Lagrangian analysis of the Chao Phraya River estuarine circulation

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***Abstract*— Bangkok metropolis and its vicinity mainly rely on the Chao Phraya River in supplying the freshwater. Salinity in the freshwater is one of the critical water quality parameters. The saltwater intrusion intensifies in the dry season when the demand for fresh water is excessively high affecting various sectors including agriculture, industry and waterworks. The situation further deteriorates in the face of climate change and sea-level rise. The ocean tides and river discharge primarily control the salinity in the Chao Phraya River. Thus the interplay between these two factors is crucial in determining the availability of freshwater. As brackish water moves, each fluid particle carries tracers such as salt, nutrients as well as other particulate matters. The transport of brackish water and its tracer content, as well as the pathways and timescales for that transport, are main facets of how the ocean tides and river discharge play a role in estuarine ecology. To this end, we perform the Lagrangian analysis to analyze the outputs of the validated estuarine circulation model, Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM). In this Lagrangian approach, large sets of virtual particles are integrated within the three-dimensional, time-evolving velocity fields. In the paper, we demonstrate and discuss the use of analysis of Lagrangian particle trajectories to improve the understanding of the Chao Phraya River estuarine circulation and dynamics.**

Keywords*— Lagrangian analysis, Estuary, Tracers

I. INTRODUCTION

The United Nation Sustainable development goal (SDG) 6 and 14 of the 2030 Agenda for Sustainable Development aims for conservation and sustainable use of management of water and sanitation and the oceans, seas, and marine resources. The SDG 6 and 14 explicitly considering the improvement of water quality in one of its target 6.2 as well as the sustainable management of coastal areas in two of its targets (14.2 and 14.5), respectively. The estuarine and coastal cities can benefit from interpreting and implementing the principles and guidelines set out under SDG 6 and 14.

In the estuarine region, the salinity gradient plays a significant role in determining the distribution of fresh water as well as communities of, plants, animals, and microorganisms within the estuary.

The ocean tides and river discharge primarily control the salinity in the estuary. Thus the interplay between these two factors is crucial in determining the availability of freshwater needed by the estuarine and coastal cities especially in the dry season when the freshwater is even more scarce. As brackish water moves, each fluid particle carries tracers such as salt, nutrients as well as other particulate matters. The transport of brackish water and its tracer content, as well as the pathways and timescales for that transport, are main facets of how the ocean tides and river discharge play a role in coastal and marine ecology.

In the literature, there are two main methods for estimating pathways in large-scale fluid flows. The first method makes use of tracers, such as the multitude of age tracers, see [1]. It is also noted that tracer studies are better suited for Eulerian methods, which make direct use of velocity fields on their native grids.

The other approach makes exclusive use of the Lagrangian perspective of fluid dynamics instead, see [2]. This method employs an ensemble of virtual Lagrangian particles with no spatial extent whose trajectories are determined by the velocity field. The velocity fields that are used to move the particles can either come from model based velocities such as hydrological/ocean/entuarine models or observational based velocities such as surface velocities based on satellites or measured by high frequency radars.

Statistics of the trajectories for these virtual particles then define particle pathways and their associated time scales. By following the flow of virtual particles and applying further analysis to conceive the effects of subgrid scale diffusion, questions about pathways and flow connectivity can be addressed. See [3] for a recent review of this technique.

This paper extends our previous study, see [4] by thoroughly applying the Lagrangian analysis on the Chao Phraya River estuarine circulation though the similar approach can be well applied in other estuaries. Section 2 explains the material and methods in detail including the hydrodynamic model and the Lagrangian particle tracking techniques. Result and discussion of the Lagrangian analysis and connection to biological and environmental connectivity are given later in section 3, followed by conclusion in section 4.

II. MATERIAL AND METHODS

In this study, in order to thoroughly investigate the dynamic of the brackish water in the Chao Phraya River estuary, we create various scenarios according to real situations in Chao Phraya River estuary by simulating various seasonal events of the estuary. A validated hydrodynamic model called Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) has been used for this purpose. The particle tracking analysis is carried out.

