10th Anniversary HEPEX Workshop, 24-26 June 2014

Toward Ensemble Forecasting of Water Quality

June 26, 2012 | College Park, Maryland US

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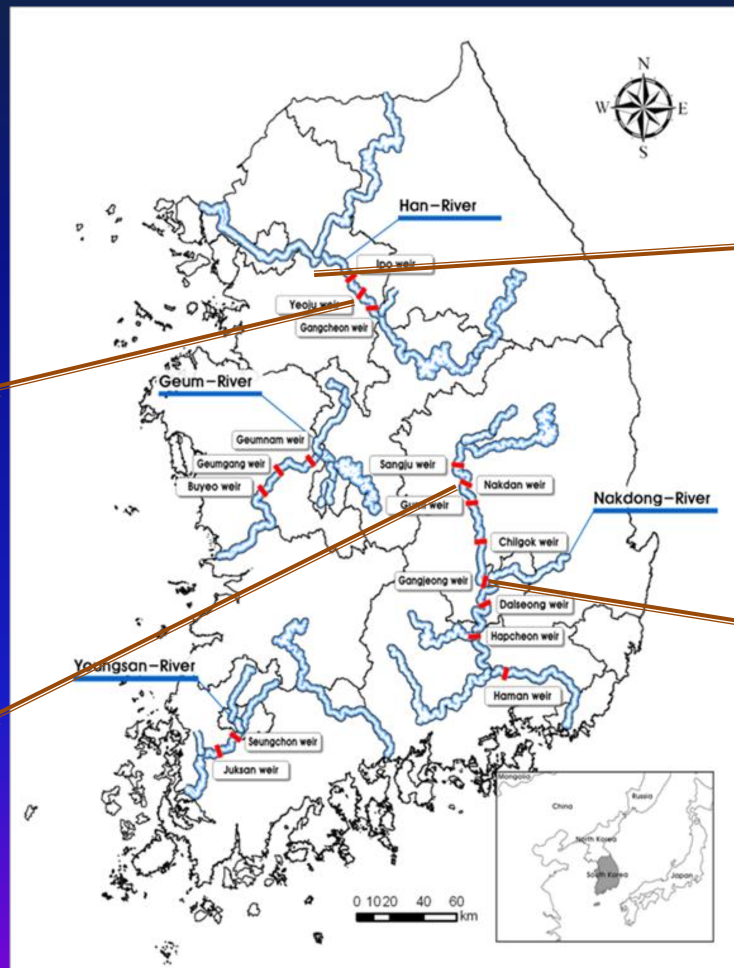
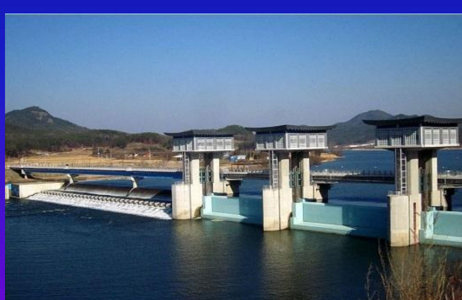
Background – the Four Major Rivers Restoration Project

❖ **Since late 2009, large-scaled river engineering works, including moveable weir installation and dredging, have been done in the four major rivers in Korea to provide (1) *water security*, (2) *flood control*, (3) *ecosystem vitality*, and (4) *new public spaces for recreation on the waterfronts*.**

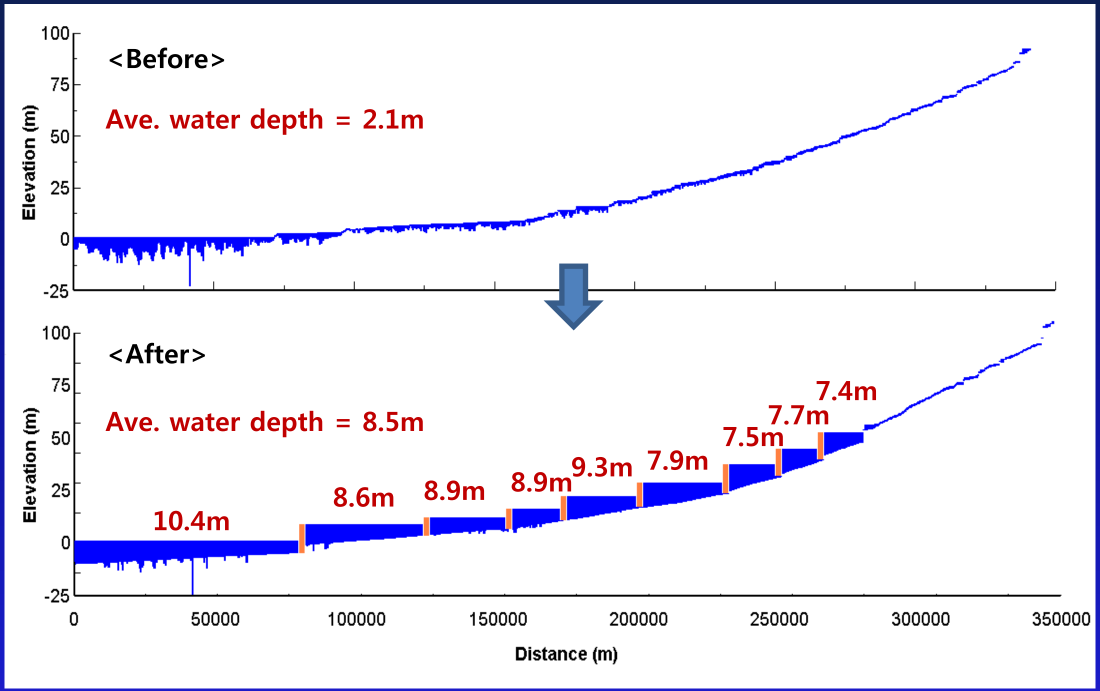




Background – the Four Major Rivers Restoration Project

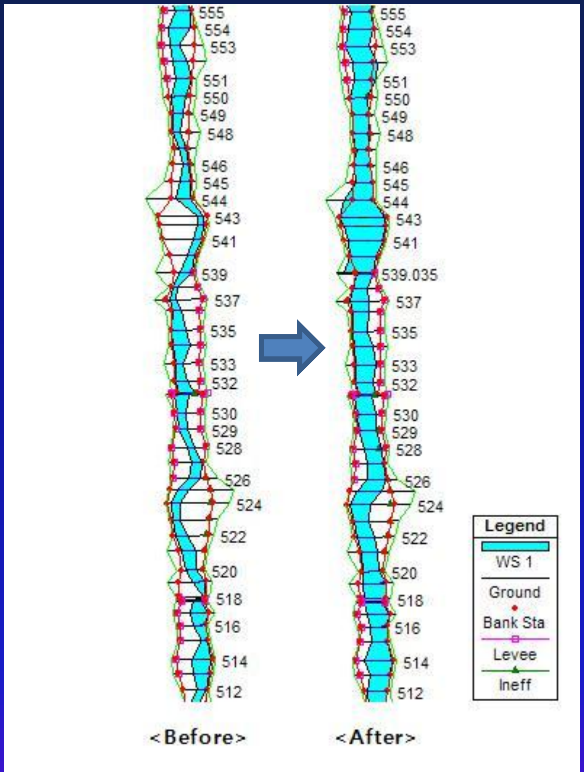
- ❖ Due to increase of residence time, chance of algal blooms may increase
- ❖ Effective operation of the weirs and dams is of importance to prevent water quality degradation

➡ **WQ forecast can be useful**



* Water depth deepened due to the in-stream weirs (EFDC model data of Nakdong River)

- Flow residence time increased significantly : for instance, 31days (before) to 168 days (after) for Nakdong River
  * from Andong dam to Nakdong estuary dam (a low flow condition of 2006 was assumed)



* Water surface of the river widened significantly due to the in-stream weirs (HEC-RAS data of Nakdong River)

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Overview of Dam and Weir Operation Process for Flushing Blooms

Monitoring

Weather data

- *Weather observation data*
- *Weather forecasting data (UM-Regional / UM-Global)*

Hydrologic data

- *Flow & stage monitoring data*
- *Dam discharge data & plan*

Water quality data

- *Manual WQ monitoring data*
- *Automatic WQ monitoring data*
- *Tele-monitoring system (TMS) data*

Prediction

Water quality Forecast

Alarm & scenarios

Action

WQ management council

- Take measures to prevent blooms
- Select flushing scenarios and request dam & weir operation

Request for flushing

Dam operation council

- Investigate available water in upstream dams and weirs
- Decide flushing based on scenarios

Gate operation request

Gate open and flushing

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Overview of Operational WQ Forecast in Korea

The outline of 7-days WQ forecast

- ***Forecast area***:
  representative upstream areas of 16 weirs in the Han, Nakdong, Geum, and Youngsan Rivers

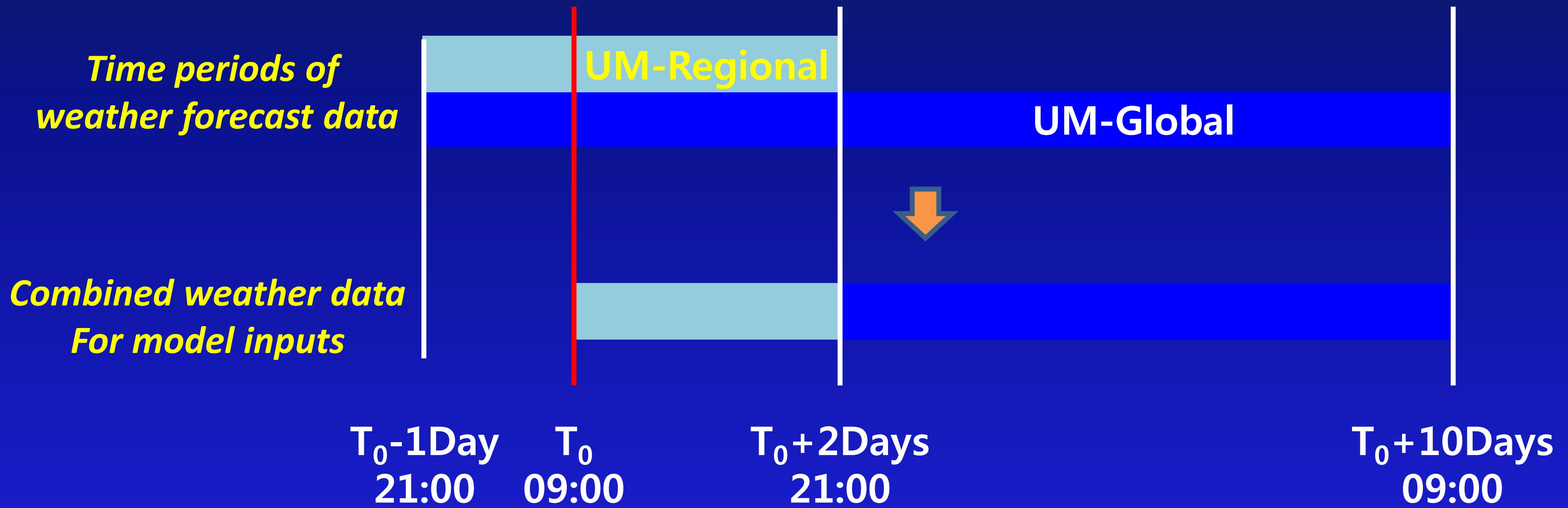
- ***Forecast variables***:
  water temp. and chlorophyll-*a* level
  - It will be extended to other WQ variables in the future (e.g., TOC & SS)

- ***Forecast model***: HSPF-EFDC coupled model

- ***Forecast report***: 7-day WQ forecast are officially announced on every Monday and Thursday and circulated to water management agencies in the Han River Basin via a dedicated website.

