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Wind Effects on the Oyster Farm Environment in Gamak Bay

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The effect of wind stresses on the flow and water quality has been examined, particularly focused on the environment of oyster farms in Gamak Bay, by a two dimensional numerical model. In autumn (wind: 45.0°, 4.3 m/s), the overall flow turned out to be stronger than any other seasons and in addition, a pair of anticlockwise and clockwise vortices has been created at the northwest of the bay. Consequently, the wind in autumn seemed efficient not only for growing oyster but also for reducing the water pollution as the flow becomes much more active. In summer an anoxic condition appeared around the northwest of the bay where the flow is stagnant. According to a field survey, the majority of oyster farms tended to be densely distributed around the areas where DO concentration is high. Furthermore, oyster farms with a high production (over 1,300 kg per hanging string of 100 m) were distributed along with approximately 4 of Ch-*a* concentration. This suggests that oyster production is closely related to the concentration of DO or Ch-*a*.

Key words: Wind stress, Oyster farms, Oxygen-deficient water masses, DO, Ch-*a*

Introduction

Gamak Bay is a semi-enclosed area of shallow water with a mean depth of 9 m and has both east and south channels to receive the seawater from outside (see Fig. 1). Gamak Bay also has an egg-shaped sea surface area of approximately 112 km^2. A form ratio of the tide is 0.22 so that semi-diurnal tides are dominant in the bay. This bay is specifically well known as one of major oyster production areas since last few decades. However, owing to an inappropriate management of fishing grounds and an inflow of partially treated sewage, the water quality is getting worse than before. In particular, recently a water front development is scheduled so that not only seawater behaviors but also water quality are expected to largely alter. Thus, the status of oyster production area is threatened. Moreover, most of the contaminants come in through the northwest of the bay and even worse, a shoal existing in the mid of the bay makes it difficult to communicate between the inner bay waters and outside of the bay.

Lee (1990) reported that a seawater after coming in the bay is divided into three distinctive water masses, that is, Yosu Harbor waters, inner bay waters and outer bay waters. However, these water masses are likely to be formed by the topography (Lee and Park, 2002). Lee and Park (1995) elucidated that tidal currents inside Gamak Bay were strongly affected by the wind. Cho et al. (1996) confirmed that a strong clockwise vortex was created at the northwest of the bay during easterly winds while an anti-clockwise vortex was created during westerly winds. This suggests that the flow environment in this region is controlled mainly by wind. On the contrary, Shin (1995) and MOMAF (2001) pointed out that only a single one of *polychaetous* benthos was found at the northwest of the bay particularly in the summer while it was abundant (over 2,000 individuals) near the east and south entrances of the bay. Lee and Park (2002) and Park (2003) also proved that oxygen-deficient water masses appeared in summer because the flows are stagnant at the northwest of the bay. Thus, it is required to make sure whether a wind action can improve a water quality at the northwest of the bay.

This study evaluated the effect of wind on the flow and water quality by numerical experiments, focused on the fishing environment of oyster in Gamak

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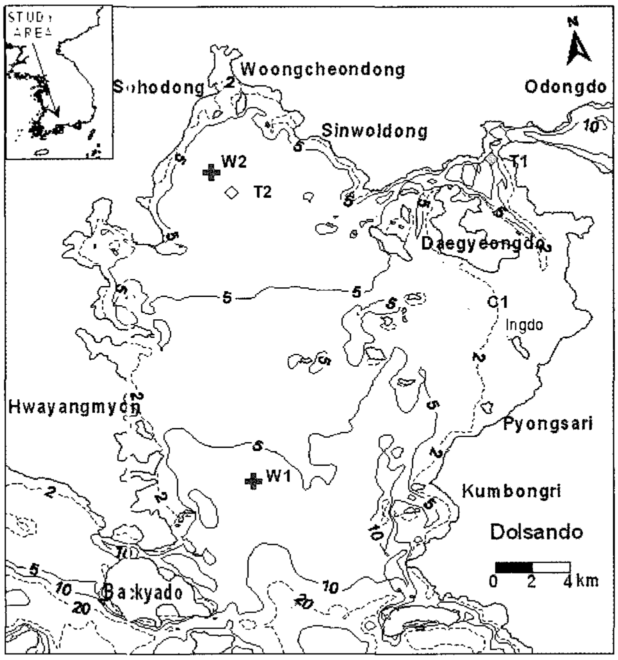


Fig. 1. Study area and oceanographic stations in Gamak Bay (W1, W2 and C1 are current measurement stations and T1 and T2 are tide observation stations and Arabic numbers are depth in meter).

Bay.

Materials and Methods

The numerical model used here is the DIVAST (Depth Integrated Velocities And Solute Transport) originally developed by Falconer (1991) in order to create flow fields. The fundamental equations consist of two-dimensional Navier-Stokes equations for momentum and continuity. From these equations, depth-integrated equations have been derived and discretized in terms of the ADI (Alternating Direction Implicit) technique and a space staggered grid system. In particular, use of a depth-integrated model with a surface wind forcing is justified in this region because a mean depth is less than 9 m. This model also adopts a moving boundary system to permit the variation in the boundaries according to the tidal stages. More details in this model can be found in the publications of Falconer and Chen (1991), Lin and Falconer (1997) and Jianhua et al. (2001). The whole computational domain consists of rectangular grids of 184×164 with spatial intervals $\Delta x = \Delta y = 100$ m in x and y directions. A simulation has been conducted for 17 days in order to cover the entire period of spring and neap tides. In this case, the amplitudes and their phases of four major tidal components have been given as the fittest open boundary conditions, in terms of trial and error method. The time interval Δt was set to 10 sec to satisfy the CFL condition that the Courant number is less than 8. Simulated results have been compared with the observed tides and currents for verification. Thirty-year wind data obtained by the Yosu Observatory (2002) was used to create flow structures particularly in summer and winter. A random walk model, originally developed by Lee and Kim (1995) was also employed for the evaluation of seawater exchange rates. Wind effects were examined through the comparison of calculated flow fields in cases of wind forcing and no wind forcing. In addition, the concentration of DO has been calculated in order to investigate the effect on oyster farms, using the equations suggested by Brown and Barnwell (1985). Here the production by photosynthesis was not included in the calculation of DO but only the decay of DO concentration due to pollutant loads was considered. Thus, calculated results might be somewhat different from observed results. Mean values obtained by Cho et al.(1996) in July, November and January were employed as initial conditions. Boundary conditions were given to be the same as initial conditions in an entire domain. Major parameters for the calculation of DO are indicated in Table 1.