A. The model and study domain

SCHISM or Semi-implicit Cross-scale Hydroscience Integrated System Model [5] is an open-source three-dimensional hydrodynamic model that used semi-implicit Finite-Element and Finite-Volume method for solving governing equations on an unstructured grid. The equations used in SCHISM are based on Naiver-Stokes equations as shown below:

$$\nabla \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0,\ \ (\mathbf{u} = (u,v)) \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = \mathbf{f} - g\nabla \eta + \frac{\partial}{\partial z}\left(\nu \frac{\partial \mathbf{u}}{\partial z}\right) \tag{2}$$

Where *D/Dt* is material derivative, *t* is time, **u** and *w* represent horizontal and vertical velocity respectively, *g* is an acceleration of gravity, η mean free-surface elevation and **f** stand for other forcing terms in momentum such as Coriolis, atmospheric pressure, baroclinic gradient, horizontal viscosity.

The study domain covers the lower Chao Phraya River basin following along the Chao Phraya River starting from Amphoe Phra Nakhon Si Ayutthaya in Phra Nakhon Si Ayutthaya province following along the river down to Chao Phraya River mouth with some extension of 20 km into the upper Gulf of Thailand. The corresponding bathymetry mesh of the area is unstructured grid contain only triangular elements in a total of 176,959 elements and 97,401 nodes with the wet and dry area as shown in Figure 1.

The scenario will be created according to the actual discharges throughout the year consists of 8 cases in total. Seven of which focus on the quantity of water discharge from upstream while the other one emphasizes the effect of water pumping. The details of each case are described in Table I. The cases of 80 and 90 cms water discharge are the dry season scenarios while 100 cms water discharge case is a typical amount of water discharge release from the dams in these past few years. Meanwhile, the cases of 800 and 1,500 cms water discharge are usually the situation in the onset of the rainy season. 2,840 cms is the maximum carrying capacity of the Chao Phraya River and 3,700 cms is the highest amount of water discharge recorded in 2011.

The difference between the two 100 cms water discharge cases is that the case with a closed water supply canal corresponds to the closed water supply canal (as shown in figure 2) for Metropolis Waterworks Authority (MWA) which normally pumps some amount of fresh water into their waterworks plant.

