TRACING FLOW PATHS:

ISOTOPE-ENABLED HYDROLOGIC MODELLING

TEGAN HOLMES, M.SC., E.I.T.

DR. TRISH STADNYK, P.ENG.

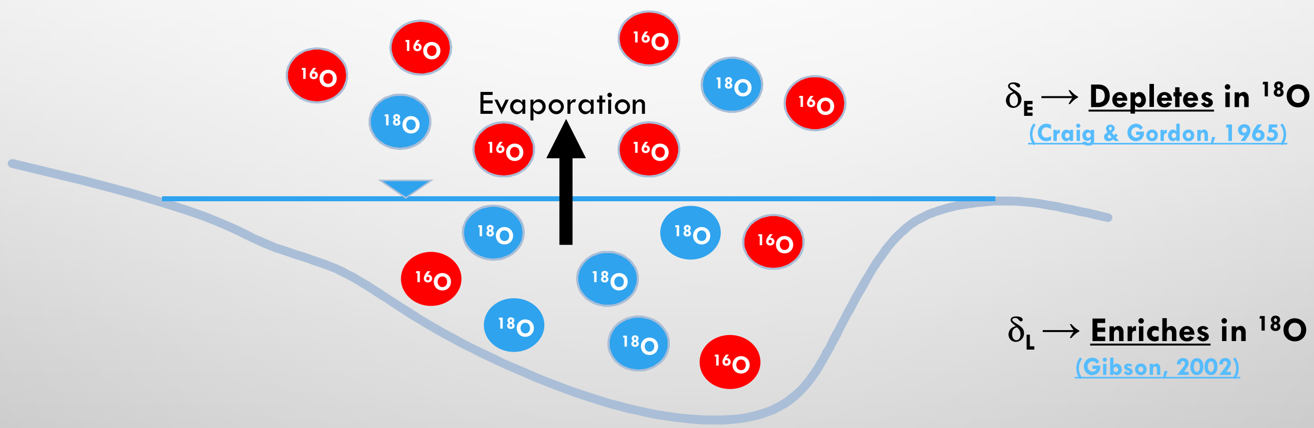
Principles of Hydrologic Modeling
23 June 2017

WHY USE TRACERS TO CALIBRATE HYDROLOGIC MODELS?

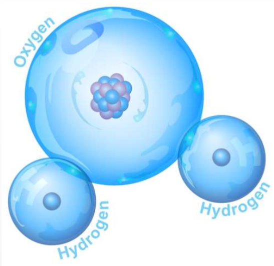
- FLOW DATA IS LIMITED (SPATIALLY AND TEMPORALLY) IN MUCH OF CANADA, INCREASING UNCERTAINTY
- DATA OTHER THAN FLOWS CAN REDUCE HYDROLOGIC SIMULATION UNCERTAINTY BY CONSTRAINING PARAMETERS (KIRCHNER 2006)
- SIMULATING A TRACER ALONG WITH FLOW ALLOWS FOR THE COMPARISON TO BOTH FLOW AND TRACER OBSERVATIONS
    - TRACERS ADD NEW INFORMATION TO CALIBRATION

STABLE WATER ISOTOPES IN HYDROLOGY ($\delta^{18}O$, $\delta^{2}H$)

- VARIOUS STABLE WATER ISOTOPES (SWI) OCCUR NATURALLY IN WATER - ^{18}O AND ^{2}H MEASURED
- EVAPORATION <u>ENRICHES</u> WATER (IN HEAVY ISOTOPES)
  - E.G., MOLECULES CONTAINING $^{1}H_2{}^{16}O$ ESCAPE MOST READILY

