GeoOttawa 2017, Ottawa, Canada, October 1-4, 2017

2016 Farvolden Lecture

Future regional groundwater resources management: integrated, connected, intelligent and intelligible

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INRS
UNIVERSITÉ DE RECHERCHE

Parallel Scientific Lives

- Multiphase flow and NAPL remediation (ARD, landfill gas, CO_2 sequestration…)
- Heterogeneity characterization of local aquifers and contaminated sites
- Shale gas environmental issues
- Study of regional aquifer systems and assessment of groundwater resources

Past Aquifer Assessment Projects

- Early days (1995 to 2008):
  - Projects in Quebec with GSC, Environment Ministry and INRS: Portneuf, Basses-Laurentides, Châteauguay, Amos Esker
  - GSC projects in Canada: Maritimes, Annapolis Valley, Prince Edouard Island
  - International CIDA project: HAP Ghana
  - Canadian military bases (training grounds)
- Since PACES start in 2009:
  - Montérégie Est, INRS & GSC
  - Chaudière-Appalaches
  - Milk River Aquifer (Alberta) (GSC project)
  - Estrie (in development)

Presentation Outline

- **Where are we?** Developments made in the study of regional groundwater resources in the past 20 years

- **What is next?** Towards integrated, connected, intelligent and intelligible management of water resources

The presentation is mostly restricted to the technical aspects of resource assessment and does not deal with governance

Objectives of Water Management

Water management must ensure:

• adequate supply	**Quantity**
• of good quality water to the population	**Quality**
• while preserving ecosystems,	**Ecosystems**
• by adapting human activities	**Governance**
• within the limits of nature	**Sustainability**

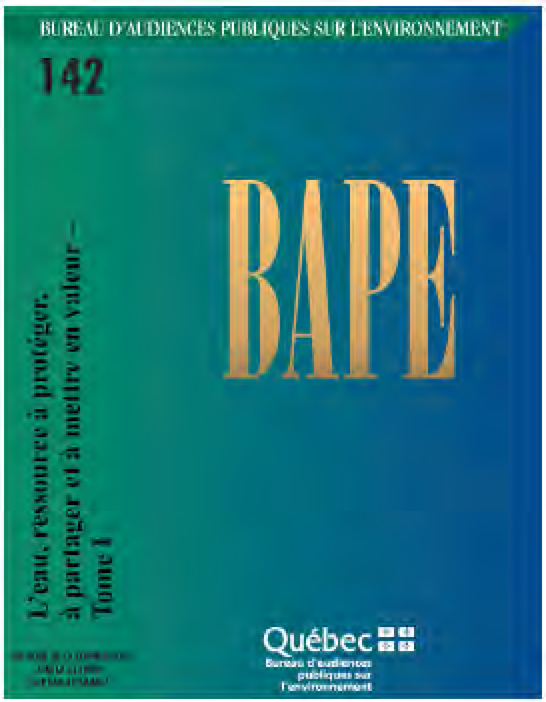
Adapter after UN Conference on Environment and Development
Rio de Janeiro, Brazil, 1992

Where are we?

Historical perspective on initiatives taken in Quebec

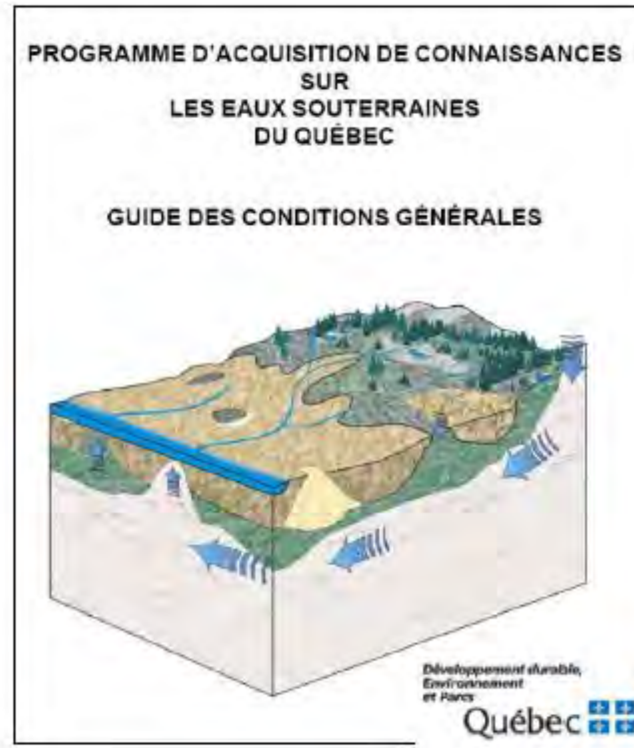
State and academic responsibilities

1. Consultation on water management (2000)



2. National water policy (2002)

3. Knowledge program (2008)



4. Inter-university research group to carry out assessments (2009)

Groupe de
Recherche
Interuniversitaire sur les
Eaux
Souterraines

Cloutier et al. (2014)

"Exemplary" initial regional projects

Projects carried out between 1995 and 2008 by the Geological Survey of Canada (GSC), the Quebec Environment Ministry and INRS: demonstrated the interest of such work and defined methodological approaches.

1. Portneuf 1995-1999

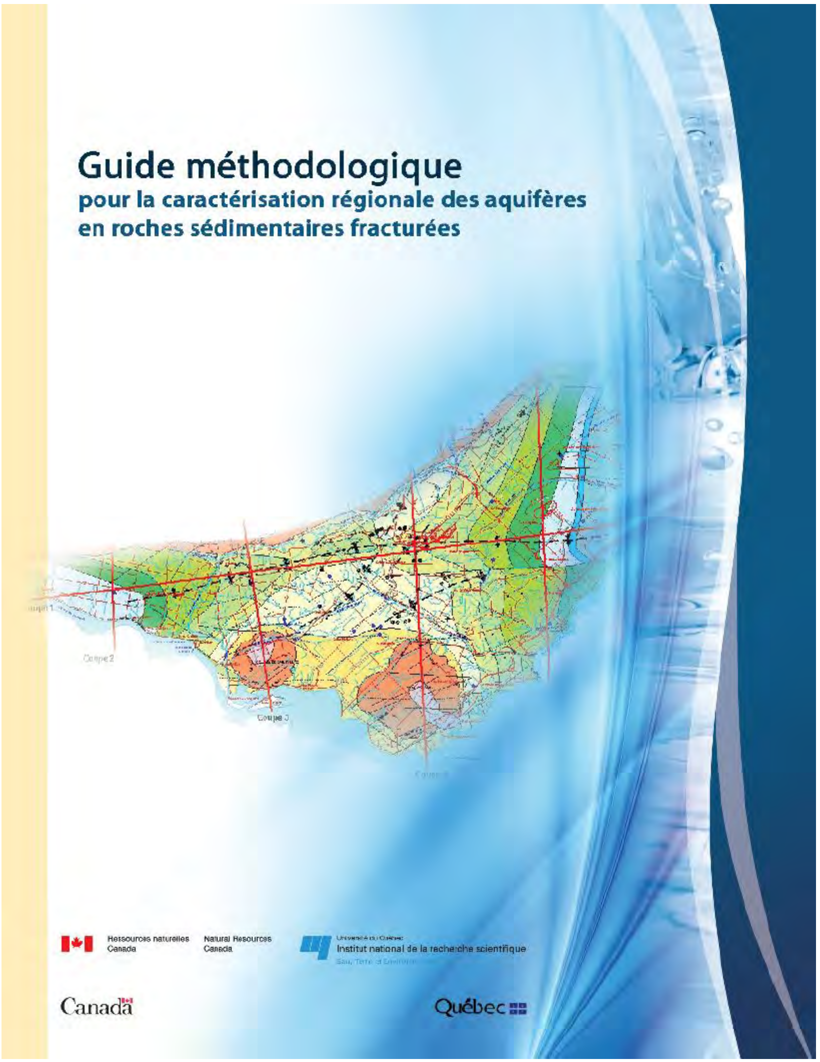
2. Basses-Laurentides 1999-2003

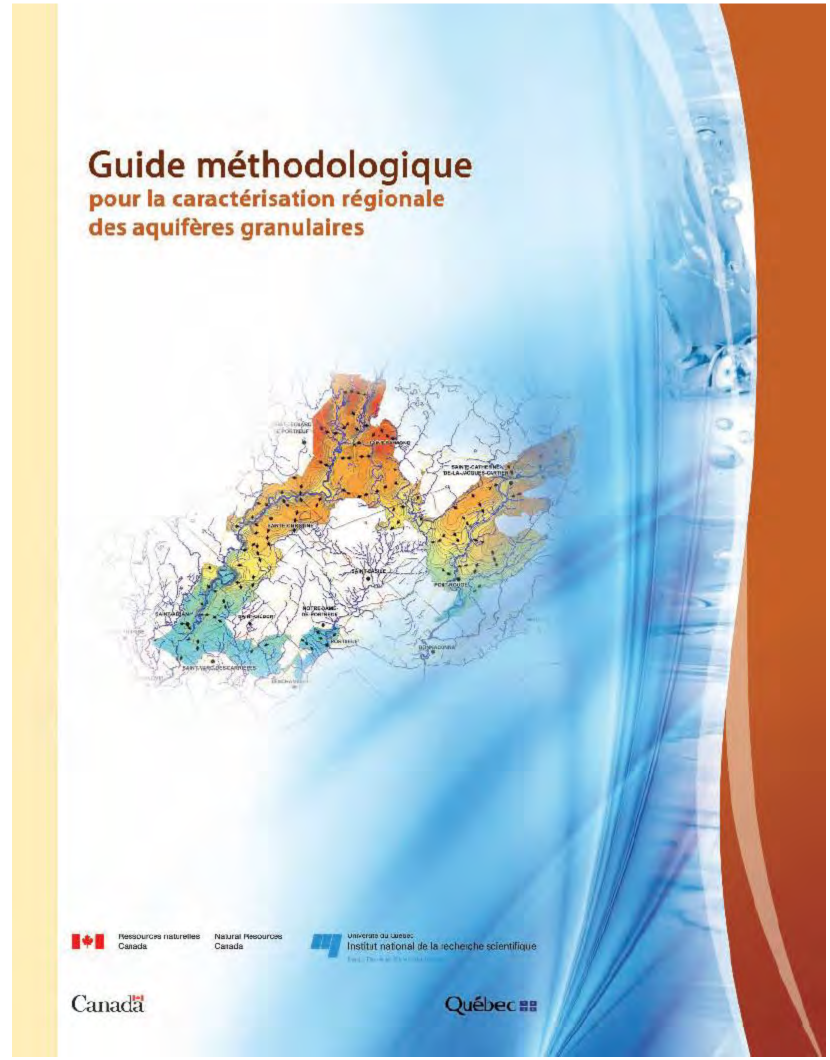
3. Châteauguay 2003-2006

4. Chaudière 2007-2008

After
Cloutier et al. (2014)

Hydrogeological mapping guides (2008)



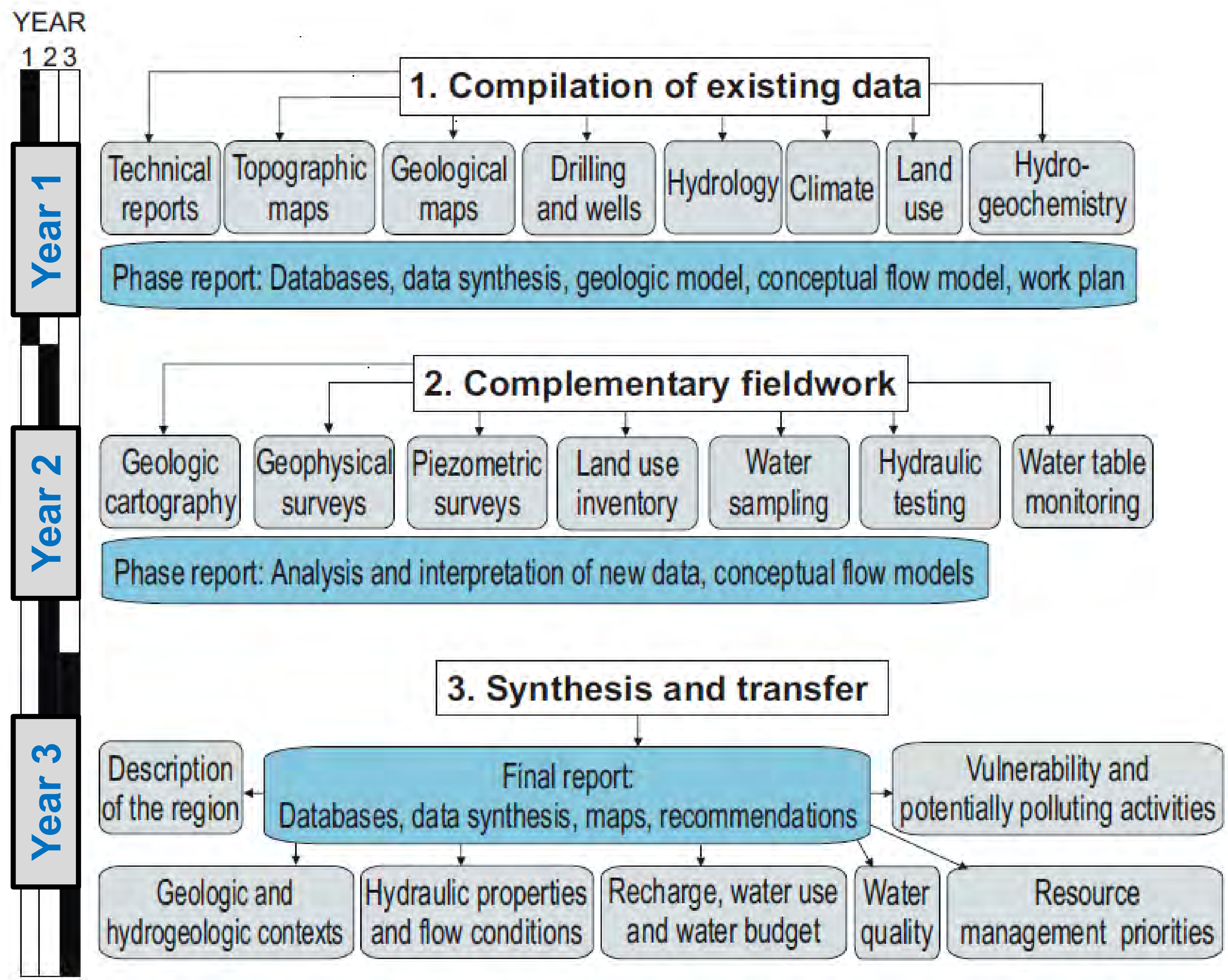


http://www.mddep.gouv.qc.ca/eau/souterraines/aquiferes/guide_granulaires.pdf

Groundwater resources assessment program

- *Programme d'acquisition de connaissances sur les eaux souterraines du Québec (PACES)*
- Assess groundwater resources in the inhabited part of Quebec (series of maps & data)
- Ultimate goal to allow sustainable management and protection of groundwater ressource
- Establish partnerships between water stakeholders (universities, basin organizations, regional municipalities…)

PACES Projects Phases and Timeline



GRIES partners in 2011…

Palmer et al. (2011)