WQ Forecasting Step: 1. Weather Forecasting

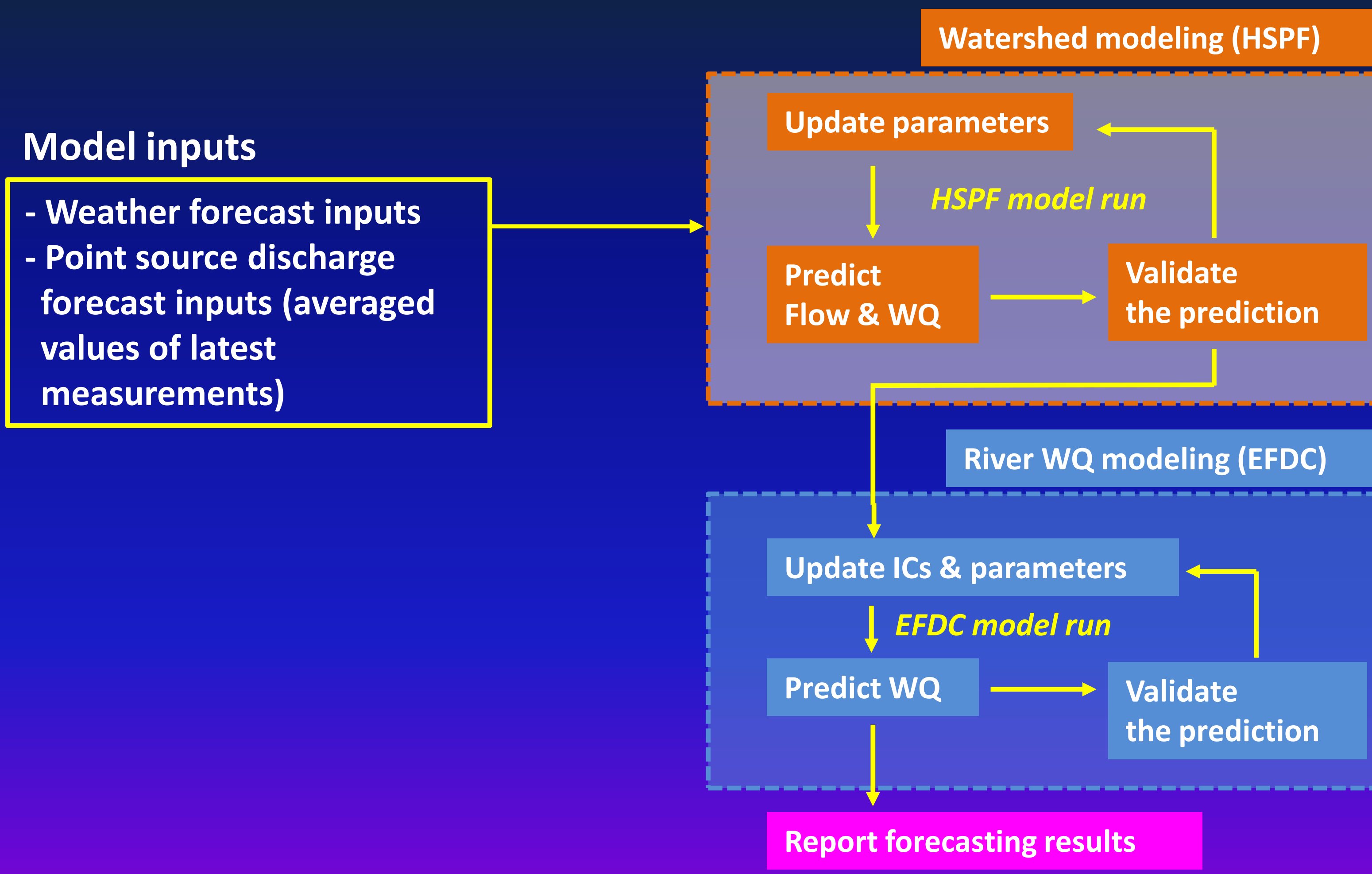
- **A weekly numerical weather prediction with a merged dataset of Global and Regional Unified Model (UM) forecasting automatically fed from the Korea Meteorological Administration serves as the atmospheric forcing in both models.**



- **The latest data are available at 21:00 PM of the day before current day (T_o).**
- **As UM-R data is available up to only 72 hours from 21:00 PM of T_o- 1Day, UM-G data is used after 21:00 PM of T_o+ 2Days.**

Overview of Operational WQ Forecast in the Han River Basin

The procedure of WQ forecast

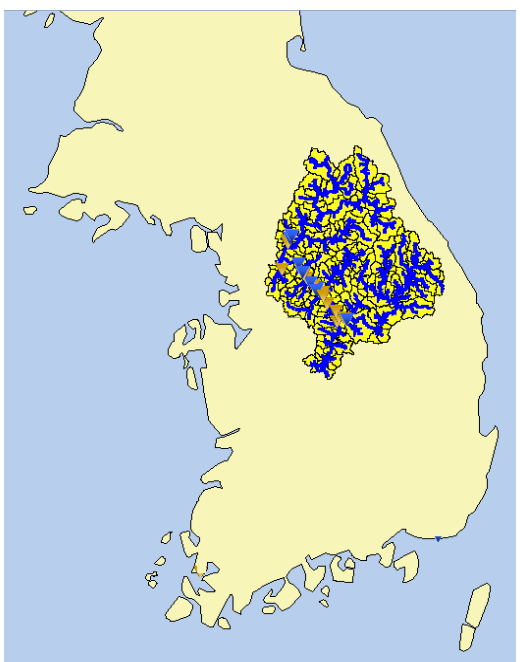


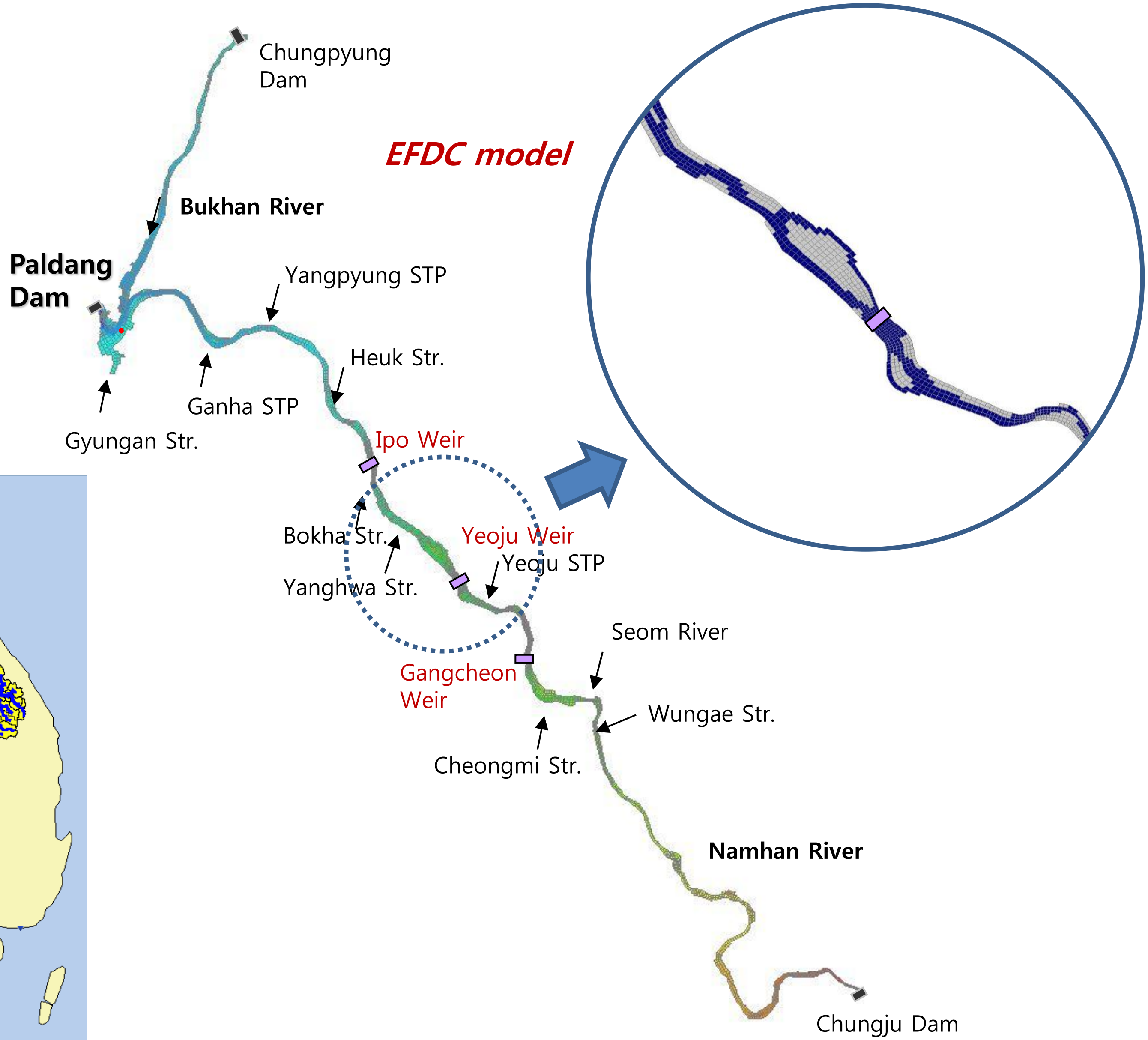
Models – HSPF watershed and EFDC river models

