Understanding Catchment Hydrological Processes Under Non-Stationary Conditions

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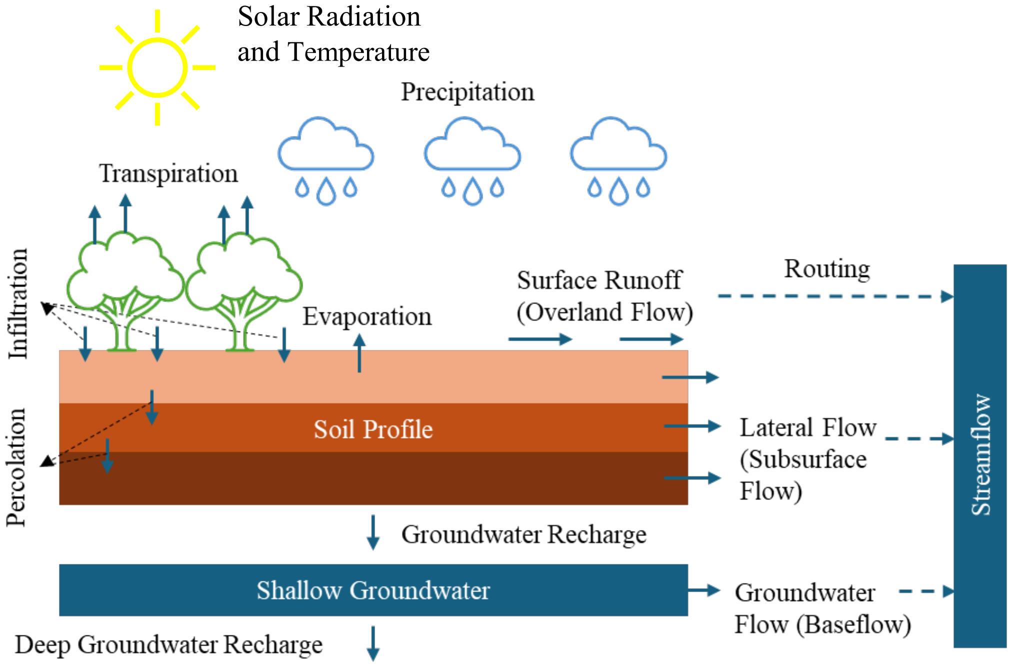
ONE BASIN CRC

THE UNIVERSITY OF SYDNEY

SWAT International Conference, Jeju-South Korea, June 2025

Introduction



Drought

Flooding

Urbanisation

Water
Supply

Agriculture

- **Processes that dynamically interact** over time
- **Support** ecosystem services, agricultural needs, and water supply

- Catchment systems are under pressures (Kimbi et al., 2024)
- Climate change and human intervention could alter catchment behaviour (IPCC, 2019; Bronstert et al., 2002)
- **Non-stationary conditions** continue to reshape catchment processes

Challenge of Non-Stationarity

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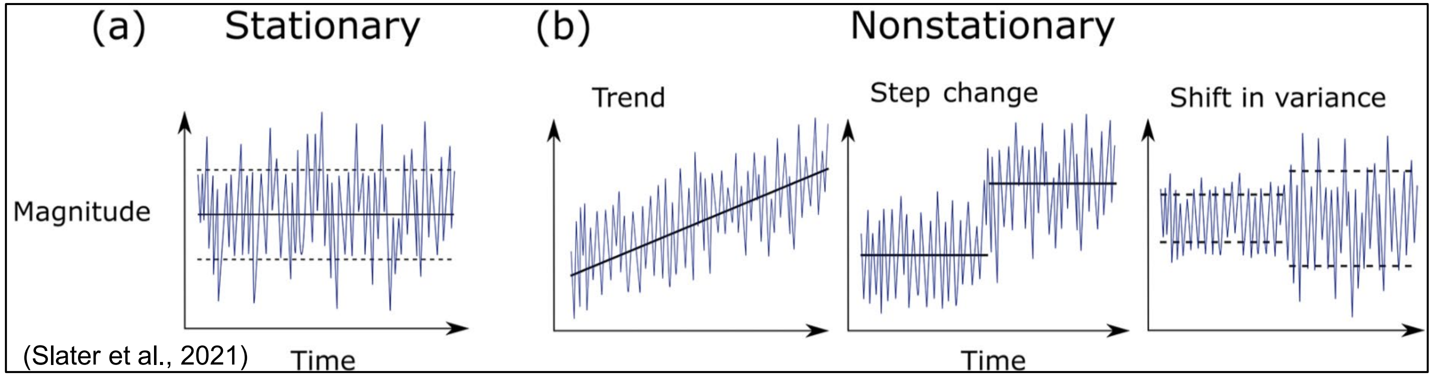

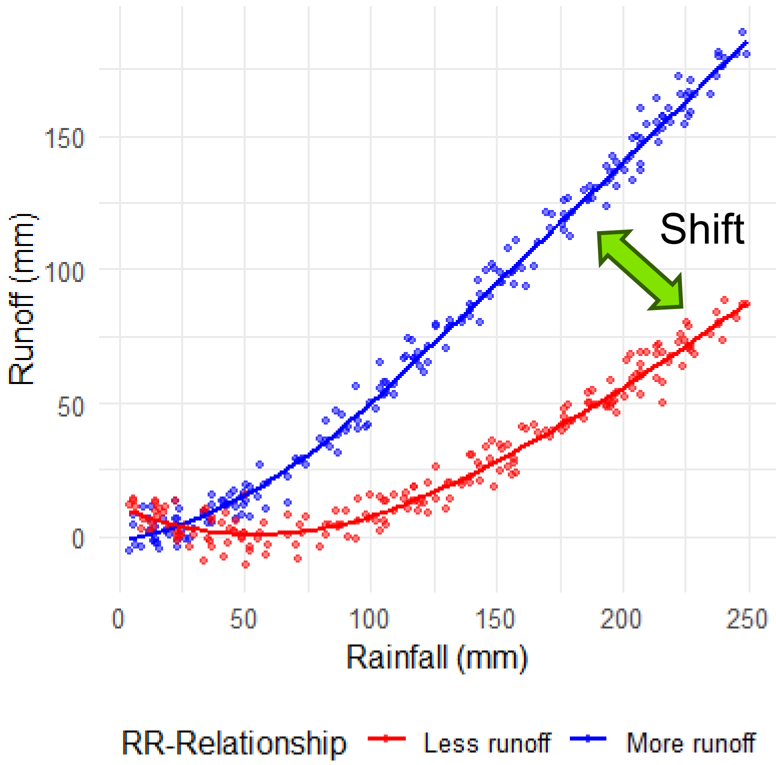

- Non-stationarity indicates **process changes** driven by significant shift in rainfall-runoff relationship (e.g., post Millenium drought) (Saft et al., 2015)
- Hydrological models tend to **underperform** under varying climate conditions, especially in dry condition (Vaze et al., 2010; Coron et al., 2012; Fowler et al., 2016)
- Various methods proposed, but **not fully resolve** the issue:
  - Machine learning → no physical meaning
  - Parameters equifinality and uncertainty issues

