

금강하구 유동·퇴적환경의 장기 변화



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라운 컨벤션, 2017. 7. 12

발표 순서

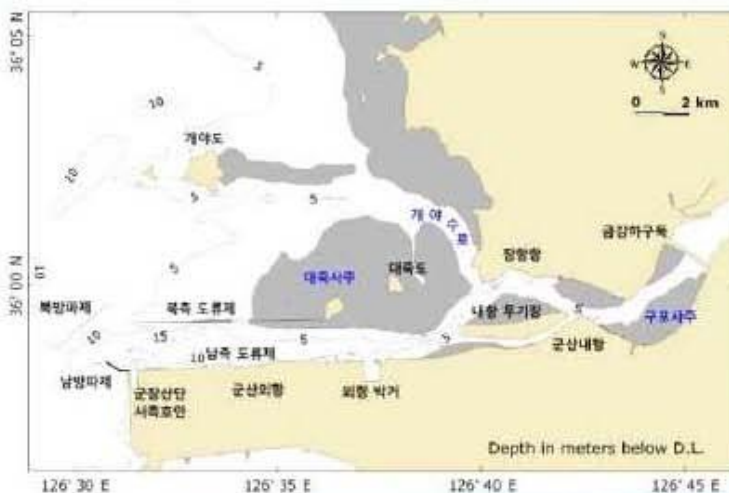
1. 금강하구 현황
2. 유동의 장기 변화
3. 퇴적의 장기 변화
4. 금강하구 통합 모델링시스템

금강하구 physical setting

- 하천 길이 401 km
- 유역 면적 9,828 km²
- 담수 방류량 5.5×10^9 m³/year (1995~2015)
- 대조차 6.0 m (군산외항 조위관측소)
- 하구 수심 최대 약 DL(-)15 m (도류제 입구)
- 염수 침입 하구둑 건설 전에 하구둑 상류 약 40 km (강경)

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하구 지형과 개발사업



개발 사업	공사 기간
금강 하구둑	83.11 ~ 88.12
금강 하구둑 운영	94.08 ~
북측 도류제	90.08 ~ 97.10
남측 도류제	92.11 ~ 98.12
군장산단 서측호안	93.05 ~ 00.05
북방파제	98.02 ~ 04.11
남방파제	06.09 ~ 09.12
내항 투기장	? ~ 06.12

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개발사업 전·후의 지형

1973년



전승수(2011)

2013년

Pleiades
2013. 10. 23

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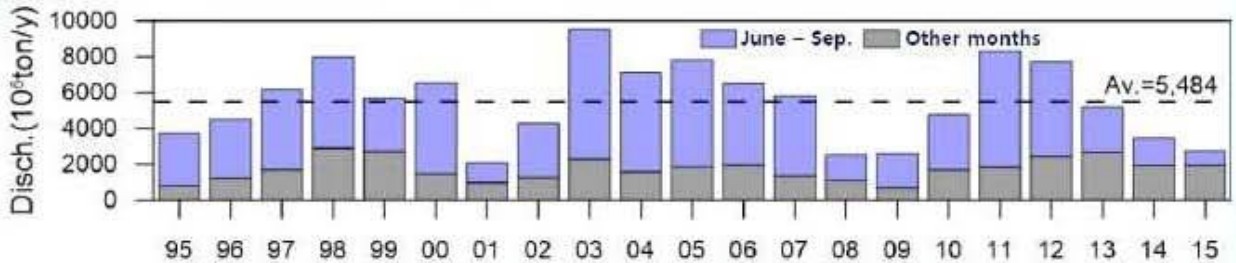
항로·박지 준설계획



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하구둑 담수 방류량

■ Annual freshwater discharge (1995~2015)



■ Monthly freshwater discharge (Sep. 1994 – Aug. 2013)

Item	Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Discharge (10 ⁶ ton)		157	159	186	233	284	525	1,329	1,258	891	299	189	195	5,707
Frequency		10	9	12	14	17	20	35	36	27	16	12	12	220
Opening hour		24	23	30	36	45	65	142	141	104	41	29	29	709
Hour per opening		2.4	2.6	2.5	2.6	2.6	3.3	4.1	3.9	3.9	2.6	2.4	2.4	3.2

- Discharge in summer (June to Sep.) : 72% of the annual

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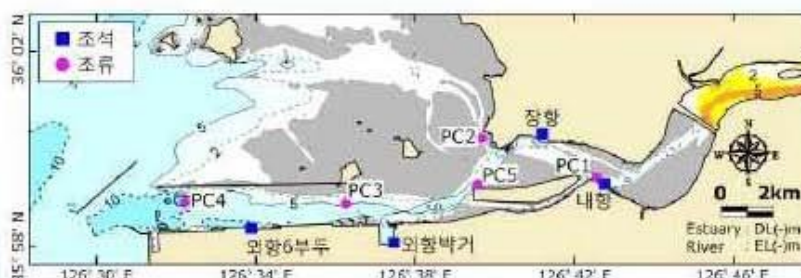
2. 유동의 장기 변화 (1/6)

갑문 작동 전·후의 조석

(단위: cm)

검조소	갑문	관측기간	평균고조위	평균해면(Ao)	평균저조위	대조차
내항	작동 전	'81~'93	606.8	374.7	150.8	566.7
	작동 후	'95~'03	621.2 (+14.4)	372.8 (-1.9)	127.0 (-23.8)	619.8 (+53.1)
외항 박거	작동 전	'81~'93	594.2	364.9	127.8	602.8
	작동 후	'95~'05	607.1 (+12.9)	366.9 (+2.0)	127.8 (0.0)	614.3 (+11.5)

- 하구둑 갑문 작동 후, 군산내항에서 평균고조위 14cm 상승, 평균저조위 24cm 하강, 대조차는 53cm (9.4%) 증가함



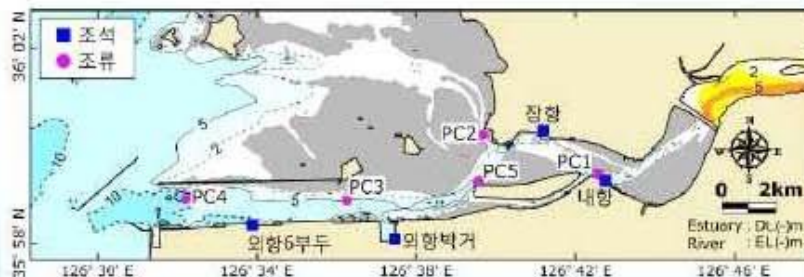
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갑문 작동 전·후의 대조기 최강유속

(단위: cm/s)

갑문	관측기간	PC4 (도류제 입구)		PC3 (도류제 중점)		PC2 (개야수로)		PC1 (내항수로)	
		창조류	낙조류	창조류	낙조류	창조류	낙조류	창조류	낙조류
작동 전	'85~'93	125	130	145	127	113	97	146	150
작동 후	'95~'99	97	72	136	98	67	64	85	74
창조류 / 낙조류		0.96 → 1.35		1.14 → 1.39		1.16 → 1.05		0.97 → 1.15	

- 갑문 작동 후 유속 감소, 주수로에서 창조류가 상대적으로 우세



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주수로의 “창조 우세” - Why?

