Modelling Holocene analogues of coastal plain estuaries reveals the magnitude of sea-level threat

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Hydrodynamic modelling of Australia’s lower Murray River demonstrates the response of a large coastal plain estuary to the mid-Holocene (7,000–6,000 yr BP) sea-level highstand. The approximately two metre higher-than-present sea level during the highstand forced the estuarine limit upstream generating an extensive central basin environment extending more than 200 kilometres from the river mouth (143 kilometres upstream of the modern tidal limit). The geomorphic history of the region does not conform to conventional estuarine facies models as, for much of the Holocene, the lower Murray River acted as a landward, gorge-confined extension of the Murray estuary. The incredibly low relief of this coastal plain system drove significant saline incursion and limited current velocities across the estuary facilitating deposition of a laminated silt-clay sequence which our results suggest may be regionally extensive. Variations to discharge, barrier morphology, or the estuary’s bathymetry result in minimal change to the estuarine palaeo-environment. The shift to the present-day fresher water distribution in the Murray estuary requires a fall in sea level to present-day conditions. The dominance of sea level as the controlling factor on this estuarine palaeo-environment highlights the significant potential impact of climate change induced sea-level rise to coastal plain estuaries.

Coastal plains and lowlands are characterised by their low gradient and commonly dense populations, with geomorphic-based risk assessments revealing their significant vulnerability to future climatic change1. Inundation associated with an increase in mean sea level threatens communities, coastal infrastructure and ecosystems, with estuaries vulnerable to the compounding influences of storm surges and strong winds, along with implications of saline incursion for irrigation and drinking water supply2. Indeed, in Australia, flooding is considered the most significant medium-term climate change hazard, with a shift to coastal inundation beyond mid-century2,3. There is, however, less emphasis on the consequences of rising sea levels for saline intrusion, particularly for low-gradient coastal plain estuaries.

The Intergovernmental Panel on Climate Change (IPCC) projects that global mean sea level will rise by 0.53–0.97 m by 2100 under a high emissions scenario, with these projections likely to be exceeded by at least 10% in Australia4. Crucially, even given a stabilisation in temperatures, global mean sea level will continue to rise for several centuries beyond 21005. Understanding the dominant drivers of environmental change within an estuarine system allows for effective management given uncertainties in future mean sea level, and determining palaeo-environmental responses to the Holocene highstand provides a useful analogue of expected change. There is a pressing need for palaeo-environmental analysis in economically significant regions to direct future natural resource management policies, particularly in intensively managed environmental systems. Developing appropriate management strategies that negate the detrimental impacts forecast in climate change projections is particularly important for lowland coastal plains where rising sea levels will undoubtedly cause problematic inundation and saline intrusion. Applying Holocene analogues to future sea-level rise scenarios is a well-recognised approach to predicting responses of coastal systems to climate change5. Here, we use the lower Murray River (LMR) and Murray estuary as a case study to demonstrate the utility of understanding Holocene analogues to plan for potential environmental change in coastal plain estuaries.

Understanding fluvial and estuarine responses to sea-level cycles through their associated depositional systems tracts may assist in predicting potential impacts of future sea-level rise. Research has shown that fluvial systems attempt to keep pace with changing base level, with shoreline advance or retreat controlling available

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accommodation and causing a shift in the nature and location of estuarine processes and depositional environments. There is a significant body of literature detailing the influence of Holocene sea-level change on the sedimentary infill and evolution of estuaries on the east coast of Australia, however, few studies specifically examine southern coast Australian estuaries, such as the Murray estuary (e.g., 12–14). The Murray estuary lies at the terminus of the Murray-Darling Basin (MDB), Australia's largest and most politically and economically important river basin (Fig. 1). The geomorphic and palaeoenvironmental history of the region has been the subject of much debate, driven by the reliance on Holocene climatic and hydrologic reconstructions to guide nationally significant water policy. This wave-dominated estuary, comprising the Lower Lakes, Coorong and Murray Mouth, is situated on a low-gradient coastal plain and developed in response to slowing sea-level rise during the transgressive period of the early- to mid-Holocene. The Murray estuary's barrier complex, comprising Sir Richard...
and Younghusband Peninsulas, began formation at approximately 8,000 yr BP, allowing for the development of the central basin lakes, Alexandrina and Albert, prior to the Holocene highstand at 7,000–6,000 yr BP16–18 (Fig. 1).