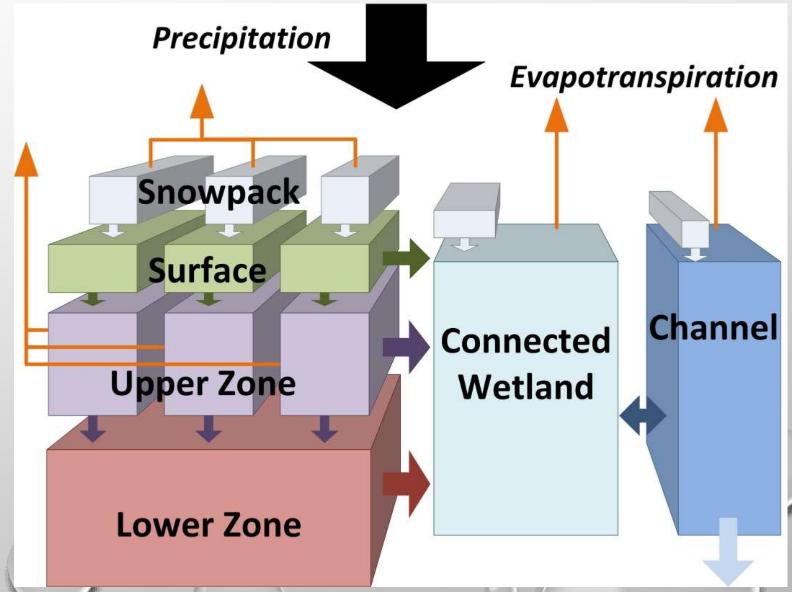


- CHANGE IN "δ" DRIVEN BY DIFFERENCES IN MOLECULAR BEHAVIOURS AND MASSES
  - SYSTEMATIC & PRESERVED LABELLING IN HYDROLOGIC CYCLE



ISOWATFLOOD

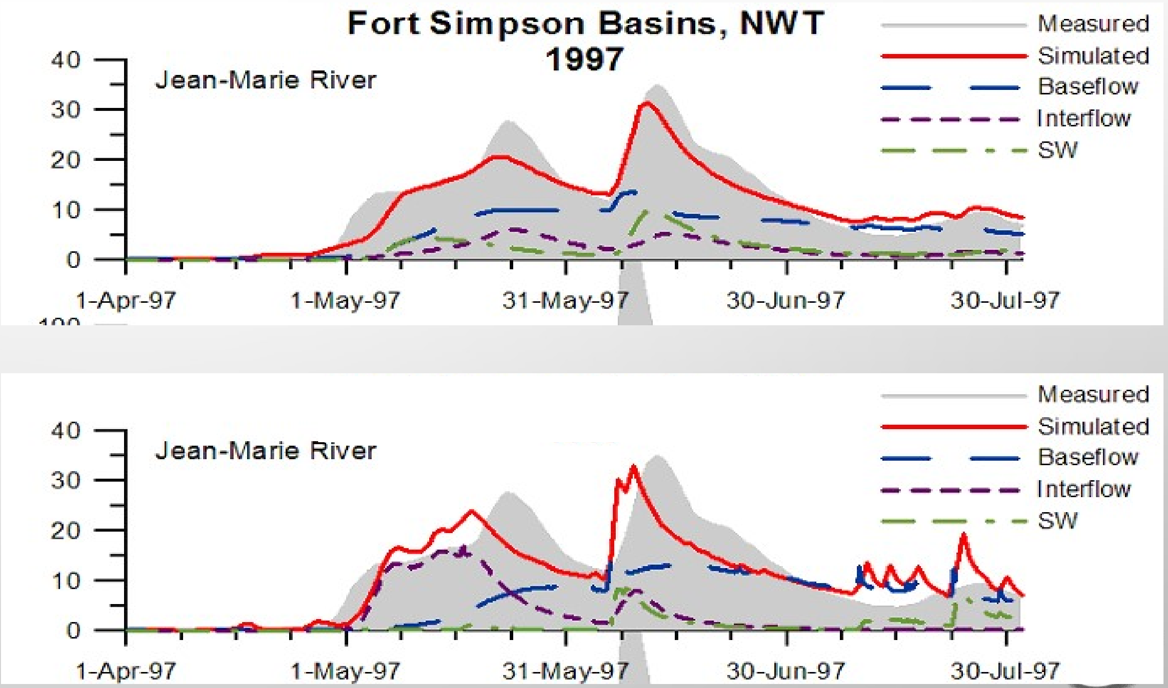
- SIMULATE ISOTOPE CONCENTRATIONS FOR ALL FLUXES & STORAGES IN WATFLOOD
    - ISOTOPES INPUT WITH PRECIPITATION
    - FRACTIONATE ISOTOPES UNDER EVAPORATION
- APPLICATIONS:
    - CONTINUOUS SIMULATION OF $\delta^{18}O$ & $\delta^{2}H$ IN STREAMFLOW
    - PARTITIONING OF EVAPOTRANSPIRATION (ET)
    - VERIFICATION OF INTERNAL STORAGES USING SWI
    - **CALIBRATION TOOL FOR WATFLOOD**



