WSML Watershed Science & Modelling Laboratory

How regionalization and parameterization of a hydrologic model affect the cascade of uncertainty in climate-impact projections

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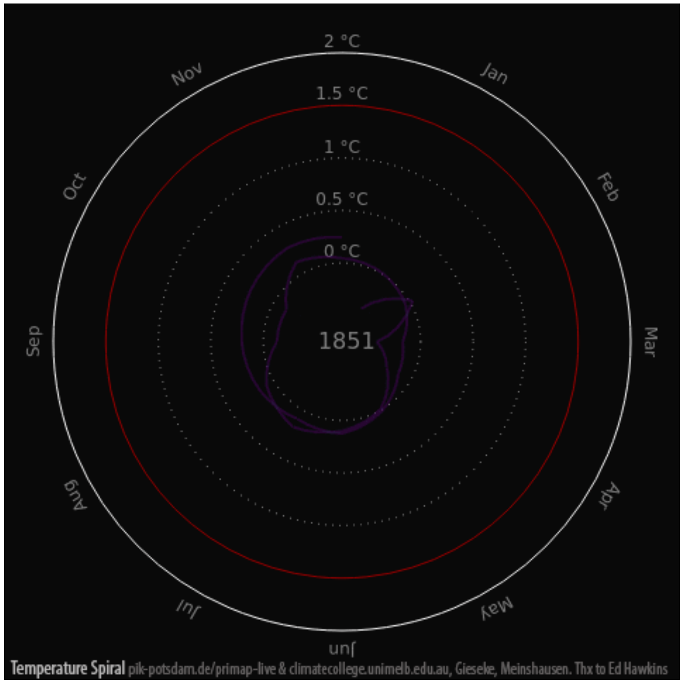
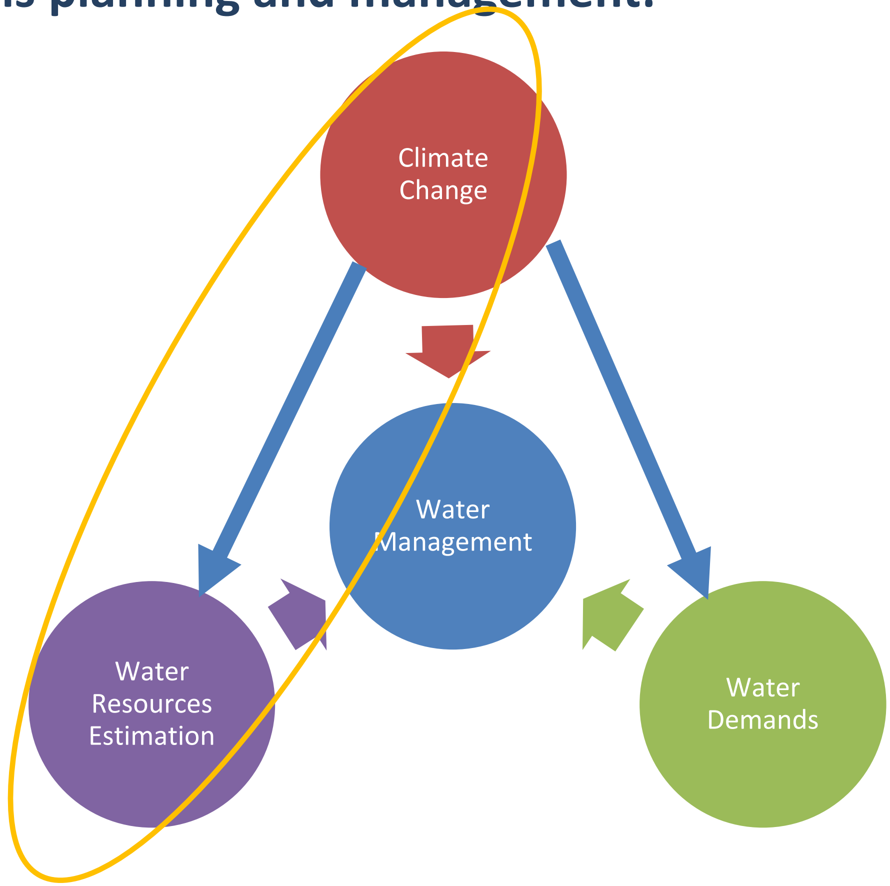
Where did the idea come from?

Integrated Water Resource Systems planning and management:



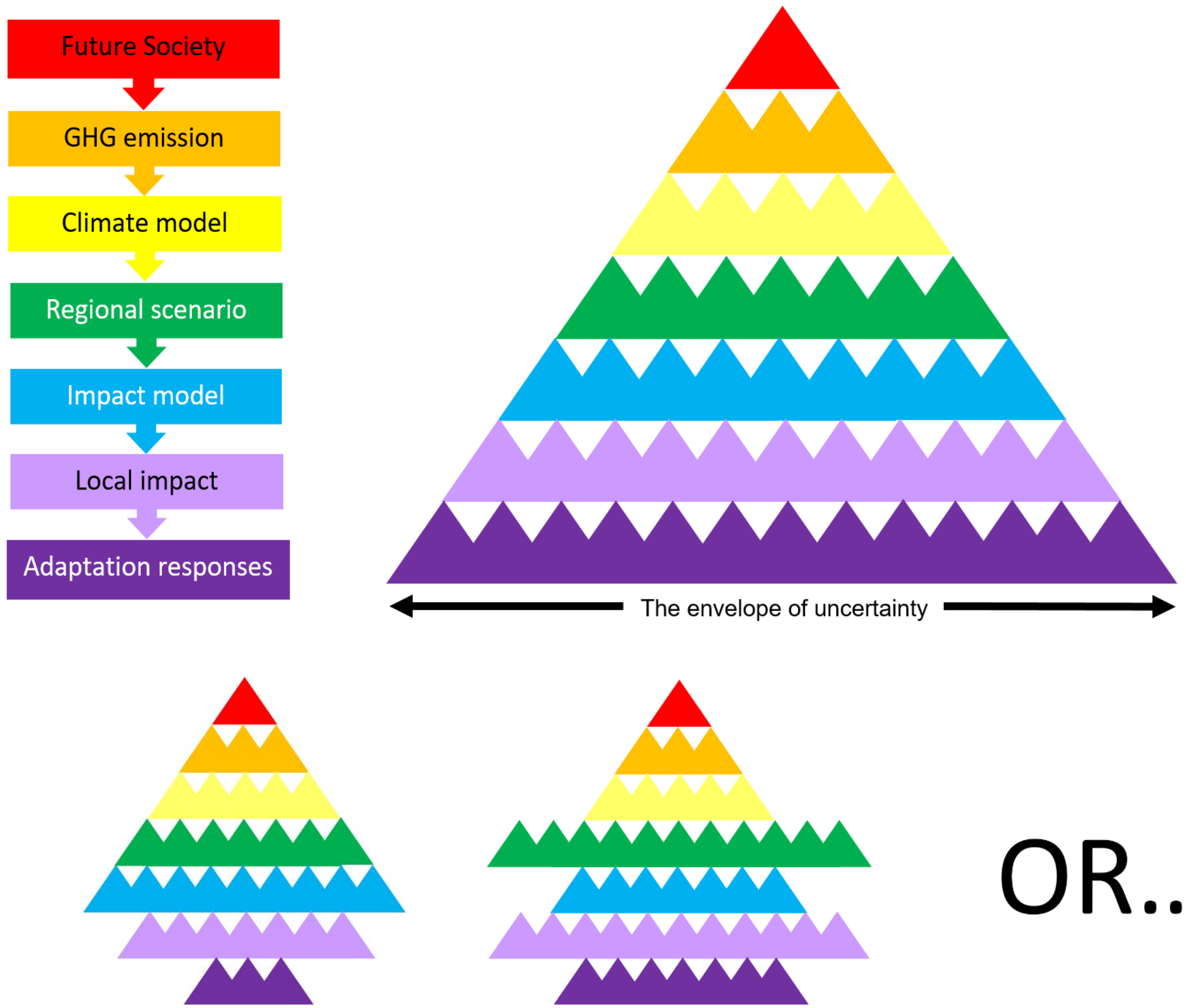
From 1880 to 2012, the average global temperature increased by 0.85 °C



We are facing a probabilistic problem instead of deterministic!

What are the uncertainty sources?

The Cascade of Uncertainty



(Wilby and Dessai 2010)

OR...

Literature Review

Uncertainty analysis in climate-impact projections

There are many methods for uncertainty estimation in climate-impact projections (i.e. recursive model and parameter identification methods, classical Bayesian approaches, methods based on frequentist statiscal inference, analysis of variance (ANOVA) and etc.);

Study	Sources of Uncertainty								Interaction of sources	Uncertainty Decomposition	Variables	Findings
	GCMs-S	GCMs-ic	GGES	SDS	DDS (RCM)	HM-S	HM-R	HM-P				Share of each uncertainty sources (major to minor)
Wilby and Harris (2006)	4		2	2		2		2	no	no	River low flow	GCM, DS, HM-P, GGES
Key et al. (2009)	5	3	1	1	8	2			no	no	Peak flow, Flood frequency	Case 1: GCM-ic, RCM, GCMs-S, HM-S, DS, GGES, HM_P Case 2: RCM, GGES, GCMs-S, GCMs-ic, DS, HM-P, HM-S
Prudhomme and Davies (2009)	3		2	1	3 (1)	2		10	no	no	River flow	GCM, DS, GGES, HM-P
Abbaspour et al. (2009)	1		3	1		1	506 Sub basin	400 to 500, 26 par	no	no	Precipitation, Temperature, BW, GWF & GWS	HM-P, HM-R , GGES
Chen et al. (2011)	6	5	2	4		3			no	no	Annual, seasonal, & peak River flow	GCMs, DS, GCM-ic, GGES, HM-S, HM-P
Pouline et al. (2011)						2	Yes	1000, 23, 12 par	no	no	River flow, Soil water, Snow water equivalent	HM-S, HM-P
Yip et al. (2011)	7	2	3						yes	yes	Temperature	2010-2055: GCMs-S, GGES, GCMs-ic, Interaction 2056-2100: GGES, GCMs-S, GCMs-ic, Interaction
Harding et al. (2012)	16		3	1		1			no	no	River flow, Precipitation, Temperature	GCM, GGES, SDS, HM-S