Han River

$23{,}000\ km^2$

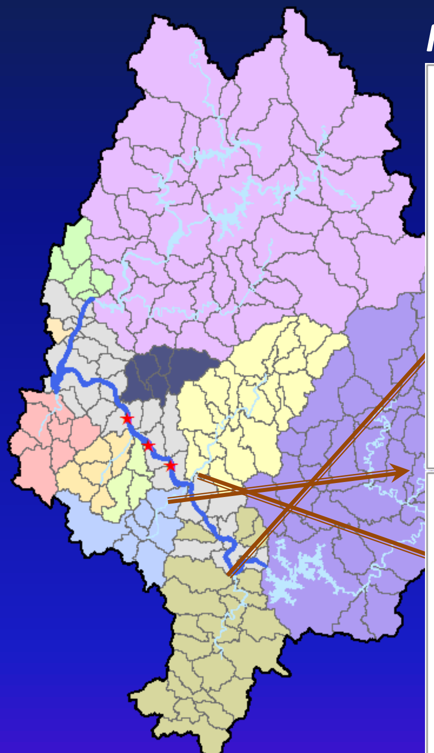
HSPF model



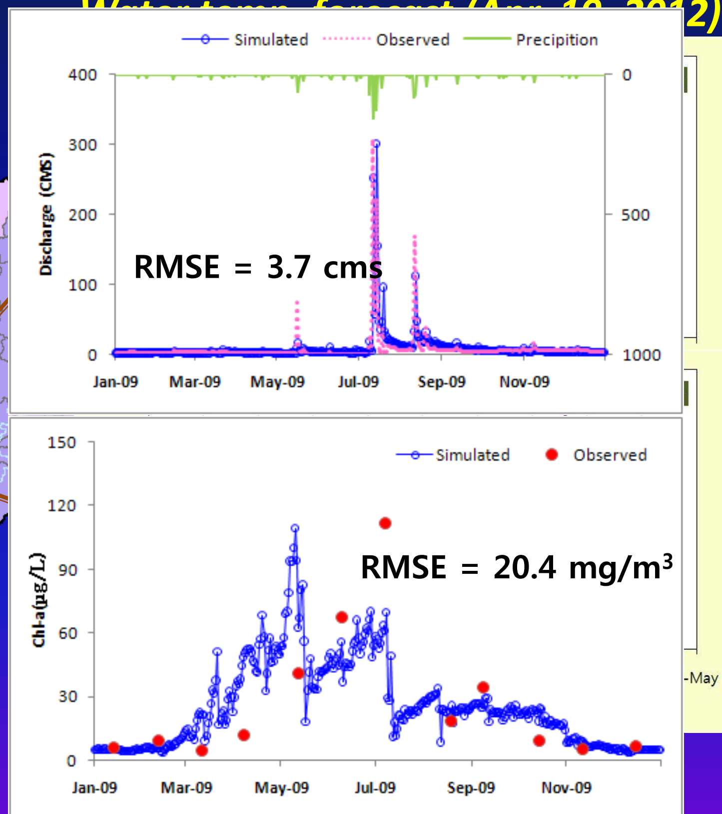


WQ Forecasting Step: 2. Tributary Flow & WQ Forecasting

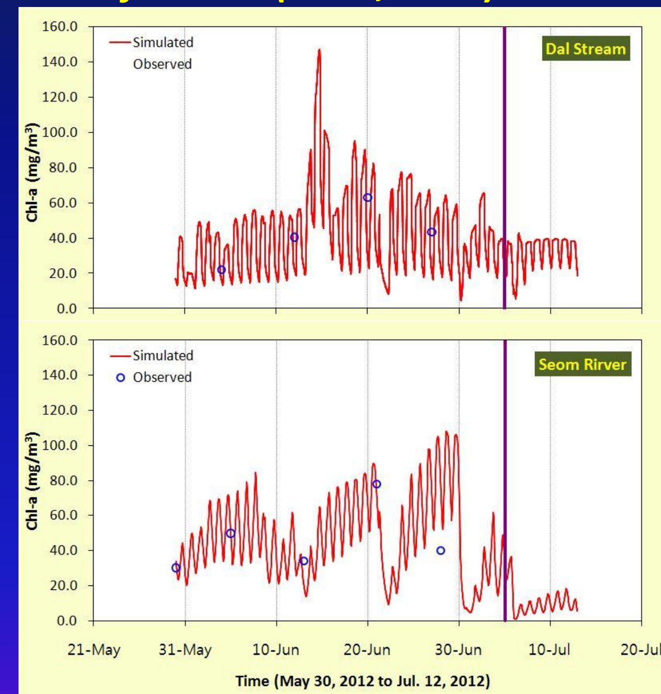
❖ **The HSPF model provides the flow and WQ forecasting data of major tributaries as the boundary conditions of EFDC model.**



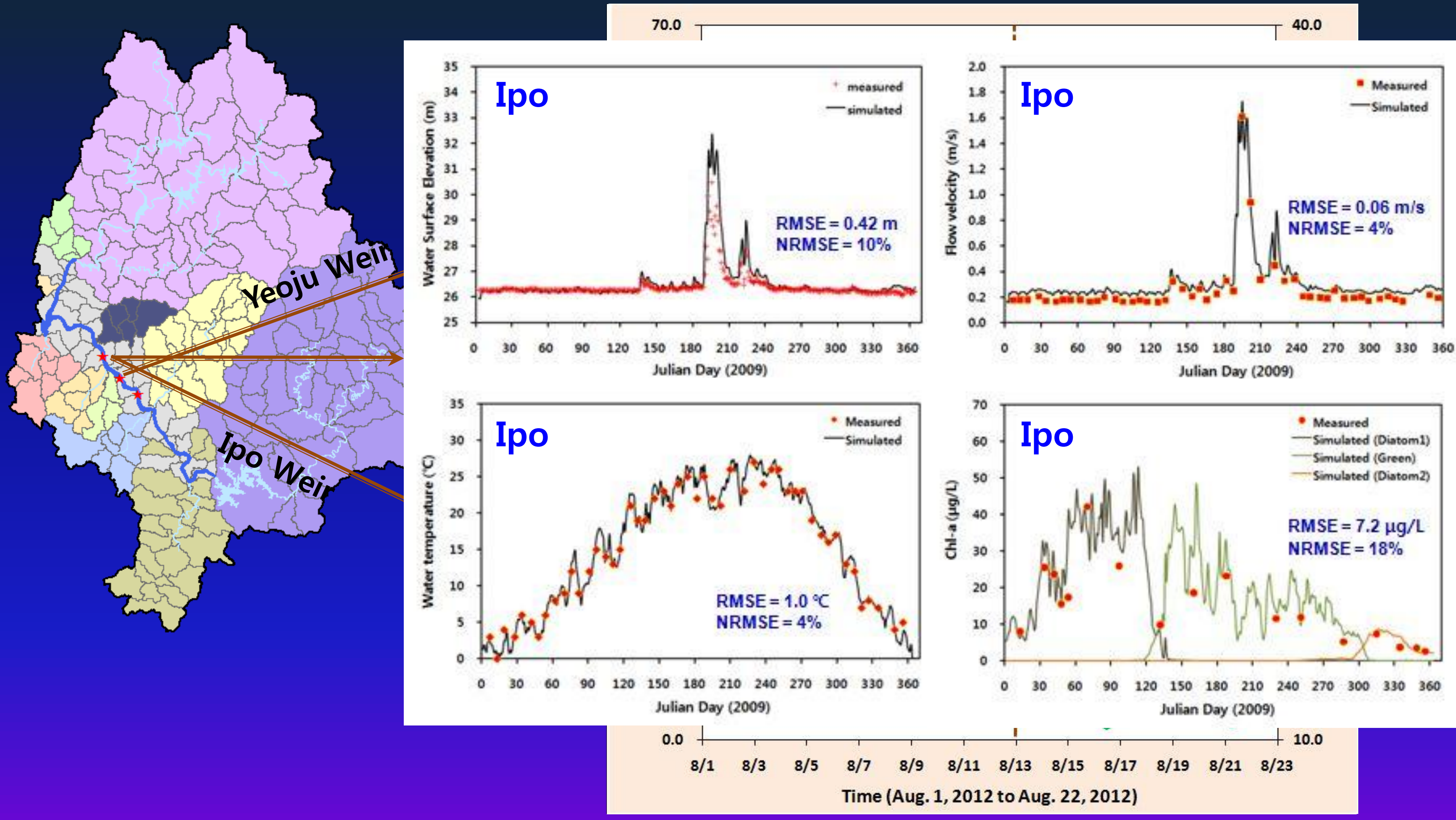
Model calibration



Chl-a forecast (Jul. 5, 2012)



