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Dispersion Modelling of Salinity in Inner Galway Bay and Lough Atalia for the Galway Harbour Extension Project

Prepared for

Galway Harbour Authority

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1. Background

Hydro Environmental Ltd was commissioned by Galway Harbour Authority to perform a detailed Dispersion modelling assessment of potential changes to water salinity in Lough Atalia and Inner Galway Bay as a result of the proposed Galway Harbour Extension. In support of this assessment extensive field work involving bathymetry, and hydrometric measurements hydrodynamics and salinity measurements was carried out in January and March 2013.

A full baroclinic (density varying) three-dimensional hydrodynamic model TELEMAC-3D had to be employed to tackle this complex problem of a buoyant freshwater flow interacting with the more dense saline tidal waters at the Mouth to Galway Docks and Lough Atalia.

Salinity Units ppt and psu

Please note that the salinity measurement data referred to in this report are in the units of psu, whereas the hydrodynamic salinity model TELEMAC-3D refers to salinities in grams of salt per kilogram of solution (g/l or parts per thousand (ppt)). The modern oceanographic definition of salinity is the Practical Salinity Scale of 1978 (PSS-78). The numeric unit from PSS-78 is psu (practical salinity unit) and is distinct from the previous physical quantity ppt (kg salt per kg water in parts per thousand). Salinity values in ppt and psu are nearly equivalent by design, and for the purposes of this assessment can be treated as equivalent.

2. Hydrology of Lough Atalia

2.1 General Description

Lough Atalia is a tidal Lough of some 39ha in area, located to the northeast of Galway Docks in Galway City. The Lough is connected to the sea via a 430m long inlet channel which has a railway bridge crossing at its north end, the Galway Harbour Enterprise Park road bridge crossing towards its southern seaward end and a low stone boulder weir located across a wide section of the channel towards the north end, (refer to Figure 1 and 2). The surrounding catchment area to the Lough is of the order of 2.2km^2 and is an urbanised catchment with approximately 30 to 40% paved area.

The bedrock geology of the catchment and the majority of the Lough is a Visean pure bedded limestone, which is classified as regionally important karstic (conduit flow) bedrock aquifer. The southern end of the Lough near the Railway Bridge is classified as a Metagabbro and Orthogneiss bedrock which is a metamorphic rock derived from igneous rock. This represents a hard and impervious rock formation whereas the Visean Limestone is softer and prone to weathering and solution. The bedrock underlying the Docks and the proposed Harbour Extension area is also shown to be Metagabbro and Orthogneiss bedrock.

The Bathymetry of Lough Atalia reveals generally a shallow bay except for a deep pocket towards the southern end of the Lough inside the inlet channel (refer to Figures 5 and 6). This deep pocket coincides with the interface between the igneous and limestone bedrock formations, with the softer limestone bedrock being eroded over time by the locally high velocities inflowing to the Lough and the igneous rock being much more resistant to erosion. There is only one identified spring feature referred to on the older OSI maps and which is marked on-site by a white Cross as St. Augustine's Well with no other springs being identified either on the OSI or GSI karst database in the vicinity of Lough Atalia.

The salinity in Lough Atalia has been shown to vary significantly with the tidal range and the River Corrib flow rate. Recorded salinities within the lough varied from 1 up to 30 psu over a range of sampling dates in 2012 and 2013. The lough is relatively shallow and is practically completely flushed in a single spring tide. The incoming spring tide initially pushes freshwater into the lough and then as the tide rises sufficiently a more saline wedge is introduced. On neap tides the tidal range (< 0.4m) is insufficient to draw the deeper saline wedge into the lough and consequently the water entering primarily comprises Corrib freshwater from the buoyant surface layer. This affect significantly lowers the salinity within the Lough during the neap tide period. As tidal cycle proceeds from neap to spring tides more saline conditions are returned to the Lough by the deeper saline flows. The magnitude of the Corrib freshwater flow has a significant effect on salinity levels within Lough Atalia being the principal source of freshwater inflow to this tidal Lough.

Because of the large attenuating effect of Lough Corrib and the control of flows and water levels in the Corrib by the OPW at the Salmon Weir sluice facilities, the magnitude of the flow rate discharging to the estuary is a gradually varying discharge with the majority of storm fluctuations dampened out by the lake control (being retained as lake storage for slower release).

Figure 1 Aerial View of Galway Docks, Claddagh Basin and Lough Atalia

Figure 2 Lough Atalia Inlet/outlet Channel, showing bridges and channel

2.2 Hydrodynamics of Lough Atalia

Hydrometric measurements carried out in Lough Atalia in January and March 2013 indicate low water levels in the Lough of 0.5 to 0.6m O.D. and highwater levels of 2.3 to 2.4m OD Malin on spring tides. This tidal range is significantly lower than the tidal range measured uside the Lough at the Galway Docks tidal gauge which registers a spring tide low water level of -2.5m O.D. and highwater level of 2.5m O.D. .

On neap tides the tidal range in Lough Atalia was found to be very weak and practically non-existent at 0.2 to 0.3m range (low water between 0.3 and 0.4m and high water 0.5 to 0.6m OD). The neap tidal range registered for this period at Galway Docks had a low water level of -0.6m and highwater level of 1.2m O.D.

The tidal inflow period on spring and neap tides was found to be approximately 2 to 2.5hours and the outflow period from the Lough being a slow release for nearly 10hours. At monitoring location S1 within the Lough the ADCP (Acoustic Doppler Current Profiler) current profiles showed a strong pulse of inflow to Lough Atalia on spring tides and reducing to little or no appreciable pulse on the neap tides (refer to Figures 3 and 4).

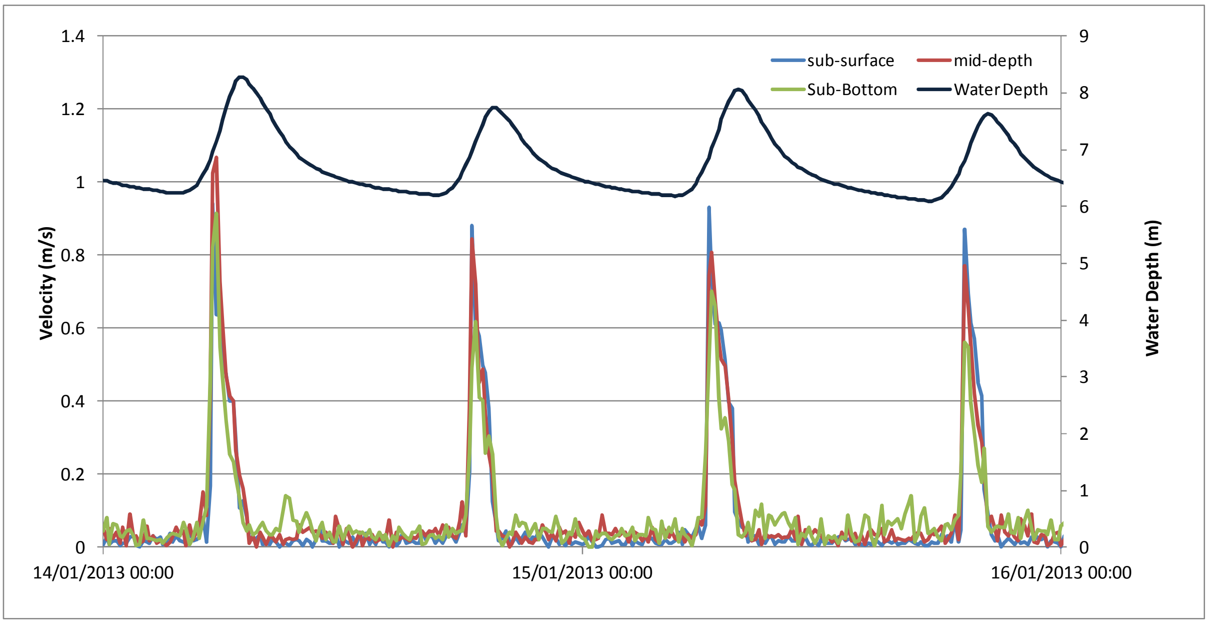


Figure 3 Spring tide observations of current speed and depth at S1 (refer to figure 6 for location) in Lough Atalia

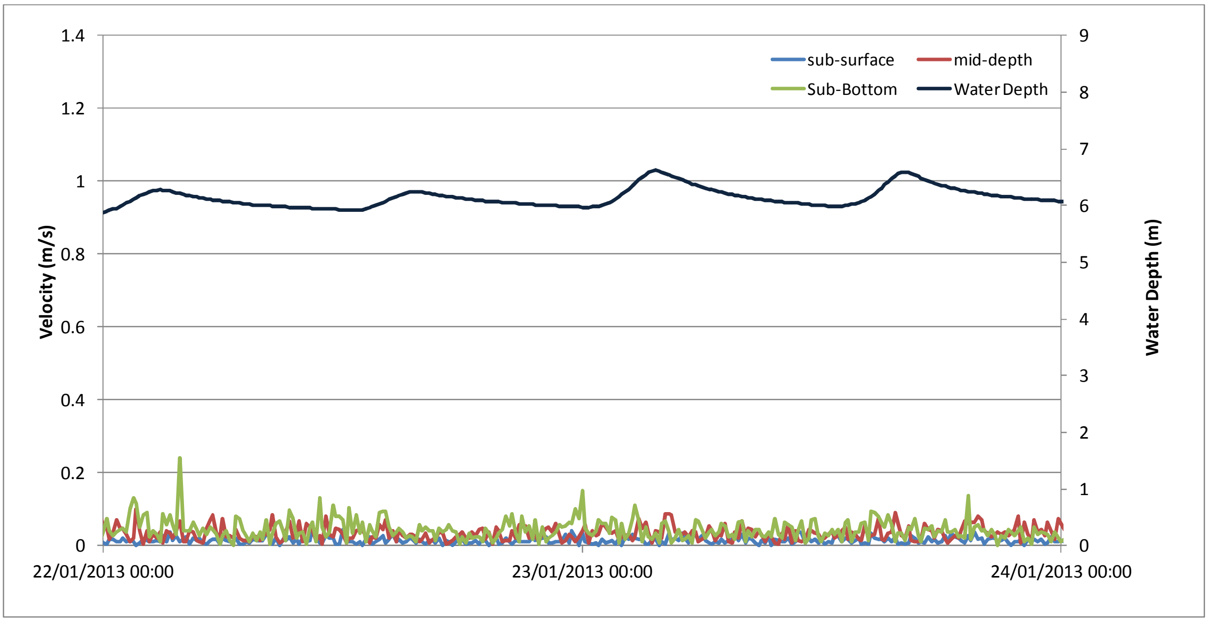


Figure 4 Neap tide observations of current speed and depth at S1 in Lough Atalia

2.3 Tidal Exchange

Lough Atalia from inside the Railway Bridge is approximately 39ha in Area. The entrance channel to Lough Atalia dictates the tidal range and tidal flows entering the Lough. This channel acts as a low profile weir maintaining a typically a low water level within the Lough of 0.3 to 0.6m O.D. Malin for neap and spring tides respectively. The channel width varies typically from 45 to 70m with the narrowest point at the Road culvert having an opening width of c. 35m. A stone boulder weir located approximately 100m downstream of the Railway Bridge crosses approximately 75% of the channel width with a top elevation of 0.8 to 1m O.D.

On a spring tide the surface area of Lough Atalia is typically 39ha at high water and 25ha at Low water. The volume of the Lough at highwater is estimated to be 771,200 m^3 (water level of 2.4m O.D.) and 197,500 m^3 at Low water (water level of 0.6m OD). This represents an exchange volume of 573,700m^3 over a tidal cycle (approx 75% of the Lough volume at highwater). This exchange volume practically flushes out the entire Lough on a single tide. This tidal exchange represents and average inflow rate over the 2.5hr inflow period of 64m^3/sec (13m^3/sec averaged over the full 12.4hr tidal cycle). The hydraulic residence time within the Lough for a spring tide is 4.2hours which is very short representing excellent flushing characteristics.

On neap tides the surface area of Lough Atalia is typically 25ha at high water and 21ha at Low water. The volume of the Lough at highwater is estimated to be 197,500 m^3 at high water (water level of 0.6m O.D.) and 139,900 m^3 at Low water (water level of 0.35m OD) This represents an exchange volume of 57,600m^3 (approx 30% of the Lough Volume at highwater). This tidal exchange represents and average inflow rate over the 2.5hr inflow period of 6.4m^3/sec (a factor of 10 lower than the spring tide rate) or 1.3m^3/sec averaged over the full 12.4hr tidal cycle. The hydraulic residence time within the Lough for a neap tide is about 30hours.

2.4 Sources of freshwater inflow

The principal source of freshwater flow to Lough Atalia is from the Corrib which enters Lough Atalia during the relatively short inflow period of 2 to 2.5hours around highwater at Galway Docks. Other potential sources of freshwater inflow is from groundwater and direct storm runoff to the Lough from the surrounding Urban Catchment via a number of storm outfalls.

Groundwater inflow contribution to Lough Atalia is estimated to be less than 0.1cumec based on an empirical baseflow equation from the FSR method (NERC 1975) for a catchment area of 2.2km^2 and annual rainfall amount of 1200mm. This rate is not significant in comparison to the tidal exchange volumes entering lough Atalia. However given the karstic nature of the limestone bedrock larger groundwater inflows cannot be ruled out, but the measured salinity data does not suggest any major groundwater inflow source. A further source of freshwater inflow is from direct storm water runoff from surrounding roads and paved areas. On balance such a contribution will generally be minor given the relatively small contributing catchment area.

Table 1 River Corrib Flow and Water Level Magnitudes – Duration Curve

DURATION PERCENTILES							
Flows equalled or exceeded for the given percentage of time (m^3/s) (Data derived for the period 1950 to 2005)							
1%	5%	10%	50%	80%	90%	95%	99%
272	230	200	82.1	35.0	28.5	24.6	9.12
Levels equalled or exceeded for the given percentage of time (mAOD Poolbeg) (Data derived for the period 1950 to 2005)							
1%	5%	10%	50%	80%	90%	95%	99%
4.37	4.04	3.84	3.32	3.02	2.96	2.93	2.85

2.5 Salinity measurements

Salinity measurements from discrete sampling surveys within Lough Atalia were carried out on 5 dates in 2012 at 21 sampling sites and for a range of depths through the water column. The dates were 4th, 10th, 16th, 24th April and 4th May 2012. Contour plots of measured salinities at 0.5 to 1m depth below surface is presented in Figure 7 for these dates.

A second series of discrete sampling surveys at 10 sites within Lough Atalia and for a range of depths through the water column was conducted in January 2013. The dates were 11th, 14th, 15th, 18th, 21st, 23rd and 24th of January 2013. Discrete sampling of salinities on the inlet channel to Lough Atalia at the Docks Enterprise Park Road Bridge was carried out for a spring and neap cycle on the 11 and 18th February 2013.

In-situ salinity probes were installed for continuous monitoring of salinity at reference sites S1 and S2 (refer to Figure 6 for locations) for the sampling period 8th Jan to 1st Feb 2013 and 12th March to the 26th March 2013. At S1 three probes were installed to measure near surface, 1.5m depth and 3m depth and at S2, 2 probes were installed near bottom (malfunctioned) and near surface at S2.

The discrete salinity surveys confirmed that spatially there is not generally significant variation in salinity concentrations with the southern end of the Lough being slightly less saline due to its proximity to the inlet channel. The different sampling dates did reveal significant variation between dates in the salinity concentration with neaps being considerably less saline than spring tide periods. The measurements showed increasing salinity with depth particularly for the deeper southern section of the Lough towards the inlet/outlet channel. In the shallower areas of the Lough the variation in salinity with depth was only slight.

The discrete sampling in the lough generally reflected the salinity observations from the continuous probes at S1 and S2. The continuous monitoring at S1 and S2 clearly capture the pulse of the incoming spring tide with a more freshwater inflow preceding a stronger more saline pulse as the incoming tidal height increases, refer to Figure 9 for spring tide monitoring at S1 (12th - 16th January 2013). The neap tide monitoring (See Figure 10) shows considerably lower salinities entering with no definite pulse being observed by the probes due to the weakness of the inflow rate. Inflow water levels are considerable lower and thus only a more freshwater surface layer enters without the deeper more saline water entering the Lough.

The measured salinities on neap tides shown in Figure 10 have salinities consistently below 2.5 psu for repeated neap tides over a 3 to 4 day period. The Corrib Freshwater Flow during this period varied from approximately 150 to 160cumec (25 to 21-percentile Corrib flow rate, (exceeded on average 77 to 91 days per annum) and the neap tidal elevation range in Lough Atalia was only 0.2 to 0.4m. The Spring tide salinities for similar Corrib flows presented in Figure 9 are significantly higher at 12 to 13psu as the tidal range allows the deeper saline wedge to enter Lough Atalia, whereas the neap tide range practically only allows the surface freshwater plume to enter.

The continuous and discrete monitoring shows that depending on the strength of the tide and the Corrib Freshwater flow (which is generally less variable) that salinities within the entire Lough can change rapidly over a number of tidal cycles. This rapid change in salinity is due to the relatively small volume in the Lough that can easily be flushed, the regular lunar variation in the tidal cycle with spring tides declining to neaps and returning to springs over a 14 day interval and other meteorological factors such as storm surges and local wind effects on the flow and tide regime.

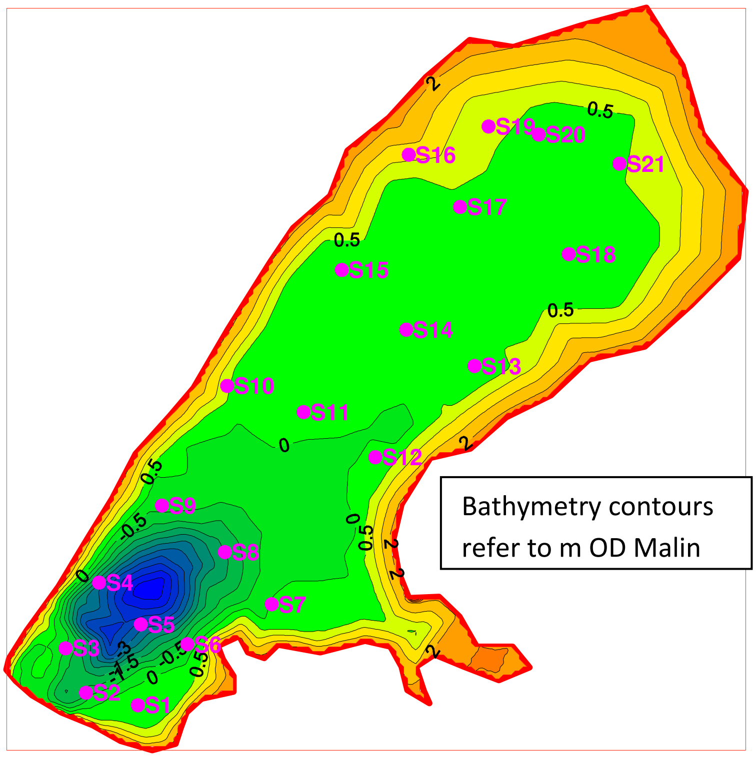


Figure 5 Sampling Locations S1 to S21 in Lough Atalia for 2012 Salinity surveys

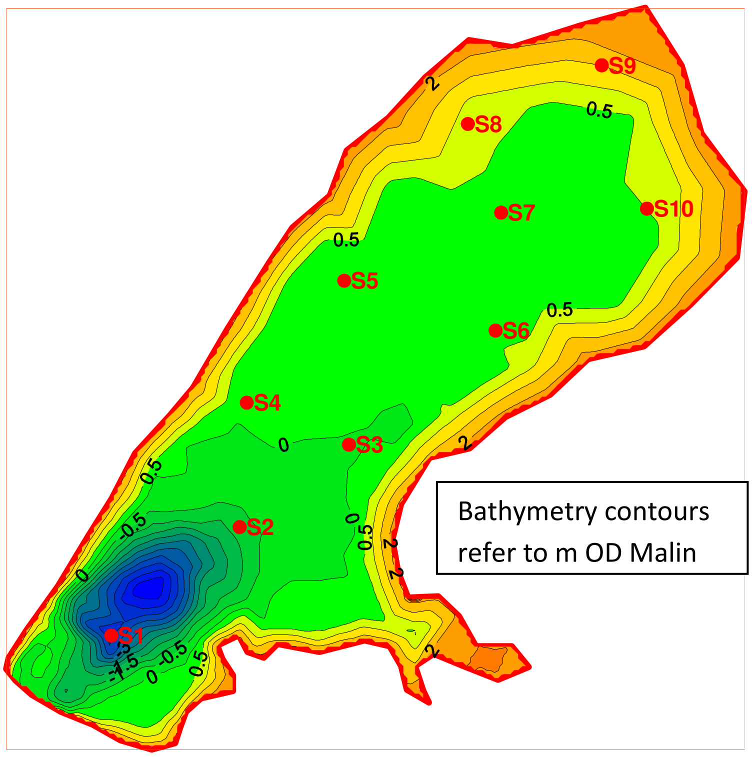


Figure 6 Sampling Locations S1 to S10 in Lough Atalia for 2013 Salinity surveys

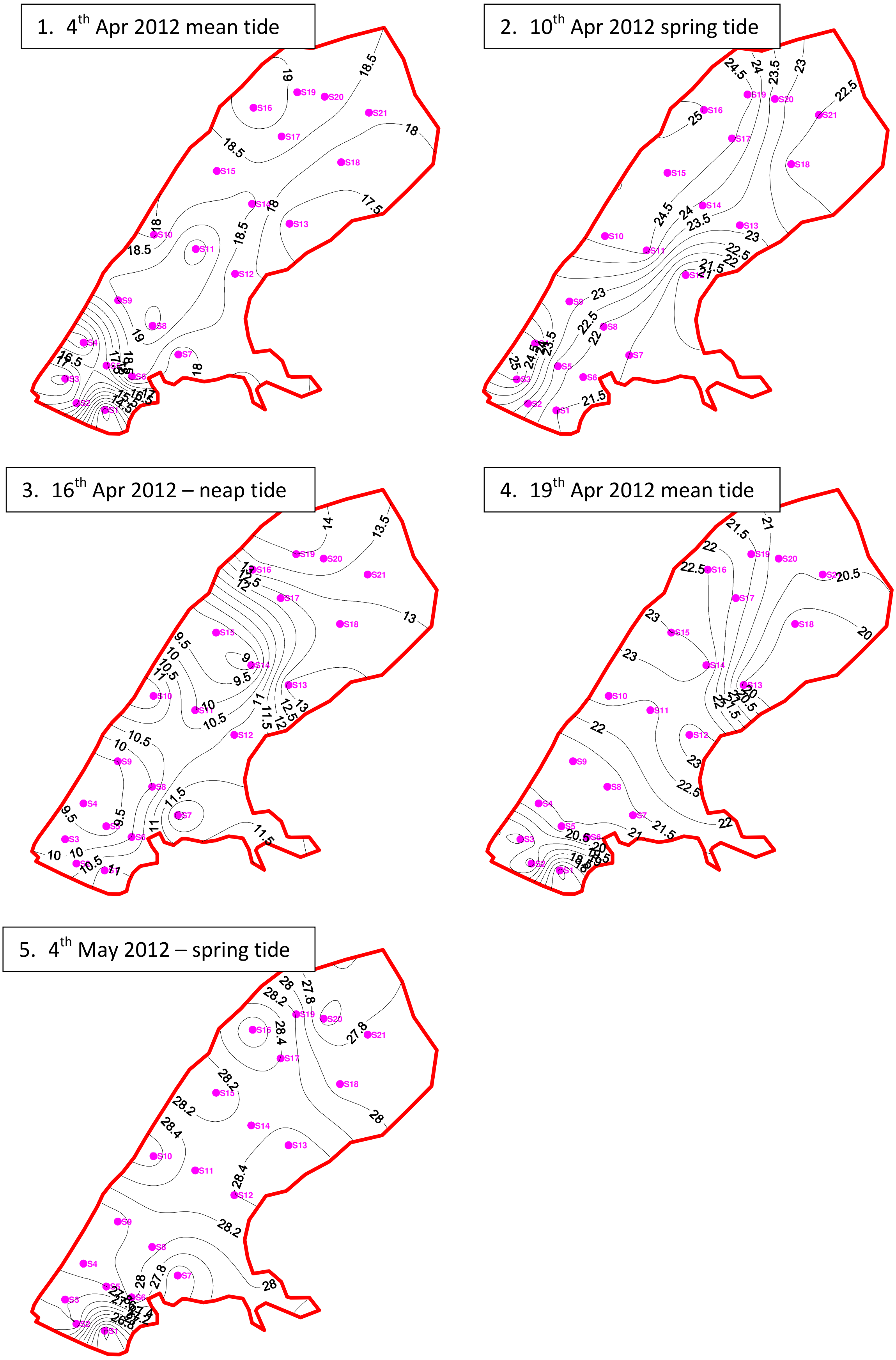


Figure 7 ***Salinity measurements (psu) at sub-surface 0.5 – 1m depth April – May 2012***

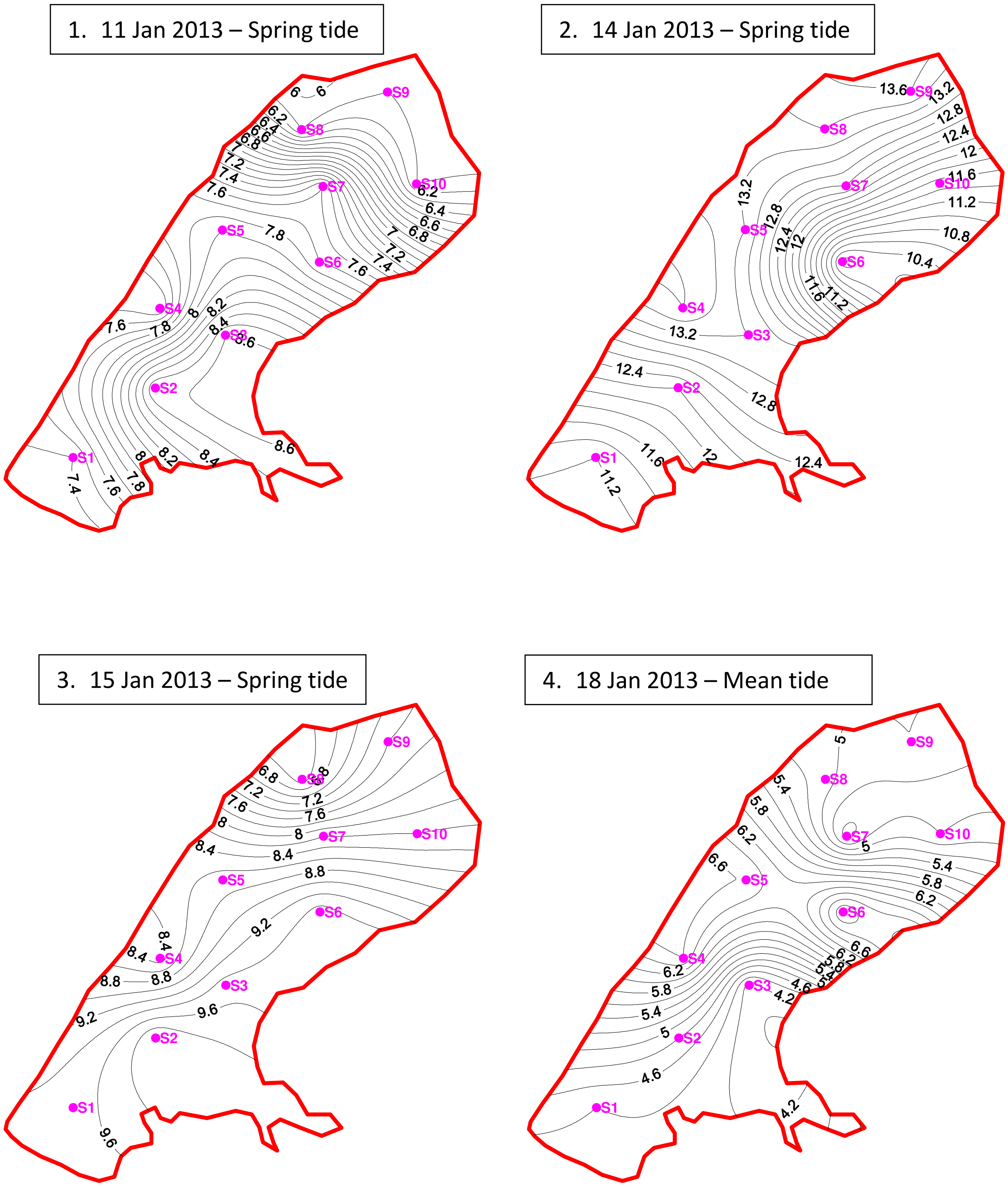
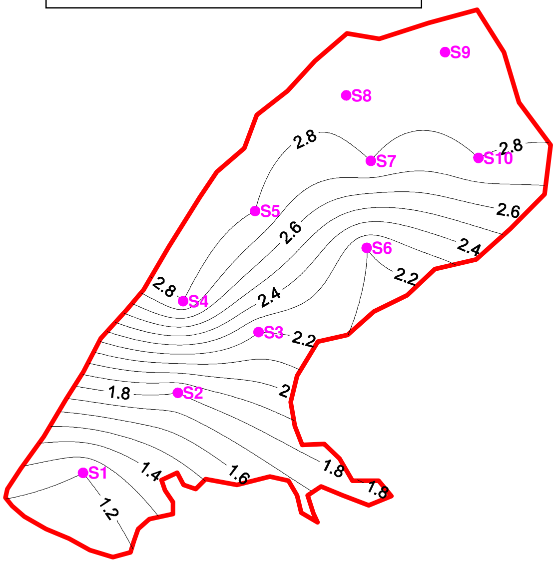
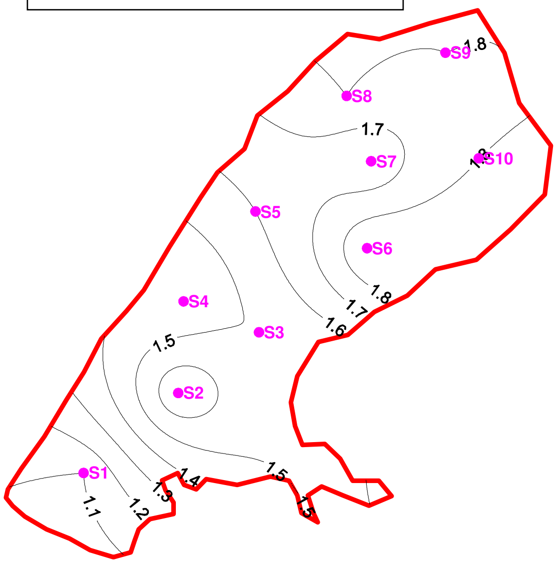


Figure 8 Salinity measurements (psu) at sub-surface (0.5m) depth (14:30 to 15:30hrs) January 2013

5. 21 Jan 2013 – Neap tide



6. 23 Jan 2013 – Neap tide



7. 24 Jan 2013 – Neap tide

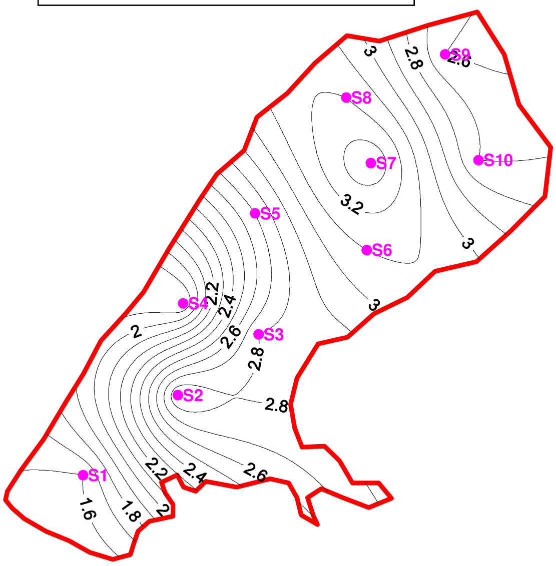


Figure 8 Cont'd. Salinity measurements (psu) at sub-surface (0.5m) depth (14:30 to 15:30hrs) January 2013

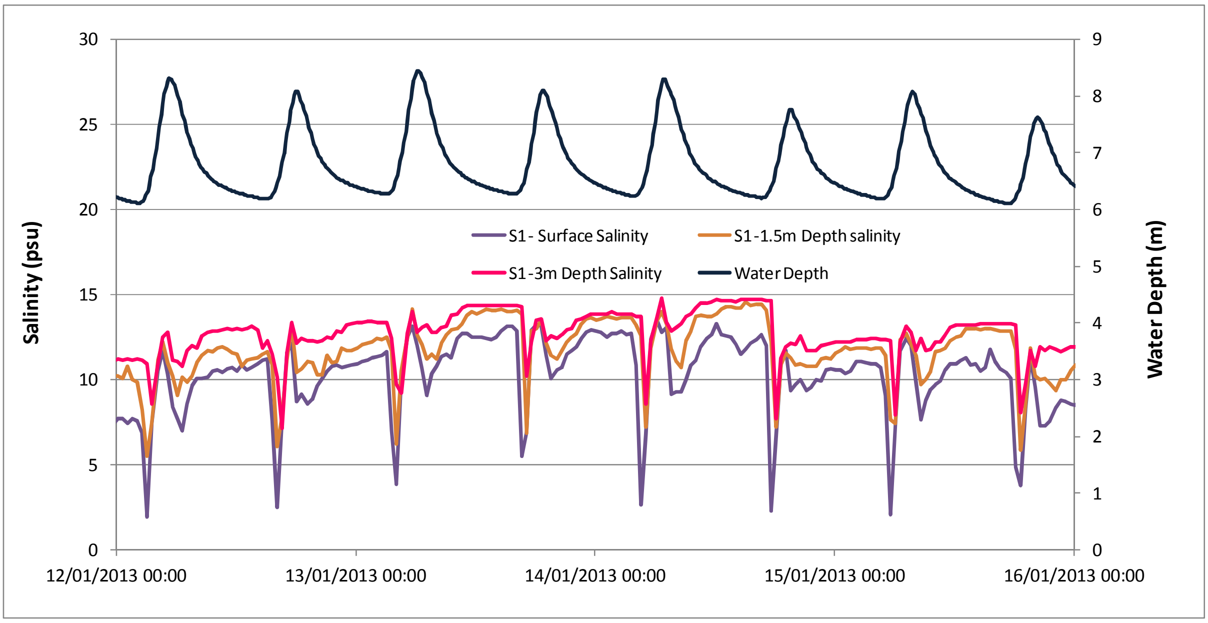


Figure 9 Salinity and Water Depth Measurements for Spring Tidal period at Site S1 - (12 to 16th Jan 2013)

