BRIBIE ISLAND GROUNDWATER RESOURCES: CHALLENGES IN DEVELOPMENT OF CONCEPTUAL AND NUMERICAL MODELS

TAULIS, M., COX, M., TODD, A., HAWKE, A., RAIBER, M. & JAMES, A.

Groundwater is a major resource on Bribie Island and its sustainable management is essential to maintain the natural and modified eco-systems, as well as the human population and the integrity of the island as a sand mass. An effective numerical model is essential to enable predictions, and to test various water use and rainfall/climate scenarios. Such a numerical model must, however, be based on a representative conceptual hydrogeological model to allow incorporation of realistic controls and processes. Here we discuss the various hydrogeological models and parameters, and hydrological properties of the materials forming the island. We discuss the hydrological processes and how they can be incorporated into these models, in an integrated manner. Processes include recharge, discharge to wetlands and along the coastline, abstraction, evapotranspiration and potential seawater intrusion. The types and distributions of groundwater bores and monitoring are considered, as are scenarios for groundwater supply abstraction. Different types of numerical models and their applicability are also considered.

INTRODUCTION

Bribie Island is a 150 km² sand-strip land mass located in the northern part of Moreton Bay, South East Queensland (Figure 1). Bribie Island’s population, presently over 16000 inhabitants, requires a steady supply of water for its domestic use. The main water resource being used on the island is groundwater, which has been sourced from the sand aquifer system via open trenches, and more recently by a borefield. These aquifers are solely recharged by precipitation. There is also extraction from a large number of shallow tube wells (spears) in the residential areas, mainly in the southwest. However, in the past there have been no requirements to the licensing of these private spears and little or no resource allocation (DSEWPC, 2009). The prolonged drought from the mid-1990’s to late 2008 resulted in major concerns over the sustainability of the groundwater resource and has made its management even more important.

Since its early development, the Bribie Island groundwater resource has been managed using numerical models as reference tools, and these were developed using information available at the time. The first formal groundwater investigations in Bribie Island commenced in the early 1960s and focused on the establishment of a municipal water supply. These earlier models were based on several different conceptual hydrogeological models, however, as more information became available models became more detailed and specific. Due to increased demands on the resource, future groundwater model development on Bribie Island warrants an assessment of previous

FIG. 1. Location map of Bribie Island in relation to Brisbane City.
models in the context of new data and a greater understanding of the system. The aim of this paper is to describe the most recent understanding and conceptualisation of the Bribie Island aquifer system which is based on an integration of new data and recent model development. The assessment presented throughout this paper is based on both conceptual and numerical groundwater modelling, and will help set goals and objectives for management strategies and future model development.

STUDY AREA AND CHARACTERISTICS

PHYSICAL SETTING

The landscape of Bribie Island averages around 5 m AHD (metres above Australian Height Datum which is equivalent to Mean Sea Level) with a maximum of 13 m AHD. Bribie Island’s topography is low-lying in comparison to the substantially higher massive dune landscapes of Moreton Island and North Stradbroke Island, which are on average 50-100 m AHD high and up to 250 m AHD.

Bribie Island has a subtropical climate with an average annual precipitation of 1400 mm/year most of which occurs in summer between November and May (rainfall > 100 mm/month). Bribie Island’s mean temperature oscillates between 16°C and 25°C and the months between May and September have the lowest temperatures (T< 20°C) each year (Figure 2). Mean annual pan evaporation, measured at the University of Queensland Bribie Island weather station, is around 1679 mm/year (DNR, 1996). Using this value, and considering a nominal pan coefficient of 0.7 (Allen, 1998), the resulting reference evapotranspiration is 1175 mm/year. This amount is in the lower range of potential evapotranspiration rate estimates (based on water balance modelling) varying from around 1000 mm/year (Williams, 1998) to 1300 mm/year (Bubb and Croton, 2000).

SURFACE HYDROLOGY

The surface drainage system of Bribie Island is poorly developed due to the porous nature of its sand mass. The land surface is incised by an elongated swale (up to 600 m wide with an area of about 600 ha) delimited by two longitudinal dunes (8 to 13 m AHD high) running north-south down the centre of the island. Sedimentation in this central swale has resulted in the evolution of a terrestrial swamp area with a small lagoon at its centre. The lagoon/swamp area is fed by throughflow and surface runoff from the adjacent dune system. The swale mainly drains northward through a small creek (Westaway Creek) (Figure 3) discharging into the northern section of the Pumicestone Passage (Figure 1) and also through the southern section of the swale via Wright’s Creek (Armstrong, 2006).

FIG. 2. Average annual precipitation and mean monthly temperature for Bribie Island (based on 1980-2008 data from NRW and BOM).
On the estuarine west coast, surface drainage is marked by a series of creeks and canals fed by runoff from Pleistocene age beach ridges and discharges into the Pumicestone Passage. On the ocean east coast and towards the southeast, surface runoff from Pleistocene dunes flows into a series of lagoons which are frequently breached by groundwater discharge or cyclonic tidal surges (Werner, 1998a). In the south and central west part of the island, the canals and lagoons have been reshaped by anthropogenic activity. The water level in these canals is artificially maintained using a weir and lock system (Werner, 1998a), and the substantial Pacific Harbour development includes a series of canals, a marina, and a golf course. Residential and light commercial land use is concentrated in the southwest and southeast of the island, and the northern two-thirds are distributed between land reserves and plantation forestry.

Quaternary sediments on Bribie Island represent a typical prograded barrier island sequence (Armstrong, 2006) with well sorted aeolian fine sands overlying a deeper sand sequence. These sands are characterised by upward coarsening (from less well sorted and poorly sorted fine-medium sands to fine-coarse sands and gravelly coarse sands); the lowest unit is formed of sandy silts. Thin silty or clayey sands that occur near the Landsborough Sandstone contact in some areas may be the product of sandstone weathering (Harbison, 1998).

Leaching of soluble and colloidal humic material near the surface has resulted in the formation of dark brown indurated and semi-indurated sands (‘coffee rock’) through a process of cementation and infilling of pores by organic matter and clays (Cox et al., 2002). This has occurred extensively over Bribie Island and has resulted in an indurated sand unit occurring within 1-10 m from the surface and up to 12 m thick.