Upstream, the LMR is entrenched within the Murray Gorge (from Overland Corner to Wellington, Fig. 1), with the valley fill only comprising sediment of the most recent cycle of lowstand, transgression and highstand5,22. This consists of two distinct facies: (1) the Monoman Formation's coarse-grained sands comprise the lower valley fill, and (2) the Coonambidgal Formation's fine-grained clays and silts comprising the upper valley fill.

The Holocene infill of Lake Alexandrina is known as the St Kilda Formation, and is a finely laminated silt-clay sequence23,24. Deposition of this sequence had commenced by at least 8,000 yr BP23,24; however, it is probable that deposition within the palaeo-channel that transited through modern-day Lake Alexandrina had commenced prior to 8,000 yr BP as dated cores within this area bottom out on laminated mud23,24. The St Kilda Formation was regionally extensive from 5,500 yr BP and has characterised the sediments of Lake Alexandrina since23,24.

Standing water or very weak current velocities are required for the deposition and preservation of a laminated silt-clay sequence25. However, recent flume studies have demonstrated mud flocc deposition as distinct laminae in current velocities up to 0.3 m/s, with laminae accumulation considered possible at higher velocities given particularly high sediment concentrations26,27. Laminations, such as those present throughout Lake Alexandrina, are undoubtedly a product of low energies and high sedimentation rates25, features characteristic of central basin environments25. Indeed, wave-dominated estuaries are known for their well-defined tripartite zonation of facies assemblages with lithofacies typically presenting a coarse-fine-coarse sequence: the marine sands of the barrier complex and flood-tide delta, the clays and silts of the central basin, and the fluvial sands of the bayhead delta and river channel25. Conventional presentations of estuarine models indicate that the point where the river debouches into the lagoon locates the transition to reduced energy and defines the landward extent of the central basin and seaward extent of the bayhead delta. However, the contentious Holocene palaeo-salinities of the Lower Lakes give rise to debate on the extent and character of the Murray estuary. Some place the upstream extent of this estuary at the Pomanda Embayment, where the LMR debouches into Lake Alexandrina16 (river kilometre (rkm) 73, Fig. 1), with other authors even suggesting that the Lower Lakes were freshwater stilling basins for the duration of the Holocene and cannot be classified as part of this estuarine zone17.

In this paper, we evaluate the range of possible responses of the palaeo-Murray estuary to the Holocene sea-level highstand. Specifically, we:

a) Conduct hydrodynamic modelling of the palaeo-Murray estuary and LMR with sensitivity testing for discharge, bathymetric surface and barrier morphology with results analysed for inundation extents, water levels and depths, flow velocity and salinity.

b) Assess the palaeo-environment that likely prevailed during the Holocene highstand and correlate model scenarios with geomorphic and sedimentary features of the region to develop a model of estuarine processes zonation and inferred resulting morphology.

c) Assess the relative influence of geomorphic and hydrodynamic drivers on the estuary during the Holocene sea-level highstand.

d) Propose the palaeo-Murray estuary, as a possible end-member exemplar of an extremely low-gradient coastal plain estuary, to demonstrate the significant threat of sea-level rise due to climate change on the environmental character of coastal plain estuaries. Particular reference is given to the understated potential impact of climate change-induced saline intrusion on the character and extent of coastal plain estuaries.

Results

Here, we model the inundation extents, water depths, flow velocities and salinities for the full extent of the LMR and Murray estuary as a function of four key morphologic and hydrodynamic forcings: (1) bathymetric surface (two end members and a best estimate), (2) sea level (Holocene highstand and present-day), (3) discharge (drought, pre-regulation average, and flood), and (4) barrier morphology (four scenarios, ranging from completely open to almost closed, to account for barrier evolution). Results are grouped into six categories based on bathymetric surface and sea level: $S_{low}WL_2$, $S_{low}WL_0$, $S_{mid}WL_2$, $S_{mid}WL_0$, $S_{up}WL_2$ and $S_{up}WL_0$ (see Methodology - Overview of model result categories and Table S1 for further information).

