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1 The impact of human activities on the flushing properties of a semi-
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9

10 **Abstract**

11 In this study, a Lagrangian particle tracking model driven by hydrodynamic fields was
12 used to investigate the changes of flushing properties in Xiaohai Lagoon resulting from
13 natural evolution and influences of human activities. Comparisons of residence times
14 between 1936 and 2001 indicate that the flushing efficiency of the lagoon has
15 deteriorated greatly during the past 7 decades. Over this period, the average residence
16 time of the lagoon has increased from 45 to 71 days, an increase of 59%. The Lagrangian
17 residual velocity has decreased from 1936 to 2001 in the large portions of the lagoon, and
18 the spatial distribution pattern of the residual current has changed significantly. The well
19 developed horizontal circulations in 1936 disappeared. Instead, the horizontal Lagrangian
20 residual velocity showed uniformly seaward motion with reduced velocity in 2001.

21 Human activities have incurred great impacts on the deterioration of flushing
22 efficiency. The reduction of river inflow imposed the most significant impact, causing an
23 increase of average residence time by 33%. The land reclamation in the lagoon came as

1 the second most significant factor, causing an increase of 15%. Closure of the North
2 Opening had posed minor impact. The model results suggest that restoring the river
3 inflow, as well as the dredging of the tidal channel and the inner lagoon, should be the
4 top proprieties for future water quality management.

5

6 *Keywords:* Residence times; Flushing efficiency; Lagrangian particle tracking; Random
7 walk model; ELCIRC; Hainan; China

8

9 **1. Introduction**

10

11 Xiaohai Lagoon is located along the east coast of Wanning County, Hainan, China (Fig.
12 1). It has a surface area of approximately 30 km² with a mean water depth of 0.8 m
13 (relative to mean sea level). Historically, it has been a main fishery port and an important
14 habitat for some precious fish, shrimp, and crab along the eastern coast of Hainan Island.
15 In recent decades, aquaculture activities have been developed tremendously in the lagoon.
16 A tidal flat area of approximately 8 km² has been reclaimed for constructing shrimp pools,
17 and a total of 5000 fishing cages have been installed along the tidal channel for fish-
18 farming. With the rapid increase of aquaculture, a lot of environmental problems have
19 arisen. More and more input of the land-based pollutants has been caused by
20 deforestation and widespread use of pesticides and fertilizers. Additionally, there have
21 been pollutants from shrimp pools, fish wastes and unconsumed fish feed and a decrease
22 of the flushing efficiency of the tidal dynamics. Consequently, the eutrophication in the

1 lagoon has become a concern. Occasional fish-kill events and subsequent huge
2 economical losses have been reported.

3 Many studies have been conducted relevant to Xiaohai Lagoon's hydrodynamics,
4 sediment transport, morphological evolution, and the inlet's stability and water quality
5 (Wang et al., 1988; Hu et al., 1997; Chen et al., 1998; Wang et al., 2003; Gong et al.,
6 2006). Chen et al. (1998) estimated that the water renewal period is approximately 120
7 days during which time 99% of the original water mass is replaced. This is based on the
8 water exchange rate defined as the ratio between the tidal prism and the total water
9 volume in the lagoon during the spring tide period and assuming that the original water
10 mass in the lagoon decreases exponentially. This simple estimation did not consider the
11 factor of return flow (Luketina, 1998). Also it did not resolve the temporal and spatial
12 variability of the flushing properties in the lagoon, which perhaps are most important for
13 environmental management. A detailed study of variation of the flushing properties in the
14 lagoon, both spatially and temporally, is urgently needed.

15 From a water quality management perspective, some major questions still remain
16 regarding the status of the flushing efficiency of the lagoon at present compared with that
17 in its pristine condition 7 decades ago. Also, what degree of changes of the flushing
18 efficiency has the lagoon experienced, and what roles have human interventions played in
19 causing these changes? We believe that proper management of the water quality in the
20 lagoon for the future becomes possible only after these problems have been adequately
21 addressed.

22 Residence time is a convenient time-scale to represent the flushing properties of
23 lagoons. There is a diversity of definitions and computation methods of this time-scale

1 (see, for example, Bolin and Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984; Oliveira
2 et al., 1997; Shen et al., 2004; Wang et al., 2004; Delhez et al., 2005; Jouon et al., 2006).
3 In this study the time scale is defined based on Takeoka (1984) as ‘the residence time at a
4 given location in the lagoon is the time it takes for a water parcel, initially located at the
5 location considered, to leave the lagoon.’ This definition stands for the spatial variability
6 of flushing properties in the lagoon. The residence time for the whole lagoon can be
7 expressed by a spatially averaged residence time (Jouon et al., 2006) or by the time at
8 which the amount of released particles that leave the lagoon is 63.21% $[(1 - e^{-1})]$, 50%,
9 or 99% of the total original amount of particles (Oliveira et al., 1997). In this paper, the
10 spatial average residence time has been utilized.

11 In this study, a calibrated model was used to provide the hydrodynamic field to drive
12 Lagrangian particle tracking to study the residence times of the Xiaohai lagoon at present
13 and 7 decades ago. Based on the analysis of model results, the cause of changes of the
14 average residence time and the spatial distribution of residence times were examined. The
15 impacts of human activities on the changes of lagoon’s flushing efficiency were
16 investigated, and some suggestions were proposed for the future water quality
17 management.

