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Groundwater discharge from the superficial aquifer into Cockburn Sound Western Australia: estimation by inshore water balance

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Abstract. Submarine groundwater discharge (SGD) into Cockburn Sound Western Australia was quantified by applying a distributed groundwater flow model to estimate the inshore aquifer water balance. Spatially averaged SGD along the coast was estimated to be 2.5–4.8 $\pm$ 0.9 m^3 day^{-1} m^{-1}. The range in estimated average SGD reflected low and high estimates of average groundwater recharge, which ranged from 0.13 to 0.24 m year^{-1} (15–28% of average annual rainfall). The error $\pm$0.9 m^3 day^{-1} m^{-1} was calculated by assuming arbitrary $\pm$20% errors in groundwater pumping and inflow across boundaries. SGD varied spatially along the coastal boundary due to variation in hydraulic connection between the coastal aquifers and ocean, and spatial variability in recharge, transmissivity and pumping. Under assumptions of low and high groundwater recharge, SGD along the coastline varied in the ranges 1.4–4.6 m^3 day^{-1} m^{-1} and 2.4–7.9 m^3 day^{-1} m^{-1}, respectively.

Introduction

Submarine groundwater discharge (SGD) can be quantified in two ways: (a) by inference from inshore water-balance considerations and (b) by direct and indirect field measurements of SGD. Each approach can be employed independently of the other, with the advantage that results can be crosschecked to reduce uncertainty in estimates. For example, field measurements of SGD should be physically realistic and feasible when considered in context of the inshore hydrogeology and aquifer water balance.

This paper describes the application of a groundwater flow model (Nield 1999) to estimate SGD into Cockburn Sound, a shallow embayment located approximately 15 km south of Fremantle in Western Australia (Figure 1*a*). Estimates of SGD from the shallow aquifer inshore from Cockburn Sound were derived from the model water budget and calculated as the imbalance of groundwater inflow, net recharge and pumping. Model simulated SGD varied along the length of the coastline due to variation in hydraulic connection between the coastal geology and ocean; spatial variability in groundwater recharge, aquifer transmissivity and pumping; and focusing of groundwater flow toward coastal embayments (Cherkauer and McKereghan 1991).

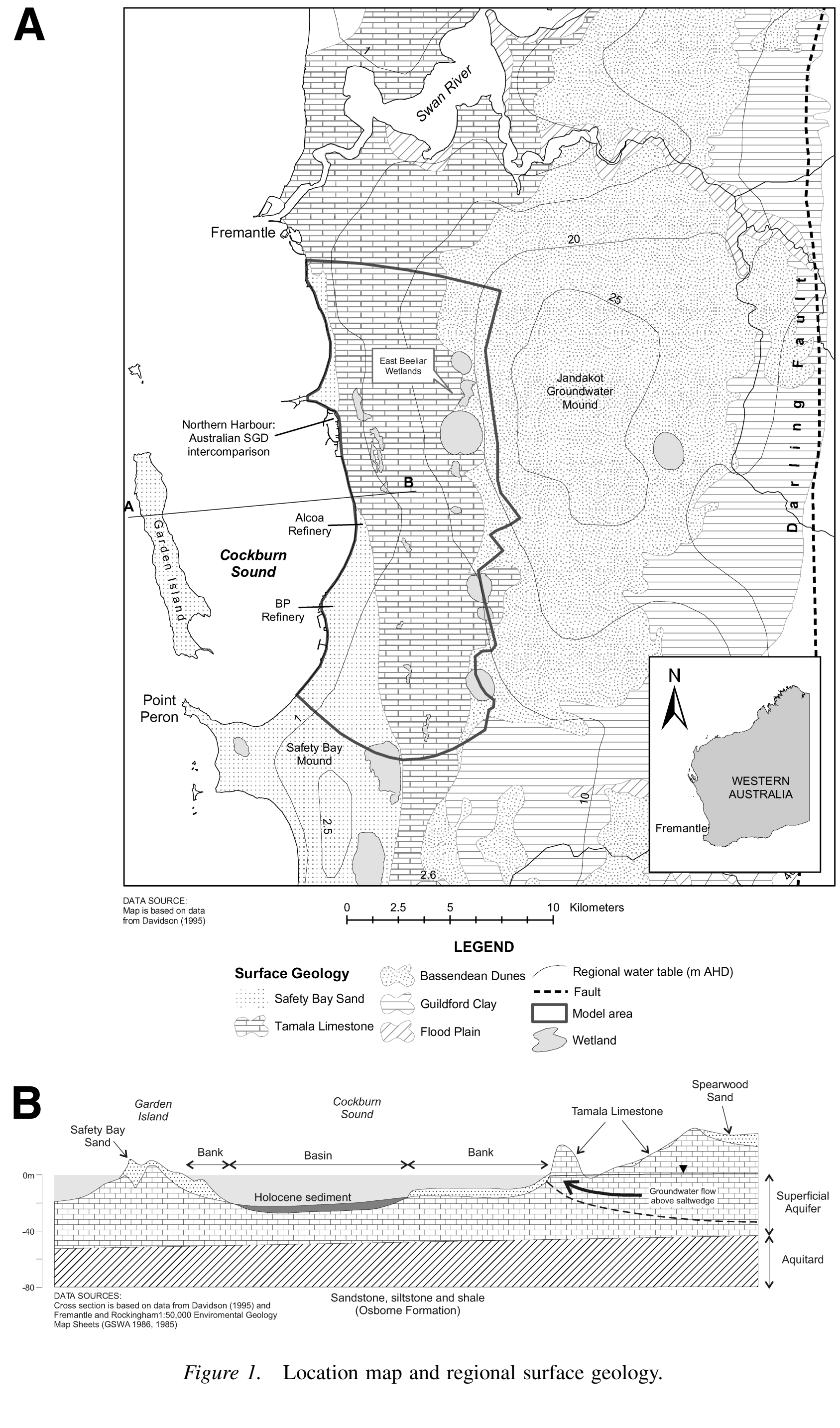

Figure 1. Location map and regional surface geology.

