Multi Station Calibration of 3D Flexible Mesh Model: A Case Study of the Columbia Estuary

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Multi station calibration of 3D flexible mesh model: a case study of the Columbia Estuary

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Abstract

A model calibration based on the distributed multi stations approach is necessary towards model implementation in the operational phase. In this study, a tree dimensional (3D) hydrodynamic and salinity dynamic model of an estuary was simulated using DFlow Flexible Mesh program, which is developed by Deltares. Specifically, this research was focused on the Columbia Estuary case study, which is situated in Oregon, United States. The preconfigured model was calibrated based on 15 measurement stations that are spread along the estuary. Furthermore, a detail portion data with an average interval of 1 minute were used during the calibration process. The model performances were improved by considering the data denial concept. The data denial concept was introduced by neglecting inconsistence data across its temporal and spatial variability. In this particular case, it was revealed that the downstream data, which have high salinity value, tends to produce high contribution to the root mean square error of the model result. In conclusion, the upstream data have immense variable fluctuation rate and therefore it is more sensitive to give lower coefficient of determination. Therefore, there must be a trade of between good estuary model performance and upstream station data reliability.

Keywords: Multi Station; Calibration; Estuary; Three-dimensional; Flexible Mesh.

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1. Introduction

The problem of estuary developments can be summarized into two key elements, *i.e.*, the needs of good water and good environment. The needs of good water can be defined as the water availability that matches with the required quality and quantity[1]. The near shore population increase in the ongoing future will also depend on the success of environment restoration[2,3].

In a practical example, when the water in estuary is too saline, then there would be a problem of hyper salinity[4,5].On the other hand, if there is an abundant fresh water input to the estuary pool, the hypo salinity problem will threaten the environment[4]. The success of the estuary development will be relied on the mannerly water and environment management[6]. This research suggests a new approach in describing salinity dynamics in an estuary. The holistic uncertainty analysis in an estuary is necessary due to salinity variability within a wide water surface coverage. Moreover, the effect on disregarding one or any measurement stations to the overall model performance will be explored. The conventional calibration mechanism is to use the single station data to calibrate the salinity model result. In spite of some improved approaches, conventional salinity calibration method was presented as a base case in several researches[7–9]. This paper explores the relevance of multi stations data usage for salinity model calibration resulted from 3D flexible mesh hydrodynamic model.

Overall, it is important for the stake holders and decision makers to understand the salinity dynamic in the estuary. The main reasons are the needs of fresh water intake for drinking water consumption and the endemic wetland conservation for environment services sustainability (Figure 1). The needs of fresh water supply[10] to the surrounding city within Columbia Estuary were expected to reach the average of 1,048 litres/ day per capita on 2030. There is a directive from the government[11] to restore 65 km^2 of wetland in 2014.

Fig. 1.The importance of salinity balance in Columbia Estuary to support the increasing society and wetland. Image by: Eric Murray, Photo taken on 11 July 2006 at 46° 10' 50.17" N 123° 49' 8.43" W, Astoria, OR[12].

2. Methodology

The case studies are adopted from Columbia River Estuary. The Columbia Estuary is the orifice of the Columbia River basin[13] that is facing the Pacific Ocean in the coordinate of 46°14′39″N 124°3′29″W. The Columbia River can be categorized as a large watershed that covers the area of around 665,370 km^2 (Figure 2). The average discharge of the Columbia River at the Beaver Army Station[14] was recorded as 6,685.61 m^3/ s.