Possible Reasons :

- 1) Amplification and phase shift of shallow water tide
- 2) Flood-dominance in main channel, but ebb-dominance in Gaeya channel on the contrary

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갑문 작동 전·후의 M_4 분조류

- Phase difference between M_2 and M_4 current

$$\Delta\theta = \theta_2 - 2\theta_1 \quad \text{where, } V_{M_2} = a_1 \cos(\omega_t - \theta_1) \quad V_{M_4} = a_2 \cos(2\omega_t - \theta_2)$$

- Effect of $\Delta\theta$ on current asymmetry

$\Delta\theta > 270^\circ$ or $\Delta\theta < 90^\circ$: stronger flood (max at $\Delta\theta=0^\circ$)

$90^\circ < \Delta\theta < 270^\circ$: stronger ebb (max at $\Delta\theta=180^\circ$)

- Observed $\Delta\theta$ and Amplitude Ratio of M_4/M_2

Period	$\Delta\theta$ ($^\circ$)		a_2 / a_1	
	KOP (PC3)	KIP (PC1)	KOP (PC3)	KIP (PC1)
1985 ~ 1991	49	20	0.14	0.14
1995 ~ 2001	323	304	0.07	0.11

- Current asymmetry due to amplification or phase shift of M_4 is **not intensified** after closing the barrier.

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갑문 작동 전·후의 대조기 조량 (수치실험)

(Unit : 10^6m^3)

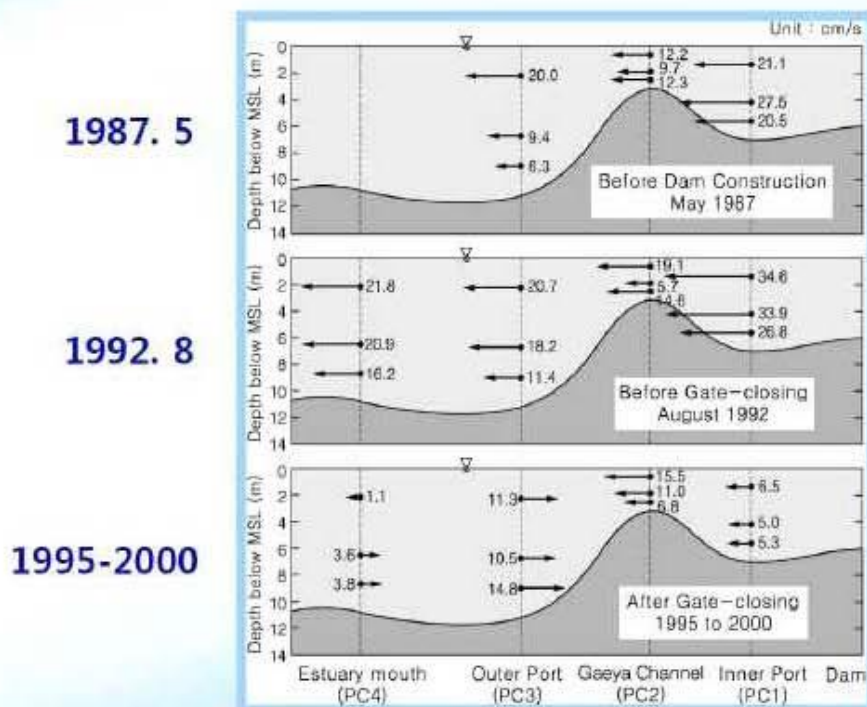
Year	KOP channel (PC3)			Gaeya channel (PC2)			KIP channel (PC1)		
	Flood	Ebb	F/E (%)	Flood	Ebb	F/E (%)	Flood	Ebb	F/E (%)
1982	166	184	90	66	52	127	140	144	97
1995	143	127	113	14	31	45	49	49	100
1999	130	119	109	17	30	57	45	45	100

■ 주수로에서 창조 우세 원인

- ✓ 조석 위상 : 주수로에서 개야수로보다 빨라짐
→ 순간 조위 : 주수로에서 개야수로보다 높아짐
- ✓ 하구둑 ? 도류제 ? 주수로 준설 ? 개야수로 퇴적 ?

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갑문 작동 전·후의 잔차류



Converted to flood direction in middle- and lower estuary after closing the barrier

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갑문 작동 전·후의 SSC (대조기)

(Unit : mg/L)

Period	PC4 (Estuary mouth)		PC3 (KOP channel)		PC2 (Gaeya channel)		PC1 (KIP channel)	
	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb
1987~1993	102	101	189	135	162	157	253	239
1995~1999	54	44	43	37	58	38	69	40

- Before closing

- ranges 100~250mg/L and increases upstream in normal weather condition

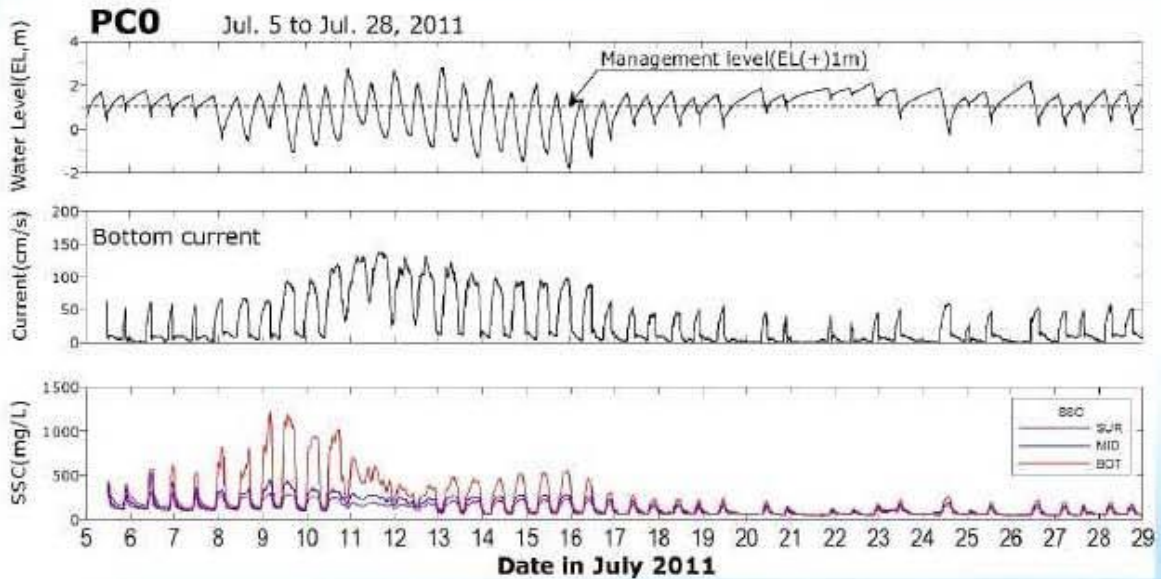
- After closing

- ranges 40~70mg/L due to reduction of current

- Higher SSC in flood phase indicates continuous upstream transport of SS

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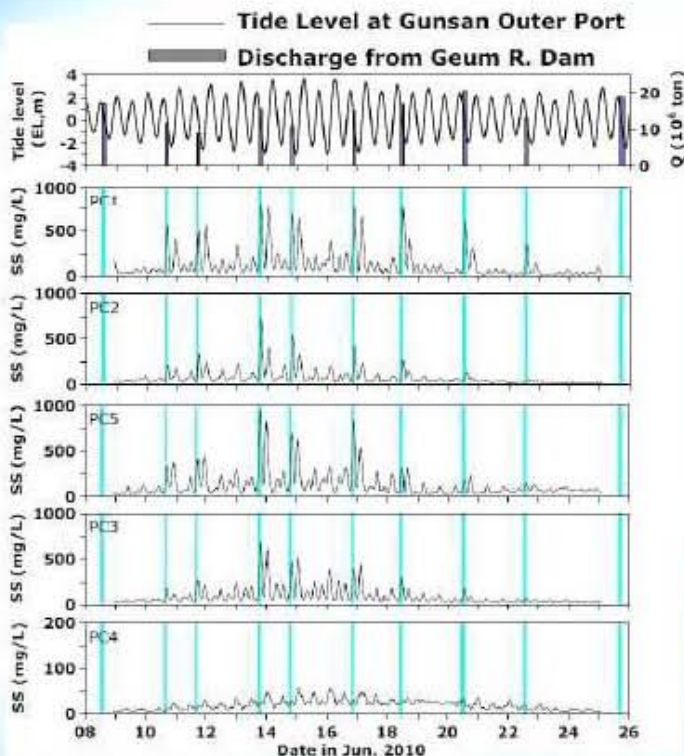
홍수기 하구둑 상류의 유속과 SSC (2011)



- 최고 농도 : 저층 1,225mg/L, 중층 531mg/L, 표층 352mg/L

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홍수기 SSC (2010.6.9-24)



- A considerable amount of sediments escaped offshore in ebb cannot be transported farther away and reenters the main channel during the subsequent flood.

