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Abstract: Pearl River is one of the most important rivers in water resource system of South China. East River, West River and North River conflux at Pearl River estuary with eight bayous flowing into South China Sea. The characteristics of flow and tide in this sea area are in complex condition. Based on systematic analysis on historical research achievements for Pearl River Estuary, a 2-D mathematics model for large scale area including shallow sea area of eight bayous, Hongkong and Macao was approached to execute hydraulic numerical simulations under different hydrographic conditions such as "98.6" flood, "2001.01" dry season and "91.12" low water period with spring, middle and micro tidal boundary conditions separately. Approaching from analysis on the calculation results of flow vector field, potential lines, coastal current and salinity distribution, the movement features and regularities for tide current and salinity at Pearl River estuary were studied with emphasis in this paper. Moreover, these research achievements have unambiguous reference values in planning exploiting projects for sea coast, harbor developing and regulating engineering at Pearl River estuary.

Key words: Pearl River Estuary; Salinity distribution; Tide; Flow field; Seacoast flow; Mathematical model

1.Introduction

Pearl estuary river system is composed of Dongjiang River, Xijiang River and Beijiang River system, and runoff come from the upstream basin flow into the sea with eight big ostiums. The basin domain including after Sixianjiao station on Xijiang and Xijiang River and Longshi station on Dongjiang River was considered Pearl delta river system. North-South directional Portrait channels and West-East directional landscape orientation channels interleaved and composed Xijiang River and Beijiang River system. From nine dragons city located at Jiulong peninsula of Hongkong Special District in the east to goose neck of Chixi peninsula in the west, the total coastline length is more than 450 Kilometers. The pearl estuary is composed of eight large entrances to the South Sea of China: Humen, Jiaome, Hongqimen and Hengmen flow into the shallow area of Lingdingyang in the eastern sea area, and Modaomen, Jitimen, Hutiaomen and Yamen located from east to west in the western sea area. Modaomen and Jitimen infuse into sea area, however, Hutiaomen and Yamen flow into the neritic sea domain of Huangmaohai estuary.

The rivernet under research connects principal rivers including Xijiang, Beijiang upstream and links severals rivers such as Humen, Jiaomen, Hongqili and Modaomen downstream etc. The water level fluctuation and riverway evolvement of Peal delta river syetem are dominated by complex dynamic influence of the runoff and tidal current. The diversity of effect intension of river situation, runoff and tidal current can approach different effect functions. The upstream river system part give priority to runoff come from Xijiang and Beijiang river, and only the tidal fluctuation condition can take more vital role during the lower rain season. On the other hand, tidal hydrodynamic fluctuation control the current complexion of downstream riverways.Tidal waves and tideway introduce swarm into these large esturary entrances and take obvious status during the full year period. as a transition catchment, the hydynamic characteritics of middle reaches is influenced by both runoff flow come from upstream watershed and tidal current generated form open sea. Tidal movement features for river system area are challenging dynamic enviroment because of the runoff, waterway diretcions, underwater landform and boundary

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conditions are complicated issues in this estuary under research. As a result, the hydrodynamic features in this river system can be generalized in one sentence as following: runoff flow take a more important role in flood period and tidal current have a more influence factor during lower water seasons.

Considering the seawater quality in Pearal delta estuary, sodium chloride is the main salt subtance following by magnesium chloride, calcium chloride and sulphate etc. Under the contributions by river discharge and ocean tidal, seawater salinity is a seasonal variable parameter fluctulates with various factors including season alternating, river discharge variation, tidal styles difference, different locations, time stages in the tiding course and wind field features. Combined with tidalway movement regularity and inherent self-particularity of this esturay area, the salt wedge dynamics features in the esturay are considered as a question needing more embedded research.

2 Description of Numerical Model for Tidal Current

2.1 Model research domain

A horizontal two-dimensional (Vertical averaged) numerical model was implemented to study the hydrodynamics, saltwater intrusion, and suspended sediment in the Pearl River entrance area. As upper numerical simulation boundary conditions, a one dimensional rivernet hydrodynamics model was build up to caluculate upper runoff procedure for 2-D Tidal Current model. To seek upstream boundary conditions not influenced by the tide, the computational domain of a model should be extended to, or beyond, the tidal limits in the tributaries as well as in the mainstream. For tidal rivers with a well-defined fall line, the tidal limits are located at fixed points. Eight specified hydrologic staions were applied as upper simulation boundarys including Dahumen, Nansha located at Jiaomen, Fengmamiao station, Hengmen station, Denglongshan mountain station, Huangjin staion, Xipaotai station sited at Hutiaomen and Guanchong staion located at Yamen. The downstream boundary is located at the river mouth where the water surface elevation and high tide salinity are specified. In order to obtain more real simulation results, the -30m isobath line at outside sea was selected as downstream boundary condition for enough calculation scope. Moreover, Zhenhai Bay located at Shangchuan island Daxingshan nearby Dayawan Bay were western and eastern simulation boundary conditon. All the water area under calculation cover 2000km^2 whose width exceed 300km and lenth about 125km. Research extension was shown in fig.1 as follow.