GROUNDWATER CHARACTER & PROCESSES
To understand the groundwater occurrence on Bribie Island a number of factors need to be considered in respect to the properties of the aquifer materials, the type of recharge and groundwater flow. These factors are summarised here and their integration is essential to develop a valid conceptual hydrogeological model of this sand island.

a) Recharge
Aquifer recharge on Bribie Island is a direct consequence of precipitation. For the shallow unconfined aquifer this process takes place almost instantaneously as water infiltrates through unconsolidated sands at the surface; however, there can also be a time lag due to the ponding of water on swampy or silty terrain, and the effect of the indurated sand layers is also important.

There have been a number of estimates of recharge carried out on Bribie Island but most of these have
been based on indirect calculations and measurements. Lumsden (1964) estimated a recharge rate equivalent to 40-45% of precipitation for the southern part of the island, within the water reserve; John Wilson & Partners (1979) generated a similar estimate (42%) based on water balance modelling. Subsequent recharge estimates have, however, been considerably lower in magnitude. Soil water balance modelling by Ishaq (1980) produced a recharge value of 13% of precipitation, while Isaacs and Walker (1983) calibrated a numerical model for the southern part of the island using a recharge value of approximately 20%. Harbison (1998) estimated recharge values of 15% and 30% for the southern part of the island based on sodium and chloride mass balance respectively. The sodium-based recharge estimate of 15% was considered by him to be more realistic as chloride analytical determinations were believed to be less reliable due to the effect of the humic content of the tannin-stained water samples on laboratory analyses.

The Department of Natural Resources produced several numerical groundwater models to estimate recharge for the whole island with rates of 8% (DNR, 1996) and 22% (Werner, 1998a) of total precipitation. Subsequently, Harbison (1998) calculated a recharge rate of 7% of precipitation, for the whole island, based on sodium mass balance calculations.

b) Aquifer characterisation

Bribie Island's sand aquifer system considered as a whole is characterised by a significant degree of heterogeneity mainly due to the presence of the indurated sand unit (Harbison and Cox, 1998; Armstrong and Cox, 2002). Laboratory falling head tests carried out by Harbison (1998) showed that the permeability of the indurated sands could be up to 4 times lower than the permeability of unconsolidated sands. Armstrong (2006) carried out in situ bailer tests that showed the hydraulic conductivity of the indurated sand layers was approximately one order of magnitude lower than for the overlying unconsolidated sands.

A summary of horizontal hydraulic conductivity values for Bribie Island is presented in Table 1. Most of the early investigations focused on the southern part of the island due to the location of water extraction trenches and a sewage treatment facility. In this general area, hydraulic conductivity values for unconsolidated sands in the range of 10 - 75 m/day were recorded. Subsequent investigations focused on the central and northern parts of the island, indicating lower values of hydraulic conductivity (typically < 25 m/day). Horizontal hydraulic conductivity (Kv) values for the indurated sand layer have been consistently low for the different investigations (0.07 - 2.5 m/day). Armstrong (2006) estimated the vertical hydraulic conductivity (Kv) of the indurated sand unit (vertical head gradient analysis) and noted that the Kv:Kv ratio for this unit is about 2:1 to 3:1. In that study, pump tests carried out in the centre of Bribie Island produced a specific storage value in the 3.5-9.7 x10^-6 range.

Recent pump tests by EHA (2007a; 2007b), prior to establishing the new borefield, were used to determine transmissivity and storativity values for the semi confined aquifer in the north-central and southern parts of the Island. In that investigation, the deeper semi-confined aquifer system was pump-tested to derive aquifer hydraulic characteristics. Test results showed the average transmissivity for the deeper aquifer system was about 167 m2/day for the whole island, and the average storage coefficient for the north-central part of the island was about 1.8 x10^-3. In addition, that work also determined vertical hydraulic conductivity values for the indurated sand unit which is treated as a leaky layer. A summary of these results for the central and southern areas is presented in Table 2.

c) Groundwater discharge

As is typical of coastal settings and notably of sand islands, groundwater is observed to discharge around the shoreline (Werner et al., 2011). Natural groundwater discharge at Bribie Island occurs through seepage faces on its eastern tidal/semi-tidal lagoons and along its estuarine and ocean shorelines, particularly at low tide (Harbison, 1998). The mean tidal amplitude around the island ranges from about 0.7 - 1.5 m but the maximum can be up to 2.4 m (Larsen, 2007).

In the south of the island, Woody Bay and Buckley's Hole (Figure 3) have been identified as areas with concave beach morphologies which could promote groundwater discharge (Harbison and Cox, 1998). The beach face adjacent to Buckley's Hole was raised in the 1960s (to control mosquito populations) which isolated this lagoon from tidal surge and wave effects. Consequently, groundwater discharge in this area lowered the salinity of Buckley's Hole to levels which are similar to fresh water (EC of around 500 mS/cm) (Harbison, 1998).

On its eastern ocean coast, Bribie Island has a straight beach morphology due to the southward
TABLE 1. Hydraulic conductivity ($K_s$) estimates for Bribie Island aquifer system