Study	Sources of Uncertainty								Interaction of sources	Uncertainty Decomposition	Variables	Findings
	GCMs-S	GCMs-ic	GGES	SDS	DDS (RCM)	HM-S	HM-R	HM-P				Share of each uncertainty sources (major to minor)
Bosshard et al. (2013)	8			2		2			yes	yes	Temperature, Precipitation, River flow	Summer and Fall: GCM Winter and Spring: HM-S and DS and GCMs
Vetter et al. (2015)	5		4			3			yes	yes	River flow (low, mean, high)	Case 1: GCMs, GGES, HM-S, Interaction Case 2: GCMs, HM-S, GGES, Interaction Case 3: GGES, GCMs, Interaction, HM-S
Hewitt et al. (2016)	7		4						yes	yes	Land-Ocean carbon fluxes	Case 1: 2010-2050: Case 1: 2050-2100: Case 2: 2010-2050: Case 2: 2050-2100: Case 3: 2010-2050: Case 3: 2050-2100:
Vetter et al. (2017)	5		4			9			yes	yes	River flow (low, mean, high)	GCMs, GGES, HM-S
Teklesadik et al. (2017)	4		4			9			no	no	River flow, ET (GWF)	GCMs-S, HM-S, GGES
This study	9		2	2	10	1	2255 Sub basin	1000, 31 par	yes	yes	Precipitation, mean temperature, BW, GWF	

Current situation, Gaps, and Our Contribution

1. There are many methods for uncertainty estimation in climate-impact projections (i.e. recursive model and parameter identification methods, classical Bayesian approaches, methods based on frequentist statiscal inference, analysis of variance (ANOVA) and etc.)
2. Using the ANOVA is comparatively recent and there is an increasing interest in using this approach for uncertainty decomposition
3. There is limited information on the effects of hydrologic model parameterization (HM-P) and regionalization (HM-R) scheme in the cascade of climate change uncertainty prediction, while the effects of hydrological model structure on overall uncertainty has been well considered in literature
4. There is a spatio-temporal variability on the order and share of different uncertainty sources.

Current situation, Gaps, and Our Contribution

Research questions:

1) How significant are the contribution of HM-P and HM-R in the overall climate-impact uncertainty chain?

2) How spatial and temporal variation of hydro-climate conditions could affect the uncertainty decomposition results?

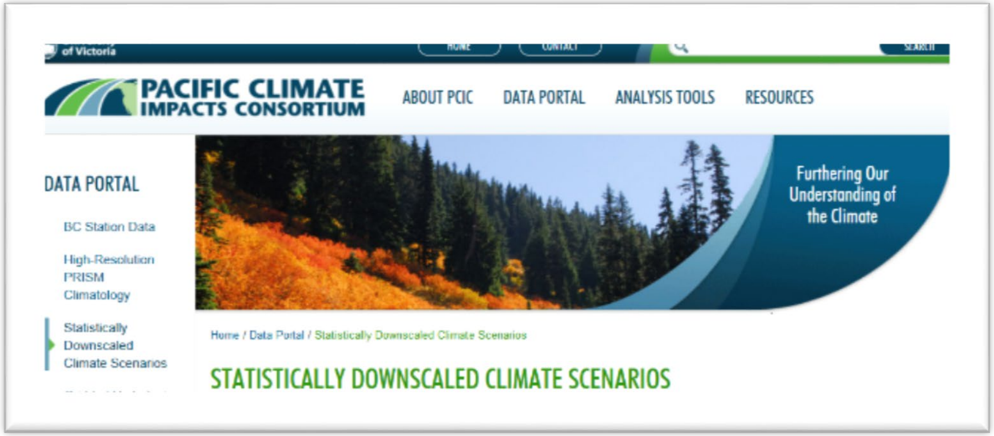
Big challenge:

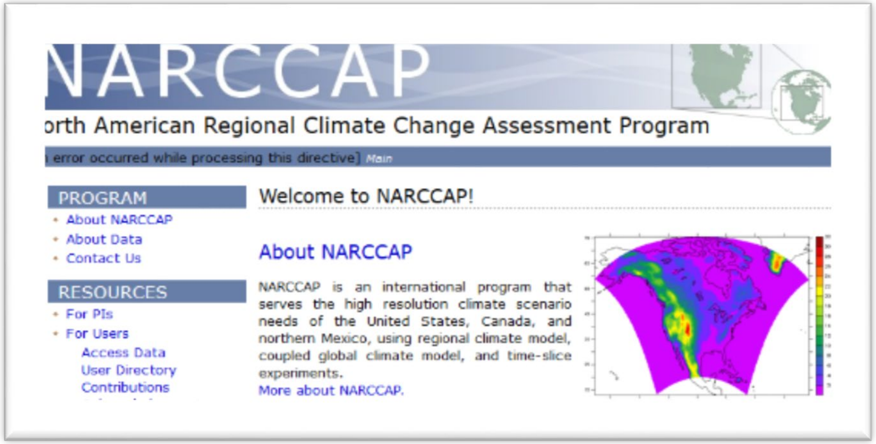
How to consider HM-R, HM-P uncertainty sources along with other sources?

Solution:

Coupling ANOVA and SUFI2 methods

Data





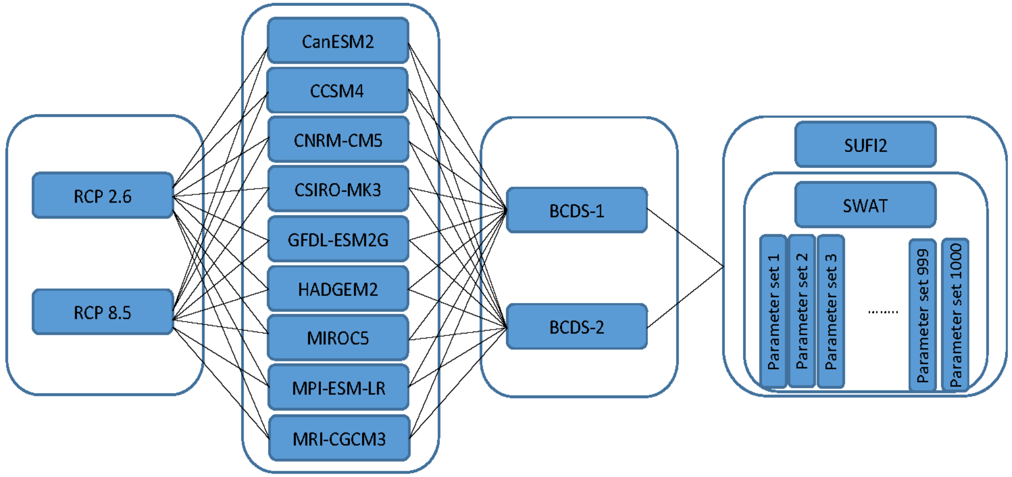
- **Climate data sources:**
  PCIC: 9 Global Climate Models
  NARCCAP: 10 Regional Climate Models

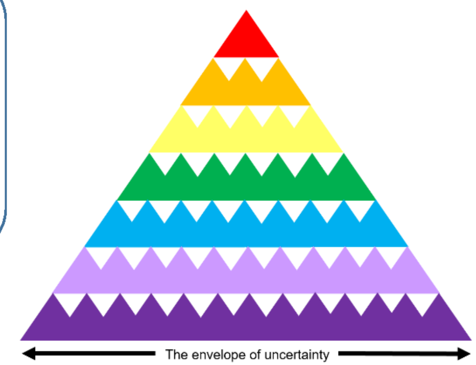
- **Representative Concentration Pathways:**
  1-Environmental friendly greenhouse gases scenario (RCP 2.6)
  2- Comparatively high greenhouse gas emissions (RCP 8.5)

- Future periods:
  2010-2035 (near future) and 2040-2065 (far future)

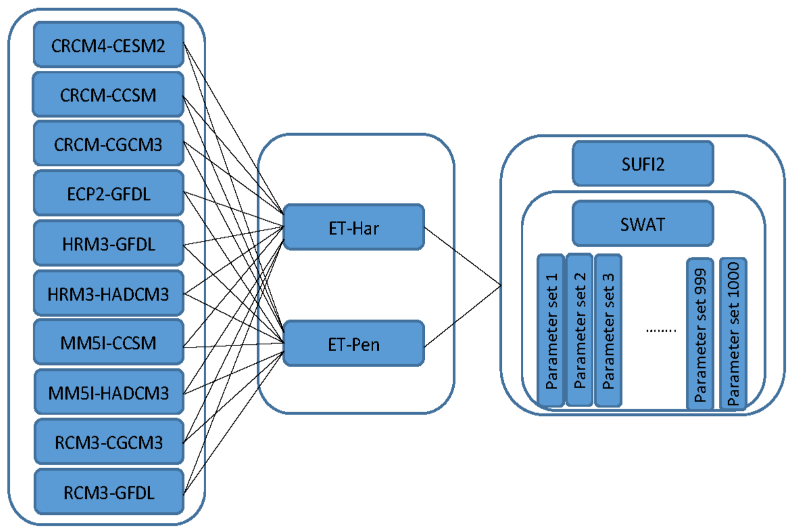
Methods

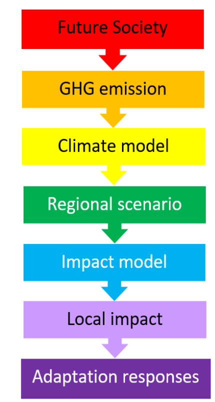
Framework-1





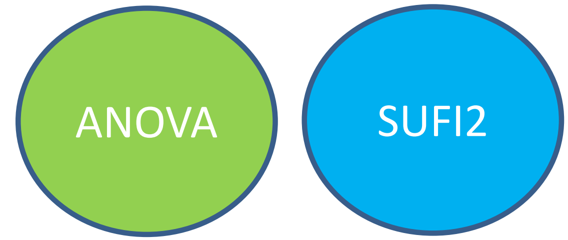
Framework-2





Framework-1

$$SST = \sum_{i=1}^{N_{RCP}} \sum_{j=1}^{N_{GCM}} \sum_{k=1}^{N_{BCSD}} \left(X_{ijk} - \bar{X}_{ooo}\right)^2$$