UQÀM
Université du Québec à Montréal

Université du Québec à Trois-Rivières

Université du Québec en Abitibi-Témiscamingue

UQAC
UNIVERSITÉ DU QUÉBEC À CHICOUTIMI

CERM
Centre d'études sur les ressources minérales

UNIVERSITÉ LAVAL

INRS
Université d'avant-garde

GEOLOGICAL SURVEY CANADA 1842 COMMISSION GÉOLOGIQUE

MRC du DOMAINE-du-ROY

CR CONFÉRENCE RÉGIONALE DES ÉLUS DE L'ABITIBI-TÉMISCAMINGUE

CRÉ Montérégie Est

C B V R B
Comité de bassin versant de la rivière Bourlamaque

MRC Abitibi

URSTM
Unité de recherche et de service en technologie minérale de l'Abitibi-Témiscamingue

Ressources naturelles Canada / Natural Resources Canada

Canada

OBVT
Organisme de bassin versant du Témiscamingue

GROBEC
GROUPE DE CONCERTATION DES BASSINS VERSANTS DE LA ZONE BÉCANCOUR

Fonds de recherche sur la nature et les technologies Québec

Ville de Rouyn-Noranda
Fierté • Solidarité • Savoir

MRC de la Vallée-de-l'Or

Ville de Saguenay

CONSEIL DES MONTAGNAIS DU LAC-SAINT-JEAN

Corporation Bassin Versant BAIE MISSISQUOI

MRCT

MRC D'ABITIBI-OUEST

Communauté métropolitaine de Québec

OBVAJ
Organisme de bassin versant Abitibi-Jamésie

M.R.C. DU FJORD-DU-SAGUENAY

CRÉ

Cégep de Thetford
Depuis 40 ans

USGS
science for a changing world

CRÉ CONFÉRENCE RÉGIONALE DES ÉLUS SAGUENAY-LAC-SAINT-JEAN

Environnement et développement durable Montérégie
Conseil régional de l'environnement de la Montérégie

irda
Institut de recherche et de développement en agroenvironnement

Agriculture, Pêcheries et Alimentation Québec
Direction de la Montérégie-Est

OBV YAMASKA
Organisme de bassin versant de la Yamaska

UPA Fédération de l'UPA de Saint-Hyacinthe

COVABAR
COMITÉ DE CONCERTATION ET DE VALORISATION DU BASSIN DE LA RIVIÈRE RICHELIEU

AGTCQ
Agence de géomatique du Centre-du-Québec

MRC DE LAC-SAINT-JEAN-EST

SOCIÉTÉ DE L'EAU SOUTERRAINE ABITIBI-TÉMISCAMINGUE
SESAT

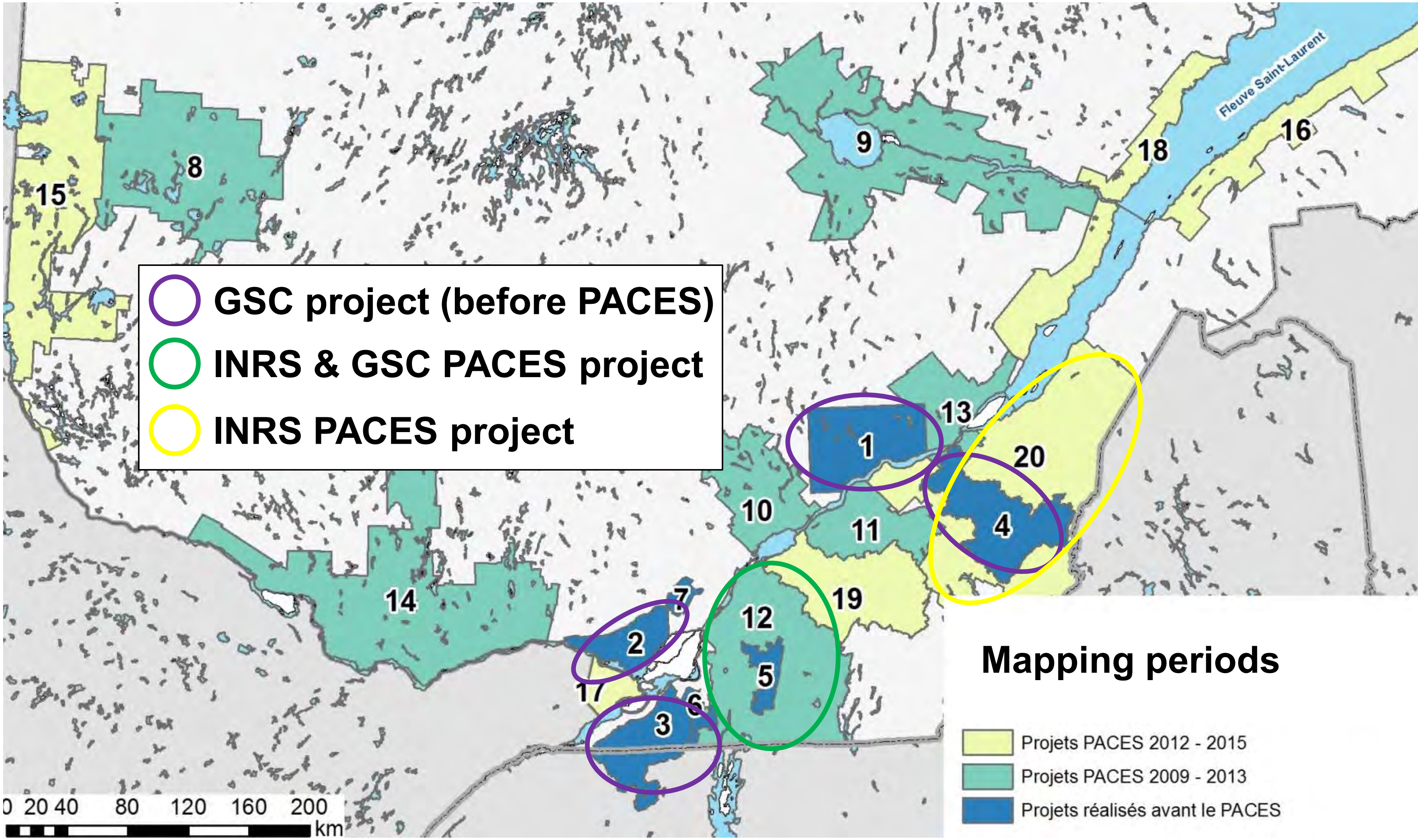
MRC de MARIA-CHAPDELAINE

L'ATINO
L'agence de traitement de l'information numérique de l'Outaouais

Agriculture and Agri-Food Canada / Agriculture et Agroalimentaire Canada

GÉOMONT

Mapping coverage (March 2015)

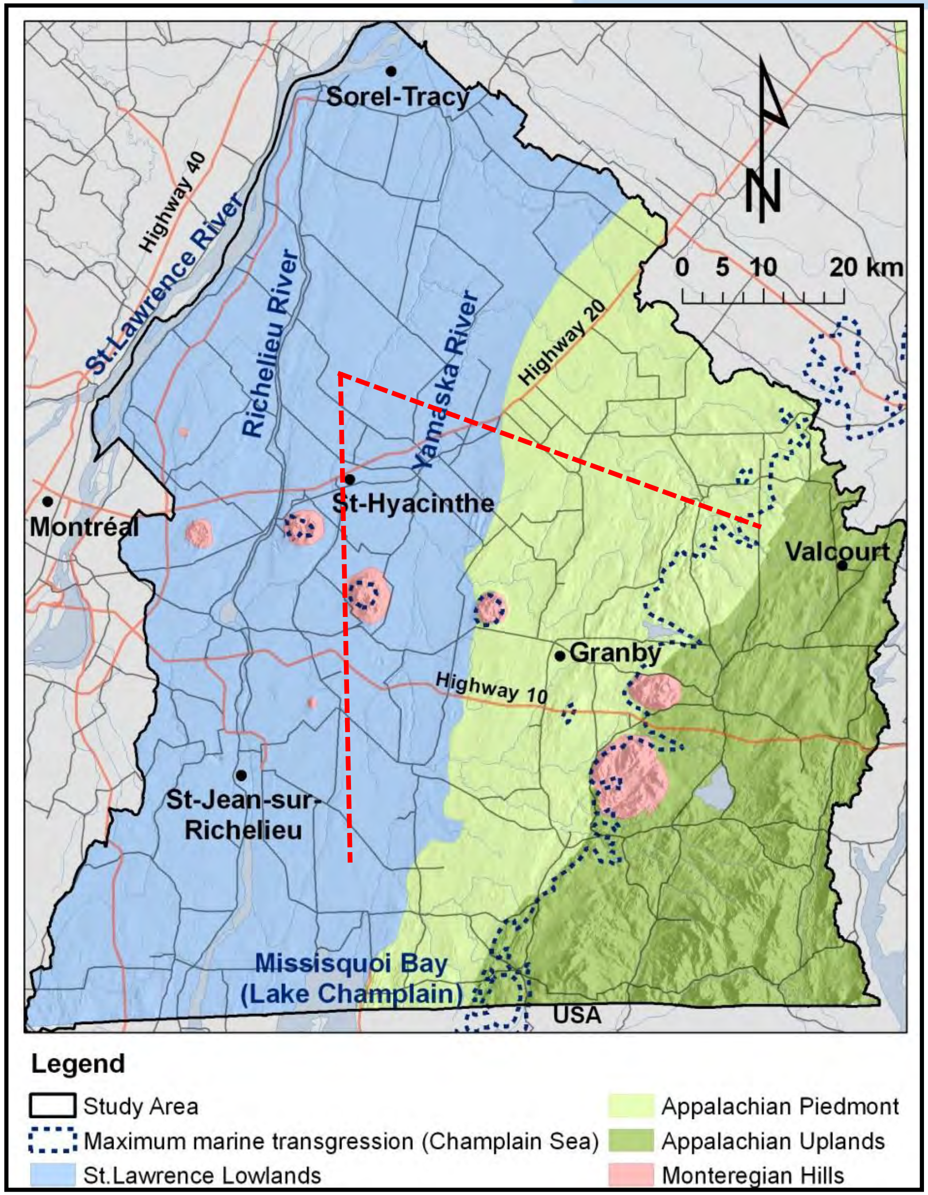


Where are we?

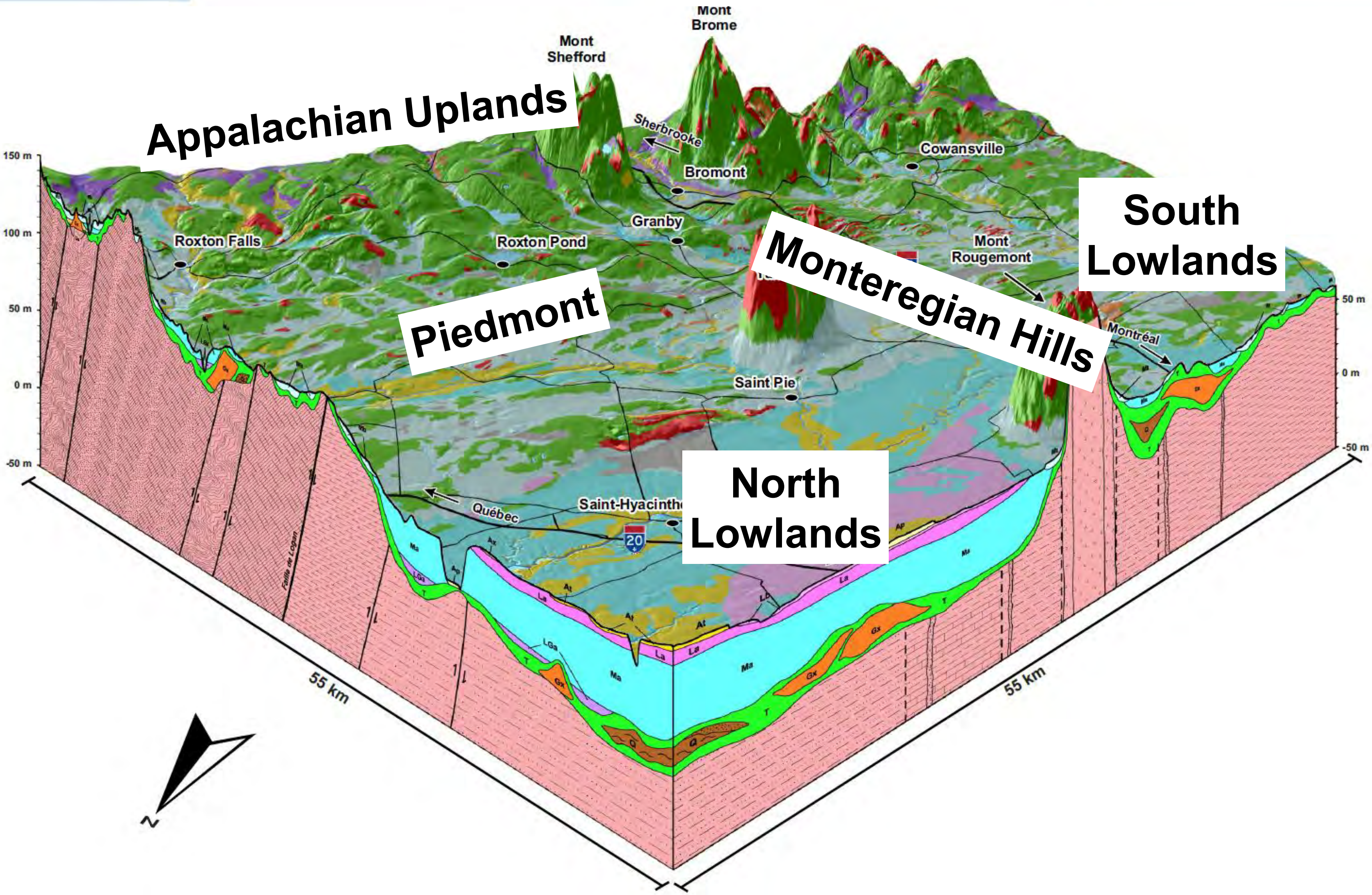
Tools developed for the study of regional aquifers

Montérégie Est Contexts

- **Area of 9218 km²**
- **108 municipalities**
- **588 000 inhabitants**
- **3 hydrological basins**
- **5 physiographic areas with distinct (hydro)geological contexts**



