A COMPARISON OF ONE- AND TWO-DIMENSIONAL MODEL SIMULATION OF THE CLYDE ESTUARY, GLASGOW

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ABSTRACT

This paper evaluates one- and two-dimensional numerical models for the simulation of estuary hydrodynamics, in this case for the Clyde Estuary, Glasgow. The evaluation is based on identification of the relative strength and limitations of two commercial numerical models, namely ISIS 1-d and MIKE21. The estuary dynamic is analysed on meso-scale domain and over a few tidal periods. On such spatial and temporal scale, the water body is under dominant influence of tidal waves and surface runoff, but also affected by wind shear and atmospheric pressure. The Clyde estuary has a meso-tidal range and long-term average river inflow of 110 m^3/s. Upstream of the city of Glasgow the estuary is fluvio dominant, but tidally dominant in the city centre and downstream of the city. The upstream reach is meandering in plan, and the downstream reach has a funnel shape of increasing width. Numerical simulations are conducted for several historical events. The relative influence of tides, storm surge, river inflow, precipitation, wind shear and air pressure is analysed. Predictions of water levels by numerical models are inter-compared and also compared to the recordings on several water gauging stations. A sensitivity analysis on the various tidal shapes, fresh water inflows, wind shear and air pressure is conducted.

1. INTRODUCTION

Around 1.8 million people, approximately two fifths of Scotland's population live in Glasgow and the Clyde Valley, with 600,000 living within the city boundaries. Current predictions of climate change suggest that atmosphere will become warmer and wetter, increased winter surface runoff, increased windiness and storm surge activity and that sea level will rise. Rises in sea level and increasingly frequent and intense tidal surges, associated with storm events, are likely to result in coastal flooding. The Scottish Executive estimates that, not allowing for flood defences, more than 93,000 properties in Scotland are presently at risk of coastal flooding and further 77,000 are at risk of river flooding. Within the tidal extent of the Clyde, there is the potential for high river flows to coincide with extreme tidal events resulting in extensive flooding. These vulnerabilities exist at the same time as increasing sedimentation due to reduced dredging along the city centre section of the river.

In May 2003 Glasgow City Council (GCC) appointed a Joint Venture of Halcrow Group Ltd. and W.A. Fairhurst & Partners (the Halcrow-Fairhurst JV) to undertake the River Clyde Flood Management Strategy study (the RCFMS study). The aim of the study was to assess the risk of

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flooding in the Glasgow area of the River Clyde integrating the latest data of extreme tides and flows. A detailed one-dimensional ISIS model was built for the 56 km long reach between Bothwell and Greenock. The RCFMS study was a basis on which further study of high water levels in the tidal reach was performed by the authors using the two-dimensional model MIKE21 HD.

The paper therefore describes two comprehensive hydrodynamic modelling studies of the Clyde Estuary, aimed at evaluation of application of one- and two-dimensional numerical models in the simulation of estuary hydrodynamics. The evaluation is based on identification of the relative strength and limitations of commercial models ISIS Flow and MIKE21 HD. The estuary dynamics is analysed on meso-scale domain and over a few tidal periods. On such spatial and temporal scale, the water body is under dominant influence of tidal waves and surface runoff, but also affected by wind shear and atmospheric pressure. The relative influence of tides, river inflow, precipitation, wind shear and air pressure on estuary hydrodynamics is analysed. Observations of these parameters were available for several historical events. Calibration of numerical models and the influence of each affecting parameter is made through comparison of observed water levels and model predictions on several locations along the estuary reach. A digital terrain model is build from a recent LIDAR and bathymetry survey data. In the RCFMS study (2004) recent survey data of the Clyde Estuary were collected, on the basis of which a detailed 3D geometry was built. It was assumed that the estuary morphology is unchanged since that date.

Tidal flows in an estuary can be modified by density variations, which can be caused by salinity or temperature gradients. 1-d and 2-d models can account the horizontal salinity gradients, but as there were no salinity observations, there effects are excluded in this study.

2 THE CLYDE ESTUARY SYSTEM

The River Clyde discharges to the west coast of Scotland. It rises in the south of Scotland, flows through arable land, passes a heavily urbanised catchment of Glasgow area and ends in its estuary in the Firth of Clyde at Greenock. Geographical position and key locations in Clyde estuary are shown in Figure 1 below.

In the past, the River Clyde has played a significant role in the commercial development of Glasgow. It was used as an inland waterway and for a ship building industry. At the end of the 17th century, the river was in its natural state, very shallow downstream of the City of Glasgow. As commerce developed, navigability should have been provided up to the City by increased channel depth. Construction of lateral training dykes was later followed by longitudinal dykes and land reclamation works. A Tidal Weir was constructed upstream of the City, to provide water for industry and recreation during low tides. Basins and docks were extensively excavated below Weir, and entire range of river regulation works remarkably changed the shape of the river course.

