | 0.15 | – | <0.0002 | – | 0.0002 | 0.16 |
| Cobalt | <0.005 | 0.6–7.2 | – | – | 0.0005 | – | - | – |
| Chromium | <0.10 | <0.01–0.47 | – | – | < 0.002 | – | 0.002 | – |
| Copper | <0.002–0.05 | <0.05–2.5 | 36 | 1.17 | 0.0024 | – | 0.03 | < 1 |
| Iron | 0.0003–.005 | 139–2 463 | 248 | 3.23 | <20 | 0.14 | < 0.05-0.06 | 0.575 |
| Lead | – | <0.1–6.3 | – | – | 0.001 | <0.1 | – | <1 |
| Magnesium | 0.077–16.3 | 197–2 239 | 1 240 | 140 | 115 | 58 | 865–3 150 | 1025 |
| Manganese | 0.0002–1.2 | 13–150 | 81 | – | 0.041 | <0.01 | – | – |
| Nickel | 0.03–0.34 | 1.2–17 | – | 0.69 | 0.0053 | – | 0.09 | – |
| Uranium | – | 0.020–0.029 | – | 0.460 | 1.76 | – | – | – |
| Zinc | 0.0005–6.9 | 1–46 | 25.3 | 0.088 | 0.0037 | 0.15 | 0.01 | 53.5 |
| Chlorophyll $\alpha$ (µg litre$^{-1}$) | 0.1–64 | 0–64 | – | –- | – | 6.5–8.5 | – | – |

Many groundwater sources, especially from SIS (Hutchinson and Flowers, 2008), are acidic (as low as pH 2.5) due to the high levels of dissolved carbon dioxide (carbonic acid leached from carbonate-based soils). This low pH might be remedied by degassing the carbon dioxide. Depending on the acidity of the water and water volume, this process might be viable (Hutchinson and Flowers, 2008).

*Other contaminants* – Chemical (nutrients, heavy metals, herbicides and insecticides, organic compounds and others) and biological (pathogens and micro-organisms) contaminants exist in groundwater. Open-cut mines (Table 3), pit lakes, surface water and shallow groundwater are more prone to contamination than deep groundwater (i.e. coal-seam water). Several publications demonstrate different types of contamination in groundwater (Doupe', Lymbery and Starcevich, 2003; Fitzpatrick *et al.*, 2005; Sarre *et al.*, 1999; Scott and Solman, 2004; Nott *et al.*, 2004; Partridge, Lymbery and George, 2008).

## CULTURED SPECIES

During the past decade, efforts were made to culture many aquatic organisms in most of Australia's states. Many experiments were conducted to look at the suitability of both fresh and marine species to groundwater (Partridge, Lymbery and George, 2008; Hutchinson and Flowers, 2008; Allan *et al.*, 2009). More than ten species of fish, microalgae, as well as *Artemia* and *Parartemia* have been tested. Most of the fish species tested were found to be susceptible to the groundwater conditions, mainly the ionic composition and pH.

Marine species such as snapper and yellowtail amberjack (*Seriola lalandi*) have been investigated using saline groundwater and/or manipulated groundwater. Although found to survive and grow (even though, in most cases, significantly less than in seawater), these species were not considered to be suitable for groundwater culture (Partridge, Lymbery and George, 2008). Barramundi, with its broad salinity susceptibility, was also tested (Partridge and Lymbery, 2008). However, its susceptibility to potassium, as well as the temperature drop during the night in inland saline areas, made this species not commercially viable for this type of culture (unless the use of an intensive indoor culture system is considered).

Other freshwater species such as silver perch that do not need potassium adjustments were also looked at (Allan, Heasman and Bennison, 2008; Allan *et al*., 2009). However, day/night water temperature fluctuations up to 5 °C limited the growth.

Black bream seems to be an ideal species for groundwater culture, being euryhaline and robust (Doupé *et al*., 2005). However, a very slow growth rate and a limited market prevents this species from becoming commercially viable.