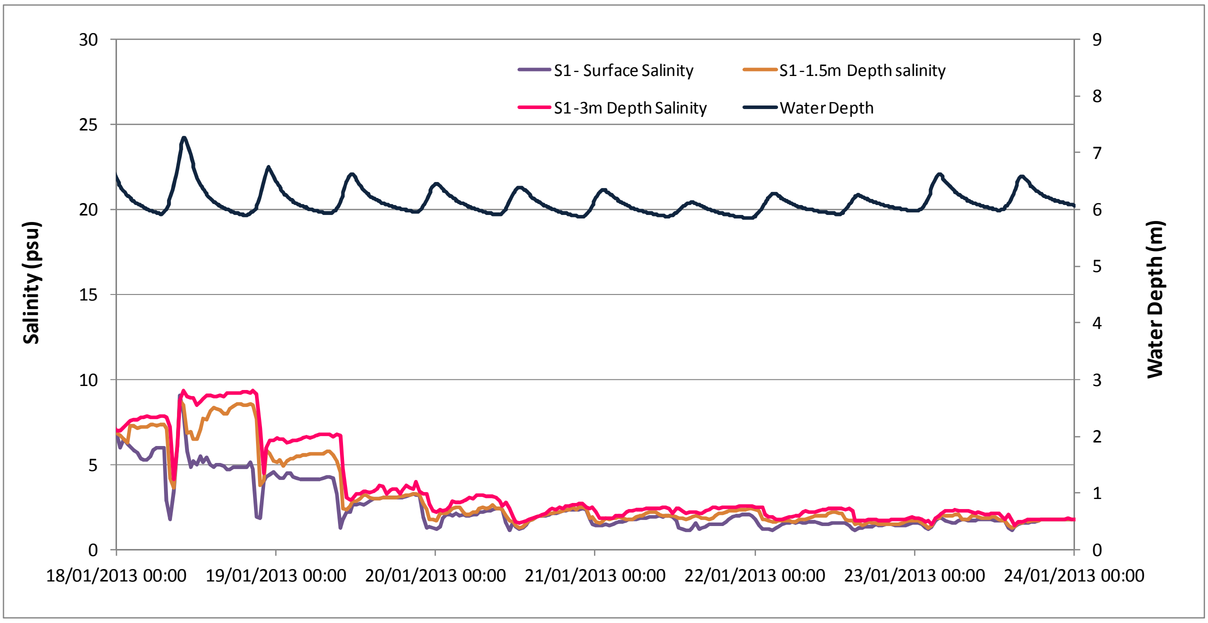


Figure 10 Salinity and Water Depth Measurements for Neap Tidal period at Site S1 - (20 to 24th Jan 2013)

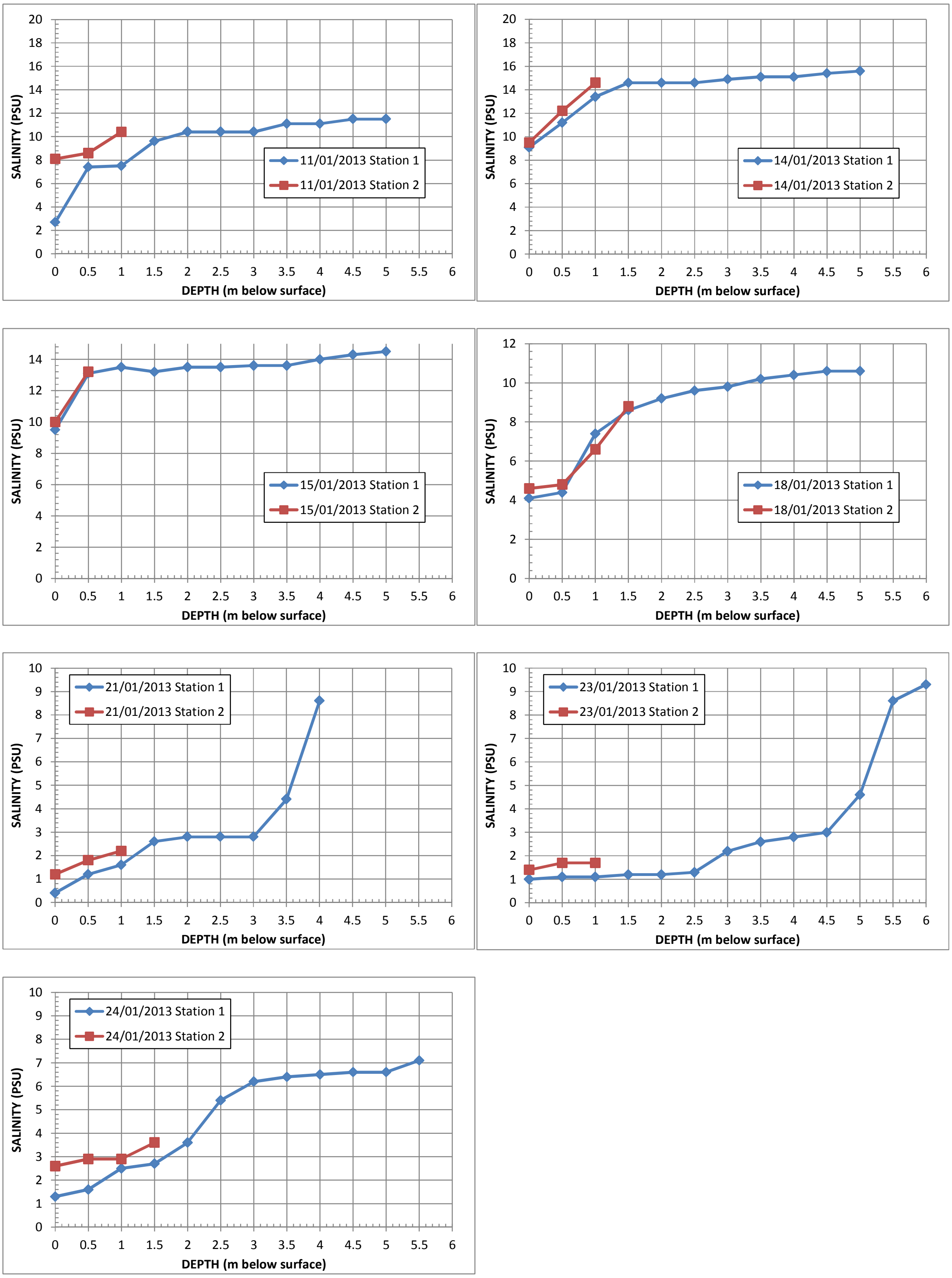


Figure 11 Measured vertical profiles of Salinity at S1 and S2 for January 2013 discrete sampling

3. TELEMAC Hydraulic Software System

3.1 Description

The TELEMAC system is the software of choice for modelling the complicated hydrodynamics of the Inner Galway Bay. Particularly given the very high computation refinement required to model the proposed Harbour extension area, the Cladding, Docks and Lough Atalia with its narrow inlet/outlet channel. TELEMAC is a software system designed to study environmental processes in free surface transient flows. It is therefore applicable to seas and coastal domains, estuaries, rivers and lakes. Its main fields of application are in hydrodynamics, water quality, sedimentology and water waves.

TELEMAC is an integrated, user friendly software system for free surface waters. TELEMAC was originally developed by Laboratoire National d'Hydraulique of the French Electricity Board (EDF-LNHE), Paris. It is now under the directorship of a consortium of organisations including EDF-LNHE, HR Wallingford, SOGREAH, BAW and CETMEF. It is regarded as one of the leading software packages for free surface water hydraulic applications and with more than 5,000 Telemac Installations Worldwide.

The TELEMAC system is a powerful integrated modelling tool for use in the field of free-surface flows. Having been used in the context of very many studies throughout the world (many thousands to date), it has become one of the major standards in its field. The various simulation modules use high-capacity algorithms based on the finite-element method. Space is discretised in the form of an unstructured grid of triangular elements, which means that it can be refined particularly in areas of special interest. This avoids the need for systematic use of embedded models, as is the case with the finite-difference method. Telemac-3D is a full three-dimensional computational code describing the horizontal and vertical velocities, water depth and free surface over space and time under barotrophic and density gradients. In addition it solves the transport of several tracers which can be grouped into two categories, active and passive, with salinity and temperature being the active tracers which alter density and thus the hydrodynamics.

3.2 Background Theory

TELEMAC-3D is a three-dimensional computational code describing the 3D velocity field (*u*, *v*, *w*) and the water depth *h* (and, from the bottom depth, the free surface *S*) at each time step. It also solves the transport of several tracers which can be grouped into two categories, namely the "active" tracers (temperature and salinity), which change the water density and act on flow through gravity), and "passive" tracers which do not affect the flow and are merely transported.

NON-HYDROSTATIC (Baroclinic) NAVIER-STOKES EQUATIONS

The following system (with an equation for W which is similar to those for U and V) is then to be solved:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-g\frac{\partial Z_S}{\partial x}+\upsilon\,\Delta(U)+F_x$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-g\frac{\partial Z_S}{\partial y}+\upsilon\,\Delta(V)+F_y$$

$$\frac{\partial W}{\partial t}+U\frac{\partial W}{\partial x}+V\frac{\partial W}{\partial y}+W\frac{\partial W}{\partial z}=-g\frac{\partial Z_S}{\partial z}+g+\upsilon\,\Delta(W)+F_z$$

Where,

h	(m)	water depth
S	m O.D.	water surface elevation
U, V, W	(m/s)	x, y and z three-dimensional components of velocity
T	^{o}C or g/l	active (acting on density) or passive tracer
ν ν_T	m2/s	viscosity and tracer diffusion coefficients
g	(m/s2)	gravitational acceleration
p	(Pa)	pressure
p_{atm}	(Pa)	atmospheric pressure
ρ_o	kg/m3 (g/l)	reference water density
$\Delta\rho$	kg/m3 (g/l)	variation in density
t	(s)	time
x, y	(m)	horizontal space component
z	(m)	vertical space component
Fx, Fy	(m/s2)	Source terms (wind, the Coriolis and the bottom friction forces)
Q	(tracer unit)	Tracer source or sink
Z_f	(m)	Bottom Depth

h, *U*, *V*, *W* and *T* are the unknown quantities, also known as computational variables.

In order to share a common core as much as possible with the solution of the equations with the hydrostatic pressure hypothesis, the pressure is split up into a hydrostatic pressure and a "dynamic" pressure term.

The TELEMAC-3D algorithm solves a hydrostatic step which is the same as in the previous paragraph, the only differences lying in the continuity step ("projection" step in which the dynamic pressure gradient changes the velocity field in order to provide the required zero divergence of velocity) and the computation of the free surface.

$$p = p_{atm} + \rho_0 g(Z_S - z) + \rho_0 g \int_z^{Z_S} \frac{\Delta\rho}{\rho_0} dz + p_d$$

In most of the simulations, salinity and temperature make it possible to compute the variations of density. The following law expresses the variation of density from these two parameters.

$$\rho = \rho_{ref}\left[1 - \left(T\left(T - T_{ref}\right)^2 - 750S\right)10^{-6}\right]$$

With T_{ref} as a reference temperature of 4℃ and ρ_{ref} as a reference density at that temperature when the salinity is zero, then ρ_{ref} = 999.972 kg/m3. That law remains valid for 0℃ < *T* < 40℃ and 0 g/L < *S* < 42 g/L.

EQUATIONS OF TRACERS

The tracer can be either active (it affects hydrodynamics) or passive in TELEMAC-3D. Temperature, salinity and in some cases a sediment are active tracers. The tracer evolution equation is formulated as:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} + W\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(\nu_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_T \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_T \frac{\partial T}{\partial z}\right) + Q$$

TURBULENCE MODEL

The Reynolds numbers ($R = UL/\nu$) reached by the currents at sea or in an estuary are excessively high and illustrate basically turbulent flows (*L*, the scale of eddies, for example, assumes the value of water depth *h* for a vertically homogeneous flow). For such a kind of flow, the turbulence-induced momentum is by far prevailing (in relation to the molecular diffusion). That diffusion is strictly defined by a tensor which represents different characteristics according to the directions.

The concept of eddy scale, however, is spatially constrained by the horizontal and vertical scales of the modelled domain. At sea, for example, a one kilometre long cape can generates eddies the dimensions of which are horizontally related to that scale. Vertically, however, the eddy size is constrained by the water depth also and even more by possible effects of stratifications.

MIXING LENGTH MODEL

In the Mixing Length Turbulence model the vertical diffusivity of velocities is computed by means of the selected mixing length model taking or not taking the effects of density into account. The mixing length model expresses the turbulent viscosity (or diffusion coefficient) as a function of the mean velocity gradient and the mixing length (i.e. Prandtl's mixing theory):

$$\nu = L_m^2 \sqrt{2 D_{ij} D_{ij}} \text{ , where } D_{ij} = \frac{1}{2}\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right)$$

The following options for the mixing length model are available

- Prandtl (default). Standard Prandtl's model. That formulation suits such flows with a strong barotropic component as the tidal flows,
- Nezu and Nakagawa. Nezu and Nakagawa model,
- Quetin. Better representation of wind drift. In windy weather, a surface boundary layer is formed and viscosity decreases,
- Tsanis. Better representation of wind drift.

The graph below shows the variations of the mixing length for the various models.

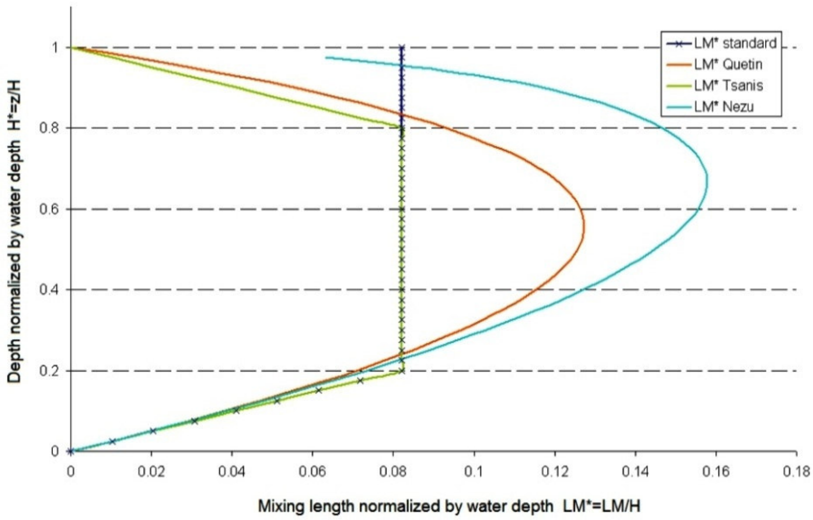


Figure 12 Mixing Length Models

In the presence of a vertical density gradient, the environment stability (respectively the instability) hinders (enhances) the vertical exchanges of mass and momentum. In order to quantify the effects of the gravity terms in the turbulent power balance, the dimensionless Richardson number is commonly used. It is a local number the value of which can obviously be different at each flow point. In order to take the mixture reduction into a stable stratified flow into account, a damping law is introduced into the turbulence model according to the Richardson number. The available damping function options are:

- Viollet,
- Munk and Anderson.

The graph below illustrates the variation of the Munk and Anderson damping function according to the Richardson number for velocity and salinity. In the case of a stable stratification, the pressure fluctuations more readily transmit a momentum flux than a mass flux and the diffusion coefficient becomes higher for the velocities than for the mass.

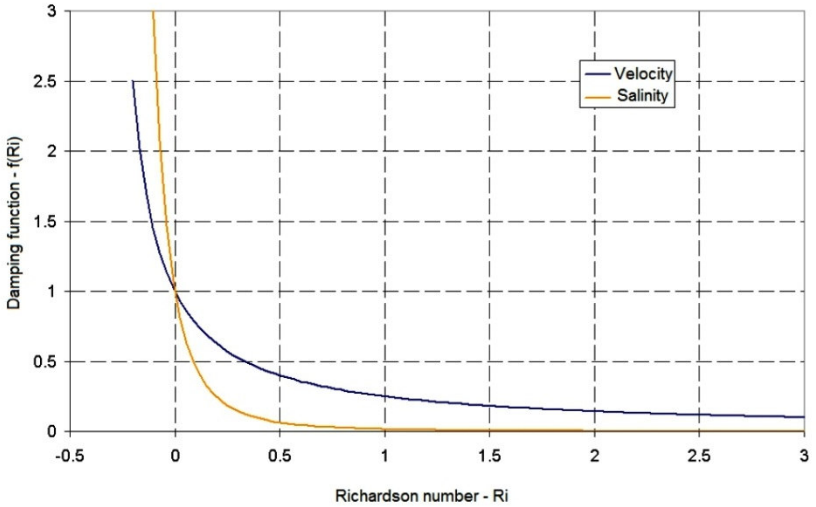


Figure 13 Munk-Anderson Dampening Function

THE DISCRETIZATION

The TELEMAC-3D mesh structure is made of prisms (eventually split in tetrahedrons). In order to prepare that mesh of the 3D flow domain, a two-dimensional mesh comprising triangles which covers the computational domain (the bottom) in a plane is first constructed, as for TELEMAC-2D. The second step consists in duplicating that mesh along the vertical direction in a number of curved surfaces known as "planes". Between two such planes, the links between the split triangles make up prisms. The computational variables are defined at each point of the three-dimensional mesh, inclusive of bottom and surface.

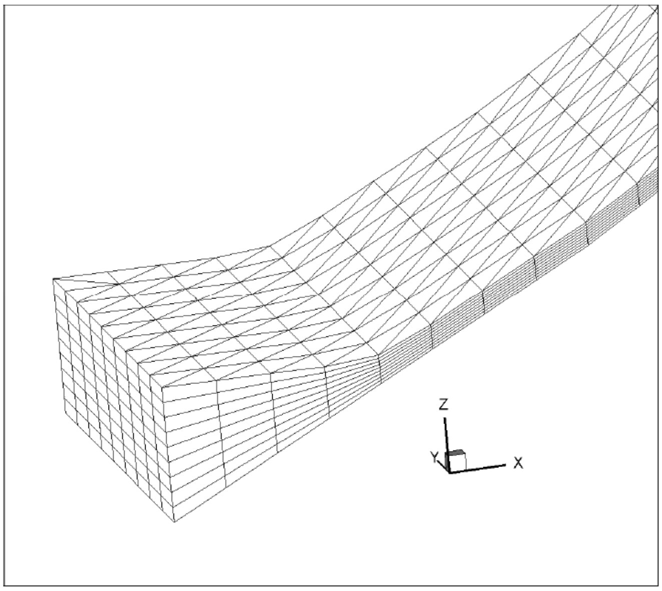


Figure 14   Three-dimensional meshing using sigma coordinates in the vertical direction

3.3 Data Sources

BATHYMETRY
The sources of data used to define the existing Bathymetry are as follows:

- Aquafact Surveys of the Approach Channel, Cladding area, Lough Atalia, the Proposed Harbour Extension area east of the approach channel.
- Survey of the Lough Atalia channel January 2013
- The Infomar (GSI) Lidar Data Set of Galway Bay – survey 22may to 14 June 2008.

MARINE & HYDROLOGICAL DATA

- Waterlevels.ie for Gauge 30061 – Corrib Estuary at Wolfe Tone Bridge
- Tide Levels for Galway Docks – Irish National Tide gauge Network
- ADCP currents and depth measurements in Lough Atalia January and March - 2013 Aquafact International
- Continuous Salinity monitoring by in-situ salinity probes in Lough Atalia January and March 2013
- Discrete Sampling surveys of Salinity in Lough Atalia – April-May 2012 and January 2013

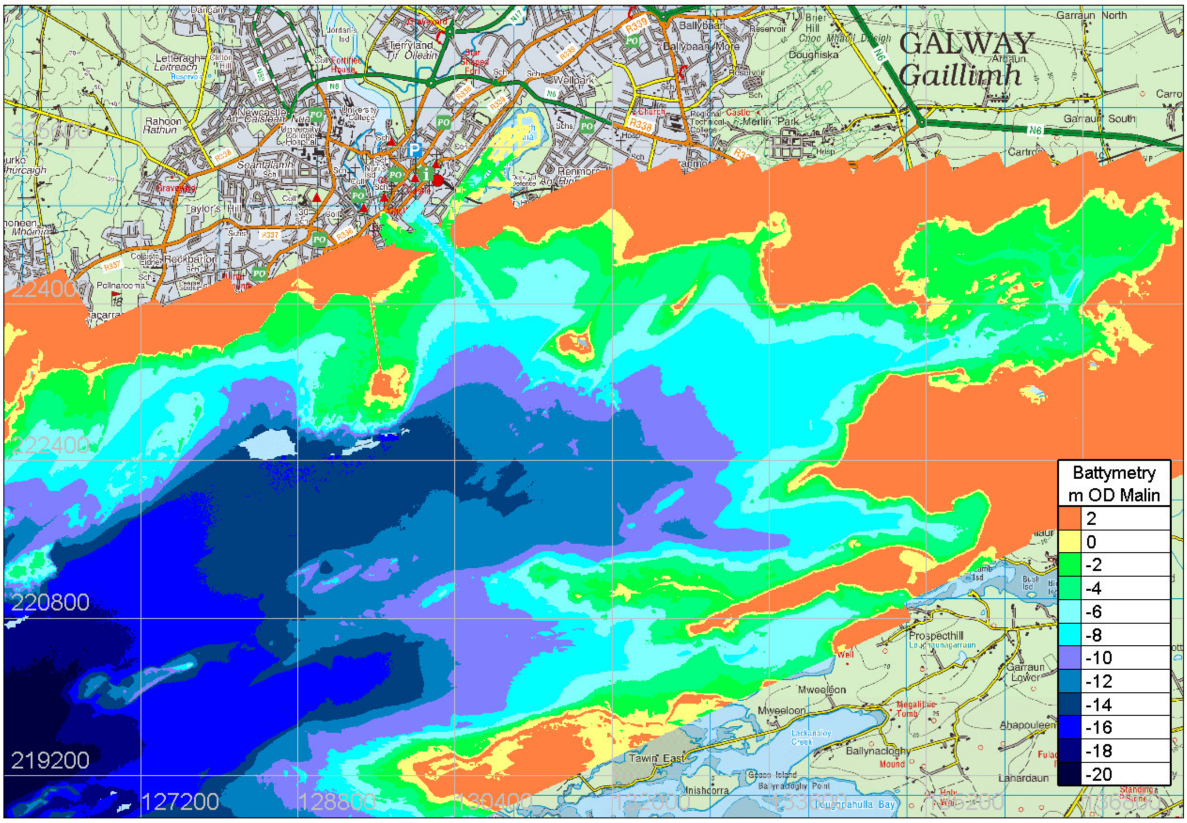


Figure 15 Bathymetry Data from GSI Lidar Aquafact Local bathymetry surveys

3.4 Model Development

Due to the high computational requirement of a full three-dimensional baroclinic model the modelled domain for assessing the impact of the Harbour Extension on salinities was confined to the inner northerly section of Galway Bay. The model domain area is presented in Figure 16 which extends from Blakes Hill at Knocknacarra and Kilcolgan Pt. on Twain Island easterly into Oranmore Bay. Very high refinement is provided in the Docks area, Lough Atalia Channel and the proposed harbour extension area (refer to Figure 17). This model domain represents a tidal waterbody of some 41 km^2 in Area.

Two models of the Study area were required to represent the existing case (without the Harbour Extension) and the proposed case (with the Harbour Extension). In order to achieve accurate comparisons between existing Case and proposed case models the same mesh structure was used, with the only difference being that the elements located within the harbour extension infill footprint are retained for the existing case and removed for the proposed case and the resultant land boundary nodes defined. This meshing approach ensures that nodal points within the live domain at which velocity, depth, surface elevation and tracer concentration are computed exactly match up and that the same resolution/refinement is achieved for both models. This approach minimises any numerical differences in the predicted results associated with the meshing effects.

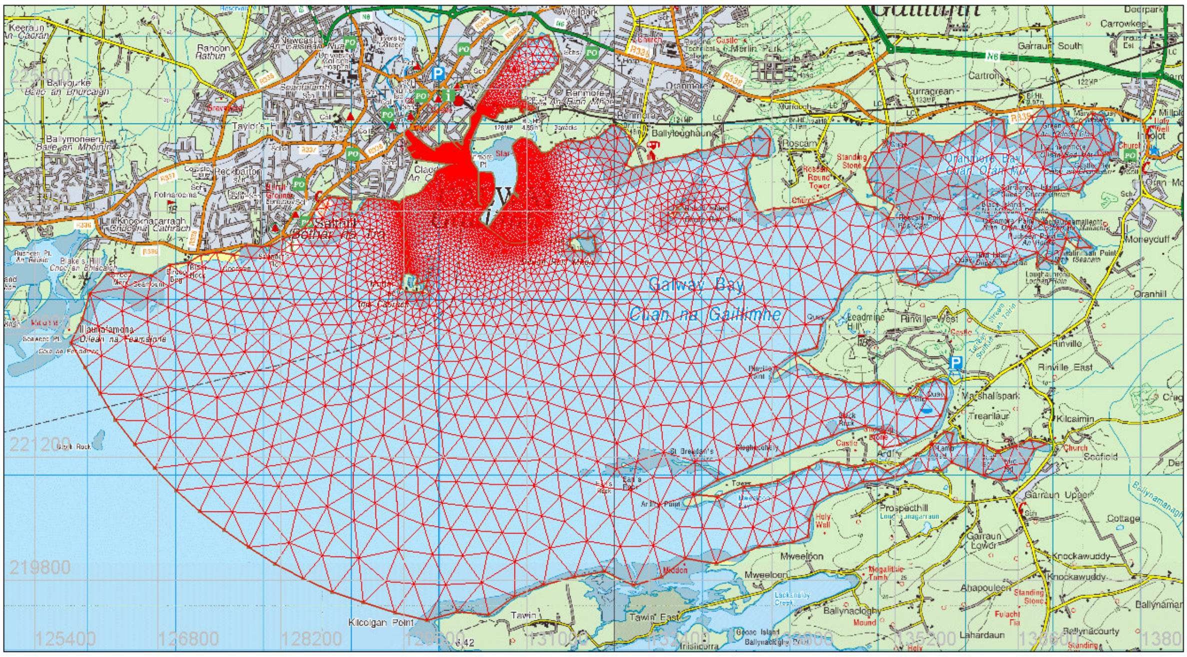


Figure 16 Extent of Three-dimensional Model Domain for Salinity Predictions

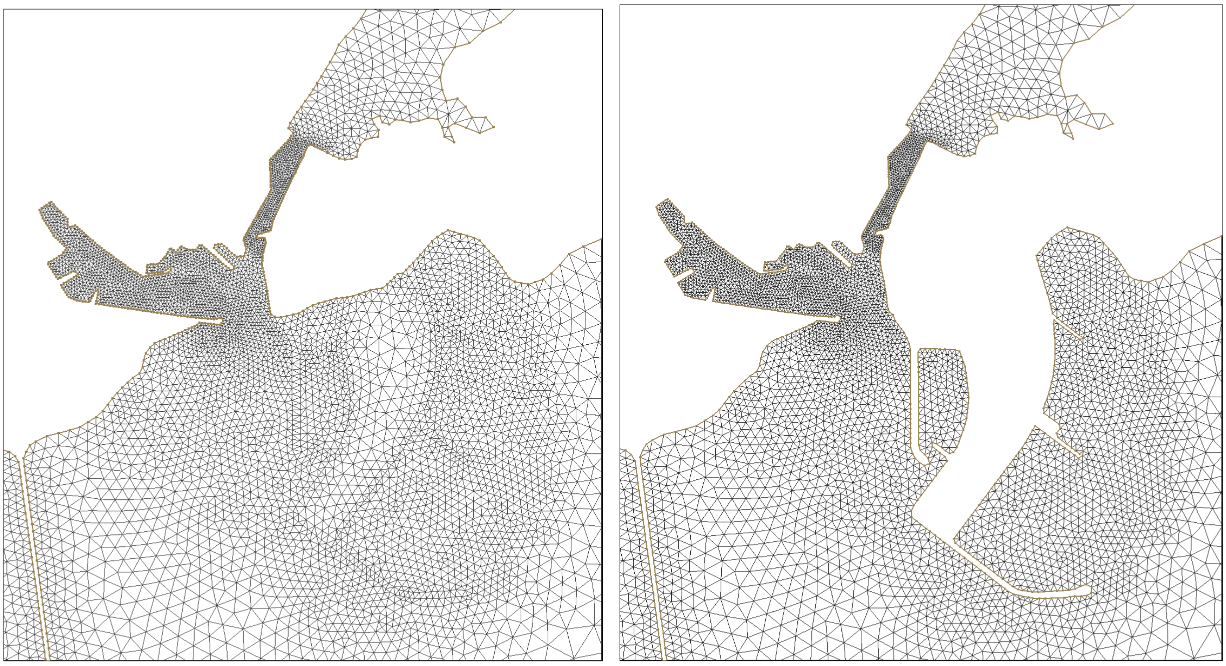


Figure 17 Model Grid structure and refinement for Existing and Proposed Development Cases

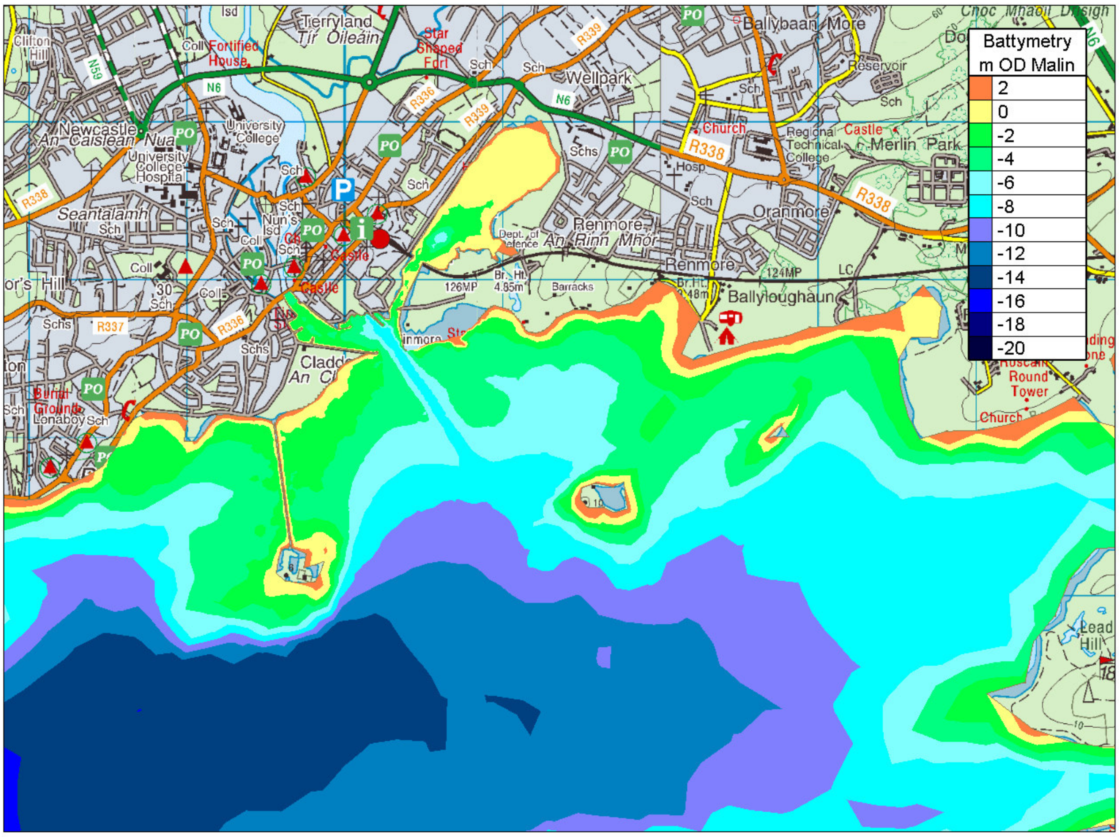


Figure 18 Modelled Bathymetry in the vicinity of the subject site – Existing Case

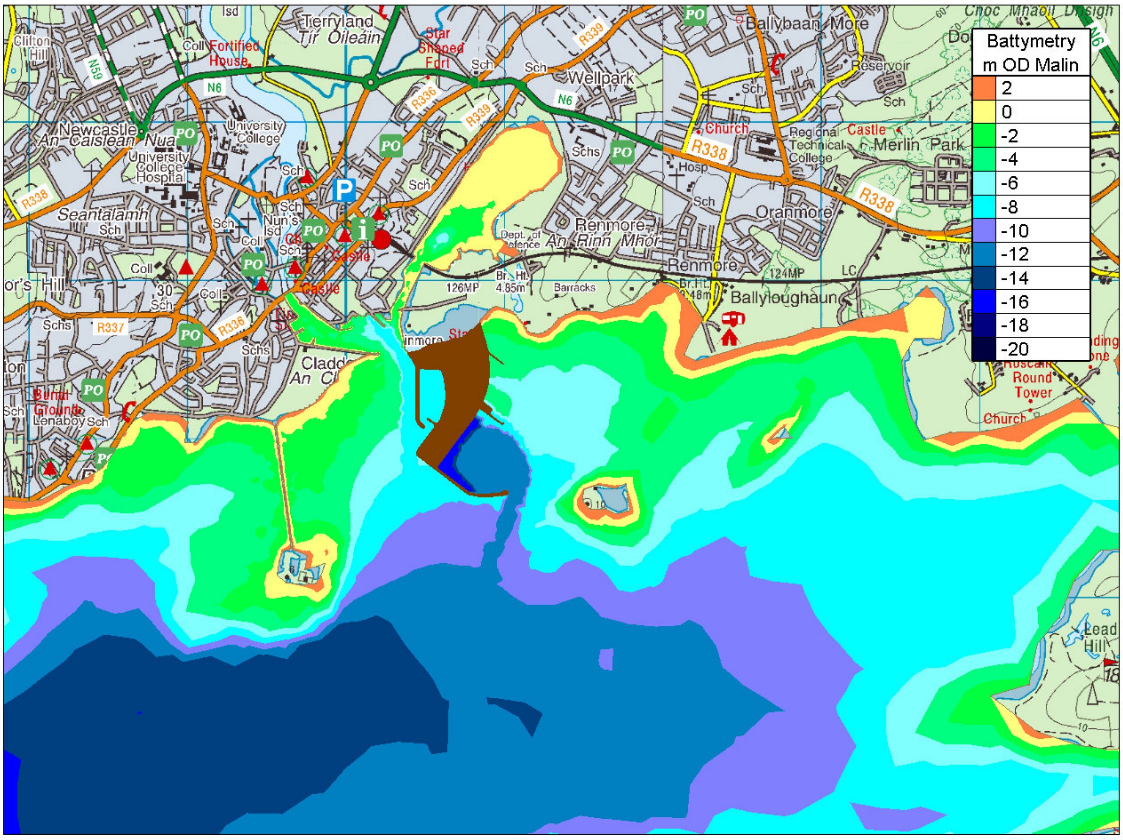


Figure 19 Modelled Bathymetry in the vicinity of the subject site – Proposed Case

The finite element mesh for the existing case model has 33,665 nodal points and 150,888 elements and the finite element mesh for the proposed case model has 32,205 nodal points and 141,120 elements. The number of vertical layers specified in the model is 5. A sigma transformation is used which sets a homogeneous distribution of levels in the vertical direction (known as a classical sigma transformation). The height of the layers vary depending on the water depth, all planes can move (refer to Figure 20).

