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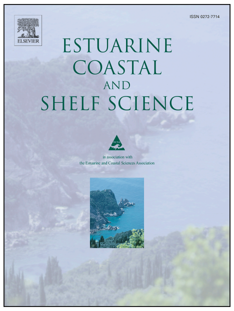

Factors influencing marked variations in the frequency and timing of bar breaching and salinity and oxygen regimes among normally-closed estuaries

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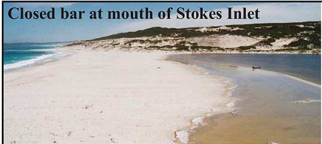
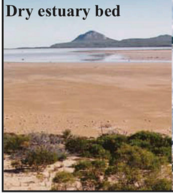
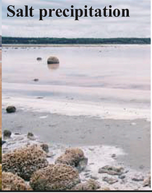


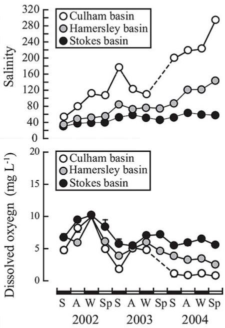
Closed bar at mouth of Stokes Inlet



Dry estuary bed



Salt precipitation



Prolonger bar closure can result in extreme hypersalinity and hypoxia

Bars only breached in response to exceptional winter rainfall or atypically high, unseasonal rainfall, often associated with cyclonic activity in summer and autumn

Bar breach at Culham Inlet

Factors influencing marked variations in the frequency and timing of bar breaching and salinity and oxygen regimes among normally-closed estuaries

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Abstract

The aim of this study was to determine the factors that influence the breaching of the bar at the mouth of estuaries that are normally-closed to the ocean and the trends exhibited by salinity and oxygen concentration in those systems during protracted periods of closure. Collated data for 1972 to 2016 demonstrate that the frequency and timing of bar breaching of three normally-closed estuaries, located along 100 km of coastline in a low rainfall region of temperate south-western Australia, differ markedly. Breaching occurred in 12 years in Stokes Inlet, ≥ eight in Hamersley Inlet and only three in Culham Inlet. Breaching in each estuary was related to relatively very high volumes of fluvial discharge. Although breaching typically occurred following exceptional winter rainfall in Stokes Inlet, whose catchment received by far the greatest winter rainfall, it usually took place in Hamersley and Culham inlets following atypically high summer and autumn rainfall, often associated with cyclonic activity. Salinity, oxygen concentration and water temperature were measured seasonally between summer 2002 and spring 2004, during which period each of these estuaries was closed to the ocean following major natural breaches of each system and the influx of substantial volumes of oceanic water. Mean salinities in the estuary basins rose by markedly different extents during the three years of closure. They thus increased from 30 in Stokes Inlet, 35 in Hamersley Inlet and 52 in Culham Inlet, to maxima of 64, 143 and 293, respectively, with the highest individual salinity of 313 in the latter estuary the greatest yet recorded for any estuary worldwide. In contrast, oxygen concentrations declined to minima of 5.5, 2.5 and 0.6 mg L^{-1}, respectively, and were inversely related to salinity in the basin of each estuary (r = -0.7 to -0.8). Although salinities in the main river of each estuary did not become as highly elevated as in its basin, they still reached 221 in that of Culham Inlet. The very different extents to which salinity increased and oxygen concentration declined among the three estuaries reflect variations in amount of rainfall and thus fluvial discharge, the area and depth of basin relative to discharge and resilience of the bar at the estuary mouth. Thus, while a suite of factors contribute to bar breaching and physico-chemical trends in normally-closed estuaries, variations in their importance as 'drivers' among estuaries should be considered when studying the ecology of a given system.

Keywords: catchment characteristics; estuary mouth; fluvial discharge; microtidal region; rainfall; south-western Australia.

1. Introduction

Estuaries are very important from a number of perspectives. For example, they are the most productive of marine ecosystems (Schelske and Odum, 1961; Whittaker and Likens, 1975; Bianchi, 2006) and thus provide a rich source of food for fishes and crustaceans, some of which contribute to commercial and recreational fisheries in many parts of the world (Lellis-Dibble et al., 2008; Able and Fahay, 2010; Sheaves et al., 2014; Creighton et al., 2015). They are also focal points for urban, industrial and agricultural development and recreational activity and are therefore often threatened by the effects of pollution and eutrophication (Jackson et al., 2001; Kennish, 2002; Tweedley et al., 2012; Potter et al., 2015). Comprehensive quantitative data for the physico-chemical and biotic characteristics of the different types of estuaries are thus required to facilitate a sound understanding of the functioning of these systems and thereby, in turn, enable their conservation and/or restoration (Hallett et al., 2016).

Estuaries are frequently categorised on the basis of their tidal regime. Davies (1964) regarded those with a tidal range greater than 4 m as macrotidal, while those with a range less than 2 m were considered microtidal and those with an intermediate tidal range as mesotidal. These three tidal regimes are reflected in different morphological and physico-chemical characteristics. Thus, at one extreme, macrotidal estuaries, such as those in the northern regions of Europe and North America, are typically funnel-shaped and experience large upstream and downstream movements of water during each tidal cycle (McLusky and Elliott, 2004; Tweedley et al., 2016). In contrast, microtidal estuaries often comprise a short and narrow entrance channel (lower estuary), that opens into a basin area (middle estuary), into which the saline, downstream reaches of the rivers (upper estuary) discharge (Potter et al., 1990; Cooper, 2001). These morphological differences are particularly pronounced in those estuaries that are located in regions such as the southern coasts of Australia and Africa (Potter et al., 1990).

In this paper, the term estuary follows the definition of Potter et al. (2010), which refined that of Day (1980, 1981) and emphasises that the crucial characteristics of an estuary include a riverine input and at least a periodic connection with the sea. In regions with Mediterranean climates, such as southern Australia and Africa, the Mediterranean Sea and the state of California, some estuaries are permanently-open, whereas others are closed from the ocean by a sand bar across their mouths, either intermittently, seasonally or for protracted periods, i.e. are normally-closed (Chuwen, 2009; Behrens et al., 2013; Tweedley et al., 2016). A normally-closed estuary has thus been defined as one that remains closed to the ocean for several years at a time (Hodgkin and Hesp, 1998), recognising that this type of estuary is often included in a common category with those that become either intermittently or seasonally-open each year (e.g. Whitfield and Bate, 2007; Wooldridge et al., 2016). Although estuaries, lagoons and lakes, which are intermittently or seasonally-open to the ocean, are widespread throughout the world (McSweeney et al., 2017), normally-closed estuaries tend to be restricted to microtidal regions and where rainfall and thus fluvial discharge is low, such as the Northern Cape of South Africa (Wooldridge et al., 2016; van Niekerk et al., 2017) and the eastern extent of the south-west drainage division in Western Australia (Tweedley et al., 2017).

The bars that form at the mouths of estuaries are produced by the wave-driven import of sediment from the marine environment and breached by the export of sediment through pressure from the build-up of water and therefore pressure within the estuary (Ranasinghe and Pattiaratchi, 1999; Behrens et al., 2013; Rich and Keller, 2013; Slinger, 2016). While the overall processes leading to bar formation and breaching are understood, there have been no long-term studies aimed at identifying and quantifying the factors that lead to the accumulation of relatively large volumes of water in normally-closed estuaries and elucidating the basis for variations in the frequency with which the bar of these estuaries is breached.

The estuaries on the extensive coastline extending eastwards from the lower-west coast of Australia tend to change from mainly permanently-open to predominantly seasonally-open to almost exclusively normally-closed. This trend has been attributed to the effects of progressive reductions in rainfall and catchment size on fluvial discharge along that coastal axis (Hodgkin and Hesp, 1998; Brearley, 2005). There are limited detailed environmental data, however, for the 21 normally-closed estuaries along this coastline, due largely to their typically remote locations and difficulties in obtaining access to a range of representative sites. Broad data for the physico-chemical characteristics of the Wellstead, Stokes, Hamersley and Culham inlets demonstrate, however, that each of these four estuaries, whose mouths lie within 180 km stretch of coastline, remain closed during protracted, relatively dry periods, but the extents to which they become hypersaline and hypoxic vary markedly (Young and Potter, 2002; Chuwen et al., 2009). A thorough understanding of the trends exhibited by salinities and oxygen concentrations during such periods is thus crucial for understanding the factors that influence the faunal characteristics of such extreme systems.

The overarching aim of this study was to elucidate the factors that lead to the breaching of the bar at the mouth of normally-closed estuaries and the trends exhibited by salinity, oxygen concentration and water temperature in those systems during protracted periods of closure. This study thus first explored the hypothesis that the frequency and timing of bar breaching of three normally-closed estuaries (Stokes, Hamersley and Culham inlets) in the 45 years between 1972 and 2016 were related to rainfall and thus fluvial discharge. Next, the changes in salinity, oxygen concentration and water temperature within the different regions of these estuaries, throughout a common period of protracted closure between 2002 and 2004, were compared. The resultant data were then used to elucidate the ways in which variations in the timing and frequency of bar breaching and the trends exhibited by physico-chemical characteristics of those estuaries during periods of closure were associated with differences in various factors. These factors were catchment size, rainfall and thus fluvial discharge, the area and depth of the estuary basin and the height of the bar. The implications of this study are relevant for understanding the dynamics of normally-closed estuaries worldwide.

2. Materials and methods

2.1. Descriptions of Stokes, Hamersley and Culham inlets

The tendency for estuaries to change from mainly permanently-open to predominantly seasonally-open to normally-closed along the ~1,400 km southwards from 31°S, 115°E (Moore River) and then eastwards to 34°S 123°E (Poison Creek) is shown in Fig. 1a. The two systems (Jerdacuttup and Gore-Dalyup) that were previously estuaries, but are now permanently-closed are also shown. The remote and normally-closed Stokes, Hamersley and Culham inlets, which are located within ~100 km of the southern coast of Western Australia, have relatively small catchment areas and wide basins (Fig. 1).