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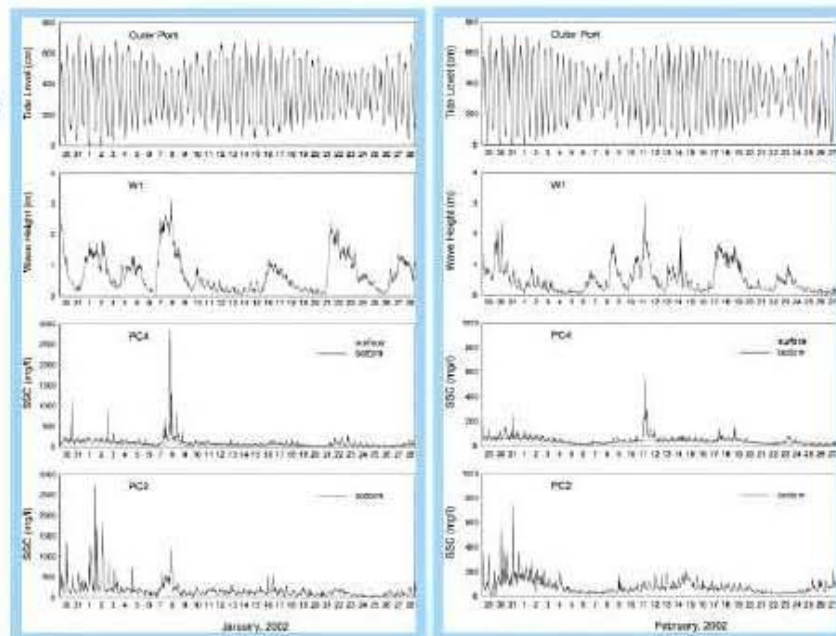
동계 SSC (PC2 & PC4, 2002)

Tide
(Outer Port)

Wave, Hs
(Offshore)

SSC
(PC4)

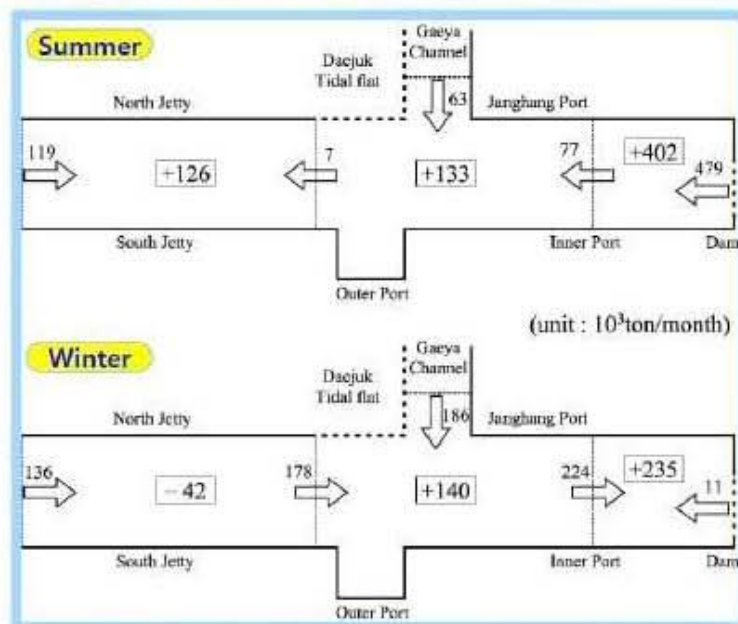
SSC
(PC2)



- SSC increases with higher wave and stronger current.
- But, response of SSC to waves is not always the case.
 - Feb. 11 at PC2, low SSC with high waves but weak currents

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금강하구의 퇴적물 수지 (2001-2002)



Summer 84% of the river-borne flux is deposited in the upper estuary.
Net flux at KIP & KOP channel is downstream.

Winter Net flux at KIP & KOP channel is upstream.

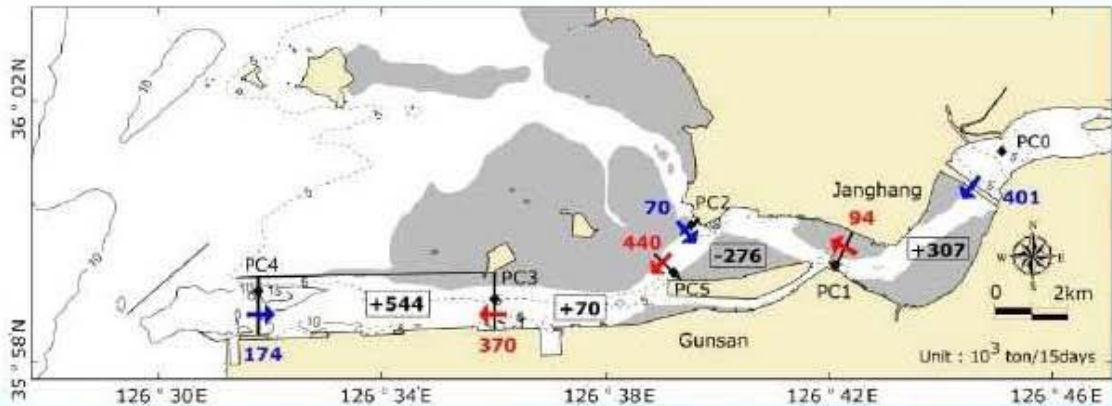
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금강하구의 퇴적물 수지 (2011.8)

(단위 : 10^3ton/15day)

기간	PC4 (도류제 입구)	PC3 (도류제 중점)	PC5 (장항수로)	PC2 (개야수로)	PC1 (군산내항)	PC0 (하구둑 상류)	총유입량
2011. 7. 30 ~ 8. 14	174.3	-370.0	-440.0	69.9	-93.7	400.6	644.8

※ '+'는 창조류 방향(PC0는 하구둑 유출량), '-'는 낙조류 방향



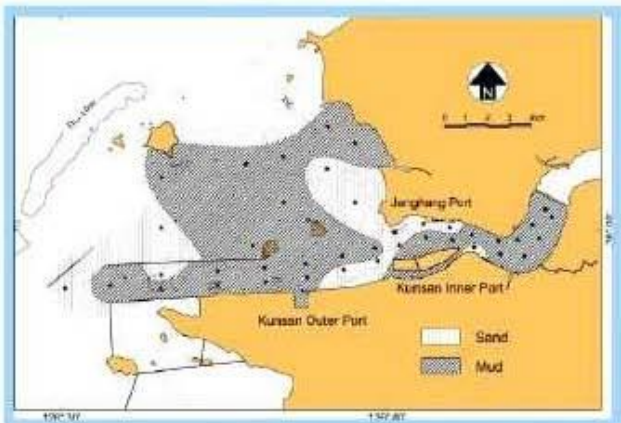
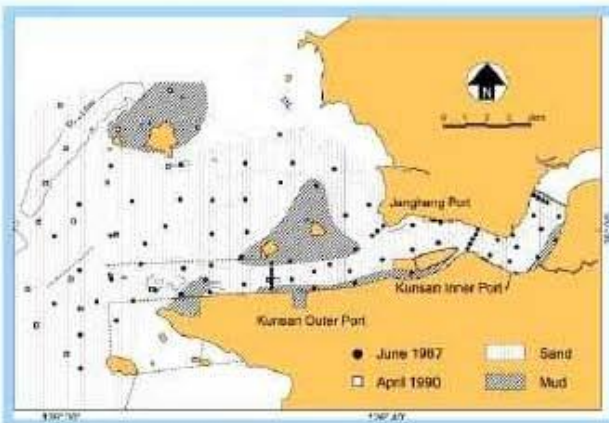
• 퇴적 : 내항~하구둑, 내항~장항항, 도류제 사이 • 침식 : 군산내항~장항수로