Other papers in this special issue describe various field measurements of SGD that were obtained along the shoreline and offshore from Cockburn Sound during an SGD intercomparison experiment in December 2000. This paper provides both hydrogeological and water-balance contexts to those studies. More generally, the groundwater flow model has been applied to quantify SGD and groundwater nutrient inputs into Cockburn Sound (PPK 2000, Smith et al. 2003).

Hydrogeology

Regional setting

The Perth Basin lies to the west of the Darling Fault (Figure 1(a)) and contains up to 12,000 m of marine and continental sediments (Davidson 1995). The stratigraphic sequence to a depth of around 2000 m below the present land surface contains Jurassic and Cretaceous age sediments that are overlain by a relatively thin covering of late Tertiary to Quaternary age deposits. These recent superficial formations are saturated above their base and form a mostly unconfined, shallow aquifer system. Groundwater recharge occurs predominantly by percolation of rainfall through well-drained sandy soils, with unutilised groundwater draining laterally toward the Indian Ocean, Swan-Canning River estuary system and other regional boundaries. This continuous process of diffuse replenishment and lateral drainage forms a number of distinct regional flow systems that are manifest as regional groundwater mounds.

Study area

The Cockburn Sound shoreline lies mostly on the western edge of the Jandakot groundwater mound and partly within the Safety Bay mound (Figure 1(a)). Over most of this area the superficial formations have a saturated thickness of approximately 25–30 m (Figure 2(a)) and unconformably overlie an erosional surface of Cretaceous sediment that act as a low-permeability base to the shallow groundwater system. Vertical exchange of groundwater between the superficial aquifer and deeper, confined aquifer system is regionally variable. Approximately 5–10% of groundwater recharge to the superficial formations in the Perth region is estimated to leak downward into confined aquifers (Davidson 1995). Nevertheless, over most of the study area, there is a competent confining layer known as the Osborne Formation at the base of the superficial aquifer that restricts leakage into underlying aquifers (Figure 1(b)). Most of the leakage from the superficial aquifer to the underlying groundwater system occurs in other areas of the coastal plain where this confining unit is absent.

The confined aquifer system of the Perth Basin extends tens of kilometres offshore beneath the seabed and is thought to discharge to the ocean at least several kilometres from the coast, possibly through offshore faults (Davidson 1995).

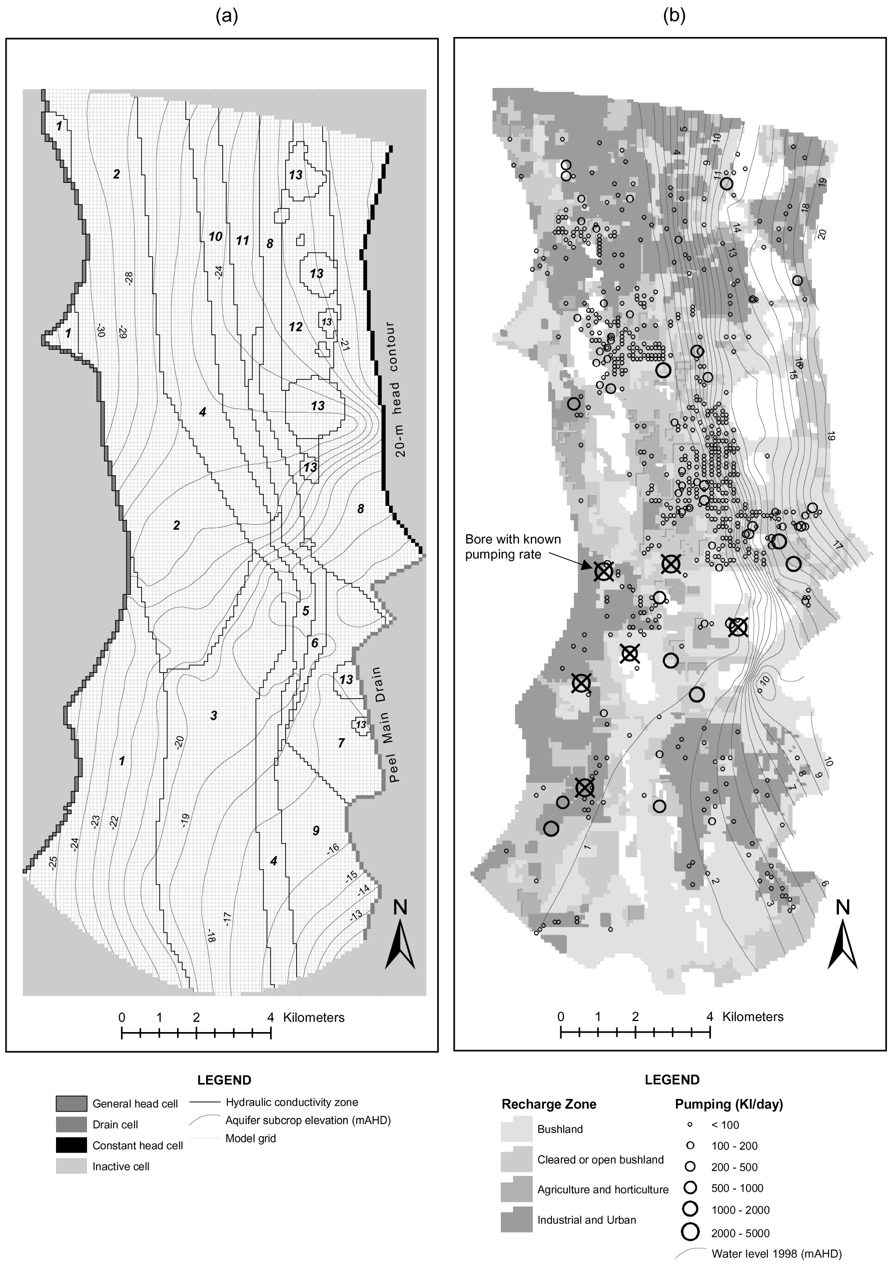

Figure 2. Numerical groundwater flow model.

Because the mechanism and location of SGD from the confined aquifer system is poorly understood it is not considered in this paper.

Stratigraphic units that comprise the superficial formations inshore from Cockburn Sound area are Tamala Limestone, Cooloongup Sand, Becher Sand and Safety Bay Sand (Davidson 1995). Collectively, these are known as the Kwinana Group.