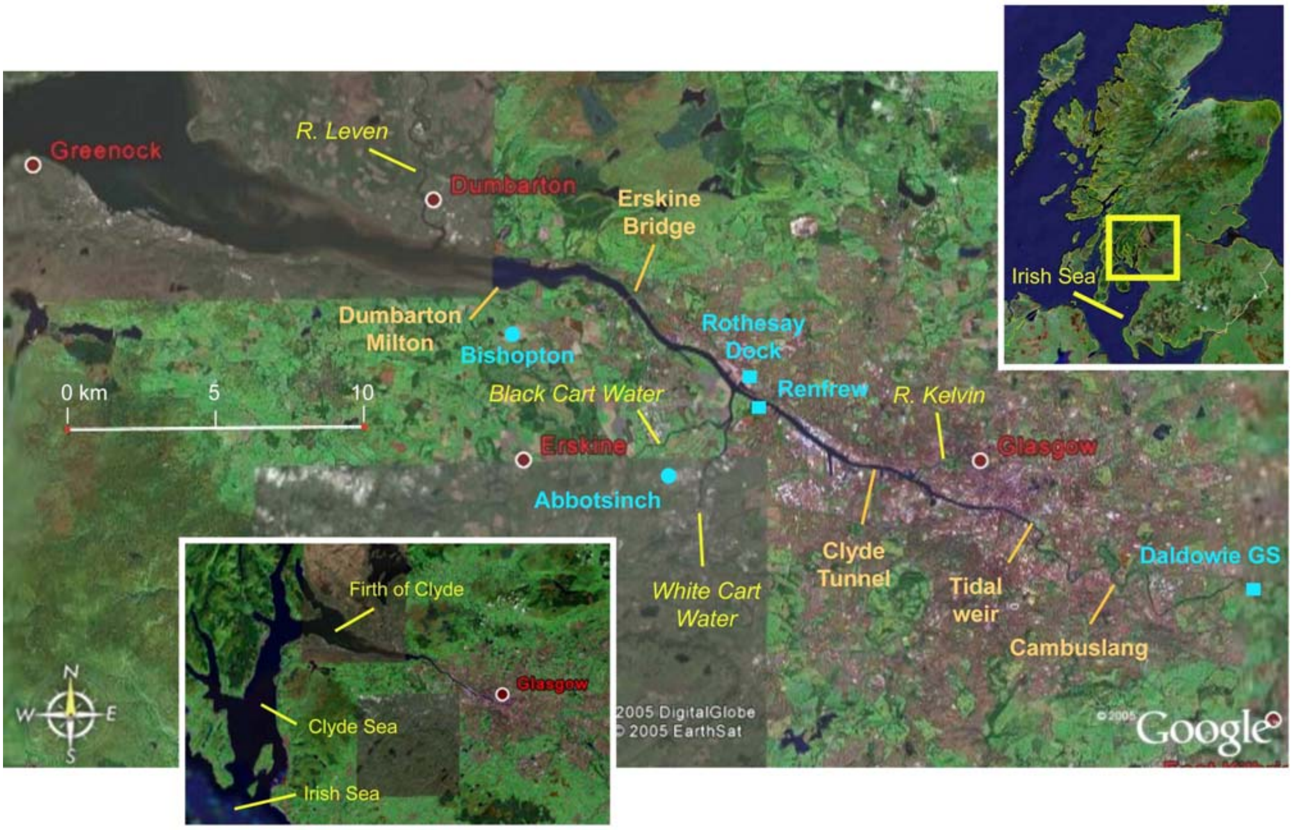

Figure 1 Geographical position and key locations in the Clyde Estuary.

The Clyde Estuary is a drowned river valley that has been inundated by rises in sea level. An extensive dredging programme has been conducted to allow ship navigation. The modern Clyde channel below the Tidal Weir is narrow and deep, with numerous bridges and docks, and river banks are constrained by quay walls and revetments. The river in Glasgow city centre is approximately 10 m deep and 200 m wide rectangularly-shaped construction. Upstream and downstream of Glasgow, the river is sustained in its natural regime. The upstream reach is meandering in plan with hydraulic depth of 4 m and width of 50 m. The downstream reach has a funnel shape of increasing width from 230 m to 3000 m. On the navigation waterway in downstream reach, river bed has constant depth of 11 m.

Tides are semidiurnal with a meso-tidal range of 3 m. Above the city of Glasgow the estuary is fluvio dominant, but tidally dominant in and downstream of the city. Long term average river inflow in the estuary is 110 m^3/s. In the Clyde Estuary main inflow is from the River Clyde, but in the estuary mass balance discharges from Clyde's five tributaries need to be accounted for. During years each major tributary was recorded based which peak flows for specific return periods were estimated, as shown in Table 1 below.

Table 1 Estimated river flow data (from Falconer 1992).

River	Average flow Q_{av} (m^3/s)	Mean annual flood Q_{1yr} (m^3/s)	10 year flood Q_{10yr} (m^3/s)	50 year flood Q_{50yr} (m^3/s)	100 year flood Q_{100yr} (m^3/s)
Clyde	45.3	434	623	810	884
Kelvin	8.3	73	87	101	107
White Cart	7.0	124	159	194	209
Black Cart	4.4	39	56	72	80
Gryffe	3.6	67	81	96	102
Leven	41.5	116	141	165	175
TOTAL	***110.1***	***853***	***1147***	***1438***	***1557***

2. DESCRIPTION AND SETUP OF MODELS

The numerical models used in this study are ISIS Flow (one-dimensional) developed jointly by HR Wallingford and Halcrow, and MIKE21 (two-dimensional) developed by DHI Water & Environment (DHI 2003). Each model is briefly described below along with the setup for the simulations.

2.1 Model description

One-dimensional model (ISIS Flow)

The one-dimensional model ISIS Flow is based on the 1-d Saint-Venant equations. To derive hydrodynamic solution of equations it uses a numerical solution based on 4 point implicit finite difference scheme. The 1-d Saint-Venant equations are derived from Reynolds Averaged Navier-Stokes equations, which are averaged over the cross-sectional area. Integration of the 2D RANS equations is performed over the width of a flow, neglecting horizontal transversal velocities. Governing equations in ISIS Flow describe conservation of mass and momentum as follows:

Conservation of mass:

$$B\frac{\partial \eta}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

Conservation of momentum:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right)+gA\frac{\partial \eta}{\partial x}+\frac{A\overline{\tau_b}}{\rho R}-\frac{B}{\rho}\tau_{sx}=0 \tag{2}$$

In these equations Q is the river discharge, η is the water stage, B is the flow top width, q is the lateral inflow per unit length, A is the flow area, R is the hydraulic radius, $\overline{\tau_b}$ is effective mean boundary shear stress. Parameter β is the Boussinesq coefficient, which takes account of the fact that the velocity distribution over the cross-section is non-uniform.

In this study the extended version of standard ISIS Flow model is used (ISIS-wind), which includes the wind shear in the momentum equations (the last term in equation 2). Parameter τ_{sx} is the component of wind shear parallel to the direction of flow and calculated from equation

$$\tau_s = C_{10}\rho_a \left|U_{10}\right| U_{10} \tag{3}$$

where C_{10} is drag coefficient, ρ_a is the density of air, and U_{10} is the wind velocity 10 m above the surface.

Strengths of one-dimensional model are quick solution of equations and easily inclusion of hydraulic structures in the model. Their limitations in the estuary models are cross-sectional averaging of velocities, exclusion of air pressure and Coriolis force effects and other simplifications involved in approximating a highly three-dimensional flow pattern to one-dimensional. These limitations may become significant in estuaries with broad or complex channel geometry.

Two-dimensional model (MIKE21 HD)

MIKE21 is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. MIKE21 HD solves the vertically integrated equations of conservation of volume and momentum (the Saint Venant equations). Equations describing depth-averaged open-channel flow are found by integrating the three-dimensional mass and momentum transport equations with respect to the vertical coordinate from the bed to the water surface, considering vertical velocities and accelerations to be negligible, w=0, $\frac{\partial w}{\partial t} = 0$, and assuming hydrostatic pressure over the water column. Depth-averaged models are used when both horizontal velocity components are important but strong vertical mixing can be promoted by bed roughness. Integration of equations over the water column leads to the following equations:

Conservation of mass:

$$\frac{\partial \xi}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \tag{4}$$

Conservation of momentum in x direction:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{C^2 \cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h \cdot \tau_{xx}\right) + \frac{\partial}{\partial y}\left(h \cdot \tau_{xy}\right)\right] - \Omega q$$
$$- fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial x}\left(p_a\right) = 0 \tag{5}$$

Conservation of momentum in y direction:

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\frac{\partial \xi}{\partial y} + \frac{gq\sqrt{p^2+g^2}}{C^2 \cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}\left(h \cdot \tau_{yy}\right) + \frac{\partial}{\partial x}\left(h \cdot \tau_{xy}\right)\right] - \Omega q$$
$$- fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial y}\left(p_a\right) = 0 \tag{6}$$

In these equations h is water depth ($=\zeta-d$), d is time varying water depth, ζ is surface elevation, p,q are flux densities in x, y direction, C is Chezy resistance, g is gravity acceleration, $f(V)$ is wind friction factor, V,V_x,V_y are wind speed and components in x and y direction, Ω is Coriolis parameter, p_a is atmospheric pressure, ρ_w is density of water, and $\tau_{xx},\tau_{yy},\tau_{zz}$ are components of effective shear stress.

