Marine outfall design—computer models for initial dilution in a current

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The Authors compared the initial dilution predictions of three mathematical models with field measurements collected by the Water Research Centre (WRC) and the Southern Authority. Judging from the results of their comparison, as summarized in Fig. 1 of the Technical Note, one would naturally conclude that the mathematical model predictions greatly overpredict the field measurements, and hence justify the observation that 'it is not possible to make definite predictions of moving water dilution'. However, both the comparison and the conclusion which follows are misleading in that the models are applied as if they were 'black boxes', without due regard to the flow phenomenon under study. In applying a mathematical model to predict initial dilution, two important points should be considered: the effect of the surface layer, and the interpretation of 'minimum dilution' as predicted by models which typically assume Gaussian concentration profiles in the cross-section of the buoyant jet.

23. Figure 2(a) shows a sewage plume in still water, and Fig. 2(b) a deflected plume in a current. In both cases a surface sewage field is always present. It is readily seen and generally accepted that there is little additional dilution above the elevation y_s . In the surface layer, the buoyant plume entrains already mixed sewage; this results primarily in a smoothing of concentration gradients rather than additional dilution.

24. In the results presented in the Technical Note, the dilution predictions were made using as input the observed depth H , ambient current U_a , and other discharge variables. As suggested in reference 17, the proper elevation at which initial dilution should be determined is y_s , i.e. the bottom of the surface field for $U_a = 0$, and for the case of a current the centre-line elevation as the plume touches the surface.

25. For $U_a = 0$, both experiments and theory²² show that the width of the plume varies linearly as $w \cong 0.3 y$, where w is defined as $2\sqrt{(2)b}$, b is the nominal jet radius defined by the Gaussian velocity profile. It can be shown that the surface layer thickness h_s is approximately $0.1 H$. In experiments of a buoyant jet in still water, the measured minimum dilution in the surface boil has been found to be in good agreement with the predicted minimum dilution at y_s —a result generally confirmed by many investigators. Since h_s/H is relatively small in still water, the error introduced by neglecting the surface layer is usually small.

26. In the presence of an ambient current, however, the situation is quite different. Because the dilution is usually much greater in moving water, the surface

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Fig. 2. Surface layer of a buoyant jet discharge from a waste water outfall: (a) sewage plume in still water; (b) deflected plume in a current

layer can account for a substantial fraction of the depth. This is evident in the flow visualization of many experiments—for example, the heated jet experiments of the Hydraulics Research Station. For $U_j/U_a < 4$, experiments show that the plume width varies linearly with the height of rise, $w \cong 0.68 y$. For the deflected plume, Fig. 2(b) shows that $h_s \cong w(y_s)$, and $H - 0.5 w(y_s) \cong y_s$. An estimation is then arrived at of $y_s = 0.75 H$ and $h_s = 0.5 H$. For the high dilutions typically obtainable in a current, the above geometrical considerations should be reasonably satisfactory although the buoyant spread at the free surface has tacitly been neglected.

27. A more accurate procedure for determining y_s would be to carry out model calculations up to the level at which $H - 0.5 w(y_s) = y_s$. Mathematical model simulations for the Hastings field experiments resulted in an average y_s/H of 0.62, with a standard deviation of 0.06, as discussed later.

28. Since the dilution in the full current dominated regime of a sewage plume in a current⁷ is proportional to y^2 , neglect of the surface layer amounts to over-predicting the dilution by a factor of $(1/0.75)^2 = 1.77$. Most of the field data can be shown to fall within the far field.

29. Mathematical models typically assume a radially symmetrical concentration profile with the peak value in the centre of the cross-section. In the plume dominated regime of a sewage plume in a current, the concentration profile in the

jet cross-section is Gaussian and the ratio of the average to minimum centre-line dilution is about 1.7 as adopted by the Authors. However, in the full current dominated regime, it is known that the concentration in the jet cross-section has a horseshoe shape, indicative of jet bifurcation into a vortex pair flow. Based on a study of complete cross-section concentration measurements on a fine grid, the ratio of the measured centre-line to average concentration is found to be in the range of 2–2.5. If the calculated average dilution is divided consistently by a factor of 2.3 to yield a predicted minimum dilution, model predictions have been found to compare well with laboratory measurements of centre-line concentrations. Using a scaling factor of 1.7 instead of 2.3 would overpredict dilution by a factor of $2.3/1.7 = 1.35$.

30. Having accounted for the surface layer and interpreted the minimum dilution in the far field, mathematical model calculations have been carried out for all the Hastings data used in references 7 and 8. For these data, the jet discharge velocity is directly measured and the tracer-determined dilution corresponds to a minimum dilution. For each field experimental condition, y_s is determined from the calculations. The ratio of the predicted minimum dilution at y_s to the measured minimum initial dilution is determined. In the terminology of the Authors, the following percentile points are calculated: $P_{50} = 0.77$, $P_{75} = 1.09$ and $P_{25} = 0.45$ (50% range = 0.77 ± 0.32 ; 80% range = 0.84 ± 0.51). A histogram of the ratio is plotted in Fig. 3 which shows that, on the whole, the dilution observed in the field is actually greater than the predicted value. This is reasonable in view of the factors which are not accounted for in the theory—ambient turbulence, wind and wave effects, and sometimes simply missing the boil. If a relative error in the prediction is defined as $(S_{\text{obs}} - S_{\text{pred}})/S_{\text{obs}}$, then the root mean square error of the prediction is around 40%.