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해저퇴적물 입도 분포

1987 & 1990

1999



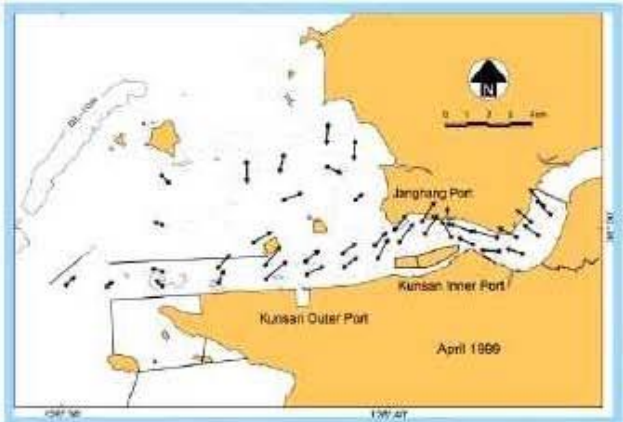
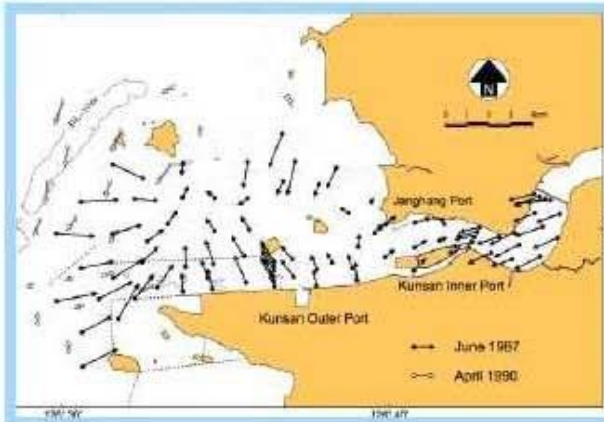
- 1987 & 1990 : **Sands** covered most of the estuary. Strong currents prevent the fine-grained sediments from depositing in the main channel.
- 1999 : **Muds** veneered most areas of the estuary. Weakened currents let the fine sediments trapped and deposited.

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퇴적물 이동경로 (Gao & Collins, 1992)

1987 & 1990

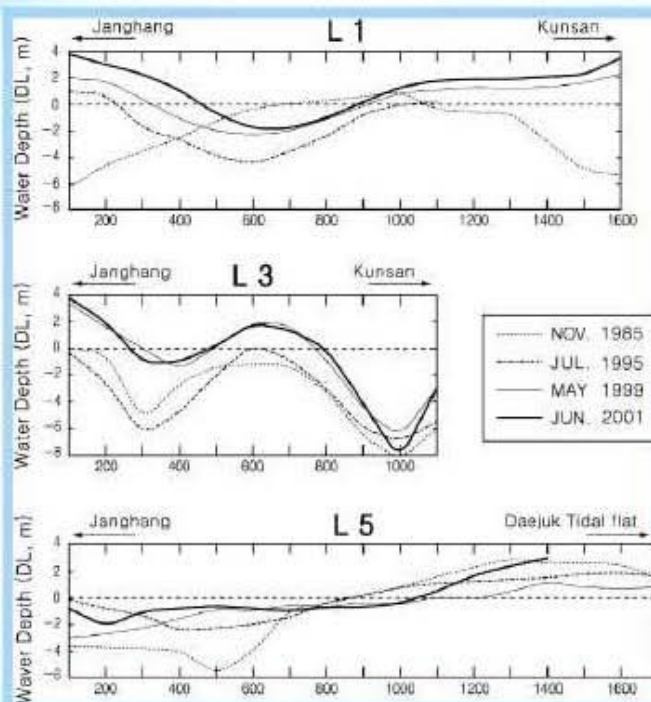
1999



- 1987 & 1990 : Sediments are transported mainly **to the ebb direction** **in the upper estuary** and toward Daejuk tidal flat from the main channel, Gaeya channel and the offshore.
- 1999 : **Upstream transport is prevailing in the main channel**, maybe due to relative intensification of the flood current.

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수로 단면 변화



L1 : Two channels were buried away.
Max. deposition of 10m
from 1985 to 2001.

L3 : Max. deposition of 5m
in the northern channel.

L5 : The deepest part is shallowed
to DL(-)2.0m from DL(-)5.5m.

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갑문 작동 전·후의 퇴적율

Sector	Area (10 ³ m ²)	Period	Sedimentation rate	
			(cm/a)	(10 ³ m ³ /a)
A	8,360	1985.11~1993.01	18.0	1,505
		1995.07~2001.06	40.8	3,411
B	9,960	1985.11~1992.07	5.9	588
		1995.07~2001.06	24.2	2,410
C	7,850	1985.11~1993.07	1.4	110
		1995.06~2001.06	20.6	1,617
D	6,670	1985.11~1993.07	3.7	247
		1995.06~2001.06	22.2	1,481
E	12,120	1985.11~1993.07	4.0	485
		1995.06~2001.06	1.4	170
F	560	1985.04~1994.03	126.6	709
		1995.05~1999.07	67.4	377



● Total sedimentation rate (except sector C)

- Before closing $3,534 \times 10^3 \text{m}^3/\text{a}$
- After closing $7,849 \times 10^3 \text{m}^3/\text{a}$
- increase by 2.2 times

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퇴적율의 장기 변화

(단위 : cm/year)

기간	E (도류제 사이)	F (외항 박거)	D (장항항~외항)	C (개야수로)	B (내항~장항항)	A (하구둑~내항)
1985~1993	4.0	126.6	3.7	1.4	5.9	18.0
1995~1999	-1.3	67.4	17.1	27.2	26.6	42.3
1999~2001	3.8	-	24.3	14.2	9.0	20.3
2001~2003	13.1	63.8	16.7	20.8	20.9	23.2
2003~2008	23.6	57.3	11.1	7.7	13.0	8.4
2008~2010	10.2	87.4	1.0	-	4.7	16.9



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요약 : 유동·퇴적의 장기 변화

- 하구둑 건설 후, 조석파가 하구둑에 반사되어 대조차가 약 60cm (11%) 증가하였음. 조류속은 크게 감소하였으며, 창조류속이 상대적으로 강화되고, 하구 입구와 중앙에서 잔차류가 상류 방향으로 변화됨.
- 하구둑 건설 전에는 조립(sandy) 퇴적물이 우세하였으나, 건설 후 세립(muddy) 퇴적물이 광범위하게 집적되었음. 세립 퇴적물의 집적은 퇴적물 운송 능력(sediment transport capacity)의 감소와 창조류 우세 환경으로의 변화에 기인함.
- 하구둑 건설 후의 퇴적물 수지 분석결과, 도류제 입구와 개야수로를 통하여 퇴적물의 순유입이 나타남.
- 하구 퇴적량은 하구둑 갑문 작동 전인 1985~1993년에 $3.5 \times 10^6 \text{m}^3/\text{y}$ 에서 1995~2001년에 $7.8 \times 10^6 \text{m}^3/\text{y}$ (2.2배)로 증가하였고, 이후 점차 감소하여 현재는 하구둑 공사 전과 유사한 수준임.