18

19 **2. Study site**

20

21 Xiaohai Lagoon is located on Hainan Island, which is the largest tropical island in
22 China. It lies along the eastern shore of Wanning County, Hainan Island, with a latitude
23 ranging from 18°47’ to 18°53’N and a longitude ranging from 110°26’ to 110°34’E. It is

1 a typically well-developed tidal inlet-lagoon system with a north-southward length of 10
2 km, and an east-westward width of 3.5 to 7.0 km. In 2001, it consists of a north sand
3 barrier, a south sand barrier, a flood-tidal delta, a sand spit, a tidal inlet, a tidal channel,
4 and an inner lagoon (Fig. 1). In this study, inner lagoon is referred to as the area where
5 the tidal channel disappears and the tidal current is weak, and separated from the outer
6 lagoon by the line which connects two coastline promontories from the tidal channel area
7 (Fig. 1). Near the inlet throat, there are two bedrock islands, Neizhi and Waizhi, which
8 are composed of granite rock.

9 Xiaohai is located within the tropical monsoonal climate zone. The average river
10 discharge from the surrounding watershed to Xiaohai Lagoon was approximately 46.72
11 m^3s^{-1} per year before the river diversion works completed in Taiyang River in 1972. After
12 that, the river discharge decreased by about half to 26.46 m^3s^{-1} . The discharges of the
13 surrounding rivers are shown in Table 1.

14 The average tidal range is 0.71 m at Neizhi Island with an irregular diurnal type. The
15 salinity at the outside of the lagoon varies from 26 to 34 ppt and varies from 9.5 to 14.0
16 ppt in the inner lagoon. The salinity is lower than 5 ppt near the river entrances. Due to
17 the shallow water depth and low freshwater discharge, the water column is generally
18 well-mixed except temporal occurrence of stratification during flood events (Hu et al.,
19 1994). Therefore, a 2-D barotropic model is suitable in this study.

20 During the past 7 decades, Xiaohai Lagoon has endured dramatic morphological and
21 hydrodynamic changes caused by both natural processes and human activities (Gong et
22 al., submitted). Prior to 1972, natural processes controlled the evolution of the system.
23 There were two openings of the inlet, the North Opening and South Opening, separated

1 by Neizhi Island. The inlet was characterized by a southward extension of the north sand
2 barrier due to the predominant southward longshore sediment transport, resulting in
3 narrowing and shoaling of the North Opening. The flood-tidal deltas underwent a series
4 of mergings and expansions. In contrast, the south sand barrier extended northwardly
5 mainly during the summer season when SE waves prevailed. The relatively large runoff
6 during summer had a great effect on flushing out the sediments and pollutants. After
7 1972, human interventions changed the morphology of the system. The North Opening
8 was closed, and the morphological evolution was characterized by a continuous extension
9 of the south sand barrier and narrowing of the inlet. A large portion of tidal flats was
10 reclaimed for constructing shrimp pools. With the morphological evolutions, the tidal
11 hydrodynamics has experienced great changes as well. The tidal propagation from the
12 nearshore into the lagoon has been impeded and the tidal amplitude in the lagoon has
13 decreased, which resulted in a decrease of the spring tidal prism from $3.68 \times 10^7 \text{ m}^3$ in
14 1936 to $0.5 \times 10^7 \text{ m}^3$ in 2001. The velocity asymmetry has changed from ebb-dominant to
15 flood-dominant, and the relative importance of the river inflow to the tidal effect has
16 increased. These morphological and hydrodynamic changes must have led to significant
17 modifications of the flushing efficiency of the lagoon.

18

19 **3. Methodology**

20

21 In this study, a Lagrangian particle tracking method was used to study the residence
22 times in Xiaohai Lagoon. Lagrangian models appear as a very handy and naturally suited
23 set of tools to investigate and model the transport pathways, mixing and estuary-ocean

1 exchange of dissolved pollutants (Dimou et al., 1993; Bilgil et al., 2005; Burwell et al.
2 1999).

3 A hydrodynamic model of Xiaohai Lagoon (Gong et al., submitted) was utilized to
4 generate the hydrodynamic fields for driving the Lagrangian particle motion. The depth-
5 averaged barotropic model of ELCIRC (Zhang et al., 2004) was used to simulate the tidal
6 hydrodynamics. The model used an unstructured orthogonal grid comprised of both
7 triangles and quadrilaterals, in which triangles were used to represent most of the model
8 domain and quadrilaterals were used to resolve the inlet and the tidal channel. The model
9 domain extended from the lagoon coastline offshore to the 80-m water depth contour.
10 The spatial resolution of the grid ranged from 1000 m near the offshore open boundary to
11 30 m in the inlet and tidal channel areas. The model was forced by water elevation of four
12 main tidal constituents (K_1, O_1, M_2, S_2) at the offshore open boundary, and river
13 discharge was specified as an inflow boundary condition. Wetting-and-drying processes
14 were properly addressed in the model. Due to the utilization of the Eulerian-Lagrangian
15 scheme for the advection term, a large time step of 60 s was used in the simulation. In
16 2001, the width of the inlet throat was approximately 60m, 2 grid cells were used to
17 resolve the inlet throat. Because finite difference scheme is applied to the orthogonal
18 quadrilateral model grid, fewer grids are needed to represent narrow inlet. Numerical
19 tests have confirmed that only few cells are need for correctly simulating inlet
20 hydrodynamics. The model has been well calibrated based on the 2001 field
21 measurement data (Gong et al., submitted).

22 Lagrangian particle tracking was performed in a 2-D mode, using a 4th order Runge-
23 Kutta (RK) scheme for particle advection. This was combined with a random walk model

1 of horizontal eddy diffusion that enables a particle-based statistical treatment of turbulent
2 mixing. The position of a particle is given as:

$$3 \quad \bar{x}(t + \Delta t) = \bar{x}(t) + \bar{u} * \Delta t + z_n \sqrt{2 * d_h * \Delta t} \quad (1)$$

4 Where \bar{x} is the particle's position, Δt is the time step, \bar{u} is the velocity vector, d_h is
5 the horizontal diffusion, z_n is a random vector normally distributed with an average
6 value of zero and unit standard deviation, which was obtained based on Press et al.
7 (1994).

