SWAT Model Calibration/Validation Using SWAT-CUP
: An Optimal Calibration Protocol for SWAT

Quantifying and Optimizing Uncertainties in Objective Functions, Computational Runs, and Multi-Site Data

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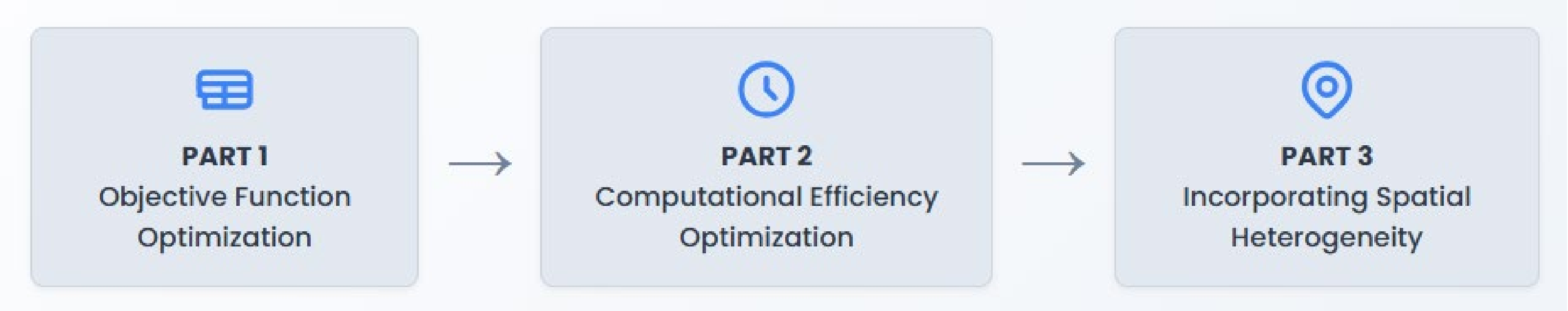
Introduction

- SWAT Model Utility and Limitations: A powerful tool for long-term hydrologic/water quality prediction, but its many parameters inherently introduce Uncertainty, compromising result reliability.



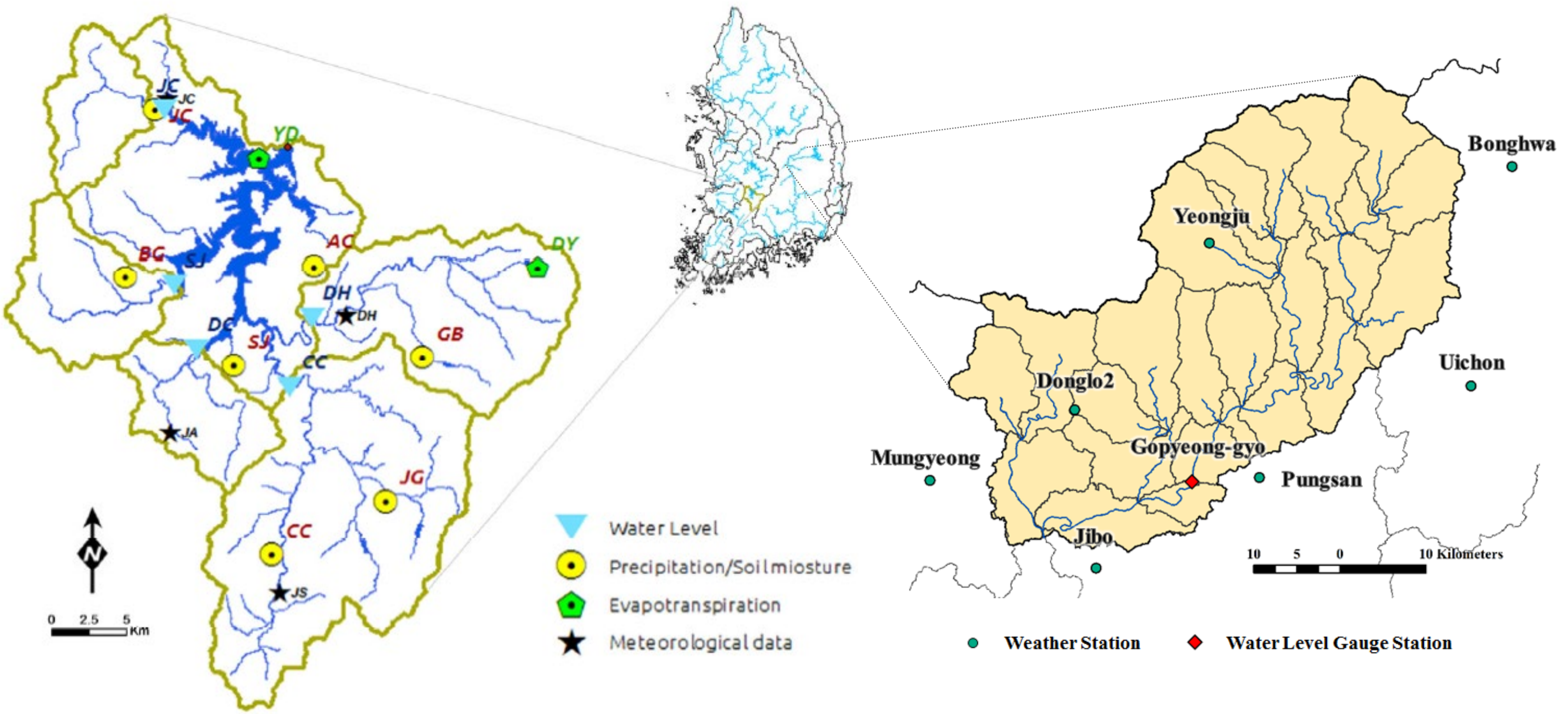
- Need for Research: A Standardized Calibration Protocol is crucial to minimize subjective uncertainties and produce reproducible, reliable results.