Model correlation with regional geomorphology and sedimentology. Given the experimental nature of modelling snapshots in geological time, constraining inundation extent to geographical features gives an indication of the plausibility of model results. The lacustrine and estuarine clays of the Malcolm soil combination (Fig. 2a; Table S2) represent the extent of Lake Alexandrina during the Holocene11. This formation, and recognised Holocene palaeo-shorelines3, are mapped against inundation extent in Fig. 2. The Malcolm soil combination is well constrained by the $S_{low}WL_2$ scenarios (Fig. 2d; Table S1), with the $S_{mid}WL_2$ scenarios proving a reasonable match overall (Fig. 2c; Table S1). The $S_{up}WL_2$ scenarios align precisely with the most expansive of the palaeo-shorelines which is consistent with the greatest Holocene extent of Lake Alexandrina31 (Fig. 2d; Table S1). The $S_{mid}$ scenarios sit at, or beyond, the middle palaeo-shoreline, considered to represent a short stabilisation period during retreat, likely in response to falling sea levels31 (Fig. 2c; Table S1). The $S_{low}WL_2$ scenarios align with the middle palaeo-shoreline, while the $S_{up}WL_0$ scenarios generate inundation akin to present-day31 (Fig. 2b; Table S1).

The inundation extent of the 1956 flood, the greatest flood on instrumental record, is also depicted in Fig. 2. This extent is not as expansive as the Malcolm soil combination within the Lower Lakes region, suggesting that water levels at the Holocene highstand were well above maximum historical records. Bank overtopping from fluvial floodwaters during the 1956 flood caused valley-wide inundation within the Murray Gorge which gives insight into the plausible response to the Holocene highstand as the LMR is backfilled. All $S_{low}$ scenarios correlate...
with the 1956 flood extent and are characterised by valley-wide inundation throughout the Murray Gorge (Fig. 2d III-IV; Table S1). The SmidWL2 scenarios inundate the entire valley, with the exception of two small areas at Big Bend (rkm 235) and Swan Reach (rkm 255; Fig. 2c III-IV; Table S1). Inundation of these two locations is reduced in the SmidWL0 scenarios along with isolated small dry areas, however, these models remain characterised by valley-wide inundation (Fig. 2c III-IV; Table S1). Conversely, even given Holocene highstand sea levels, the Sup scenarios are charactered by a channel with fringing swamps upstream of Mypolonga (rkm 130), as was evident prior to levee construction and land reclamation in the 19th century32. A significant flood (D+ scenarios) is required to induce valley-wide inundation (Fig. 2b III-IV; Table S1). Our results suggest that the period of sea-level fall from highstand in the late-Holocene saw a significant shift in the geomorphic character of the LMR (Fig. 2c III-IV vs. 2b III-IV). Overall, model results are well correlated to regional geomorphology and sedimentology, and are consistent with research into the sedimentary infill and geomorphological evolution of barrier estuaries identified on the east coast of Australia (e.g7,8,33.), therefore, the model is deemed sensible and valid as a basis for further exploratory analysis.

Figure 2. Geologic overview of the study area and maps showing maximum inundation extent under average discharge and modern-day barrier conditions (Dmod scenarios). (a) Simplified surface geology showing Holocene and Pleistocene stratigraphic formations. Inundation extents are shown for (b) Smid (c) Slow and (d) Smid scenarios at +2 m sea level (WL2; light blue) and +0 m sea level (WL0; dark blue). Panels I and II encompass sub-sections of Lake Alexandrina detailing the flood tide delta and Murray Mouth, and the Cooke Plains Embayment respectively. Panel III details a 10 rkm representative sub-region of the lower portion of the LMR (centered on Tailem Bend, rkm 91). Panel IV details a 10 rkm representative sub-region of the upper portion of the LMR (centered on Swan Reach, rkm 255). The inundation extent of the 1956 flood (grey) is given as an indicative regional modern-day analogue of the plausible extent of inundation caused by backfilling during the Holocene highstand. The Malcolm soil combination (dark grey outline) represents the maximum Holocene inundation extent of the Lower Lakes (Lakes Alexandrina and Albert; I and II)31. Palaeo-shorelines (black) allude to the maximum Holocene extent of Lake Alexandrina and a period of stability following retreat to the present-day shoreline (II)31. Maximum inundation extents remain comparable in other model scenarios not depicted here, with non-significant fluctuations in inundation across the Lower Lakes (I and II), with the exception of a significant flood event (D+ scenarios) which induces valley-wide inundation throughout the LMR (III and IV), consistent with 1956 flood extents.