2.2 Integrated Hydrodynamic and Sediment Movement Equation

Applying coordinate transforming method, this complex calcunation domain was converted into regular numeration format for more convenient mathmatic tractability. In simulated coordinate system, the hydrodynamic and sediment movement equation for the 2-D horizontal integrated numerical model is

$$\frac{\partial(H\varphi)}{\partial t}+\frac{\partial}{\partial\zeta}\left(C_\eta Hu\,\varphi\right)+\frac{\partial}{\partial\eta}\left(C_\zeta Hv\,\varphi\right)=\frac{\partial}{\partial\zeta}\left(\Gamma_\varphi H\frac{C_\xi}{C_\eta}\frac{\partial\varphi}{\partial\xi}\right)+\frac{\partial}{\partial\eta}\left(\Gamma_\varphi H\frac{C_\xi}{C_\eta}\frac{\partial\varphi}{\partial\eta}\right)+\mathrm{S}_\varphi \qquad (1)$$

Where u and v, averaged velocities in the ζ -and η- dirctions respectively, H is water depth, river width, g is gravity acceleration, φ is the symbol of velocities in the ζ -and η- dirctions, S is sediment concentration coefficient, S_φ is sediment concentration, C_ζ and C_η are coefficients in orthogonal curve coordinates difined as $C_\zeta=\sqrt{x_\zeta^2+y_\zeta^2}$, $C_\eta=\sqrt{x_\eta^2+y_\eta^2}$, x and y are horizontal coordinate axial lines.

A implicit and explicit direction alternative difference method (ADI method) method was choosed to disperse differential equations for this numerical model.Then, the quick pursuing scheme solution was adopted to solving these mathematics equations.