- Overall Objective: Propose a **systematic methodology** to minimize uncertainty in **SWAT-CUP**

Study Area

*Yongdam Dam Watershed,
South Korea

*Naeseong-cheon Watershed,
South Korea



*2002.10.01~2018.12.31.

*2007.01.01~2015.12.31.

Methods

**SWAT model parameters selected and their initial value/settings for SWAT-CUP calibration; The information of objective function in SWAT-CUP*

Parameter	Description	File	Min.	Max.	Initial value	Unit	SWAT-CUP Setting		
							Lower	Upper	cal. Method
ALPHA_BF	Baseflow alpha factor (days)	.gw	0	1	0.048	days	0.048	0.952	Add
CN2	SCS runoff curve nur								
SURLAG	Surface runoff lag ti								
CH_N1	Manning's "n" value for the trib								
CH_N2	Manning's "n" value for the r								
ESCO	Soil evaporation compensa								
CH_K2	Effective hydraulic conc in main channel allu								
SOL_AWC	Available water capacity of t								
CANMX	Maximum canopy stc								
EPCO	Plant uptake compensatic								
GW_REVAP	Groundwater "revap" co								
SOL_K	Saturated hydraulic cond								
GW_DELAY	Groundwater delay(d								
REVAPMN	Threshold depth of water in aquifer for "revap" to occ								
GWQMN	Threshold depth of water in aquifer required for return flow								
RCHRG_DP	Deep aquifer percolation								
SFTMP	[OPTINAL] Snowfall ten								
SLSUBBSN	Average slope leng								
SMFMN	Minimum melt rate for snow d (occurs on winter sols								
SMFMX	Maximum melt rate for snow (occurs on summer sol								
SMTMP	Snow melt base temperature.	.bsn	-20	20	0.5	℃	-25%	25%	Multiply by
SOL_Z	Depth from soil surface to bottom of layer.	.sol	0	3500	sol file	mm	-25%	25%	Multiply by
TIMP	Snow pack temperature lag factor.	.bsn	0	1	1	-	-1	0	Add