EQUIFINALITY CONCEPT

Stadnyk-Falcone, 2008
Stadnyk et al., 2013

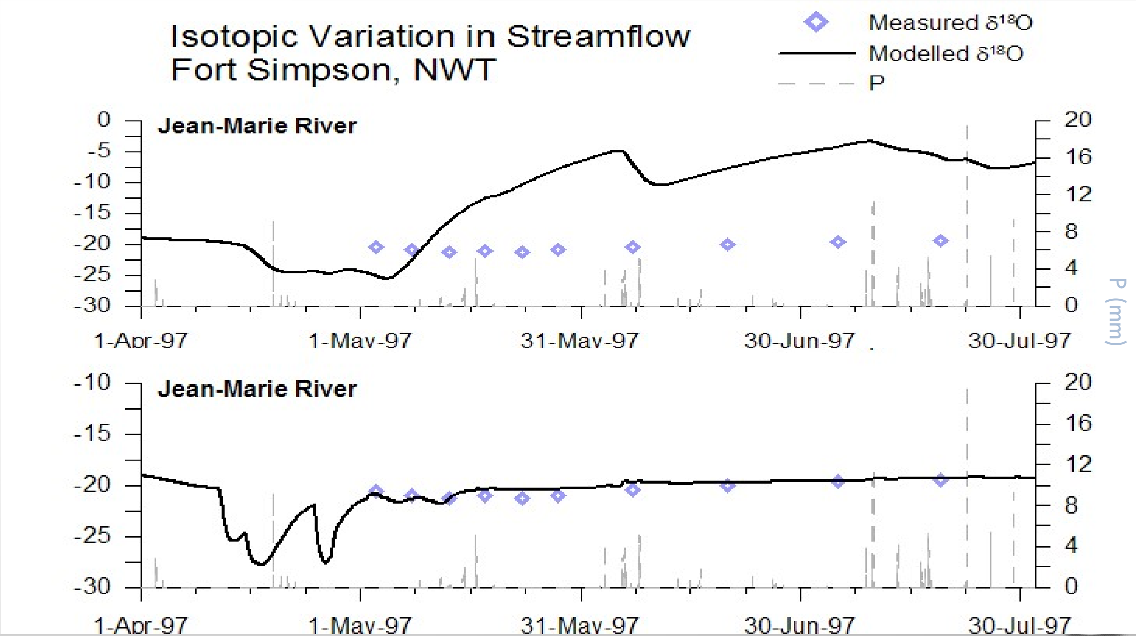
- DIFFERENT MODEL PARAMETERS CAN GIVE EQUIVALENT STREAMFLOW SIMULATION
- IS ONE MORE CORRECT THAN ANOTHER?
  - STATISTICALLY EQUAL TOTAL Q
  - INTERNAL PROCESSES DIFFERENT
  - E.G., SURFACE RUNOFF, INTERFLOW, BASE FLOW
- STREAMFLOW DATA ALONE CANNOT DETERMINE WHICH PARAMETERIZATION BETTER REPRESENTS THE REAL HYDROLOGIC SYSTEM



CONSTRAINING EQUIFINALITY

Stadnyk-Falcone, 2008
Stadnyk et al., 2013

- SIMULATE ISOTOPES IN STREAMFLOW ($\delta^{18}O$):
  - IDENTIFY 'INCORRECT' (UNREALISTIC) CALIBRATIONS
  - ISOTOPE SIMULATION MORE SENSITIVE TO INTERNAL STORAGE & FLOW PATH
    - DRIVEN BY EVAPORATION
  - REDUCE MODEL UNCERTAINTY
    - FEWER PARAMETER COMBINATIONS ARE ACCEPTABLE



CALIBRATING WITH ISOTOPES

Holmes, 2016
Holmes et al., in prep.