Results and Discussion

Verification of model

Fig. 2 represents the comparison of tidal curves between the computed results and observed ones at stations T1 and T2. The computed results favorably agree with the observed ones. Fig. 3 compares tidal current ellipses obtained from field observations with model results for station W1. The computed tidal current ellipse appeared a little smaller than the observed one but the direction of a major ellipse is consistent. The difference of magnitude in a tidal current ellipsis may arise because field data was taken at 1 m below the sea surface while the computed data denotes a depth-mean value.

Effect of wind on the flow

Fig. 4 indicates rose diagrams of wind for 30 years observed in Yosu Wind directions of SSW or S in summer, NE in autumn and NW in winter are prevalent. However, in the spring winds are changeable and there is no predominant direction. Thus,

Table 1. Input data for water quality model

Mesh size	x=y=100 m
Water depth	Chart datum+MSL

Season	Wind Direction (°)	Wind Speed (m/s)	Salinity (psu)	Temp. (℃)
Summer	202.5	3.7	31.35	25.5
Autumn	45.0	4.3	31.49	16.7
Winter	315.0	5.6	33.70	4.9

Initial (Boundary) Condition for water quality calculation

Season	DO (mg/L)	COD (mg/L)	NH_4^+-N (μg-at/L)	NO_2^--N (μg-at/L)	NO_3^--N (μg-at/L)
Summer	6.848	2.59	0.34	0.07	5.80
Autumn	8.037	1.77	0.15	0.66	1.03
Winter	10.213	2.18	0.23	0.24	2.44

Items of pollutant loads

Location	DO (mg/L)	COD (mg/L)	NH_4^+-N (μg-at/L)	NO_2^--N (μg-at/L)	NO_3^--N (μg-at/L)
Peongsacheon	9.61	0.90	166.71	9.72	297.31
Yeondeungcheon	5.04	6.90	1,005.18	15.87	209.78
Bongsancheon	6.93	5.69	1,021.53	8.28	29.82
Kukdongcheon	4.54	6.55	1,232.24	37.43	134.00
Woongcheon	9.04	5.94	402.88	11.41	223.06
Seonso A	4.99	6.62	1,091.04	16.10	30.62
Seonso B	7.41	7.46	894.46	9.19	26.54
LG Company Apartment	4.74	7.63	1,208.87	31.25	32.88
Kumho Apartment	5.10	8.34	528.68	25.20	164.26
Yongjucheon	7.50	1.14	183.37	9.60	885.03

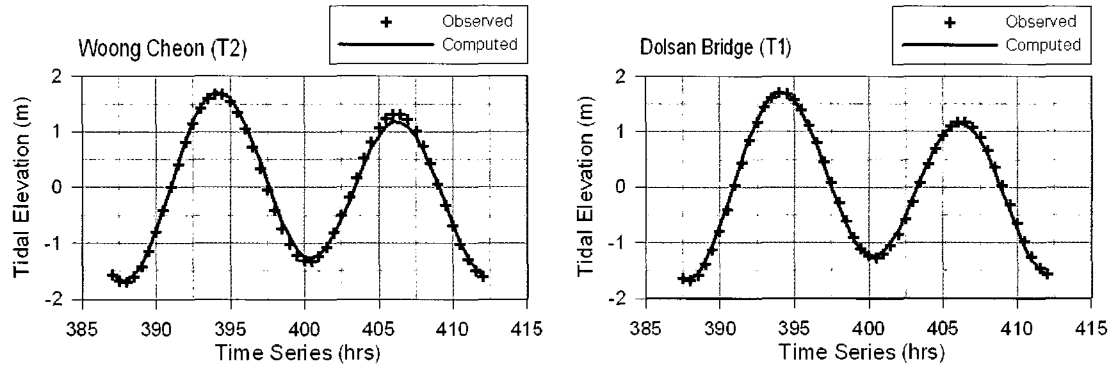


Fig. 2. Observed and calculated water elevations at Stations T1 and T2.

this study considers only 3 seasons as a specific condition of wind except the spring. According to the calculated results by Park (2003), the seawater nearly simultaneously comes in Gamak Bay through the east and south channels during the flood tide and goes out through the opposite side during the ebb tide.

On the contrary, Fig. 5 denotes residual currents for each season in case of wind forcing and in case of no wind forcing. It turned out that a tidal residual flow is identified as a strong out-going flow at the east channel and a pair of large clockwise and anti-clockwise vortices at the south channel because of a topographical effect. However, when the monsoon is considered for each season, tidal residual flows reflect their season's wind characteristics, as shown in Fig. 5, where the wind denotes seasonal average values over 30 years. First, in summer (wind: 202.5°, 3.7 m/s), around the northwest region and Daegyeong-do Island to the east of the bay, the flow becomes