MIKE21 HD simulates the variation of water levels and flows in response to a variety of forcing functions. Possibility of including effects of air pressure, precipitation, wave radiation stresses and Coriolis force on estuary hydrodynamics, along with 3D description of geometry, gives sometimes significant advantage to the 2-d models comparing to the 1-d models. The water levels and depth averaged flows are resolved on a square or rectangular grid covering the area of interest. A detailed description of the flow module can be found in Abbott at el. (1981).

2.2 Model setup

The ISIS model of the Clyde estuary was setup in the 2004 RCFMS study. During incipient stage of the study, recent survey data were collected. It included DTM of topography from LIDAR survey in 2003, and single and multi-beam bathymetry survey in 2004. Based on this data model cross-sections were developed and covered 56 km long corridor from Blairston to Greenock (Figure 2 below). In order to take into account the flood plain storage, 21 reservoir units are introduced to the model. Flow disturbances by numerous bridges are introduced in the model by orifices. The Tidal Weir is also represented in the model, by one large sluice gate operated by automatic rules. River discharges into estuary from the River Clyde and its tributaries are included by 7 inflows. The river hydrographs are based on the SEPA 15 min data recordings. Model also includes water quantity from 5 urban areas as lateral inflows. Urban inflows are estimated using the Modified Rational Method. The tidal boundary is located at Greenock, for which recorded tidal data were available by Clydeport and Baptie Group. Bed friction factor is introduced through Manning’s friction factor. The factor for the river channel and floodplains varies throughout the reach. To account wind shear effect on water levels, extended version of ISIS is used (ISIS-wind). The effects of wind are applied through the longitudinal component of wind speed. Wind data were obtained from the Met Office, and included hourly wind speed and direction from two meteorological stations Abbotsinch and Bishopton (Figure 1).

The MIKE21 model bathymetry is setup using surveys from the RCFMS study. The LIDAR and bathymetry data are combined into a single database with bed level specified relative to Ordinance Datum (OD). The finial model grid extends in tidally dominant reach in the Lower Clyde (red rectangle in Figure 2 below), and covers area of approximately 5.5×28 km. The grid resolution is 20 m in x and y direction, resulting in approximately 390.000 computation points. The model has two open boundaries, upper as inflow boundary from the River Clyde and lower as tidal boundary at Greenock. Inflows from 5 tributaries are introduced as internal inflow sources. The wind force is included in the model, assuming that wind speed and direction are constant over the model area in given time step. The exercise on air pressure affect is made, for which hourly air pressure data were available from MetOffice for Bishopton station. After calibration of model, combined effect of wind shear and air pressure is performed. Bed resistance for the model is defined by Manning’s friction factor, and is different for the channel and for the floodplains.

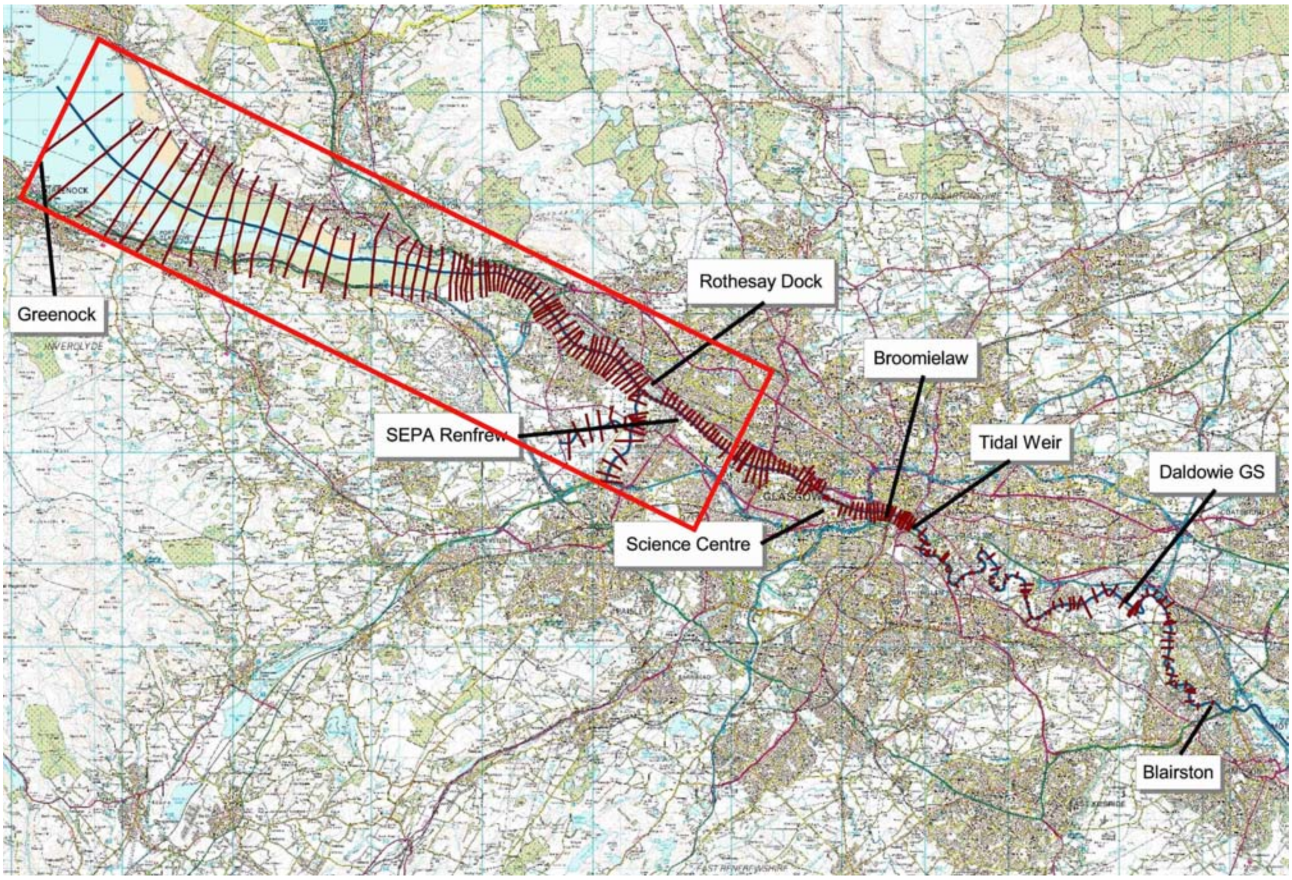

Figure 2 Extent of 1-d and 2-d model of the Clyde Estuary.