<table>
<thead>
<tr>
<th>Area</th>
<th>Aquifer material</th>
<th>$K_s$ (m/day)</th>
<th>Location</th>
<th>Test type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>Silty sand</td>
<td>0.25</td>
<td>North and centre of central swale</td>
<td>Falling head</td>
<td>(Harbison, 1998)</td>
</tr>
<tr>
<td></td>
<td>Foreshore and beach sand (unconfined)</td>
<td>8</td>
<td>North and south of central swale</td>
<td>Falling head</td>
<td>(Harbison, 1998)</td>
</tr>
<tr>
<td></td>
<td>Foreshore and beach sand (unconfined)</td>
<td>25</td>
<td>North and south of central swale</td>
<td>Grain size analysis</td>
<td>(Harbison, 1998)</td>
</tr>
<tr>
<td></td>
<td>Sand (unconfined)</td>
<td>6</td>
<td>Island centre</td>
<td>Bailier test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td></td>
<td>Shallow organic reach sands</td>
<td>1 to 3</td>
<td>Central swale</td>
<td>Bailier test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td></td>
<td>Indurated sand</td>
<td>0.09 - 0.25</td>
<td>Island centre (south of central swale)</td>
<td>Bailier test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td>Centre</td>
<td>Weakly indurated brown sands</td>
<td>25</td>
<td>Island centre (south of central swale)</td>
<td>Pump test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td></td>
<td>Sandy silts with lenses of clay and fine sand</td>
<td>1</td>
<td>Island centre (south of central swale)</td>
<td>Pump test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td></td>
<td>Medium sand (lenses of fine and coarse sand)</td>
<td>5 - 7</td>
<td>Island centre (east side over paleovalley)</td>
<td>Pump test</td>
<td>(Armstrong, 2006)</td>
</tr>
<tr>
<td></td>
<td>Sand (unconfined)</td>
<td>0.33 - 18.5</td>
<td>Island Centre (East of White Patch)</td>
<td>Slug Test</td>
<td>(HLA Envirosiences Pty Limited, 2002)</td>
</tr>
<tr>
<td></td>
<td>Indurated sand</td>
<td>0.07 - 2.5</td>
<td>Island Centre (East of White Patch)</td>
<td>Slug Test</td>
<td>(HLA Envirosiences Pty Limited, 2002)</td>
</tr>
<tr>
<td></td>
<td>Sand (semi-confined, basal aquifer)</td>
<td>0.13 - 4.7</td>
<td>Island Centre (East of White Patch)</td>
<td>Slug Test</td>
<td>(HLA Envirosiences Pty Limited, 2002)</td>
</tr>
<tr>
<td>South</td>
<td>Indurated sand</td>
<td>0.4 - 2.5</td>
<td>Bribie Island south (Black Hole trench)</td>
<td>Falling head</td>
<td>(Harbison, 1998)</td>
</tr>
<tr>
<td></td>
<td>Sand (unspecified)</td>
<td>13</td>
<td>Bribie Island south. Vicinity of trench system</td>
<td>Grain size analysis</td>
<td>(Lumsden, 1964)</td>
</tr>
<tr>
<td></td>
<td>Sand (unspecified)</td>
<td>17</td>
<td>Bribie Island south</td>
<td>Grain size analysis</td>
<td>(Ishaq S., 1980)</td>
</tr>
<tr>
<td></td>
<td>Sand (unspecified)</td>
<td>15 - 75</td>
<td>Bribie Island south</td>
<td>Pump test</td>
<td>(Ishaq S., 1980; John Wilson &amp; Partners, 1979)</td>
</tr>
</tbody>
</table>

Longshore drift which has resulted in the formation of foredunes. Nielsen (1999) presented aquifer water level measurements and the depth of the saline interface for a transect across the narrow northern part of Bribie Island. Although the measured interface was usually not very sharp, these measurements show that the fresh water lens tends to thin out on the eastern coast but closes abruptly on the landward side. This situation allows for seepage face development on the eastern coast and, in areas of low elevation behind the beach ridge, groundwater discharges into a series of lagoons.
TABLE 2. Summary of aquifer properties

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>North-Central Bore field</th>
<th>Southern Bore field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical Parameter</strong></td>
<td><strong>Aquifer Transmissivity (m²/day)</strong></td>
<td><strong>Storage coefficient</strong></td>
</tr>
<tr>
<td>Minimum</td>
<td>19</td>
<td>7.68 x 10⁻⁶</td>
</tr>
<tr>
<td>Maximum</td>
<td>1572</td>
<td>2.44 x 10⁻⁵</td>
</tr>
<tr>
<td>Average</td>
<td>165</td>
<td>1.83 x 10⁻⁴</td>
</tr>
<tr>
<td>Median</td>
<td>103</td>
<td>2.13 x 10⁻⁴</td>
</tr>
<tr>
<td>Minimum</td>
<td>49</td>
<td>NA</td>
</tr>
<tr>
<td>Maximum</td>
<td>432</td>
<td>NA</td>
</tr>
<tr>
<td>Average</td>
<td>168</td>
<td>NA</td>
</tr>
<tr>
<td>Median</td>
<td>118</td>
<td>NA</td>
</tr>
</tbody>
</table>

After EHA (2007a, 2007b)

For the island overall, numerical modelling by Werner (1998a) identified the central swale as a region of groundwater discharge in which evaportranspiration exceeds groundwater recharge. In addition, Harbison (1998) identified lateral movement of shallow unconfined groundwater from high slope ridges adjacent to the wetlands of the central swale.

There are a number of fire-fighting trenches on Bribie Island which act as groundwater drains. In general, these drains are located in the central part of the island both within pine forest plantations and further south near Bongaree (Figure 3).

d) Hydrochemistry

Bribie Island surface waters, which are mainly within wetlands, generally have a low pH (<4.5) due to the presence of organic acids and carbonic acids in acid soils. In some of the tidal lagoons, however, pH tends to be significantly higher (pH>6) due to the temporally variable mixing of saline water. Surface waters and shallow groundwater typically have the same major ion chemistry (waters of the Na(Mg)-Cl type) and similar chemical ratios as rainfall samples. A plot of Na vs. Cl for surface and groundwater samples from Bribie Island aquifer (Harbison and Cox, 1998) shows that the ratio of Na to Cl is relatively constant throughout the different water bodies, indicating limited ion-exchange and the absence of halite dissolution. This similarity suggests the development of surface-groundwater interactions with rainfall as the primary source of recharge (Armstrong, 2006) and slow aquifer residence times. These processes account for limited geochemical reactions between the unconfined aquifer materials and infiltrating recharge waters.