WQ Forecasting Step: 3. River WQ Forecasting



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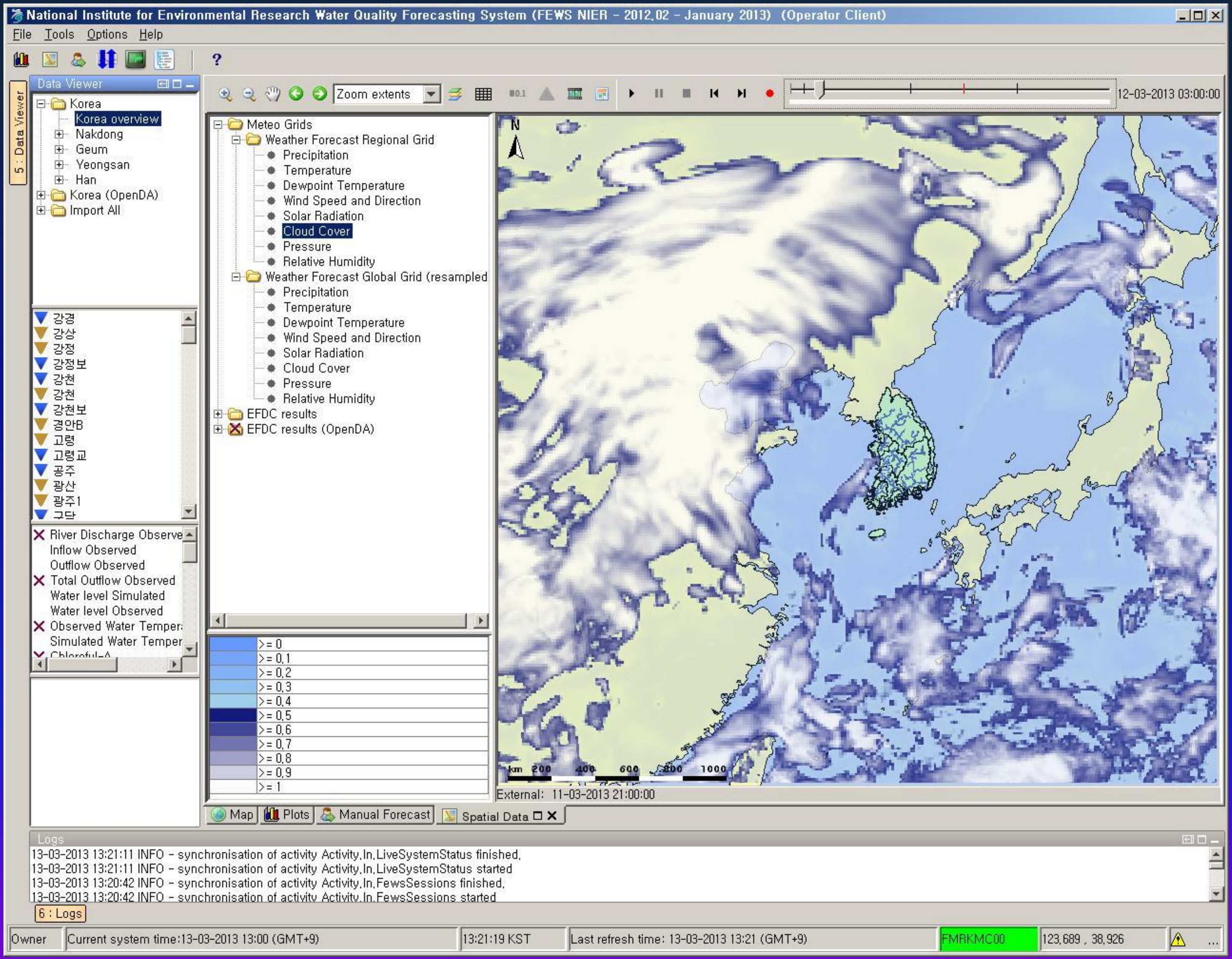
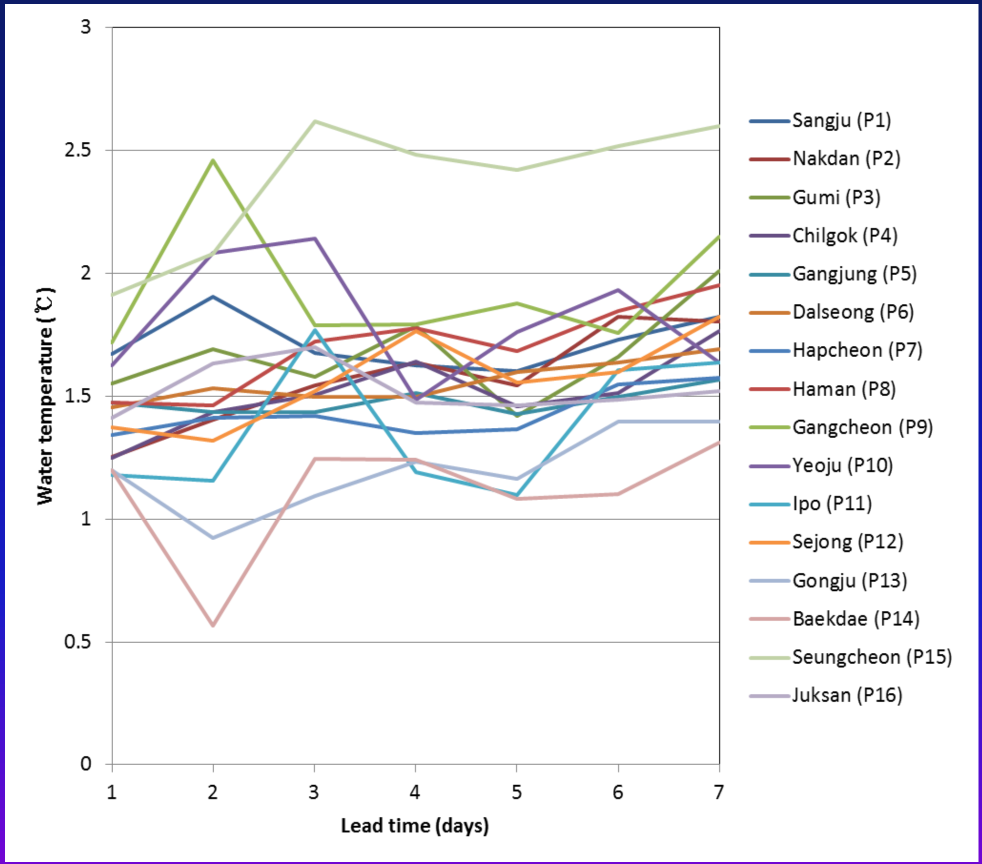
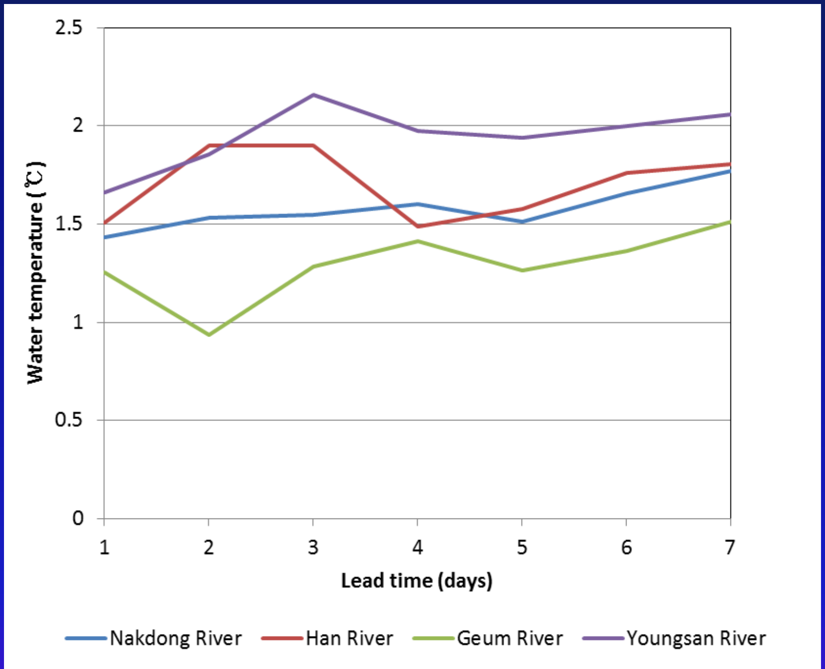
7. Water Quality Forecast System



Forecasting Performance: A Summary of the first 2 years forecast

❖ The RMSE of water temperature forecast for each location tends to increase with lead time but not significantly





▲ Variation of the mean RMSE for each river with lead time

◄ Variation of RMSE for each location with lead time

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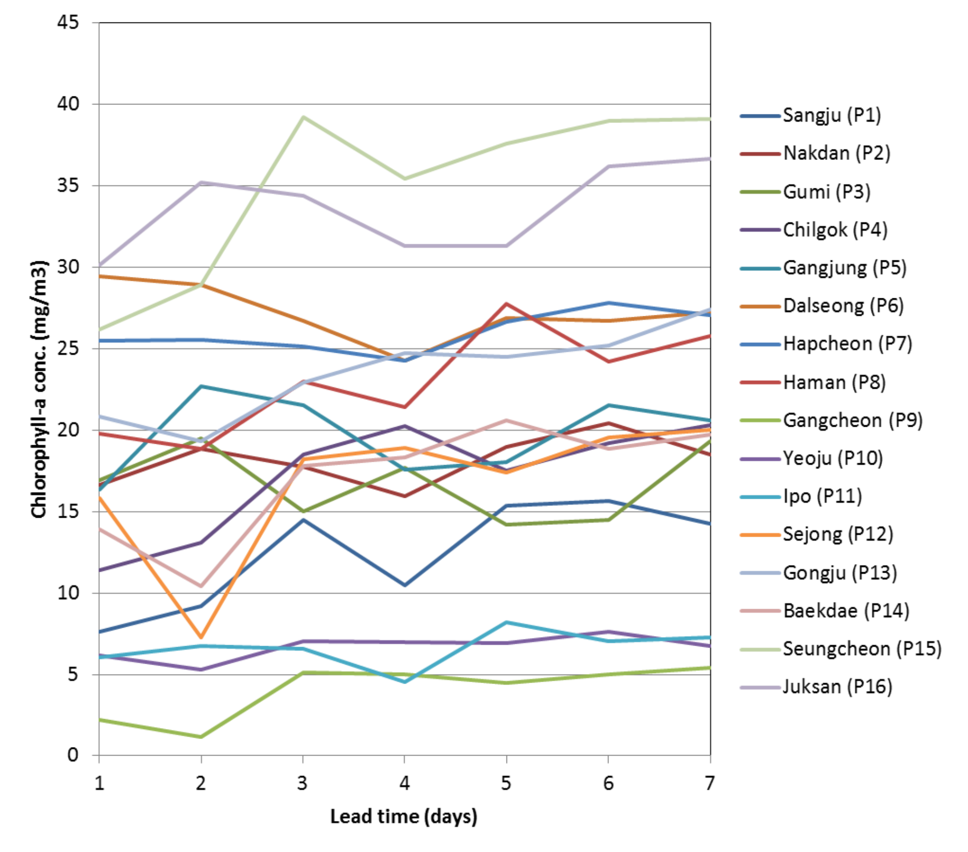
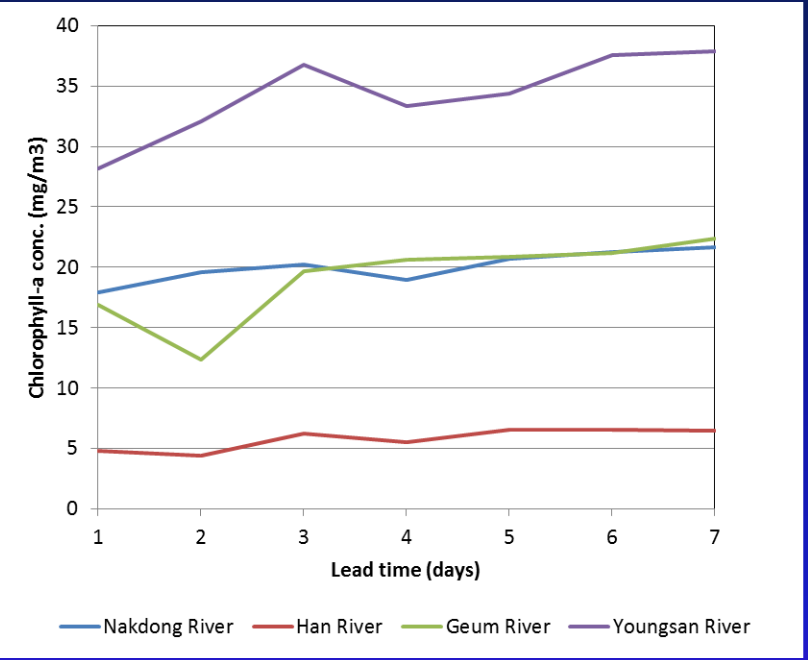
Forecasting Performance: A Summary of the first 2 years forecast

