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Simulating Bacterial Dispersion from Coastal Sewage Outfalls Using the QUICKEST Scheme

by
Yun Ho Kang[(1)] and Moon Ock Lee[(2)]

QUICKEST법을 사용한 연안해역에서 박테리아 확산의 수치모의

강윤호[(1)] , 이문옥[(2)]

Abstract

To improve water quality particularly for sea bathers along the Fylde coastal zone near Blackpool, North West England, waste water from a sewage outfall is studied using a mathematical model. The explicit second order accurate central scheme and the third order accurate QUICKEST scheme are used to represent the diffusion terms and the advection terms of the advective-diffusion equation, respectively. Hydrodynamic model is run for a coarse and fine grid, of 1km and 200m, respectively, obtaining good agreement with measured data. Water quality model is then used to predict faecal coliform levels in the region for four different scenarios, including discharges from:- (i) Fleetwood outfall, (ii)River Ribble for summer condition, (iii)River Ribble for winter condition, and (iv)combined sewer overflows for the Blackpool and Fleetwood communities. Main findings from the simulations are:- (i) Fleetwood outfall has a negligible impact on the beaches with respect to pathogen levels; (ii) Discharge from River Ribble for both summer and winter conditions is predicted in the range of coliform levels 10 -500 counts/100ml along the beach at Lytham St. Annes; and (iii) The CSO effluent discharges are predicted not to advect out into offshore by stronger tidal currents.

요 약

영국의 북서 Fylde 연안역에서, 수영객들을 위한 수질을 개선하기 위해, 방류구에서 흘러나온 오수를 수치모의실험을 통하여 연구하였다. 수질모델의이류확산방정식에서 확산항과 이류항은 양해법 이차정밀도의 중앙차분법과 삼차정밀도의 QUICKEST 법을 사용하여 표현하였다. 수리역학모델은 광역과 세부역으로 나누어지며,이때 격자는 각기 1km와 200m를 사용하였고, 모의실험의 (유속과조위)결과는 관측값과 잘 일치하였다. 그 다음 단계로서 수질모델을 사용하여 faecal

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(1) Research Fellow, Yosu Regional Environmental Technology and Development Center, Yosu National University,Yosu, 550-749, Korea
(2) Associate Professor, Dept. of Ocean Eng., Yosu National University, Yosu, 550-749, Korea

coliform 의 농도분포를 예측하였다. 이 때 4가지의 시나리오가 사용되었다:-(i) Fleetwood outfall,(ii) River Ribble for summer condition,(iii)River Ribble for winter condition 그리고 (iv) Combined Sewer Overflows. 모의 실험의 주요 결과는 다음과 같다:- (i) Fleetwood 방류구에서 방류된 coliform은 Fylde 연안에 거의 미치지 않는다;(ii)여름과 겨울,Ribble에서 유입된 coliform은 Lytham St.Annes에서 10-500(counts/100ml)농도분포를 보였다;(iii)CSO에서 방류된 오수는 해안에서 벗어나 offshore로 이동되지 못하는 것으로 예측되었다.

Keywords: bathing water quality, sewage outfall, QUICKEST scheme, storm overflows, T90

1. Introduction

The Fylde coast of Lancashire is famous for its seaside resort of Blackpool and neighbouring towns of Fleetwood and Lytham St Anne's, which relies heavily on tourism and leisure as a source of income (see Fig. 1). The fact caused considerable local concern that none of the beaches in the area were included in the original list of 27 bathing beaches submitted in 1979 by the UK Government to the EC Commission for designation under the Bathing Water Directive(CEC[1976]). Routine sampling of the bathing water has shown that although investment of large sums of money has achieved significant improvements, the most popular beaches regularly fail to meet the bacteriological standards of the Directive (Head et al. [1990]). Considerable pressure has been exerted on North West Water (NWW) to make a commitment to undertake further improvements which would lead to compliance. In 1986 the UK Government accepted the European Community Directive Concerning the Quality of Bathing Water embodied in the 1976. The standard has been applied to a large number of beaches around the UK coast. NWW was given the specific task of improving the sewage discharge arrangements for coastal areas in the vicinity of about 30 newly identified bathing areas. From the Fylde Coast studies it was apparent that whilst improvements in treatment for all discharges in the vicinity of the identified bathing waters would probably lead to compliance for most of the coast, this was not the case for the two beaches at Lytham St Anne's(Head and Crawshaw[1992], Head et al.[1992]). The bacteriological quality was affected by the inputs to the Ribble Estuary, particularly that from Preston Sewage Treatment Work.