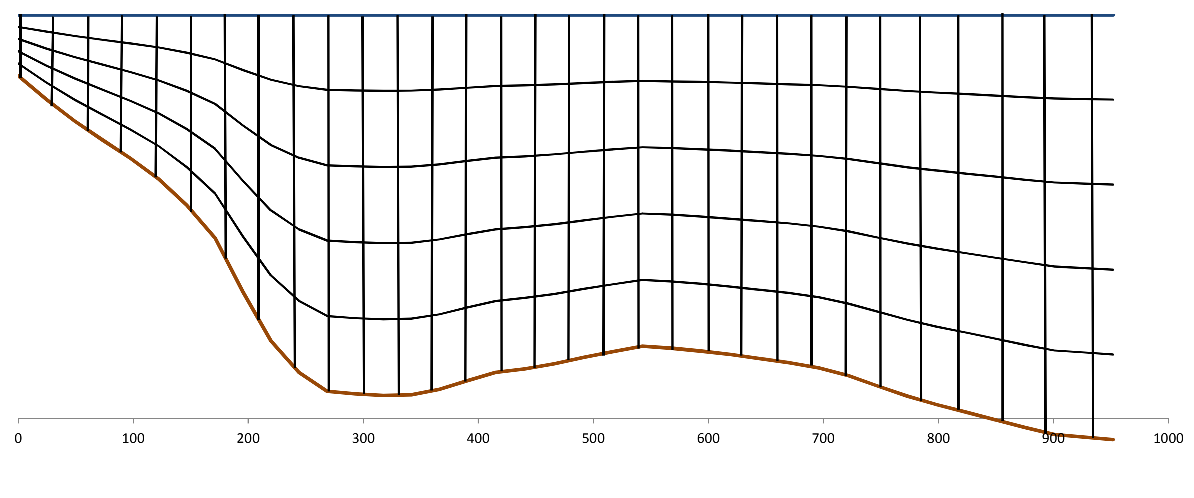


Figure 20 Representation of 5 vertical Layers in sigma coordinates

2.5 Boundary Conditions

The boundary conditions specified in the model was tidal elevation along the western open sea boundary and the River Corrib discharge on the north boundary downstream of Wolfe Tone Bridge.
The OPW flow duration curve for their Wolf Tone Gauging site (refer to Table 1 presented earlier) is used to specify the design flow events and the gauged daily flows for the Wolf Tone Gauging site specified for the relevant calibration periods.

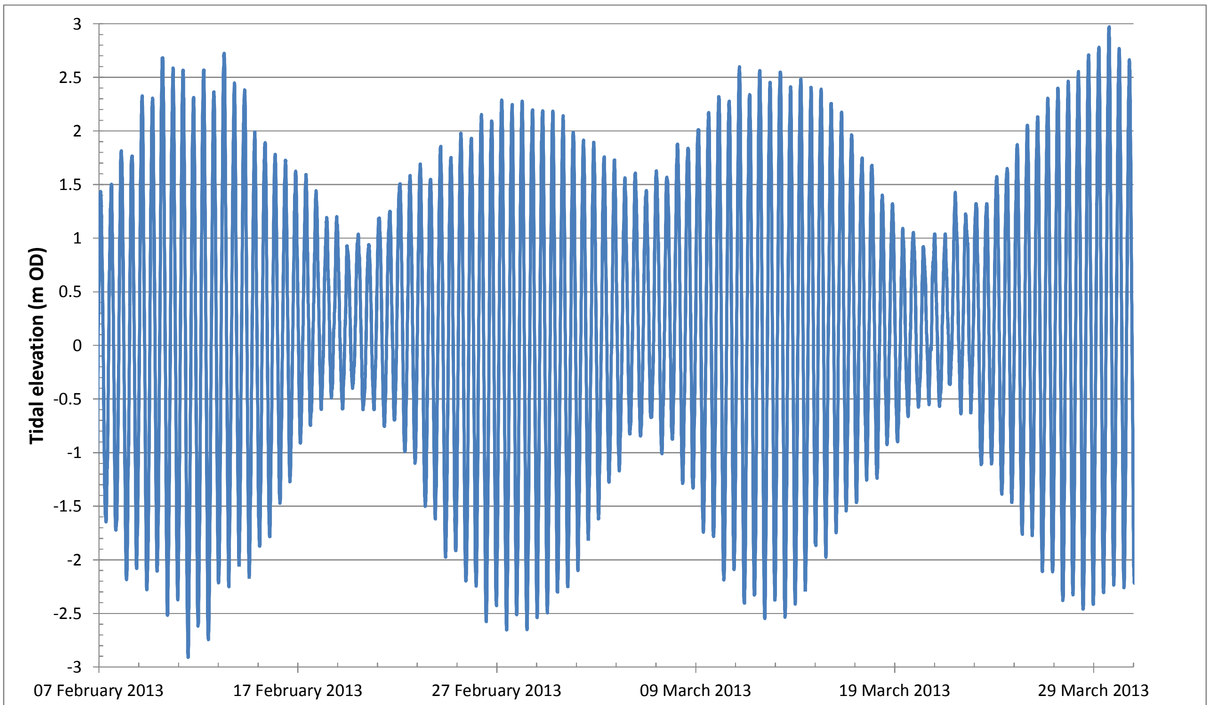


Figure 21 Tidal Data for Galway Docks

Table 2 **Tidal Heights in the Galway Bay**

Water level m O.D. Site	MHW Springs	MHW Neaps	MLW Neaps	MLW Springs	Highest Astronomical Tide
Galway Bay - Inner	2.19	0.99	-0.91	-2.31	2.75

3.6 Dispersion Model Calibration

The three-dimensional hydrodynamic and dispersion model was calibrated against continuous measurements of current speeds, depth and salinity concentrations in Lough Atalia for January and March 2013 monitoring periods. The recorded tidal elevations and Corrib flows for these calibration events are presented in Figures 22 and 23. Both calibration events cover the spring neap tidal range and River Corrib flows of 145 to 175cumec for the January 2013 event and 55 to 70cumec for March 2013 event.

The model calibration parameters for tuning the model equations to achieve best agreement was bed roughness, horizontal and vertical viscosity and diffusion coefficients. The Lough Atalia inlet channel was artificially roughened to achieve good agreement with the measured velocities and water depths in Lough Atalia, refer to Figures 24 to 29 for January calibration event and Figures 32 to 36 for the March event. The model captures the pulse of inflow through raised velocities over a 2 to 2.5hr period and the slow reduced velocities during the outflow period. Importantly it also captures the reduced range in tide levels within Lough Atalia relative to the Galway docks and the significantly reduced tide levels and velocities associated with neap tides.

The Salinity calibration involved selecting a density driven baroclinic model to achieve suitable agreement with measured time series of salinity at sites S1 and S2 (refer to Figure 6 for location). Originally a hydrostatic model was run in which density obeyed the hydrostatic law and salinity treated as a passive tracer. The results from this model produced poor agreement with measurement and tended to mix over the depth the Corrib freshwater flow with almost freshwater conditions produced in Lough Atalia with little variation between Spring and neap tides. A Baroclinic model which is considerably more computationally demanding was used and through the introduction of the Prandtl mixing length vertical turbulence model with Munk Anderson damping for stratification much more realistic results were produced for Lough Atalia, refer to Figure 30 and 31 for January 2013 events and Figure 39 for March 2013 events.

As can be seen from these figures reasonable agreement is achieved with the measured salinities and replicating the trend of spring tides introducing higher saline concentrations and the neap tides producing considerably lower salinities, which are almost steady, non-varying over the neap tidal cycle due to the low tidal range within Lough Atalia. The actual measured data in comparison to the model predictions show greater variation in salinity concentrations over the tidal cycle with neap tides consistently less saline within Lough Atalia than the modelled salinities. The model is unable to achieve this range in salinity due to unavoidable numerical mixing in the horizontal and vertical layers associated with the numerical scheme. However the salinity calibration results show that the model is sufficiently capable of predicting salinities and salinity variation within Lough Atalia and is considered fit for the purpose of predicting relative difference in salinity between the existing and proposed cases.

The measured data for neap tides at only moderate winter Corrib flows of 150 to 160 cumec (on average exceeded at least 77 to 91days per annum) show almost freshwater like conditions within

Lough Atalia (i.e. measured salinities consistently below 2.5 psu). For larger flows of 1 to 5percentile occurrence (230 to 272cumec), on average 4 to 18days per annum it is expected that the salinities in Lough Atalia will tend towards nil salinity throughout the neaps tides.

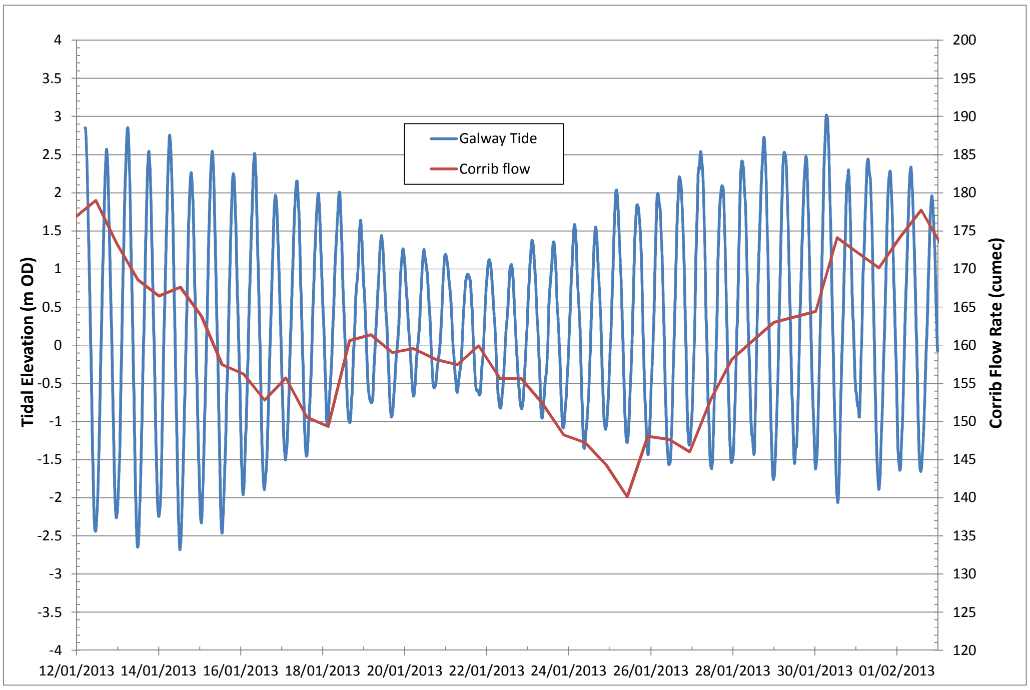


Figure 22 Boundary conditions specified for the January 2013 Salinity Calibration Simulation

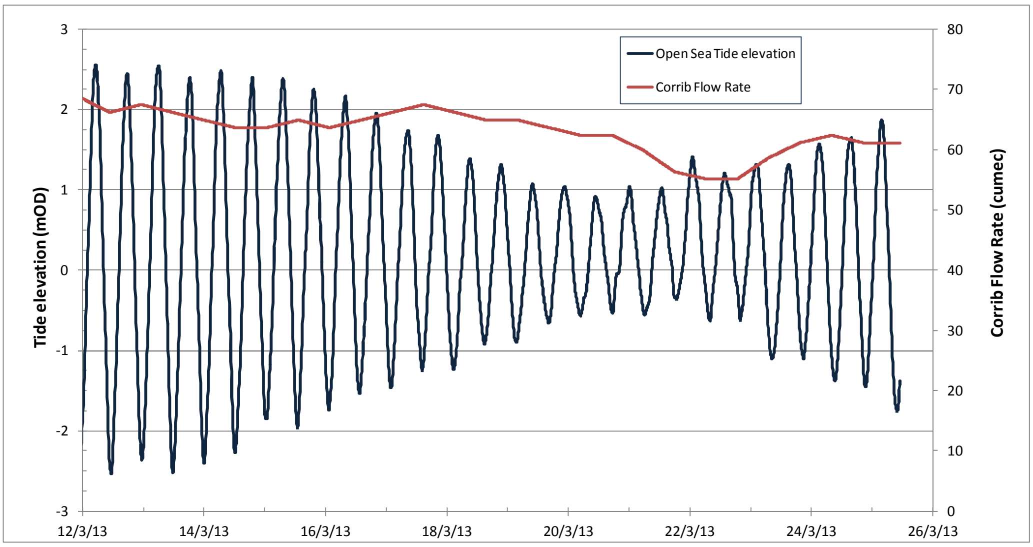


Figure 23 Boundary Conditions Specified for March 2013 Salinity Calibration Simulation

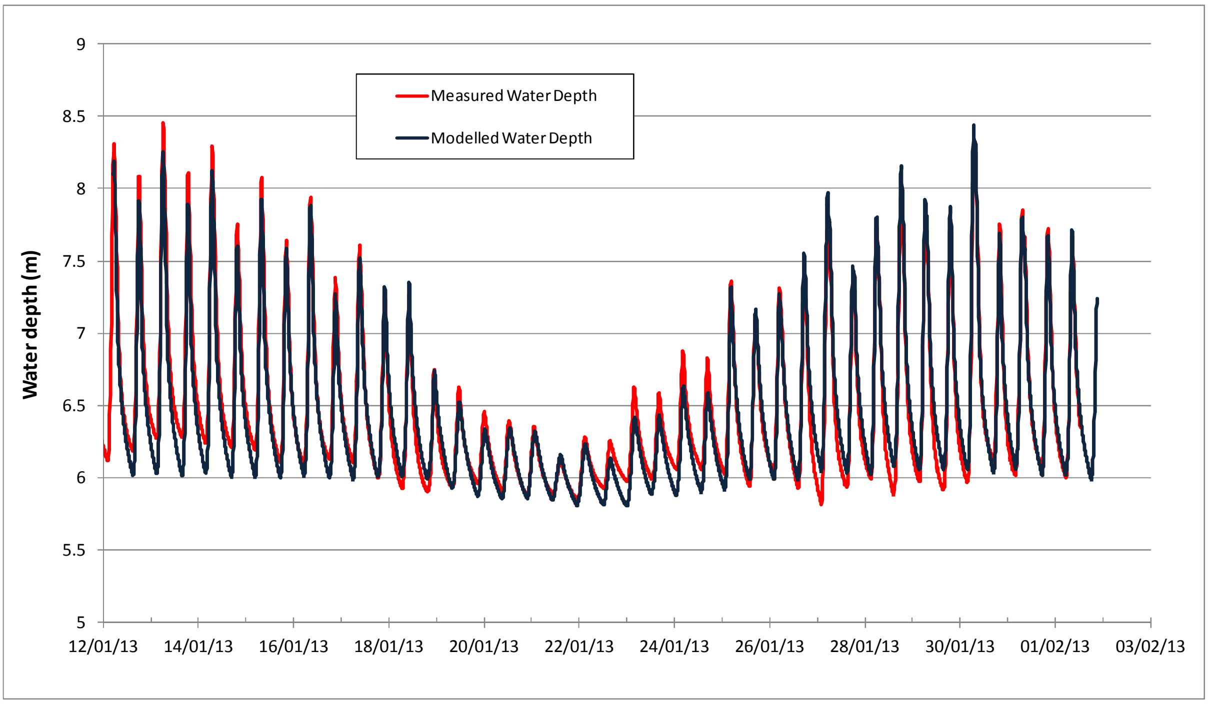


Figure 24 Comparison between measured and computed (modelled) water depth at reference Site S1 in Lough Atalia 12th January to 1st Feb 113

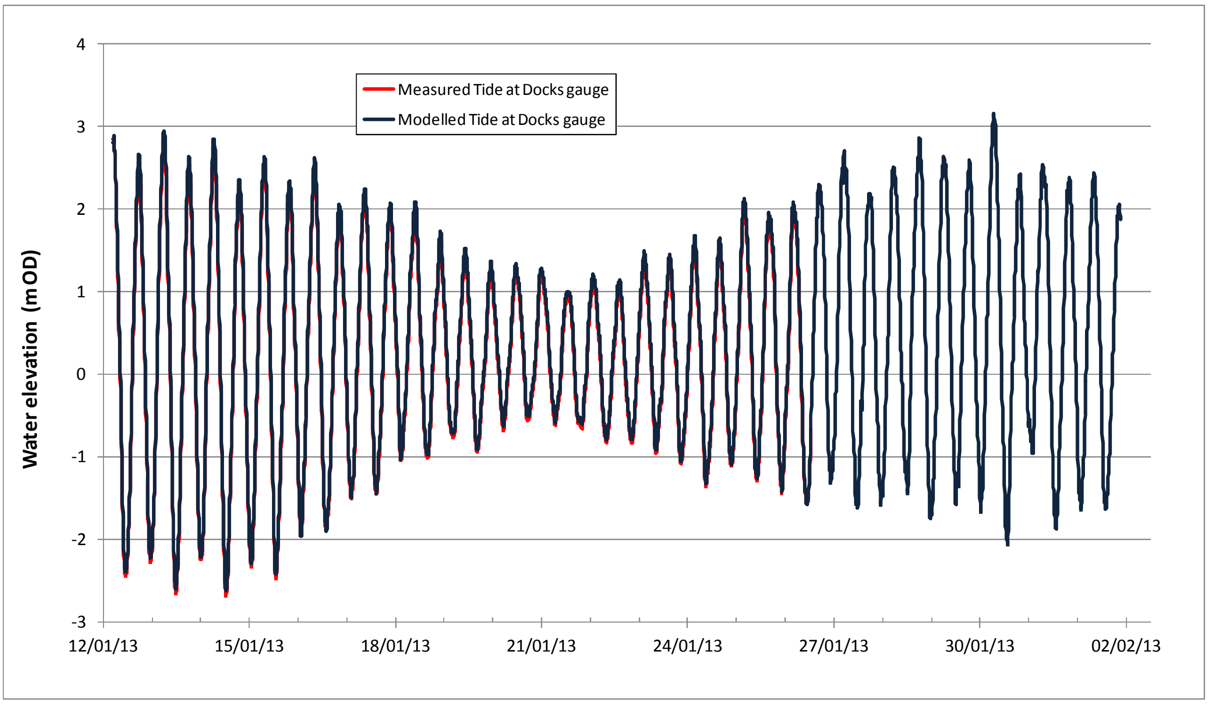


Figure 25 Comparison between measured and computed (modelled) tide elevation at Galway Docks gauge 12th January to 1st Feb 2013

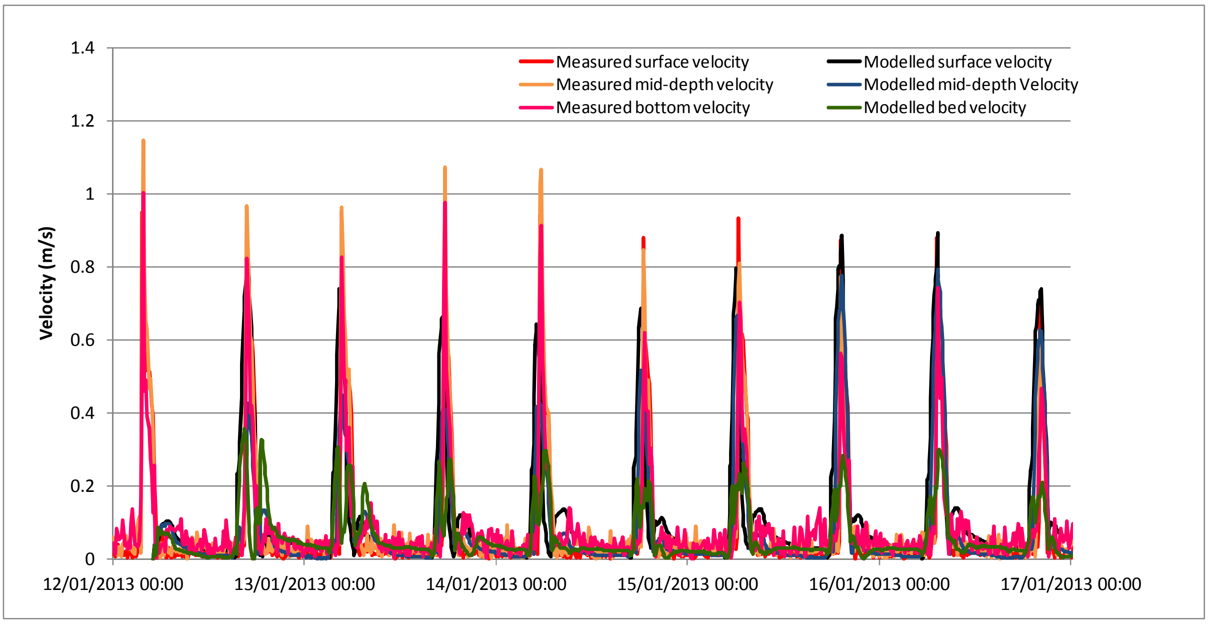


Figure 26 Comparison between measured and computed tide velocities at S1 for the monitoring period 12th January to 17th Jan 2013

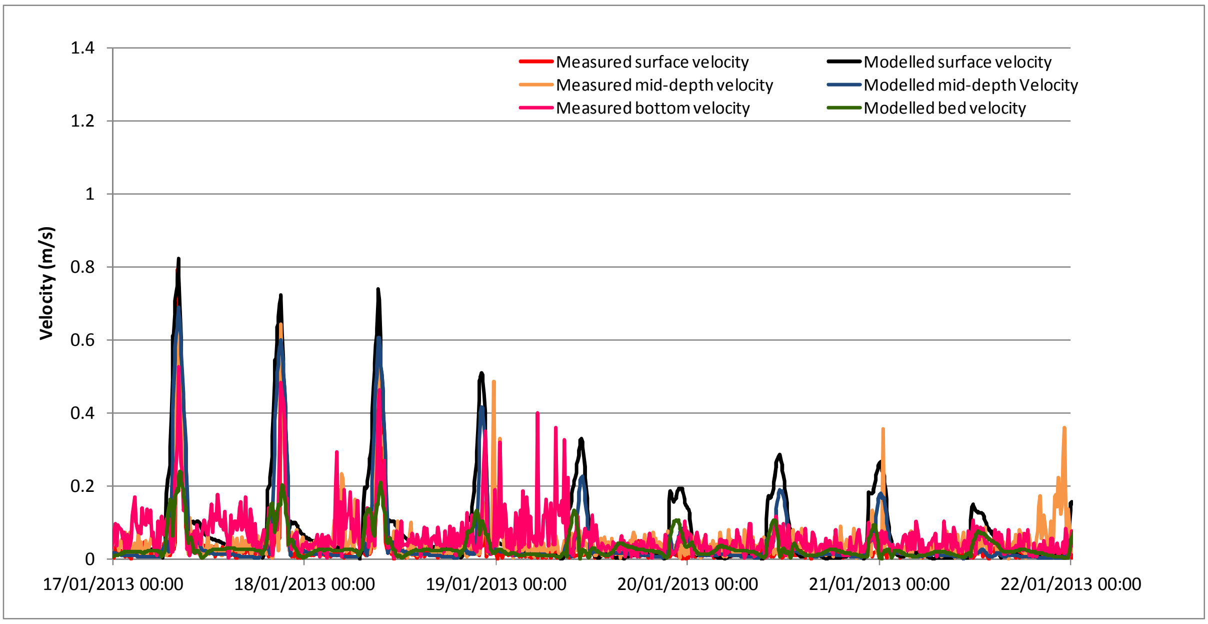


Figure 27 Comparison between measured and computed tide velocities at S1 for the monitoring period 17th Jan to 22nd Jan 2013

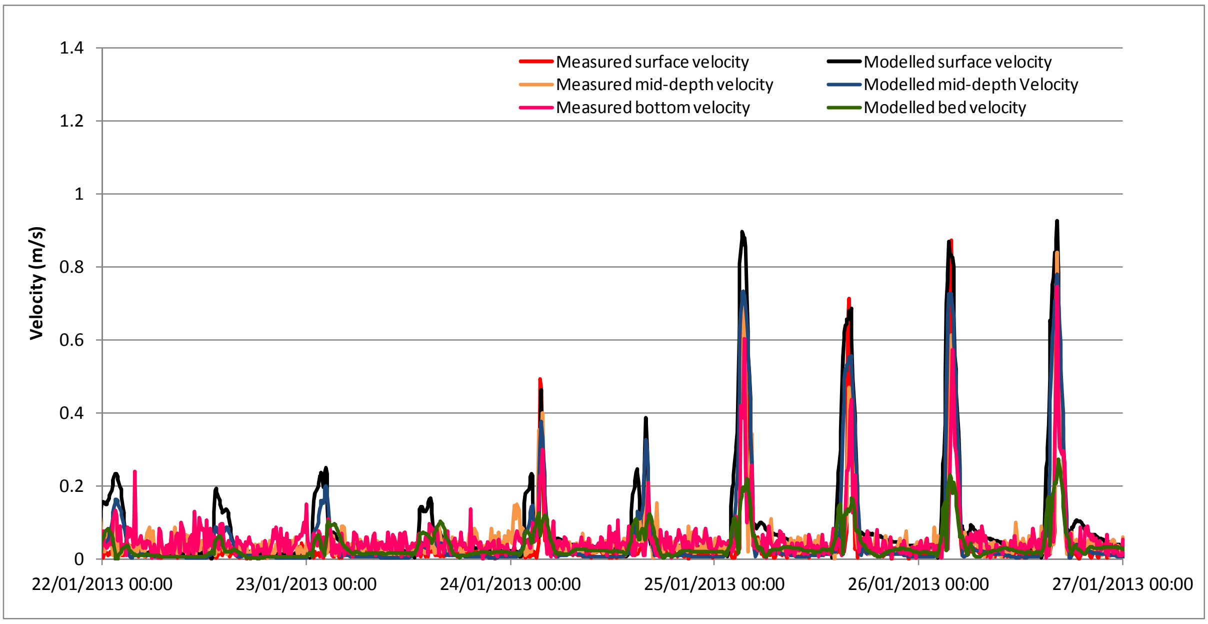


Figure 28 Comparison between measured and computed tide velocities at S1 for the monitoring period 22nd Jan to 27th Jan 2013

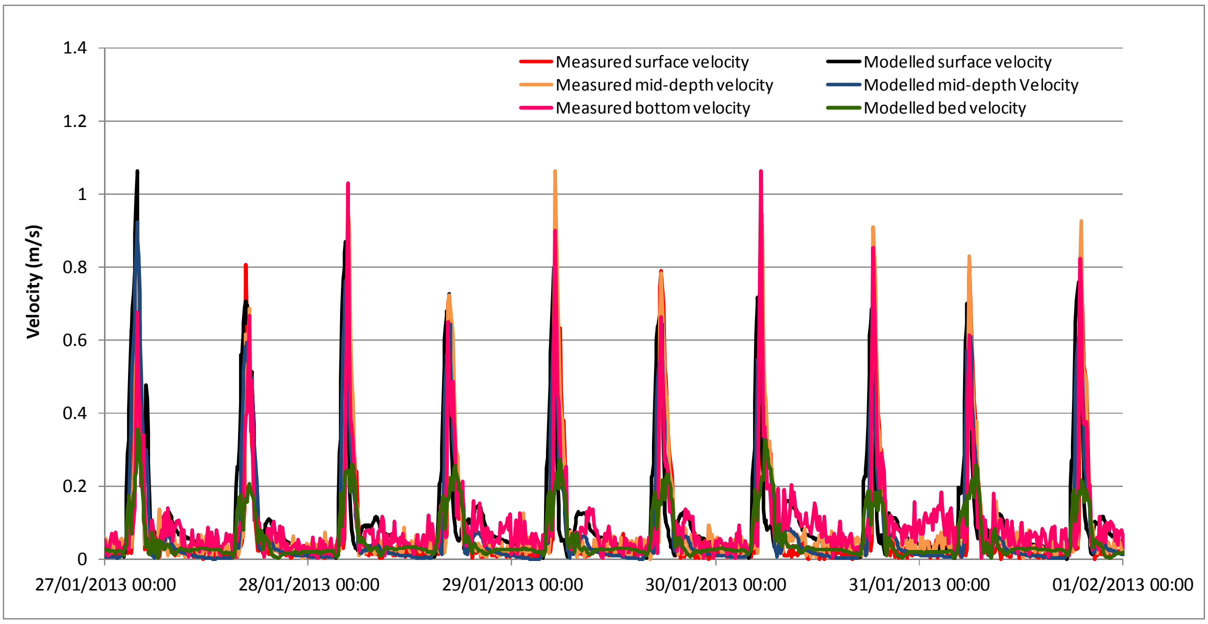


Figure 29 Comparison between measured and computed tide velocities at S1 for the monitoring period 27th Jan to 1st Feb 2013

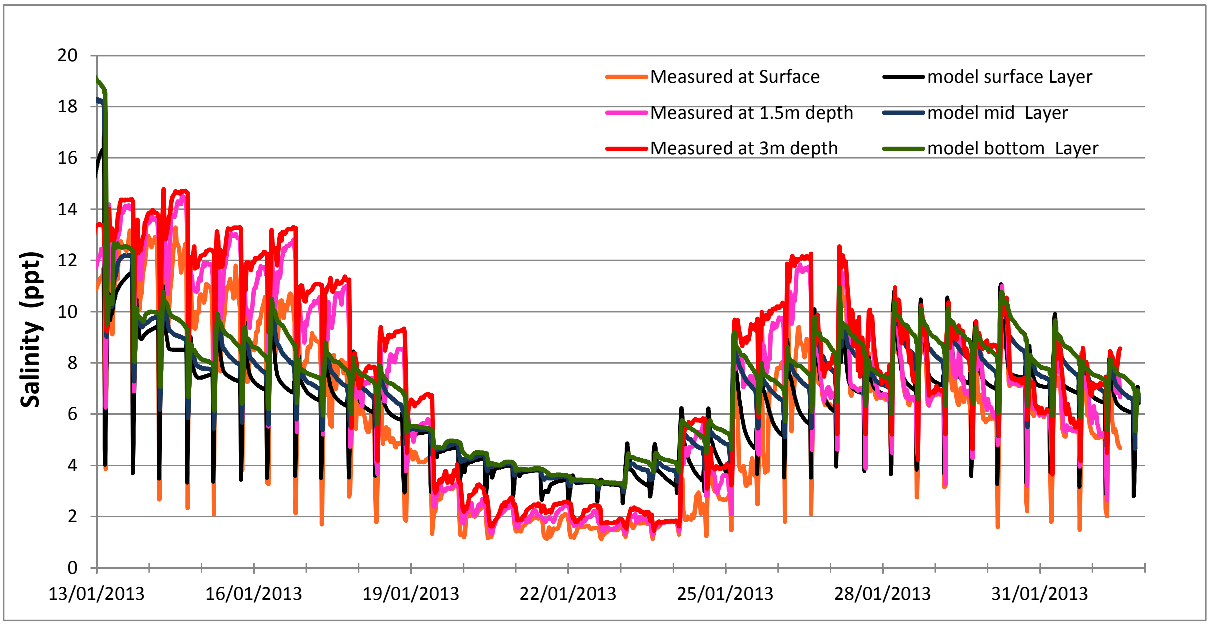


Figure 30 Measured V's Computed Salinities in Lough Atalia at Site S1 for January monitoring period

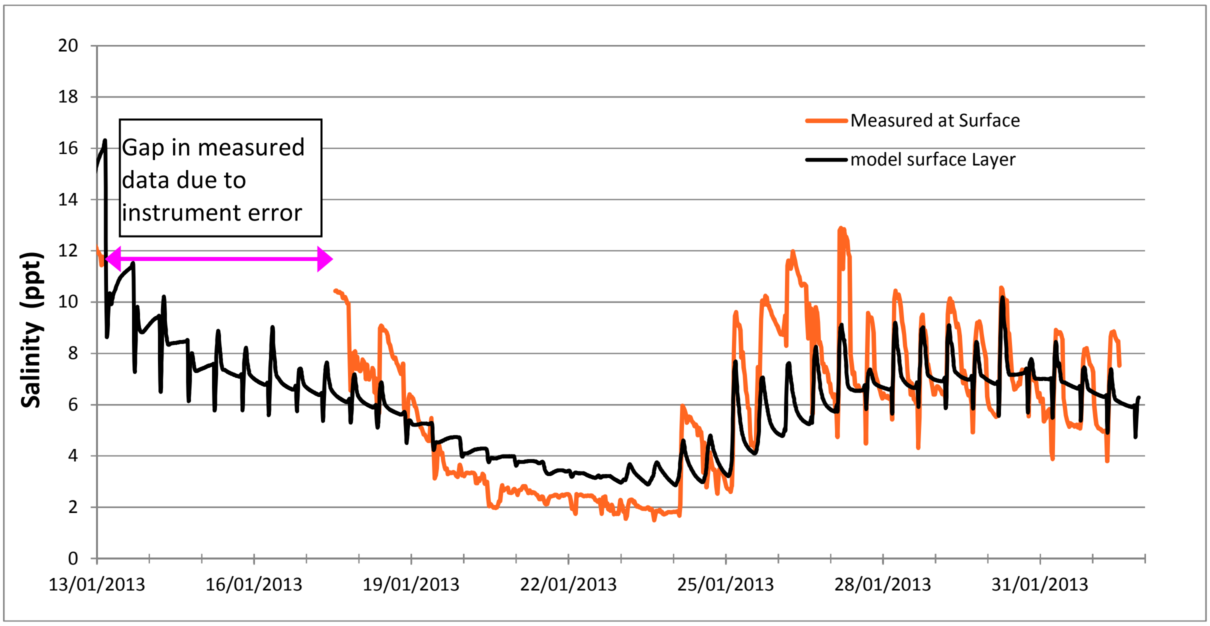


Figure 31 Measured V's Computed Salinities in Lough Atalia at Site S2 for January monitoring period

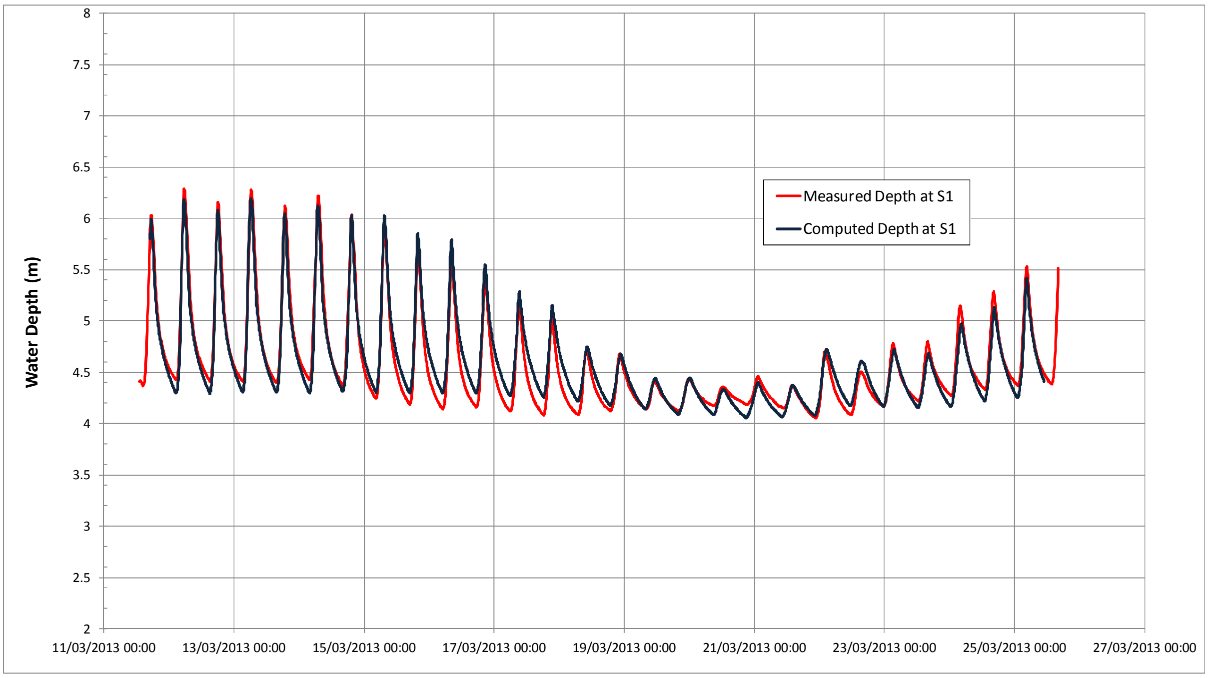


Figure 32 Computed and measured water depth at S1 for March 2013 Monitoring period