The characteristics of the above three normally-closed estuaries are described, employing data derived from Hodgkin and Clark (1989b, 1990) and Brearley (2005). Photographs, taken during the study of seasonal changes in environmental variables (2002 to 2004) and subsequently in 2014 and 2017, are used to illustrate the extreme changes that occur in these systems and to show a sand bar at the mouth of an estuary before and during breaching.

2.2. Rainfall and fluvial discharge

Monthly rainfall were obtained from weather stations in the catchments of Stokes and Culham inlets, and from another close to that of Hamersley Inlet, in each year between January 1972 and December 2016, the years for which such data were available for each of these systems (Bureau of Meteorology, 2017). These stations and this time period were chosen as they provided the most comprehensive and comparable historical rainfall data for the three catchments during the above years. Two-tailed tests of the significance of Pearson's correlations were used to determine whether annual rainfall in the catchment of each of the three estuaries changed over the years between 1972 and 2016 ($P < 0.05$). Annual fluvial discharges were available for the Young River of Stokes Inlet in 38 of the above 45 years (Department of Water Western Australia Water Information Reporting, 2017). A one-tailed test of Pearson's correlation was employed to confirm that the natural logarithm of fluvial discharge was positively correlated with the natural logarithm of rainfall in Stokes Inlet in those 38 years ($P < 0.05$), having first established that the relationship between discharge and rainfall was described better by a log-log than linear or log-linear relationship. Since, between 1972 and 2016, annual fluvial discharges were available for only 14 of those years for the Phillips River (Culham Inlet), and for just one year for the Hamersley River (Hamersley Inlet), it was not possible to derive a reliable relationship between fluvial discharge and rainfall for those estuaries.

The years in which the bar at the mouths of Stokes, Hamersley and Culham inlets were recorded as breached between 1972 and 2016 were obtained from Hodgkin and Clark (1989b, 1990) and environmental officers of the Western Australian Department of Biodiversity, Conservation and Attractions. The years and months that the bar breached in Stokes and Culham inlets are considered comprehensive. Bar breaches of Hamersley Inlet may not always have been recorded as this estuary is located within an extensive National Park, and thus in an unpopulated area, and its mouth is only visited opportunistically by environmental officers. Furthermore, as the mouth of this estuary remains open for only a few weeks (Hodgkin and Clark, 1990), the timing of any visit is critical for detecting a bar breach.

One-way Analysis of Variance (ANOVA) was used to test the hypothesis that annual rainfall in the catchment of Stoke Inlet and Hamersley Inlet and fluvial discharge from the main river of Stokes Inlet (Young River), differed significantly in the years when the bar at the mouth of each estuary was breached from those when the mouth of that estuary remained closed. Levene’s test showed that fluvial discharge required a fourth-root transformation to meet the test assumptions of homogeneity of variance.

A shade plot (Clarke et al., 2014) was constructed to illustrate the amount of rain that fell at the weather stations representing the catchment of each estuary in each month between January 1972 and December 2016. The months and years when the bar of each estuary was breached are superimposed on the plot. Comparisons of the characteristics of normally-closed estuaries and their catchments were restricted to Stokes, Hamersley and Culham inlets as data were derived from local sources and comparable detailed information for other systems elsewhere were not readily available.

2.3. Salinity, oxygen concentration and water temperature

Salinity, dissolved oxygen concentration and water temperature were measured at widely distributed sites in nearshore, shallow and offshore, deeper waters in the basins (middle estuary) of Stokes, Hamersley and Culham inlets and in the saline lower reaches of the main river (upper estuary) of both the Stokes and Culham inlets (Fig. 1c,d,e). Measurements were recorded seasonally in each system between summer 2002 and spring 2004. An inability to access the Hamersley River by boat from the basin after spring 2002, and at any time from adjoining land due to dense vegetation and very steep banks, meant that the above variables could no longer be measured in this river after spring 2002. The above three environmental variables were also measured in nearshore and offshore waters of the entrance channel of Culham Inlet (lower estuary) and in nearshore waters of perennial, upstream pools of the Hamersley and Phillips rivers.

Salinity, dissolved oxygen concentration and water temperature were measured using a Yellow Springs Instrument (YSI) Model 85 Handheld Oxygen, Conductivity, Salinity and Temperature System. Each of these physico-chemical variables was measured in the middle of the water column at nearshore sites and at both the surface and bottom of the water column at offshore sites. As the YSI meter only records salinities up to 80, the measured conductivities, on those occasions when salinities exceeded this value, were converted to a salinity using the Practical Salinity Scale 1978 (Lewis and Perkin, 1981), except when salinities were extremely high when they were derived from a series of dilutions with freshwater. Dissolved oxygen concentrations at salinities greater than ~80 were calculated from the percent oxygen saturation recorded by the YSI meter using the equation of Weiss (1970). One-tailed Pearson’s correlations were employed to test that dissolved oxygen concentration was negatively correlated with salinity in the basins of each estuary and the main river of Stokes and Culham inlets ($P < 0.05$), noting that there were insufficient data to apply this test to the river Hamersley Inlet.

3. Results

3.1. Characteristics of Stokes, Hamersley and Culham inlets

The surface area of the basin, which constitutes the vast majority of the total area of normally-closed estuaries, was greatest for Stokes Inlet (14 km^2) and least for Hamersley Inlet (2 km^2), with corresponding catchment areas of 5,300 and 1,268 km^2 (Table 1). The mean and median annual rainfall were far greater for Stokes Inlet than for either Hamersley or Culham inlets (Table 1). The mean annual fluvial discharge was also greatest for Stokes Inlet (11.9 GL y^{-1}) and least for Hamersley Inlet (1.2 GL y^{-1}). The catchments of each estuary have been subjected to extensive land clearing, ranging from 68% in Stokes Inlet to 37% in Hamersley Inlet (Table 1; Fig. 1b). The ratio of discharge to basin area decreased progressively from the Stokes to Hamersley to Culham inlets, whereas the depth of their basins followed the reverse trend (Table 1).

The short and narrow entrance channel, characteristic of microtidal estuaries in southern Australia and Africa, is illustrated in the photographs of Culham Inlet, with the sand bar at its mouth fully formed in 2013 (Fig. 2a) and breached with a large outflow of water to the ocean in 2017 (Fig. 2b). A comparison of Figs 2a and 2b demonstrates how very strong outflows can dramatically modify the entrance channel of normally-closed estuaries and destroy infrastructure, such as roads constructed across them. A breach of this magnitude also occurred in 2000, prior to the commencement of the three year seasonal study of physico-chemical variables in the three estuaries between 2002 and 2004 (see later).

The wide basin of Culham Inlet was full of water in 2013 (Fig. 2a), following appreciable rainfall, and virtually dry in 2004 (Fig. 2c), at which time salt was precipitating out of solution (Fig. 2d). While the catchment in the National Park to the west of the basin of this estuary is largely uncleared, substantial areas have been cleared for agriculture elsewhere in the catchment (Figs 1b, 2a). Water levels in Hamersley Inlet decreased markedly from the commencement of the three year seasonal study. This led to discontinuity between the waters of the basin and Hamersley River (Fig. 2e) and also within the river, with the latter becoming separated into a series of isolated pools upstream by a substantial rock bar that became exposed as water levels declined (Fig. 2f).

3.2. Relationship between catchment rainfall and bar breaching

3.2.1. Stokes Inlet

Total annual rainfall, recorded at the weather station in the catchment of Stokes Inlet between 1972 and 2016, ranged widely from minima of just 327 mm in 1994 and 342 mm in 2002 to maxima of 782 mm in 1999 and 813 mm in 2013, with a mean and median of 550 and 540 mm, respectively (Fig. 3a). Rainfall showed no conspicuous tendency to increase or decrease over those 45 years, which is reflected in the lack of a significant change with year (r = 0.223, P = 0.142). Total annual fluvial discharge in the Young River in the 38 of those years between 1972 and 2016 for which reliable flow data are available, also varied greatly. Thus, it ranged from minima of 0.05 GL in 1990 and < 1 GL in another nine years to > 30 GL in 1986, 1989 and 1999 and as high as 60.8 GL in 2007 (Fig. 3b). In these 38 years, the natural logarithm of fluvial discharge was linearly correlated with the natural logarithm of rainfall (r = 0.494, P = < 0.001), with the relationship between fluvial discharge (y) and rainfall (x) described by the equation $\ln y = 5.50 \ln x – 34.05$ (r^2 = 0.244).

The bar at the mouth of Stokes Inlet was breached in 12 of the 45 years between 1972 and 2016 (Fig. 3a). The mean rainfall of 643 mm in the years when the bar was breached was far greater than the mean of 516 mm for the other 33 years (F = 17.4, P = < 0.001, n = 45). In eight of the 12 years when breaching occurred, annual rainfall exceeded 640 mm, a level reached in only three of the years when the bar remained intact. In the 38 years for which there were reliable data for discharge, the mean flow for the years when the bar broke was 25.6 GL compared with only 2.0 GL when the estuary mouth remained closed (F = 60.9, P = < 0.001).

At a monthly and thus finer temporal scale, 10 of the 12 breaches of the bar of Stokes Inlet occurred between June (early winter) and October (mid spring), and thus following the onset of highly seasonal ‘winter’ rainfall (Fig. 4a, b). Bar breaching also occurred in January 2007, immediately following heavy cyclonic rainfall (185 mm) in that month, as occasionally occurs in summer (Fig. 4).