3. CALIBRATION OF MODELS

The models applied in this study are calibrated and validated through the comparison of predicted water levels by models and measurements at a number of stations along the estuary reach. During the calibration process, combinations of different values of bed friction factors are applied. In ISIS model for the tidal reach of estuary, value Manning's friction factor of n=0.019 $m^{-1/3}s$ for channel and n=0.120 $m^{-1/3}s$ for floodplain is adopted. In the 2-d model values of initial surface elevation, eddy viscosity and wetting/drying depths of grid cells are also alternated.

Quantitative analysis of time series provided a general assessment of the model performance, and is carried out for different historical events. Observations of tides, river inflows and wind were available for two days period in '91, ‘99, ’00, ’01 and ’02. These events covered tidal, fluvial and MHWS events respectively. To allow direct comparison between the models, the same boundary conditions are applied in each case. Predicted water levels are inter-compared on two gauging stations in the tidal reach: Rothesay Dock and Renfrew (shown in Figure 2). Summarized time-series comparison of the predicted and observed water levels during one historical event (27th-29th of January 2002) are further presented.

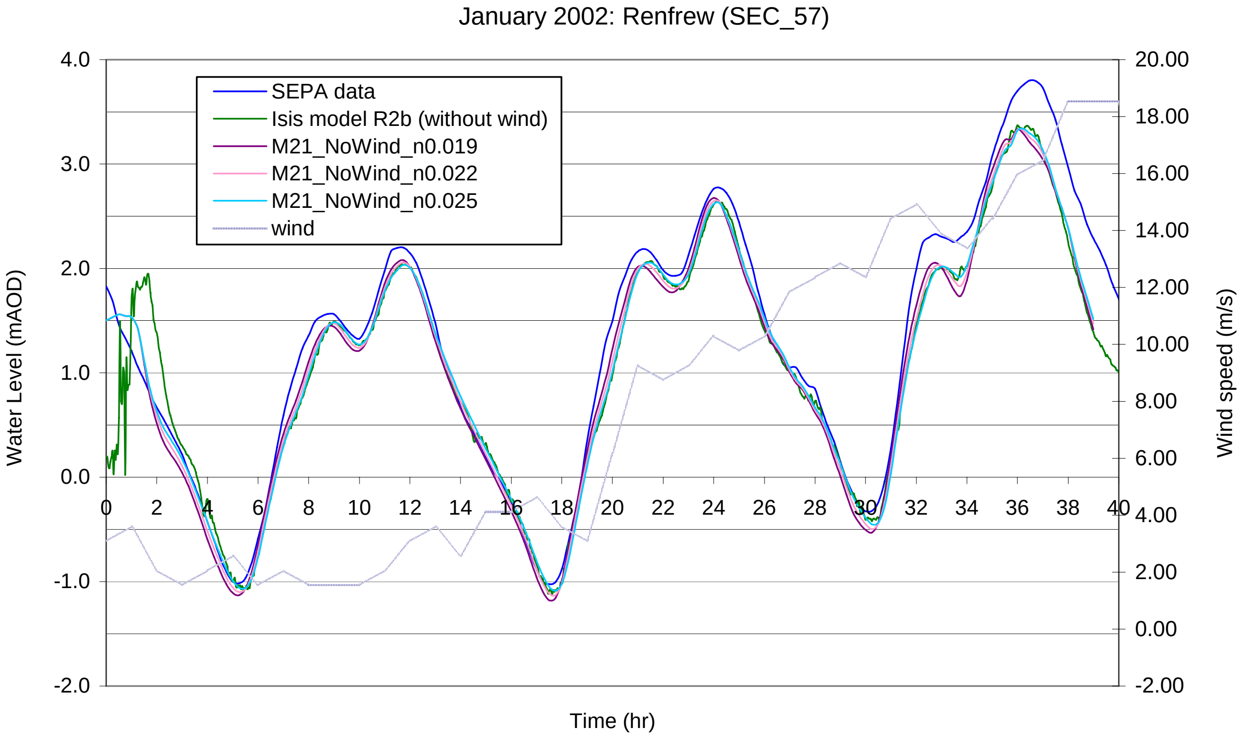

Figure 3 Comparison of time series of observed and predicted water levels for Renfrew station. Observations (dark blue), ISIS (green), MIKE21 (n=0.019 dark red, n=0.022 orange and n=0.025 light blue), wind speed (grey).

In Figure 3 above, model output results from ISIS model (n=0.019) are shown together with output from MIKE21 for three different Manning's numbers: 0.019, 0.022 and 0.025 $m^{-1/3}s$. Both models exclude wind and air pressure effects. The wind speed is shown in grey. Comparison of MIKE21 results for different frictions factors show no major discrepancy. Decrease of friction factor slightly increases tidal range (~0.15 m). A tidal basin of the Clyde estuary produces a complex tidal hydrograph; hence incoming tide shows a double peak in the upstream reach. Both models reproduce well the phase and amplitude of the tide up to hour 30. Timing of high tide is well predicted both in ISIS and MIKE21 model. The largest discrepancies between models are during ebb tides (~0.10 m at hour 30). After hour 30 both models underestimate peak tide by 0.5 m and its duration. Reason for that is the wind effect on the tide. During the event the wind was mainly westerly. Over sufficient long and wide fetch of the lower estuary, wind effect increased tidal hydrograph in the city.

In MIKE21, the horizontal turbulence shear stresses are modelled using Boussinesq's eddy viscosity concept. Two different turbulent closures can be employed: constant eddy viscosity and Smagorinsky sub-grid scale concept. Constant eddy viscosity coefficient can be specified as a constant value for the entire computation domain or specified at each grid point. If choosing Smagorinsky approach, the factor C_s must be specified, and is usually in the interval from 0.25 to 1.0. Studying the Elbe estuary, Ems estuary and Hamburg harbour Stoschek (2000) demonstrated that using C_s value in range between 0.4 - 0.7, model results fit well eddy diameter and its dynamic behaviour (drift, rotation, velocity). In modelling tide-driven currents and residual eddies Babu (2005) used the value of C_s=0.5. Here the Smagorinsky factor of C_s=0.5 is chosen.

