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Climate change overtakes coastal engineering as the dominant driver of hydrologic change in a large shallow lagoon

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Abstract. Ecosystems in shallow, micro-tidal lagoons are particularly sensitive to hydrologic changes. Lagoons are also highly complex transitional ecosystems between land and sea, and the signals of direct human disturbance to the lagoon can be confounded by variability of the climate system, but from an effective estuary management perspective the effects of climate versus direct human engineering interventions need to be identified separately. Although many estuarine lagoons have undergone substantial human interventions, such as artificial channels, the effects from the interaction of climate change with engineering interventions have not been well evaluated. This study developed a 3D finite-volume hydrodynamic model to assess changes in hydrodynamics of the Peel-Harvey Estuary, a large chocked-type lagoon, considering how attributes such as water retention time, salinity and stratification have responded to a range of factors, focusing on the drying climate trend and the opening of a large artificial channel over the period from 1970 to 2016, and how they will evolve under current climate projections. The results show that the drying climate has fundamentally changed the hydrology by comparable magnitudes to that of the opening of the artificial channel, and also highlight the complexity of their interacting impacts. Firstly, the artificial channel successfully improved the estuary flushing by reducing average water ages by 20-110 days; while in contrast the reduced precipitation and catchment inflow had a gradual opposite effect on the water ages, and during the wet season this has almost counteracted the reduction brought about by the channel. Secondly, the drying climate caused an increase in the salinity of the lagoon by 10-30 PSU; whilst the artificial channel increased the salinity during the wet season, it has reduced the likelihood of hypersalinity (>40 PSU) during the dry season in some areas. The impacts also varied spatially in this large lagoon. The southern estuary, which has the least connection with ocean through the natural channel, is the most sensitive to climate change and the opening of the artificial channel. The projected future drying climate is shown to slightly increase the retention time and salinity in the lagoon, and increase the hypersalinity risk in the rivers. The significance of these changes for nutrient retention and estuary ecology are discussed, highlighting the importance of these factors when setting up monitoring programs, environmental flow strategies and nutrient load reduction targets.

1 Introduction

Hydrologic features such as water circulation and retention, and the pattern of saline water intrusion, are critical in shaping estuarine ecosystems. The interactions between freshwater runoff pulses with ocean water can create complex hydrodynamics that subsequently structures coastal biogeochemical processes, including the distribution of sediment and nutrients, and areas favourable for primary productivity (e.g. Cloern et al., 2017; Kasai et al., 2010; Legović et al., 1994; Watanabe et al., 2014). Whilst nutrient loads are the primary determinant affecting the long-term trophic state of coastal waters (Howarth and Marino, 2006; Williamson et al., 2017), the time-scales associated with water retention and mixing are critical in mediating the relationship between nutrient inputs and the ensuing water quality response, including the likelihood of nuisance algal blooms or hypoxia (e.g. Ferreira et al., 2005; Knoppers et al., 1991; Paerl et al., 2006; Zhu et al., 2017). The retention of water and hydrodynamic patterns that emerge in any given site are largely dependent upon local geomorphological features, though increasingly coastal engineering and changes in river hydrology disturb natural patterns of water exchange (Almroth-Rosell et al., 2016; Dufour et al., 2001; Gong et al., 2008; Kjerfve et al., 1996; Knoppers et al., 1991; Odebrecht et al., 2015) . Understanding and predicting these hydrologic changes is critical to underpin adaptive approaches to estuary water quality management and ecological restoration.

Coastal lagoons and embayments with low rates of ocean exchange are particularly sensitive relative to other estuary forms. The typical low flushing rates leads to high rates of deposition of sediment and particulate matter, and accumulation of nutrients (e.g. Newton et al., 2014, 2018; Paerl et al., 2014). They are also productive ecosystems and often experience conflicting interests between the ecosystem services they provide and the pressures from urban development and agricultural expansion (Basset et al., 2013; Newton et al., 2014; Pérez-Ruzafa et al., 2011; Petersen et al., 2008; Zaldívar et al., 2008). In most cases, salt intrusion mediates lagoon salinity and drives a difference between the surface and bottom salinity (salinity stratification). In highly seasonal systems this effect leads to notable oxygen depletion and establishes hypoxia in the bottom boundary layer (Bruce et al., 2014; Cottingham et al., 2014; Huang et al., 2018). In Mediterranean climate regions, further concerns of hypersalinity through evaporation during the long dry summer and autumn months also exist (Potter et al., 2010). As a result, the hydrodynamics of coastal lagoons are frequently modified through the creation of artificial channels built to enhance hydrologic connectivity to the ocean, and increase nutrient export (e.g. Breardley 2005; Manda et al., 2014; Prestrelo and Monteiro-Neto, 2016), or indirectly by engineering projects associated with dredging and coastal management (e.g. Ghezzo et al., 2010; Sahu et al., 2014).

Changes in lagoon hydrology result from variability in river flows, and meteorological and ocean conditions, alongside (sporadic) human interventions associated with coastal engineering developments. Tracking these long-term changes remains an ongoing challenge since the signals of human disturbance are often confounded by variability of the climate system and lost in the dynamic estuarine conditions (Cloern et al., 2016; Feyrer et al., 2015). Although the impacts of climate change on estuarine hydrology have been shown to significantly affect the water quantity and quality of many estuaries (e.g. Ducharne et al., 2007; Liu and Chan, 2016; Lloret et al., 2008; Whitehead et al., 2009), the interacting effects of introducing human interventions in conjunction with climate change trends are not necessarily easy to predict. For example, the opening of an artificial channel and a drying climate can both introduce more ocean water into an estuary. On the other hand, the drying climate enhances water residence time, which may cancel out flushing benefits from the artificial channel. The combined effects are further complicated in large lagoon-type estuaries with complex morphology, where complicated patterns of water retention and stratification can develop (e.g. Ferrarin et al., 2013). From a lagoon management perspective, it is necessary to attribute the impacts from climate and human activity factors to better plan the necessary estuary and catchment management activities, including adaptation strategies for associated with nutrient load targets and, in some cases, environmental water provision.

Here we explore these ideas through reconstruction of the long-term hydrologic evolution of a large estuarine lagoon in Western Australia: the Peel-Harvey Estuary (PHE). The PHE system has been subject to both a notable drying climate trend and substantial coastal modification in the form of an opening of a large artificial channel, coastal development and dredging. The artificial channel, termed the "Dawesville Cut" (hereafter referred as "the Cut"), was built in 1994 with the purpose of increasing the flushing of the lagoons and reducing nutrient concentrations. In parallel, the impact on inland water resources of recent climate trends has been particularly acute in the PHE catchment, which was acknowledged by the IPCC AR4 identifying this region as one that has experienced amongst the greatest impact on divertible water resources in the world

(Bates et al., 2008; Izrael et al., 2007). From the 1970s, rainfall has decreased by 16% and stream flows have declined by more than 50%, a trend which has appeared to accelerate since the 2000s (Silberstein et al., 2012). Whilst the nutrient and phytoplankton concentrations have been successfully reduced by the construction of the channel (Brearley, 2005), the long-term river flows have shown a clear trend of decreasing inputs to the estuary with concerns for the conditions of the tidal riverine portions of the system (Gillanders et al., 2011; Hallett et al., 2018). A series of water quality improvement plans (e.g. Environmental Protection Authority, 2008; Rogers et al., 2010) continue to be developed to promote estuary health, however, ongoing concerns about the current and future water quality and ecologic condition of the system (Valesini et al., 2019) requires knowledge of spatiotemporal changes in water retention, stratification and salinisation to support adaptation efforts.

It is therefore the aim of this study to develop a methodology to disentangle drivers of change of the PHE system, over the period from 1970 to 2016, and outline the expected future trajectory of lagoon conditions. To this end we employ a 3-dimentional finite-volume hydrodynamic model for analysis of environmental drivers on estuarine hydrology by comparing current and counter-factual modelling scenarios to enable attribution of the drivers of change. To enable the long-term reconstruction of the model simulations for periods before the instrument record, and for future conditions, we drive the model with a hybrid set of weather and hydrological boundary condition data from observations and supporting models. The results of simulations are presented to analyse the sensitivity of water retention time, salinity and stratification within the lagoon to selected factors. By untangling the effect of the drying climate versus the Cut opening, through time and space, we explore the results through the lens of nutrient load reduction targets and biodiversity management implications. We anticipate the approach adopted here can be useful to assist in the climate change adaptation efforts for other estuarine lagoons in mid-latitude regions.

2 Methods

2.1 Site description

PHE is a large shallow coastal estuary-lagoon system located approximately 75 km south of Perth in Western Australia (Figure 1), which is listed under the Ramsar convention for wetlands of international significance. The estuary has a complex morphometry and comprises two shallow lagoons, one is the Peel Inlet, a circular inlet to the north, and the other the Harvey estuary, an oblong lagoon attached to the Peel Inlet at its north-eastern edge, with a combined area of approximately 133 km^2. The estuary experiences a micro-tidal regime (tidal range < 1 m) and connects to the ocean via two channels: 1) the Mandurah Channel, a natural but narrow 5 km long channel with water depths varying between 2 m and 5 m; and 2) the Cut, an artificial channel of about 2.5 km long, 200 m wide and between 6 and 6.5 m deep, built in 1994 (Bicknell, 2006; Environmental Protection Authority, 2008). The coastal catchment of the estuary is drained by three major river systems: the Serpentine, Murray and Harvey Rivers (Figure 1), and numerous minor drains. The riverine portions depicted are tidal and experience marine water intrusion for extended periods throughout the year. The system experiences a Mediterranean-type climate characterised by a strong seasonal pattern of cool wet winters and hot dry summers, with almost all of the annual rainfall occurring during the cooler months of May to October (Finlayson and McMahon, 1988; Gentilli, 1971).