The breaching of the bar of Stokes Inlet in June 1999 was associated with a combination of substantial cyclonic rainfall in the summer and consistent rainfall in the winter of 1999. The continued input of water through rainfall was sufficient to keep the bar open until summer 2000, when cyclonic rainfall again increased the scouring of the bar and thus accounted for the estuary remaining open until April 2000 (Ian Hughes, Department of Biodiversity, Conservation and Attractions pers. comm.). This highly atypical protracted period of opening proceeded the commencement of the detailed seasonal study of salinity, dissolved oxygen concentration and water temperature in the three estuaries (see later).

3.2.2. Hamersley Inlet

Between 1972 and 2016, annual rainfall close to the catchment of Hamersley Inlet ranged from 223 mm in 1994 to 645 mm in 1992, with a mean of 438 mm (median = 475 mm; Fig. 3c). As with the catchment of Stokes Inlet, rainfall was not correlated with year (r = 0.198, P = 0.096, n = 45). Mean annual rainfall, in the eight years when the bar of this estuary was recorded as breached, was greater than when it was not breached, i.e. 484 vs 428 mm, respectively (Fig. 3c), a difference that was marginally not significant (F = 2.0, P = 0.051, n = 45). However, one or more breaches may have occurred in years of particularly high rainfall, but went unrecorded (see Materials and Methods and Discussion).

At a seasonal level, the bar of Hamersley Inlet was breached in summer or autumn in five years, during or following atypically high, unseasonal rainfall, often associated with cyclonic activity. It also breached in late winter (August) of two years and in late spring (November) in another year after greater than usual winter and spring rainfall, respectively (Fig. 4b). Although the bar of the remote Hamersley Inlet was not recorded as breached in 1992 or 2011, the two years of greatest annual rainfall in the catchment of this system, both of these years followed a year(s) of below average rainfall and, in 1992, rainfall was spread throughout much of the year (Figs 3c; 4b).

3.2.3. Culham Inlet

Mean annual rainfall at the weather station in the catchment of Culham Inlet over the above 45 years was 445 mm (median = 452 mm), with a minimum of 239 in 1972 and a maximum of 680 in 2016 (Fig. 3d). Although rainfall (y) was positively correlated with year (x) in Culham Inlet, the relationship, which was described by the regression equation y =

$2.58x + 386$, $r^2 = 0.122$, was not particularly strong ($r = 0.349$, $P = 0.019$, n = 45). As with Hamersley Inlet, there are limited reliable data for fluvial discharge in this estuary. The bar at the mouth of Culham Inlet was recorded as breached in only three years between 1972 and 2016, including in January 2000, during particularly strong cyclonic activity, and previously in May 1993, when rainfall was atypically very high for that month. The third breach, i.e. in April 2016, was artificially induced to overcome the threat that the large volume of water, that was accumulating in the basin following three months of relatively high rainfall, would spill over onto surrounding agricultural land (Fig. 4).

From the above data, the bar at the estuary mouth broke more frequently in Stokes (12 years) and Hamersley (≥ 8 years) inlets, than in Culham Inlet (3 years; Fig. 4b). Each of the three estuaries were open concomitantly only in early 2000, recognising that the bar of Stokes Inlet was breached in June 1999 and remained open, whereas those of the other two estuaries were not breached until January 2000. Thus, each estuary was open for a period prior to the commencement of the seasonal study of phyisco-chemical variables in 2002 to 2004 (see below), when the mouth of each of these estuaries remained closed to the ocean (Fig. 4b).

3.3. Salinity, water temperature and oxygen regimes

3.3.1. Stokes Inlet

Mean seasonal salinity in nearshore, shallow waters of the basin of Stokes Inlet rose markedly and progressively in each season from 30 in summer 2002 to 59 in autumn 2003, but then declined to 46 in spring 2003, following appreciable winter rainfall (Fig. 5). It subsequently increased to a maximum of 64 in autumn 2004 and remained just below this level in the winter and spring of that year. As with salinity, the mean seasonal dissolved oxygen concentrations initially increased in 2002 from ~5 mg L^{-1} in summer to ~10 mg L^{-1} in winter, but subsequently followed an essentially reverse trend as salinity increased further (Fig. 5). The relationship between oxygen concentration and salinity was strongly negative ($r = -0.70$; $P = 0.007$, n = 12).

Salinities in nearshore waters of the Young River of Stokes Inlet were typically slightly less than those in the basin in all seasons except in the winter and spring of 2003

(Fig. 5). Dissolved oxygen concentrations in that river ranged from 5-12 mg L^{-1} and tended to be slightly greater than in the basin, especially during marked declines in salinity (Fig. 5). In contrast to the situation in the basin, oxygen concentration in the Young River was not significantly correlated with salinity (r = -0.40; P = 0.097, n = 12).

In each season, salinities and oxygen concentrations at the surface and bottom of the water column in offshore waters of the basin were essentially the same (Fig. 5), i.e. these waters were not stratified, and very similar to those in nearshore waters (Fig. 5). Salinities at the surface and bottom of the offshore waters of the river were similar to those in nearshore waters in all seasons except winter and spring of 2003, when only surface salinity declined precipitously (Fig. 5).

Mean seasonal water temperatures in nearshore waters of both the basin and Young River, which were always similar to the surface and bottom of the water column of their respective offshore waters, rose to their maxima during summer (e.g. 28 °C in 2003) and declined to their minima in winter (e.g. 12 °C in 2003; Fig. 5).

3.3.2. Hamersley Inlet

In the basin of Hamersley Inlet, mean seasonal salinities in nearshore waters rose from 35 in summer 2002 to 143 in spring 2004 (Fig. 4a). After salinities had risen to nearly 60 in spring 2002, the mean seasonal oxygen concentrations declined from greater than 6 mg L^{-1} to a minimum of 2.5 mg L^{-1} in spring 2004, thus exhibiting the reverse trend to salinity (r = -0.80; P = 0.001, n = 12; Fig. 6).

Mean salinities at sites in the Hamersley River in 2002 increased from 33 in summer to 59 in spring, after which this region could not be sampled (see Materials and Methods). Mean dissolved oxygen concentrations in that river were always $\geq$ 5 mg L^{-1} and reached 10 mg L^{-1} in winter 2002 (Fig. 6). From autumn 2003, mean salinities in one of the upstream pools that formed in the Hamersley River ranged only from 16 to 24 and were thus far lower than the 75-143 recorded in the basin during that period (Fig. 6).

Water temperatures in the basin underwent pronounced seasonal changes, ranging from a minimum of 11 °C in winter 2003 to a maximum of 26 °C in summer 2004 (Fig. 6).

The highest mean temperature in the upstream pool, i.e. 29 °C in summer 2004, was greater than any temperature recorded in the basin or river (Fig. 6).

Salinity, oxygen concentration and temperature at both the surface and bottom of the water column in offshore waters of the basin of Hamersley Inlet (data not shown), and also of its river in each season of 2002 when this region could be sampled, were essentially the same as those in the respective nearshore waters of each region of that estuary (Fig. 6).

3.3.3. Culham Inlet

In nearshore waters of the basin of Culham Inlet, mean seasonal salinities rose progressively from 52 in the summer of 2002 to 175 in the following summer, after which they declined to 110 in winter 2003 and then rose sharply to 293 in spring 2004 (Fig. 7). Oxygen concentrations in the basin declined from their maximum of 10 mg L^{-1} in winter 2002 to 0.7 mg L^{-1} in spring 2004, coincident with the overall trend for salinity to increase ($r = -0.80$; $P = 0.001$, n = 12). However, dissolved oxygen did rise in autumn and winter 2003 when salinity decreased (Fig. 7).

Mean seasonal salinities were always less in nearshore waters of the Phillips River of Culham Inlet than in the basin and markedly so in autumn 2003, when, following increased fluvial discharge, salinities in the river declined precipitously from 125 to as low as 17 (Fig. 7). Although regional differences in salinity were marked in spring 2004, i.e. 199 vs 293, mean salinities in the preceding two months were only slightly lower in the river, i.e. 206 and 207, than in the basin, i.e. 222 and 248 (Fig. 7). Mean dissolved oxygen concentrations in the Phillips River followed a similar trend as in the basin, with a maximum of 13.3 mg L^{-1} in autumn 2002 and a decline to a minimum of 2.0 mg L^{-1} in winter and spring 2004 (Fig. 7). As in the basin, oxygen concentration in that river was negatively correlated with salinity ($r = -0.71$; $P = 0.005$, n = 12).

Salinities at the surface and bottom of the water column in offshore waters of the Phillips River were the same or similar in all seasons except autumn 2003, when they declined to 19 and 78, respectively, thus resulting in considerable stratification of the water column (Fig. 7). Oxygen concentrations in the surface and bottom waters followed a similar overall trend to those in nearshore waters, but with those at the surface typically greater than those at the bottom of the water column (Fig. 7).

In the entrance channel of Culham Inlet, mean seasonal salinities ranged only from 37 to 44 and those in the part of the Phillips River, which had become isolated as a pool, ranged only from 12 to 29 (Fig. 7). The surface and bottom salinities in offshore waters of the entrance channel were essentially the same in each season as those in nearshore waters (Fig. 5d). Mean dissolved oxygen concentrations always exceeded 6 mg L^{-1} in the surface waters of the entrance channel and 4 mg L^{-1} in the upstream pool and sometimes exceeded 9 mg L^{-1} in both regions (Fig. 5). Within the entrance channel, oxygen concentrations were similar throughout the water column in all seasons except summer and autumn 2002 and summer 2004, when they were lower and < 5 mg L^{-1} in bottom waters (Fig. 7).

Mean seasonal water temperatures, in both the basin and Phillips River, reached their maximum of ~27 °C during summer or spring and declined to their minima of 10-15 °C in winter (Fig. 7) and were typically very similar at the surface and bottom of the water column in offshore waters of the Phillips River (Fig. 7). The seasonal trends in water temperature in the entrance channel and upstream pool were similar to those in nearshore waters of the basin and Phillips River and were largely uniform throughout the water column of the entrance channel (Fig. 7).