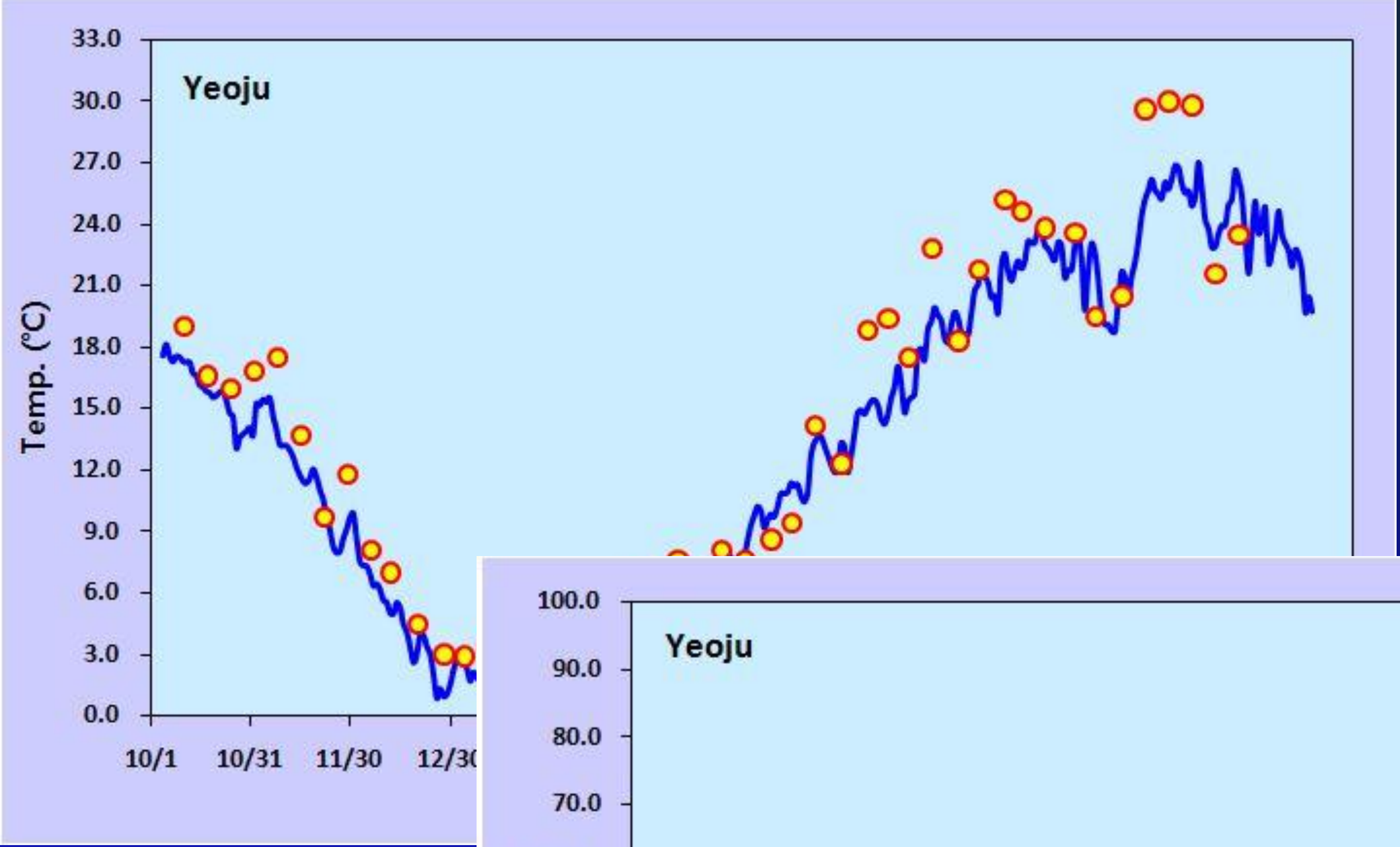
❖ The RMSE of chlorophyll-a forecast for each location increases with lead time: the RMSE of some locations such as the two (P15, 16)in Youngsan River and P6, 7 in Nakdong River are significantly high



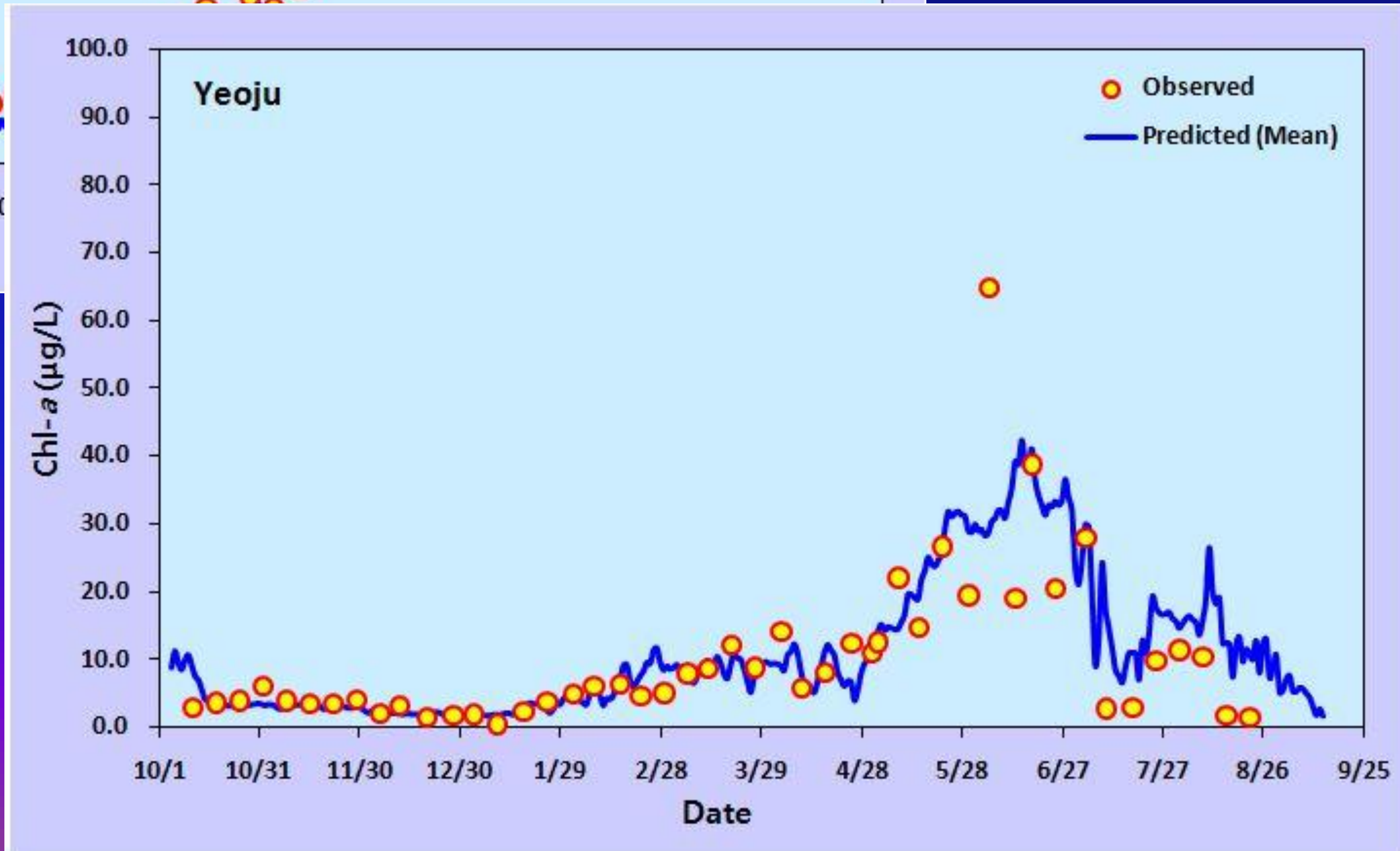


▲ Variation of the mean RMSE for each river with lead time

◄ Variation of RMSE for each location with lead time



Yeoju
Temp. (°C)
33.0
30.0
27.0
24.0
21.0
18.0
15.0
12.0
9.0
6.0
3.0
0.0
10/1
10/31
11/30

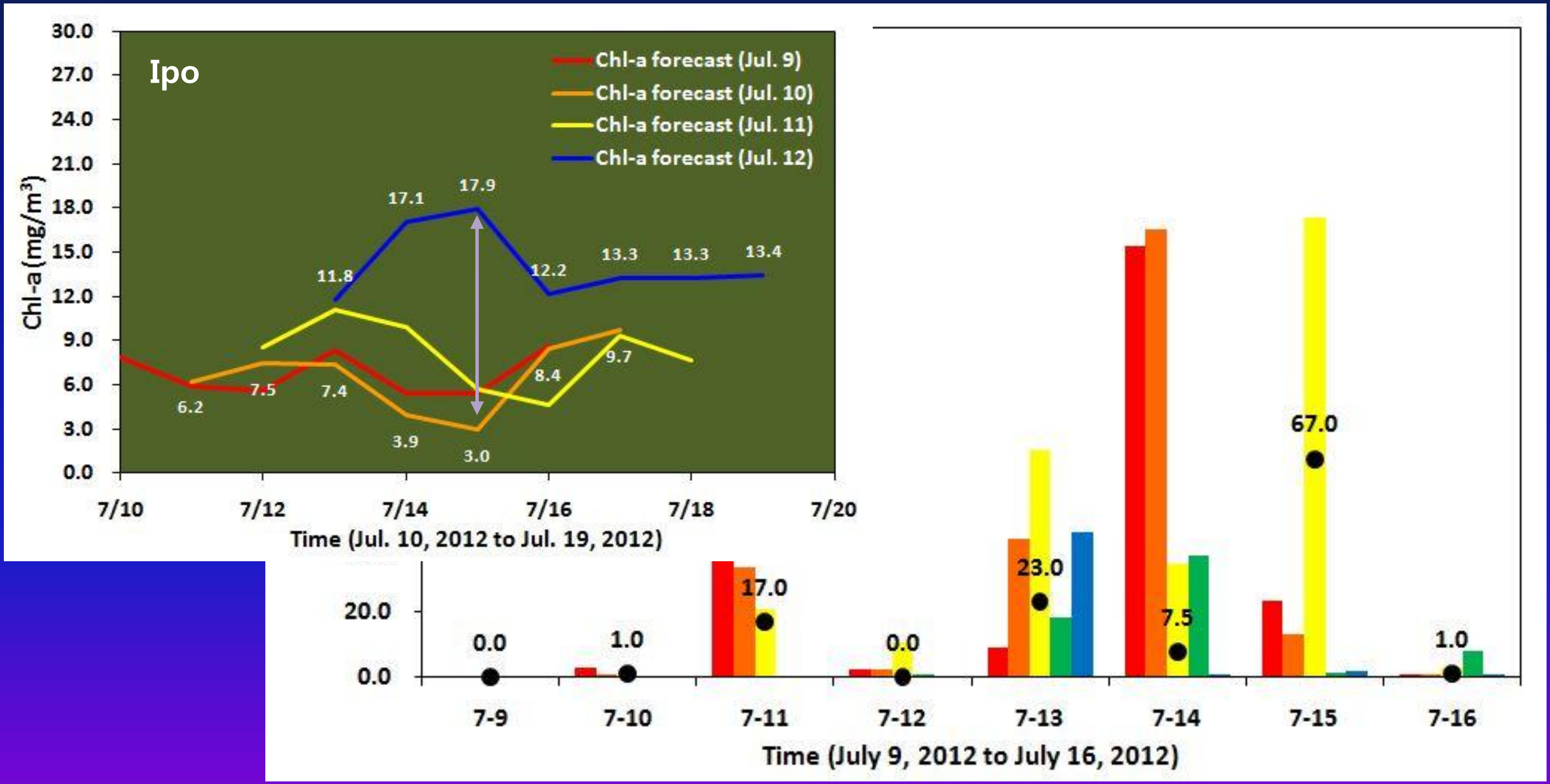


Yeoju
Observed
Predicted (Mean)
Chl-a (μg/L)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
10/1
10/31
11/30
12/30
1/29
2/28
3/29
4/28
5/28
6/27
7/27
8/26
9/25
Date