In South Australia, Hutchinson and Flowers (2008) conducted proof-of-concept grow-out experiments with Japanese meagre (mulloway) in intensive and semi-intensive systems supplied with saline groundwater from SIS. The results demonstrated high survival and good growth rates but also identified high levels of dissolved carbon dioxide in groundwater, which was a limiting factor that would need to be addressed to improve performance of this species. Based on these results, an expression of interest for commercial use of saline groundwater from SIS in South Australia was presented. However, no commercial investment has eventuated to date.

Rainbow trout (*Oncorhynchus mykiss*) farming was trialled both in New South Wales (Allan *et al*., 2009; Johnston, 2008) and Western Australia (WA) with small commercial production in WA. Currently, a very small production (a few tonnes per year) of trout is carried out in WA using groundwater.

Currently, only the microalgae, *Dunaliella salina* and *Artemia* are cultured on a large scale in Australia. *D. salina* is cultured both in South Australia (SA) and WA for its natural carotenoids by Cognis Australia (the company owns both sites in SA and WA and supplies more than 60 percent of the world's natural β-carotene).

*Artemia* is cultured both extensively and intensively. In SA, *Artemia* is cultured in large shallow natural saline ponds, with no added nutrients or feed, while in WA, the *Artemia* production is of a high-intensity and adjunct to the *D. salina* production lakes (Kolkovski, Curnow and King, 2010).

## FARMING SYSTEMS

Different rearing systems were tested over the years. Recently, Partridge, Lymbery and George (2008) and Allan *et al*. (2009) reviewed many of these systems.

*Pond-based systems* – Allan, Banens and Fielder (2001) suggested that pond culture might be the most commercially viable production system for inland aquaculture. Ponds are considered to be the lowest capital investment system with, usually, the lowest maintenance costs. However, aside from biomass limitation, the potential areas for pond culture (salt affected areas, SIS water discharge areas, etc.) are located in inland areas (Figure 5), where temperatures in large water surface bodies, such as ponds, vary significantly between seasons with high daily fluctuations (Partridge, Lymbery and George, 2008; Allan *et al*., 2009; Hutchinson and Flowers, 2008).

Allan *et al*. (2009) tested floating solar covers that completely cover a 500 $m^2$ Japanese meagre (mulloway) pond. The floating covers increase mean minimum winter and summer temperature by 1.5 °C and 3 °C, respectively, and had little effect on the major water quality parameters compared to uncovered, ambient ponds. The authors reported

FIGURE 5
**Cage system within evaporation pond at the Inland Saline Aquaculture Research Centre (ISARC), New South Wales**

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that after 12 months of grow-out, Japanese meagre cultured in solar-covered ponds achieved 20 percent more biomass than Japanese meagre in uncovered ponds. However, the commercial feasibility of covers (capital investment vs weight gain) was not reported.

Complete static pond systems are virtually impossible in arid and semi-arid areas of Australia due to the high evaporation rate and the need to compensate it. Luke, Burke and O'Brien (1987) calculated that five hectares of ponds in Western Australia's Wheatbelt (southeast region of Western Australia) would require 350 m$^3$/day of water during the summer months to compensate for evaporation.

Partridge, Lymbery and George (2008) also noted that even in static ponds, it might be that potassium ions will still need to be added due to the high affinity between this ion and the clay soils. The need for ion supplementation might not be commercially feasible for large-scale production systems. Allan *et al.* (2009) also reported reduced growth in static trout ponds due to build-up of organic matter.

It was considered that flow-through pond systems adjoining the evaporation basins and SIS might be viable, as long as there was no need for ion supplementation (Partridge, Lymbery and George, 2008). The ponds' discharge into evaporation basins is believed to result in very little environmental impact. However, even with a high flow-through regime, water temperature fluctuation in arid and semi-arid areas will still present significant issues.

However, Allan *et al.* (2009) reported that trout growth might be feasible. The authors reported good growth rates over a period of three months. Trout stocked at 40 g had an average wet weight of >310 g with near 100 percent survival during the winter months. The survival decreased as pond temperature exceeded 21 °C, suggesting that even 60 percent daily water exchange was insufficient to reduce the temperature increase.