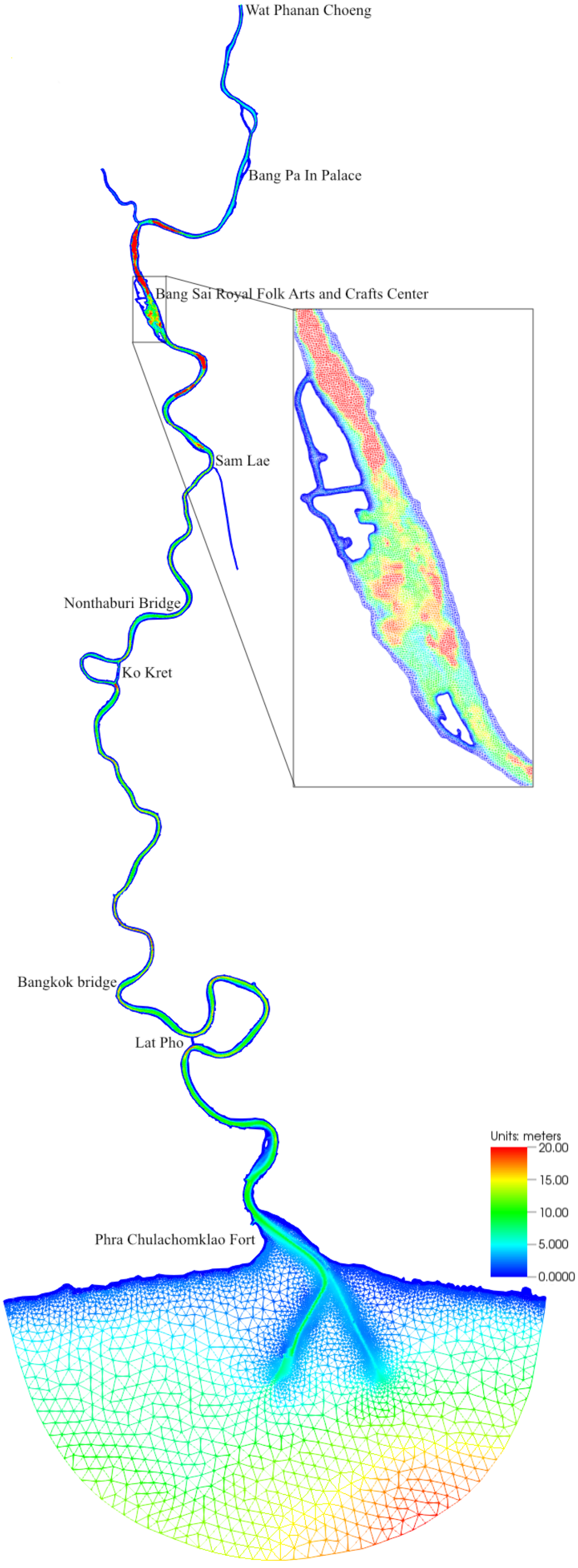

Fig. 1 The study area and the corresponding mesh

TABLE I. SCENARIO SETTING

Scenario No.	**Scenario**	
	Upstream water discharge (cms)	***Water supply canal***
1	80	Open
2	90	Open
3	100	Open
4	800	Open
5	1,500	Open
6	2,840	Open
7	3,700	Open
8	100	Closed

All of the scenario cases are run for 95 days in the model time to obtained water velocity field outputs for the particle tracking analysis. The spin-up time for all cases is 15 days.

Fig 2 Left: normal domain, Right: closed water supply canal domain

B. Lagrangian Particle Tracking

The Lagrangian particle tracking (LPT) is a technique to trace virtual particles that put into velocity field of any fluid, in this case is the velocity output of the Chao Phraya River obtained from scenarios above. The LPT method used in the current study is the off-line type, meaning that the model and LPT are not running at the same time. Instead, one can perform simulations first to obtain the velocity field data from each simulation scenario and later apply LPT algorithm to calculate the path and location of virtual particles at each time step by solving the following system of equations:

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{v}(\boldsymbol{X}(t), t) \tag{3}$$

Where $\boldsymbol{X}$ represents the trajectory of the particle in x, y and z direction, t is time and $\boldsymbol{v}$ is velocity field in three dimensions.

The virtual particle has no mass nor dimension to represent a parcel of water that moves along the river. We start by releasing a total of 8,000 particles spreading into a rectangular shape with the distance between each particle of one meter at the start location near the upstream area as shown in figure 3. The particles are set to be released at midnight of the 15th day in model time simultaneously. After that, the new location of the particles is recorded in every 10 minutes for further analysis. In this study, we will focus on two main topics:

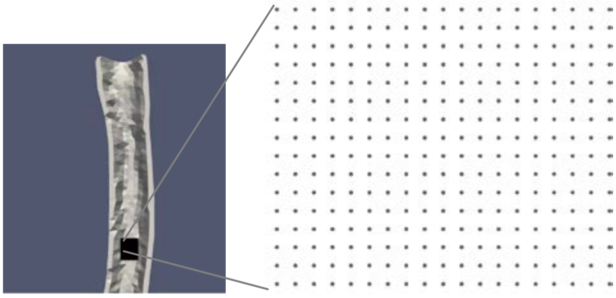

Fig. 3 Particle releasing area and placement

- Transit times – The total time particle spend between the release point and sea.
- Dispersion and Diffusivity – The particle dispersion and its rate of change, the diffusivity, are the fundamental Lagrangian diagnostics of use for understanding tracer transport in flows. Here, we interest in single-particle diffusivity and double-particle diffusivity which can be written as the following equations:

$$\kappa(t) \equiv \frac{1}{2}\frac{d}{dt}\langle \boldsymbol{X}^2(t) \rangle \tag{4}$$

$$\kappa_R(t) \equiv \frac{1}{2}\frac{d}{dt}\langle \boldsymbol{r}^2(t) \rangle = \frac{1}{2}\frac{d}{dt}\left\langle \sum_{m \neq n}\left[\boldsymbol{X}^{(m)}(t) - \boldsymbol{X}^{(n)}(t)\right]^2 \right\rangle \tag{5}$$

Where ***X(t)*** is the trajectory of particle and < > represents the ensemble mean. Specifically, single-particle diffusivity quantifies the ensemble-mean rate of particle dispersion from an initial location and double-particle diffusivity is considered as relative diffusivity which the time rate of the mean square pair separation.

