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Evaluation of ecological flow restoration using PHABSIM and SWAT considering long-term watershed environmental changes

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- **Research background and necessity**
  - Progress and Changes in the watershed environment (land development, groundwater use, soil erosion, road development, forest growth, etc.) for several decades affects watershed hydrology, stream water quality resulting in threats increase of aquatic ecosystems health.
  - In South Korea, the measures to secure ecological flow in a watershed scale are necessary through the vulnerability assessment, and the legal and institutional improvement are challenges.
  - Water environment must be managed through water quality-quantity-aquatic ecosystem linkage.

  - We have 2 laws for streamflow maintenance.
    - **Water Environment Conservation Act**
      - Environmental-Ecological flow (2017): the flow rate to maintain the fish habitat function of the river
        - Survey and Assessment of Aquatic Health: 880 locations in 2011, 960 locations in 2012, and 3,880 locations in 2020
    - **River Law**
      - River maintenance flow (2007): the minimum flow rate necessary to maintain normal functions and conditions of rivers in consideration of the use of river water, such as living, industry, agriculture, environmental improvement, power generation, maintenance, etc.
      - water for environmental improvement
        - water artificially supplied at the request of the beneficiary in order to utilize some sections of the river or some areas to improve and maintain the social environment in terms of habitability (114 locations).

    - Through the revision of the Government Organization Act in 2018, water management work is unified to the Ministry of Environment. (before, River Law to Ministry of Land, Infrastructure and Transport)

- **River Maintenance Flow**
  - Basic technical concept → *minimum flow to prevent physical degradation*
- **Ecological Flow**
  - Biodiversity-focused → *protect aquatic life and ecosystem health*
- **Environmental Flow**
  - Most comprehensive → *integrates nature and human needs for sustainable water use*

Term	Initial Emergence and Background	Key Proponents or Institutions
River Maintenance Flow	emerged in the **1960s–1970s** in Japan and Korea to address **urban river degradation**, such as odor and drying	Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT); Korea Ministry of Environment
Ecological Flow	emerged in the **1970s–1980s** in the U.S. and Europe to support **fish habitat preservation**	**USGS** and scientist **Bovee**, developer of the **PHABSIM** model (1978)
Environmental Flow	formalized in the **late 1990s–2000s** as an **integrated water management concept** including ecological and social needs	**IUCN**, **World Bank**, **WWF**, formalized by the **Brisbane Declaration (2007)**

Category	River Maintenance Flow	Ecological Flow	Environmental Flow
Definition	Minimum flow to maintain basic river functions (e.g., odor control, preventing drying)	Flow required to sustain aquatic ecosystems, including habitat and biodiversity	Flow regime (quantity, timing, quality) needed to sustain ecosystems and human well-being
Main Purpose	To maintain physical and visual aspects of urban/artificial rivers	To support biodiversity, species survival, reproduction, and migration	To ensure **ecological integrity** and **sustainable human use** of water resources
Key Considerations	Flow quantity, minimum water quality, odor prevention	Biological needs: depth, velocity, spawning, habitat area	Integrated: flow quantity, seasonality, frequency, water quality, sediment, vegetation, and human uses
Basis for Determination	Simple statistical hydrologic values (e.g., minimum/average flows)	Habitat-based models (e.g., PHABSIM, WUA)	Comprehensive assessment using IHA, ELOHA, and social-ecological criteria
Application Scope	Mostly **urban/artificial rivers**	**Natural/ecological rivers**, national ecological networks	**Entire watersheds**, national/international policy, transboundary water management
Human Use Consideration	Not considered or minimal	Indirectly considered	**Explicitly considered**: livelihoods, traditional/cultural water uses
Typical Flow Level	**Lowest** (only enough to prevent degradation)	Higher than maintenance flow, based on ecological needs	**Varies widely**, includes dynamic range of natural flow regime
Representative Examples	Korean government river maintenance flow standards, urban river policies	PHABSIM, habitat simulation tools	IHA (Indicators of Hydrologic Alteration), ELOHA, UN/World Bank guidelines
Conceptual Level	**Technical/operational**	**Ecological/scientific**	**Integrated Water Resources Management (IWRM) core concept**

1970s

drying

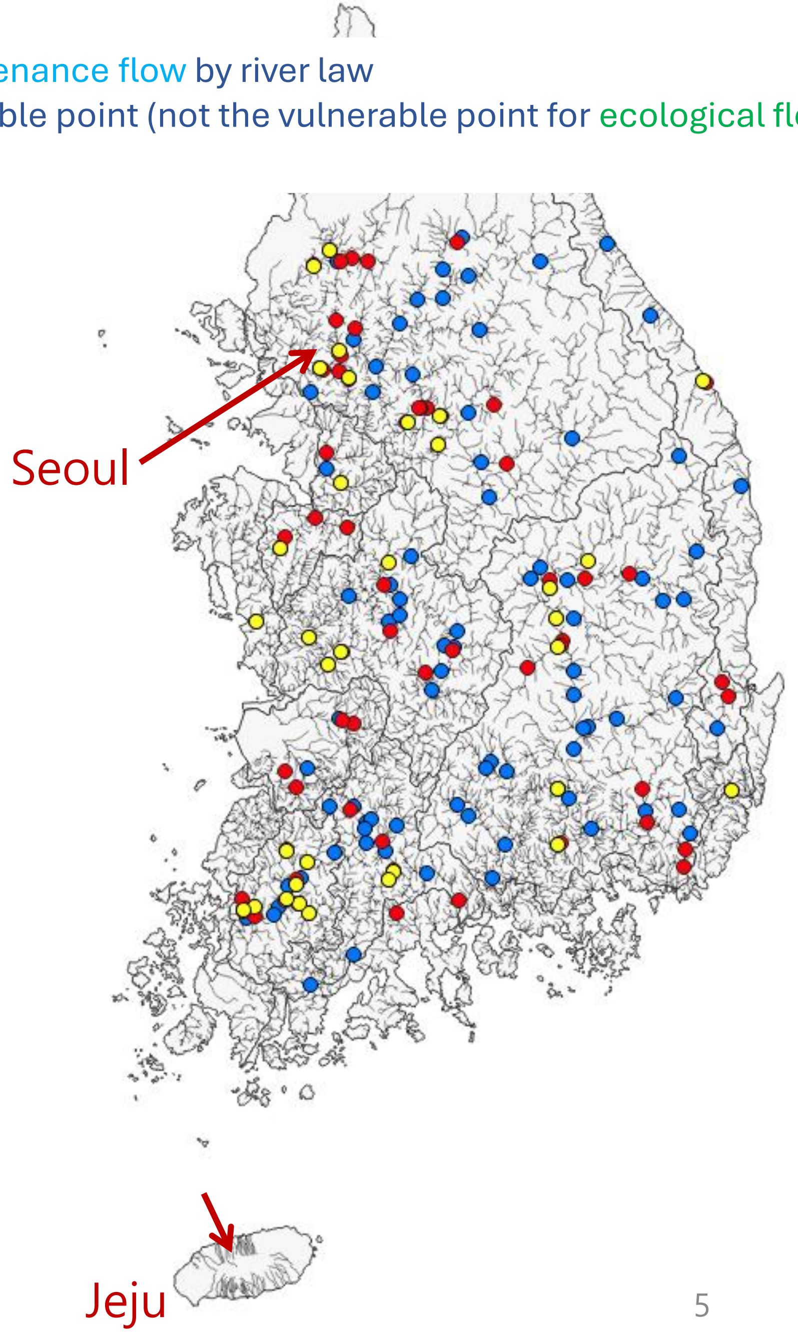
2000s ~

Suwon Seoho stream

13 years effort, Ecological River Restoration Project

- since 2002 by Ministry of Environment
- one of Gyeonggi province- 75 streams

- ①Locations of river maintenance flow by river law
- ②Aquatic ecology vulnerable point (not the vulnerable point for ecological flow)
- ①&②



Ecological Flow Estimation Methodologies

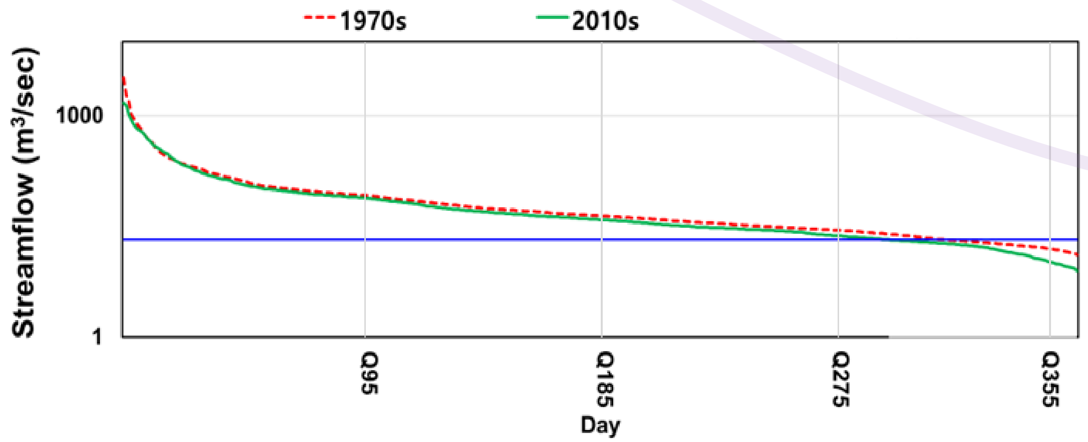
- **Hydrological methodologies-** 61 methods, covers 30%
  - Tennant(Montana) method(1976), Range of Variability Approach(1996)
- **Hydraulic rating methodologies-** 23 methods, covers 11%
  - Generic Wetted Perimeter method(1989)
- **Habitat simulation methodologies-** 28%, adopts 58 countries
  - Physical HABitat SImulation Model, PHABSIM; Bovee, 1982; Milhous et al., 1989; Nestler et al., 1989; Stalnaker et al., 1994; Milhous, 1998a
  - Riverine HABitat SIMulation program (RHABSIM; Payne and Associates, 2000)
- **Holistic methodologies-** 16 methods, covers 7.7%
  - Building Block Methodology (BBM) (King and O'Keeffe, 1989)+Holistic Approach (Arthington et al., 1992)
  - Downstream Response to Imposed Flow Transformations (DRIFT), Metsi Consultants (2000)
- **Combined methodologies and other approaches-** 16.9%
  - Country-specific, combined hydraulic and biotic Basque method (Docampo and De Bikun˜a, 1993)
  - River invertebrate prediction and classification system (RIVPACS; Wright et al., 1996)

Steps to Estimate Ecological Flow Using PHABSIM

- Step 1: Field Data Collection
- Step 2: Define Target Species and Life Stage
- Step 3: Develop Habitat Suitability Curves
- Step 4: Hydraulic Simulation
- Step 5: Calculate Weighted Usable Area (WUA)
- Step 6: Flow-Habitat Relationship

Consider

- competing between water uses
- the possibility of securing
  - we need a reference value for the reality.



Determining Flow for Fish Growing Period

- Step 1: Identify the Growing Period
  - Based on local biology or literature (e.g., May to September for many temperate species).
  - Consider temperature and food availability.
- Step 2: Use HSI for Growing Fish
  - Focus on juvenile/rearing habitat preferences.
  - Depths and velocities suitable for feeding and shelter.
- Step 3: Extract WUA During Growing Period
  - From WUA vs. discharge curves, identify:
    - Minimum flow providing adequate WUA
    - Optimum flow for maximum growth habitat
- Step 4: Set Flow Recommendation
  - Based on WUA thresholds (e.g., maintain at least 80% of max WUA).
  - Consider flow variability, water quality, and temperature.

