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Formation and Evolution of Turbidity Maximum in the Keum Estuary, West Coast of Korea

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금강 하구에서의 최대혼탁수 형성 및 변화에 대한 연구

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Abstract

A series of anchor stations were occupied along the Keum Estuary during six different periods of tidal and fluvial regimes. The results clearly show that the formation and evolution of the turbidity maximum play an important role in the sedimentary processes in this environment.

The turbidity maximum in the Keum Estuary is primarily related to the tidal range at the mouth and is caused by the resuspension of bottom sediments. In this estuary, the turbidity maximum is not a permanent feature and shows semidiurnal, fortnightly and seasonal variations.

Repetition of deposition and resuspension of fine sediments occur in response to the variation in current velocity associated with semidiurnal tidal cycles. The core of turbidity maximum shifts landward or seaward according to the flood-ebb succession.

The turbidity maximum also shows a fortnightly variation in response to the spring-neap cycles. Thus, the turbidity maximum degenerates during neap-tide and regenerates during spring-tide.

The freshwater discharge is also an important factor in the formation and destruction of the turbidity maximum. The increase in freshwater discharge in rainy season can create an ebb-dominant current pattern which enhances the seaward transport of suspended sediments, resulting in the shortening of residence time of suspended materials in the estuary. Thus, under this high discharge condition, the turbidity maximum exists only during spring-tide and starts to disappear as the tidal amplitude decreases.

요약 : 금강 하구의 에스추어리 환경에서 6차에 걸친 야외조사 및 정선관측이 행해졌다. 각 조사시기는 모두 다른 조차와 하천배수량의 조건을 보여 주는 기간이었다. 이 연구의 결과로서 금강 하구에서의 세립질 퇴적물 퇴적작용에 최대 혼탁수의 형성과 그 변화가 미치는 영향이 지대함이 나타났다.

금강 에스추어리의 최대 혼탁수는 일차적으로 입구에서의 조차가 클 때는 나타나는 현상이며, 바닥 퇴적물의 재부유에 의해 형성되어진다. 이 환경에서는 최대 혼탁수가 지속적으로 유지되어지지 않고, 반일, 반월 및 계절주기의 변화를 나타낸다.

반일 조석주기 동안에는 조류 유속의 변화로 말미암아 세립질 퇴적물의 퇴적과 재부유가 반복되어진다. 한편, 최대혼탁수의 중심은 창조류와 낙조류가 반복되는 것에 상응하여 상-하류 이동을 반복한다.

최대 혼탁수는 대조기-소조기의 변화에 따른 15일 주기의 변화를 나타낸다. 이렇게 하여, 최대 혼탁수는 소조기 동안에 쇠퇴하고 대조기 동안에 확장된다.

하천 배수량의 계절변화도 또한 최대 혼탁수의 생성과 소멸에 중요한 영향을 미친다. 우기에 하천배수량이 증가하게 되면 조류가 낙조류 우세를 나타내고, 부유퇴적물들은 쉽게 외해로 유출되어 에스추어리 내에서의 체류시간이 감소되어진다. 따라서, 이와 같은 많은 하천배수량의 시기에는, 최대 혼탁수의 발달은 오직 대조기 동안으로만 국한되어지며, 조차가 감소함에 따라 최대 혼탁수는 소멸한다.

INTRODUCTION

The phenomenon called turbidity maximum has been reported in many estuaries and is believed to exist in most, if not all, estuaries of the world. Its importance in the estuarine sedimentary processes of fine materials, as well as its evolution pattern in temporal and spatial contexts, is now well understood thanks to many pioneering and tenacious studies (Allen et al., 1974, 1977, 1980; Gelfenbaum, 1983; Nichols, 1974; Schubel, 1968, 1969; etc.). But, most of these studies and hence our understanding have been confined to estuaries of the partially-mixed type. For the well-mixed type of estuaries in particular, there is a gap in our knowledge of the natural processes.

The Keum Estuary (Fig. 1), which is located in the south-western part of the Korean Peninsula, shows the characteristics of a well-mixed estuary. This well-mixed character is closely related to the shallow depth of the estuary and the large tidal-range at its mouth. In the summer of 1983, we observed the turbidity maximum formed under the spring-tide and low river discharge conditions (Lee, 1984, 1985). The present study was planned with the aim of understanding the evolution of this turbidity maximum under varying environmental conditions. In an estuarine environment, the two most important sources of dynamic energy are freshwater-flow and tide. We can also consider wind and wave energies, but their magnitude is much smaller in scale, compared to the tidal and fluvial energies, especially in a well-mixed, macrotidal estuary. So, the objective of the present study is to elucidate the evolution pattern of the turbidity maximum in response to systematic variations in tidal range and river discharge, and to extend the findings to the general case of well-mixed estuaries.

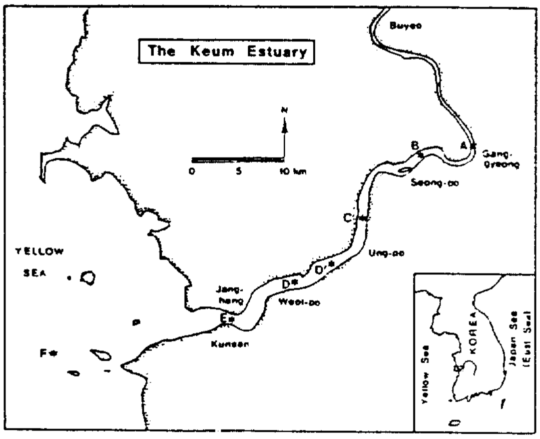

Fig. 1. Index map showing the study area and anchor stations.

STUDY AREA

The Keum River, which feeds the estuary and debouches into the Yellow Sea, has a total length of 400 km and a drainage basin of about 10,000 km^2, composed mostly of Precambrian metasedimentary rocks. The annual fresh water discharge is about 6 billion tons, most of which is concentrated in the summer rainy season causing a great seasonal variation in the river flow (Fig. 2).