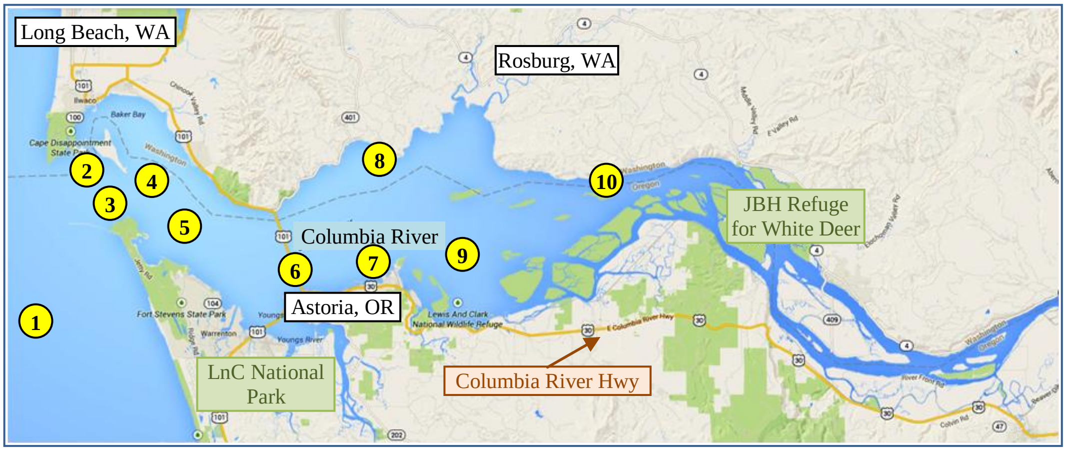

Fig. 2.The distribution of the observation stations that are elaborated in the holistic calibration analysis.
The station id from left to right are ogi02 (1), jetta (2), sta2o (3a), sta3o (3b), sta5o (3c), sandi (4), dsdma (5), am169 (6), coaof (7), grays (8), cbnc3 (9), and eliot (10). Base map source: www.maps.google.com

The selected estuary has plenty of data availability which has led to proper salinity model arrangements. The consideration in choosing The Columbia Estuary as a case study is based on data availability, prior research model existence, and the niche of salinity stratification in Columbia Estuary[15]. Thereafter, the salinity model was run for each parameter value using Delft 3D Flexible Mesh Software from Deltares[16].

2.1. Multi Station Measurements

An arrangement of measurement stations is necessary to capture salinity stratifications in estuary. It comes due to the fact that the interaction of river discharge and tidal fluctuations shape the salt stratification pattern[17,18]. Moreover, the variability of the sediment transport pattern had also some important correlation with the salinity profile[19,20]. Therefore, it is not ample to justify the salinity variation in the planar direction and evenin the vertical directions.

Static salinity measurement station locations were established based on several consideration clauses. Firstly, the salinity station usually located on or nearby the existing water level or water quality station (eg. at Columbia River[21] and San Francisco Bay[22]). The next consideration is to situate a salinity station nearby the shore, platform, or static object (bridge, pile, anchorage, etc.) that is present in the estuary (e.g. at Everglades National Park[23]). However, due to the fact of salinity variation and stratification in estuary, the salinity measurement station network arrangement must be specifically considered. It would be improper if the salinity measurement objective must be purely adjusted to other estuary variable measurement purposes.

This research tried to analyse the impact of a certain salinity measurement station data to the overall model performance. The aim was to recommend a better or more detail measurement effort in the sensitive location. The sensitive location was where the nearby measurement station data denial will produce a significant change to the overall model performance.

2.2. Flexible Mesh Model

In order to solve the 3D (three-dimensional) shallow-water equations, Delft 3D-Flow Flexible Mesh software had been occupied. The shallow water equations convey the conservation law of mass and momentum. In brief, the 3D differential equations of shallow water equations, which are usually called as simplified Navier Stokes Equations, can be stated as (equation 1 to 4)[24]:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -g\frac{\partial \eta}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(v\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -g\frac{\partial \eta}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(v\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -g\frac{\partial \eta}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(v\frac{\partial w}{\partial z}\right)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