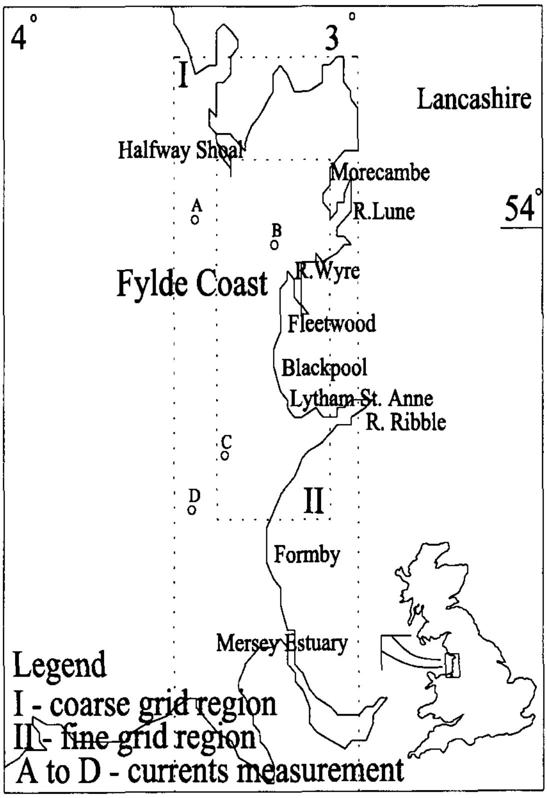


Fig. 1 Map showing computational domains of coarse and fine grids and current measurement points

The main aims of this study were to set up a hydrodynamic and water quality model of the coastal waters along the Fylde Coast and Ribble Estuary, North West England, and to predict the velocity and faecal coliform distributions at a finer grid scale than 500m taken previously (Crawshaw and Head [1988]). The fine grid model simulations were undertaken at a grid size of 200m, with the main objectives being to predict the faecal coliform distributions around the Lytham St. Annes region, *i.e.* just south of Blackpool. The main cause for concern has been the measurement of higher than expected faecal coliform counts along the beach at Lytham St. Anne's, and the failure of the beach to comply with the EU Bathing Water Directive in spite of improvements to the wastewater treatment facilities in the area. In addition to using the model to predict the faecal coliform levels in the region at a relatively fine grid scale, a number of scenarios were to be studied to establish the likely main source of the faecal coliform levels along this section of the coast; including discharges from:- (i) Fleetwood Waste water Treatment Work outfall to Lune Deep (Lune Deep Outfall),(ii)River Ribble for summer conditions(*i.e.* low flows), (iii)River Ribble for winter conditions (*i.e.* high flows), and (iv)combined sewer overflows for the Blackpool and Fleetwood communities.

2. Hydrodynamic Model

A hydrodynamic model, depth integrated 2 dimensional model(see details in Falconer[1976], Falconer[1993]) was set up for the coastal region based on existing Admiralty Chart bathymetric data and recorded tidal elevations. A coarse grid model was set up firstly to cover a region from the mouth of the Mersey Estuary in the south to Morecambe Bay in the north, and from the Ribble Estuary in the east to some 40km westwards into the Irish sea(Fig. 1). This model then provided the hydrodynamic and water quality boundary conditions for a fine grid model of the region, with the domain spanning from Formby in the south to Morecambe in the north, and from the mouth of the River Ribble to 24km west to Halfway Shoal (see Fig. 2).

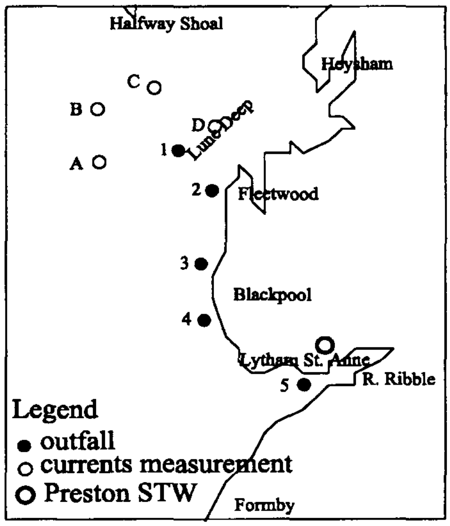


Fig. 2 Map showing fine grid computational domain, points of current measurements and outfalls

2.1 Model Specification

The coarse grid computational domain was set-up with dimensions of 120km×40km, using a mesh of 120×40 grid squares with a uniform spacing of 1km. At the centre of the sides of each grid square a representative depth of the basin bed elevation below datum was required. For this purpose bathymetric data given on the Admiralty Chart were used, together with additional data obtained for the Morecambe Bay region. The open seaward boundary was assumed to be a water elevation boundary, with the tidal elevation for both spring and neap tides being specified at the southern point along the boundary. The flow along the western open boundary was assumed to be normal to the boundary, as indicated by the general flow patterns given in the tidal atlas, with the free surface slope along the boundary including the effects of the earths rotation. The other main open boundary inputs included the discharges from the rivers Ribble and Mersey, with these being specified in the model in the form of discharges per unit width.