Tamala Limestone is a calcareous eolianite that contains various proportions of quartz sand, fine-grained to medium-grained shell fragments and minor clay lenses. The limestone typically exhibits secondary porosity in the form of numerous solution channels and cavities. Garden Island (Figure 1 (a and b)) is an offshore outcrop of Tamala Limestone and part of a former drowned dune ridge (Searle et al. 1988). A roughly parallel sand and limestone ridge is located onshore from the coast just east of the contact between the Tamala Limestone and Safety Bay Sand. Tamala Limestone also outcrops as submarine reef in the Warnbro–Cockburn Depression, which lies between these two ridges.

Cooloongup Sand and Becher Sand unconformably overly the Tamala Limestone. Cooloongup Sand consists of fine-grained to coarse-grained feldspathic quartz with variable amounts of shell material (up to 25%). Becher Sand originated in the near-shore marine environment and consists of grey, fine-grained to medium-grained quartz and skeletal sand that is mostly structureless and bioturbated. It extends along the coastal margin and is typically 10–15 m thick. The base of the unit can locally contain a layer of silty calcareous clay that is rich in shell fragments and which acts as an aquitard between the Tamala Limestone and overlying sands.

Safety Bay Sand unconformably overlies Tamala Limestone and Becher Sand and consists of cream, unlithified, calcareous, and fine-grained to medium-grained quartz sand and shell fragments. Traces of fine-grained, black heavy minerals are also present. Safety Bay Sand is clearly visible along the coastal margin as white, aeolian sand dunes and offshore as submarine banks.

Groundwater flow

Groundwater in the superficial formations flows generally in a westerly direction and discharges into Cockburn Sound along the coastal margin of the aquifer. There are virtually no surface drains because the coastal sands are permeable enough to prevent significant surface runoff. Table 1 summarises aquifer hydraulic properties that have been estimated for the superficial formations in the study area. Note that the aquifer transmissivity is simply the product of the hydraulic conductivity and saturated thickness of aquifer, and indicates the aquifer's ability to transmit groundwater.

The coastal strip of aquifer has extremely large transmissivity and small hydraulic gradients due to secondary porosity in Tamala Limestone. Large hydraulic conductivity values in the range 20–1000 m day^{-1} are normally associated with coarse sediments such as coarse sand and gravel that are relative free of silt, clay and finer-grained sands that resist groundwater flow (Bouwer 1978). Inshore from Cockburn Sound, large aquifer transmissivity is related to solution features and

Table 1. Estimated hydraulic properties of the superficial aquifer.

Reference/source	Property/value	Location/method
Bodard (1991a)	$T = 190–235$ $k = 10–30$ $S = 0.3$ (unconfined) $B = 10$	Safety Bay Sand
Bodard (1991b)	$T = 1700–2600$ $k = 100–250$ $n = 0.3$ $S = 0.3 \pm 1.5$ (unconfined) $S = 0.02$ (confined) $B = 10$	Tamala Limestone
Walker (1994)	$k = 100–250$ (aquifer unspecified)	BP Refinery, slug testing of 20 bores
Davidson (1995)	$k = 6–50$	Cockburn Sound area, superficial aquifer
Nield (1999)	$T = 40000$ (superficial)	Alcoa Kwinana Refinery; pump test
Nield (1999)	$k = 400–1660$ (low recharge) $k = 800–3000$ (high recharge)	Cockburn Sound coastal strip; Cockburn Groundwater Area model calibration, superficial aquifer
PPK (2000)	$T = 13000$ (JBTB1 early-time data) $T = 9400$ (JBTB1 late-time data) $T = 19900$ (JBMB9S recovery) $T = 23800$ (JBMB9S early-time data) $S = 2.0E{-}06$ (as above) $T = 54200$ (JBMB9D early-time data) $S = 1.4E{-}01$(as above) $T = 9000$ (JBTB2 early-time data) $T = 28800$ (WPM5C early-time data)	Inshore from Northern Harbour; constant rate pump tests on bores JBTB1 and JBTB2 (observation bores JBMB9S, JBMB9D, WPM5C, JBMB1), superficial aquifer

	$S = 9.0E-02$ (as above) $T = 39700$ (JBMB1early-time data) $S = 1.0E-01$(as above) $T = 25000$ (adopted mean value) $S = 1.0E-01$(adopted mean value)	
Nield in PPK (2000)	$k = 900$ (superficial)	Northern Harbour; groundwater model calibration
Smith and Hick (2001)	$k = 53 - 174$ (Safety Bay Sand)	Northern Harbour, tidal method

Symbols and units – n: porosity [1]; k: saturated hydraulic conductivity [$m\,d^{-1}$]; i: hydraulic gradient [1]; B: aquifer saturated thickness [m]; $T = kB$: aquifer transmissivity [$m^2\,d^{-1}$]; S: aquifer storage coefficient [1].

subterranean channels in the limestone, which can transmit large volumes of groundwater, rather than the presence of coarse sediments. The values of hydraulic conductivity estimated from pumping tests in the limestone tend to be relatively large and contain significant and expected variability due to variation in local structure of the limestone.

From consideration of Darcy's Law (see below), it is clear that large values of hydraulic conductivity lead to relatively flat groundwater tables because less hydraulic gradient is required to transmit an equivalent volume of groundwater. Figure 2(b) depicts groundwater table contours derived from water level data collected during April 1998 at a time of year when groundwater levels were close to their minimum seasonal values. Maximum values in late spring are approximately 0.4 m higher. Water table slopes near to the coast are small and the 1-m water table elevation is generally a minimum of 2 km inshore from the coast but is typically around 4 km from the coast throughout much of the study area.

A relatively narrow band of lower-permeability sediments run roughly parallel to the coastline along the contact between Tamala Limestone and Bassendean Dunes approximately 5 km inshore (Figure 1(a)). A marked steepening of hydraulic gradient across this flow restriction implies a significant decrease in aquifer transmissivity. The East Beeliar Wetlands, a north–south chain of lakes and swamps, are surface expressions of higher groundwater levels that are effectively dammed on the eastern side of the flow restriction. Horizontal hydraulic gradients within the study area vary by a factor of approximately 50, indicating a similar magnitude of variation of hydraulic conductivity.