Palaeo-environment at the Holocene highstand. Our results show that the palaeo-environment at the Holocene highstand was likely to have been estuarine throughout the Lower Lakes and well upstream into the LMR (Figs 3a I–III, 4a and S1a–c). All WL0 highstand scenarios result in an estuarine environment with significant marine incursion in the Lower Lakes, meanwhile all WL2 scenarios result in a brackish environment within the Lower Lakes, with fluvial discharge supressing significant marine incursion to the barrier and flood tide delta complex (Figs 3a, 4a and S1). This trend is apparent across all scenarios irrespective of discharge, barrier morphology and bathymetric surface (Figs 3, 4a and S1), with a shift to fresher water dependent upon a fall in sea level to present-day conditions (Figs 3a, 4a and S1). Holocene highstand sea levels also induce valley-wide inundation under Smid morphology, with the Smid and Slow morphologies resulting in a significant increase in the areal extent of the Lower Lakes (Fig. 2). These results demonstrate that sea level is the driving factor controlling the environmental character of the Lower Lakes and LMR. This is apparent through the difference in maximum palaeo-salinities observed with a change in sea level (Figs 3a, 4a and S1) when compared with the near-identical results produced by sensitivity testing for discharge (Figs 3b and 4a), barrier morphology (Figs 3c and 4a) or bathymetric surface (Figs 3a and 4a).

Estuarine processes zonation and inferred resulting morphology. Flow velocity vectors are used to define the upstream extent of the backwater zone for each scenario (Figs 4b and S2). The maximum upstream
extent in Slow scenarios is Blanchetown (rkm 275), regardless of sea level, such that the SlowWL0 scenarios present significantly different backwater zones when compared to other WL0 scenarios (Figs 4b and S2; Table S1). Given that the bathymetry of the Slow scenarios is almost certainly not representative of the mid- to late-Holocene when sea levels had receded to present-day, the backwater zone during this period is best constrained by the SmidWL0 and SupWL0 scenarios, confining the backwater zone to the region downstream of Tailem Bend (rkm 91; Figs 4b and S2; Table S1). Under all bathymetric conditions, the backwater zone extended well into the LMR supporting the hypothesis that Lake Alexandrina and the LMR were subject to a single depositional environment that produced a regionally extensive central basin depositional sequence at the Holocene highstand (Figs 4b and S2). We suggest that, prior to anthropogenic modifications of the flow regime, this central basin sequence was continuing to accumulate within the entirety of Lake Alexandrina; top-of-core modern dates across the regionally extensive laminated sequence support this hypothesis.

The possibility of deposition and preservation of a laminated sequence is limited to regions where the maximum flow velocity magnitude is <0.3 m/s (25–27) (see grey shaded areas in Figs 5 and S3), which encompasses a minimum of 82% of the model domain. Suitable conditions for the deposition of a laminated sequence throughout Lake Alexandrina apply in all scenarios (Figs 5 and S23) and explain the regionally extensive presence of this laminated central basin deposit that has characterised Lake Alexandrina’s Holocene stratigraphy since 5,500 yr BP (23). Variation in barrier morphology (Fig. 5a–c or d–f) or LMR/Lower Lakes bathymetry (Fig. 5a,d or b,e or c,f) makes a negligible difference in the regional capacity to generate a laminated central basin deposit (maximum 7% and 3% change respectively).