The coastal zone is characterized by a semidiurnal, macrotidal regime, with a mean tidal range of 4.3 meters. Average spring-and neap-tidal ranges at Kunsan, located near the entrance of the estuary, are reported as 5.7 and 2.8 meters respectively, demonstrating a wide range of variation in the tidal energy input into the estuary. The spring-tidal saline water penetrates up to about 60 km upstream and forms an extensive estuarine environment.

FIELD OBSERVATIONS

Six series of field observations were made under different tidal and fluvial conditions, as shown in Table 1. During each field period, one or more anchor stations (A-F) were occupied continuously over a tidal cycle. At each

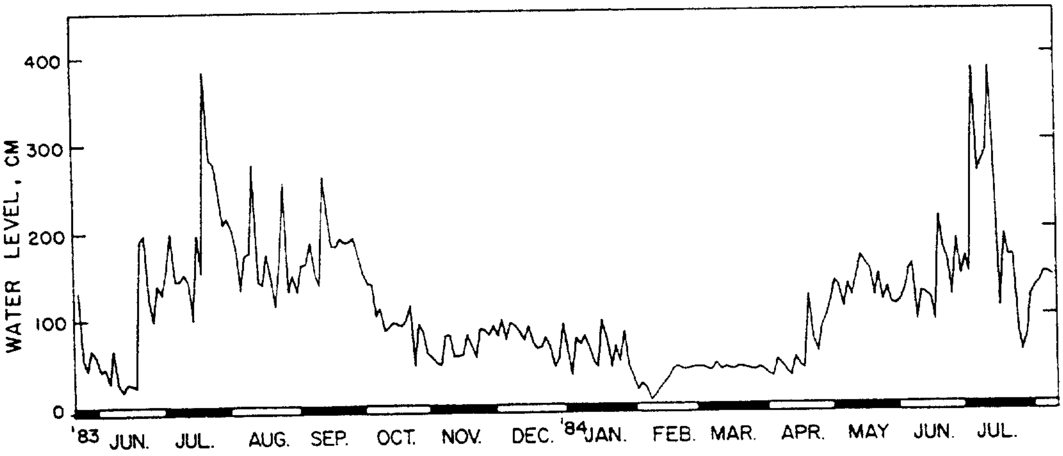

Fig. 2. Fluctuation of the Keum River discharge represented by the water level at Ma-am, located at about 110 km upstream from the month.

station, current direction and velocity were measured at 3 depths (surface, mid-depth and 1 m above bottom) at one hour intervals using a CM-2 current meter (Toho Dentan) along with water sampling using a Van Dorn sampler. In addition, surface water samples along the estuary were collected during each field period to see the areal distribution of suspended sediments.

The suspended particulated matter (SPM) concentration was determined by filtration of water samples through preweighed 0.45 μm Nuclepore filters. Salinity was measured either in the field using a T-S measuring bridge system or in the laboratory by an Autosal salinometer.

RESULTS AND DISCUSSION

Fluvial Inputs

Fresh water discharge and suspended sediment transport of the Keum River were monitored by water level fluctuation at Ma-am, located at about 100 km upstream from the mouth, and by filtration of water samples collected at Gong-ju, located at several kilometers downstream from Ma-am, respectively.

The estimated total freshwater discharge for 1984 was about 5.1 billion cubic meters, which corresponds to the annual average flow rate of 163 m^3/sec. Most of this discharge was concentrated in the summer months: the

Table 1. Tidal and Fluvial Regimes during the Six Observation Periods

Observation Period	6/10-15 1983	8/3-5 1983	7/15-16 1984	7/24-25 1984	11/23 1984	4/14 1985
Average Tidal Range at Kunsan (cm)	532	283	460	246	670	270
Average Water Level at Ma-am (cm)	32	180	295	163	136	≤40
Stations Occupied	A,B,C,D,E,F	C,D'	C,D	D,E	C	C
Remarks	Spring-tide Low-discharge	Neap-tide High-discharge	Spring-tide Extremely High-discharge	Neap-tide High-discharge	Spring-tide Moderate-discharge	Neap-tide Low-discharge

amount discharged during July, August and September comprised about 64 % of the total. The maximum flow occurred during September with a mean monthly rate of 537 m^3/sec and the minimum flow during March with a mean monthly rate of 23 m^3/sec.

Total suspended sediment transport of the Keum River was estimated at 170 thousand tons for 1984, which corresponds to the annual mean SPM concentration of 34 mg/*l* in the fresh water zone. About 83 % of the total suspended sediments were transported during the above mentioned three months of summer. The suspended sediment was composed mostly of clay-sized inorganic particles and has a mean diameter of 9 phi (2μm). The grain size composition of the Keum River SPM appeared to be relatively constant and does not vary appreciably in response to the variations of the river discharge or the total SPM concentration.

Variations of SPM in the Estuary over Semidiurnal Tidal Cycle

The variations of current speed, water depth and SPM concentration observed in the fields are shown in Figures 3-8. In the following, we will discuss the characteristic dynamic features of tidal currents and the variations of SPM during the semidiurnal tidal cycle.

June 10-15, 1983: This was the period of low river discharge and spring-tide. Tidal asymmetry was demonstrated by the longer duration of ebb flow than flood. This asymmetry becomes greater in the upstream direction. The maximum current speed occurred at all stations during the flood, at about 1 to 1.5 hours after the low water slack. Six anchor stations occupied during this period were: A (42), B (33), C (22), D (10), E (0) and F (– 17). The numbers in parentheses show the distance of the station from Kunsan, expressed in km.

The SPM concentration was overall high during this period. Two factors appeared to affect the local SPM level; 1) the cyclic deposition and resuspension of sediments in response to the variation of the current speed, and 2) the flood-ebb variation caused by the combined effects of longitudinal gradient in SPM level and the upstream-downstream movement of water masses during the tidal cycle. In a general manner, the former factor affected mainly the SPM level of the bottom water while the effect of the latter was most obvious in the surface water (Fig. 3).