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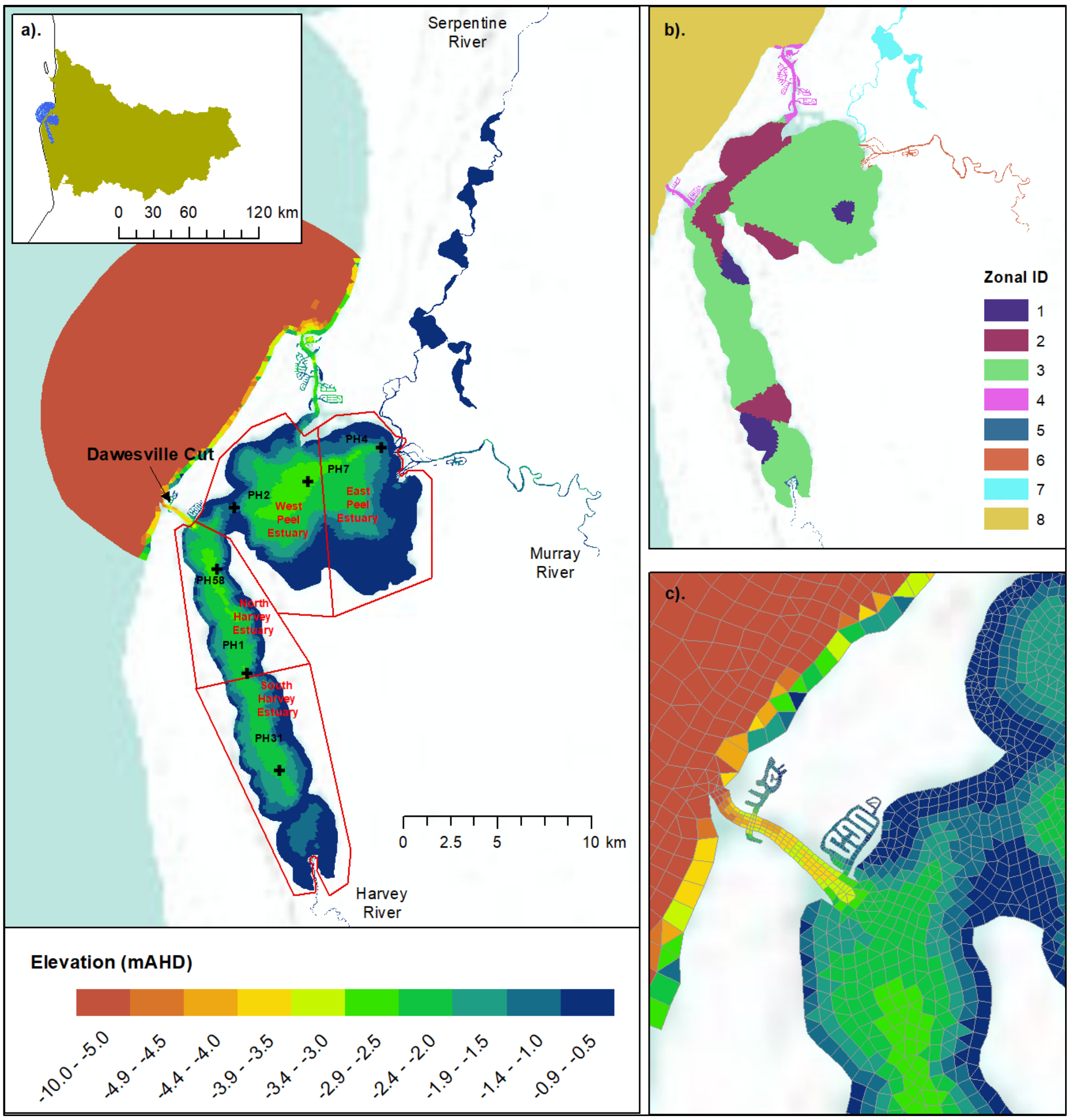

Figure 1. (a) Model domain of the Peel-Harvey Estuary and three main rivers: Serpentine River, Murray River, and Harvey River, the tidal portion of each is depicted up to the gauge location. The colours indicate the water depths of the study domain; the black crosses within the estuary indicate the 6 monitoring sites, and the red polygons indicate the areas for result analysis. b) Zonal categorization of the model domain according to the area and aquatic vegetation biomass (see Table 1), and c) a zoom-in view of the artificial channel Dawesville Cut, constructed in 1994 to improve ocean flushing.

2.2 Modelling Approach

2.2.1 Hydrodynamic model and numerical methods

The TUFLOW-FV (BMT WBM, 2013) hydrodynamic model was adopted, using a flexible-mesh (finite volume) approach to resolve the variations in water level, horizontal salinity distribution and vertical density stratification in response to tides,

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inflows and surface thermodynamics. The mesh consists of triangular and quadrilateral elements of different size that are suited to simulating areas of complex estuarine morphometry. To meet accuracy requirements, fine-grid resolution (mean mesh area ~12000 m^2) was used within the lagoons and coarse resolution was implemented towards the ocean boundary. The vertical mesh discretization adopted a hybrid sigma-z coordinate allowing multiple surface Lagrangian layers to respond to tidal elevation changes. The layer thickness was 0.2 m at depths of 1.0 – 5.0 m that gradually increased to 0.5 m in deeper water and then five uniformly-distributed sigma layers were then added above the fixed-thickness layers. The finite volume numerical scheme solves the conservative integral form of the nonlinear shallow water equations in addition to the advection and transport of scalar constituents such as salinity and temperature. The equations are solved in 3D with baroclinic coupling from both salinity and temperature using the UNESCO equation of state (Fofonoff and Millard, 1983).

Surface momentum exchange and heat dynamics are solved internally within TUFLOW-FV. In the current application, turbulent mixing of momentum and scalars has been calculated using the Smagorinsky scheme in the horizontal plane and through coupling with the General Ocean Turbulence Model (GOTM) for vertical mixing with option of second-order k-ε turbulence closure. The bottom shear stress was calculated using a roughness-length relationship assuming a rough-turbulent logarithmic velocity profile in the lowest model layer. The roughness length, z_0, settings were based on the area type (e.g. coast, rivers, and estuary) and the estimated biomass of aquatic vegetation within the cell. For this purpose, the modelling bottom was categorized into eight zones (Figure 1b) where the benthic characteristics and associated z_0 in each zone were specified (Table 1). While the setting of z_0 affected the water advection and uncertainty remains in the spatial (and temporal) variability in the z_0, it is important to note that the modelled τ and salinity do not change fundamentally over a reasonable range of z_0, as shown in the results of the model sensitivity tests described later.

Table 1. Zonal characters and roughness length z_0 setting in the model domain.

Zonal ID	Areas	Aquatic Vegetation Biomass (g Dry Weight/m^2)	z_0
1	South/North Harvey Estuary, East Peel Inlet	100-230	0.03
2	South/North Harvey Estuary, West Peel Inlet	50-100	0.02
3	Harvey Estuary and Peel Inlet	0-50	0.01
4	Dawesville Cut	N/A	0.003
5	Harvey River	N/A	0.003
6	Murray River	N/A	0.003
7	Serpentine River	N/A	0.003
8	Coastal ocean	N/A	0.002

The water retention time was assessed with two hydrodynamic time parameters. The first was water age, which was defined as the time the water had spent since entering the estuary through boundaries (either the ocean or rivers). The water age, τ, was computed in each computational cell using the AED2 plugin to the hydrodynamic model, which simulated a conservative tracer subject to a constant increase with time (‘aging’) and mixing, using a method as described in (Li et al. 2019). This method therefore provided the temporal and spatial variation in water retention, $\tau = \tau(x, y, z, t)$. The second time parameter was the bulk flushing time, τ_f, which represents a bulk retention parameter that assumes a fully-mixed ‘lumped’ approach and describes the general exchange character of the estuary (Monsen et al., 2002). Following Sheldon and Alber (2006), the bulk flushing time was calculated as:

$$\tau_f = \frac{V}{Q_{FW} + R_o Q_{SW}}$$

where V is the estuary volume (=187.5 GL), Q_{FW} is the freshwater inflow rate, Q_{SW} is the average seawater flow rate over a tidal period, and R_o is the exchange fraction of the seawater fluxes that contributes to flushing. The values of Q_{FW} and Q_{SW} are derived from the hydrodynamic model outputs. The value of R_o is dependent upon the local coastal mixing features (Fischer et al., 1979; Rynne et al., 2016; Shi et al., 2019), and was set to 0.15 for Mandurah Channel and 0.12 for the Cut.

Multiple concepts of hydrodynamic time parameters (flushing time, residence time, water age, export time, etc.) have been used in coastal hydrology research and their comparison has been intensively discussed (e.g. Jouon et al., 2006; Monsen et al., 2002; Sheldon and Alber, 2006), noting that each of the parameters are different in their definition and application. Here, we used the time parameters to investigate how the bulk flushing time and the heterogeneity of the local water age changed in response to the climate induced changes and the opening of the Dawesville Cut.

2.2.2 Climate change context and simulation rationale

Historical observations of nearby precipitation and the gauged data of the major Murray River inflow have shown a decreasing trend from 1970 to the present (Figure 2), though variability from year to year is noticeable. The average annual precipitation has declined by 15% when comparing the period 1994-2016 relative to 1970-1993, and this led to a dramatic decrease of annual inflow volumes, most notable in the past decade.