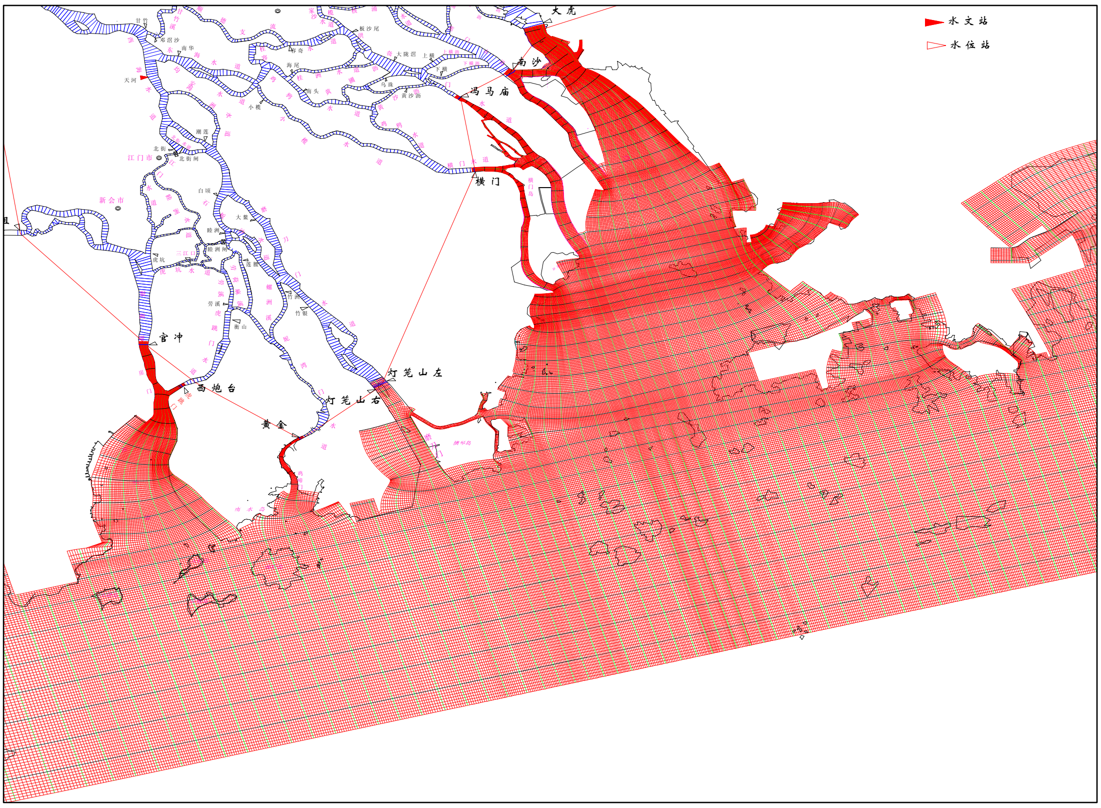


Fig.1 Calculation grids of numerical model domain for Pearl River estuary

2.3 Boundary condition and Solving for wetting and drying

Considering the real upstream and downstream conditons of this numerical simulation, typical monitoring hydrographic datas for water levels and real-time runoff courses were applied to the boundary conditons setting under different hydrographic and hydrodynamic conditions. For calculation stability reasons, time step of calculation should be selected with stirct requirement as follow: $\Delta t/2 < \alpha \cdot \Delta s \big/ \sqrt{gH_{\max}}$,where α is a fator coefficient between 1 and 3.

One of the major advantages of the formulations natural and robust handling of wetting and drying. We retain their approach in moving boundary technology method at calculation domain border lines. Turn into bottomland without flow during ebb tiding period , moreover, submersed domain will be transformed into calculation water area in flood time.

The model was calibrated against tidal height datas obtained at several locations along the estuary. Because of the shortage of hydrodynamic datas from the river system, an accurate calibration using the methods described by Fread and Smith (1973) was possible.The model was calibrated by adjusting the Manning's n until a best fit between predicted and observed tidal ranges along the estuary was obtained. Considering the reason of this paper lenth, calibrated datas under representative hydrology such as flood season, middle period and low-water seasons for the whole Pearl estuary domain mathematics model were described in refereces No.4 listed at the ending of this paper.

3. Tiding and hydrodynamic Characterics of Pearl estuary

3.1 Tiding and hydrodynamic Characterics

As representive hydrodynamic symbols of river discharge and ocean, tide at the entrance to the estuary and freshwater discharge are two physical significant hydrodynamic mechanism at estuary domain. With the diversity of dynamical conditons at the Pearl estuary regin, these primary eight river entrances can be classed as two styles entrances: tidal current dominated entrances like as Humen, Jiaomen and Yamen; river runoff typical entrances including Modaomen and the others. The averaged range of tide at these eight entrances is 0.86～1.63m, and during flood tide, measuring datas show that water quantity flow into the estuary at Humen station is most prodigious with most range of tide. The ratio of tide water and river discharge are about 0.26~0.31 among them. As described listed above, Modaomen is the main flood dischrge gateway of Xijiang River during flood season with most water quantity of annual runoff and lowest ratio of tide water and river discharge.

The tide style at Pearl estuary is irregular and composited with one day half period. Two springs and two neaps will occured during one day and a great tiding period and a low tiding period will last three days separately in half moon. The tide current show disparate characterics between different hydrology years. Tide rising and ebb-tide process show evident orderliness. With influence and restriction caused by river discharge,landform status and boundary conditons, the tide current movement mechanism at estuary domain is full of complexity puzzles.The river system domain will be impacted by salty seawater during the whole year. With great runoff from upstream darinage basin in flood season, salinity intrusion can only affect the domain near these estuary entrances, but less or not so at top section of river net inland.As a result, tide hydrodynamic phenomena can be intensified in low rain season for feeble discharge water quantity. Research outcoming shows that river runoff and ocean tiding motivity at estuary are twain hydrodynamic forces which are opposited and subsisted on each other.