Forecasting Errors : Input data uncertainty

Weather prediction

- Large uncertainties in numerical weather prediction (particularly, the rainfall amount in Global UM forecasting)



Forecasting Errors : Boundary condition uncertainty

HSPF model prediction uncertainty

❖ The impact of tributary flow and algal/nutrient levels generated from the HSPF prediction on the water quality of the main channel is significant

❖ For some locations, the effect of initial conc. adjustment vanishes too quickly due to low retention time, the forecast result is dominated by the HSPF prediction for tributaries

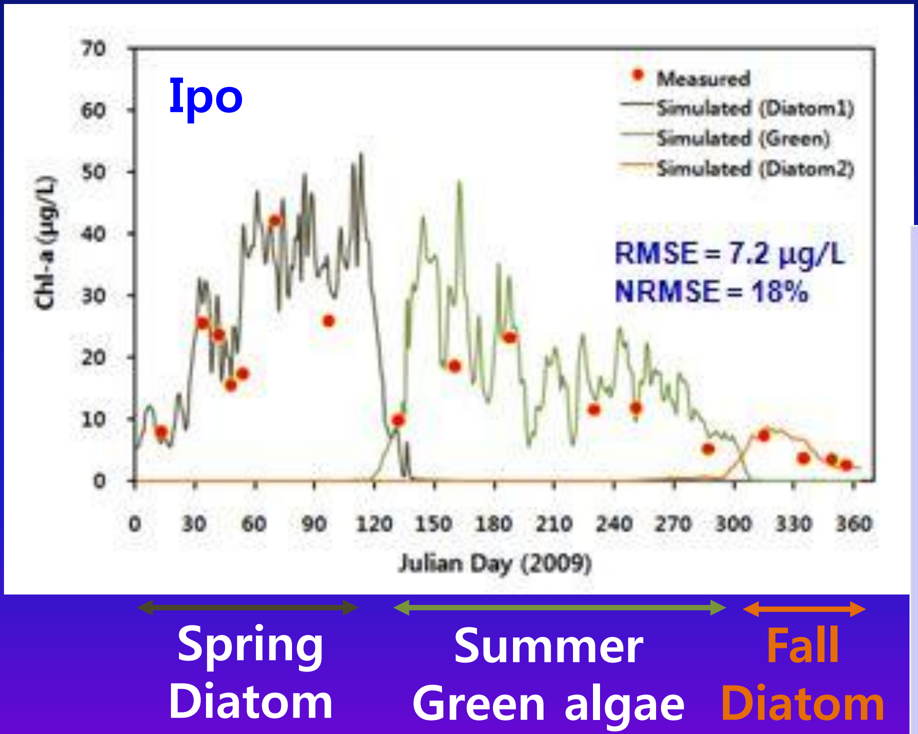
※ The effects of data assimilation on WQ vary from location to location.
- SHR main channel (the weir area): 1-3 days
- Paldang reservoir: over 10 days

❖ Thus, if we can utilize real-time observation data, we may reduce errors by both producing forecast more close to observation time and keeping the effect of initial conc. adjustment

Forecasting Errors : Model structure uncertainty

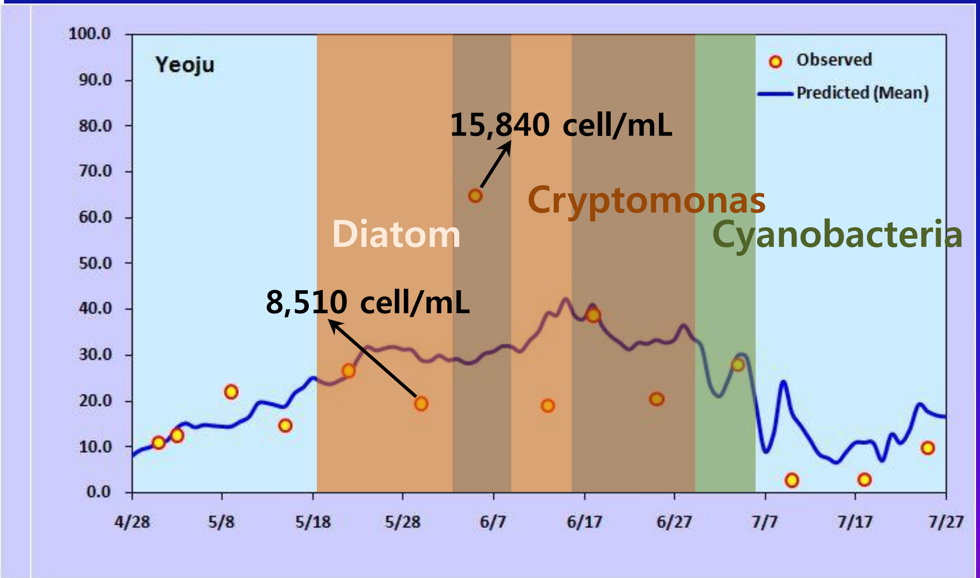
Algal succession

❖ The algal dynamics simulation model was designed with three algal groups (spring diatom, summer green algae, and fall diatom) considering the general pattern of algal succession historically reported in the rivers



❖ Is this assumption always valid?

- May not be enough to fully capture the spatio-temporal variation of algal level (particularly, in summer).



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Forecasting Errors : Initial condition uncertainty

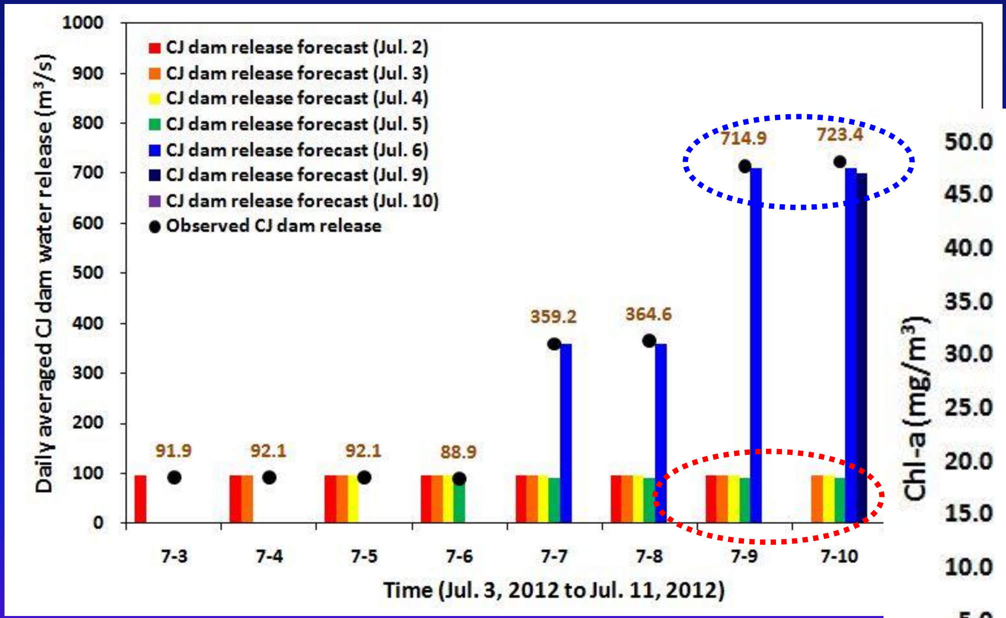
Initial chlorophyll-a conc. of EFDC model

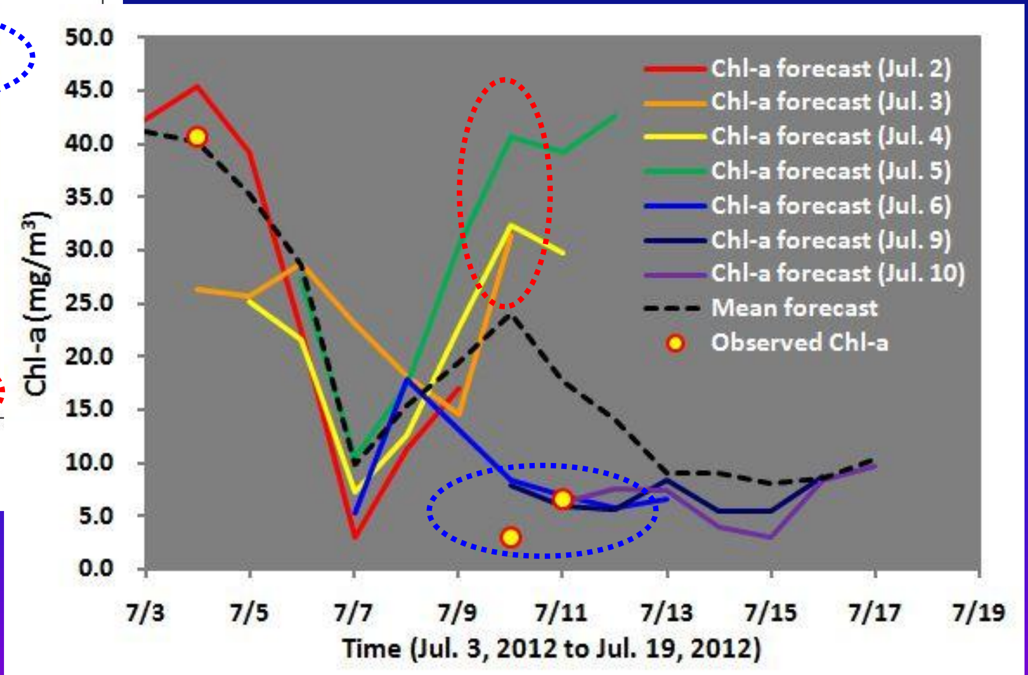
- Initial chlorophyll-a conc. of EFDC model grids was adjusted for every forecast with weekly observation data, which were available, however, only in 7 to 10 days after observation
- Thus the lead time of 1 day in the previous slides is in fact 8~11 days if the time from the initial concentration adjustment is considered
- Currently, real-time observation data is available but not used for the adjustment due to lack of reliability

Forecasting Errors : Input data uncertainty

Dam and weir operation

- It is very difficult to predict the amount of upstream dam water release, particularly during the summer because it depends on the real-time weather forecast and other objectives
(electricity generation, water quality improvement, etc.)