- **PRINCIPLE:** USING NUCLEAR (ISOTOPES) TECHNIQUES IMPROVES MODEL CALIBRATION
  - I.E., REDUCES THE NUMBER OF ***ACCEPTABLE*** MODEL PARAMETER SETS
- **METHODS:** THREE CALIBRATION ERROR FUNCTIONS OR E(θ) TESTED TO EVALUATE MODEL 'FIT':

1. FLOW-ONLY (F): NASH-SUTCLIFFE ERROR

$$E(\theta) = \overline{NSE}$$

2. SINGLE-ISOTOPE ($\delta^{18}O$): NASH-SUTCLIFFE ERROR FOR FLOW AND NORMALIZED RMSE FOR $\delta^{18}O$

$$E(\theta) = \overline{NSE}/5 + \overline{NRMSE}_{O^{18}}$$

3. DUAL-ISOTOPE ($\delta^{18}O$ & D^2H): NASH-SUTCLIFFE ERROR FOR FLOW AND NORMALIZED RMSE FOR $\delta^{18}O$ AND δ^2H

$$E(\theta) = \overline{NSE}/5 + \left(\overline{NRMSE}_{O^{18}} + \overline{NRMSE}_{H^2}\right)/2$$

- SEPARATE CALIBRATIONS PERFORMED (2010-2014), RESULTING IN THREE FINAL PARAMETER SETS

CALIBRATION RESULTS

Holmes, 2016
Holmes et al., in prep.

Average Statistics for flow and isotope simulations (calibration)

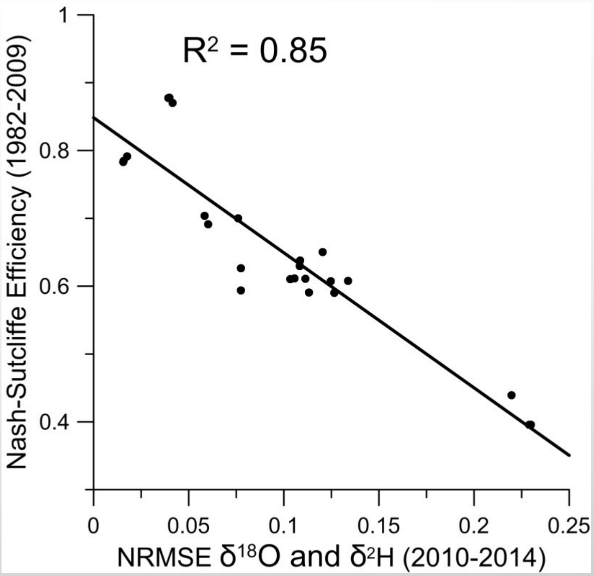
	NS	R^2	%Dv	NRMSE $\delta^{18}O$	NRMSE δ^2H
F	0.670	0.700	-2.92	0.063	0.049
O	0.664	0.692	-1.93	0.053	0.051
OH	0.663	0.692	-1.66	0.054	0.043

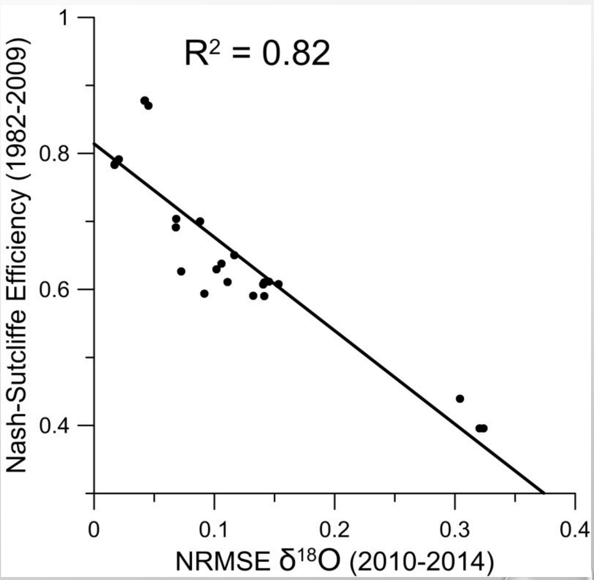
- **OUTCOME:**
  - FLOW-ONLY CALIBRATION (F) HAS HIGHEST SCORE (NS)
  - ISOTOPE CALIBRATIONS (O AND OH) HAVE BETTER ISOTOPE SIMULATIONS AND LOWER FLOW VOLUME ERROR ($\%D_V$)

MODEL PERFORMANCE VALIDATION

Holmes, 2016
Holmes et al., in prep.

- **GOAL:** ASSESS LONG-TERM MODEL PERFORMANCE DURING A VALIDATION PERIOD (1982-2009)
- **OUTCOMES:**
  - FLOW CALIBRATION DOESN'T PREDICT LONG-TERM PERFORMANCE
  - ISOTOPE CALIBRATIONS CAN ESTIMATE LONG-TERM MODEL PERFORMANCE
    - MORE ROBUST MODEL
  - LITTLE BENEFIT ADDED BY ^2H





MODEL VERIFICATION

Holmes, 2016
Holmes et al., in prep.

