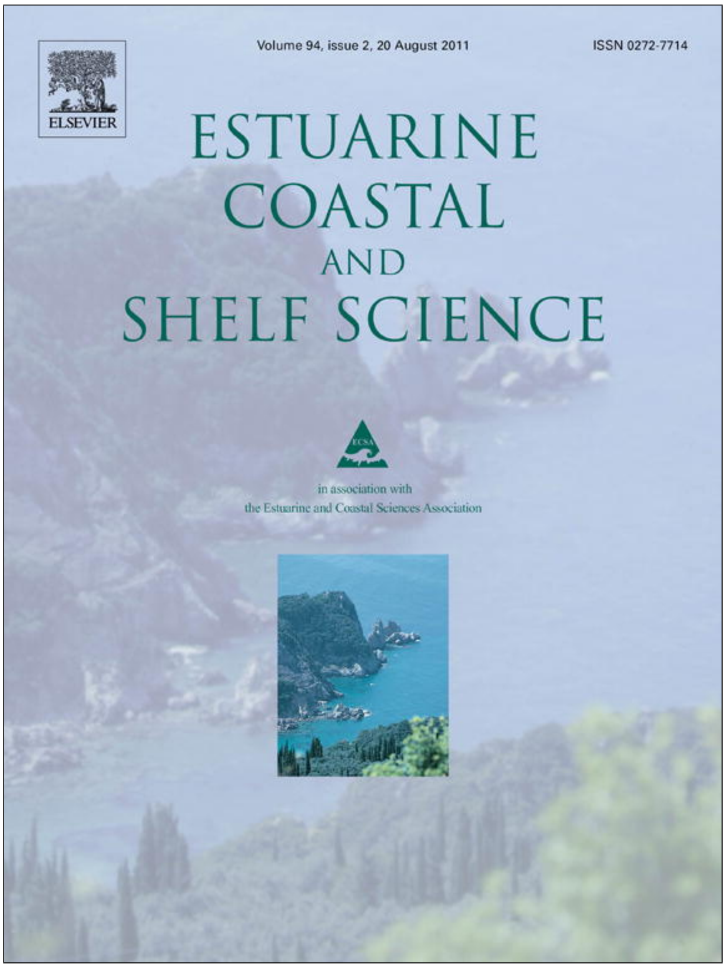
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Short communication

Global extent and distribution of artificial, residential waterways in estuaries

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ABSTRACT

Artificial residential waterways are now widespread in the world's estuaries. We used the global mapping tool, Google Earth, to determine that there are nearly 4000 linear km of artificial waterways globally, covering an area of 270 km^2. Residential waterways constructed as open, flow-through canal estates are at their greatest extent in North America (77% of global linear extent), where systems are typically longer and narrower, with more openings and dead-ends than systems elsewhere. The remaining canal estates are spread across all other continents except Antarctica: Asia (7%), Europe (7%), Oceania (7%), South America (0.9%), and Africa (0.6%). A relatively recent design change from open canals to artificial estuarine lakes with tidal barriers has occurred on all continents except Africa, most extensively in Australia (14 km^2 area, 57 independent systems). The extremely large expansion in artificial residential waterways aimed at increasing opportunities for waterfront living by humans has also modified and expanded estuarine habitat available to aquatic biota. Research can best underpin planning and management of these types of waterways by focussing on their value as habitat and their provision of other goods and services.

1. Introduction

An increasing human population is placing pressure on coastal habitats in many places worldwide (Kennish, 2002) and the uncontrolled expansion of urban development is one of the most serious anthropogenic disturbances affecting estuarine environments (Lee et al., 2006; Dennison, 2008). Artificial habitats often have different physical properties to the natural habitats that they replace as they are built to serve engineering and planning purposes such as preventing erosion or providing hard structures in a predominantly soft environment. Large-scale urban development has resulted in both the destruction and creation of habitat for wildlife in estuaries and hence the extent to which the created habitats mimic natural habitat is the subject of investigation in many places (Chapman and Underwood, 2009).