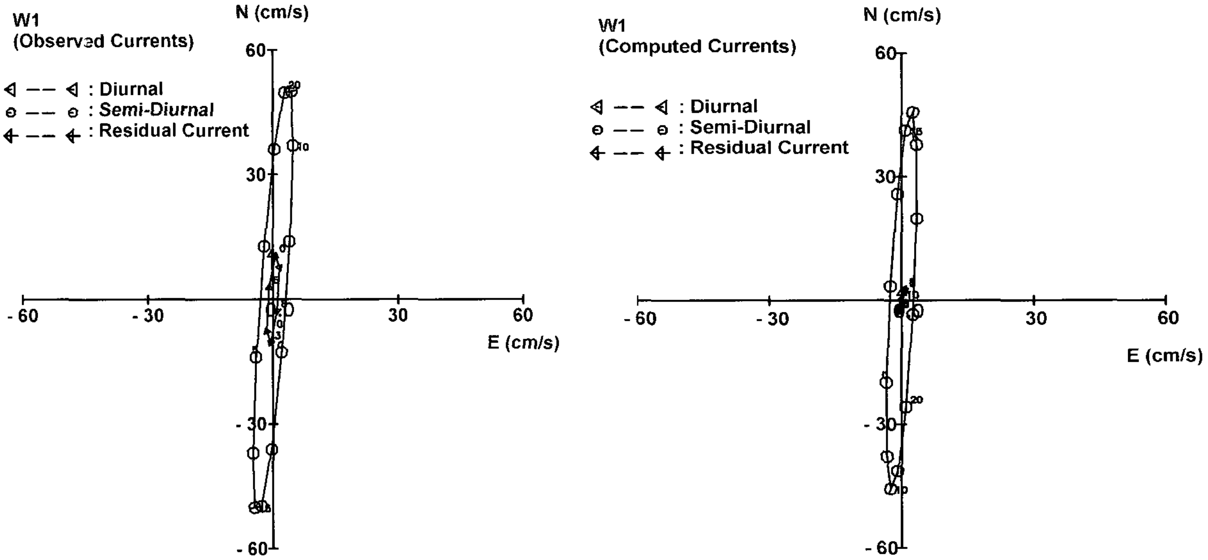


Fig. 3. Observed and calculated tidal current ellipses at Station W1.

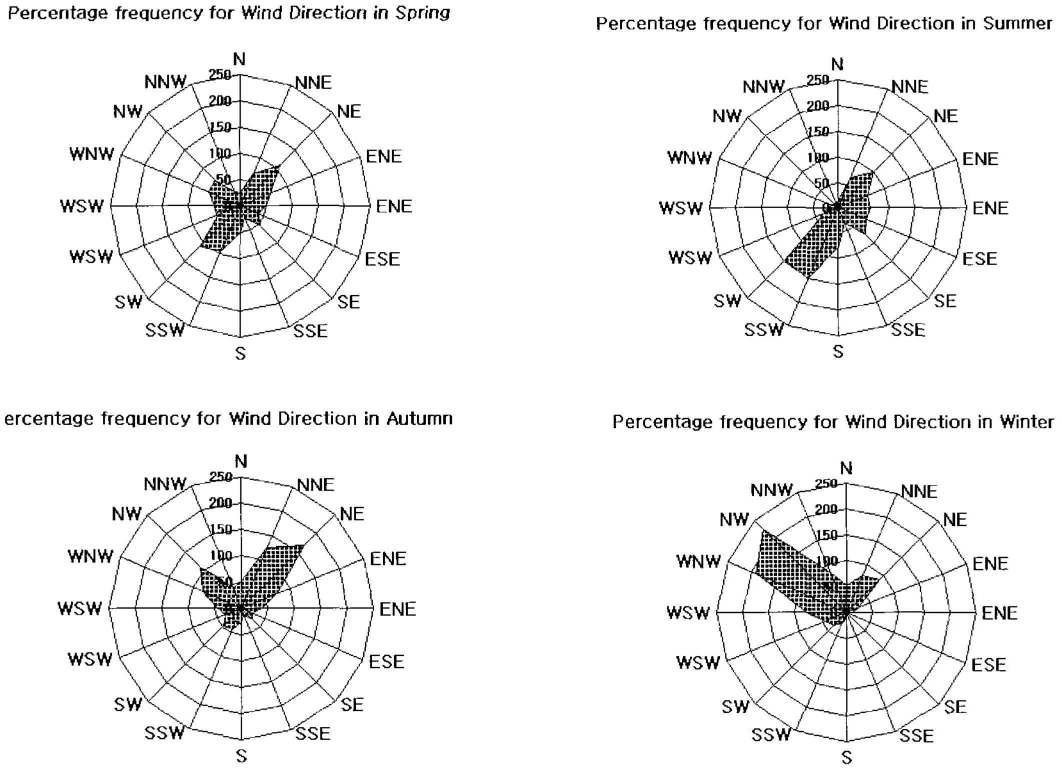
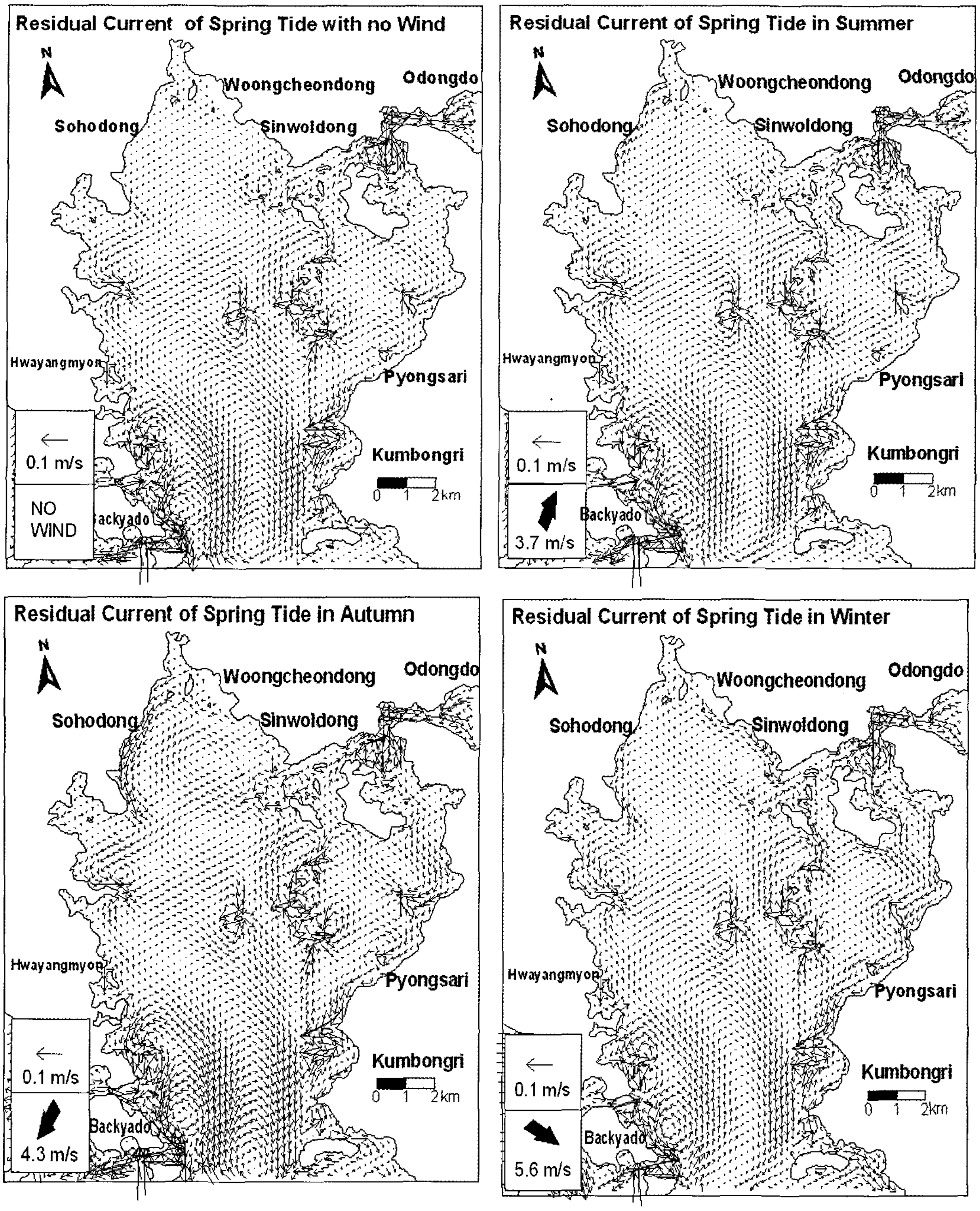


