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Bathymetric rejuvenation strategies for morphologically degraded estuaries

Ian M. Kidd [a], [*], Jenny Davis [b], Mike Seward [c], Andrew Fischer [a]

[a] Institute for Marine and Antarctic Studies, University of Tasmania, Launceston, Tasmania, Australia
[b] Institute for Applied Ecology, Charles Darwin University, Darwin, Australia
[c] Seward Maritime, PO Box 3038, Launceston, Tasmania 7250, Australia

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ABSTRACT

Bathymetric adjustment of estuaries created by anthropogenic stressors is a common global issue. Typical stressors are tidal levees, jetties, infilling, barrages and flow redirection. Removal or alleviation of stressors should in part, reinstate previous conditions. Generic and site specific rehabilitation strategies were assessed using a simple regime model (FORM) for the excessively silted Tamar River estuary in Tasmania, Australia. The model calculated the net sediment adjustment resulting from each strategy and was applied to evaluate projects designed to mitigate previously identified stressors and two separate barrages. Results show that a combination of projects involving removal or mitigation of stressors potentially eroded $>7 \times 106$ m^3 of silt over the study area whereas both barrages caused silt accretion, one potentially doubling the volume of silt accumulated since the early 1800s. It was concluded that a substantial rejuvenation of the estuary was possible utilising various strategies, including creating a tidal lake, removing tidal levees, reconstituting an old meander system, and creating an additional waterway, whilst mainly negative trade-offs would result from installation of a barrage. In a general sense, the recommended strategies would apply to similarly degraded estuaries elsewhere.

1. Introduction

Environmental degradation of estuarine systems is a common global problem arising from multiple anthropogenic stressors including pollution, loss of riparian vegetation, alteration to hydrodynamics by levees and restrictions to silt movement (causing sediment accretion or erosion), urban and waterfront development, and sewage effluent (Moss et al., 2006). Many estuaries in the UK (e.g. the Hubble, Tees, Humber and Thames) and Europe have been restricted to the extent that they are now effectively tidal canals, with some changes dating back to Roman times (Morris and Mitchell, 2013). Bathymetries are restricted by hard-walled levees, and flows have been decimated by loss of storages, barrages and weirs (Morris and Mitchell, 2013; Morris, 2013). Urban development on old intertidal flats means that hysteresis (Suding and Hobbs, 2009) is now present and restoration to a previous state is not possible. In the USA the non-regulatory National Estuary Program (NEP) works *"to improve the waters, habitats and living resources of 28 estuaries across the country"* (https://www.epa.gov/nep accessed July 2016). Projects span the east and west coasts and Puerto Rico. In the late 2000s restoration of rivers lakes and estuaries was a $2billion per year industry in the USA with 64 dams removed in 2008 (http://www.water.ca.gov/fishpassage/docs/dams/dams08.pdf accessed July 2016). Williams et al. (2002) cite an early example from 1637 in the town of Cley in Norfolk, England where dyke removal and thus an increased tidal prism was recommended to flush sediment from the estuary.

Any increase in the tidal prism equates to the same volume of silt lost from the inter-tidal zone; it is a 1:1 zero sum game (Kidd et al., 2016), assuming tidal range is unaffected and tidal prism exchange with ground water is negligible. The tidal prism is the action and the silt loss is the reaction. The reverse is not true as equilibrium can only re-establish by further silt accretion (Davis and Kidd, 2012; Dennis et al., 2000). Kidd et al. (2016) developed a simple first order response model (FORM) to describe coastal-plain estuaries with boundary conditions of convergence, synchronicity, tidal range, storage volumes of intertidal flats, the tidal prism of tributaries and river width. FORM calculates the

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[*] Corresponding author. Australian Maritime College, University of Tasmania, Locked Bag 1395, Launceston, Tasmania 7250, Australia.
E-mail address: imkidd@utas.edu.au (I.M. Kidd).

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bathymetric change in terms of sediment volumes following permanent adjustment of a boundary condition.

The Tamar River estuary in Tasmania, Australia has been subject to multiple anthropogenic stressors resulting in the loss of important ecosystem services and values (Davis and Kidd, 2012). The degradation which has occurred since European settlement in 1806 is typical of degradation over many hundreds of years (to millennia) in other estuaries around the globe. In the Tamar, two major stressors have been identified: a reduction of the tidal prism in the main estuary due to extensive canalisation of the upper estuary; and the loss of freshwater flow from a major tributary (due to diversion for the generation of hydroelectricity). Sustainable remediation strategies which address these stressors have been suggested by Davis and Kidd (2012) including, a tidal lake, reinstatement of tidal wetlands (by removal of dykes/levees) and redirection of power station outflow. In a general sense and depending on the nature of the stressors, the strategies modelled in this study are equally applicable to estuaries elsewhere. On their website PIANC (2011) state that ‘working with nature gives a good chance of (project) success, whereas working against nature guarantees failure’, which is essentially the rationale of Davis and Kidd (2012); remove the stressors and let natural processes take their course.

As a preliminary evaluation of the proposals of Davis and Kidd (2012), FORM was used to predict bathymetric outcomes over the upper most 32 km of the Tamar River estuary (the silt belt) and give a prognosis for four specific trouble spots in the upper estuary. In addition, a new meander system and two barrage installations were considered. The aim was to identify those strategies having a high probability of success, whilst identifying trade-offs of other proposals which do not address the known stressors. Implications for asymmetrical tides, existing storages and other ecosystem services are considered.