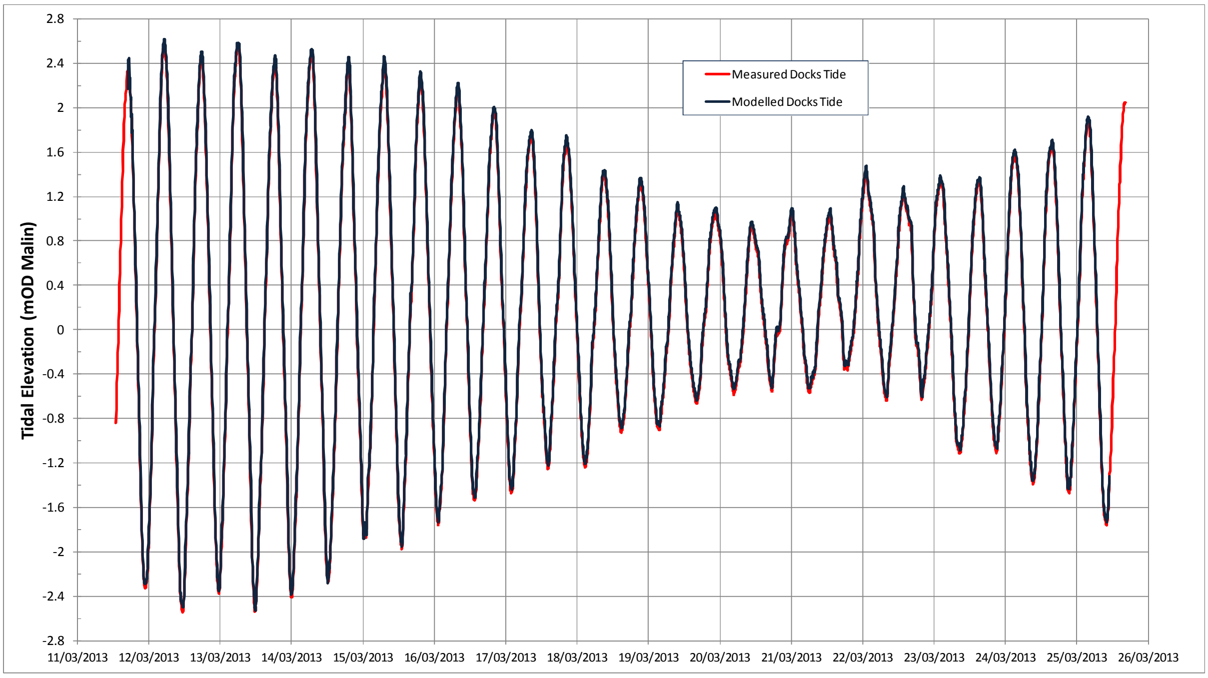


Figure 33 Comparison between measured and computed(model) tide elevation at Galway Docks gauge for 11 to 26th March 2013 monitoring period

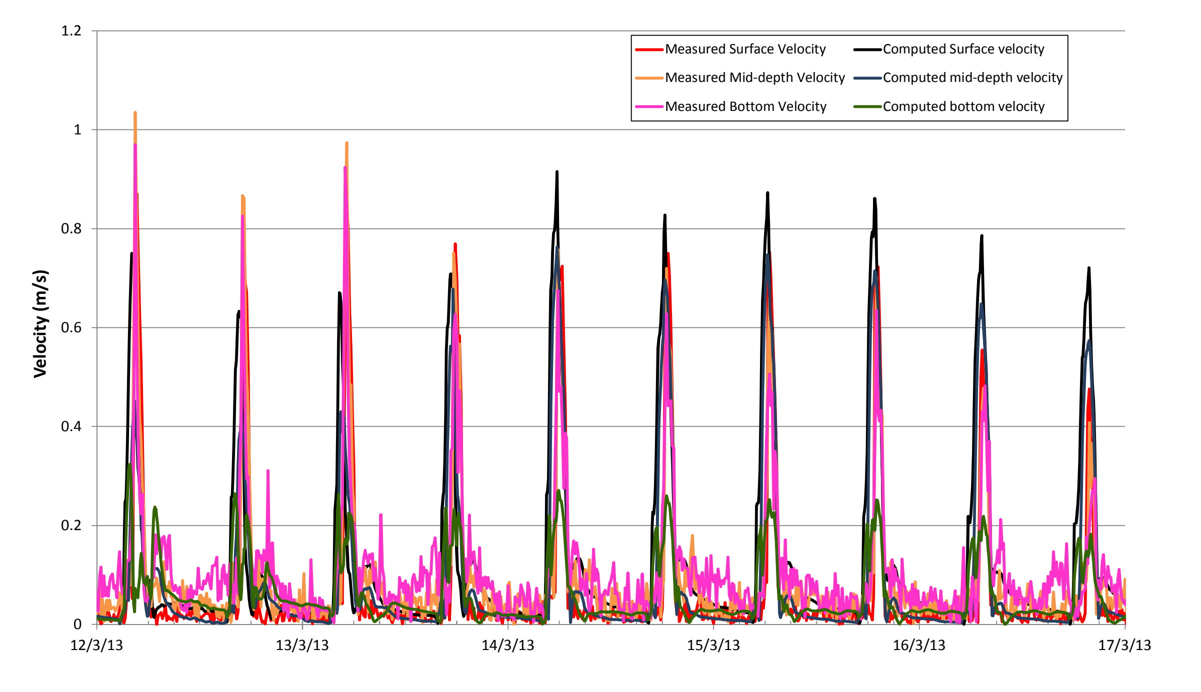


Figure 34 Comparison between measured and computed tide velocities at S1 for the March monitoring period 12th March to 17th March 2013

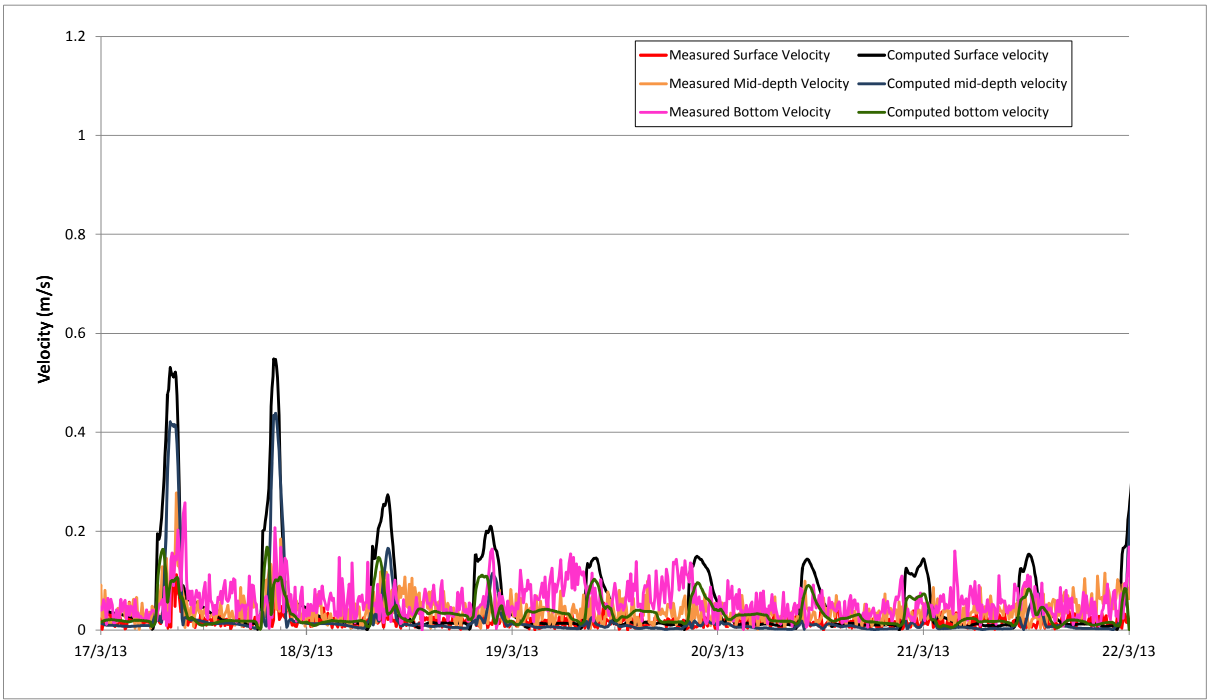


Figure 35 Comparison between measured and computed tide velocities at S1 for the March monitoring period 17th March to 22nd March 2013

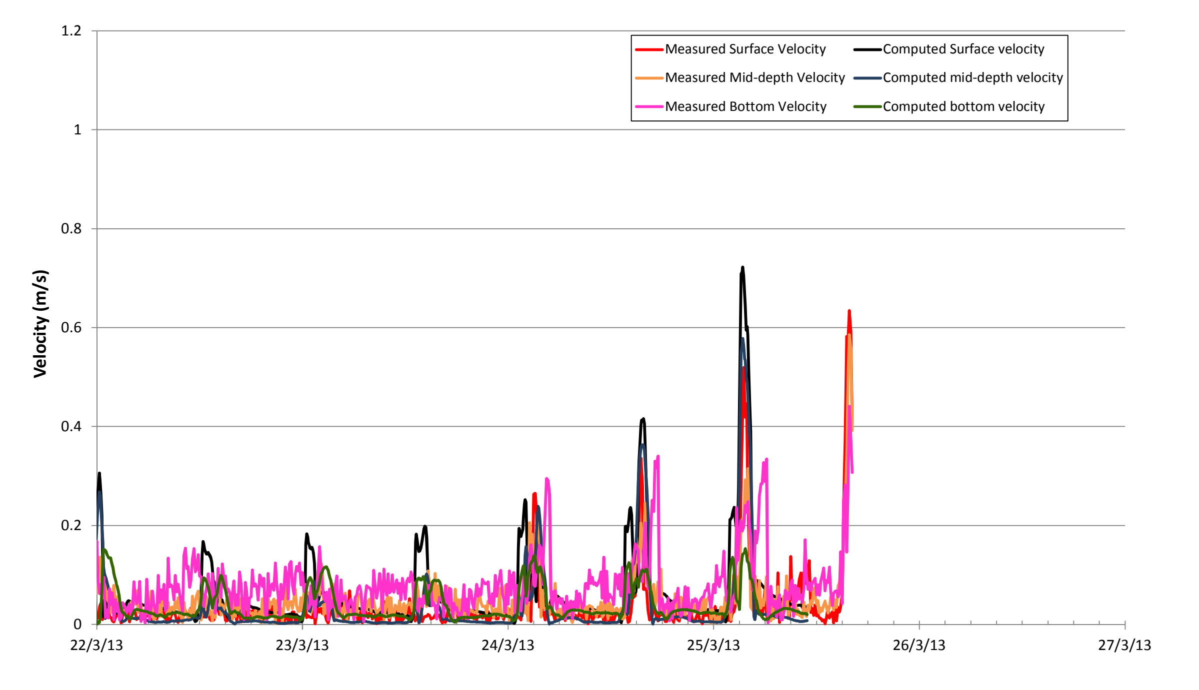


Figure 36 Comparison between measured and computed tide velocities at S1 for the March monitoring period 2nd March to 26th March 2013

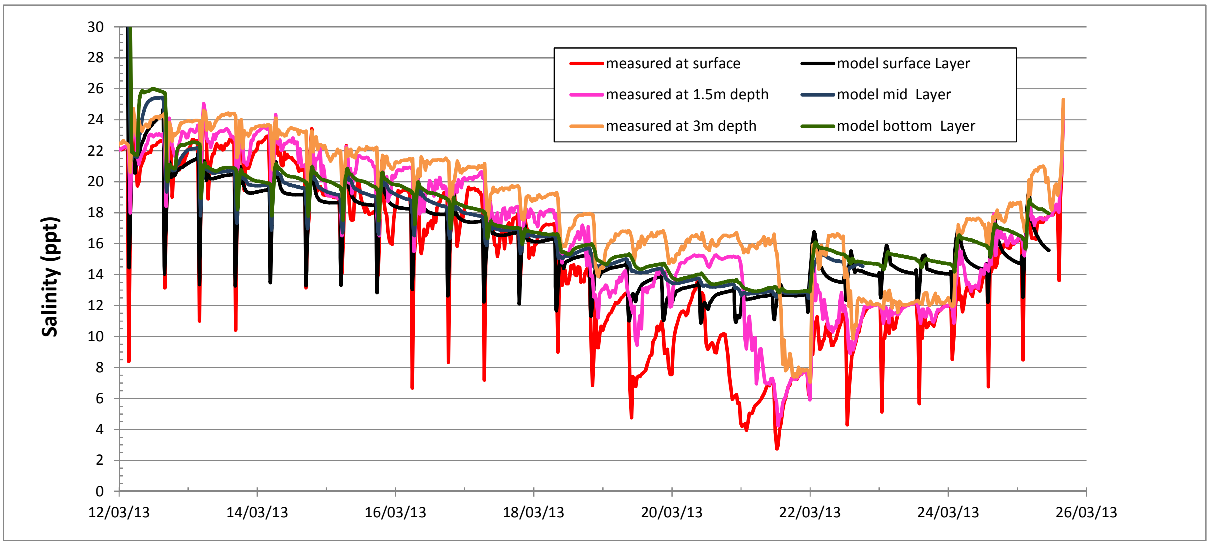


Figure 37 Measured V's Computed Salinities in Lough Atalia at Site S1 for March monitoring period

Refer also to Figures 32 and 33

4. Salinity Simulations

4.1 Introduction

A range of model simulation runs were performed with and without the proposed Galway Harbour Extension to assess and quantify the overall impact of the development on salinity levels in Lough Atalia, the Galway docks and approaches area and in vicinity of the proposed Harbour Extension. Model simulations were performed for a range of open sea tide and freshwater inflows from the Corrib. All other sources of freshwater inflow (i.e. small streams, storm outfalls, groundwater baseflow and springs) were ignored as their flow contribution was considered minor in comparison to the River Corrib source.

The model simulations were performed for a 16.5 day period (32 tidal cycles) and a time step of 2 seconds. This was sufficient to attain equilibrium salinity concentrations within Lough Atalia and in the vicinity of the Harbour Extension area, as it provided a 2.5day warm-up period and 14day spring-neap-spring cycle. The time varying tidal curve specified at the open sea western boundary to drive the model simulations is presented below in Figure 38.

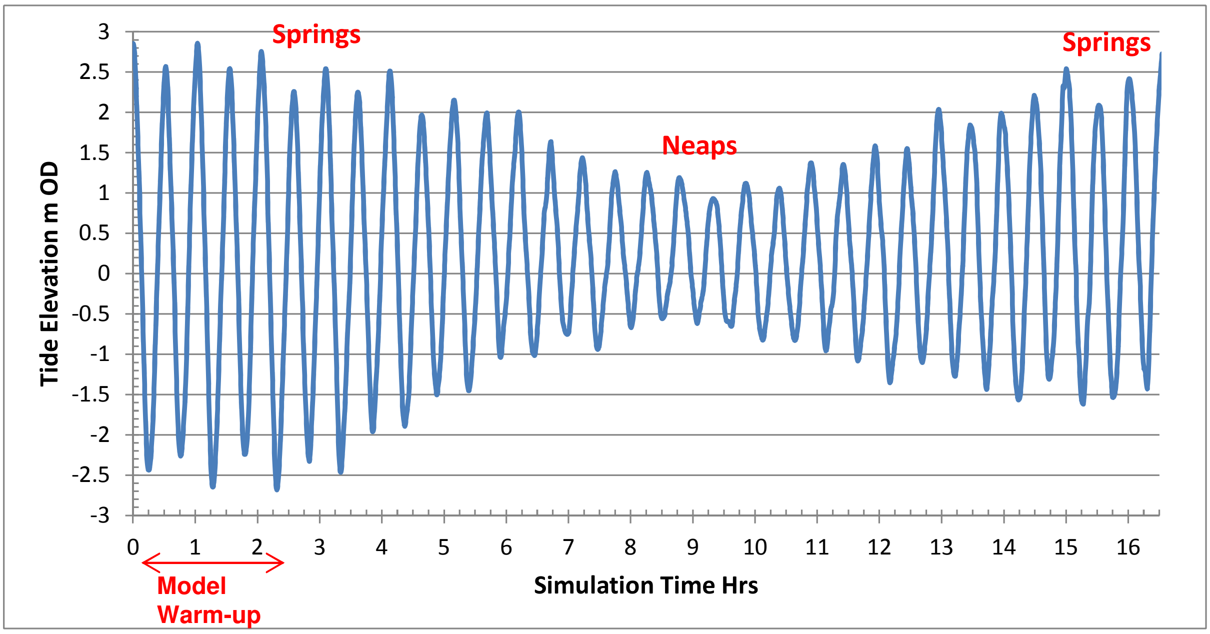


Figure 38 Open Sea Tidal conditions used in salinity simulations

Using the River Corrib flow duration curve information at Wolfe Tone Bridge gauge (30061) (refer to Table 1 in Section 3) the following range of flow conditions were examined in order to quantify the overall impact on salinity by the proposed development:

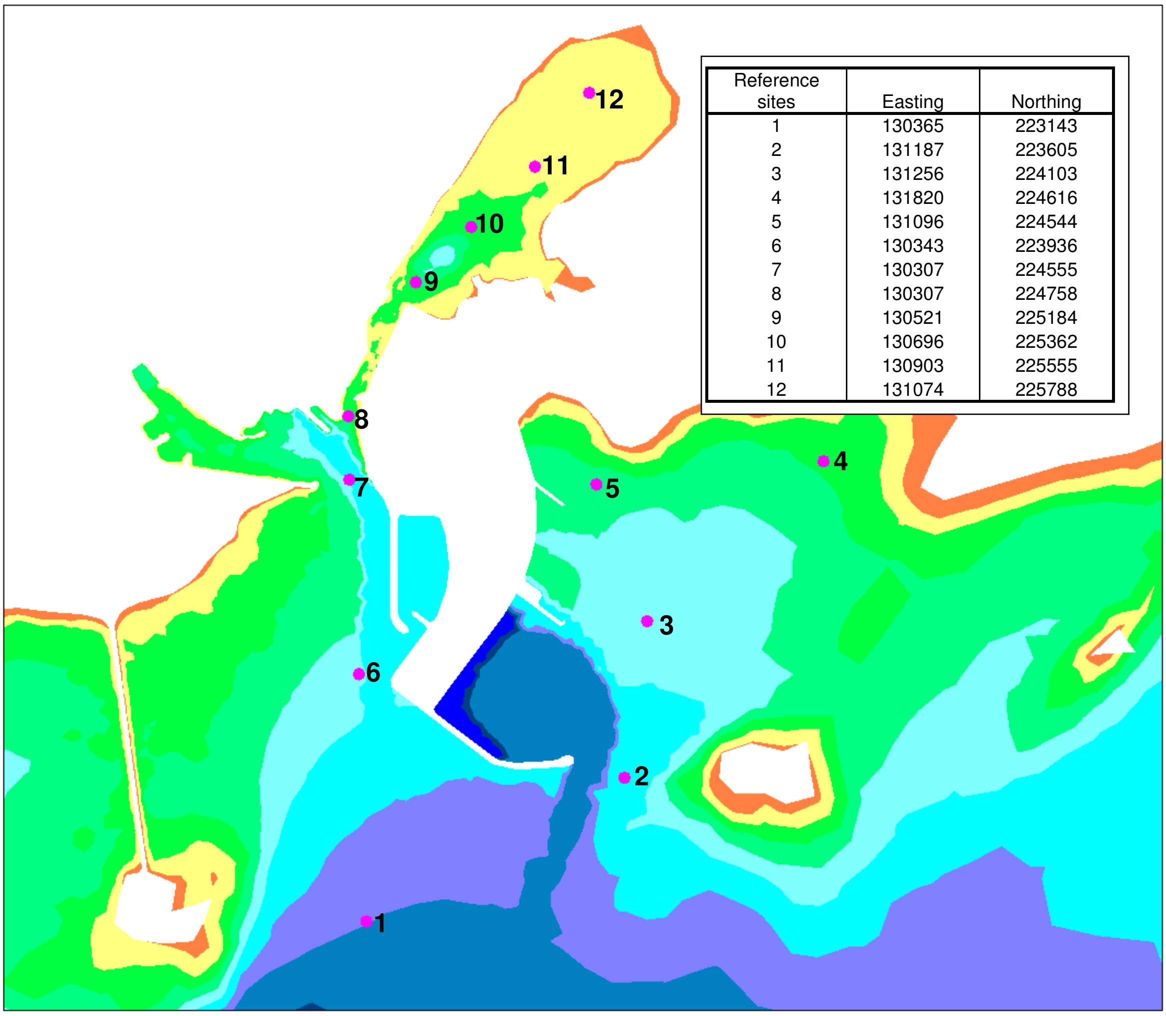
1. 99-percentile River Corrib low flow of 9.1 cumec
2. 90-percentile River Corrib flow of 28.5cumec
3. 50-percentile River Corrib flow of 82 cumec
4. 10-percentile River Corrib flow of 200 cumec
5. 1-percentile River Corrib flood flow of 272cumec

These flows were specified as constant inflows as opposed to a time varying flow hydrograph. This approach is considered reasonable and appropriate for the River Corrib given the highly damped nature due to the large Lough Corrib and its flow regulation by OPW at the Salmon Weir Sluice Barrage in Galway City.

4.2 Simulation results

In order to compare the predicted salinities with and without the proposed Harbour Extension, a number of reference sites within Lough Atalia the Approach Channel and the proposed harbour extension area were selected. At these reference sites time series of salinity concentrations were generated and analysed for each simulation run so as to directly compare the change in salinity value. These reference sites are presented below in Figure 39.

A salinity of 33 ppt was specified at the western open sea boundary and 0 ppt in the Corrib and an initial starting condition of 32 ppt throughout the bay. Simulations were then run for a 16.5day (32 tidal cycle period (spring-neap-spring) so as to obtain equilibrium conditions within the area of interest and particularly for the final 14 tidal cycles representing neap to spring tides.



Reference sites	Easting	Northing
1	130365	223143
2	131187	223605
3	131256	224103
4	131820	224616
5	131096	224544
6	130343	223936
7	130307	224555
8	130307	224758
9	130521	225184
10	130696	225362
11	130903	225555
12	131074	225788

Figure 39 Reference site for time series output of computed salinities

For each simulation run the temporal mean for the final 14 tidal cycles (neaps to springs) was performed and salinity contour plots of these mean salinities with and without the proposed development in the bottom, mid-depth and surface layers are presented in Figures 46 to 60. These demonstrate the stratification between the freshwater surface layer and the underlying saline layers, with the bottom layer being the most saline. The plots also demonstrate the sheltering effect that the harbour extension will have on the buoyant freshwater outflow resulting in more saline conditions to the East of the harbour extension (Renmore Bay area) and less saline conditions to the west and south of the development.

For each of the five hydrodynamic simulations summary tables of the salinity predictions at the 12 reference sites for proposed and existing cases, along with a summary of salinity differences are presented in Tables 3 to 17. Times series plots of surface mid column and bottom salinities for existing and proposed cases at sites 5 (Renmore area), 7 (off Nimmo's Pier) and 9 (Lough Atalia) for each of the five hydrodynamic runs are presented in Figures 61 to 75. These time series plots illustrate the effect of the development on salinities for spring-neap-spring tidal cycles.

4.3 Discussion of Results

Renmore area

The tide simulations for various freshwater inflows from the Corrib show the deflection of the Corrib freshwater plume westward due to the harbour extension site with freshwater only arriving into Renmore Bay area on the subsequent flooding tide. In the existing case there is a wider area for the plume to disperse with no physical structure to prevent the plume migrating east and southeast on the ebbing tide and thus availing of a greater area for dispersion. With the proposed development, the Corrib plume is directed more southwards with reduced opportunity for the freshwater plume to directly disperse into the Renmore Bay area on the returning tide. The modelling demonstrates significant increases in salinity to the east of development with greatest changes occurring to the northeast of proposed harbour extension, with the model reference sites 3, 4, and 5 showing an average rise in salinity of 2.4, 4.2 and 5.4ppt respectively.

Lough Atalia

The impact of the proposed harbour extension on salinity in Lough Atalia (using reference Sites 9, 10, 11 and 12 of Figure 39) and integrating the results over the five hydrodynamic simulation runs considered gives an overall predicted reduction in the mean salinity within Lough Atalia of 1.29ppt, refer to Table 3 below for summary of salinity Predictions for Lough Atalia. Figure 40 to 44 present the tidal average and tidal maximum and minimum salinities for neap to spring tides and demonstrate the impact of the harbour extension on salinities in Lough Atalia.

Both the simulation results and the measured salinity data (presented in Section 2) for Lough Atalia show considerable temporal variation in salinity concentrations under tidal and river flow conditions. The measured and predicted salinities in Lough Atalia range from 30 ppt (psu) to low salinities of less than 1ppt and a mean salinity of 12.1 ppt. This Lough has a short residence time being easily flushed by the tide and thus represents a very dynamic system with significant changes in salinity occurring over a relatively short periods of time, significant changes occur; (i) within a spring tidal cycle, (ii) over a number of tidal cycles between spring and neaps and (iii) seasonally with changes in the River Corrib freshwater flow conditions. The predicted reduction in salinity, refer again to Table 3 and Figure 45, for the various tide and flow conditions of 0.59 to 1.51ppt (mean reduction of 1.29ppt) is minor relative to the range of salinities encountered within the Lough. The smallest predicted impact by the proposed harbour extension occurs when the Corrib is in low flow.

Table 3 Summary of Lough Atalia Salinity Results

		Existing mean Salinity (ppt)	Proposed mean Salinity (ppt)	Change in mean Salinity (ppt)
Hydro 1 Neap-Spring with 99% low flow (9.1m^3/s)	5.5%	27.29	26.70	-0.59
Hydro 2 Neap-Spring with 90% flow (28.5m^3/s)	24.5%	20.419	19.22	-1.19
Hydro 3 Neap-Spring with 50% flow (82m^3/s)	40%	11.36	9.85	-1.51
Hydro 4 Neap-Spring with 10% flow (200m^3/s)	24.5%	3.76	2.49	-1.27
Hydro 5 Neap-Spring with 1% flood flow (272m^3/s)	5.5%	1.68	0.69	-0.99
Overall Mean	100%	**12.06**	**10.77**	**-1.29**

The salinity within Lough Atalia for a given Corrib Flow condition is lowest on neap tides and highest on spring tides. On spring tides sufficient tidal depth is available towards the latter stages of the flood tide (as it approaches highwater) to push the more dense saline bottom layer into Lough Atalia. The variation between minimum and maximum salinities is also higher on spring tides as the initial stages of the incoming flood tide introduce the fresher surface layer (i.e. when the tidal depth is small) followed as the depth increases by the deeper saline layer (See Figures 40 to 44). As the tidal cycles weaken towards neap tides the tidal depth and range reduces significantly such that the fresher surface layer becomes the predominant inflow into Lough Atalia resulting in significantly lower salinities. On neap tides during large floods flows practically the complete inflow is freshwater from the upper surface layer. There is limited tidal storage in Lough Atalia due to its relatively small surface area and the shallow water depth, resulting in high exchange / flushing rates (i.e. 75% of the highwater lough volume is replaced on a single spring tide and 30% on a single neap tide). Therefore the transition from spring to neap tides at times of large flood flows results in a lowering of the lough salinities to practically those of freshwater over the 2 to 3 days of neap tides. Even on Spring tides at the more extreme flood flow conditions in the Corrib the salinity in the Lough will practically become nil, in the pre development circumstances.

Figure 45 demonstrates the impact of the harbour extension on typical Neap and Spring tides for the complete range of Corrib Freshwater Flows. The exceedance probability of these flows derived from the flow duration curve for the Corrib at Wolfe Tone Bridge gauge is also shown. This graph suggests that nil salinity within Lough Atalia occurs at approximately 301cumec for the existing case and reducing to a rate of 285cumec for the proposed harbour extension case on neap tides. A Corrib flow of 301cumec occurs 0.135% of the time, or 0.5days in an average year (for the existing case), whereas, a flow of 285cumec occurs 0.345% of the time, or 1.25days in an average year (for the proposed case).

Therefore the probability of a nil salinity occurring during neap tides (given that these tides occur approximately one third of the time) is 0.045% for existing case and increasing to 0.115% for the proposed case.

The same analysis for spring tides gives nil salinity occurring at 368cumec for the existing case and 329cumec for the proposed case. The probability of these flows being equalled or exceeded is 0.022% (2hours in an average year) for the existing case and 0.070% (6hours in an average year) for the proposed Harbour development case.

Therefore the probability of a nil salinity occurring during spring tides (given that these tides will occur approximately one third of the time) is 0.007% for existing case and increasing to 0.023% for the proposed case.

Integrating over both spring and neap tides the overall probability of nil salinity occurring in a given year in Lough Atalia is 0.08% (or 7 hours in an average year) for the existing case and increasing to 0.21% (or 18hours in an average year) for the proposed harbour extension case.

4.4 Conclusions

The tide simulations for various freshwater inflows from the Corrib show the deflection of the Corrib freshwater plume westward due to the harbour extension site resulting in reduced dispersion and lower salinities (i.e. more fresh) in the upper water column layers off Nimmo's pier (mouth to Lough Atalia and Galway Docks) and west of the Harbour extension site. The impact of this reduced dispersion of the Corrib freshwater plume is to introduce a slightly fresher water into Lough Atalia resulting in a slight lowering of the salinity concentration there. Conversely considerably more more saline conditions are predicted east of the Harbour Extension in the Renmore Bay area and north of Hare Island.

Within Lough Atalia the measurement and model study combined show for both existing and proposed cases that the lowest salinities and tidal variation of salinities is when the River Corrib is in flood (maximum flows) and the tide range is at its minimum (i.e. neap tides). The measured and modelled data indicates that the salinity within Lough Atalia will tend towards complete freshwater (nil salinity) during the Larger flood flows. On neaps tides the tidal range is extremely weak and the water introduced on the inflowing period is from the surface layer and is basically freshwater. The Lough is relatively small and shallow with a high exchange/flushing rate which eliminates any significant build-up / storage of salinity in the Lough that could be used to maintain salinities during neap and Corrib flood flow periods. The high flushing rate of the Lough ensures a dynamic Lough having large temporal variation in salinities over a single tidal cycle, over lunar cycles and seasonally.

The Impact of the Harbour Extension Development on salinity concentrations within Lough Atalia is to reduce salinities by on average by 1.29ppt over the complete range of flow and tide conditions. Given the relative range of salinities within the Lough from c. 30ppt to nil ppt, this reduction of 1.29ppt in salinity, which is only 10% of the mean salinity, is not considered significant. The model analysis also demonstrates that the range of salinities (maximum to minimum) within Lough Atalia will not alter as a result of the harbour extension, only the frequency of occurrence will change, as demonstrated by Figure 45.

Periodic large and extreme flood flows in the Corrib will reduce salinities to practically nil in Lough Atalia for both the existing and proposed cases, principally during neap tides but also on spring tides for a less frequent more extreme flood flow. Over the full tidal range the probability of nil Salinity in a given year occurring within Lough Atalia will increase from 0.08% to 0.21% (7 to 18hours in an average year).