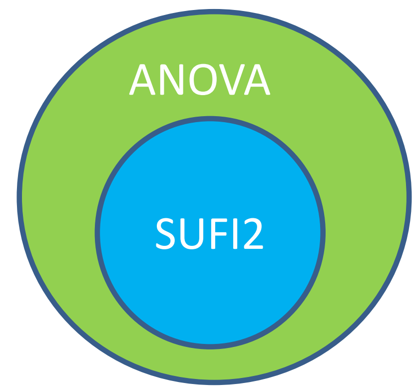
X_{ijk} is the value of hydro-climate variable X

$\bar{X}_{ooo}$ is the overall mean

Using 2.5, 50, and 97.5 quantiles out of 1000 SWAT runs

$$\boxed{SST = \sum_{i=1}^{N_{RCP}} \sum_{j=1}^{N_{GCM}} \sum_{k=1}^{N_{BCSD}} \left(QX_{ijk} - \overline{QX}_{ooo}\right)^2}$$

$Q_{2.5}, Q_{50}, Q_{97.5}$



$$SST = SS_{RCP} + SS_{GCM} + SS_{BCSD} + SSI$$

$$SSI = SS_{RCP*GCM} + SS_{RCP*BCSD} + SS_{GCM*BCSD} + SS_{RCP*GCM*BCSD}$$

$$SS_{GCM} = N_{RCP} N_{BCSD} \sum_{j=1}^{N_{GCM}} \left(\overline{QX}_{ojo} - \overline{QX}_{ooo}\right)^2$$

$$SS_{RCP} = N_{GCM} N_{BCSD} \sum_{i=1}^{N_{RCP}} (\overline{QX}_{ioo} - \overline{QX}_{ooo})^2$$

$$SS_{BCSD} = N_{RCP} N_{GCM} \sum_{k=1}^{N_{BCSD}} (\overline{QX}_{ook} - \overline{QX}_{ooo})^2$$

$$SSI = \sum_{i=1}^{N_{RCP}} \sum_{j=1}^{N_{GCM}} \sum_{k=1}^{N_{BCSD}} \left(QX_{ijk} - \overline{QX}_{ioo} - \overline{QX}_{ojo} - \overline{QX}_{ook} + 2\overline{QX}_{ooo}\right)^2$$

unequal population size of different sources (in our study: GCMs population size = 9, RCPs population size = 2 and bias correction-downscaling methods (BCSD) population size = 2)

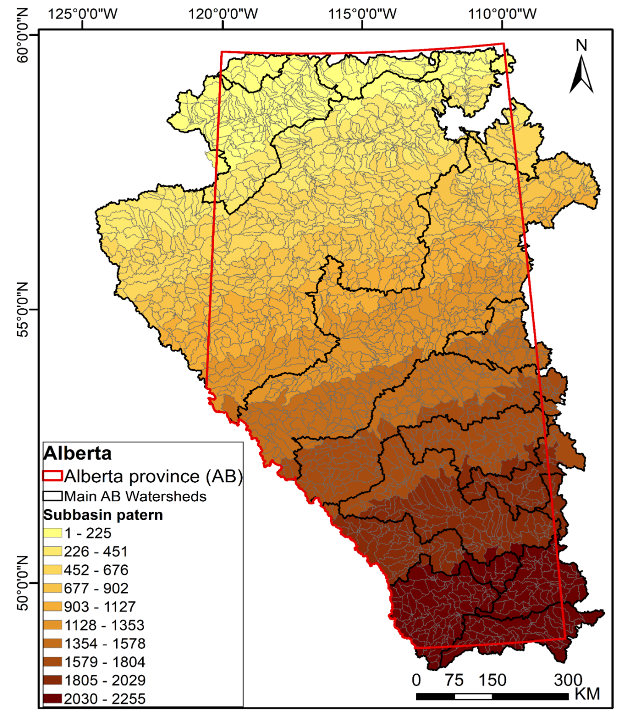
$$\eta_U^2 = \frac{1}{36} \sum_{m=1}^{36} \frac{SS_U(m)}{SST(m)}$$

$\eta^2_{RCP}, \eta^2_{GCM}, \eta^2_{BCDS}, \ \eta^2_{RCP*GCM}, \eta^2_{RCP*BCSD}, \eta^2_{GCM*BCSD}, \eta^2_{RCP*GCM*BCSD}$

Case Study:

- **Study area:** 2255 subbasins were delineated using SWAT with a 200 km^2 drainage area

- **Model calibration-validation (1983-2007):** at 129 hydrometric stations
  - Sensitive parameters: 33
  - Number of Parameters after parametrization and regionalization: 1400
  - Number of parameter Sets: 1000



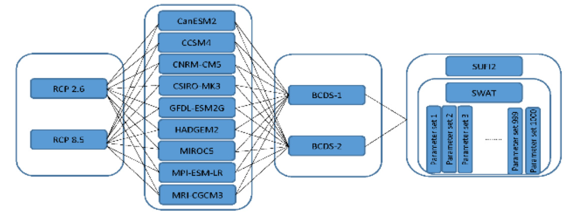
Reference:
Setting up a hydrological model of Alberta: Data discrimination analys prior to calibration, *Environmental Modelling & Software, 2015.*

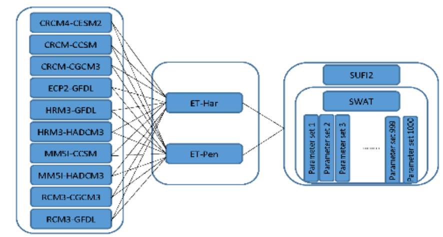
Hydrological Model Regionalization and Parameterization

Name of variables	Definitions
SURLAG.bsn	Surface runoff lag time (days)
SUB_SFTMP().sno	Snow fall temperature (ºC)
SUB_SMTMP().sno	Snowfall melt base temperature (ºC)
SUB_SMFMX().sno	Maximum melt rate for snow during the year (mm/ºC-day)
SUB_SMFMN().sno	Minimum melt rate for snow during the year (mm/ºC-day)
SUB_TIMP().sno	Snow pack temperature lag factor
CN2.mgt	SCS runoff curve number for moisture condition II
ALPHA_BF.gw	Base flow alpha factor (days)
REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)
GW_DELAY.gw	Groundwater delay time (days)
GW_REVAP.gw	Groundwater revap. coefficient
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
RCHRG_DP.gw	Deep aquifer percolation fraction
EPCO.hru	Plant uptake compensation factor
ESCO.hru	Soil evaporation compensation factor
SOL_AWC().sol	Soil available water storage capacity (mm H_2O/mm soil)
SOL_K().sol	Soil conductivity (mm/hr)
SOL_BD().sol	Soil bulk density (g/cm^3)
SOL_ALB().sol	Moist soil albedo
OV_N.hru	Manning's n value for overland flow
CH_N2.rte	Manning's n value for main channel
CH_K2.rte	Effective hydraulic conductivity in the main channel (mm/hr)
POT_FR.hru	Fraction of HRU area that drains into pothole.
POT_VOLX.hru	Maximum volume of water stored in the pothole (mm)
POT_VOL.hru	Initial volume of water stored in the pothole (mm)
TMPINC().sub	Daily temperature adjustment within a month (% change)
RFINC().sub	Daily rainfall adjustment within a month (% change)
AUTO_NSTRS.mgt	Nitrogen stress threshold that triggers fertilization
AUTO_EFF.mgt	Fretilizer application efficiency
AFRT_SURFACE.mgt	Fraction of fertilizer applied to top 10mm of soil
AUTO_WSTRS.mgt	Water stress threshold that triggers irrigation

- Sensitive parameters: 33
- Number of Parameters after Parametrization and regionalization: 1400
- Number of parameter Sets: 1000

Climatic-Hydrologic Scenarios





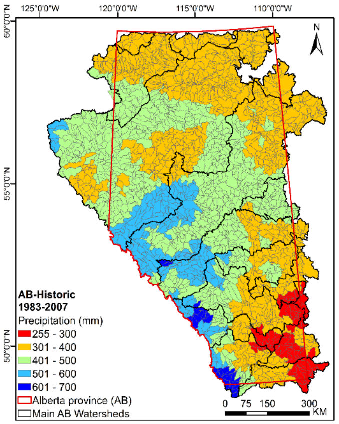
Scenarios	Description	Acronym
Sc 1	Historic, 1983-2007	Historic
Sc 2-10	9 GCMs, RCP 2.6, downscaled, 2010-2035	GCM-RCP2.6-D-S1
Sc 11-19	9 GCMs, RCP 2.6, downscaled, 2040-2065	GCM-RCP2.6-D-S2
Sc 20-28	9 GCMs, RCP 2.6, not downscaled, 2010-2035	GCM-RCP2.6-ND-S1
Sc 29-37	9 GCMs, RCP 2.6, not downscaled, 2040-2065	GCM-RCP2.6-ND-S2
Sc 38-46	9 GCMs, RCP 8.5, downscaled, 2010-2035	GCM-RCP8.5-D-S1
Sc 47-55	9 GCMs, RCP 8.5, downscaled, 2040-2065	GCM-RCP8.5-D-S2
Sc 56-64	9 GCMs, RCP 8.5, not downscaled, 2010-2035	GCM-RCP8.5-ND-S1
Sc 65-73	9 GCMs, RCP 8.5, not downscaled, 2040-2065	GCM-RCP8.5-ND-S2
Sc 74-83	10 RCMs, 2040-2065, Hargreaves	RCM-Har-D-S2
Sc 84-93	10 RCMs, 2040-2065, Penman-Monteith	RCM-Pen-D-S2