Previous estimates of SGD

Table 2 summarises previous estimates of SGD into Cockburn Sound. While some of the tabulated values were reported directly in the referenced literature, others were implied by the reported values of hydraulic gradient, hydraulic conductivity and aquifer thickness. In these cases, SGD in Table 2 was calculated by applying Darcy's Law (Bouwer 1978)

$$q = k\ i$$

where q is specific discharge – defined as the rate of groundwater flow per unit area of aquifer orthogonal to the flow direction [LT^{-1}]; k is hydraulic conductivity in the direction of flow [LT^{-1}]; and i is the hydraulic gradient in the direction of flow [1]. It can be seen that hydraulic conductivity is simply a proportionality constant that is a function of both the porous medium and fluid properties. Multiplying the specific discharge at the coast by the aquifer thickness at the coast yields an estimate of SGD in units of volume per unit time per unit length of coastline [$L^3\,T^{-1}\,L^{-1}$]. Thus, for an aquifer that is 10-m thick at the coast with hydraulic gradient 0.001 and hydraulic conductivity $100\,\mathrm{m\,d^{-1}}$, $\mathrm{SGD} = 100 \times 0.001 \times 10 = 1\,\mathrm{m^3\,d^{-1}\,m^{-1}}$.

Bodard (1991a) estimated that groundwater pore velocities in the area of the BP Refinery (Figure 1(a)) varied in the range 15–73 m year^{-1} in coastal sands and 270–

Table 2. Previous estimates of SGD.

Reference/source	SGD [$m^3\,d^{-1}\,m^{-1}$]	Location/method	Assumed values
Bodard (1991a)	2.3–5.2 (superficial) 0.1–0.6 (sand) 2.2–4.6 (limestone)	BP Refinery, flownet	Sand: $v = 15$–73, $B = 10$, $n = 0.3$; Limestone: $v = 270$–562, $B = 10$, $n = 0.3$
WAWA (1993)	3.0 (superficial)	Cockburn Groundwater Area, flownet water balance (1992 scenario)	Hamilton Hill: $k = 100$–200; Henderson: $k = 100$–200; Kwinana Beach: $k = 500$–800
Appleyard (1994)	0.7–2.5 (superficial) 0.1–0.5 (sand) 0.6–2.0 (limestone)	Cockburn Sound, flownet	$k = 10$–50, $i = 0.001$–0.003
Davidson (1995)	2.5 (superficial)	Jandakot groundwater mound, regional flownet	$T > 4000$
HGM (1998)	3.0–8.0 (superficial)	Northern Harbour Jervoise Bay, offshore CTD profiling	–
PPK (2000)	5.0 (mean) 3.0–8.0 (seasonal)	Northern Harbour Jervoise Bay, flownet	$T = 25000$, $i = 0.0002$
PPK (2000)	3.0–9.0 (superficial)	Northern Harbour, harbour salinity measurements	–

Symbols and units – v: groundwater pore velocity [$m\,d^{-1}$]; n: porosity [1]; B: saturated thickness of aquifer unit [m]; k: saturated hydraulic conductivity [$m\,d^{-1}$]; i: hydraulic gradient [1]; $T = kB$: aquifer transmissivity [$m^2\,d^{-1}$].

562 m year^{-1} in Tamala Limestone. Based on average saturated thickness of sand equal to 10 m, average thickness of limestone equal to 10 m, and porosity 0.3 for both sand and limestone, the estimated groundwater velocities equate to SGD of 0.1–0.6 $m^3\,d^{-1}\,m^{-1}$ from the sand and 2.2–4.6 $m^3\,d^{-1}\,m^{-1}$ from the limestone. These add to give total SGD from the superficial formations of between 2.3 and 5.2 $m^3\,d^{-1}\,m^{-1}$. Note that pore velocity, which refers to the average velocity of groundwater moving through interstitial spaces between the aquifer sediment grains, must be multiplied by the aquifer porosity to calculate specific discharge.

WAWA (1993) estimated that total SGD into Cockburn Sound in 1992 was 75,342 $m^3\,d^{-1}$. A flownet approach was used and a hydraulic conductivity value of 200 $m\,d^{-1}$ was assumed for the superficial formations. Distributed uniformly over 25 km of coast, this is equivalent to an average SGD of around 3.0 $m^3\,d^{-1}\,m^{-1}$.

Appleyard (1994) calculated that SGD into Cockburn Sound was in the range 0.1–0.5 $m^3\,d^{-1}\,m^{-1}$ from superficial sands and 0.6 to 2 $m^3\,d^{-1}\,m^{-1}$ from Tamala

Limestone. Hydraulic conductivity values between 10 and 50 $m\,d^{-1}$ were assumed and applied with gradients between 0.001 and 0.003 to compute SGD.

Based on groundwater flownet calculations, Davidson (1995) estimated that total SGD along the coastline of the Jandakot mound was approximately 66,450 $m^3\,d^{-1}$, which equates to average SGD along the shoreline of around 2.5 $m^3\,d^{-1}\,m^{-1}$. Transmissivity of the superficial formations was assumed to be greater than 4000 $m^2\,d^{-1}$.

More recently, PPK Environment and Infrastructure (2000) estimated that average SGD into Northern Harbour was approximately 5 $m^3\,d^{-1}\,m^{-1}$ based on average transmissivity 25,000 $m^2\,d^{-1}$ and average hydraulic gradient 0.0002. The estimated seasonal range of SGD in that study was 3–8 $m^3\,d^{-1}\,m^{-1}$.

Thus, previous estimates of SGD from superficial formations, based on flownet analyses, have varied between 0.7 and 8 $m^3\,d^{-1}\,m^{-1}$; a factor of approximately 10. A number of the estimates arrived at similar final values for SGD but were based on significantly different values of hydraulic conductivity and hydraulic gradient, which vary between some estimates by an order of magnitude. These differences highlight the inherent uncertainty in flownet analyses that are based on water level data alone. Improved estimates of SGD are possible if other aspects of the inshore water balance (e.g., groundwater recharge and pumping) are explicitly incorporated into calculations.