Gaps → Limited understanding of future climate impact on water balance → Streamflow focus overlooks internal process changes → Spatially distributed models underexplored in non-stationarity → No method links model to process shift

Research Aim and Objectives

Main Aim:

Investigate how catchment hydrological processes respond to non-stationary conditions using a more process-based spatial hydrological model (SWAT+ model)

Objectives:

1. Identify dominant hydrological processes in the catchment
2. Understand how these processes shift under varying climatic conditions
3. Evaluate the extent to which model simulations reflect these changes by using parameter sensitivity analysis

Study Area

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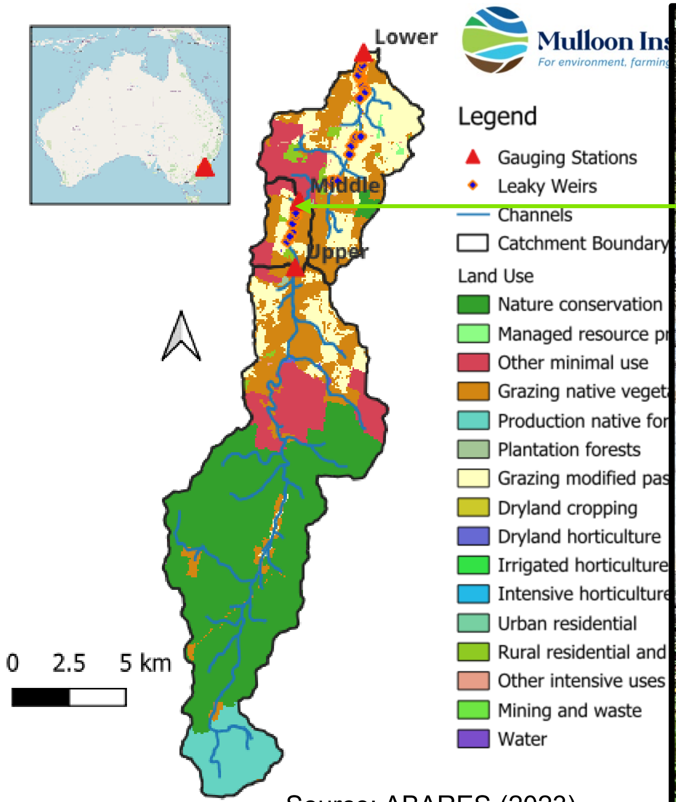
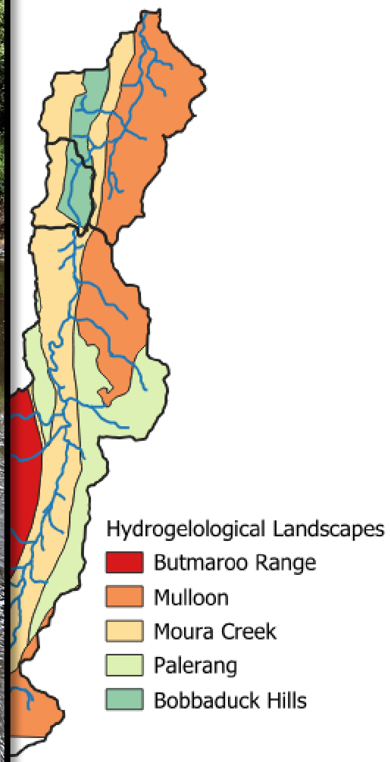


Source: ABARES (2023)

Typical Leaky Weir



Land Use:
60% Forest *(Nature and Conservation)*
35% Grasslands *(Native and Modified)*
5% Others *(Horticulture and Residential)*

Soil Types *(USDA Soil Taxonomy):*
53% Entisols with Sandy clay loam texture
44% Alfisols with Sandy clay loam texture
3% Others

Hydrogeological Landscapes:
Significant lateral subsurface flow
Limited surface runoff → intense rainfall
Groundwater fluctuates seasonally

Source: NSW DCCEEW (2016)

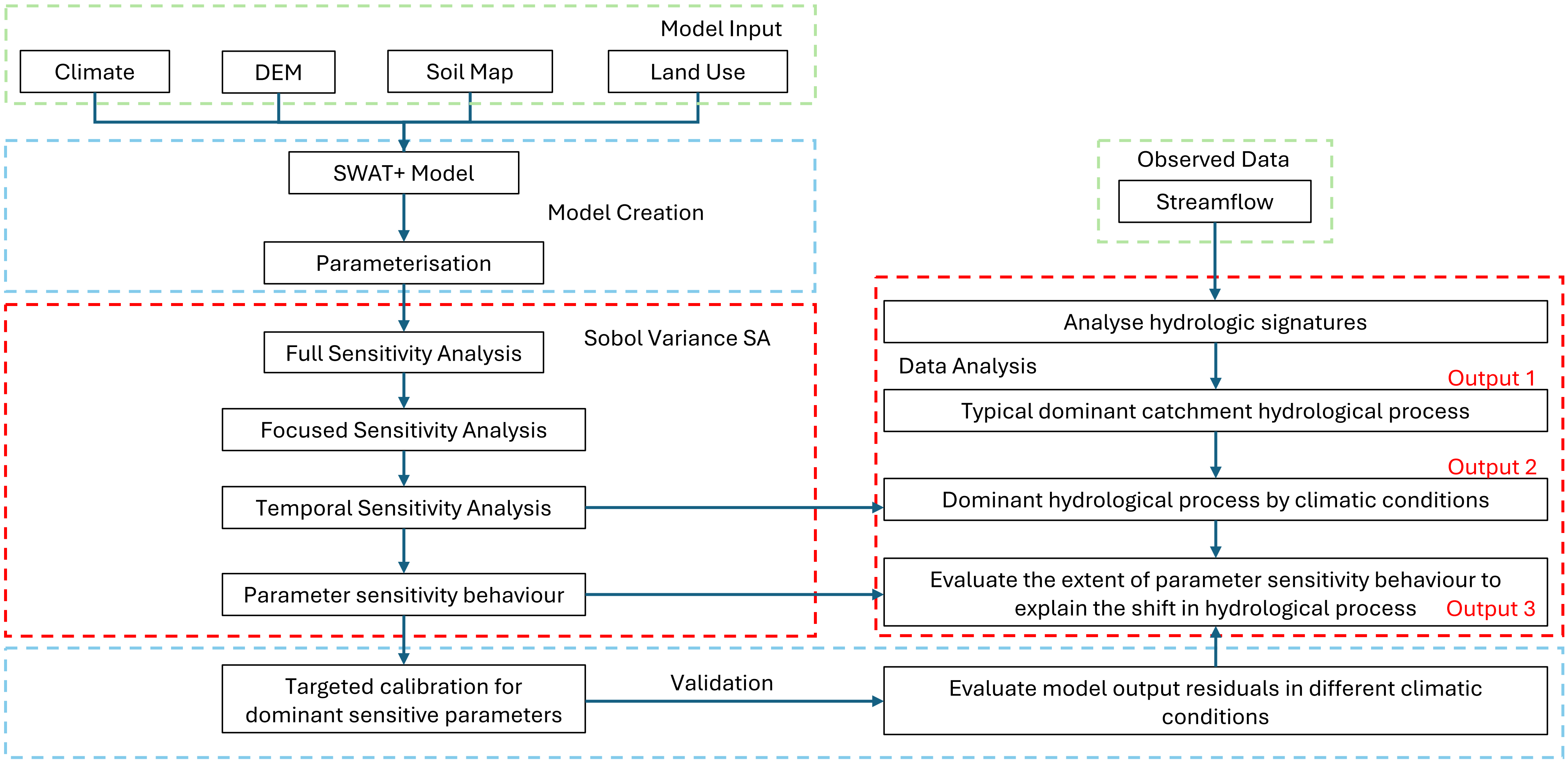
Catchment Properties:
- Temperate climate with a mild summer
- Annual average precipitation: 800 mm
- Elevation: 700-1345 m
- Total area: 15,689 ha