Fig. 4. Rose's diagrams of wind for thirty years observed in Yosu (The unit of wind speeds is expressed in 10^{-1} m/s).

stronger but the whole pattern of the flow is similar compared to the case of no wind. Secondly, in autumn (wind: 45.0°, 4.3 m/s), the whole flow appears to be stronger than in any other season and particularly, a pair of anticlockwise and clockwise vortices is created in the northwest region. As mentioned above,


Residual Current of Spring Tide with no Wind

Residual Current of Spring Tide in Summer

Residual Current of Spring Tide in Autumn

Residual Current of Spring Tide in Winter

Fig. 5. Residual currents in cases of no wind forcing and wind forcing at each season.

the northwest of the bay is normally known as a weak flow area and heavily contaminated by municipal sewage. Consequently, the wind in autumn seemed beneficial to relieve the water pollution particularly in the northwest. Lastly, in winter (wind: 315°, 5.6 m/s), a southward flow appears to dominate all over the coastline, except some minor eddies around the islands.

Lee and Chang (1982) illustrated that approximately 87% of the seawater exchange in Gamak Bay is fulfilled through the south channel and in addition, the exchanged amount of seawater is larger during the ebb tide (41%) than the flood tide (26%). Therefore the monsoons in autumn and winter are helpful for a seawater exchange of the bay while the monsoon in summer is rather harmful to the exchange of seawater.

Relationship between water masses and oyster production

Fig. 6 represents distribution of oyster farms, in February 2002, where the key denotes the amount of oyster production (kg) per hanging string of 100 m. We notice that oyster farms are densely distributed along with the strong flow as indicated in Fig. 5, while no farm exists around the northwest area of the bay. In 2002, oyster farming facilities were occupied only in 522 ha of the 1,000 ha of the licensed area. Thus approximately 3,600 metric tons of oysters were produced that year in Gamak Bay. In general, the facilities for oyster farming are accommodated from June or July, and oysters are actually harvested between December and next May. Therefore a major season for oyster growing can be from August to November. It is well known that a food supply is the most important factor in the growth of oyster (Ito and Imai, 1955). However, as shown in Fig. 5, wind conditions in autumn, i.e. oyster growing season are more likely to have an effect on oyster farming.

In 2001, when compared the oyster production of 2 typical areas where two different water bodies are prevailing, 1,185 metric tons of oysters were produced at the farms in Kumbongri, while 920 metric tons of oysters were produced at the farms in Hwayangmyun. Although the total production was different in two areas, oyster production from a unit hanging string was the same. They produced 210 kg of oysters per hanging string of 100 m in each area. This means that water bodies did not affect the unit production of oyster in two areas.

The bay can be grouped into 3 areas in terms of water mass distribution, that is, the inner bay water, Yosu Harbor water and the outer bay water, as shown in Fig. 7 (Lee and Cho, 1990; Lee, 1992). These water masses obviously reflect topographical effects of the bay. In particular, the oceanic fronts between water masses exist where residual currents are very weak or the currents cross together. Of these water masses, only the inner bay water is stagnant and polluted. Furthermore, according to the report by Shin (1995), this water can be also characterized by the distribution of a benthic animal, *polychaete*. This species is found all the areas in Gamak Bay but it is never found at the northwest that is located in the inner bay water area because both the waters and seabed are polluted (see Fig. 8). In particular,

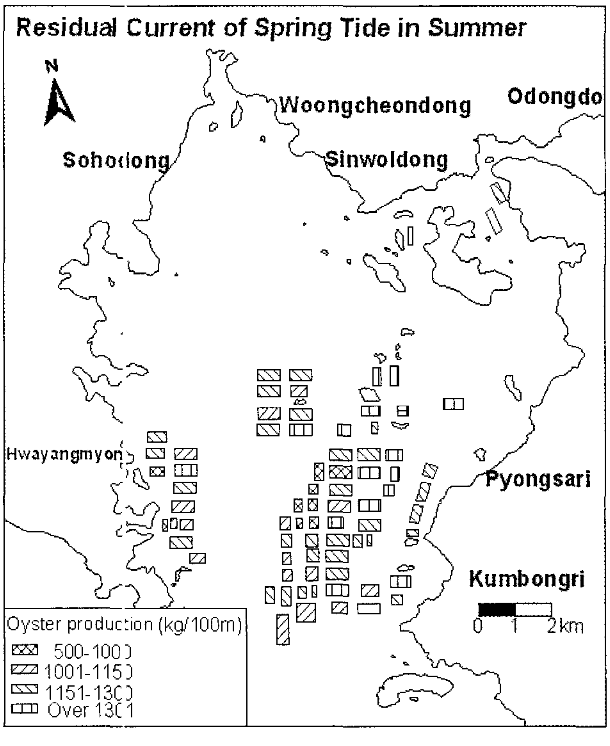


Fig. 6. Sketch of mariculture farms for oyster production in Gamak Bay in February, 2002.