Groundwater flow model

This study makes use of a preexisting groundwater flow model (Nield 1999) developed for the Water and Rivers Commission and Kwinana Industries Council to aid groundwater allocation planning in the Cockburn Groundwater Area. The model, which was constructed in MODFLOW (McDonald and Harbaugh 1988), is implemented in Visual MODFLOW version 2.8.2 (Waterloo Hydrologic 2000) in this study. Model geometry, finite difference grid, boundary conditions, pumping wells, layer elevations and spatial distributions of hydraulic conductivity and groundwater recharge are depicted in Figures 2(a and b).

The finite difference grid consists of 26,596 cells, which are each 100×100 m. Superficial formations inshore from Cockburn Sound are represented as a single-layer, unconfined aquifer with impermeable base. A single-layer model was justified on the basis that Tamala Limestone is highly transmissive and most groundwater flow in the superficial formations is conducted laterally through secondary porosity in the limestone. It was assumed that groundwater movement in overlying sands is predominantly downward (vertical) into the limestone in response to local rainfall recharge. Contours corresponding to bottom elevations of the superficial formations (Figure 2(a)) vary from around -12 m Australian height datum (AHD) at the southeast corner of the model domain to approximately -30 m AHD in the vicinity of Northern Harbour.

A line of general head cells was used to represent the coastal boundary and conductance values were assigned that varied according to which geological unit

Table 3. Conductance and external head.

Conductivity zone	Geological unit	Low-recharge scenario		High-recharge scenario	
		Conductance [m d^{-1}]	External head [m]	Conductance [m d^{-1}]	External head [m]
1	Safety Bay Sand	500	−0.05	1000	−0.05
2	Tamala Limestone	1000	−0.05	2000	−0.05

contacted the ocean. Table 3 lists the conductance and external head values used. Where Tamala Limestone is exposed along the shoreline, the assigned conductance value was higher than at locations where the aquifer discharges to the ocean through overlying, relatively lower-permeability sand. External head along the coast was set equal to mean sea level of −0.05 m AHD.

Constant head cells were specified along the inland boundary. Head was set equal to 20 m AHD along the northern portion of boundary, corresponding to the 20-m water table elevation contour (Figure 2(a)). Along the southern portion of boundary, head was set equal to invert levels along the Peel Main Drain. The north and south boundaries of the model lie along assumed lines of regional groundwater flow and were specified as no-flow boundaries.

Groundwater recharge

Recharge is a key water balance component that affects the model estimates of SGD; however, there is significant uncertainty in quantifying recharge. Low groundwater recharge implies less groundwater flow through the aquifer and low SGD, while high recharge implies larger SGD. Two scenarios were simulated to provide estimates of SGD under assumptions of low and high groundwater recharge.

Spatial distributions of recharge in the modelling were assigned according to a previous classification of land use and vegetation cover by the Western Australian Water and Rivers Commission (unpublished). This classification included the categories bushland, cleared or open bushland; agriculture and horticulture; and industrial and urban, as depicted in Figure 2(b). Each land-use code was assigned a net groundwater recharge rate, as a percentage of mean annual rainfall, based on subjective estimations of runoff potential, infiltration and vegetation water use. The resulting recharge distributions for low- and high-recharge scenarios are depicted in Figure 4(a and b). The unshaded (white) areas in these figures correspond to the wetland areas depicted in Figure 1(a) and a tailings impoundment area used for disposing minerals processing waste. These areas constitute approximately 10% (1880 ha) of the total model area. The tailings impoundments were considered to contribute negligible groundwater recharge because they are required to be hydraulic sealed to minimise leakage of liquor and related groundwater contamination. The wetland areas include permanent lakes, sumplands (seasonally inundated) and damplands (seasonal water logged) that represent surface expressions of the groundwater table within interdunal depressions in the land surface. On the basis that evapotranspiration from wetlands is in all probability greater than direct rainfall, these areas were assumed to contribute negligible groundwater recharge. In fact, it is more likely that they represent net groundwater discharge areas.

Long-term mean annual rainfall at Perth Regional Office from 1876 to 1992 was 0.87 m yr^{-1} (Commonwealth Bureau of Meteorology 2003). The groundwater recharge rates assigned to the different land use categories varied between 0 and 30% of long-term mean annual rainfall (0–0.26 m yr^{-1}) in the low-recharge scenario, and between 0 and 40% (0–0.35 m yr^{-1}) in the high-recharge scenario. The equivalent average recharge rates applied over the entire model domain were 15% of long-term mean annual rainfall (0.13 m yr^{-1}) and 28% of long-term mean annual rainfall (0.24 m yr^{-1}) in the low and high-recharge scenarios, respectively. 'Average areal actual evapotranspiration' in the Perth region is estimated to be 700–800 mm yr^{-1} (Commonwealth Bureau of Meteorology 2001), which is approximately the same as long-term mean annual rainfall. Nevertheless, 'average point potential evapotranspiration', which is a better surrogate for open-water evaporation, is significantly larger at 1800–2000 mm yr^{-1}. It is likely that evapotranspiration rates from lakes, sumplands and damplands lie somewhere between these two estimates but because wetlands represent less than 10% of the model area and estimation of recharge in the remaining 90% is uncertain, the assumption of zero net groundwater recharge beneath wetlands is considered reasonable for the purpose of the modelling.

From the above, it is evident that estimation of groundwater recharge in the study area based on regional rainfall and evapotranspiration figures is difficult. In addition, few field studies of groundwater recharge have been conducted. Previous estimates at locations outside of the study area have varied dependent upon the method employed and type of land cover. In an area of Banksia woodland north of Perth, Thorpe (1989) obtained estimates of net groundwater recharge in the range 43 ± 19 to $13 \pm 8\%$ of mean annual rainfall using the environmental tritium method. Farrington and Bartle (1989) obtained estimates at the same location equivalent to 22.6% of mean annual rainfall using a water-balance technique, and 19.6% using the chloride-balance method. Earlier, Sharma and Hughes (1985) had estimated groundwater recharge below Banksia woodland to be approximately 15% of mean annual rainfall based on measured chloride profiles. Their analysis also indicated that up to 50% of the total annual recharge may occur as flow through preferential pathways.