Meaning:
Moderately high infiltration rate → lateral flow *(Alfisols—Forest and upslope)*
Floodplain soil allow for lateral flow pathways *(Entisols—Grasslands and Floodplain)*

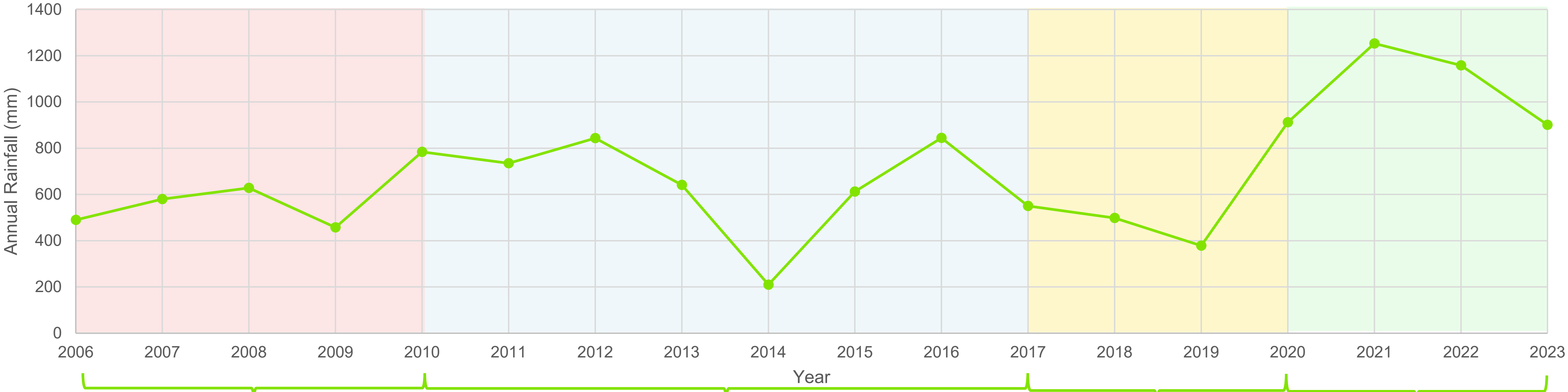
Hypothesis of Hydrological States

No.	State	Description	Catchment memory	Runoff generation	Dominant Process(es)
1	Dry w/ baseflow	Dominant baseflow maintains streamflow; lateral flow is minimal due to low soil moisture and unsaturated subsurface layers.	High, slow water release	Minimal	Baseflow
2	Dry w/o baseflow	No or negligible streamflow; lateral flow and baseflow are inactive due to dry conditions and low storage.	Weak or exhausted—reduced storage	Minimal	Quickflow (if any)
3	Wet w/ baseflow	Lateral flow dominates during storm events (peak flow) due to saturated soils; baseflow sustains inter-event streamflow	Strong—storage supports both fast and slow flow components.	Saturation excess	Quickflow and Baseflow
4	Wet w/o baseflow	Streamflow is event-driven; baseflow is disconnected or minimal. Lateral/surface flow dominates with quick hydrograph rise.	Limited—wetting is recent or shallow; deeper connectivity is not established	Predominantly saturation excess	Quickflow

Methodology



Climate Periods



Millenium Drought

Post-Millenium

Tinderbox Drought

Post-Tinderbox (Wet)

Source:
Millenium Drought (van Dijk et al., 2013; Peterson et al., 2021)

Drought Periods as the non-stationary conditions

Source:
Tinderbox Drought (Devanand et al., 2024; Falster et al., 2024)

Hydrological Signatures

Process Representation	Signatures	Description
Water partitioning (streamflow and loss)	TotalRR	Total runoff ratio
Catchment Storage	AverageStorage	Average storage derived from average baseflow and storage-discharge relationship
Baseflow	BFI	Baseflow derived from separation method divided by total streamflow
Baseflow recession	BaseflowRecessionK	Exponential constant fitted to master recession curve (MRC)
Infiltration Excess Flow (Horton)	IE_Effect	IE Importance
	IE_Thresh	Threshold to allow IE
	IE_Thresh_Sig	IE significance test
Saturation Excess Flow (Dunne)	SE_Effect	SE Importance
	SE_Thresh	Threshold to allow SE (amount of rainfall)
	SE_Thresh_Sig	SE significance test
Storage Depth in relation to runoff generation	Storage_Thresh	Storage depth needed to produce quickflow
	Storage_Thresh_Sig	Storage depth significance test

- Hydrological signatures as representation of actual catchment processes (McMillan et al. 2022)
- Toolbox for Streamflow Signatures in Hydrology in MATLAB (TOSSH; Gnann et al., 2021)