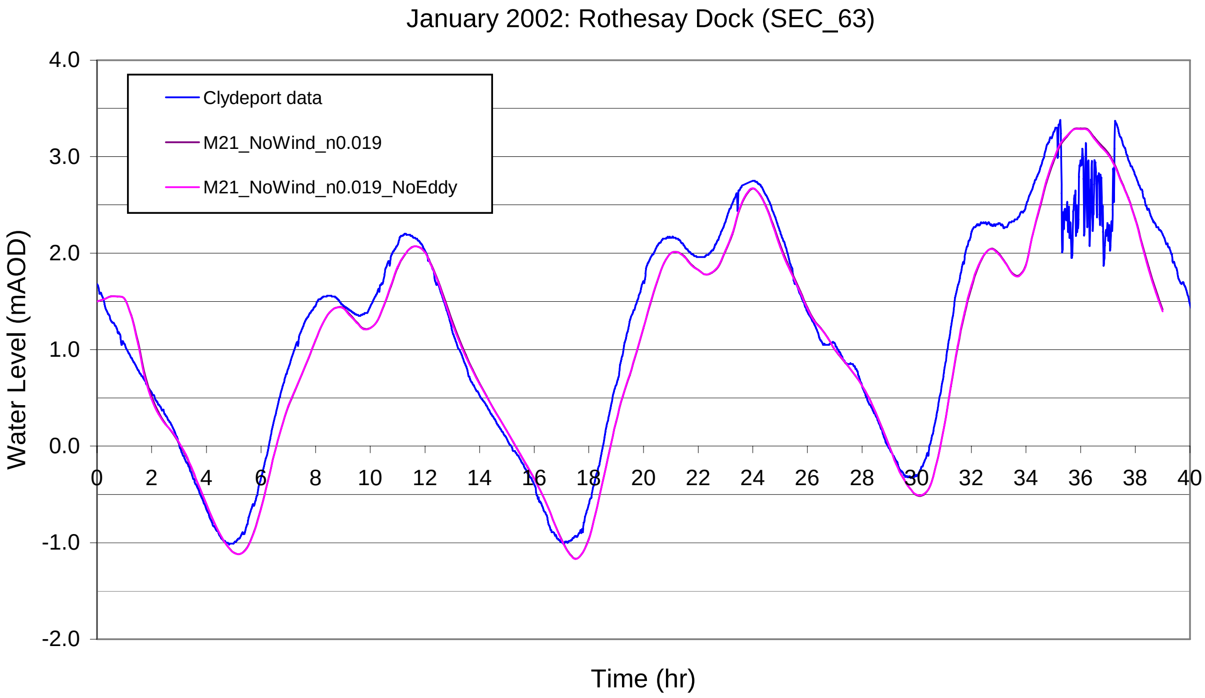

Figure 4 Comparison of time series of observed and MIKE21 predicted water levels for Rothesay Dock station for different eddy viscosity scenarios.

Figure 4 above shows two MIKE21 runs for different eddy viscosity scenarios. The model run using Smagorisky approach using factor C_s=0.5 (dark red), and model run using zero Reynolds' stresses (cyan). There are no major discrepancies between water level results. This implies that the horizontal diffusion of momentum is minimal, and that in macro tidal estuaries energy dissipation of tidal wave is mainly due to vertical momentum diffusion, i.e. the friction of water flow over the rough bed. On studying spring and neap tides in the Humber Estuary, Wright (2000) gained similar results. On 30 km model extent, 1-d model (MIKE11) and Delft3D model (with possibility of 2-d and 3-d computations) predicted similar water levels, with standard deviation of $\pm$0.20 m from observed values. Higher deviation of $\pm$0.3 m was observed at the head of the estuary and smaller of $\pm$0.10 m at the mouth.

The variation of different initial water surface elevation in MIKE21 showed no influence on model results. Numerical stability was obtained for the time step interval of Δt=5s, which gave maximal Courant number of 2.7. Wetting and drying depths were also altered, and values of 0.05 for drying depth and 0.1 for wetting depth were adopted.

The quantitative judgment of the model results showed that the 1-d and 2-d model are able to satisfactorily predict shape and propagation of tidal wave in low wind conditions. Observed double peak is reasonably well predicted. Excluding wind force in model runs, both models underestimate the tidal peak during strong wind conditions. In further exercises of MIKE21 model, Manning's number of n=0.019 $m^{-1/3}s$ for the channel and n=0.120 $m^{-1/3}s$ for floodplain is used, together with zero turbulent viscosity coefficient.

4. NUMERICAL SIMULATIONS

Using the models described above, several combinations of simulations are carried out including different river inflows, wind conditions and air pressures. The effect of air pressure is not coupled in the ISIS model, and its influence is analysed instead using the MIKE21 model. In the simulation runs air pressure was assumed to be constant over the whole domain in given time step.

4.1 River inflows

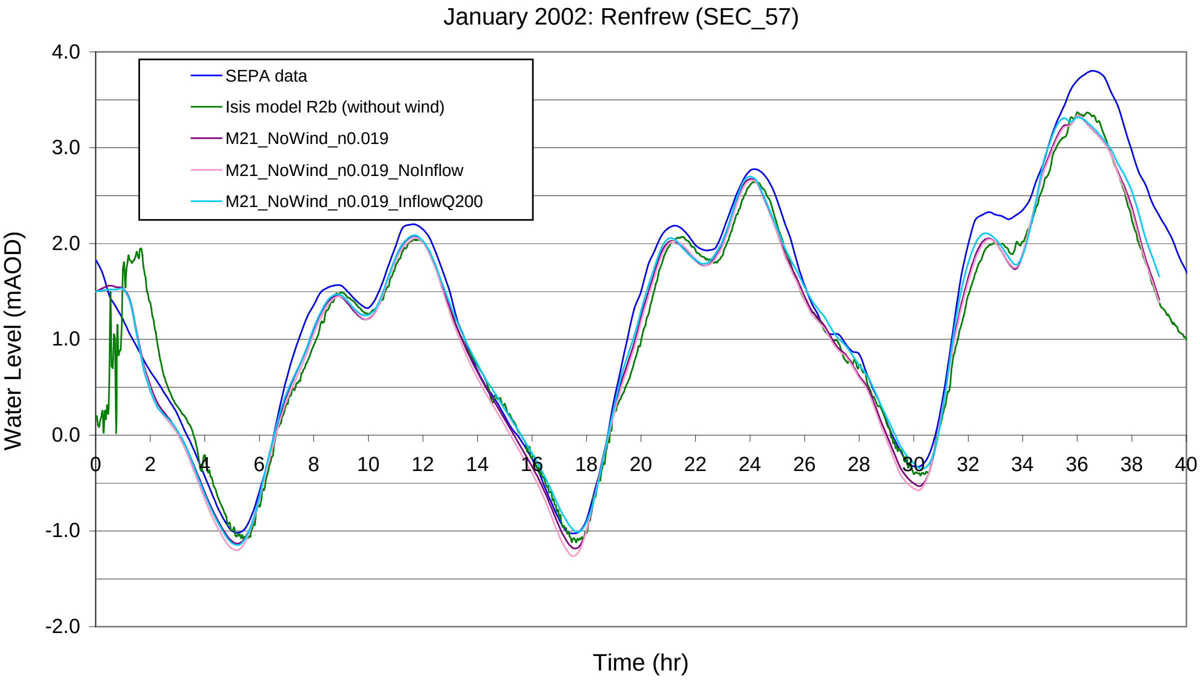

Figure 5 MIKE21 water levels at Renfrew for different inflow scenarios.