Figure 3. Key representative maps comparing maximum salinity reached relative to sea level, bathymetric surface, discharge and barrier morphology. (a) An increase in sea level from WL0 present-day conditions (IV–VI) to WL2 Holocene highstand conditions (I–III) significantly increases marine incursion, extending to the upper reaches of Lake Alexandrina and pushing the brackish limit further up the Murray Gorge. There is negligible change to the overall palaeo-environmental character of the region between end-member and best-estimate Holocene bathymetries (I–III or IV–VI). (b) Variance in flow from drought (D−) to flood (D+) scenarios (I–III) is unable to alter the palaeo-environmental character of the region. (c) Variance in barrier morphology from completely open (B0) to modern-day (Bmod) outlet scenarios (I–IV) is also unable to alter the palaeo-environmental character of the region. The isohaline (black line) delimits the brackish limit (equivalent to 1 psu) with the percentage area of each salinity class seaward of the isohaline given relative to total inundated area. The hatched box highlights the common scenario between the three panels: scenario SmidWL2DavBmod. Within (a) all maps shown are pre-regulation average discharge with modern-day barrier morphology scenarios (I: scenario SmidWL2DavBmod; II: scenario SmidWL2DavBmod; III: scenario SmidWL2DavBmod; IV: scenario SmidWL2DavBmod; V: scenario SmidWL2DavBmod and VI: scenario SmidWL2DavBmod; Table S1). To demonstrate representative salinities at the Holocene highstand, SmidWL2 scenarios are shown within (b): (I): scenario SmidWL2DavBmod; II: scenario SmidWL2DavBmod; III: scenario SmidWL2DavBmod and (e) (I: scenario SmidWL2DavBmod; II: scenario SmidWL2DavBmod; III: scenario SmidWL2DavBmod; IV: scenario SmidWL2DavBmod). Salinity is measured based on the classification scheme of Tooley (51).
Overall, the SlowWL2 and S midWL2 scenarios are well constrained by the Malcolm soil combination, and palaeo-shorelines, representing the maximum Holocene inundation extent of the Lower Lakes which suggests the suitability of interpolating these results to the palaeo-environment at the Holocene highstand (Fig. 2; Table S1). These results show that the Holocene highstand probably generated valley-wide inundation within the entire Murray Gorge at least as far upstream as Blanchetown (rkm 282; Fig. 2), which coincides with the minimum propagation of the tidal limit of the Murray estuary (Fig. 6). Given this single central basin depositional environment, we infer the presence of a laminated sequence within the valley-wide LMR perhaps extending as far upstream as Walker Flat (rkm 206; Fig. 6), a hypothesis that will be tested by a complementary sedimentary analysis in a subsequent study. During the late-Holocene, we suggest that the bayhead delta prograded downstream to Mypolonga (rkm 130), where there is a notable shift in the geomorphic character of the levees and fringing swamps, before anthropogenic modification inhibited further natural estuarine evolution from 1900 onwards.

**Sensitivity testing.** Examples of the influence of bathymetric surface on maximum palaeo-salinitities are shown in Figs 3 and 4a and on inundation extent in Fig. 2. The LMR is characterised by a main channel with fringing swamps under S up scenarios, while the S mid and S low scenarios exhibit valley-wide inundation (Fig. 2; Table S1). Within the Lower Lakes, the modelled inundation extent is comparable to present-day shorelines under...
Sup scenarios, with the $S_{\text{mid}}$ and $S_{\text{low}}$ morphologies extending inundation across the Cooke Plains Embayment (Fig. 2; Table S1). Variation in palaeo-salinities is facilitated by Lake Alexandrina's palaeo-channel within the $S_{\text{mid}}$ and $S_{\text{low}}$ morphologies, forcing marine influence upstream, pushing the brackish limit well within the Murray Gorge and causing the majority of the LMR to be characterised by brackish-fresh water (Figs 3a, 4a and S1b–c,e–f; Table S1). By comparison, the Sup scenarios allow for a brackish-fresh channel within the LMR while the fringing swamps largely remain fresh (Figs 3a, 4a and S1a,d; Table S1). The presence, or infill of, this palaeo-channel also alters the palaeo-salinity of Lake Albert (Figs 3a and S1). Overall, however, variation in bathymetric surface alone is insufficient to alter the palaeo-environment of the region, as demonstrated by comparing the results presented in Figs 3a and 4a. Despite the uncertainty in the precise location of a $S_{\text{mid}}$ Holocene highstand best-estimate morphology, variation in barrier morphology exerts its greatest influence within the barrier and flood tide delta complex and attenuates rapidly; by the mid-section of the Lower Lakes the impact of barrier morphology is negligible (Figs 3c and 4a). The variety of postulated early- to mid-Holocene chain-of-islands evolution events in the barrier complex does not change the character of the palaeo-environment, as demonstrated by the near identical maximum palaeo-salinities and 10 psu (marine-brackish) limits presented in Figs 3c and 4a respectively.