8 Due to the relatively large timestep used in the hydrodynamic model, the timestep
9 was divided into multiple sub-time steps to track particles for meeting the Courant-
10 Friedrichs-Levy (CFL) condition. During every sub-time step, the movement of the
11 particle due to advection was calculated by the 4th order RK scheme following Blanton
12 (1993). Combined with a quick search algorithm embedded in ELCIRC for determining
13 the destination cell into which the particle moved, the velocity at the particle's position
14 was obtained by linear interpolation if the particle was in a triangle cell or by bilinear
15 interpolation if in a quadrilateral cell. When the particle moved across a land boundary or
16 from a wet cell to a dry cell, only the tangential velocity at the edge was used to prevent
17 the particle being transported outside of the land boundary or moving into land areas.

18 In this study, the model was configured to represent both 2001 and 1936 bathymetries
19 and river discharges, respectively, for different modeling scenarios. The bathymetries of
20 the lagoon in 2001 and 1936 are shown in Figs.1 and 2, respectively. In each case, the
21 model was run with the particles released at slack before ebb, peak ebb, slack before
22 flood, and peak flood during both spring and neap tides. For each simulation, the particles
23 were placed in every nodal point in the lagoon and the simulation lasted for 180 days.

1 Because small portion of particles located near both eastern and western corners of the
2 inner lagoon were almost trapped completely, 180 days were used as truncation without
3 losing significance. The diffusion coefficient was set as $0.01 \text{ m}^2\text{s}^{-1}$ uniformly based on
4 Oliveira et al. (1997). The definition of ‘once-through’ instead of ‘re-entrant’ residence
5 time (Oliveira et al., 1997) was used because the current is strongly ebb-biased in the
6 inlet and a long-shore current prevails outside the inlet (see later sections). The time at
7 which the particle left the inlet was recorded as the residence time of that particle. For the
8 particles that still stayed in the lagoon at the end of the simulation, the residence times
9 were specified as 180 days. The results obtained for eight particle release simulations
10 were averaged to represent the residence times in the lagoon in each scenario.

11

12 **4. The change of residence times from 1936 to 2001**

13

14 The distribution of residence time of 2001 is shown in Fig. 3a. The average residence
15 time of the lagoon was 71 days. The distribution pattern of the residence time showed
16 that the particles located near the inlet and in the tidal channel areas escaped the inlet
17 quickly within 2 days. The residence time increased from the tidal channel to the inner
18 lagoon gradually. A sharp transition of residence time was visible in the middle of the
19 inner lagoon from the tidal channel to the entrance of Beipo River. The residence times at
20 the western side were shorter than those at the eastern side, which mainly resulted from
21 the additional freshwater discharges of 2 small rivers located along the western side of
22 the inner lagoon (Fig.1). Two dead zones existed at both the western and eastern corners
23 of the inner lagoon where the residence times were longer than 150 days.

1 The spatial distribution of residence times of 1936 is shown in Fig.3b. The average
2 residence time of the lagoon was 45 days, indicating an increase of the average residence
3 time by 59% from 1936 to 2001. The distribution pattern of the residence times in 1936
4 was greatly different from that in 2001. A horizontal circular pattern was visible. The
5 particles in the downstream portion of the eastern side of the lagoon escaped the lagoon
6 quickly within 2 day. The residence times gradually increased both towards the west and
7 upstream. The 10-day contour protruded over most of the inner lagoon mainly along the
8 eastern side of the lagoon. This circular pattern was mainly caused by the bathymetry.
9 There were three sub-flood tidal deltas located near the inlet in 1936 (see Fig. 2a-b).
10 There were two tidal channels separated by the flood tidal delta and connected the tidal
11 inlet with the inner lagoon, which were referred as the northern tidal channel and the
12 southern tidal channel, respectively. The distribution pattern suggested that the particles
13 in the northern tidal channel moved into the lagoon and escaped through the southern
14 tidal channel. Therefore, the residence time at the northern tidal channel was longer than
15 that at the southern tidal channel. The particles near the entrance of Beipo River could
16 move out of the lagoon within 15 days, which was much more rapid than that for the
17 2001 simulation. In 1936, the areas of the dead zones at the western and eastern corners
18 of the inner lagoon were significantly smaller than those in 2001.

19 To gain insight of the mechanism causing such a change of residence time from 1936
20 to 2001, the Lagrangian residual currents during these two different years were computed
21 from the model results, which are shown in Figs. 4a and 4b, respectively, for 2001 and
22 1936. Because the dominant tidal constituents in Xiaohai Lagoon area are K_1 and O_1 , we
23 computed the Lagrangian residual velocity as the particle displacement between its

1 location at its release time and its location 25 hours later divided by this time interval.
2 When the particles left the inlet within 25 hours, the particles moved southward due to a
3 strong alongshore current. Since the locations of the particles at Hour 25 were separated
4 from the starting location by the shoreline, the Lagrangian residual velocity can not be
5 correctly estimated. Therefore, Lagrangian residual velocity was not computed for these
6 particles in the lagoon. The results of 8 simulations with different particle release times in
7 each year were averaged to obtain the mean residual velocities in 2001 and 1936,
8 respectively. Examples of trajectories of selected particles at different parts of the lagoon
9 released at peak flood during spring tides are shown in Figs. 5a and 5b, respectively

10 It can be seen that the residual current in the tidal channel area was strong and directed
11 uniformly seaward in 2001. The residual current along the central axis of the lagoon was
12 relatively strong, which was mainly caused by the freshwater discharge from the Beipo
13 River. The residual current was stronger at the western side than that at the eastern side.
14 Two null residual velocity zones were observed at both corner zones of the inner lagoon.