FIGURE 6
**Semi-intensive tank aquaculture system at Waikerie Inland Saline Aquaculture Centre (WISAC), South Australia**

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Economic analysis for rainbow trout culture in raceways (Johnston, 2008) indicated that farms with a 200 tonnes/year production capacity might be viable and could produce an attractive rate of return on investment.

*Tank culture* – Production of Japanese meagre (mulloway) in large tanks supplied with groundwater from an SIS was found to be feasible at the Waikerie Inland Saline Aquaculture Centre, South Australia (Hutchinson and Flowers, 2008; Figure 6). The authors also tested the water chemistry from several sections of a major SIS and the systems disposal basin over 12 months.

The authors reported that the trials demonstrated that the level of salinity and potassium of SIS groundwater collected from the discharge point to the Stockyard Plain Disposal Basin did not significantly affect growth and metabolism of Japanese meagre (mulloway) in tanks.

Although potassium was only 40 percent of seawater levels, there was no effect on survival or growth. The authors pointed out that the elevated levels of dissolved $CO_2$, resulting in low pH, was a major issue with groundwater and needed to be addressed. To reduce the levels of dissolved $CO_2$, a degasser column with high ratio of air to water (>10:1) was installed to treat all incoming groundwater before use in culture systems. A similar problem with high $CO_2$ was also identified in the northwest of Western Australia, where bore (well) water was used for culturing common dolphinfish (*Coryphaena hippurus).* A degassing column (5 m high × 1 m Ø) increases the water pH from 6.5 to 7.9.

*Enclosed tanks* – A new tank system was developed to culture *Artemia*. The tanks are completely enclosed, aside from the manhole at the top. The designed 32 000 litre tanks addressed the biosecurity issues of rearing *Artemia* near *D. salina* ponds. The system includes an individual filtration system to each tank and unique aeration system to support high-oxygenated water at high salinities (Kolkovski, Curnow and King, 2010).

*Shallow lakes* – Shallow lakes and large shallow ponds are used for the production of microalgae. Currently, the only microalga cultured in Australia is *D. salina*. The private company Cognis Australia cultures the algae both in Western Australia (Hutt Lagoon, Port Gregory) and South Australia (Whyella). The lagoons were divided by dykes on the bed of the coastal lagoon, taking advantage of the impermeable hyper-saline crust. The ponds are shallow (0.2–0.4 m) to allow light penetration and high evaporation. The required salinity is managed by pumping seawater or beach wells through inlet channels diverted to each of the production ponds. The production process is summarized by Borowitzka (1995, 1999). The rate of harvesting and the growth period varies with changing climatic conditions throughout the year. The ponds are unlined and there are no mixing devices; the only mixing is by wind and thermal action.

An innovative system designed to reduce nutrients input into ponds by collecting the solid wastes was developed in Western Australia (McRoberts Aquaculture Systems – Partridge *et al*., 2006). The system was designed to increase the production of the static pond by installing the semi-intensive floating tank system (SIFTS) tanks in the ponds. Partridge *et al*. (2006) described a series of growth experiments with Japanese meagre (mulloway), barramundi and rainbow trout using a prototype unit conducted in (relatively) small ponds using saline groundwater (14 g/litre). The SIFTS units' design and construction materials incorporate a reinforced liner, which forms a "suspended tank" fixed to a moulded module. These modules provide buoyancy to the structure, as well as a working platform around the tank. Large volumes of water are pumped through the SIFTS using air-water-lifts, which allow high stocking densities of fish to be cultured, without the need for pure oxygen. However, the authors did not encourage commercial interest in the use of SIFTS for inland saline aquaculture in Western Australia due to system limitation and constraints of available groundwater in large quantities, restricting the system to static ponds (Allan *et al*., 2009).

## ACTIVITY IN AUSTRALIA

Across Australia, man-made or naturally occurred salination of land and water is causing major impacts on agricultural production, rural infrastructure, drinking water, irrigation and aquatic biodiversity (Allan, Banens and Fielder, 2001). Aquaculture has been identified as one of the potential adaptive uses of saline groundwater.

In 1997, the Australian Centre for International Agricultural Research organized the first national workshop on inland saline aquaculture. Following this workshop, the Fisheries Research and Development Corporation (FRDC) supported the preparation of a research and development plan for developing commercial saline aquaculture in Australia (Allan, Digman and Fielder, 2001).