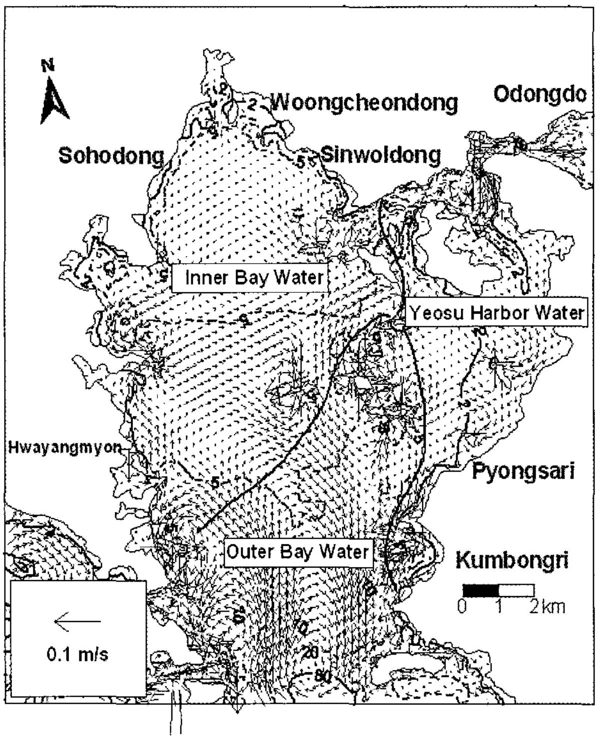


Fig. 7. Distribution of three water masses in Gamak Bay (The Arabic number is depth in meter).

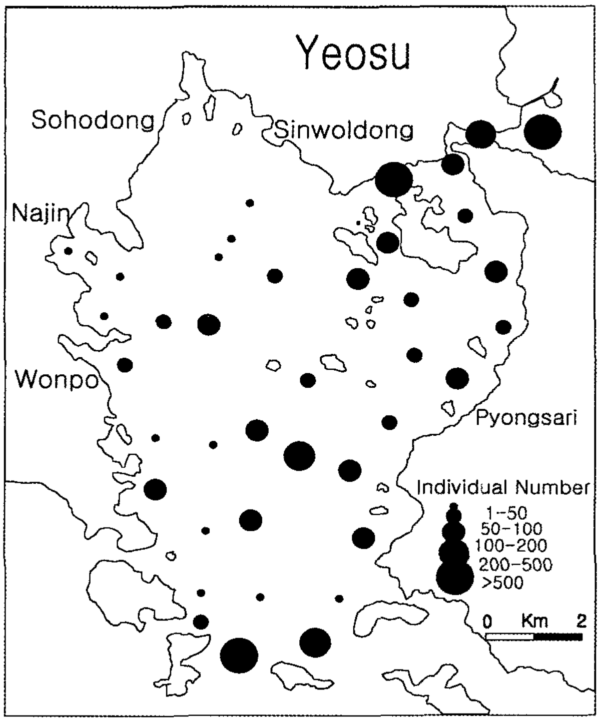


Fig. 8. Density of a *polychaete*, collected all over the year (Shin, 1995).

distribution of water masses or flow patterns has a close relationship with the seabed topography, based on Fig. 7. Yoon (2000), Cho et al. (1996) and Cho et al. (2001) found that concentration of chlorophyll-*a*, which is a criterion of food for oysters, was much higher at the boundaries between these 3 water masses than in any other regions of the bay. This explains that the position of the boundaries depending upon the wind conditions plays an important role for the growth of oysters. Therefore, in order to secure a high productivity of the oyster we should be keen on flow pattern and distribution of water masses (Lee and Park, 2002).

Effect of wind on the distribution of DO concentration

DO (Dissolved Oxygen) is one of the most important factors estimating the amount of cultured fish or an environmental indicator of farm water (Nakamura, 1991). Thus, the effect of wind on the distribution of DO concentration has been examined. For convenience, the total load of nutrients out of 10 different land sources, such as rivers or sewage treatment plant, was assumed to be constant, regardless of season, and then DO has been calculated by the equation of nutrient budget with mean water temperature and mean salinity in each season (see Table 1). The open boundaries had the same value of DO as the other region in the bay, and the initial values of DO in open boundaries were 6.85 mg/L in summer, 8.04 mg/L in autumn and 10.21 mg/L in winter. For verification, a field data observed in February 2001 was used, as indicated in Table 2 and Fig. 9. In particular, this study did not consider the production of DO by photosynthesis but considered the variation of DO concentration by pollutant loads. Accordingly, the computational results may have values slightly different from a field data.

Fig. 10 represents the computed concentrations of DO at the high water of spring tide in summer, autumn and winter. All these are results after 400 hr simulation because it needed to be stable. First when there is no wind in summer (upper panels in Fig.10), DO

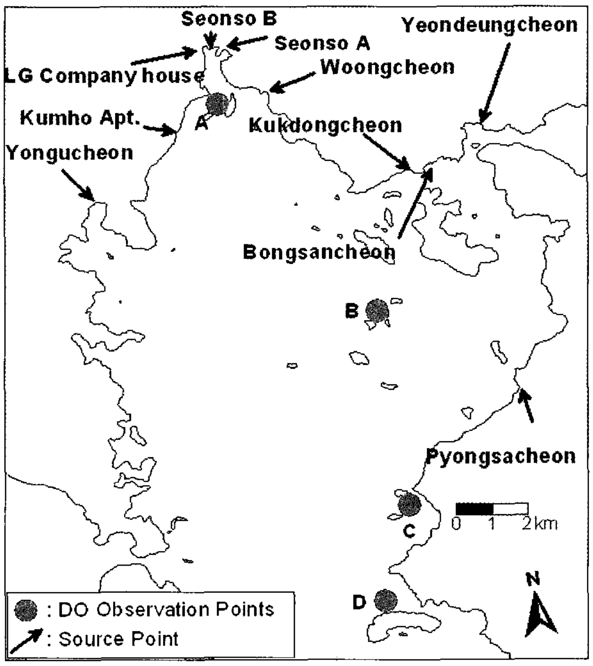


Fig. 9. Field survey stations of DO concentration in Gamak Bay in February, 2002.