For the fine grid domain a grid of 200×120 grid squares was set up, with a uniform grid spacing of 200m, and thereby giving a domain of 40km×24km. The model covered the region indicated in Fig.2, *i.e.* from Morecambe in the north to Formby in the south and from Halfway Shoal in the west to the head of the Ribble Estuary. The open boundary conditions were obtained from the coarse grid model, with velocity components being specified along the western seaward boundary, discharges given for the rivers Ribble, Wyre and Lune, and with water elevations specified along the northern and southern boundaries.

2.2 Calibration

The coarse grid hydrodynamic model was first calibrated by comparing the predicted velocities at sites A,B,C and D with the values specified on the Admiralty Charts Nos. 1981 and 2010 and with water elevations cited for Heysham, Fleetwood and Formby. As seen in Fig. 3, the measured and predicted velocities were

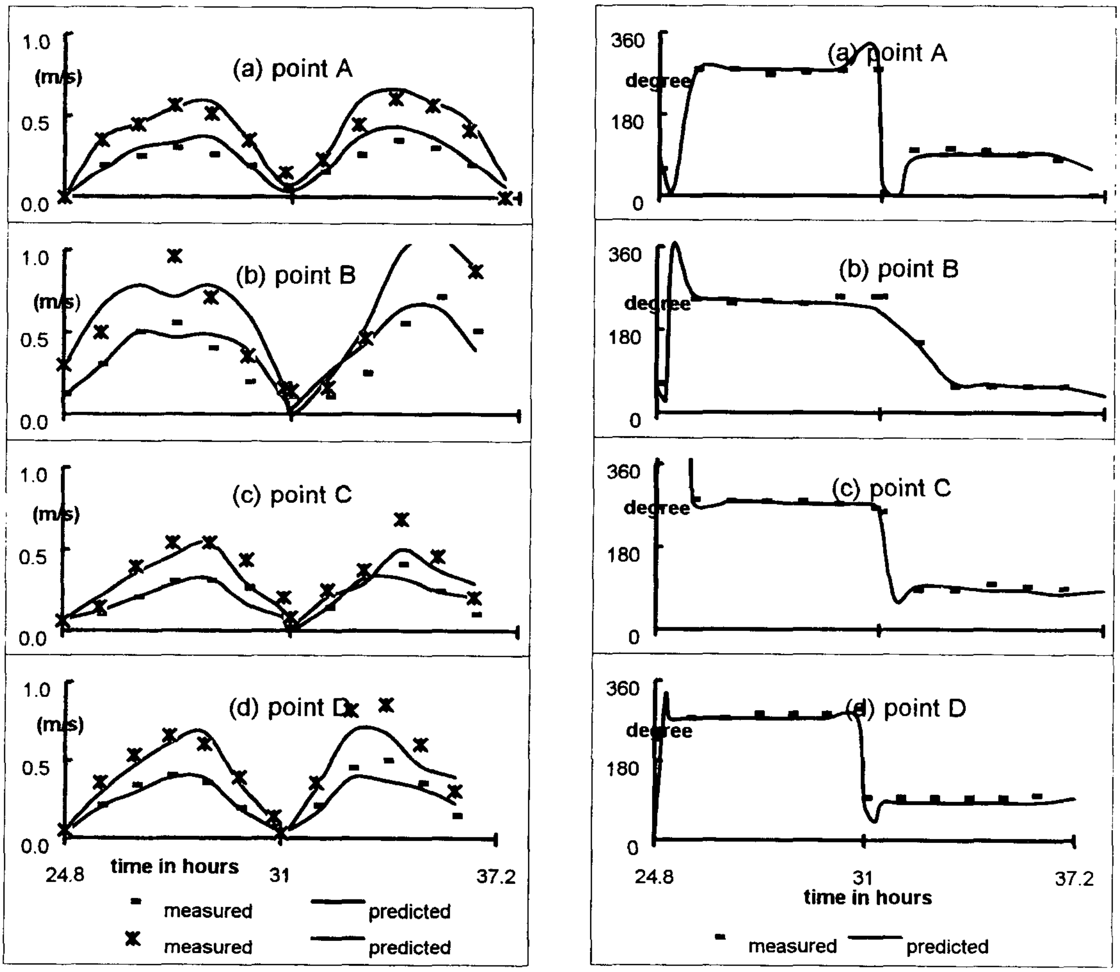


Fig. 3 Comparison of measured and predicted velocities for coarse grid model at four points (left: magnitude of velocity components, right: direction of currents)