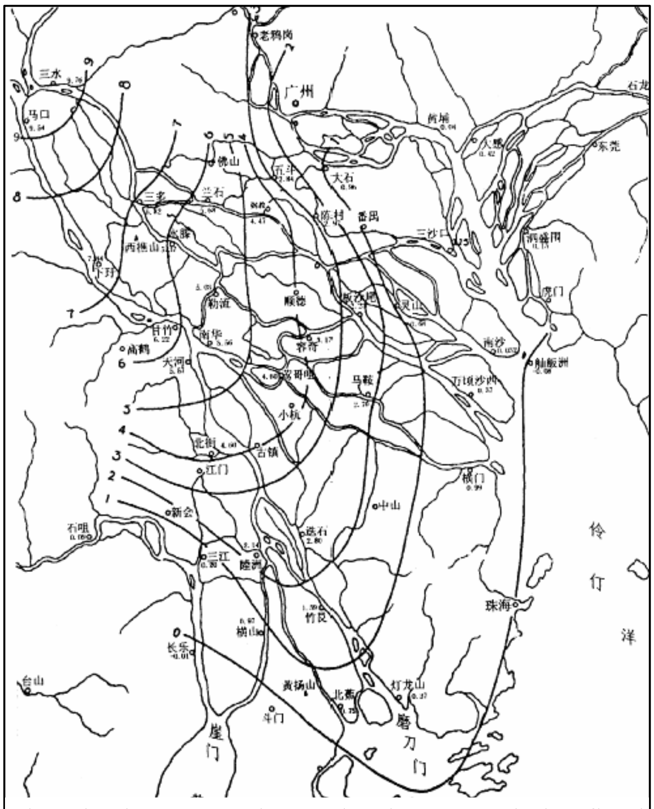


Fig.2 the day averaged water level contours during flood season of Pearl delta estuary (1968.6.27)

3.2 Tide level Characterics

For paper length reason, only the day averaged water level contours during flood season of Pearl delta estuary domain was shown in Fig.2. Water level contours figure indicate water levels at different entrances is variant at instantaneous time obviously.

The isoline of zero tide water level did not beyond the entrances to outside ocean at Yamen and Shiziyang martime stations. The one meter isoline of tide height reach the river cross sections located at Dashi and Panyu etc. where near Dahu hydromatic station no more than 30 kilometers. On the contrast, the one meter isoline of tide height only reach Zhupaisha station where part from

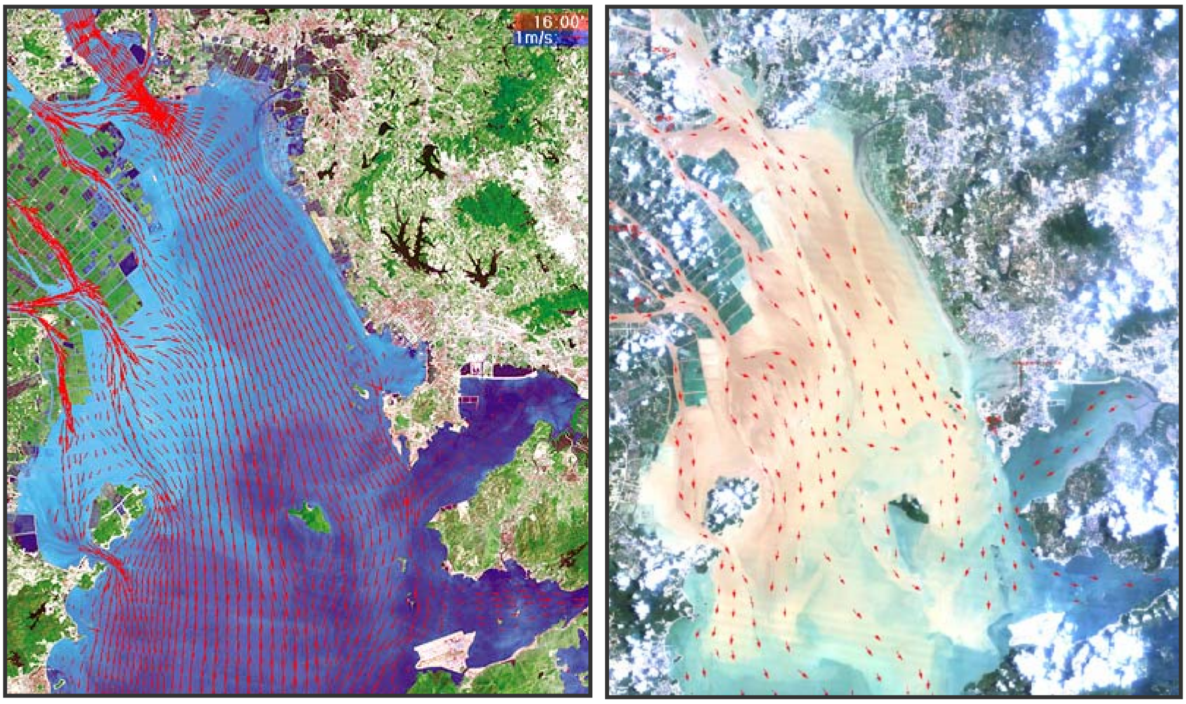
Denglongshan station 2 kilometers at Modaomen water channels. The water level contours approach the ocean more nearly at the domains river discharge dominated.