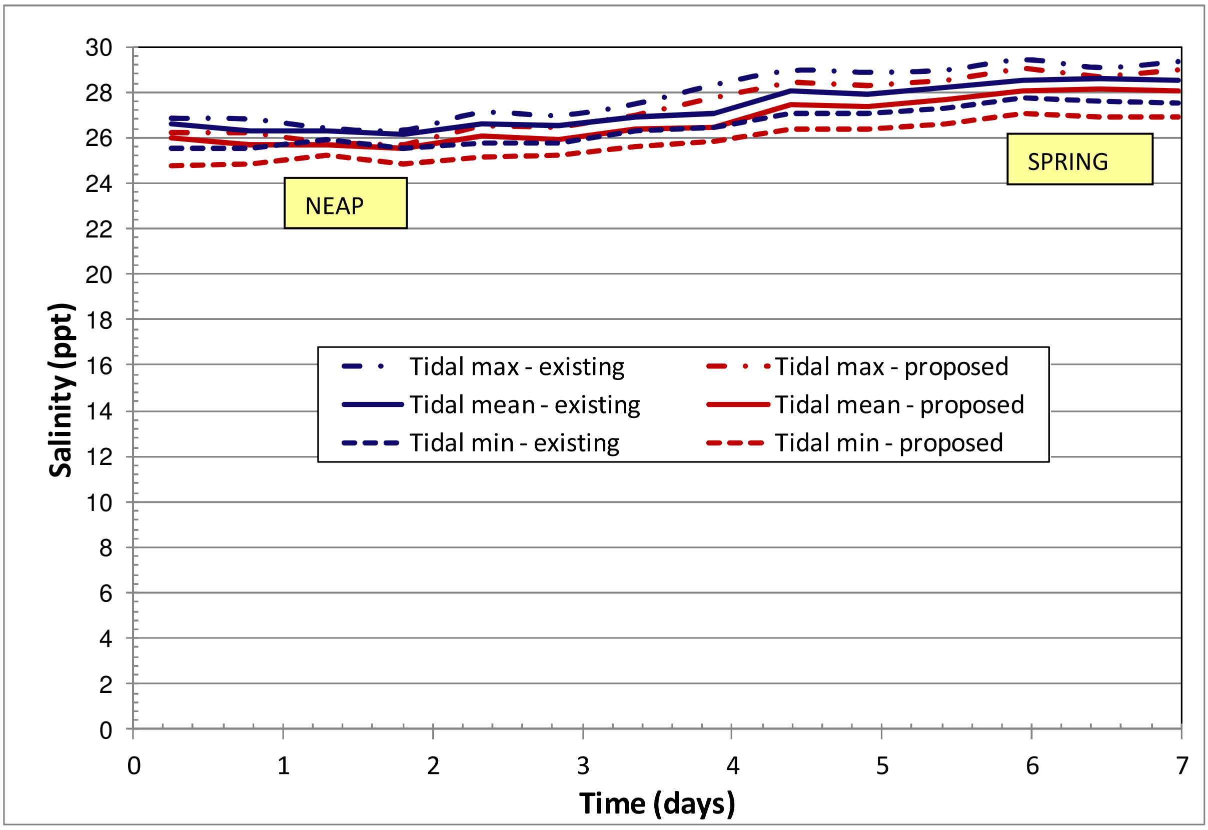


Figure 40 Predicted Tide averaged, maximum and minimum Salinities in Lough Atalia for 99-percentile Corrib Low Flow with and without Harbour Extension

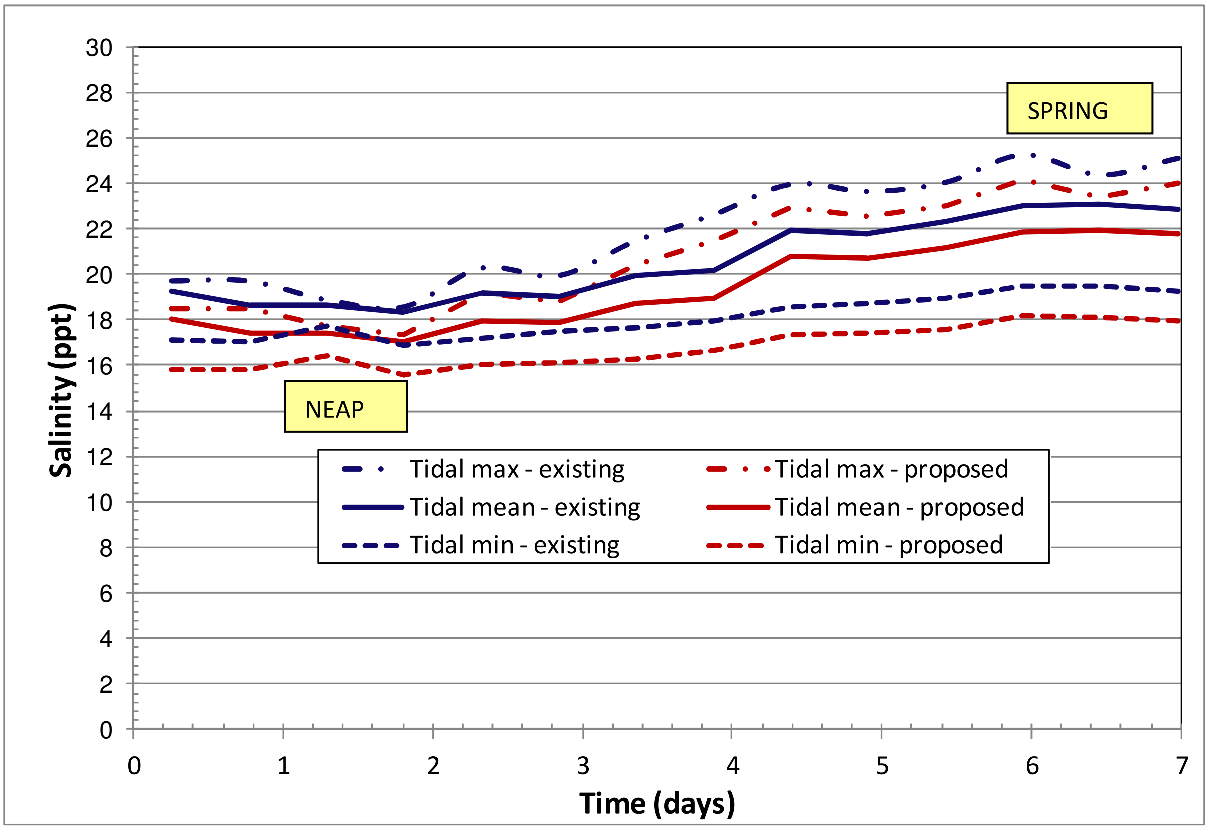


Figure 41 Predicted Tide averaged, maximum and minimum Salinities in Lough Atalia for 90-percentile Corrib Flow with and without Harbour Extension

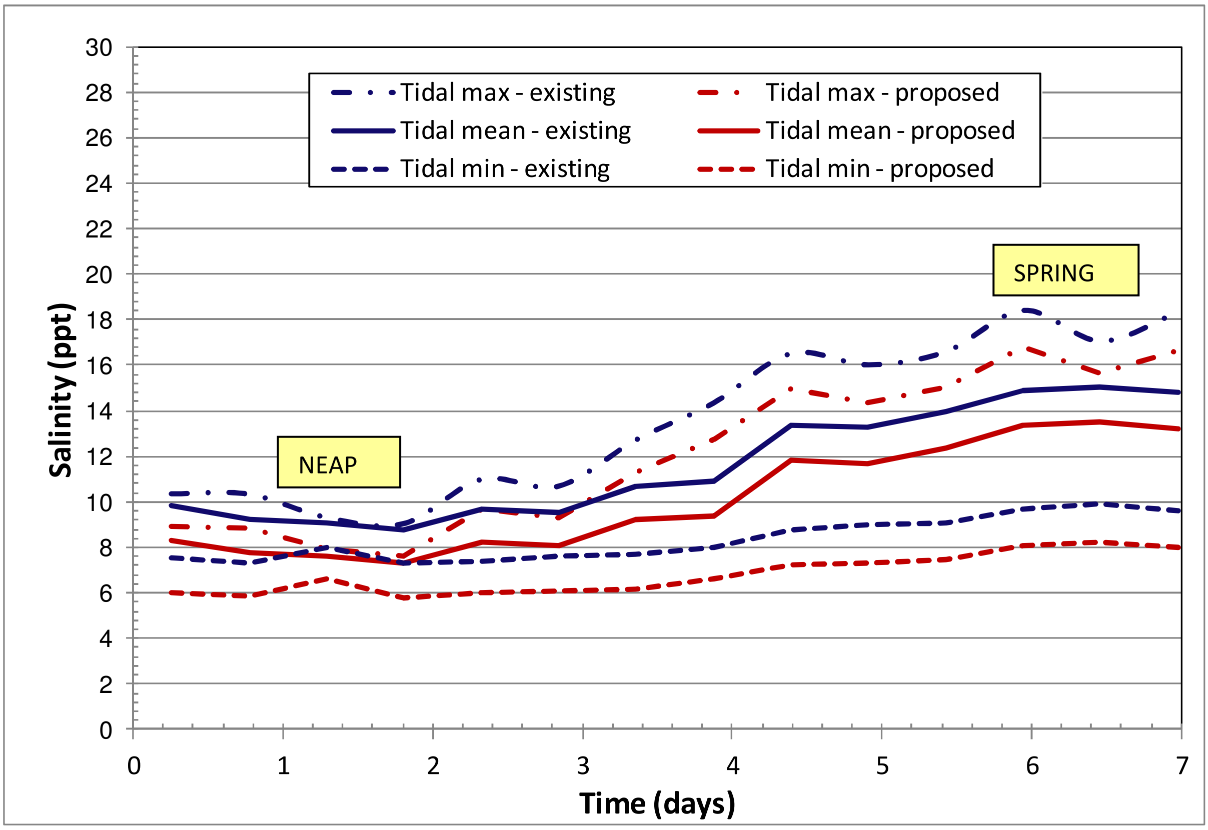


Figure 42 Predicted Tide averaged, maximum and minimum Salinities in Lough Atalia for 50-percentile (median) Corrib Flow with and without Harbour Extension

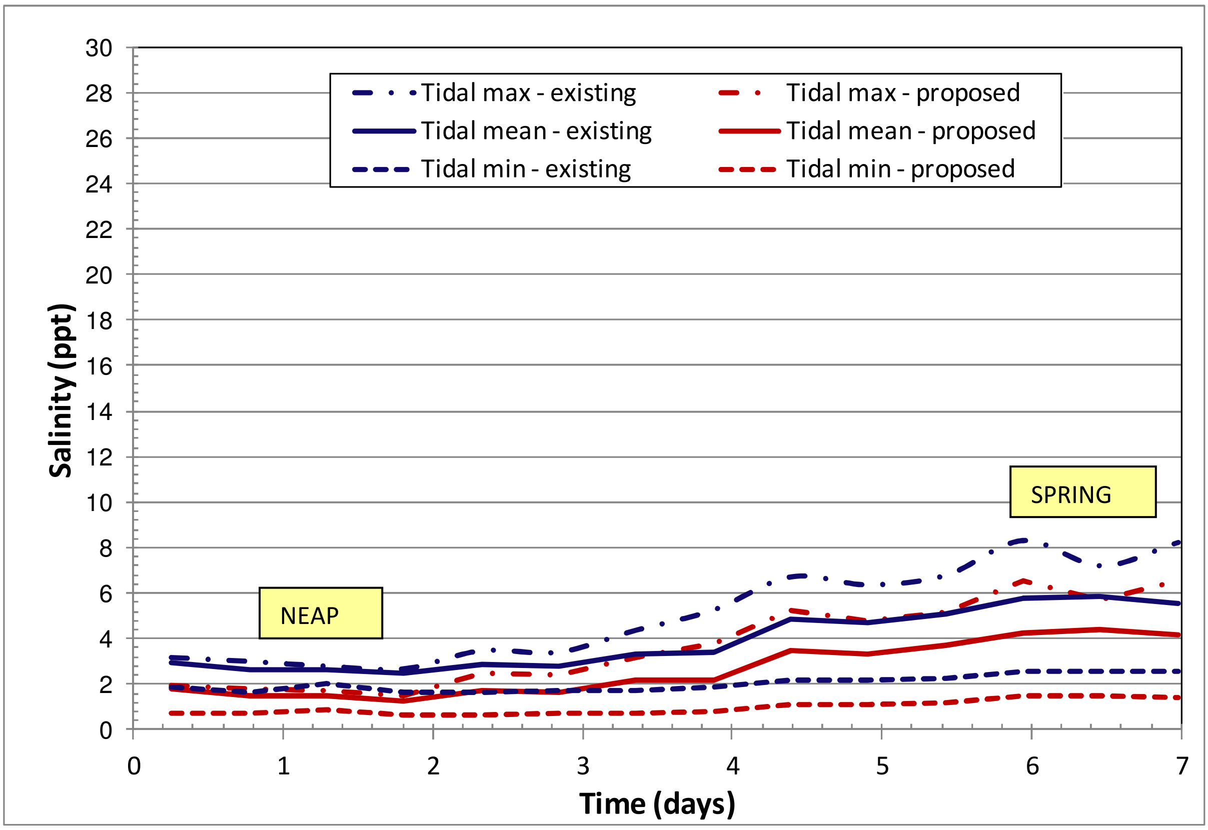


Figure 43 Predicted Tide averaged, maximum and minimum Salinities in Lough Atalia for 10-percentile Corrib Flow with and without the Harbour Extension

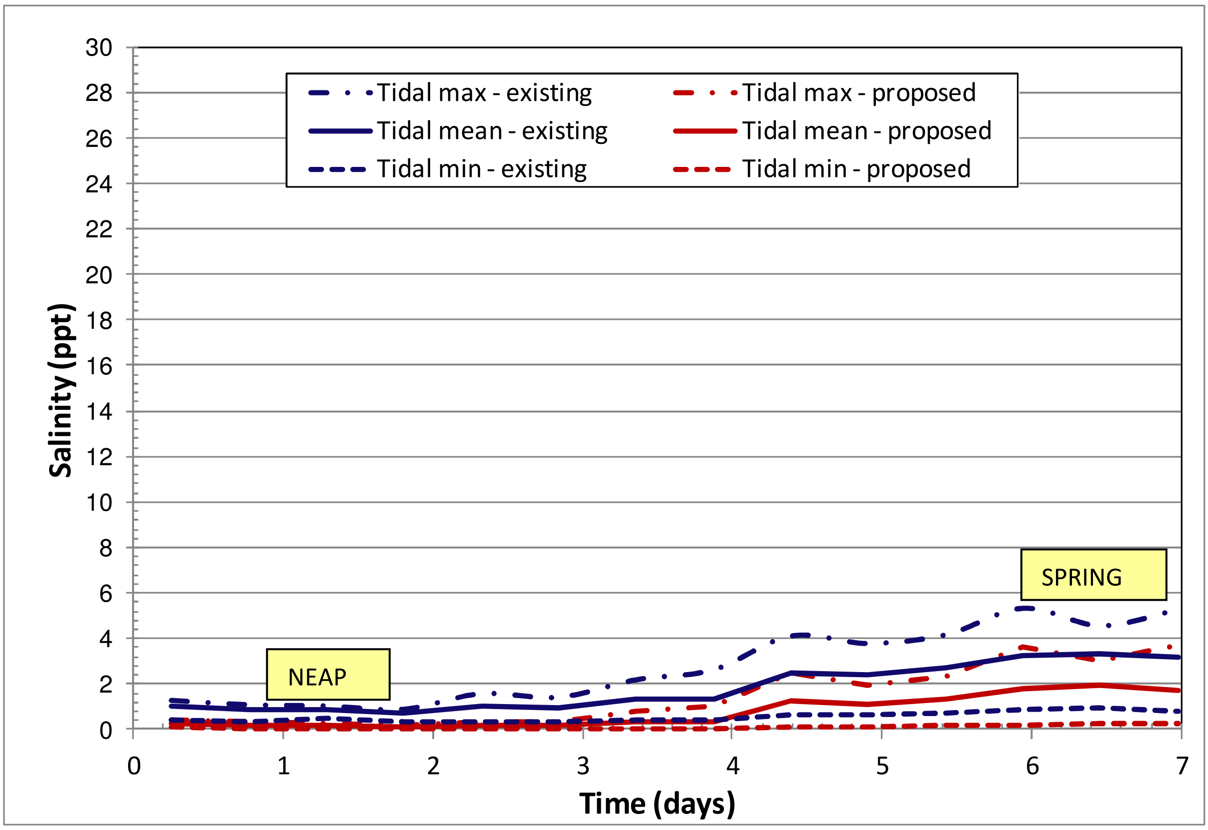


Figure 44 Predicted Tide averaged, maximum and minimum Salinities in Lough Atalia for 1-percentile Corrib Flood Flow with and without the Harbour Extension

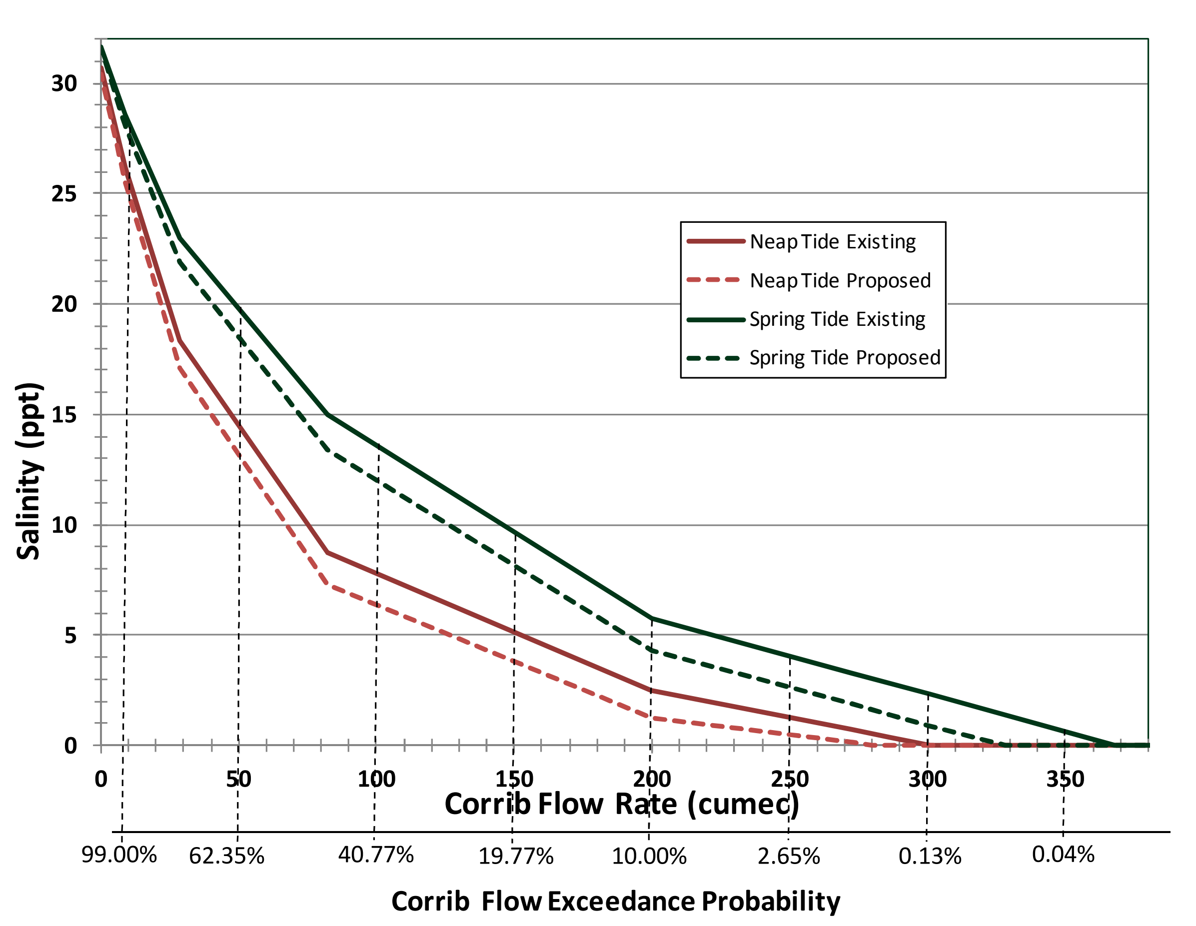


Figure 45 **Predicted Mean Tidal Salinity for Spring and Neap Tides in Lough Atalia V's Corrib Flow Rate for complete range of Corrib Freshwater Flow Conditions (0cumec to 400cumec)**

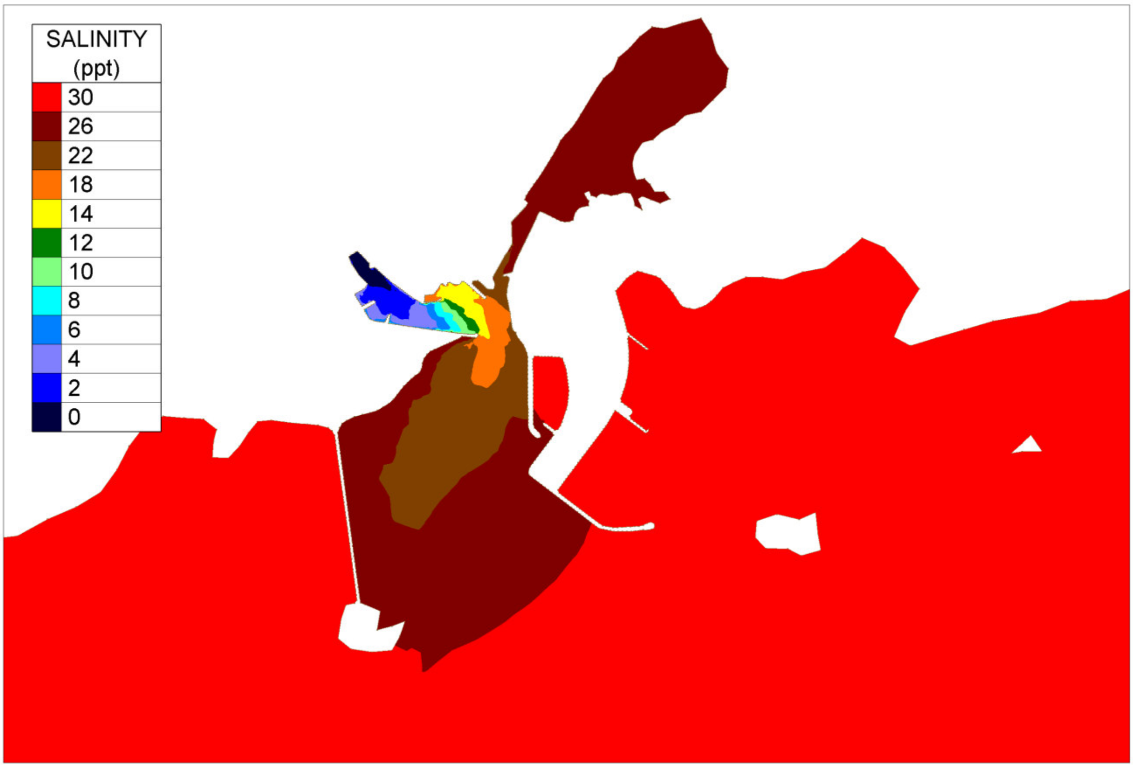


Figure 46 Mean Salinity concentration in bottom layer for existing and proposed cases under 99-percentile Corrib Low Flow (9.1 cumec)

Figure 47 Mean Salinity concentration in mid-depth layer for existing and proposed cases under 99-percentile Corrib Low Flow (9.1 cumec)

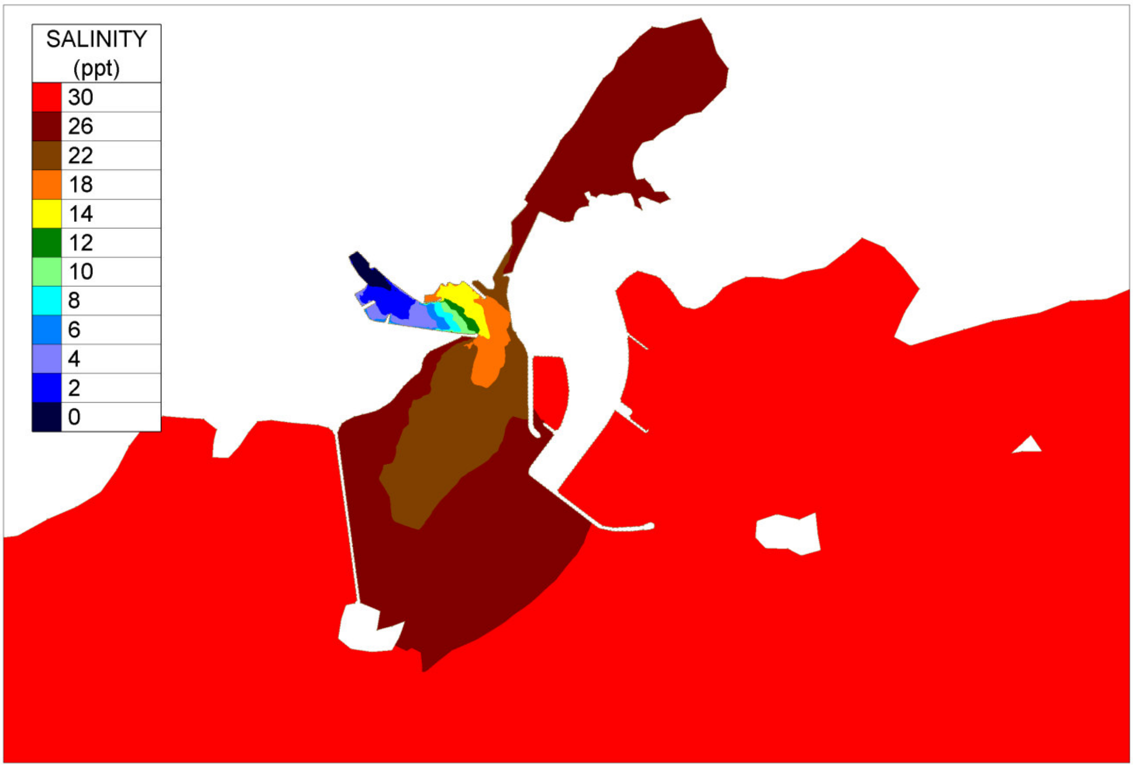
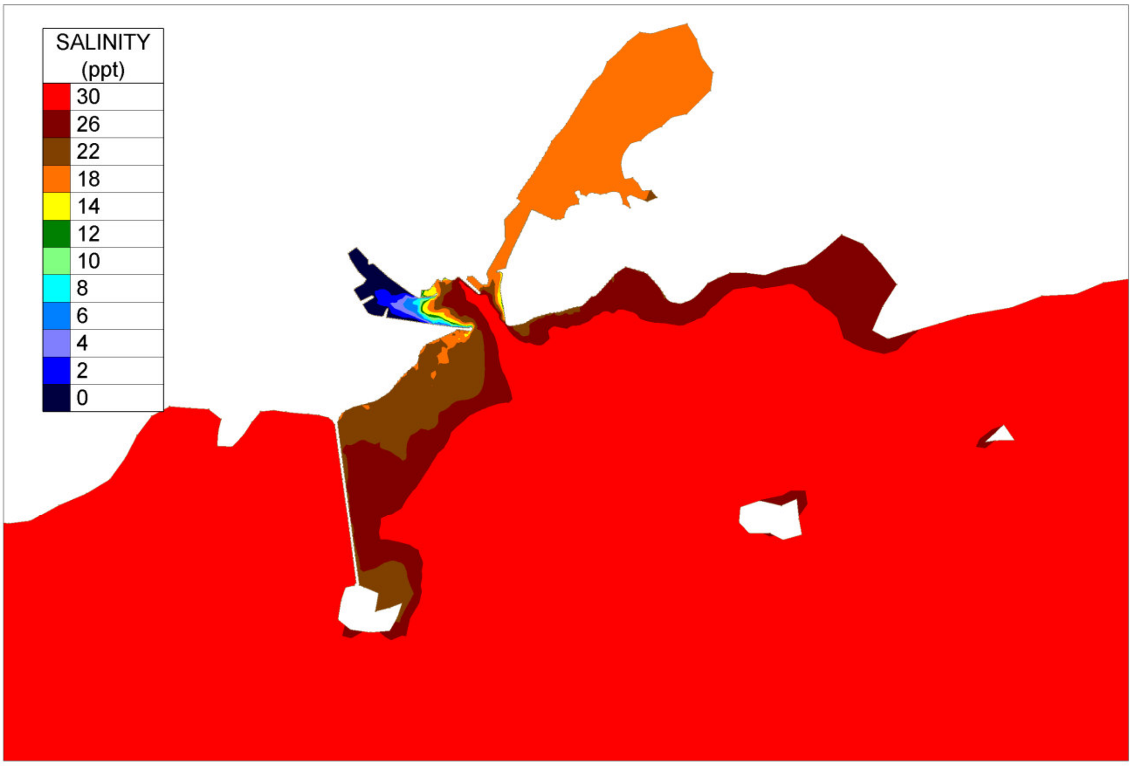


Figure 48 Mean Salinity concentration in surface layer for existing and proposed cases under 99-percentile Corrib Low Flow (9.1 cumec)



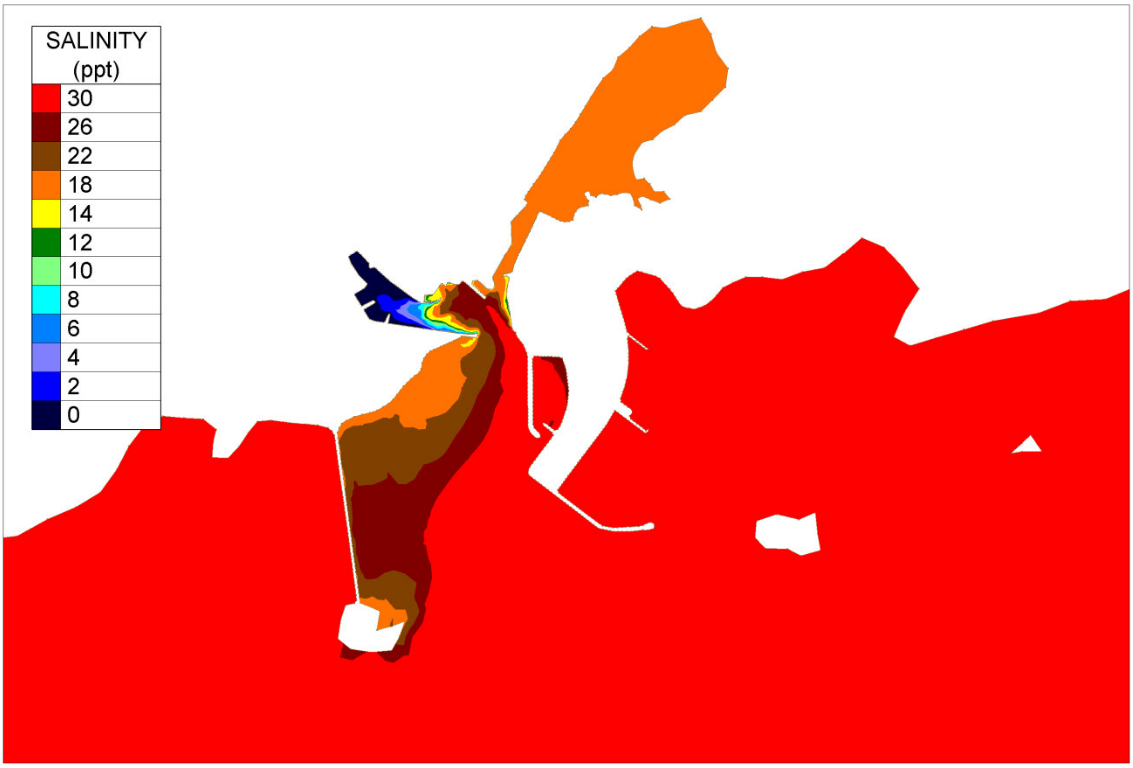


Figure 49 Mean Salinity concentration in bottom layer for existing and proposed cases under 90-percentile Corrib Flow (28.5cumec)

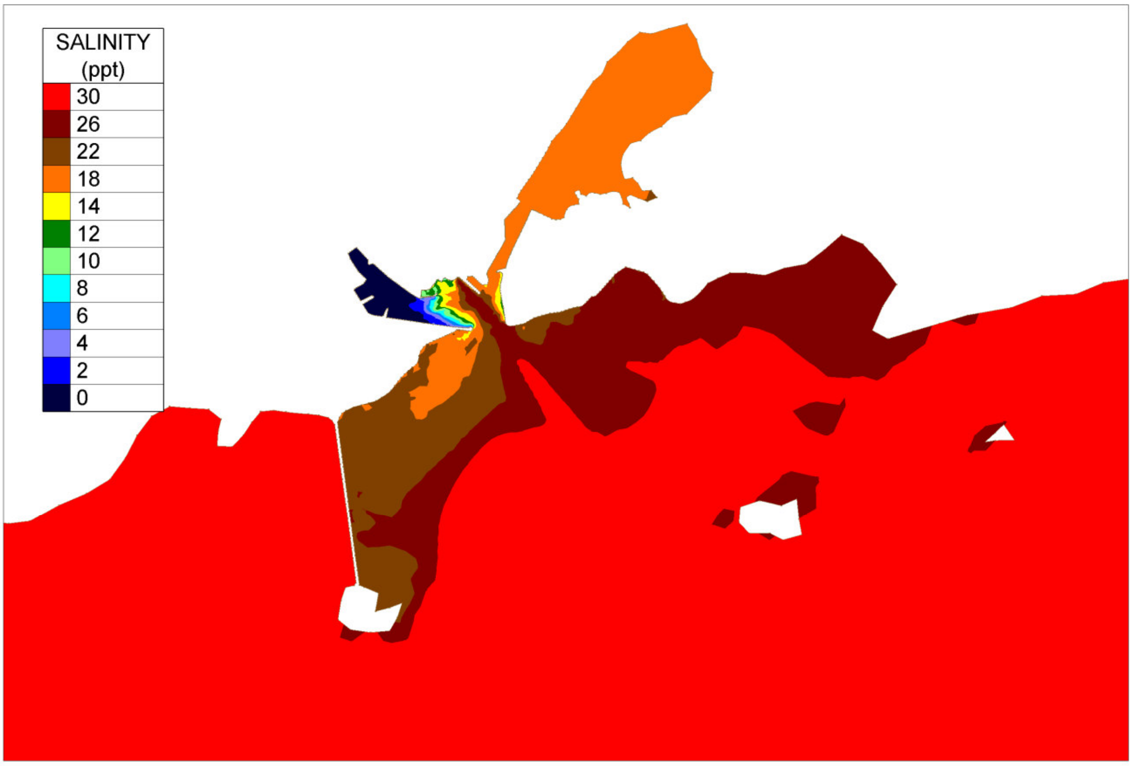


Figure 50 Mean Salinity concentration in mid-depth layer for existing and proposed cases under 90-percentile Corrib Flow (28.5cumec)