Estuaries typically have minimal fringing land suitable for waterfront residential living. To capitalise on the demand for coastal real estate with water frontage, property developers have claimed extensive areas of low-lying coastal land for construction of artificial residential waterway developments. They can be constructed either by: (1) dredging and claiming natural wetlands such as areas of saltmarsh or mangrove (defined as Heavily Modified Water Bodies; European Commission, 2003), or (2) creating them in terrestrial environments beyond natural tidal levels as new and additional habitat not previously available to aquatic biota (defined as Artificial Water Bodies; European Commission, 2003). Systems constructed using each of these methods occur in estuaries across a variety of different geomorphological types (see definitions in Elliott and McLusky, 2002; Durr et al., 2011), and occasionally on open coasts where they nevertheless have brackish water at least some of the time because, by design, they take local freshwater runoff. In Europe, where the development of formal definitions for different types of Transitional Waters is most advanced, the categorisation of waterways has significant implications for the type of water quality and/or ecosystem health monitoring required by law (McLusky and Elliott, 2007; Lucena-Moya et al., 2009; Uriarte and Borja, 2009).

Artificial residential waterways differ from the shallow wetland habitats they replace (Morton, 1992). They are usually deeper (to increase navigational access), have disturbed and oxidized coastal soils (potentially forming sulphuric acid during construction), receive high loads of untreated urban stormwater from surrounding residential areas, and experience poor water

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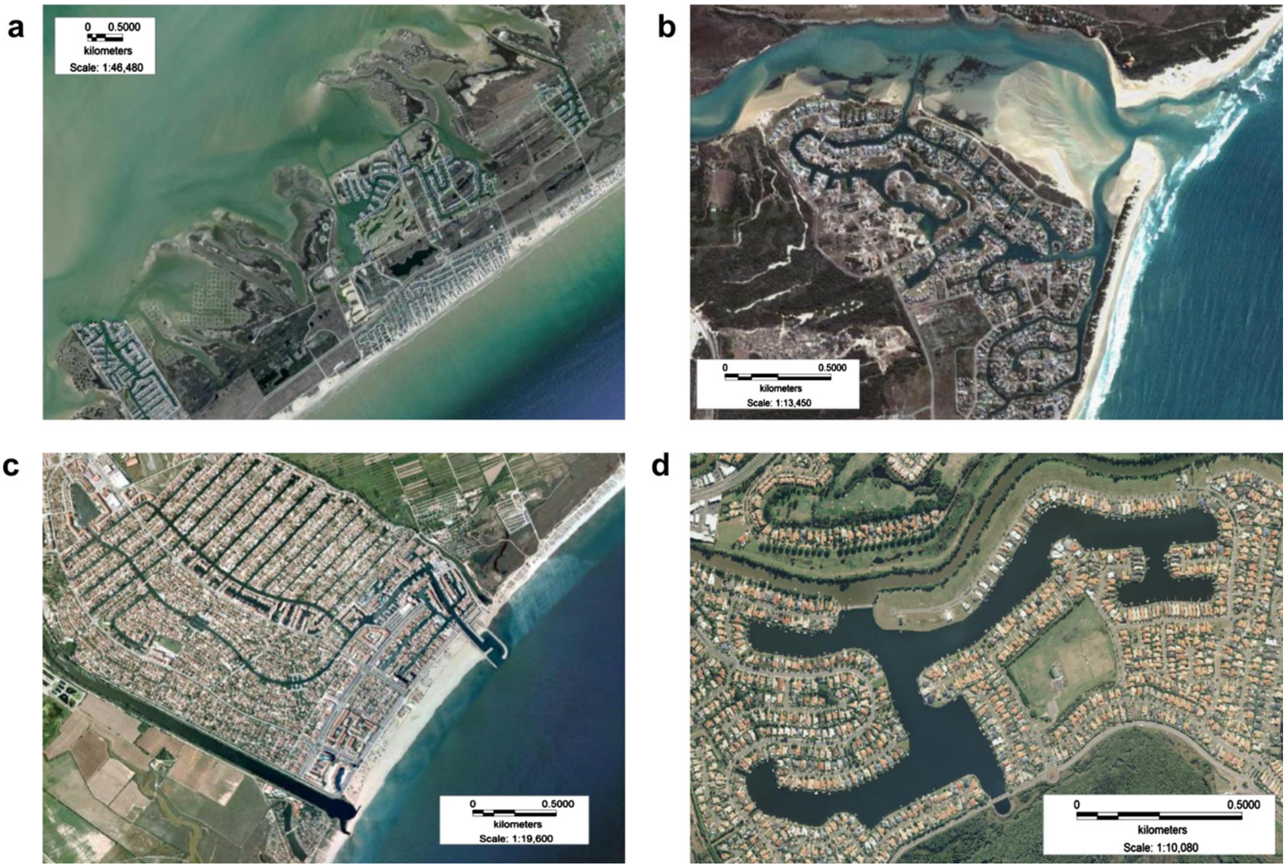