In salinity dynamic analysis, some set of differential equations were addressed the quantity change of a certain dependent variable regarding to time and space. The principle is that there should be a balance between the quantity of variable that goes in, goes out, and stay in the selected entity. In the other words, there should be no quantity loss within the system. Thus, the general transport equation of salt (c_i) in equilibrium water flow can be written as[16,25]:

$$Transientcomponent + Convectioncomponent = Diffusioncomponent + Sourcecomponent$$

$$\frac{\partial \rho c_i}{\partial t} + \nabla.(\rho\vec{u}c_i) = \nabla.(\Gamma\nabla c_i) + S_c$$

The equation 5and 6 infer that the general transport equation contains four major components, which are transient, convection, diffusion, and source components (S_c). The $c_i$coefficient denotes the dependent variable of salt concentration, which also can be replaced by other substrate concentration that goes with the flow. The velocity term was symbolized by the $\vec{u}$sign. The gamma symbol (Γ) indicates the diffusivity of the transported substrate. Moreover, the flowing fluid density, which is in this case water density, was signified by rho (ρ).

Each of the transport equation components has its physical terminology. The accumulation of the transported substrate in a selected control volume (flow element) is quantified by the transient component. The convective component is explaining the amount of material transported due to the flow velocity. The gradient of concentration of the transported material gives contribution to the transport rate in terms of diffusion component. The source component is to accommodate the effect of boundary, pressure and gravity force to the transport rate. This fact explains the correlation between water level and flow velocity equation and the general material transport equation.

It is hard or at least still ongoing research by scientists, to solve complex material transport cases by the analytical (mathematical) method. Therefore, whether the finite different, finite element, finite volume numerical solutions is utilized in most of these cases. The aim is to derive some linear system of equations for each of given element in the computational domain. Once some number of linear equations could be derived, then it would be possible to calculate some unknown variable values in each time step.

2.3. Model Calibration Procedure

The salinity model performances were assessed by three statistical indicators. Those statistical indicators are coefficient of correlation (R), coefficient of determination (R^2), and root mean square error (RMSE). The coefficient of correlation was used to get the linear correlation strength and direction between the measured and simulated data. It can be stated also that the coefficient of correlation will measure the linearity of the two compared data.

In complement, the coefficient of determination calculation was also put into practice to depict the variance (difference) of simulated data compared to the measured data. Likewise, the root mean square error measure was also considered to quantify the intrinsic error that is produced by the model in representing the field measurement data. The conventional formula that is implemented in this research to calculate the *R*, R^2, and *RMSE* are stated by equation 7, 8, and 9 as follows:

$$R = \frac{\sum_{i=1}^{n}\left(f_i - \bar{f}\right)(c_i - \bar{c})}{\left(\sqrt{\sum_{i=1}^{n}(f_i - \bar{f})^2}\right)\left(\sqrt{\sum_{i=1}^{n}(c_i - \bar{c})^2}\right)}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(c_i - f_i)^2}{\sum_{i=1}^{n}(c_i - \bar{c})^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(c_i - f_i)^2}{n}}$$

The field observed salinity data (c_i) and model simulated salinity result (f_i) among a number of records (n) are evaluated by comparison. During the performance analysis, the each scenario of the Columbia Estuary model performance was measured as integrated calibration period performance, instead of single point performance. Therefore, a discrete overall model performance analysis had become indispensable because of the observation data discontinuity. In the other words, the simulated data will be compared in each time step with a corresponded observation data. In the time when there is no observed salinity value availability at that certain time step, for example in Not a Number (*NaN*) observation value, the assessment process will be passed over to the subsequent time step. As a result, the calibration disarrangement to wing to the data incompleteness can be minimized.

The model calibration scenario had been done by enrolling three (3) calibration procedures. First of all, the model was calibrated based on water level data to acquire the optimum bed roughness (manning coefficient) value, which are 0.018. The next step is to calibrate the model in terms of resulted velocity. Therefore, the model was calibrated in term of viscosity and diffusivity parameter to obtain an acceptable salinity result. As a result, an optimum values had been set for vertical diffusivity (5×10^{-5} m^2/s), horizontal diffusivity (0.1 m^2/s), vertical viscosity (5×10^{-5} m^2/s), and horizontal viscosity (1 m^2/s). The ratio between vertical and horizontal viscosity and diffusivity (Schmidt Number[26]) also had been thoroughly thought during the analysis. The detail calibration processes had been described in the literature[27].