Subsurface in Montérégie Est



Types of Data Needed

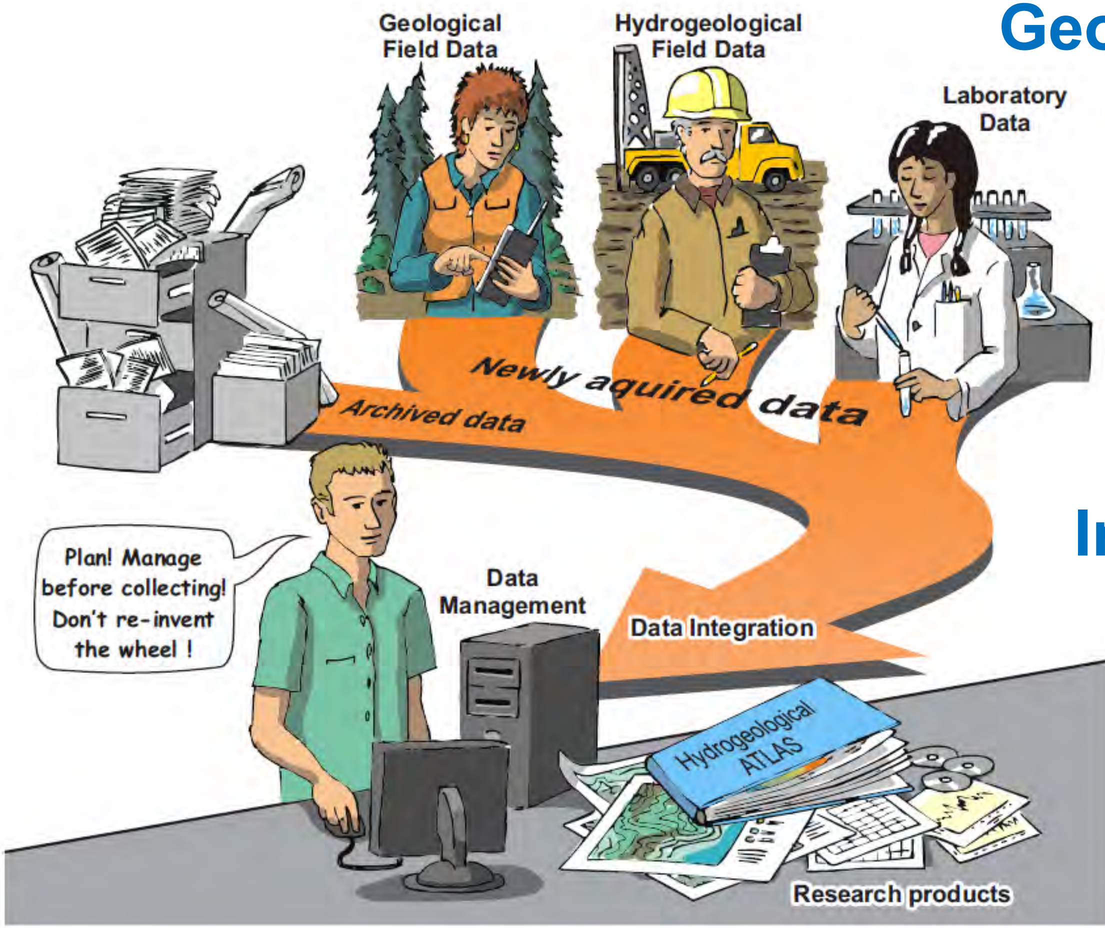
Geophysical &
Hydrogeological

Geological

Geochemical

Diverse
Existing
Data

Integration
Interpretation
Modeling



Rivera, ed. (2014) Canada's Groundwater Resources

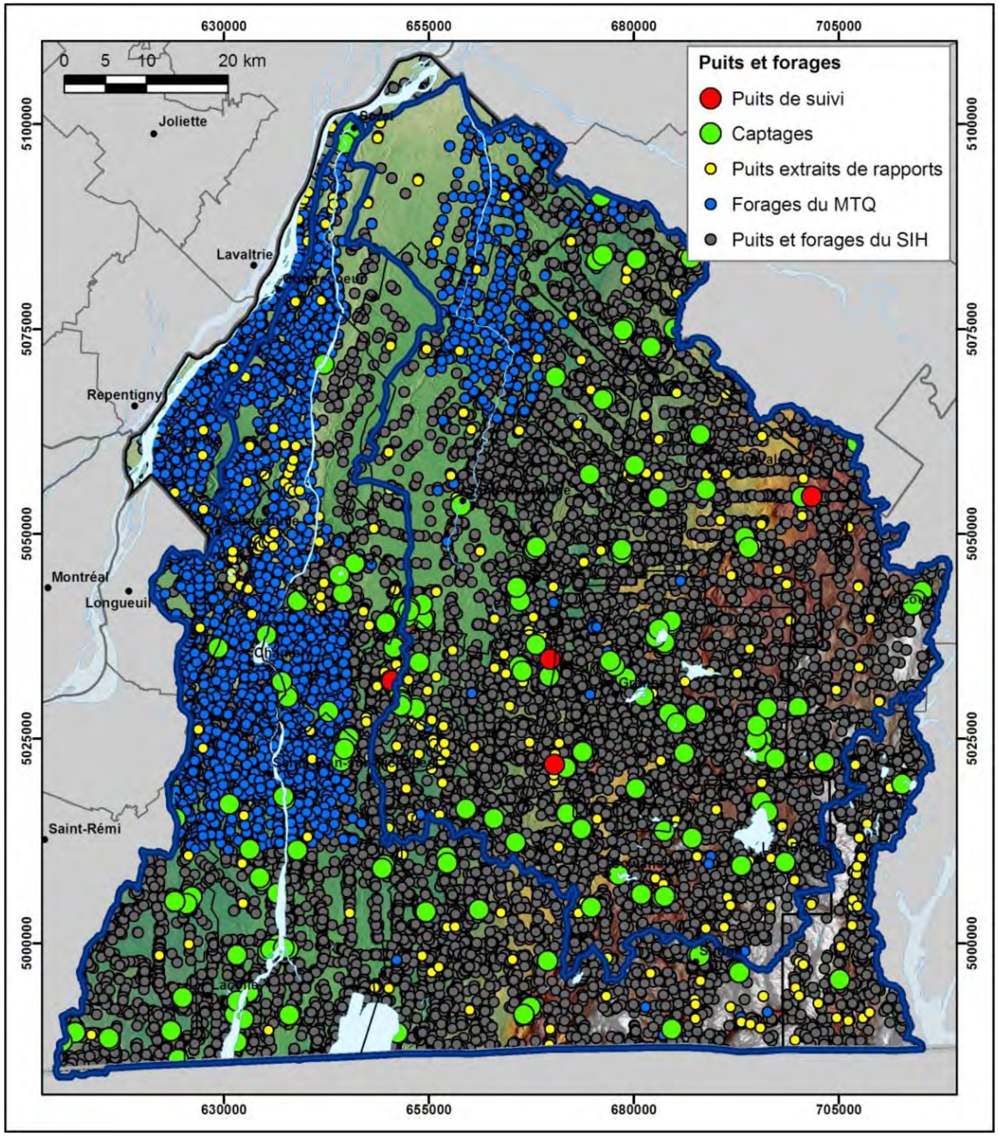
Gather existing numerical data

Wells & boreholes

- SIH: ~ 30000
- MTQ: ~ 5000
- Reports: ~ 600
- Supply wells: 228 (108 municipal)
- Monitoring wells: 4
- Other: SIGPEG et geothermal

Weather and streams

- Weather data (DSEE) (55 stations, 16 with more than 30 y of data)
- Stream flow data (CEHQ) (54 stations, including 9 with water quality)



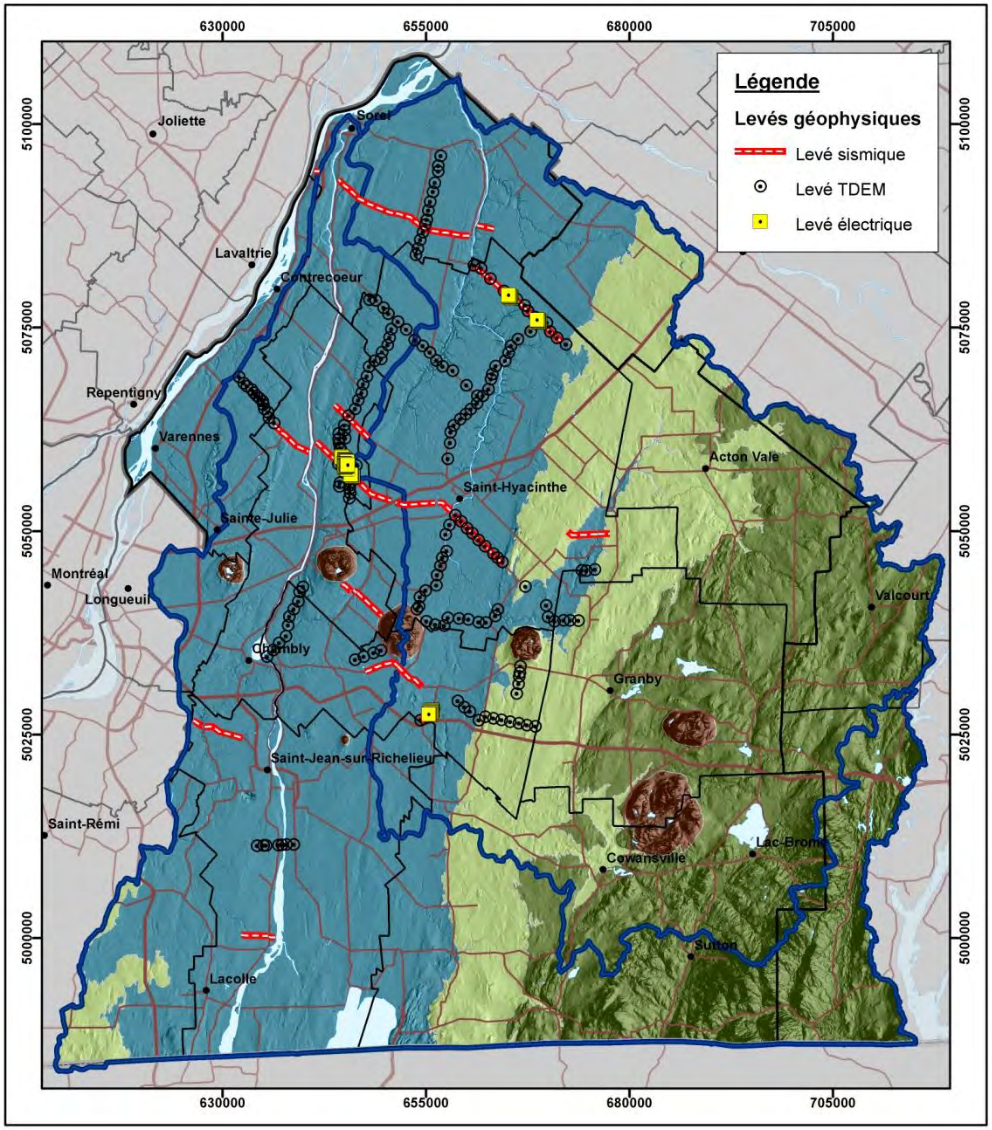
Geophysical surveys

Work carried out

- 13 seismic lines: 105 km
- 186 TDEM sites: 383 km
- 3 electrical resistivity surveys: 7 km (2D sections)

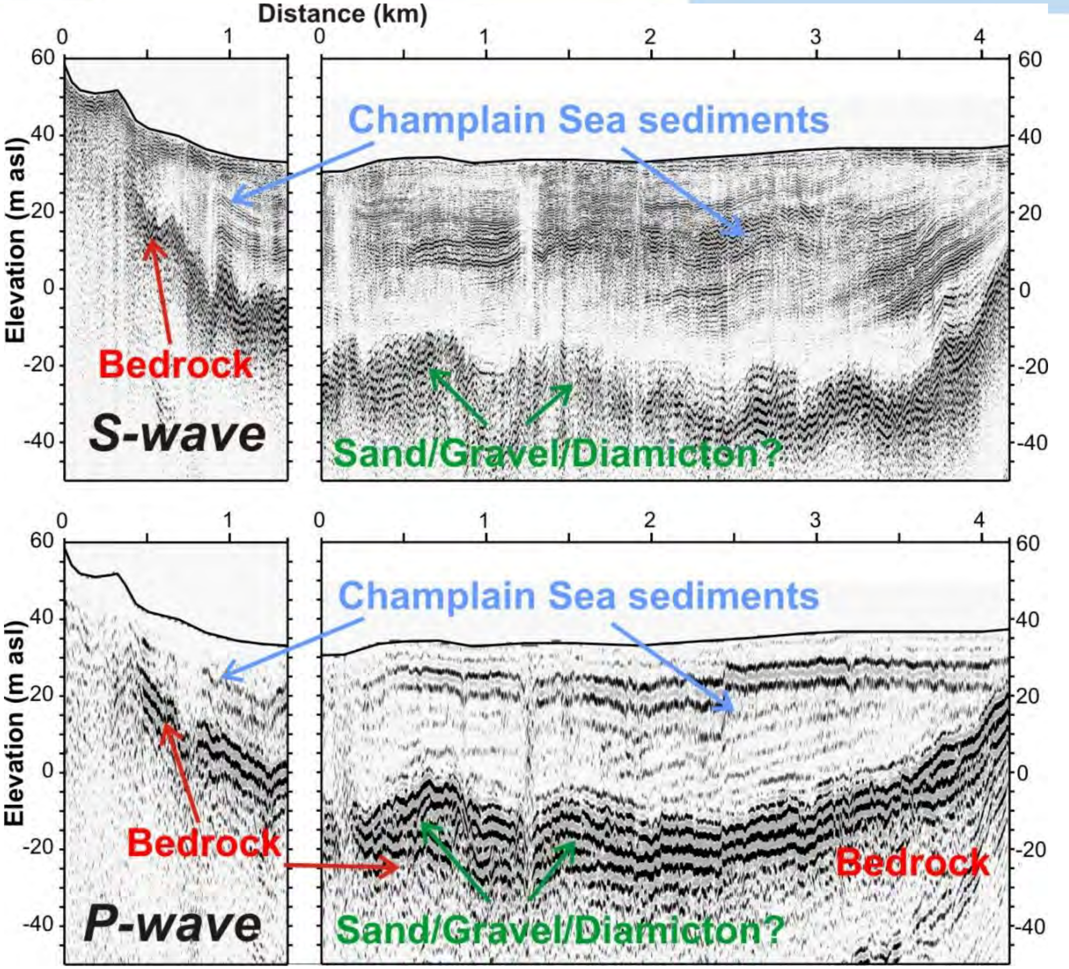
Applications

- Define sediment thickness and depth to rock aquifer
- Define hydrostratigraphy and sediments architecture



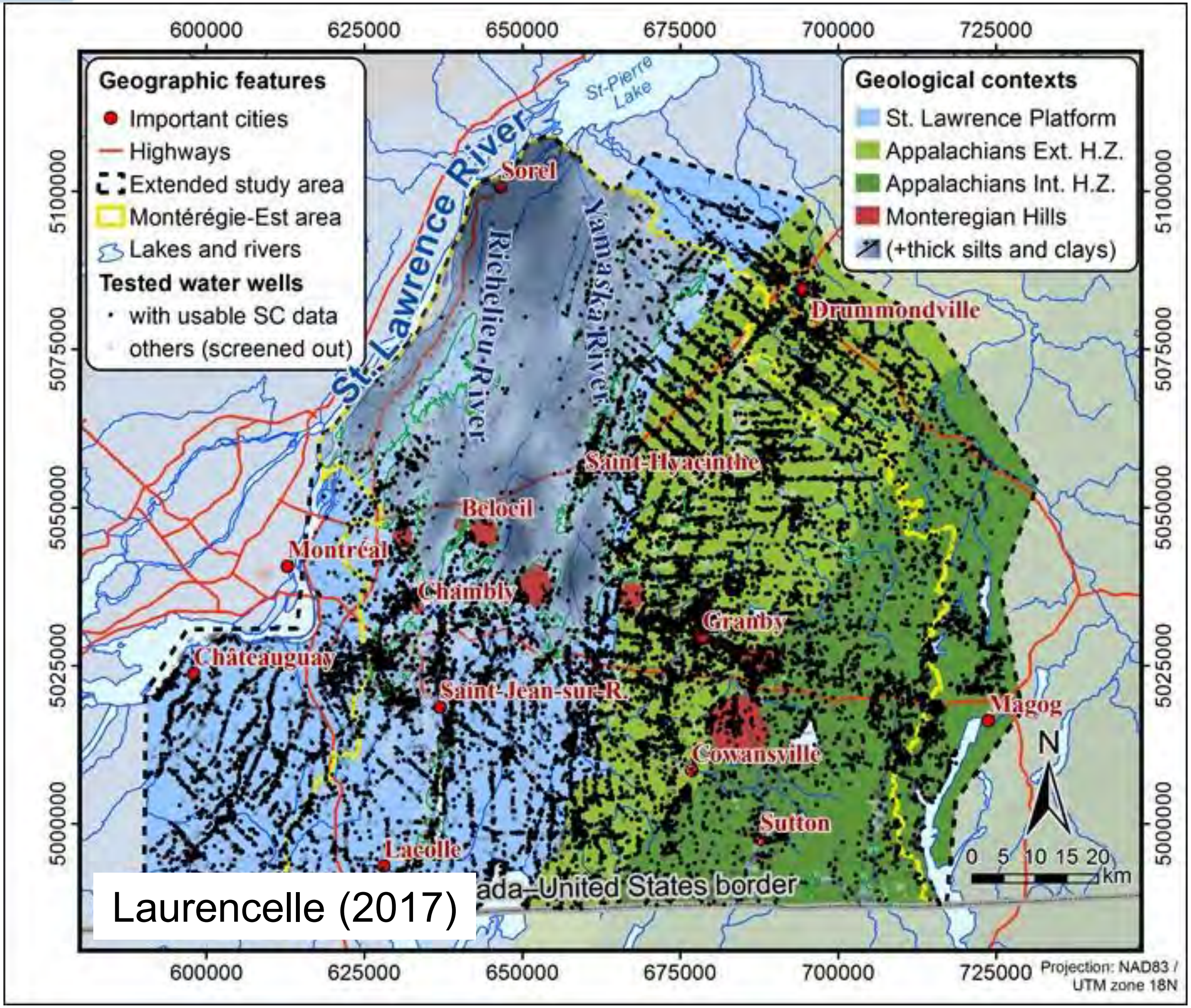
Sismique (105 km) – Montérégie Est

Minivib-landstreamer data acquisition system in operation (Photo from A. Pugin).