As discussed above, after confluence of Xijiang river and Beijiang river at Makou and Sanshui stations, the water levels contours with great camber run to curve from beelines. Flood flow slowly in west and east water channels, however flood run down with a great velocity at Modaomen which locat at central section of research domain. The flood dicharge velocity was weakened by the tide dynamic force at entrances like Huangmaohai and Shiziyang. Historical monitoring datas show that averaged annual runoff volume of Modaomen channels is more than $9.23\times10^{8}m^{3}$ which contributes about 28.3% of total flow in this investigated area.

A “high water pressure area” was created by Xijiang river and Beijiang river runoff flow at the main delta dominated catchment. At the two side limbs of the main delta, a “low water pressure area”was generated at flat ground under Xiliuhe River and Tanjiang River for low water level near ocean surface. As a result, a biggish horizontal water gradient exist between these domains. Following the advancing direction to east-south, the feature of unbalanced sediment is more remarkable. Moreover, during the flood season, the apparent spatial distribution difference of hydrodynamic characterics will be enhenced.

3.3 Velocity Characteristics

A further test of the model was conducted by comparing predicted velocity distributions with the observed remote sensing pictures based on satellite technology. Calculation results obtain by applying integrated numerical model show the tide height and velocity can coincided with this real remote sensing datas. A flow field comparsim between the calculation and remote sensing was given in fig.3 which show the most ebb-tide veloctiy during the “98.6” flood season. Several conculsions can be generalized as fllow:(1) low flow veloctiy in spring tide period and high flow velocity in ebb-tide period during flood



(a) Calculation result (b)Remote sensing photo

Fig.3 Most ebb-tide veloctiy field comparsim between the calculation and remote sensing in the “98.6” flood season

season.(2)A approximate north-south directional reciprocating flow field arise at Lingdingyang ocean area following the periodical tiding movement.(3) During spring and falling tide period, flow velocity of at east side are greater than west section at cross-sections from Dahaodao channels to Zhuhai of Modaomen channels.(4) the flow velocities of Lingdingyang channels and Fanshi channels are same numberical values during spring and falling tide period with lower flow velocity at middle and west channels.

In general, the model performed reasonably well. However, these results give confidence that the model was simulating the principal hydrographic features of the estuary. The most flow velocity field of Pearl estuary was drawn in Fig.4 which show the calculation result obtained by applying integrated numerical model at spring tide in "2001.2" low water season.

During spring season, the most surface tide volocity can reach 1.9m/s after 6 hours following the most tide height at Lingdingyang water channels in summer. And the velocity locate the most bottom velocity can rise to 1.35 m/s after 5 hours following the most tide height at Jinxingmen channel. In January, the most surface velocity and bottom velocity can exceed 1.48m/s and 1.28m/s seperately which emerge at water area between Huangmaodao island and Jiuao island after 4 hours following the most tide height.

During neap season, the most surface tide volocity can reach 0.52m/s after 6 hours following the most tide height at Lingdingyang water channels in summer. And the velocity locate the most bottom velocity can rise to 0.42m/s after 1 hours following the most tide height at Jinxingmen channel. In January, the most surface velocity can exceed 0.67m/s after 6 hours following the most tide height at Lingdingyang water channels, and bottom velocity can reach 0.55m/s which emerge at water area between Huangmaodao and Jiuao island after 4 hours following the most tide height.