As recharge water percolates vertically through a sand aquifer system containing carbonaceous materials, bicarbonate concentrations tend to increase due to mineral dissolution (Freeze and Cherry, 1979). This has been observed in samples from wells screened in the deeper (partially confined) aquifer system in Bribie Island (Armstrong, 2006). Elevated calcium concentrations in some of these samples have been attributed to shell fragment dissolution (Harbison, 1998). As water percolates to deeper parts of the aquifer, oxygen is depleted and anaerobic decomposition of organic matter follows sulphate reduction; this is evidenced by samples with low sulphate concentrations (Harbison, 1998). This process is accompanied by the production of hydrogen sulphide (H₂S) which has been detected as a strong odour in shallow spears and spears screened immediately below the indurated sand unit (Harbison, 1998). However, the hydrogen sulphide odour is not present in deeper parts of the aquifer, and this has been attributed to gas loss and volatilisation (Armstrong and Cox, 2002). Another possible explanation for the absence of hydrogen sulphide from deeper bores is that, as sulphate is depleted during the initial stages of anaerobic decomposition, the decomposition of organic matter shifts to methyl-group fermentation and carbon dioxide reduction (Kjeldsen et al., 2002); these processes do not yield hydrogen sulphide gas.
Bribie Island, iron and aluminium have been identified as dominant minor elements which play an important role in the formation of indurated sand units.

Apart from investigations by Nielsen (1999), the position and character of the saltwater/freshwater interface around Bribie Island has not directly been established within previous investigations. However, salinity data collected from bores at the time of drilling suggest that high salinity (EC > 1200 mS/cm) occurs at approximately 20 m below ground level (bGL) south of Woorim (Figure 3), with high salinities observed at shallow depths (~7 m bGL) at the very south end of Woorim immediately north of Skirmish Point (EHA Pty Ltd, 2007b). A salinity gradation was determined during those investigations but the salinity was not high enough to determine the depth of intersection with the toe of the seawater wedge. The indurated layer has been shown to influence groundwater flow near the coastlines, including the character of the interface (Harbison, 1998) and demonstrated within a 3D visualisation model (Hawke et al., 2011).

RESOURCE UTILISATION

Groundwater extraction has taken place on Bribie Island since the beginning of human settlement in the area, but was intensified in the early 1960s with rapid population expansion due to the construction of the Bribie Island Bridge which joined Bribie Island with the mainland (Harbison, 1998). Groundwater extraction has been largely carried out through a municipal trench system in the southern part of the island but also through private spears in populated centres. In addition, a new borefield has been established as a replacement of the current trench extraction system for the central part of the island. This borefield is currently under testing and evaluation.

Groundwater extraction by private spears in Bribie Island is generally carried out for garden irrigation and not for drinking water purposes. Further, water abstracted using these spears tends not to comply with aesthetic requirements (iron stained and hydrogen sulphide odour). For a long time this activity was carried out without formal controls as spears < 6 m depth did not need to be registered; nowadays total abstraction is still unmeasured and carried out without flow restrictions. In 1997, Harbison (1998) conducted a survey of private water spears on about 8% of the streets in Bribie Island and concluded that about 32% of the 4400 surveyed households had operating spears. This finding suggests there could be around 1417 spears in Bribie Island which could be abstracting up to 1 ML/day, if water from the spears is used for half of the water requirements by each household. Most of the spears are thought to be located at Bongaree (38%) and Woorim (30%), followed by Bellara (19%) and Banksia Beach (13%).

Groundwater extraction for potable water supply has been managed since the early 1960s by Cabwater (Caboolture Shire Council’s water and sewerage service provider; local governments have now amalgamated into Moreton Bay Regional Council (MBCR)). In 1962, six production wells and a 2.2 ML/day water treatment plant were installed southwest of Woorim (Harbison, 1998). Subsequently, in the period between 1966 - 1967, 21 additional extraction wells were drilled within the south east section of the island. In 1970, the groundwater extraction area was classified as a water reserve and in 1971, iron-fouling of well screens became a problem so the groundwater extraction operation was converted to a trench extraction system (Harbison, 1998). This trench is about 3 km long and 5 m deep and extends westward from the previous extraction area (Werner, 1998a). The trench is cut through the indurated sand unit to the underlying sands so groundwater from both the unconfined and semi-confined aquifers can seep into it. In subsequent years, the trench system was expanded to include a second trench (“Black Hole”) located at about 1 km north east of the first trench (Figure 3). In 1977, the water level in the main trench was drawn down to a minimum of -1.2 m AHD (John Wilson & Partners, 1979); in the period between 1992 and 1995 the water level in the main trench was drawn down to about 0 m AHD (Harbison, 1998). In 2003, annual groundwater extraction from the main trench system was about 630 ML (EHA Pty Ltd, 2007c). In general, groundwater from the Black Hole has been extracted on a limited basis and has been pumped to the eastern end of the main extraction trench.

Subsequent problems with the trench system have resulted from increased water demand and groundwater security issues. This initiated a series of investigations towards the establishment of a new bore field for Bribie Island. EHA (2006) proposed a revised groundwater extraction system consisting of 15 bores pumping at 5.5 ML/day while maintaining the current effluent application rate of 4.9 ML/day. However, the 1995-2008 drought that affected Queensland initiated subsequent pressure demands imposed by the State Government (amendments to the Water Regulation
2000) which mandated a substitution of 10 ML/day from Bribie Island groundwater (EHA Pty Ltd, 2007c). In addition, management of the groundwater resource on Bribie Island passed from the Moreton Bay Regional Council to the state government Seqwater in 2008. This resulted in new bore fields being proposed in the central and southern sections of Bribie Island. Operating recommendations were made by EHA but full-scale pumping from these wells has not yet been undertaken due to various delays, including environmental impact testing. In October 2009 the Woorim water treatment plant ceased operating, and in December 2010 pumping from the trench system ceased due to ongoing groundwater contamination problems in the south of the island; only minimum groundwater abstraction (~ 1 ML/day) has been allowed to take place from the golf course located in the vicinity of Woorim (Bell I, 2011).

A second water treatment plant was constructed in 2008 north of Bongaree in the central part of the island at Banksia Beach. This water treatment plant can process up to 7.2 ML/day of raw water and has an outflow at Bellara. Sewage effluent is treated in sedimentation ponds in the south of the island and evaporated through infiltration beds located at 1.8 km south of the main extraction trench.

FIELD INVESTIGATIONS
Field investigations at Bribie have been conducted almost concurrently with groundwater extraction projects. The first major field campaign was carried out by the Geological Survey of Queensland (GSQ) between 1963 and 1964 (Lumsden, 1964), and included the drilling of 31 boreholes with a depth of approximately 14 m in the southern end of the island. The subsequent groundwater extraction project (21 extraction wells in 1966-1967) that resulted from this investigation provided additional bore log data that complemented the original study. In 1980, a second GSQ investigation (Ishaq, 1980) resulted in 26 additional drill hole logs which served as the basis for describing the stratigraphy in the southern part of the island (see Ishaq drill holes in Figure 4).