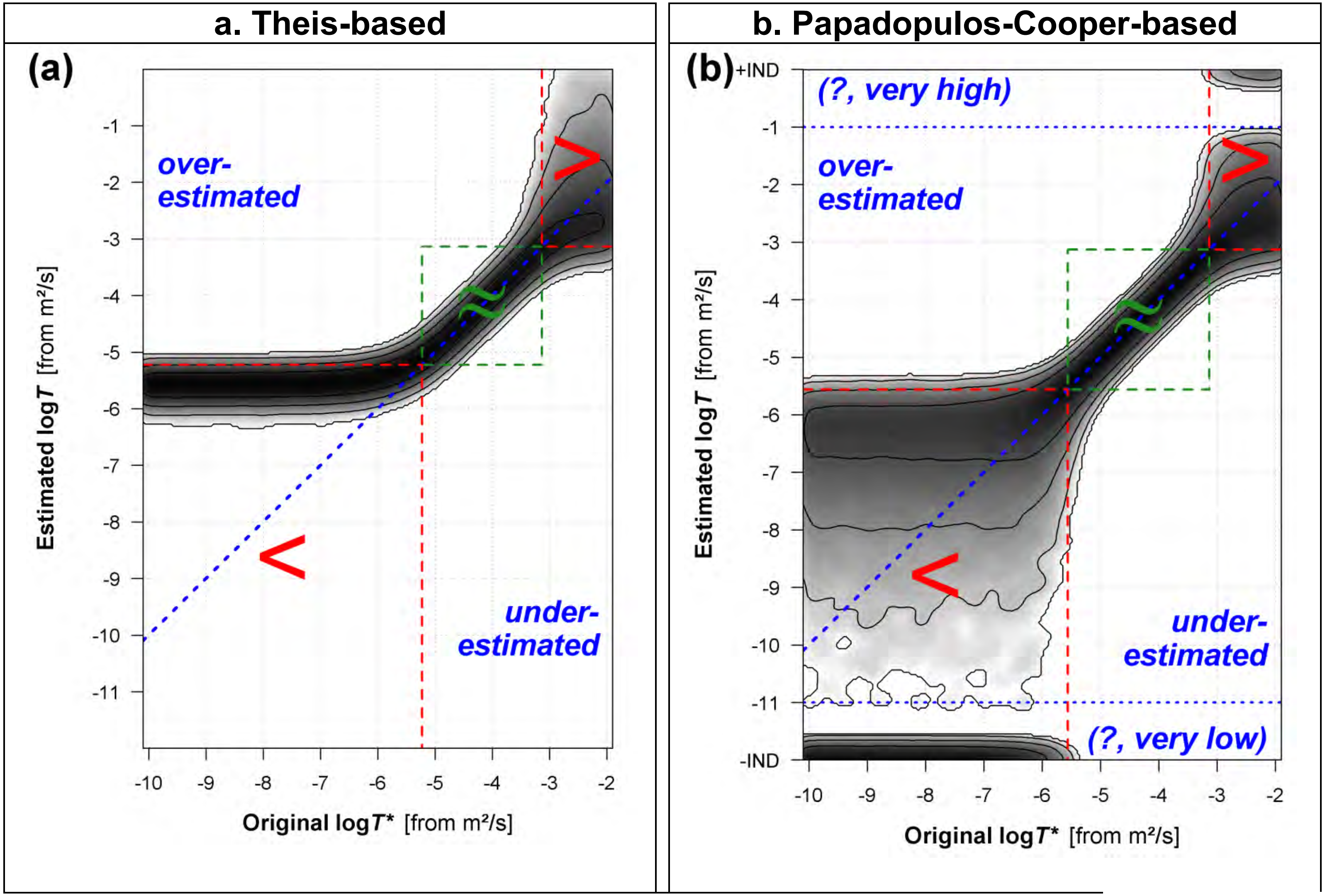
Seismic line between Mont St Hilaire and Rougemont (Processing and figure from A. Pugin)

Specific Capacity (Q/s) Tests (≈18,000)



Laurencelle (2017)

Reliability of Transmissivity from Q/s

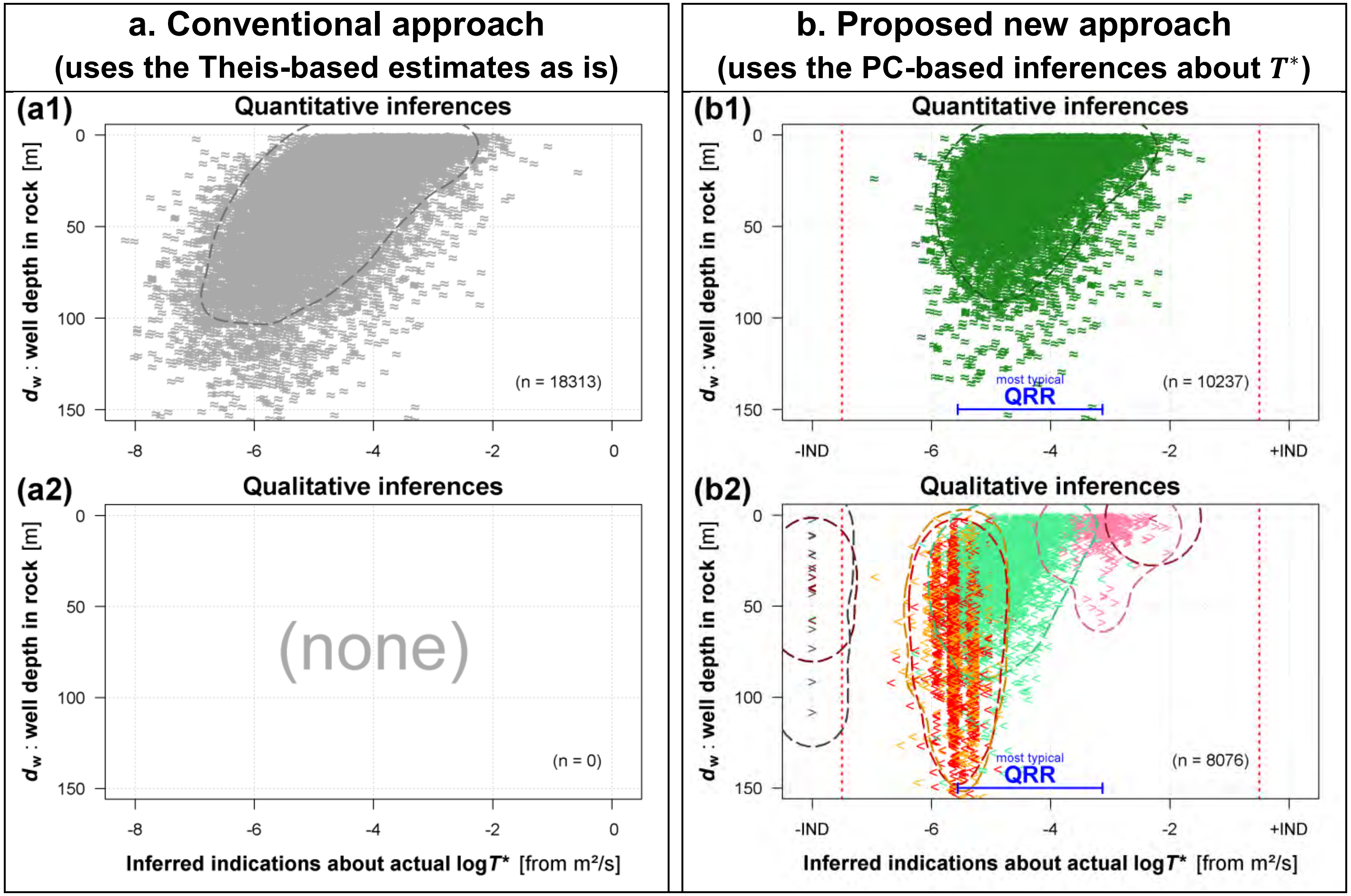


Laurencelle (2017)

Transmissivity from Specific Capacity

Transmissivity from Theis model

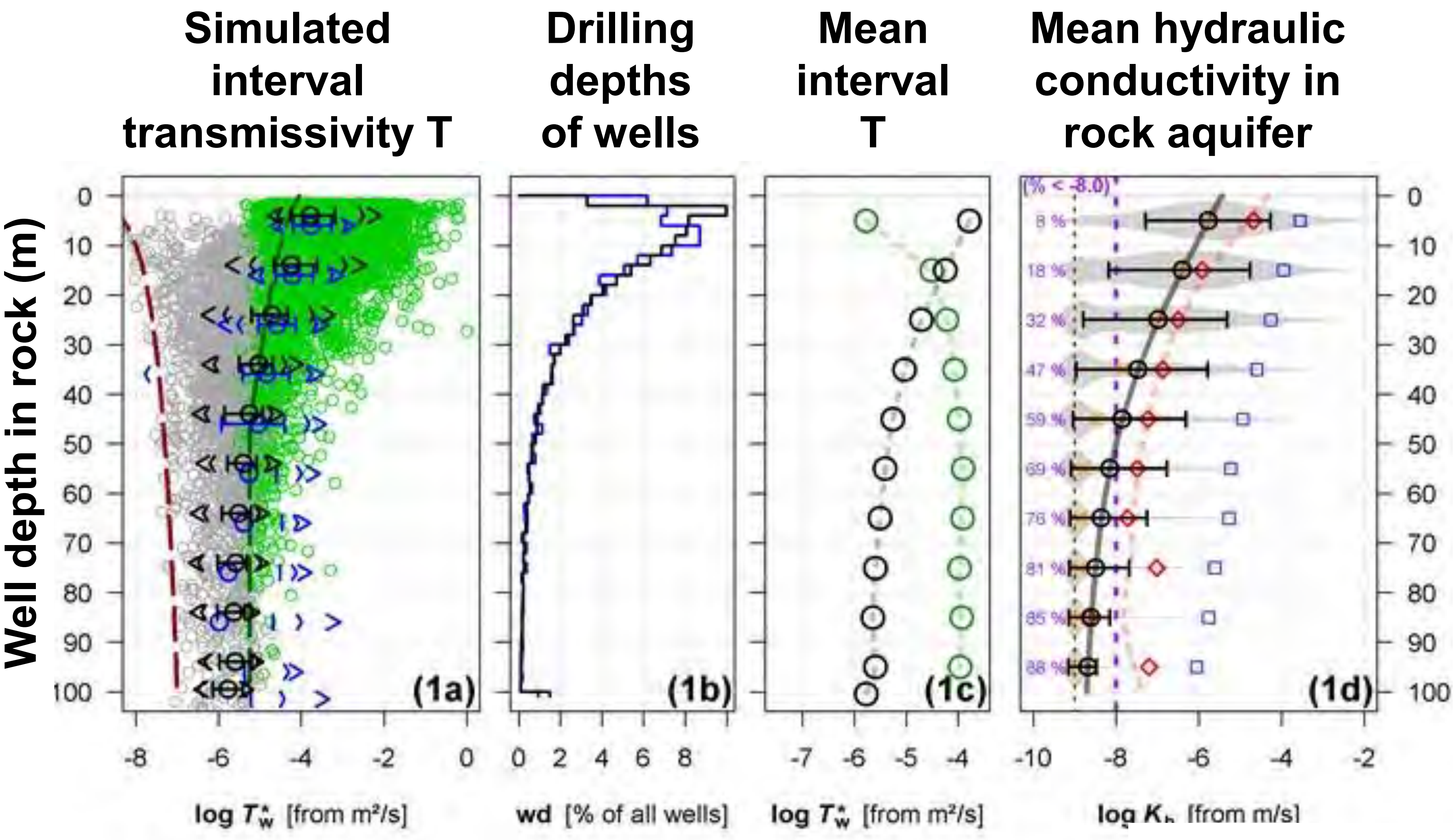
Transmissivity from Papadopulos-Cooper model



Laurencelle (2017)