Scenarios	Scenario-set
GCMs-RCP2.6-D-S1	Scenario-set1
GCMs-RCP2.6-ND-S1	
GCMs-RCP8.5-D-S1	
GCMs-RCP8.5-ND-S1	
GCMs-RCP2.6-D-S2	Scenario-set2
GCMs-RCP2.6-ND-S2	
GCMs-RCP8.5-D-S2	
GCMs-RCP8.5-ND-S2	
RCMs-Har-D-S2	Scenario-set3
RCMs-Pen-D-S2	

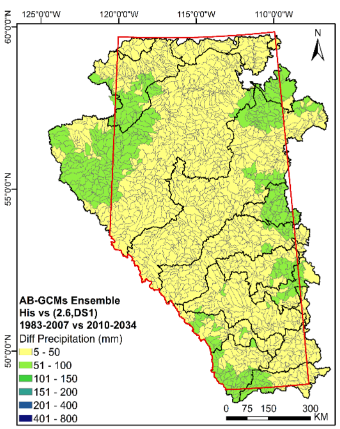
Results

Precipitation

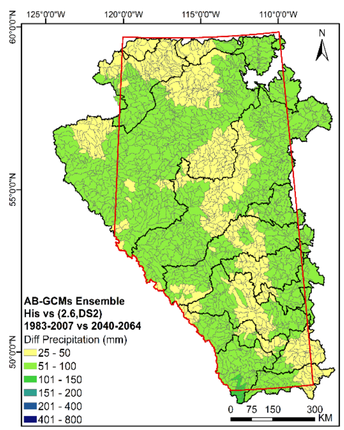
Historical-1983-2007



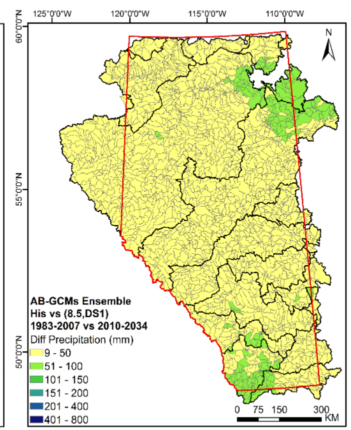
RCP2.6-2010-2035



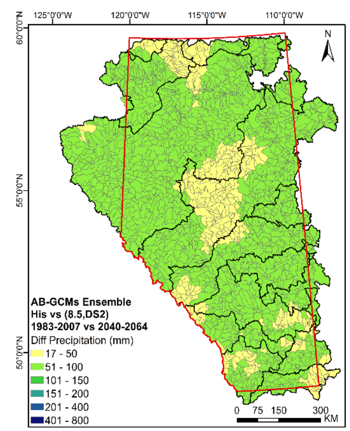
RCP2.6-2040-2065



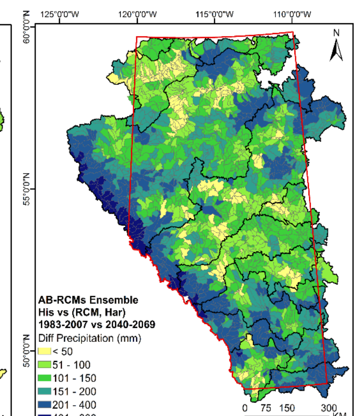
RCP8.5-2010-2035



RCP8.5-2040-2065



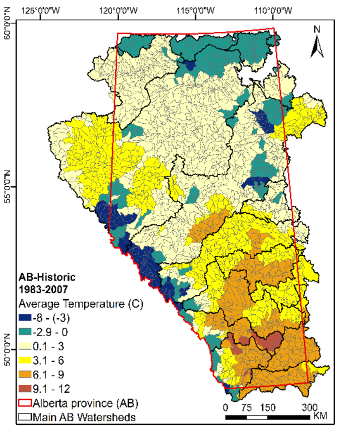
RCM-2040-2065



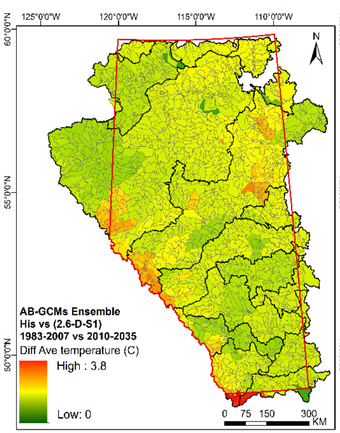
Results

Average Temperature

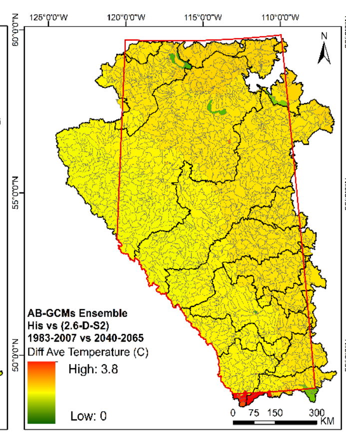
Historical-1983-2007



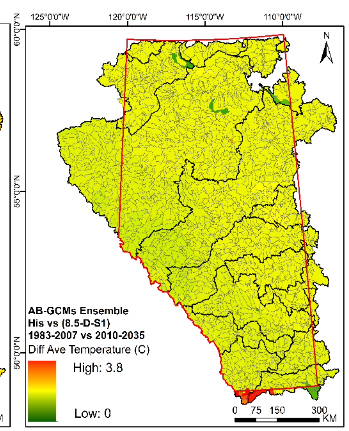
RCP2.6-2010-2035



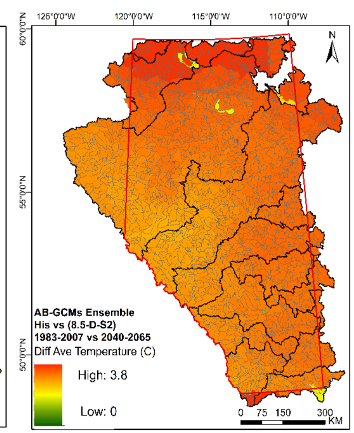
RCP2.6-2040-2065