Years with inflow rates close to the 10-year moving average were selected for hydrologic modelling simulations to explore in more detail the hydrologic changes occurring within these years (depicted relative to the trend in Figure 2b). Due to the concern that the drying climate will continue into the 21st century (Silberstein et al., 2012; Smith and Power, 2014), we also undertook model simulations to investigate potential hydrologic changes under future conditions representative of 2040 and 2060, by considering reduced streamflow and rising sea levels. The runoff declines were based on the mean projection by Smith and Power (2014) that suggested the total runoff to the rivers and estuaries within the WA region will drop by about 0.96% per year, corresponding to the projected reduction in precipitation of 0.27% per year, on average. Sea level rise was also included in the future scenarios, estimated from the long-term (1897 – 2000) tide gauge observations at the Fremantle tide gauge station that shows a sea level trend of 1.50 mm/yr (Kuhn et al., 2011). These estimates may be biased due to a possible accelerated sea level rise towards the end of the 21st century (IPCC, 2007; Kuhn et al., 2011), but we highlight these future scenarios were set up with a focus to investigate the changing hydrology into a future from the projected drying climate trend.

For the modelling years after 1994, when the artificial channel was constructed, we also ran "no-Cut" counter-factual scenarios, which assumed the Dawesville Cut engineering intervention was not constructed, in order to separate the impact of the artificial channel on hydrology relative to the "with-Cut" scenarios (Table 2).

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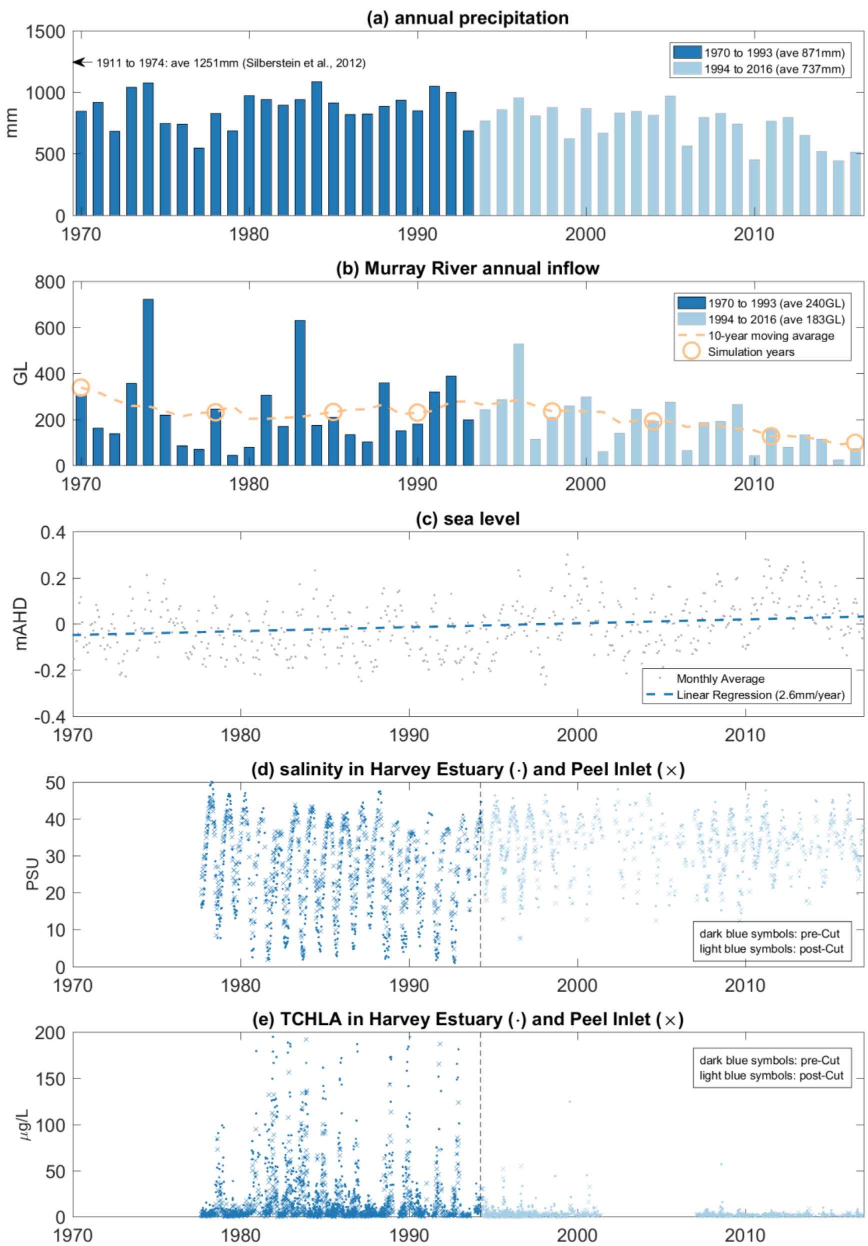

Figure 2. Historical record of (a) annual precipitation rate; (b) Murray River annual inflow rate; (c) monthly-average sea level at Fremantle gauge station; (d) salinity at Harvey Estuary and Peel Inlet; and (e) total chlorophyll-a (TCHLA) in Harvey Estuary and Peel Inlet since 1970 to 2016.

Gauged flow rate data for the Murray River, Serpentine River and Harvey River were applied to the hydrodynamic model whenever they are available. For the missing periods in the gauged flows and the ungauged drains, the output from the Source

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(eWater®) catchment modelling platform (Kelsey et al., 2011; Welsh et al., 2013), operated by the Western Australia Department of Water and Environmental Regulation, was used to estimate flows by carefully comparing the measured and modelled flow data. Groundwater inputs was previously estimated to represent only ~1% of total water inputs (Black and Rosher, 1980), and therefore was ignored from the modelling simulations.

Various data sources were used to set up meteorological inputs due to the study period spanning a long time back to 1970, when meteorological observations were not routinely available across the modelling domain at hourly frequencies. The first data source was the local Mandurah weather station located beside the natural channel of the estuary. This dataset provided hourly records since 2001. The hourly fields over the period 1981-2000 were obtained from regional climate model simulations for Southwest Australia at a 5 km resolution (Andrys et al., 2015; Kala et al., 2015). These simulations were carried out using the Weather Research and Forecasting (WRF), one of the most widely used regional climate models. Andrys et al. (2015) showed that the WRF model was able to adequately simulate the climate of SWA, and these simulations have also been used to assess the impacts of current and future climate on temperature and precipitation (Andrys et al., 2016, 2017) as well as climate indices relevant to viticulture for SWA (Firth et al., 2017). The WRF simulations of Andrys et al. (2015) have also been benchmarked against other regional climate model simulations across the Australian continent and shown to perform well in simulating both temperature and precipitation (Di Virgilio et al., 2019) as well as heat-wave events (Hirsch et al., 2019). For the years before 1981 the weather conditions measured at the nearby Halls Head weather station (4.2 km away from the Mandurah station) were used.

A summary of all historical simulations and future scenarios is provided in Table 2. The total inflow into the estuary of the chosen simulation years shows a general decrease from past to future, except for the year 1978 when the total inflow rate was less than that in 1985 and 1990. This was due to an exceptionally low inflow rate within the Harvey River, produced from the catchment model output, which had an effect mostly on the Harvey Estuary. We still include this year to show the historical evolution during the past decades.

Table 2. Summary of simulated scenarios and their annual precipitation, catchment inflow volumes, mean sea level, and Cut-opening information.

Simulation Category	**Simulated Year**	**Annual precipitation (mm)**	**Annual Catchment Inflow (GL)**	**Annual Mean Sea Level (mAHD)**	**Cut Opening**	***Sensitivity tests***
Pre-Cut years	1970	846.4	705.9	-0.043	No	
	1978	827.5	591.6	-0.024	No	
	1985	911.7	564.0	-0.033	No	
	1990	849.2	515.8	-0.071	No	Yes
Post-Cut years	1998	876.2	490.4	-0.027	Yes	Yes
	2004	813.7	478.0	-0.027	Yes	
	2011	766.0	378.9	0.156	Yes	
	2016	514.4	244.2	0.017	Yes	
No-Cut scenarios	1998	876.2	490.4	-0.027	No	
	2004	813.7	478.0	-0.027	No	
	2011	766.0	378.9	0.156	No	
	2016	514.4	244.2	0.017	No	
Future Scenarios	2040	481.1	187.9	0.053	Yes	
	2060	453.3	138.9	0.083	Yes	
	2040	481.1	187.9	0.053	No	
	2060	453.3	138.9	0.083	No	

2.2.3 Model performance evaluation and sensitivity tests

The model accuracy in reproducing the key hydrologic features was assessed by using the salinity and temperature data measured at six monitoring stations along the estuary (Figure 1). Monthly salinity and temperature datasets were obtained from the Marine and Freshwater Research Laboratory of the Murdoch University (1977-2001) and the Western Australia Water Information Reporting website (http://wir.water.wa.gov.au/) (2002-2017). For each variable, we evaluated the model quantitatively against the monitored data using three skill metrics: correlation coefficient (r), mean absolute error (MAE), and model skill score (SS). Comprehensive evaluation was conducted for all the simulation years, except for 1970 when the long term monitoring had not started yet. The evaluation focused on the salinity and water temperature of the surface and bottom water at the 6 monitoring stations within the estuary. Surface elevation records obtained from the gauged stations in the centre of Peel Inlet, provided by the Department of Transport of Western Australia, were also used to validate the modelled surface elevation in year 1990 (a modelled year before the Cut opening) and 1998 (a modelled year after the Cut opening).