15 The Lagrangian residual current in the lagoon was much stronger in 1936 than in 2001.
16 The areas in the lagoon adjacent to the southern tidal channel had a large seaward
17 residual velocity (The seaward current in the southern tidal channel is not shown due to
18 the particles have escaped into the open sea in less that 25 hours). The seaward current
19 was also strong along most of the western side of the lagoon, and was present near the
20 entrance of Beipo River. At the region of the outmost part of the northern tidal channel,
21 the residual current was landward. The landward current continued along the shallow
22 areas between the northern and southern tidal channels, and extended further upstream
23 into the inner lagoon. From the existence of these current distributions, two large

1 horizontal eddies were formed. There was a clockwise one in the western side of the
2 lagoon, and an anti-clockwise one in the eastern side of the lagoon.

3 From the change of Lagrangian residual currents from 1936 to 2001, it can be
4 observed that the tidal currents have become weaker due to the great dissipation of tidal
5 energy from 1936 to 2001 (Gong et al., submitted), resulting in the decrease of the
6 Lagrangian residual current as a whole. In 1936, with the coexistence of two tidal
7 channels, the mass transport took different pathways. The particles at the northernmost
8 part of the northern tidal channel and the shoals between the northern and southern tidal
9 channels were mainly transported landward, whereas at the southern tidal channel they
10 were transported seaward. The 2 eddies around the tidal channel and inner lagoon made
11 the mass transport more complex. In 2001, the southern tidal channel and the surrounding
12 tidal flat had been reclaimed as land, the mass transport became more concentrated in one
13 tidal channel. A dividing line is visible between the tidal channel and the entrance of a
14 main inflowing river-Beipo River, which separated the inner lagoon into west and east
15 parts. The mass transport between the inlet and the inner lagoon was more like a back-
16 and-forth movement.

17 Fig. 5a shows the trajectories of selected particles released at different parts of the
18 lagoon in 2001 for a period of 90 days. Fig. 5b shows the trajectories of particles in 1936
19 for a period of 22.5 days. It can be seen that particles were transported mostly southward
20 along the nearshore coast once the particles escaped from the lagoon and could not
21 reenter the lagoon, justifying the use of the “once through” definition of residence time in
22 this study. In 2001, all the particles in the tidal channel area could be transported out of
23 the inlet, while the particles along the center line of the inner lagoon moved out of the

1 lagoon slowly. Particles located at the side corners were trapped in the inner lagoon. It
2 can be seen that particles near the Beipo River followed different pathways to move out
3 of the lagoon in the 2001 and 1936 simulations. For examples, in 2001, a particle at the
4 entrance of Beipo River (particle 8) moved along the eastern side of the inner lagoon,
5 entered into the tidal channel, and escaped from the inlet. In the 1936 simulation, the
6 particle at the same location moved to the western side of the inner lagoon, then drifted
7 into the southern tidal channel by the residual current and escaped from the inlet.
8 Although the particle traveled through a very large cross-sectional area, it moved out of
9 the lagoon rapidly. The well-developed horizontal circulation was clearly seen in this
10 transport pattern and played a role in decreasing the average residence time of the lagoon.

11

12 **5. The impacts of human activities on the change of residence times**

13

14 The natural evolution of the system had been interrupted greatly by human
15 interferences since 1972. To concentrate the flow in the South Opening, an effort was
16 made to close the North Opening artificially. Meanwhile, Taiyang River was diverted
17 directly into the ocean for irrigation and river flood mitigation purposes that resulted in
18 the river inflow to the lagoon being reduced by 50%. The old flood-tidal delta and nearby
19 tidal flats were reclaimed and merged into land area. As a result, the southern tidal
20 channel disappeared. A large bend was formed from the inlet throat to the inner lagoon
21 along the tidal channel. Impacted by these human activities, the dynamics of the lagoon
22 had been altered. It was expected that the flushing ability of the lagoon would also be
23 changed.

1 To understand the influences of human interruptions on the change of flushing
2 efficiency, another suite of model experiments were conducted. Since most of these
3 human activities were conducted shortly after 1972, the 1975 bathymetry was selected as
4 the baseline bathymetry for the study. This bathymetry is shown in Fig. 2c-d. In 1975, the
5 North Opening was closed. The freshwater discharge in 1975 (i.e., reduction of 50% of
6 the flow before 1972) was used as river inflow. For the baseline simulation, the particle
7 release times were the same as those in previous model simulations. For comparison
8 studies, three model runs were conducted with respect to scenarios with restoration of
9 river inflow to the level before 1972, keeping the North Opening open, and with land
10 reclamation in the lagoon.

11 The distribution of residence times in the lagoon for the baseline situation is shown in
12 Fig. 6a. The average residence time was 73 days. It can be seen that the particles could
13 generally escape the lagoon quickly in the tidal channel area. It required a longer time for
14 the particles to be transported out of the lagoon in the northern side shoal areas along the
15 channel. The particles' movement became slow in the center of the inner lagoon. It
16 appeared that the particles took two pathways to move out of the lagoon from both the
17 west and east sides. There were 2 tongue-shaped areas extending from the tidal channel
18 area into the inner lagoon with shorter residence times. The possible cause of that was
19 due to the existence of a shoal between the end of tidal channel and the center of the inner
20 lagoon, constricting the particles in the center of the inner lagoon from transporting
21 seaward. The influence of this topography was evident in causing the contours of
22 residence time of 20 and 25 days to protrude into the tidal channel from the inner lagoon.
23 In the side corners of the inner lagoon, the residence times became longer.