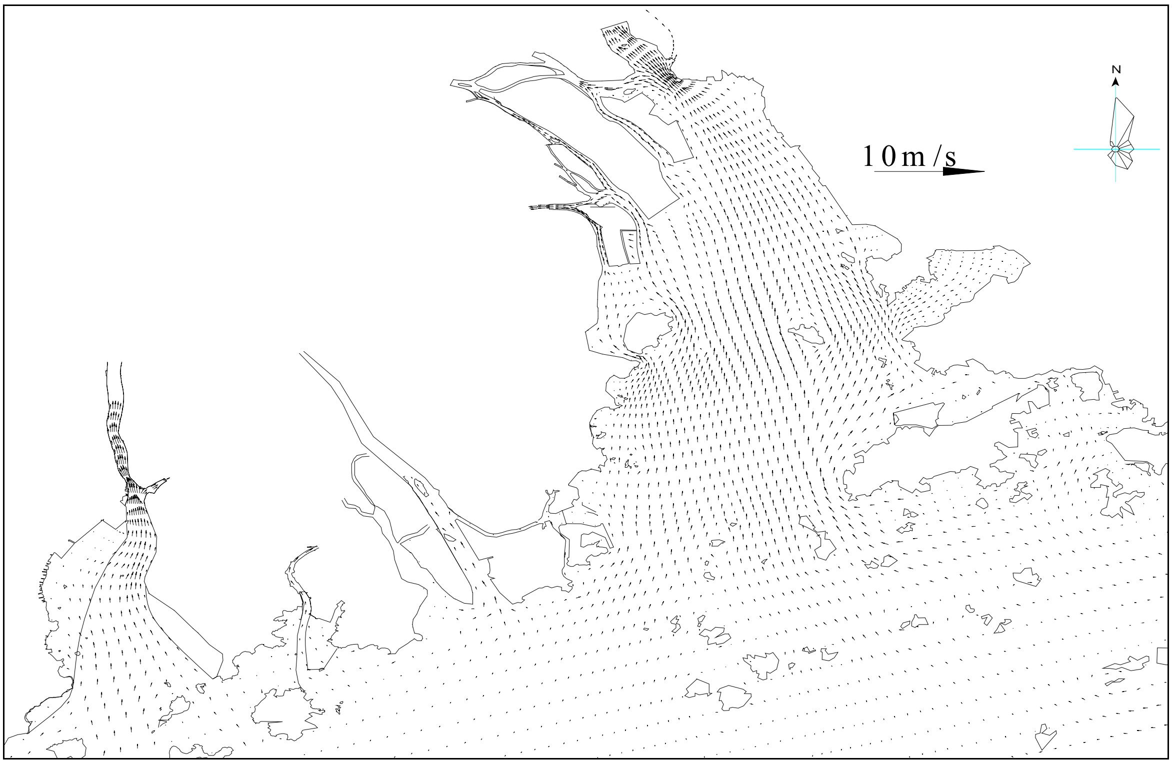


Fig.4 The most rising tide velocity field of Pearl estuary in "2001.2" low water season

3.4 Coastwise Flow

Flow direction at Lingdingyang enrance to outside ocean area turn into west-south direction during ebb tide period, and the shallow coastwise flow take a importan role to infulence offing domain at Pearl estuary. With the coastwise flow persistent force, processed sediments and suspended sediments flow into the sea at Lingdingyang estuary following southwesten direction which contribute the development of Lanmensha underwater island. Presently, consistent causes of formation for the coastwise were not obtained by sholars on estuary hydrodynamic. One classic academic view consisder several factors including tidal currents movement, maritime landform and Coriolis force, can give great effects on the format and phases of coastwise flow, however tidal range at the west domain are less than the east domain in Pearl esturay. Our solutions indicate that this numerical model can simulate the hydrodynamic features of the sepecial coastwise flow sucessfully.

4. Salinity tide distribution at Pearl Estuary

4.1 Time diversification

Mostly, after the arrival of raining season, water quantity of upstream discharge and typhoon status for salinity boosting or lightening are main resons which can difine the diversifications in months or seaons difference. During flood season, between March and Sept, salinity water boundary was pressed down following abundant discharginge into the ocean, and a majority of salty region fade away for fresh floodwater flushing. However, salt water can crush into the estuary domain caused by storm tide intrusion and typhoon movement in autumn season.

Following the decreaseing of discharge flow gradually, salty concentration of water tide will increases duratively in Oct. and Dec. Salinity concentration will reach peak value in spring season.

In salty tide effected area, salinity day-changing process show same variable feature with sea level changing curve fundamentally, time spot of maximal and minimal salty concentration appear at sea level rising ending and falling edding.Twice flood tide and twice low neap spots will be monitored in one full day. Since the sepecial tide in this area belongs to irregular semi-diurnal tides, the unequal phenomenon of sea water level distribution unbalanced in full daytime is comparatively notable. As a result, the corresponding twice maximal salinity distribution under maximal sea water level are distinct with each other as the different twice minmal salinity contour under twice neap sea water level.

4.2 Salinity distirbution on riverways

The perpendicular salinity distribution of cross-sections was dominated by the commixture procedure type of the fresh water and brinish seawater mainly. With the oecan tiding rising near the enstuary entrance, the high salinity water wedges into inner domain of river system from cross section bottom. As we all know, this hydrodynamic feature like this is named so-called Density Current phenomenon. Based on mixing degree between the river discharge water and ocean current, different salinity concentration at vertical cross section are obserbed at the mixing contacting interface along water profundity.

Under ordinary circumstances, salinity concentration enhances from top to bottom of cross-section gradually. The more nearby the lower reaches, the distributive feature in perpendicularity direction is more notable obviously, especially nearby at rising ending in tide periodic time.