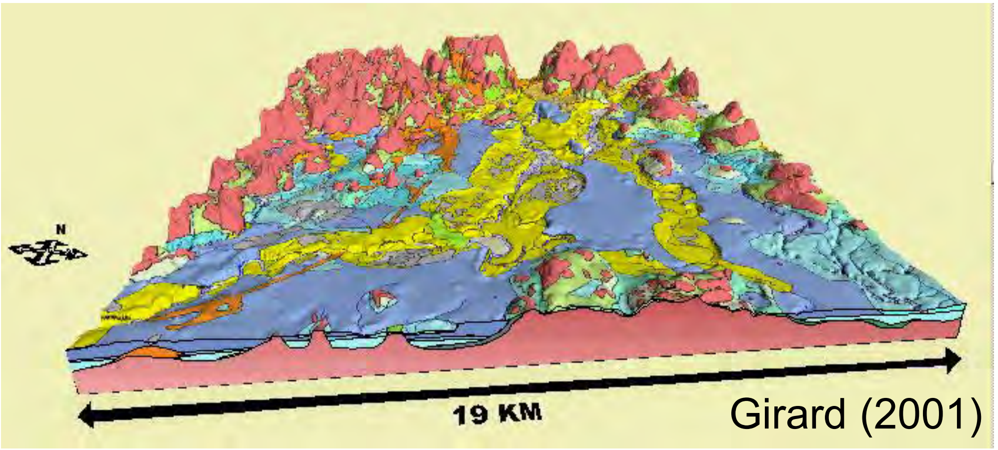
Regional K(z) Considering Driller Bias

Monte Carlo simulations with fracture and driller bias models

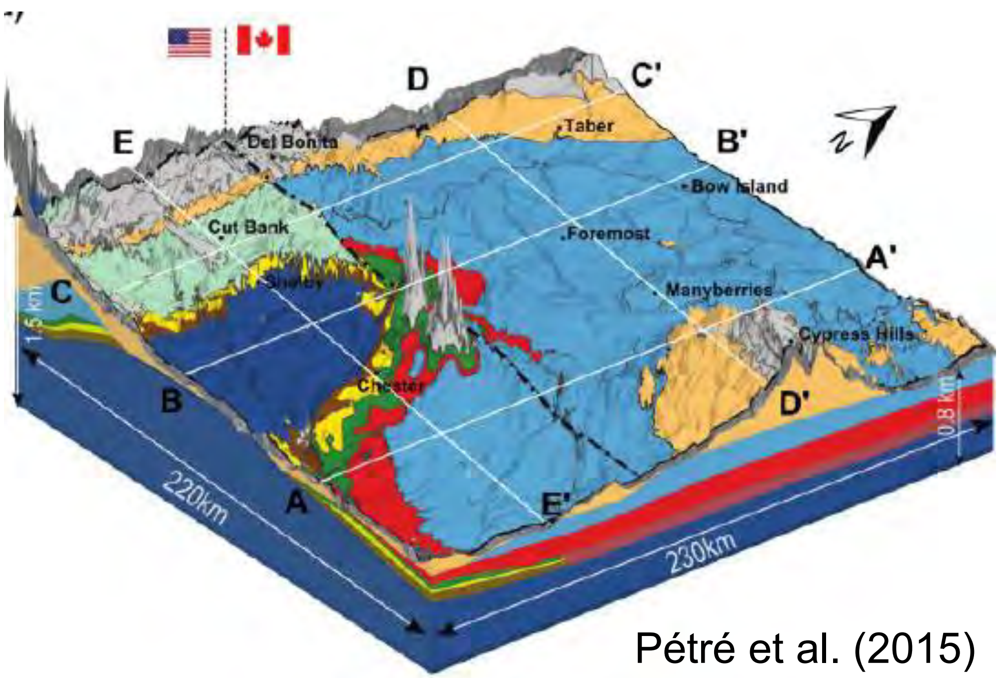


Laurencelle (2017)

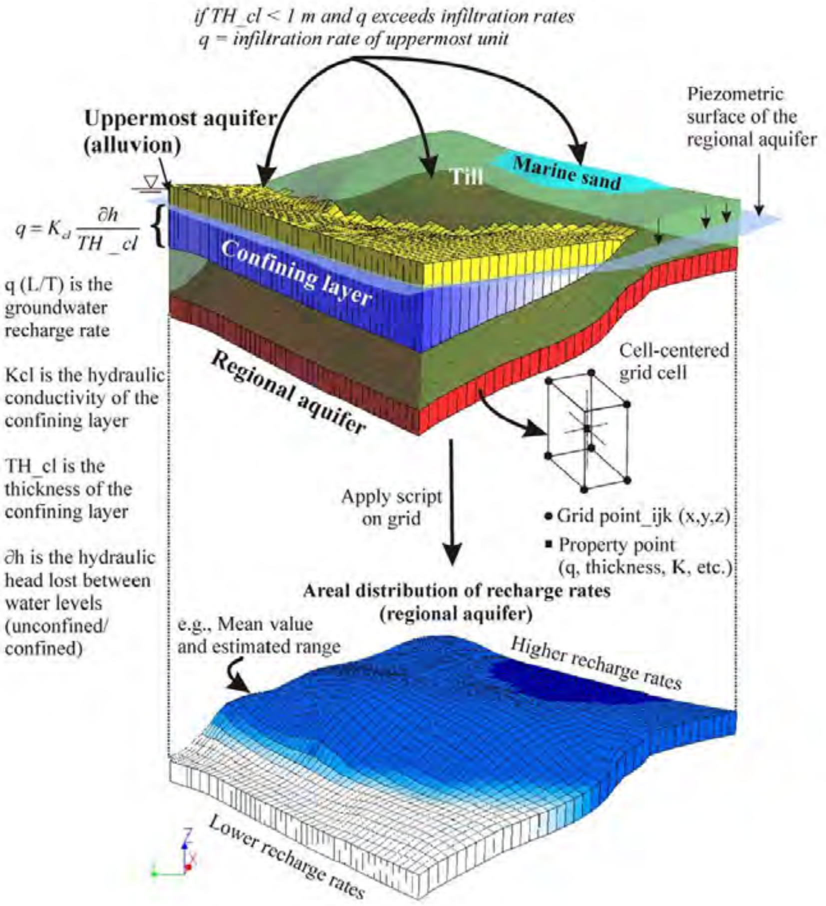
3D Geological Models



Girard (2001)



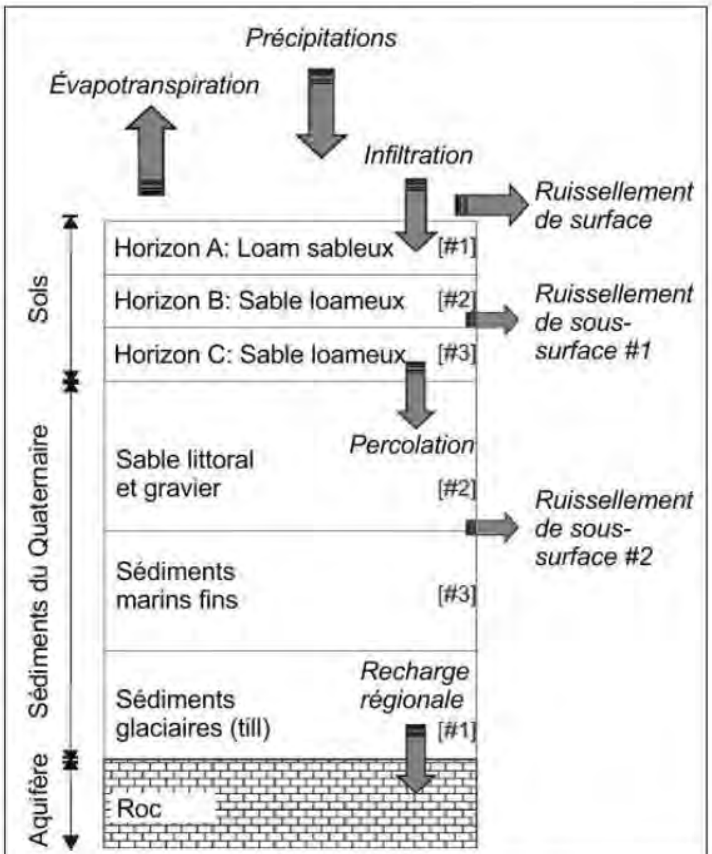
Pétré et al. (2015)

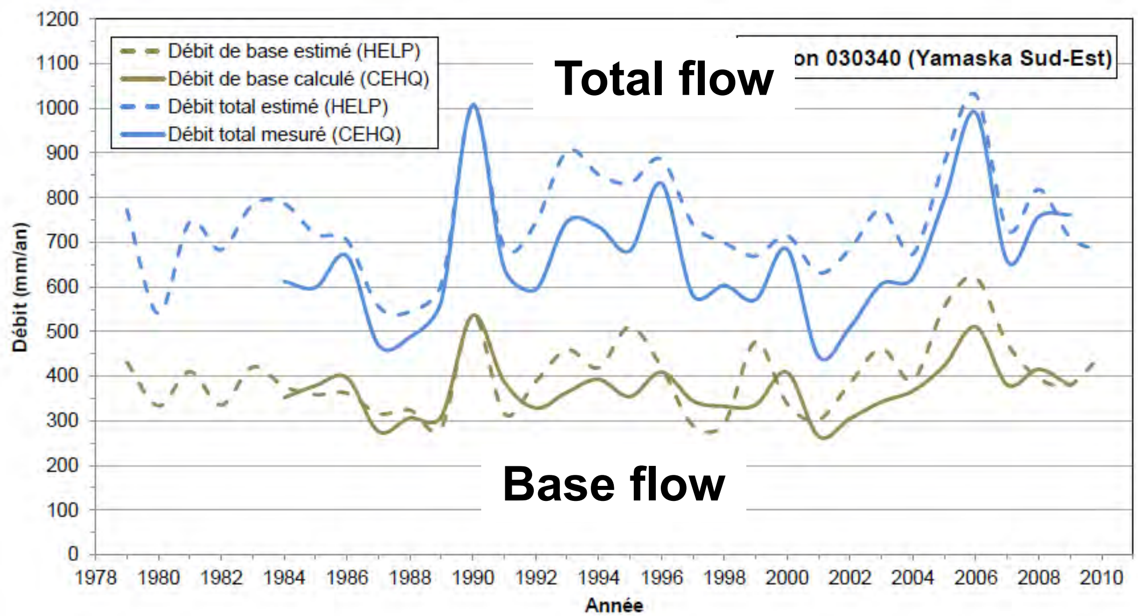


Ross et al. (2002)

Spatial Distribution of Recharge

HELP: 1D infiltration by hydrological balance based on weather data and aquifer conditions (soils, slope, vegetation…)



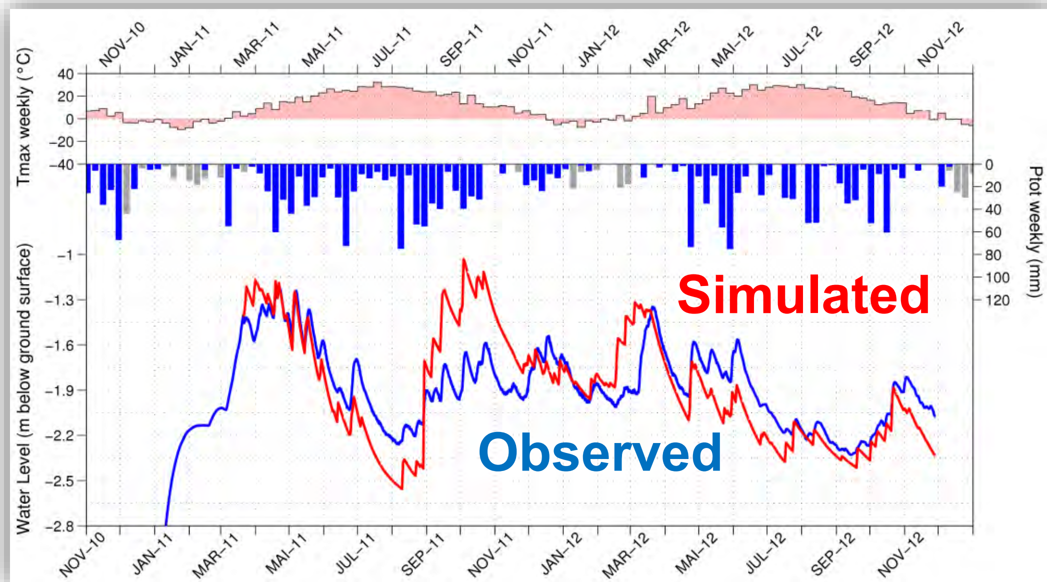


Recharge estimate verified with stream flow (total and base flow) within a hydrological basin

Based on approach of Croteau et al. (2010)

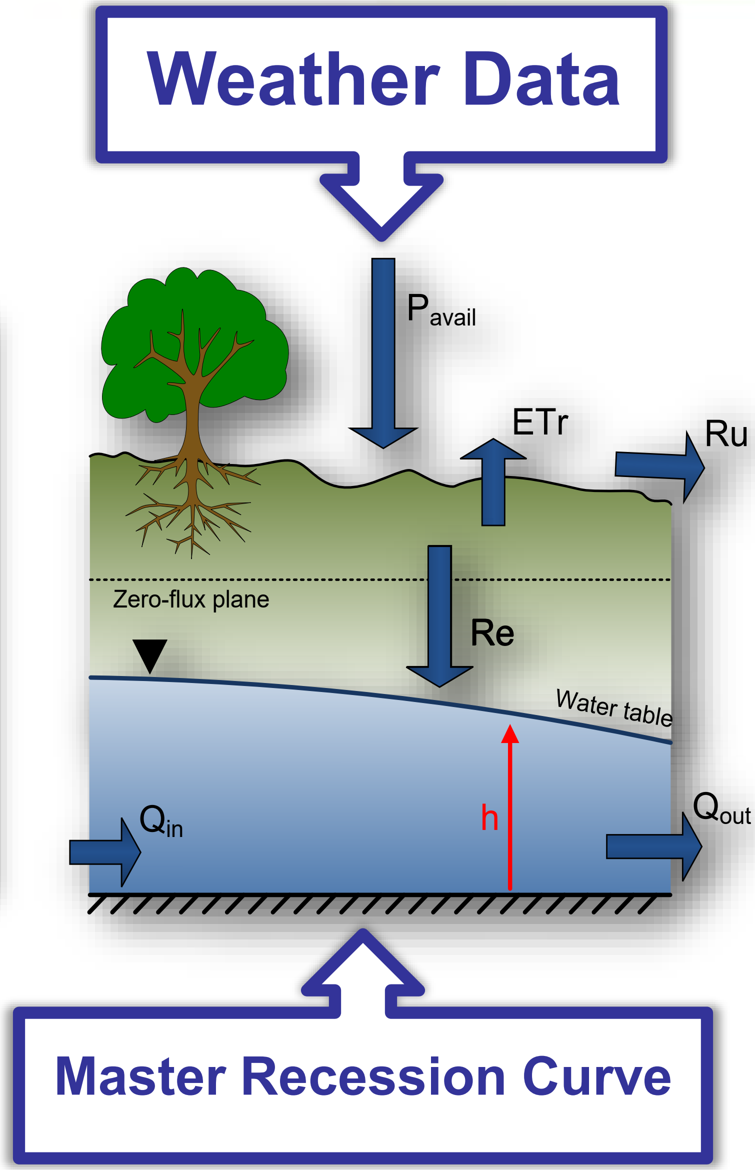
Recharge from SMB and Hydrographs

Soil moisture balance parameters are optimized to the water level measurements

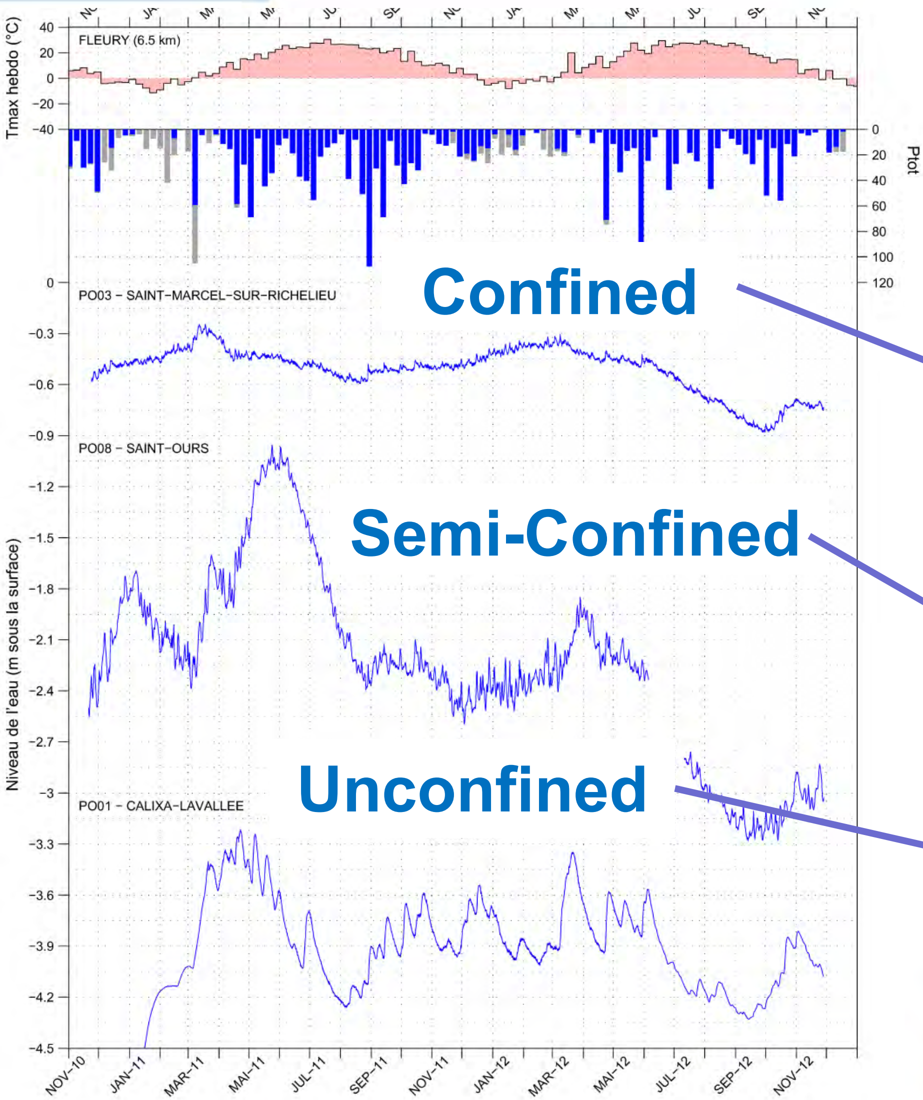


Recharge is calculated from the calibrated model

Gosselin (2016)