Table 2. DO concentrations obtained from a field survey on 18th February, 2001

Stations	Sohodong (A)	Daegyeongdo (B)	Hangdae (C)	Gunnaeri (D)
DO (mg/L)	9.82	10.68	9.20	10.19

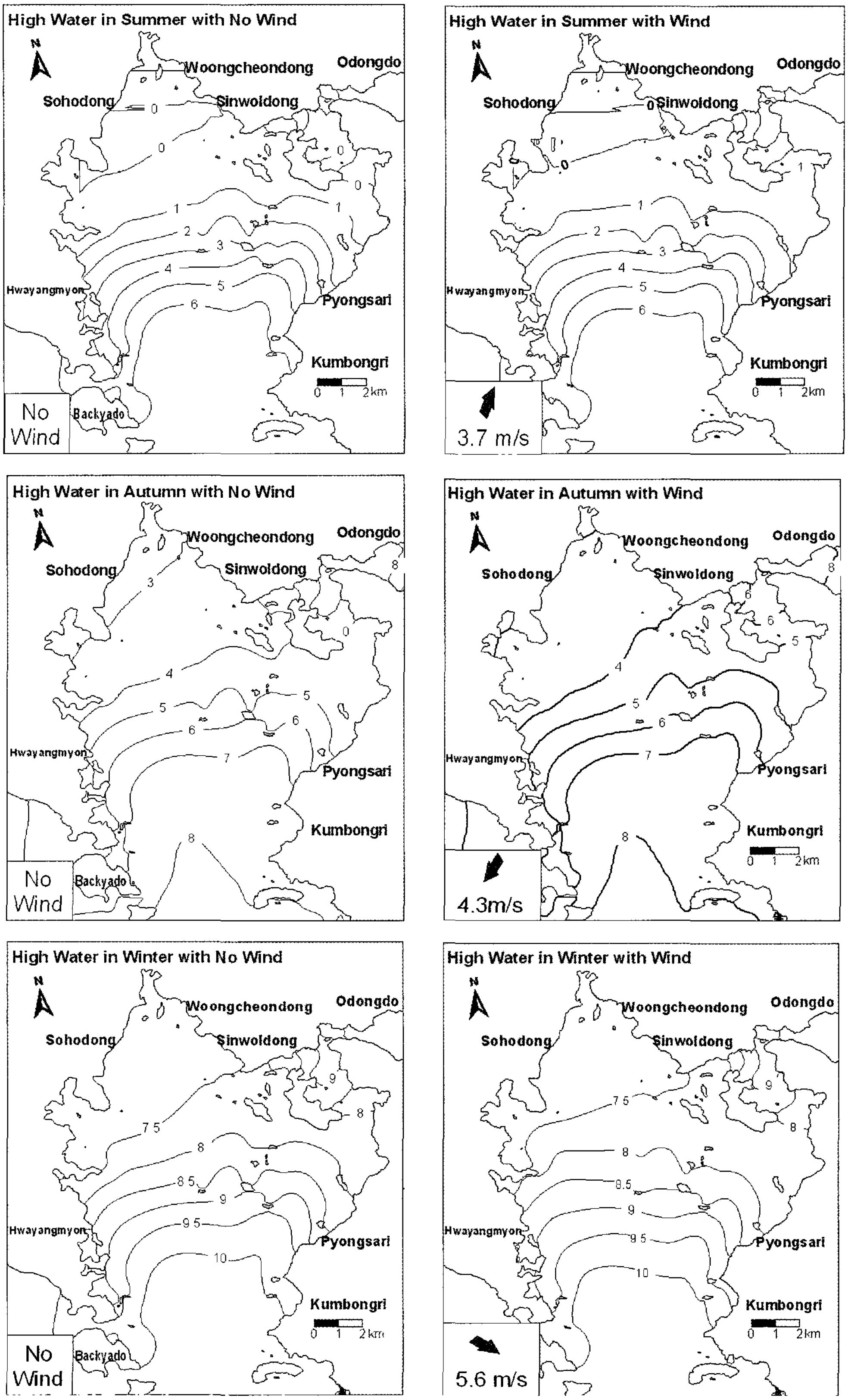


Fig. 10. Computed DO concentration (unit: mg/L) at high water spring tide in summer, autumn and winter with wind (right panels) and without wind (left panels).

concentration maintains 0-6 mg/L. However, except for the regions near the south and east channels, oxygen-deficient water masses, having a DO concentration of less than 2 mg/L, cover the mid-northern part of the bay. Such low DO concentration can be lethal to any kind of aquatic animals. For example, mortality of shellfish was reported when DO concentration was less than 5 mg/L near seabed (EBFC, 2000). Besides, even if a southerly wind is considered in summer, DO concentration is not improved at all. Secondly when there is no wind in autumn (middle panels in Fig. 10), DO concentration maintains 1-8 mg/L near the two main channels. However, oxygen-deficient water masses exist in a very limited area of the northwest of the bay. On the contrary, when the wind is northeasterly, DO concentration maintains 3-8 mg/L and DO concentration tends to decline a little bit toward the east coast of the bay. In addition, oxygen-deficient water masses completely disappear in the northwest region, even if DO distribution in the whole area is similar to the case of no wind. Thirdly in winter (lower panels in Fig. 10), DO concentration maintains 7-10 mg/L and shows a similar pattern, independent to wind stresses. These results qualitatively agree with the field data obtained by Cho et al. (1996). As a result, in the northwest of