III. RESULTS AND DISCUSSION

A. Model validation

We employ the hydrodynamic model called Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) in in this study. The model has been validated against the observation data. Figure 4 shows the validation results of the water level from the model and observed water level at CPY015 (Bangkok bridge) and CPY014 (Nonthaburi Bridge) stations for the year 2017. The results show good agreement between the model output and the observed data for both dry and wet season. Thus, the model output can be used for further analysis.

B. Transit times

The time taken for water to transit between defined regions is a property of the flow that provides a useful understanding of the estuary circulation. By considering the entry and exit of particles from an enclosed region in our case is the lower Choa Phraya River, transit times can also be interpreted as a residence timescale as well. In this study, we are primarily interested in the transit between the releasing point, i.e., Amphoe Phra Nakhon Si Ayutthaya and the river mouth.

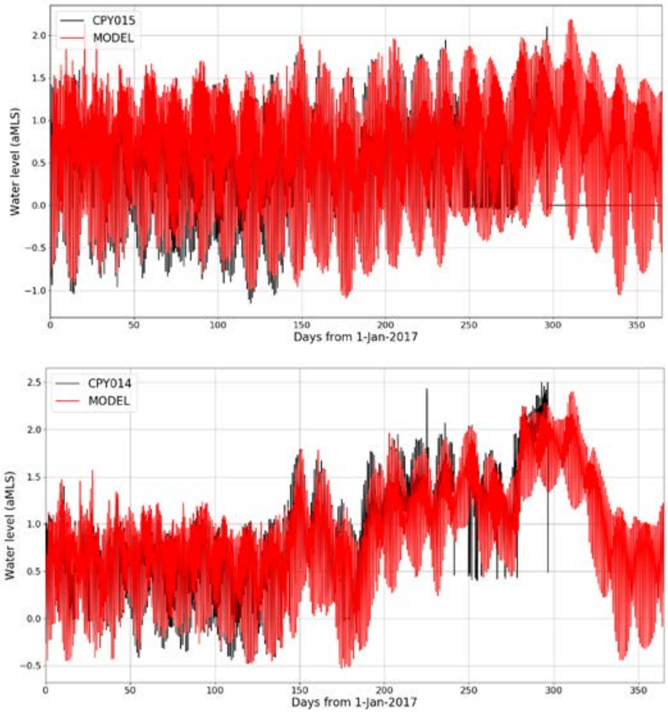

Fig. 4 Validation results at CPY015 (Bangkok bridge) and CPY014 (Nonthaburi Bridge) for the year 2017.

The transit time can be directly derived in a Lagrangian framework by determining the transit time of particles. The results of the transit times for all of the scenario are presented in Table II. Table II shows that for the dry period the transit times can be as much as two months however in the wet period the transit time is significantly reduced to around two days. We also find that as fresh water is drawn out of the river the overall transit times are indeed increased. Interestingly, the transit times for Sam Lae are slightly decreased as fresh water is drained out from the river.

TABLE II. TRANSIT TIMES

Scenario No.	**Transit times (days)**			
	Sam Lae	***Pak Kred***	***Lat Pho***	***River mouth***
1	14	19.7	32.5	61
2	13	16.2	31	49
3	11.8	15.9	28.9	45
8	12	15.1	23.8	32
4	1.9	2.5	3.9	6
5	1.15	1.5	2.3	3.8
6	0.76	0.98	1.4	1.8
7	0.63	0.85	1.1	1.6

Lagrangian particle tracking can also be used to assess the total distance travelled by the particle in the lower Chao Phraya River. Figure 5 depicts the total distance travelled by the particle from the releasing point, i.e., Amphoe Phra Nakhon Si Ayutthaya to the river mouth. Interestingly, the distance travelled by the particles in the dry period is almost four times more than that in the wet period where the travelled distance is approximately 130 km similar to the actual river following distance from the releasing point to the river mouth. This finding indicates that the tracers are mainly moved back and forth due to the tidal effects in the dry period while the tracers are instead directly flushed out in the wet period.