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금강하구 환경이슈와 모델링 목표

■ Environmental issues in the Geum River Estuary

- Siltation in the navigation channel & tidal flat
- Deteriorated water quality
- Algal blooming in the upper estuary
- Reduced laver production in the lower estuary

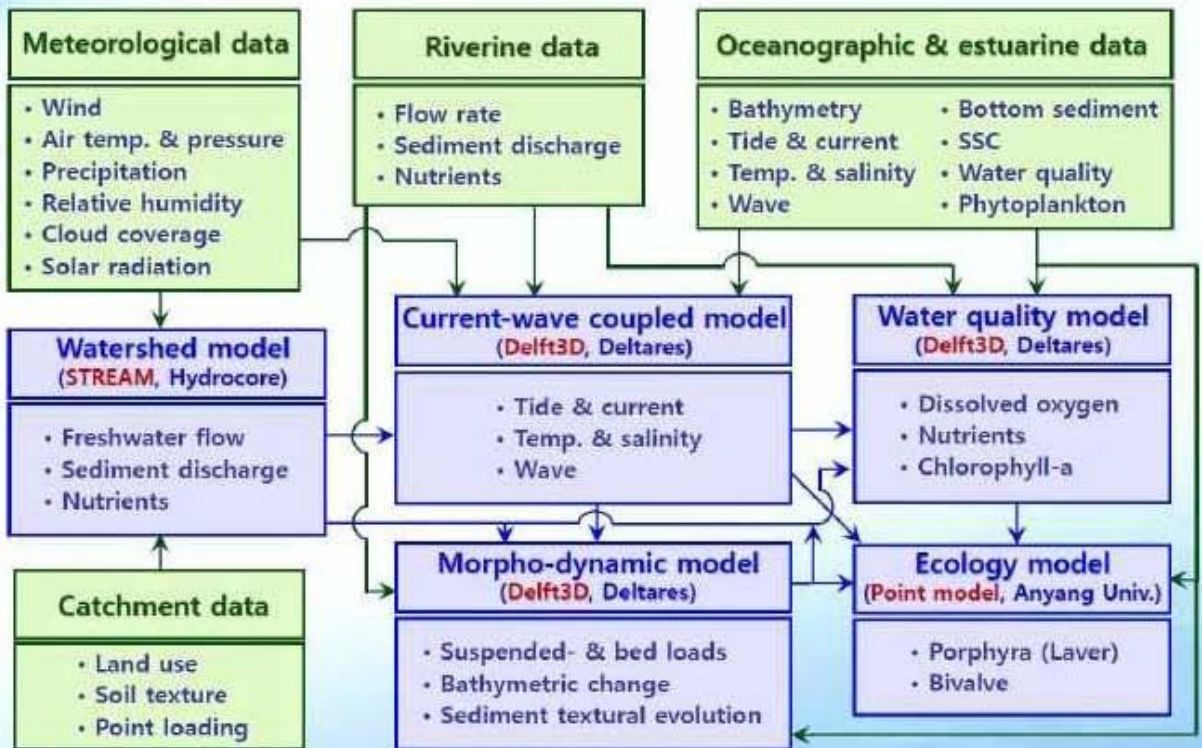
■ Aims of the modeling study

- To provide strategic measures for improving the estuarine environment
- To develop now-cast / forecast system for the estuarine water quality
- To provide, if any, early warning of environmental risks

※ 하구역 종합관리시스템 개발연구 II (해양수산부, KIMST, 2014~2018)

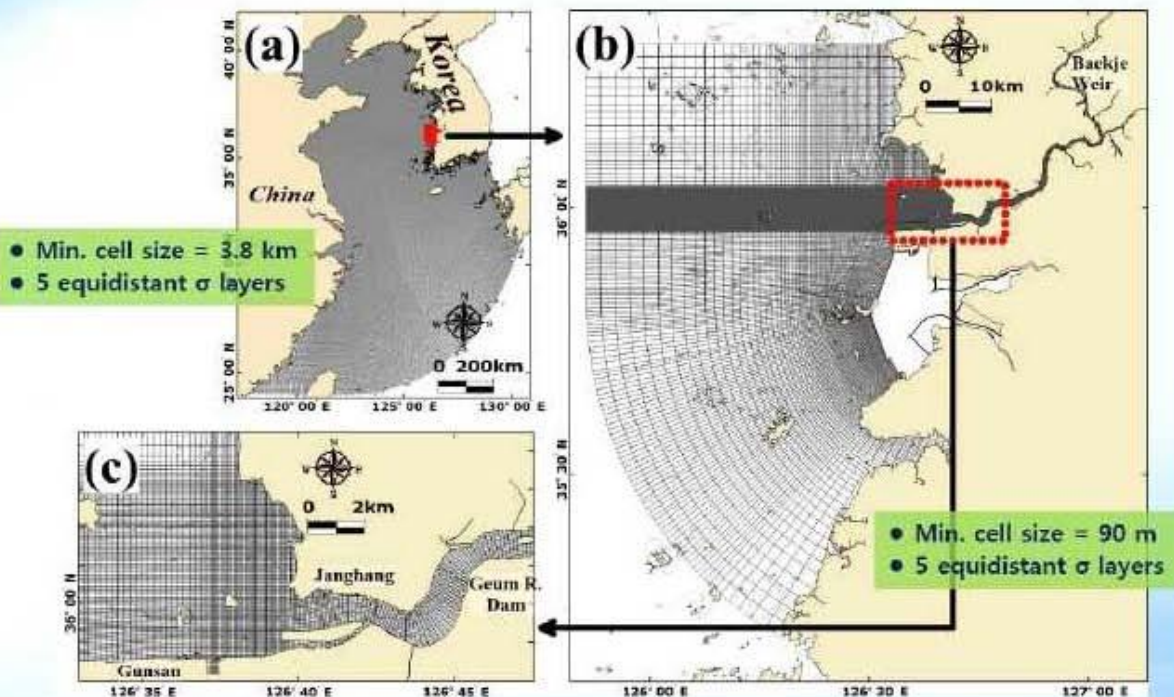
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금강하구 통합모델링 흐름도



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모형 구축 : Delft-3D



(a) YECS (Yellow & East China Sea) model, (b) GRE (Geum River Estuary) model

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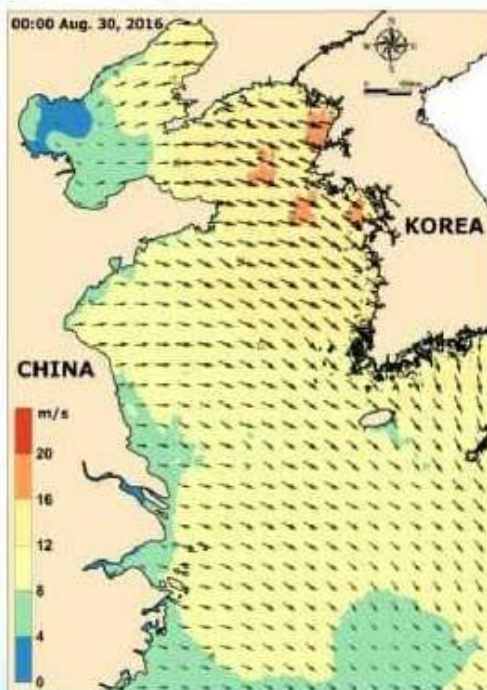
모델 보정 & 검정

- ✓ Calibration for 1 year of 2014
- ✓ Validation for 1 year of 2015

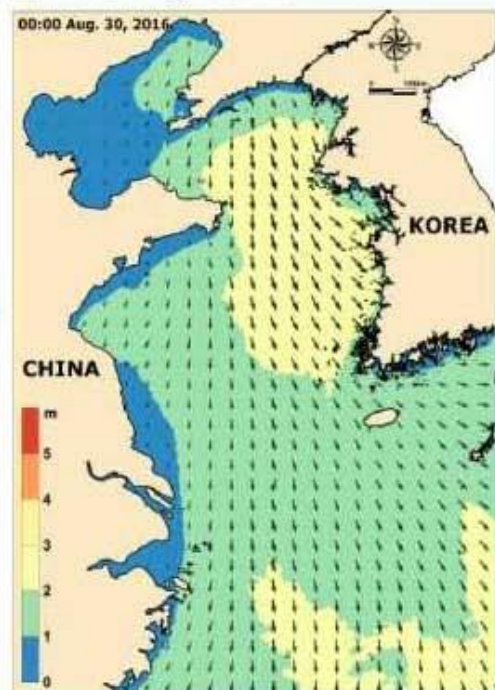
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파랑 모델링