The interest in desert aquaculture (i.e. inland saline aquaculture, usually located in arid or semi-arid areas) has occurred because of the potential advantages and benefits it offers, as well as a solution to the increased salination problem. These advantages and benefits include:

- Providing opportunities to increase aquaculture production in Australia that, like in many other countries, is limited by a shortage of suitable coastal sites with the necessary characteristics for successful production. Such sites are often reserved for housing or tourist-related development, or judged to be of too high environmental value for aquaculture, while "unwanted" land and water affected by salination provides opportunities for inland saline aquaculture.
- Establishment of cost savings attributed to the low cost of land compared to coastal locations.
- In some situations, aquaculture species growth advantages are provided by the constant elevated water temperature of saline groundwater over-production in ambient water temperature conditions.
- Ability to operate production facilities in a biosecure manner due to the location and water supply from deep aquifers being isolated from parasites and diseases and their vectors.

Combined, these factors stimulate interest in finding ways to exploit saline groundwater resources for commercial aquaculture. The majority of research and development activities during the past decade were concentrated in the use of saline water for aquaculture. Several reports, business plans and scientific publications were generated (www.australian-aquacultureportal.com/saline). Allan, Heasman and Bennison (2008) and Allan *et al.* (2009) summarized the research and development carried out within the participating states. However, aside from microalgae and *Artemia* production, almost all the activity remained at the experimental/research stages.

*Victoria* – The Victorian Government through the Department of Primary Industries is strongly supporting a multi water-use, integrated agri-aquaculture systems (IAAS) approach to diversification of the irrigated agriculture sector in the Victorian reaches of the Murray-Darling Basin. The primary focus of Victorian IAAS development is to add value and sustainability to irrigation water through application of multi water-use systems based on open-water cage culture of Murray cod (*Maccullochella peelii*) in large-scale private irrigation storages. The most recent IAAS developments in Victoria as part of the Our Rural Landscape initiative are reported by Gooley *et al.* (2007). Present Victorian Government-funded IAAS research and development activity is being delivered as part of the Aquaculture Futures Initiative for the period 2008–2009 to 2011–2012. Research and development priorities include development of better management practices for open-water cage culture of Murray cod, as well as development of a marker-assisted selective breeding programme for a large-scale supply of high performing, elite strains of Murray cod seed stock.

Currently, there is no Victorian Government-funded research and development on inland saline aquaculture.

*Queensland* – The Queensland Department of Primary Industries and Fisheries investigated the potential for inland saline aquaculture in several regions where groundwater salinity is suitable for shrimp production. Research effort has focused on determining the suitability of groundwater for prawn farming at salinities ranging from almost fresh to full-strength seawater. In 2002, these studies were applied to a series of trial ponds in collaboration with an existing red claw crayfish (*Cherax quadricarinatus*) farm at Bauple, north of Brisbane (Collins *et al*., 2005). Investigations were conducted to assess the suitability for aquaculture to utilize waste groundwater produced as a by-product during coal seam gas (methane) extraction. This research and development was undertaken in collaboration with an energy company that operates power generation systems in the Darling Downs where extensive coal-seam gas resources are being exploited. (Source: Modified from www.australian-aquacultureportal.com).

*New South Wales* – The Inland Saline Aquaculture Research Centre (ISARC) was established by the NSW Government in partnership with Murray Irrigation Limited (MIL). MIL operates the Wakool-Tullakool Subsurface Drainage Scheme at Wakool, NSW. This is the largest saline groundwater evaporation scheme in Australia, pumping up to 13 000 000 $m^3$ per annum of saline groundwater to 1 600 hectares of evaporation ponds. ISARC was constructed in a corner of one of the evaporation ponds.