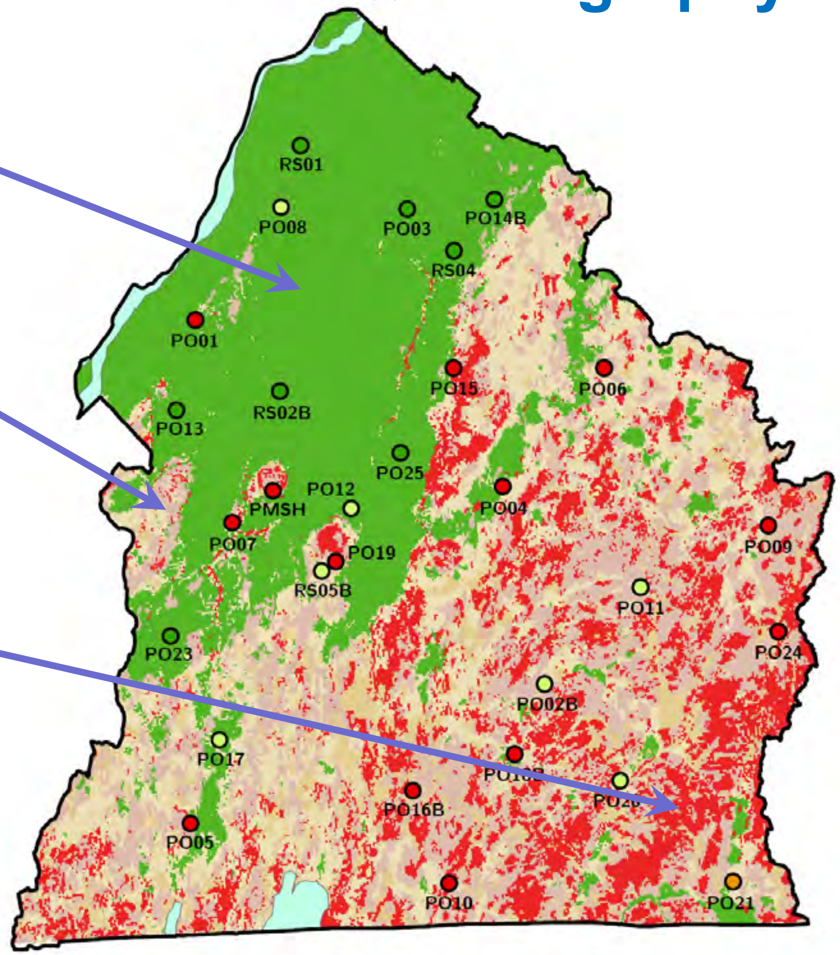


Aquifer Confinement from Well Hydrographs



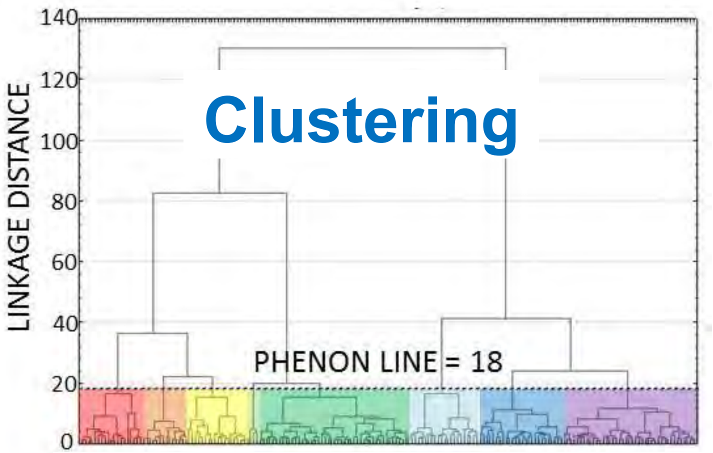
Gosselin (2016)

Confinement from Barometric Response Function & stratigraphy



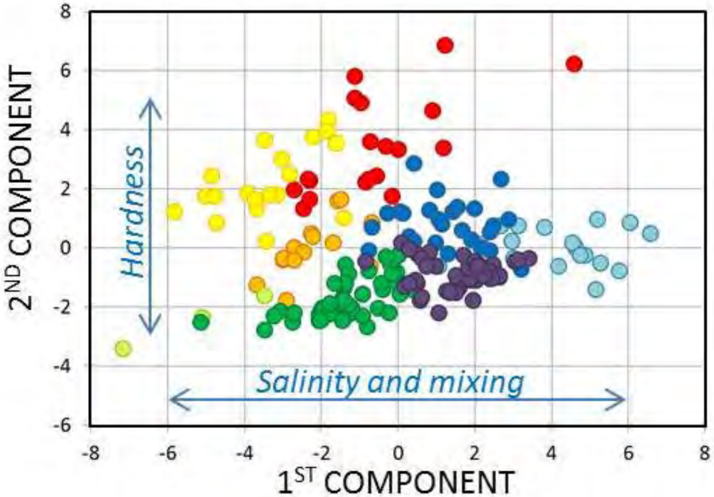
Water Types from Multivariate Analysis

A)

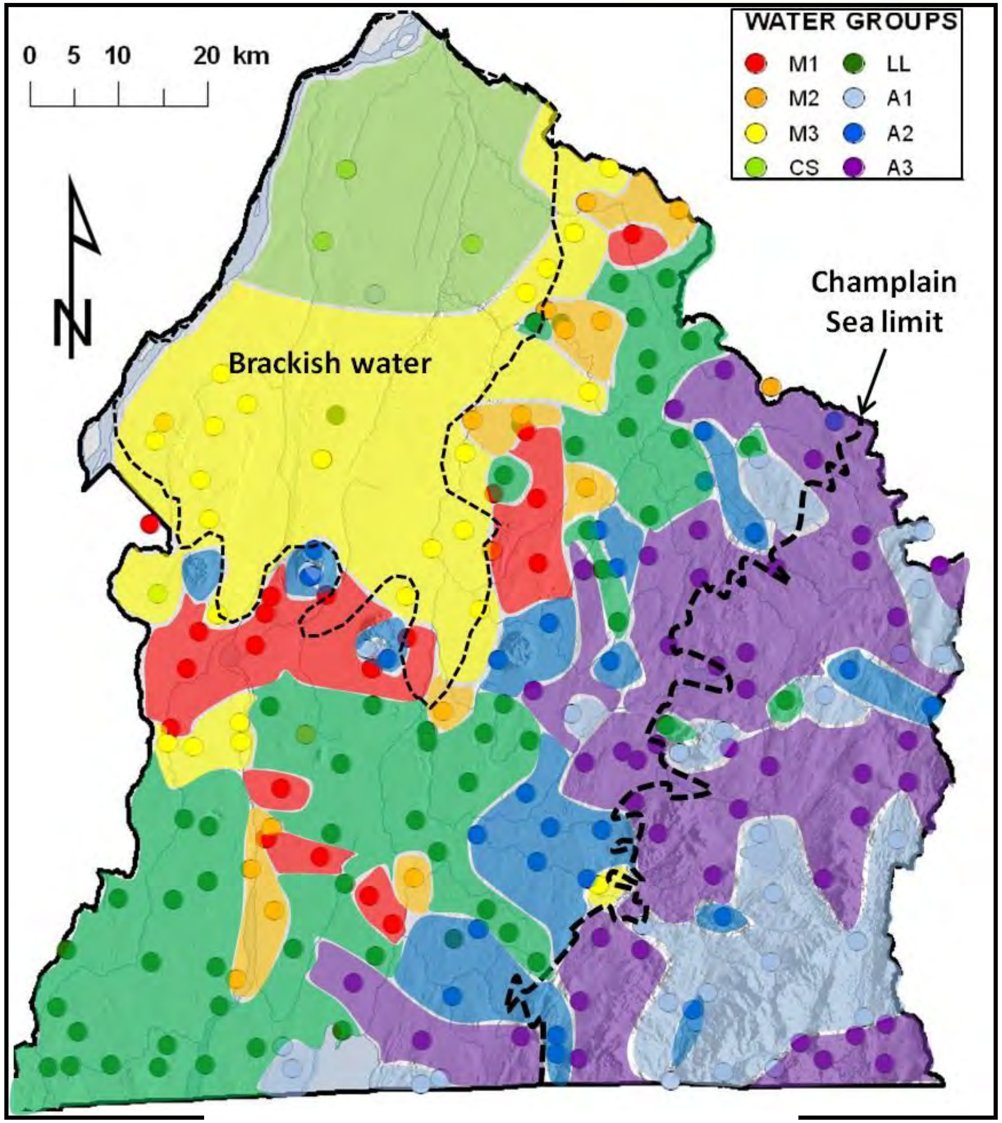


Principal Components

C)

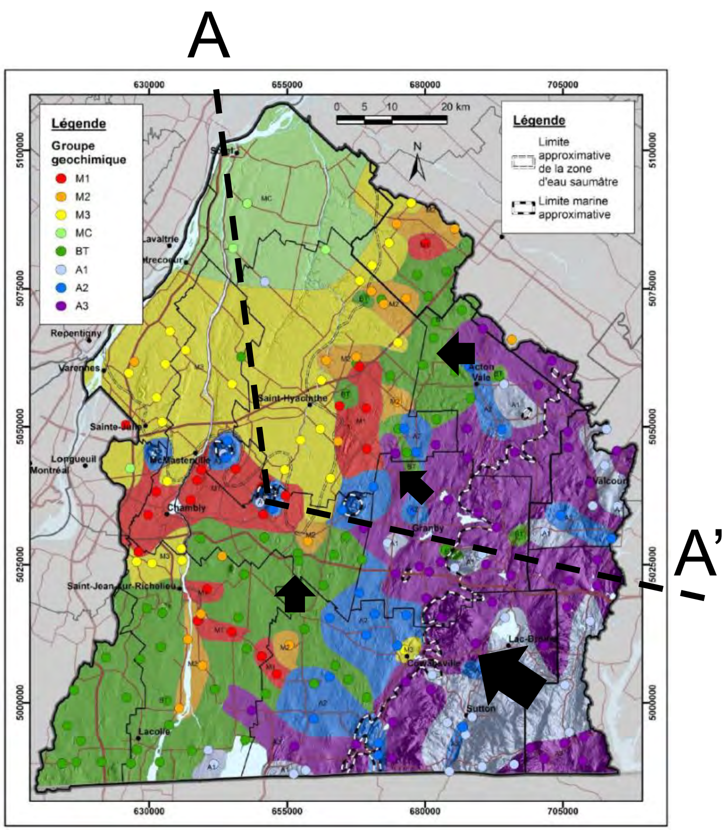


B)



Beaudry et al. (submitted)