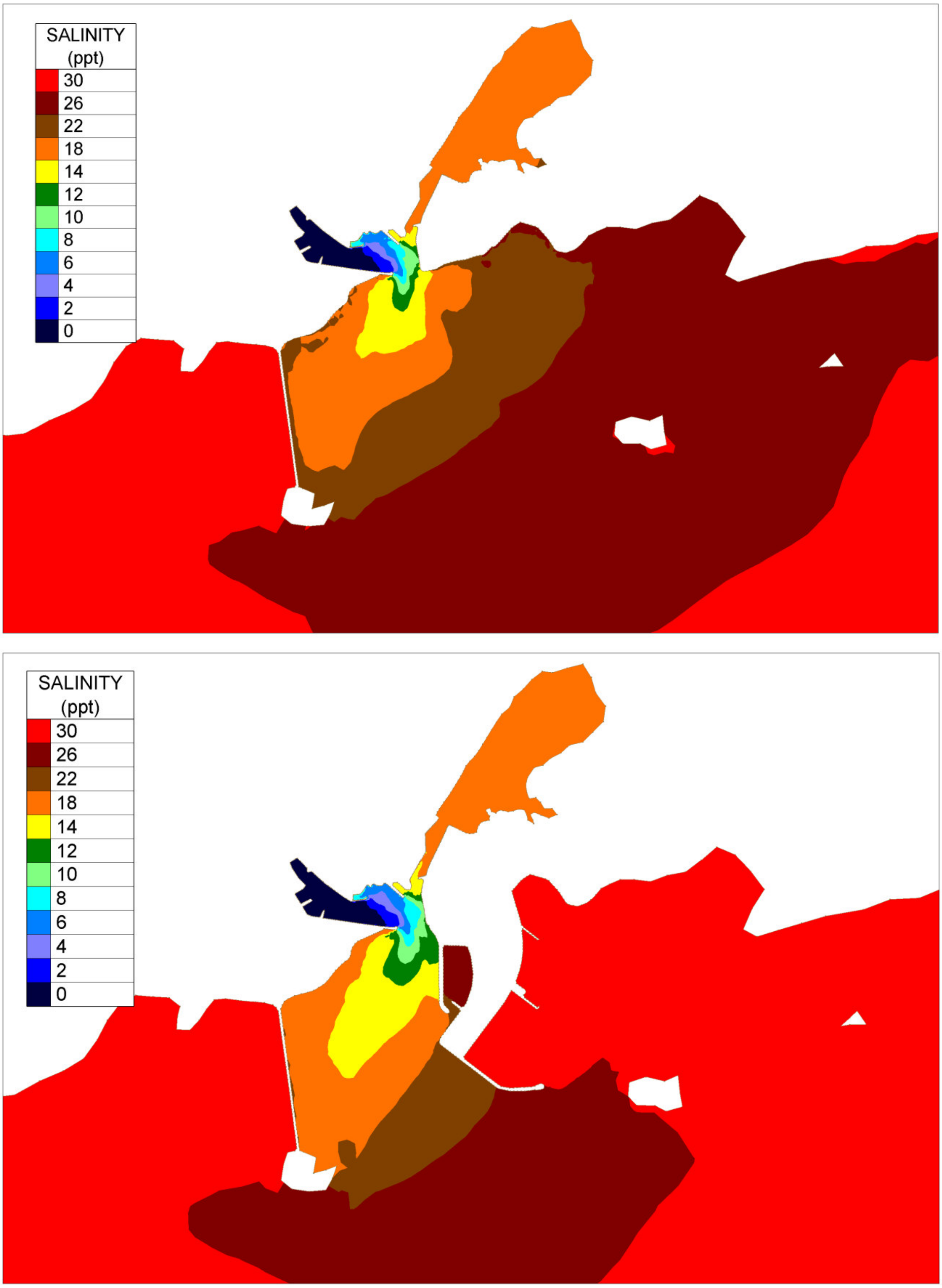
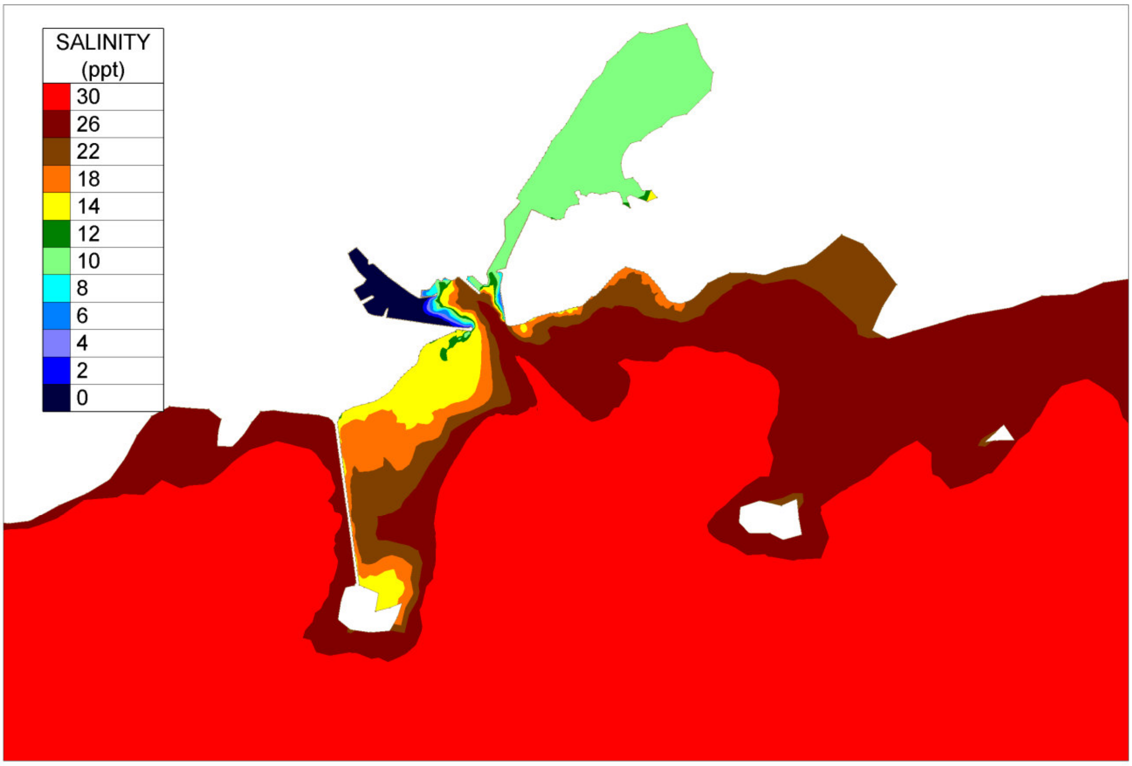


Figure 51 Mean Salinity concentration in surface layer for existing and proposed cases under 90-percentile Corrib Flow (28.5cumec)



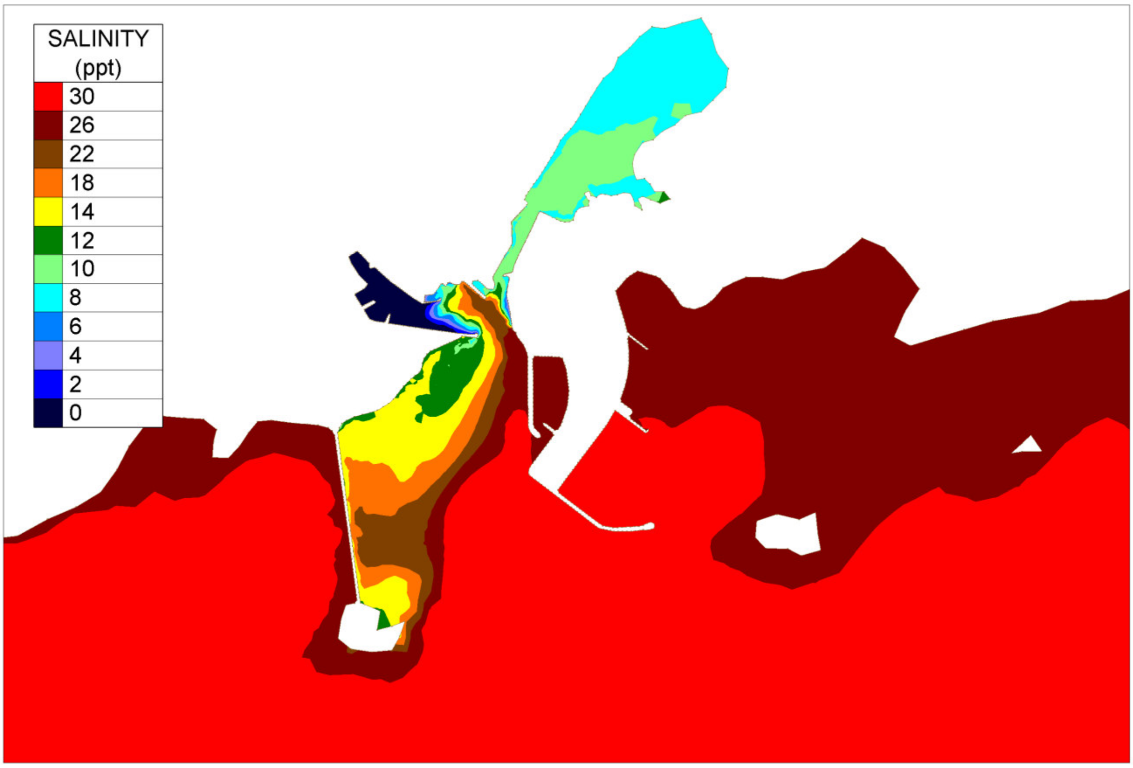
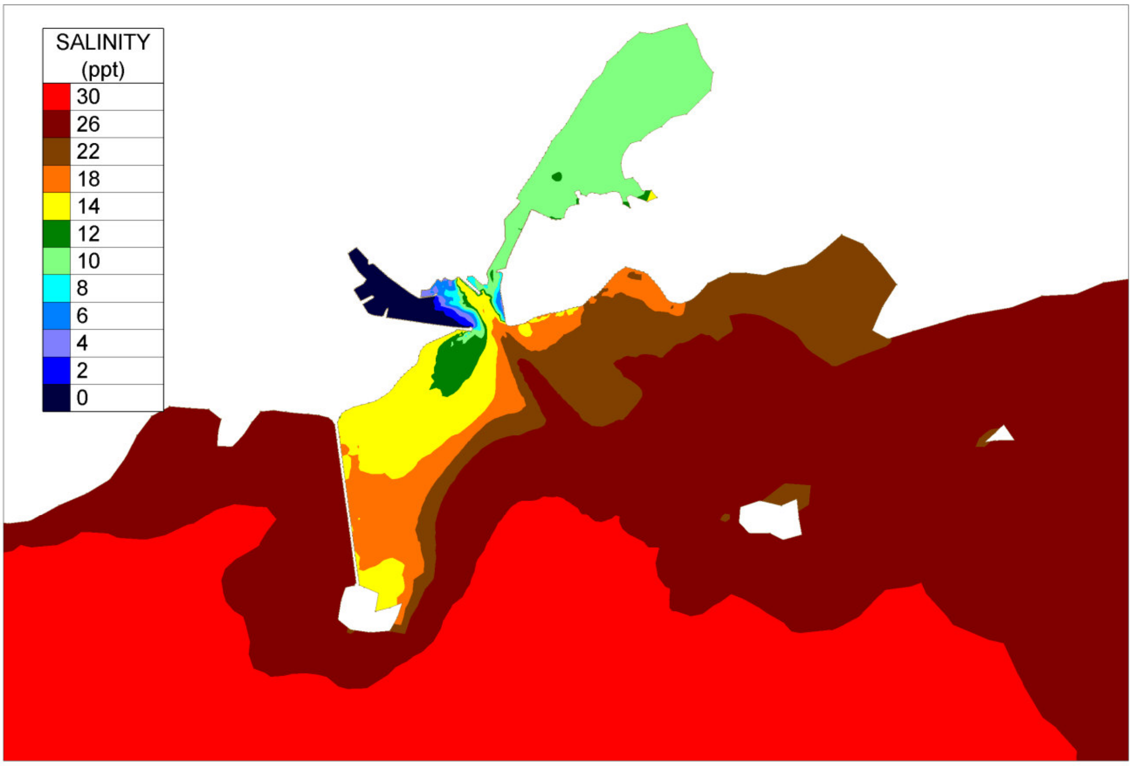


Figure 52 Mean Salinity concentration in bottom layer for existing and proposed cases under 50-percentile Corrib Flow (82cumec)



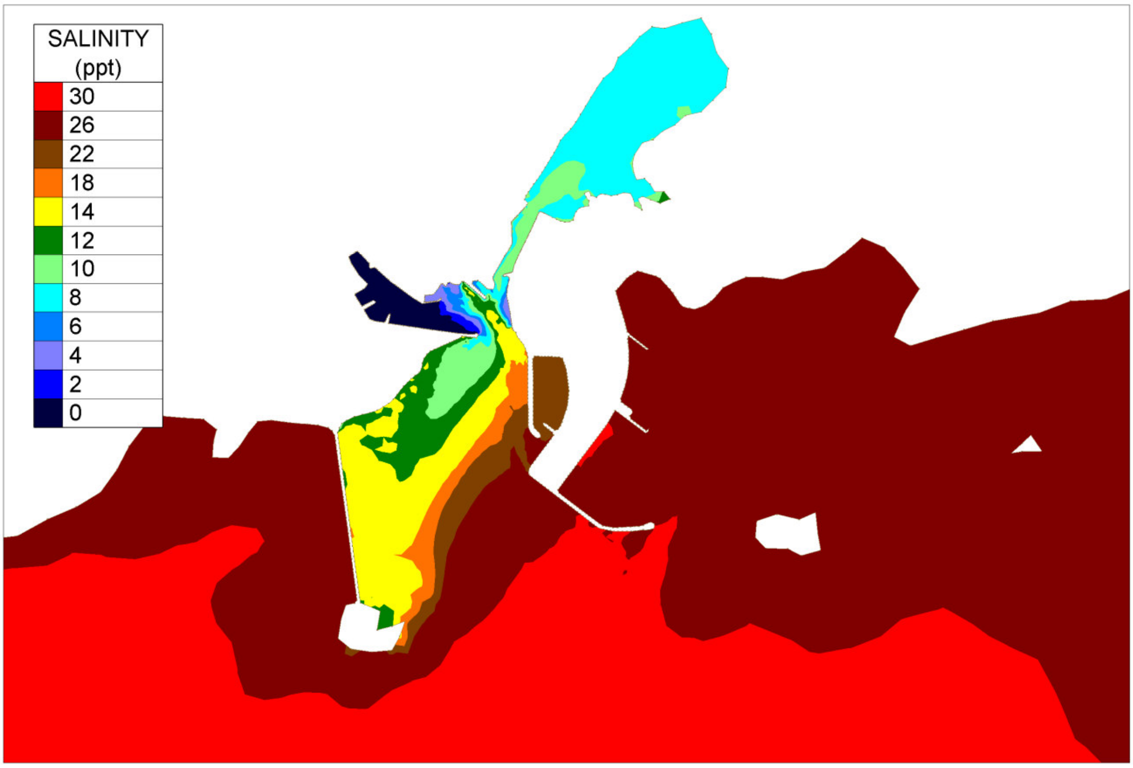


Figure 53 Mean Salinity concentration in mid-depth layer for existing and proposed cases under 50-percentile Corrib Flow (82 cumec)

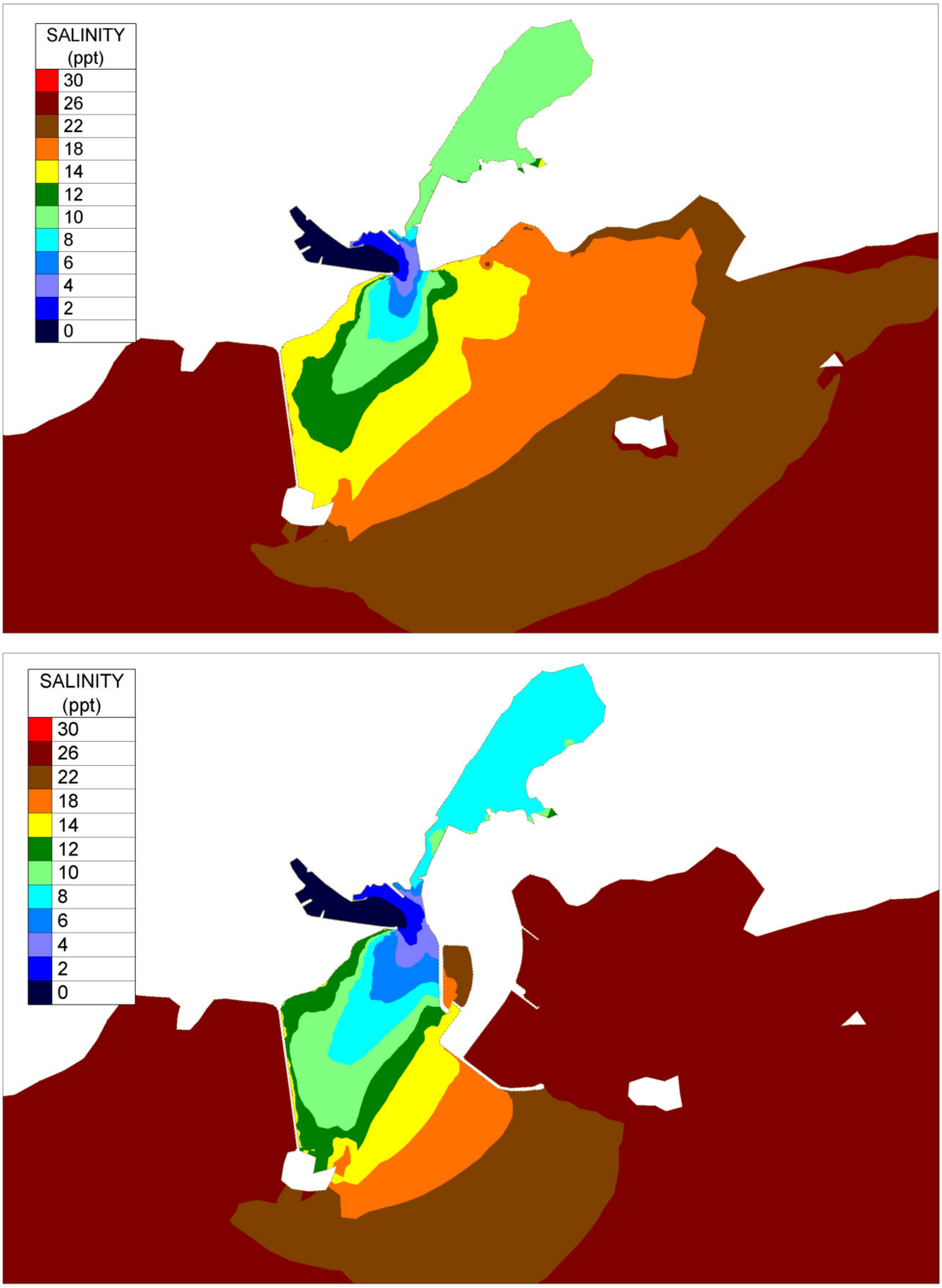


Figure 54 Mean Salinity concentration in surface layer for existing and proposed cases under 50-percentile Corrib Flow (82cumec)

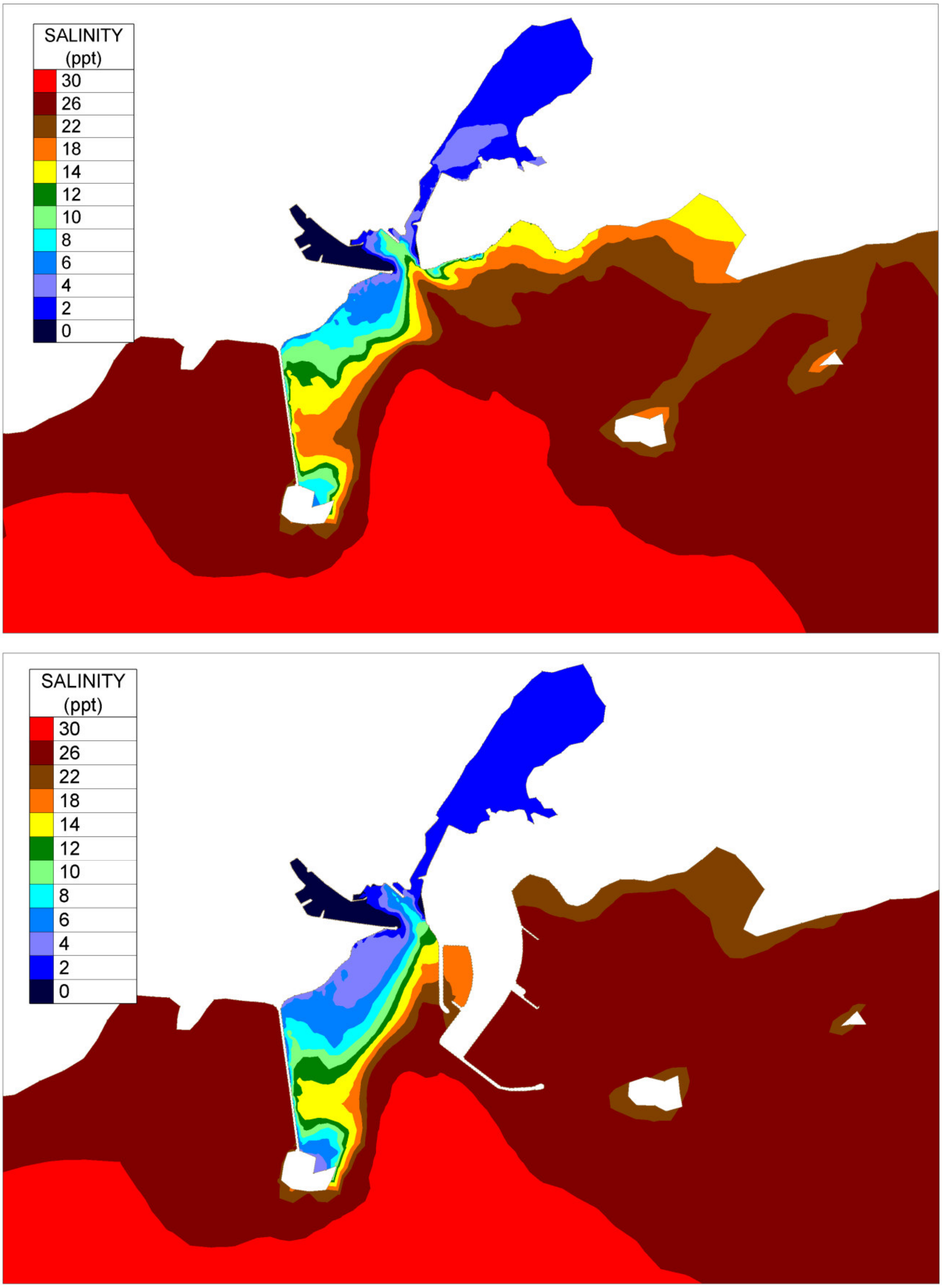


Figure 55 Mean Salinity concentration in bottom layer for existing and proposed cases under 10-percentile Corrib Flow (200cumec)

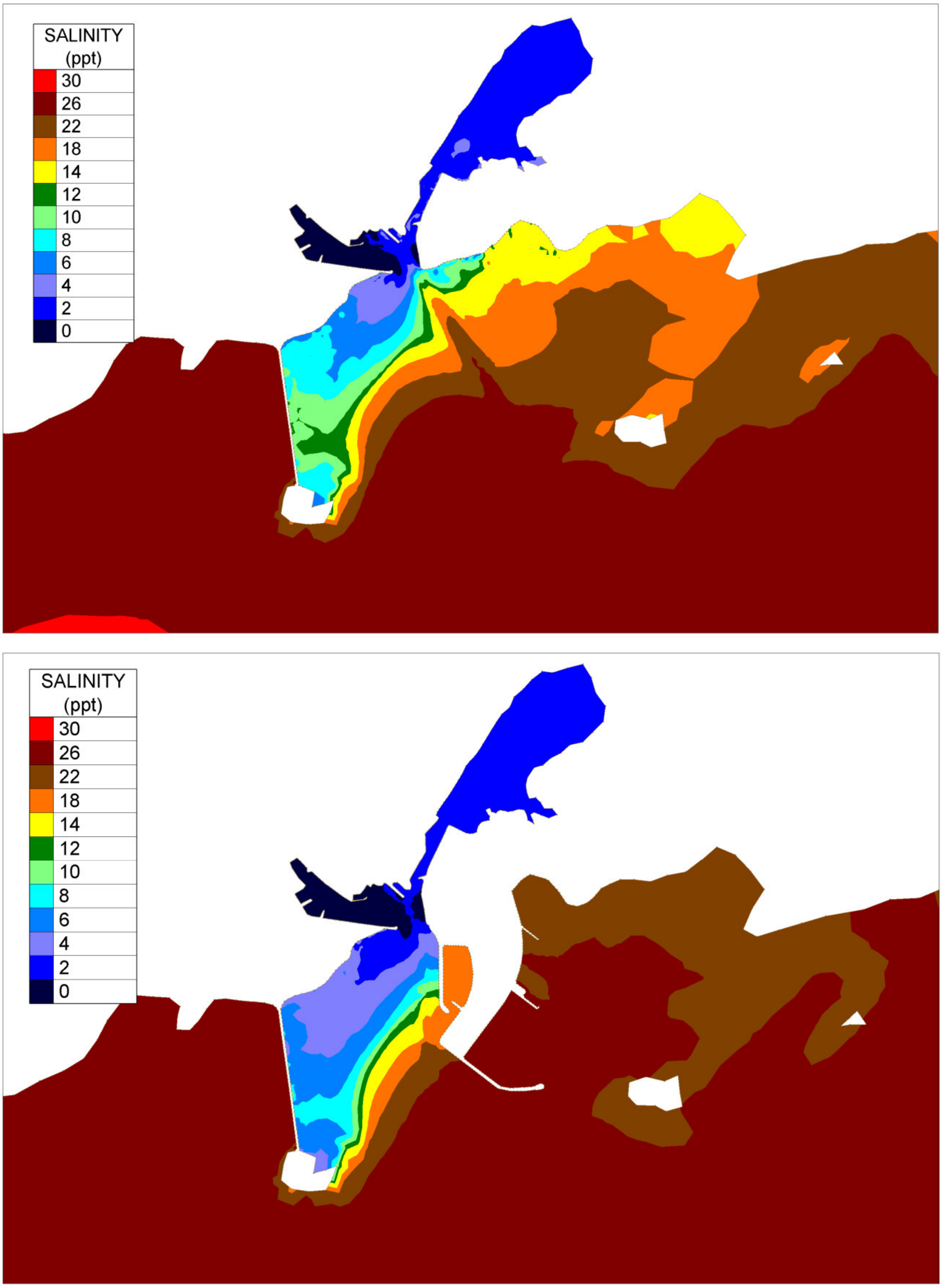
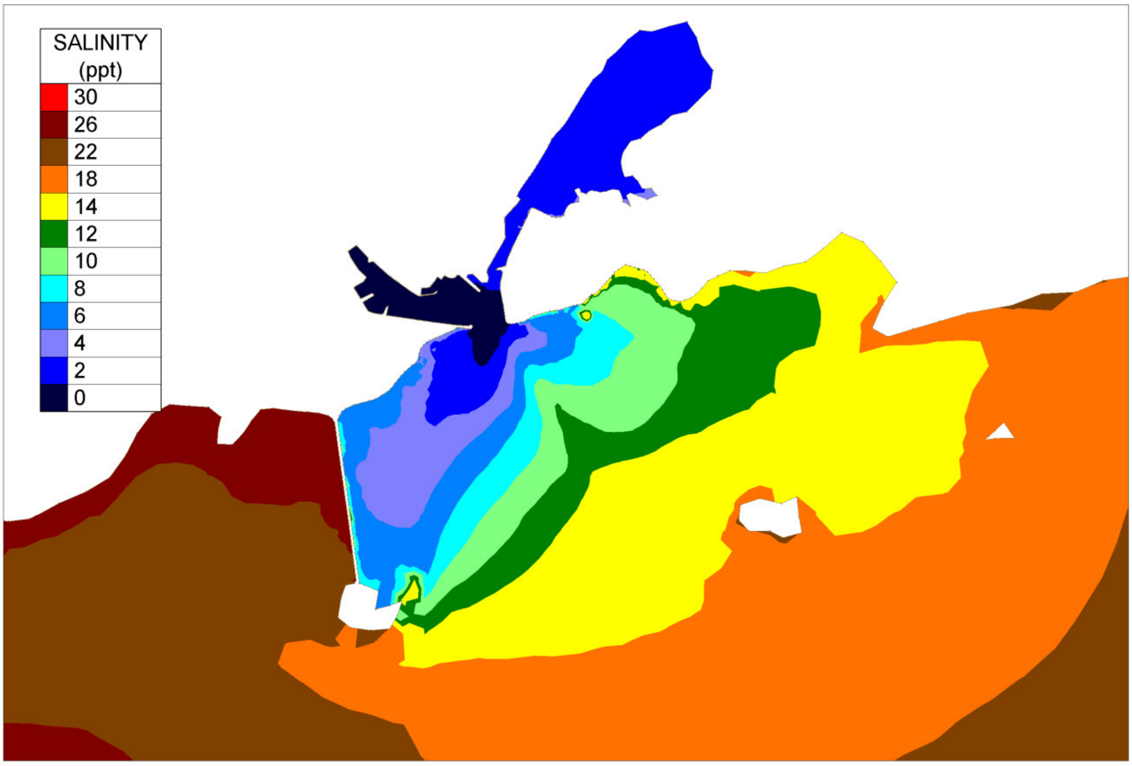


Figure 56 Mean Salinity concentration in mid-depth layer for existing and proposed cases under 10-percentile Corrib Flow (200cumec)



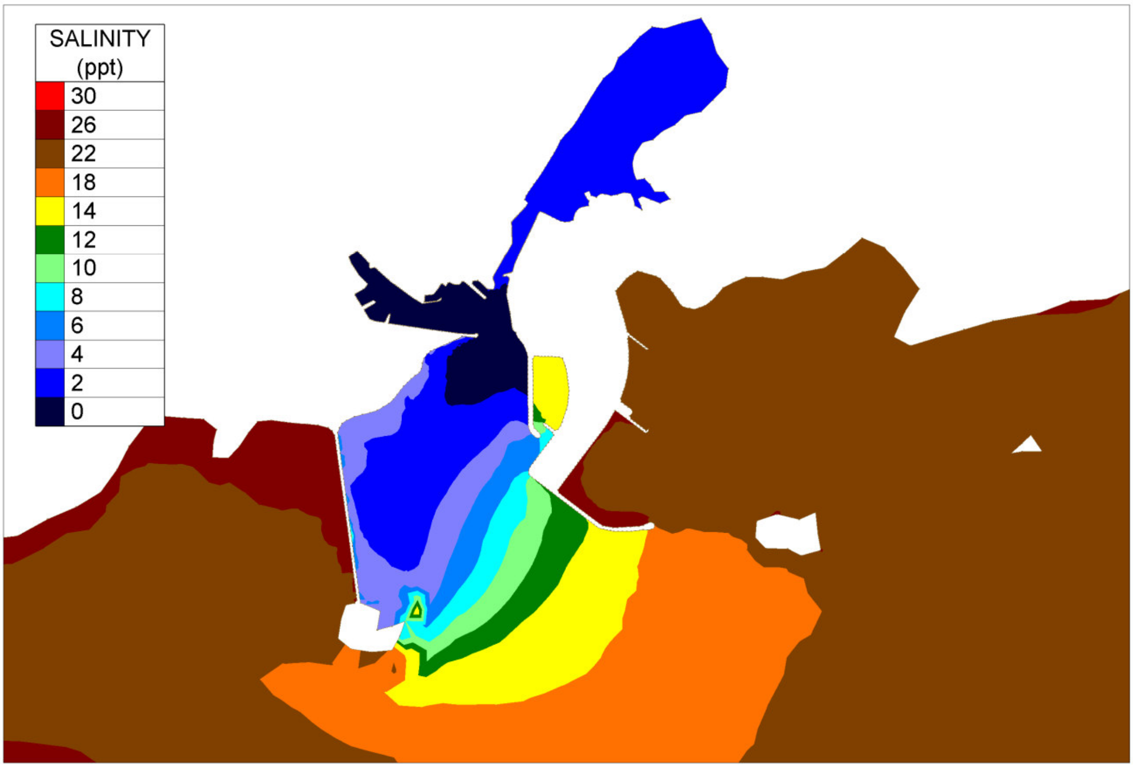
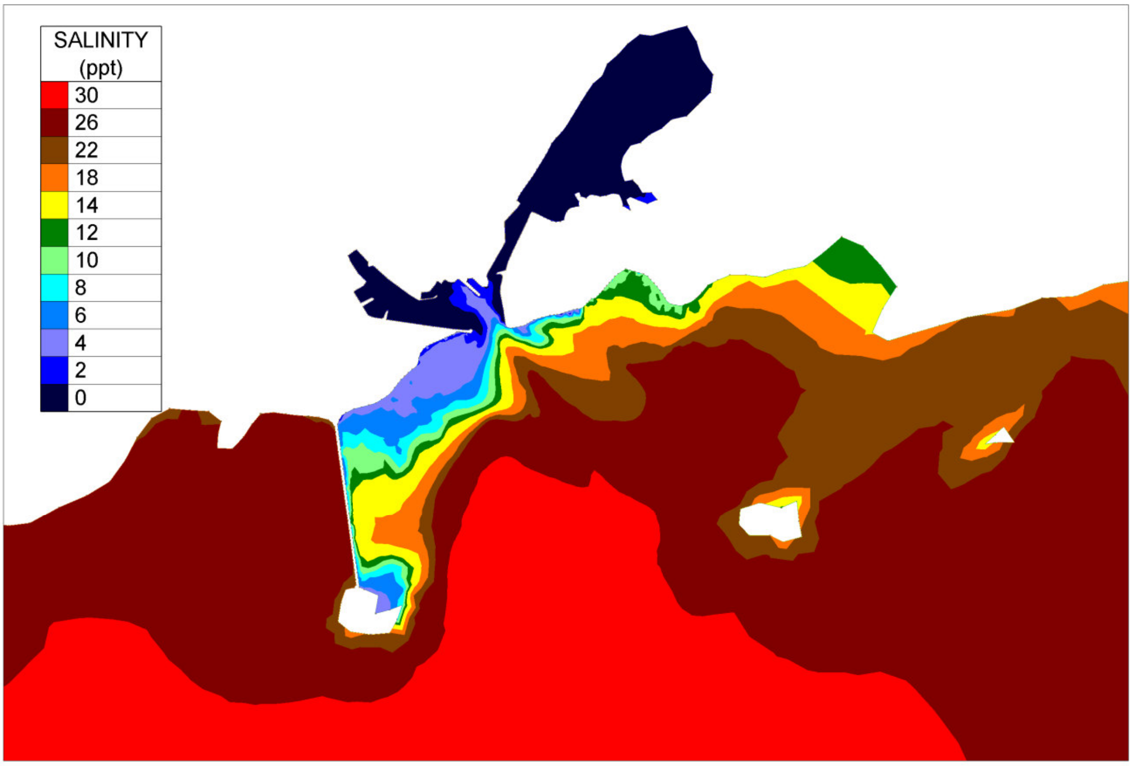


Figure 57 Mean Salinity concentration in surface layer for existing and proposed cases under 10-percentile Corrib Flow (200cumec)