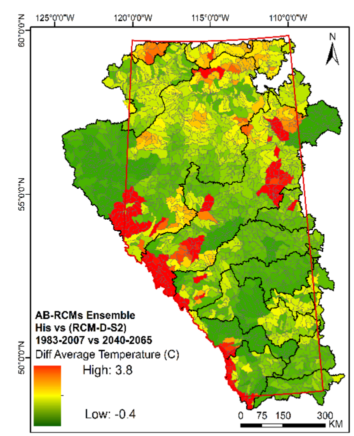
RCP8.5-2010-2035



RCP8.5-2040-2065



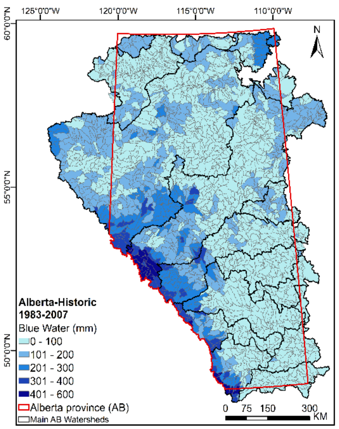
RCM-2040-2065



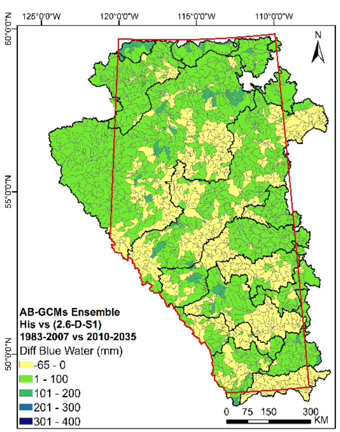
Results

Blue Water

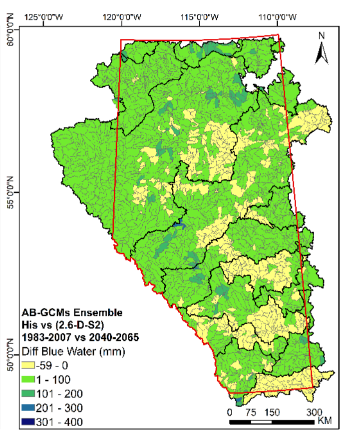
Historical-1983-2007



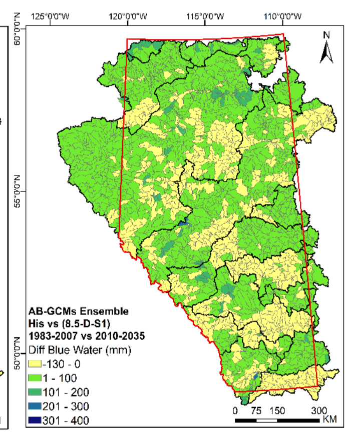
RCP2.6-2010-2035



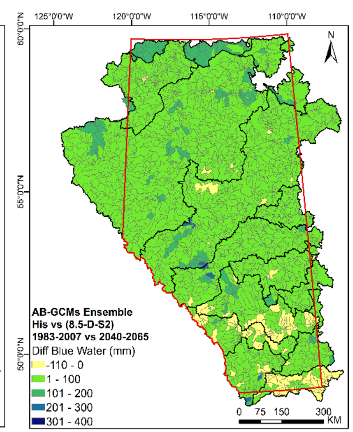
RCP2.6-2040-2065



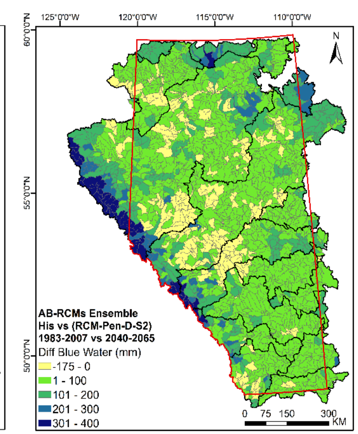
RCP8.5-2010-2035



RCP8.5-2040-2065



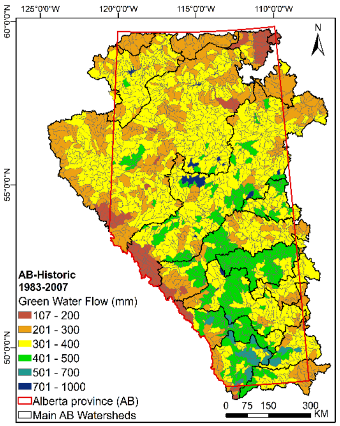
RCM-2040-2065



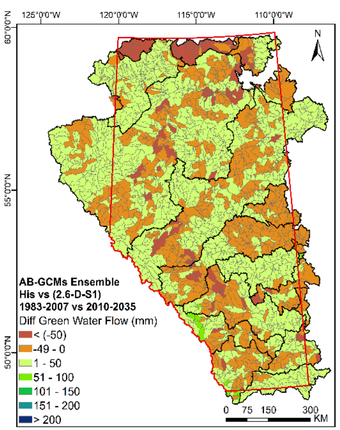
Results

Green Water Flow

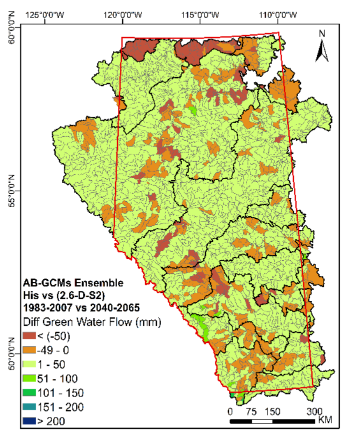
Historical-1983-2007



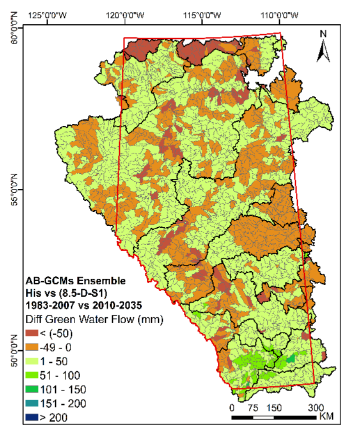
RCP2.6-2010-2035



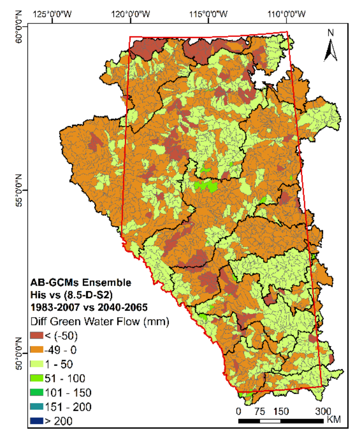
RCP2.6-2040-2065



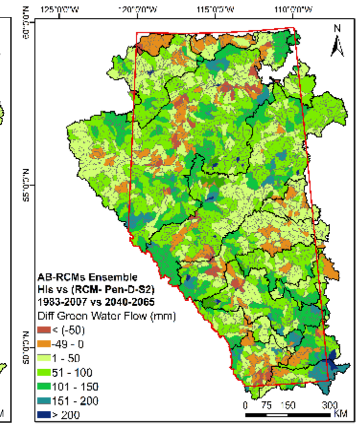
RCP8.5-2010-2035



RCP8.5-2040-2065



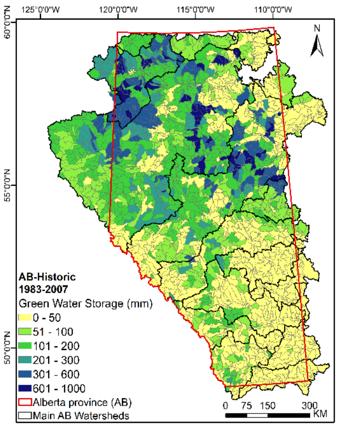