Fig. 1. Google Earth example of artificial residential waterways, a) canal estate in Galveston Bay (Texas, USA) 29°11′40.69″N, 94°58′57.51″W; b) canal estate in Kromme Estuary (South Africa) 34°08′47.74″S, 24° 49′59.74″E; c) canal estate in Empuriabrava Bay (Spain) 42°14′56.39″N, 3°7′7.10″E; and d) lake estate separated from the adjacent estuary via a tidal control device on the Gold Coast (Australia) 27°53′07.76″S, 153°20′28.89″E.

circulation and water quality, particularly in low-flow, dead-end areas (Lindall et al., 1973). These characteristics raise the issue of their value as fish habitat (Lindall and Trent, 1975; Waltham and Connolly, 2006) and their potential role in reducing pollutant loads before estuarine waters enter the sea (Gaston et al., 2006).

In many places, constructed estuarine waterways have proliferated by connecting more and more canals to existing systems, without regard to the hydraulic consequences (Waltham and Connolly, 2007). Increasing the tidal compartment of canal estates and adjoining estuaries leads to higher tidal velocities in the lower reaches, which causes foreshore erosion and undercuts revetment walls, damaging residential properties and infrastructure (Zigic et al., 2005). In response, property developers have begun to shift the design of residential waterways from open-flow canal estates to developments separated from downstream waters via tidal control devices (e.g. locks, weirs, gates, pipes). These can be built further landward without adverse consequences for the downstream tidal prism (Zigic et al., 2005).

The extent of estuarine residential waterways has previously been quantified for specific locations, e.g. Florida Keys, USA, has 175 km of linear habitat (Kruczynski, 1999); Venice, Italy, has 40 km of linear habitat (Dabala et al., 2005). It is clear from the scientific literature that canals are much more widespread than this, viz.: Texas and Maryland, USA (Trent et al., 1972; Maxted et al., 1997); South Africa (Baird et al., 1981) and Australia (Morton, 1989; Connolly, 2003). Given the potential for a major, new artificial habitat to be important in estuarine science, we measured the global extent and geographic characteristics of artificial residential waterways using the global mapping tool Google Earth.

Table 1
Extent and distribution of artificial residential waterways in estuaries globally and for each continent.

Continent	Canal			Lakes			Total	
	Length (km)	Area (km^2)	Number of systems	Length (km)	Area (km^2)	Number of systems	Length (km)	Area (km^2)
Africa	23	1	6	0	0	0	23	1
America (Nth)	2949	166	131	11	5	19	2960	171
America (Sth)	37	13	8	1	1	3	38	14
Asia	285	33	21	15	10	8	300	43
Europe	276	8	23	4	1	4	279	9
Oceania	264	21	36	117	14	57	381	35
Total	3843	242	225	148	31	91	3981	273