1

2 *5.1. Influence of river flow reduction*

3

4 The change of freshwater discharge can lead to a change of advection and residual
5 circulation. Freshwater inflow is one of the dominant factors of residence time change in
6 large estuaries (Shen and Lin, 2004). It was expected that residence time of the lagoon
7 would change correspondingly resulting from the 50% reduction of river inflow from
8 1972 to 1975. A scenario with restoration of river discharge to the level before 1972 was
9 simulated. The result is shown in Fig. 6b. The difference of residence between increase of
10 river and baseline condition is shown in Fig. 7a. It can be clearly seen that the residence
11 time of the whole lagoon decreased significantly with the increase of river inflow
12 compared to the baseline result (Fig. 6a). The average residence time of the lagoon
13 became 54 days, showing that the average residence time increased 33% after reducing
14 the river inflow. Compared to the baseline situation, the particles in the inner lagoon and
15 along the tidal channel could transport out of the lagoon more rapidly. A sharp transition
16 of residence time was evident along the central axis linking the end of the tidal channel
17 and the entrance of Beipo River. The residence time was shorter along the east side of the
18 lagoon than along the west side. Except for the particles in the side corners of the inner
19 lagoon, most of the particles could move out the lagoon during the simulation period. The
20 influence of the shallow area between the end of the tidal channel and the inner lagoon on
21 residence time in the central portion of the inner lagoon was reduced, probably resulting
22 from strong advection enhanced by the increase of freshwater discharge.

23

1 5.2. Influence of closure of the North Opening

2

3 The flushing efficiency of a lagoon depends on both the tide and freshwater water
4 discharges. The characteristics of tidal propagation from the outside into the lagoon can
5 be changed once the morphology of the inlet is changed. However, the influence of
6 closure of the North Opening on the lagoon residence time is not clear. A scenario with
7 the North Opening open was conducted. In order to amplify the effect, we set the width
8 of the North Opening to be 140 m, which is about 2 times of the width in 1972. The result
9 is shown in Fig. 6c. The average residence time became 72 days, which was slightly
10 reduced compared to the result of the baseline condition. The distribution pattern of the
11 residence times was similar to the baseline result. The main change took place at the
12 northern tidal channel. With the North Opening open, particles at the northern tidal
13 channel could transport through the North Opening freely to open sea. However, for most
14 of the lagoon, the changes were minor, showing that closing the North Opening had a
15 minor effect on the flushing efficiency of the lagoon.

16

17 5.3. Influence of land reclamation

18

19 Increase of land reclamation in the lagoon will decrease the total volume of the lagoon.
20 Additionally, the change of morphology of the lagoon due to land reclamation can have a
21 profound impact on the dynamics of the lagoon. With the increase of human activities of
22 land reclamation, the southern tidal channel and the nearby tidal flats became land, which
23 resulted in narrowing of the entrance to the inner lagoon and decreasing the intertidal

1 zone. Consequently, it restricted the tides from propagating into the lagoon and reduced
2 the tidal prism.

3 To understand the influence of land reclamation on residence time of the lagoon, a
4 scenario was conducted by merging the southern tidal channel and the nearby tidal flats
5 to the southern bank. The new geometry resembled the condition of 2001 except that the
6 water depth in the tidal channel and the inner lagoon was larger than in 2001. With the
7 land reclamation, the southern tidal channel no longer existed and the only channel that
8 connected the inlet and the inner lagoon was through the northern tidal channel. The
9 model result after land reclamation is shown in Fig. 6d. The difference between increase
10 of land reclamation and baseline condition is shown in Fig. 7b. The average residence
11 time was 84 days, an increase of 15% compared to the baseline result. The contours of
12 residence time generally shifted seaward. The 25-day contour lines before land
13 reclamation were virtually replaced by the 50-day contour lines. The areas, where
14 residence time exceeded 150 days, increased significantly in the east corner of the lagoon.
15 With the decrease of tidal prism, the relative effect of river discharge became more
16 important. The impact of river discharge from the Beipo River on the residence time can
17 be seen along the central axis of the inner lagoon, which separated the eastern and
18 western regions of the lagoon.

19

20 **6. Discussion**

21

22 *6.1. Sensitivity of diffusion coefficient*

1 The accuracy of the residence time calculation using Lagrangian particle tracking
2 depends on a number of factors. The release time of the particles with respect to tidal
3 phase is one of them (Awaji, 1982; Oliveira et al., 1997; Bilgil et al., 2005). Usually, the
4 residence time calculated from an ebb time release is shorter than that calculated from a
5 flood time release. The tidal range can also play a role in residence time. In a common
6 sense, the larger tidal range during the spring tide increases tidal prism and, thus,
7 increases tidal velocity and leads to a shorter residence time than occurs during the neap
8 tide. However, the study of Oliveira et al. (1997) demonstrated that this is not always the
9 case. In their study, larger tidal ranges do not always lead to faster removal of particles
10 and the removal rate depends on the release time. Another important factor is the
11 horizontal diffusion coefficient. As stated by Oliveira et al. (2006a), the choice of the
12 horizontal diffusion coefficient in the particle tracking simulations should be based on the
13 physics represented in the model and on the horizontal grid resolution. A coefficient of
14 0.01 was used in their study. Another study in the Guadiana Estuary by Oliveira et al.
15 (2006b) showed that the differences in residence times between the two simulations with
16 different diffusion coefficients are small compared to the variability related to the release
17 times, and are much smaller than those associated with a reduction of river flow. In
18 contrast, the simulation experiments conducted by Bilgil et al. (2005) showed that the
19 presence of diffusivity is of prime importance to the exchange. Their results showed that
20 allowing even weak diffusion is sufficient to cause a significant decrease in the fraction
21 of particles retained, but increasing the diffusivity by a factor of 10 leads to little further
22 exchange, except in those areas dominated by diffusion.

1 In this study, the residence time has been calculated by averaging eight simulations
2 with particles released at slack before ebb, peak ebb, slack before flood, and peak flood
3 during both spring and neap tides. Therefore, the effects of the release time relative to
4 tidal phase and the tidal range have been taken into consideration. On the other hand, the
5 sensitivity of the model results with regard to the diffusion coefficient needs to be
6 examined further.