At station A, the average SPM concentration during the tidal cycle was 199 mg/*l* (68-663 mg/*l*) at surface and 672 mg/*l* (150-2529 mg/*l*) at bottom. The SPM concentration was generally higher during the flood, due to the longitudinal concentration gradient. The effect of resuspension could also be observed when the current speed exeeded a certain limit, about 20 cm/sec at near-bottom. This resuspension effect was most significant in the bottom water and particularly during the flood current.

At station B, the average SPM concentration was 690 mg/*l* (74-2251 mg/*l*) at surface, 852 mg/*l* (328-1898 mg/*l*) at mid-depth and 1063 mg/*l* (418-2141 mg/*l*) at bottom. General patterns of SPM variation during the tidal cycle in this station were similar to those at station A, showing higher concentrations during the flood and marked resuspension effect. Occasionally in the course of the flood current, the surface water showed a higher SPM content than the bottom water, suggesting a vigorous turbulent mixing under the strong flood current and also a patch-like distribution of SPM in this environment.

At station C, the average SPM concentration was 596 mg/*l* (70-1193 mg/*l*) and 1469 mg/*l* (278-3566 mg/*l*) at surface and bottom, respectively. Here, the SPM concentrations were generally higher during the ebb at surface and during the flood at bottom. At station D, the average SPM concentration was

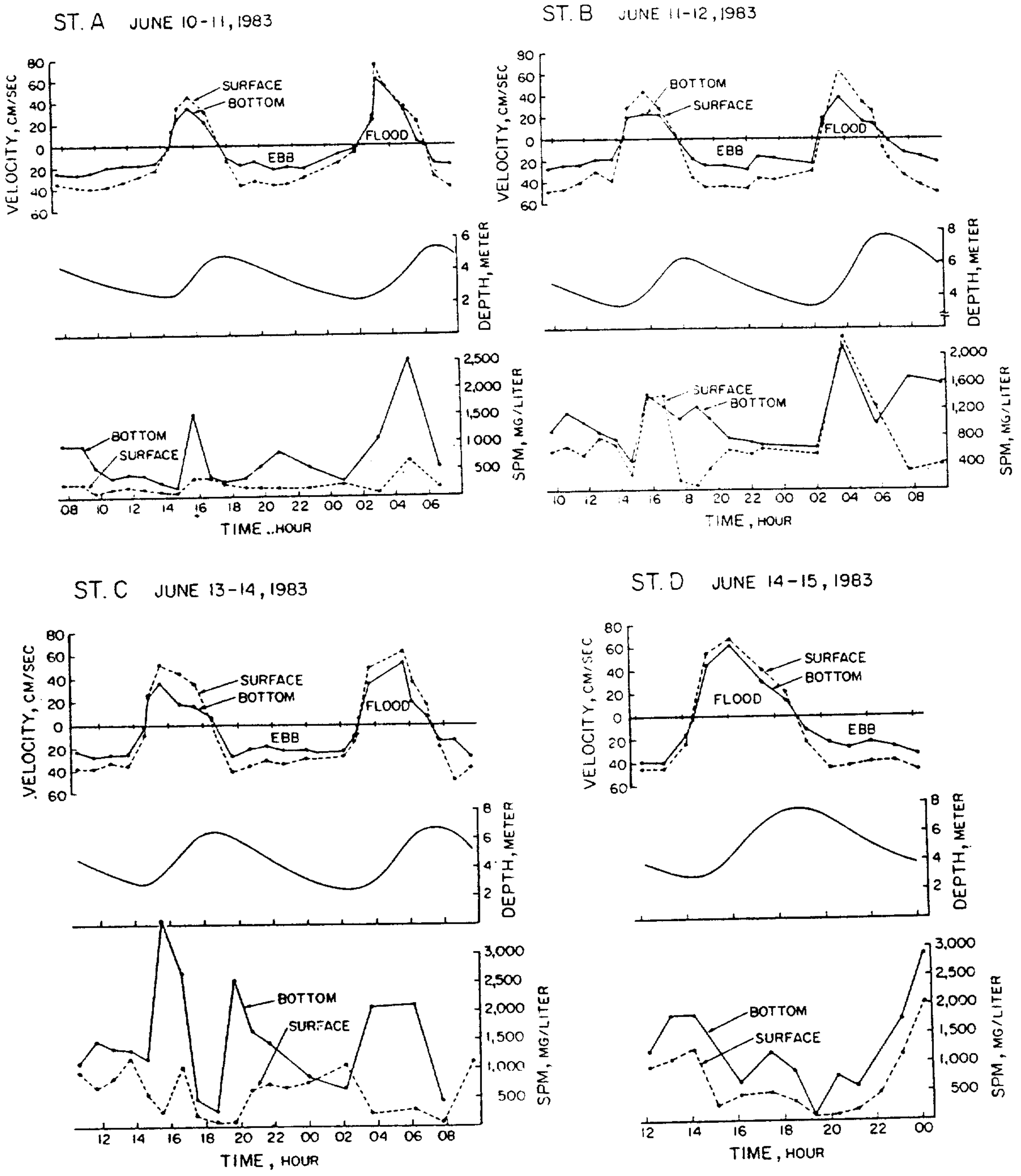

Fig. 3. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, June 10-15, 1983 (St. A,B,C,D)

667 mg/*l* (45-2016 mg/*l*) at surface and 1240 mg/*l* (64-2891 mg/*l*) at bottom. Both for surface and bottom waters, the SPM concentrations were higher during the ebb than during the flood, indicating a relative dominance of the longitudinal concentration gradient effect over the resuspension effect in controlling the SPM content in this location.