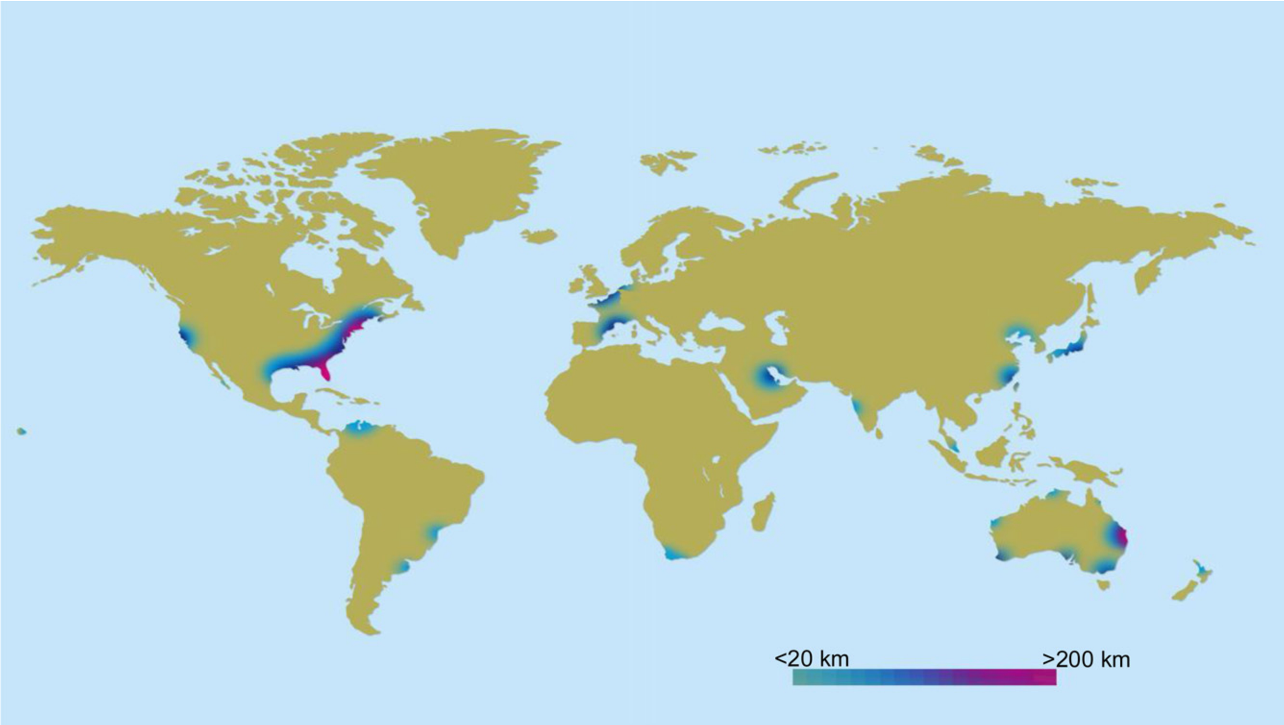

Fig. 2. Global extent of artificial residential estuarine systems (canal and lake estates combined), by country and (where relevant) state or province within country. Colour gradient represents total linear length (km).

2. Methods

We used Google Earth to:

(1) record the location of artificial residential waterways;
(2) determine the length, width, surface area, number of openings and dead-ends in each system; and
(3) compare the extent of the two different artificial residential waterway designs: canals (Fig. 1a, b and c) and lakes (Fig. 1d).

The total linear extent was measured using the scale ruler function in Google Earth. Google Earth has become a useful mapping tool and is considered accurate when measuring distances across low-relief surfaces such as estuaries and sandy coastlines (Nicolas et al., 2010; Harris et al., 2011). Area was determined by calculating the average width of each system (of three widths measured at haphazardly selected points, one in the distal first third, one in the mid third and one proximate to the confluence with the downstream waterway) and then multiplying by the linear length. The number of openings and dead-ends for each system was also recorded.

As we could not physically visit each identified system to confirm whether it was an artificial residential waterway or a natural estuary with some urban modification of the foreshore, we established the following set of criteria and definitions. An artificial residential waterway:

(1) has >50% of its edge appearing straight or unnaturally smooth;
(2) has >50% of its perimeter being utilised for residential living;
(3) is defined as a "canal estate" unless the average width is >100 m, or there is an obvious control device restricting tidal exchange with the source estuary, in which case it is defined as an "artificial lake", and
(4) excludes waterways that are primarily boat havens or marinas.

We used several methods to determine that systems were estuarine. Waterways with entrances from coastal rather than truly estuarine waters were included. These were considered to be estuarine by design, as they receive local freshwater runoff from urban stormwater and/or stream flow. For the more extensive artificial systems, we searched for local references or maps indicating the boundary between fresh and brackish waters. The determination of freshwater reaches led, notably, to the exclusion of the renowned artificial waterways of Amsterdam, Netherlands, which when constructed were partly brackish and partly fresh, but have since been rendered entirely fresh by the construction of weirs seaward of the canals. In Florida, where the extremely large area of artificial waterways now obscures the extent of estuarine waters, we were guided by local maps of the original extent of estuaries; where these were unavailable we only included systems up to 3 km from the coastline (where the coastline was defined to include the boundary of natural inlets), a distance based on the typical distance we noted where maps existed (and, if anything, possibly underestimating the extent of estuarine waters and therefore canals).

The dates of aerial images used in Google Earth were the most up-to-date available at the end of 2007, although we also examined earlier, archived images to overcome situations where the details of systems were obscured by cloud cover.