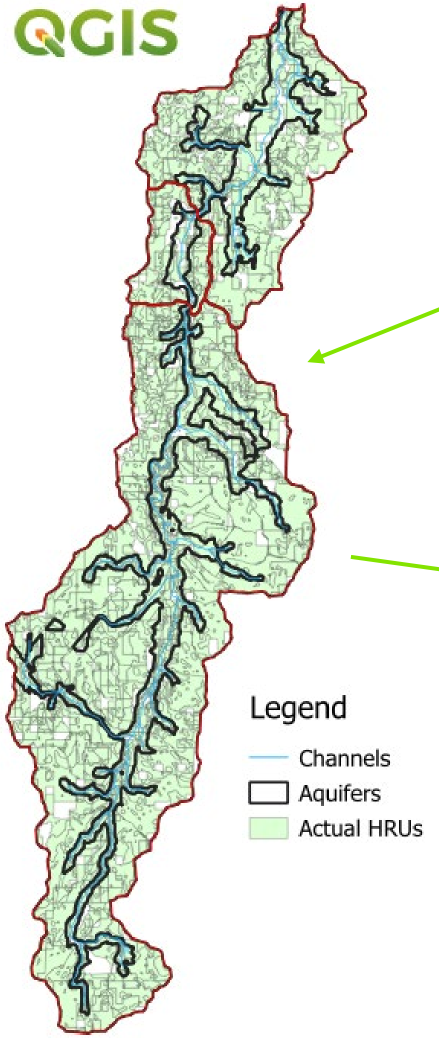
- TotalRR (*ET, GW Recharge, and Streamflow*)
- BFI and RecessionK (*GW flow*)
- IE, SE, Storage (*Quickflow*)

- Overall dataset (2007-2023) helped to identify dominant catchment behaviour → **Output 1**
- Signatures by climate period→ **Output 2**

SWAT+: Model Setup

- Model was built using QSWAT+ version 3.00 (SWAT model extension in QGIS)
- The model simulation in RStudio using the R package **SWATrunR** (Schürz, 2023, version 0.9.4)
- Slope classification: 0-8%, 8-30%, >30% (FAO, 1976)
- Limit Hydrologic response units (HRUs) with **15%** threshold (land use and soil type)
- Set stocking grazing → when aboveground biomass exceeds **2000 kg/ha** (typical Australian practice)
- Analysis performed using High Performance Computer (HPC-GADI)
- As a result: **882 HRUs** and **149 LSUs**

QGIS



SWAT Soil & Water Assessment Tool

SWATrunR

THE UNIVERSITY OF SYDNEY
Sydney Informatics Hub

NCI AUSTRALIA

SWAT: Parameterisation

SWAT+ Parameters	Change	Range
cn2.hru	Percent change	±50%
cn3_swf.hru	Absolute change	±0.5
esco.hru	Absolute value	0-1
epco.hru	Absolute value	0-1
perco.hru	Absolute change	±0.5
surlag.bsn	Absolute value	0.05 - 24
awc.sol	Percent change	±80%
k.sol	Percent change	±80%
z.sol	Percent change	±50%
bd.sol	Percent change	±50%
alpha.aqu	Absolute value	0-1
flo_min.aqu	Absolute change	±50%
bf_max.aqu	Percent change	±50%
revap_co.aqu	Absolute value	0.02-0.2
deep_seep.aqu	Absolute value	0.001-0.4
chk.rte	Percent change	±50%
chw.rte	Percent change	±50%
chd.rte	Percent change	±50%
canmx.hru	Percent change	±50%

- Selected parameters represent hydrological process
- Parameters were spatially-defined based on dominant land use or sub-catchments

$$\boxed{Q_{out} = Q_{surf} + Q_{lat} + Q_{gw} - T_{loss}}$$

WB component → SWAT+ parameter:
ET → esco, epco
(Qsurf) Surface runoff → cn2, cn3_swf, surlag, ovn
(Qlat) Lateral flow → latq_co, **awc**, **bd**, **z**, k
(Qgw) Gw flow → perco, alpha, flo_min, revap_co, deep_seep, **awc**, **bd, z**
Routing → chk, chd, chw, chn

Sensitivity Analysis: Sobol Method

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Why?

Quantifies process influence

Climate-responsive

Global coverage

Semi-agnostic parameter value

$$V(Y) = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots + V_{1,2,\ldots,d}$$

Where:
V(Y) is the total variance of the model output/metric
V_i is the variance contribution of individual input X_i
V_{ij} represents the interaction effects between inputs X_i and X_j
Higher-order terms account for multi-variable interactions

$$S_i = \frac{V_i}{V(Y)}$$

The **first-order Sobol index** (S_i) measures the direct effect of X_i on output

$$S_{Ti} = \frac{V_i + \sum_j V_{ij} + \ldots}{V(Y)}$$

The **total Sobol index** (S_{Ti}) accounts for both direct and interaction effects

Practical Insight

- If **Si ≈ Ti**, works independently (no strong interactions)
- If **Si is small** but **Ti is large**, important due to interaction
- If **both Si** and **Ti are small**, minimum influence

- Sensobol R Package (Puy et al., 2022)
- First and Total order indices were calculated using Jansen method (Jansen, 1999)
- We assume that **high Si or Ti** mean that the parameter/hydrological process is **dominant**

Full SA (n = 7,500) → Focused SA (n = 13,500) → Temporal SA (n = 13,500) → Output 3

Time-varying sensitivity index (model output at time i)

Sensitivity Analysis Flow

Metrics: NSE, KGE, Refined Index of Agreement

Result: Dominant Hydrological Process

Hydrologic Signature	Value			Unit
	Upper	Middle	Lower	
TotalRR	0.21	**0.28**	0.20	-
BFI	0.46	0.45	**0.32**	-
BaseflowRecession K	0.17	**0.08**	0.16	-
AverageStorage	122.67	100.07	**67.01**	mm
IE_effect	-0.12	-0.13	-0.23	-
IE_thresh	13.56	15.24	**9.95**	mm
IE_thresh_sig	0.00	0.00	0.01	p-value
SE_effect	**0.80**	0.95	0.98	-
SE_thresh	66.98	63.46	**22.04**	mm
SE_thresh_sig	0.00	0.00	0.00	p-value
Storage_thresh	49.71	50.35	**30.97**	mm
Storage_thresh_sig	0.00	0.00	0.00	p-value

Key insights

- **ET & deep loss dominate**:
  only 20-28% of rainfall becomes streamflow
- **Moderate baseflow contribution**:
  slow flow contributes around 32-46%
- **Indication of Leaky Weir effect**:
  slower recession in mid-catchment
- **Storage pattern**:
  Highest in upper (forest)
- **High infiltration**:
  no significant IE observed
- **Dominant SE**:
  higher threshold indicate good water retention capacity
- SE process → **lateral subsurface flow**

Result: Dominant process by climate conditions

Period	SE_thresh	SE_thresh_sig	TotalRR	BFI	AverageStorage	RecessionK
Millenium Drought	54.93	0.00	0.04	0.57	5.09	#N/A
Post-Millenium	135.50	0.00	0.27	0.63	109.23	0.06
Tinderbox Drought	34.71	0.00	0.02	0.40	53.14	0.20
Post-Tinderbox	21.58	0.00	0.31	0.33	90.80	0.15