■ Wind by UM



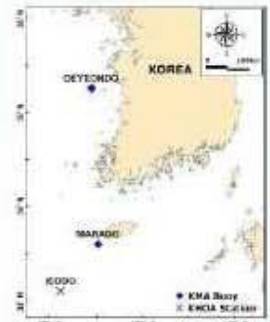
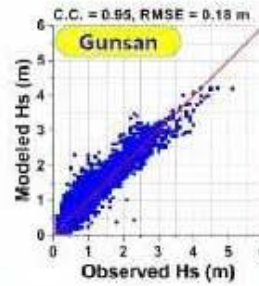
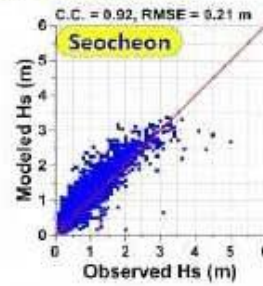
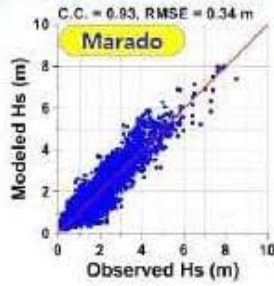
■ Wave by SWAN



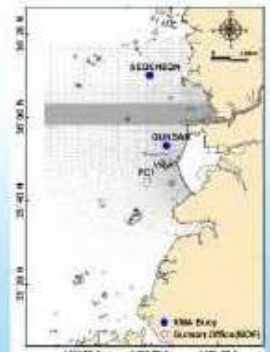
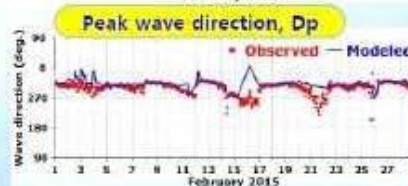
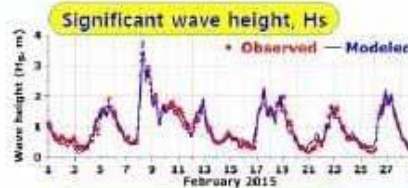
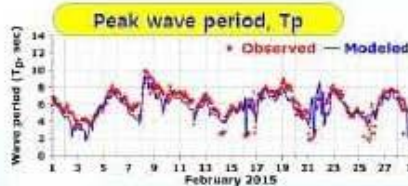
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파랑 모델의 보정·검정

■ Comparison of Hs in 2014 to 2015



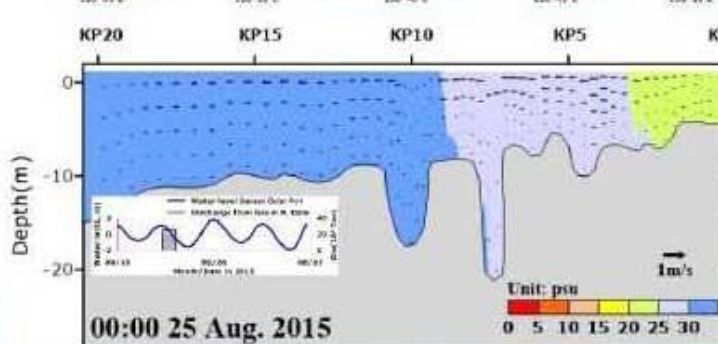
■ Comparison of Hs, Tp & Dp at PC1 in Feb., 2015



※ Wind input : CFSv2 (Δt 1h, ΔS 20km) from NOAA

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물리·유동 모델링 : 유속, 염분

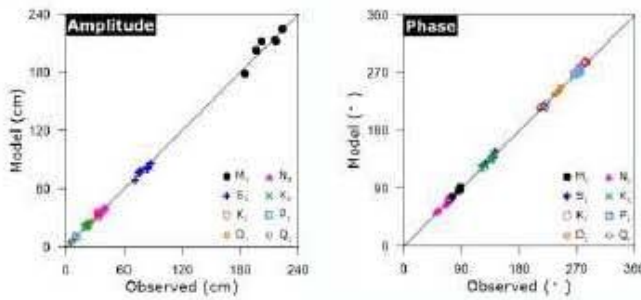


- Vertically stratified in the upper estuary following freshwater run-off from the dam
- Stratified during ebb, but well-mixed during flood

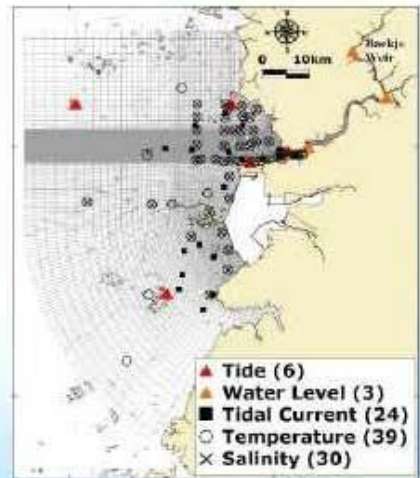
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물리·유동 모델의 보정·검정 : 조석, 조류