3. Results

The model performance analyses were considering twelve (12) field salinity measurement stations. From those stations, nine (9) of them are static stations and the rest three (3) stations were impermanent stations of the Mega Transect Project in 2005. The static stations are extended along the estuary, from the seaside to the upstream neck of the Columbia Estuary. On the contrary, the three (3) stations of the Mega Transect Project were concerted at the mouth of the estuary. Actually, there were still several other stations within the study area.

The simulated data has a narrower assortment of variability among the high salinity value and low salinity value in contrast with the observed one. Likewise, the observed data has higher rate of salinity change gradient, whether or not the simulated salinity is progressively changing. Referred from the time series plot (Figure 3), in general the computed results are underestimating the field measurement data. The salinity model had given a restrained result with a holistic model performance achieved as 0.77 (R^2). The holistic root mean square error of the model is reasonably small, which is in the order of 3.67 ppt. Overall, it can be demonstrated that the model can capture the consequence of tidal wave ebb and flow to the estuaries salinity. The simulated data at the upstream located station have a tendency to lessen the state of the holistic model performance by its consideration.

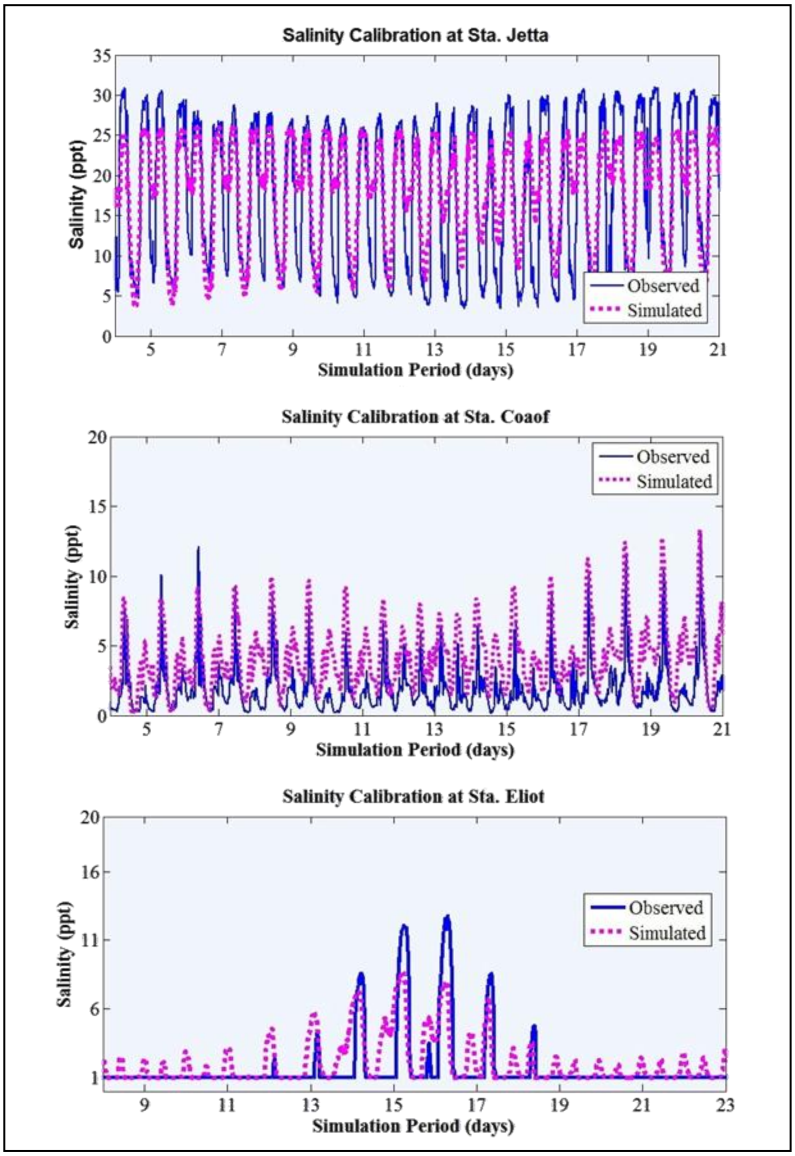

Fig. 3. Time series model performance comparison of observed and simulated salinity.
Remarks: Salinity at the seaside (Sta. Jetta), centre side (Sta. Coaof), and upstream side (Sta. Eliot) of the estuary.

Table 1.The salinity model performance analysis result based on several observations station data.

ID	1	2	3a	3b	3c	4	5	6	7	8	9	10	ē
Station	Ogi02	Jetta	Sta2o	Sta3o	Sta5o	Sandi	Dsdma	Am169	Coaof	Grays	Cbnc3	Eliot	Average
R	0.399	0.8161	0.8345	0.2478	0.7342	0.8709	0.7851	0.718	0.676	0.7193	0.501	0.6259	0.6607
r2	0.9985	0.9185	0.9942	0.9211	0.9954	0.9662	0.9153	0.8625	0.6199	0.3895	0.3546	0.3137	0.7708
Rmse	1.2728	5.583	2.345	7.61	2.1439	4.4181	5.2227	5.4313	3.1548	3.1578	1.1715	2.5121	3.6686

The green highlighted values are representing the downstream side station model performance of the estuary. Subsequently, the yellow highlighted are indicating the model ability correspond to the mid estuary located station. In addition, the upstream estuary located stations model performance is expressed by the maroon highlighted value.