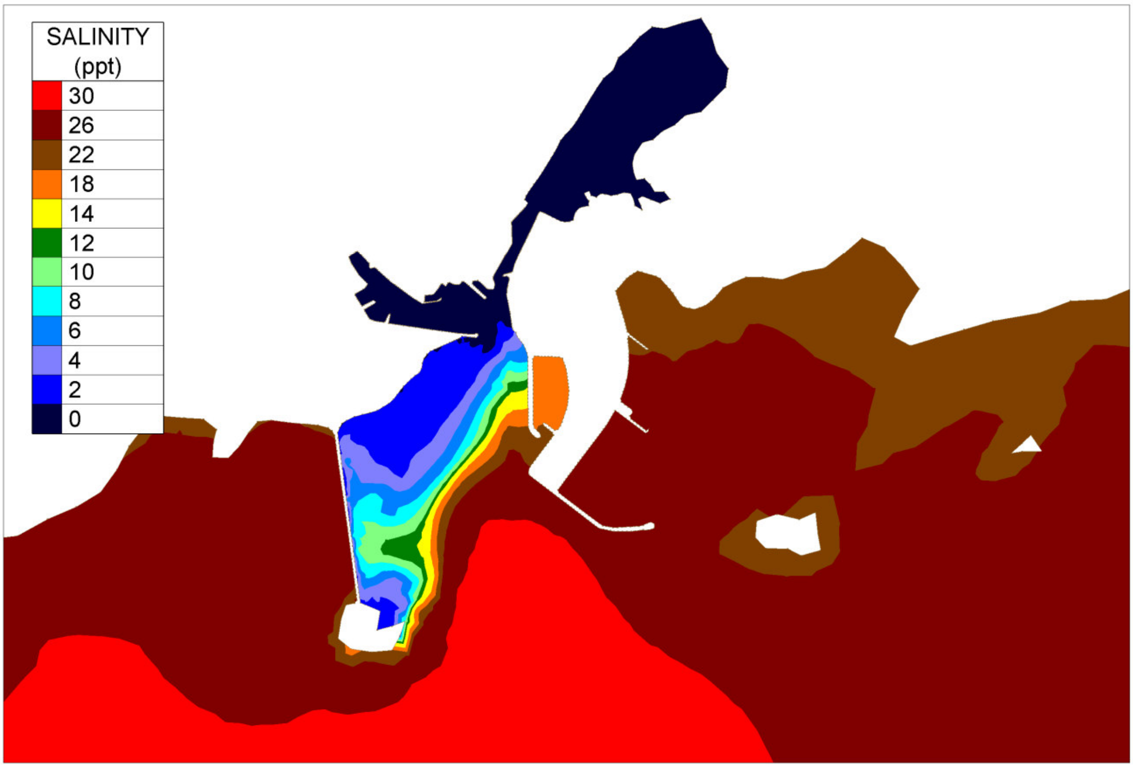
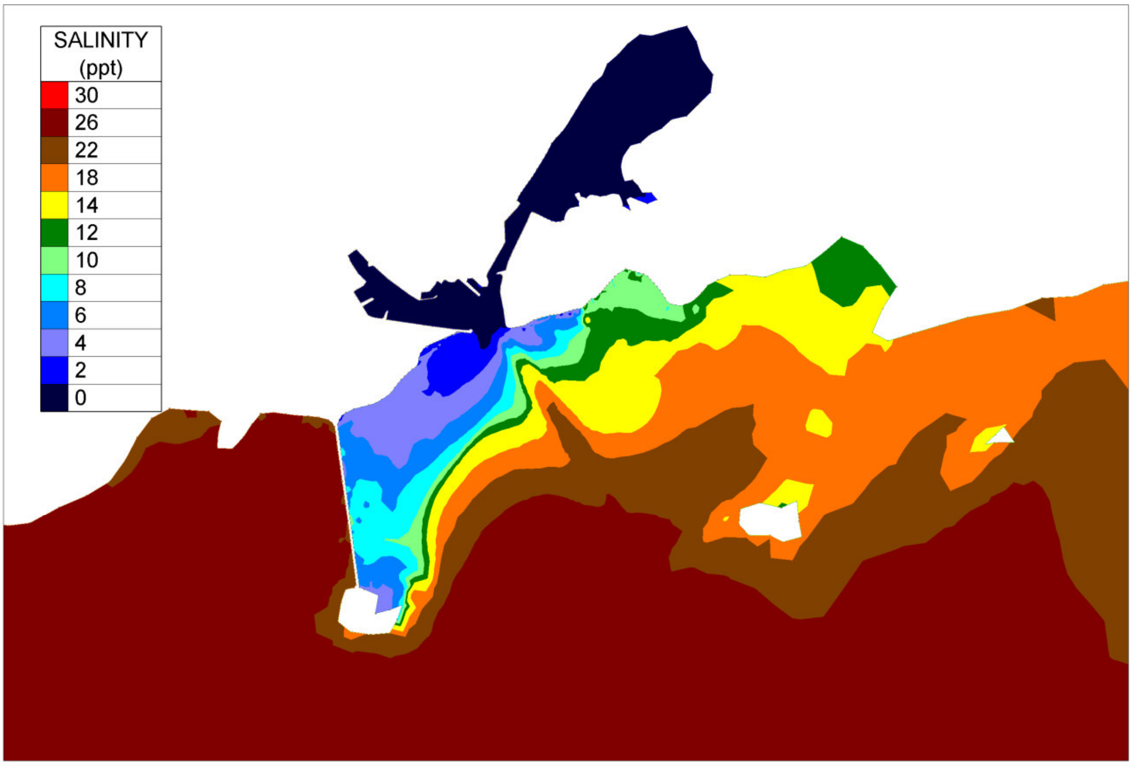


Figure 58 Mean Salinity concentration in bottom layer for existing and proposed cases under 1-percentile Corrib Flood Flow (272cumec)



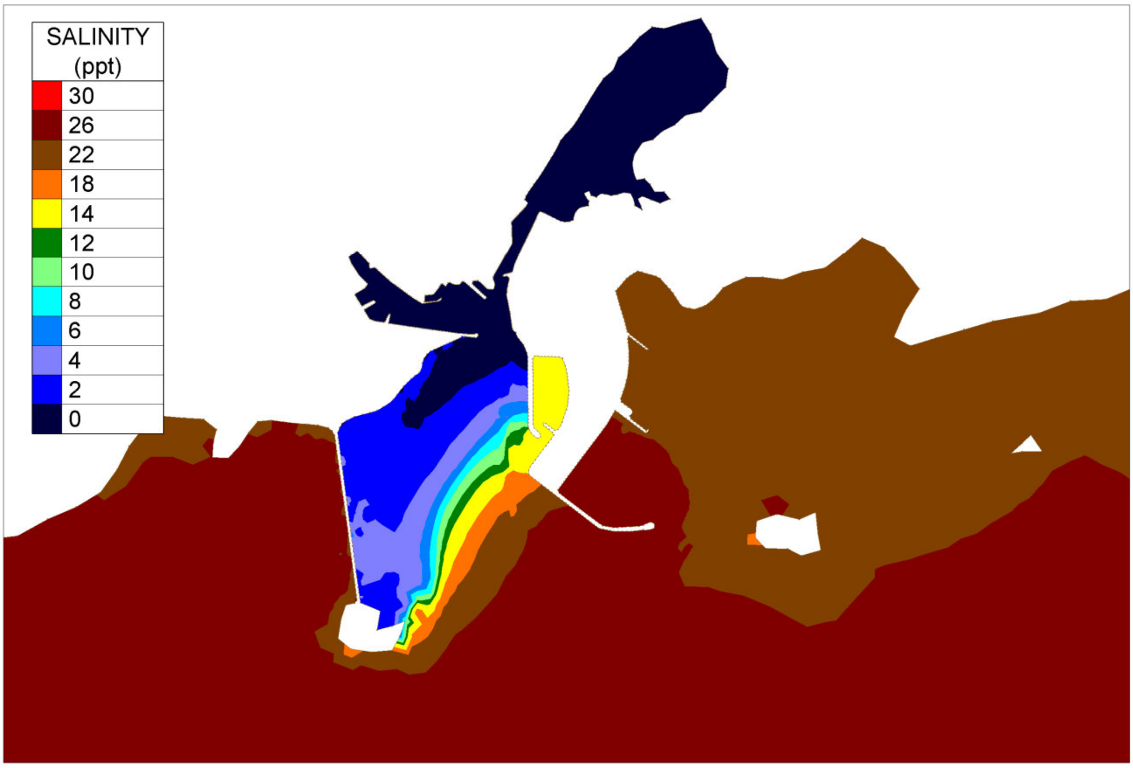


Figure 59 Mean Salinity concentration in mid-depth layer for existing and proposed cases under 1-percentile Corrib Flood Flow (272cumec)

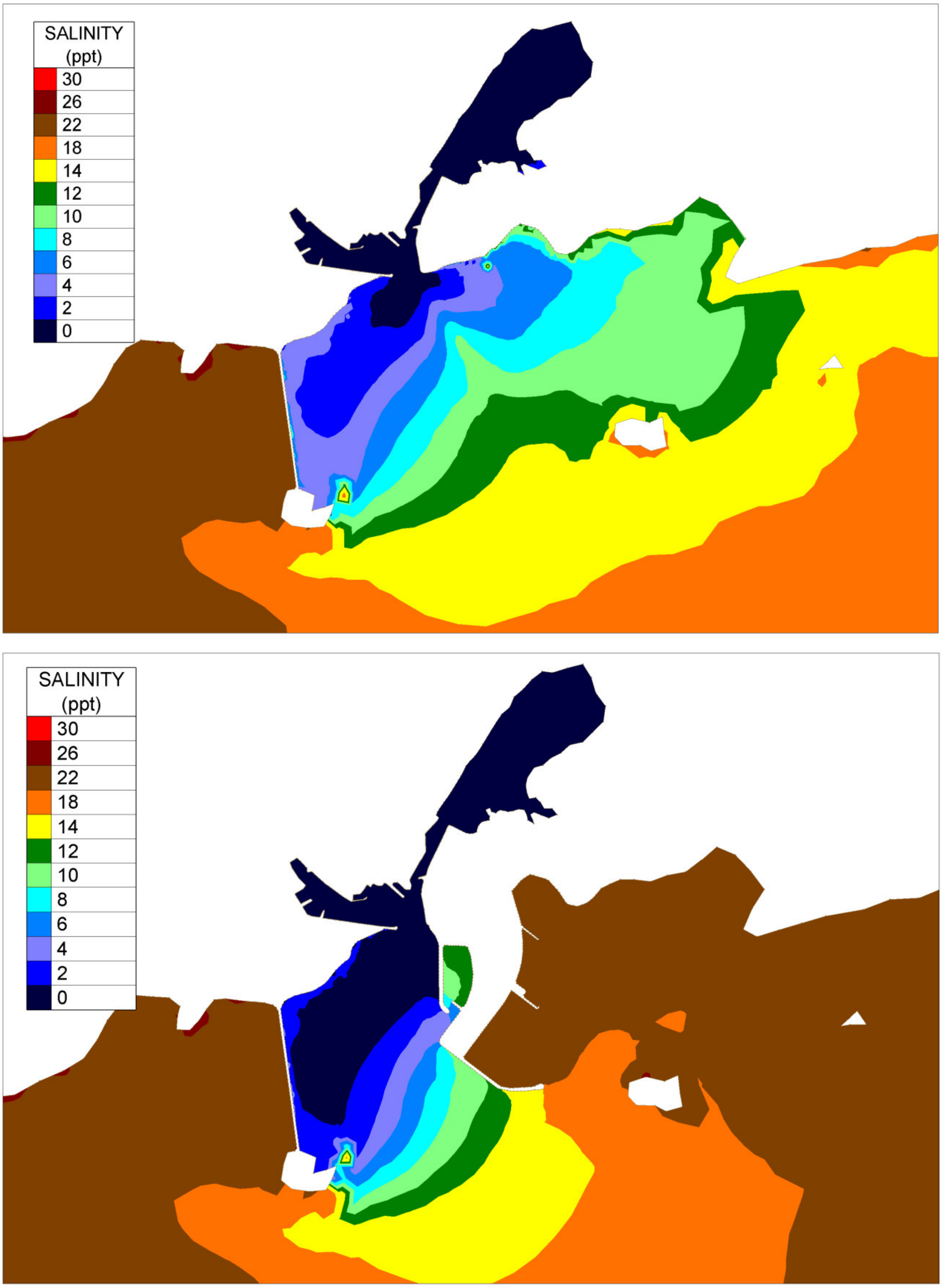


Figure 60 Mean Salinity concentration in surface layer for existing and proposed cases under 1-percentile Corrib Flood Flow (272cumec)

Table 4 Salinity Concentrations for neap to spring tides under 99-percentile low flow in Corrib – Existing Case (without development)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	32.31	29.74	30.81	32.71	32.16	32.48	32.87	32.58	32.75
2	32.02	30.27	30.91	32.64	31.86	32.34	32.8	32.19	32.63
3	31.31	29.2	30.28	32.39	31.44	32.01	32.76	32.08	32.52
4	32.03	29.28	30.54	32.03	30.75	31.42	32.25	31.4	31.9
5	30.99	26.39	29.41	31.91	29.05	31.1	32.43	29.5	31.77
6	30.69	25.22	27.89	32.43	30.18	31.88	32.79	32.22	32.62
7	25.76	15.58	21.31	31.54	26.64	30.2	32.51	29.96	31.94
8	29.17	21.98	26.03	30.62	25.56	27.76	31.83	25.57	28.44
9	29.39	25.5	27.2	29.41	25.62	27.31	29.44	25.89	27.45
10	29.1	26.13	27.12	29.11	26.2	27.25	29.15	26.36	27.48
11	29.09	26.29	27.22	29.09	26.28	27.29	29.09	26.28	27.32
12	28.26	26.64	27.25	28.27	26.65	27.29	28.29	26.66	27.31

Table 5 Salinity Concentrations (ppt) for neap to spring tides under 99-percentile low flow in Corrib – Proposed Case (with Harbour Extension)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	32.02	29.58	30.4	32.64	32.16	32.47	32.87	32.49	32.76
2	32.38	30.51	31.65	32.58	31.87	32.35	32.75	32.15	32.53
3	32.12	31.53	31.88	32.56	32.07	32.31	32.64	32.12	32.43
4	32.19	31.7	31.94	32.21	32.03	32.11	32.27	32.06	32.17
5	32.14	31.87	32.05	32.22	32.08	32.14	32.31	32.09	32.2
6	29.92	23.45	26.91	32.25	28.82	31.45	32.8	31.82	32.64
7	25.71	14.43	20.45	31.08	25.09	29.61	32.37	28.88	31.78
8	28.76	21.19	25.43	30.27	24.97	27.2	31.65	24.9	27.96
9	28.98	24.8	26.62	29.01	24.91	26.75	29.05	25.22	26.89
10	28.66	25.47	26.52	28.7	25.55	26.67	28.75	25.72	26.91
11	28.65	25.64	26.62	28.66	25.64	26.69	28.65	25.64	26.72
12	27.73	26.01	26.64	27.74	26.02	26.68	27.77	26.04	26.7

Table 6 Difference in Salinities (ppt) between the Existing and Proposed Case for neap to spring tides under 99-percentile low flow in Corrib

Reference Sites	Surface Layer (5)	Mid depth Layer (3)	Bottom Layer (1)	Depth averaged
1	-0.41	-0.01	0.01	-0.14
2	0.74	0.01	-0.1	0.22
3	1.6	0.3	-0.09	0.60
4	1.4	0.69	0.27	0.79
5	2.64	1.04	0.43	1.37
6	-0.98	-0.43	0.02	-0.46
7	-0.86	-0.59	-0.16	-0.54
8	-0.6	-0.56	-0.48	-0.55
9	-0.58	-0.56	-0.56	-0.57
10	-0.6	-0.58	-0.57	-0.58
11	-0.6	-0.6	-0.6	-0.60
12	-0.61	-0.61	-0.61	-0.61

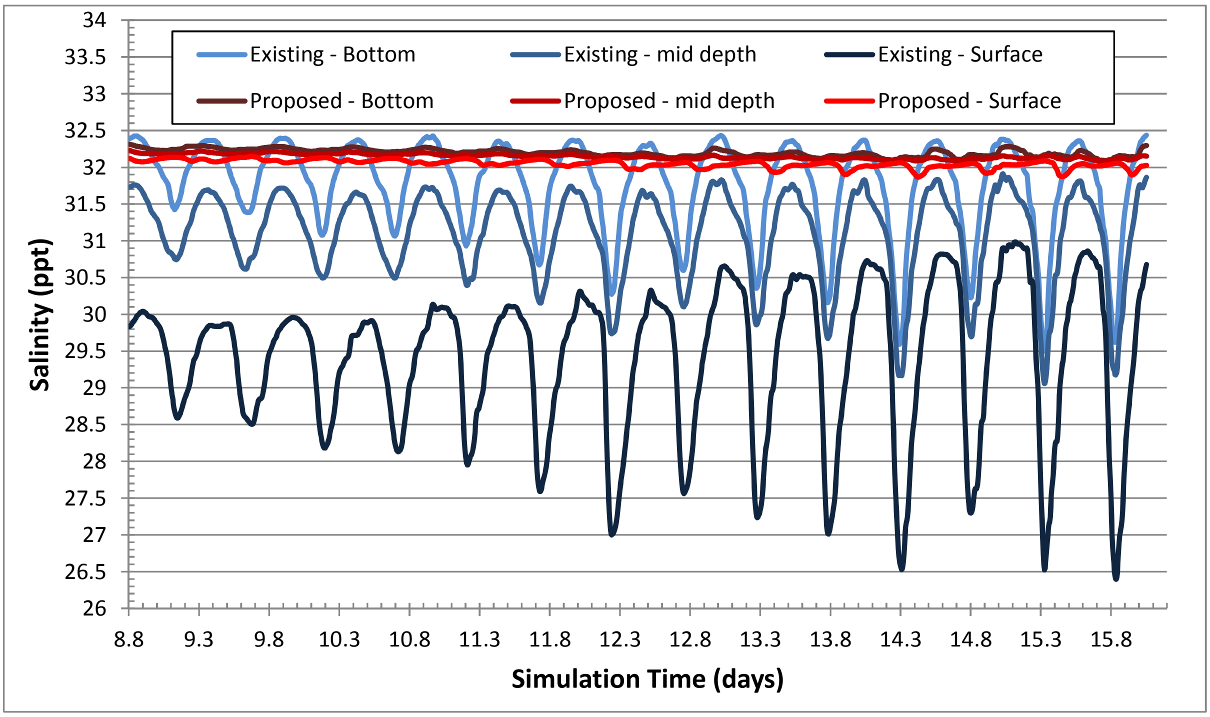


Figure 61 Time Series Output of Salinities for Site 5 existing and Proposed Cases neap to spring tide under 99-percentile Low Flow

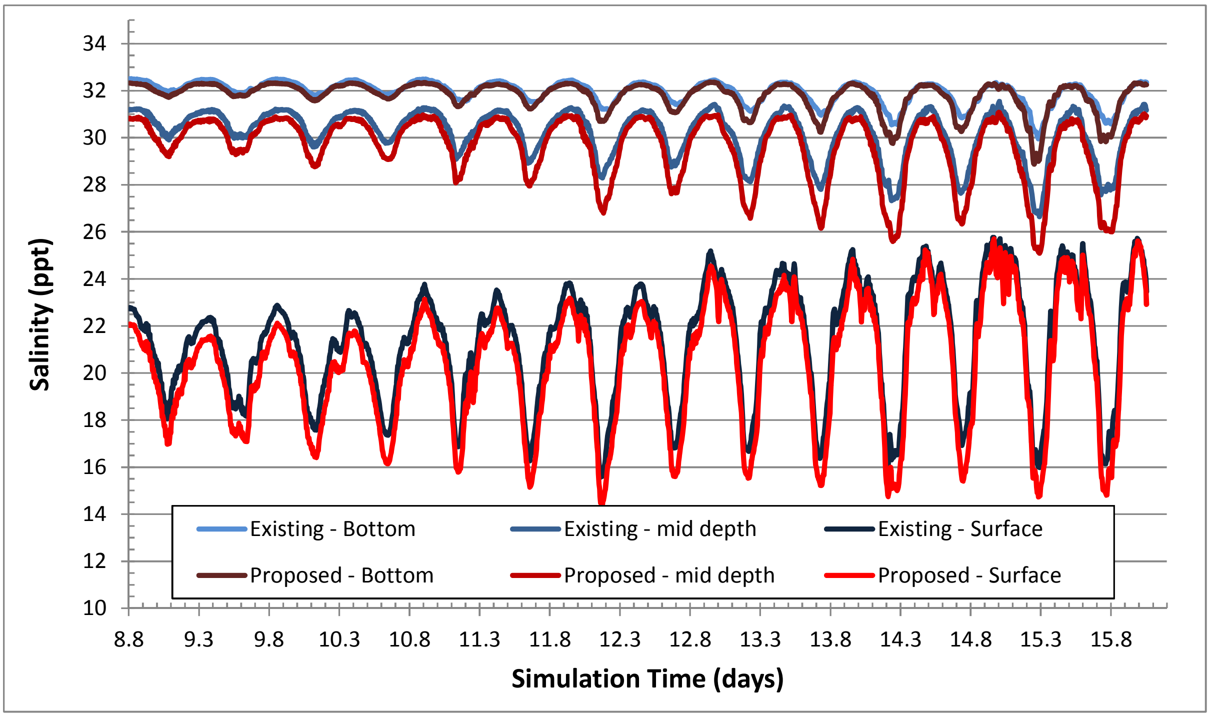


Figure 62 Time Series Output of Salinities for Site 7 Existing and Proposed cases neap to spring tide under 99-percentile Low Flow

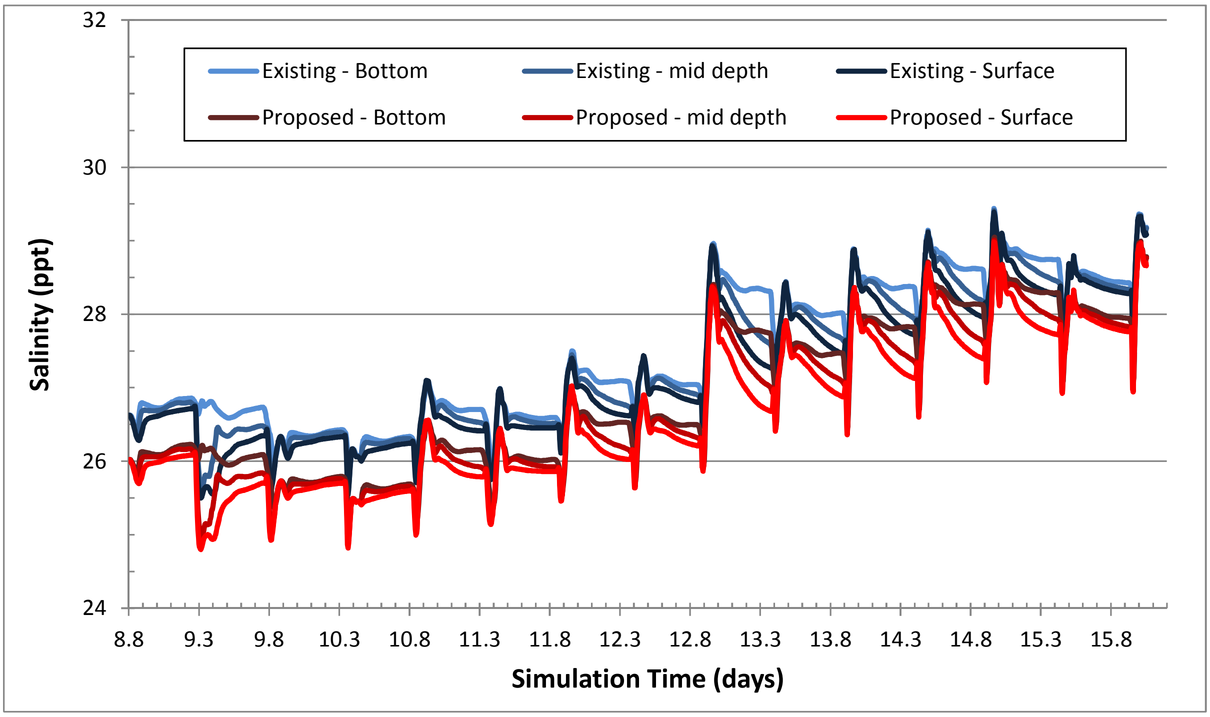


Figure 62 Time Series Output of Salinities for Site 9 in Lough Atalia Existing and Proposed cases neap to spring tide under 99-percentile Low Flow

Table 7 Salinity Concentrations for neap to spring tides under 90-percentile flow in Corrib – Existing Case (without development)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	30.76	25.73	27.45	32.37	31.50	32.10	32.85	32.31	32.70
2	29.41	25.83	27.31	32.11	30.24	31.58	32.72	31.25	32.42
3	28.88	23.62	26.36	31.85	29.56	30.91	32.62	31.22	32.18
4	30.37	24.03	26.84	30.60	27.02	29.01	31.74	28.69	30.49
5	28.09	19.37	24.67	30.75	23.45	28.49	32.06	24.22	30.21
6	26.48	15.63	21.22	31.98	26.64	30.69	32.72	32.12	32.49
7	18.13	5.13	11.17	29.69	18.22	26.21	32.03	26.37	30.72
8	24.33	12.71	18.17	27.70	16.24	21.10	30.41	17.62	22.76
9	25.03	16.86	20.26	25.14	17.11	20.55	25.27	17.87	20.93
10	23.96	18.03	20.02	24.41	18.24	20.40	24.67	18.61	20.88
11	23.82	18.40	20.15	23.97	18.42	20.34	24.16	18.43	20.51
12	22.24	19.02	20.23	22.27	19.04	20.33	22.75	19.06	20.43

Table 8 Salinity Concentrations (ppt) for neap to spring tides under 90-percentile flow in Corrib – Proposed Case (with Harbour Extension)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	29.19	24.68	26.54	32.39	31.30	32.02	32.86	32.14	32.68
2	31.38	27.75	29.70	32.05	30.58	31.58	32.54	31.32	32.09
3	30.91	29.79	30.47	31.90	31.05	31.44	32.27	31.26	31.85
4	31.39	29.97	30.54	31.40	30.84	30.99	31.51	31.03	31.20
5	30.99	30.49	30.79	31.19	30.97	31.07	31.51	31.10	31.27
6	25.34	14.74	20.16	31.33	23.54	29.26	32.67	31.27	32.38
7	17.46	3.71	9.84	28.66	14.32	24.58	31.67	22.53	29.90
8	23.39	11.32	16.93	26.64	14.66	19.91	29.66	16.29	21.64
9	23.92	15.56	19.07	24.04	15.82	19.37	24.17	16.61	19.79
10	22.78	16.79	18.82	23.29	16.99	19.21	23.57	17.37	19.71
11	22.64	17.15	18.93	22.79	17.17	19.13	23.03	17.18	19.31
12	21.10	17.79	19.02	21.11	17.81	19.11	21.60	17.83	19.22

Table 9 Difference in Salinities (ppt) between the Existing and Proposed Case for neap to spring tides under 90-percentile flow in Corrib

Reference Sites	Surface Layer (5)	Mid depth Layer (3)	Bottom Layer (1)	Depth averaged
1	-0.91	-0.08	-0.02	-0.34
2	2.39	0	-0.33	0.69
3	4.11	0.53	-0.33	1.44
4	3.7	1.98	0.71	2.13
5	6.12	2.58	1.06	3.25
6	-1.06	-1.43	-0.11	-0.87
7	-1.33	-1.63	-0.82	-1.26
8	-1.24	-1.19	-1.12	-1.18
9	-1.19	-1.18	-1.14	-1.17
10	-1.2	-1.19	-1.17	-1.19
11	-1.22	-1.21	-1.2	-1.21
12	-1.21	-1.22	-1.21	-1.21

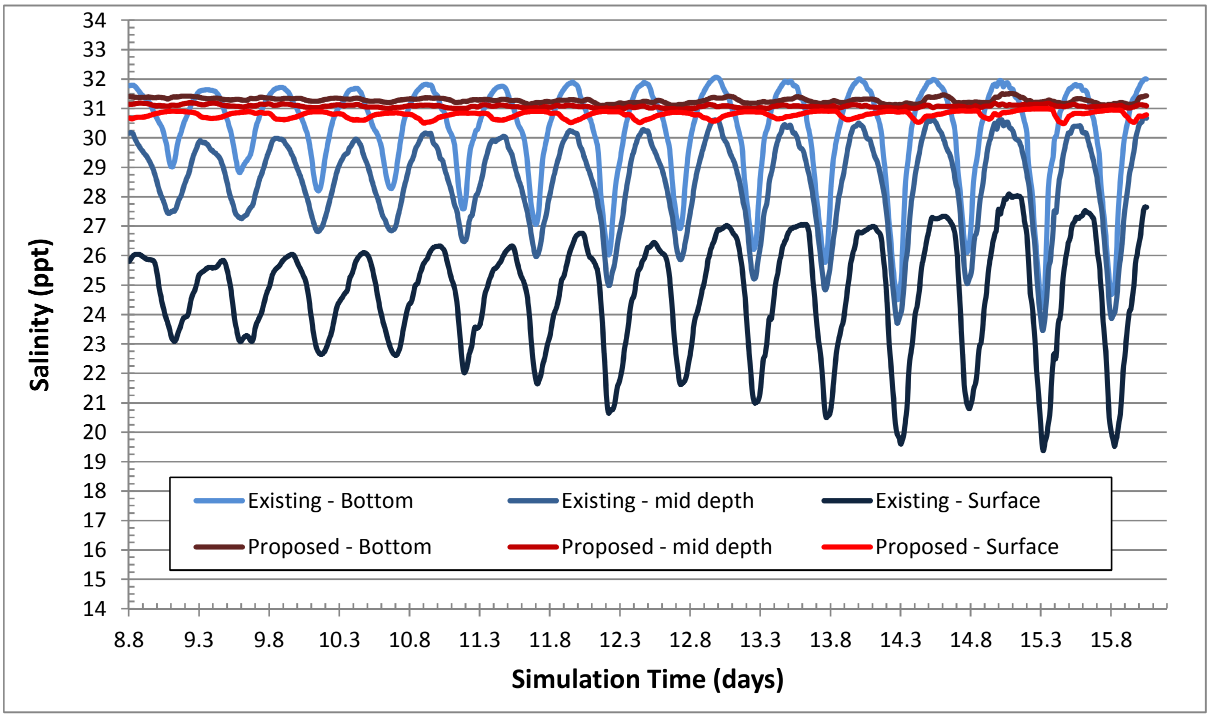


Figure 64 Time Series Output of Salinities for Site 5 existing and Proposed Cases neap to spring tide under 90-percentile Flow

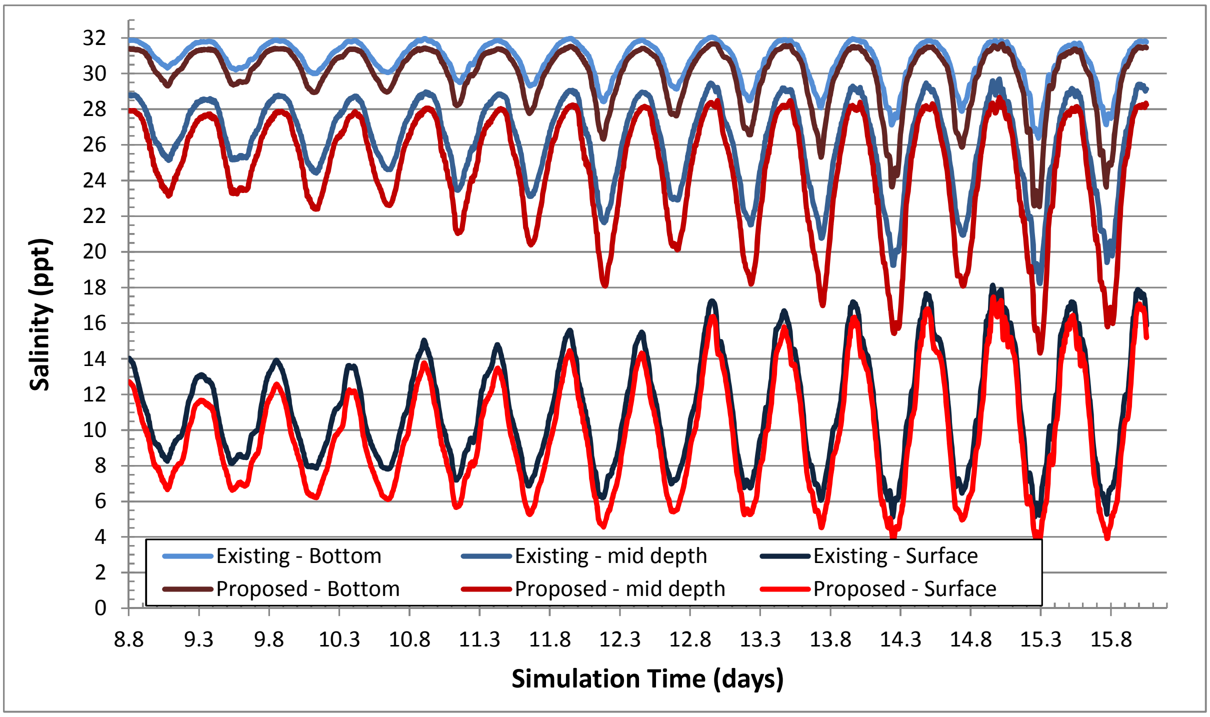


Figure 65 Time Series Output of Salinities for Site 7 Existing and Proposed cases neap to spring tide under 90-percentile Flow

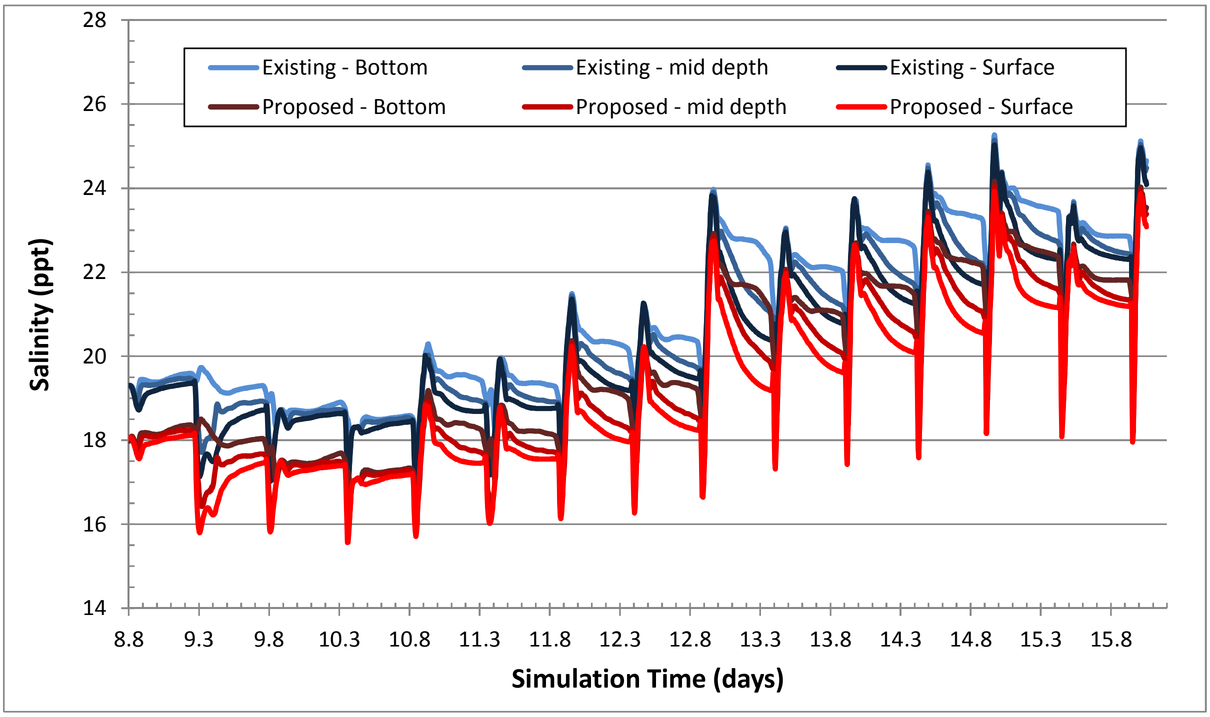


Figure 66 Time Series Output of Salinities for Site 9 in Lough Atalia Existing and Proposed cases neap to spring tide under 90-percentile Flow

Table 10 Salinity Concentrations for neap to spring tides under 50-percentile flow in Corrib – Existing Case (without development)

Reference Sites	Surface Layer (5) max	min	mean	Mid-depth Layer (3) max	min	mean	Bottom Layer (1) max	min	mean
1	27.46	19.80	22.33	31.13	29.70	30.62	31.89	31.14	31.67
2	25.07	19.68	22.25	30.62	27.29	29.54	31.62	29.35	31.17
3	24.40	16.00	20.82	30.20	25.23	28.28	31.39	28.77	30.70
4	24.80	16.92	21.42	27.99	20.65	24.72	30.29	22.32	27.47
5	23.29	10.97	18.43	28.34	15.31	23.99	30.63	16.39	27.02
6	21.07	8.05	14.40	30.28	20.29	27.39	31.70	30.72	31.35
7	10.51	0.99	4.16	25.15	4.14	17.79	30.41	15.58	27.27
8	16.95	4.29	9.42	21.28	6.55	11.95	26.78	7.95	14.34
9	18.02	7.28	11.19	18.19	7.49	11.58	18.40	8.23	12.17
10	16.39	8.41	10.83	17.21	8.64	11.37	17.66	9.03	12.04
11	15.80	8.79	10.92	16.11	8.83	11.19	16.66	8.84	11.51
12	13.90	9.48	11.04	14.02	9.51	11.18	14.88	9.54	11.35