generally in close agreement at all sites. The biggest discrepancy between both sets of results occurred at site B, where the 1 km grid size was too coarse to pick up accurately the Lune Deep Trench. As expected, the water elevations agreed closely for all three sites (Fig. 4). In addition predicted flow fields over the domain were illustrated in Figure 5 to give insights as to how effluents would be dispersed by tidal currents in the study region.

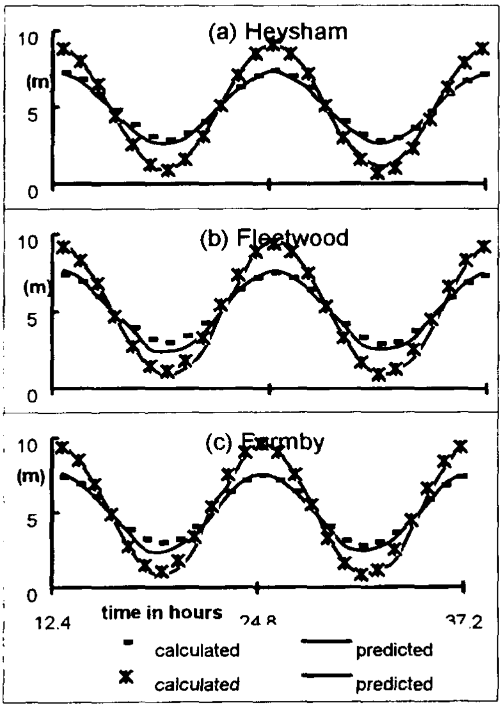
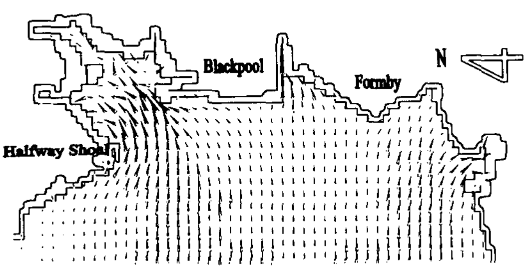
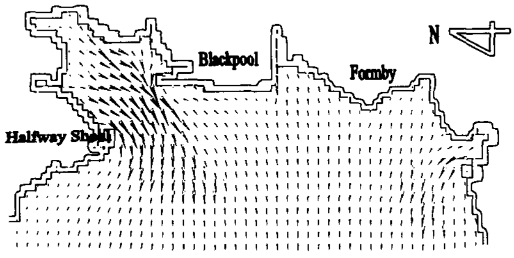


Fig. 4 Comparison of measured and predicted water elevations for coarse grid model at three points



(a)



(b)

Fig. 5 Predictions of flow field over the Fylde coast at a) mid-flood with maximum speed of currents - 1.45m/s and b) mid-ebb with 2.58m/s for spring tide respectively

For the fine grid hydrodynamic model, velocity comparisons were undertaken for sites A,B,C and D as shown in Fig. 6, and with measured and predicted water elevations being compared at Heysham and Fleetwood (see Fig.7). For this case the agreement between the measured and predicted velocities at each of the sites was reasonably encouraging, although surprisingly the degree of agreement between both sets of results was not generally as good as that for the coarse grid model. This was thought to be due to the relatively simple approximations for momentum conservation made along the open boundaries and the incompatibility of the fine and coarse grid bathymetric data. Also, for the fine grid model the simple mixing length turbulence model (Rodi[1984]) would have been more critical, although no relevant data were available to fine-tune the relevant coefficients. Furthermore, it must always be borne in mind that Admiralty Chart velocity data can only provide an estimate of the actual velocities at any point for a particular set of hydrodynamic and meteorological conditions. As the grid size is refined then finer flow details, such as wind and turbulence effects, become more significant. Notwithstanding the difference between the predicted velocities and the Admiralty Chart data, it was felt that the model could still be used as an indicative tool to predict typical