Conceptual Geochemical Model

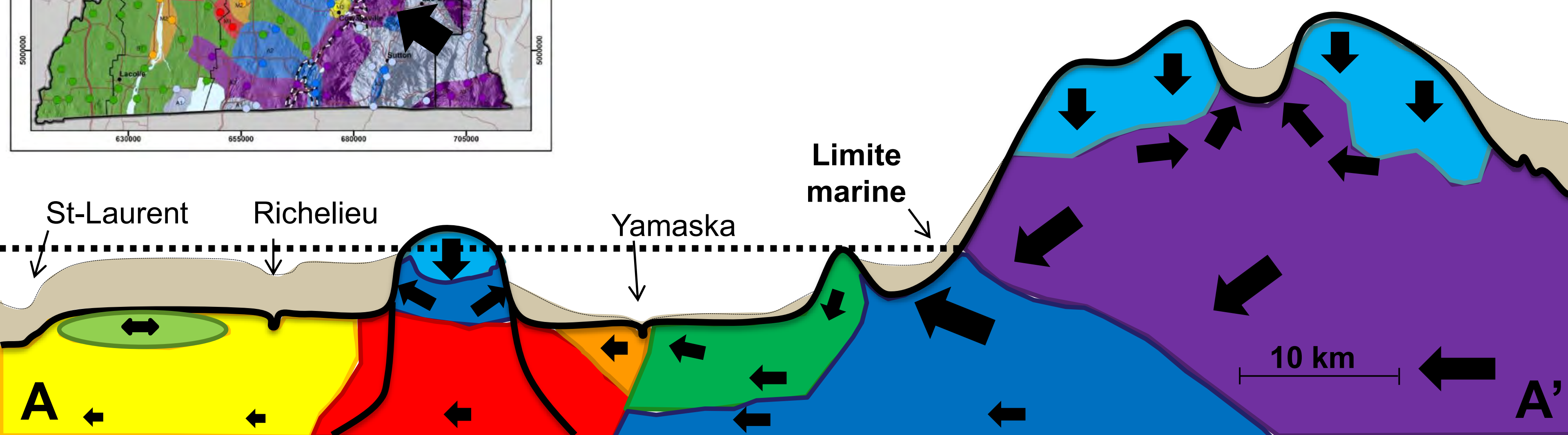


Recharge: mostly Appalachian & Monteregian and less in southern Platform

Long flow paths from Appalachians to Piedmont and to Appalachian valleys

Partial leaching of Champlain Sea water

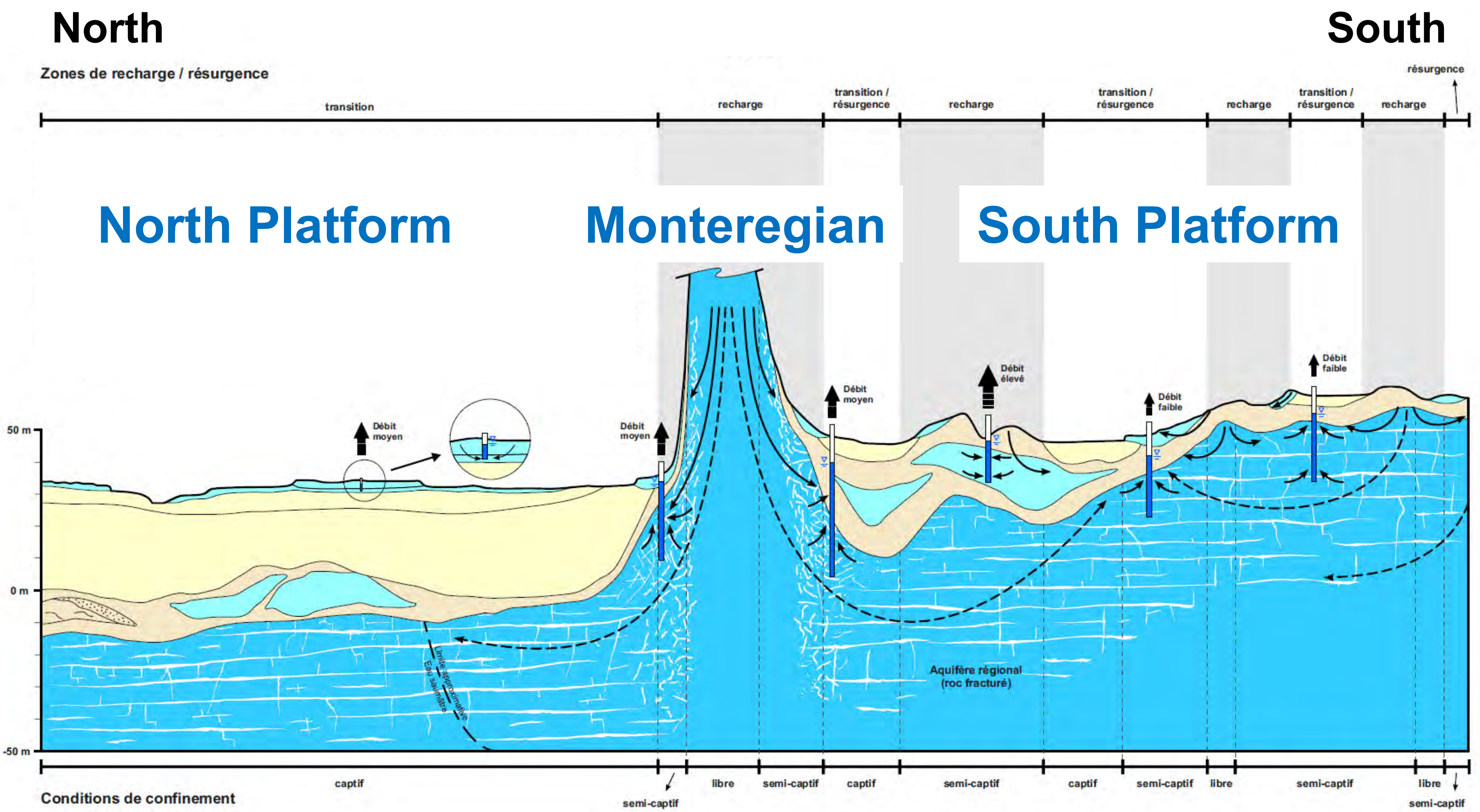
"Monteregian" water presumed of deep origin and geochemically quite evolved



Transfer is required to support management

- Information transfer (more than data) to allow management by regional stakeholders
- The form of information transfer must allow the *empowerment* of stakeholders (they must be able comprehend and use the information)
- Most hydrogeological maps and data must be "translated" to allow the transfer of their info
- The form of information transfer must also allow the identification of issues and priority areas requiring decisions or actions

Conceptual Models to Explain Contexts



Production and Use of Indicators

Sustainable Management Objectives

Quantity

Quality

Well-being

Ecosystems

Governance

→ **Sustainable Management Indicators**

PACES Data & Maps

↓

Sustainable Management Indicators

↓

State of Groundwater Resources

↓

Priority Issues and Areas

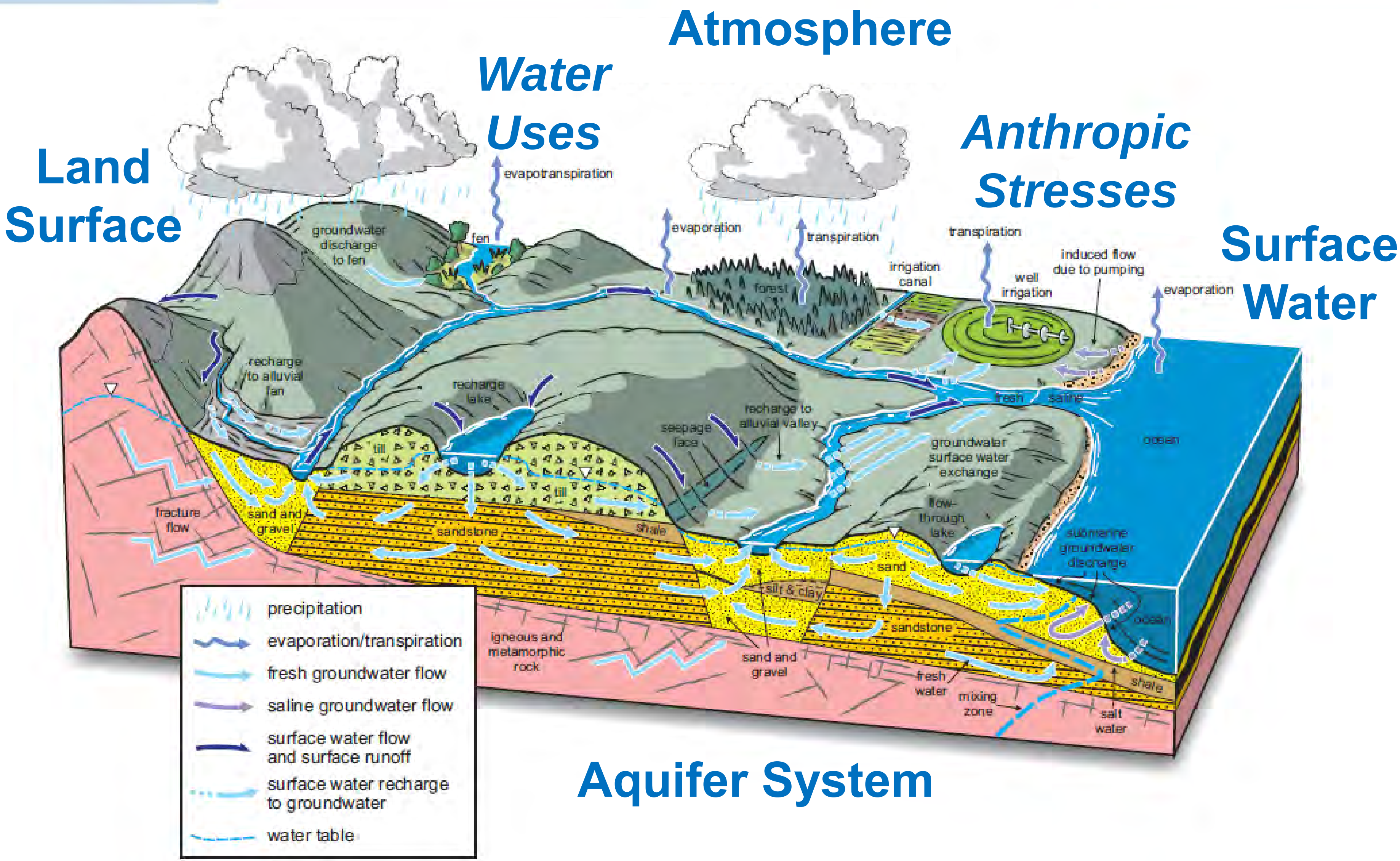
↓

Identification of Corrective Actions

What is next?

Components of regional water resources management

Flow System Components



Rivera, ed. (2014) Canada’s Groundwater Resources

Knowledge about the Flow System

Land Cover Maps

Water Use Inventory

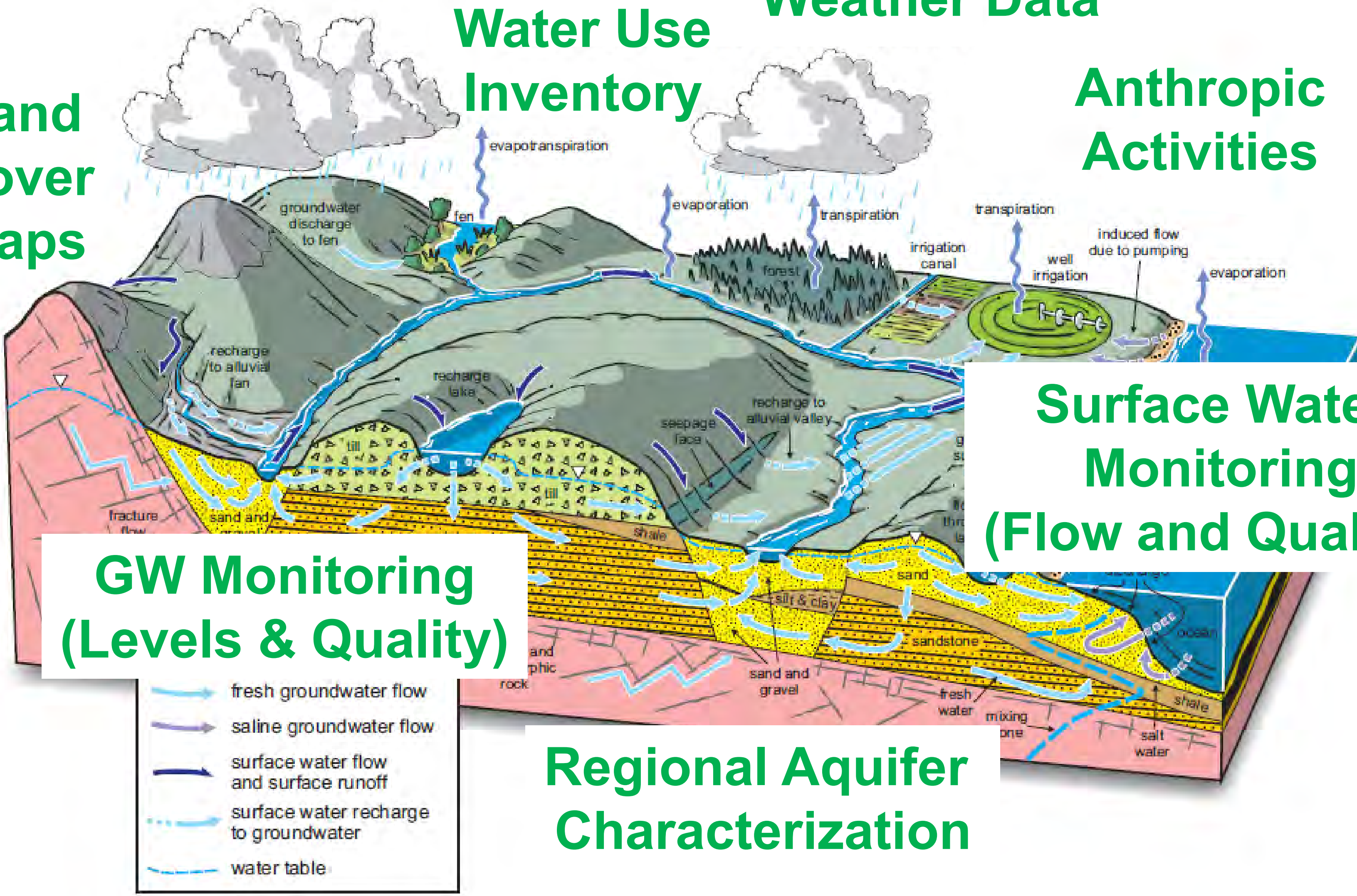
Weather Data

Anthropic Activities

Surface Water Monitoring (Flow and Quality)

GW Monitoring (Levels & Quality)