Groundwater abstraction

More than 700 pumping wells exist within the modelled area of aquifer and these abstract a significant volume of shallow groundwater. Bore locations and pumping rates that were incorporated into the model are indicated in Figure 2(b).

Table 4. Hydraulic conductivity.

Conductivity zone	Hydraulic conductivity [$\mathrm{m\,d^{-1}}$]	
	Low-recharge scenario	High-recharge scenario
1	400	800
2	1660	3000
3	540	1000
4	500	900
5	25	30
6	6	8
7	34	34
8	20	20
9	120	120
10	25	35
11	10	14
12	30	30
13	60	60

Average pumping rates were assigned in the model if abstraction data were available; however, this was rare and most bores were assigned pumping rates equal to 80% of the licensed groundwater allocation limit. Licensed abstraction limits were obtained from the allocation database of the Water and Rivers Commission, the State Government agency responsible for groundwater allocation and regulation. Abstraction from bores for which pumping rates were either known or could be reliably estimated (Figure 2(b)) summed to only 36% of the total estimated abstraction, which introduced significant uncertainty into the aquifer water balance. Due to insufficient data, it was not practical to compare licensed and actual abstraction rates from particular bores to assess whether assigning pumping rates equal to 80% of the licensed groundwater allocation limit was a valid approach. Abstraction data was available for only six, large-capacity bores used by industry. It was considered that pumping from these bores would likely provide a poor surrogate for groundwater withdrawal by the hundreds of other groundwater users within the study area.

Many of the abstraction locations were known to be approximate, as they refer to site locations rather than bore locations but they were thought to be sufficiently accurate for the purpose of regional flow modelling. Artificial groundwater recharge at two sites was simulated using groundwater injection bores at these locations.

Model calibration

Nield (1999) calibrated the low- and high-recharge scenarios by trial and error. Hydraulic conductivity values in each zone of Figure 2(a) were adjusted to obtain suitable matches between the observed and modelled hydraulic heads inshore from

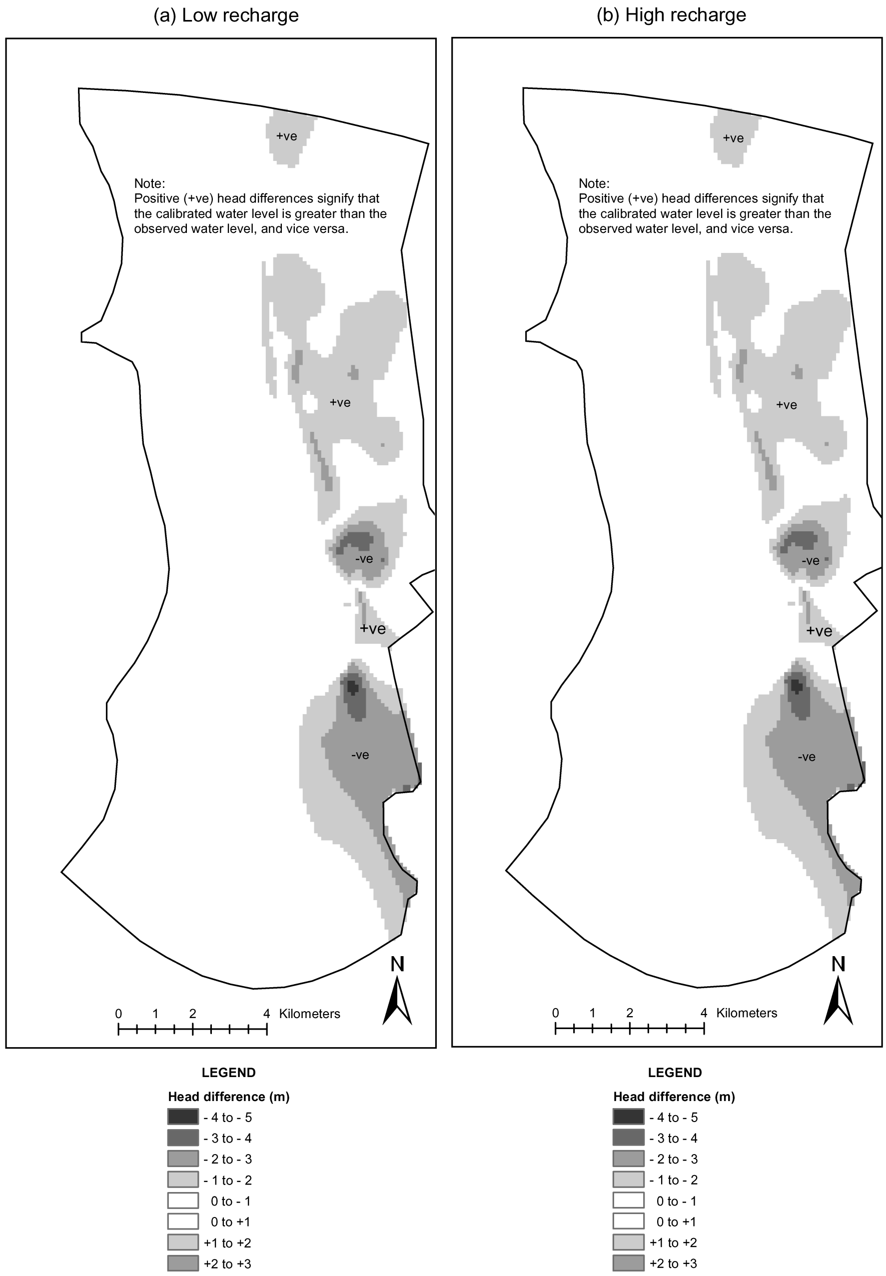

Figure 3. Differences between observed and model simulated groundwater levels.

