THE EFFECTS OF FRONTAL SYSTEMS ON MIXING IN ESTUARIES

R.W. Duck[1] and J. McManus[2]

[1]*Department of Geography, University of Dundee, Dundee, DD1 4HN, Scotland r.w.duck@dundee.ac.uk*
[2]*School of Geography and Geosciences, University of St Andrews, St Andrews, Fife, KY16 9AL, Scotland jm@st-andrews.ac.uk*

ABSTRACT

The existence of salinity and suspension gradients in estuarine waters has been known for two centuries. The recognition of the presence of transverse fronts delineating the boundary between saline and fresh waters, and later detection of other frontal systems along the principal direction of flow, have led to reassessment of the nature of mixing in estuaries. Fronts serve to inhibit dispersion and compartmentalise the water mass. Convergent flows with important velocity components towards fronts at the surface induce the surficial foam and flotsam bands by which their locations are seen. In the presence of fronts, diffuse and point source pollutants released into marginal waters will not become transferred to the main body of the tidal prism and may not become dispersed widely. In the past, most models of pollutant dispersion in estuaries have assumed uniform dispersion across the entire water mass. In this paper, this fundamental assumption is challenged.

Keywords: diffuse pollution, dispersion, estuaries, frontal systems, point source pollution.

INTRODUCTION

Salinity and suspension concentration variations have been known to exist in estuaries since the pioneering observations of Fleming (1816) on the Tay Estuary of Scotland. Fleming collected water samples from the surface, mid-depth and near the bed in the centre of a channel at four stages of a spring tide, and determined the salt and suspension content after evaporation to dryness. From his observations he concluded that the near bottom waters were generally of higher salinity than those at the surface and that the interface between the two took the form of an inclined plane sloping upstream.

Subsequently salinity variations within estuaries have provided the physico-chemical basis for the long-established classification of estuaries into 'salt wedge', 'partially-mixed' and 'well-mixed types' (Pritchard, 1967; Dyer, 1986). In the salt wedge estuary the relatively fresh water lies upon the more saline bottom waters along a readily detectable boundary, a type of frontal system or front, known as the halocline, which extends across the estuary.

The advent of remote sensing technology permitted Klemas and Polis (1977) to identify the presence of longitudinal fronts, which are typically recognised by the presence of foam bands on the water surface, extending 'for tens of miles' in the Delaware Estuary, U.S.A. Largier (1993) provided a general description of a front as 'a meeting of waters', with a fuller definition, 'a region characterised by an anomalous local maximum in the horizontal gradient of some water property (e.g. temperature, salinity, nitrate concentration, chlorophyll concentration)'.

In the last two decades the presence of transverse estuarine fronts dividing waters of contrasting salinities, suspended sediment concentrations and thermal characteristics has been increasingly explored (Simpson and Nunes, 1981; Simpson and Turrell, 1986). In many estuaries axially convergent longitudinal frontal systems also give rise to adjacent water masses with contrasting physical, chemical and sedimentological characteristics (Lavoie *et al*., 1985; Nunes and Simpson, 1985; Bowman, 1988; El-Sabh, 1988; Huzzey and Brubaker, 1988; Turrell and Simpson, 1988). Multiple longitudinal fronts are present in many estuaries, five being detected across some reaches of the Tay Estuary, during the rising tide (Anderson 1989). Both the influent and effluent waters become subdivided into a series of longitudinal slices some of which shear past each other and others meet along convergent fronts. Fronts may originate at headlands or positions of marked subsurface bathymetric change, but many relate to the margins of longitudinal sandbanks, the positions of which may subsequently become frontally controlled (McManus, 2000).

POLLUTANTS IN ESTUARIES

Throughout the world estuaries have long provided foci for settlement and industry. Under ideal circumstances the mobility of the tidal prism, with its net seaward progress, has provided a means of removing wastes discharged into the waters. However, unless carefully controlled, the effluent discharges from point sources may be carried landward with the rising tide before being carried seaward on the falling stage of the tide, perhaps to remain migrating up and down the estuary for several tidal cycles before reaching the open sea.