Sensitivity testing for discharge reveals that the flood event has a greater influence on palaeo-salinities when compared to drought, however, only under $S_{\text{up}}$WL scenarios is a flood sufficient to supress Lake Alexandrina to fresher conditions (Fig. 4a; Table S1). Drought conditions have a more pronounced impact on palaeo-salinities.
under present-day sea levels (WL0) when compared to WL2 scenarios (Fig. 4a). This zonation is extrapolated into inferred resulting morphology at the Holocene highstand (grey italicised text). The Murray estuary’s barrier and flood tide delta complex occupied the region seaward of Point Sturt and Point McLeay (rk 40). The central basin occupied the entirety of the Lower Lakes, Lakes Alexandrina and Albert, and extended upstream within the Murray Gorge plausibly as far as Walker Flat (rk 206, minimum Monteith at rk 102, and median Mannum at rk 147). Upstream, the bayhead delta occupied a low-energy backwater zone at least as far as Blanchetown (rk 282). During the late-Holocene, the bayhead delta prograded downstream to Myponga (rk 130). Our results contrast conventional barrier estuary facies models (black text), which place the upstream limit of the central basin at the point where the river debouches into the lake or lagoon (i.e., Pomanda Embayment, rk 73). The Murray estuary's laminated central basin deposits have previously been identified in sediment cores (grey points) taken from within the conventional limits of the central basin (grey shaded area)\textsuperscript{23}. Our results suggest that this laminated sequence characterises the Holocene depositional fill within the Murray Gorge at least as far upstream as Monteith (rk 102) and plausibly as far as Walker Flat (rk 206; grey and blue shaded areas).

**Discussion**

Here, we assess the palaeo-Murray estuary’s response to the Holocene highstand exploring the hydrologic, hydrodynamic and geomorphic influences on the regional palaeo-environment. The experimental hydrodynamic modelling approach adopted in this study allows for the relative importance of drivers of palaeo-environmental change to be determined. Sensitivity testing for sea level, discharge, bathymetry and barrier morphology indicates sea level to be the determining factor for environmental characterisation of the palaeo-Murray estuary and the probable primary driver of change during the region’s Holocene evolution. The experimental hydrodynamic modelling approach used here subjects end-member conditions to a sensitivity analysis giving a range of plausible responses rather than an explicit replication of reality. For instance, the \( S_{\text{up}} \) (Pleistocene-Holocene boundary) surface is certainly deeper than reality at the Holocene highstand, and the \( S_{\text{up}} \) (pre-regulation) surface certainly shallower. The negligible difference in results obtained through this end-member approach signifies that our models can in fact be extrapolated to represent a reasonable approximation of reality at the Holocene highstand.

The modelled estuarine environment at highstand is well constrained by global-scale estuary initiation at 8,200 yr BP following a significant meltwater pulse from the Laurentian ice sheet\textsuperscript{34}. This event triggered major coastal change worldwide as the resulting accelerated rise in sea level caused a landward ‘jump’ in the estuarine zone\textsuperscript{34}. On a local scale, within the Lower Lakes, flood tide delta and barrier complex stratigraphic\textsuperscript{23,31,35}, diatom\textsuperscript{23,38} and midden analyses\textsuperscript{37} support the designation of the regional palaeo-environment as estuarine at the Holocene highstand. However, our results demonstrate that the estuarine palaeo-environment was not limited solely to this region. We show that the +2 m Holocene highstand drove the estuarine limit much further upstream causing an enlarged low-energy backwater setting that occupied much of the LMR (minimum tidal limit rk 282; Fig. 6). The low relief of this coastal plain facilitated an elongated central basin within the confines of the Murray Gorge, likely extending as far upstream as Walker Flat (rk 206), where the silt-clay laminated sequence that characterises the central basin deposits within Lake Alexandrina\textsuperscript{23,24} are inferred to extend (Fig. 6).
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the estuarine limit can extend significantly further inland than expected when evaluating modern-day geomorphology in the context of conventional estuarine facies models. The importance of sea level in controlling the character of the Murray estuary, irrespective of fluvial discharge, bathymetry and barrier morphology, suggests the impacts of future sea-level rise due to climate change on coastal plain estuaries may be underappreciated. Our results are broadly applicable to low-gradient coastal plain estuaries with wave-dominated entrances, particularly those with large catchments and low discharges. However, consideration must be applied to the nature of the incised valley and valley fill, dynamics of fluvial discharge and tidal regime, as well as the rate of sea-level rise/fall when transferring these results to other coastal plain estuaries. The extent and impact of sea-level rise as a driver of environmental change is largely a consequence of the inherently low gradient of these systems. This characteristic low gradient of coastal plain estuaries facilitates the landward extension of the estuarine zone rendering lower portions of the conventionally fluvially dominated zone particularly vulnerable to saline intrusion and potentially unable to support potable water or irrigation supplies. The economic and social implications of our findings to the LMR and Murray estuary, and comparable coastal plain estuaries more broadly, are considerable.