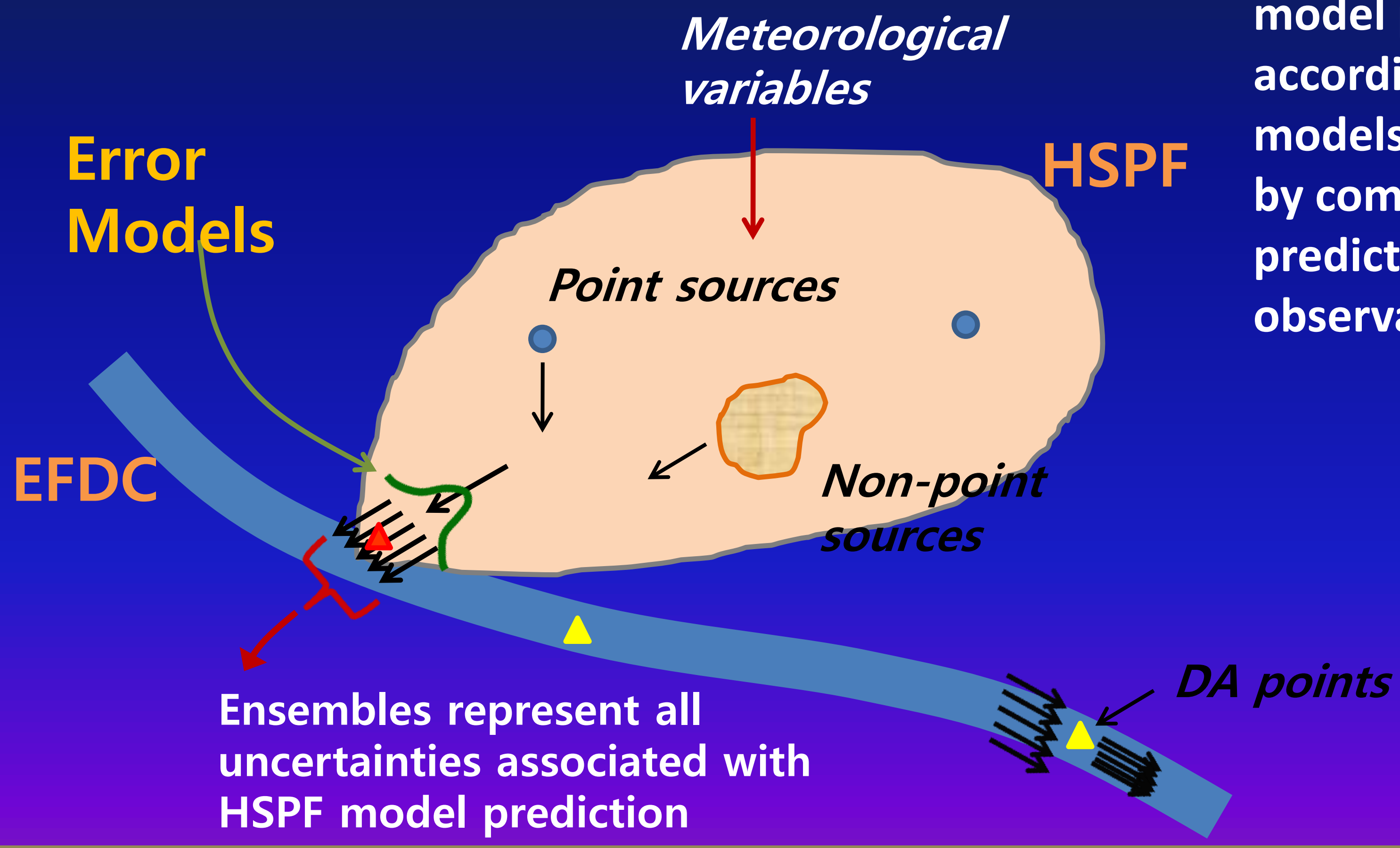




Toward Ensemble Forecasting : Data assimilation

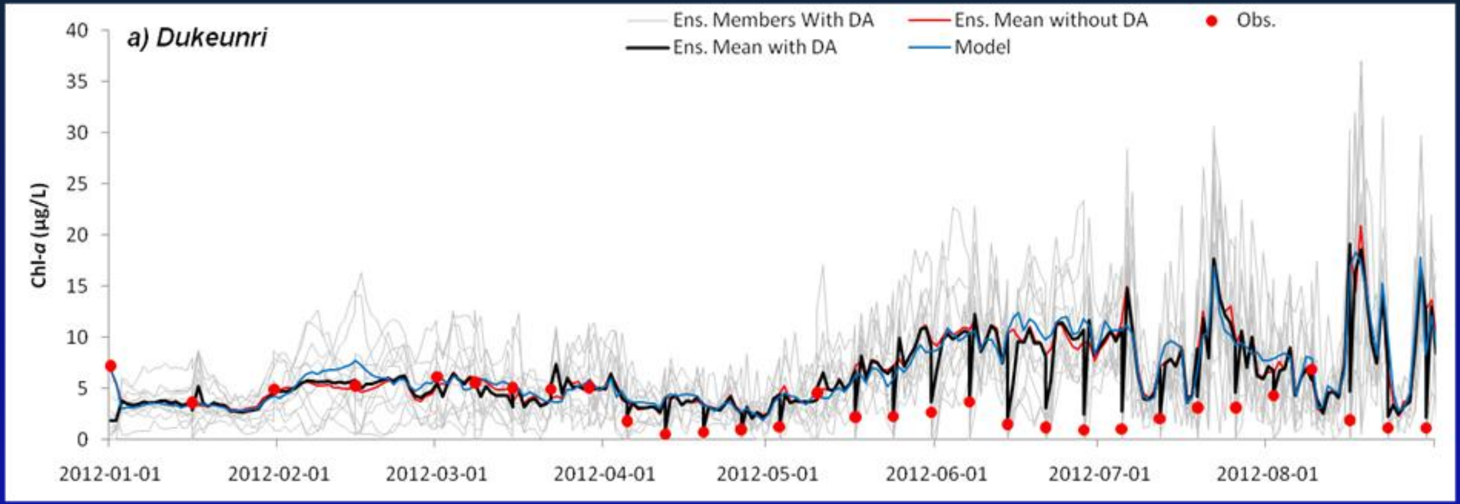
Ensemble Kalman Filter for EFDC model

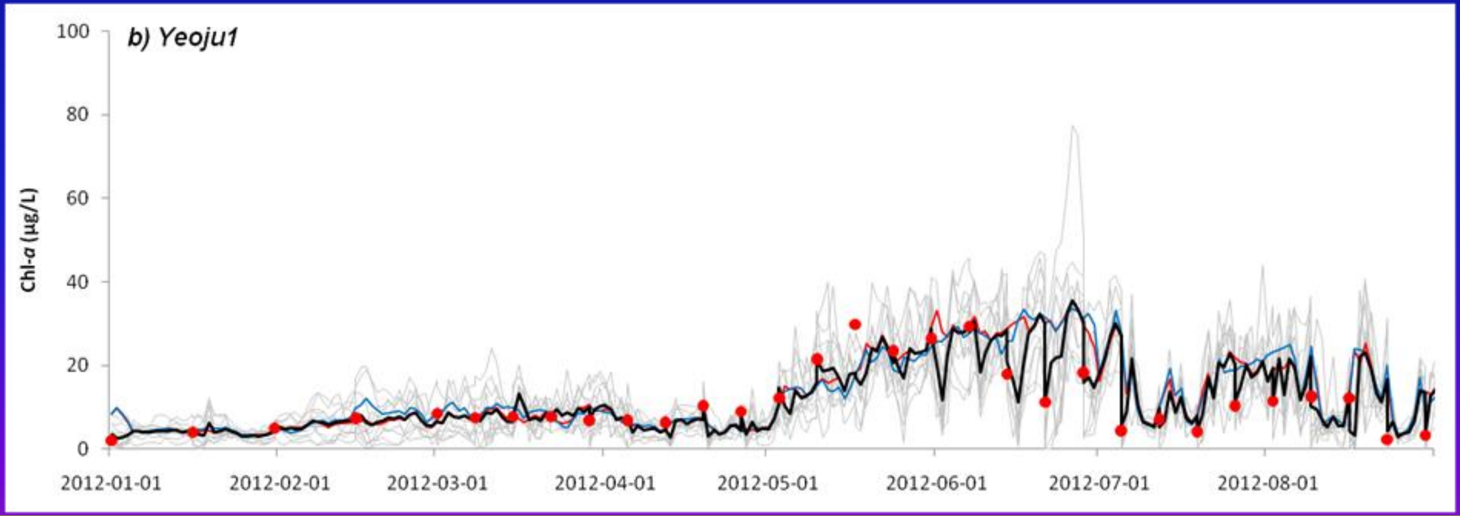
❖ Ensemble representation of EFDC model prediction is created by applying perturbation to HSPF model prediction according to error models, which are built by comparing model prediction and observation