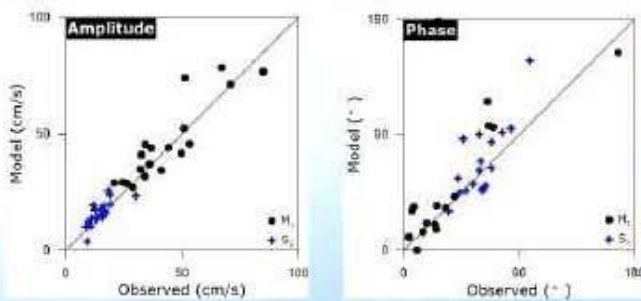
Tide



Monitoring stations



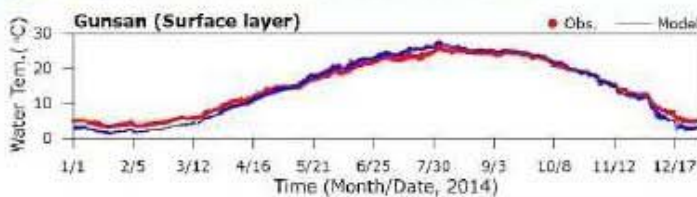
Tidal current



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물리·유동 모델의 보정·검정 : 수온, 염분

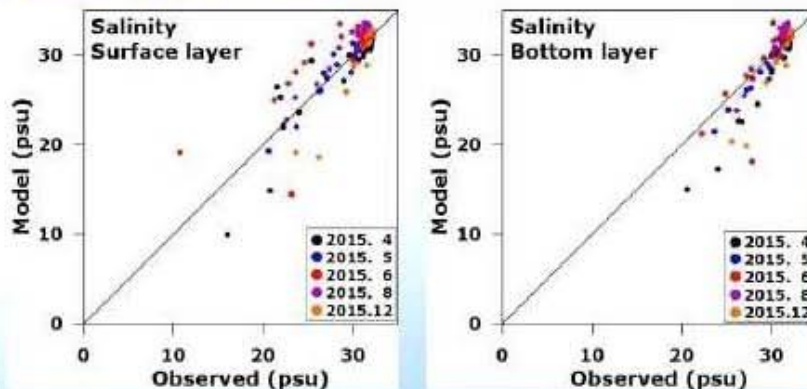
Temp., Gunsan Outer Port in 2014



Monitoring stations



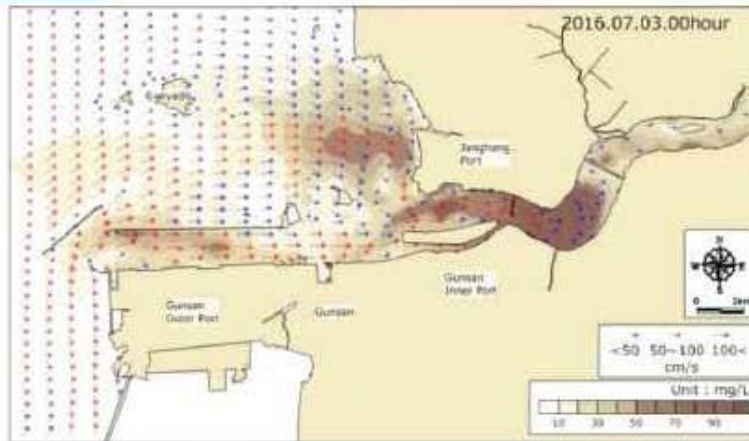
Salinity, spatial in 2015



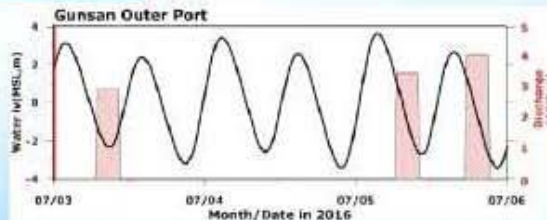
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퇴적 모델링 : 유속, SSC

SSC, bottom



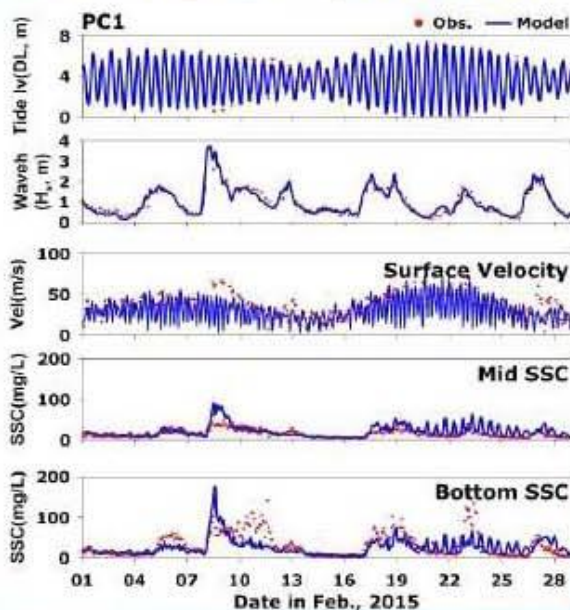
Tide & Freshwater run-off



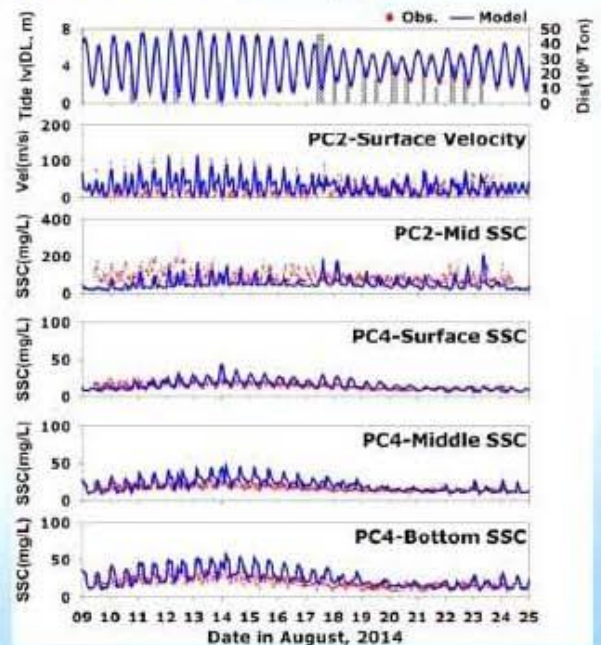
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퇴적 모델의 보정·검정 : SSC

■ Offshore (PC1, 새만금) in Feb., 2015



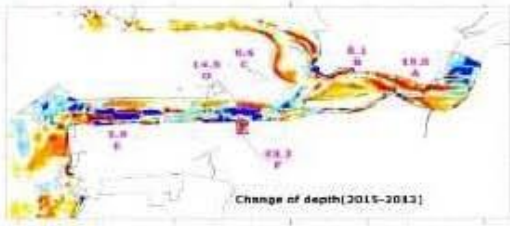
■ Main channel in Aug., 2014



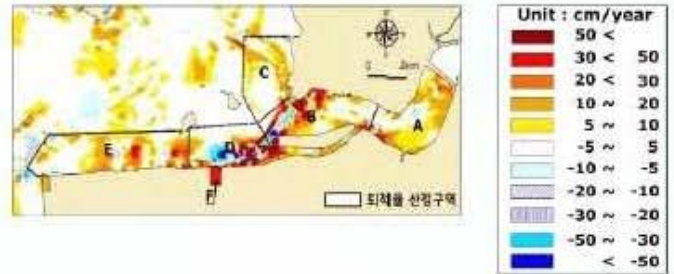
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퇴적 모델의 보정·검정 : 퇴적율

■ Soundings in Oct. 2013 & Oct. 2015



■ Modeling from Jan. 2014 to Dec. 2015



■ Modeling from Jan. 2014 to Dec. 2015

(Unit: cm/year)

	E	F	D	C	B	A	Total
Sounding	5.8	43.3	14.5	8.6	8.1	19.0	10.9
Model	6.6	42.4	16.8	5.4	13.1	7.9	10.0

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모델 재현율

Variable	Parameter	Skill score		Skill index	Data type	No. Of stations (Cal / Val)
		Calibration (2014)	Validation (2015)			
Wave	Hs	0.95	0.95	IOA	Hourly	2
Tide	Semi-range	0.99	0.98	ARE	8 tidal constants	6
	Phase-lag	1.00	0.99			
Tidal current	Amp.	0.87	0.83	"	2 tidal constants	19 / 5
	Phase-lag	0.89	0.92			
Temperature		0.98	0.99	IOA	Hourly, spatial	11 / 39
Salinity		0.57	0.85	"	Hourly, spatial	2 / 31
SSC		0.64	0.62	"	Hourly, spatial	4 / 5
Sed. rate		0.70		ARE	Sub-sector	6

$$IOA = 1 - \frac{\sum_{i=1}^n (M_i - O_i)^2}{\sum_{i=1}^n (|M_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

(Index of agreement; Willmott, 1982)

$$ARE = 1 - \left(\sum_{i=1}^n \left| \frac{O_i - M_i}{O_i} \right| \right) / n$$

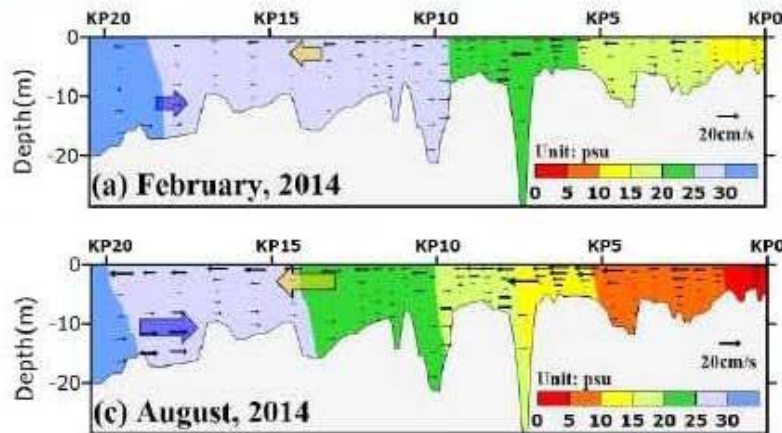
(Absolute relative error)