An aerial survey of 26 estuaries in England and Wales has shown the presence of foam bands indicating the presence of axially convergent frontal systems in no less than 15 cases (Brown *et al*., 1991). These authors also point out that buoyant pollutants, concentrated along the foam bands along with flotsam and detritus, may become stranded on the margins of emergent estuarine sandbanks on the falling tide. Furthermore, Szekielda *et al*. (1972) noted that when surface water films were accreted into foam lines along estuarine fronts, metal enrichment of 'thousands of times greater' than background could result for chromium, copper, lead, mercury, silver and zinc. Phytoplankton chlorophyll also collects along such boundaries and is transported into the water column by down-welling. Similarly Klemas and Polis (1977) suggested that fronts strongly influence pollutant dispersion, by 'capturing' oil slicks and other pollutants concentrated in surface films and drawing them down into the water column.

In an early study Klemas (1980) reported suspension concentrations as determined by Secchi disc depth varying between 1.0 and 2.2 m across a transverse wedge front, and 0.4 to 1.6 m across a longitudinal front, indicating well defined changes in water transparency. Other authors (e.g. Pinckney and Dustan, 1990; Reeves and Duck, 2001) have drawn attention to the sharp turbidity gradients associated with some estuarine fronts. Reeves and Duck (2001) further suggested that the patchiness in suspended sediment concentrations associated with estuarine turbidity maxima (Dyer, 1994) may actually be due to compartmentalisation of these zones by fronts. By implication, if the suspended sediment concentrations are sub-divided by fronts, so too will be any associated pollutants.

The existence of inclined zones of disturbance in the water column extending from the surface to the bed along the planes of longitudinal fronts was demonstrated by Duck and Wewetzer (2001) who noted sharp contrasts in bedform size and geometry on either side of where the front impinges with the bed. In the Rio de la Plata, South America, Acha *et al*. (2003) have demonstrated the role played by a 'bottom salinity front' as a barrier causing the accumulation of litter debris on the landward side of a transverse front.

Where the water mass is sub-divided by the presence of fronts there is an inhibition to free exchange of pollutants throughout the water column. Indeed, the exchange of waters across a frontal boundary may be one of the most significant factors in determining how quickly a pollutant introduced at the coast in dispersed (Simpson and James, 1986). For example, near the northern shore of the Tay Estuary (Fig. 1) Ferrier and Anderson (1996) have shown that there was an almost twenty-fold increase in the concentration of *E. coli* on opposite sides of a longitudinal front (19600 cf. 1070 per 100 ml) developed during the falling tide. Before the significance of fronts had been recognised, West and Williams (1971) had also determined *E. coli* concentrations from the end of a pier on the southern shore of the same estuary, showing that variations in the numbers of coliforms present approximately followed the sinusoidal tidal curve. However, there was a very large increase in the counts in half an hour at the middle of the falling phase of the tide (Fig. 2). There was a simultaneous step decrease in the salinity at that point. Salinity readings from a mooring point 50 m offshore have since identified that the step change in surface salinity is related to lateral migration of a longitudinal front bringing contrasting water bodies to the measuring point (Fig. 3). Similar step changes in the salinity have been observed at many other sites in this estuary (McManus, 2003).