Bushfire in January 2020

Saturation Excess (SE) Dominates:

- Higher SE threshold in wet periods indicate better soil moisture retention
- Lower thresholds during droughts suggest reduced storage
- Lower post-Tinderbox, likely due to bushfire-induced soil degradation

Higher storage & flow in wet periods:

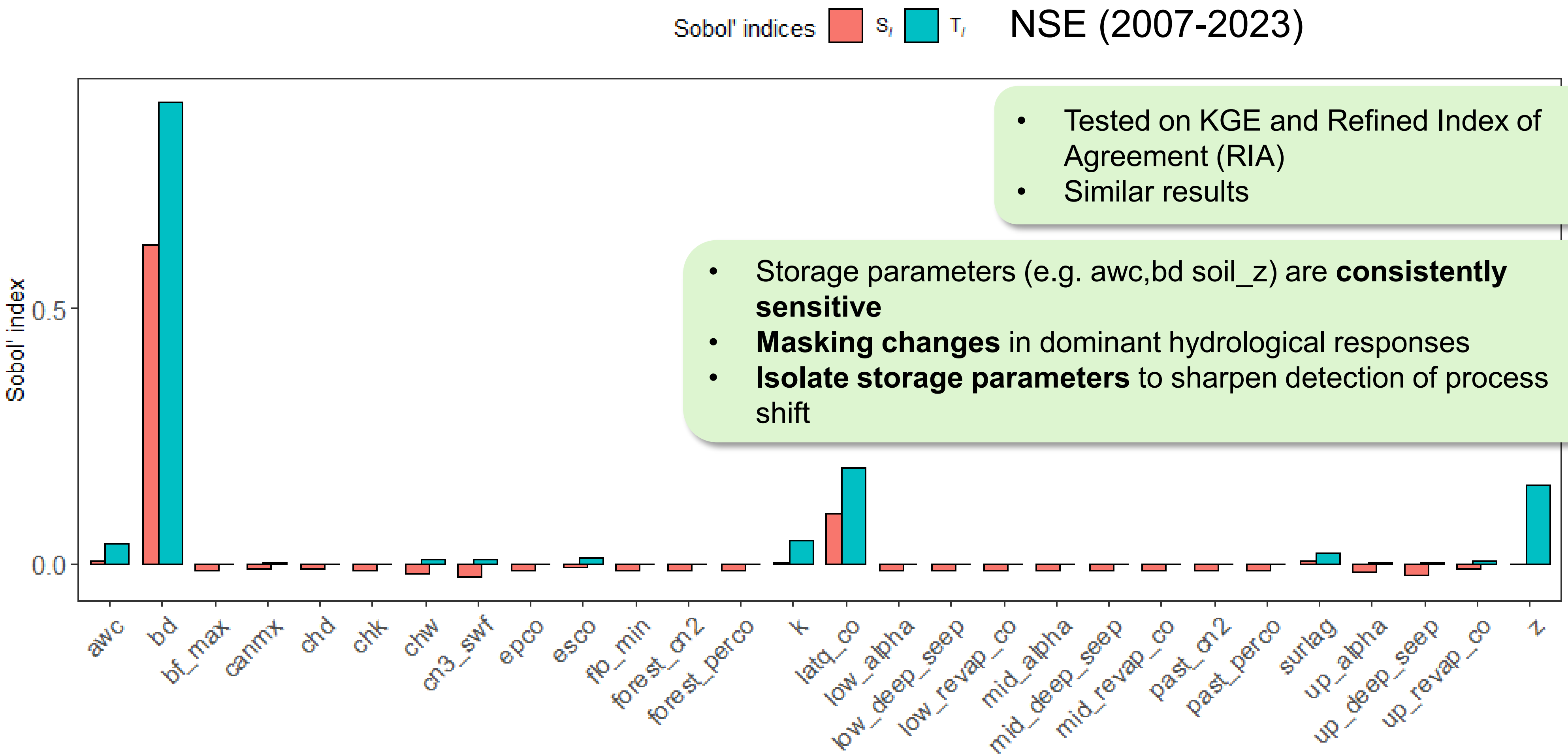
- TotalRR and AverageStorage are greater in wetter conditions
- Lower recession values indicate slower recession, meaning water stays linger in the system

Interpretation:

Catchment hydrology is **strongly climate-sensitive** (changing), catchment ability to store water is less in drought and post-droughts show recovery

Result: Full SA

NSE (2007-2023)