Methodology
Overview of model result categories. The study area encompasses the LMR from Blanchetown (rkm 282) downstream to the barrier complex and modern-day Murray Mouth (Fig. 1). Using TUFLOW FV, a 2D finite volume numerical model, we simulate 72 scenarios and conduct sensitivity testing for bathymetric surface (two end members and a best estimate), sea level (Holocene highstand and present-day), discharge (drought, pre-regulation average, and flood), and barrier morphology (four scenarios, ranging from completely open to almost closed, to account for barrier evolution). Results are grouped into six categories based on bathymetric surface and sea level (Table S1). The Pleistocene-Holocene stratigraphic boundary and pre-regulation surfaces represent bathymetric end-members to constrain the entire range of plausible bathymetries at the Holocene highstand. These are denoted as $S_{low}$ and $S_{mid}$ respectively. A best estimate of bathymetry at the Holocene highstand is given by the $S_{mid}$ surface. Accounting for the approximately 2 m variance in sea level between the Holocene highstand and present day gives the six modelled categories: $S_{low}$$W_{L1}$, $S_{low}$$W_{L0}$, $S_{mid}$$W_{L2}$, $S_{mid}$$W_{L1}$, $S_{mid}$$W_{L0}$, and $S_{mid}$$W_{L0}$ (Table S1). For each of these six categories, all possible combinations of discharge and barrier morphology were modelled. The three discharge scenarios of drought, pre-regulation average and flood are denoted by $D_{−}$, $D_{av}$ and $D_{+}$ respectively (Table S1). The four barrier morphologies of completely open, two evolutionary phases, and modern-day are denoted by $B_{0}$, $B_{−}$, $B_{+}$, and $B_{mod}$ respectively (Fig. 1c–f; Table S1). We obtain inundation extents, water heights and depths, flow velocities and salinities for the full extent of the LMR and Murray estuary for each of the 72 modelled scenarios.

Numerical model set up. Hydrology is simulated using TUFLOW FV, a 2D finite volume numerical model. The model domain spans some 282 rkm from Lock 1 at Blanchetown to the Murray Mouth and extending 2 km offshore. A base model was provided by BMT WBM and was the subject of vigorous calibration (Supplementary methods: Model calibration). Stitched topography and bathymetry for the region was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and provided by the South Australian Department of Environment Water and Natural Resources (DEWNR) for use in this study. Outside the extent of this dataset (1956 flood extent), a 1 second Digital Elevation Model (DEM), provided by Geoscience Australia (GA), was applied and the two datasets interpolated together using ArcGIS. This mesh was then modified to extend the model domain to encompass the entire width of the Murray Gorge, as well as the inclusion of the modern-day barrier complex and extension of the Lower Lakes based on the palaeo-maximum inundation shoreline and Holocene estuarine stratigraphy. Tides were imposed based on historical data taken from Victor Harbour between 1st January – 28th February 2014 to remove the uncertainties associated with tidal prediction (Fig. S4). Drought ($D_{−}$) and pre-regulation average ($D_{av}$) scenarios were run for 20 days while flood ($D_{+}$) scenarios were run for 31 days, which was a sufficient period for models to run beyond the spin-up phase and reach steady state, as confirmed by a review of hydrograph phasing. All models were run at a 5 minute timestep. A comparative analysis of 24 and 1 hour outputs confirmed that the 24 hour outputs were representative and, to save computational time, were subsequently applied to all scenarios. Initial salinity was applied at each cell based on salinity data taken from 25 gauging stations throughout the region at the peak of the Millennium drought. This was deemed appropriate as the barriages are in place to curtail saline intrusion and therefore regional salinities are held fresher than would naturally occur. Due to the potential influence of stratification of the estuary a representative subset of models were run in 3D to assess the suitability of adopting computationally efficient 2D models for this study. Refer to Supplementary methods: Comparison of 2D and 3D simulations for further information. The bottom drag model adopted for this study is the Manning’s coefficient, with a global value of 0.025 applied to the entire model domain. This value is supported by sensitivity testing and calibration performed by BMT WBM on the base model provided for this study, and aligns with sensible values given hypothesised Holocene regional palaeo-environmental conditions. Refer to Supplementary methods: Model calibration for further information.

