Integrated Modelling for Water Resources Management and Decision Support

First Annual General Meeting

Saman Razavi, July 18-19, 2018

Integrated Modelling Program for Canada
Global Water Futures

Research Themes

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THEME A: Integrated Earth Systems Modelling

A1: Atmospheric Modelling
A2: Hydrologic Modelling
A3: Water Quality Modelling
A4: River Ice Modelling
A5: Model Intercomparison
A6: Floodplain Mapping
A7: Uncertainty Characterization

THEME B: Water Management Modelling, Coupling Human-driven and Natural Systems

B1: Basin-wide Water Resource Modelling
B2: Environmental Demands
B3: Hydro-economic Modelling

IMPC

THEME C: Decision Making under Uncertainty and Non-stationarity

C1: Future Scenario Generation
C2: Optimization and Multi-Criteria Decision Analysis

THEME D: User Engagement and Knowledge Mobilization

D1: Outreach and User Engagement
D2: Decision Support Systems

The Status Quo:
Fragmentation in Modelling and Management

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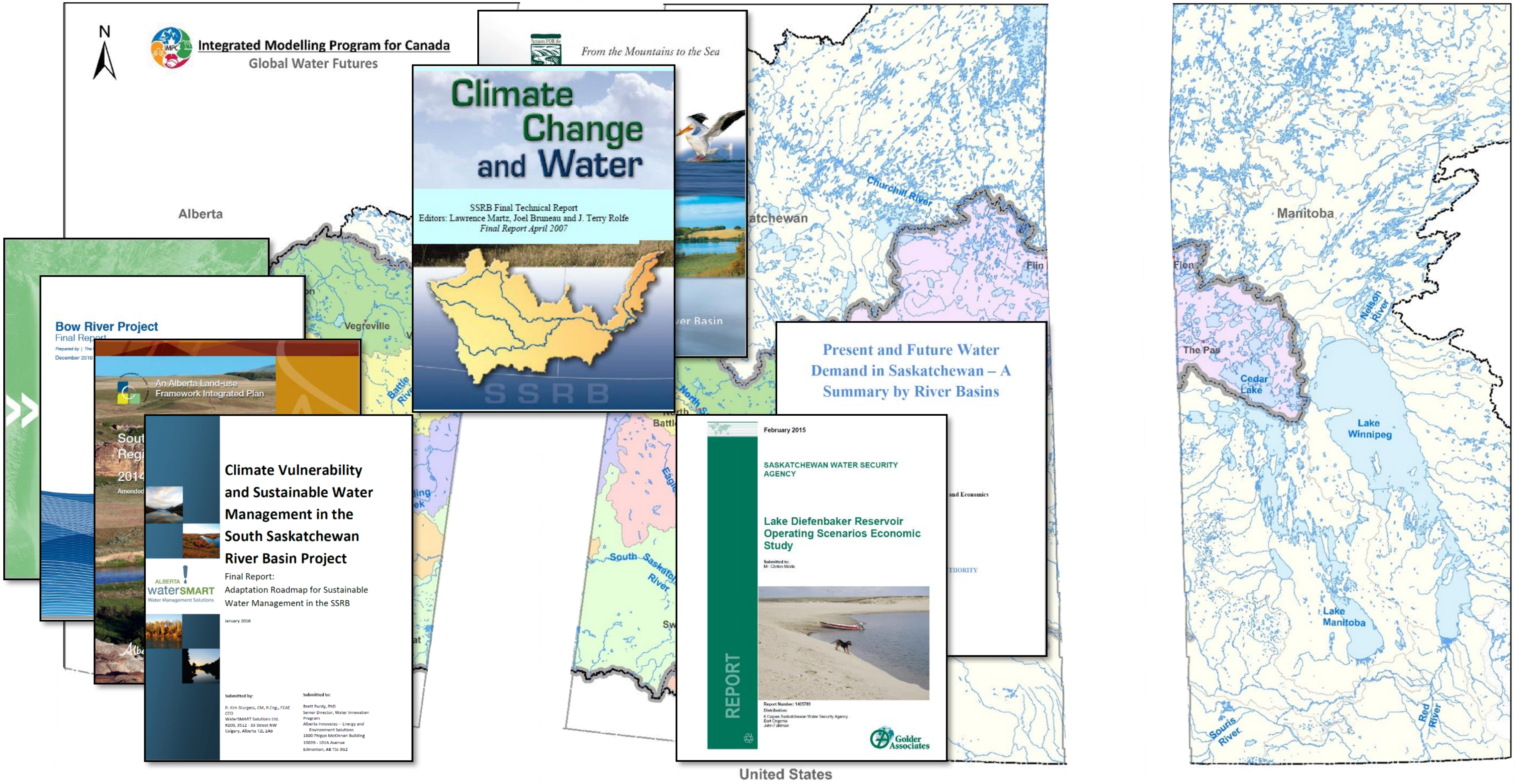

Objective:
Integrated Modelling for Basin-Wide Decision Support

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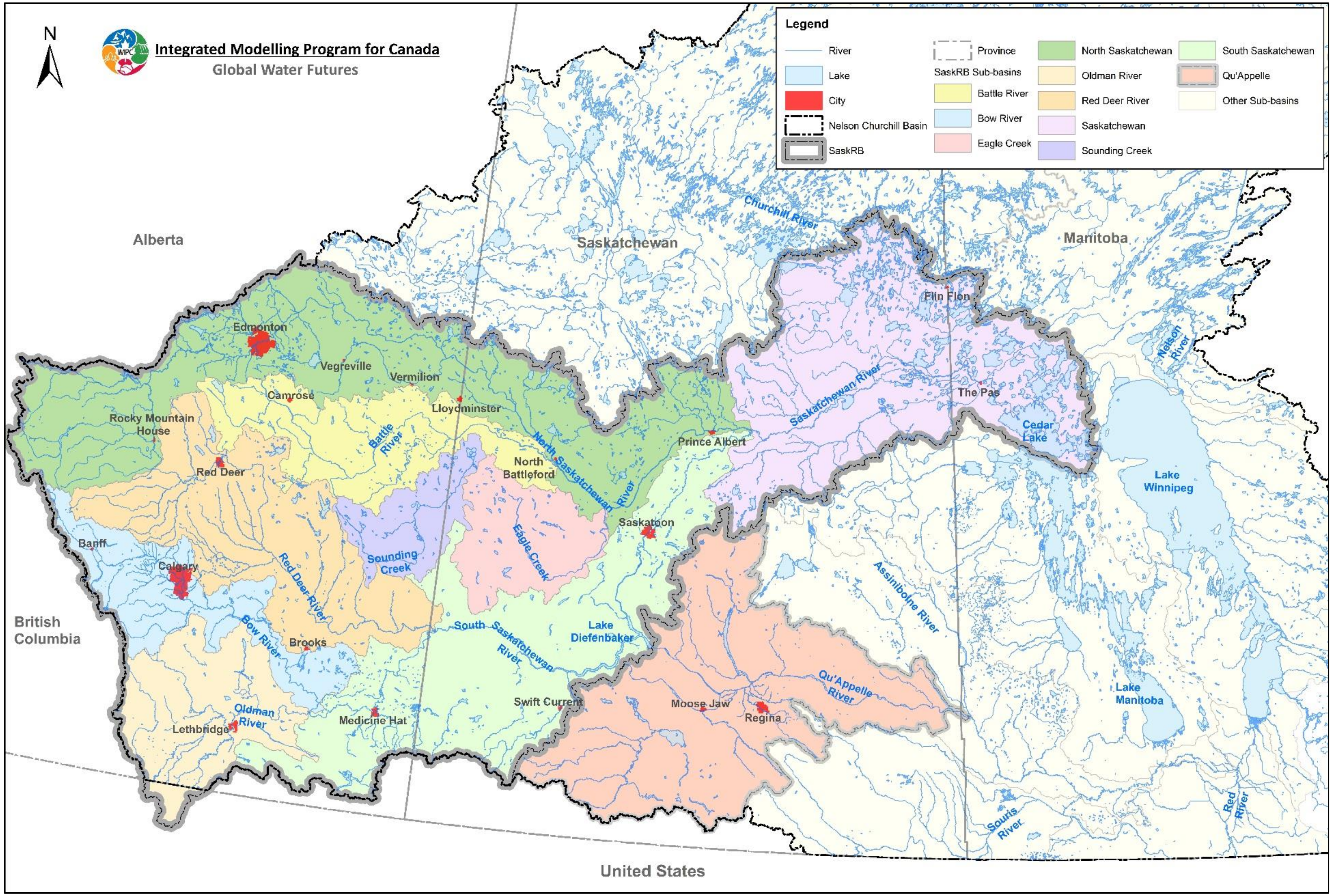

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Progress on Water Resources Systems Modelling