O_i : Observed data
 M_i : Model data
 n : Number of data

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계절별 하구 순환

Monthly mean salinity & residual current in 2014



Longitudinal section along thalweg

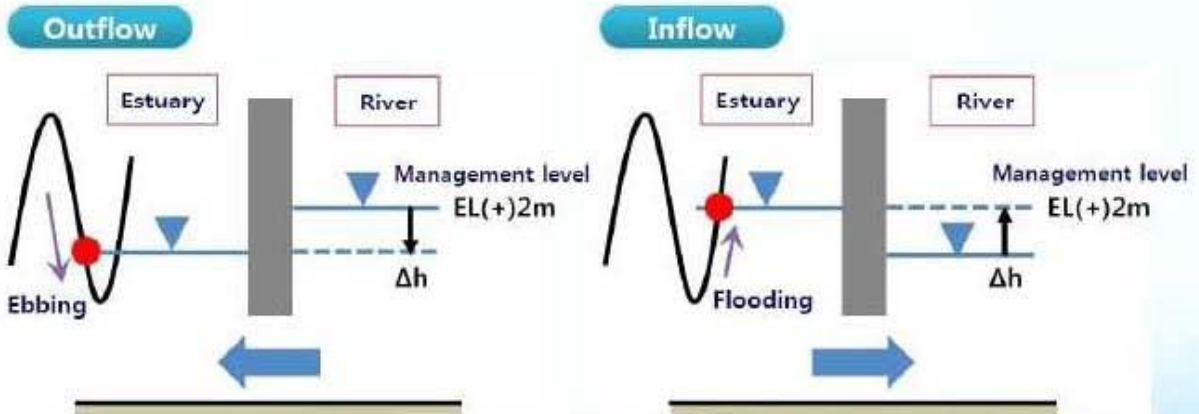


- Two-layer circulation throughout the year
- Strengthened in summer due to intense freshwater run-off
- Implies persistent upstream transport of sediments and pollutants etc.

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하구둑 갑문을 통한 부분 해수유통 모델링

Sluice gates operation condition



- If $\eta_{\text{sea}} < \eta_{\text{river}} \rightarrow$ **outflow** by $\Delta h \rightarrow$ gate closing
- If $\eta_{\text{sea}} > \eta_{\text{river}} \rightarrow$ **inflow** up to management level \rightarrow gate closing
- Gates be opened only if $|\eta_{\text{sea}} - \eta_{\text{river}}| > 0.2 \text{ m}$

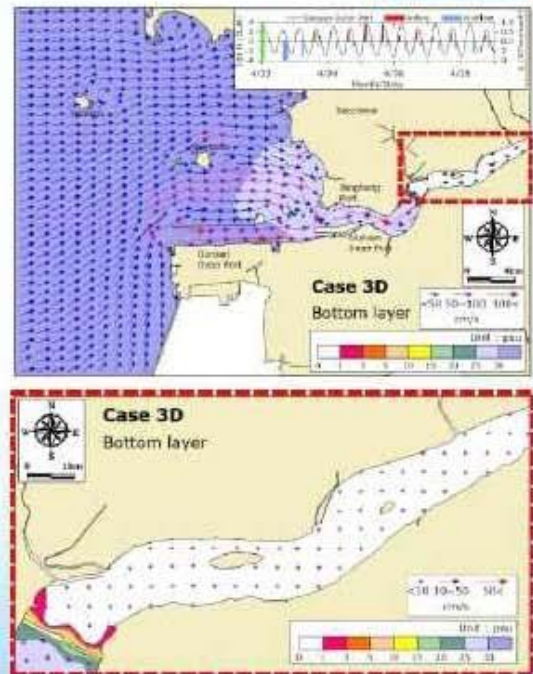
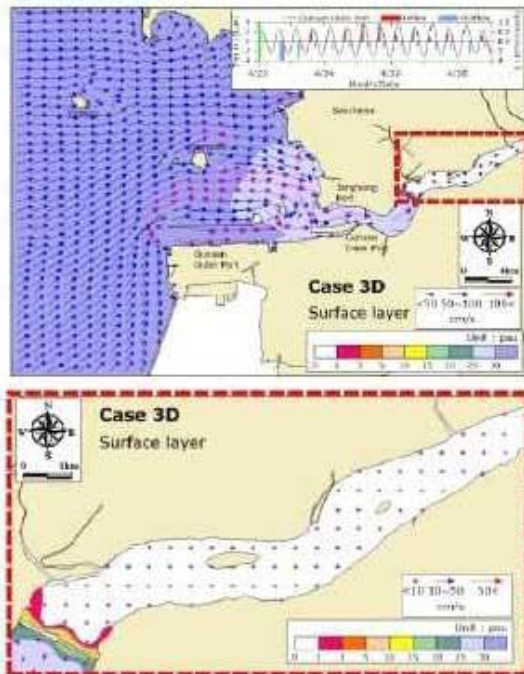
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부분 해수유통 모델링 : 시험 모의

Surface

■ Current vectors and salinity

Bottom

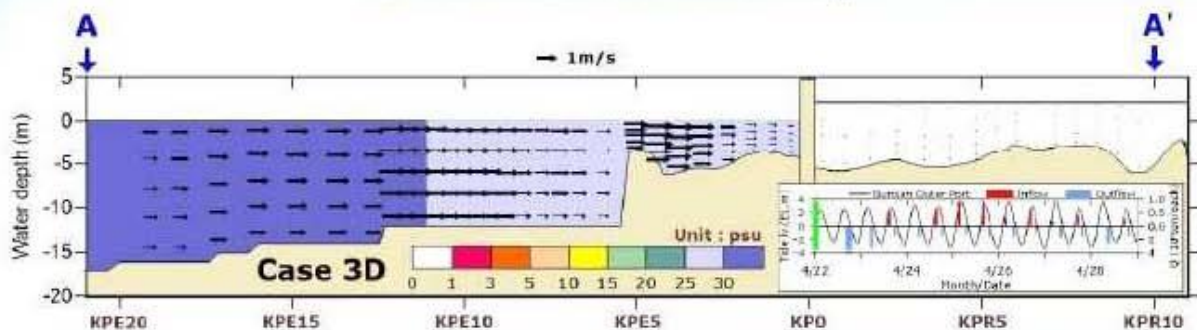


※ Case 3D : Seawater exchange scenario for dry year, $\Delta h = 5$ cm

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부분 해수유통 모델링 : 시험 모의

■ Current vectors and salinity



※ Case 3D : Seawater exchange scenario for dry year, $\Delta h = 5$ cm

Longitudinal section along thalweg



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부분 해수유통 : 향후 과제

- 부분 해수유통시 Δh 와 유입시간 제한으로, 하구호의 염분 확산범위 조절 가능
- 해수 유입량(염분 확산범위) 시나리오별 하구호의 수질, 저질, 퇴적 및 생태계 개선효과에 대한 정량적 예측·평가 필요
- 농·공업용수 취·양수원의 상류 이설시 문제점 및 경제성 검토 필요
- 서천측 갑문 또는 방조제 하단 터널 신설시의 효과, 문제점 및 경제성 검토 필요
- 해수유통시 염분의 지하수 침투에 의한 농경지의 염해 피해 검토 필요

통합 모델링시스템 : 향후 과제

■ Further efforts to refine the modeling system

- To better represent the vertical stratification
- To improve the intra-tidal flocculation processes
- To better reproduce the high phosphorus concentration

■ Management scenario projection

- To explore the sediment and nutrient budgets for various scenarios
- To provide strategic measures for improving the estuarine environment

■ Real-time prediction

- To develop now-cast / forecast system for the estuarine water quality
- To provide, if any, early warning of environmental risks

■ Recommendation of an appropriate observation system

- To facilitate the scenario projections and real-time prediction