A second major field investigation was carried out by DNR between 1992 and 1996 (DNR drill holes in Figure 4). This resulted in the installation of a series of observations wells throughout the island and establishment of a monthly monitoring programme (Harbison, 1998). Between 2006 and 2007 (as part of a third major campaign) about 20 new bores in the central part of the island (BRxxN series) and five bores in the south (BRxx-P and BRxx-S series) were drilled and pump tested to assess their suitability as future water production wells (EHA Pty Ltd, 2007a; EHA Pty Ltd, 2007b). Figure 4 shows the location of these bores (EHA drill holes) in relation to the location of bores drilled throughout previous field campaigns.

PAST MODEL DEVELOPMENT
Numerical groundwater model development for Bribie Island has evolved from simple conceptualisations based on an idealised uniform sand mass to more complex models which incorporate aquifer heterogeneity. This evolution in conceptualisation has taken place as more information has become available after field investigations and hydrogeological analyses have been completed. Some of the major model development initiatives for Bribie Island are summarised as follows:

- Isaacs and Walker (1983): developed a finite difference model for the southern part of Bribie Island. This model was calibrated considering a constant hydraulic conductivity of 25 m/day and a recharge rate of 300 mm/year (about 22% of precipitation). The model described the drawdown due to water abstraction from the main extraction trench and the groundwater migration rate from the sewage disposal beds (18 m/year). As a result of these conclusions, effluent discharge was proposed for the southeast of the island in order to produce a groundwater mound between the extraction trench and the ocean, and to limit groundwater discharge into the sea. Consequently, about 66% of the sewage effluent was directed to outlets south of the golf club.

- Werner (1998a): steady state and transient MODFLOW groundwater models were developed to assess the effect that harvesting commercial pine plantations would have on Bribie Island’s groundwater resources. Although peaty sand layers containing indurated sand horizons were acknowledged as having semi-confining properties, this island-wide model was conceptualised as a single unconfined aquifer unit. In addition, groundwater flow was characterised as being predominantly controlled by the sea around the island, which was modelled as constant head boundaries. These boundaries were set at 0.3 m AHD to account for salt water density effects (even though mean seal level is about 0.0 m AHD). Pine plantation removal was simulated by adjusting the model.
evapotranspiration parameters, and recharge rates were treated independently of this. Groundwater head calibration was achieved with 1992-1995 water levels using PEST (Doherty, 1995). This approach yielded hydraulic conductivity values ranging from 5 to 150 m/day and recharge values of 20% of annual precipitation for the steady state model and 22% for transient simulations. Calibration of transient simulations resulted in a specific yield value of 0.128. This model was subsequently used to assess the effect of a proposed groundwater extraction bore field located along forestry roads in pine plantation areas located in the central part of the island (Werner, 1998b).

- Spring (2006): Developed a two layer MODFLOW model, for the whole of Bribie Island, describing the unconfined aquifer system (shallow sands) and the semi-confined aquifer unit (deeper system). The indurated sand unit was implicitly modelled as an actual physical unit which was virtually represented by incorporating the calculated vertical leakage term between the two modelled layers. Model calibration was carried out using PEST (Doherty, 1995) and parameters for hydraulic conductivity, drainage, evapotranspiration, and vertical leakage were estimated. First phase calibration using PEST yielded hydraulic conductivity values of 18 m/day for the upper aquifer, 0.8 m/day for the lower aquifer, and a vertical leakage factor of 2.5 × 10⁻⁴ m/day between the two units. The central swale was found to be a feature of significant groundwater discharge and was modelled as a drain feature.

- EHA (2007a): constructed a MODFLOW model based on the previous 1998 model (Werner, 1998a) but incorporating the new bore field currently under consideration. This model included a three layer conceptualisation taking into account the perched sands as an unconfined aquifer system, the indurated layer as a leaky aquitard, and the deeper sands as a semi-confined aquifer unit. However, the model domain only covered the central part of the island with no-flow boundaries north and south of a proposed north-central bore field. In addition, the model layers were not directly based on the actual geometry of the hydrogeological units and the model was not calibrated against observed water levels in the shallow or deeper systems for transient simulations.

- Jackson (2007): Produced a four-layer model using Visual MODFLOW for the central part of Bribie Island, south of the pine plantation and north of the main extraction trench. The main objective of this model was to incorporate the effect of the central swale and the localised surface catchment that was a natural feature before the Pacific Harbour development. The top layer (layer 1) was used to model the unconfined aquifer while the bottom layer (layer 4) was used to represent the semi-confined aquifer system. The layers in between the top and bottom layers (layers 2 and 3) were used to represent the indurated sand unit. In this model, the ocean, tidal creeks, and lagoons were represented as constant head boundaries north and south of the model domain. In addition, the central swale and some of the canals were modelled using the Visual MODFLOW drain package. This model provided some information about the local groundwater system in terms of water budgets and flow directions but, due to limited data on the indurated sands, it does not quantify local flows accurately.

MODELLING CHALLENGES AND DEVELOPMENT
As more field-based information about the Bribie Island aquifer system and hydrologic processes has become available over the years, expectations for successful model development have become increasingly higher. Thus, the main challenges ahead include: a) conducting a holistic approach to data collection and evaluation; b) producing information based on adequate data analyses, and c) generating realistic conceptualisations and modelling based on sound data interpretations.

a) data collection
Data on specific hydrogeological processes at Bribie Island have often been sparse and disparate. For example, initial recharge rate estimates for the southern part of the island were in the range of 40-45% of precipitation (Lumsden, 1964; John Wilson & Partners, 1979) whereas later estimates were 13-20% of precipitation (Ishaq, 1980; Isaacs and Walker, 1983; Harbison, 1998). Similarly, hydraulic conductivity estimates for sand aquifers have ranged from 0.1 to 75 m/day for different parts of the island. The wide range of values is due to differences in the types of aquifers being tested (e.g. unconfined vs. semi-confined), host lithology variations, and variation in the accuracy of measuring techniques (e.g. falling head tests, slug tests, pumping tests, and grain size analyses). Similarly, drill-log data has been generated at different times and with different objectives. Lithological descriptions...
have been generated by either drillers or trained geologists, and these factors need to be taken into account when developing a geological interpretation of the data. Consequently, putting these data in context for groundwater flow model development constitutes an important challenge.