A Survey of Modelling Platforms

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#	1	2	3	4	5	6	7	8	9	10	11	12
Program Name	WEAP	MIKE HYDRO Basin	Colorado DSS	WRMM	RiverWare	HEC-ResSim	FreeWAT	SWAM	REALM	CaWAT	OASIS	WRISM (CalSIM)
Price	$250 - $1000 US Dollars / 2yrs	$380 CAD + applicable charges (shipping, etc)	FREE	Not available for public use	$2360 - $4160 US Dollars / yr	FREE	FREE	Not available for public use	FREE	N/A	Not Free	Free and open source
Allocation Algorithm	Prioritized (lp-solve)	Prioritized, Fract. of flow (1. p.68)	Prioritized, MDSA algorithm (1.p.10)	Prioritized, Out-of-Kilter algorithm (p.1-2)	Flexible Rule-based allocation, CPLEX (p. 5)	Only Release Allocation, (2.p.11-82)	Surface/Ground- water rights (3.p.13,3.p.18)	Colorado DSS MDSA algorithm (p. 3-1)	Penalty func., RELAX Algorithm (1.p.23)	N/A	Linear solver XA, developed by Sunset Software Technology	open source CBC and commercial XA
Time step	1 – 365 days	Seconds (1.p.3)	Daily & monthly (1.p.5)	1-365 days (p.1-7)	Hourly to yearly (p. 3)	TBD	TBD	Monthly (p. 1-1)	Hourly, Daily, Weekly, Monthly, etc (1.p.26)	Monthly, Monthly (2.p.5)	Anything between 5 min to 1 year	1 day or 1 month
Demand Sites	Agriculture, Urban, Industry, etc.	Agriculture, Urban, Industry, etc (1. p.101)	Agriculture, Urban, Industry, etc	Agriculture, Urban, Industry, etc (p.1-5)	General water users (p. 1460)	N/A	Irrigation	Agriculture, Urban, Industry (p.2-5, p.2-10)	Agriculture, Urban, Industry, etc	N/A	Irrigation, withdrawals, hydropower, environmental flows etc.	Irrigation, withdrawals, hydropower, environmental flows etc.
GUI	YES	YES	YES	YES	YES	YES	YES based on QGIS	YES basen on MS Excel	YES	MS Excel Env (1.p. 4)	Yes	Yes
API	YES	YES (3)	N/A	N/A	RCL (p. 1)	YES (only internal)	N/A	N/A	N/A	N/A	Yes	Yes
Scenario Analysis	YES	YES (2. p.7)	YES (2.p.7)	N/A	YES (p. 1)	YES (2.p.13-i)	N/A (1.p.13)	N/A	YES (1. .p. 132)	N/A	Yes	Yes
Rainfall-Runoff Modeling	Simp. FAO, MABIA, PGM, SMM	NAM, UHM (1. p.49)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Link to SWAT (1.p. 4)	No – link to other model	No – link to other model
Irrigation Demand	Based on FAO56	FAO 56 (1. p.109)	ASCE Pen-Mont (2.p.3)	Jensen-Haise eq. (p. c-2)	N/A	N/A	[probably] FAO 56 (1.p.56)	Blaney Criddle eq. (p. 2-10)	FAO 56 (4.p.4)	Link to AquaCrop (1.p.4)	No	No
Water Quality Modeling	DO, BOD, Temp. Link to Qual2k	BOD, DO, NH4, NO3, P, user defined, (1. p165)	N/A	N/A	DO, TDS, TDG, Temperature (p. 1)	N/A	N/A	N/A	Salinity, Turbidity, Temp, etc (1.p.31)	N/A	Yes – up to three conservative constituents	No – link to other model
Groundwater Modeling	Link to MODFLOW Link to MODPATH	Linear reservoir (1&2 aquifer) (1.p.50)	Link to MODFLOW (3.p.33)	N/A	N/A (p. 117)	N/A	MODFLOW* (1.p.iii)	N/A	N/A	N/A	No	No
Reservoir Operation	YES	YES (1. p.132)	YES (1.p.254)	YES (p.1-5)	YES (p. 1)	YES	N/A	YES (p. 2-3)	YES (1.p.48)	N/A	Yes	Yes
Financial Analysis	Simple Cost - Benefit	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No	No
Internal Scripting Interface	VBS, PHP, Ruby, Python, Perl, JS	N/A	Self-developed commands (3.p.227)	N/A	RiverWare Policy Language (p. 1)	Jython (2.p.14-49)	N/A	N/A	YES, REALM macro language (3.p.2)	N/A	Yes OCL (Operations Control Language)	Yes WRESL (Water Resources Simulation Language)
Hydropower Modeling	YES	YES (1. p.147)	N/A	YES (p.1-5)	YES	YES (2.p.11-44)	N/A	N/A	N/A	N/A	Yes	Yes
Calibration Algorithm	PEST Algorithm	SCE, PSE (2. p. 24)	TBD	N/A	N/A	YES but Unknown (2.p.14-39)	UCODE_2014 (6.p.21)	N/A	N/A	N/A	No	No
Input Data	Manual Time series, [illegible]	.dfs0 and shapefiles	[illegible]	[illegible]	[illegible]	HEC-DSS time series	ASCII, istSOS, .sqlite,	[illegible]	[illegible]	[illegible]	Microsoft Access and	HEC DDS and text file

Short-Listed Models

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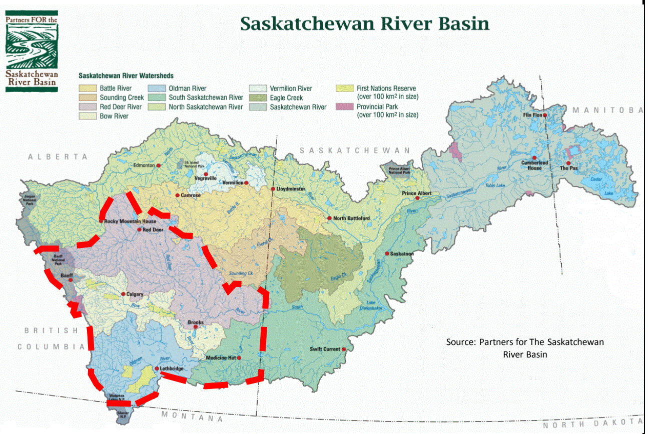
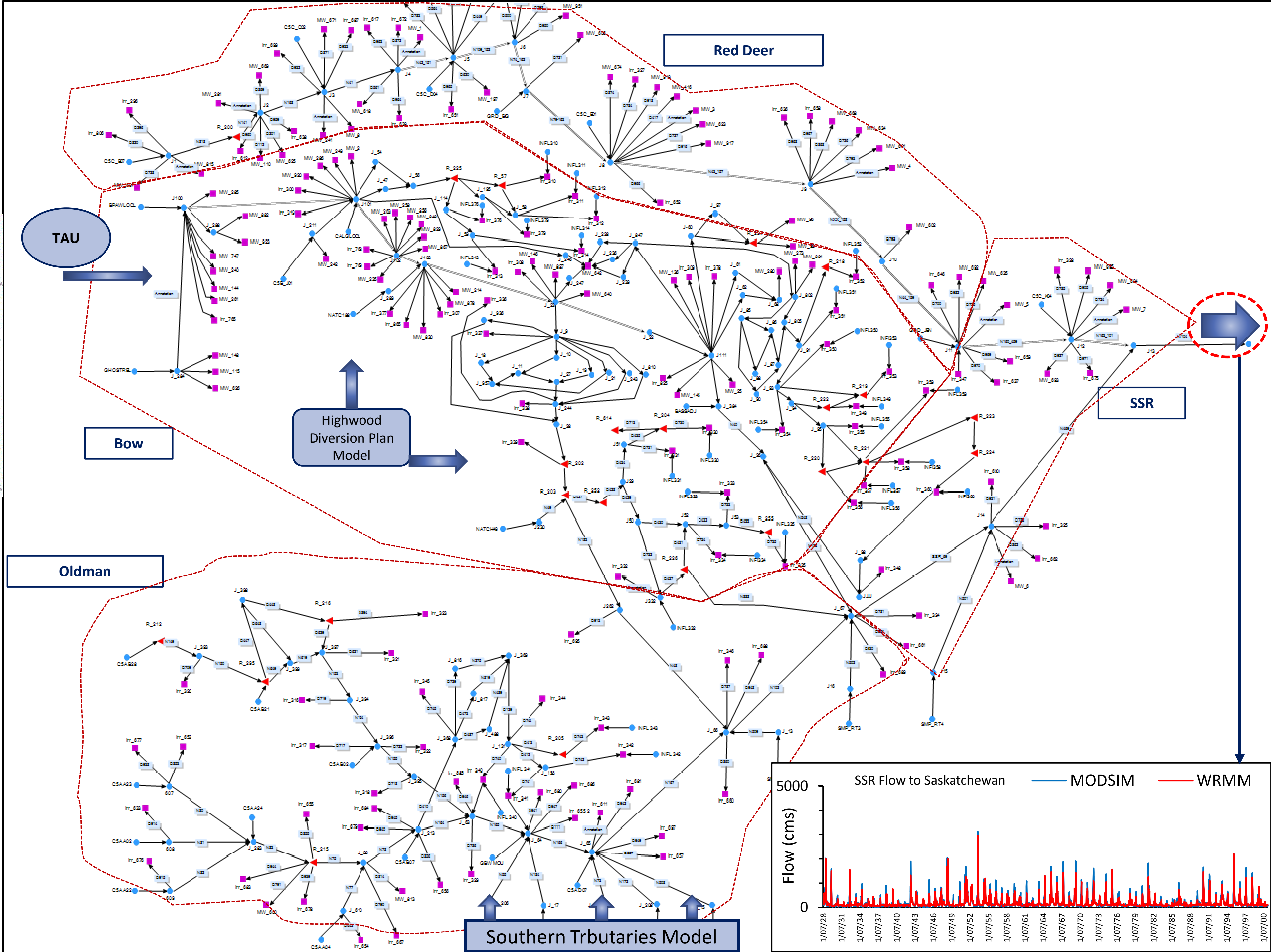
	WRMM	WEAP	MODSIM	WRIMS
Freeware	Not available for public use	\$250–\$1 000 for 2 year single license	Free	Free
Open source	No	No	No	Yes
Time step	1–365 days	1–365 days	15 minutes– 1 month	1 day or 1 month
GIS interface	No	Yes	Yes	No
Additional functionality	No	Rainfall-runoff, water quality, financial analysis	Link to external models	Linked to external DLLs- water quality, flow routing
Previously linked to other models	No	SWAT	SWAT, MESH, QUAL2K, GA, PSO, ANN	IWFM, CalLite, PRISM, APSIDE, DSM2-SJR
Automation	Yes	Yes	Yes	Yes

Important Criteria:

- Open Source
- Free for Public Use
- Flexibility in representing operating policies
- potential for extension
- Technical Support

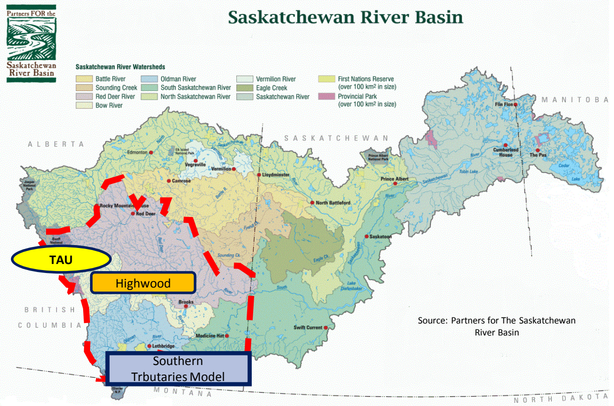
MODSIM-DSS (Progress To Date)





Mustakim Ali

MODSIM-DSS (Progress To Date)