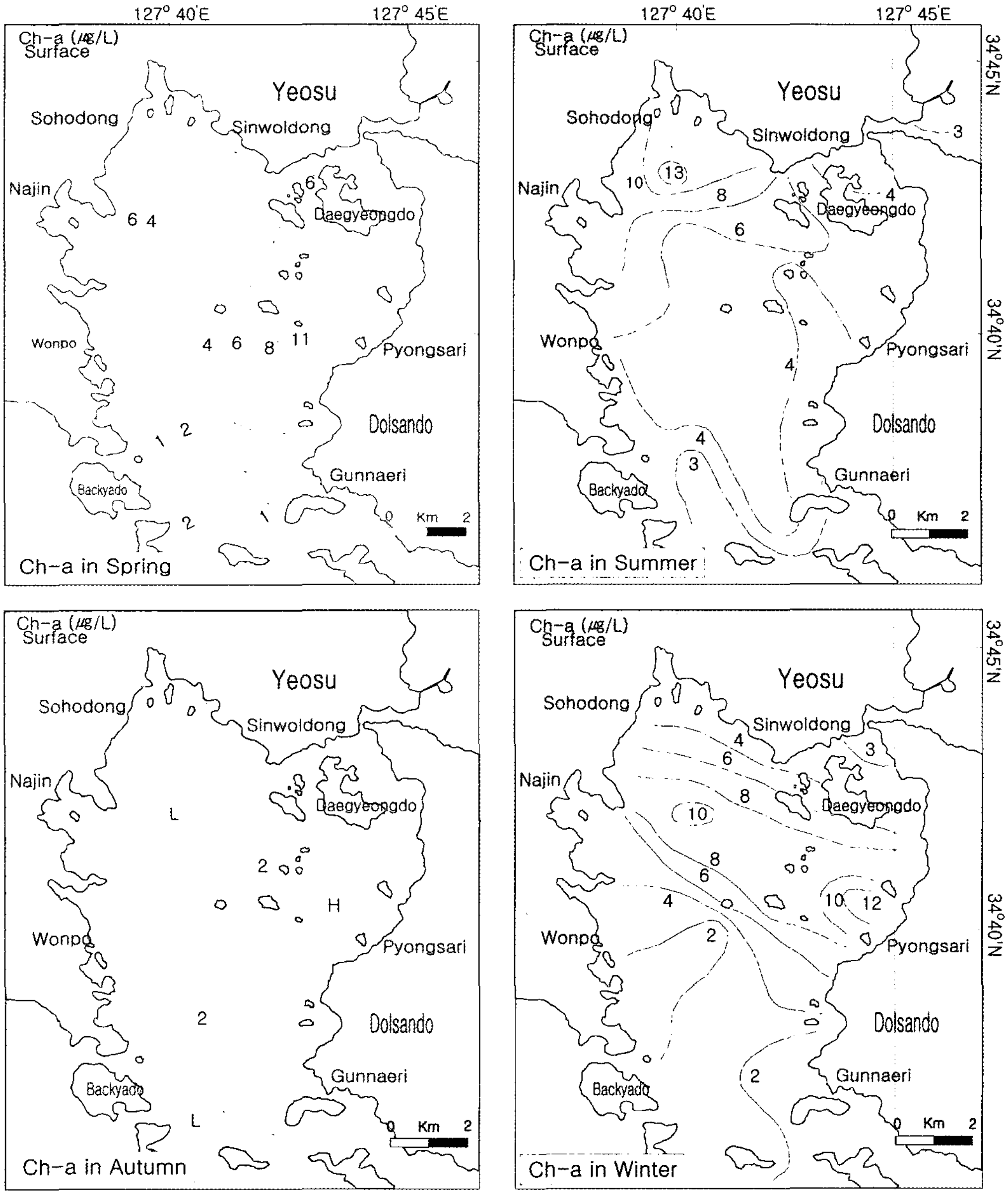


Fig. 11. Distribution of surface layer Ch-*a* concentration for each season (Yoon, 2000).

the bay oxygen-deficient water masses are easy to appear, except in winter. This environmental condition can not accommodate benthic animals at all, as shown in Fig. 8.

Relationship between Ch-*a* concentration and oyster production

Amount of nutrient in seawater determines production of oyster by means of primary production. Thus concentrations of Ch-*a* can be a measure of food for oyster. Fig. 11 represents the distribution of surface layer Ch-*a* concentration for each season, investigated by Yoon (2000). Ch-*a* concentration tends to be higher at the east part than at the west part, except for summer. This tendency is likely to have a close relation to the flow pattern, as illustrated in Fig. 5. Because the outer bay water with a low concentration of nutrients comes in the bay and then flows northward along the west coastline while the inner bay water with a high concentration of nutrients flows out southward along the east coastline. As indicated in Fig. 6, the majority of oyster farms are densely distributed southeastward so that they are largely influenced by the outer bay water. Of these, in particular, farms are more distributed at the east area than at the west area. It is evident that this reflects the distribution pattern of Ch-*a* concentration in the bay.

Lee (1995) pointed out that concentration of Ch-*a* is an important factor for the growth of oysters in Gamak Bay in winter. Fig. 12 shows the relationship between Ch-*a* concentration and oyster production. High production areas of more than 1,300 kg per hanging string of 100 m, appeared to exist within the area of more than 4 μg/L of Ch-*a* concentration, regardless of surface and bottom layers. It is understandable that production of oyster has a relation qualitatively with Ch-*a* concentration. Consequently, in order to secure a high productivity in oyster farming in Gamak Bay, the priority should be taken to reduce the load of organic matters such as COD in the northwest region.

High production areas proved to exist along the area of a high concentration of Ch-*a*. Therefore they seemed to be closely related to each other. Nevertheless, we still do not know what factors mostly affect the fishing environment. Especially in a semi-enclosed shallow region with dense farming facilities, such as Gamak Bay, the influence of drag forces by those facilities should be considered in the analysis of the flow and water quality (Lee et al., 1995; Nakamura, 1991). In future, we would like to evaluate quantitatively the environment factors that control the oyster production, for instance including calculation of phytoplankton in Gamak Bay.