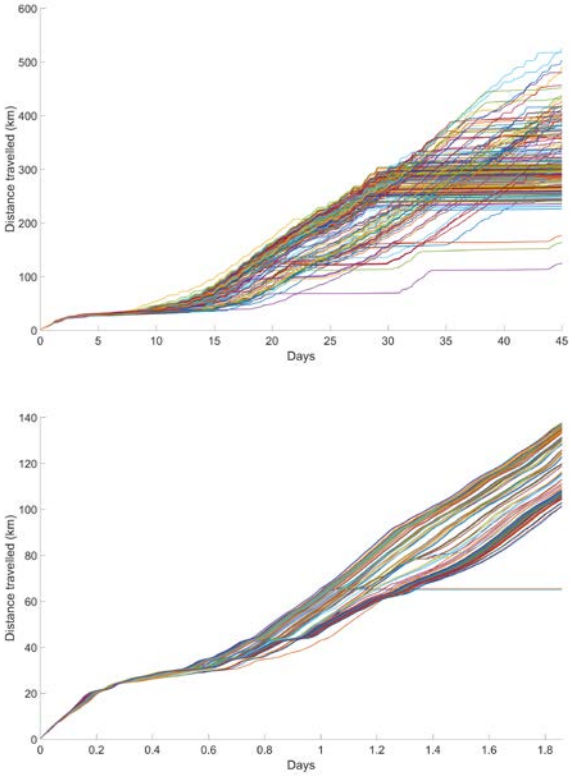

Fig. 5 Accumulative distance travelled by the particle in, top: dry season (100 cms) and bottom: wet season (2840 cms)

C. *Dispersion and diffusivity of the Chao Phraya River estuarine circulation*

The single- and double-particle diagnostics as indicated in equations 4 and 5 for all simulated trajectories are presented in Figure 6 to Figure 10. For the dry season the results from the scenarios with the upstream discharge of 80, 100 cms are presented in Figure 6 and 7 and the results from the scenarios with the upstream discharge of 800 and 2840 cms are presented in Figure 9 and 10. The scenario with a closed water supply canal is also present in Figure 8.

In order to fully understand the diffusivity, we need to clarify further what single-particle diffusivity measures. As mentioned earlier the single-particle diffusivity quantifies the ensemble-mean rate of particle dispersion from an initial location.

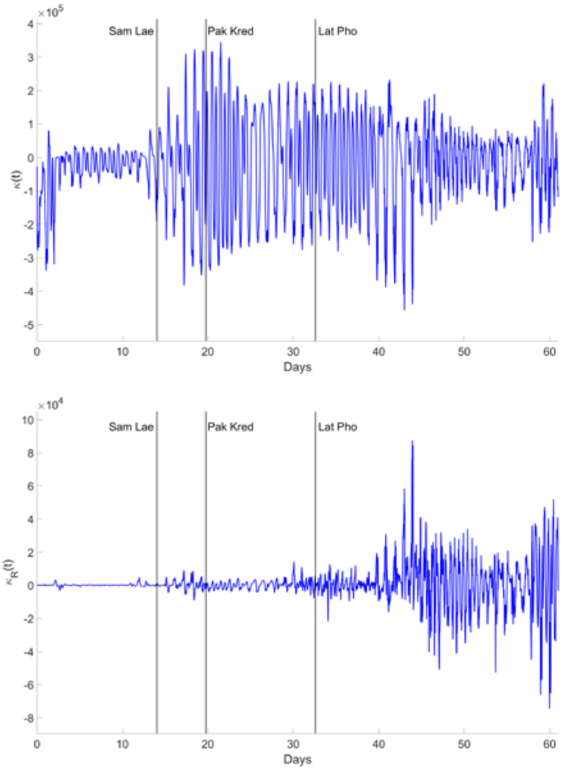

Fig. 6 Top: single- and double-particle diffusivity, bottom, for the case 80 cms upstream discharge.