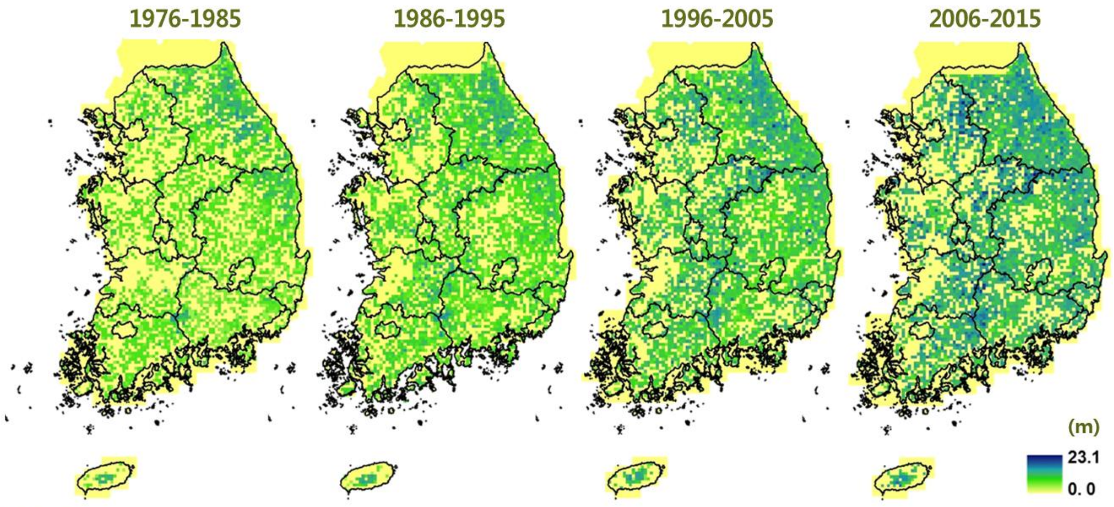
Flow (m^3/s)	WUA (m^2/1000 m)
2	150
4	300
6	420
8	460 (max)
10	430

- Optimum flow = 8 m^3/s
- Minimum recommended flow = 6 m^3/s
  - (to maintain >90% of max WUA)

reference value

Streamflow reducing factors

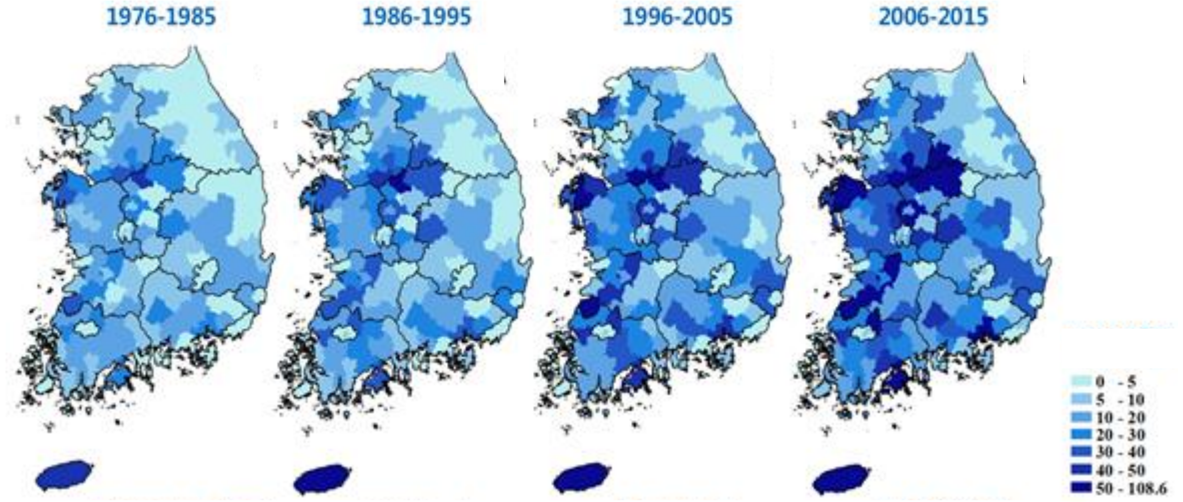
Forest grown up



3.1 m | 3.3m | 3.6m | 4.1m

Tree growth height

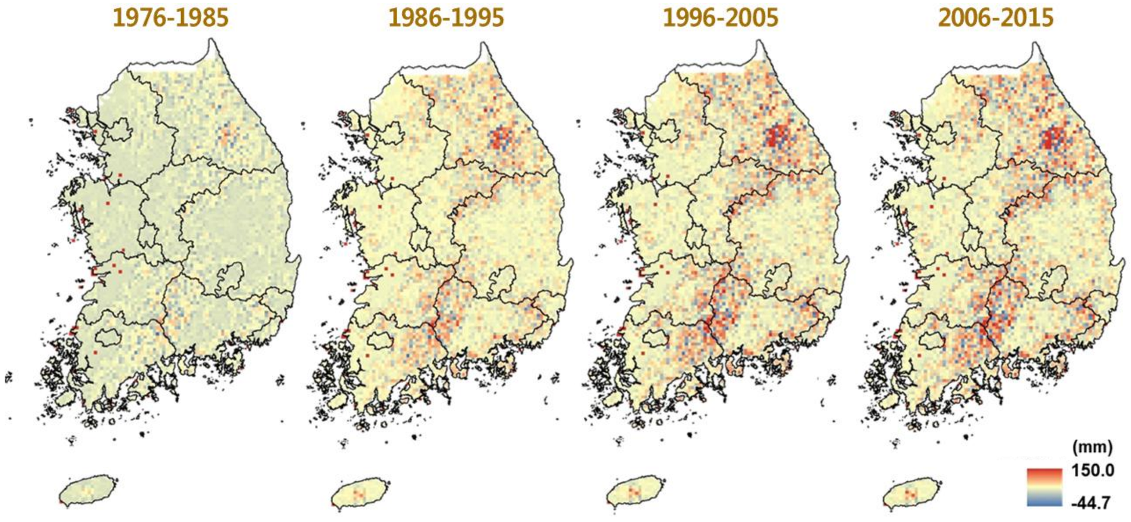
Groundwater use increased



$3.4*10^6$ m^3 | $7.9*10^6$ m^3 | $13.2*10^6$ m^3

Groundwater use increase amount

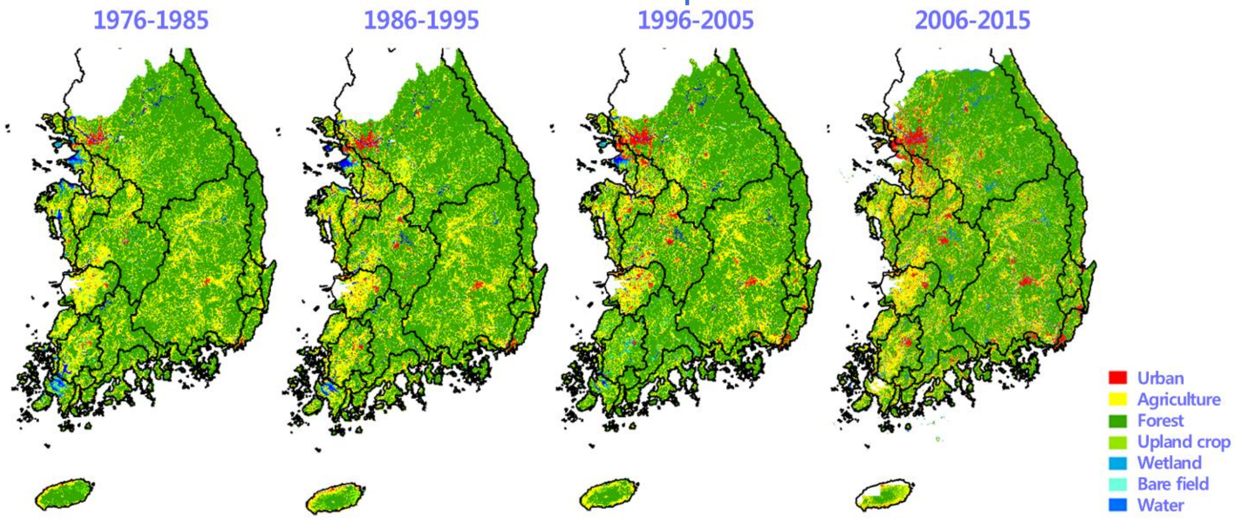
Soil eroded



4.3 mm | 8.4 mm | 13.4 mm | 15.5 mm

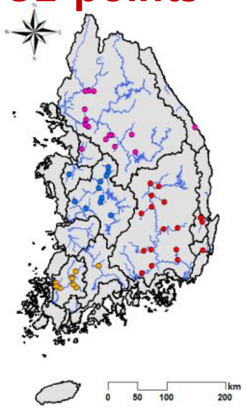
Cumulative erosion depth

Land developed



Integration of SWAT, CE-QUAL-2, and PHABSIM to secure ecological flow

52 points



Monitoring data

기상청 Korea Meteorological Administration — Meteorological data

물환경정보시스템 Water Environment Information System — Water quality data

WAMIS 국가수자원관리종합정보시스템 — Hydrological data

SWAT Input

Soil & Water Assessment Tool SWAT

- Meteorological data
- GIS: DEM, land cover, soil type, water resources unit map
- RS: NDVI, LAI
- Streamflow, dam & weir releases, groundwater level data
- Water Quality (SS, T-N, T-P, Chl-a) data

Water Quality Research Group
CE-QUAL-W2 Hydrodynamic and Water Quality Model

CE-QUAL-W2 Input

- Meteorological data
- Intake water data
- TMS data

PHABSIM
Water velocity, depth
Cross-section
Roughness coefficient
Channel depth, width
HIS (field investigation)

HEC-RAS

SWAT
Flow Duration Curve • High flow (Q10) • Wet condition (Q95) • Mid-range flows (Q185) • Dry conditions (Q275) • Low flows (Q355)

Output

SWAT
Streamflow (CMS)
DO (kg/day)
PO4 (kg/day)
NO3 (kg/day)
NH4 (kg/day)
Water temperature (℃)
Chl-a (ppm)
TOC (measured)

Input

CE-QUAL-W2
Streamflow (CMS)
DO (mg/L)
PO4 (mg/L)
NO3 (mg/L)
NH4 (mg/L)
Water temperature (℃)
Chl-a (mg/m^3)
OM group (mg/L)

Output

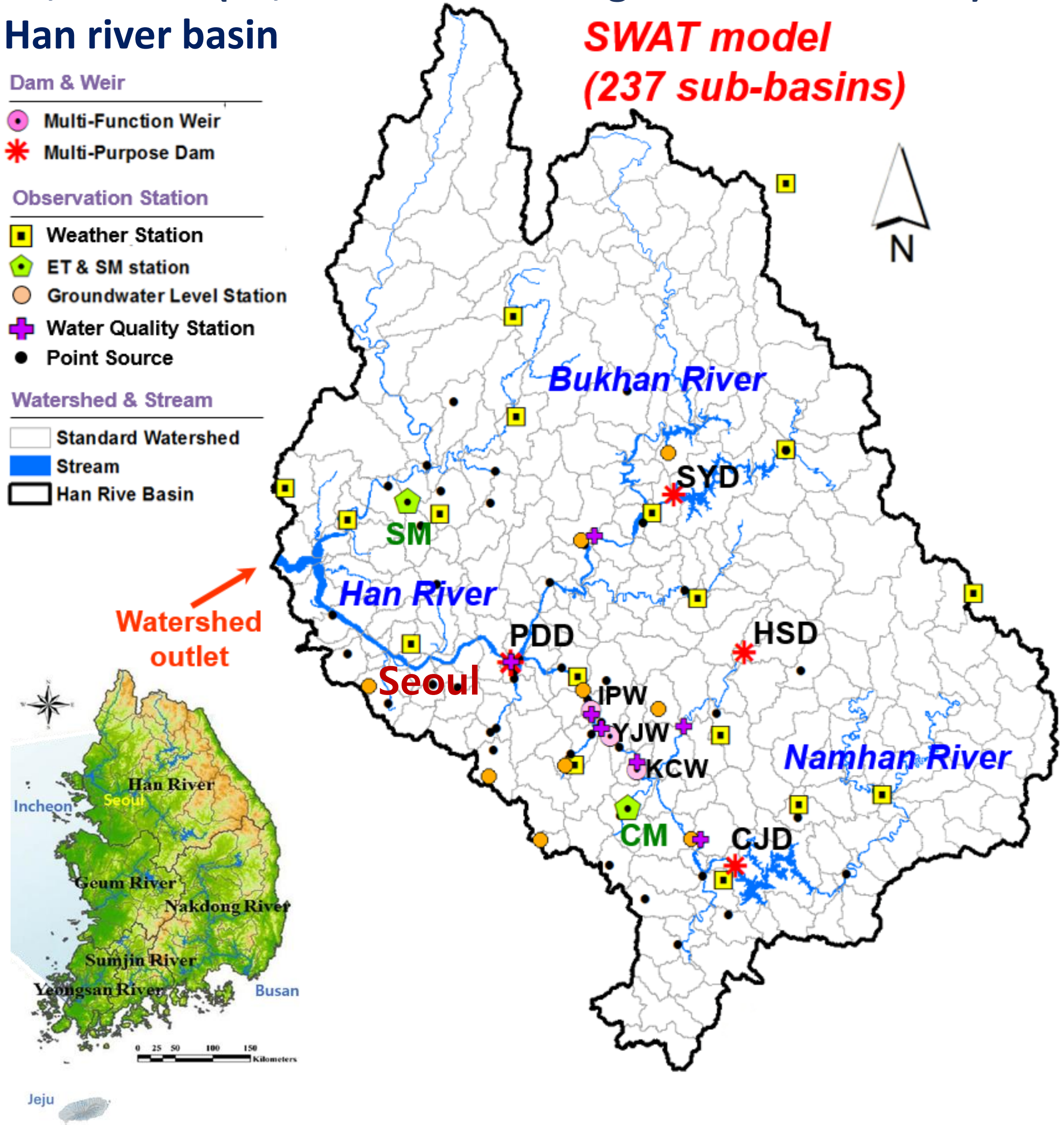
Required ecological flow (WUA, m^2/1000m)

