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Environmental consequences of a power plant shut-down: A three-dimensional water quality model of Dublin Bay

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ABSTRACT

A hydro-environmental model is used to investigate the effect of cessation of thermal discharges from a power plant on the bathing water quality of Dublin Bay. Before closing down, cooling water from the plant was mixed with sewage effluent prior to its discharge, creating a warmer, less-saline buoyant pollutant plume that adversely affects the water quality of Dublin Bay. The model, calibrated to data from the period prior to the power-plant shut-down (Scenario1), assessed the water quality following its shut-down under two scenarios; (i) Scenario2: continued abstraction of water to dilute sewage effluents before discharge, and (ii) Scnenario3: sewage effluents are discharged directly into the Estuary. Comparison between scenarios was based on distribution of *Escherichia coli* (*E. coli*), a main bathing quality indicator. Scenarios1 and 2, showed almost similar *E. coli* distribution patterns while Scenario3 displayed significantly higher *E. coli* concentrations due to the increased stratification caused by the lack of prior dilution.

1. Introduction

Thermal discharges into marine waters may cause serious perturbations in the natural marine environment. The change in the temperature regime and the associated reduction in the saturation levels of dissolved oxygen both adversely impact on aquatic and benthic communities (e.g. Choi et al., 2012; Chuang et al., 2009; Martinez-Arroyo et al., 2000; Syed Mohamed et al., 2010).

Another major environmental consequence is the increased stratification of receiving waters (e.g. Jiang et al., 2003; Kolluru et al., 2003; Lowe et al., 2009; Wu et al., 2001). These can profoundly limit the assimilation of polluting discharges by preventing the mixing between the warmer upper levels and the cooler water underneath. Moreover, if pollutants are added to the flow with, or subsequent to, the thermal discharge the pollution will, nearly invariably, remain in the upper, warmer layer (Ellis et al., 1989). The presence of pollutants in the discharged cooling water has been reported in a number of studies (see Langford, 1990). These include chlorine (Fernandez Torres and Ruiz Bevia, 2012; Ma et al., 1998; Marcos et al., 1997), heavy metals (Abdul-Wahab and Jupp, 2009; Baba et al., 2003; Gong et al., 2010), and flue-gas desulpherisation effluents (Liu et al., 2003; Mohsen, 2004; Van Den Hende et al., 2011).

Discharging municipal wastes to the same receiving waters may considerably exacerbate the stratification. The fate and transport of pollutants from sewage works into coastal waters is well-documented (e.g. Bouvy et al., 2008; Dhage et al., 2006; Mozetix et al., 2008; Nicholson et al., 2011; Vijay et al., 2010), however there is a lack in literature on the interaction between municipal sewage effluents and thermal discharges from power generation plants, when both occur together, despite their importance as highlighted by Bedri et al. (2011). The worst case scenario of such interaction occurs when municipal sewage effluents are directly mixed with cooling water prior to discharge. This was typically the case in the Liffey Estuary, Dublin which has received combined discharges from Ireland's largest power generation station at Poolbeg and Ringsend sewage treatment plant creating a warm, less-saline layer that remained buoyant on the water surface. The effect of the combined discharge is two-fold; (i) the heated discharges reduces oxygen levels in the Estuary (O'Boyle et al., 2009) which in turn negatively impacts on the estuarine fish species, some of which are of international conservation importance (Hartnett et al., 2011; Jovanovic et al., 2007) and are listed in the EU Habitats Directive 92/43/EEC (EEC, 1992), and (ii) the buoyant sewage plume affects the compliance of waters of Dublin Bay (into which the Liffey Estuary flows) to the microbial standards of the Bathing Water Directive 2006/7/EC (EC, 2006) at beaches of high recreational and national importance (ERU, 1992; Wilson et al., 2002).

In 2010, the Poolbeg power generation plant was closed as part of a competition agreement with the Irish Energy Regulators to facilitate the introduction of additional energy providers to the

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Irish market. As a result the thermal discharges into the Estuary have ceased and this is expected to alleviate the stress on the aquatic life in the Estuary. However, due to the continued municipal sewage discharge from Ringsend the effect of the shut-down of the power plant on the water quality in the Estuary and inner Bay requires investigation. The available annual records of microbial water quality monitoring data are not sufficient to investigate this question, because (i) the data records consists of discrete samples collected only during the bathing season (May–September); and (ii) lack of long term data for the period after the Poolbeg plant shutdown. Therefore there is a need to use a numerical model to study the effect of the cessation of thermal discharges on the water quality of Dublin Bay.

Numerical models have become valuable tools for studying the effect of discharges into the marine environment. These models vary in level of complexity and modelling approaches as they can be length scale and entrainment models (e.g. Daviero and Roberts, 2006; Donker and Jirka, 2007; Frick et al., 2003; Jirka, 2004, 2006), or particle tracking models (e.g. Havens et al., 2010; Korotenko et al., 2004; Miyake et al., 2009; Perianez and Caravaca, 2010), or hydrodynamic models (e.g. Casulli and Walters, 2000; Falconer, 1986; Hervouet, 2007; Lesser et al., 2004; Warren and Bach, 1992). While the first two types are most suitable for representing the mixing processes in the vicinity of the discharge outfalls (near-field), hydrodynamics models allow for accurate and robust representation of processes in both near- and far-field regions of the discharge outfalls. Hydrodynamic models can be two-dimensional (depth-averaged) for well-mixed conditions (e.g. Abbaspour et al., 2005; Cea et al., 2011; Kashefipour et al., 2006) or three-dimensional where vertical mixing is absent/limited in the vicinity of the outfall due to density variation (e.g. Bedri et al., 2011; Kolluru et al., 2003; Liu et al., 2007; Signell et al., 2000). Hence a three-dimensional hydrodynamic model is needed in the current case study to represent the density-driven flow processes.