3.4. Comparisons of salinity and oxygen concentration among the three estuaries

Mean salinities in the basins of Stokes, Hamersley and Culham inlets increasingly diverged from their respective minima of 30, 35 and 52 in summer 2002, to reach maxima of 64, 143 and 293 three years later (Fig. 8). Although salinities typically increased progressively throughout the three years in the basins of each system, they did decline markedly in Culham Inlet in autumn and winter 2003. As with the basins of Culham and Stokes inlets, salinities in the rivers of these two systems increasingly diverged from differences of only 9 to as high as 155 between the commencement and completion of the study (Fig. 8).

After winter 2002, dissolved oxygen concentrations in Stokes, Hamersley and Culham inlets followed essentially the reverse trends of those of salinity (Fig 8). Oxygen concentrations thus declined from maxima of ~10 mg L^{-1} in each estuary to 5.7 in Stokes Inlet, 3.8 in Hamersley Inlet and 1.7 in Culham Inlet in summer 2003, but were ~5.5 mg L^{-1} in each estuary in autumn 2003. Subsequently, concentrations in Stokes Inlet did not decline further, whereas those in Hamersley and Culham inlets fell to 2.5 and 0.7 mg L^{-1}, respectively. The downward trends in oxygen concentration in the river of Stokes and Culham inlets largely parallel those in the basin, with respective values of 5.9 and 2.0 mg L^{-1} at the conclusion of the three years (Fig. 8).

Water temperature in the basin of each estuary and river of Stokes and Culham inlets followed the same highly seasonal pattern of change, with no pronounced differences between or within estuaries (cf. Fig.5, 6, 7).

4. Discussion

The collation and analysis of past and present data from a range of sources elucidated the years and months in which the bar at the mouth of each of three normally-closed estuaries, which lie within 100 km along the south-western Australian coast, were recorded as breached between 1972 and 2016. This then enabled the extents to which the amount and timing of rainfall in the catchment of each estuary, acting as a surrogate for fluvial discharge, together with the characteristics of the estuary basin and bar, influence breaching. The closure of the mouths of each of the above estuaries for three years, following a recent breaching, provided a unique opportunity to describe the trends shown by salinities and oxygen concentrations during a protracted period when each of these systems was isolated from the ocean. The markedly different extents to which salinity and oxygen concentrations changed helped elucidate the ways in which these variables are associated with fluvial discharge and the size and depth of the estuary basin during such periods. The implications of this unique study will enhance the ability to interpret the results recorded for the physico-chemical and faunal characteristics in those estuaries elsewhere in the world which likewise become disconnected from the ocean for protracted periods.

4.1. Bar breaching

4.1.1. Relationships with rainfall and fluvial discharge

The results demonstrate that fluvial discharge in Stokes Inlet was strongly correlated with rainfall, as with those systems in Mediterranean climatic regions that open regularly to the ocean (e.g. Elwany et al., 1998; Whitfield and Bate, 2007; Rich and Keller, 2013). The bar at the mouth of Stokes Inlet was shown typically to be breached in years when annual rainfall exceeded 640 mm, which led to greatly increased fluvial discharge and thus to a build-up of large volumes of water in the basin behind the bar. At a finer temporal scale, the breaching of the bar of Stokes Inlet was always associated with particularly heavy rainfall, almost invariably in early winter and mid spring, but in one year during atypical cyclonic activity in summer. The crucial role played by the resultant marked increase in fluvial discharge in the breaching of the bar of this estuary parallels that recorded for the Great Brak Estuary in South Africa (Slinger, 2016) and the San Dieguito Estuary in California (Elwany et al., 1998), which open far more frequently and, as a consequence, do not become markedly hypersaline.

In contrast to Stokes Inlet, the bars of Hamersley and Culham inlets were breached predominantly in summer and autumn following atypically high, unseasonal rainfall, often associated with cyclonic activity. The different timing of the breaching of Stokes Inlet is presumably related to the rainfall in late autumn to mid spring being far greater in the catchment of that estuary than in those of the other two estuaries. Thus, the mean monthly catchment rainfall for those six months was 62 mm in Stokes Inlet, compared with only 43 mm in both Hamersley and Culham inlets, thereby resulting in far lower fluvial discharges. Moreover, the ratio of mean annual discharge to basin area is 1.5 times greater for Stokes Inlet than Hamersley Inlet and 2.7 times greater than Culham Inlet, therefore enhancing, to a greater extent, the accumulation of water in the basin of this system for a given rate of discharge.

Although the breaching of the bar of an estuary during summer and autumn was often associated with extreme cyclonic rainfall, the number of years in which such breaching occurred differed greatly among estuaries. This reflects marked variations in the magnitude of the rainfall produced among catchments by such cyclonic activity in a given year. For example, the passage of category 2 cyclone Tina through south-western Australia in January 1990 (Joint Typhoon Warning Center, unpublished data) led to 113 and 108 mm of rainfall in the adjacent catchments of Hamersley and Culham inlets, respectively, compared with only 43 mm in that of Stokes Inlet (Fig. 4), which is located ~100 km further east. It is thus not surprising that the bar of Stokes Inlet was not breached in that year. Although the catchments of Hamersley and Culham inlets received similar amounts of cyclonic rainfall in the summer of 1990, the bar of only the first of those estuaries was breached in that year. Furthermore, between 1972 and 2016, the bar of Culham Inlet was breached in only three years, compared with at least eight in the adjacent Hamersley Inlet, and had remained intact in Culham Inlet for the 53 years prior to 1972 (Hodgkin, 1997).

4.1.2. Frequency and duration of breaching and bar characteristics

The far fewer times that Culham Inlet becomes open to the sea than Hamersley Inlet, and also Stokes Inlet, imply that its bar is particularly resilient to the effects of increases in the volume of water in the basin and/or the volume of water rarely becomes sufficient to breach the bar. As the volume of water required for breaching increases with bar height (Rich and Keller, 2013), it is relevant that the bar at the mouth of Culham Inlet may reach 3-5 m above sea level, compared with only ~2 m in Hamersley and 1.5-2 m in Stokes inlets (Hodgkin and Clark, 1989b, 1990; Hodgkin, 1997). In addition, the wide basin of Culham Inlet is only 1 m deep (Hodgkin, 1997), which, even with heavy rainfall during cyclonic events, limits the volume it can retain before water flows out and over the low-lying surrounding land.

While the bar was breached less frequently in Culham Inlet than in the nearby Hamersley Inlet, the mouth of Culham Inlet was open to the ocean in May 1993 and yet there was no record of this having occurred in Hamersley Inlet. This provides an example of one of a few occasions when a breaching of the bar of Hamersley Inlet might have been expected, but was not detected. While there are only opportunistic records of bar status and seasonal field observations of Hamersley Inlet, the consistency of the salinity trends between 2002 and 2004 and the discontinuity between the waters of the river and basin in the last two of those years, produced as a result of evaporation, strongly imply that, as with Culham Inlet, Hamersley Inlet remained closed during the above three relatively dry years.

Although the duration that an estuary remains closed to the ocean is related to the volume of fluvial discharge and the capacity of the estuary to store water, the length of time a system remains open to the ocean is influenced by the volume of discharge through the estuary mouth (Ranasinghe and Pattiaratchi, 1999; Behrens, 2012; McSweeney et al., 2016). This is illustrated by comparing the rainfall (and thus implicitly discharge) for Stokes Inlet (whose catchment received greater rainfall than those of Hamersley and Culham inlets) with those previously recorded between 1968 and 1988 for Broke Inlet, ~450 km further west along the southern coast of Western Australia. The latter seasonally-open estuary lies in a region of far higher rainfall (i.e. mean annual rainfall in 1968-1988 was 1,275 mm in Broke Inlet vs 539 mm in Stokes Inlet; Bureau of Meteorology, 2017), thus leading to greater fluvial discharge and accumulation of water in its basin (Hodgkin and Hesp, 1998). In those 21 years, the Stokes, Hamersley and Culham inlets became open in six, five and zero years, respectively, compared with as many as 19 years with Broke Inlet (Hodgkin and Clark, 1989a,b, 1990). Moreover, the estuary mouth was open, on average, for four weeks in Stokes Inlet, with a range of only four to six weeks, compared with an average of 16 weeks, with a maximum duration of 26 weeks in Broke Inlet (Hodgkin and Clarke, 1989a,b). Although the length of time the mouths of Hamersley and Culham inlets were open has not been recorded, anecdotal reports indicate that this typically lasts for only “a few weeks” (Hodgkin and Clark, 1990).

4.2. Comparisons between salinity and oxygen regimes in the three estuaries

4.2.1. Salinity trends

The presence of mean salinities of 30 in the basin of Stokes Inlet, at the commencement of seasonal sampling in summer 2002, was due to the release of very substantial volumes of estuarine water through the breaching of the bar and their subsequent replacement largely with tidal waters from the ocean and fluvial discharge from its tributaries. This was facilitated by the mouth of this estuary remaining open for an atypically protracted period from June 1999 to April 2000, as opposed to a typical duration of about four weeks (Hodgkin and Clark, 1989b). A mean salinity of 35 in Hamersley Inlet in summer 2002 is consistent with the bar at the mouth of this estuary having been severely breached in January 2000, as a result of heavy cyclonic rainfall in that month. Although the bar of Culham Inlet was also breached in January 2000, the wide and particularly shallow basin of this estuary makes it especially susceptible to loss of water through evaporation, which accounts for it having already become hypersaline, i.e. 52, by summer 2002.