Table 11 Salinity Concentrations (ppt) for neap to spring tides under 50-percentile flow in Corrib – Proposed Case (with Harbour Extension)

Reference Sites	Surface Layer (5) max	min	mean	Mid-depth Layer (3) max	min	mean	Bottom Layer (1) max	min	mean
1	25.10	18.13	21.06	31.14	29.17	30.43	31.90	30.85	31.62
2	29.05	24.00	26.22	30.57	28.06	29.54	31.35	29.34	30.55
3	28.54	26.45	27.65	30.00	28.77	29.29	30.78	29.26	30.11
4	29.36	26.83	27.84	29.38	28.29	28.58	29.81	28.70	29.06
5	28.65	27.62	28.16	29.05	28.48	28.70	29.77	28.79	29.15
6	19.32	7.53	13.32	29.27	16.45	24.65	31.63	28.75	30.95
7	9.56	0.17	3.13	23.82	0.83	14.39	29.86	1.15	24.30
8	15.68	3.16	8.07	19.60	4.95	10.42	25.81	6.37	12.74
9	16.39	5.79	9.68	16.56	6.01	10.08	16.78	6.74	10.69
10	14.75	6.92	9.32	15.59	7.15	9.85	16.04	7.55	10.53
11	14.18	7.31	9.40	14.48	7.35	9.68	15.02	7.35	9.99
12	12.31	8.02	9.52	12.41	8.05	9.66	13.25	8.08	9.82

Table 12 Difference in Salinities (ppt) between the Existing and Proposed Case for neap to spring tides under 50-percentile flow in Corrib

Reference Sites	Surface Layer (5)	Mid depth Layer (3)	Bottom Layer (1)	Depth averaged
1	-1.27	-0.19	-0.05	-0.50
2	3.97	0	-0.62	1.12
3	6.83	1.01	-0.59	2.42
4	6.42	3.86	1.59	3.96
5	9.73	4.71	2.13	5.52
6	-1.08	-2.74	-0.4	-1.41
7	-1.03	-3.4	-2.97	-2.47
8	-1.35	-1.53	-1.6	-1.49
9	-1.51	-1.5	-1.48	-1.50
10	-1.51	-1.52	-1.51	-1.51
11	-1.52	-1.51	-1.52	-1.52
12	-1.52	-1.52	-1.53	-1.52

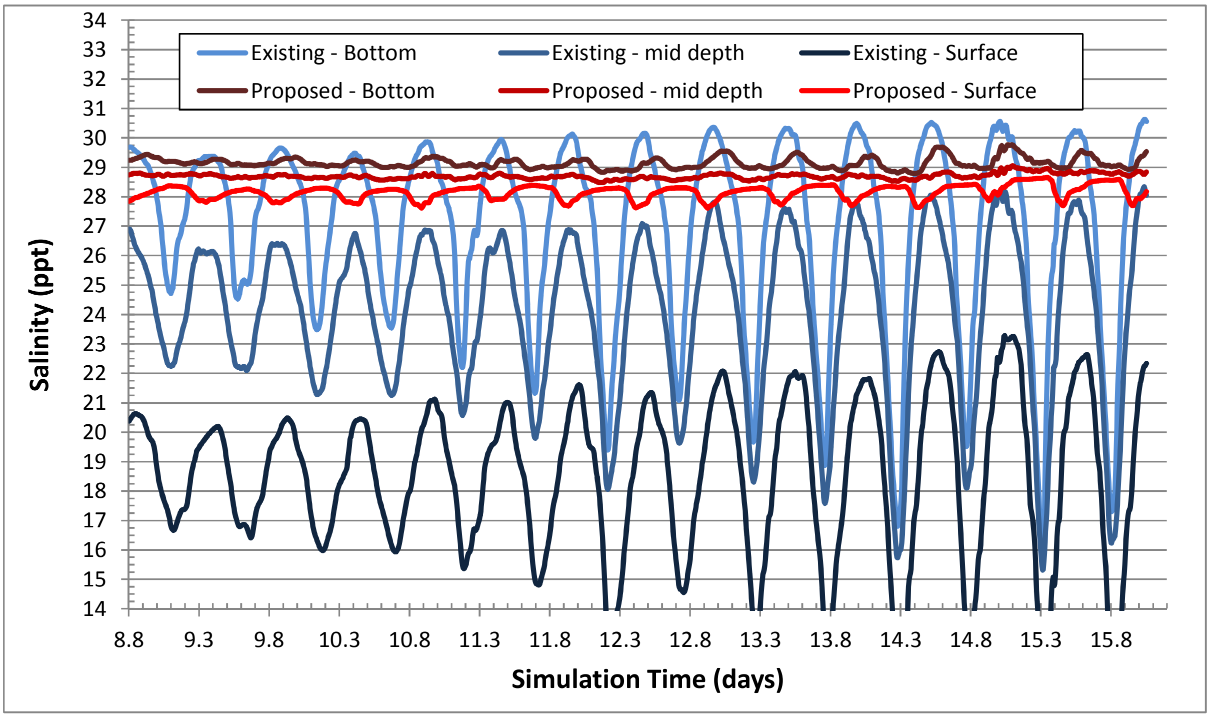


Figure 67 Time Series Output of Salinities for Site 5 existing and Proposed Cases neap to spring tide under 50-percentile Flow

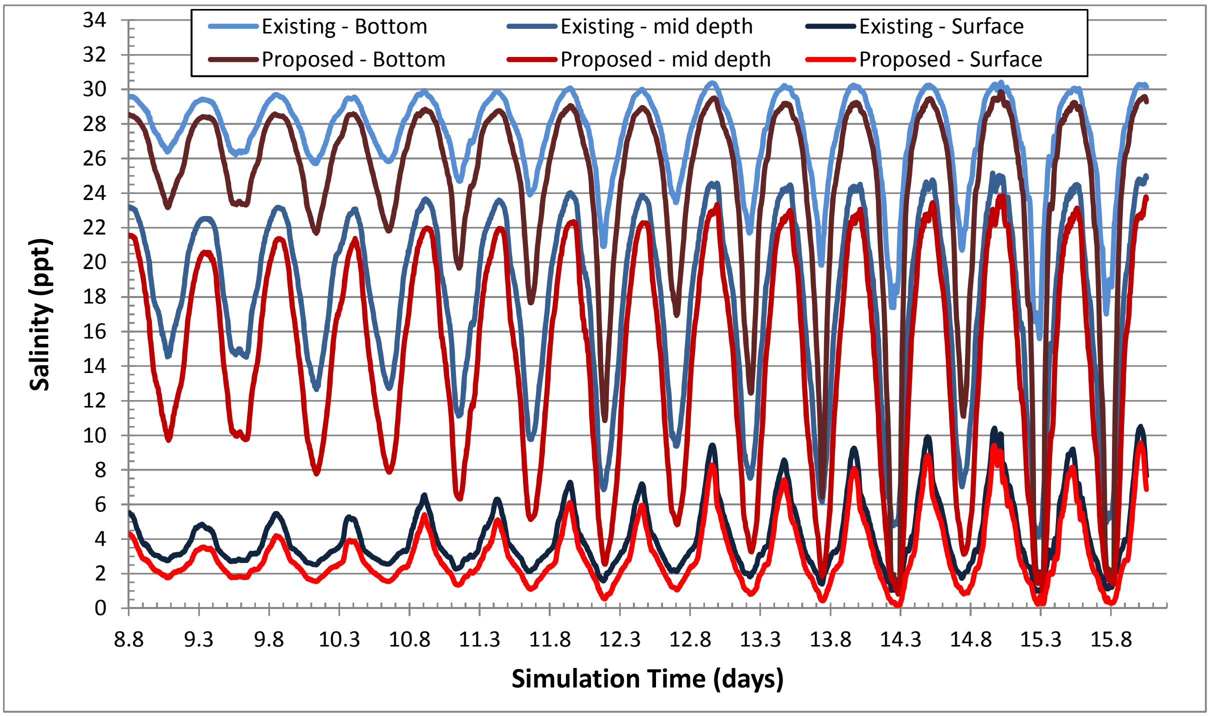


Figure 68 Time Series Output of Salinities for Site 7 Existing and Proposed cases neap to spring tide under 50-percentile Flow

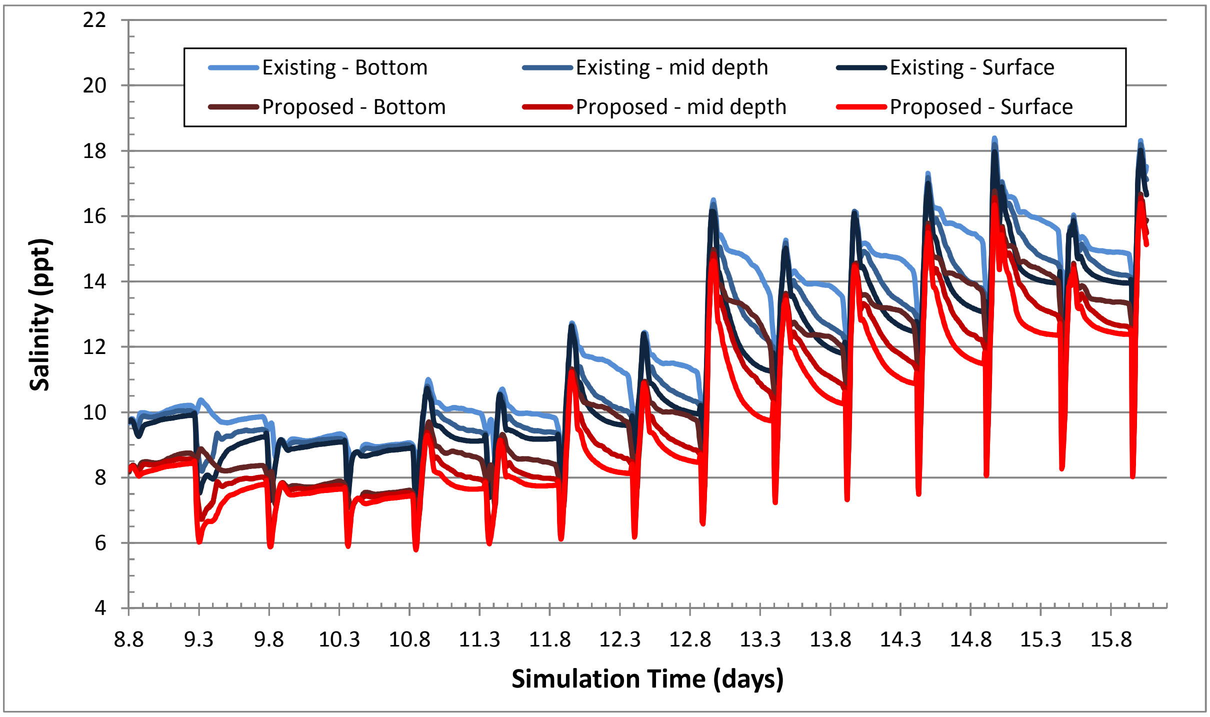


Figure 69 Time Series Output of Salinities for Site 9 in Lough Atalia Existing and Proposed cases neap to spring tide under 50-percentile Flow

Table 131 Salinity Concentrations for neap to spring tides under 10-percentile flow in Corrib – Existing Case (without development)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	21.66	12.44	15.62	29.64	27.37	28.91	30.91	29.76	30.56
2	20.06	10.82	16.26	28.59	22.61	26.71	30.61	27.52	29.82
3	17.98	6.36	13.28	27.88	16.61	23.92	30.12	24.37	28.96
4	18.12	6.52	13.77	23.99	10.43	18.28	28.23	13.84	22.72
5	16.99	1.90	10.49	24.32	3.67	16.90	28.69	4.50	21.61
6	14.50	2.82	8.04	27.41	11.86	21.06	30.65	28.21	30.12
7	3.51	0.00	0.81	15.31	0.02	4.44	27.66	0.05	14.34
8	7.06	0.66	3.09	10.43	1.13	3.89	18.85	1.98	5.34
9	8.00	1.62	3.68	8.13	1.70	3.89	8.31	1.99	4.18
10	6.95	2.27	3.50	7.56	2.38	3.76	7.89	2.62	4.13
11	6.35	2.50	3.56	6.63	2.50	3.68	7.07	2.50	3.78
12	4.97	2.88	3.61	4.99	2.89	3.66	5.46	2.90	3.72

Table 14 Salinity Concentrations (ppt) for neap to spring tides under 10-percentile flow in Corrib – Proposed Case (with Harbour Extension)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	max	min	mean	max	min	mean	max	min	mean
1	19.46	10.38	14.31	29.68	26.14	28.39	30.89	29.61	30.50
2	25.62	18.40	21.57	28.61	24.78	26.83	30.09	26.72	28.71
3	25.45	22.11	23.88	27.47	25.73	26.44	29.12	26.64	27.96
4	26.51	22.89	24.30	26.63	24.92	25.37	27.52	25.54	26.24
5	25.65	23.75	24.71	26.35	25.21	25.58	27.63	25.67	26.38
6	12.08	0.97	6.68	25.54	5.14	16.59	30.55	20.17	28.73
7	2.74	0.00	0.44	12.30	0.00	2.35	25.90	0.01	9.12
8	5.82	0.09	2.09	8.34	0.25	2.63	16.41	0.74	3.71
9	6.36	0.61	2.42	6.46	0.67	2.63	6.56	0.83	2.92
10	5.42	1.08	2.24	5.97	1.17	2.48	6.30	1.41	2.84
11	4.89	1.28	2.30	5.10	1.29	2.40	5.46	1.29	2.48
12	3.55	1.69	2.35	3.55	1.71	2.39	3.90	1.71	2.44

Table 15 Difference in Salinities (ppt) between the Existing and Proposed Case for neap to spring tides under 10-percentile flow in Corrib

Reference Sites	Surface Layer (5)	Mid depth Layer (3)	Bottom Layer (1)	Depth averaged
1	-1.31	-0.52	-0.06	-0.63
2	5.31	0.12	-1.11	1.44
3	10.6	2.52	-1	4.04
4	10.53	7.09	3.52	7.05
5	14.22	8.68	4.77	9.22
6	-1.36	-4.47	-1.39	-2.41
7	-0.37	-2.09	-5.22	-2.56
8	-1	-1.26	-1.63	-1.30
9	-1.26	-1.26	-1.26	-1.26
10	-1.26	-1.28	-1.29	-1.28
11	-1.26	-1.28	-1.3	-1.28
12	-1.26	-1.27	-1.28	-1.27

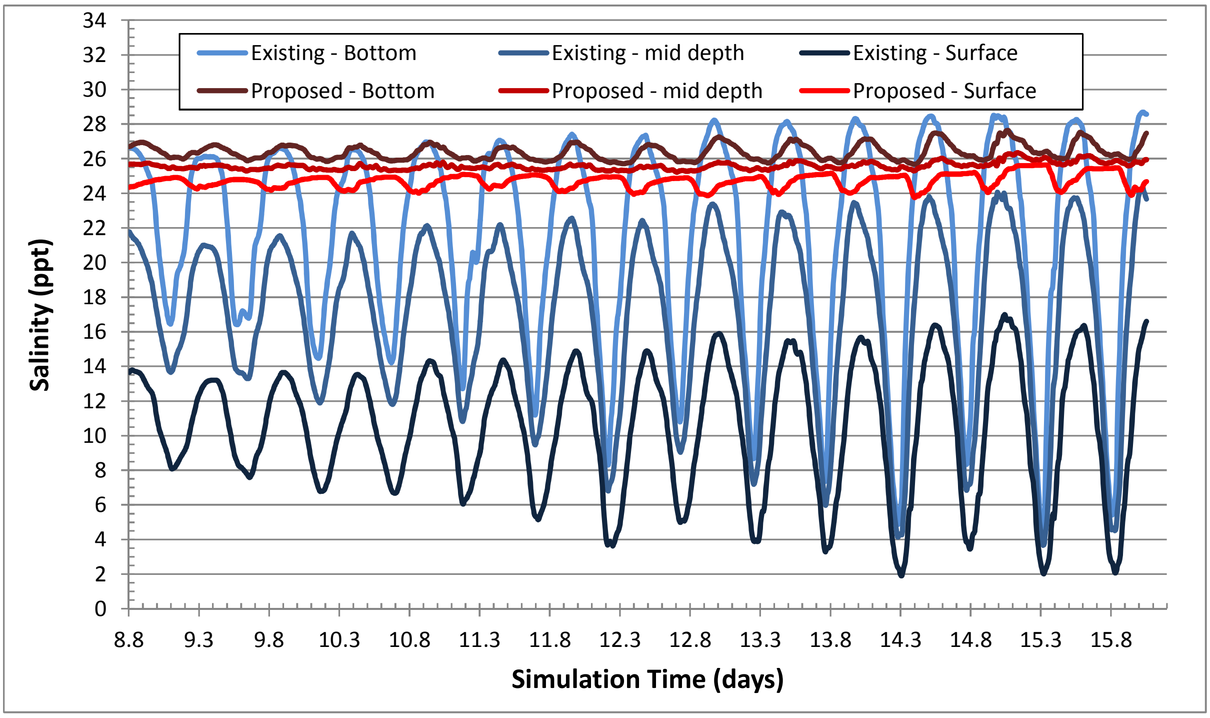


Figure 70 Time Series Output of Salinities for Site 5 existing and Proposed Cases neap to spring tide under 10-percentile Flow

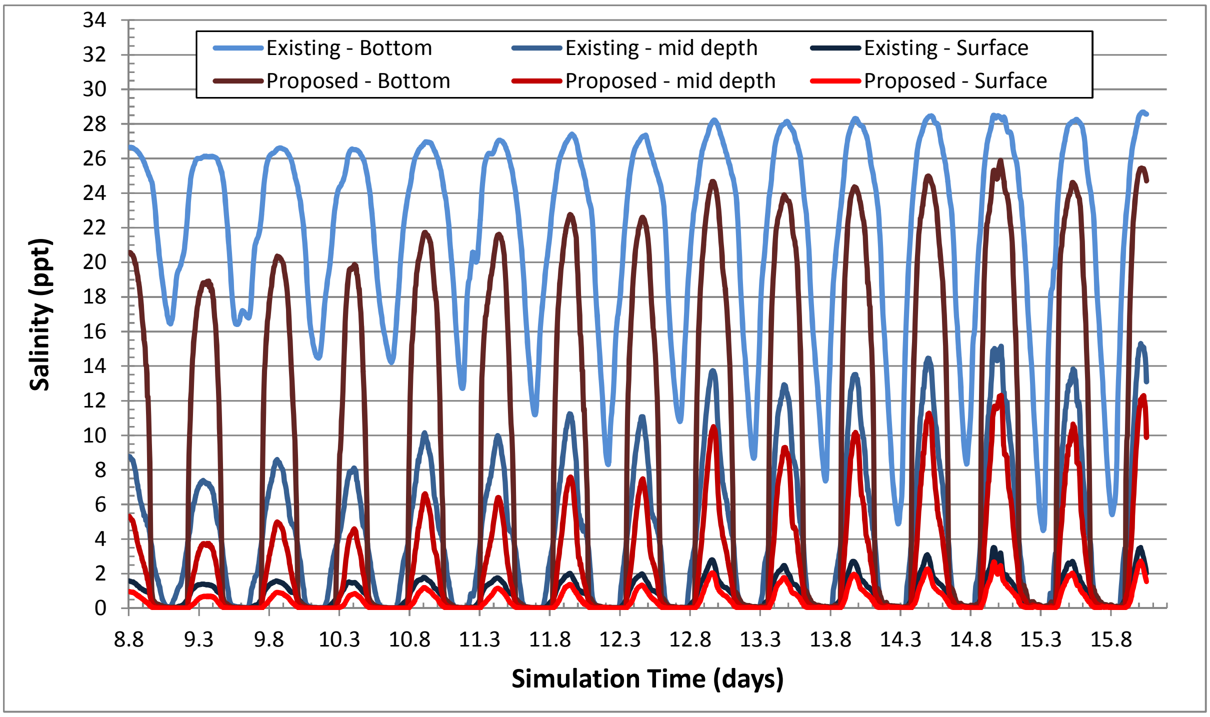


Figure 71 Time Series Output of Salinities for Site 7 Existing and Proposed cases neap to spring tide under 10-percentile Flow

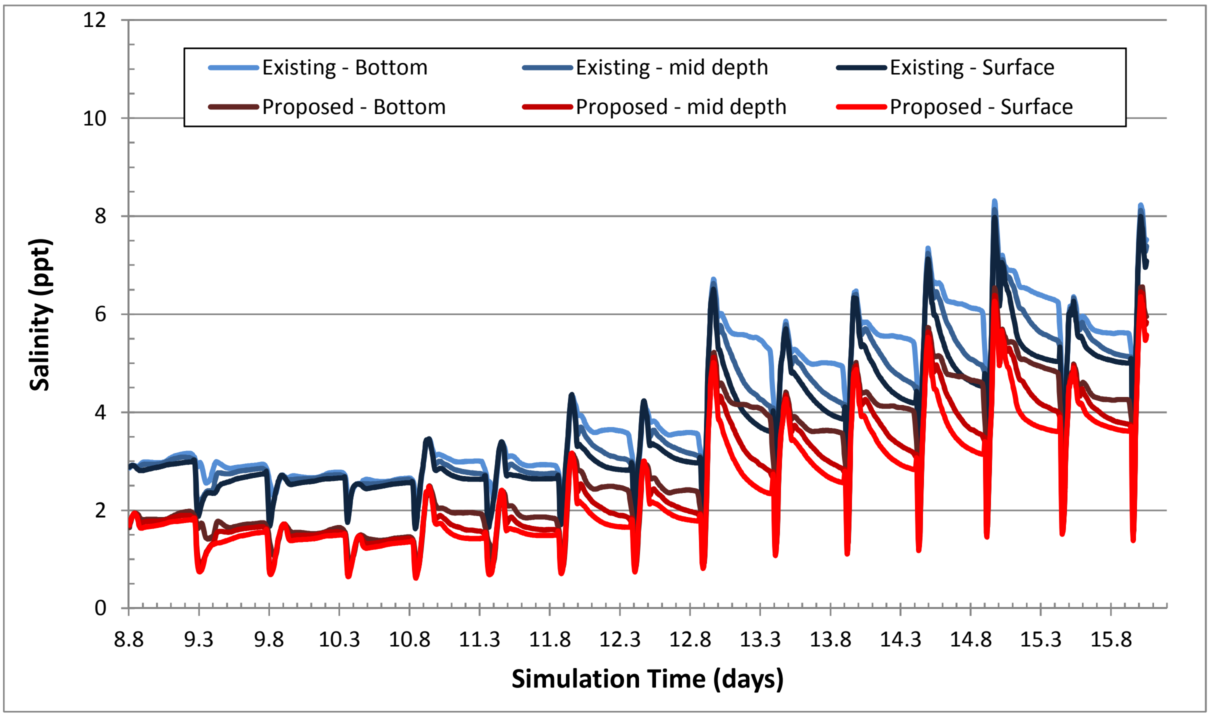


Figure 72 Time Series Output of Salinities for Site 9 in Lough Atalia Existing and Proposed cases neap to spring tide under 10-percentile Flow

Table 16 Salinity Concentrations for neap to spring tides under 1-percentile flood flow in Corrib – Existing Case (without development)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**
1	17.80	10.43	13.47	29.34	26.69	28.56	30.91	29.65	30.50
2	17.78	7.35	13.51	28.01	20.42	25.83	30.47	27.67	29.74
3	15.60	3.38	10.09	26.88	12.51	21.48	30.12	22.59	28.78
4	15.74	4.41	10.25	22.31	6.72	15.08	27.32	9.93	20.37
5	14.61	1.75	7.17	22.27	3.23	13.24	27.88	3.92	18.74
6	12.25	1.57	6.51	25.87	8.28	18.61	30.63	26.01	29.87
7	1.97	0.00	0.26	9.52	0.00	1.53	25.82	0.00	7.36
8	4.48	0.04	1.49	6.53	0.08	1.78	13.60	0.27	2.45
9	5.09	0.31	1.63	5.20	0.33	1.80	5.34	0.38	2.05
10	4.27	0.61	1.48	4.74	0.65	1.68	5.06	0.81	1.98
11	3.82	0.72	1.52	4.00	0.73	1.60	4.41	0.73	1.66
12	2.56	1.04	1.56	2.56	1.04	1.59	2.86	1.04	1.63

Table 17 Salinity Concentrations (ppt) for neap to spring tides under 1-percentile flood flow in Corrib – Proposed Case (with Harbour Extension)

Reference	Surface Layer (5)			Mid-depth Layer (3)			Bottom Layer (1)		
Sites	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**
1	16.63	8.25	11.97	29.34	24.72	27.71	30.89	29.31	30.43
2	24.42	16.68	19.87	27.72	23.54	25.94	29.91	25.78	28.25
3	24.32	20.72	22.56	26.53	24.70	25.49	28.86	25.73	27.35
4	25.60	21.62	23.10	25.63	23.78	24.25	26.69	24.44	25.27
5	24.53	22.44	23.52	25.43	24.13	24.52	26.85	24.60	25.48
6	9.59	0.11	4.73	23.12	0.46	12.99	30.38	3.12	26.94
7	1.25	0.00	0.09	6.32	0.00	0.51	22.52	0.00	3.03
8	3.24	0.00	0.64	4.44	0.00	0.78	9.91	0.00	1.09
9	3.54	0.02	0.66	3.63	0.02	0.78	3.72	0.02	0.94
10	2.62	0.08	0.57	3.11	0.08	0.68	3.43	0.11	0.87
11	2.29	0.14	0.60	2.41	0.14	0.63	2.74	0.14	0.65
12	1.22	0.29	0.62	1.21	0.29	0.63	1.31	0.29	0.65

Table 18 Difference in Salinities (ppt) between the Existing and Proposed Case for neap to spring tides under 1-percentile flood flow in Corrib

Reference Sites	Surface Layer (5)	Mid depth Layer (3)	Bottom Layer (1)	Depth averaged
1	-1.5	-0.85	-0.07	-0.81
2	6.36	0.11	-1.49	1.66
3	12.47	4.01	-1.43	5.02
4	12.85	9.17	4.9	8.97
5	16.35	11.28	6.74	11.46
6	-1.78	-5.62	-2.93	-3.44
7	-0.17	-1.02	-4.33	-1.84
8	-0.85	-1	-1.36	-1.07
9	-0.97	-1.02	-1.11	-1.03
10	-0.91	-1	-1.11	-1.01
11	-0.92	-0.97	-1.01	-0.97
12	-0.94	-0.96	-0.98	-0.96

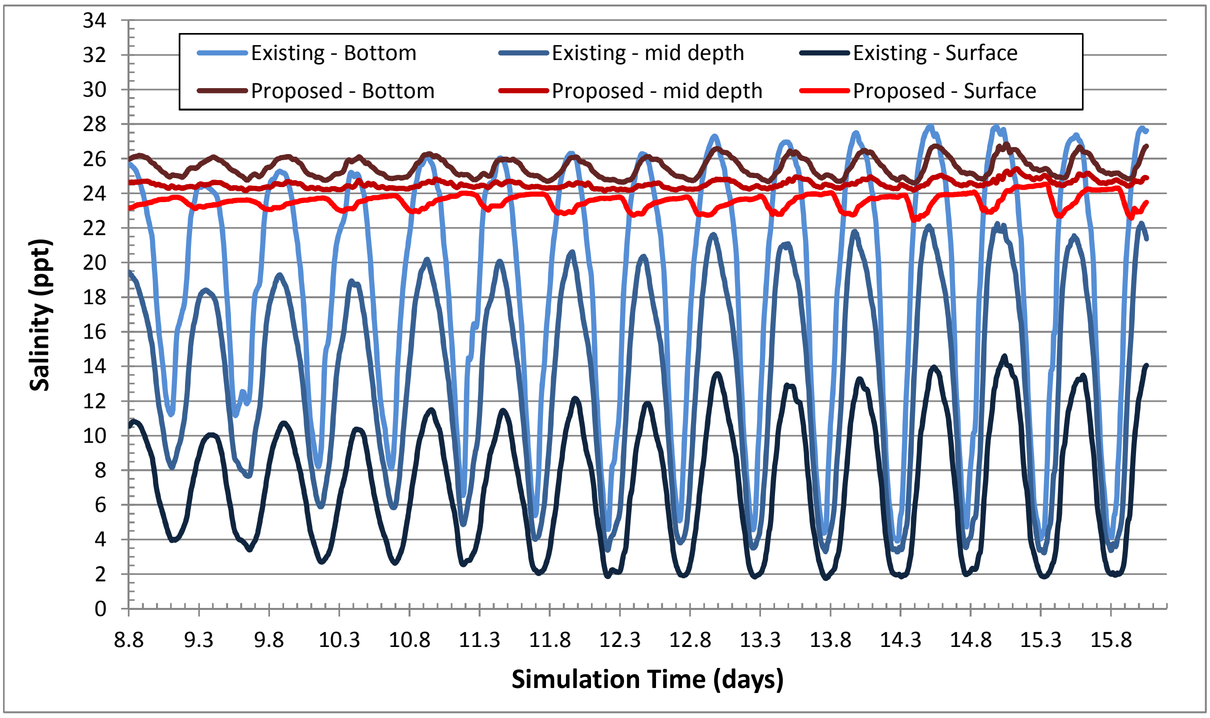


Figure 73 Time Series Output of Salinities for Site 5 existing and Proposed Cases neap to spring tide under 1-percentile Flood Flow

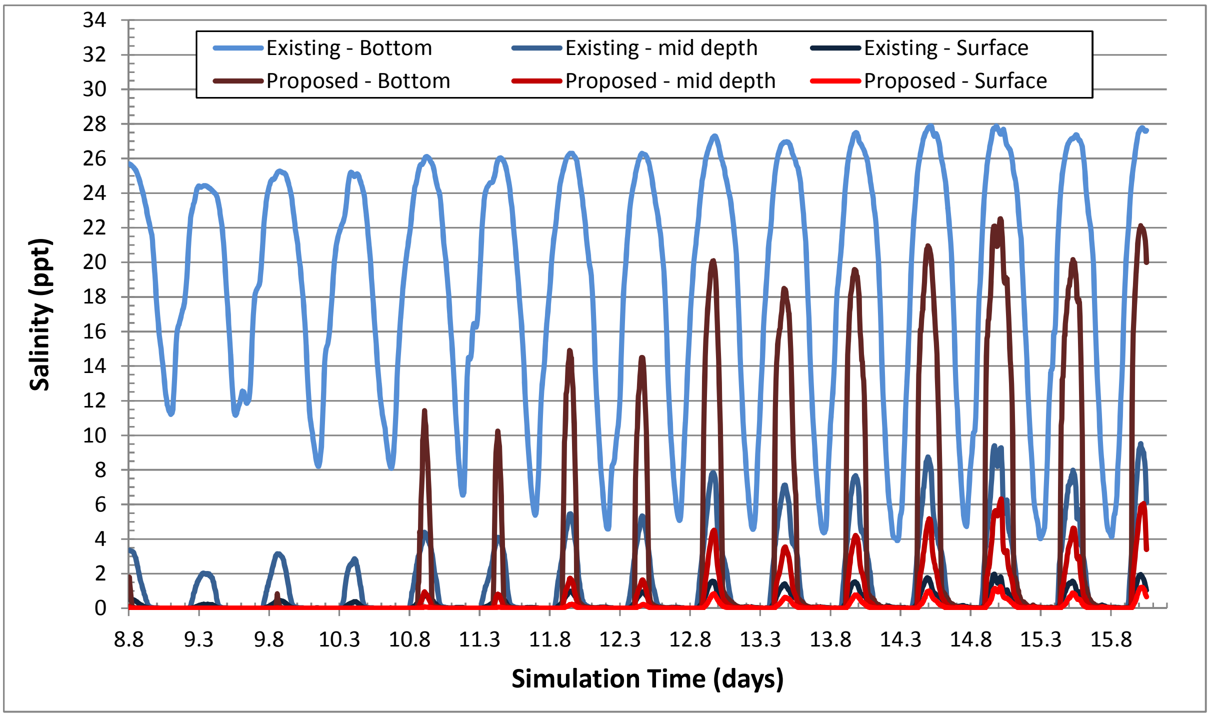


Figure 74 Time Series Output of Salinities for Site 7 Existing and Proposed cases neap to spring tide under 1-percentile Flood Flow

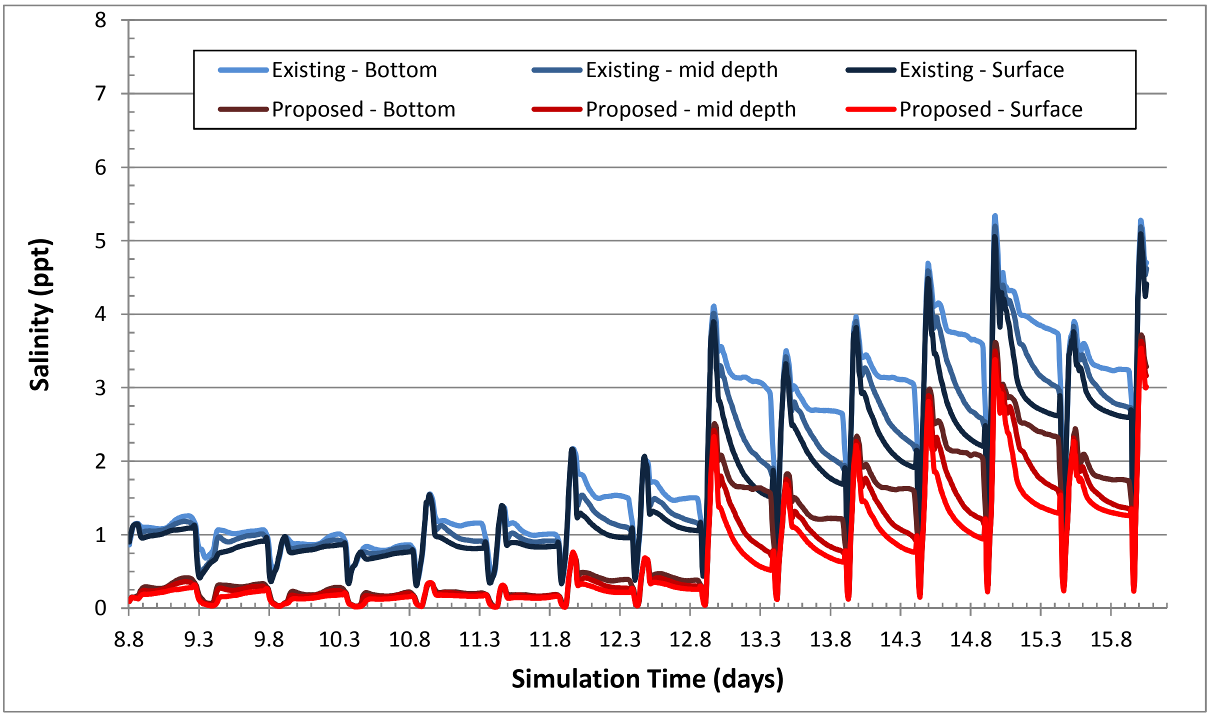


Figure 75 Time Series Output of Salinities for Site 9 in Lough Atalia Existing and Proposed cases neap to spring tide under 1-percentile Flood Flow