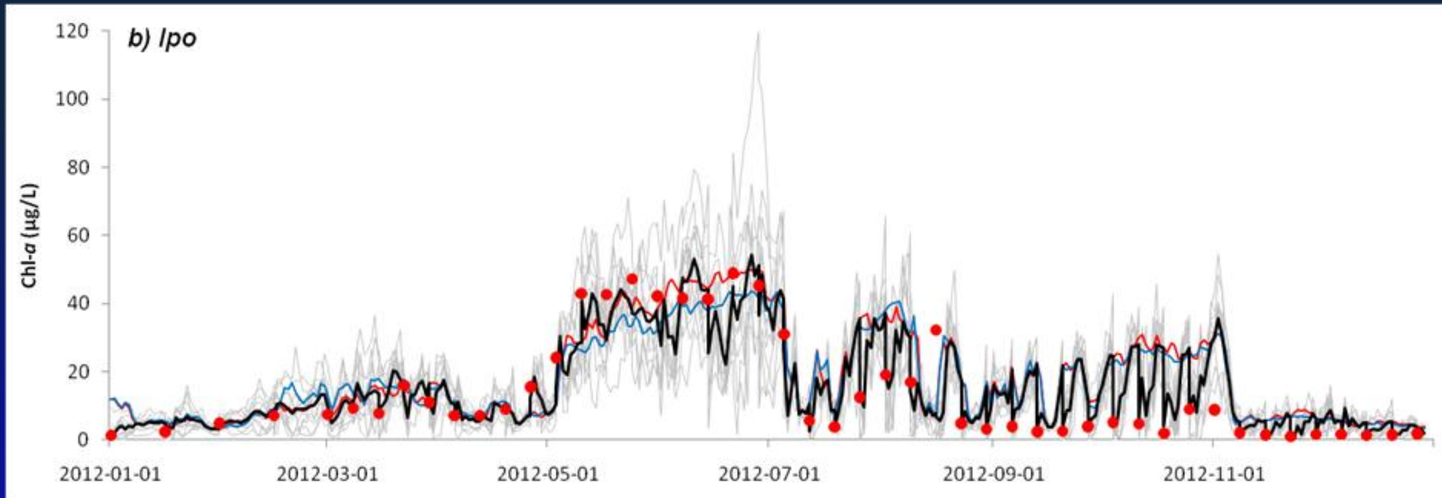


Ensembles represent all uncertainties associated with HSPF model prediction

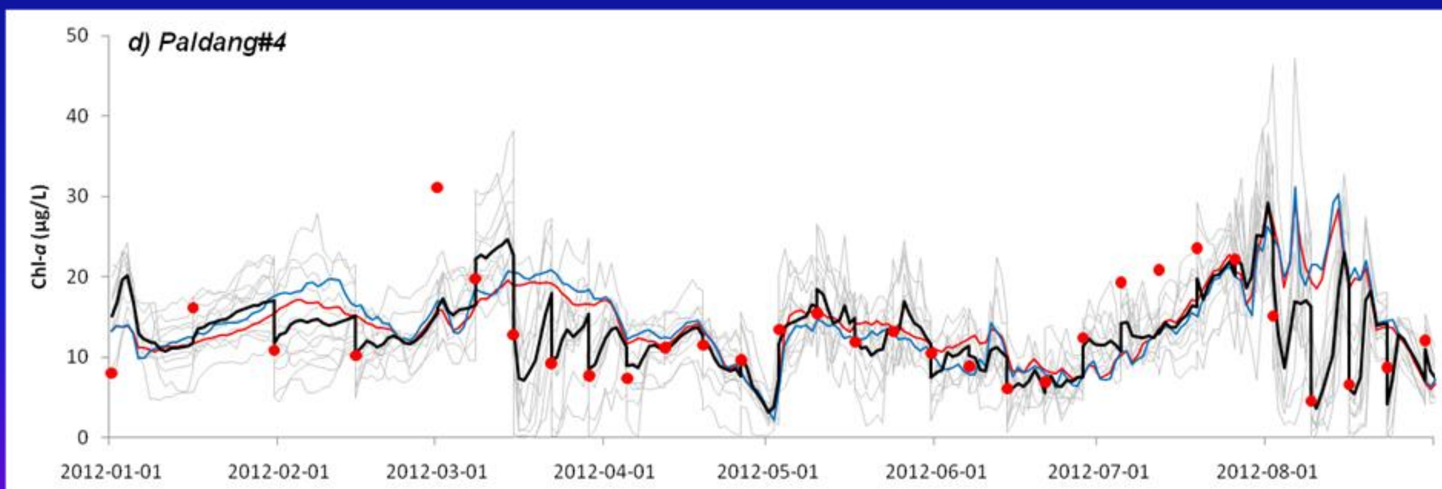
❖ Chlorophyll-a DA results for some points in Han River : in the order from most upstream to downstream points, Dukeunri, Yeoju1, Ipo, Paldaing 4







b) Ipo
Chl-a (µg/L)
120
100
80
60
40
20
0
2012-01-01
2012-03-01
2012-05-01
2012-07-01
2012-09-01
2012-11-01



d) Paldang#4
Chl-a (µg/L)
50
40
30
20
10
0
2012-01-01
2012-02-01
2012-03-01
2012-04-01
2012-05-01
2012-06-01
2012-07-01
2012-08-01

Toward Ensemble Forecasting : Data assimilation

Ensemble Kalman Filter for EFDC model

❖ **Both RMSE and CRPS are significantly reduced when EnKF is applied for all DA points in Han River**

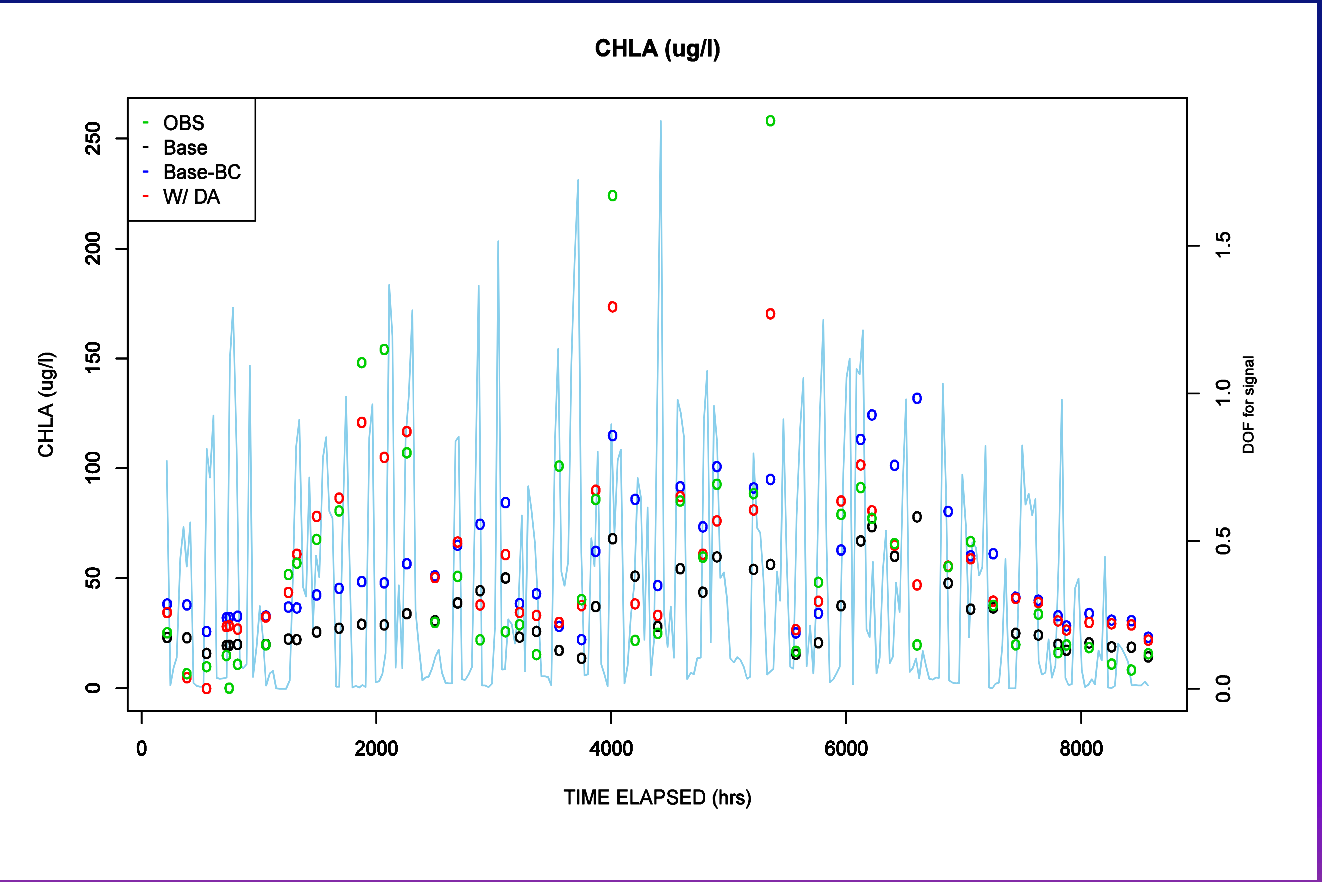
Station	Chlorophyll-a (μg/L)			
	Assimilation		Open-loop	
	RMSE	CRPS	RMSE	CRPS
Deokeunri	0.9	5.2	5.9	8.4
Yeoju #1	3.0	7.0	8.1	10.1
Yeojubo	2.8	9.5	9.8	13.5
Ipo	7.0	10.3	10.1	14.4
Gangsang	3.8	13.6	15.1	19.3
Paldangdam #3	7.3	6.4	12.3	7.3
Paldangdam #2	4.2	4.5	6.0	4.8
Paldangdam #5	10.8	6.1	18.6	9.8
Sambongri	4.0	5.3	8.5	6.4
Paldangdam #4	3.8	5.5	6.6	6.7

Toward Ensemble Forecasting : Data assimilation

MLEF (Maximum Likelihood Ensemble Filter) for HSPF model

❖ **MLEF(Zupanski 2005) Ensemble data assimilator was developed, which updates all the 28 HSPF state variables**

❖ **Unlike the original MLEF method, the formulation is extended to account for dynamical model errors by state augmentation.**



Toward Ensemble Forecasting : Data assimilation

MLEF (Maximum Likelihood Ensemble Filter) for HSPF model

Variable	$RMSE_{BASE}$	$RMSE_{BC-BASE}$	Reduction in RMSE by BC-BASE over BASE (%)	$RMSE_{BC-DA}$	Reduction in RMSE by BC-DA over BASE (%)
BOD (mg/l)	2.2	1.9	12.1	1.4	33.1
CHL-a(ug/l)	52.8	47.1	10.8	21.5	59.3
DO (mg/l)	2.2	2.2	0.0	2.0	9.7
NO3 (mg/l)	3.4	1.7	51.2	1.7	51.2
PO4 (mg/l)	0.4	0.2	60.5	0.2	60.5
TW (mg/l)	2.2	1.6	24.1	1.5	29.2
Flow (cms)	11.2	9.2	18.1	6.7	40.7

Summary

- Operational weekly water quality forecast (water temp. and chl-*a* level) has been conducted in Korean rivers for prevention of algal blooms in the four major river basins.
- The forecast results during the first 2 years (Jan. 2012 to Dec. 2013) showed forecast errors of varying magnitude due to various uncertainty sources including :
  - Time-delayed measurement data to update initial conc. of EFDC model
  - HSPF model prediction uncertainty input which dominates EFDC model prediction due to short retention time
  - Numerical weather prediction and hydraulic structure operation uncertainty
  - Not enough model or modeling skill to capture complexity of algal succession
- To deal with such uncertainty, ensemble DA techniques such as EnKF and MLEF are applied to the current operational forecast framework
- Work is ongoing to develop strategy for end-to-end ensemble water quality forecasting