This facility has supported investigations on the survival and growth of several species in saline groundwater, including silver perch, Japanese meagre (mulloway), giant tiger prawns (*Penaeus monodon*), kuruma prawns (*Penaeus japonicus*), rainbow trout, New Zealand rock oysters (*Saccostrea glomerata*), and snapper (Allan, Heasman and Bennison, 2008; Allan *et al*., 2009; Doroudi, Allan and Fielder, 2003; Doroudi *et al*., 2006; Fielder, Bardsley and Allan, 2001). Pilot-scale trials with trout resulted in very good growth rates (initial wet weight of 37 g and final average wet weight of 298 g after three months with 100 percent survival). Production trials (2006/2007) have identified that the best opportunity for commercial inland saline aquaculture development in southern New South Wales is (relatively) medium-scale (200 tonnes/year) farming of rainbow trout. Currently, the major limitation to inland saline aquaculture in this area is the lack of saline groundwater following a number of years of drought that has caused the water table to retreat progressively deeper (Allan, Heasman and Bennison, 2008).

The Department of Primary Production was involved in co-coordinating with the National Aquaculture Council, the fragmented inland saline aquaculture research in Australia through several federal-funded projects. This involved an earlier resource inventory (Allan, Banens and Fielder, 2001) and national research and development plan (Allan, Digman and Fielder, 2001). Results from the following project (2004–2008) are summarized in the final report (Allan, Heasman and Bennison, 2008). Currently, there is no NSW Government-funded research on inland saline aquaculture.

*South Australia* – The South Australia Research and Development Institute (SARDI) has previously investigated the use of saline groundwater for aquaculture at Cooke Plains Inland Saline Aquaculture Research Centre (CPISARC). This facility was established in collaboration with the Coorong District Council and the research was conducted from 1997 to 2003. At this location, the source of saline groundwater was a shallow aquifer 1–2 m below the soil surface in an area impacted by dry land salinity that is extensive in this region. The volume of saline groundwater available at this location was limited with water temperature varying seasonally and similar to ambient soil temperature. The species cultured at CPISARC were Japanese meagre (mulloway), snapper, brine shrimp (*Artemia* spp.), Pacific oyster (*Crassostrea gigas*), seaweed (*Ulva* sp.) and microalgae (*Dunaliella salina*).

The South Australia Research and Development Institute has identified that saline groundwater from a major SIS in the Riverland region offers an opportunity for aquaculture, including the consistent supply of a relatively high volume (350 litre/sec) of pressurized water with a relatively stable elevated water temperature (20–22 °C) and moderate salinity (19–21 g/litre). This situation differed to other states where available saline groundwater was supplied from evaporation ponds from a large subsurface drainage scheme (NSW) or naturally occurring saline lakes (WA). A semi-intensive aquaculture system was installed by SARDI at the Waikerie Inland Saline Aquaculture Centre (WISAC) to investigate the use of SIS discharge water for aquaculture. Research and development activities undertaken at WISAC established Japanese meagre (mulloway) as a potential species (Hutchinson and Flowers, 2008).

Small-scale operations exist for inoculating and harvesting *Artemia* in saline lagoons. The private operator is seeding natural lagoons with *Artemia* cysts and harvests them from time to time. This is an extensive operation with an estimated 10 $m^3$ harvest per annum. The only major commercial operation is *D. salina* (Cognis Australia) culture in large ponds in Whyella.

*Western Australia* – Although during the past decade research into the development of inland saline aquaculture was given some priority and funding from both Federal and State agencies, this is not the case anymore.

The Western Australian (WA) inland saline aquaculture research effort was comprised of researchers from Challenger TAFE (Technical and Further Education, Tertiary Education Institute) Aquaculture Development Unit (ADU), CY O'Connor TAFE, Western Australia Department of Agriculture and Murdoch University. Collectively, these organizations made up the Inland Saline Aquaculture Applied Research Group (ISAARG). Particular effort has been directed towards development of the SIFTS patented by McRobert Aquaculture Group and the ADU (see 'systems' section). Species investigated for inland saline aquaculture in WA include barramundi, Japanese meagre (mulloway), snapper, black bream, rainbow trout, ornamental fish (range of species, mostly live-bearers) and black tiger prawn. No commercial activities resulted from the ISAARG research efforts.

The only commercial desert aquaculture in Western Australia is *D. salina* and *Artemia* aquaculture at Hutt Lagoon, Port Gregory (Figure 7). (Source: Updated extracts from www.australian-aquacultureportal.com).