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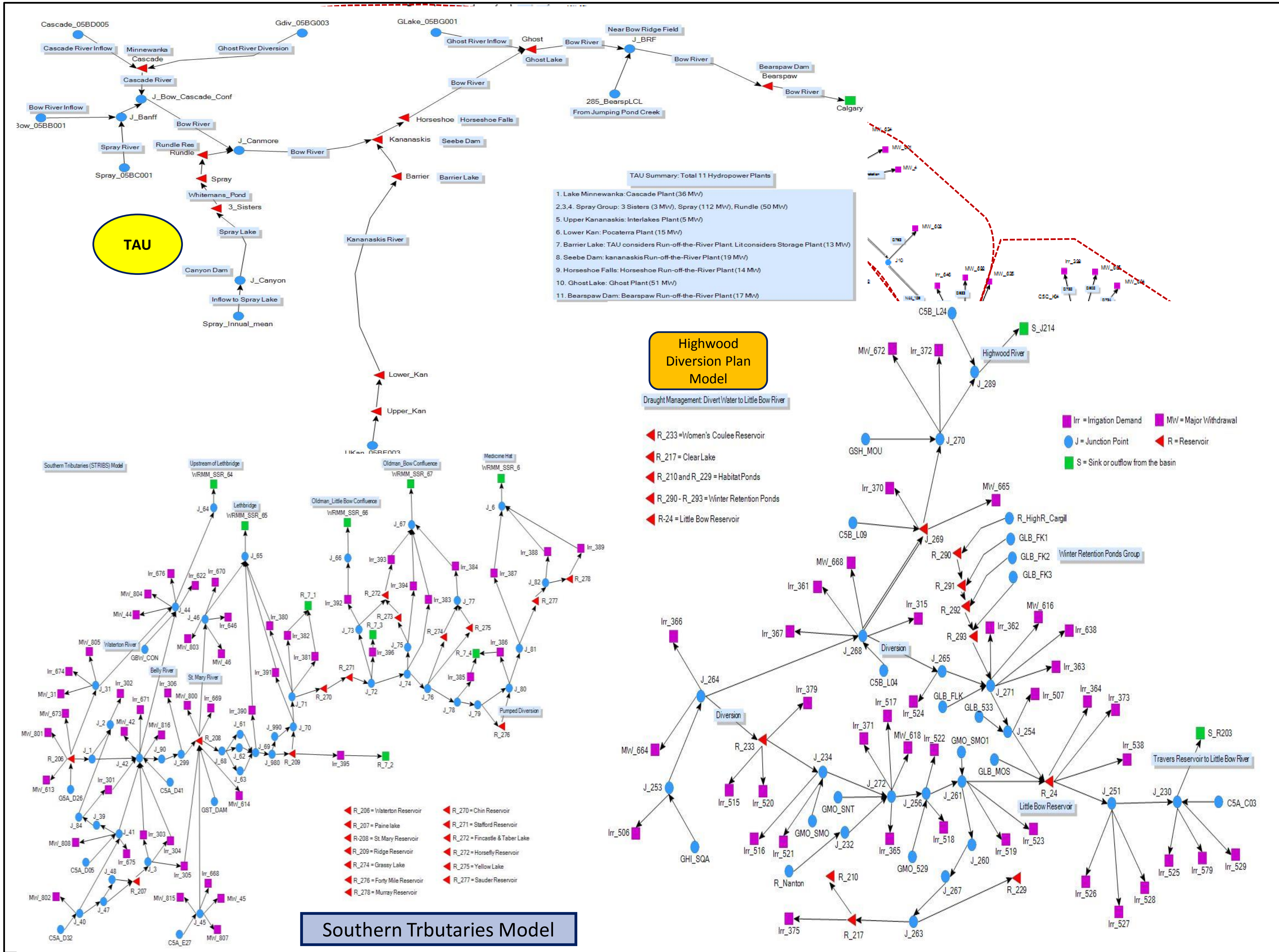
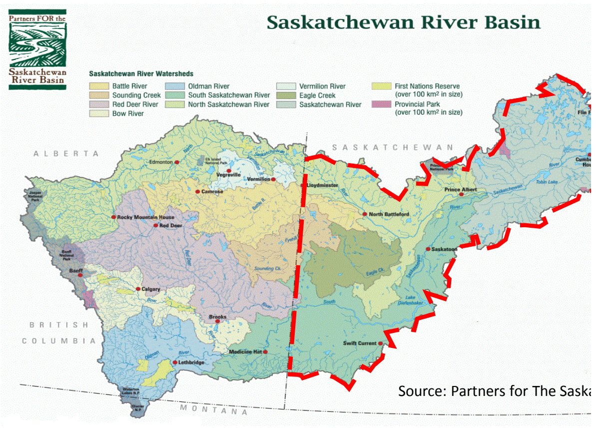


MODSIM-DSS
(Progress To Date)



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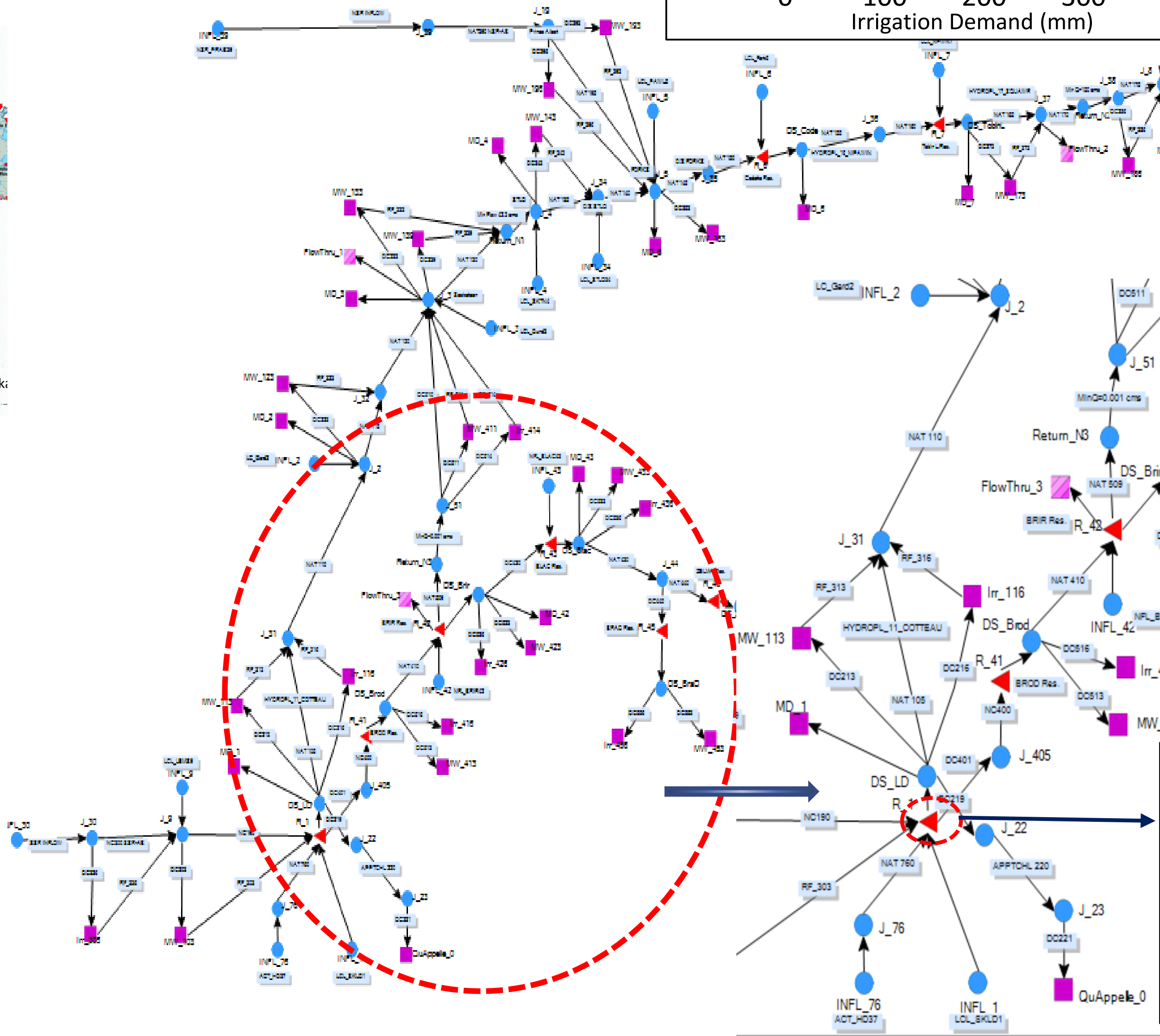

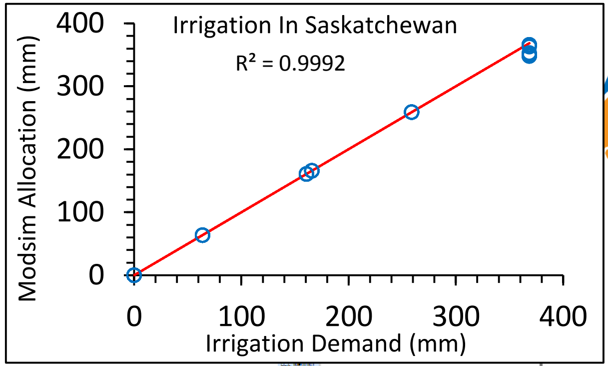

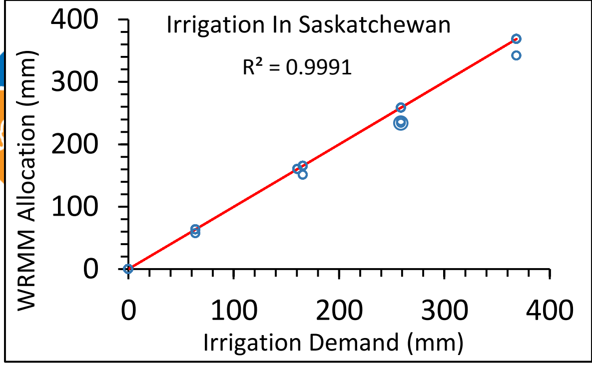

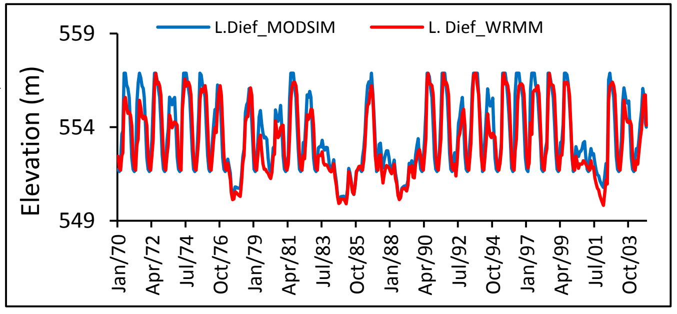

WEAP
(Progress To Date)

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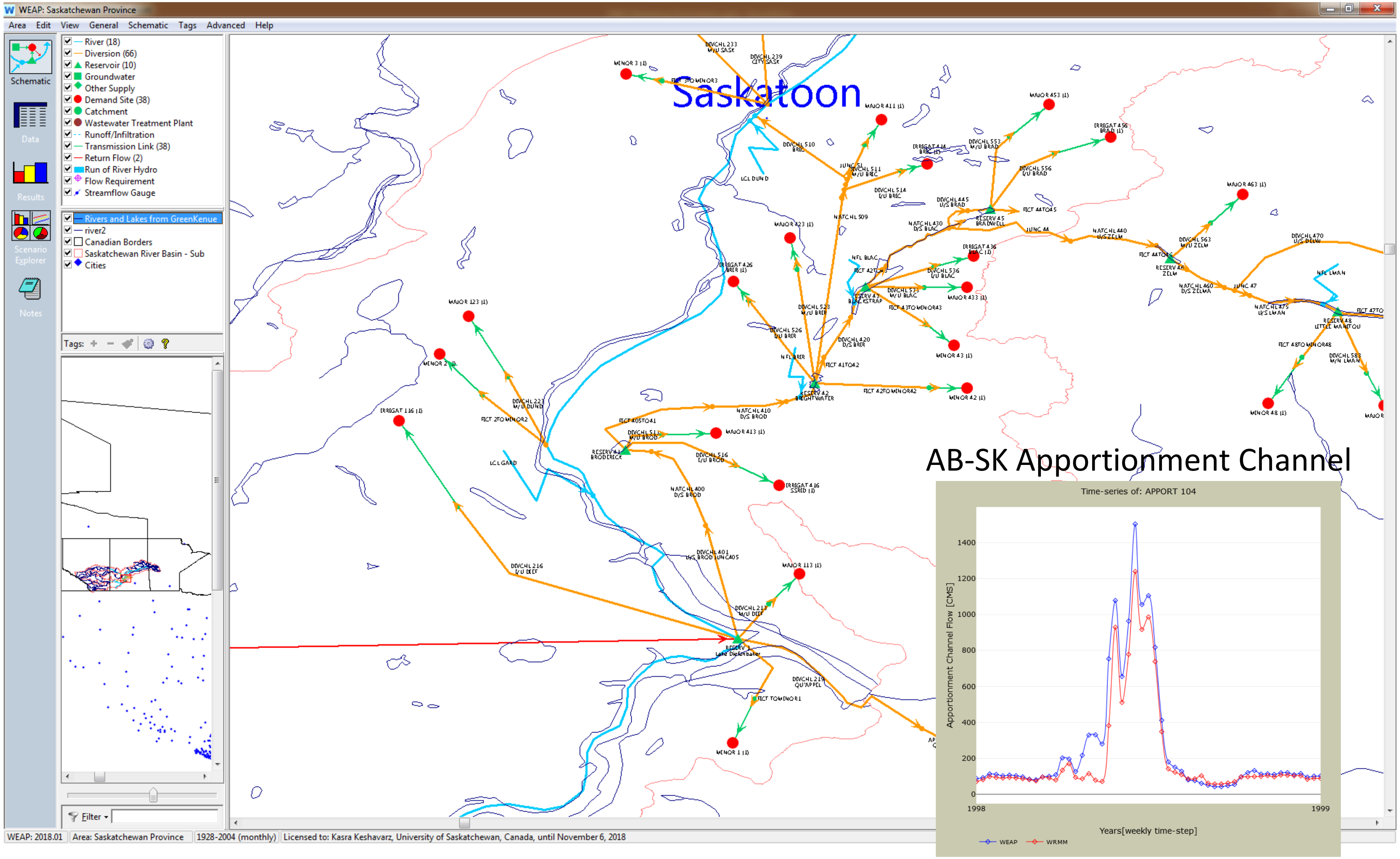