Determine necessary ecological flow and days based on 1976 → Apply BMPs to improve stream water quality under the secured ecological flow condition and present watershed environment → Compare water velocity distribution, water depth and perimeter increases before and after securing ecological flow

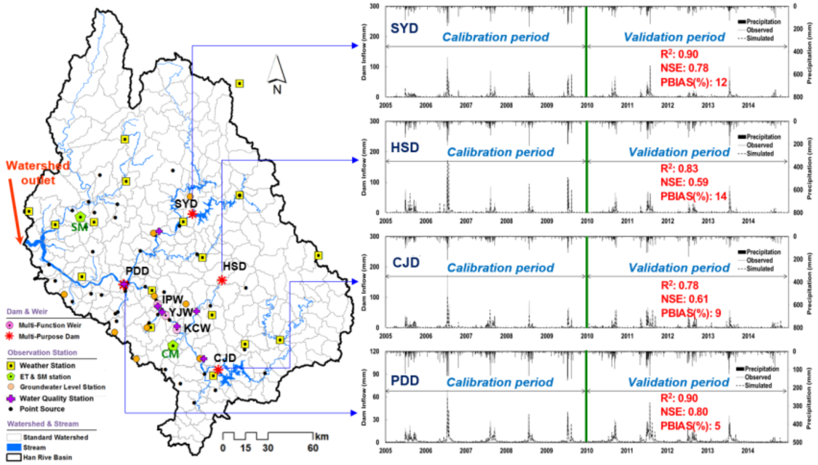
SWAT streamflow & water quality modeling

25,953.6㎢ (35,770.41㎢ including North Korea areas)

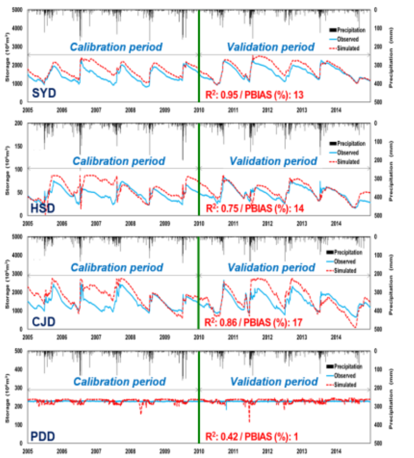
Han river basin



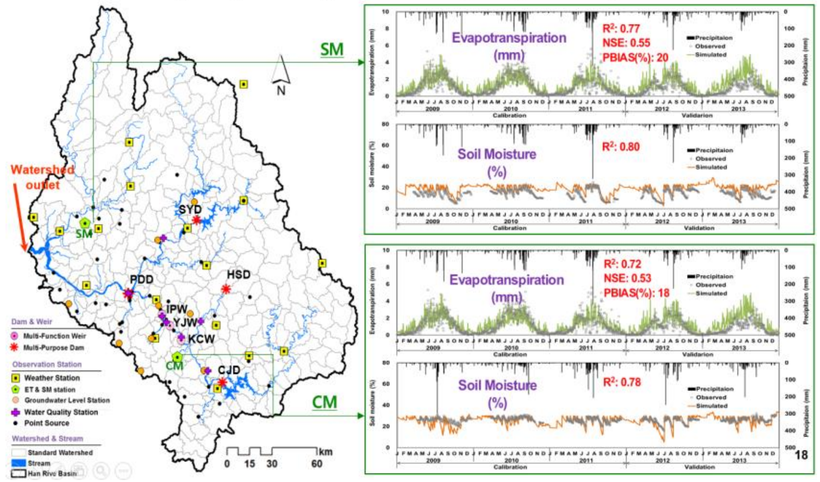
Dam inflows



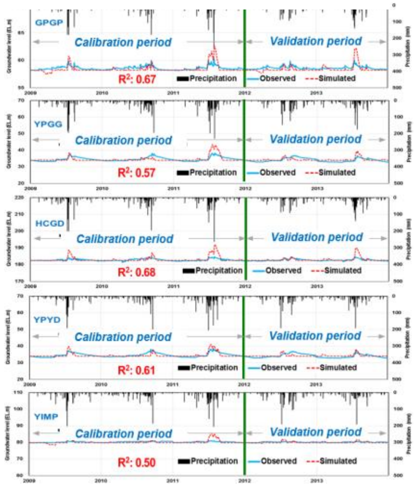
Dam water level



ET & Soil Moisture

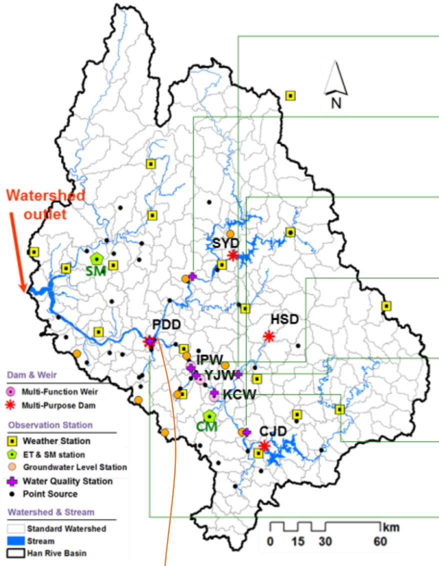


Groundwater level

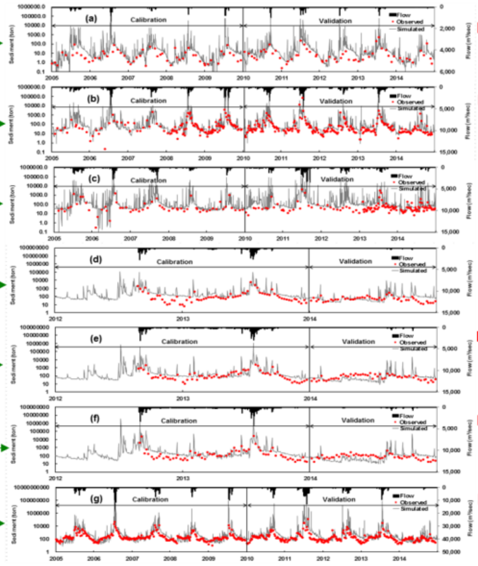


SWAT streamflow & water quality modeling

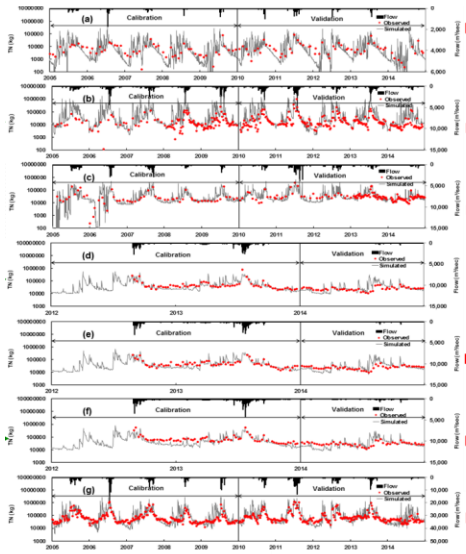
✓ Calibration : 5 years (2005-2009) / Validation : 5 years (2010-2014)



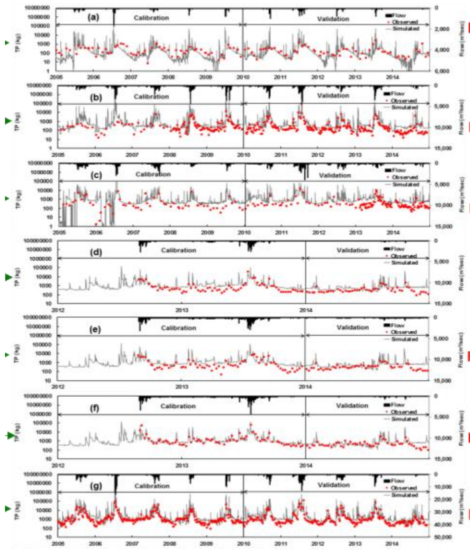
Suspended solid



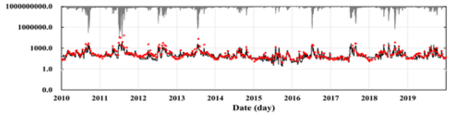
Total Nitrogen

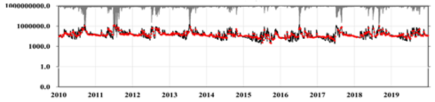


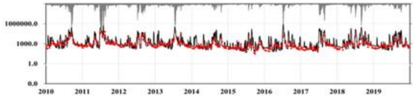
Total Phosphorus



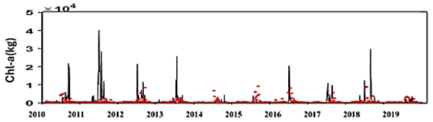
Calibration: 6 years (2010-2015) Validation: 4 years (2016-2019)