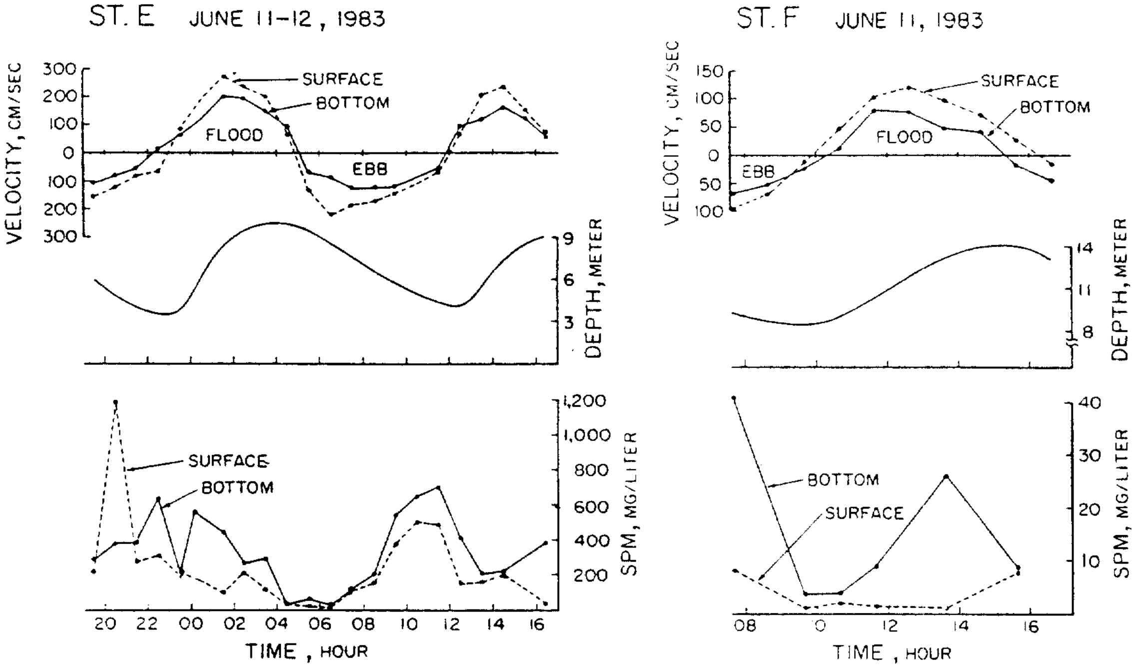

Fig. 3. Cont. (St. E,F)

At station E, the average SPM concentration was 237 mg/*l* (14-1183 mg/*l*) at surface, 283 mg/*l* (31-615 mg/*l*) at mid-depth and 332 mg/*l* (21-712 mg/*l*) at bottom. The up- and downstream movement of water masses related to the flood-ebb succession appeared to control the observed temporal SPM variation in this station over a semidiurnal tidal cycle. Hence, the maximum concentration occurred near the end of the ebb and the minimum near the end of the flood, both at surface and bottom. At station F, an offshore station located at about 17 km from Kunsan Harbour, the SPM concentration varied between 1.4-8.7 mg/*l* at surface, between 2.9-11.4 mg/*l* at mid-depth and between 4.1-27.4 mg/*l* at bottom in the course of the tidal cycle. Here, no influence of the estuarine turbid water masses could be observed in the temporal SPM variation. The seaward limit of the estuarine turbid water influence occurred at about 8 km downstream of Kunsan Harbour, near the estuary mouth.

August 3-5, 1983: This was the period of high river discharge and neap-tide. During this period two anchor stations were occupied, stations C and D ', located at about 22 km and 16 km upstream from Kunsan, respectively. The maximum current speed occurred during the ebb current at both stations, forming an ebb-dominant current pattern (Fig. 4). The residual velocity, calculated over a tidal cycle, was oriented downstream through the entire water column at both stations.

The SPM concentration during this period was overall low and varied within greatly reduced ranges compared to the period of spring-tide and low river discharge. At station C, the SPM concentration varied between 10.8-48.6 mg/*l* at surface (av. 31 mg/*l*) and between 47.4-80.3 mg/*l* at bottom (av. 63 mg/*l*). At surface, the SPM concentration was higher during the ebb than during the flood, while at bottom, the temporal variation of SPM followed generally that of the bottom current speed. At station D ', the SPM con-

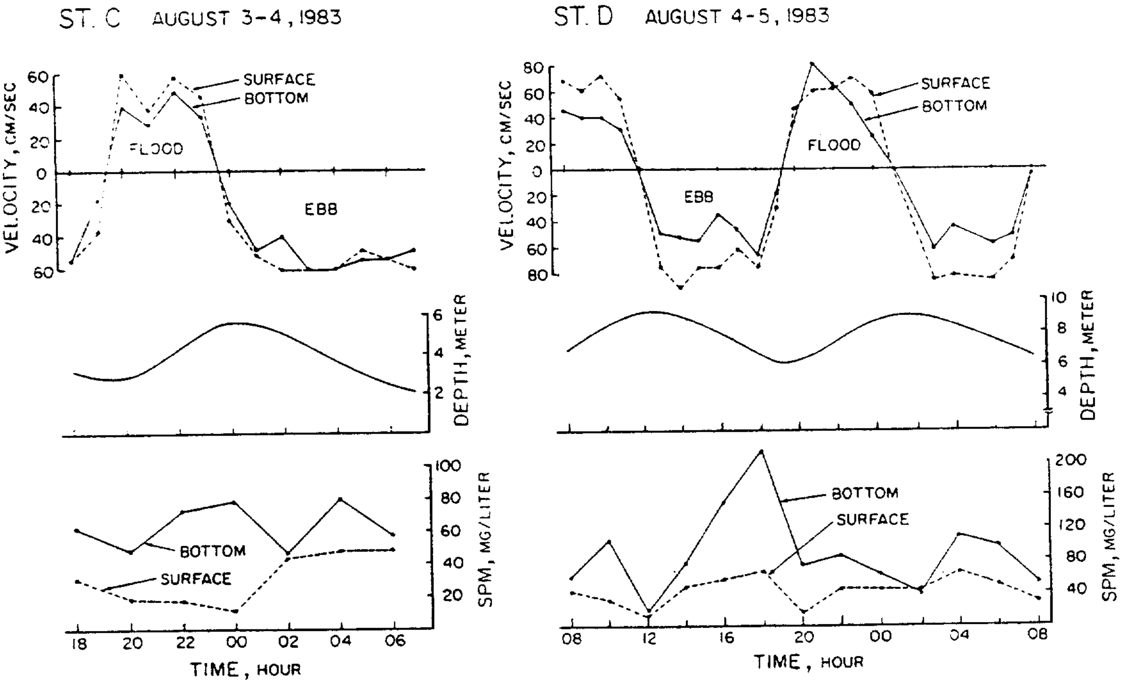

Fig. 4. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, August 3-5, 1983 (St. C,D')

centration varied between 14.2-66.7 mg/*l* at surface (av. 42 mg/*l*) and between 17-217 mg/*l* at bottom (av. 89 mg/*l*). The SPM concentration during the ebb was generally higher than that during the flood and the maximum occurred near the end of the ebb current.