Although mean salinities in the basin of Stokes, Hamersley and Culham inlets ranged only from 30 to 52 in summer 2002, the extents of their subsequent increases varied markedly over the next three relatively dry years, during which each of these systems remained closed. Thus, while mean salinity reached a maximum of 64 in Stokes Inlet, it rose to as high as 143 in Hamersley Inlet and 293 in Culham Inlet. Indeed, the highest individual measurement of 313 at a site in Culham Inlet even exceeds the 295 recorded in the Laguna Tamaulipas, a very shallow lagoon in northern Mexico (Copeland, 1967; Tunnell and Judd, 2002), and it is thus apparently the highest salinity yet recorded for an estuary anywhere in the world. Although the maximum mean salinity of 143 in Hamersley Inlet was high, salinities of 150 have been recorded in estuaries such as the Coorong in South Australia and Lake St Lucia in South Africa (Whitfield et al., 2006; Dittmann et al., 2015) and as high as 223 in the Groen Estuary in an arid zone of South Africa (Wooldridge et al., 2016).

The remarkable and far higher salinities attained in the basins of Culham Inlet and, to a lesser extent, Hamersley Inlet than in the basin of Stokes Inlet can be attributed, at least in part, to a particularly high evaporative loss of water in Culham Inlet during warm, dry periods. Indeed the estimated 1,490 mm of surface evaporation from Culham Inlet accounts for as much as 85% of the total annual pan evaporation of 1,754 mm measured in the nearby town of Esperance, which is considered representative of this region (Black and Rosher, 1980; Hodgkin, 1997). This evaporative loss far exceeds the annual rainfall of 445 mm in the catchment of Culham Inlet. The greater loss of water through evaporation in the wide basin of

Culham Inlet is a consequence of a larger surface area to volume ratio, which reflects its shallowness. Indeed, the upwards progression in maximum salinity attained from Stokes Inlet to Hamersley Inlet to Culham Inlet mirrors a decline in maximum depth, i.e. 4, 1.3 and 1 m, respectively (Hodgkin and Clark, 1989b, 1990).

The exceptionally high salinities produced in Culham Inlet, during its protracted closure, by very high rates of evaporation and low fluvial discharge closely parallels that which occurs in the Laguna Tamaulipas. This lagoon is thus likewise very shallow, i.e. typically < 1 m deep, closed from the ocean for periods and in an area where evaporation greatly exceeds rainfall, but differs from Culham Inlet in that it does not receive discharge from a river (Hildebrand, 1980; TDWR, 1983; Tunnell and Judd, 2002).

Although differences in evaporative loss in the basins of the three estuaries contributed to the markedly different increases in salinity in those systems, other factors also played a role in producing these variations. For example, as total annual flow relative to the size of estuary basin decreased progressively from Stokes Inlet to Hamersley Inlet to Culham Inlet, the amount of reduced salinity water entering the basins via fluvial discharge was relatively greater in Stokes Inlet than in Hamersley Inlet, which, in turn, was greater than in Culham Inlet.

4.2.2. Inverse relationship between oxygen concentrations and salinity

In contrast to the trends exhibited by salinity and dissolved oxygen concentration in the basins declined least in Stokes Inlet and most in Culham Inlet. This is due largely to the solubility of oxygen decreasing with increases in the amount of dissolved solids, in this case NaCl (Weiss, 1970; Sherwood et al., 1991). For example, in a laboratory study undertaken at 25 °C, oxygen concentrations at saturation decreased from ~8 mg L^{-1} at a salinity of 0, to ~4.5 mg L^{-1} and only ~2.5 mg L^{-1} at salinities of 100 and 200, respectively (MacArthur, 1915). Decreases in the solubility of oxygen with increasing salinity thus largely accounts for mean dissolved oxygen concentrations remaining > ~5 mg L^{-1} in Stokes Inlet at all salinities (30-64), but declining to ~2.5 mg L^{-1} at a salinity of 143 in Hamersley Inlet and ~0.7 mg L^{-1} at a salinity of 293 in Culham Inlet. The ability to track, through seasonal measurements over three years, the marked increases in salinity and declines in oxygen concentration in the basin of each estuary provided field data that statistically confirmed that these two variables were strongly and inversely related under natural conditions.

As in their basins, mean salinities in the main tributaries of Stokes Inlet (29) and Culham Inlet (38) were both close to that of full strength seawater in summer 2002 and subsequently diverged markedly, attaining maxima of 59 and 207, respectively. It is thus highly relevant that average rainfall between 2002 and 2004 was greater in the catchment of Stokes Inlet (523 mm) than Culham Inlet (365 mm). This accounts for mean annual discharges being 3-4 times greater in the tributaries of Stokes Inlet than Culham Inlet (Pen, 1999; Brearley, 2005). As with the basins, dissolved oxygen concentrations declined more markedly in the main river of Culham Inlet than in that of Stokes Inlet after autumn 2003, due to salinities rising to a greater extent in the river of the former estuary. This accounts for the strong inverse relationship between oxygen concentration and salinity in the river of Culham Inlet.

4.3. Implications

The comparisons of bar breaching and the salinity and oxygen regimes of three normally-closed estuaries in the same region emphasise that differences in catchment rainfall, fluvial discharge, size and depth of basin and resilience of the bar among estuaries of this type can result in marked difference in the frequency and timing of bar breaching. These differences, in turn, influence the extent to which the waters of these systems become hypersaline and hypoxic. When the increase in salinity and decline in oxygen are particularly pronounced, the faunas of these systems become increasingly stressed and thus lead to massive mortalities of susceptible species (Hoeksema et al., 2006). The development of these extreme conditions result in a progressive reduction in the number of species and abundance of fishes in normally-closed estuaries, as demonstrated by Young and Potter (2002) for the Wellstead Estuary, which is located to the east of the three estuaries that constituted the basis for the current study. Likewise, data for the highly modified Lake St Lucia in South Africa and a lagoon (Laguna Tamaulipas) in Mexico demonstrate that the number of fish species was inversely related to salinity and that the individuals of very few species survived beyond 120 (Copeland, 1967; Whitfield et al., 2006). The very different extents to which salinity increased and oxygen declined in the Stokes, Hamersley and Culham inlets during a protracted period of closure is being used to elucidate the ‘tolerance’ of the various species to extreme changes in the abiotic environment in these estuaries and thus the resilience of fish communities in normally-closed estuaries in general.

While rainfall in the westward parts of south-western Australia has decreased by 25% over the last ~100 years (Hughes, 2003; Hope et al., 2015), it did not decline in the catchments of the Stokes, Hamersley and Culham inlets in the years between 1972 and 2016. Climate models predict, however, that winter rainfall in these catchments will decline in the future due to a southwards shift in winter storms (Andrys et al., 2017; Hallett et al., 2017). As the bar at the mouth of Stokes Inlet is typically breached when winter rainfall is particularly heavy, such changes would be likely to reduce the frequency with which the mouth of that estuary becomes open to the ocean. This could lead to increases in salinity and declines in oxygen concentrations in this estuary during increasingly protracted periods of closure. Winter declines in rainfall would be less likely, however, to reduce the frequency of breaching in Hamersley and Culham inlets, since winter rainfall in the catchment of these systems is lower than that of Stokes Inlet and breaching typically occurs in summer or autumn following atypically heavy, unseasonal rainfall, often associated with cyclonic activity. As some climate models predict an increase in summer rainfall and others a reduction in the region of Hamersley and Culham inlets (Andrys et al., 2017), it is not possible to predict whether the frequency of bar breaching in these systems will change in the future.

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Figure legends

Fig. 1. Maps showing a) location of permanently-open, seasonally-open, intermittently-open and normally-closed estuaries in the south-western Australian drainage division (grey shading), with the location of that drainage division in Australia shown in inset. Permanently-closed refers to systems that no longer open to the sea. b) Areas of cleared (light grey) and uncleared native vegetation (dark grey) in the catchments of Stokes, Hamersley and Culham inlets and morphology of the basin and rivers of c) Stokes, d) Hamersley and e) Culham inlets, including location of upstream pools in the latter two estuaries.

Fig. 2. Photographs of Culham Inlet showing a) estuary full of water in 2013 and bar intact, b) bar breached with large outflow of water in 2017, c) estuary basin virtually dry in 2004 and d) salt precipitation on dry estuary bed. Photographs of Hamersley Inlet showing discontinuity between e) waters of estuary basin and mouth of river and f) waters in upstream pools in the river. Photograph 2d taken by Paul Cory.

Fig. 3. Annual rainfall in catchments of a) Stokes, c) Hamersley and d) Culham inlets between 1972 and 2016 and b) annual discharge in the Young River of Stokes Inlet in the 38 of those years for which there were reliable data. Years in which the bar at the mouth of an estuary was breached are shown in white and the year (2000 in Stokes Inlet) in which the mouth continued to remain open after the previous year is shown as stripes. *, annual discharge not available. Relationship between annual rainfall and year in Culham Inlet, which was significant, is shown as dashed line (for details see results).

Fig. 4. a) Mean monthly rainfall ±1 SE at a station in each of the catchments of Stokes, Hamersley and Culham inlets between 1972 and 2016. b) Shade plot showing monthly rainfall in the same catchments in each year between 1972 and 2016. Rectangular boxes denote years of bar breaching; X, month of natural bar breaching; A, month of artificial bar breaching; intensity of shading, monthly rainfall.

Fig. 5. Mean seasonal salinities (Sal), dissolved oxygen concentrations (DO) and water temperatures in nearshore, shallow (S) and offshore, deeper (B) waters of basin and estuarine reaches of the Young River of Stokes Inlet between summer 2002 and spring 2004. In this Fig. and Figs 6-8, SE are presented for a mean, when based on three or more values, and as either + or - 1SE when SEs for two means overlap.