- **PRINCIPLE:** USE OBSERVED ISOTOPE DATA TO VERIFY SIMULATED HYDROLOGIC STORAGES
  1. COLLECT OBSERVED ISOTOPE DATA FROM STORAGES (E.G., LAKES, WETLANDS, GROUNDWATER)
  2. COMPARE WITH SIMULATED INTERNAL MODEL STORAGES

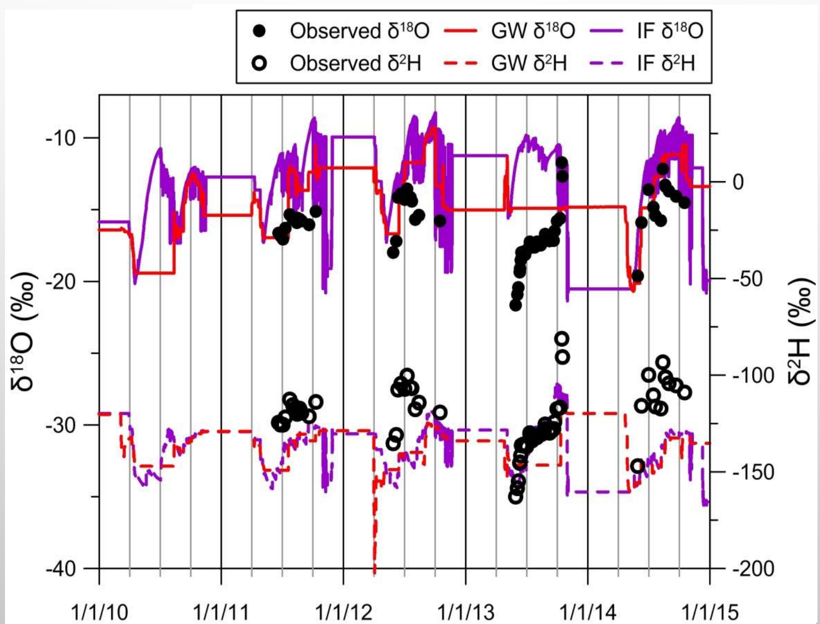
- **GOAL:** DEMONSTRATE VALUE-ADDED BY NUCLEAR (ISOTOPE) MODELING TECHNIQUES

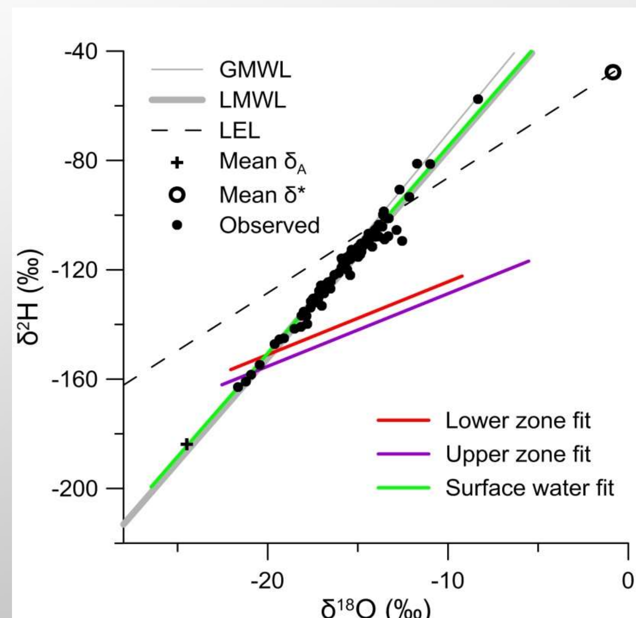
APPLYING VERIFICATION RESULTS TO CALIBRATION

Holmes, 2016
Holmes et al., in prep.