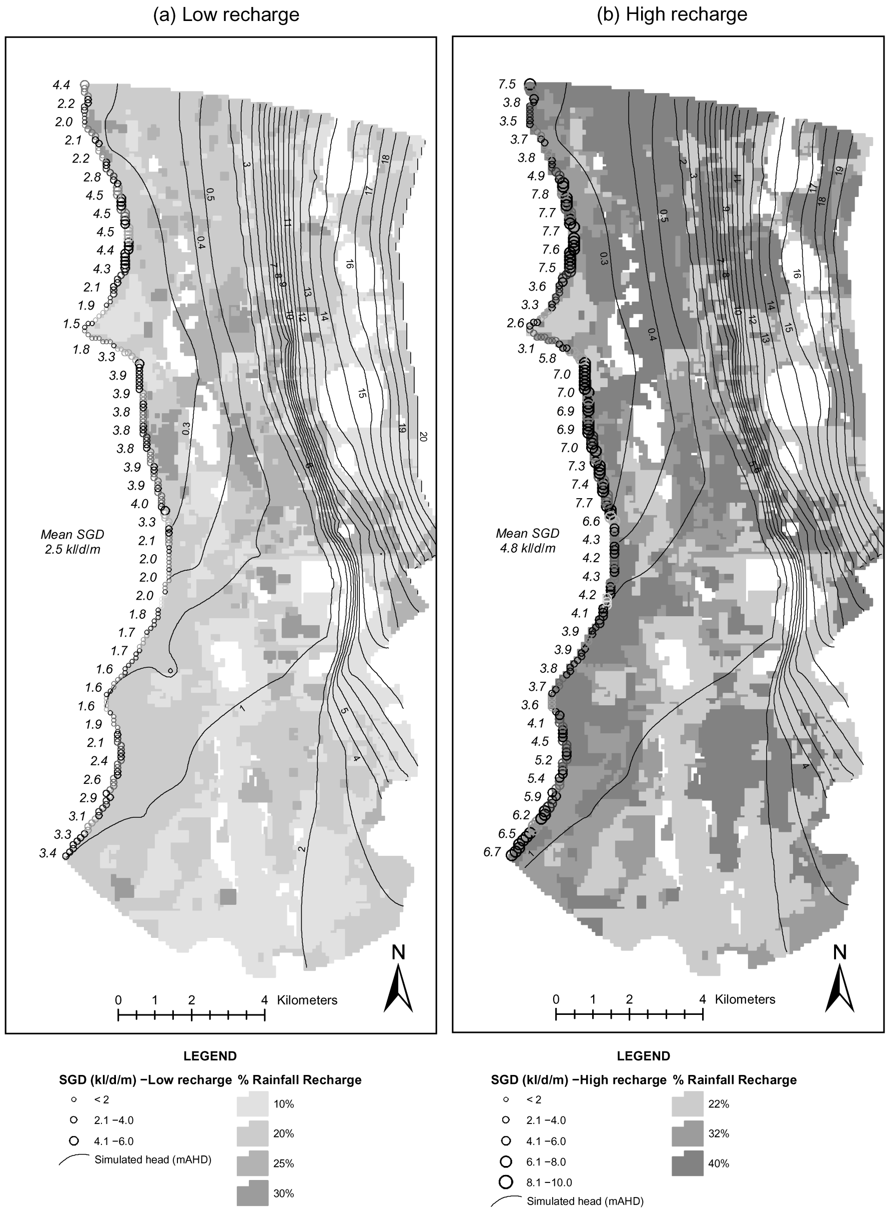

Figure 4. Model simulated SGD.

Cockburn Sound. Calibrated values of hydraulic conductivity are presented in Table 4, spatial differences between observed and model-simulated groundwater levels are illustrated in Figure 3, and the model-simulated groundwater table contours are

Table 5. Model water balance for low-recharge scenario.

Balance term	Flow in [$m^3 d^{-1}$]	Flow out [$m^3 d^{-1}$]	Net flow [$m^3 d^{-1}$]
Inland boundary	56982	−6855	50127
Groundwater recharge	65288	0	65288
Groundwater abstraction	0	−58245	−58245
Artificial recharge	3836	0	3836
SGD	0	−61007	−61007
Total	126106	−126107	−1

Mean SGD = 61007/24000 = 2.5 $m^3 d^{-1} m^{-1}$ of shoreline.

depicted in Figure 4(a and b). Conductance values of the coastal boundary cells (Table 3), which reflect the hydraulic connection between the coastal aquifer and ocean, were also adjusted during calibration.

Table 4 reveals that for the high-recharge scenario, larger values of hydraulic conductivity were required to simulate the observed water table elevations and hydraulic gradients compared to the low-recharge scenario. More generally, it is known that if the groundwater recharge rate is increased or decreased then the hydraulic conductivity of the aquifer must be proportionally increased or decreased, respectively, to maintain the model calibration. This relationship arises because the groundwater flow model is based on Darcy's Law (Bouwer 1978), which states that the rate of flow and hydraulic gradient are linearly related by hydraulic conductivity. Table 4 reveals that the observed water table configuration inshore from Cockburn Sound was reasonably well simulated for a range of different, plausible combinations of groundwater recharge and hydraulic conductivity (see Table 1). Uncertainty due to non-uniqueness is common in groundwater modelling exercises because there is normally significant uncertainty in the model input variables.

Results and discussion

SGD from each coastal boundary cell is depicted in Figure 4(a and b) for both low- and high-recharge scenarios. The modelled distributions of SGD along the coast varied mainly in response to change in hydraulic connection between the aquifer and ocean. SGD was largest along two sections of coastline, north and south of Woodman Point, where Tamala Limestone directly contacts the ocean. Smaller variations in SGD occurred in response to variability in recharge intensity inshore from the coast and variation in the density and distribution of pumping bores. In the low-recharge scenario, SGD from the coastal boundary cells varied spatially between 1.4 and 4.6 $m^3 d^{-1} m^{-1}$. This increased to between 2.4 and 7.9 $m^3 d^{-1} m^{-1}$ in the high-recharge scenario.

The model water budgets for both recharge scenarios are presented in Tables 5 and 6. They confirm that SGD and groundwater pumping (out flows) were balanced by groundwater recharge and flow across the inland boundary (in flows). Because

Table 6. Model water balance for high-recharge scenario.

Balance term	Flow in [$m^3 d^{-1}$]	Flow out [$m^3 d^{-1}$]	Net flow [$m^3 d^{-1}$]
Inland boundary	55186	−7046	48140
Groundwater recharge	121750	0	121750
Groundwater abstraction	0	−58245	−58245
Artificial recharge	3836	0	3836
SGD	0	−115480	−115480
Total	180772	−180771	1

Mean SGD = 115480/24000 = 4.8 $m^3 d^{-1} m^{-1}$ of shoreline.