Fig. 6. Mean seasonal salinities (Sal), dissolved oxygen concentrations (DO) and water temperatures in nearshore, shallow waters of the basin of Hamersley Inlet between summer 2002 and spring 2004 and in the estuarine reaches of the Hamersley River and upstream pool in those seasons when those regions could be sampled. In each season, the means for each variable at the surface and bottom of the water column at each offshore site and corresponding nearshore site were essentially the same.

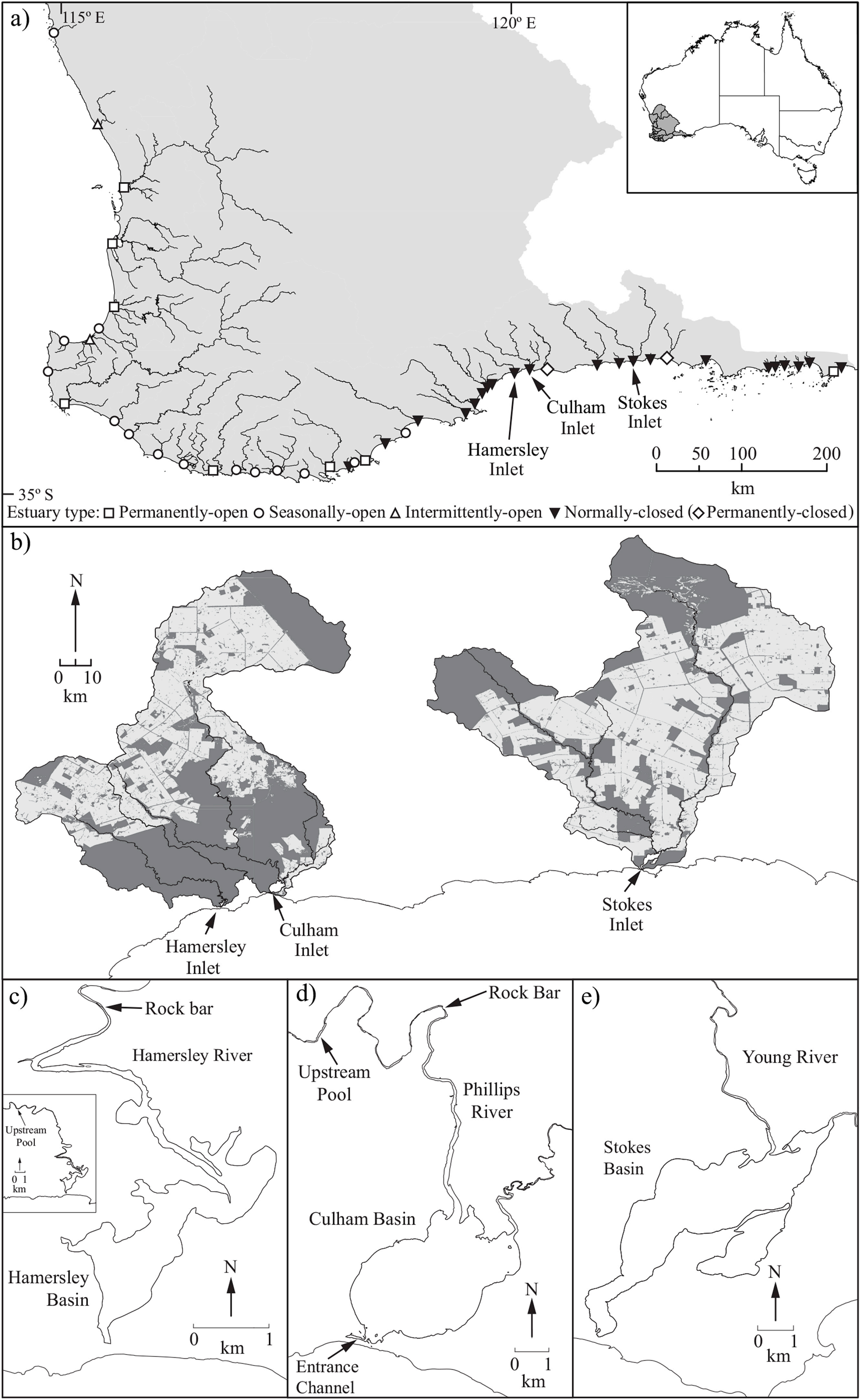
Fig. 7. Mean seasonal salinities (Sal), dissolved oxygen concentrations (DO) and water temperatures in nearshore, shallow (S) waters of the basin, estuarine reaches of the Phillips River, entrance channel and upstream pool of Culham Inlet and of offshore, deeper (B) waters of the Phillips River and entrance channel between summer 2002 and spring 2004.

Fig. 8. Comparisons of mean seasonal salinities (Sal) and dissolved oxygen concentrations (DO) in the basins of Stokes, Hamersley and Culham inlets and in the estuarine reaches of the main river of Stokes and Culham inlets between summer 2002 and spring 2004.

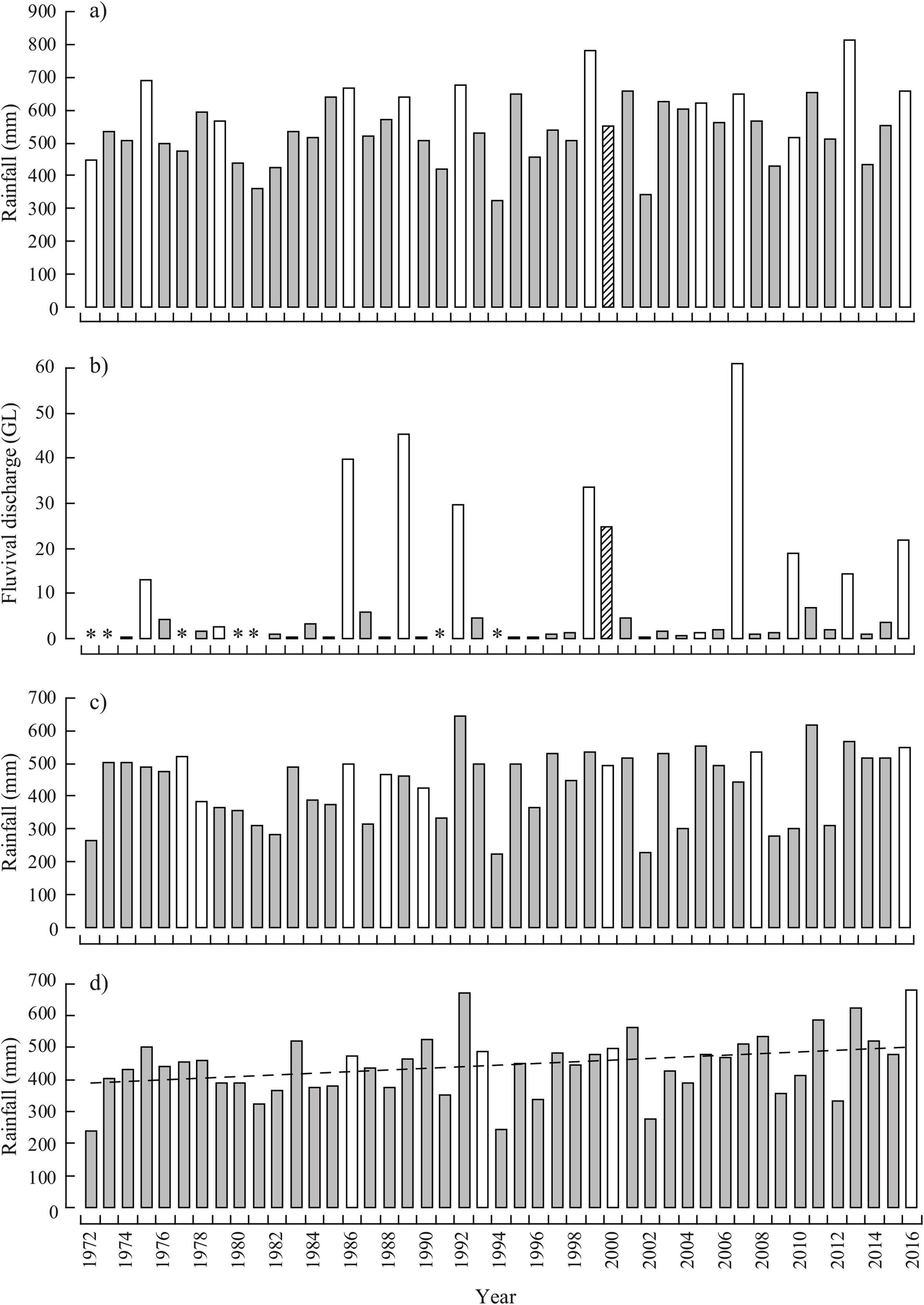
Table. 1. Characteristics of the Stokes, Hamersley and Culham inlets and their catchments.