The SPM concentration of the Keum River freshwater flowing into the estuary was estimated on the average at 30 mg/*l* for this period. This value is nearly identical with the average surface SPM concentration within the estuary. So, during this period no turbidity maximum was formed in the Keum Estuary.

July 15-16, 1984: This was the period of extremely high river discharge and medium tidal range. The greatly reinforced fluvial regime induced stronger ebb currents in the estuarine zone which attained a maximum velocity of up to 2 m/sec. Stations C and D, located at about 22 km and 10 km upstream from Kunsan, were occupied during this period. At both stations the maximum current speed occurred during the ebb and the residual velocities were all oriented downstream. The magnitude of residual velocities was also greatly increased in accordance with the increased fluvial discharge (Fig. 5).

The SPM concentration during this period was relatively high. It varied, at station C, between 84-361 mg/*l* at surface (av. 200 mg/*l*) and 87-437 mg/*l* at bottom (av. 255 mg/*l*). Both for surface and bottom waters, higher SPM concentrations were observed during the ebb current than during the flood. The intensely turbulent nature of the ebb current could be deduced from the surface water SPM concentrations which were virtually same as those of bottom waters during the ebb. At station D, the SPM concentration varied between 99-174 mg/*l* at surface (av. 130 mg/*l*) and between 130-1030 mg/*l* at bottom (av. 370 mg/*l*).

The results that emerged from this period contrast with those from June 1983. In June

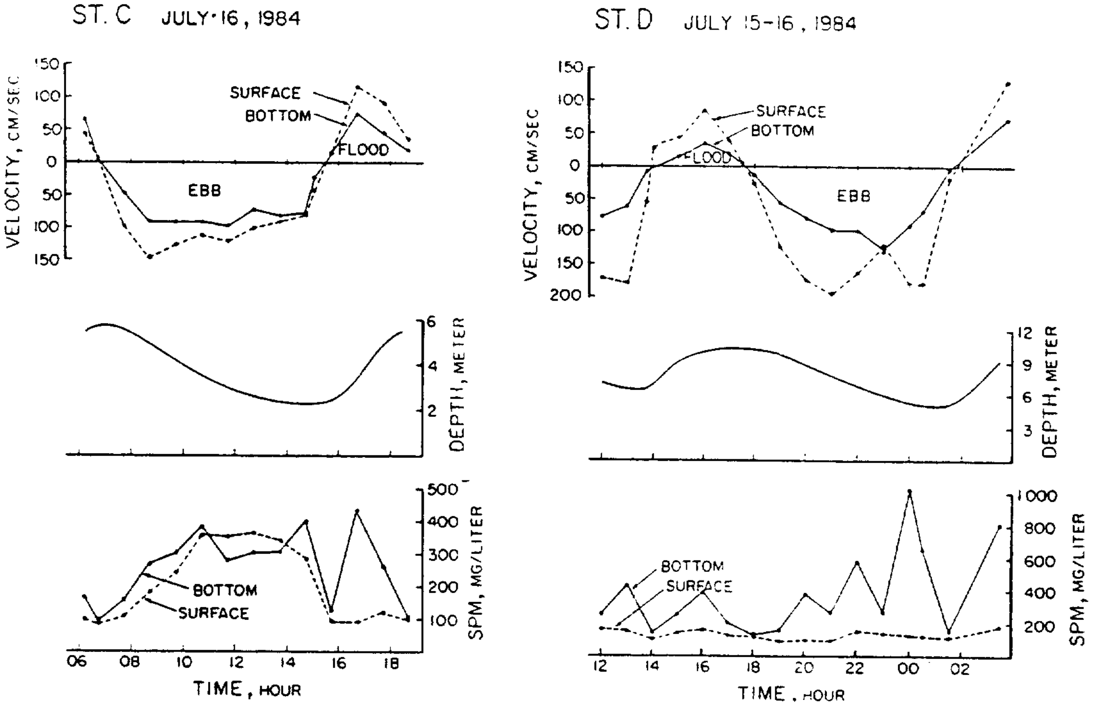

Fig. 5. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, July 15-16, 1984 (St. C,D)

1983, the resuspension occurred mainly during the strong spring-tidal flood current and the resuspended fine sediments could not escape the estuary because of the relatively weak ebb current. The consequence might be the repeated deposition-resuspension cycle in a nearly closed system, which resulted in highly elevated SPM concentrations, exceeding 500 mg/*l* in most parts of the estuary. On the other hand, during this period the strong ebb current was as effective as, or even more effective than, the flood current in eroding bottom sediments. This, supported by the extended duration of ebb current under the reinforced fluvial regime, facilitated the seaward escape of the resuspended fine sediments. Consequently, the SPM level during this period, though high, could not attain the level of the June 1983.

July 24-25, 1984: This was the period of relatively high river discharge and neap-tide. During this period, stations D and E were occupied. At both stations, the ebb current was stronger than the flood and the residual velocities were all oriented seaward (Fig. 6).