*Demonstration research facilities* – Research or demonstration facilities that focus on inland saline aquaculture were established in a few states, including Queensland, New South Wales, South Australia and Western Australia. At all locations, demonstration facilities were used to hold open days and to provide a source of biological and technical information to potential investors, government officials and members of the public.

A federal-funded communication and coordination project was established to facilitate and coordinate the research and development work on a national level (Allan, Heasman and Bennison, 2008). As part of the project, an investment directory was developed, providing a single point source for information on inland saline aquaculture. This contained contact details of researchers, salinity managers, government policy

FIGURE 7
***Dunaliella salina* production ponds, at Lagoon, Western Australia**

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makers and those involved with farming. A research and development priorities plan was highlighted and a comprehensive risk analysis framework developed (www.australian-aquacultureportal.com).

## IMPEDIMENTS TO DEVELOPMENT

*Water source* – The biggest constraint to commercial development of inland saline/desert aquaculture in NSW, Victoria and Southern Australia (SA) is the deficit of saline groundwater as a result of severe, long-term drought in most of the eastern and southern Australia regions and specifically in the Murray-Darling Basin (MDB) system (Allan, Heasman and Bennison, 2008; Allan *et al.*, 2009). The extended drought has meant that little or no freshwater irrigation has been available and no significant rainfall (and in some parts, none at all) in the MDB for several years. As a result, the groundwater table has not been recharged and the saline groundwater table significantly dropped. Therefore, salinity interception schemes were reduced and were not needed. Allan, Heasman and Bennison (2008) reported that in the Wakool-Tullakool subsurface drainage scheme, the pumping volume of saline groundwater dropped from 35 000 $m^3$/day to 4 000–5 000 $m^3$/day.

*Suitable species* – Although some fish species, such as Japanese meagre (mulloway), were identified as potential species for saline aquaculture, most of the species tested were found to be not suitable for saline aquaculture due to improper water ion profile and water temperature. Although ions can be supplemented to the rearing system, it does not seem to be commercially viable in large systems. In many areas, species could only be reared part of the year, while during the rest of the year, the growth would be suspended or the fish would die. For example, barramundi and Japanese meagre could be grown in the warmer months of the year but would not survive (barramundi) or will stop growing (Japanese meagre) during the winter months. Trout is the opposite example as it grows very well during the winter, but does not survive the summer months. Although Partridge, Lymbery and George (2008) suggested that alternate species according to the season might be possible, this option is yet to be tested on a commercial basis.

Water quality, in many cases, is also presenting a major obstacle with low pH, salinity and, as mentioned above, ion profile. Indeed, each one of these obstacles can be resolved, but at a cost. In large commercial-scale operations, this option would, in all likelihood, not be viable.

*Environmental, social and economic issues* – In many cases, groundwater sources are located in rural Australia, making transportation to and from aquaculture locations expensive. Cost of labour, power and associated work with the establishing aquaculture venture is expensive. For example, in most cases, fish feed needs to be transported from Tasmania or Queensland to Western Australia, a few thousands kilometres away, significantly adding to existing feed costs. These costs are especially high compared to neighbouring countries in Southeast Asia. Therefore, it will be hard to compete on the frozen white flesh segment market, although it might be possible to compete in some niche markets (as proven with rainbow trout). In many cases, people interested in starting an aquaculture venture are farmers that are interested in diversifying their activities. In these cases, the scale of production is usually limited to a few tonnes, making these ventures unfeasible.

*Markets* – Australian markets are relatively small, with a population of only 22 million and moderate seafood consumption compared to other countries such as Japan, Mediterranean countries, etc. Although niche markets exist for certain species (trout, live and fresh barramundi and others), in general, it is hard to compete with the influx of imported frozen seafood from Southeast Asia.

FIGURE 8
***Artemia* production system, at Lagoon, Hutt Lagoon Western Australia**

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## SUCCESS STORY
## *Dunaliella salina* and brine shrimp culture

During the last five years, the Department of Fisheries – Western Australia (DoFWA) and Cognis Australia developed a unique system incorporating rearing *Artemia* sp. in tanks adjunct to *D. salina* rearing ponds (Kolkovski, Curnow and King, 2010) (Figure 8).