3. Results

Artificial residential waterways are present on every continent except Antarctica, with a collective total of nearly 4000 linear km globally, and an associated surface area of over 270 km^2 (Table 1, Fig. 2). North America has the greatest extent of canal estates, representing 77% of the global linear length and 69% of global surface area (Table 1). Individual canal systems in North America are on average longer and narrower, with a greater number of

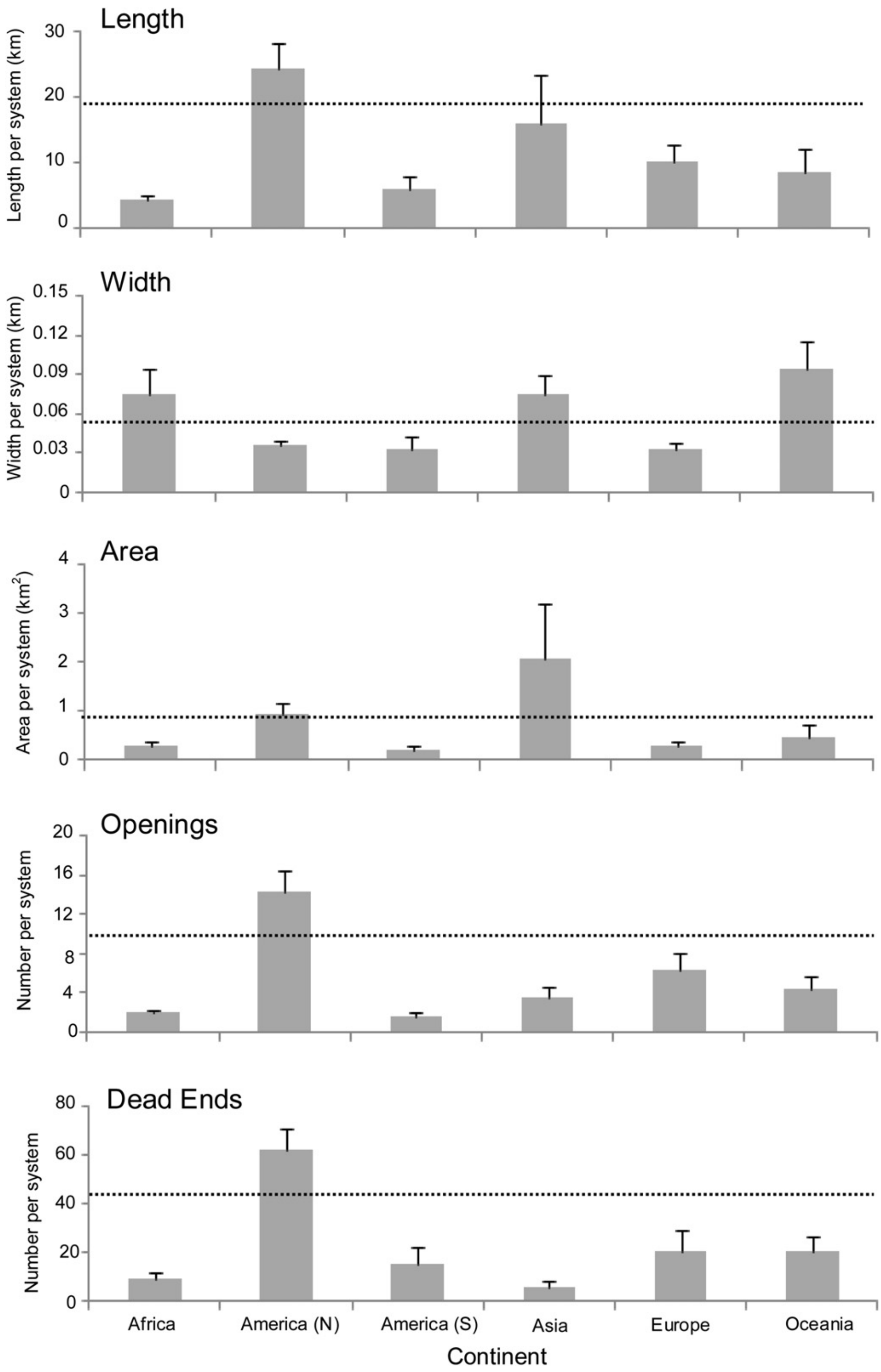

Fig. 3. Quantification of design characteristics (mean, SE) of canals (excludes lakes) for each continent. Dashed line is global mean based on all canal systems combined (number of canals is shown in Table 1).

openings and dead-ends per system than elsewhere (Fig. 3). Within North America, most canal estates are in Florida (Miami, Tampa Bay and Cape Coral) with 1915 km linear length (65% of North American total) and 160 km^2 area (60% of North American total). Other concentrations of canal estates in North America occur in the states of New Jersey, California, Louisiana and Texas (Fig. 1).