Kasra Keshavarz

WRIMS: Water Resource Integrated Modeling System

(Progress To Date)

- Developed by California department of Water Resources.
- Called CALSIM, in applications to California.
- Instead of a GUI, based on the Water Resources Simulation Language (WRESL) for flexible operational criteria specification.

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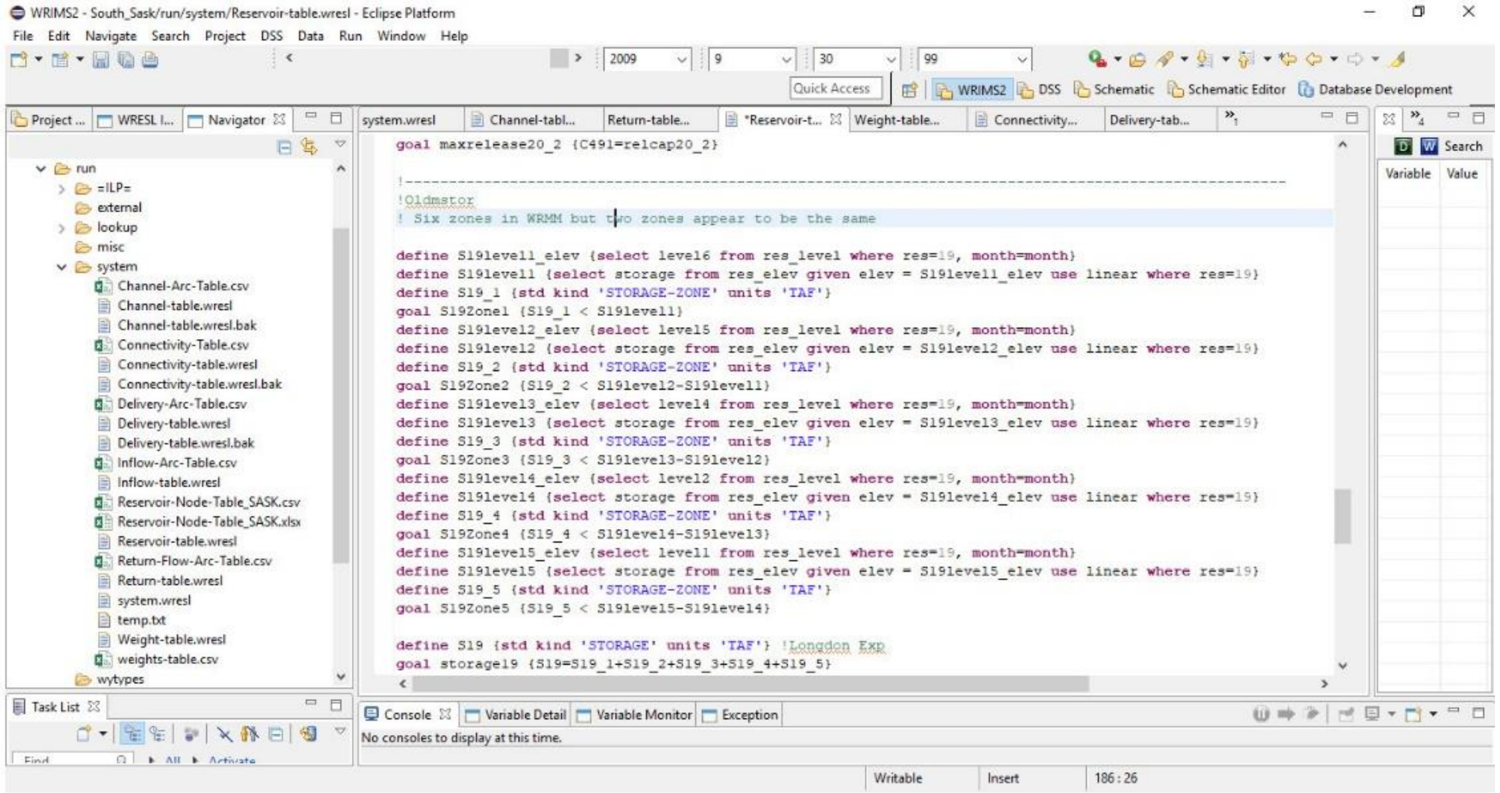

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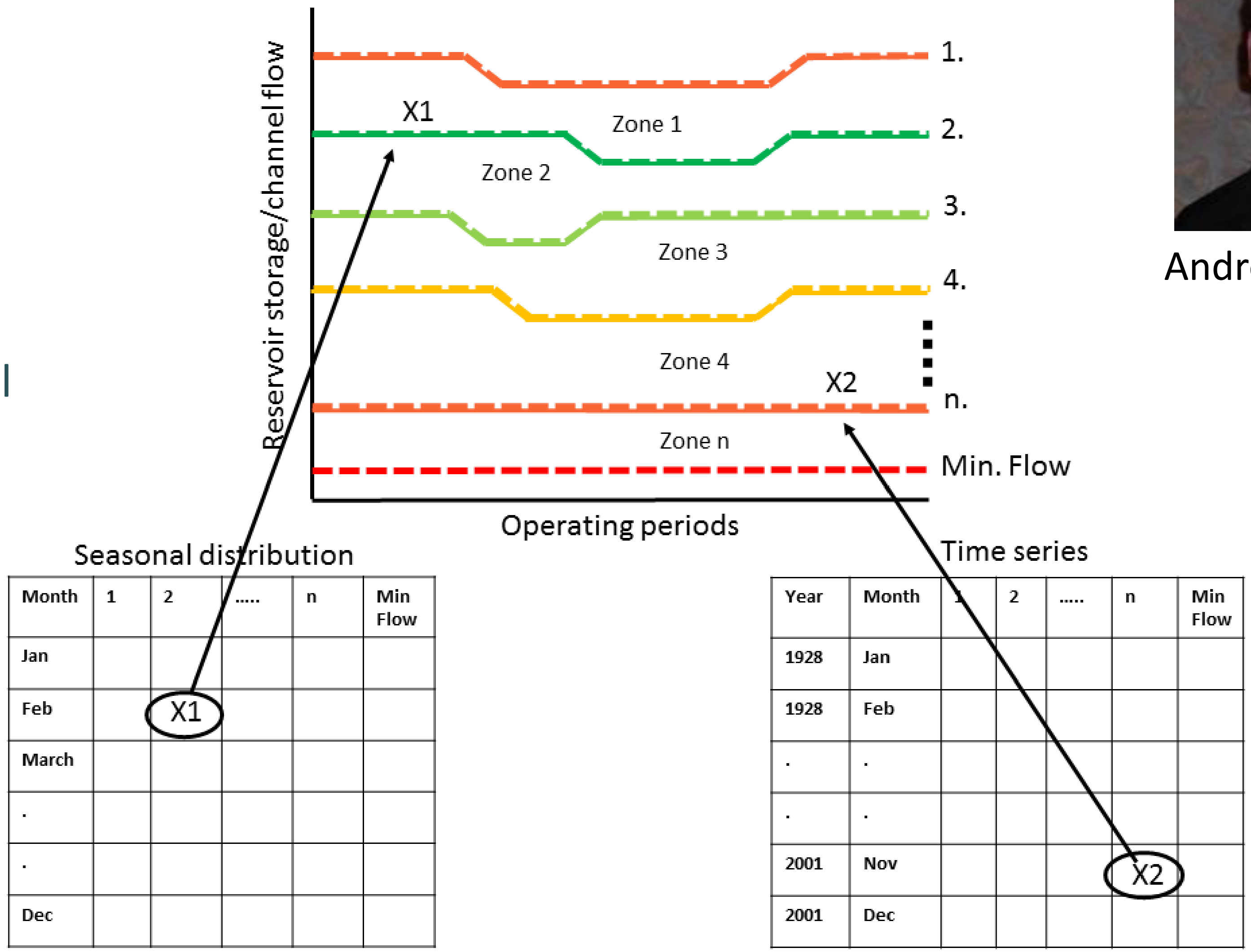
WRIMS: Water Resource Integrated Modeling System
(Progress To Date)

- WRIMS can represent the complex WRMM operating policy for SaskRB
  - Unlimited number of operating zones
  - Unlimited priorities
  - Apportionment channel
- River Routing
- Uses database system designed for efficient storage and retrieval
- Debugging facilities
- Link to external models



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WRIMS: Water Resource Integrated Modeling System
(Progress To Date)

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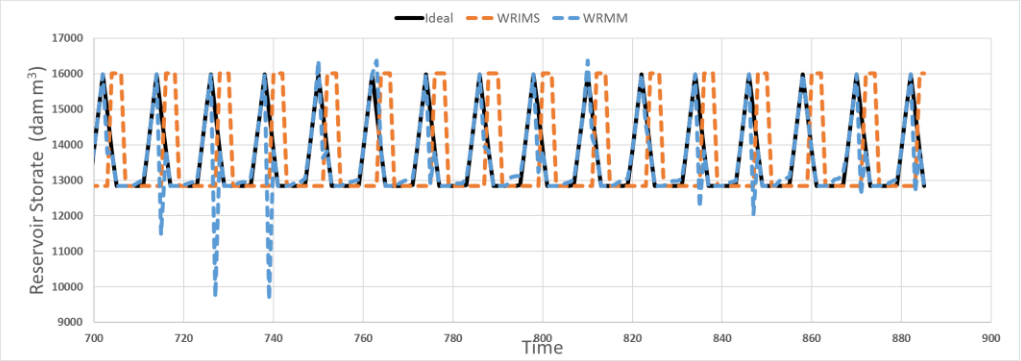
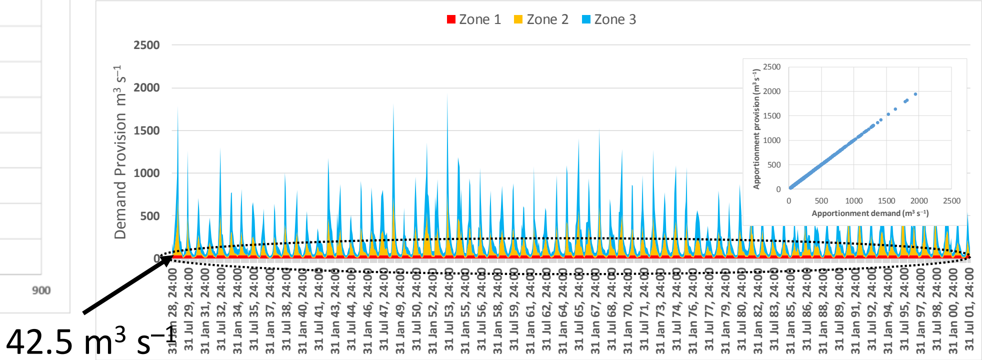
Some Preliminary Model Results