Salinity distribution of lateral cross setions along riverways has the similar characterics with tidal current contour shap correspondingly. In general, salty degree is minimal at tiding ebbing time for special situations, lateral distribution difference is not obvious for adequate water admixture.

At the beginning of tide current rotating, water salinity near both banks of river are more greater than the middle domain of river cross sections. Then, when the velocity of the entire cross-section turn to upstream domain, main current and salinity concentration in deep domain of middle are more greater than both banks on two sides of flowways; After tide rising peak value, salinity degree at middle channel will diminishes fristly for faster falling current velocity than two side banks. At last, the salinity distribution recover to the beginning condition of tide falling ending time moment.

It is degressive tendency of salinity degree along the varibable direction from downstream area to upstream catachment. The tracing distance and alterative degree of salt water were infeluenced by various vital factors including water discharge quanlity from upper reaches, salinity degree at estuary entrance domain, tide movement intensity, wind direction and wind power , riverway landform etc.

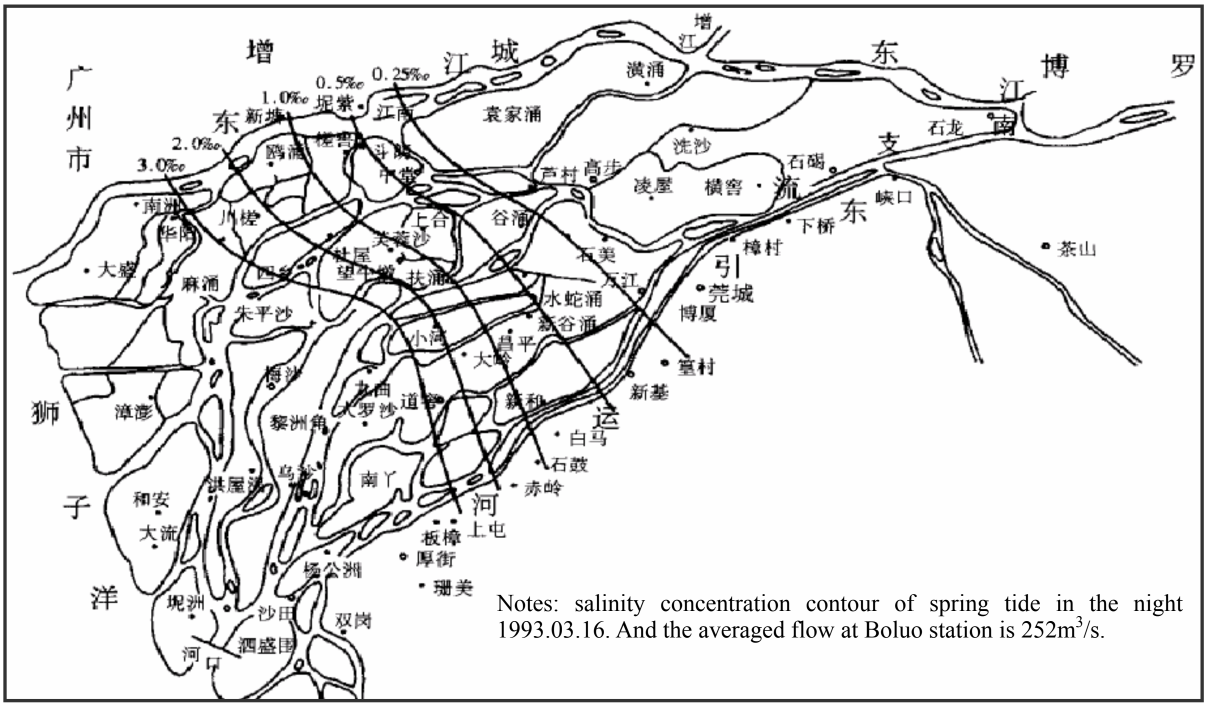


Fig.5 The salinity concentration contour of Dongjiang River delta territary at “Am 02:00,1993.03.16 ”

4.3 Salinity Characteristics at Pearl Estuary entrance

Through analysis on the surveyed datas at sites nearby the Pearl estuary entrance to the ocean, seacoast mass percent concentration of salinity is only 4 ‰~ 14 ‰, however, the salinity concentration of supercrust seawater beyond 20 ‰. At Pearl esturay, the salinity concentration isolines of seawater curves to the domain of outerside sea. It is sensitive that runoff from the superior watershed is the main factor which affect the the seawater intrusion consequence.With relative low discharge and strong tiding into Lingdingyang, this waterway is a most pathway for salinity intrusion as the same as Yamen. Tide and runoff dynamic forces are important elements which detemine the salt intrusion distance. In general, annual or months with greater tide movement seawater intrusion interface can reach more faraway inland position at these entrances with low ratio between runoff and tiding flow quantity.