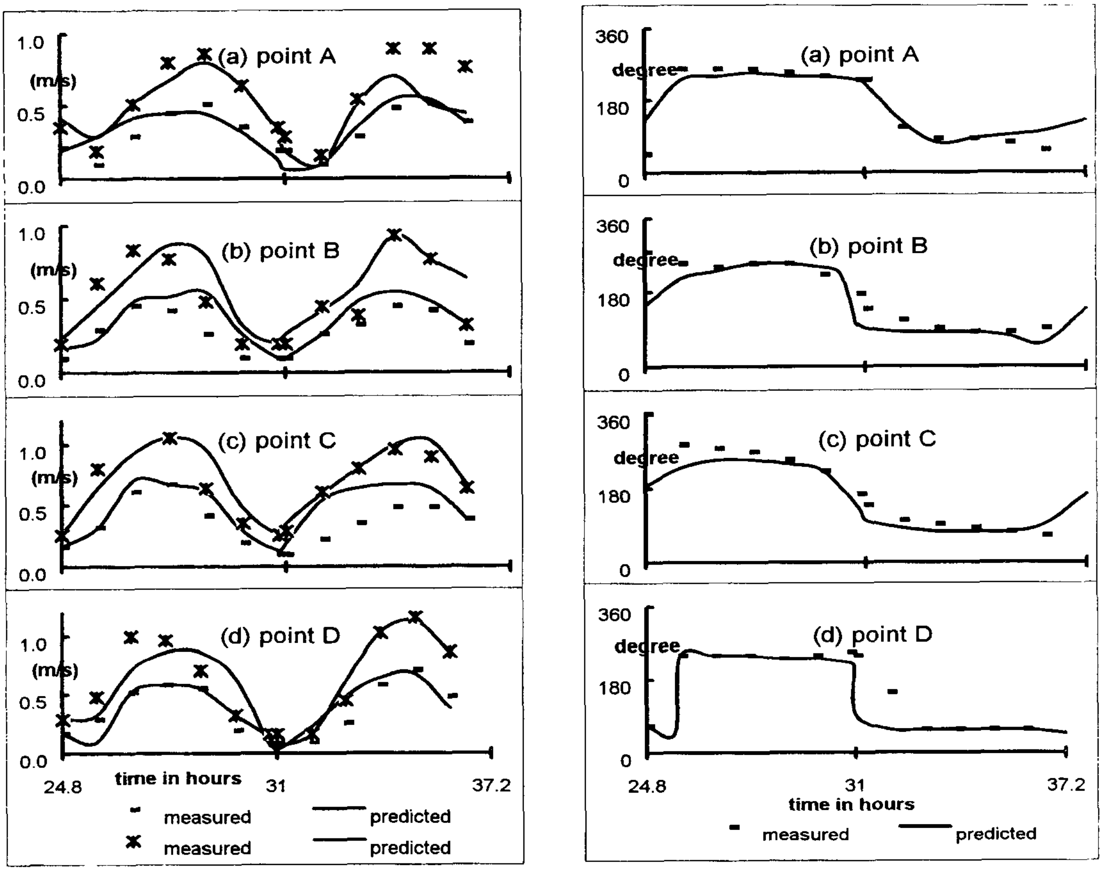


Fig. 6 Comparison of measured and predicted velocities for fine grid model at four points (left: magnitude of velocity components, right: direction of currents)

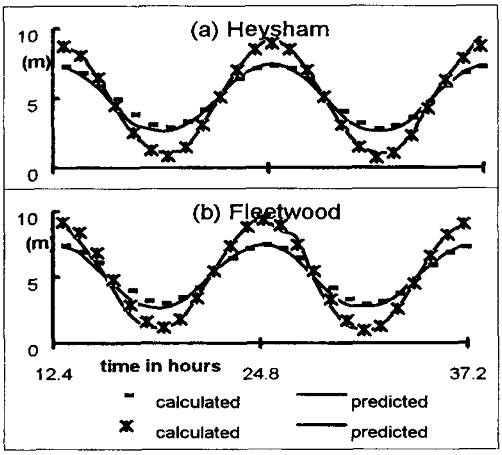


Fig. 7 Comparison of measured and predicted water elevations for fine grid model at two points

values of the velocities and faecal coliform levels in the Lytham St. Anne's region.

For the water elevation predictions at Heysham and Fleetwood, these values were in closer agreement with the measured data than for the coarse grid model. This result was more consistent with what one would normally expect, *i.e.* closer agreement between predicted and measured results at finer grid resolution, although it should also be borne in mind that water elevations are easier to measure accurately.