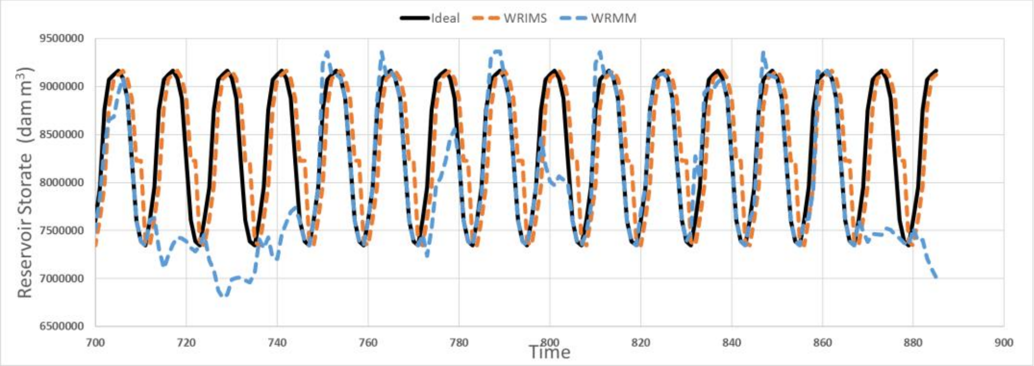
Simulated Broderick Reservoir Storage



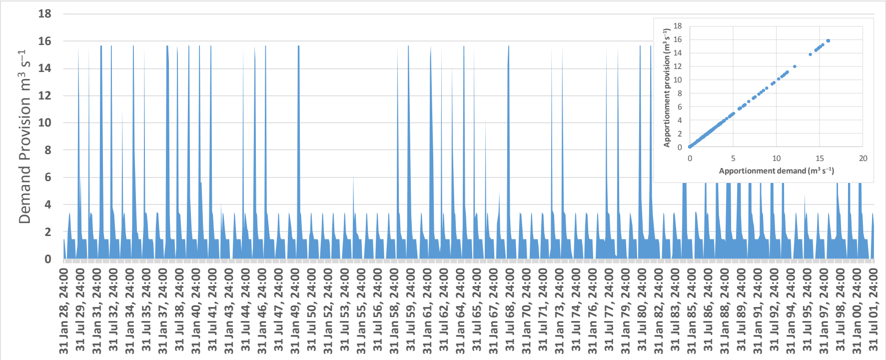
Alberta Apportionment Channel



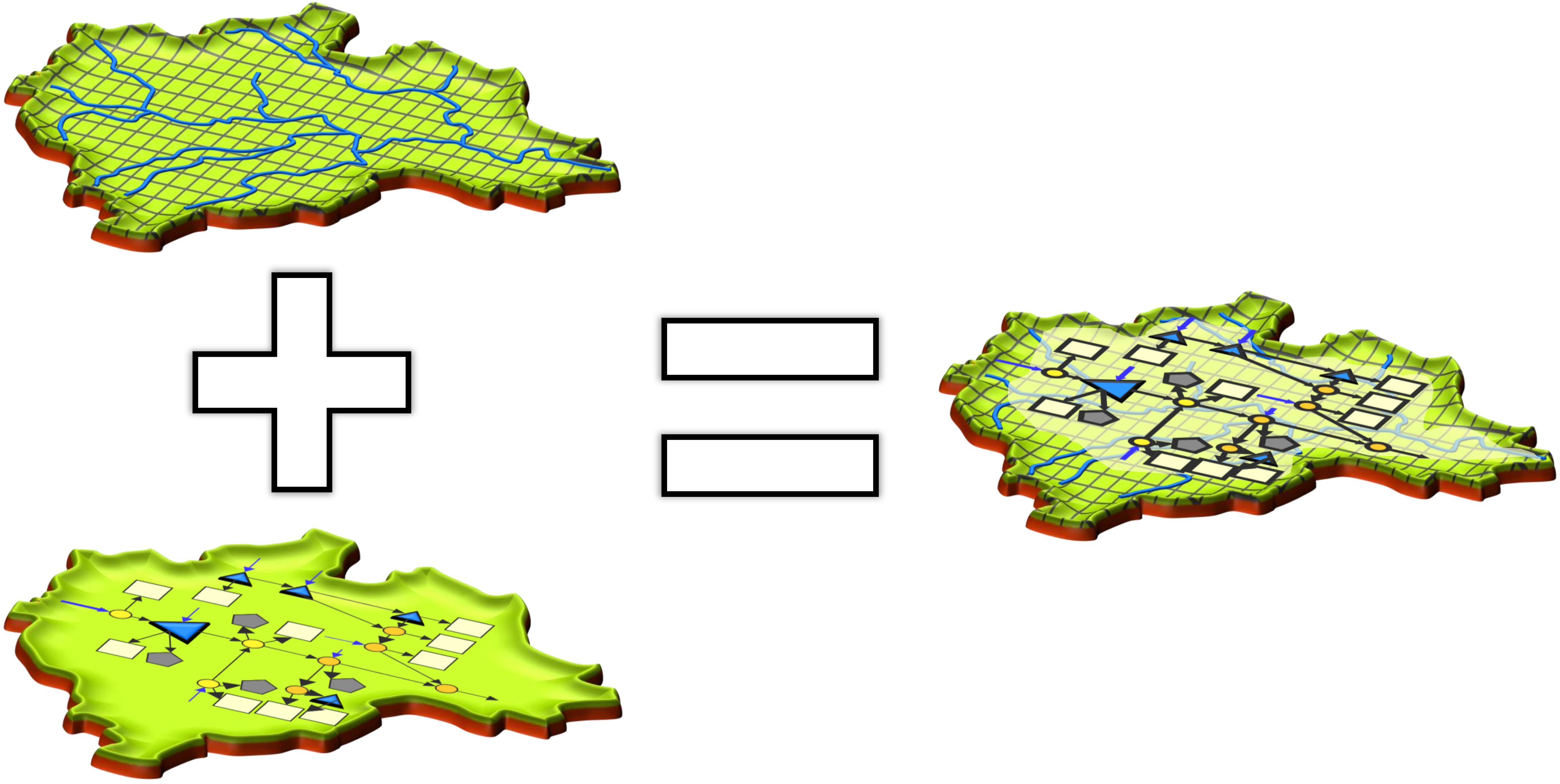
Simulated Lake Diefenbaker Storage



Saskatchewan Apportionment Channel



Coupling Hydrology and Water Management



Coupling Hydrology and Water Management

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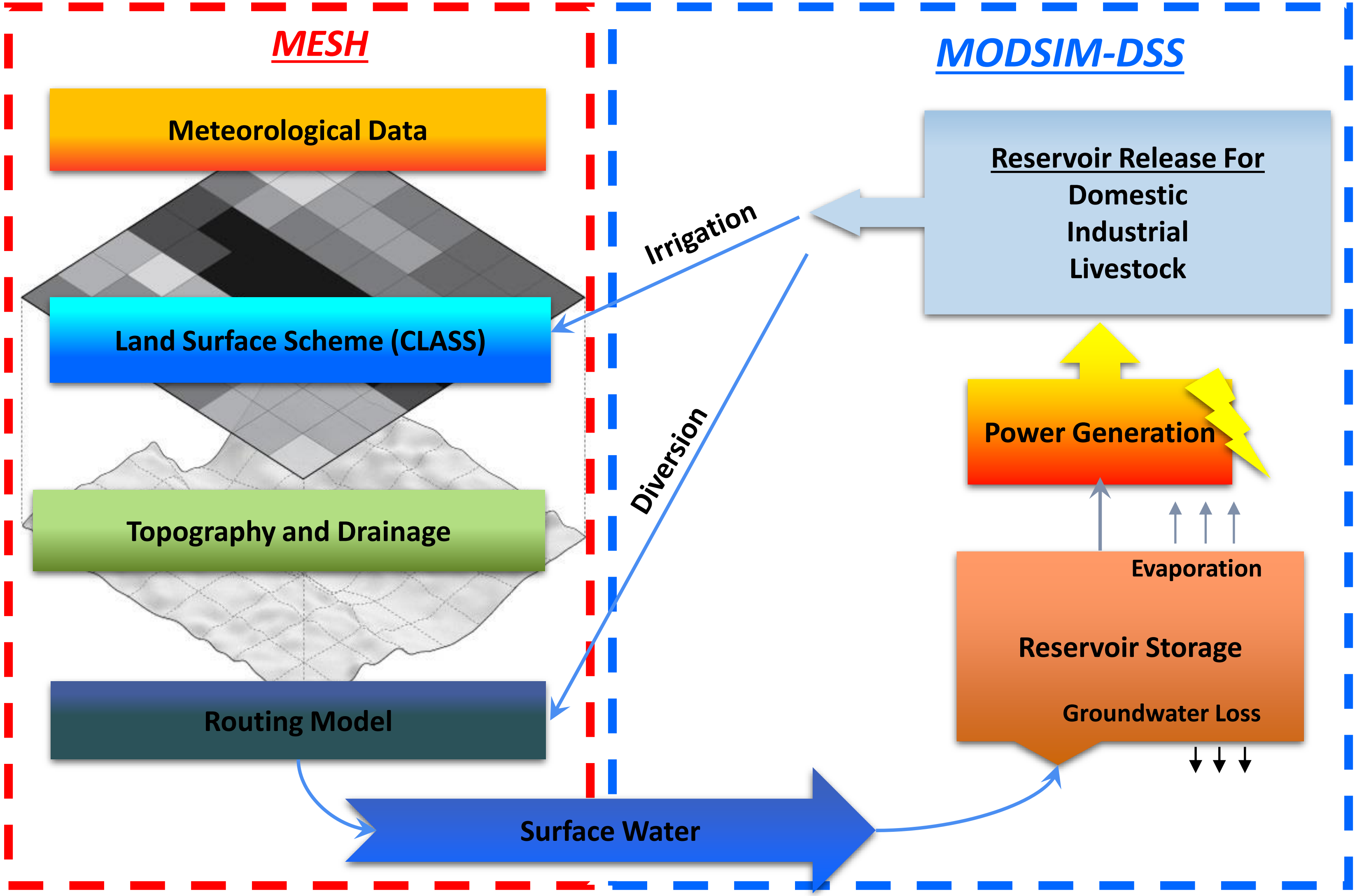