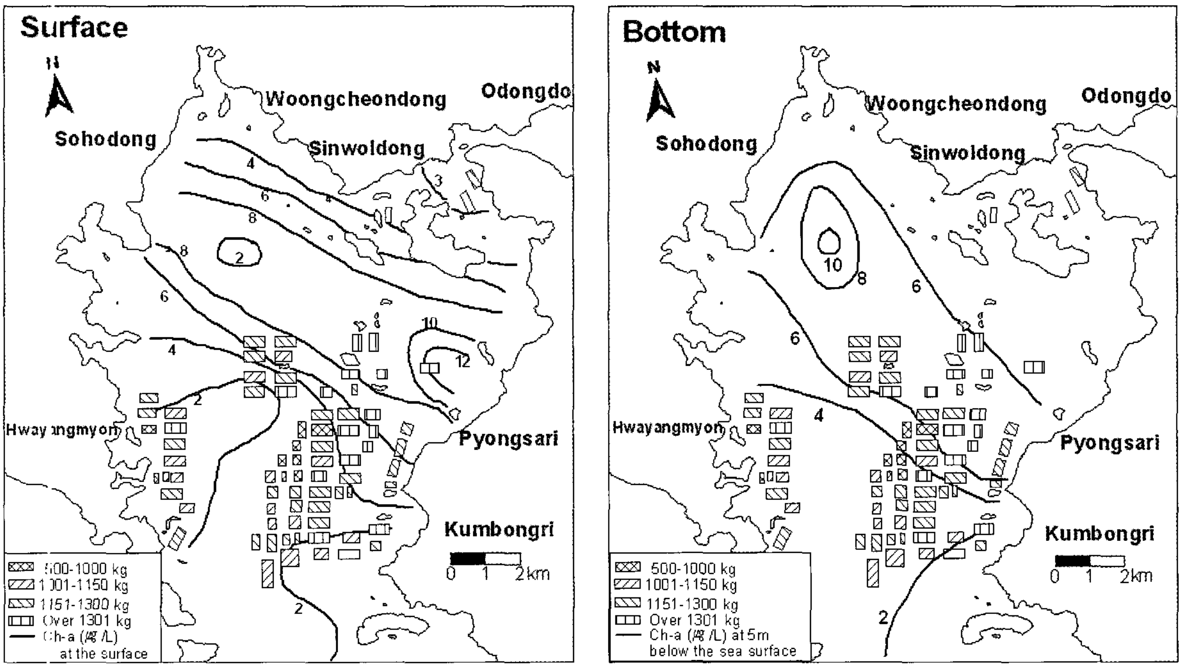


Fig. 12. Relationship between Ch-*a* concentration in December and oyster production at the surface (left) and bottom layer (right).

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References

Brown, L.C. and T.O. Barnwell. 1985. Computer Program Documentation for the Enhanced Stream Water Quality Model QUAL2E. Environmental Research Laboratory, U.S. EPA, Athens, GA, Report, No. EPA/600/3-85/065, 1-141.

Cho, E.I., C.G. Park and S.M. Lee. 1996. Calculation of environmental capacity for oyster farms in Gamak Bay. J. Kor. Fish. Soc., 29(5), 709-715.

Cho, H.S., Y.H. Pang, S.H. Park and H.C. Shin. 2001. Water quality and seabed environments around marine culture farms in Gamak Bay. Proc. Kor. Mar. Eng., Yosu, Korea, pp. 67-70.

Falconer, R.A. 1991. Review of modeling flow and pollutant transport processes in hydraulic basins. Proceedings of the 1st International Conference on Water Pollution Modeling, Measuring and Prediction, Computational Mechanics Publications, Southampton, UK, pp. 3-23.

Falconer, R.A. and Y. Chen. 1991. An improved presentation of flooding and drying and wind stress effects in a two-dimensional tidal numerical model. Proceedings of Institution of Civil Engineers, London, UK, 2, pp. 659-678.

EBFC (Environmental Bureau of Fukuoka City). 2000. Data Report of water quality observation at Hakata Bay in 1993 to 1999. Fukuoka, Japan, pp. 78-105.

Ito, S. and T. Imai. 1955. Ecology of oyster bed (I) On the decline of productivity due to repeated cultures. Tohoku J. Agr. Res., 5, 9-26.

Jianhua, T., L. Qingxue, R.A. Falconer and B. Lin. 2001. Modeling and assessment of water quality indicators in a semi-enclosed shallow bay. J. Hydr. Res. 39(6), 611-616.

Lee, M.C. and S.D. Chang. 1982. Seawater exchange in Gamak Bay. J. Kor. Oceanol. Soc., 17(1), 12-18.

Lee, G.H. and K.D. Cho. 1990. Distributions of water temperature and salinity in Gamak Bay. J. Kor. Fish. Soc., 23(1), 25-39.

Lee, G.H. 1992. Seawater behaviors in Gamak Bay. J. Kor. Fish. Tech., 28(2), 117-131.

Lee J.S. and H.J. Kim. 1995. Sensitivity analysis of diffusion solution by a random walk model. J. Kor. Soc. Civil Eng., 15(5), 1267-1277.

Lee, M.O. and S.J. Park. 2002. Wind effect on the seawater behavior and fishing environment. Proceedings of Japanese Fisheries Engineering, Jap. Soc. of Fish. Eng., Kagoshima, Japan, pp. 64-67.

Lee, Y.C. 1995. Influence of nutrients on the growth of oysters in Gamak Bay. M.S. Thesis, Pukyong National University, Busan, Korea, pp. 39.

Lin, B. and R.A. Falconer. 1997. Tidal flow and transport modeling using the ULTIMATE QUICKEST scheme. J. Hyd. Eng., ASCE, 123(4), 303-314.

MOMAF (Ministry of Marine Affair and Fisheries). 2001. Research for the enforcement plan of model waters management in environment management waters. Technical Report, 1, Seoul, Korea, pp. 275.

Nakamura, M. 1991. Fisheries Civil Engineering, Kogyozizitsushinsha, Tokyo, Japan, pp. 215-266.

Lee, J.S. and I.H. Park. 1995. The evaluation of flow resistance by hanging culture facilities and a numerical model. J. Kor. Fish. Soc., 28(5), 607-623.

Park, S.J. 2003. Wind effect on the marine environment and oyster farms in Gamak Bay. Ms. Eng. Thesis, Yosu National University, Yosu, Korea, pp.80.

Shin, H.C. 1995. The population of *polychaetous* animals in Gamak Bay. J. Kor. Oceanol. Soc., 30(4), 250-261.

Yosu Observatory. 2002. Monthly and annual bulletins, Korea Meteorological Administration.

Yoon, Y.H. 2000. Characteristics of variations of phytoplankton population and marine environment at the north of Gamak Bay. Proc. Fish. Sci. Institute, Yosu National University, 9, 429-436.

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