3. Water Quality Model

The governing solute transport equation can be expressed in the depth integrated form

(Falconer and Chen[1991]). The depth averaged dispersion-diffusion coefficients in *x, y* directions are given by Preston [1985] as follows in two dimensions:-

$$D_{xx} = \frac{(k_l U^2 + k_t V^2 H\sqrt{g})}{\sqrt{U^2+V^2}C} + D_w \quad (1)$$

$$D_{yy} = \frac{(k_l V^2 + k_t U^2) H\sqrt{g}}{\sqrt{U^2+V^2}C} + D_w$$

$$D_{xy} = D_{yx} = \frac{(k_l - k_t) UVH\sqrt{g}}{\sqrt{U^2+V^2}C}$$

where *U, V*=depth averaged flow speed in *x, y* directions, *H*=total depth of flow, *kl*= longitudinal depth averaged dispersion constant (dimensionless), *kt*=depth averaged turbulent diffusion constant (dimensionless), *C*=Chezy value, *g*=gravity acceleration, *Dw*=wind induced dispersion coefficient. For values of *kl* and *kt* these can be set to minimum values assuming a logarithmic velocity distribution, wherein *kl*=5.93 (Elder[1959]) and *kt*=0.15 (Fischer[1973]). However, in practical studies these values tend to be rather low (Fishcer *et al.*[1979]), with measured values for *kl* and *kt* ranging from 8.6 to 7,500 and 0.42 to 1.61 respectively. In the present study, these values are set as 13.0 and 1.2, which have worked good at various coastal studies (Falconer and Cahyono[1994]) .

The fate processes of faecal coliform in marine environments can be explained by physical and bio-geochemical processes including dispersion, sedimentation, solar radiation, osmotic stress, water turbidity and predation by natural microbiota. Solar radiation is known to be the dominant factor, where the inactivation rate of bacteria exposed to sunlight is typically up to two decades greater than the same bacteria kept in dark (Bell *at al.*[1992]). The T90 is defined as time during which 90% of faecal coliform dies off. It was reported that T90 is very low (2 hours or less) in cases of low turbidity, high levels of sunlight radiation on summer days and very high (exceeding 4 days) in winter with overcast sky and high turbidity (Gameson and Gould [1975], Gould and Munro [1981]).

In this study faecal coliform is expressed as first order decay functions, taking account of die-off rates, with the dispersion-diffusion terms excluded here for convenience:-

$$\frac{DSH}{Dt} = -KSH \quad (2)$$

where *D/Dt* =total derivative, *S*=depth averaged concentration of coliform, and *K*= coliform die-off rate (s^{-1}). The range of values for *K* appropriate for inclusion in the model are 0.05 to 4.0 day^{-1}.

The advection terms in the water quality constituent transport equation was represented using the QUICKEST scheme. Leonard[1979] has developed a third-order accurate scheme for the unsteady advection-diffusion equation called QUICKEST: Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms. This scheme is more accurate than other schemes (*e.g.* second-order central and second-order upwinding schemes), since it is third-order accurate, the leading truncation error is a dissipative spatial fourth order derivative (Lin and Falconer[1997]).

4. Effluent Discharge Simulations

The Fylde Coast is located along the North West Coast of England, with the coast including the major sea-side resort of Blackpool. The region of interest primarily stretches from the River Ribble Estuary in the south to Fleetwood and Morecambe Bay to the north. The treated sewage effluent discharge for the region is mainly via a new outfall (Fig. 2). Sewage after secondary treatment is discharged by gravity into a depth of 30m at Lune Deep Channel some 5km north west of Fleetwood (Head and Crawshaw[1992]). The other main sewage treatment work in the region is Preston Sewage Treatment Work, which discharges into the middle reaches of the Ribble Estuary. There are also three major combined sewer overflows along the Blackpool coastal region, although these overflows only discharge into the coastal zone under extreme storm conditions. The locations of the storm water outfalls are in a range of 1.5 to 2 km from land and below low water (Head *et al.* [1992]).

Table 1 Flow and coliform inputs for each outfall

Outfall	Discharge (m^3/s)	Faecal coliform (counts/100ml)	Discharge Feriod
Fleetwood(1)	2,17	0.5×10^6	High to Low Water
Preston(5)	1.00	0.5×10^6	High to Low Water
Combined Sewer Overflows (2, 3and 4)	2.00	0.5×10^6	1.5hours before and after mid-ebb

For the discharge and faecal coliform count levels assumed in the model for various outfalls, these are given in Table 1, together with the time and duration of each discharge. The River Ribble was modelled for high and low, *i.e.* winter and summer, discharges of 10.63 and 59.81 m^3/s respectively. The T90 decay rate for faecal coliform was assumed to be 50 hours, giving an unduly low decay rate, and thereby leading to conservative faecal coliform predictions in the model.