The basic Columbia Estuary salinity model had performed outstanding job in representing salinity dynamic at the downstream area of the estuary (Table 1). However, the computer-generated performances at the upstream located stations are still far from the limit of satisfactory. Based on the time series plot (Figure 3), most of the time the model results are underestimating the field measurement data. However, around the midpoint vicinity of the estuary, the model tends to overvalue the observation data. The observed data has a wider range of variability between the high salinity value and low salinity value weighted against to the simulated one. It can be proven that the model can capture the effect of tidal phase fluctuation to the salinity dynamics. After all, the idea of using data denial to improve the multi station calibration of the salinity model will be expressed in the subsequent part of the analysis.

3.1. Data denial approach

An excellent perceptive of estuary dynamic can merely come with an integrated measurement data instrument. Nonetheless, the data availability and continuity matters are still becoming the demanding nuisances. It grows to be tricky to perform a holistic hydrodynamic analysis in the estuary. Therefore, the data denial concept was introduced to fill the gaps of data inconsistency by considering the niche and distinctive factor of the studied estuary.

The data denial concept can be applied to observe the station data significance among the overall salinity model performance. The salinity model performance is appraised by neglecting some stations data existence. Furthermore, the data denial concept is valuable to provide guidance on supplementary station installation decision and station operation organization in the estuary. The data denial concept relevance to the Columbia Estuary model had revealed that the model errors are mainly come from upstream station data evaluation. By denying several upstream station data, the model performance can be intently said to be improved (Figure 4). Therefore, denying upstream data during the salinity model performance analysis can give a pseudo interpretation. In contrast, in most of the cases the upstream measurement station has incomplete or discontinuous data record. It is very obvious that there is a bargain between good salinity calibration outcome and upstream station data availability.