31. The calculations are made using a newly developed Lagrangian model²³

Fig. 3. Comparison of initial dilution predictions of a Lagrangian jet model with field data for the Hastings outfall; the histogram of the ratio of predicted to measured dilution is shown

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which has been validated against data over a wide range of situations. The model is applicable to a horizontal jet in a cross-flow, with a three-dimensional trajectory characteristic of the Hastings outfall discharge.

32. By interpreting the model predictions in a manner which is supported by laboratory experiments and theory, it has been shown that the field data corroborate the mathematical predictions to a large degree. Broadly similar conclusions would be expected with other well-validated models. A successful verification of mathematical models for a line diffuser in stratified fluid has also recently been reported for an outfall diffuser at Port Valdez, Alaska.²⁴

33. We fully agree with the Authors on the difficulties and uncertainties associated with field measurements, and the need to be cautious when estimating moving water dilutions. In any event, the ultimate initial dilution is governed by advective processes on a much larger scale, for example tidal exchanges. Nevertheless, it is our view that mathematical models are potentially powerful tools which can be used to great advantage in conjunction with field data.

34. The mixing of a turbulent buoyant jet discharge in a current is a complicated flow phenomenon. Although existing models still have shortcomings, substantial progress in buoyant jet modelling has been made over the past two decades. Deficiencies in the earlier models, for example the model by Fan, have largely been overcome in better models which require only a couple of semi-empirical coefficients determinable from basic laboratory data. These constants are not varied or adjusted in applications. For a balanced view of the models in general use, the reader is referred to the many interesting discussions of Alam's paper.²⁵

35. The difficulty with putting the models to good use is that they are often specialized. In view of the complexity of the physical mixing processes, and the wide variety of discharge and ambient conditions, the average user has little guidance on the limitations of a particular model for a given application, or the interpretation of results. Microcomputer based expert systems²⁶ have recently been developed to provide engineers with more reliable guidance on initial mixing analysis.

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The discussors suggest that we are overly pessimistic in our assessment of the EPA outfall models, basing this view on two main points: firstly, that application of the models should take into account the surface effect; secondly, that in a horseshoe shaped cross-section, the minimum dilution should be related to the average by a factor of 2.3 instead of the 1.7 used by us.

37. We agree that there will be a surface field, which, as the discussors point out, will be of the order of one-tenth of the depth for a jet discharging into still water. It is also true that this effect can probably be safely ignored in most still water cases. However, it is highly debatable to suggest, as the discussors seem to do, that for all cases involving a current, the surface layer should be assumed to be about half of the total depth. There must, of course, be a smooth transition between the condition of zero current and some small, but measurable, current. Relatively small currents might be expected to cause a surface layer which approximates very closely to that which would be observed in still water. It is noticeable that the WRC reports indicate that there was a significant boil at most of the outfalls studied. This is significant because the presence of a boil will become less noticeable as the jet is bent over by a strong current, as indicated in Fig. 2(b).

Furthermore, it is probable that the geometry of the surface layer will depend not on the absolute magnitude of the current velocity, but on some function which would involve the velocity ratio (current/jet), the densimetric Froude number or its equivalent, and the relative depth (Y/D). Table 4 shows the values of these parameters for the WRc study. This indicates that the velocity ratio varied by a factor of 84 from its minimum to maximum value. Depth ratios varied by a factor of 17 and the densimetric Froude numbers by 16.5. With this variability, it does not seem reasonable to assume that the surface layer is related to total depth by a constant factor. At Hastings, the current velocity varied from 0.03 m/s to 0.42 m/s. It is open to question whether or not these small velocities created a significant surface layer.

38. The cross-section of a jet in still water is approximately circular with a Gaussian concentration distribution. As a current develops, this shape will begin to change. A horseshoe shaped cross-section will gradually develop, showing two points of high concentration, and, as the current speed increases, the jet may bifurcate and separate into two streams. Again, the point must be made that this is a gradual process with a smooth transition between still and moving conditions. The remarks made earlier regarding the surface layer also apply to any attempt to determine the shape of the cross-section or the factor relating minimum to average dilution. At Hastings, there was no indication of bifurcation, and only one point of maximum concentration was observed. This suggests to us that the cross-section was probably not too dissimilar to that which would be observed in still water, and that the factor of 1.7 used to relate minimum and average dilution was reasonably correct.

39. In summary, the discussion suggests that we have taken too pessimistic a view of the various models tested. We certainly agree that our view is pessimistic, and that no attempt was made to find extenuating circumstances which would provide a closer match between theory and measurement. Certainly it is possible to get better agreement, as the discussion has shown, by reducing the effective depth and increasing the multiplicative factor for average dilution. The problem is that there is little good solid information to suggest how this should be done. Although the discussors found reasonably good agreement between field measurement and the EPA models, using the values they selected for depth of the surface layer and for the ratio minimum/average dilution, other combinations could have given the same, apparently good, results. However, no measurements were made of these values in the field studies reported, and it is possible, bearing in mind the variability commented on earlier, that the better fit found by the discussors was, at least partly, fortuitous. In addition, it should be remembered that the values used by the discussors are not, necessarily, transferrable to other moving water situations where the ranges of dimensionless variables are different from that experienced here. The discussion, therefore, might be considered to provide an overly optimistic view of the models which were examined, with the truth lying somewhere between these two extreme views. We certainly agree that mathematical models are potentially powerful and useful tools; however, with the present state of knowledge, their value is primarily in enhancing basic understanding of the phenomenon rather than in predicting dilutions which are likely to occur in the field.

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