For the sensitivity analysis of the model on fresh water inflows (Figure 5), three inflow scenarios were accounted in MIKE21 model: observed inflows (dark red), no inflow (red) and inflows for 200 year return period (light blue). Prediction of the highest peak discharge for the River Clyde in 200 year is 800 m^3/s, which is nearly four times higher than observed flow in Jan 2002 event. Model runs included observed tides at downstream boundary and excluded wind and air pressure influence. It can be seen that fluvial inflow has some influence on the lowest water levels (during the ebb tide difference between "NoInflow" and "Q200" scenario is ~0.25 m), but no influence on high tides. This exercise shows that fluvial inflow has no major influence on water levels in the lower estuary.

4.2 Wind shear stress

In one-dimensional numerical models, as well in ISIS, wind shear stress is neglected in the transverse direction (perpendicular to flow direction). In MIKE21 the driving force due to the wind blow over the model area is calculated from quadratic law as,

$$f_{wind} = C_w \frac{\rho_{air}}{\rho_{water}} W^2 \ [\mathrm{m^2/s^2}]$$

where C_w is the wind friction coefficient, ρ is the density (the ratio equals to 1/800) and W is the wind velocity in m/s 10 m above the sea surface. Wind friction coefficient for strong and moderate wind is usually 0.0026, whereas smaller coefficient 0.0013 can be used for weak winds.

For the Jan 2002 event the observed data from two meteorological stations were available: from Bishopton station, 59 m above mean sea level. The simulations were conducted with varying wind speed and direction during simulated period. It was assumed that at one time point wind speed and direction are constant over the domain. In MIKE21 constant wind friction coefficient of 0.0026 was used. The downstream boundary and inflow boundaries accounted observed data.

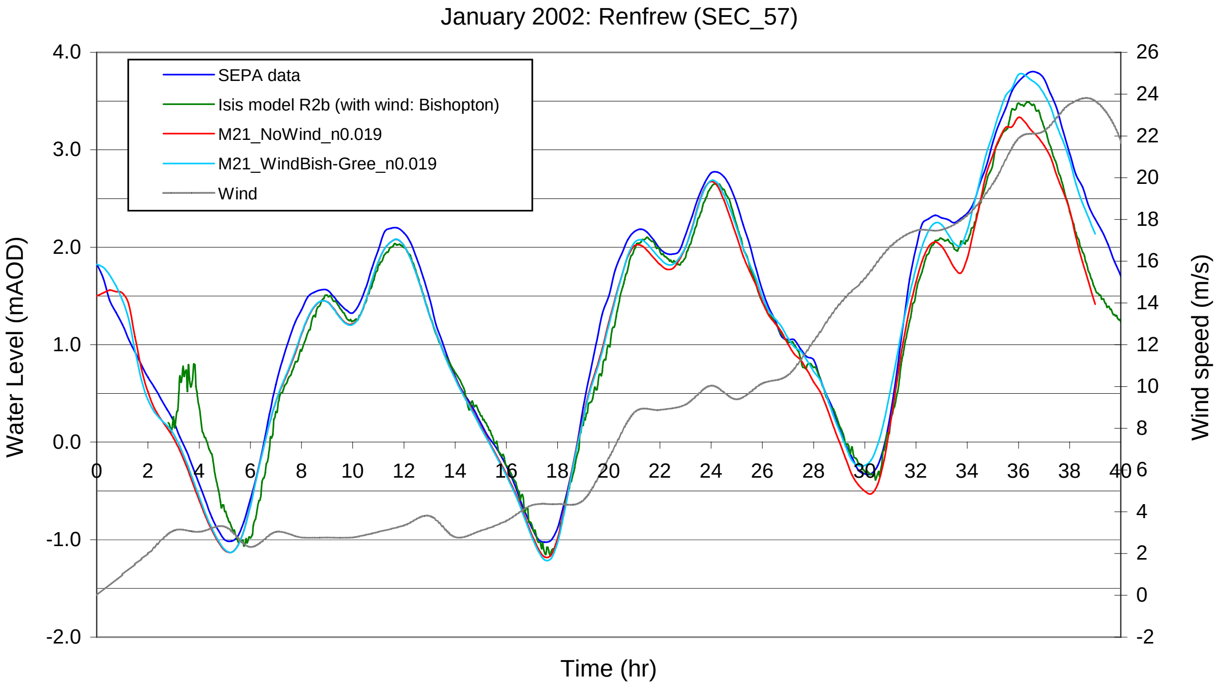

Figure 6 Predicted water levels with wind influence at Renfrew.

In Figure 6 above, the model output from the ISIS model with wind included (green) are shown together with MIKE21 output without (red) and with wind effect (light blue). During the Jan 2002 event wind was mainly south-westerly. Comparing ISIS and MIKE21 predictions with observed values (dark blue) it can be seen that wind influence in MIKE21 model can be detected after hour 28 when wind speed rises over 10 m/s. Until about 30 hours, MIKE21 and ISIS models give similar prediction. Peak water levels at hour 36 are under predicted in ISIS by 0.30 m, but reasonably well predicted in MIKE21. Duration of peak tide is underestimated in ISIS while reasonably well predicted in MIKE21. Comparison of two MIKE21 outputs implies that wind can increase a high tide for 0.50 m and a duration for 1 hour. Eventually, when strong westerly winds coincide with the timing of a rising limb, tide is distorted with increasing of its peak and duration. In such circumstances 2-d model gives satisfactory prediction.

4.3 Combined effect of wind and air pressure

Addition of air pressure should be cautiously included in the model simulations. Tide at Greenock is a product of astronomical tide from the Irish Sea and its deformations while drifting through the Clyde Sea and the Firth of Clyde. The air pressure acts over the whole water body, and the astronomical tide is also influenced. Eventually, observed tide at Greenock includes all this effects.

Including observed tide for the downstream boundary, together with the observed air pressure, would double effect of air pressure in the model. Therefore, model runs should account only astronomical tide at downstream boundary. The assessment of internal meteorological forcing is made on the basis of SEPA tide predictions for Greenock, which exclude air pressure effects.