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Ideas for the Development of the Framework for Decision Support

The Four Elements
to be considered for decision support

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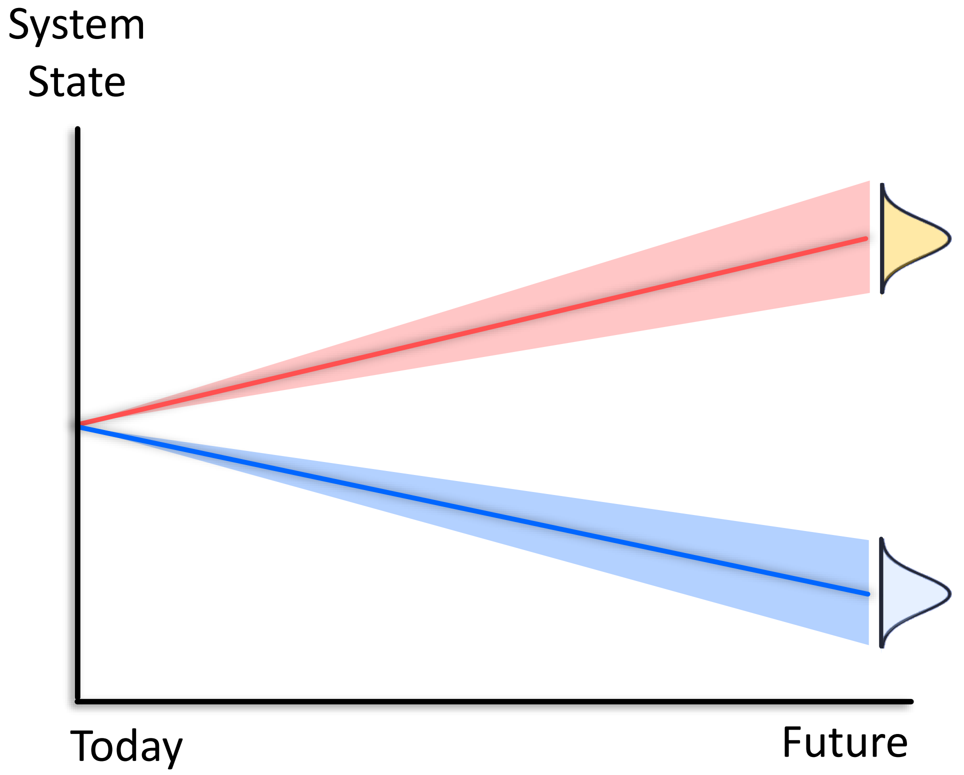
(1) Future States of the World

A future with deep uncertainty as a result of drivers such as climate, technological, socio-economic, and political change.

- Drivers out of control of the decision makers
- Need for a range of plausible future scenarios
- Need for addressing both local and global uncertainty
- Examples include:
  - Supply/climate change scenarios (inflows, precipitation, temperature, etc.)
  - Demand scenarios (population growth, irrigation expansion, etc.)
- Inputs from Changing Cold Regions Network (CCRN)



Maier et al. (2016 EMS); Herman et al. (2015 WRPM)

The Four Elements
to be considered for decision support

(1) Future States of the World
(2) Decision Alternatives

- Controllable by our decision makers:
  - They may be pre-specified by the decision makers
  - or be based on search via optimization or sampling (experimental designs)
- These include development, management, or adaptation scenarios (static/dynamic):
  - Non-Structural/Operating Scenarios (alternative operating rules, license sharing, conservation strategies, etc.)
  - Structural Scenarios (new reservoir, diversion, levee, irrigation expansion, etc.)
- These need to be built in or coupled with "the water management model"

The Four Elements
to be considered for decision support

(1) Future States of the World
(2) Decision Alternatives
(3) Performance Metrics

How the system will perform with a *decision alternative* under a *given future state of the world*.

- Hydro-economic indicators (B3) and indicators for environmental and cultural flows (B2)
- Classic metrics such as reliability, vulnerability, and resilience
- Trade-offs

(4) Robustness Metrics

How the system performance will be *insensitive to deviations* from the state(s) or assumptions the system was designed for.

- Satisficing: *Not seeking optimal performance*, but meeting sufficient requirements.
- Regret-based: minimizing the cost or implications of incorrect decisions.

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Two Recommendations from Herman et al. (2015, WRPM)

Herman, J. D., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2015). How should robustness be defined for water systems planning under change?. *Journal of Water Resources Planning and Management*, *141*(10), 04015012.

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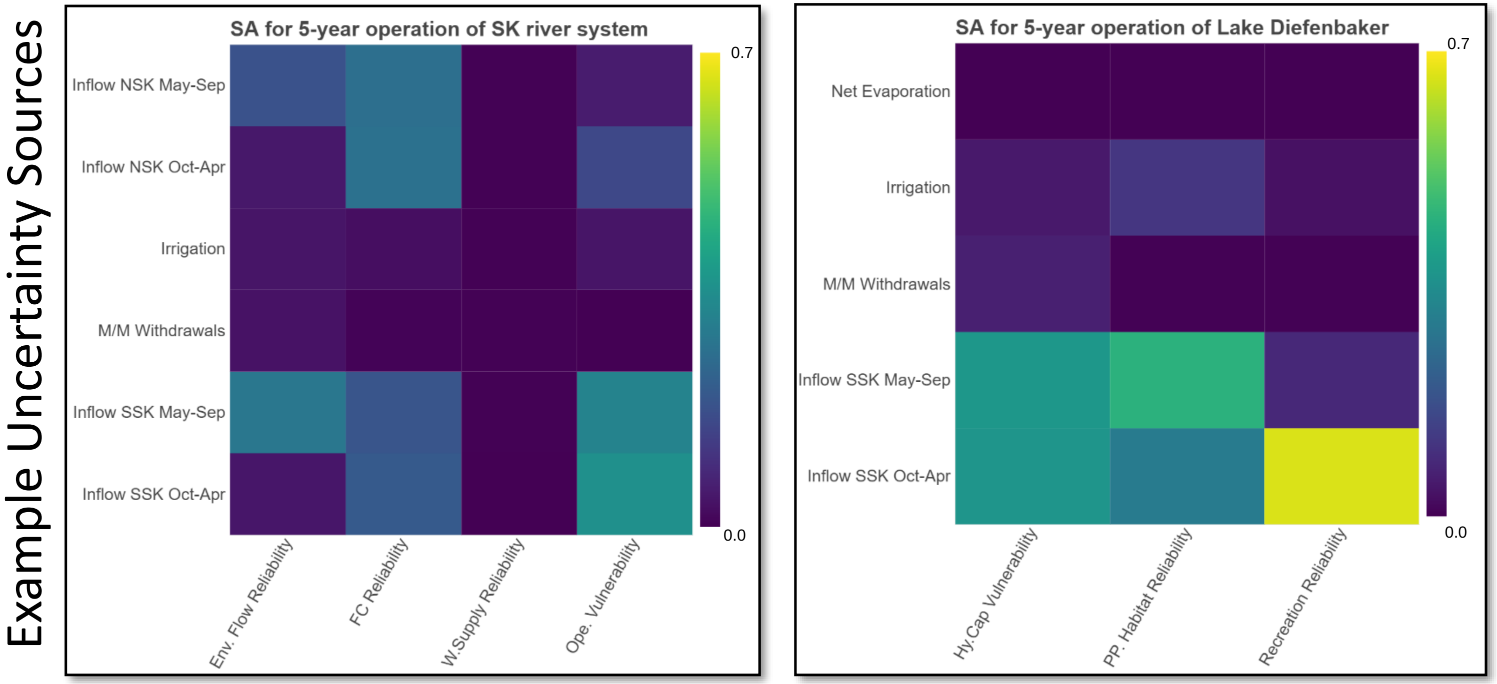
(1) Decision alternatives should be searched rather than pre-specified.

(2) Dominant uncertainties should be discovered through sensitivity analysis rather than assumed.