At station D, the SPM concentration varied between 14-127 mg/*l* at surface (av. 62 mg/*l*) and between 18-893 mg/*l* at bottom (av. 230 mg/*l*). It was generally higher during the ebb at surface, but higher during the flood at bottom. The higher bottom water SPM level during the flood observed in this period may speak for a more effective bottom erosion by the flood current than that by the ebb current. At station E, located on the channel just in front of Kunsan Harbour, the SPM concentration varied between 7-41 mg/*l* at surface (av. 16 mg/*l*) and between 8-215 mg/*l* at bottom (av. 65 mg/*l*). The minimum values of both the surface and bottom waters of this station represented the SPM concentration of the offshore waters. Both at surface and bot-

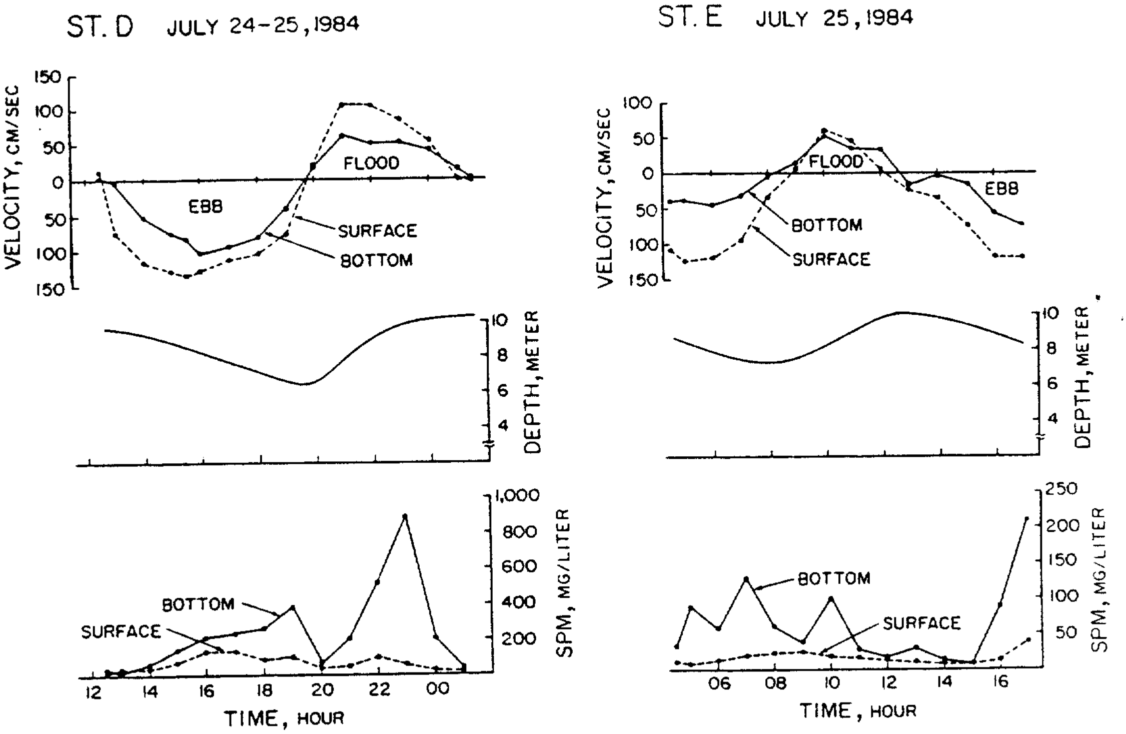

Fig. 6. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, July 24-25, 1984 (St. D,E)

tom the concentration was much higher during the ebb than during the flood, suggesting effective seaward transport of suspended sediments during this period.

November 23-24, 1984: This was the period of medium river discharge and spring-tide. During this period, station C was occupied where the maximum current speed, 195 cm/sec, occurred during the ebb and the residual velocity was oriented downstream through the entire water column (Fig. 7).

The SPM concentration varied between 273-1023 mg/*l* at surface (av. 510 mg/*l*) and between 325-4049 mg/*l* at bottom (av. 1165 mg/*l*), showing similar concentration ranges with those of June 1983 for the same station. The bottom water SPM content was exceedingly high during the flood compared to that during the ebb while it was not obvious for surface water, indicating that the elevated concentration at bottom during the flood was

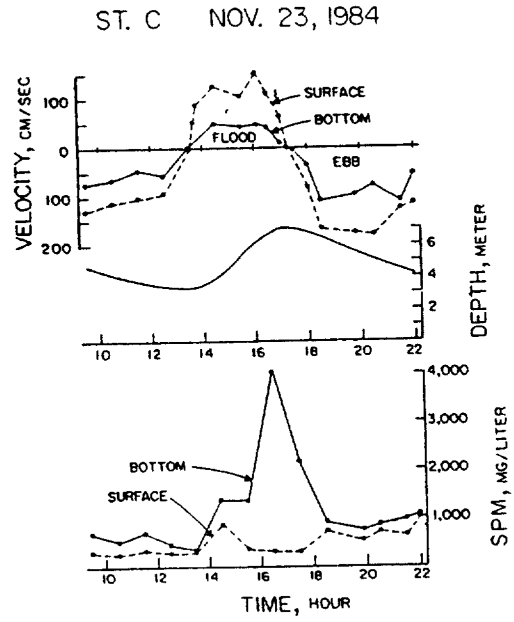

Fig. 7. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, November 23, 1984 (St. C)

principally due to the resuspension. A more effective erosion of bottom sediments by spring-tidal flood current compared to that by ebb current was also shown in other field observations. This may be explained by the difference in water depth, which becomes greater during the spring-tide period, between the high- and low-water levels and by more turbulent nature in general of the flood current caused by the density effect.

The surface SPM concentrations, observed during this same period along the whole length of the estuary, revealed that a turbidity maximum had developed within the estuary, in a comparable but somewhat smaller size. This turbidity maximum shifted seaward by about 10-15 km compared to that developed in June 1983. The larger fluvial discharge compared to June 1983 may account for the contracted and seaward-shifted development of turbidity maximum during this period..

April 14, 1985: This was the period of low river discharge and neap-tide. Station C was occupied on this day. The maximum current speed occurred during the flood and the residual velocities were oriented downstream through the entire water column (Fig. 8).

The SPM concentration varied between 43-258 mg/*l* at surface (av. 132 mg/*l*) and between 68-1150 mg/*l* at bottom (av. 343 mg/*l*). The highest concentration occurred during the flood at both surface and bottom. During the high- and low-water slacks, on the other hand, virtually no difference in concentration between the surface and bottom waters was observed, indicating that the SPM variation over tidal cycle was mainly due to the repeated resuspension and deposition.