The current study focused on the impact of reduced inflow, due to drying climate and the Cut, on the estuary hydrology. However, the perturbations of environmental factors such as air temperature, tide elevation, and benthic vegetation could also affect the local hydrology, and so their influence on the modelling results was explored. To evaluate the effects of these factors, the sensitivity of the τ and salinity was assessed relative to changes in: (1) air temperature (±1 degree, representing 100 year change of local air temperature); (2) tidal elevation (±0.15m, representing 100 year change of local tide record); and (3) bed roughness length (±50%, representing 50% change of bed roughness). The ranges of these environmental factors were carefully selected based on the historical records. Two years, 1990 and 1998, representing a year before the Cut-opening and another year with the Cut, respectively, were selected for these model sensitivity tests.

3 Results

3.1 Model reconstruction of historical conditions

The monitored and modelled salinity and temperature at the centres of the two lagoons in the pre- and post-Cut years demonstrate the ability of the model to accurately capture the seasonal cycle in response to the catchment inflows (Figure 3). In summer and early autumn the flow rates were low, followed by high salinity and weak salinity stratification in the two lagoons. In contrast, there were large inflows to the estuary in winter and early spring. The peaks of the inflows occurred in winter (July – September), followed by a significant drop in the salinity in the estuary due to the freshwater flushing. However, differences in the salinity response to freshwater flushing can be observed between the pre-Cut year (1990, left column of Figure 3) and the post-Cut year (1998, right column of Figure 3). In 1990 when the estuary had limited connection without the opening of the Cut, the salinity stratification was small in the Harvey Estuary. The salinity dropped to below 5 PSU, indicating the hydrology of Harvey Estuary was mainly dominated by the Harvey River flushing. Whilst during 1998, with greater ocean connection due to the opening of the Cut, stronger salinity stratification was observed in the Harvey estuary, and the minimum salinity was lifted to over 10 PSU due to more seawater intrusion from the Cut. The water temperature also showed a clear seasonal signal, ranging from about 10 °C in winters to 30 °C in summers. The differences in the water temperature observed in the centres of two lagoons, and between the surface and bottom waters, were small.

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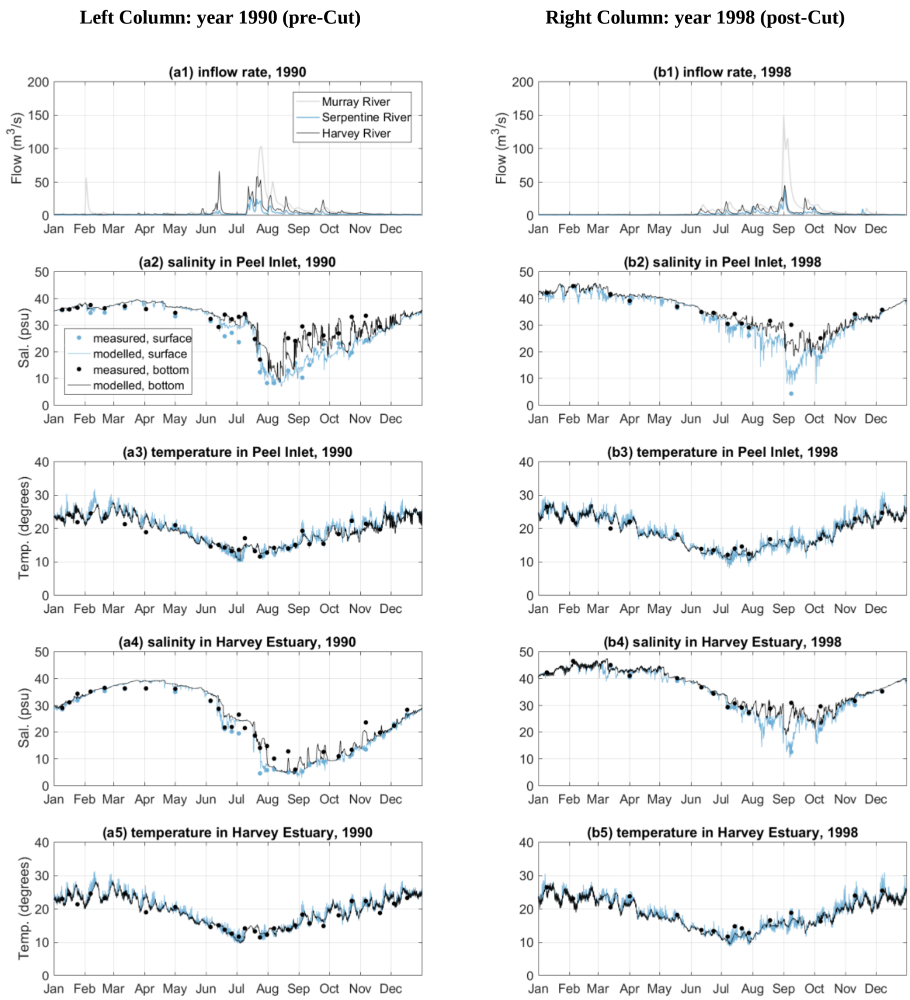

Figure 3. Annual variation in 1990 (left column, a) and 1998 (right column, b) of (1) inflow rate of the three main rivers; (2) monitored and modelled surface and bottom salinity at the centre of Peel Inlet (site PH7 at Figure 1); (3) monitored and modelled surface and bottom water temperature at the centre of Peel Inlet; (4) monitored and modelled surface and bottom salinity at the centre of Harvey Estuary (site PH1 at Figure 1); (3) monitored and modelled surface and bottom water temperature at the centre of Harvey Estuary;

The opening of the Cut also affected the surface elevations of the estuary (Figure 4). The tide elevations in the ocean showed similar characteristics in 1990 and 1998 in terms of the annual mean sea level (-0.071 mAHD and -0.027 mAHD in 1990 and 1998, respectively) and tidal range (both < 1 m). However, the surface elevation measured at the centre of the estuary had significantly different characteristics in these two years. The estuary surface elevation in 1998 had a much wider range of -0.6 m to 0.8 m compared to that in 1990 of -0.4 m to 0.4 m, indicating an enlarged tidal-prism and higher magnitude of water exchange with the ocean due to the opening of the Cut.

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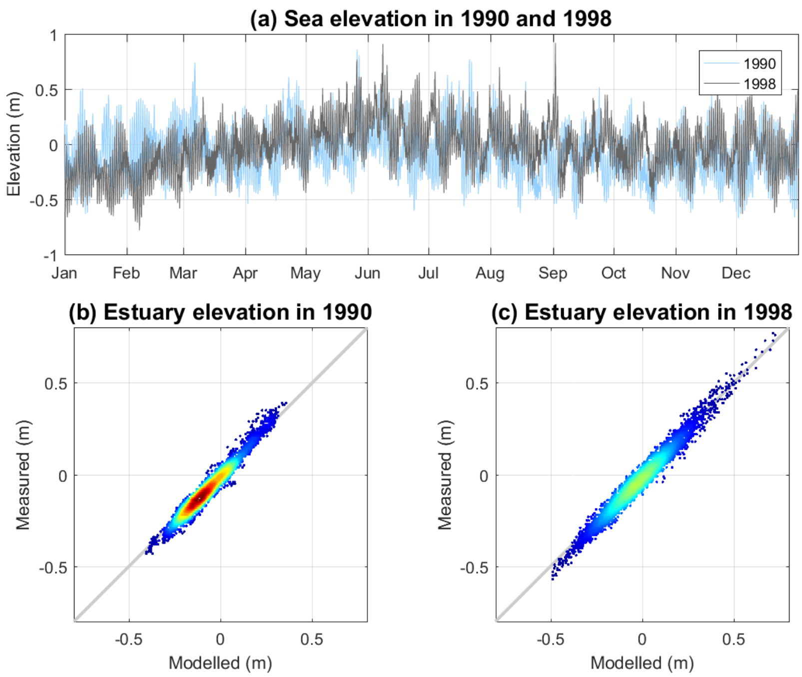

Figure 4. (a) Sea level variation in 1990 and 1998; (b) modelled vs. measured surface elevation in the centre of Peel Inlet in 1990 (r=0.9795), the grey line indicates the 1:1 ratio; and (c) same as figure b except for year 1998 (r=0.9841). The colour from blue to red in figure b and c indicates the data density from minimum to maximum.

In general, the model reproduced the temporal variations of salinity and temperature in both the surface and bottom well (Table 3). The mean regression coefficient r for the salinity from six monitoring sites is above 0.81, and for the water temperature is above 0.85 except in the year 1970, when a mean r of 0.72 was obtained, which may have been due to poor boundary forcing for this year. The model skill scores are generally higher than 0.61 for both salinity and temperature in all historical years, suggesting the model has captured the major features of the hydrodynamic response to the external forcing of tide and freshwater inputs.

Table 3. Summary model performance statistics at 6 monitoring stations (indicated as dark crosses in Figure 1) in the selected historical years.