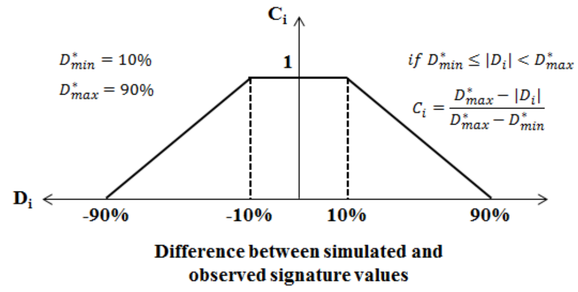
Objective Function	Formulation	Range
Coefficient of Determination (R^2)	$R^2=\left(\frac{\sum_i(Q_{m,i}-\bar{Q}_m)(Q_{s,i}-\bar{Q}_s)}{\sqrt{\sum_i(Q_{m,i}-\bar{Q}_m)^2}\sqrt{\sum_i(Q_{s,i}-\bar{Q}_s)^2}}\right)^2$	0 to 1
Modified Coefficient of Determination (bR^2)	$bR^2=\begin{cases}\lvert b\rvert R^2 & \text{if } \lvert b\rvert\le 1\\ \lvert b\rvert^{-1}R^2 & \text{if } \lvert b\rvert>1\end{cases}$	0 to 1
Nash-Sutcliffe Efficiency (NS)	$NS=1-\frac{\sum_i(Q_m-Q_s)_i^2}{\sum_i(Q_{m,i}-\bar{Q}_m)^2}$	-∞ to 1
Modified Nash-Sutcliffe Efficiency (MNS)	$MNS=1-\frac{\sum_i\lvert Q_m-Q_s\rvert_i^p}{\sum_i\lvert Q_{m,i}-\bar{Q}_m\rvert_i^p}$	-∞ to 1
Kling-Gupta Efficiency (KGE)	$KGE=1-\sqrt{(r-1)^2+(\alpha-1)^2+(\beta-1)^2}$	0 to 1
Percent Bias (PBIAS)	$PBIAS=100\times\frac{\sum_i(Q_m-Q_s)_i}{\sum_i Q_{m,i}}$	-∞ to ∞
RMSE-Observations Standard Deviation Ratio (RSR)	$RSR=\frac{\sqrt{\sum_i(Q_m-Q_s)_i^2}}{\sqrt{\sum_i(Q_{m,i}-\bar{Q}_m)^2}}$	0 to ∞
Ranked Sum of Squared Error (SSQR)	$SSQR=\frac{1}{n}\sum_i[Q_{i,m}-Q_{i,s}]^2$	0 to ∞

* R is the correlation coefficient between measured and simulated data; b is the slope of regression line between measured and simulated data; $Q_{m,i}$ and $Q_{s,i}$ are the ith measured and simulated values, respectively; $\bar{Q}_m$ and $\bar{Q}_s$ are the mean measured and simulated values, respectively; n is the total number of observations; $\alpha=\sigma_s/\sigma_m$ and $\beta=\sigma_s/\sigma_m$ where σ_m and σ_s are the standard deviation of the measured and simulated data, and μ_m and μ_s are the mean of measured and simulated data, respectively.

Methods

PART 1 | Research Design for Objective Function

✓ **Research Question**: "Which objective function best reproduces the watershed's hydrological behavior?"



✓ **Study Area**: Naeseong-cheon Watershed, South Korea.

✓ **Calibration Method**: Individually apply 8 objective functions (R^2, bR^2, NS, MNS, KGE, PBIAS, RSR, SSQR).

✓ **Evaluation Method**: A comprehensive assessment of **Hydrological Similarity**, considering hydrograph shape characteristics beyond simple statistics.

Methods

PART 2 | Research Design for Computational Efficiency

✓ **Research Question**: "What is the optimal combination of simulation runs/iterations to obtain a stable parameter solution at a minimum computational cost?"

✓ **Methodology**: Fixed MNS as the objective function and compared 4 scenarios with varying numbers of runs.

Case	Number of Simulation Runs	Strategy
Cases 1-3	250, 500, 1,000 fixed	Fixed Volume Strategy
Case 4	**Initial 1,000 → Subsequent 500**	**Hybrid Strategy**

Methods

PART 3 | Research Design for Multi-Site Calibration

✓ **Research Question**: "How can multi-site, multi-variable data be effectively utilized to reflect a watershed's **Spatial Heterogeneity**?"

One-by-one Calibration Process

Step 1: Calibrate Headwater Sub-basins (All Run)
Independently calibrate upstream sub-basins and fix their optimal parameters.