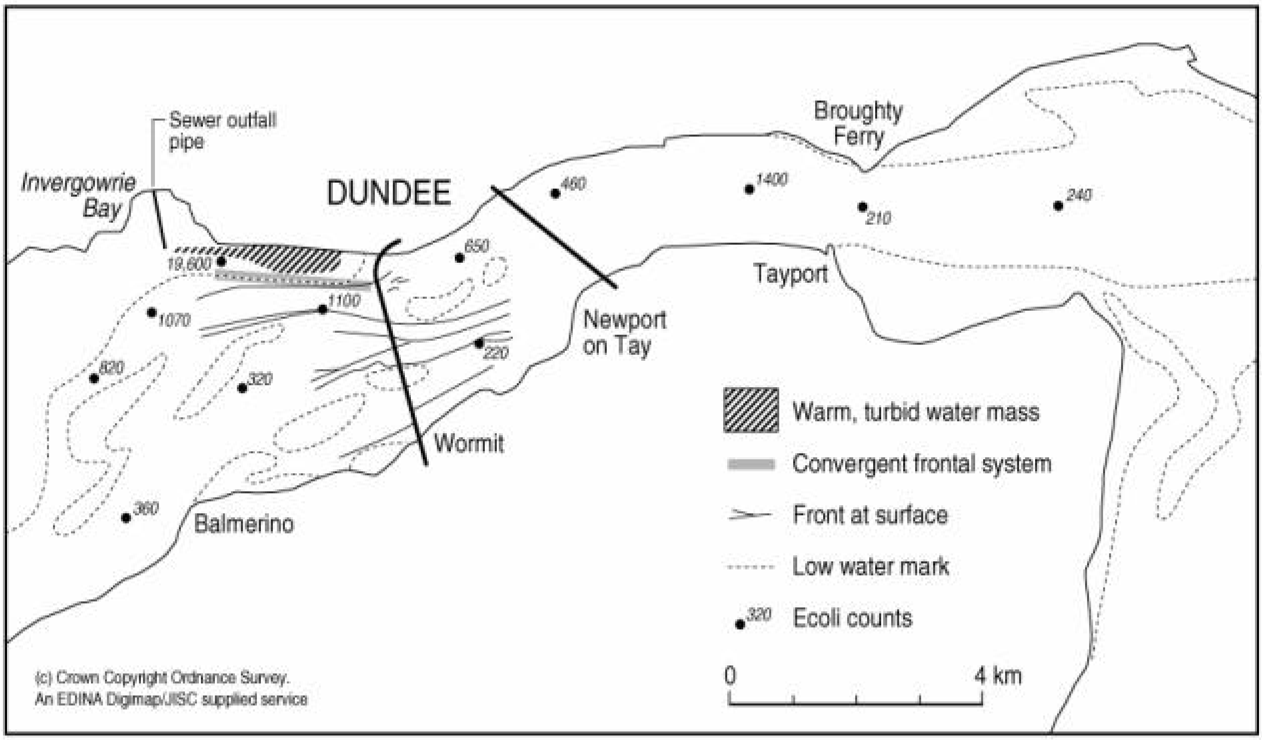

Fig. 1. Concentrations of E. coli *bacteria per 100 ml, 4 hours after high water, Tay Estuary (after Ferrier and Anderson, 1996).*

DIFFUSE POLLUTION

In addition to point source pollution, estuaries commonly receive diffuse pollution from many activities with no single discrete source. These include nutrients from over application of fertilisers and manure; faecal and other pathogens from livestock; contaminated sediment particles; pesticides; and organic wastes, e.g. slurries. Sediments, from fluvial, marine or resuspended sources, typically include many fine particles that have active surfaces to which contaminants (e.g. phosphorus) may be adsorbed.

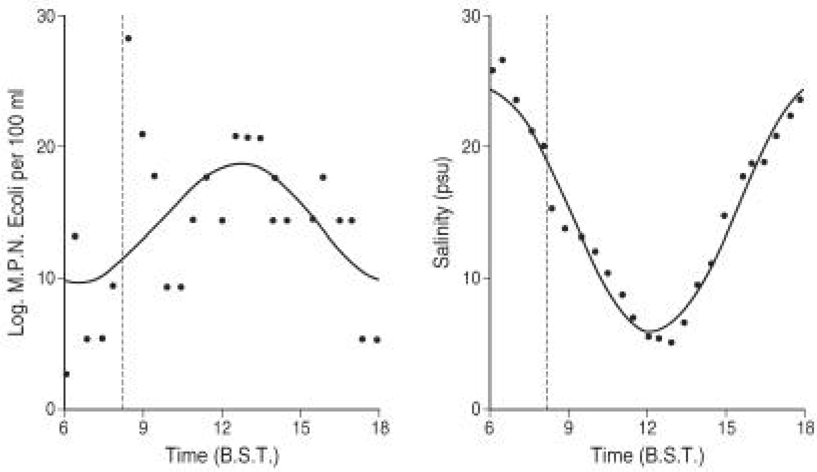

Fig. 2. Variations in E. coli *concentrations (M.P.N. = most probable number) and salinity with time, Tay Estuary. Broken vertical lines indicate the large increase in the* E. coli *counts in half an hour at the middle of the falling phase of the tide and the simultaneous step decrease in salinity (after West and Williams, 1971).*