Simulated year	Model performance of salinity (mean±std)			Model performance of temperature (mean±std)		
	r	***MAE***	***SS***	***r***	***MAE***	***SS***
1970	N/A	N/A	N/A	N/A	N/A	N/A
1978	0.95±0.02	3.24±0.54	0.85±0.02	0.72±0.16	1.89±1.10	0.58±0.23
1985	0.97±0.01	2.18±0.14	0.92±0.01	0.97±0.01	0.94±0.09	0.91±0.03
1990	0.95±0.02	2.60±0.18	0.87±0.05	0.94±0.02	1.31±0.10	0.81±0.04
1998	0.94±0.03	2.04±0.43	0.74±0.29	0.95±0.02	1.66±0.28	0.73±0.14
2004	0.81±0.20	3.78±1.47	0.61±0.34	0.85±0.05	1.60±0.28	0.62±0.15
2011	0.88±0.14	3.69±0.84	0.75±0.19	0.94±0.03	1.43±0.19	0.65±0.15
2016	0.87±0.11	3.54±0.81	0.74±0.23	0.96±0.01	1.13±0.08	0.88±0.02

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3.2 Sensitivity to air temperature, benthic properties, and sea level variation

The sensitivities of modelled salinity and τ to air temperature, tide elevation, and bed roughness are shown in Figure 5. The changes in the air temperature of ±1 °C have minor effects on both the salinity and τ in both years of 1990 and 1998. The influence of air temperature on the hydrology was mostly through evaporation, and resulted in changes in salinity of less than 0.9 PSU, and 0.5 days changes in τ. Secondly, the changes in the mean tide elevation of ±0.15 m led to changes in salinity of up to 2.2 PSU and 8.4 days in τ. Thirdly, the bed friction also had a noteworthy impact on the salinity and τ by modifying the water movement and therefore benthic layer mixing at near-bed level. The presence of benthic vegetation was shown to affect salinity by up to 2.8 PSU in the Harvey Estuary, while a maximum change in the τ of 8.6 days was observed in the same location.

In summary, the modelled salinity and τ were affected by the changes in the sea level variation and bottom vegetation presence, but the effects of these environmental factors were still small when compared to that caused by the reduced flow over the past decade and the Cut-opening, which is shown in the next sections. For example, the maximum change in τ observed in the sensitivity test runs was 8.6 days, caused by the enhanced bottom roughness in the 1990 scenario, compared to the magnitude of 20-100 days caused by the reduced flow from 1970 to 2016 (see more details in below). The maximum changes in the salinity observed in the sensitivity test runs was 2.8 PSU, caused by the reduction of tide level in the Harvey Estuary, compared to the magnitude of 10-30 PSU changes in the salinity caused by the reduced flows from 1970 to 2016 (see more details in below).

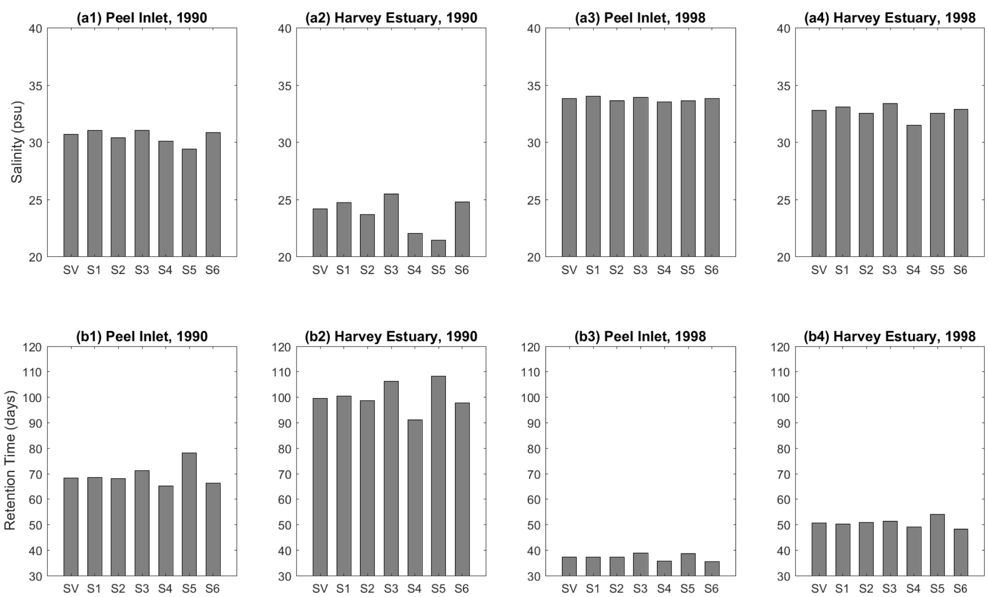

Figure 5. Sensitivity of the modelled annual-mean salinity and retention time in the Peel Inlet and Harvey Estuary. SV: standard scenario; S1: +1 degree in air temperature scenario; S2: -1 degree in air temperature scenario; S3: +0.15 m in tide elevations scenario; S4: -0.15 m in tide elevations scenario; S5: +50% in bed roughness scenario; S6: -50% in bed roughness scenario.

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3.3 Response of water retention to climate change and Cut-opening

Water retention is highly dynamic depending on seasonal flows, tidal conditions, and in different regions of the estuary. The evolution of water age, τ, over time has shown a general increase from1970 to the present, superimposed on the effect of the Cut, however, with some considerable variation across the two lagoons (Figure 6). Firstly, the wet season (winter and spring) was more sensitive to the changes in the drying climate. In the "no-Cut" scenarios (assuming the artificial channel was not constructed), it was predicted that τ would have increased in the Peel Inlet from about 50 days in 1970 to nearly double in 2016, and increased from approximately 50 days in 1970 to nearly 150 days in 2016 in the Harvey Estuary, solely due to the drying climate trend. In contrast, the dry season (summer and autumn) conditions did not show significant changes over time in most parts of the estuary, except in the south Harvey Estuary, which is furthest from the channels. The opening of the Cut had a prominent effect by reducing τ by about 20-45 days in the Peel Inlet, and more profoundly by 50-100 days in the Harvey Estuary. Yet the drying climate effect on the water age has largely cancelled out the flushing effect by the Cut in some regions. The increases in τ from 1998 to 2016, due to reduced inflows, are of the same magnitude as the level of reduction caused by the Cut opening. For example, the Cut opening reduced the τ by 28 days in the west Peel Inlet in 1998, yet the τ increased by 27 days from 1998 to 2016 due to the reduced flows. Lastly, the Harvey Estuary was most influenced by the climate changes and the Cut opening. North Harvey Estuary, directly adjacent to the Cut, was most impacted by the Cut opening, and the τ was reduced by more than 110 days. The south Harvey Estuary, which is furthest from both the channels, was more sensitive to climate change, showing the greatest variation over the most recent decade. The projected climate is expected to increase the τ further in the Harvey Estuary in spring, but a relatively smaller impact at other sites and seasons.

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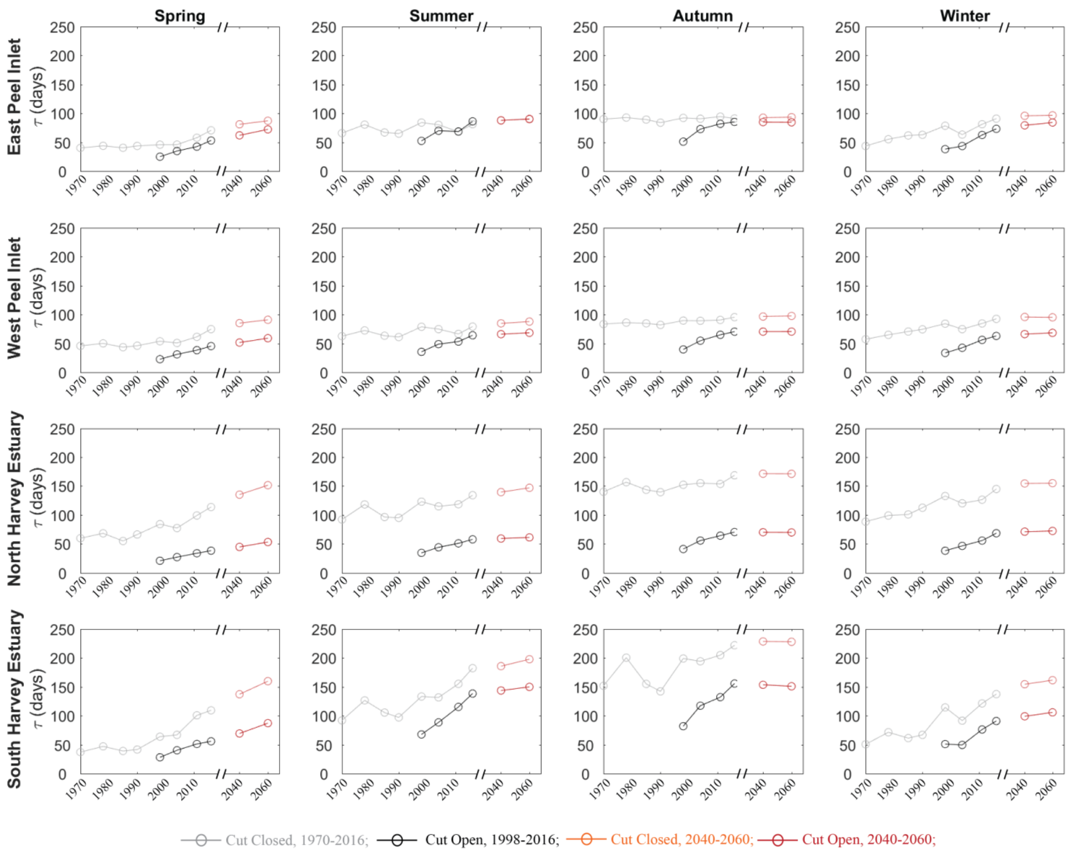

Figure 6. Mean water retention time, $\boldsymbol{\tau}$, in east Peel Inlet, west Peel Inlet, north Harvey Estuary, and south Harvey Estuary (see Figure 1 for their domain definition) in simulated years and future scenarios. The data were categorized into four seasons: spring (September, October, November), summer (December, January, February), autumn (March, April, May), and winter (June, July, August).