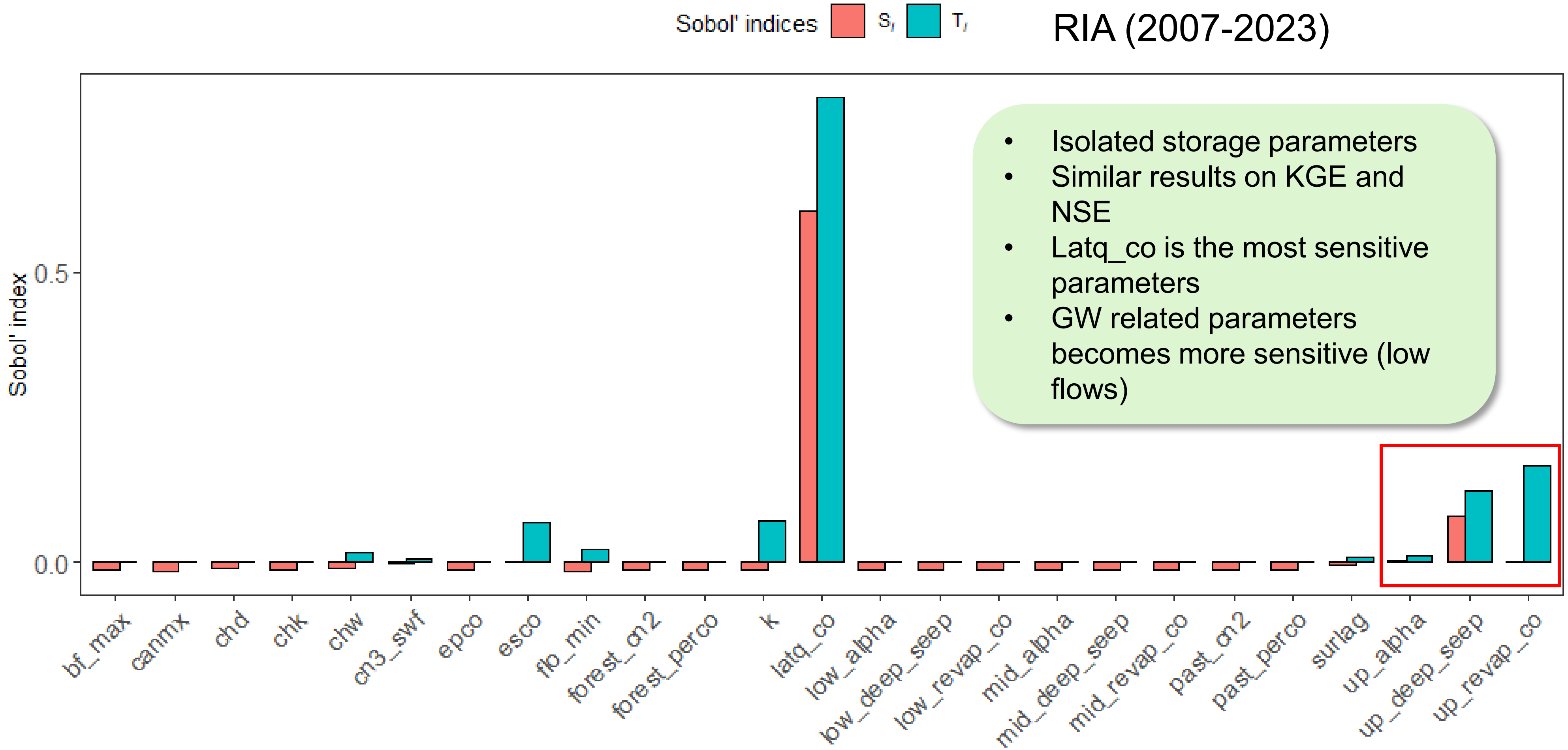


- Tested on KGE and Refined Index of Agreement (RIA)
- Similar results

- Storage parameters (e.g. awc,bd soil_z) are **consistently sensitive**
- **Masking changes** in dominant hydrological responses
- **Isolate storage parameters** to sharpen detection of process shift

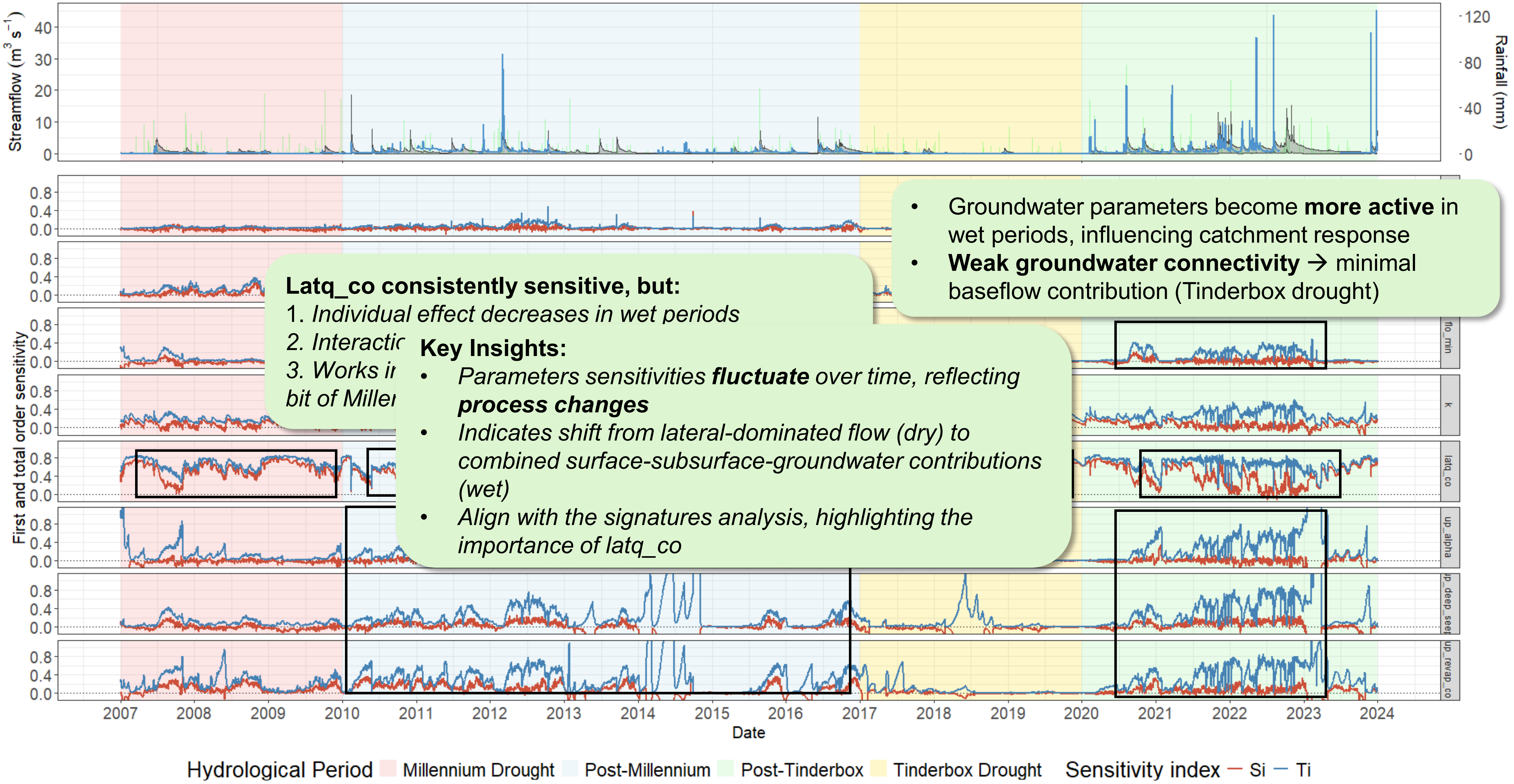
Result: Focused SA

RIA (2007-2023)



- Isolated storage parameters
- Similar results on KGE and NSE
- Latq_co is the most sensitive parameters
- GW related parameters becomes more sensitive (low flows)

Temporal SA: Upper Catchment



Latq_co consistently sensitive, but:

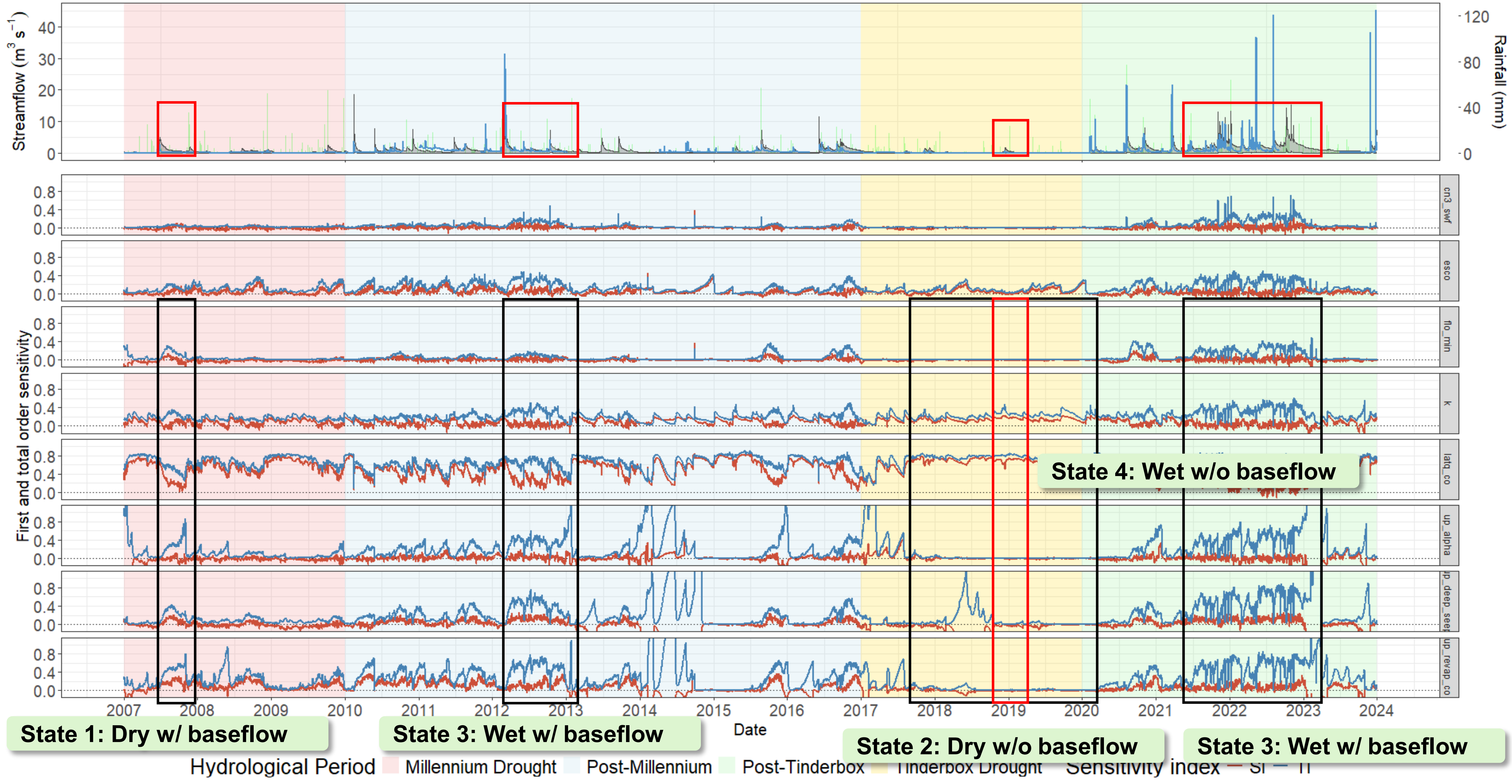
1. *Individual effect decreases in wet periods*
2. *Interactic*
3. *Works ir*

bit of Miller

Key Insights:

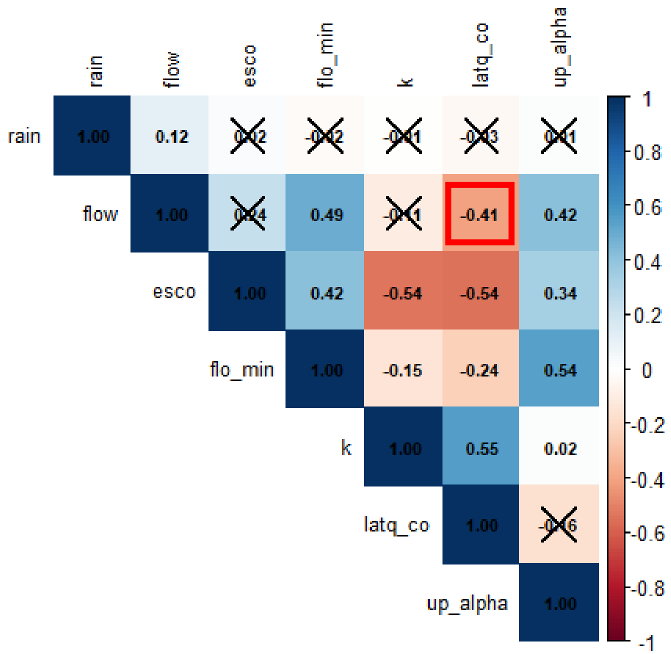
- *Parameters sensitivities **fluctuate** over time, reflecting **process changes***
- *Indicates shift from lateral-dominated flow (dry) to combined surface-subsurface-groundwater contributions (wet)*
- *Align with the signatures analysis, highlighting the importance of latq_co*

- Groundwater parameters become **more active** in wet periods, influencing catchment response
- **Weak groundwater connectivity** → minimal baseflow contribution (Tinderbox drought)