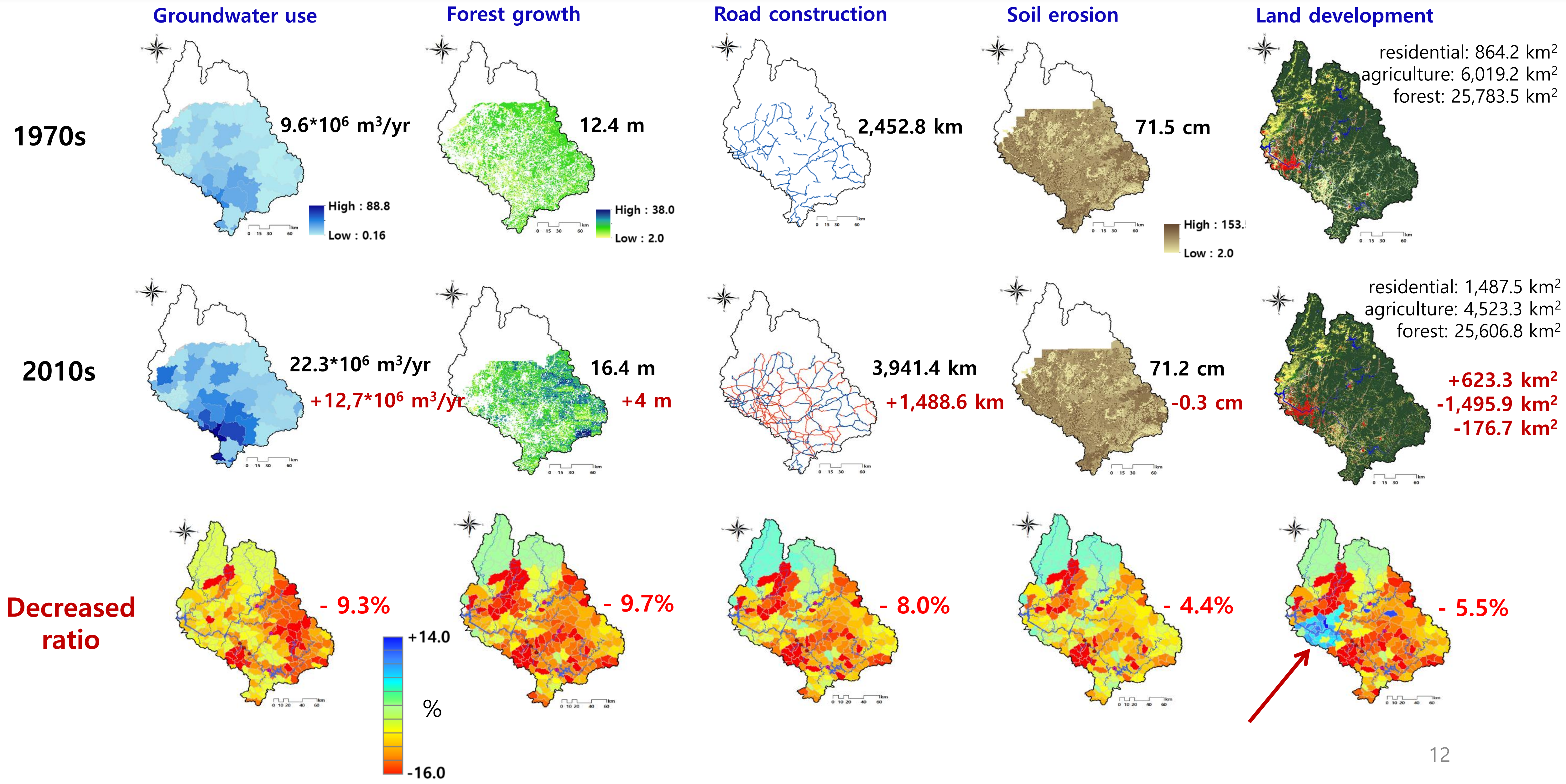




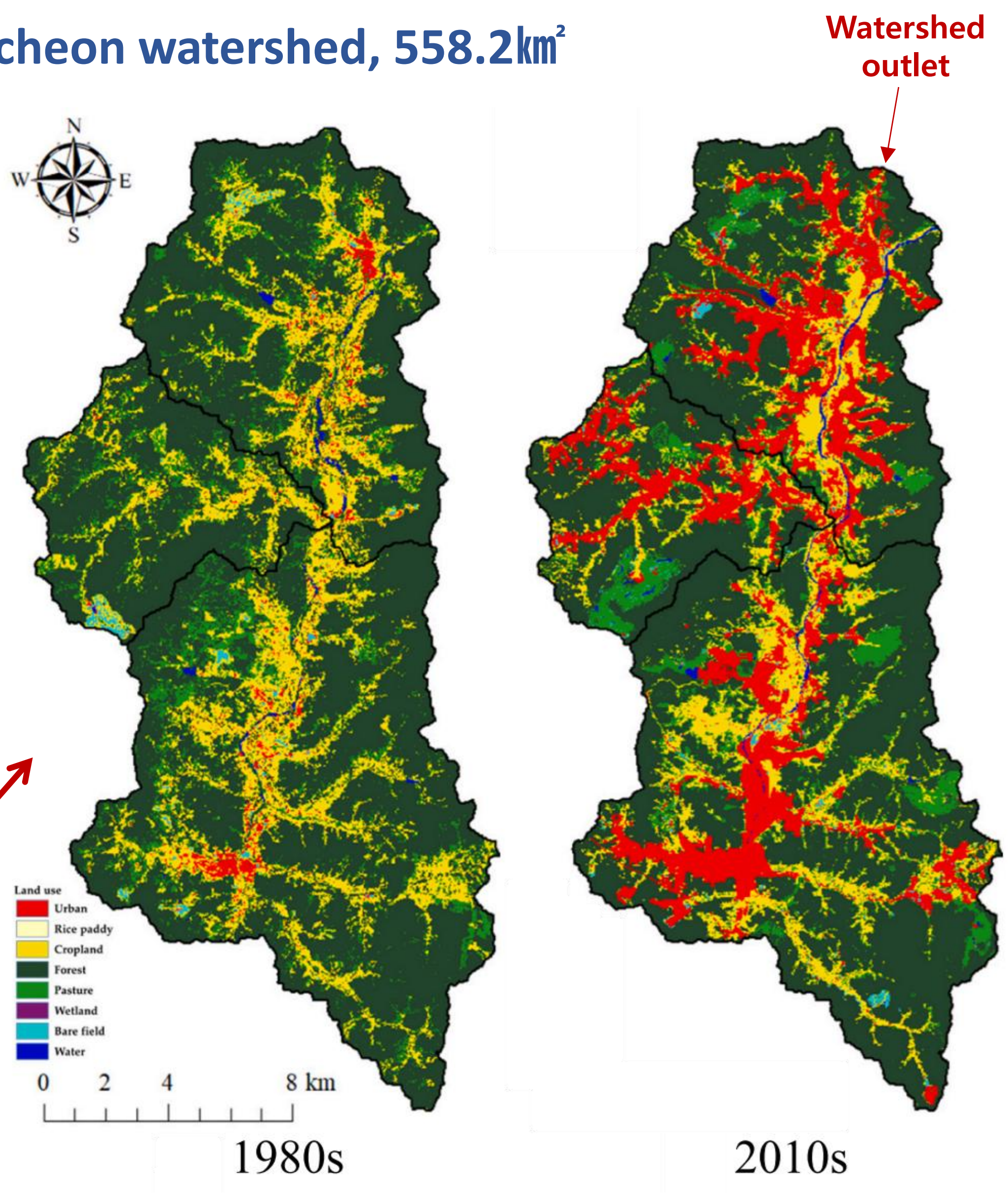
Chl-a



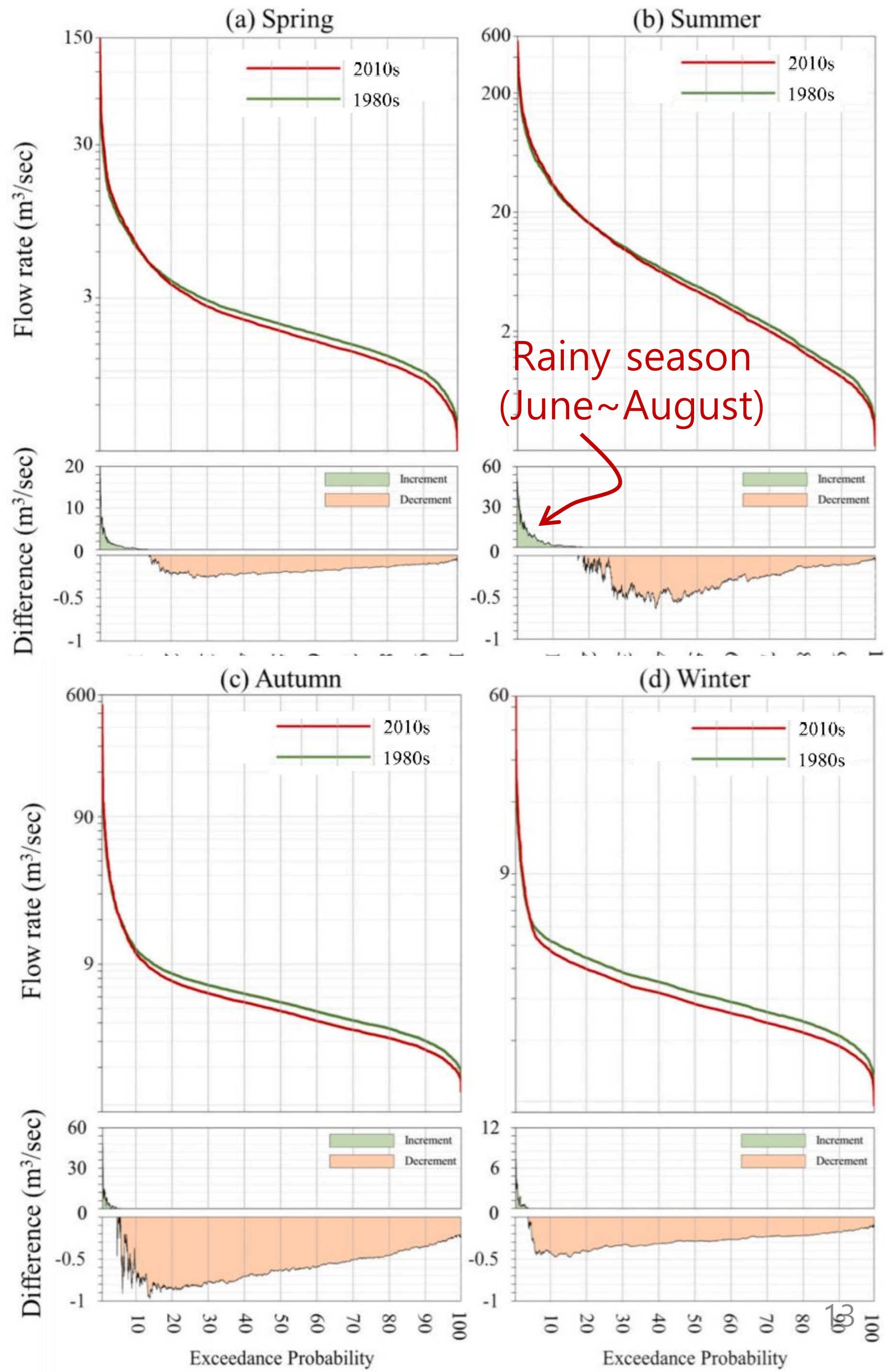
SWAT modeling results by applying 1970s & 2010s watershed environments