7 The above model simulations used a uniform diffusion coefficient of $0.01 \text{ m}^2/\text{s}$. To
8 test the sensitivity of the selection of the diffusion coefficient on the residence time, we
9 conducted a series of model experiments with respect to the use of different diffusion
10 coefficients. A baseline simulation was conducted using 2001 bathymetry without
11 freshwater discharge and without diffusivity. All particles were released at slack before
12 ebb during spring tide. The simulation lasted for a total of 90 days. The average residence
13 time of all particles is 79 days. Model results with the use of different diffusion
14 coefficients are shown in Fig. 8. It can be seen that including a weak diffusion can
15 sharply decrease the average residence time, while further increasing the diffusivity
16 results in a slight decrease of the average residence time. Model experiments involving
17 the annual mean river inflow in 2001 were also conducted. The results with different
18 diffusion coefficients are also shown in Fig. 8. It can be seen that the average residence
19 time of the lagoon is greatly reduced. The results show that the impact of horizontal
20 diffusivity on residence time is insignificant compared to the influence of river discharge.
21 It suggests that the use of a small diffusion coefficient in the model simulations is
22 reasonable.

23

6.2. Influence of hydrodynamics on the residence time

Model simulation shows that the average residence time has increased greatly from 1936 to 2001. This change should be largely attributed to the corresponding hydrodynamic changes in the lagoon. A comparison of tidal propagation from the near-shore coast to the inner lagoon is shown in Fig. 9. The model results show that tidal dissipation increases continuously. The tidal energy dissipation was less than 1/10 in 1936 due to its relatively large depth and the open connection between the lagoon and the sea. In 1975, the amplitude of K_I decreased to approximately 1/3 of its value outside the inlet, as did the amplitude of O_I . The amplitude of M_2 in the inner lagoon was about 1/6 of that outside the inlet. In 2001, the amplitudes of K_1 and O_1 have decreased to be about 1/7-1/8 of their values outside the inlet, and the amplitude of M_2 in the inner lagoon was about 1/14 of its value outside the inlet. With the narrowing and shoaling of the tidal inlet, the dissipation of tidal energy increasingly resulted in poor circulation of the water in the inner lagoon.

Along with the tidal energy dissipation, the tidal prism of the lagoon experienced the same trend of decrease as the tidal amplitude. In 1936, the spring tidal prism of the lagoon was $3.68 \times 10^7 \text{ m}^3$. In 1975, it decreased to $1.114 \times 10^7 \text{ m}^3$, and in 2001 it decreased to $0.5 \times 10^7 \text{ m}^3$.

With the above notable changes of the tidal dynamics and morphological evolutions, the Lagrangian residual current also changed significantly. In 1936, strong horizontal circulation was well developed in the lagoon. Although the particles took complex pathways to be transported out of the lagoon, the residence time was much less due to

1 strong residual current. In 2001, the residual current became uniformly seaward, but
2 much weaker. Particles moved back-and-forth very slowly, and this resulted in the
3 increase of the residence time in the lagoon.

4 It is noteworthy that the spatial variability of the flushing properties of the lagoon is
5 important. For example, the spring tidal prism decreased from $1.114 \times 10^7 \text{ m}^3$ in 1975 to
6 $0.5 \times 10^7 \text{ m}^3$ in 2001 and the volume of the lagoon below the mean low water decreased
7 from $3.836 \times 10^7 \text{ m}^3$ in 1975 to $2.887 \times 10^7 \text{ m}^3$ in 2001. The estimated flushing times
8 $((V+P)/(P+R))$, where V is the water volume below mean low water, P is the tidal prism,
9 R is the river discharge during a tidal cycle) were 3 and 5 days in 1975 and 2001,
10 respectively. However, based on our model results, the average residence time in 1975
11 was longer than that in 2001. The difference can be attributed to the spatial variation of
12 the flushing capability. Since the lagoon is not spatially homogeneous, using a simple
13 method to estimate the flushing time is not accurate. The decrease of the average
14 residence time from 1975 to 2001 can be partially attributed to the change of
15 bathymetries, such as the disappearance of the shoal between the tidal channel and the
16 inner lagoon, which could have decreased the residence times at the tidal channel area
17 and the inner lagoon, thus decreasing the average residence time in 2001.

18

19 6.3. *Measures to improve the flushing efficiency of the lagoon*

20

21 From the above studies, the flushing efficiency of Xiaohai Lagoon has deteriorated
22 greatly from 1936 to 2001, with the average residence time increasing 59 %.

1 For the improvement of flushing efficiency of the lagoon, firstly, completely or
2 partially restoring the river inflow to its level before 1972 can be the most effective way;
3 secondly, combined with other harnessing measures for improving the stability of the
4 tidal inlet and mitigating river inundation disaster, dredging of the tidal channel and the
5 inner lagoon can also make great difference. Reopening the North Opening can have little
6 effect on improving the flushing efficiency of the lagoon and should not be considered as
7 an effective management option.

8

9 **7. Conclusion**

10

11 In this study, the hydrodynamic model with Lagrangian particle tracking was used to
12 investigate the changes of flushing properties in Xiaohai Lagoon and the impact of
13 human activities on these changes. The simulations of the 1936 and 2001 circulations
14 demonstrated the flushing efficiency of the lagoon has deteriorated greatly from 1936 to
15 2001. The average residence time increased from 45 to 71 days, with an increase of 59%.
16 The general Lagrangian residual velocity has decreased from 1936 to 2001, and the
17 residual current pattern has changed from the existence of strong horizontal circulations
18 in 1936 to a simple weak seaward current in 2001. Consequently, the spatial distributions
19 of the residence times also endured great changes.