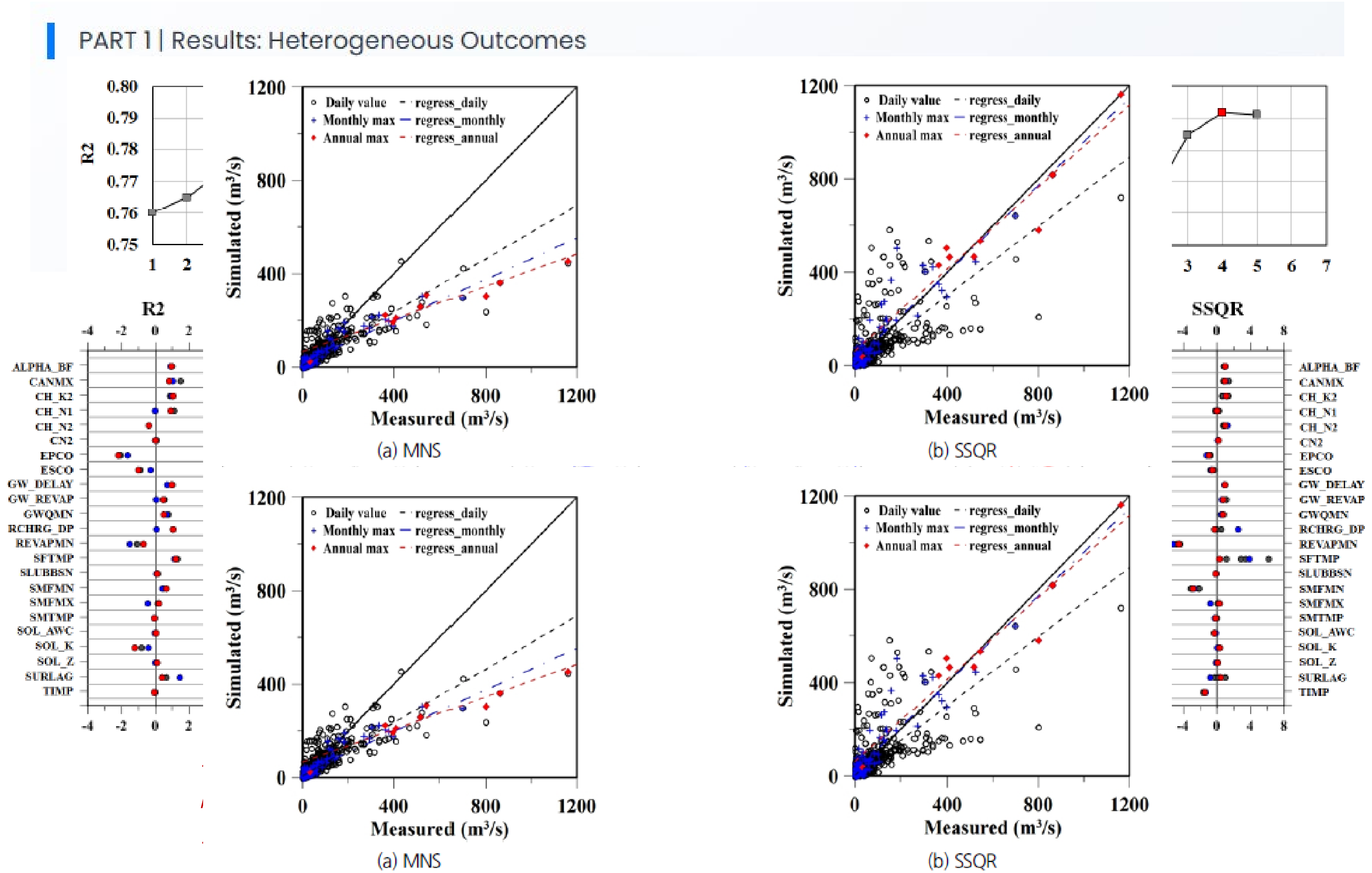
↓

Step 2: Calibrate Downstream Sub-basins (Partial Run)
With upstream parameters fixed, calibrate only the sub-basins affecting the next downstream gauge.

↓

Step 3: Repeat Process
Continue sequentially down to the final watershed outlet.

Results


PART 1 | Results: Heterogeneous Outcomes
R2
SSQR
Daily value
Monthly max
Annual max
regress_daily
regress_monthly
regress_annual
Simulated (m³/s)
Measured (m³/s)
(a) MNS
(b) SSQR
ALPHA_BF
CANMX
CH_K2
CH_N1
CH_N2
CN2
EPCO
ESCO
GW_DELAY
GW_REVAP
GWQMN
RCHRG_DP
REVAPMN
SFTMP
SLUBBSN
SMFMN
SMFMX
SMTMP
SOL_AWC
SOL_K
SOL_Z
SURLAG
TIMP

Results

PART 1 | Conclusion & Recommendations

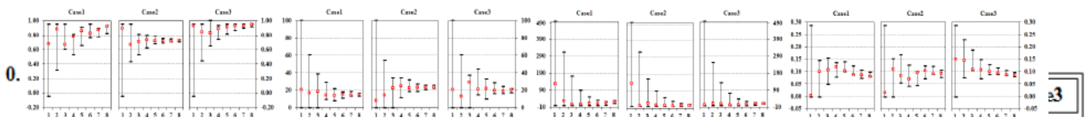
✓ **Conclusion**: The choice of objective function is a critical first step that directs the calibration outcome and must be made **strategically based on the analysis goal**.