Gyeongan-cheon watershed, 558.2㎢

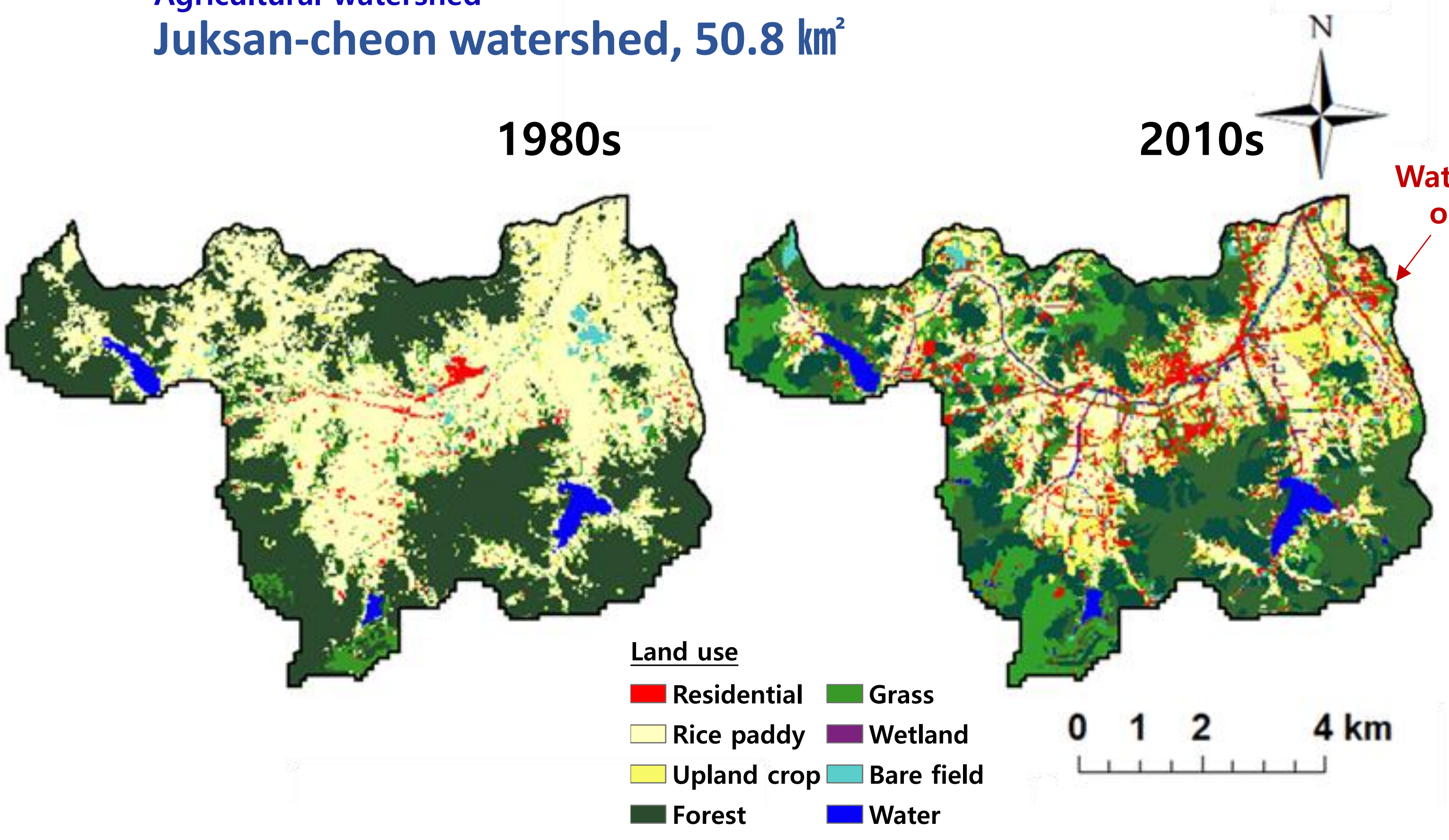


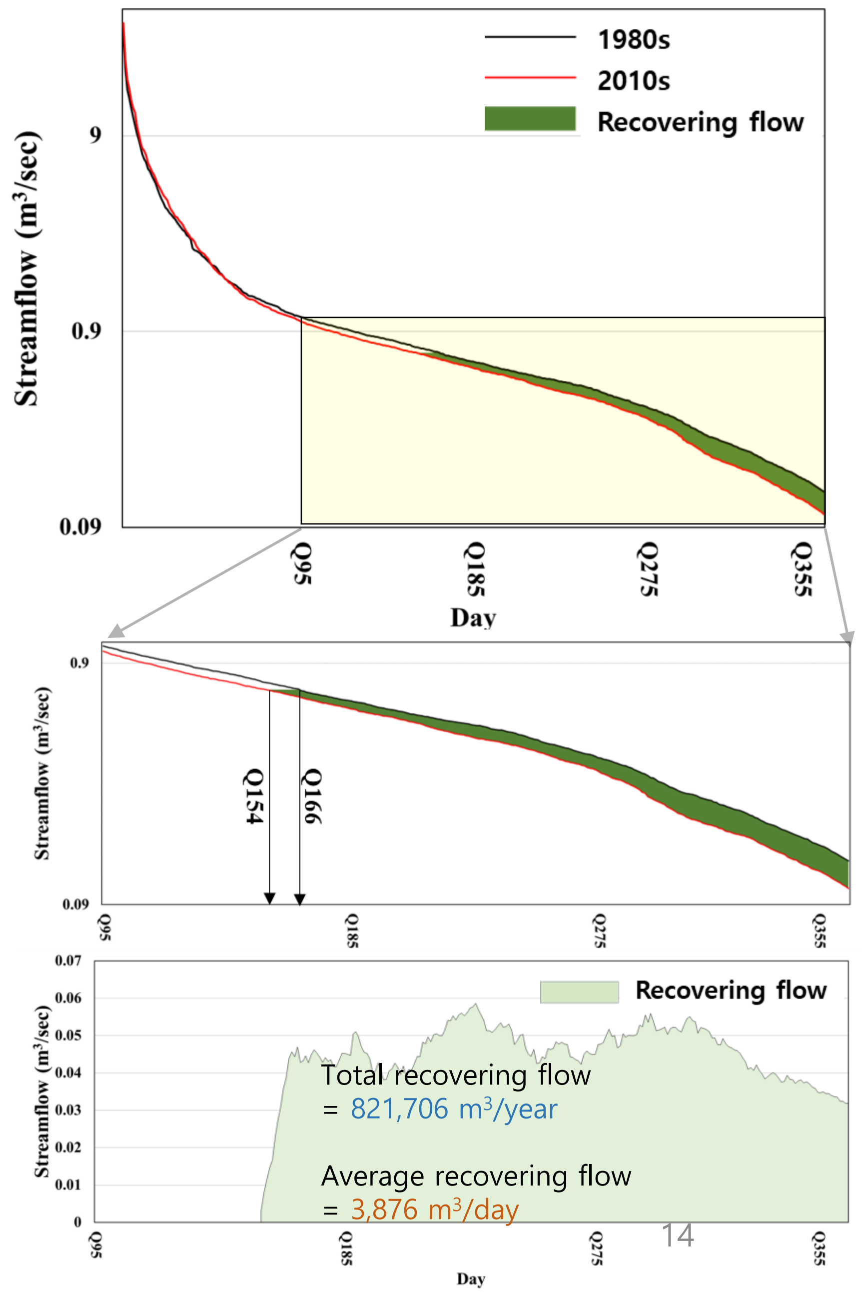
Land development watershed



Agricultural watershed

Juksan-cheon watershed, 50.8 ㎢





	Urban	Rice paddy	Upland crop	Forest	Grass	Wetland	Bare field	Water
1980s (km²)	0.7 (1.4%)	21.7 (42.0%)	3.0 (5.9%)	22.1 (42.9%)	2.7 (5.3%)	-	0.5 (0.9%)	0.8 (1.5%)
2010s (km²)	4.1 (7.9%)	9.2 (17.8%)	6.9 (13.3%)	23.3 (45.3%)	4.9 (9.4%)	0.7 (1.4%)	1.2 (2.4%)	1.2 (2.4%)
Change (km²)	+3.4	-12.5	+3.9	+1.2	+2.1	+0.7	+0.8	+0.4
Change (%)	+6.5	-24.2	+7.5	+2.4	+4.1	+1.4	+1.5	+0.8

Geum river basin 9,912.15㎢

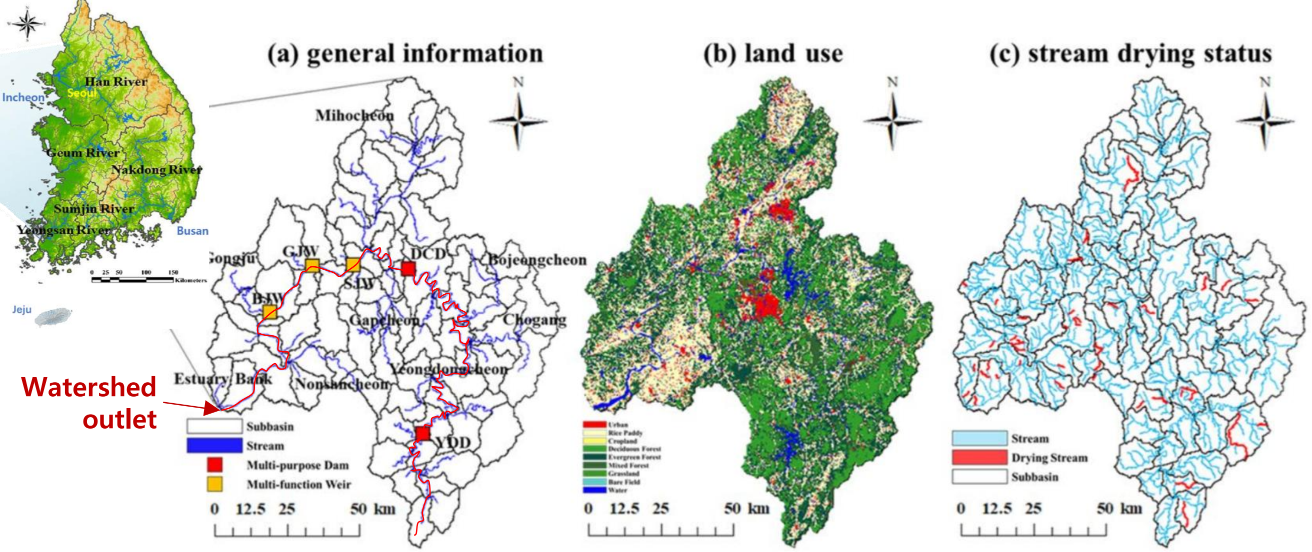
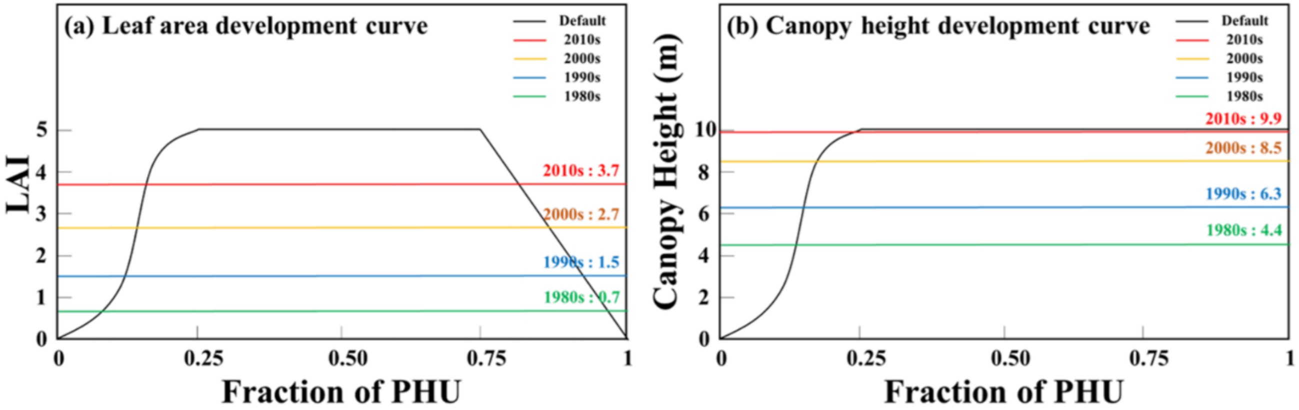
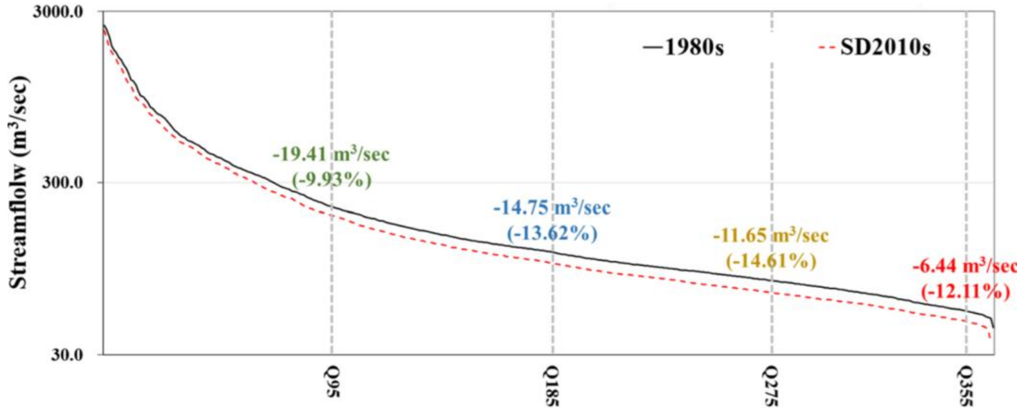
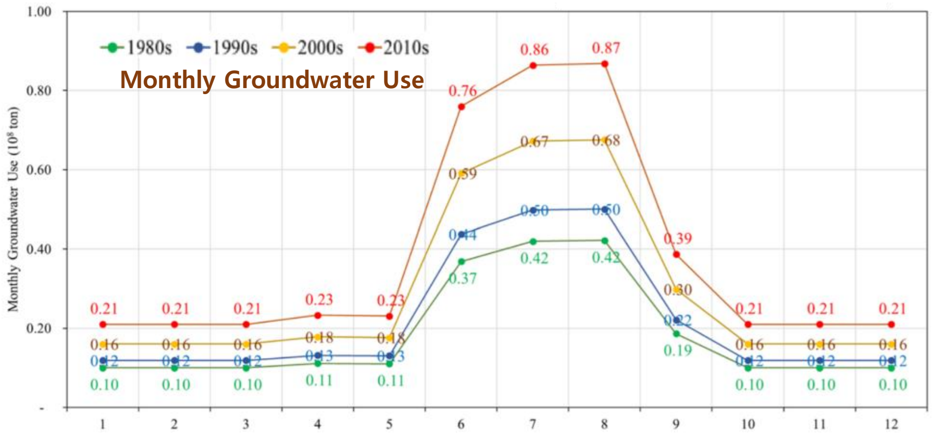