Nhu Do

Some very preliminary Results for SK



Example Performance Metrics

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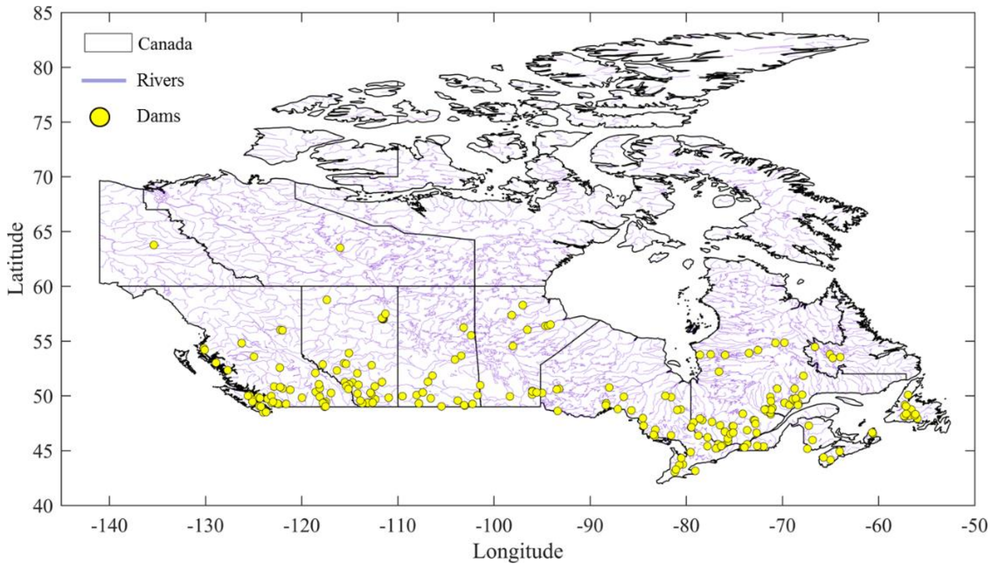
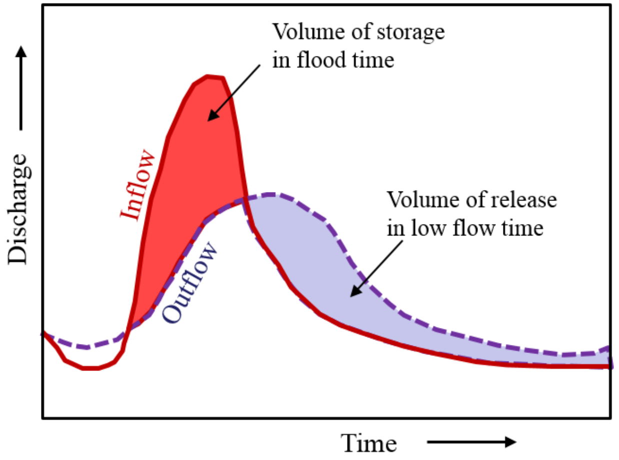
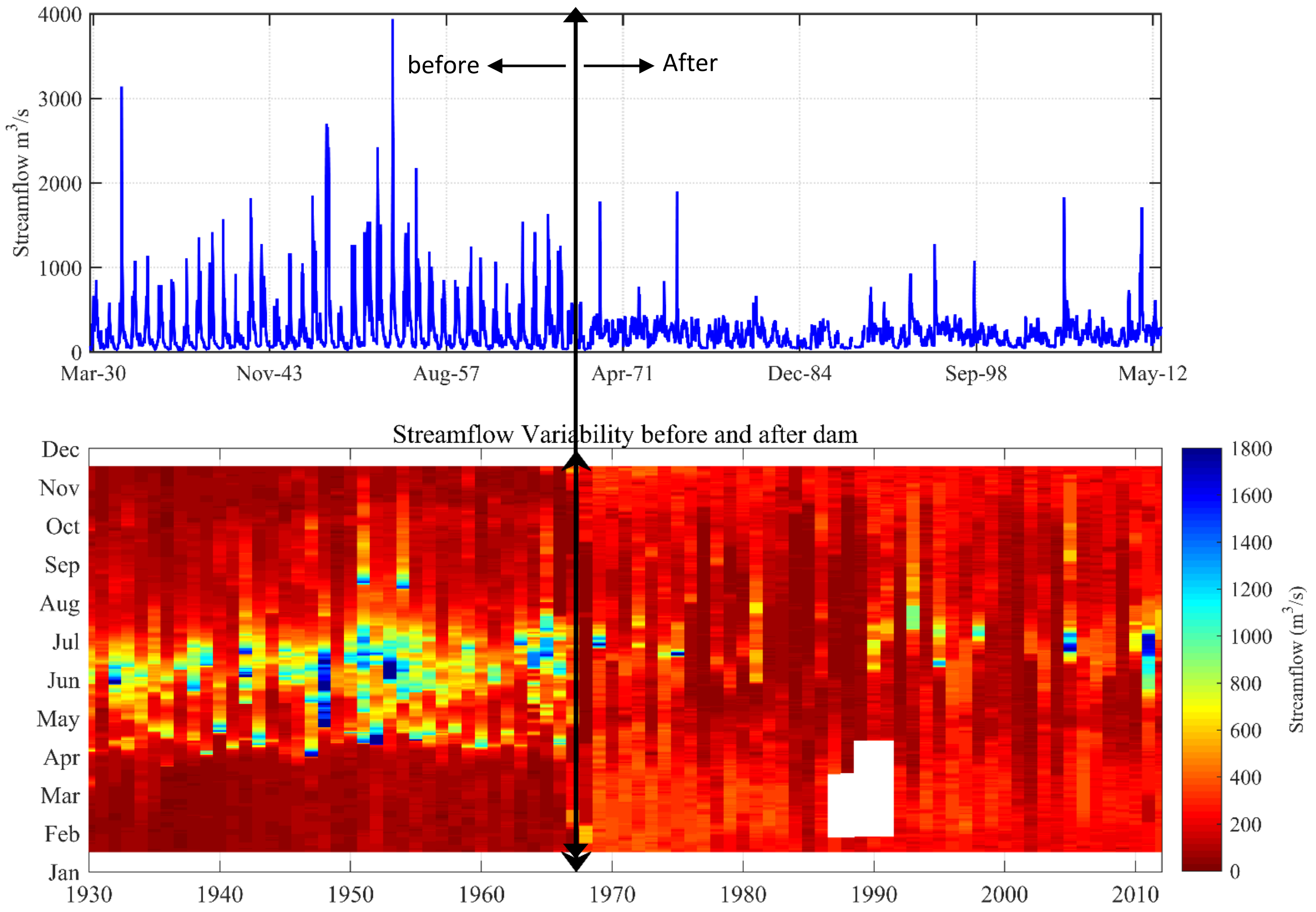
Our watersheds are heavily regulated…





Lake Diefenbaker



Challenges

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- Institutional Fragmentation: the lack of coordination across federal, provincial and local level of governments. The direction of the fragmentation is both ‘vertical’ and ‘horizontal’ (Renzetti and Dupont, 2017).

- Poor linkage between advanced hydrologic modelling, water systems modelling, and decision making processes.

- Economics have played relatively limited role in Canadian water resources management in the past (Renzetti and Dupont, 2017).

- The complexity of water resources systems, especially due to uncertainty in human behaviour and political processes.

Objectives

- Develop a high-fidelity water system/management model to simulate basin-wide system performance across Sask-Nelson River Basin under (1) various hydro-climatic conditions and (2) current and alternative futures of water policies and infrastructure.
    - ✓ This model will simulate alternative human behaviours in operations and governance (different policy options), and interventions into the hydrologic system (new inter- and intra-basin transfers, reservoirs, irrigation, etc.).
- Couple the water resource system model with the state-of-the-art land surface-hydrology and water quality models.
- conduct "participatory modelling" where stakeholders are engaged in and contribute to the co-development of the model from beginning to end to ensure the transparency of the underlying assumptions, strengths and limitations, and intended uses (linked to Theme C).

Bringing the pieces together …

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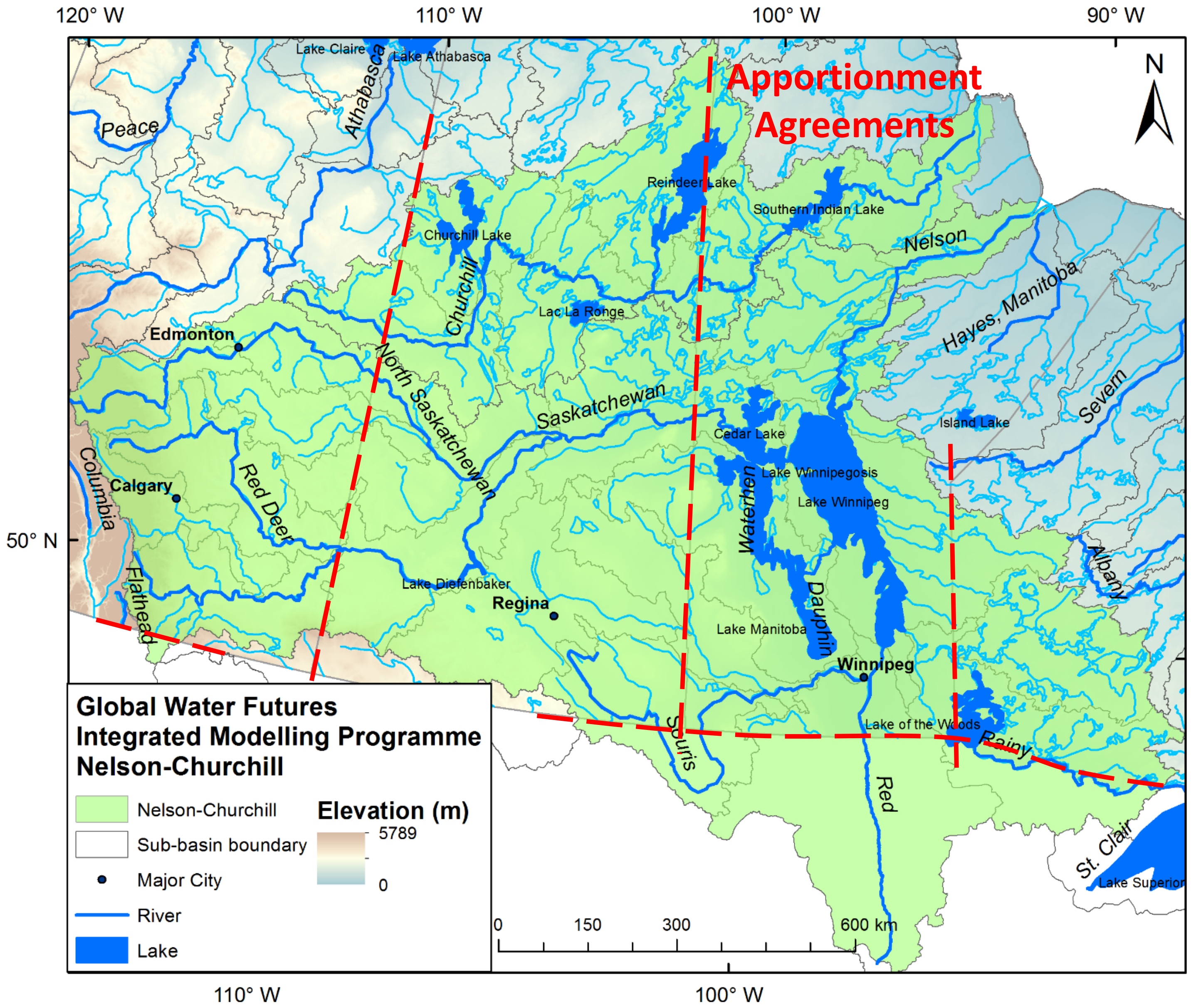

Water Management Issues:

- Transboundary water issues,
- “Localized” approach to water management,
- Indigenous water needs,
- Over-allocation and competing demands,
- Environmental flows, etc.

Hydrologic Prediction Issues:

- Complex hydrology (Rockies, prairies, boreal forest),
- Floods and drought,
- River ice,
- Lakes and wetlands,
- Heavily regulated catchments,
- Land cover change & atmospheric feedback loops, etc.

Water Quality Issues:

- Eutrophication and nutrient transport,
- Algal blooms,
- Manure and fertilizer application,
- Contamination due to oil and gas extraction, etc.

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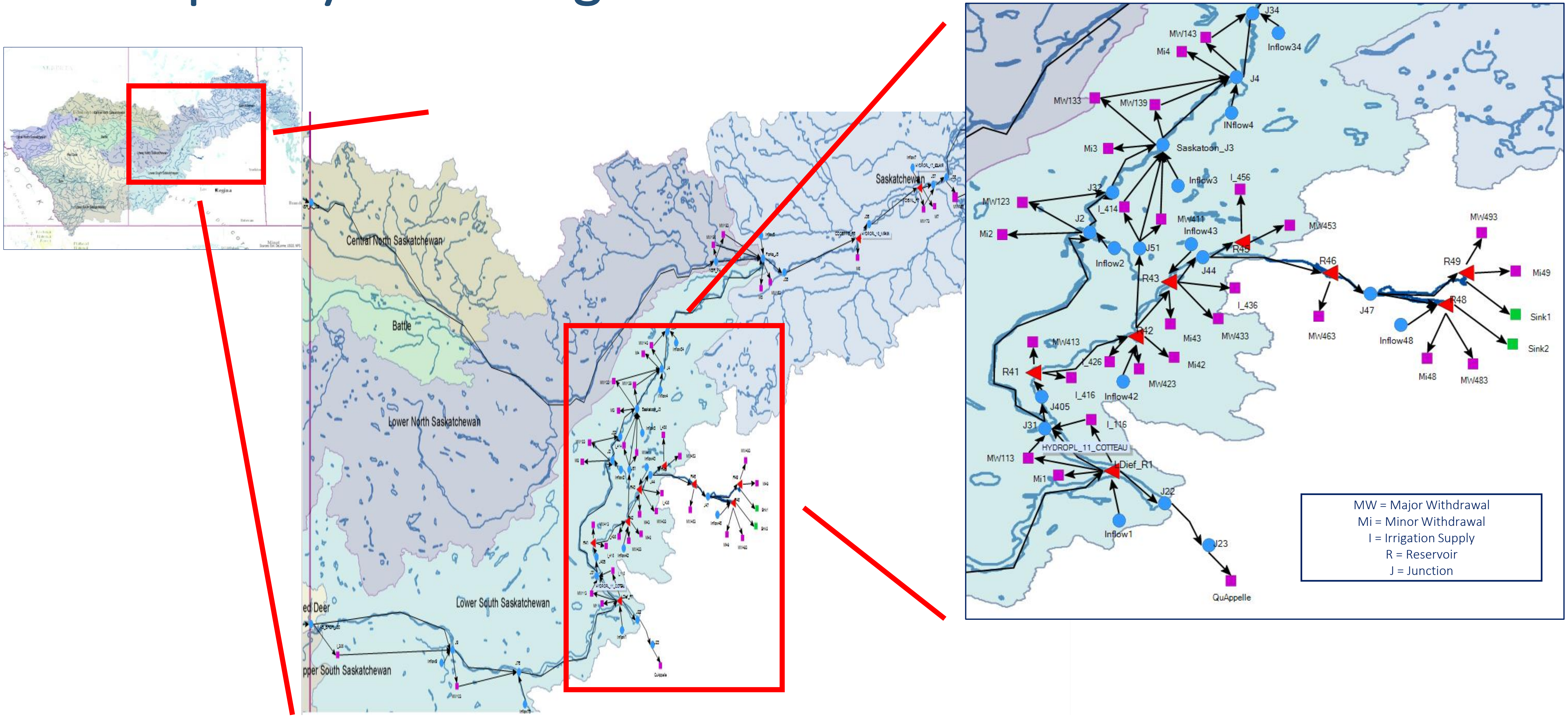
Preliminary Modelling Started to be Brought in Participatory Modelling …