The bulk flushing time τ_f also showed significant reduction in summer and winter due to the Cut-opening (Figure 7). The values of τ_f were much smaller than the average modelled water age in the wintertime, about 50% lower in the Cut-closed scenarios and 34%-58% lower in the Cut-open scenarios. This was not surprising as the bulk flushing time method assumes the water body is fully-mixed and corresponds to the time for the seawater and freshwater inflows to replace the lagoon water, whereas the water age method considered the heterogeneity in the spatial distribution of water retention and mixing. The spatial difference in water retention is further illustrated in Figure 8, which shows a plan-view of the seasonally-averaged water ages. The water age in the areas adjacent to the Cut entry point has been largely reduced by the Cut-opening, yet the south Harvey Lagoon and some parts of the east Peel Inlet still showed high water retention. Furthermore, the τ_f showed minor response to the drying climate after the Cut construction, indicating the exchange fraction of the seawater fluxes have been over-estimated.

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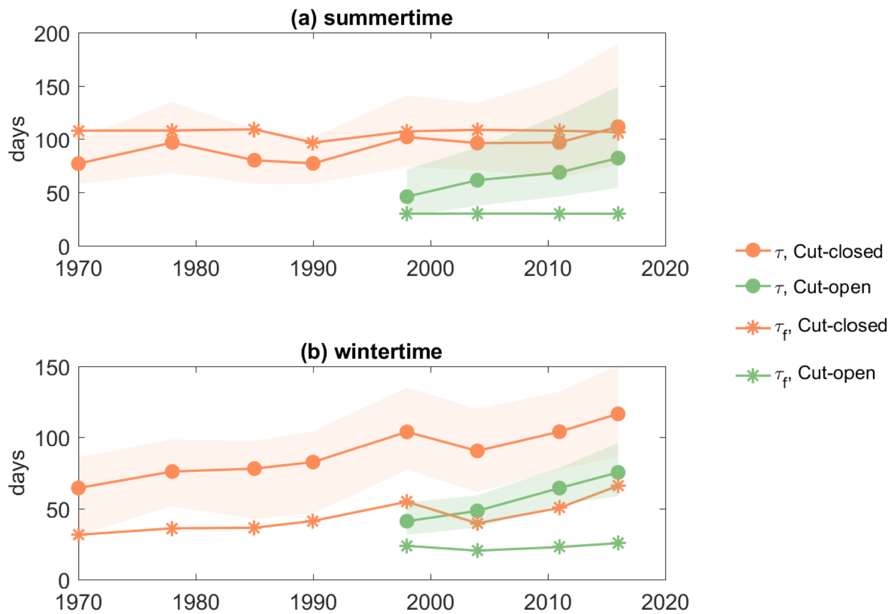

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360 **Figure 7.** Comparison of average modelled water age (τ) and calculated bulk flushing time (τ_f) in (a) summertime and (b)
361 wintertime in the PHE. The shaded areas indicate the 10% and 90% percentiles of modelled water ages.

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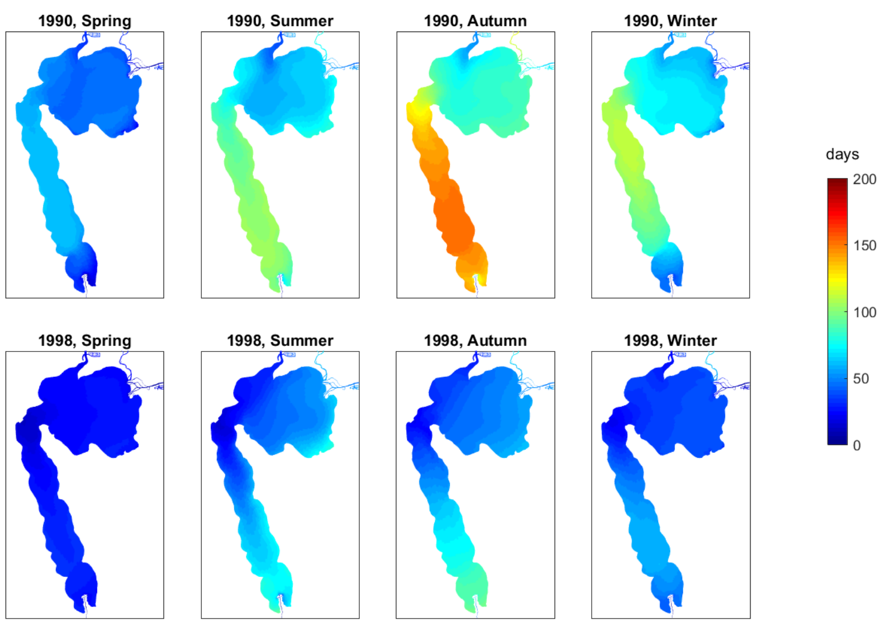

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364 **Figure 8.** Spatial distribution of season-averaged water age in 1990 (top panels) and 1998 (bottom panels).

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3.4 Responses of salinity and stratification to climate change and the Cut-opening

Similar to τ, the changes in salinity in response to the drying climate showed large variability in space and time, and the impact of the Cut-opening acted to increase salinity in the wet season, but reduced hypersalinity risks (>40 PSU) in the dry season (Figure 9). In the "no-Cut" scenarios, the mean salinity during the wet season increased from <20 PSU in 1970 to over 30 PSU in 2016. During the dry season, the changes in salinity were relatively smaller over time. The Cut-opening could increase or decrease the salinity in the estuary, depending on the salinity within the estuary at the time, compared to the ocean salinity of approximately 36 PSU. If the estuary salinity was lower than the ocean salinity, the Cut-opening tended to increase the salinity level, and vice versa. For example, the salinity in the north Harvey Estuary increased from 17.5 PSU to 28.3 PSU in the spring of 1998 by the Cut-opening, yet reduced from 51.8 to 39.8 PSU by the opening of the Cut in the autumn. The Cut-opening has a relatively smaller influence on the salinity of Peel Inlet, which is connected with the ocean via not only the Cut but also the Mandurah Channel. The projected climate is expected to slightly increase the salinity in the Peel Inlet and Harvey Estuary, mostly in the winter and spring periods.

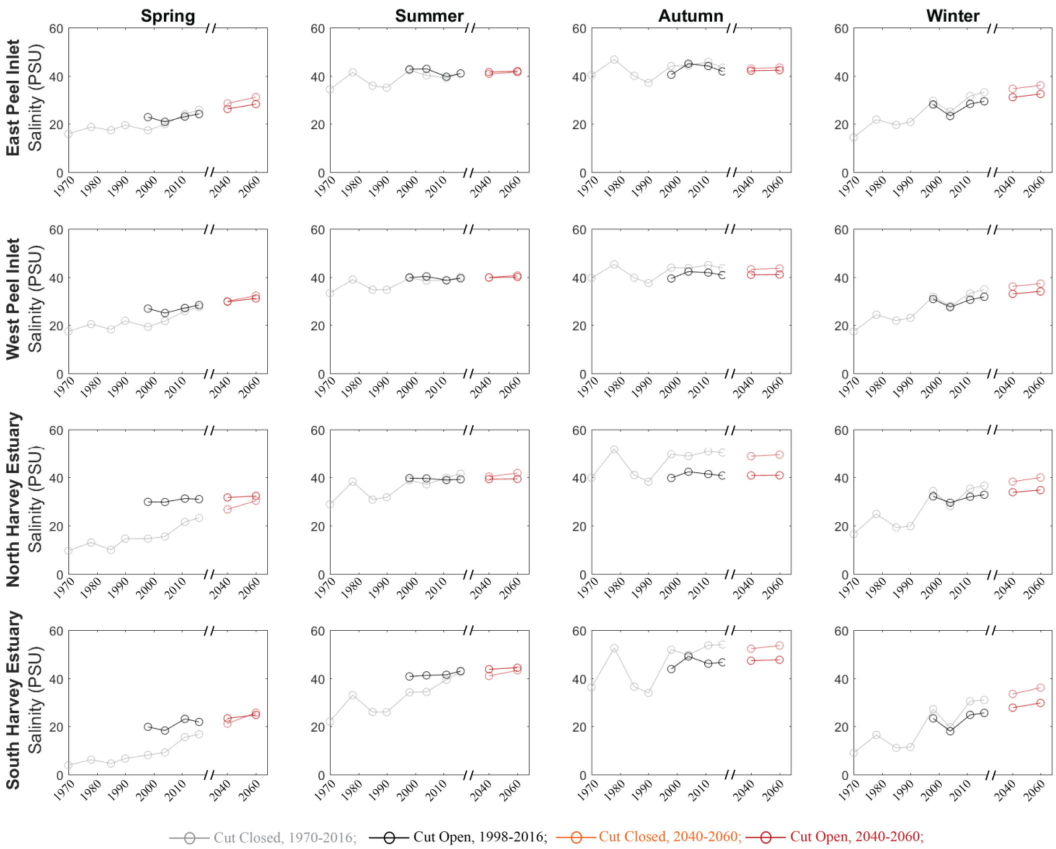

Figure 9. Changes of mean salinity in PHE in simulated years and future scenarios. Same as Figure 6 the changes are categorized into four zones and four seasons.