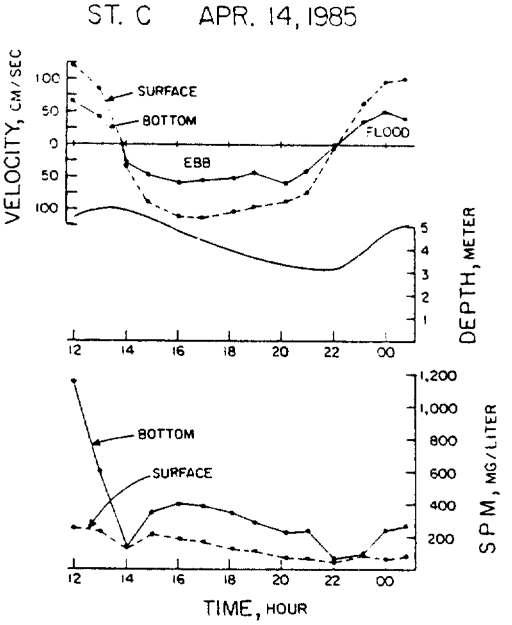

Fig. 8. Variation of the current velocity, depth and SPM concentration during the semidiurnal tidal cycle, April 14, 1985 (St. C)

Effects of Tidal and Fluvial Regimes on the Estuarine SPM

Variations of SPM concentration during a semidiurnal tidal cycle at a fixed point in estuaries are, as discussed in the previous section, primarily related to the periodic change of current speed and the upstream-downstream movement of water masses by flood- and ebb-currents. Suspended sediment transport in estuaries is known to be related to the circulation patterns of water, which result from a complex interaction between river and tidal flows (Ippen, 1966; Dyer, 1972). Therefore, any changes in either fluvial or tidal regimes will influence the SPM distribution within the estuary through modifications of such characteristics as the saline intrusion, the net non-tidal circulation and the patterns of current velocity distribution over the tidal cycle. In order to understand the estuarine SPM variation in space and time, it is thus necessary to analyze the effects of both the different fluvial and tidal conditions.

Influence of river discharge under spring-tide condition: June 10-15 (1983), July 15-16 (1984) and November 23 (1984) can be grouped as periods of spring-tide in spite of some differences in tidal range. The average tidal range at Kunsan during these periods was 532 cm, 460 cm and 670 cm, respectively, which all exceed the annual mean tidal range. On the other hand, the river discharge varied greatly and the above three periods fell under the categories of low discharge, extremely high discharge and medium discharge, respectively.

The common features of these spring-tide periods are the development of a distinct turbidity maximum and the high level of SPM concentration whithin the estuary. The different fluvial discharge influenced the saline intrusion and located the limit of the intrusion near Ganggyeong, about 40 km upstream from Kunsan during the low discharge and at about 5 km upstream from Kunsan during the extremely high discharge. On the other hand, the maximum current speed occurred during the flood current (flood dominant) under the low discharge condition while, under the elevated discharge conditions, it occurred during the ebb current (ebb dominant). The SPM concentration, though it was generally high during these spring-tidal periods, was highest under the low discharge condition.

Influence of river discharge under neap-tide condition: August 3-5 (1983), July 24-25 (1984) and April 14 (1985) belonged to the periods of neap-tide with average tidal ranges of 283 cm, 246 cm and 270 cm, respectively. The fluvial condition during these periods varied from high river discharge for the first two periods to low river discharge for the last one.

The common features observed during these neap-tidal periods are the generally low level of estuarine SPM concentration and the absence or vague development of turbidity maximum. The saline intrusion was influenced by the change in river discharge. Its limit occurred near Kunsan under high river discharge condition but extended to about 20 km upstream from Kunsan during the low river discharge. The maximum current speed, over a semidiurnal tidal cycle, occurred during the ebb under the high discharge condition and during the flood under the low river discharge. Though the SPM concentration was generally low during these neap-tidal periods, it was even lower when the river discharge was large.

Influence of tidal range under low river discharge condition: June 10-15 (1983) and April 14 (1985) were periods of similar fluvial conditions of low discharge but their tidal conditions were different,the former under spring-tide and the latter under neap-tide. The only common feature observed during these low discharge periods could be found in the flood-dominated current patten, i.e. the maximum current speed occurred during the flood current. The SPM concentration levels of these two periods differed greatly, indicating the predominance of tidal range in its controlling. On the other hand, compared to other periods of similar tidal ranges which were under high river discharge conditions and thus showed ebb-dominant current pattern, the above two periods showed higher SPM concentrations. These higher SPM concentrations might be related to the flood-dominant current pattern.

Evolution of Turbidity Maximum in the Keum Estuary

From the above comparisons it becomes evident that the periodic changes in fluvial and tidal regimes exert their influences on the estuarine SPM through different mechanisms, as is shown schematically in Figure 9. The tidal range at the estuary mouth, which varies as a fortnightly spring-neap cycle, controls primarily the resuspension of bottom sediments. The resuspension of bottom sediments appears to be the most important process in controlling the SPM concentration in the Keum Estuary. The SPM concentration increases as the tidal range at the estuary mouth increases and *vice versa.*

The change in river discharge, which shows on the whole a seasonal pattern, further modi-

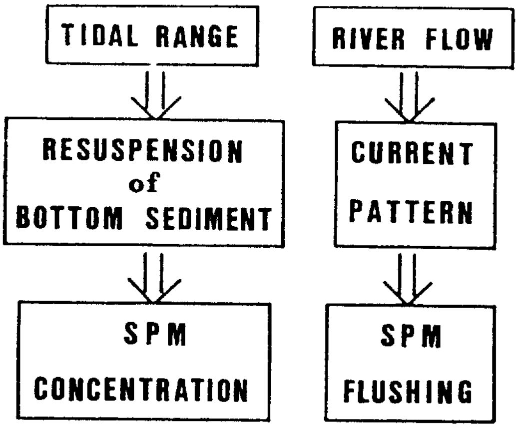

Fig. 9. Schematic presentation of the different mechanisms through which the variation in tidal and fluvial regimes control the estuarine SPM.

fies the estuarine SPM level. This modification is most probably related to the changes in the flood-ebb asymmetry in current velocities. The flood-dominant current pattern during the low discharge period results in higher SPM concentrations of flood waters, owing to the more effective resuspension by stronger flood current. This hinders most of the resuspended materials from escaping the estuarine zone. As a consequence, suspended sediments are transported within the estuary as in a semi-closed circuit. On the other hand, the ebb-dominant current pattern during the high discharge period may facilitate the seaward escape of SPM because of the increased erosion efficiency of strengthened ebb current and of the seaward shift of mixing zone during this period. Consequently, given the same tidal range, the SPM concentration cannot attain such high values as those of the low discharge period.