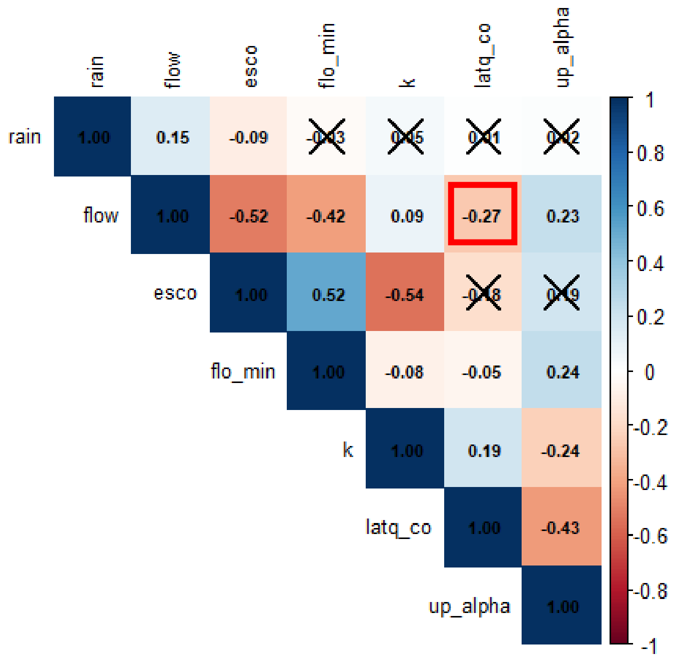


Temporal SA: Upper Catchment

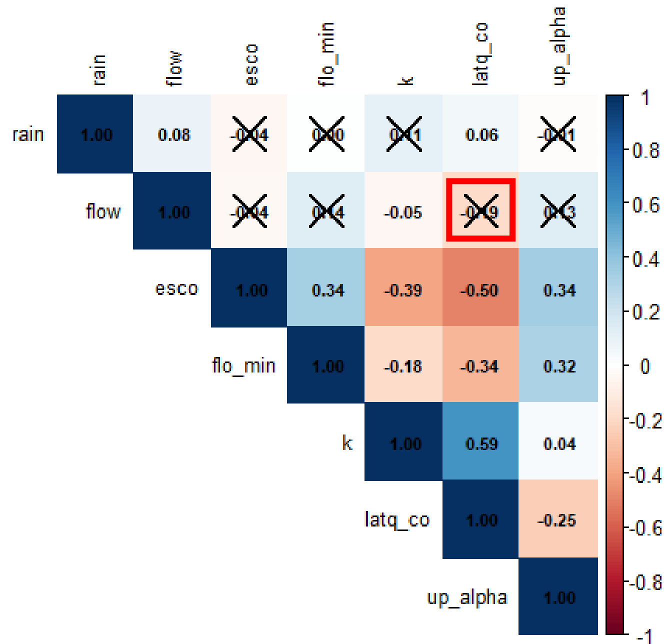
Millennium Drought



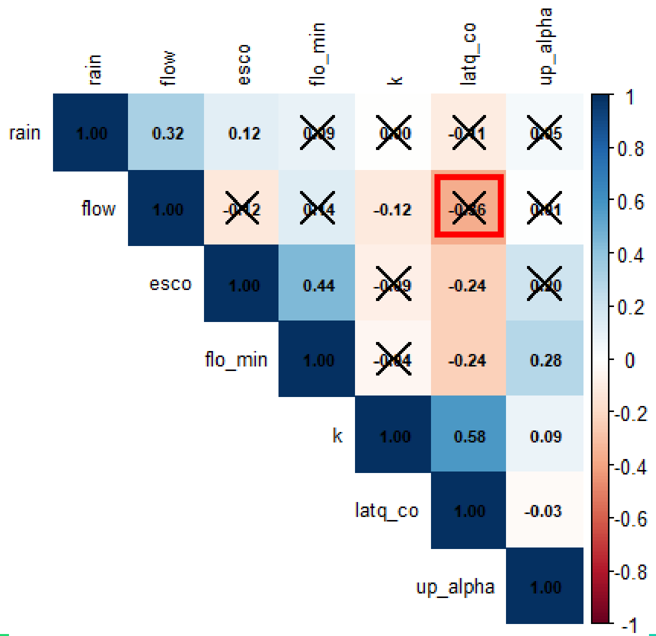
Tinderbox Drought



Post-Millennium Drought



Post-Tinderbox Drought



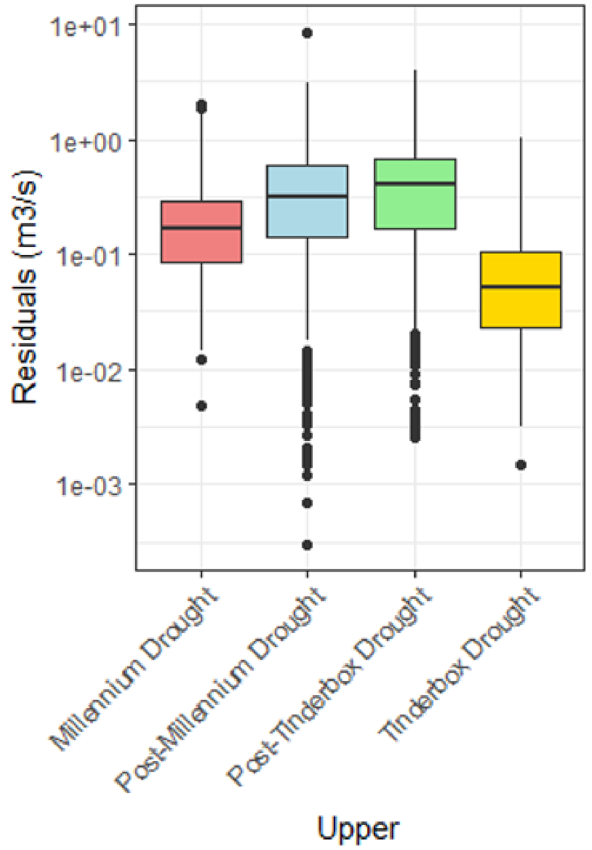
- **Spearman correlation** used to assess link between observed rainfall/streamflow and individual parameter sensitivities (Si index)
- **No significant correlation** found between **latq_co** and **streamflow** during **wet periods**
- **Confirms shift** from dominant lateral flow (dry) to multi-components flow processes (wet)
- Highlights **evolving role of hydrological drivers** under varying climatic conditions

Validation

period	mean	sd	median	min	max	var
Millennium Drought	0.238	0.275	0.168	-0.984	1.998	0.076
Post-Millennium Drought	-0.050	1.081	-0.013	-27.721	8.630	1.168
Post-Tinderbox Drought	-0.071	2.775	0.227	-38.436	3.988	7.700
Tinderbox Drought	0.103	0.169	0.048	-0.479	1.016	0.029

Simple Calibration Test

- Latin Hypercube Sampling (LHS) → 1,000 simulations
- Latq_co and k only, best parameter set based on KGE, PBIAS, and RIA
- Post-drought: latq_co shifts from individual (Si) to interaction effect (Ti)
- Higher variance in post-drought → other parameters/processes are needed to be calibrated
- Lateral flow alone is less dominant in wet conditions



Discussion & Conclusion

Key Findings
- Both methods (signatures and SA) confirm shift in catchment processes
- Change in hydrological processes depend on groundwater connectivity
- Signatures analysis alone can be misleading
- Temporal SA provides deeper insight into internal process shifts

Limitations
- Storage parameters heavily influence other parameters
- Parameter interactions should be explored under ample vs. limited storage scenarios
- True sensitivity may lie outside predefined parameters bounds
- Infrastructure impacts the analysis in mid and low sub-catchments (e.g., leaky weirs)

!

Implications
- SWAT assumes stationary soil properties, struggle to capture non-stationarity
- This result can be used as basis to select/develop model structure to better capture observed processes shift
- Representation of nature-based infrastructure in the model is needed

Mulloon Catchment by *Mulloon Institute*

Acknowledgement

This research is part of a PhD project funded by:

Richard Claude Mankin Scholarship

The University of Sydney

One Basin CRC

Thank you

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More info on the project:

Datasets

Data	Resolution	Source
DEM	30 m	Geoscience Australia
Land use	50 m	Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)
Soil map	250 m	DSOLmap and MapSWAT
Climate (rainfall, temperature, solar radiation, relative humidity, wind speed)	Daily	Mulloon Institute and SILO
Streamflow	Daily (three gauges)	Mulloon Institute

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