RCM-2040-2065



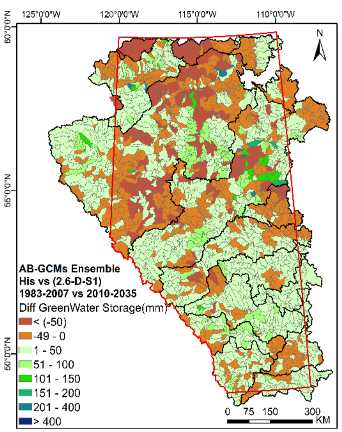
Results

Green Water Storage

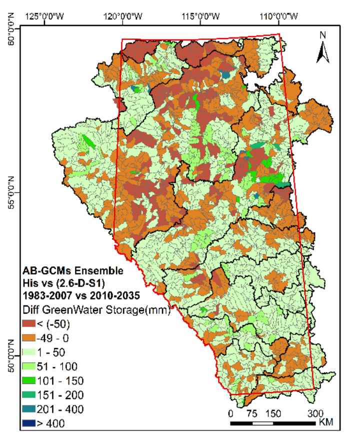
Historical-1983-2007



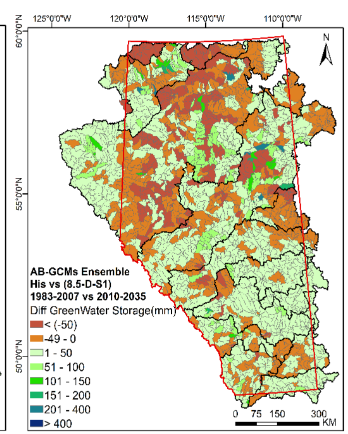
RCP2.6-2010-2035



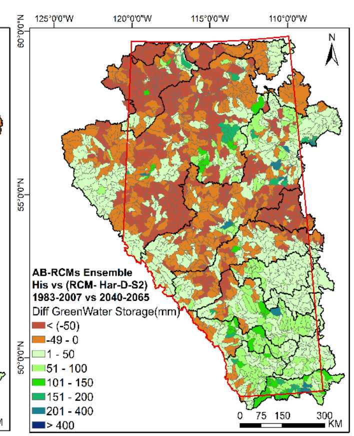
RCP2.6-2040-2065



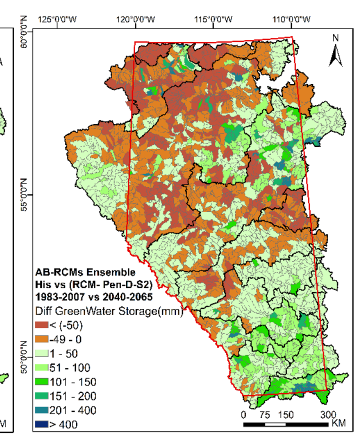
RCP8.5-2010-2035



RCP8.5-2040-2065



RCM-2040-2065

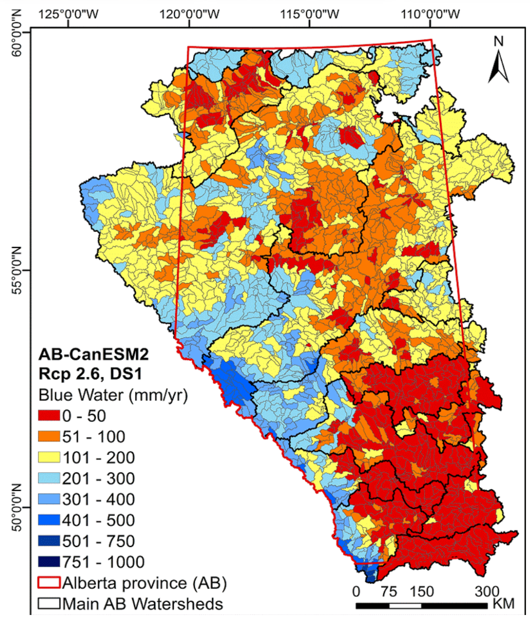


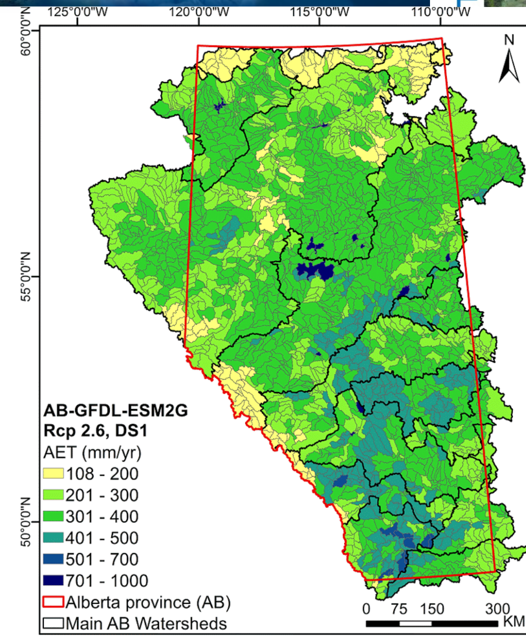
Uncertainty

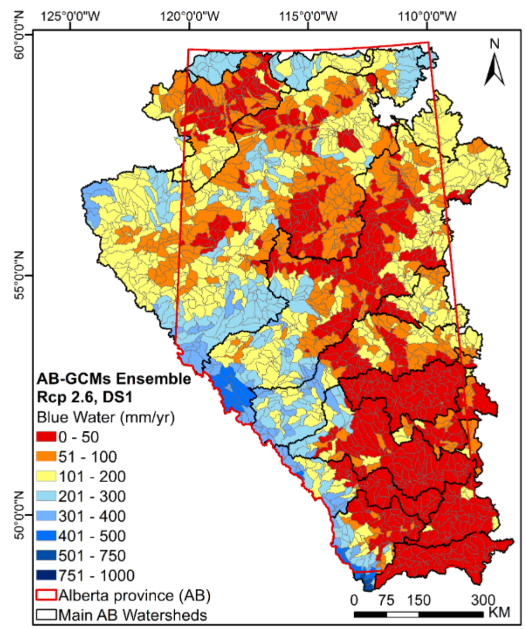
Blue Water

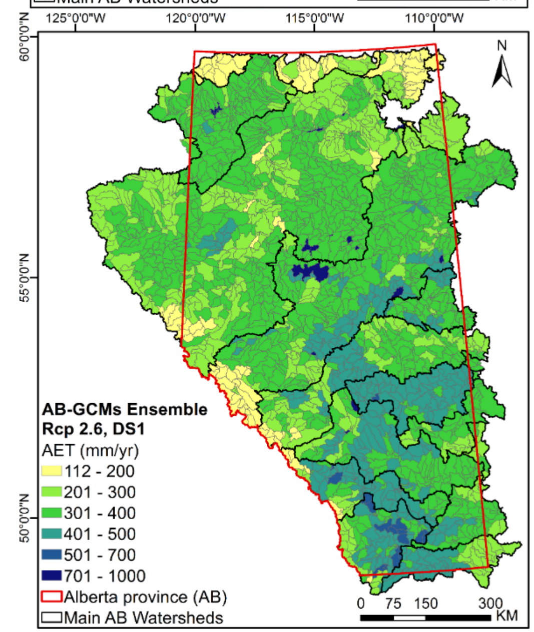
&

Actual Evapotranspiration

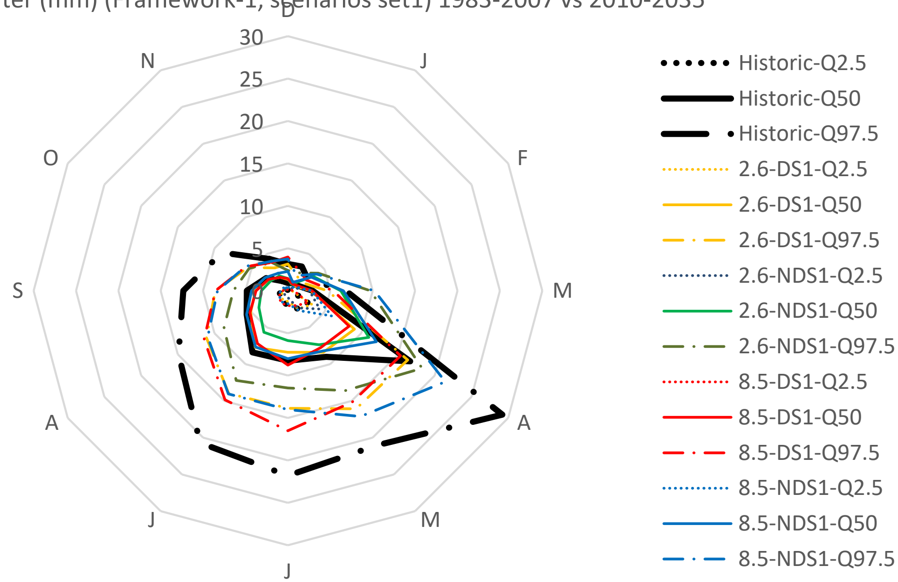




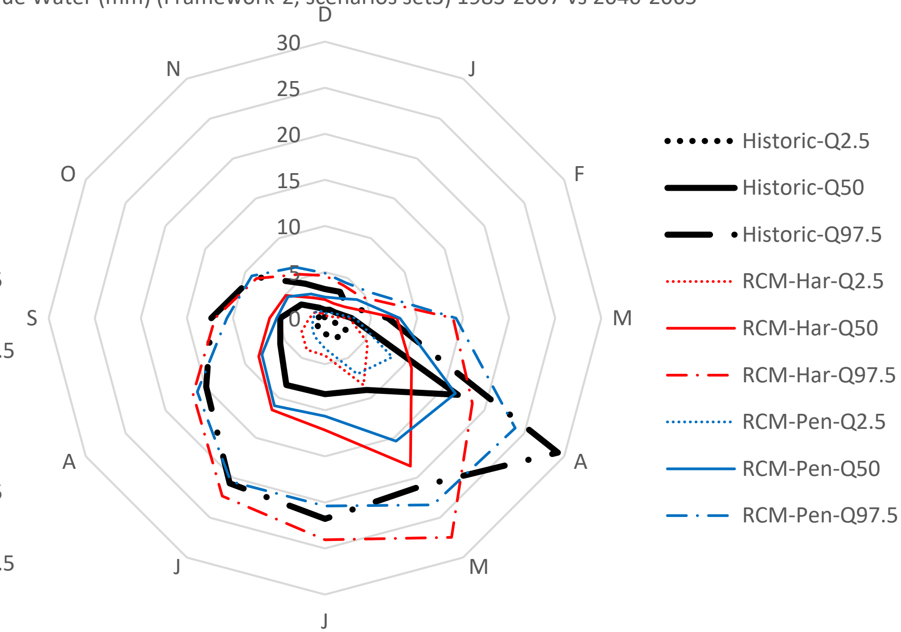




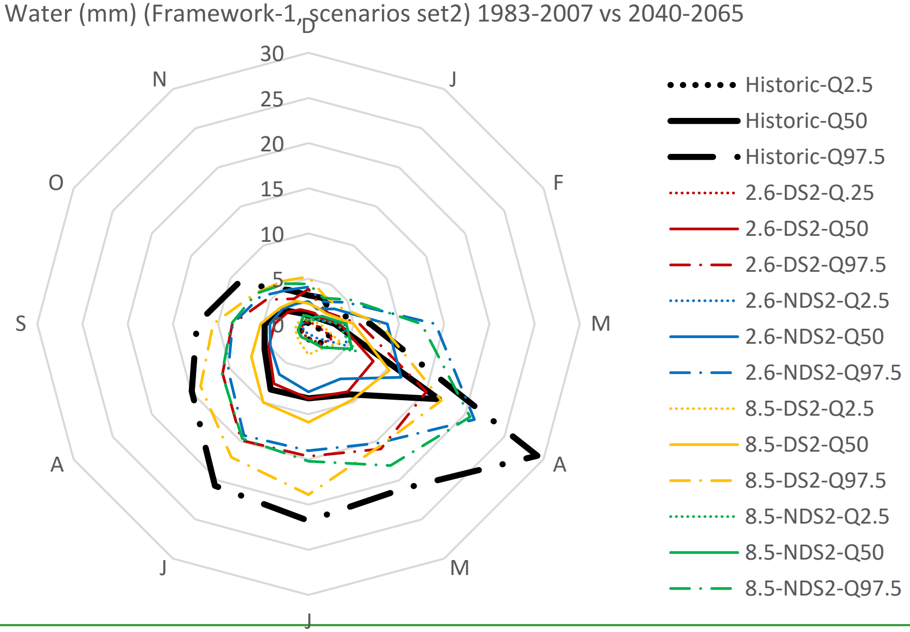
Blue Water (mm) (Framework-1, scenarios set1) 1983-2007 vs 2010-2035



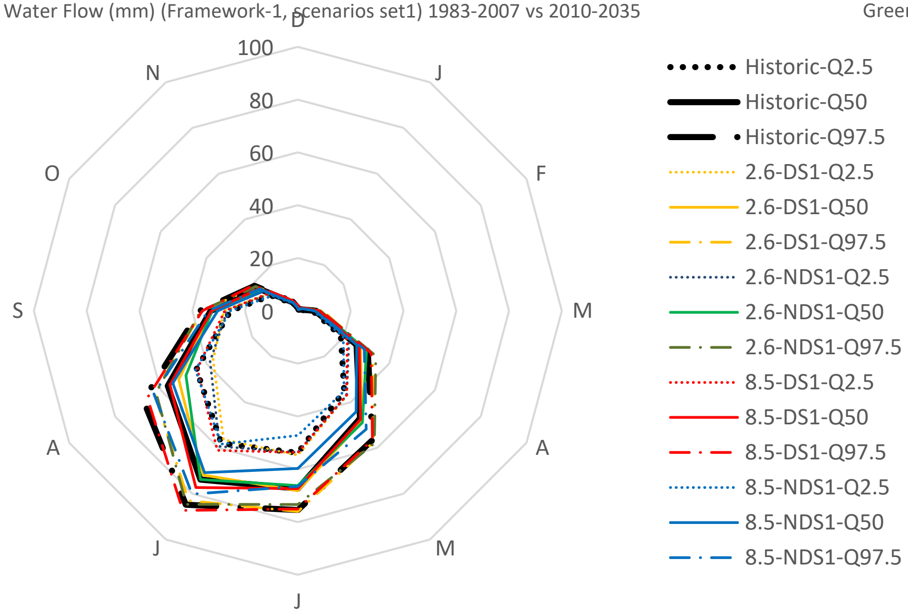
Blue Water (mm) (Framework-2, scenarios set3) 1983-2007 vs 2040-2065