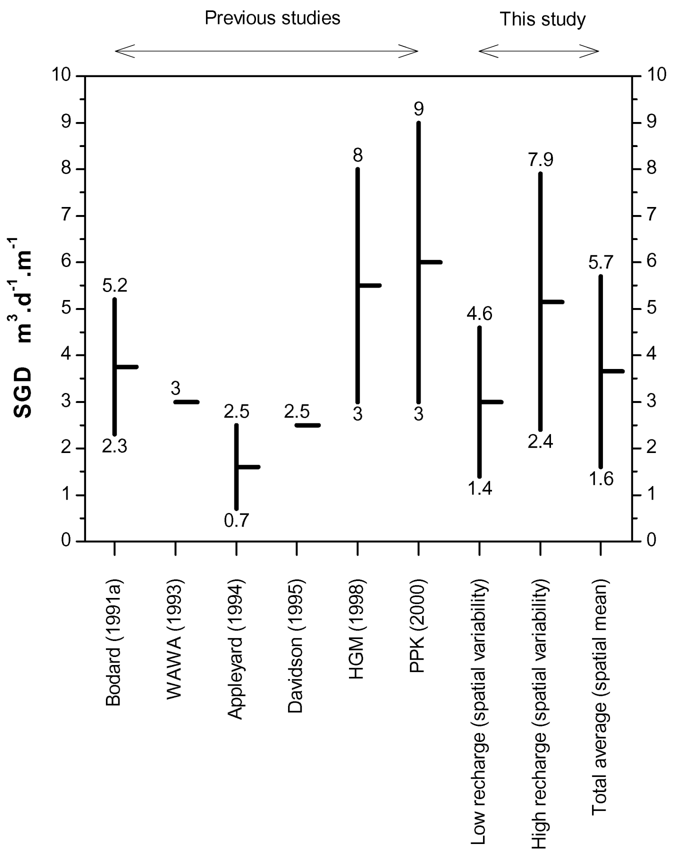

Figure 5. Comparison of the results from this study to previous estimates of SGD in Table 2.

all terms in the water balance are similar order of magnitude, uncertainty and errors in estimations of groundwater inflow, recharge and pumping are all manifest as similar order-of-magnitude error and uncertainty in SGD. Total SGD in the low-recharge scenario was 48% of total groundwater out flow from the model and groundwater abstraction from bores was approximately 46%. The remaining 6% of out flow was minor discharge to the Peel Main Drain. In the high-recharge scenario, SGD increased to 64% of total out flow and pumping reduced to 32%. Based on these estimates, none of the water balance terms can be neglected as insignificant.

Allowing for low and high estimates of groundwater recharge, and arbitrary ±20% errors in pumping and groundwater flow across the inland boundary, mean SGD is estimated to be in the range $2.5–4.8 \pm 0.9\,\mathrm{m^3\,d^{-1}\,m^{-1}}$. Thus, total average SGD could be between 1.6 and $5.7\,\mathrm{m^3\,d^{-1}\,m^{-1}}$, which is a factor of variation of approximately 3.5. This order-of-magnitude uncertainty stems from uncertainty in the reliability and accuracy of the available hydrologic and hydrogeologic data. Figure 5 presents a graphical comparison of these results with the previous estimates of SGD in Table 2. Note that these various estimates were derived for different geographical locations along the Cockburn Sound coastline (see Table 2 and Figure 1 for locations) and some of the variation between estimates may reflect true spatially variability in SGD along the coast.

Conclusions

Based on aquifer water-balance considerations, spatially averaged SGD across the coastline adjacent to Cockburn Sound was estimated to be $2.5–4.8 \pm 0.9\,\mathrm{m^3\,d^{-1}\,m^{-1}}$. Most of this groundwater is believed to discharge to the ocean via preferred pathways (subterranean channels) in Tamala Limestone. The estimated range in SGD, $2.5–4.8\,\mathrm{m^3\,d^{-1}\,m^{-1}}$, corresponds to low and high estimates of average groundwater recharge. The error, $\pm 0.9\,\mathrm{m^3\,d^{-1}\,m^{-1}}$, was calculated based on arbitrary ±20% errors in pumping and groundwater inflow across boundaries. The magnitude of these errors could be larger.

Differences in hydraulic connection between the aquifer and ocean were observed to have the largest affect on spatial variability in SGD. Nevertheless, spatial distributions of SGD simulated in this study cannot be corroborated against independent data, and are considered to have large uncertainty. For example, the model can be successfully calibrated using conductance values that result in significantly different spatial distributions of SGD, compared to those depicted in Figure 4 (a and b). The model provides regional-scale estimates of SGD that do not take account of the detailed hydrogeology and associated flow paths and rates that control SGD at the local scale.

It is concluded that the estimated values of total average SGD are consistent with the available regional hydrogeological and hydrologic data for the study area. The model estimates provide a suitable context for comparing and contrasting independent estimates of SGD based on direct and indirect measurement techniques. Nevertheless, results from local-scale measurements are affected by local-scale processes and should not be constrained by regional-scale estimates derived from the modelling. Effects such as the focussing of flow through preferred pathways may result in local SGD rates that are significantly larger or smaller than the regional-scale estimates. Temporal effects such as sea level changes will also result in SGD rates that vary significantly in time from the long-term average SGD.

In conclusion, it is worth reiterating that only a rudimentary analysis of the uncertainty in the aquifer water balance was carried out for this study. Groundwater inflow from up-gradient in the aquifer, areal groundwater recharge, and groundwater pumping were all significant compared to the estimated values of SGD – which were derived from these water balance terms. Thus, the uncertainty in each water-balance term was manifested as similar-magnitude uncertainty in the SGD estimates. With better data, it is possible that probabilistic descriptions of the model input variables could be developed and applied to investigate the relations between variability and uncertainty in the model inputs and the resulting sensitivity in SGD estimates. Such a study would provide good opportunity for future research and publication in this field, with important results for both water resources and coastal managers.

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