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Hypersalinity was often observed in the summer and autumn seasons in the Peel Inlet from both the 'with-Cut' and 'no-Cut' scenarios. The Harvey Estuary shows an increasing salinity with the drying climate in summer and becomes hypersaline after 2011. High salinity with values over 50 PSU was observed in autumn in South Harvey Estuary in the 'no-Cut' scenarios, whilst the Cut-opening reduced the hypersalinity risks in autumn in the Harvey Estuary. The relationships of the hypersalinity and the catchment inflows are further investigated with monitoring data at six regular monitoring sites (Figure 10), which highlights the maximum salinity recorded in autumn has increased with reduced inflows, especially in the period before the Cut-opening. Opening of the Cut reduced the maximum salinity at the sites near the Cut (site PH2 and PH58) under an annual flow threshold of about 1000 GL/year. The hypersalinity risk increases with distance from the channels, especially in site PH31 in the south Harvey Estuary where salinity >45 PSU was often observed after the Cut-opening. The maximum salinity can also be affected by other factors, such as unseasonal rainfall events in summer, which brought down the maximum salinity measured in March (Figure 10). However, it can be concluded that the hypersalinity risks have increased in response to the catchment drying trend, and the Cut-opening has reduced the sensitivity of maximum salinity to the changes in inflow rates.

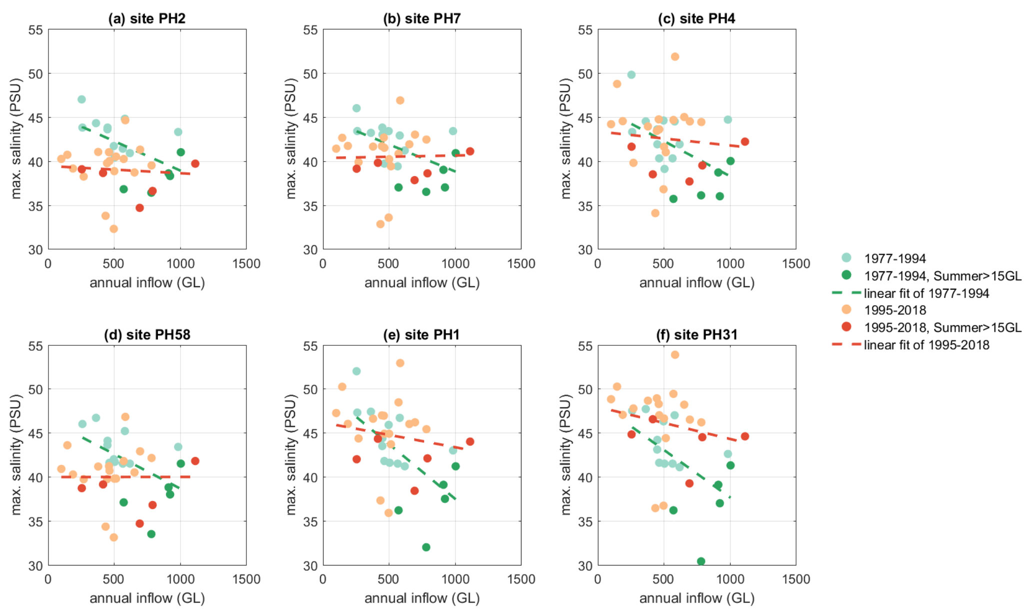

Figure 10. Maximum salinity recorded in March/April and the annual inflow in the hydrologic year (March to March) at 6 monitoring sites (see the site locations in Figure 1). The darker symbols indicate the years with accidental summer rainfall events and caused the catchment inflows higher than 15 GL.

The magnitude of salinity stratification (salinity difference between the bottom and surface water) in winter and spring has shown a declining trend with the drying climate, while the variations were small in summer and autumn (Figure 11). The opening of the Cut has enhanced the rate of ocean water intrusion, which creates stronger salt-stratification during the wet

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season when it interacts with the freshwater inflows. The salt stratification was reduced to mostly < 2 PSU in the 2060 projection scenario, indicating a weaker salt-stratification due to the reduced freshwater inflows and sea level rise.

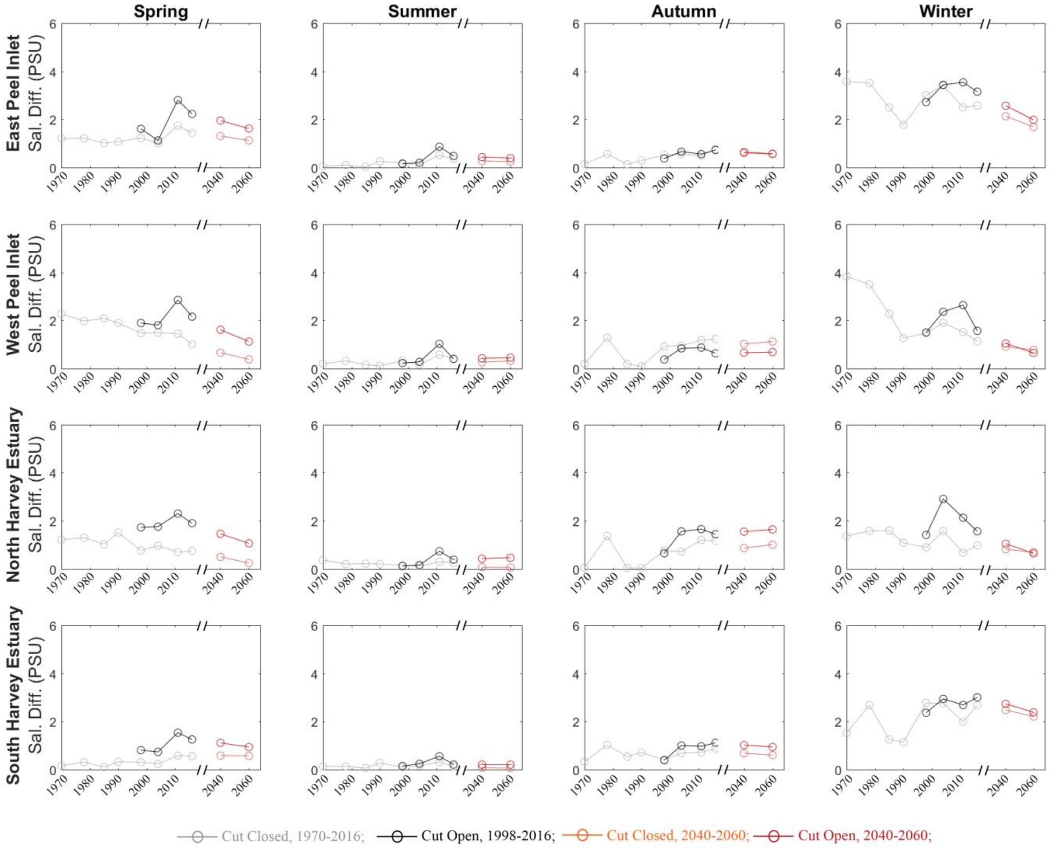

Figure 11. Changes of mean salinity difference between surface and bottom waters in PHE in the simulated years and future scenarios. Same as Figure 6 the changes are categorized into four zones and four seasons.

4 Discussion

4.1 PHE hydrological dynamics in time and space

We have shown the changes in the water retention and salinity within the morphologically complex PHE system, in response to long-term changes in the relative mixture of water resources from the ocean, catchment and rainfall. The signals of climate change and human interventions in these changes, have been analysed by comparing results from the modelling scenarios to attribute each of their relative impacts separately. With the assistance of a 3D hydrodynamic model, we firstly identified the major drivers of PHE hydrology as the gradual but persistent drying trend, and the acute changes caused by the opening of the artificial channel and associated coastal engineering activities. Scenarios of declining precipitation and catchment runoff with and without the artificial channel were also explored to compare their impacts.

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The results clearly showed the hydrology in PHE was profoundly changed corresponding to the reduced precipitation and catchment inflow as well as to the opening of the artificial channel, although other factors such as changes in air temperature, sea level rise, and benthic vegetation also affected the hydrology in much smaller scales. The results have highlighted magnitudes of hydrologic changes introduced by the drying climate, and the complexity of the interacting impacts from climate and the artificial channel in time and space. Firstly, the artificial channel successfully improved the estuary flushing by reducing average water age by 20-110 days; while in contrast the reduced precipitation and inflow had a gradual opposite effect on the water age, and during the wet season this has almost counteracted the reduction brought about by the channel. Secondly, the drying climate caused an increase in the salinity by 10-30 PSU; whilst the artificial channel increased the salinity during the wet season, it has reduced the likelihood of hypersalinity (>40 PSU) during the dry season in some areas.

The climate factor had not been considered in previous reports evaluating or predicting the consequence of the Cut-opening when it was originally designed (Lord, 1998; Manda et al., 2014; Prestrelo and Monteiro-Neto, 2016), as the focus was on the flushing benefit to reduce the accumulation of nutrients and algal biomass. The findings from this study suggest that climate change has been taking effect over the period when the Cut was implemented, and from the view point of particular metrics, it is now over-taking the effect of the Cut. The lessons from this case-study highlight the need to look more broadly at environmental impacts when designing or operating large-scale engineering projects on coastal lagoons, due to the potential for long-term non-stationarity in contributing river flows.

Of relevance to management, the impacts also varied spatially in this large lagoon. The water age and salinity have showed distinct responses to the climate change and Cut-opening with various connection with the rivers and ocean (Figure 6 and 9). The southern estuary, which has the least connection with the ocean through the natural channel, is the most sensitive to climate change and the opening of the artificial channel. The bulk flushing time also showed significant reduction corresponding to the Cut-opening, however, it was less sensitive to the drying climate. The results of water age distribution indicated that incomplete mixing had led to area-specific retention of water, which has been labelled previously as the 'sticky water' effect (Andutta et al., 2012); in this case the concept of bulk flushing time therefore needs to be used with caution in such a large choked-type lagoon, because it only gives an average estimation of water retention for the whole estuary and fails to consider the strong gradients in lagoon hydrodynamics. Understanding these patterns can be important to help understand local effects on lagoon ecology (e.g. crab larval recruitment) and processes related to nutrient deposition and retention within the sediment.