EXAMPLE: SOIL WATER (EVAPORATIVELY-INFLUENCED) AND GROUNDWATER (NON-EVAPORATED)

- OBSERVED DATA SHOWS SOME EVAPORATION INFLUENCE
- SIMULATED SOIL EVAPORATION LOSS INITIALLY TOO HIGH
- POSSIBLE APPLICATIONS:
  - USE TRACERS TO INFORM PARAMETER RANGES
  - CALIBRATE INTERNAL STORAGES
    - PRE-SET VALUES
    - MULTI-OBJECTIVE CALIBRATION



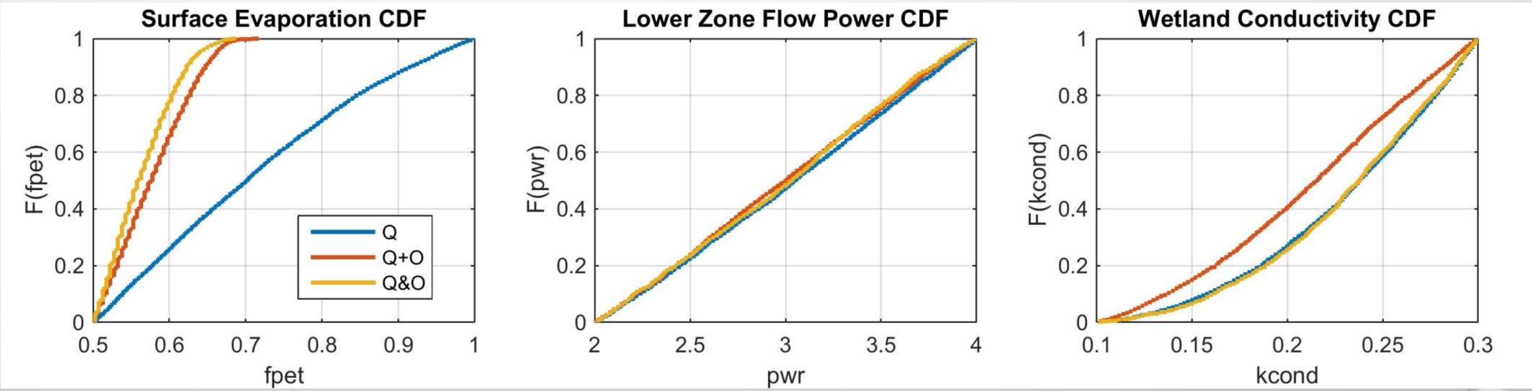


IMPROVING PARAMETER IDENTIFIABILITY

- CAN TRACERS REDUCE PARAMETER UNCERTAINTY?
  - MONTE CARLO METHOD (UNIFORM DISTRIBUTION FOR 9 PARAMETERS)
  - KGE USED FOR BOTH FLOW AND ISOTOPE SIMULATIONS
  - 100,000 EVALUATIONS
- ISOTOPE ERROR IN BEHAVIORAL DEFINITION IMPROVES IDENTIFIABILITY FOR ET RELATED PARAMETERS

- BEST METHOD IS USING ISOTOPE ERROR AS ANOTHER REQUIREMENT FOR BEHAVIORAL SIMULATIONS

KGE_Q AND KGE_O > THRESHOLD

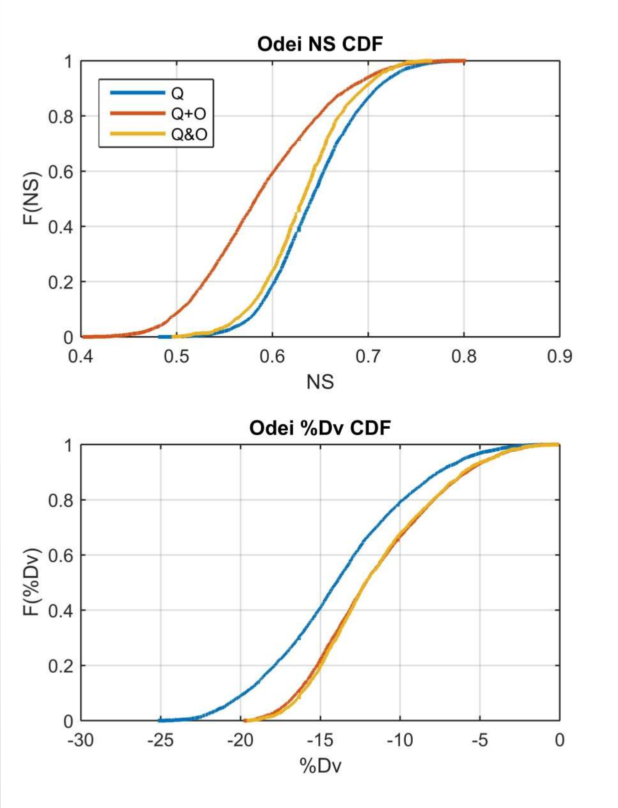


REDUCING EQUIFINALITY

- BY REQUIRING BOTH THE FLOW AND TRACER SIMULATION TO MEET A THRESHOLD
  - LARGE REDUCTION IN BEHAVIORAL SETS
  - IMPROVED DISTRIBUTION FOR VOLUME ERROR
  - NO SIGNIFICANT IMPACT ON TIMING ERROR