✓ **Recommendations**:

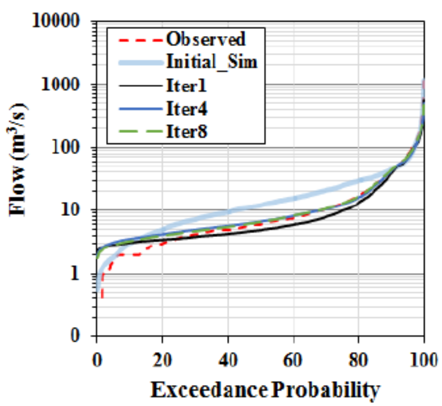
- ✓ **For long-term runoff & water balance → Recommend MNS**
- ✓ **For flood & extreme event analysis → Recommend SSQR**

Results

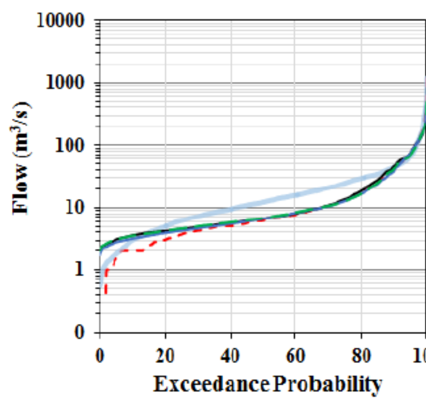
PART 2 | Results: Apparent vs. True Convergence



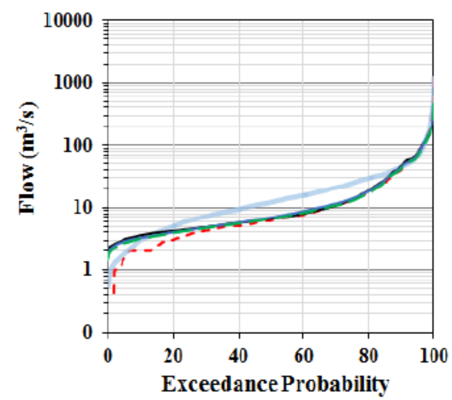
Cases		Case2			Case3			Case4		
# of sim. run		500			1,000			1,000	500	500
# of sim. iteration		1st	4th	8th	1st	4th	8th	1st	4th	8th
Obj. Func.	MNS	0.61	0.64	0.64	0.61	0.64	0.64	0.61	0.63	0.64
Uncertainty Index	p-factor	0.82	0.72	0.49	0.83	0.65	0.29	0.83	0.71	0.29
	r-factor	0.55	0.28	0.11	0.55	0.15	0.04	0.55	0.23	0.05