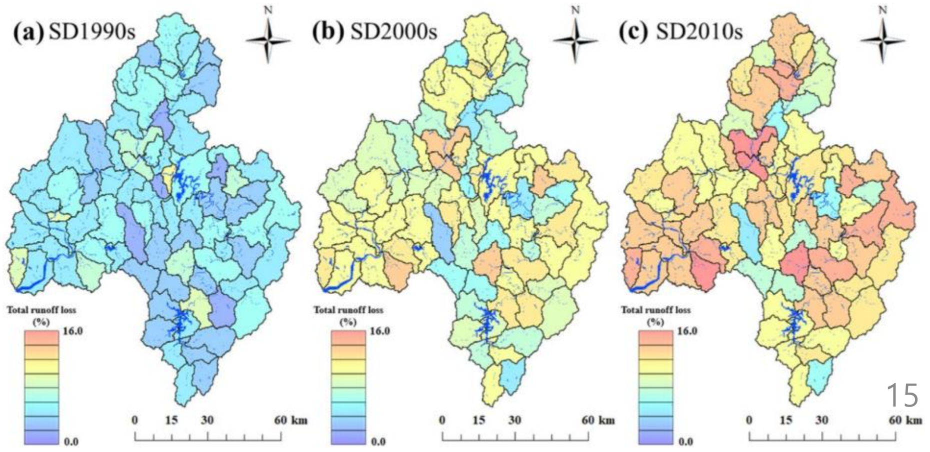
Table 5 Hydrologic responses to stream drying scenario

Scenario	TR (mm/year)	ET (mm/year)	SR (mm/year)	LF (mm/year)	GF (mm/year)	PE (mm/year)	GWR (mm/year)
1980s	687.5	501.7	181.6	353.4	180.0	186.5	186.9
SD1990s	669.0 (–2.7%)	508.4 (+1.3%)	180.9 (–0.3%)	350.6 (–0.8%)	164.5 (–8.6%)	183.0 (–1.9%)	170.6 (–8.7%)
SD2000s	643.9 (–6.3%)	516.1 (+2.9%)	180.1 (–0.8%)	347.4 (–1.7%)	142.3 (–20.9%)	178.9 (–4.1%)	147.5 (–21.1%)
SD2010s	626.6 (–8.9%)	520.6 (+3.7%)	179.6 (–1.1%)	345.7 (–2.2%)	126.2 (–29.9%)	176.5 (–5.4%)	130.6 (–30.1%)



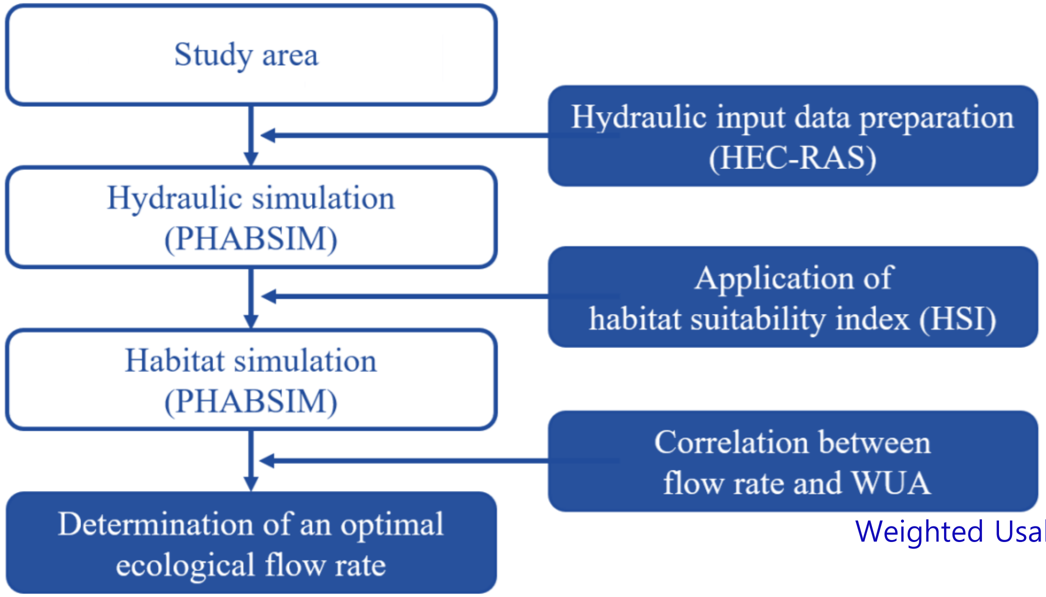






PHABSIM ecological flow

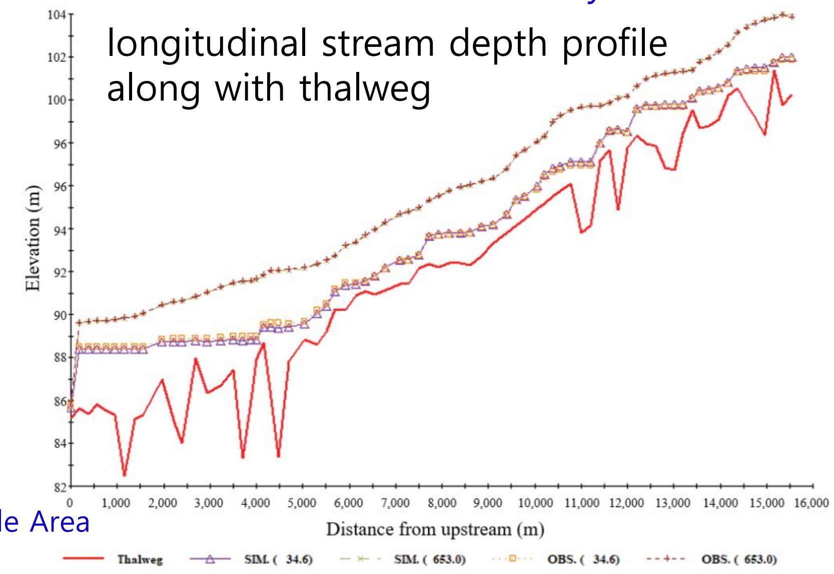
Estimation of an Optimum Ecological Stream Flow in the Banbyeon Stream Using PHABSIM - Focused on Zacco platypus and Squalidus chankaensis tsuchigae –
Park, Jinseok · Jang, Seongju · Song, Inhong
Journal of the Korean Society of Agricultural Engineers, 62(6), 2020. 11



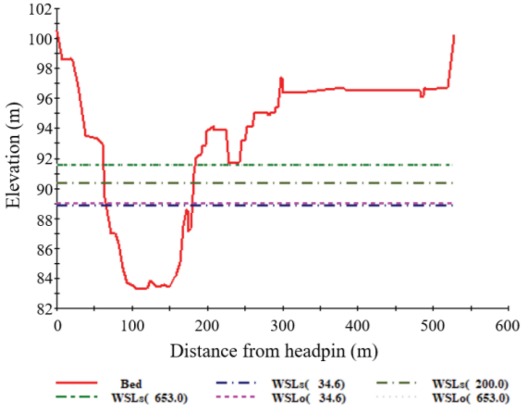
Weighted Usable Area

PHABSIM hydraulic simulated result

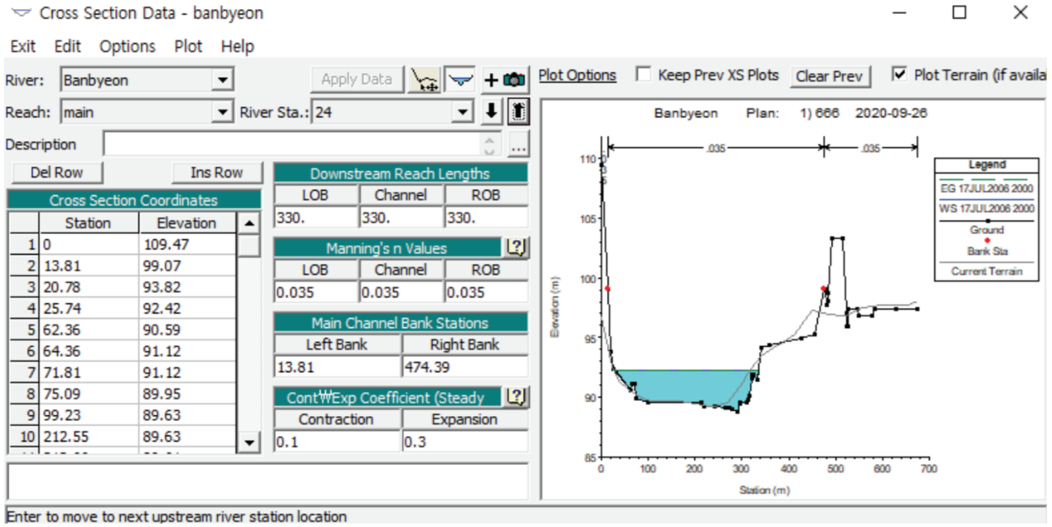
longitudinal stream depth profile along with thalweg



water surface level at target cross section



HEC-RAS stream cross section



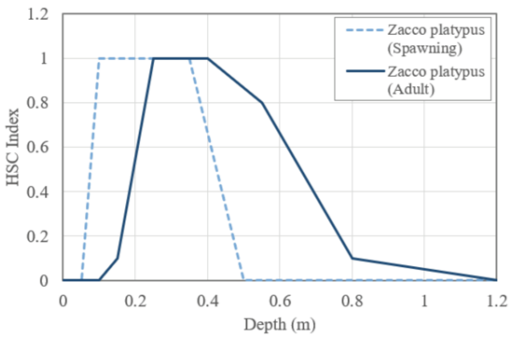
Habitat Suitability Curve (HSC) index estimated for the representative fish species