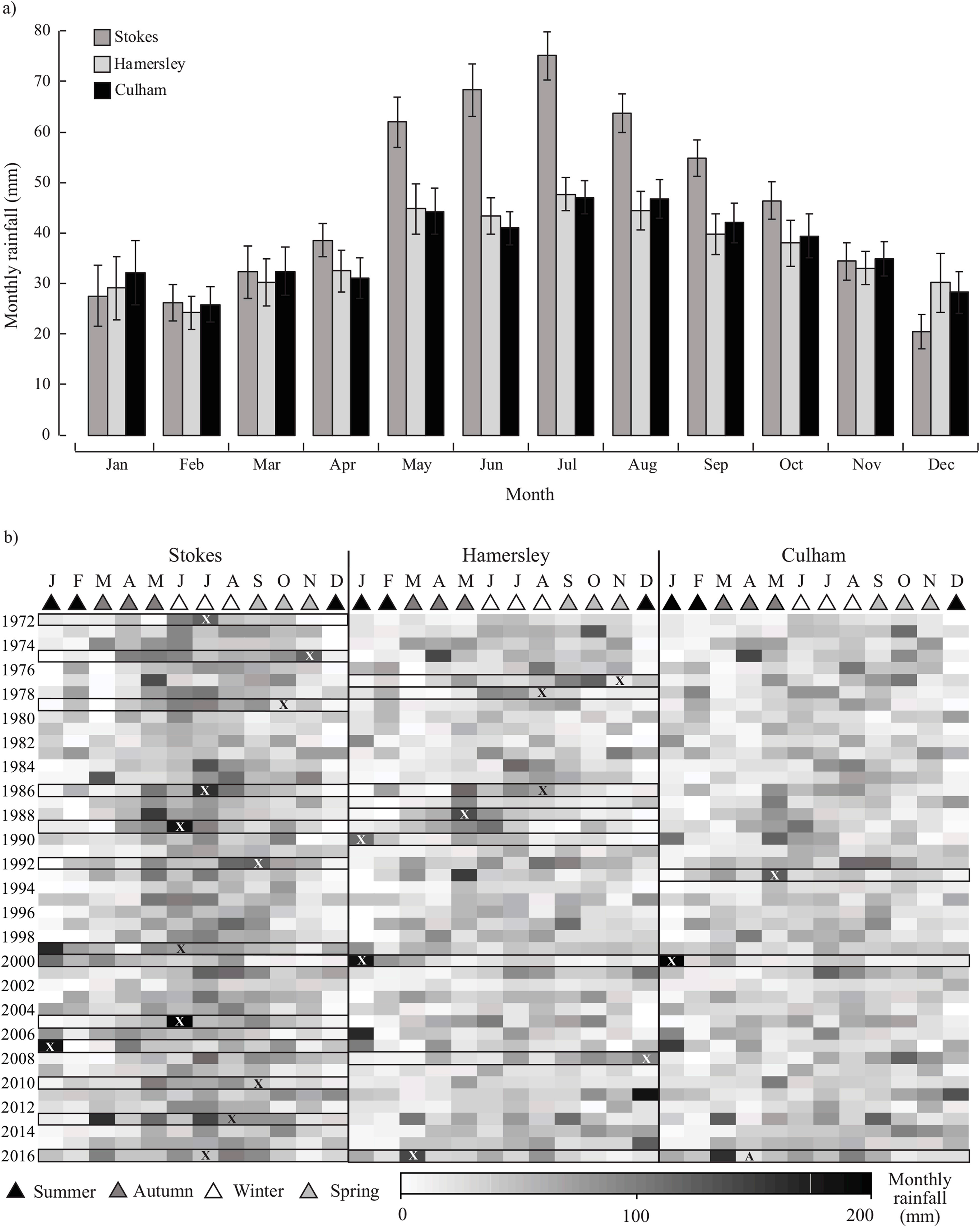
	Stokes Inlet	Hamersley Inlet	Culham Inlet
Basin area (km^2)[a]	14	2	11
Max. depth of basin (m)[a]	4.0	1.3	1.0
Height of bar (m)[a]	1.5-2	2	3-5
Catchment area (km^2)[b]	5,300	1,268	3,780
Mean annual rainfall (mm)[c]	550	438	445
Median annual rainfall (mm)[c]	540	475	452
Clearing (%)[b]	68	37	50
Discharge (GL)[d]	11.88	1.16	3.40
Discharge/basin area	849	580	309

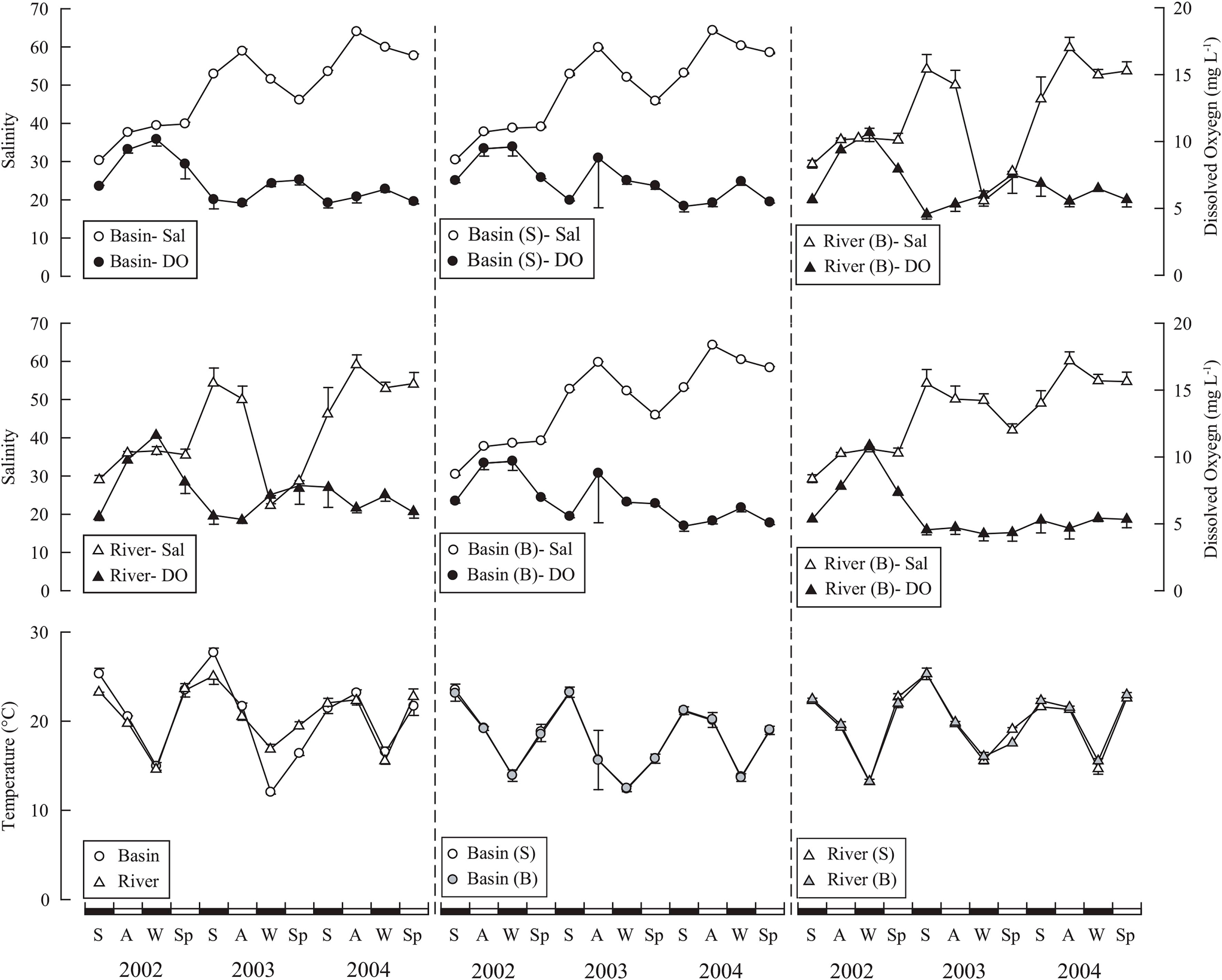
[a] = Hodgkin and Clark (1989a, 1990); [b] = West Australian Department of Environment and Conservation (unpub. data); [c] = Bureau of Meteorology (2017); [d] = Pen (1999), Brearley (2005).

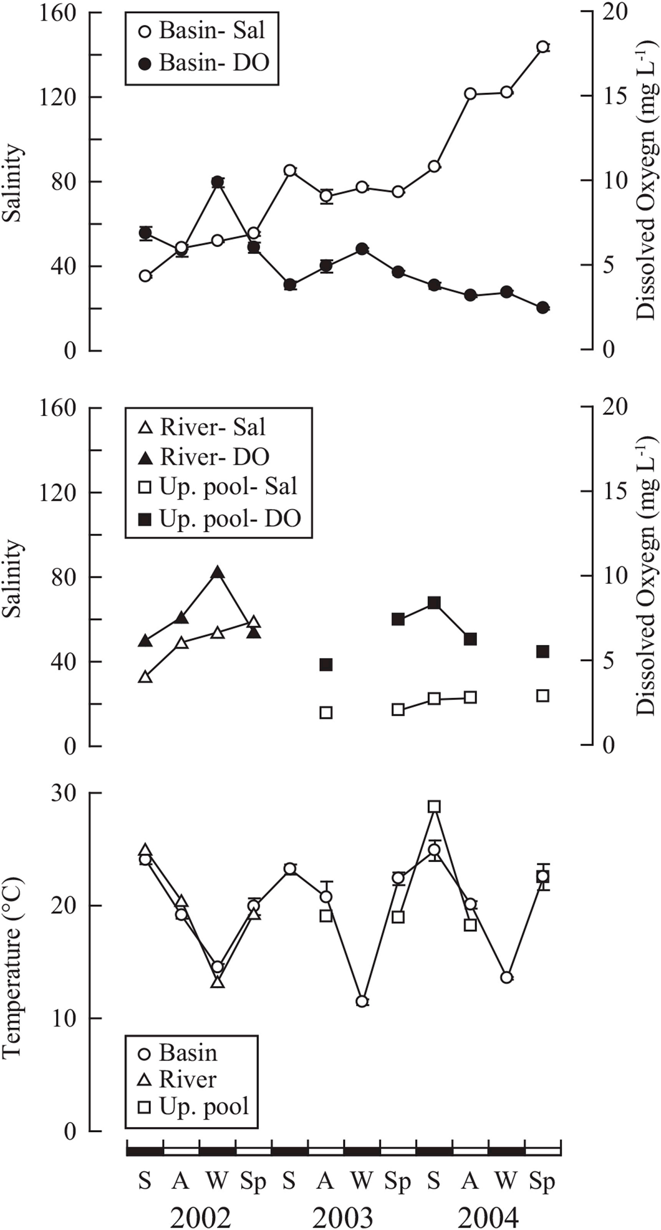

a)
115º E
120º E
Culham Inlet
Stokes Inlet
Hamersley Inlet
0 50 100 200
km
35º S
Estuary type: □ Permanently-open ○ Seasonally-open △ Intermittently-open ▼ Normally-closed (◇ Permanently-closed)
b)
N
0 10
km
Hamersley Inlet
Culham Inlet
Stokes Inlet
c)
Rock bar
Hamersley River
Upstream Pool
0 1
km
Hamersley Basin
N
0 km 1
d)
Rock Bar
Upstream Pool
Phillips River
Culham Basin
N
Entrance Channel
0 1
km
e)
Young River
Stokes Basin
N
0 1
km