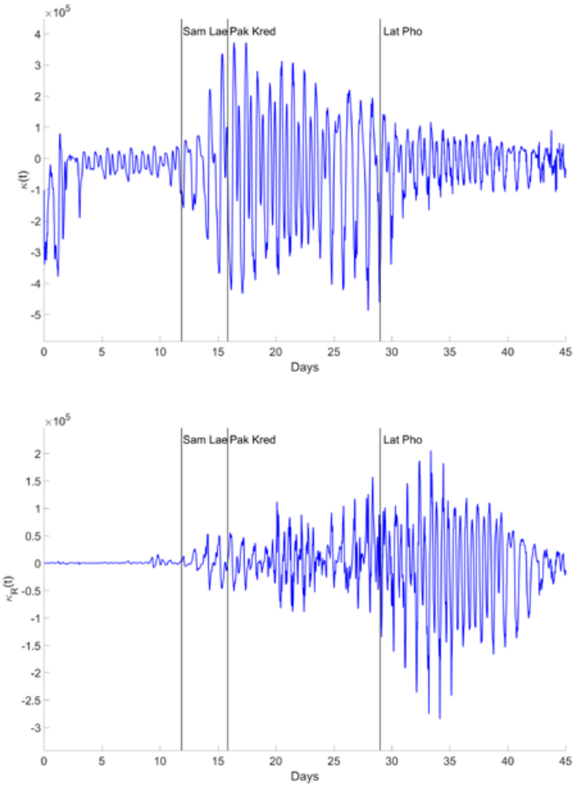

Fig.7 Top: single- and double-particle diffusivity, bottom, for the case 100 cms upstream discharge.

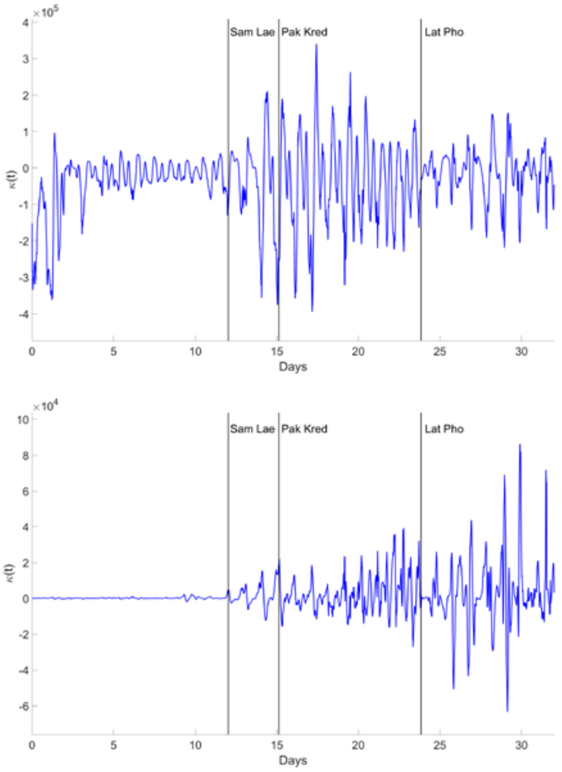

Fig. 8 Top: single- and double-particle diffusivity, bottom, for the case 100 cms upstream discharge with closed water supply canal.

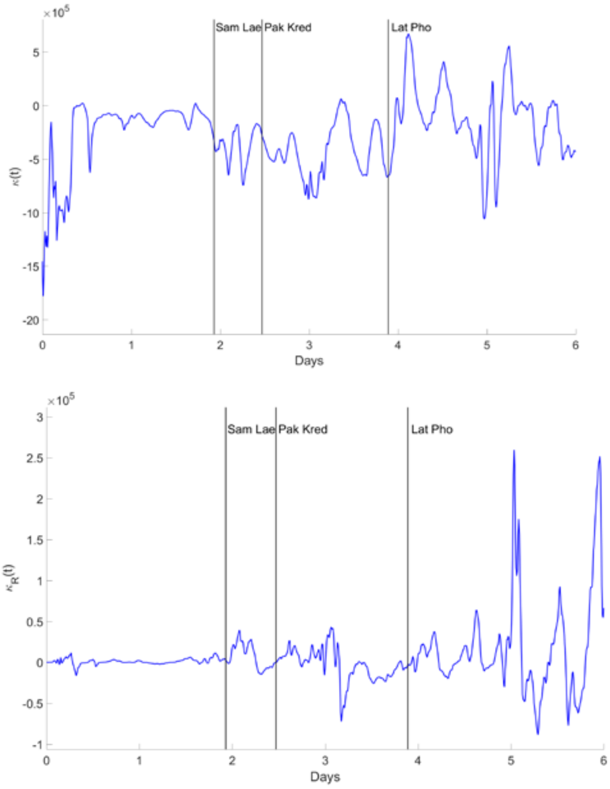

Fig. 9 Top: single- and double-particle diffusivity, bottom, for the case 800 cms upstream discharge.