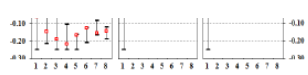
(a) Case2



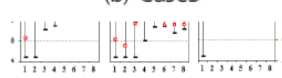
(b) Case3



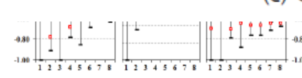
(c) Case4



(u) r_SOL_Z.sol



(v) a_SURLAG.bsn

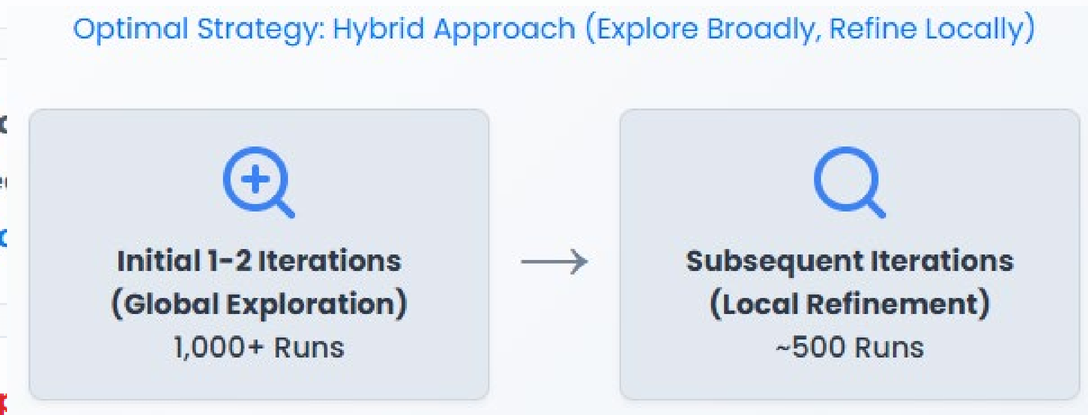


(w) a_TIMP.bsn

Results

PART 2 | Conclusion & Optimal Protocol

✓ **Key Finding**: A **sufficient number of initial runs (e.g., ≥1,000)** plays a **decisive role** in effectively exploring the wide parameter space (Global Exploration) to identify a stable pool of candidate solutions.



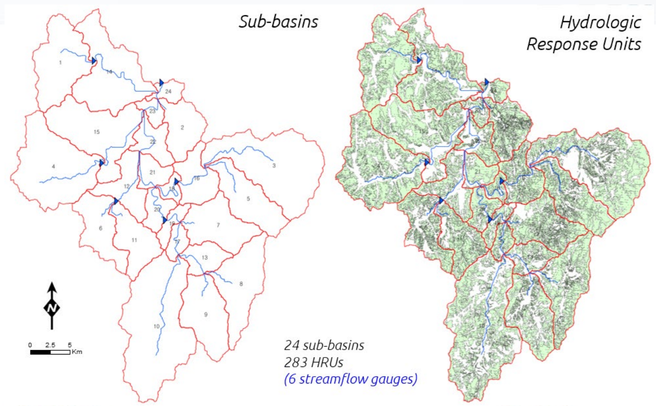
✓ **Efficienc** … oad, it achieve … oth **efficienc**

✓ **This imp … ctive function value alone.**

Results

PART 3 | Results: Superiority of Sequential Calibration

Model Performance Comparison at Watershed Outlet



0.85

Sequential

0.52

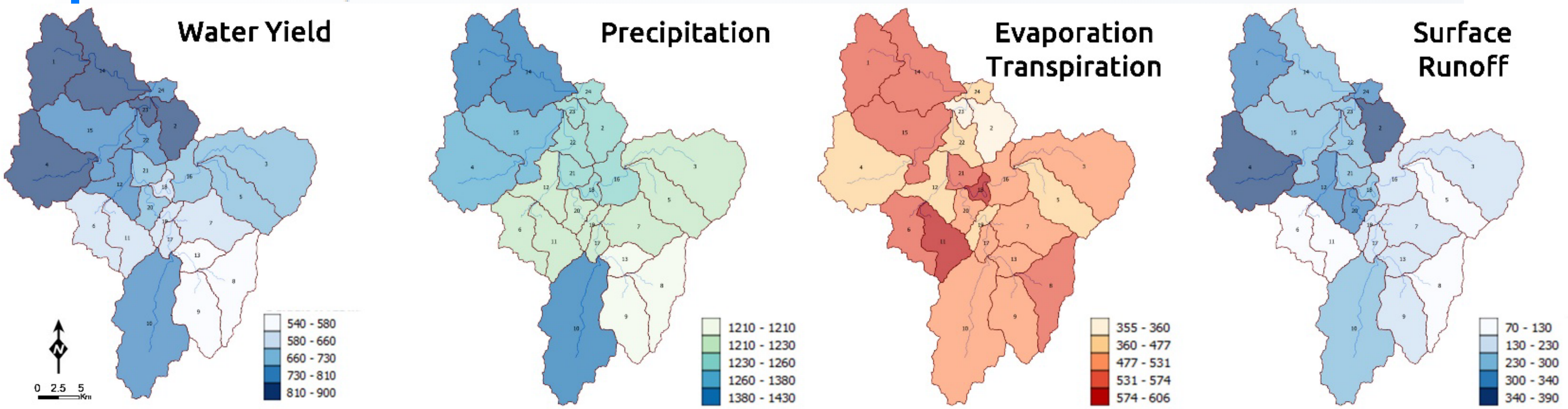
Lumped

Nash-Sutcliffe Efficiency (E_{NS})

Sequential calibration shows overwhelmingly superior performance by maximizing the model's **Physical Realism**.