Predicted distributions of faecal coliform discharged from Fleetwood outfall, combined sewer overflow and River Ribble are shown at mid flood and mid-ebb phases, respectively, as follows.

It can be seen in Fig. 8 that the effluents from the new outfall at Lune Deep Channel were dispersed mainly along the channel, since tidal currents are bi-directional along the channel and very strong, *i.e.* 2 m/s flow speed at mid-ebb phase. Hence, the new outfall has a negligible environmental impact over the Fylde coast with respect to pathogen levels. Water from Ribble estuary was predicted in higher levels of coliform distribution at river mouth (see Fig. 9), which meant that riverine plume was not strong enough to be spread far distant from the mouth but subject to tidal currents. Also, it was predicted that winter and summer conditions resulted in almost identical coliform levels in the range 10-500 counts/100ml along the beach at Lytham St. Anne's. Three Combined Sewer Overflows discharging only under extreme storm condition were simulated

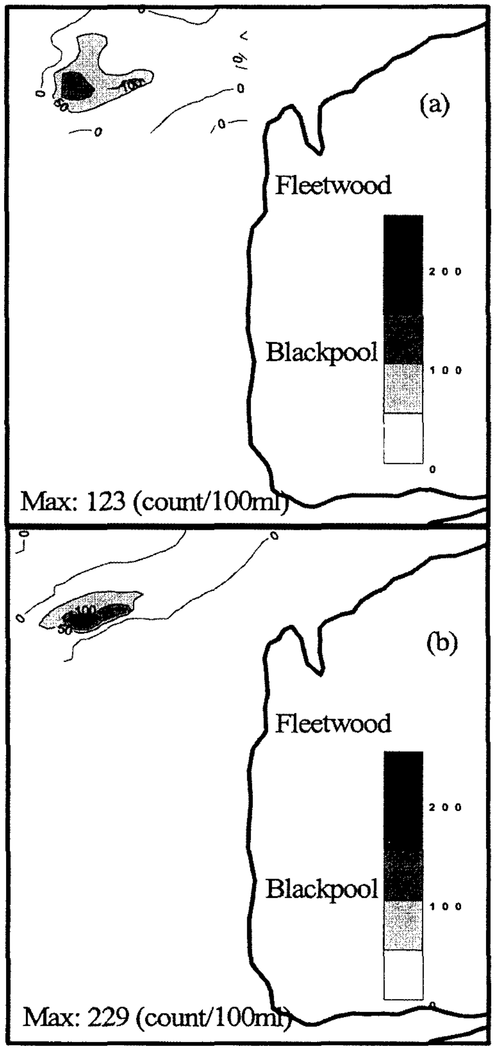


Fig. 8 Predicted distributions of faecal coliform discharged from Fleetwood outfall at a) mid-flood and b)mid-ebb phases

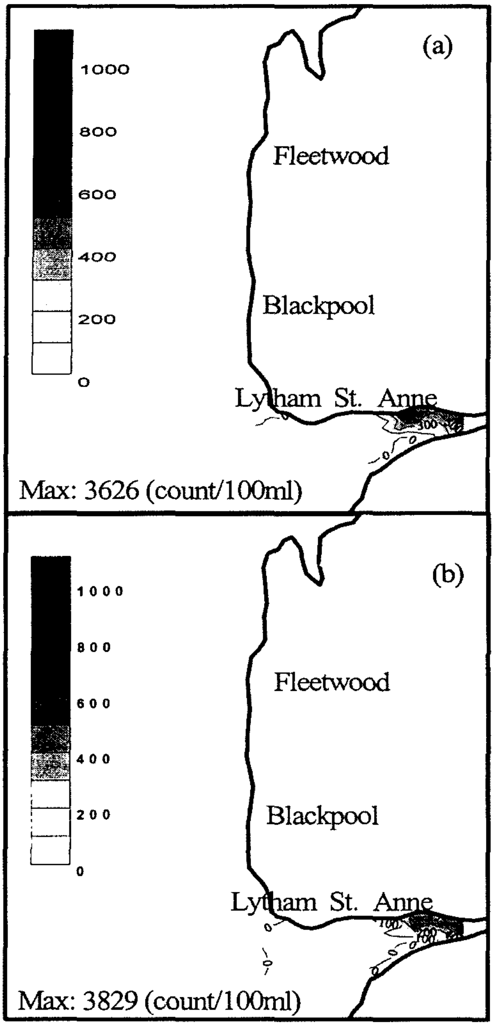


Fig. 9 Predicted distributions of faecal coliform discharged from River Ribble overflow at a)mid-flood and b)mid-ebb phases