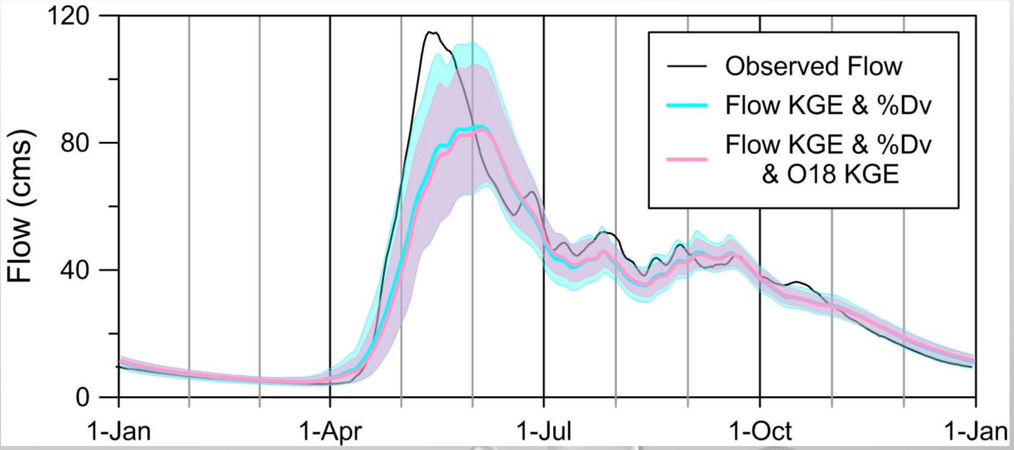
Behavioral parameter sets using different thresholds for KGE:

Threshold	KGE_Q	$(KGE_Q + KGE_O)/2$	KGE_Q & KGE_O
0.5	30.4%	27.9%	17.4%
0.6	15.6%	15.4%	7.3%
0.7	5.1%	4.2%	1.5%



REDUCING FLOW SIMULATION UNCERTAINTY

- OVER 30 YEAR HISTORICAL FLOW SIMULATION USING TRACERS TO DEFINE THE ENSEMBLE
  - DID NOT SIGNIFICANTLY CHANGE THE MEAN FLOW SIMULATION
  - REDUCED THE 95TH PERCENTILE BOUNDS
- ALSO USING VOLUME ERROR IN DEFINITIONS ACTUALLY INCREASES THE IMPROVEMENT FROM USING TRACER



VALUE ADDED BY TRACER-AIDED MODEL CALIBRATION

- TRACERS CAN ADD ADDITIONAL INFORMATION TO CALIBRATION
    - IMPROVE SIMULATION OF TRACED PROCESS(ES)
    - BETTER IDENTIFICATION OF PARAMETERS RELATED TO TRACED PROCESS(ES)
    - LITTLE TO NO NEGATIVE IMPACT ON FLOW SIMULATION STATISTICS
    - POSSIBLE IMPROVEMENTS FOR FLOW STATISTICS IN VALIDATION

- BETTER CALIBRATION INFORMATION, LESS UNCERTAINTY, IMPROVED RELIABILITY

QUESTIONS?