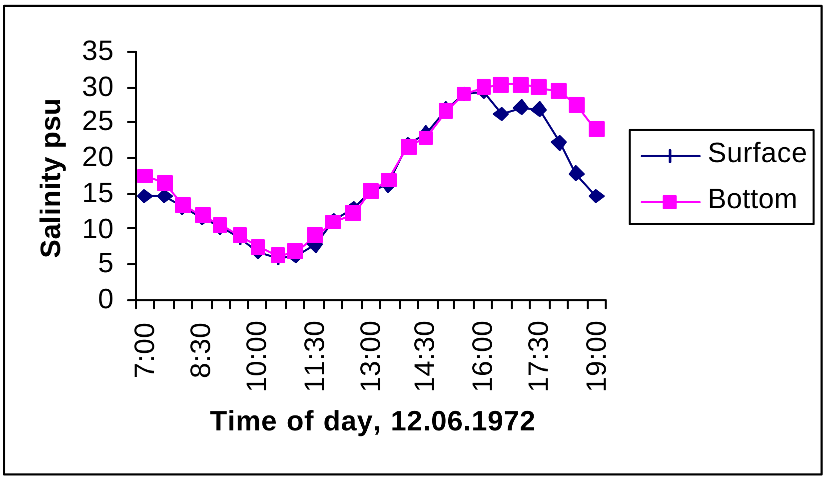

Fig. 3. Variations of surface and bottom salinity with time from a point 50 m offshore from which the data of Fig. 2 were acquired. The step change in surface salinity at 16.30 hours is related to lateral migration of a longitudinal front bringing contrasting water bodies to the measuring point.

Measurement of suspended sediment concentrations in the surface waters of the Tay Estuary at high tide may be interpreted within the context of the longitudinal frontal systems recognised by Ferrier and Anderson (1997). In Fig. 4 the relative displacements of waters containing measured suspension concentrations are shown, with the small arrows indicating adjacent water masses that migrate at differing velocities. In the past, when attempting to model pollutant dispersion in estuaries, the fundamental assumption has customarily been made that free interchange across the water body in any given reach was normal, and therefore that discharges entering the water body would rapidly become uniformly dispersed through it. The recognition of the existence of longitudinal fronts, which serve to divide the water into a series of longitudinal slices, undermines this assumption.

DISCUSSION AND CONCLUSIONS

On the basis of the findings of the many studies reviewed above, until the patterns of frontal systems have been established through the tidal cycle within any given estuary, ideally permission for no new discharges into the waters should be granted. Then we recommend that, where possible, discharges should be made into the larger bodies of water, as defined between longitudinal fronts, rather than directly into the marginal waters where they will not become transferred to the main body of the tidal prism and may not become dispersed widely. Likewise, an understanding of the dynamics of the movements of diffuse pollutants in estuaries cannot be achieved without an understanding of the natural compartmentalisation of the waters by frontal systems.

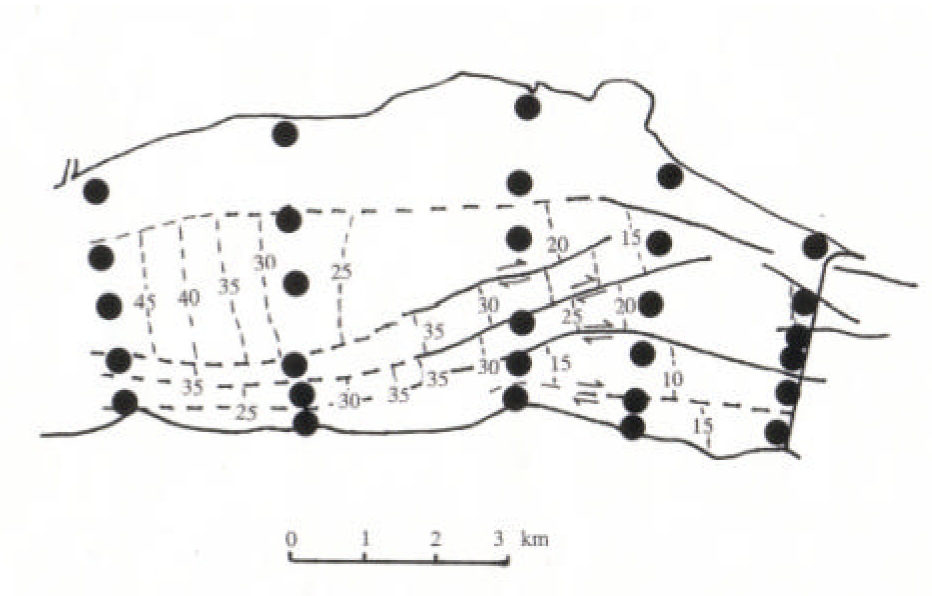

Fig. 4. Variation in suspended sediment concentrations (solid circles show sampling points, light broken lines show contours of values in mg l^{-1}) within 1 hour of high water in the middle reaches of the Tay Estuary. The relative displacements of waters with differing suspended sediment concentrations by longitudinal fronts are shown, with the small arrows indicating adjacent water masses that migrate at differing velocities.

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