b) data analysis
A comprehensive data analysis can take different forms depending on the nature of the available information. In the case of bore log data, new stratigraphy data have been used along with previous data to generate more accurate geological models. Various studies at QUT have compiled raw drill-log data from all available sources, and have developed a lithotype classification of the main lithologies present in the island. Sources of data include drillhole information dating from the 1960s (Ishaq, 1980; Lumsden, 1964), the Groundwater Database administered by the Queensland Department of Environment and Resource Management (DERM), and more recent drilling programmes (Armstrong, 2006; EHA Pty Ltd, 2006; EHA Pty Ltd, 2007b). Lithotypes were loaded into GOCAD 3D geological modelling software (Mallet, 1992), and a geological model was developed based on a high resolution (LiDAR) surface elevation model (DEM) and bore to bore correlation of the four main lithological groupings (units) present. Stratigraphic surfaces were developed for major unit boundaries, including an indurated sand unit (Figure 4) and the Landsborough Sandstone basement contact (Figure 5), as well as shallow and deep sand units and a sandy silt unit. A 3D block model was then generated from this information using GOCAD which was then imported into a GVS model.

FIG. 4. Oblique view of Bribie Island showing the surface and extent of the indurated sand unit in relation to the island shoreline. Locations of drill holes from major sources are shown; QUT research holes are incorporated into the DERM data.
A groundwater flow model for a sand island such as Bribie Island should account for all recharge sources, sinks, and abstractions. While much of these data are available, there are information gaps which require some estimation or projection. For example, there is a lack of data to define the large number of shallow spears being used for domestic purposes, and the quantity of groundwater being abstracted. This makes it difficult to adequately account for this type of abstraction in a modelling exercise. Not including spears would translate into an overestimation of hydraulic conductivity or an underestimation of recharge values. A good estimate of spear abstraction can be carried out using surveys such as the one by Harbison (1998). According to this estimate,
spear abstraction could be approximately 0.38 ML/day at Bongaree, 0.3 ML/day at Bellara, and 0.13 ML/day at Banksia Beach. Such estimates of spear abstraction were not included in previous modelling work.

c) System conceptualisation and modelling

New Bribie Island data analyses have led to a more accurate conceptualisation of the total aquifer system. The study by Harbison (1998) suggested a conceptualisation consisting of a shallow unconfined aquifer and a deeper semi-confined aquifer separated by leaky aquitard layer (indurated sand in Figure 4).

In addition, Armstrong and Cox (2002) presented the water table and potentiometric surfaces for these two distinct aquifer systems for an east-west transect section through the centre of the island. Subsequent pump tests carried out by EHA (2007a; 2007b) noted that, in almost all of the long-duration pumping tests carried out during their investigations, the plot of drawdown vs. log of time resulted in a curve approaching a slope of zero; this is the typical response of a leaky aquifer system (e.g. Freeze and Cherry, 1979). The confining effect of the indurated layer is also evident through colour examination of groundwater samples from Bribie Island. Harbison (1998) observed in some cases that groundwater samples from sand units above the indurated sand layer are dark brown in colour, whereas deeper groundwater samples (below the indurated sand layers) are generally colourless. During that study, it was also noted that the pH of shallow groundwaters was generally more acidic than pH for deeper groundwater (pH~3.5 vs. pH~5.0). It is therefore clear that understanding the hydrogeology and the effect of the indurated sand unit are fundamental steps to the development of a numerical flow model.

3D subsurface conceptualisation

A useful tool in the understanding of groundwater system conceptualisation is 3D visualisation. One such tool is the 3D Groundwater Visualisation System (GVS) software developed by QUT (James et al., 2010). GVS is a visualisation framework which incorporates existing data such as surface topography, geological logs and bore information into a hydrogeological scene. The GVS model can also display time series data such as water levels, rainfall and salinity (EC). Independent models developed externally (e.g. using GOCAD) can be imported into the GVS software. The resultant GVS model for Bribie Island has been used to develop a good understanding of groundwater system geometry and time series analyses, and has provided an effective framework to support the numerical groundwater modelling process.

The conceptualised Bribie Island 3D hydrogeological model is presented in Figures 6 and 7 which show oblique hydrogeological cross-sections from the GVS model. With this conceptualisation, four hydrogeological “units” have been summarised based on a re-examination of all available drill logs (Hawke et al., 2011). These units are (a) the unconfined or “perched” aquifer system represented by unconsolidated
TABLE 3. Structure of improved MODFLOW model for Bribie Island

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydrogeological unit</th>
<th>Aquifer type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>layer type 1: Unconfined</td>
<td>unconsolidated sands</td>
</tr>
<tr>
<td>2</td>
<td>layer type 3: Confined/Unconfined</td>
<td>indurated sands</td>
</tr>
<tr>
<td>3</td>
<td>layer type 3: Confined/Unconfined</td>
<td>lower sands</td>
</tr>
<tr>
<td>4</td>
<td>layer type 3: Confined/Unconfined</td>
<td>sandy silts</td>
</tr>
</tbody>
</table>

sands (Upper Sands), (b) the indurated sand unit shown as a dark brown layer immediately below the Upper Sands, (c) the semi-confined (leaky) aquifer unit represented by a layer of Lower Sands resting on a layer of Sandy Silts (d).

The Upper Sand unit has a thickness ranging from 2 m to 6 m throughout most of the Island, and comprises mainly well sorted aeolian fine sands that form Pleistocene and Holocene beach ridges mapped at the surface. The unit overlies either indurated sands or the less well sorted sands of the Lower Sand unit throughout most of the Island, but thickens considerably (up to around 30 m) at the southern end and along the eastern margin of the Island where it infills an erosional surface that cuts through nearly to basement. The indurated sand unit grades into the Lower Sand unit, which comprises predominantly fine-medium sand and coarse sand lithotypes, but also minor sandy clays and fine sand. The Lower Sand unit appears to unconformably overlie finer sediments of the Sandy Silts unit, incising into the lower unit significantly in some areas (Figures 6 and 7).