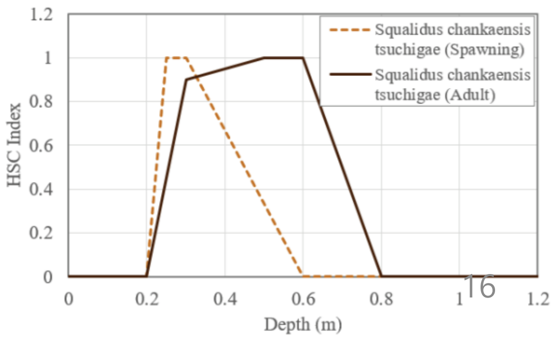
minnow, pale chub

Zacco platypus

Korean gudgeon
small carp

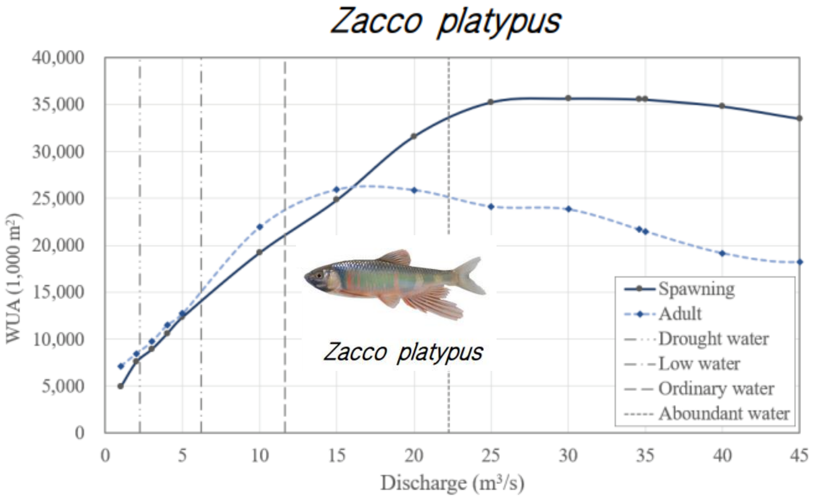
Squalidus chankaensis tsuchigae

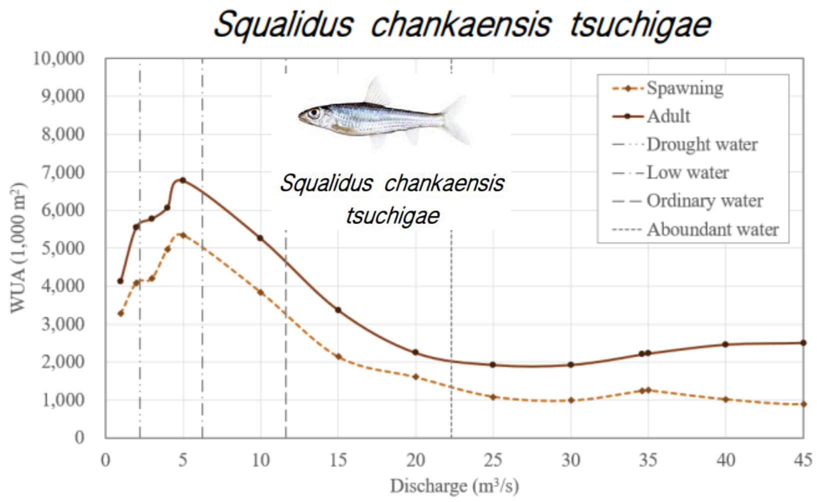




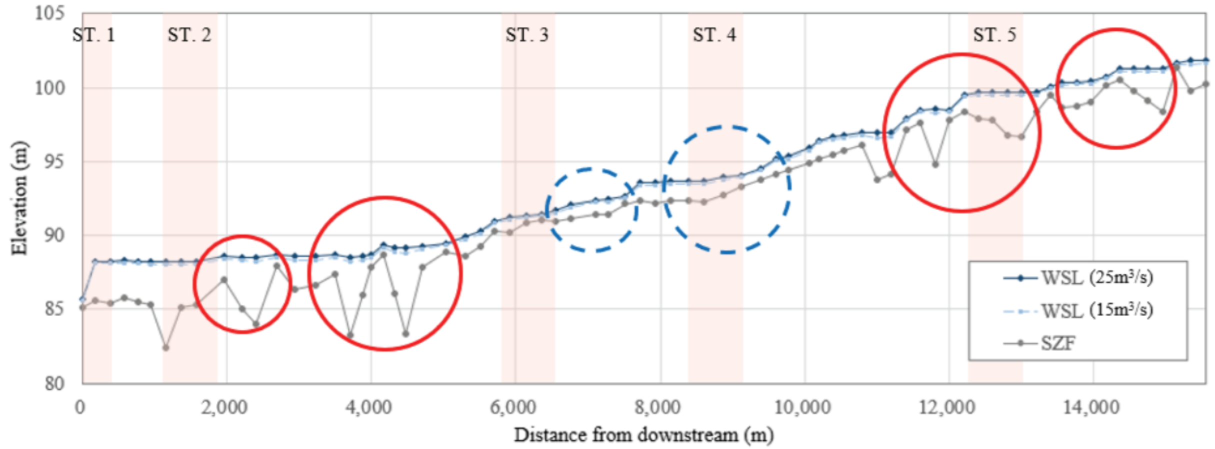
PHABSIM ecological flow

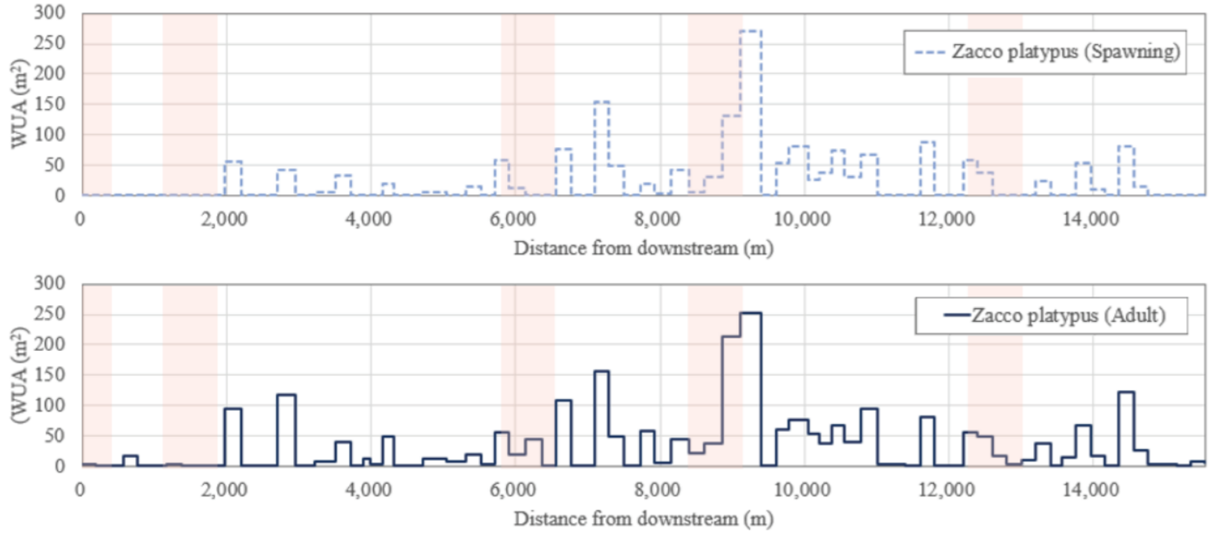
Weighted usable area (WUA) estimated for the representative fishes





Longitudinal profile of water surface level and WUA at the optimal ecological flow rate for Zacco platypus

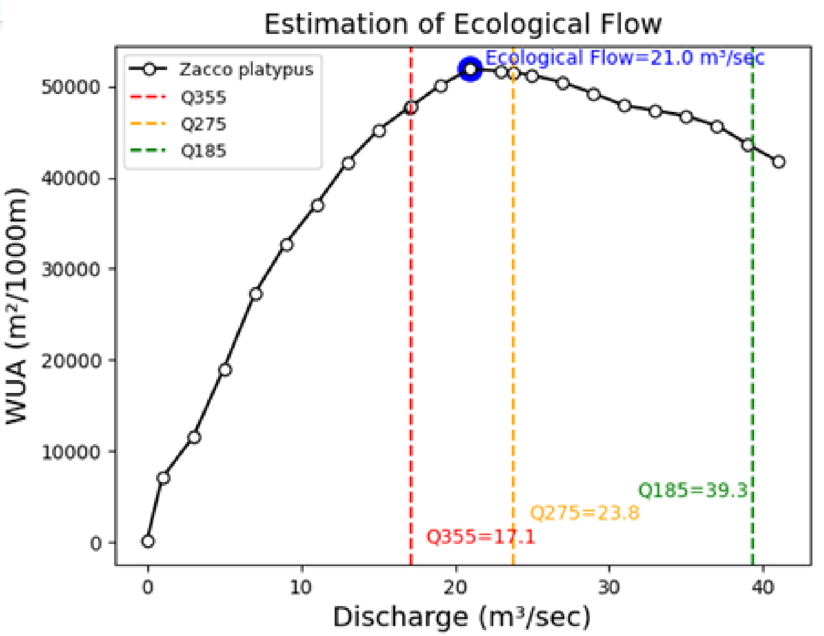




Securing days and amount of ecological flow to recover 2010s Q to 1970s Q

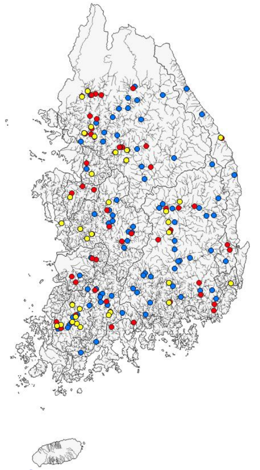
Watershed area (2,983.0 km²) Unit: m³/sec

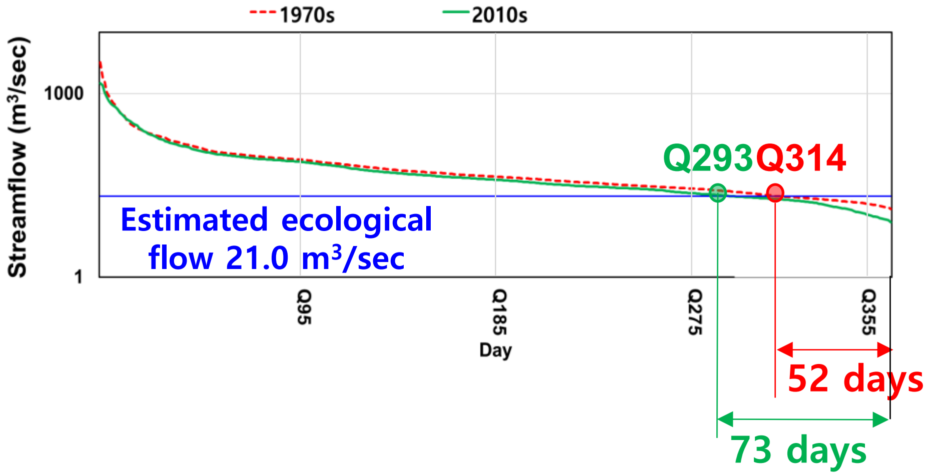
Flow duration	1970s (1)	2010s (2)	(2)-(1)
Q95	82.42	75.69	-6.73
Q185	43.54	38.76	-4.78
Q275	27.87	23.44	-4.43
Q293	24.93	20.98	-3.95
Q314	20.90	18.75	-2.15
Q355	15.74	10.43	-5.31