2. Methods

2.1. Site description

The Tamar River estuary in Tasmania, Australia comprises three distinct waterways, the estuary and two major tributaries, the North and South Esk Rivers (Fig. 1). The North Esk is tidal for ~11.7 km with a tidal prism of 1,700,000 m^3 making it the more dominant of the tributaries and is, in reality, a continuation of the main estuarine channel. For the purposes of this study, The South Esk River is the first tributary and the Tailrace is the second tributary. The Esk Rivers meet at the city of Launceston (population of 90,000), approximately 70 km upstream of the estuary mouth. The lower ~30 km is a ria, confined by the bed rock of a horst and graben structure, whereas the upper estuary has the funnel-shape of a coastal-plain estuary which flows through softer silts and clays. The study area is from the high tide boundary in the North Esk River (0 m) to the limit of the silt belt 32 km downstream (Rosevears).

The estuary was classified as a mesotidal drowned river valley by Edgar et al. (2000). Tides are hyper-synchronous (Dyer, 1997; Kidd et al., 2014) and increase from 2.34 m at the mouth to 3.25 m at Launceston (Foster and Nittim, 1987). Flow velocities are asymmetrical with flood tides peaking at 0.4 m s^{-1} and ebb tides reaching 0.3 m s^{-1} (Foster et al., 1986) although higher velocities (~0.6 m s^{-1}) were recorded by Kidd and Fischer (2016) as the system neared equilibrium. Sediment which has flocculated at the salt water boundary is carried upstream and deposited in the upper Tamar River estuary, lower South Esk (Yacht Basin) and lower North Esk estuary, but only in times of low freshwater inflows (Foster et al., 1986), (Fig. 2). At equilibrium this effect is balanced by the combined mechanisms of dwell at high water and high velocities before low water which induce sediment flux in the downstream direction (Kidd and Fischer, 2016).

Drinking water is drawn from both Esk Rivers and the Trevallyn Dam on the South Esk River feeds water to a hydro-electric power station via a diversion tunnel. The outflow from the station meets the estuary at the Tailrace (Fig. 1). Prior to the building of the Trevallyn Dam (1955) and the flow redirection through the Tailrace, the South Esk River flow varied from a monthly mean of ~20 m^3 s^{-1} in years of low rainfall, to ~150 m^3 s^{-1} during years of high rainfall (Foster et al., 1986). The mean power station use is 50 m^3 s^{-1} which includes 20 m^3 s^{-1} due to an inter-basin transfer. In 2011 the power station operators (Hydro Tasmania) increased discharge through the Cataract Gorge from 1.5 m^3 s^{-1}–2.5 m^3 s^{-1} for environmental reasons, although the legal requirement is only 0.43 m^3 s^{-1}.

Secondarily treated effluent from a waste water treatment plant enters the estuary opposite the power station outflow at Ti-tree Bend and from several other sites. The upper reaches of the estuary have undergone considerable in-filling, realignment, and draining (Davis and Kidd, 2012) resulting in a ~30% loss of tidal prism since settlement. Reduction of flow in the first tributary is a major stressor as is the realignment of the mouth of the North Esk River. The stressors combined with the cessation of dredging in the 2000s, have resulted in excessive silt accretion as the estuary establishes a new equilibrium between the tidal flows and cross-sectional areas. This causes problems at (Site #1) the Seaport marina 11.5 km from the tidal limit of the North Esk, (Site #2) Kings Wharf (12.5 km), (Site #3) Rosevears (27 km) and (Site #4) the Yacht Basin (11.7 km) (Fig. 2).

The study area includes Tamar Island wetland (Fig. 1) between 17 km and 22 km from the head which has undergone a huge silt accretion since settlement (Fig. 3). This is an important habitat for migratory species which are protected by the Japan Australia Migratory Bird Agreement (JAMBA) and the China Australia Migratory Bird Agreement (CAMBA). In the early 1900s, excavation commenced on a diversion across Stephenson's Bend; known as Hunter's Cut (Fig. 1). The objective was to mitigate flood effects but the attempt failed due to instability of the banks.

A floating marina at the mouth of the North Esk is severely affected by silt (Fig. 2). Rowing and sailing have been seriously curtailed, and soft mud banks represent both a physical and health hazard (BMT_WBM, 2008; Seen et al., 2004). Studies have been commissioned (BMT_WBM, 2008; Foster et al., 1986) on the silt accretion issue with recommendations including: do nothing; run the power station against the flood tide; continue dredging; and installing a barrage. Davis and Kidd (2012) rejected each of these and suggested projects acting against the stressors they identified in the system.

Visually, the first tributary (the Yacht Basin) appears to be the main estuary but this is not the case (Fig. 4). Foster and Nittim (1987), disregarded the influence of the main estuary from 0 m to 11,700 m (the North Esk River) because of the small watershed and riverine flow <10 m^3 s^{-1} compared with the combined discharge of the first and second tributaries >50 m^3 s^{-1}, emanating from a much larger watershed. However, the first and second tributaries have lesser influence on estuarine hydrology due to the small tidal prism of each, albeit floods through the Cataract Gorge are the major scouring mechanism for the Yacht Basin and Home Reach. Suspended sediment concentrations increase as a power function of river discharge (Campbell and Bauder, 1940), so Foster and Nittim (1987) were correct in that most silt enters the estuary through these tributaries but the large tidal prism of the main estuary (the North Esk River) provides the greatest influence on the equilibrium position. This is a paradigm shift in the understanding of the hydrology, sedimentary processes and problems in the estuary.