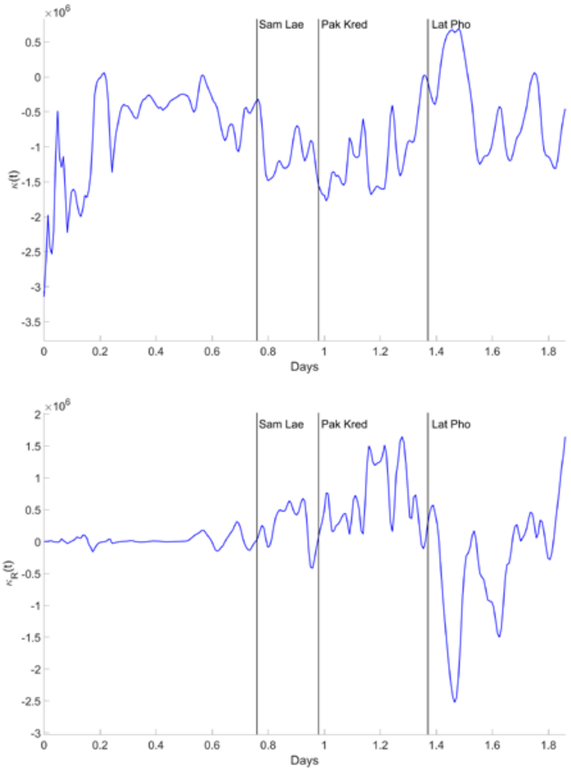

Fig. 10 Top: single- and double-particle diffusivity, bottom, for the case 2840 cms upstream discharge.

Thus, the lower magnitude of single-particle diffusivity should refer to a stationary or no-moving particle at that instant. For the larger magnitude, since the river is mainly aligned in the north south direction, we can infer directly that a more substantial positive magnitude of single-particle diffusivity is associated with flow tide while a larger positive magnitude of single-particle diffusivity is associated with the ebb tide. For the double-particle diffusivity, we can see directly from equation five that the lower magnitude of this number indicates that the two particles move in sync with each other. The larger magnitude of such number is, however, indicates that the pair particles instead move independently from one another in the way that particles move away for positive value or toward each other for negative one, respectively.

The results in the dry season show that the particles are transported down to the river mouth while experiencing the tidal effects the particles are still able to move in sync with each other until Sam Lae. The closer to the river mouth the more particles move independently from one another which can be the results from the tidal effects.

For the wet season, particles, however, are mainly moving directly along with each other. This should be the effect from the high discharge volume carrying out the particles to the river mouth more directly.

There is no significant difference in results from the case of 100 cms with and without a closed water supply canal. However, for the dry season, the results from the scenario with the upstream discharge of 80 cms and 100 cms suggest an interesting finding. In the case of 80 cms upstream discharge, the lower number of double-particle diffusivity can be observed from the releasing point to Lat Pho indicates that the particles are mainly packed together while transported down to the river mouth. That number for the case of 100 cms upstream discharge is much greater indicating a better mixing in this case. Here, Lagrangian particle trajectories can be used to study how water moves around in the estuary. Additionally, Lagrangian particles can also be interpreted as passively drifting (biological) or pollutant particulates. Thus, the diffusivity can be used to measure the dispersion of larvae of a marine organism or pollutants at the whim of the currents.

Thus, in the dry season, the amount of upstream discharge to the lower Chao Phraya River can also be important in both pushing the level of salinity down and enhancing the dispersion in the river. This is important as an incident of pollution leak into the river that polluted parcel of water can travel into the water supply canal and causes trouble to water supply system and riverside communities and business.

IV. CONCLUSION

This study, we focus on using the Lagrangian Particle Tracking technique to investigate the tracer transport of the Chao Phraya River in a various situation when the amount of upstream discharge is conforming to seasonal variation. The hydrodynamic model, SCHISM have made simulated scenario outputs for the LPT technique. The analysis shows that transit time increment is directly related to decrement of the amount of upstream discharge. Besides, the distance travelled by the particles in the dry period is almost four times more than that in the wet period. The further analysis reveals the influence of tides on particle movements in every scenario; flow tide pushes particles up north and ebb tide pulls particles seaward. The double-particle analysis reveals that the closer to the river mouth the more particles move independently from one another resulting from the tidal effects. The study also finds from the diffusivity analysis that in the dry season, the amount of upstream discharge to the lower Chao Phraya River can also be essential to the enhancement of the dispersion in the lower Chao Phraya River.

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