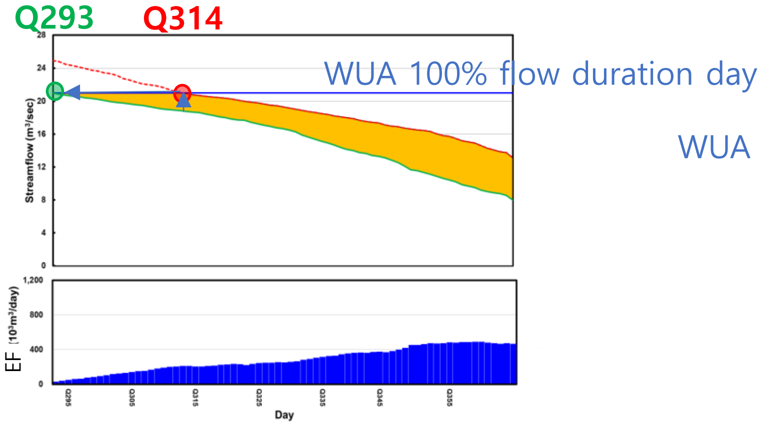
▪ **WUA ecological flow (m³/s)**

WUA	100%	90%	80%	70%	60%	50%	25%
EF	21.00	16.13	13.09	10.69	8.64	6.82	2.93



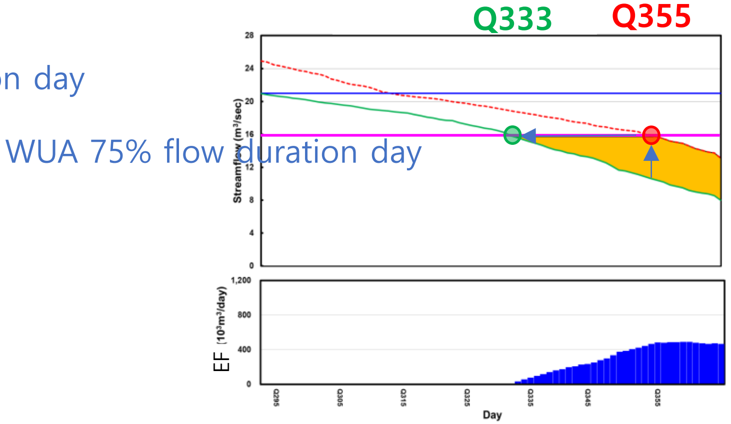


WUA 100% flow duration day recovery of 2010s Q to 1970s Q



Securing days: 73 days
Average amount: 3.01 m³/s
(260,064 m³/day)

Streamflow recovery of 2010s Q355 to 1970s Q355

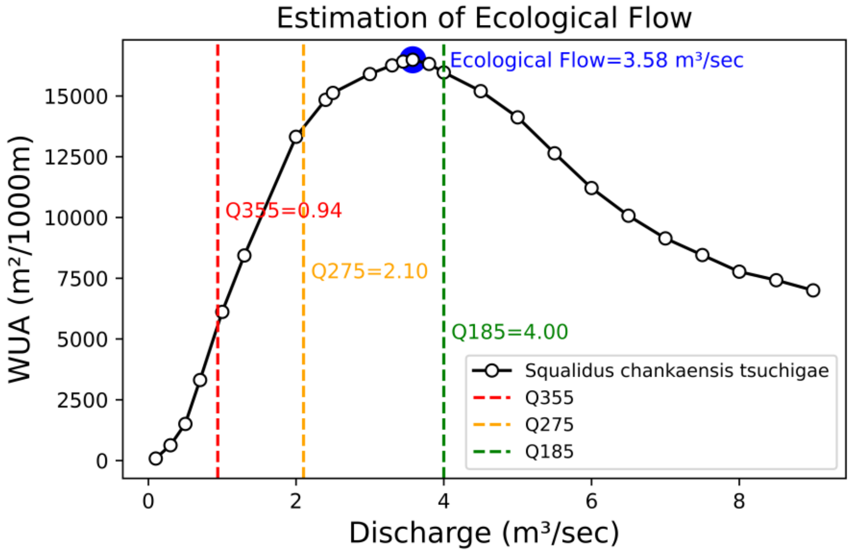


Securing days: 33 days
Average amount: 3.46 m³/s
(298,944 m³/day)

Securing days and amount of ecological flow to recover 2010s Q to 1970s Q

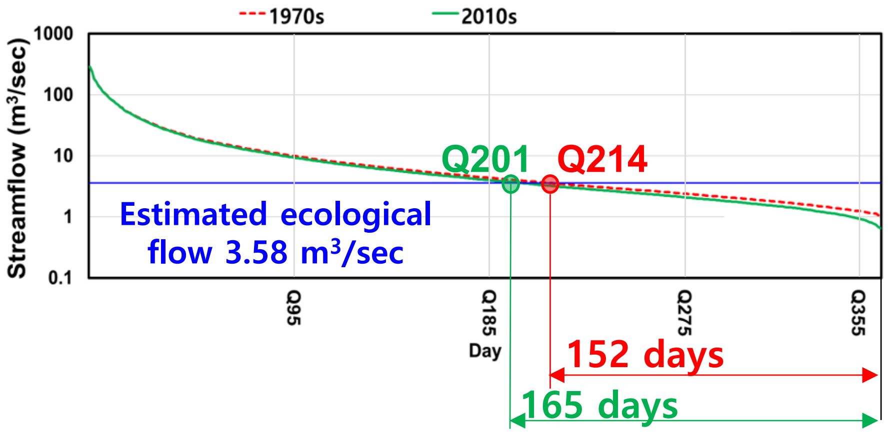
Watershed area (492.3 km²) Unit: m³/sec

Flow duration	1970s (1)	2010s (2)	(2)-(1)
Q95	9.94	9.37	-0.57
Q185	4.37	4.00	-0.37
Q201	3.91	**3.56**	-0.35
Q214	**3.58**	3.21	-0.37
Q275	2.41	2.10	-0.31
Q355	1.26	0.94	-0.32

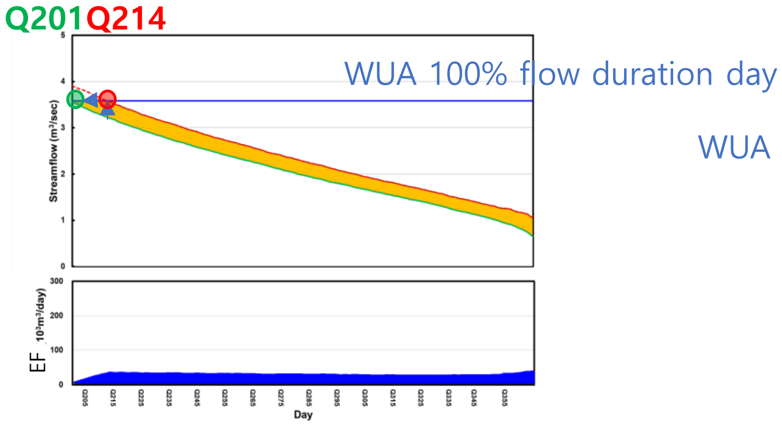


- **WUA ecological flow (m³/s)**

WUA	100%	90%	80%	70%	60%	50%	25%
EF	3.58	2.40	1.98	1.69	1.46	1.26	0.80

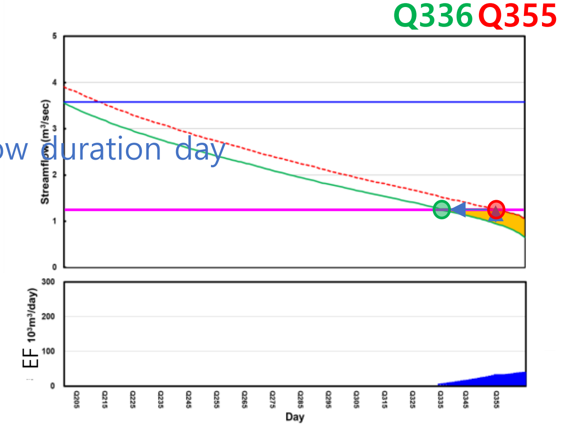


WUA 100% flow duration day recovery of 2010s Q to 1970s Q



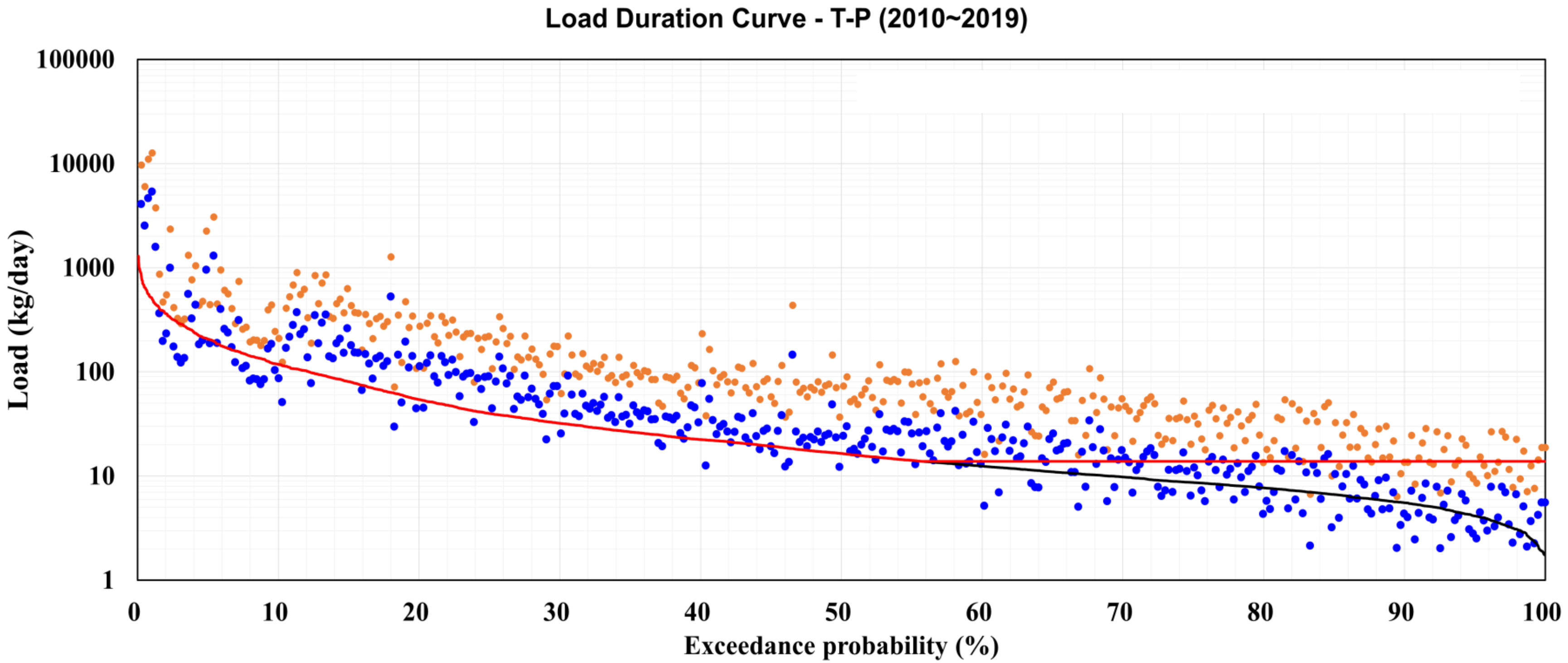
Securing days: 165 days
Average amount: 0.30 m³/s
(25,920 m³/day)

Streamflow recovery of 2010s Q355 to 1970s Q355



Securing days: 31 days
Average amount: 0.22 m³/s
(19,008 m³/day)

BMPs application to improve stream water quality after securing ecological flow



Flow duration	Ave (mg/L)		Excess rate (%)	
	Obs.	BMPs (30%)	Obs.	BMPs (30%)
Q95 (10%~40%)	0.075	0.031	100.0	94.9
Q185 (40%~60%)	0.056	0.019	100.0	87.2
Q275 (60%~90%)	0.044	0.014	98.3	62.4
Q355 (90%~100%)	0.037	0.011	100.0	46.2

Guidelines for Estimating the Flow Rate of River Maintenance
(2009, Ministry of Land, Transport and Maritime Affairs)

- The required flow rate considering the river ecosystem shall be calculated according to the procedures of 1. investigation of biological distribution and habitat environment, 2. selection of representative and surrogate species considering ecological and social importance and protected species, 3. investigation of habitat environment such as habitat hydraulics and water quality, 4. investigation of marginal section setting and hydraulic characteristics, and 5. calculation of required flow rates, etc.

- The calculation of necessary flow rate may be calculated by applying mathematical method, habitat simulation method, or simplified method such as uniform flow formula, depending on available data and the necessity.

constant for all period

Guidelines for the Calculation of River Maintenance Flow
(2024, Ministry of Environment)

- The necessary flow rate in consideration of the river ecosystem shall be in accordance with the method of calculating the environmental-ecological flow rate prescribed in Article 22 (3) of the Water Environment Conservation Act, but may be adjusted as necessary.

PHABSIM

- The required flow rate may be set differently for each period by reflecting the life history of the target fish.

SWAT+PHABSIM