The Indurated Sand unit is defined as a lithological grouping comprised mainly of strongly to weakly indurated sands with significant humic and clay content. Lithology of the unit and its thickness vary appreciably as the degree of cementation and induration varies. The unit is seen to pinch out and/or split around its periphery, and in places the unit includes some minor lenses of non-indurated sands within it. The indurated layer has been defined so as to assign average properties of this part of the sedimentary sequence. The 3D geological model shows that the indurated sand layer is present over approximately 60% of the island, and has a thickness of up to around 13 m at its centre and gradually thins near the coastline (Figure 4).

The Sandy Silts unit comprises predominantly sandy silts and clays that appear to infill topographic lows in the Landsborough Sandstone paleosurface. The unit is best developed in the central area of the Island within a paleovalley incised into the Landsborough Sandstone basement. Here it includes significant lenses of coarse sand lithotypes. The Sandy Silts unit may be weathered basement in some areas where it is thin, as it is often difficult to distinguish between the two lithologies from some drill logs, and during drilling.

The Landsborough Sandstone paleosurface is strongly weathered to clay in many areas, and is considered to be a hydraulic lower boundary for the purposes of the island groundwater model. The surface dips generally eastward and includes the west to east trending paleochannel, also identified by Harbison (1998), beneath the central part of the island. The GVS visualisation provides more detail to the bedrock surface and shows the paleochannel has two branches. The elevation of the paleochannel is about -30 m AHD with minimum elevations of up to -45 m AHD on its western limit; the paleochannel is divided by a basement high of about -18 m AHD extending from west to east (Figure 5).

Bribie Island groundwater flow modelling

The current groundwater modelling conceptualisation of the Bribie Island aquifer system is based on the following:

- An unconfined or “perched” aquifer system (Upper Sands unit);
- presence of an aquitard layer (Indurated Sand unit);
- a semi-confined aquifer system (Lower Sands unit beneath the Indurated Sand unit);
- a layer of lower permeability within the semi-confined aquifer system (sandy silts sitting on top of Landsborough Sandstone bedrock).

These aquifer units can be imported into a finite difference grid by using the MODFLOW package. Because MODFLOW requires each layer to have a minimum thickness to assure conservation of mass (Waterloo Hydrogeologic Inc, 2003), it is
not possible to make grid layers directly disappear within the modelling domain. This presents an important challenge in the case of Bribie Island because the indurated sand unit tends to pinch out before reaching the coastline and the layers below the Upper Sand unit are not present in the southern part of the island (Figure 7). However, it is possible to deal with these issues by reducing the thickness of cell layers to a very small thickness within the specific areas where these hydrogeological units are absent. In addition, it is possible to assign specific property values to individual grid cells in order to represent the geological units which should be present over the pinch out layers. Although these measures can often be a cumbersome process, the use of 3D visualisation software makes it relatively straightforward to implement these alternatives as identification of potential geometric constraints is enhanced. Another alternative for dealing with these issues would be to change the solution to a finite element approach using a package such as FEFLOW (Diersch, 2001) which directly allows the pinching out of mesh layers.

Previous Bribie Island groundwater models have not directly incorporated the presence of the Indurated sand unit as an aquitard layer separating the sand mass into an unconfined upper aquifer system and a semi-confined lower aquifer unit for the whole island. However, the current level of information allows development of such a model which can be implemented using the model definition in Table 3.

In MODFLOW, the properties of model layers are defined during the initial stages of model definition and these can be grouped in 3 general types. For example, with layers of type 1, the transmissivity of each cell varies with the saturated thickness of the aquifer whereas layers of type 3 can also represent confined conditions if the layer is fully saturated. In the case of full saturation the confined storage coefficient is used to calculate the rate of change in storage.

Calibration of such a model can be challenging as water level data and pumping schedule information are not always available. In steady state mode, for example, there are no long term water level data for periods without groundwater abstraction (or constant groundwater abstraction). On the other hand, the data necessary to calibrate a transient flow model is lacking (e.g. missing data from main trench extraction records and no records for private spear abstraction). These problems can be solved by estimates in the form of basic interpolations as performed by DNR (1996) or based on surveys as done by Harbison (1998). In addition, complete records for treated effluent are required for the sewage disposal ponds located in the south of the island.

Disparity in aquifer recharge estimates can add to uncertainty during groundwater flow model development. One way to deal with this would be to carry out unsaturated flow modelling to help understand recharge distribution around the island prior to predictive modelling with either MODFLOW or FEFLOW. Processes such as precipitation, infiltration, and evapotranspiration can be modelled using this approach which would result in adequate recharge estimates. This can be easily done in future studies using the HELP model or SWAT (Jyrkama et al., 2002; Kim et al., 2008), thus providing further insight into Bribie Island hydrology.

Modelling scenarios to include in transient simulations should include different groundwater abstraction schedules (private and municipal), effluent discharge, and potential variations in groundwater recharge. These scenarios should include past and current pumping conditions as well as future water requirements. For example, in 2003 groundwater abstraction was approximately 630 ML/year from the main trench (EHA Pty Ltd, 2006) and some of the alternatives sought by the council, based on EHA’s recommendations, include:

a) Additional abstraction of 4-7 ML/day from the central island borefield
b) 2.3 ML/day from 10 bores pumping at this collective rate in the central borefield and 3.2 ML/day from five bores replacing the main trench system at the southern borefield. This would also consider a treated sewage application rate of 4.9 ML/day south of the main trench system.
c) Pumping scenarios yielding an extra 10 ML/day (emergency direction) from all the bore fields but with some limitations based on the maximum well yield from abstraction bores within the southern borefields and main trench systems.

CONCLUSIONS

Numerical simulation modelling of the Bribie Island aquifer system has become important given the population increase and growing water requirements; there is particular concern for potential seawater intrusion and maintaining adequate groundwater supply to ecosystems. Such modelling typically
evolves and becomes more refined as more data becomes available and a better system understanding is achieved. However, different sources of information and data disparity constitute an additional challenge that precedes future groundwater studies. Integrating existing data and information through a visualisation system such as GVS has enabled compilation of all of the relevant Bribie Island information to help form the framework for a future groundwater simulation model.