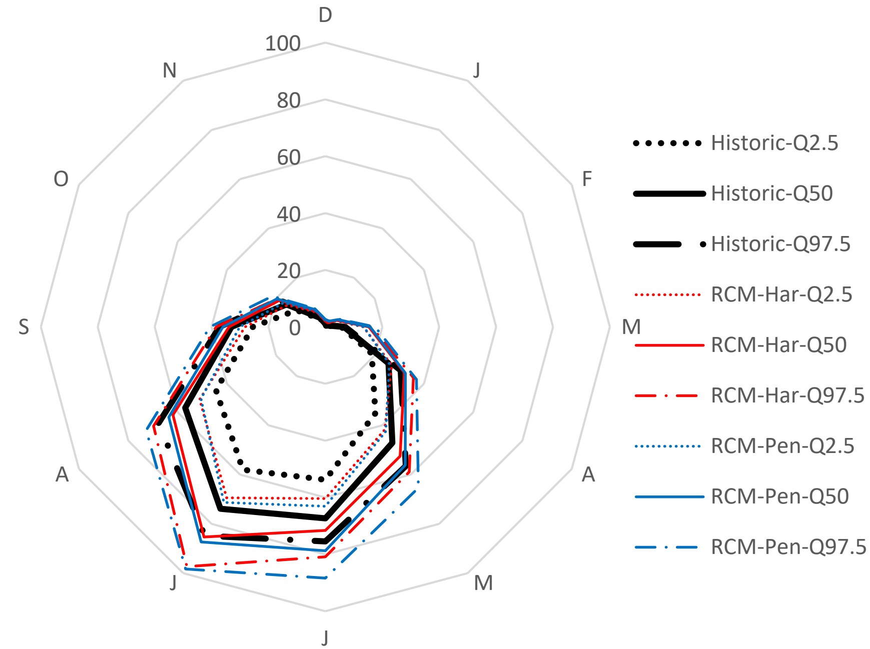
Blue Water (mm) (Framework-1, scenarios set2) 1983-2007 vs 2040-2065



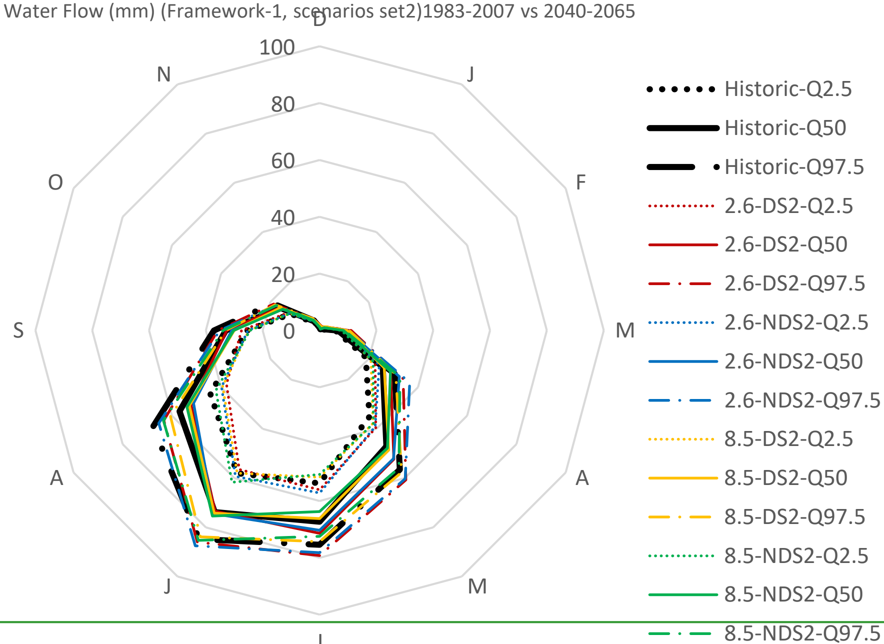
Green Water Flow (mm) (Framework-1, scenarios set1) 1983-2007 vs 2010-2035



Green Water Flow (mm) (Framework-2, scenarios set3) 1983-2007 vs 2040-2065



Green Water Flow (mm) (Framework-1, scenarios set2)1983-2007 vs 2040-2065



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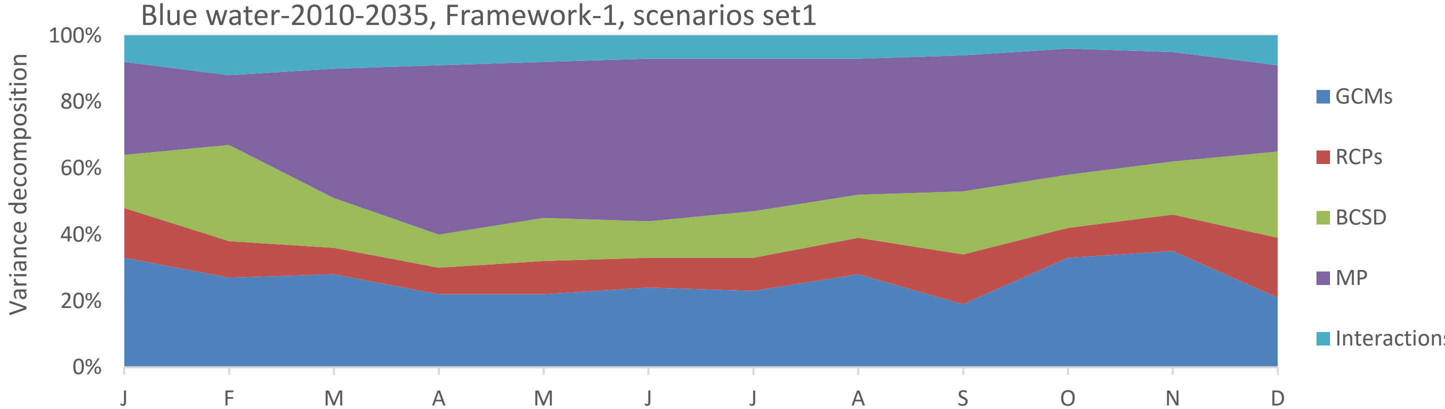
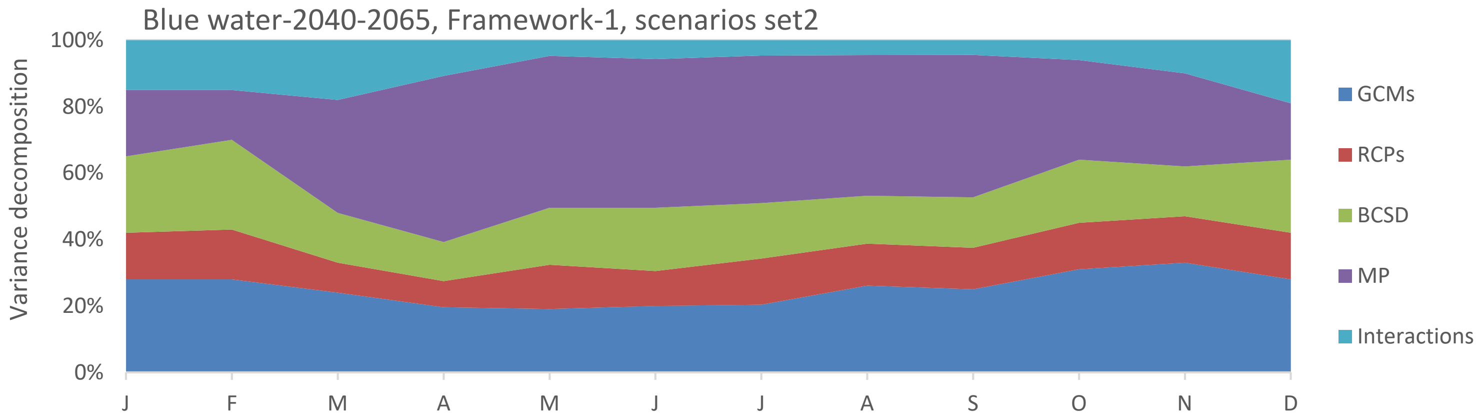
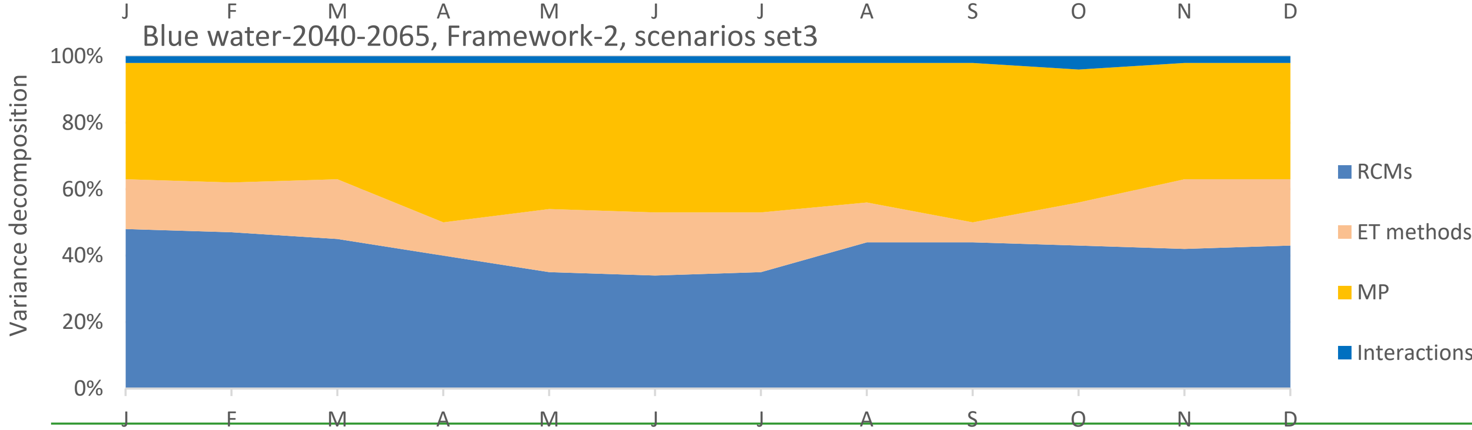
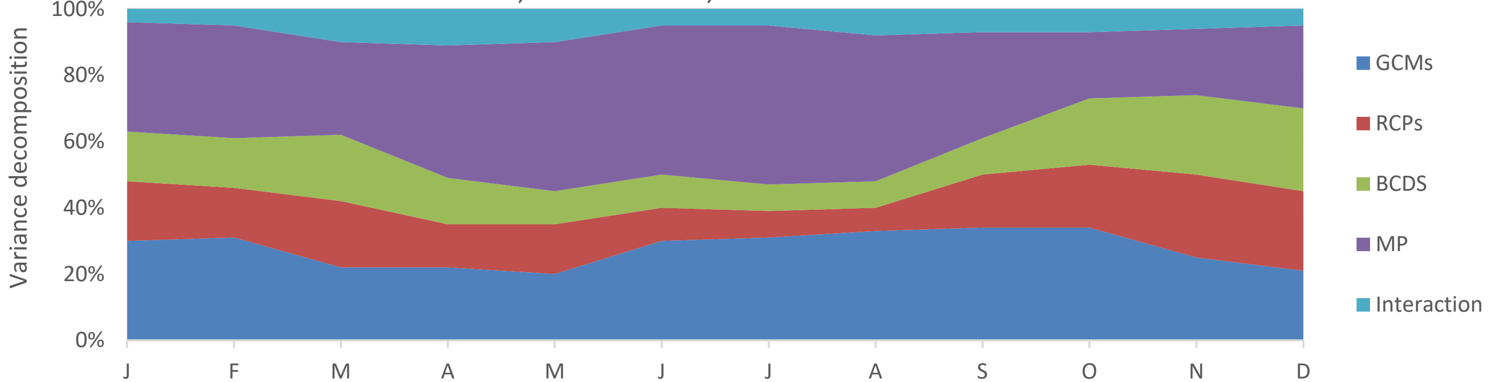