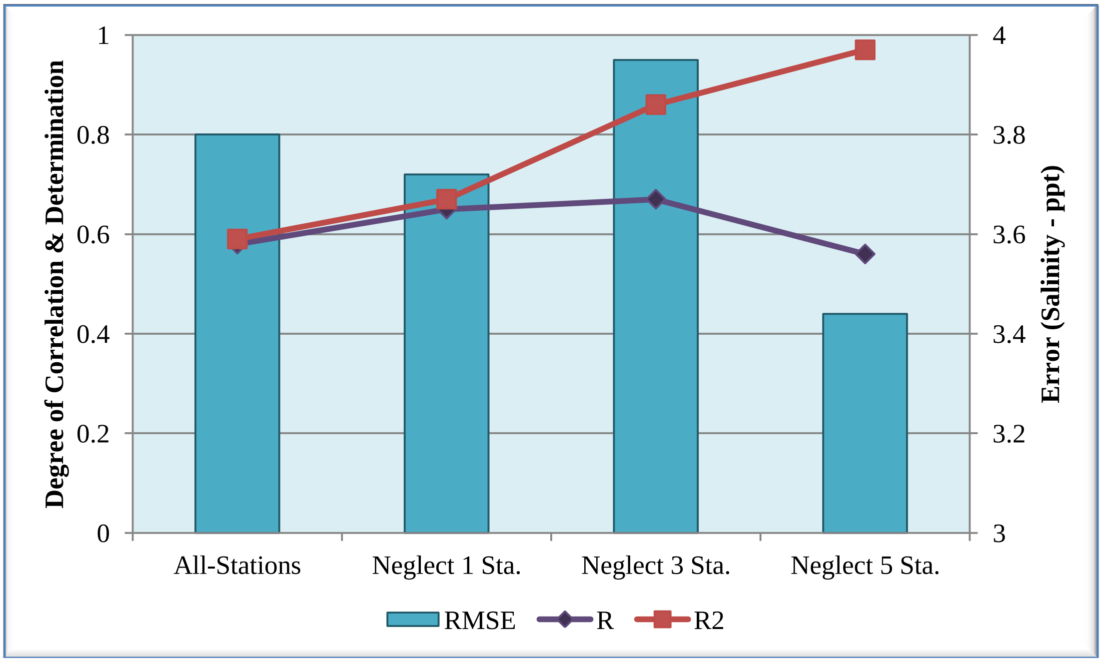

Fig. 4. Holistic salinity model performance in an assorted data denial scenarios (Diffusivity = 10^{-4}, *Schmidt Number = 1*).

Remarks:

(a) Neglecting 1 (one) observation station data, which is Station Eliot.

(b) Neglecting 3 (three) observation stations data, which is Station Eliot, Grays, and Cbnc3.

(c) Neglecting 5 (five) observation station data, which is Station Eliot, Grays, Cbnc3, Coaof, and Dsdma.

The effort of denying several measurement station data had made the overall model to have a better performance. This tendency can be proven by a lower RMSE and higher R and R^2 results (Figure 4). In detail, the model performance became better when the upstream station data is neglected. It also had been shown that the model result is more sensitive to the upstream station data. As a result, it can be inferred that the decision to include a certain measurement station in the multi station calibration process will affect the calibration quality. Therefore, it would be recommended to do separate analysis for upstream and downstream Columbia Estuary that has different model physical parameter setting for each of them.

The aim of salinity modelling is different with purely hydrodynamic modelling. Notwithstanding the fact that salinity modelling needs a reliable hydrodynamic analysis, the salinity modelling depends on more physical variable compared to hydrodynamic model. In practical approach, the ability to capture salinity dynamic is more vital rather than assessing detail salinity concentration value at a moment. Therefore, the paradigm in salinity calibration must be directed to salinity trend analysis rather than salinity value only.

3.2. Estuary stratification

The 3 dimensional salinity modelling result had endow with proof of salinity stratification phenomena in the Columbia Estuary. The longitudinal salinity profile can be visualized by looking at a glimpse snapshot of the estuary stratification stipulation, which was happened at a definite time during the simulation period (Figure 5). Unto *Dsdma* station location, it was figured out that the salinity concentration close by the water surface is dissimilar to the one underneath. In addition, it can be notorious that the frontier between saline water and fresh water was situated between *Dsdma* and *Coaof* station. It is highly recommended to put measurement station between these two locations by the intention to capture detail depiction of this salt intrusion boundary.