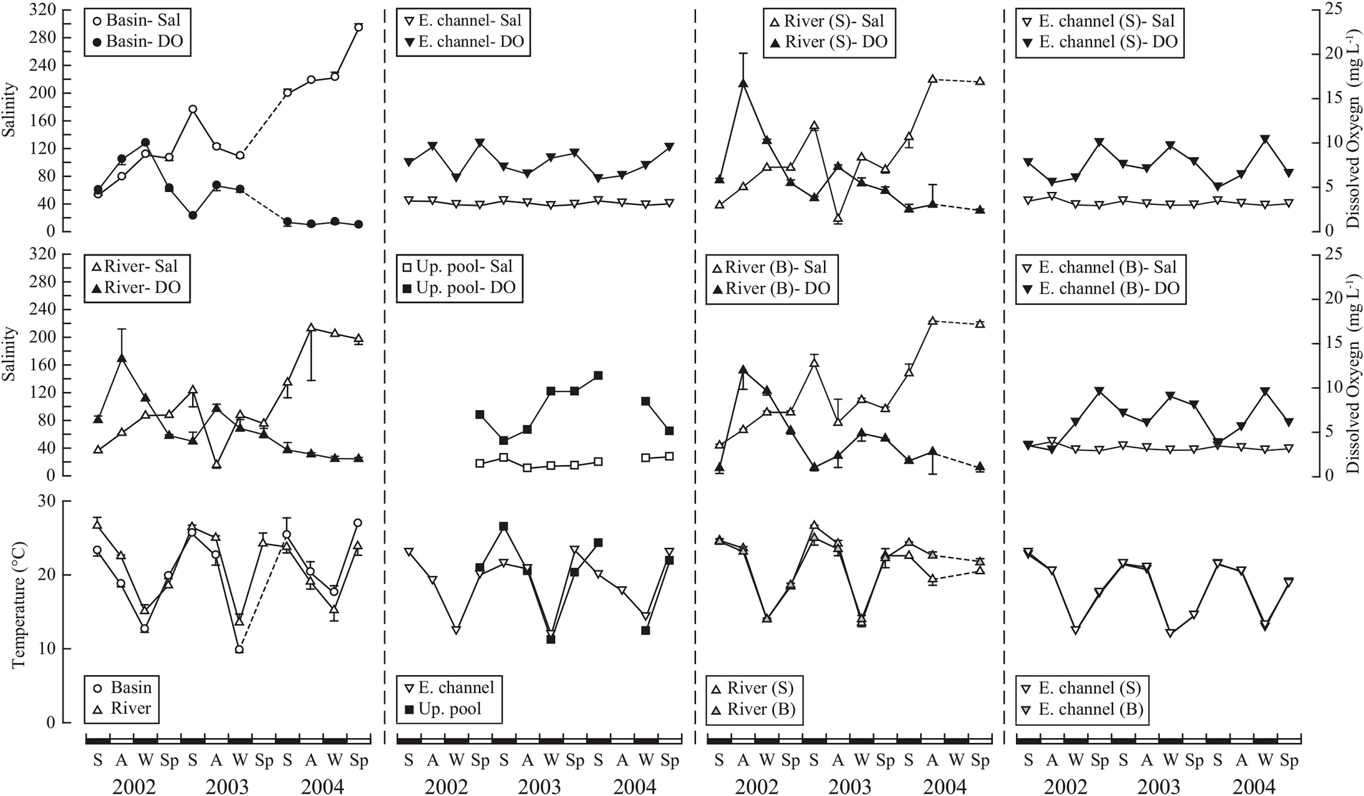

a)
b)
c)
d)
e)
f)

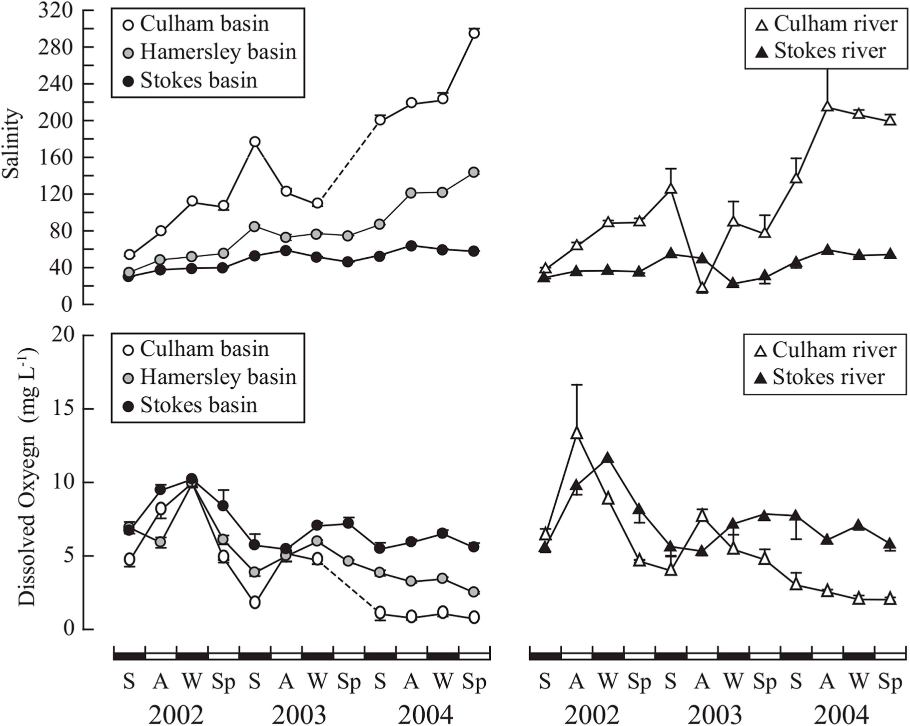

a)
Rainfall (mm)
0
100
200
300
400
500
600
700
800
900
b)
Fluvival discharge (GL)
0
10
20
30
40
50
60
* *
*
* *
*
*
c)
Rainfall (mm)
0
100
200
300
400
500
600
700
d)
Rainfall (mm)
0
100
200
300
400
500
600
700
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Year


a)
Stokes
Hamersley
Culham
Monthly rainfall (mm)
0
10
20
30
40
50
60
70
80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
b)
Stokes
Hamersley
Culham
J F M A M J J A S O N D
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
X
A
Summer
Autumn
Winter
Spring
0
100
200
Monthly rainfall (mm)


Salinity
Dissolved Oxyegn (mg L-1)
Temperature (°C)
○ Basin- Sal
● Basin- DO
○ Basin (S)- Sal
● Basin (S)- DO
△ River (B)- Sal
▲ River (B)- DO
△ River- Sal
▲ River- DO
○ Basin (B)- Sal
● Basin (B)- DO
△ River (B)- Sal
▲ River (B)- DO
○ Basin
△ River
○ Basin (S)
● Basin (B)
△ River (S)
▲ River (B)
0 10 20 30 40 50 60 70
0 5 10 15 20
0 10 20 30
S A W Sp S A W Sp S A W Sp
2002 2003 2004


Basin- Sal
Basin- DO
Salinity
Dissolved Oxyegn (mg L^{-1})
0
40
80
120
160
0
5
10
15
20
River- Sal
River- DO
Up. pool- Sal
Up. pool- DO
Salinity
Dissolved Oxyegn (mg L^{-1})
0
40
80
120
160
0
5
10
15
20
Temperature (°C)
0
10
20
30
Basin
River
Up. pool
S
A
W
Sp
S
A
W
Sp
S
A
W
Sp
2002
2003
2004


Salinity
Dissolved Oxyegn (mg L⁻¹)
Temperature (°C)
320
280
240
200
160
120
80
40
0
25
20
15
10
5
30
Basin- Sal
Basin- DO
E. channel- Sal
E. channel- DO
River (S)- Sal
River (S)- DO
E. channel (S)- Sal
E. channel (S)- DO
River- Sal
River- DO
Up. pool- Sal
Up. pool- DO
River (B)- Sal
River (B)- DO
E. channel (B)- Sal
E. channel (B)- DO
Basin
River
E. channel
Up. pool
River (S)
River (B)
E. channel (S)
E. channel (B)
S
A
W
Sp
2002
2003
2004



Salinity
0
40
80
120
160
200
240
280
320
○ Culham basin
● Hamersley basin
● Stokes basin
△ Culham river
▲ Stokes river
Dissolved Oxyegn (mg L-1)
0
5
10
15
20
○ Culham basin
● Hamersley basin
● Stokes basin
△ Culham river
▲ Stokes river
S
A
W
Sp
S
A
W
Sp
S
A
W
Sp
2002
2003
2004
S
A
W
Sp
S
A
W
Sp
S
A
W
Sp
2002
2003
2004

Highlights

1. Bars of 3 estuaries breach after exceptional winter or cyclonic summer rainfall
2. Breaching frequency differed among estuaries but all remained closed in 2002-2004
3. During closure of these estuaries for >3 years, salinities rose to 64, 143 and 293
4. Oxygen concentrations declined markedly and inversely to salinity (r = 0.7 to 0.8)
5. Bar state, catchment features and discharge influence estuarine characteristics