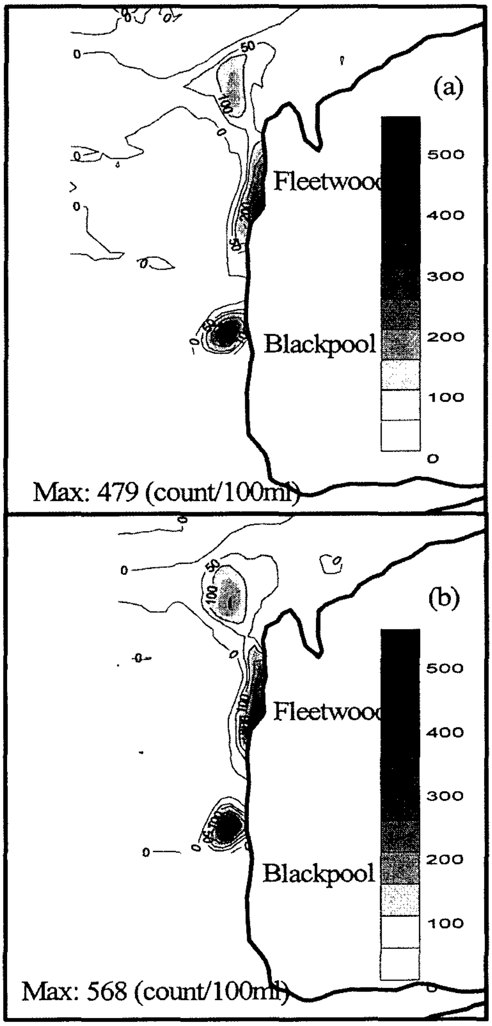


Fig. 10 Predicted distributions of faecal coliform discharged from combined sewer at a)mid-flood and b)mid-ebb phases

and resulted in (Fig. 10) that effluents were dispersed along the Fylde coast beaches and not transported offshore. It is notable that the CSOs had a great effect to the beaches at the north of Blackpool. The CSO effluent discharges were not predicted to advect out into offshore by stronger tidal currents, where the effluent would have been more rapidly dispersed and potential problems minimised. Crawshaw and Head[1988] investigated the effects of different degrees of treatment and outfall locations of CSOs using microbiological and chemical tracers. However, their study was focused in cases during only dry weather and periods of light rain. Hence, comparison with the present study was not made directly, although their study confirmed that the effects of the discharge from Preston STW were confined to the waters off Lytham as seen in Fig.9. It should be noted that field measurements were not available from North West Water such that this study was intended to focus solely in predictions without calibration.

5. Conclusion

Four different effluents cases were considered, including discharges from:- Lune Deep outfall, River Ribble - summer condition, River Ribble-winter condition, and combined sewer over-flows. The main findings from the corre-sponding spatial predictions of coliform level can be summarised as follows:-

(i) The finer grid for the computation domain used in this study obtained better resolution of predictions of velocity and solute concentration than the previous study. In particular solute concentration could be predicted much accurately due to the refined advection terms calculated in a finer spatial scale. The third order accurate QUICKEST scheme also contributed to resulting in stable and accurate representation of non-linear terms such as plug source of outfall effluents along the coast.

(ii) The effluent discharge from the new outfall at Lune Deep has a negligible impact on the coliform levels along the foreshore of the Fylde Coast, even with the relatively high T90 value considered in this study.

(iii) Water from the Ribble estuary is predicted to advect onto the foreshore at Lytham St. Annes. For both summer and winter riverine flows and coliform input levels of 0.5×10^6 counts/100ml, with a conservative decay rate of 50 hr, the model predicts coliform levels in the range 10-500 counts/100ml along the beach at Lytham St. Anne's. The influence of water from the Ribble on coliform concentrations is small on the Lytham beaches. However, any higher input concentrations in the River Ribble *i.e.* Preston STW, would lead to almost proportional levels along the beach.

(iv) The relatively high loads from the three combined sewer overflows between Blackpool and Fleetwood were predicted to advect along the foreshore and potentially must be taken into consideration when examining compliance with the EC Bathing Water Directive at adjacent beaches. However, it is notable that although the predictions show the CSOs to have a greater effect to the north of Blackpool, compliance with the Directive is worse to the south. The CSO effluent discharges were also not predicted to advect out into offshore by stronger tidal currents, where the effluent would have been more rapidly dispersed and potential problems minimised.

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