The other recommendation is to have several salinity measurement data in vertical depth direction of each observation locations. As a minimum prerequisite, it would be amply functional to have the measurement at the near surface layer and at the near bottom layer of each measurement point. Through this resolution, the specific estuary stratification profile can be deduced in a distinct way. Moreover, based on the simulation results, the salt intrusion can reach about 40 km from the estuary mouth (Station *Eliot*) for the period of the high tide. On the contrary, the effect of fresh water discharge from the river can flush the salty water till approximately 23.5 km from the estuary mouth by the proof of several 0 ppt salinity occasions at Station *Cbnc3* during the simulation period.

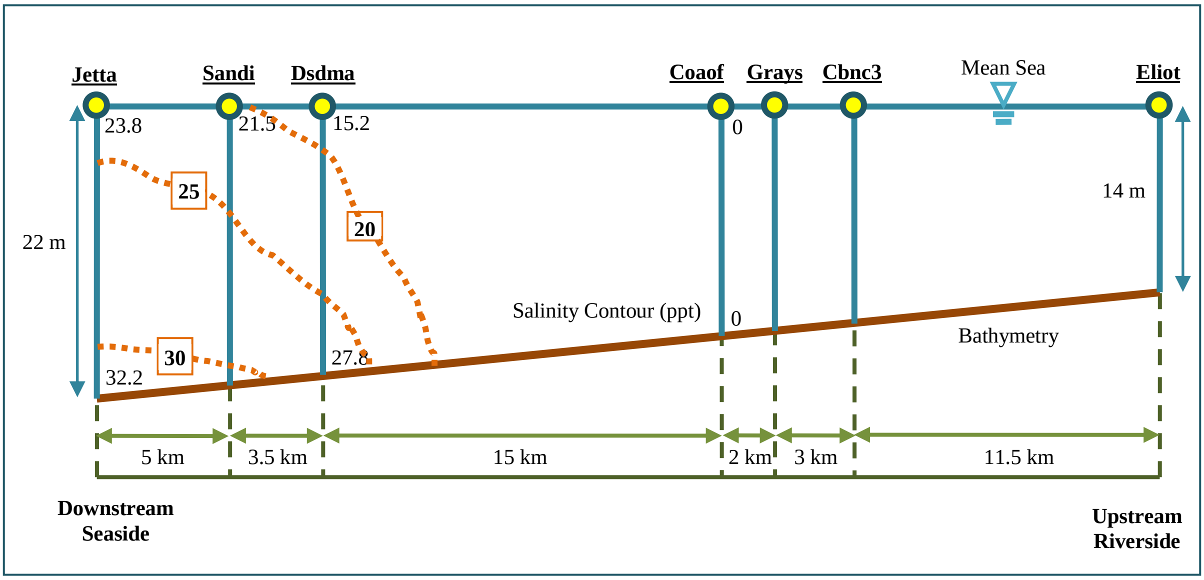

Fig. 5. Longitudinal drawing of salinity profile at Columbia Estuary derived from calibrated model result.
The salinity profile was taken from model simulation outcome at 7 September 2005 (00:00). The longitudinal section was taken in the innermost point of the cross section. In addition, this figure has vertical exaggeration of 5×10^{-5}, which is the proportion between bathymetrical depth and the longitudinal distance of the figure[27].

4. Conclusions

The application of multi station calibration had given a better understanding of salinity dynamic in the estuary. The salinity dynamic profile in the estuary is mainly affected by hydrodynamic interaction between the river discharge and the tidal fluctuation in a certain time and location[27]. The salinity dynamic in the estuary is highly governed by the associated advection and diffusion process (represented by the coefficient of eddy viscosity and diffusivity). The proper assignment of boundary condition and initial condition of the estuary model are will take an impact in model result in short term salinity modelling. Overall, the data denial concept can be used to test out a measurement station impact and importance regarding to the multi station calibration of 3D flexible mesh model in representing salinity in the estuary.

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