ACKNOWLEDGMENTS:

GNIP, CNIP and GNIR

REFERENCES

- Delavau C., Stadnyk T., Birks J. (2011). Model based spatial distribution of oxygen-18 isotopes in precipitation across Canada. *Can. Water Resourc. J.*, 36(4): 313-330.
- Delavau C, Chun KP, Stadnyk T, Birks SJ, Welker JM (2015). North American precipitation isotope (d^{18}O zones reveled in time series modelling of precipitation ^{18}O across Canada and the northern United States. *Water Resourc. Res.*, 51(2): 1284-1299. doi: 10.1002/2014WR015687
- Delavau, C., Stadnyk T.A. (in revision). Simulating Oxygen-18 throughout the hydrologic cycle utilizing isoWATFLOOD with time series $\delta^{18}O_{ppt}$ forcing. Submitted to *Hydrol. Earth Sys. Sci.* 2016-539.
- Delavau 2016. Development of Precipitation δ^{18}O Isoscapes for Canada and Application within a Tracer-Aided Hydrological Model. Ph.D. Thesis, Department of Civil Engineering, University of Manitoba. 296p. http://hdl.handle.net/1993/31946
- Holmes, 2016. Assessing the Value of stable water isotopes in hydrologic modelling: a dual-isotope approach. M.Sc. Thesis, department of Civil Engineering, University of Manitoba. 200p. http://hdl.handle.net/1993/31724
- Holmes, T., T. Stadnyk, C. Welch (in preparation). Hydrologic model calibration using stable water isotopes: a dual isotope approach. For Submission to *Hydrol. Process.* in March 2017.
- Holmes, T., T. Stadnyk, C. Welch (in preparation). Can tracer-aided models reduce equifinality? For Submission to *J. Hydrol.* in May 2017.
- Kouwen, 2016. WATFLOOD/CHARM Canadian Hydrological And Routing Model. 251p. http://www.civil.uwaterloo.ca/Watflood/downloads/manual16.pdf. Retrieved from http://www.civil.uwaterloo.ca/Watflood/index.htm
- Smith A, Delavau C., Stadnyk TA (2015). Hydrologic Assessment of the lower Nelson River basin using stable water isotope investigations. *Can. Water Resour. J.,40(1): 23-25.* doi: 10.1080/07011784.2014.985512
- Smith, A., T.A. Stadnyk (2016). Assessment of a lumped coupled flow-isotope model in data scarce Boreal catchments. Accepted by *Hydrol. Processes.* doi: 10.1002/hyp.10835.
- Smith, A., C. Welch, T. Stadnyk (in preparation). Assessing the seasonality and uncertainty in evapotranspiration partitioning using lumped flow-isotope modeling. For submission to *J. Hydrology* in February 2017.
- Smith, A., C. Welch, T. Stadnyk (in preparation). Assessing the effects of isotopic evapotranspiration partitioning using storage selection functions. For submission to *Water Resour. Res.* in February 2017.
- Stadnyk T., St. Amour N., Kouwen N., Edwards T.W.D., Pietroniro, A., & Gibson, J.J. (2005). A groundwater separation study in Boreal wetland terrain: the WATFLOOD hydrological model compared with stable isotope tracers. *Isotopes in Environmental and Health Studies*, *41*(1), 1-20.
- Stadnyk-Falcone, 2008. Mesoscale Hydrological Model Validation & Verification using Stable Water Isotopes: The isoWATFLOOD Model. Ph.D. Thesis, Department of Civil & Environmental Engineering, University of Waterloo. 384p. http://hdl.handle.net/10012/3970
- Stadnyk T., Delavau C., Kouwen N., Edwards T.W.D. (2013). Towards hydrological model calibration and validation: simulation of stable water isotopes using the isoWATFLOOD model. *Hydrol Processes, 27*(25): 3791-3810.
- Stadnyk TA, Gibson JJ, Longstaff F (2015). Basin-scale Assessment of Operational Baseflow Separation Algorithms. *J. Hydrol. Eng.,* 20(5). doi: 10.1061/(ASCE)HE.1943-5584.0001089, 04014074.
- Stadnyk T, Dow K, Wazney L, Blais E (2015). The 2011 Red River Flood: Causes, Assessment and Damages. *Can. Water Resourc. J.,* doi: 10.1080/07011784.2015.1008048.
- Welch, C., A. Smith, and T. Stadnyk (in preparation). Regional controls on isotopic composition in a cold regions, high-latitude basin. For Submission to *Water Resour. Res.* in spring 2017.
- Wruth et al 2013. Incorporation of non-stationary landcover into WATFLOOD climate change scenarios. M.Sc. Thesis, Department of Civil Engineering, University of Manitoba. 177p. http://hdl.handle.net/1993/23208
- Untereiner, E., G. Ali, T.A. Stadnyk (2015). Spatiotemporal Variability of Water Quality and Stable Water Isotopes in Intensively Managed Prairie Watersheds. *Hydrol. Processes 29(18):* 4125-4143.