20 For the factors that caused these changes, human activities have incurred great impacts
21 on the deterioration of flushing efficiency. The reduction of river inflow imposed the
22 most significant impact, causing an increase of average residence time of 33%. The land
23 reclamation in the lagoon came as the second most significant factor, causing a increase

1 of 15%, while closing the north inlet posed a relatively minor impact. For the future
2 water quality management, restoring the river inflow and dredging of the tidal channel
3 and the inner lagoon should be placed at the top priorities.

4

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6

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1

2 List of tables:

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4 Department, 1991)

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1 List of figures

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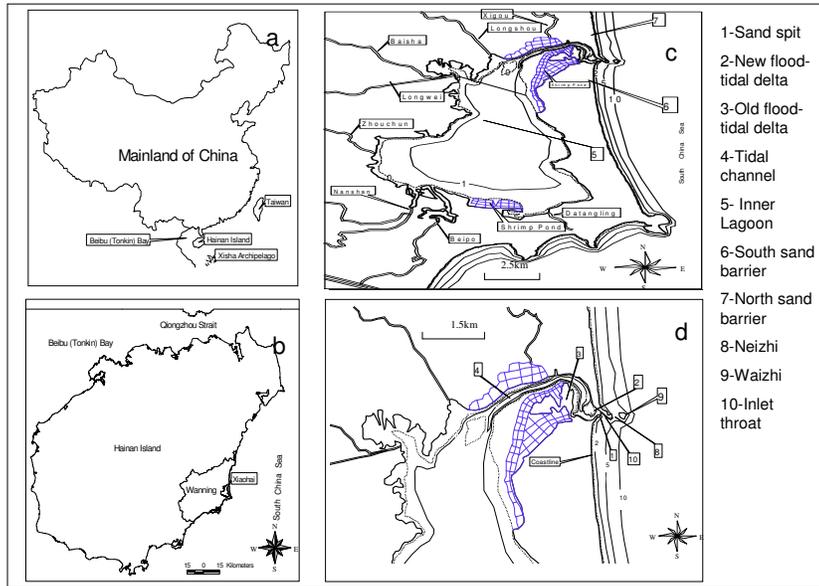
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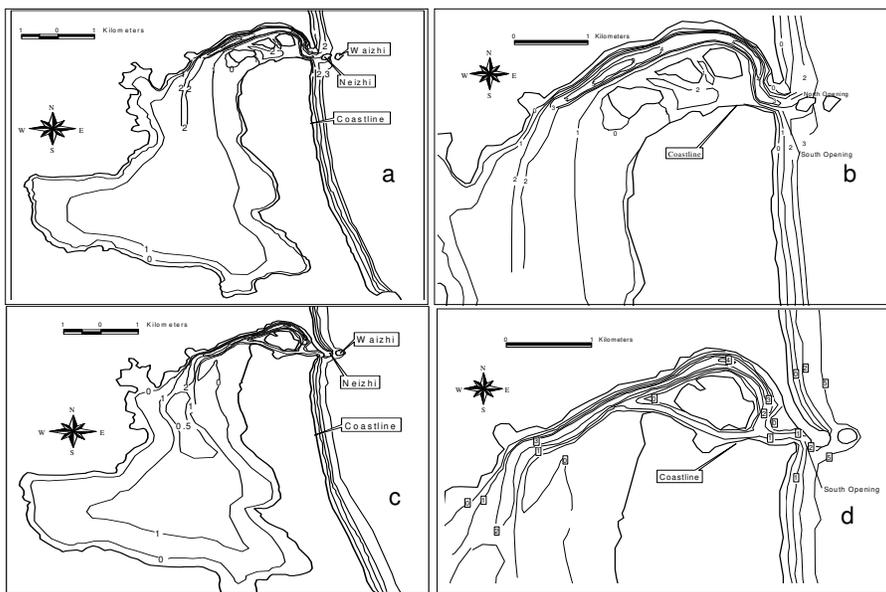
19 Fig. 8. Sensitivity of influence of horizontal diffusivity on residence time calculation with
20 and without river flow. Particles were released at slack time before ebb during spring
21 tides)

22 Fig.9. The tidal propagation characteristics from the near-shore coast to the inner lagoon



1

Fig. 1



1

Fig.2

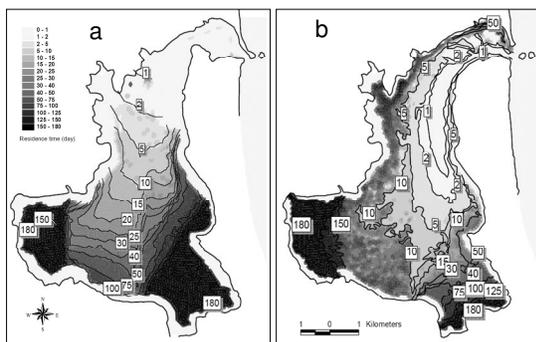


Fig.3

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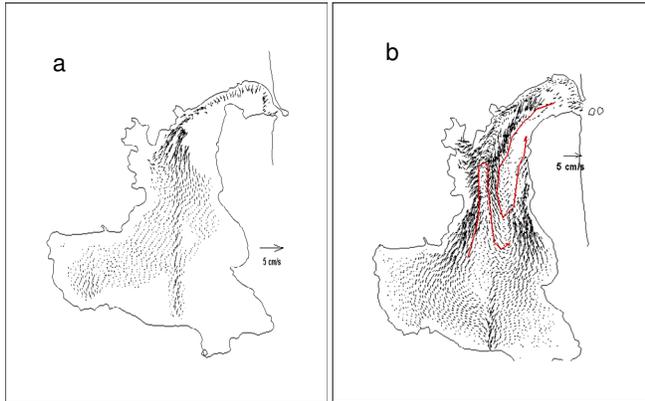