There are two water flow grooves and three estuary beachs in the sea domain of Lingdingyang gulf. With high salty water in east domain and low salty distribution at east sea area, the west beach is the most large one with shallow water. From the northeast to southwest in Lingdingyang gulf, a "S" shape salinity distribution trend can be see obviously. In general, during low water discharge period with great tiding hydrodynamic force, 30‰ salinity concentration of mass percent can intrude the east groove which located at the northern domain of inner Lingdingdao island. The 2‰ mass percent salinity concentration can almost trace to these eastern river entrances mentioned all above.Especially, the 2‰ salty isoline can troude to Dahu hydrographic staion in Humen riverway.

As the main stream of Xijing catachment, runoff from Modaomen waterway is the crown of these eight entrances doors to outside ocean. Regardless of low water period and flood season, the phenomenon of stratified salty water is essential feature in this area with active brine wedge movement. During low water period with high tide, 30‰ isoline of brinishness line locate at continent mouth (right side of Dahengqin area), moreover, the 2‰ isoline of salinity concentration line can reach the cross section of Denglongshan sluice. In severe drought year, maximal salinity concentration this cross section is 17 ‰ in February 25, 1965. On the opposite, in flood period with rising tiding, the continental sea district is controlled mainly by fresh water runoff except minority entrances to outside oecan with about 5‰ low mass percent concentration of salinity.

Huangmaohai entrance locates at the west domain of this ocean estuary under research whose tide power is next only to the Humen entrance. Sea area is controlled by salty tide during low water season, salty contour run out to estuary entrance like a ligule following the deep groove of waterways. The 20‰'s salty contour line can reach the the upstream river section beyond Yaowan. With spring tide in winter, Huang Chong section brinishness is more than 8‰. In flood period, the salty concentration of continental sea district above esturay entrances is smaller than 20‰ generally. However, the salinity concentration of domain near outside ocean will rising unambiguously despite the sufficient runoff from the upstream catchments.

5. Conclusions

The model described in this paper reproduces many of the salient features of tide movement and salt intrusion in the Pearl estuary located at the south of China. The hydrodynamics were accurately simulated, with the measured tidal range reproduced by the model at several locations along the estuary. Simulations of salinity at the location showed that the full range of observed salinity was reproduced with spring and neap tides movement.

Characteristics of tide and salinity predominated by runoff and tide hydrodynamic forces at Pearl estuary was discussed in details in this paper. Based on adequate analysis and generalization on historical research productions for Pearl estuary's flow field, a integrated 2-dimensional numerical simulation model was implied to study the movement regluarities of tide hydrodynamic and salinity concentration for the whole shallow sea includinhg Hongkong and Macao.ect important domains . Then, three representative flood hydrograph courses including the "98.6","91.12" and "2001.02" under real great, middle and neap tide boundary conditions were reproduced by this model. Considering the real observed detes as references datas, current vector field during rising and ebb tide, water level contours, coastwise flow and salinity distribution were obtained with particular illustration.The principal aim of this study was to examine water level and salinity distribution in the estuary under various river flows, and to determine the importance of variations in the riverine salinity concentration to the estuary. The model showed that estuary salinity concentrations are predominantly controlled by the river end member during strong rainfall events.

The Pearl estuary, a microtidal estuary in the south of China, has a largely seasonal cycle of salinity variation due to the low tidal amplitude and strongly seasonal rainfall. Moreover, this representative esturary have semi-diurnal, diurnal or fortnightly periodicities in salinity variation. The temporal variation of the position of the salt wedge in the upper reaches of the Pearl estuary was analysed using field datas and a vertical averaged, two-dimensional numerical simulation model for very wet (98.6) years and very dry (2001.02)in the recent rainfall history. The salt wedge dynamics in the estuary are considered to have two phases: salt wedge dominated during late winter and early spring characterized by very low freshwater discharge; salt wedge waning or absent in summer and autumn with high flow.At last, the essential features of salt intrusion in the estuary were accurately simulated and several essential characteristics for tide movement and salinity distribution were summarized following with aborative analysis on actual monitoring datas and numerical simulation results which are concernful on the route to cure and protect the ecological enviroment of Pearl estuary for human being and nature in the future. Moreover, these research achievements have unambiguous reference values in planning exploiting projects for coast, harbor developing and regulating engineering at Pearl River estuary.

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