Artificial lakes make a relatively small contribution to the overall extent of artificial residential waterways (3% and 10% of the global linear length and surface area respectively; Table 1). The greatest number of artificial lake systems occurs in Oceania (63% global number and 45% global surface area). Within Oceania, a major concentration of lakes occurs in Australia, on the Gold Coast, Queensland (more than 95% of the total Oceania number and 97% of the total Oceania surface area). Lake designs showed few patterns across continents (data not shown), except that lakes in Asia were notably larger than elsewhere (area of Asian lakes on average > 1 km^2, all other continents < 0.5 km^2).

4. Discussion

This is the first quantification of the global extent of artificial residential waterways in estuaries. Their extent is far more widespread than previously reported in the peer-reviewed literature, extending beyond the few locations identified (i.e. limited locations in North America, Europe, Australia, and South Africa). The global total linear length of artificial residential waterways is comparable to the entire length of the Mississippi River, USA (3765 km), and with a total surface area equivalent to 38000 FIFA football fields. In many cases these constructed waterways have replaced natural coastal habitats (e.g. mangroves and saltmarsh; Kinch, 1979; Baird et al., 1981; Morton, 1992), although more recently some have been constructed from terrestrial habitat, in which case they represent a major extension to habitat available to aquatic biota (Waltham and Connolly, 2007).

The greatest extent of flow-through canal estates is in North America, and specifically in the state of Florida. Generally, canal estates in North America are more highly ramified, meaning that individual systems typically exceed the global average for canal length, number of openings and number of dead-ends. The high degree of ramification may underlie the lower abundance and diversity of fish and macroinvertebrates in canals than in adjacent natural estuaries that has been shown in the USA (Trent et al., 1972; Kinch, 1979; Maxted et al., 1997). It might also have contributed to the poor water quality, algal blooms and hypoxic conditions experienced in some canal estates in USA (Maxted et al., 1997; Kruczynski, 1999). Attempts have been made to improve water quality in these systems by installing mechanical aeration devices and pumping systems to increase circulation (e.g. in Florida, Kruczynski (1999).

The position of canal estates in low-lying, estuarine areas means that they are likely to be greatly influenced by any changes to coastal waters. Under climate-induced increases in water temperature, and perhaps also because of increased dissolved CO_2 concentrations, water column productivity in coastal areas is likely to be stimulated (Najjar et al., 2010). This typically results in, at times, lower dissolved oxygen concentrations, which will exacerbate the issue of low dissolved oxygen that sometimes occurs in the dead-ends of canal systems (Maxted et al., 1997; Kruczynski, 1999; Waltham and Connolly, 2007). Coastal inundation as sea levels rise is particularly critical in low-lying, estuarine environments (Scavia et al., 2002), precisely the position that canal systems occupy. A major incidental, unplanned consequence of canal estate development is that, because of their hard edges and residential buildings immediately on the water line, the future climate adaptation option of allowing the coastline, and its associated habitats, to retreat is precluded.

Artificial lakes with restricted tidal exchange are present in most continents, especially in Australia. While this design change has been considered an engineering success because it reduces hydraulic velocities while still allowing further landward development to occur (Zigic et al., 2005), there is as yet little information about the effect of this reduced connectivity on water quality, or on the use of artificial lakes by aquatic organisms (Moreau et al., 2008; Sheaves et al., 2010). The option of building lakes could, in fact, be useful in the sequestration of anthropogenic pollutants and subsequently the protection of natural coastal wetlands, in much the same way that artificial wetlands are used in the treatment of sewage effluent and thus protection of downstream receiving waters (Greenway, 2005).

There is very limited scientific literature on canal water quality and ecology, with only a handful of peer-reviewed publications available to support urban planning and restoration decisions for new development proposals (several of those being published more than thirty years ago). The very substantial extent of artificial residential waterways makes them deserving of greater attention from estuarine scientists. There exists an opportunity for collaborative international research to provide comparative data on their ecological role, for example, as additional fish habitat. Such research should attempt to determine global patterns in ecosystem structure and function, to take our understanding beyond the patchy local knowledge currently available. One of the major challenges facing coastal managers is being able to sustain the ecosystem goods and services provided by natural habitats while still allowing human land-use changes (Dobson et al., 2006). Where canal estates replace natural wetland habitats there might well be a net loss of services. On the other hand, the creation of aquatic habitat in canals constructed in terrestrial ecosystems might enhance the quality of the overall aquatic habitat (sensu Elliott et al., 2007), and is a topic worthy of further research. New information arising from such research would assist in the management of existing systems and better inform future urban planning decisions.

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