External meteorological forcing

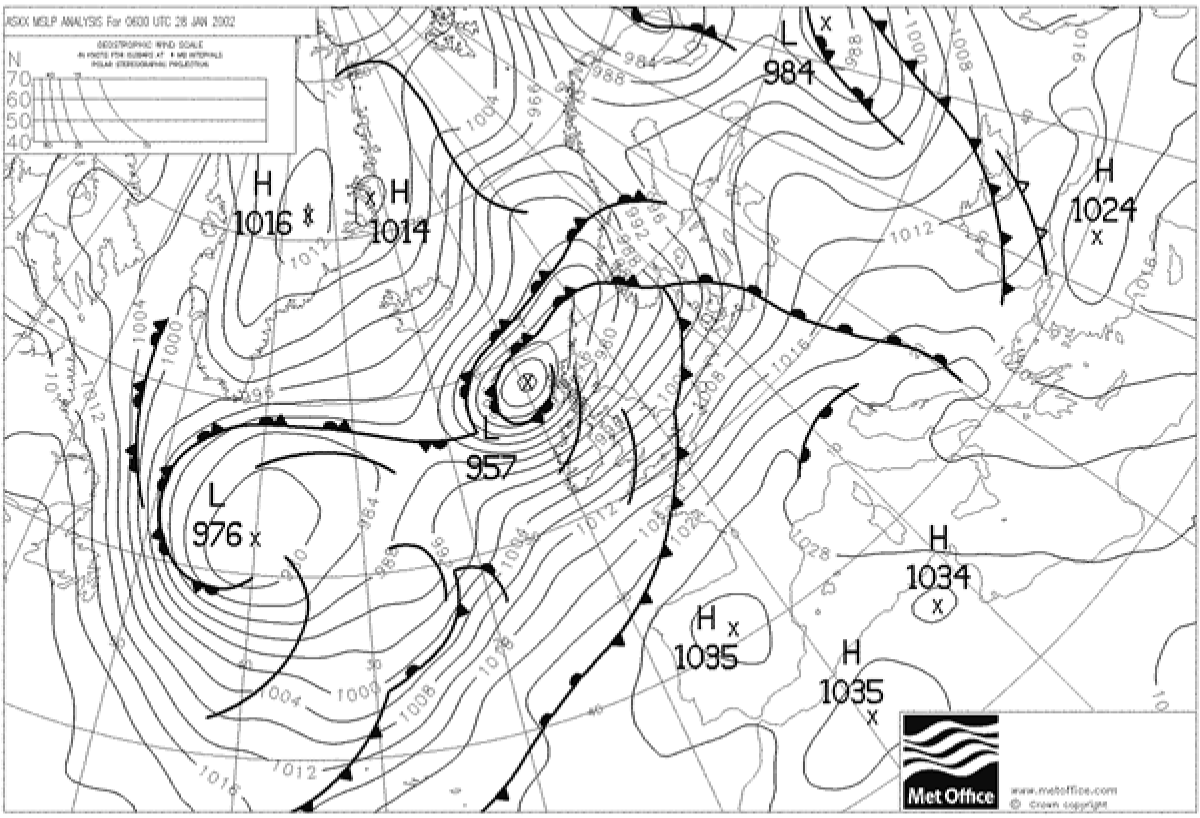

Figure 7 Air pressure map for the 28th Jan 2002 (Met Office).

For the prediction of tidal levels in the Firth of Clyde, SEPA (with Jacobs Babtie) developed a MIKE21 model on 500 m grid resolution. The model comprises an astronomical tide model, a surge model and a one-dimensional model of the River Clyde. The surge model uses 12 km grid surge data from the Met Office continental shelf model and wind forecasts as input in the MIKE21 model. MIKE21 model then forecasts propagation of the surge within the Firth of Clyde on a 500 m grid. This modelling suite was developed and extensively validated against recorded tide data.

In Jan 2002 event, a deep ocean tide was probably initially exaggerated by the storm surge over the West coast of Scotland. Figure 7 above shows a synoptic chart at the 06:00 hour (equals hour 30 in the model time scale) where the deep depression in air pressure is evident (957 hPa). For the Jan 2002 event, predicted and recorded tides at Greenock are shown in Figure 8 below. Predicted SEPA tidal data were provided from the Heatlie MSc study (2004) and were available for 28th Jan (from hour 24 to 44), shown by blue line. It can be seen that tide at Greenock is significantly under predicted (1.3 m at hour 36).

To assess the effect of air pressure to tidal levels the mean sea level variations are shown in Figure 8 (green line), together with air pressure variations (grey line). The falling of air pressure is immediately followed by the rising of mean sea levels, and confirms strong connection of tides and air pressure variations. At the hour 36, air pressure was 987 hPa, and 25 hPa below normal air pressure gives 0.25 m rise of the tide. The rest of 1.05 m tidal increase to overall 1.3 m tidal difference at hour 36 was probably due to the storm surge over the Irish Sea. Eventually, on the 28th Jan the storm surge significantly exaggerated astronomical tide from the Irish Sea, which was not forecasted by SEPA MIKE21 model. By including only air pressure effect, the forecast of the high tide at Greenock probably could have been 0.25 m better.

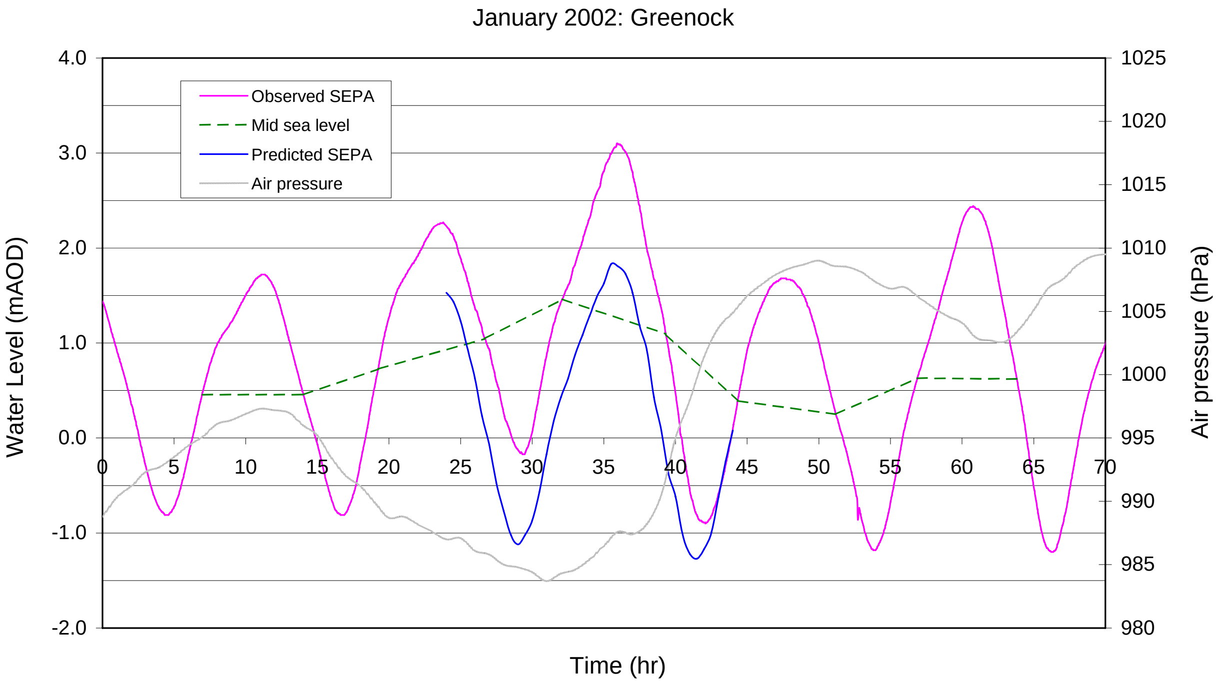

Figure 8 SEPA predicted and observed tide at Greenock in Jan 2002.