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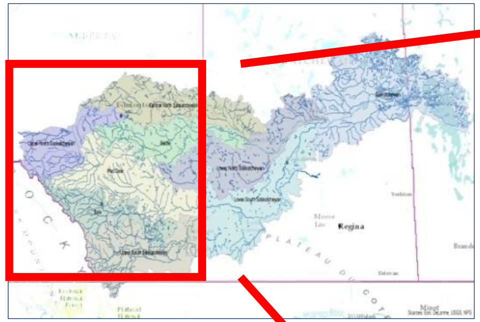
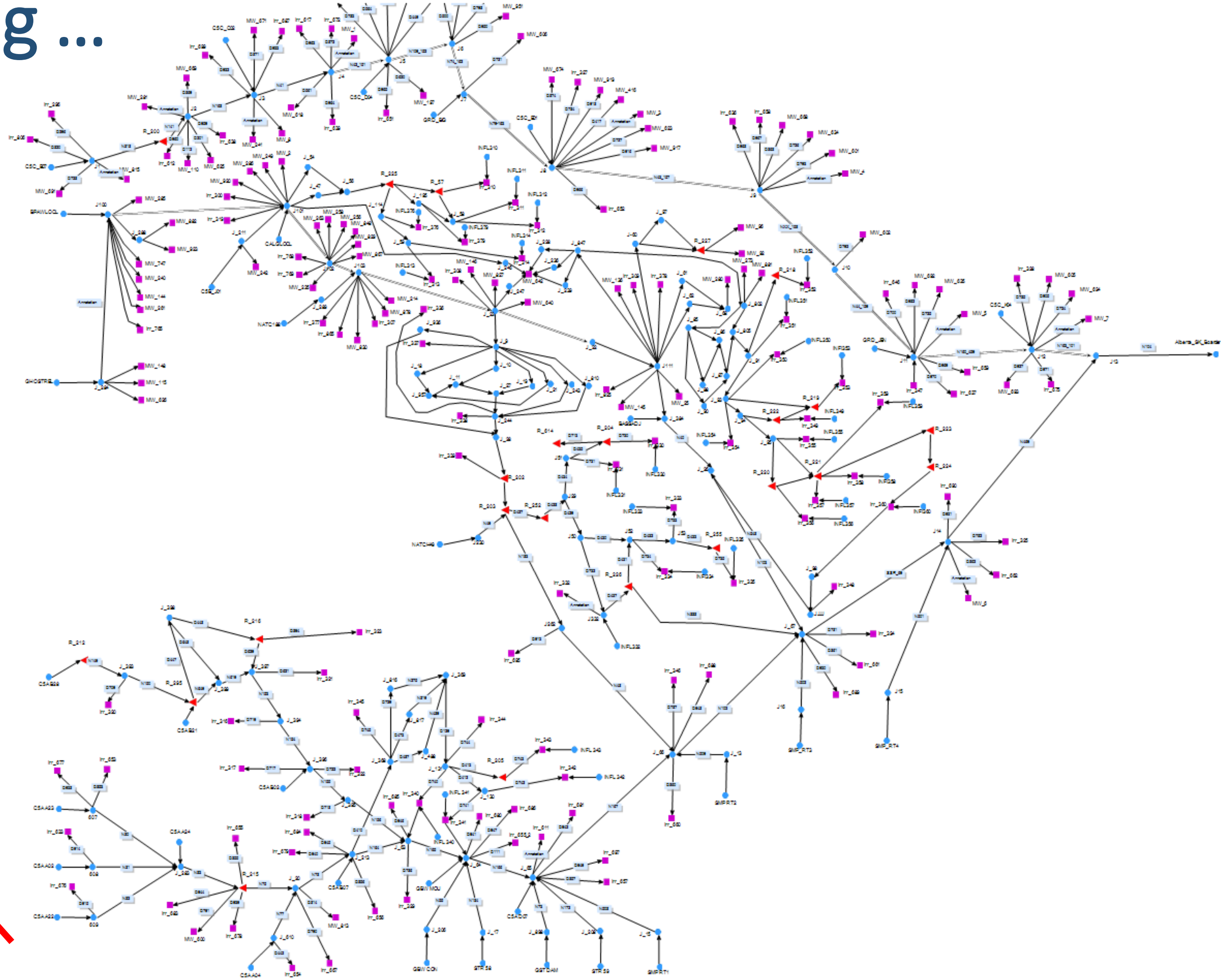
Preliminary Modelling Started to be Brought in Participatory Modelling …



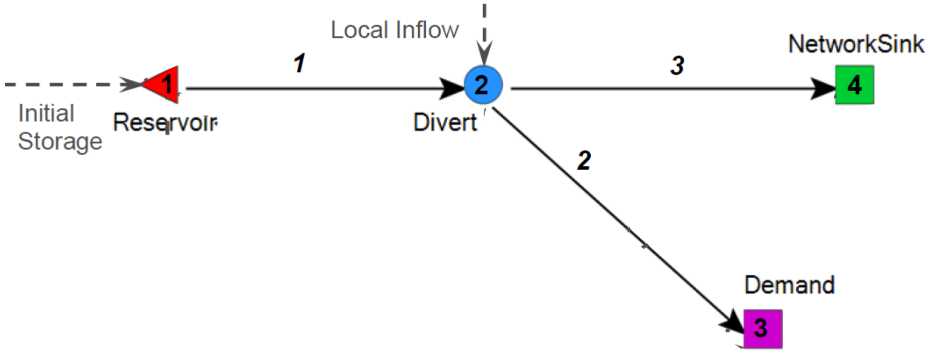


MODSIM-DSS and WEAP:
River Basin Management Decision Support Systems

- Based on Network Flow Algorithms.

- Modellers are only responsible for defining the physical flow network.

- All artificial nodes and links are added automatically by the model.



Network Flow Algorithm

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MODSIM simulates water allocation mechanisms in a river basin through sequential solution of a network flow optimization problem for each time period *t* = 1,...,*T* :

link cost → c_k; link flow → q_k

$$\text{minimize} \sum_{k \in A} c_k \, q_k$$

subject to:

$$\sum_{k \in O_i} q_k - \sum_{j \in I_i} q_j = b_{it}(\mathbf{q}) \quad \text{for all nodes } i \in N$$

$$l_{kt}(\mathbf{q}) \le q_k \le u_{kt}(\mathbf{q}) \quad \text{for all links } k \in A$$

Optimization is primarily conducted as a means of accurately *simulating* the allocation of water resources in accordance with operational priorities based on system objectives, operational experience, water rights, and other ranking mechanisms, including economic factors.

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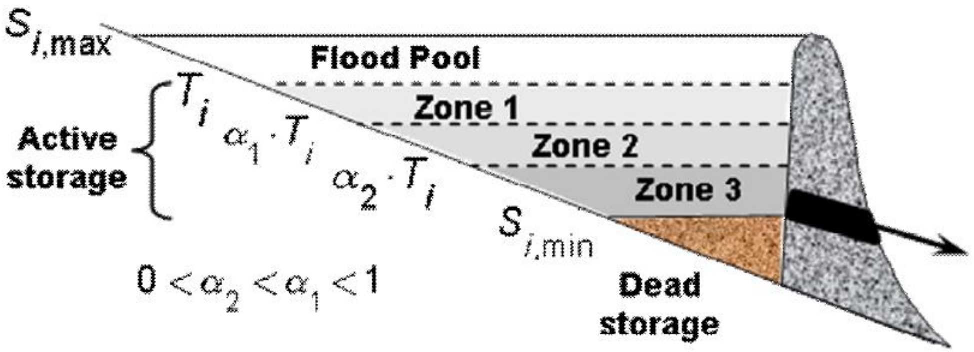
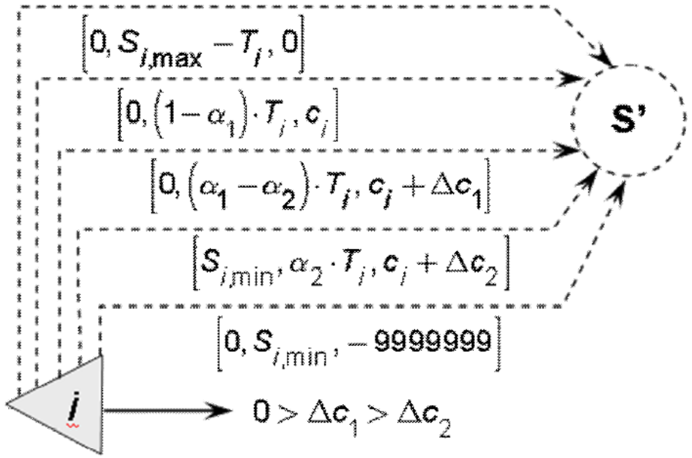
Reservoir Information and Priorities





Cost $c_i = -(50000 - 10 \cdot OPRP_i)$

Priority Number

where *OPRPi* is an integer priority ranking from 1 to 5000, with lower numbers indicating a higher ranking, resulting in a negative cost.

This priority (penalty function) concept applies to different (consumptive/non-consumptive) demands.

Two General Approaches

- Point-based Operation
  - Focused to address and satisfy local issues and needs
  - Minimal consideration about other elements in a watershed
  - Easy to implement and efficient to include in watershed models
  - Effective to reproduce the historical patterns of operation
  - Future operations?
- System-based Operation
  - From a systems perspective, tries to operate all the elements in a “system” together such that the benefits across the system is maximized.
  - More work and data to implement. Some previous attempts to include them in watershed models (difficult).
  - Is expected to better simulate what might happen in the future operations.
  - Powerful and commonly used tools for decision making and support.

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