Regional Aquifer Characterization



Rivera, ed. (2014) Canada’s Groundwater Resources

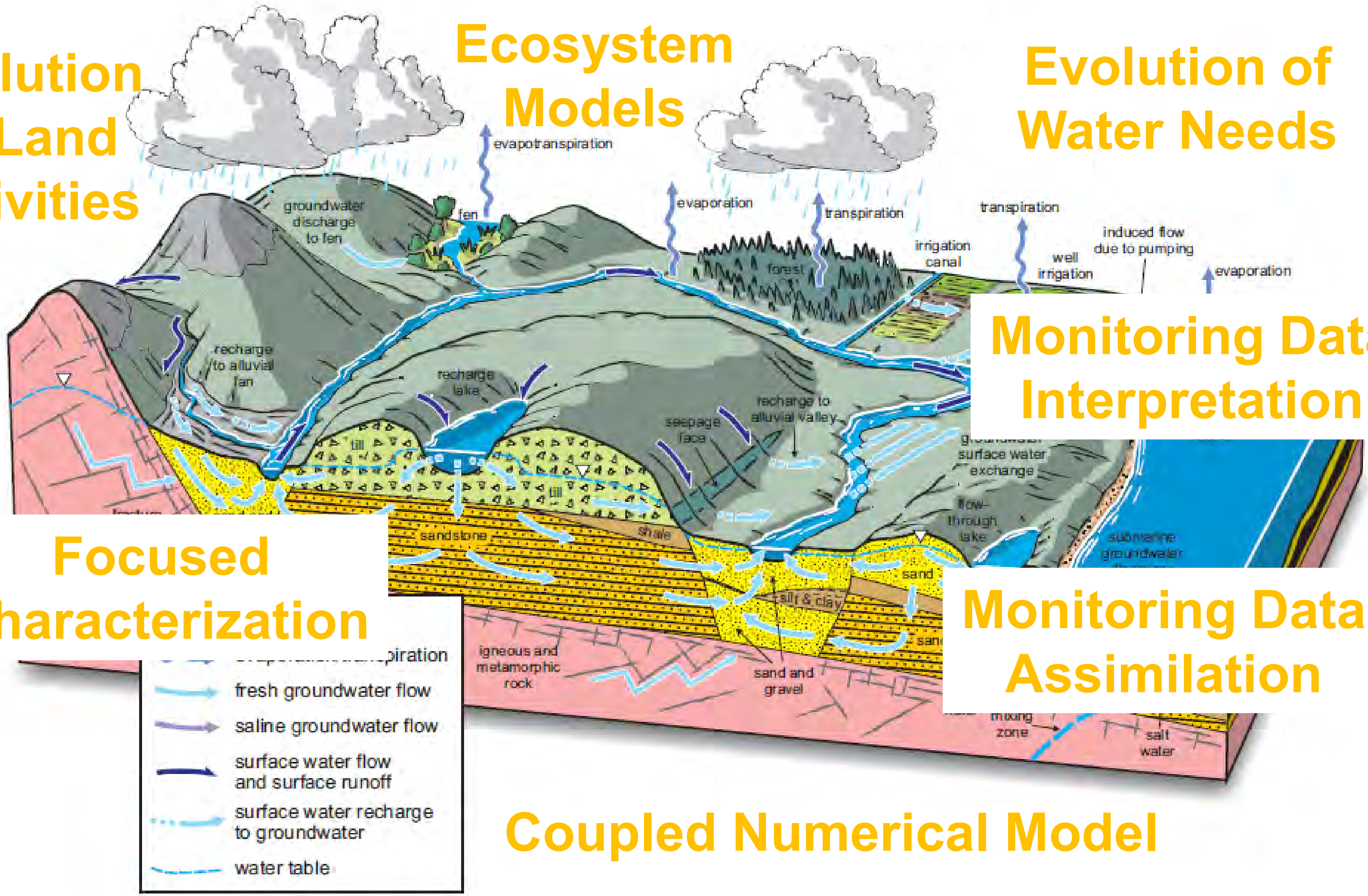
Understanding of the Flow System

Climate Models

Evolution of Land Activities

Ecosystem Models

Evolution of Water Needs



Monitoring Data Interpretation

Focused Characterization

Monitoring Data Assimilation

Coupled Numerical Model

Rivera, ed. (2014) Canada's Groundwater Resources

Components of Water Management Plan

Land Use Planning

Ecological Flows

Climate Adaptation

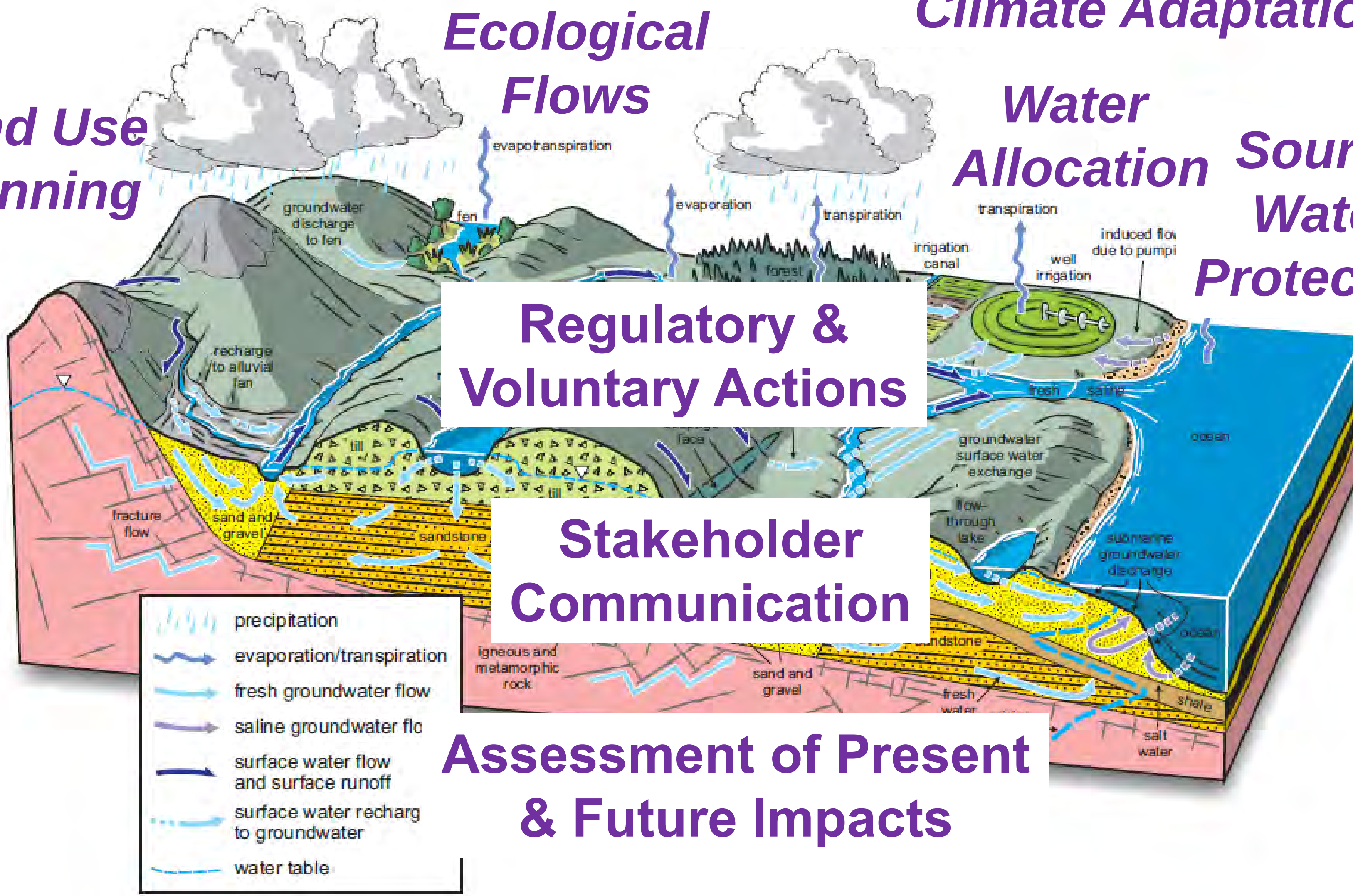
Water Allocation

Source Water Protection

Regulatory & Voluntary Actions

Stakeholder Communication

Assessment of Present & Future Impacts

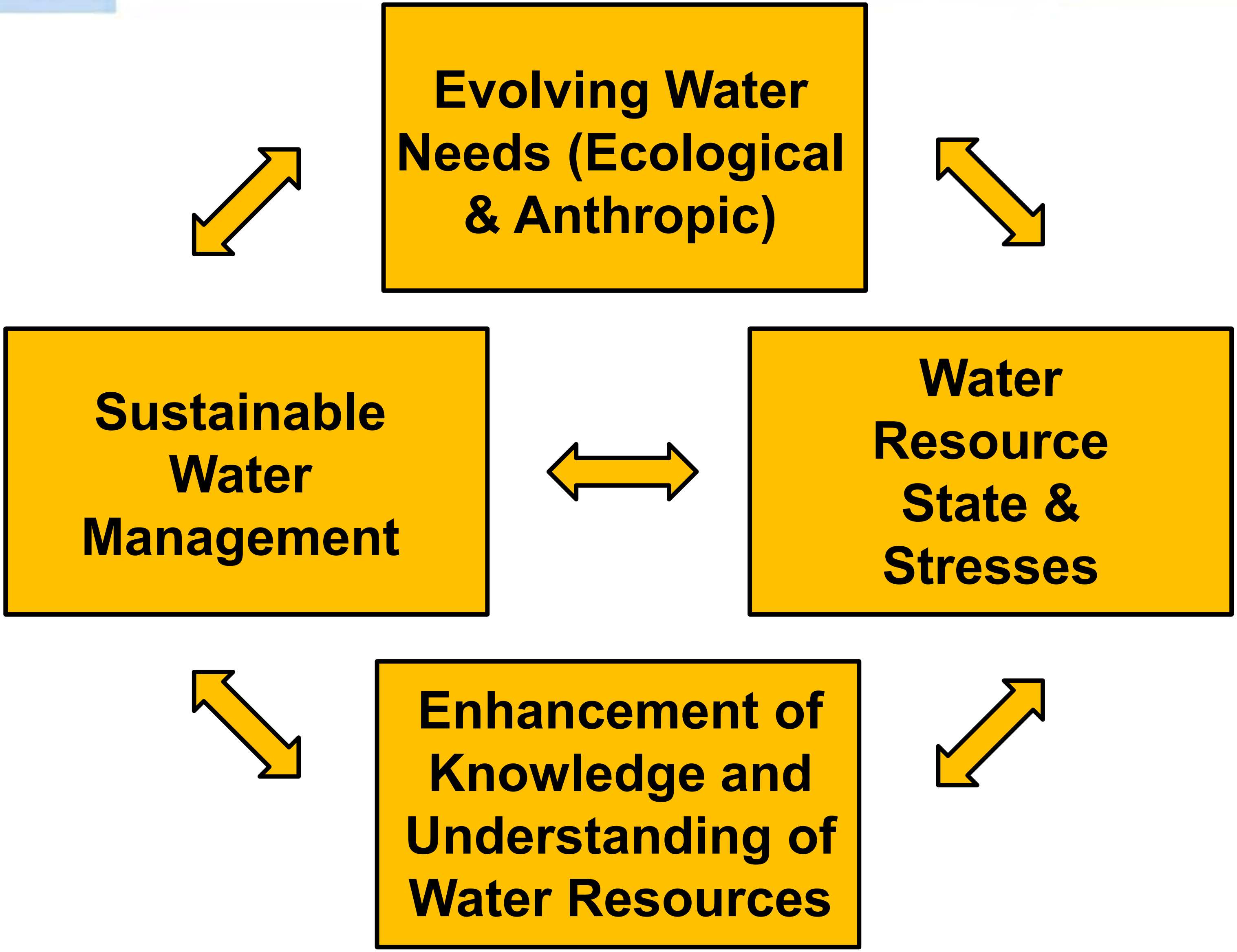


Rivera, ed. (2014) Canada's Groundwater Resources

What is next?

Integrated, connected, intelligent and intelligible management

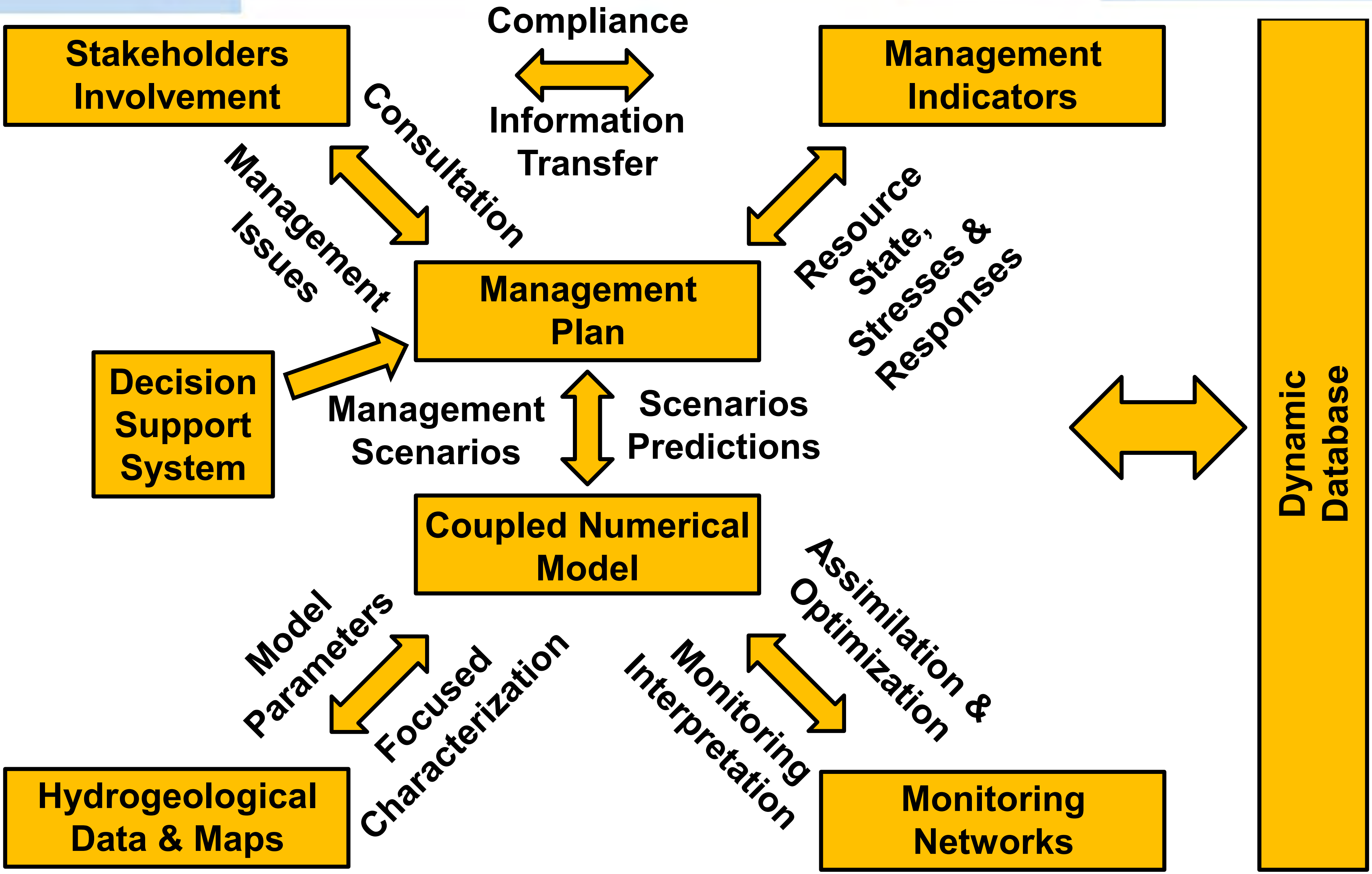
Basis of Sustainable Water Management



Integrated Water Management

- Considers surface water and groundwater
- Protects source water and regional resources
- Integrated use of numerous tools
  - Database (static and dynamic data)
  - Hydrogeological characterization
  - Monitoring (weather, rivers, groundwater)
  - Coupled model (surface & subsurface)
  - Decision support system
  - Management plan
  - Sustainable management indicators
  - Stakeholders involvement

Integrated Management Tools



Connected Water Management

- Continuously available state of resources:
  - Raw monitoring data: integrated weather, surface water and groundwater data
  - Interpreted monitoring data: conditions and trends of monitored variables (e.g. water level trends, baseflow predictions)
- Sustainable groundwater management indicators integrated at different scales
- Water uses reported yearly
- Assimilation of transient monitoring data to optimize the numerical model

Intelligent Water Management

- Management has to be based on a deep understanding of the flow system and the capability to predict outcomes of decisions
- A process has to allow the continuous improvement of the system understanding through the linkage of monitoring & modeling with data assimilation & model optimization
- Requires “living” numerical models that are developed and maintained for decades
- Also requires a decision support system to identify available actions and tools

Intelligible Water Management

- Water management has to involve stakeholders, which requires that they understand the resources and the implications of management decisions
- Have to translate the understanding of the system to make it understandable:
  - Conceptual models of flow systems
  - Sustainable management indicators
- Requires a formal training and information transfer program
- A decision-support system can guide choices

Some Steps in the "Right" Direction

- Governance by watershed organizations (OBV)
- PACES groundwater resources knowledge base
- On-going south St. Lawrence integrated project:
  - Coupled surface water-groundwater models
  - Groundwater monitoring system management
  - CC impact on recharge & baseflow prediction
- Sustainable groundwater management indicators
- BC-ATES decision-support system
- RQES information transfer program
- Monitoring data assimilation algorithms
- Combined allocation of surface water & GW
- Habitat preservation (T^o) & link of surface-GW

Final thoughts…

Tools Needed for Water Management

- Dynamic database integrating all needed inputs and outputs of management tools
- Knowledge of the water flow system
- Management and use of monitoring systems
- “Living” coupled surface-subsurface model
- Optimization of model through assimilation
- A decision-support system
- Water management plans
- Sustainable water management indicators
- Stakeholders involvement through information transfer programs

Many Developments are Needed

- Resource knowledge base (complete the PACES coverage in Quebec)
- Shift to integrated water management (surface water and groundwater)
- Optimize and exploit monitoring data
- Efficient coupled numerical models
- Monitoring data assimilation workflows
- Effective information transfer to stakeholders
- Governance of groundwater (OBV)
- Land management considering water (MRC)
- Source water protection (Municipalities)

Thanks

- The Canadian Geotechnical Society (CGS) and the Canadian National Chapter of the International Association of Hydrogeologists (IAH-CNC).
- Institut national de la recherche scientifique (INRS).
- My colleagues and collaborators at INRS, the Geological Survey of Canada, Laval University, the Université du Québec network, Université de Rennes 1 and ELTE Budapest.
- The 70 grad students that I have had the pleasure to work with, and who made me so proud.
- Engineering and hydrogeology consultants.
- My mentors, Ian Hutcheon at the University of Calgary and Pierre Gélinas at Laval University.
- My spouse, children, parents and familly.

Multi-disciplinary approach

Participants & collaborators
Basses-Laurentides Project – Circa 2000
(GSC, INRS, U. Laval, MDDELCC, Env. Canada, USGS)

INRS

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