Internal meteorological forcing

In order to justly simulate combined effect of wind and air pressure, MIKE21 model run included SEPA predicted tide at downstream boundary, together with observed inflows and observed air pressure and wind data. These results are compared to simulations without wind and air pressure influence. Figure 9 shows several outputs: model run without wind and air pressure influence (dark blue), model run only with air pressure effect (light blue) and model run with combined effect of wind and air pressure (red). To include the effect of wind shear coefficient, it was altered as linear increase from 0.0016 to 0.0026. Varying wind coefficient (yellow) made no significant change to the model run with constant wind coefficient 0.0026 (red). Model outputs with air pressure influence (light blue line) and without it (dark blue line) confirm influence of air pressure on water levels. Model output with air pressure and wind influence (red line) imply that the internal meteorological forcing could have increased high tide for 0.80 m and its duration for nearly 4 hours during 28th January.

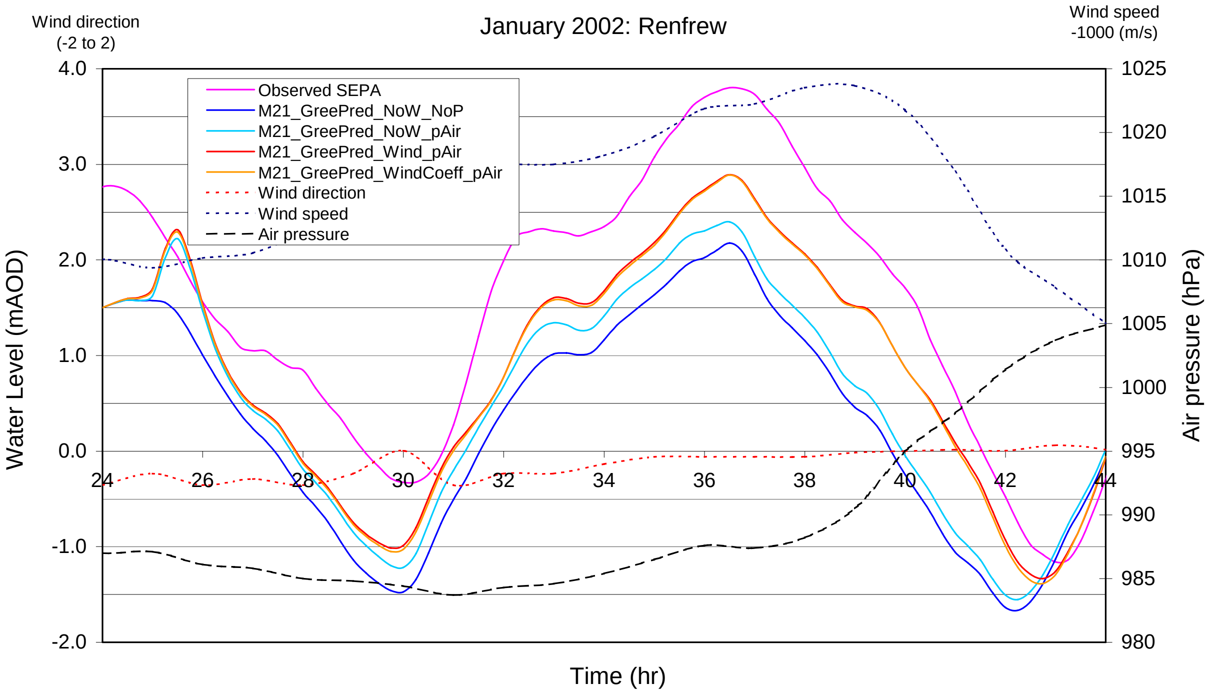

Figure 9 MIKE21 predicted water levels for meteorological forcing at Renfrew.

As demonstrated earlier, ISIS model predicted 0.30 m lower peak tide level than MIKE21 model, and no increase of high tide duration. Hence, ISIS model would probably forecast 0.50 m lower high tide and shorter retention then MIKE21 forecast. Eventually, if combined effect of wind and low air pressure emerge, 1-d model (ISIS) cannot give satisfactory prediction of high water levels in the estuary.

5. CONCLUSIONS

Based on the comparison of water levels between 1-d and 2-d model predictions and observations, following tentative conclusions may be derived. Firstly, exclusion of wind effect showed that both models predicted similar water levels, but lower than those observed. Even though the estuary is hyper-synchronous and the funnelling amplification effect is bigger than frictional damping, there was no difference in predictions between 1-d and 2-d models. Furthermore, even though the estuary downstream is more like a compound channel, the effect of lateral momentum transfer is too small to show-up in a 2-d model. Secondly, inclusion of wind effect showed smaller differences between predicted and observed water levels by both models, but the difference in MIKE21 model was smaller than in ISIS-wind model. Based on the comparison of water level predictions in 2-d model, for simulations with and without meteorological conditions, the following conclusions may be derived. As the 10 hPa lower air pressure gives 10 cm water level increase, it follows that the influence of air pressure is significant in predictions of estuary flood levels. Inclusion of observed meteorological conditions has shown that the combined effect of wind and air pressure increased flood levels by 80 cm. Finally, for the flood level predictions in macro tidal estuaries both 1-d and 2-d models can be recommended. However, as 1-d models still do not include air pressure effect and as they (ISIS-wind) give less satisfactory predictions than 2-d models (MIKE21) of wind shear effect, the utilisation of 2-d models is recommended for flood level predictions in estuaries with strong wind and air pressure influence.

ACKNOWLEDGEMENTS

The authors would like to thank Jim Fleming of Glasgow City for access to the LIDAR data and ISIS model, Marc Becker of the Scottish Environment Protection Agency (SEPA) for providing some meteorological data, Miguel Piedra and Linda Hemsley of Halcrow Group for support and access to the River Clyde Flood Management Strategy study data and modelling results.

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