The microalga *D. salina* is cultured in large, shallow ponds in Hutt Lagoon, Port Gregory, WA (600 km north of Perth). The lagoon is divided into very large and shallow ponds in a similar way to salt works evaporation ponds. Salinity is monitored and kept at its optimum by pumping seawater through incoming water channels (Figure 8). The algae, usually green at low salinity, produce carotenoids (mainly beta-carotene) in a high salinity environment. As the algae reach the required level of carotene, they are harvested and concentrated into a paste using a proprietary process. The water returned to the ponds and the carotenoids are then extracted from the algae biomass, which is then discarded. Several years ago, a natural bloom of *Artemia* occurred in the ponds.

The company teamed up with DoFWA to eradicate the *Artemia* from the algae ponds. Following successful removal of the *Artemia* from the ponds, it was suggested to try to culture the *Artemia* in separate ponds. A research and development project was launched and funded by the FRDC (a federal funding agency). Early attempts to culture *Artemia* were conducted in 18 $m^3$ shallow ponds, where a number of issues were identified.

The primary concern with pond production was contamination of the biomass product. Therefore, the decision was made to culture *Artemia* in covered flow-through tanks, which would allow much more control over the quality of the product. However, at this point, adequate filtration, aeration, culture media delivery and culture methods needed to be developed in order to succeed.

Of great concern to Cognis was the issue of biosecurity, due to the fact that *Artemia* are the primary pest species for the *D. salina* production. Therefore, in parallel to developing culture systems and techniques for growing *Artemia*, biosecurity such as outlet screening, safety control and spillage containment needed to be developed.

The rearing system is based on closed plastic-moulded (aside from the manhole at the top) 32 000 litre tanks with a water inlet and filters that retain the *Artemia* in the tank on the outlet (see Figure 8).

Development efforts were given to design a new, innovative filtration system that allow the flow of tens of thousands of litres per hour through the screens without damaging the *Artemia* or becoming blocked with the *Artemia* waste.

An outlet biosecurity/harvest screen was also designed, constructed and installed within the main drainage manifold. This apparatus enabled the harvesting and separating of different size *Artemia* and cysts in one pass. Effluent is then safe to return to the ponds directly into the effluent channel. The returned water is rich with nutrients from the *Artemia* waste, helping fertilizing the algae ponds.

The *Artemia* tanks receive a mix of seawater and pond water to adjust and optimize the salinity. The *Artemia* is also receiving the algae biomass and water (still containing high level of algae cells) after the extraction of carotenoids.

This link between the algae production and the *Artemia* production made the project commercially-viable with the existing infrastructure for the algae production, as well as skilled operators that can work on both production systems.

The system is vertically integrated, linked to feed (*D. salina*) production on-site, packaging and freezing facilities. Currently, the main product is frozen biomass. Other products such as cysts, feed attractant (patented) and enriched *Artemia* will follow shortly.

While there are other *Artemia* grow-out sites around the world, the majority of them are based on open ponds, low-tech production systems and investment. The *Artemia* rearing system at Hutt Lagoon, WA is the first super-intensive *Artemia* rearing system in the world.

## THE WAY FORWARD

During the past decade, intensive efforts were invested in 'inland saline' aquaculture in Australia both by federal and state agencies. Water sources, suitable species and culture systems were investigated and developed. However, in most cases, the high investment and strong interest by potential investors, farmers and companies did not translate to commercial projects. One of the reasons for the lack of commercialization is the severe drought in Australia's eastern states. Over the last ten years, the emphasis has gone from a national priority to address salinity (with a multi-billion dollar budget) to a lack of water in many areas. For example, in the NSW SIS schemes, all 60–70 pumps have been turned off for the first time in 30 years. In addition, the landowners who would have been expected to invest in inland saline aquaculture have no financial means due to the drought.

Unfortunately, very little, if any, research and development funding is currently available for arid/semi-arid and inland saline aquaculture. Coupled with the reduced availability of groundwater across Australia, the development of large-scale commercial aquaculture ventures based on groundwater in the Australian arid/semi-arid areas does not appear to be viable in the near future.

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