Based on these different roles of tidal and fluvial regimes in controlling the estuarine SPM concentration, it is possible to construct a model, which describes the evolutionary paths of the turbidity maximum in the Keum Estuary, a well-mixed macrotidal estuary (Fig. 10). According to the periodicity involved, three cyclic patterns with different time scales can be suggested: flood-ebb cycle, spring-neap cycle and high-low discharge cycle.

During a semidiurnal tidal cycle, repeated sedimentation and erosion occur in response to the change in current speed. Due to the rapid settling and sedimentation at the current slacks, the turbidity maximum shows a minimum extent at both high and low water slacks. With increases in current speed, erosion and resuspension of bottom sediments occur and the turbidity maximum becomes expanded over a wider zone. The alternation of flood and ebb currents, on the other hand, makes the center of the turbidity maximum zone migrate landward and seaward successively over tidal cycles. The distance of this semidiurnal migration of the turbid core is about 15-20 km in the Keum Estuary, which is almost identical with those reported from the Gironde Estuary or the Columbia River Estuary (Allen et al, 1974; Gelfenbaum, 1983). Similar semidiurnal patterns in the turbidity maximum evolution have been reported from other macrotidal estuaries as the Gironde, the Aulne and the Seine (Allen et al., 1977, 1980; Avoine et al., 1981).

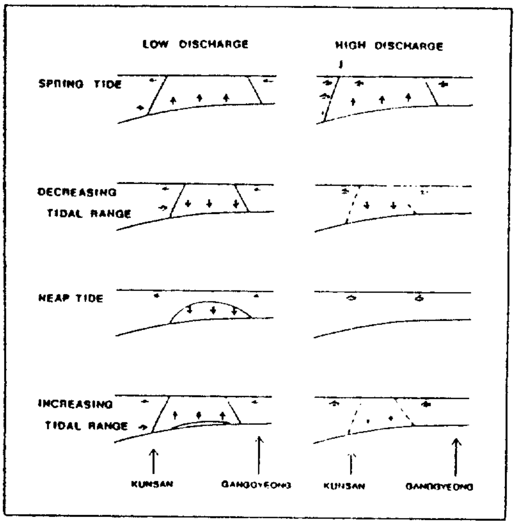

Fig. 10. Schematic diagram representing the evolution of turbidity maximum in the Keum Estuary.

During a fortnightly cycle of tidal range, tidal energy input into the estuary varies considerably which affects both the maximum current speed and the time-velocity asymmetry in tidal current. Accordingly, there is a great difference between the periods of spring-tide and neap-tide in the amount of sediment resuspension as well as in its ratio to sedimentation during one tidal cycle (Allen et al., 1977). In this respect, the extensive development of turbidity maximum and its elevated SPM level during the spring-tide can be accounted for by the dominance of resuspension over sedimentation. As the tidal range at the estuary mouth decreases, weakened flood current, which is more effective than ebb in bottom erosion, lowers the ratio of resuspension to sedimentation and, therefore, the SPM concentration in the turbidity maximum. During the neap-tide, sedimentation dominates over resuspension in most parts of the estuary and, eventually, the turbidity maximum disappears. In this respect, the turbidity maximum of the Keum Estuary is an unsteady feature which is fed and maintained by the resuspension of bottom sediments. This type of fortnightly variation of the turbidity maximum is reported also in a mesotidal estuary (Gelfenbaum, 1983) as well as in many macrotidal estuaries cited above.

Because the river discharge is controlled basically by the amount of precipitation on its drainage basin, its variation shows a seasonal pattern. Under the influence of monsoon, wet and dry seasons are relatively well separated from each other, inducing the high and low discharge periods respectively. As was discussed earlier in this section, change in river discharge modifies the flood-ebb asymmetry in current velocity and duration, which affects the flushing time of both water and suspended sediments. In this manner, most of fine sediments transported by the river during the low discharge period may not escape the estuarine zone and thus nourish the turbidity maximum. The seaward transport of estuarine sediments seems to occur mostly during the high river discharge period.

CONCLUSIONS

Major findings obtained from the present study can be briefly summarized as follows:

1) The turbidity maximum in the Keum Estuary is primarily caused by the erosion and resuspension of botton sediments. The fluvial sediment transport, though it constitutes the ultimate source of estuarine sediments, does not have any direct control on the formation of the turbidity maximum.

2) Variations in tidal and fluvial conditions exhibit different mechanisms from each other in controlling the SPM concentration within the estuary and, therefore, the evolution of turbidity maximum. According to their periodicity, three cyclic evolutionary paths can be described, i.e. the semidiurnal, fortnightly and seasonal cycles.

3) During a semidiurnal tidal cycle, the turbidity maximum shrinks and expands repeatedly following the variation in current speed. In addition, the zone of high turbidity migrates up- and downstream in response to the flood-ebb succession.

4) During a fortnightly cycle, the turbidity maximum degenerates and regenerates repeatedly according to the variation in tidal amplitude. The turbidity maximum in the Keum Estuary is an essestially spring-tidal feature though it can persist under relatively small tidal ranges when the flood-dominant current pattern occurs during the dry season.

5) Seasonal variation in river discharge controls the seaward transport of the estuarine fine sediments, through modifications of the flood-ebb asymmetry and the flushing rate of suspended sediments. Consequently, the turbidity maximum develops more extensively both in space and time under the low discharge condition. On the contrary, it can

be observed only during the spring-tide under the high discharge condition.

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