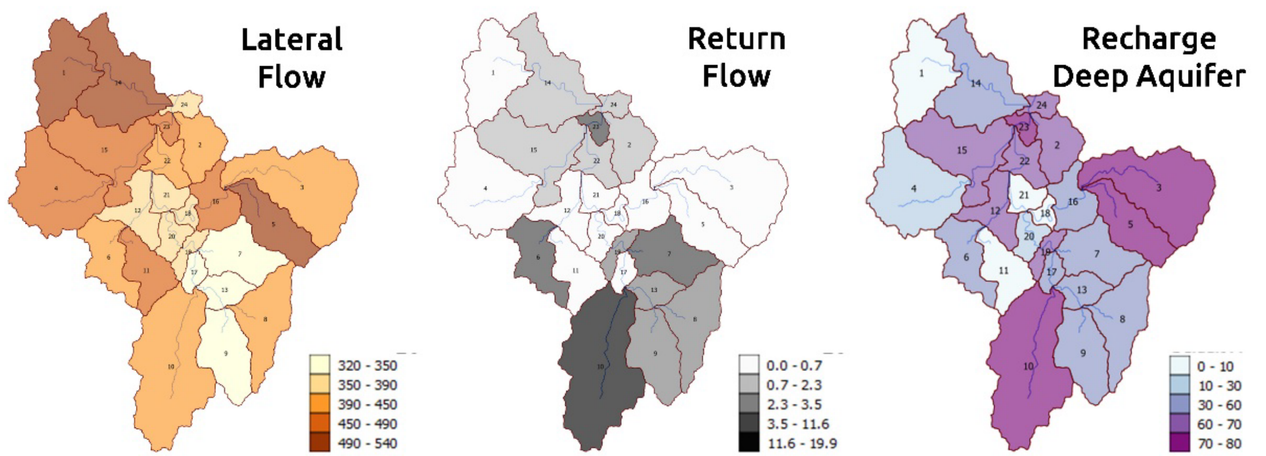
Results

PART 3 | Results: Significance & Limits of Multi-Variable Calibration



Water Yield =
Surface Runoff
+ Lateral Flow
+ Return Flow
+ Recharge to Deep Aquifer

Precipitation =
Evaportranspiration
+ Water Yield
+ Water in Shallow Aquifer



Results

PART 3 | Conclusion & Implications

- ✓ **Significance**: Using multi-variable data (soil moisture, ET) allows for a comprehensive validation of each **water balance component**, increasing calibration reliability.

- ✓ **Limitation**: A **Scale Mismatch** exists between point-scale observations (e.g., sensors) and area-scale simulations (sub-basin average).

- ✓ **Conclusion**: For watersheds with available multi-site data, the **Sequential Calibration method** provides statistically and physically superior results.

- ✓ **Implications**: To truly enhance the model's predictive power, an **advanced calibration strategy coupled with high-quality observation networks is essential**, as single-site calibration can misrepresent internal processes.

Conclusions

Final Conclusion | The Optimal SWAT Calibration Protocol

1

Strategic Objective Function

Prioritize **MNS** (for mean flow) or **SSQR** (for peak flow) based on the analysis goal.

2

Efficient Computational Runs

Apply the **Hybrid Strategy**: Initial global exploration (≥1,000) → Subsequent local refinement (~500).

3

Tailored Calibration Strategy

For multi-site data, use **Sequential Calibration** to reflect spatial heterogeneity.

Publications (KWRA)

Yu, J., J. Noh, and Y. Cho*, 2020. SWAT model calibration/validation using SWAT-CUP I: analysis for uncertainties of objective functions. Journal of Korea Water Resources Association, 53 (1), 45-56.

Yu, J., J. Noh, and Y. Cho*, 2020. SWAT model calibration/validation using SWAT-CUP II: analysis for uncertainties of simulation run/iteration number. Journal of Korea Water Resources Association, 53

(5), 347-356.

Cho, Y.*, 2020. SWAT model calibration/validation using SWAT-CUP III: multi-site and multi-variable model analysis. Journal of Korea Water Resources Association, 53 (12), 1143-1157.

Thanks for listening!