The three-dimensional model, TELEMAC-3D (EDF, 1997; Hervouet, 2007), is used in this study to simulate the stratification status, in the estuary before and after the power-plant shut-down, and its subsequent effect on the transport and fate of pollutants. The model was first calibrated based on measured hydrodynamic and water quality data from the period before the cessation of thermal discharges (Scenario1). Then, the calibrated model is used to assess the bathing water quality in the inner Bay for the period following the shut-down of the power generation plant and continued sewage discharges, under two likely scenarios: (i) do nothing scenario where sewage effluent is discharged directly into the Estuary, and (ii) dilution scenario: where a continued abstraction of estuary water is used to dilute sewage effluent before being released into the estuary.

In this paper, Section 2 describes the study area and the main environmental pressures on its water quality. The main equations of TELEMAC-3D are outlined in Section 3, followed by a description of the configuration of the model to represent the study area and choice of the modelling scenarios to study. The modelling results are presented in Sections 5 and 6, and the conclusions drawn from these results are summarised in Section 7.

2. Case study

The study area comprises the Liffey Estuary and Dublin Bay, on the east coast of Ireland. Dublin Bay, bounded by the rocky headlands of Howth Head and Dalkey on its Eastern side (Fig. 1), is about 10 km wide at its mouth and has an area of about 100 km^2. The bed of the bay slopes gently seawards (to the East) from low water to a depth of about 12 m, thereafter it slopes more steeply to reach 20–25 m approximately on the line between the headlands. The Bay receives freshwater inflows from the Liffey River.

The Liffey Estuary covers a wide area of 5 km^2 and is narrowed down at its outlet by the North and South Walls. The Estuary is macro-tidal (Dyer, 1973) having a mean tidal range of 2.75 m and average mean spring and neap tides of 3.6 m and 1.9 m respectively (Mansfield, 1992).

The main freshwater inflow into the Estuary is from the Liffey River which flows through the City of Dublin. This is regulated by an upstream hydro-electric plant and dam resulting in a smoothly varying inflow of freshwater (approx. 12.42 m^3/s) with considerable attenuation of its floods. The river is tidal all the way through the City of Dublin up to distance 10.5 km upstream of Poolbeg.

Two main structures lie, close together, on the south bank of the Liffey Estuary: the Electricity Supply Board (ESB) power generation plant at Poolbeg and Ringsend Sewage Treatment Works. The ESB power generating facility at Poolbeg, Dublin (Fig. 2) was, when working, the largest gas and oil plant in the country with an installed capacity of 1020 MW.

The steam-driven generating equipment required 2.1 million cubic metres a day of once-through seawater to cool the heat exchanger and discharged the heated water into the estuary at a temperature of 7–9 °C above ambient. Before being discharged (approximately 120 m upstream of the discharge weir), the cooling water from this plant was mixed with the sewage effluent from Ringsend Treatment Works creating a warm and less saline pollutant plume that remains buoyant on the water surface in the Estuary. The ESB power plant was closed down in 2010 following an agreement between the ESB and the Irish Energy Regulators.

In 2003, Ringsend (STW) was expanded to cater for a population equivalent of 1.7 million. A 10.5 km submarine pipe (Fig. 2) was constructed to bring wastewater from North Dublin to Ringsend. The plant includes primary, secondary treatments, and Ultra-Violet disinfection (used only during the bathing season) to help meet EU Bathing Water Directive (2006/7/EC) standards for microbial water quality indicators (*Escherichia coli* (*E. coli*) and Intestinal Enterococci (IE)) at recreational beaches on the north and south inner Bay (e.g. Dollymount, Sandymount and Merrion Strand).

In the past, prior to the Poolbeg plant shut-down, a number of ad hoc water quality surveys were conducted (e.g. Bedri, 2007; Crisp, 1976; DCC, 2002, 2003; Mansfield, 1992) to monitor water quality parameters including *E. coli* and IE in the Liffey Estuary and Dublin Bay. At the present, the only on-going monitoring programme is that carried out by Dublin City Council (DCC) during the months of May–September at bathing sites to test their compliance with the *E. coli* and IE standards of the EU Bathing Water Directive (2006/7/EC). However, the *E. coli* and IE data record is insufficiently detailed to deduce any changes in the microbial water quality trends after the shut-down of the power plant at Poolbeg and therefore it has not been included in the current study.

3. TELEMAC-3D model

The TELEMAC-3D model, developed by the National Laboratory of Hydraulics and Environment of Electricité de France, was selected for the study because it includes the following essential features: (1) the use of a finite element unstructured grid which allows selective refinement of the mesh at key locations in the domain and boundary fitting (sigma transformation) method for vertical discretisation; (2) density-driven hydrodynamics allowing for a robust treatment of the stratified plume, essential for this study; (3) heat exchange with the atmosphere; (4) the availability of a range of options for vertical turbulence modelling including the