Morphology. To best resolve bathymetry and topography at highstand, three surfaces were created: (1) a pre-regulation surface ($S_{pre}$) provided a modern-day end member, (2) the depth to the Monoman – Coonambidgual Formation transition provided a Late Pleistocene – Early Holocene end member ($S_{low}$), and (3) a best estimate of highstand bathymetry and topography ($S_{mid}$). Details on the creation of the three bathymetric surfaces, and chain-of-islands evolution of Sir Richard and Younghusband Peninsulas used to inform the four modelled barrier morphologies are given in Supplementary methods: Morphology.

Sensitivity testing. Sensitivity testing for barrier evolution was based on the chain-of-islands model with the location of possible palaeo-outlets interpreted from Bourman and Murray-Wallace, de Mooy and
Four barrier configurations were tested ranging from the complete removal of Sir Richard and Younghusband Peninsulas to the modern-day Murray Mouth (Fig. 1c–f; Table S1). Three discharge conditions were tested: two held constant at the Millennium drought low flow ($D_{low}$; 152 m$^3$/sec) and pre-regulation average flow ($D_{avg}$; 419 m$^3$/sec), and one variable to simulate a flood, with pre-regulation average discharge ($D_{avg}$) increasing to the peak of the 1974 flood ($D_{peak}$; 1,883 m$^3$/sec) and decreasing again47,49 (Table S1).

There have been numerous sea-level studies across Australia, with the majority stemming from east coast datasets19,49. As a consequence of isostatic and climatic influences, and localised geomorphology, there is wide variability across the Australian coast in both the magnitude and timing of the Holocene sea-level highstand19. Highstand estimates must therefore be derived from the regional setting of the study area which, for the Murray estuary, limits data to studies from the Gulf of St Vincent and the Spencer Gulf in South Australia. Immediately prior to the highstand (8,000–7,500 yr BP), sea level reached present day levels19,20,50 with the magnitude of the subsequent highstand ranging from +1 m up to +3 m across the southern Australian coast19,20. This study adopts a best approximation of a +2 m highstand at 7,000–6,000 yr BP19,20, a value which has been adopted by other studies of the Holocene palaeo-Murray estuary18. Our models were run twice – once using present day tides (WL0) and again at present day tides plus 2 m to simulate Holocene highstand conditions (WL2; Table S1).

Post-processing. Salinity was classified based on chloride concentration using Tooley’s57 scheme: fresh <0.1 g Cl/L, fresh-brackish 0.1–0.5 g Cl/L, brackish-fresh 0.5–1 g Cl/L, brackish 1–5 g Cl/L, brackish-marine 5–10 g Cl/L, marine-brackish 10–17 g Cl/L, and marine >17 g Cl/L. Salinity was assessed using maximum salinities observed post model burn-in phase. We considered maximum rather than average salinity as, due to constraints in computational power giving a 5-fold increase in model run time, salinity is not resolved in 3D therefore results do not account for a salt wedge at depth but rather depict a freshwater plume at the surface. Directional vectors were assessed within the present-day channel (and not fringing swamps) such that a direct comparison could be drawn between the three model scenarios regardless of inundation extent or bathymetrically-controlled primary flow path. Velocity magnitude was considered relative to the critical threshold of 0.3 m/s25–27 and representative models were re-run to assess tidal signatures from water levels at 1 hour outputs.

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Author Contributions
A.M.H., H.E.P. and T.C.T.H. designed the study. A.M.H. and H.E.P. developed and ran the models, and analysed and interpreted the results. A.M.H. wrote the manuscript with substantial contributions from all co-authors.

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