climate models and hydrological model parameterization and regionalization are the dominant sources of th uncertainty

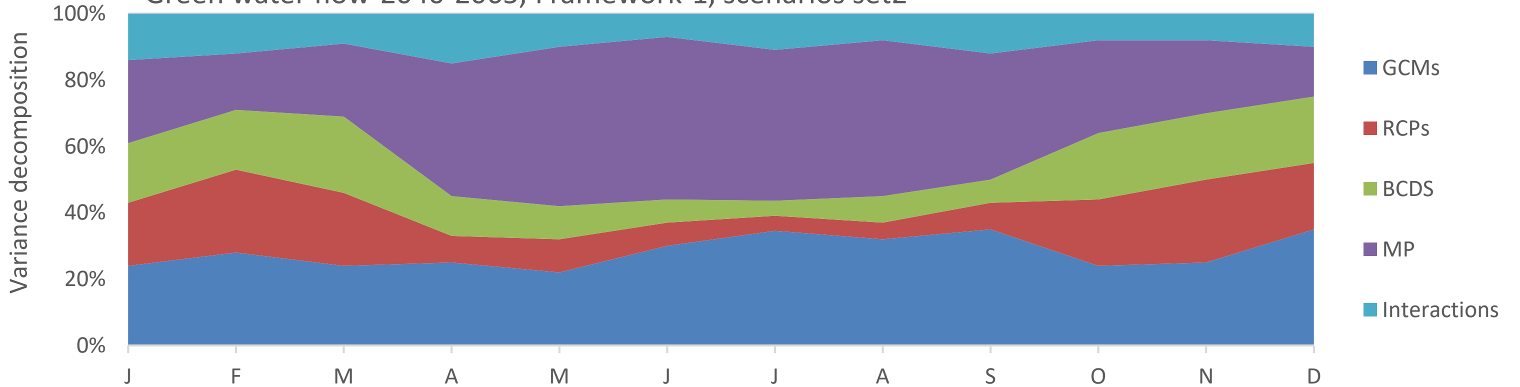




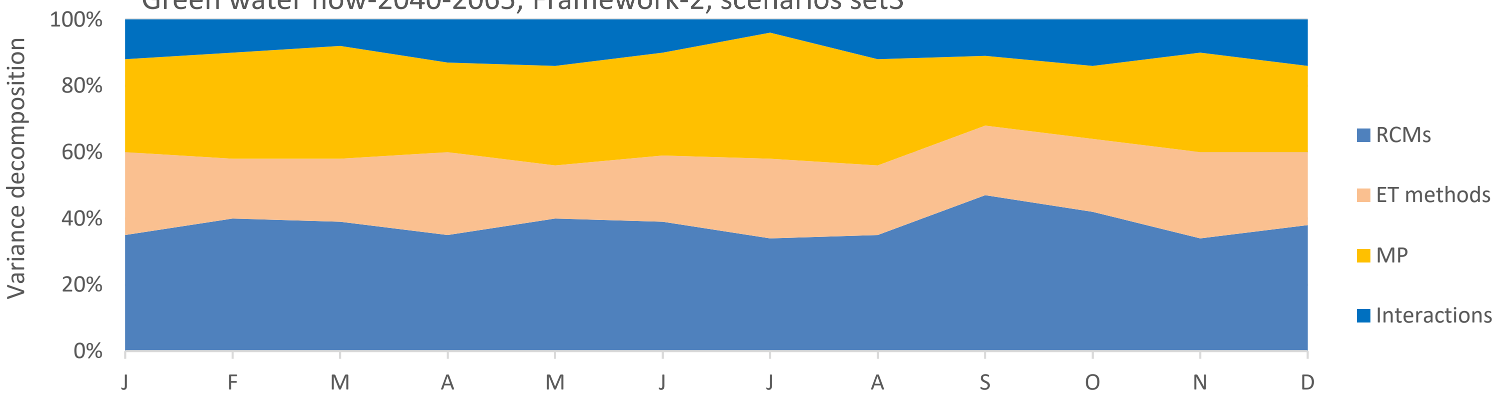
Green water flow-2010-2035, Framework-1, scenarios set1



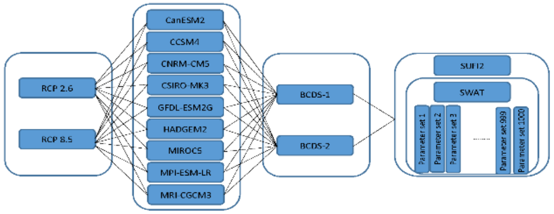
Green water flow-2040-2065, Framework-1, scenarios set2

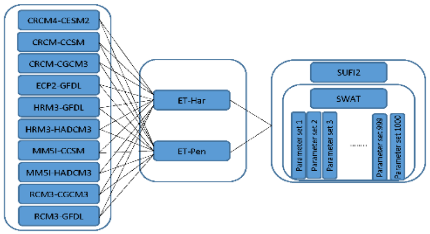


Green water flow-2040-2065, Framework-2, scenarios set3



Share of different uncertainty sources





Scenarios	Scenario-set
GCMs-RCP2.6-D-S1	Scenario-set1
GCMs-RCP2.6-ND-S1	
GCMs-RCP8.5-D-S1	
GCMs-RCP8.5-ND-S1	
GCMs-RCP2.6-D-S2	Scenario-set2
GCMs-RCP2.6-ND-S2	
GCMs-RCP8.5-D-S2	
GCMs-RCP8.5-ND-S2	
RCMs-Har-D-S2	Scenario-set3
RCMs-Pen-D-S2	

Scenario-set		Blue water (%)	Green water flow (%)
Framework1-Scenario-set1	GCMs	26.3	29.6
	RCPs	11.3	17.3
	BCDS methods	16.4	16.3
	HM-P and HM-R	38.3	29.0
	Interaction	7.7	7.8
Framework1-Scenario-set2	GCMs	26.0	30.7
	RCPs	12.8	14.9
	BCDS methods	18.4	14.4
	HM-P and HM-R	32.3	29.6
	Interaction	10.5	10.4
Framework2-Scenario-set3	RCMs	51.1	40.0
	ET methods	7.1	22.3
	HM-P and HM-R	38.3	26.0
	Interaction	3.5	11.8

Summary

Higher discrepancy between RCMs results (from NARCCAP) compared to GCMs results (from PCIC), likely due to the further bias correction that we applied to the GCMs and the resolution of GCMs grid compared to the RCMs

We found higher agreement between GCMs outputs under the RCP8.5 scenario compared to the RCP2.6 scenario. The reason for higher consistency between the RCP8.5 outputs is the minor role of natural variability relative to the significant impacts of carbon emission scenario.

For both RCP scenarios, we found that there is slightly more discrepancy between the results in the near future 2010-2035 scenario as compared to the far future scenario, i.e. 2040-2065 period

The GCMs result showed an increase of 8-16 mm for precipitation in the near future scenarios and 31-36 mm increase for the far future. The results of RCMs indicated an average increase of 112 mm for the province with a SD of 70 mm for far future.

All scenarios predicted an increasing trend for mean temperature in the province for both near and far future. GCMs projected an average increase of 1.3-1.4^{o}C and 1.7-3 ^{o}C for near and far future, respectively, while RCMs predicted an average increase of 1.7 ^{o}C for the 2040-2065 period

We found that blue water resources increase with an average of 20-46 and 53-52 mm in far future with GCM and RCM data, respectively. The former has an SD of 31-37mm while the latter has a SD of 88 mm, which shows lower consistency between RCMs.

Increasing temperature, precipitation and blue water resources in Alberta could draw attention to a higher chance of flooding in future compared to the historical period.

Using ANOVA-SUFI-2 method we found that the climate models and hydrological model parameterization and regionalization are the dominant sources of the uncertainty

During spring and summer seasons the climate models share of a large degree of uncertainty, which is in line with the findings of Wilby and Harris, (2006); Kay et al., (2009); Bosshard et al., (2013) and Vetter et al., (2015). For the winter and spring, our results showed that the dominant contributors are still climate models and hydrological model parameters.

Thank you for your attention