A comprehensive resource management program can benefit from integrating all available data and information from different models, and result in new models to aid decision makers. In the case of Bribie Island, data from field investigations (e.g. bores), monitoring programs (e.g. water level measurements), rainfall records, flow records (e.g. from water treatment plant), and a GOCAD 3D geological model have been integrated into a Bribie Island GVS model. This GVS model, which can be visually interrogated, is a useful tool to use along with previous information (groundwater flow models, recharge estimates, and aquifer characteristics) to produce an updated groundwater flow model.

The final conceptual hydrogeological model for Bribie Island is based on an unconfined sand aquifer system and a deeper semi-confined aquifer system separated by an aquitard layer (indurated sand) over a large proportion of the Island. No previous modelling attempts have produced a whole-island model explicitly depicting the presence of the indurated sand layer. However, the current level of system understanding allows for this modelling advancement. This model can also include the basement paleochannel at the centre of the island, which is an important feature highlighted within this study. Based on this conceptualisation, a Bribie Island numerical flow model can be calibrated taking into account the whole range of possibilities for aquifer properties (e.g. hydraulic conductivity) and recharge estimates from previous investigations. Once calibrated, the final model will be used to run a series of scenarios based on current and future groundwater requirements to adequately manage the resource.

ACKNOWLEDGEMENTS
This work has been carried out by a team of QUT researchers working on different aspects of the Bribie Island groundwater system. The Bribie Island GVS model was part of Seqwater funded project finished in April 2011. We would like to kindly acknowledge the Moreton Bay Regional Council (MBRC), the Queensland Department of Environment and Resource Management (DERM), the Bureau of Meteorology (BOM), and Maritime Safety Queensland for providing important data and information used throughout this study.

LITERATURE CITED


WERNER, A. 1998b. Supplementary report on modelling the proposed additional groundwater extractions from Bribie Island (unpub report). Department of Natural Resources.

WERNER, A. D., ALCOE, D. W., ORDENS, C. M., HUTSON, J. L., WARD, J. D. & SIMMONS, C.


AUTHOR PROFILES

Mauricio Taulis is an Environmental Engineer who specializes in Hydrogeology. He holds a Civil Engineer degree from Universidad de Chile, an ME (Natural Resources) from Lincoln University, and a PhD in Environmental Engineering from the University of Canterbury (New Zealand). Mauricio is interested in environmental issues related to both quantity and quality of water. He is particularly interested in addressing environmental related issues associated with full-scale groundwater abstraction in sedimentary basins (including Coal Seam Gas depressurisation operations). In addition, Mauricio's modelling expertise spans from sanitary landfill hydrology to groundwater flow modelling.

Dr Malcolm Cox is an Associate Professor in Faculty of Science & Technology, QUT, Brisbane. He is a Key Researcher in the QUT Institute for Sustainable Resources, and a CI in the Australian National Centre for Groundwater Research & Training. Cox has over 30 years international research experience in groundwater, notably conceptual hydrogeological models and hydrochemistry. His experience covers much of the Pacific Basin and includes geothermal systems as well as water resources, groundwater and surface water interaction, coastal settings, and environmental geochemistry. In recent years he has led a group integrating geoscience and software development to produce 3D visualisation models of groundwater systems.

Andrew Todd is a Geologist, with an MSc degree in Earth Sciences from the University of Waikato, New Zealand, majoring in Sedimentology and Water Resource Management. His professional experience includes 15 years in coal exploration and sub-surface mapping in the NZ and Australian coal mining industry, 3 years in community-based projects on waterway monitoring, rehabilitation and groundwater monitoring and hydrogeological assessment. At QUT's Institute for Sustainable Resources (ISR) involved in geological modelling and hydrogeological input into development of 3D Groundwater System Visualisation models.

Amy Hawke holds a Bachelor of Mathematics and a Bachelor of Information Technology from QUT. She is currently working with High Performance Computing & Research Support and the Institute for Sustainable Resources at QUT on the development of the Groundwater Visualisation System. This has included building groundwater visualisation models at various locations primarily in Queensland as well as software development for the system.

Dr. Matthias Raiber completed his PhD on the study of groundwater and surface water resources and the spatial and temporal variability of groundwater recharge in the basalt plains of western Victoria in 2008. After completion of his PhD, Matthias worked as a groundwater scientist at the Institute of Geological and Nuclear Sciences (GNS Science) in New Zealand, where he used environmental tracers, statistical analysis of groundwater data sets and 3D geological modelling to investigate groundwater systems at the regional and national scale. Since July 2010, Matthias works as a postdoctoral research fellow at Queensland University of Technology and the National Centre for Groundwater Research and Training (NCGRT), where his work includes the development of a 3D geological model of the Clarence-Moreton Basin and the study of the impact of drought and episodic flood events on groundwater recharge to alluvial aquifers in southeast Queensland.

Allan James is an IT specialist working with High Performance Computing and Research Support at Queensland University of Technology. Allan's work is focused on developing software for interactive 2D and 3D visualisation and animation of scientific data, including 3D conceptual groundwater models of environmental data for community understanding, impact assessment, policy and management; software to support expert elicitation; and development of dynamic web-based systems for the capture, retrieval and display of data.

View This Item Online: https://www.biodiversitylibrary.org/item/290002
DOI: https://doi.org/10.5962/p.357749
Permalink: https://www.biodiversitylibrary.org/partpdf/357749

Holding Institution
Royal Society of Queensland

Sponsored by
Atlas of Living Australia

Copyright & Reuse
Copyright Status: In copyright. Digitized with the permission of the rights holder.
Rights Holder: Royal Society of Queensland
License: http://creativecommons.org/licenses/by-nc-sa/4.0/
Rights: http://biodiversitylibrary.org/permissions

This document was created from content at the Biodiversity Heritage Library, the world’s largest open access digital library for biodiversity literature and archives. Visit BHL at https://www.biodiversitylibrary.org.

This file was generated 17 June 2023 at 07:02 UTC