Fig. 4

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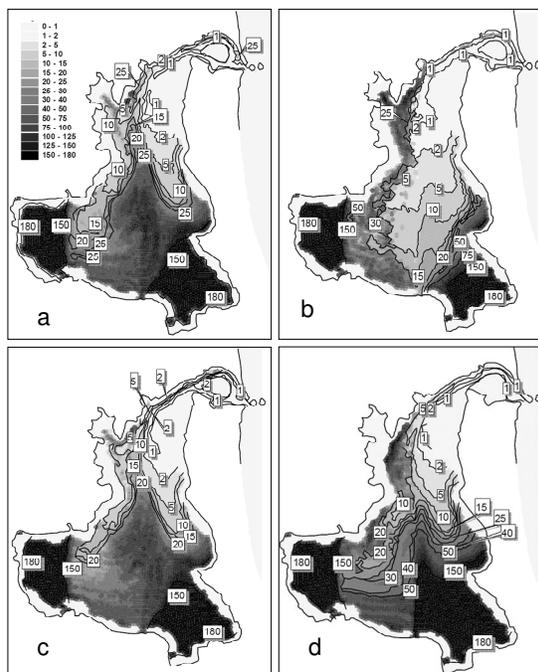


Fig.6

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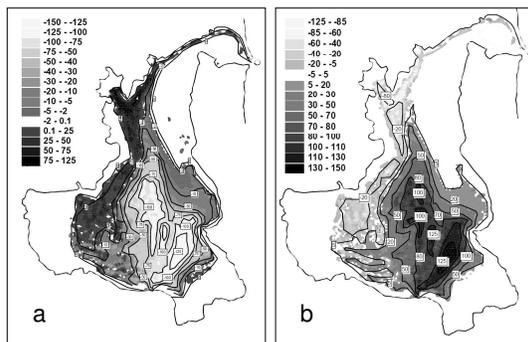


Fig.7

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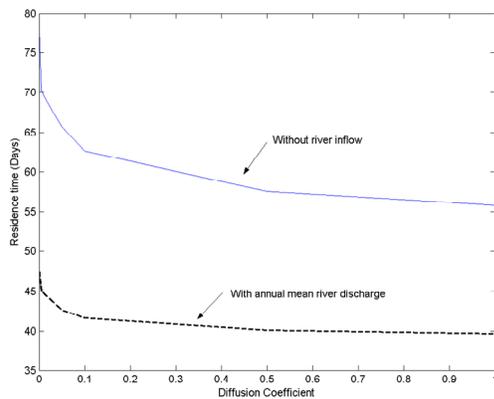
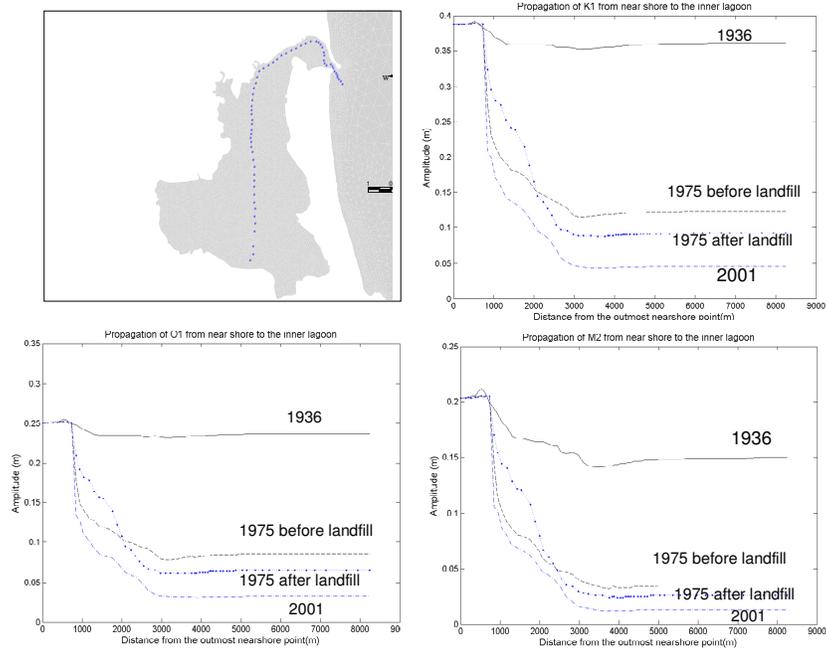


Figure 8

1



1 Fig.9

3 Table 1. The river discharge into Xiaohai Lagoon (based on the Wanning Hydraulics
4 Department, 1991)

5 Table 1. The river discharge into Xiaohai Lagoon (based on the Wanning Hydraulics
6 Department, 1991)

7

<u>River Name</u>	<u>Watershed area(km²)</u>	<u>Annually mean discharge(m³/s)</u>
<u>Old Taiyang River</u>	<u>576.000</u>	<u>20.260</u>
<u>Datanalin Creek</u>	<u>2.680</u>	<u>0.133</u>
<u>Beipon Creek(downstream of Taiyang diversion works)</u>	<u>30.350</u>	<u>4.820</u>
<u>Nanshan River</u>	<u>97.080</u>	<u>1.506</u>
<u>Zhouchun Creek</u>	<u>8.000</u>	<u>0.397</u>
<u>Louwusi River</u>	<u>138.200</u>	<u>7.844</u>
<u>Longshou River</u>	<u>133.750</u>	<u>6.740</u>
<u>Ninon river</u>	<u>42.250</u>	<u>2.087</u>
<u>Baishi river</u>	<u>36.150</u>	<u>1.794</u>
<u>Other sources</u>	<u>22.690</u>	<u>1.126</u>
<u>Total</u>	<u>After 1972</u>	<u>533.000</u>
	<u>Before 1972</u>	<u>1109.000</u>

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