Aside from changes in flushing and the mean salinity fields within the lagoon, the changes in the climate and ocean flushing also altered the hydrology in the tidal reaches of the rivers connecting to the PHE. The annual variability of salinity along the rivers (Figure 12) indicated there is an increasing risk of hypersalinity in the Serpentine River (connecting to the PHE from the north) and an upward movement of the salt-wedge in the Murray River (the major inflow connecting PHE from the east). For example, the mean salinity at the Serpentine River mouth was about 20 PSU in 1970, then increased to 24 PSU in 1998 and projected to increase to over 30 PSU in 2060. In the upstream areas of the Serpentine River, the mean salinity increased from about 15 PSU in 1970 to near 35 PSU in 2060. While there is less hypersalinity risk in the Murray River due to larger volumes of freshwater flushing, there is also a trend of increasing salinity along the river with the drying climate. The differences between the Cut-closed and Cut-open scenarios in year 1998 are much smaller than those caused by the drying climate, which indicates that the drying climate is the major cause of the salinity changes in the rivers.

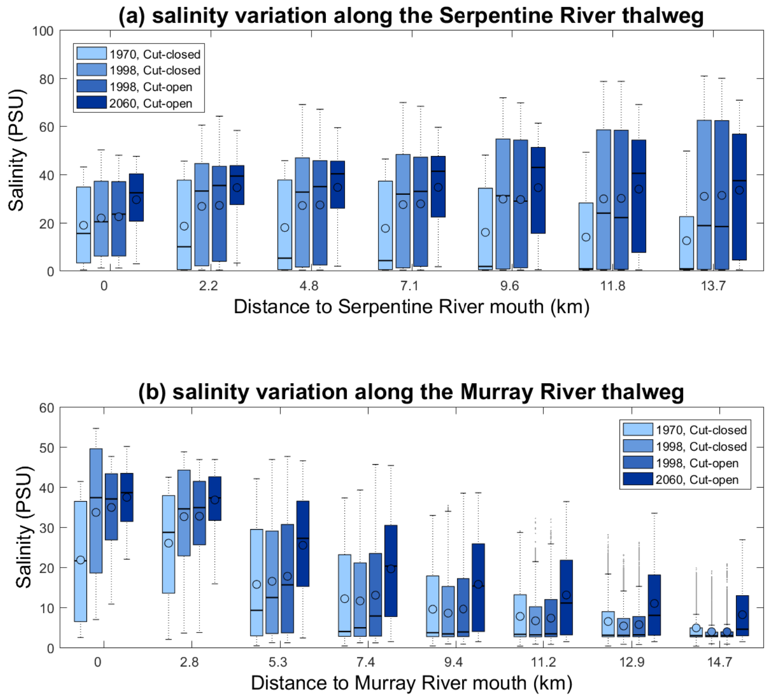

Figure 12. Longitudinal gradient in annual salinity variability in four selected scenarios (1970, 1998 without the Cut opening, 1998 with the Cut opening, and a future scenario 2060 with assumptions of reduced flow and sea level rise) moving upstream along the (a) Serpentine River and (b) Murray River.

4.2 Applications for estuary ecosystem management

The Cut had an obvious and dramatic effect on increasing the export of nutrients that would have otherwise been retained (Figure 13). Since the Cut opening in 1994 the main monitoring stations have shown TN as being stable around 0.5mg/L and TP has declined from 0.05 to 0.02 mg/L over time. Importantly, the increasing rate of exchange has made the estuary concentration of nutrients less sensitive to the inflow load (as demonstrated by the reduction in slope of 11c and 11d). The results have also revealed an increase in τ associated with the drying climate that has eroded some of the benefits associated with increased flushing following the construction of the Cut, and further reductions in flows will cause less flushing and will likely lead to a tendency for increasing nutrient accumulation over time.

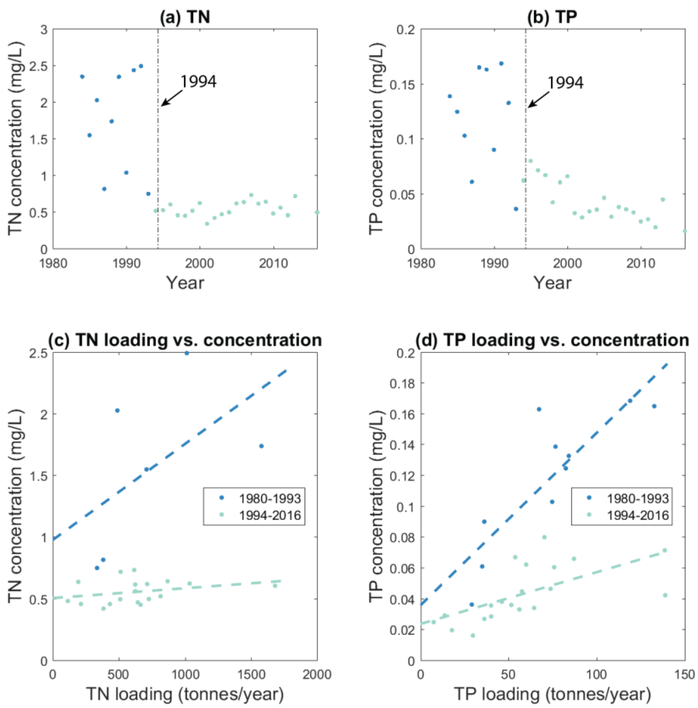

Figure 13. Changes in the mean nutrient concentration of (a) TN and (b) TP in the Peel-Harvey Estuary (based on the average of the 6 main monitoring stations), and their relationship with the total annual nutrient loading (c and d).

The hydrologic changes led not only to changes in the nutrient concentrations but also the mean salinity, with potential ramifications for the ecological community. In particular, the phytoplankton biomass dropped dramatically since the Cut opening (Figure 2) due to the improvement of ocean connectivity and flushing, but also due to a less desirable salinity regime in summertime for the toxic cyanobacteria *Nodularia spumigena* that plagued the Harvey Estuary before the Cut opening. Field observations also showed that the biomass of macroalgae has decreased in the Peel Inlet, while it has increased in the Harvey Estuary since the Cut opening, which potentially reflects the reduced nutrient concentrations, increased salinity and greater light availability (Pedretti et al., 2011). The biomass of some benthic macroinvertebrates, such as the blue swimmer crabs (*Portunus armatus*) and the Western king prawn (*Penaeus latisulcatus*) also showed an increase with the Cut opening and the reduced flow in recent years (Bradby, 1997; Johnston et al., 2014). The changes in the biological communities corresponding to the hydrologic changes seem to remain in the predicted future as the projected drying climate led to constant low flushing and high salinity in this estuary.

4.3 Uncertainty of future hydrology

This study has investigated the hydrologic changes in selected historical years and under projected future drying climate. However, the drying climate was predicted with a combination of climate models (Smith and Power, 2014) and the annual perturbations in future climate and their impacts on the hydrology remain the subject of uncertainty. As shown in Cloern et al. (2016), the hydrology of lagoons has been changing at a faster pace in the past decade from a combination of human activity

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and climate variability. The sea level of the ocean adjacent to the PHE has been rising at faster speeds in the past decades (Kuhn et al., 2011). The PHE catchment is also undergoing fast development due to the increasing population and agricultural expansion (Kelsey et al., 2011). Intensification of human activities, such as water consumption and diversion, will further affect the lagoon's hydrology and associated ecosystem, but how these factors will change in future remains unclear. Therefore, our results related to the future prediction are simply to indicate the possible changes of hydrology under the projected drying climate in order to highlight the general trend and allow for prioritisation of adaptation strategies such as environmental water allocation policies. Continuous monitoring on the hydrology and water quality of the lagoon and its catchment must therefore be prioritised to closely observe further hydrologic change in order to provide prompt actions for management.

5 Conclusions and outlook

This study has sought to analyse the hydrologic changes in the Peel-Harvey Estuary to a range of drivers, and focused on the effects of the recent climate change trend on the hydrologic evolution in the Peel-Harvey Estuary, relative to the changes brought about by construction of the Dawesville Cut. Our results suggested the climate change in the past decades has a remarkable effect on the hydrology with the same magnitude as that caused by the opening of an artificial channel, and also highlighted the complexity of their interactions. The artificial channel was effective in reducing the water retention time especially in areas close to the channel, while the drying climate trend has acted to increase the water retention time. The artificial channel enhanced the ocean intrusion, which had a mutual effect with the drying climate to increase the estuary salinity during the wet season, but it had opposite effect of reducing the hypersalinity during the dry season. The artificial channel increased the seawater fluxes and the salinity stratification, mostly in the Harvey Estuary, while the drying climate reduced the salinity stratification in the main body of the estuary. The changes in nutrient levels and habitat of pelagic and benthic communities related to hydrology are also discussed, which showed the communities are sensitive to the hydrologic changes. Consideration of the projected drying trend is essential in designing management plans associated with planning for environmental water provision and setting water quality loading targets.

Data availability

The datasets generated during the current study are available from the corresponding author on request.

Author contribution

All the authors contributed to the design of the study. Peisheng Huang carried the hydrology modelling work and prepared the first draft of the manuscript. Karl Henig provided the catchment outputs of the inflow rates and nutrient concentrations. Jatin Kala and Julia Andrys provided the WRF weather data. Matthew R. Hipsey was the project leader and provided technical and financial supports. Jatin Kala and Matthew R. Hipsey helped to interpret the model data and write the article.

Competing interests

The authors declare no competing financial or non-financial interest.

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