PREFACE TO THE SPECIAL ISSUE

Results from the Quebec Groundwater Knowledge Acquisition Program

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Groundwater is a crucial supply of freshwater worldwide. It is estimated that groundwater represents more than one third of water withdrawals used for irrigation, domestic, and manufacturing purposes (Döll et al. 2012). In Canada, about 30% of the population (nearly 10 million inhabitants) depends on groundwater for their water supply (CCA 2009). In the Province of Quebec, 20% of the population relies on groundwater for its drinking water over 90% of the inhabited territory (MDDELCC 2018).

Globally, several pressures impact the state of groundwater ressources, including urbanization, land and water uses, pollution and climate variability (WWAP 2009). The intensification of industrial and agricultural activities, that can lead to contamination and overexploitation, as well as natural climate variability and climate change, are threats to Canada's groundwater (CCA 2009; Rivera et al. 2004). It has been recognized at different levels of organizations that the lack of knowledge on groundwater resources and aquifers, as well as the difficulty in accessing water related data, are major obtacles to the implementation of sustainable management of groundwater resources (Government of Québec 2002; CCA 2009; WWAP 2009).

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To face this challenge in the Province of Quebec, a unique and systematic program of regional hydrogeological mapping, the Groundwater Knowledge Acquisition Program (*Programme d'acquisition de connaissances sur les eaux souterraines* - PACES), was implemented in 2008 by the Québec Ministry of the Environment (*Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques - MDDELCC*) to ensure the protection and long-term sustainability of groundwater resources (MDDELCC 2018). The proposed methodology for the PACES program was based on the experience developed during previous hydrogeological mapping projects in Quebec (pre-PACES projects; Figure 1), including the Portneuf granular aquifers (Fagnan at al. 1999), the Basses-Laurentides fractured aquifer system (Savard et al. 2013), the Châteauguay River Watershed (Nastev and Lamontagne 2010), as well as the Basse and moyenne-Chaudière agricultural region (Tecsult 2008).

The general objective of the PACES was to provide an integrated portrait of the groundwater resources of Quebec's municipal regions, both in terms of groundwater quantity and quality, to better protect and sustainably manage groundwater resources. A total of thirteen regional hydrogeological mapping projects of PACES were completed during the 2009-2015 period (Abitibi-Témiscamingue-1 and -2, Bécancour, Bas-Saint-Laurent, Charlevoix–Haute-Côte-Nord, Chaudière-Appalaches, Communauté métropolitaine de Québec, Mauricie, Montérégie-Est, Nicolet–Saint-François, Outaouais, Saguenay–Lac-Saint-Jean, Vaudreuil-Soulanges; Figure 1). These projects were led by research teams from seven Quebec universities (Institut national de la recherche scientifique centre Eau Terre Environnement - INRS-ETE, Université Laval, Université du Québec à Chicoutimi-UQAC, Université du Québec à Montréal-UQAM, Université du Québec à Rimouski-UQAR, Université du Québec en Abitibi-Témiscamingue-UQAT, and Université du Québec à Trois-Rivières-UQTR), in collaboration with regional stakeholders (e.g. Regional Conference of Elected Officials, *Conférence régionale des élus* – CRÉ); Regional County Municipalities, *Municipalités regionals de comtés* – MRC; Watershed Organizations, *Organismes de bassins versants* – OBV), provincial (Ministry of Ariculture, *Ministère de l'Agriculture, des Pêcheries et de l'Alimentation* – MAPAQ; Ministry of Energy and Natural Ressources, *Ministère de l'Énergie et des Ressources naturelles* – MERN) and federal (Natural Resources Canada) partners. A unique and efficient inter-university collaborative approach was developed to share equipment and services, co-supervise graduated students, and develop common protocols, from field data acquisition to map production (Palmer et al. 2011). All the PACES projects thus used uniform databases and similair methodologies for development of thematic maps, allowing comparisons between regions. Four new projects were initiated in 2018, with funding from the MDDELCC, and will use the same methodology, thus completing the territory coverage in many regions of the Quebec Province (Figure 1; the new projects are named ACES for *Acquisition de connaissances sur les eaux souterraines*).

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Figure 1. Location of completed and current groundwater characterization projects in the Province of Quebec. The map illustrates the pre-PACES projects (PORT (dark grey)/Portneuf; AFSOQ/Basses-Laurentides; CHAT/Châteauguay, and CHAUD-A (dark grey)/Basse-Chaudière), the PACES projects from 2009-2015 (AT1 and AT2/Abitibi-Témiscamingue–1 and 2, BEC/Bécancour, BSL/Bas-Saint-Laurent, CN/Charlevoix–Haute-Côte-Nord, CHAUD-A (light grey)/Chaudière-Appalaches, CMQ/Communauté métropolitaine de Québec, MAUR/Mauricie, MONT/Montérégie-Est, NSF/Nicolet–Saint-François, OUT/Outaouais, SLSJ/Saguenay–Lac-Saint-Jean, Vs/Vaudreuil-Soulanges), and the ACES projects that started in 2018 (KRT/Bas-Saint-Laurent-Témiscouata, ESTR/Estrie, LAUR-M/Laurentides, LANAU/Lanaudière, MAUR-E/Mauricie-Est, and PORT (hatched)/Portneuf).

The collaborative approach between university researchers lead to the creation in 2011 of the Quebec Groundwater Network (*Réseau Québécois sur les Eaux Souterraines* – RQES; www.rqes.ca). The mission of the RQES is to consolidate and extend collaborations between university researchers and the Québec Ministry of the Environment, and other governmental and non-governmental organizations, consultants, educational institutions and additional organizations interested in groundwater, with the objective of facilitating groundwater knowledge transfer to water managers. The PACES projects allowed an unprecedented regional scale groundwater characterization of southern Quebec. Nevertheless, despite this major advance, the adequate integration and use of the hydrogeological information in land management remains a challenge, due to the complexity related to data and map interpretation and to the lack of dedicated knowledge transfer initiatives. To face this critical issue, the RQES developed a knowledge exchange strategy that is based on a series of interactive workshops undertaken in all the PACES regions. These workshops helped to optimize the adequate use of quantitative hydrogeological data in land management with the objective of better protecting groundwater resources (Ruiz 2016).

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The purpose of this Special Issue was to bring together a sample of the vast new knowledge that was created by the PACES projects across the Province of Quebec between 2009 and 2015. Many of the scientists who were involved in these projects have responded positively to the invitation. This Special Issue contains ten contributions from university researchers and private consultants on relevant topics such as aquifer geometry and hydraulic properties, hydrogeochemistry and isotopic tracers, residence times, and groundwater flow modelling.

The studied PACES regions are distributed over a large area of the meridional portion of the Province of Quebec (Figure 1). The territory has highly diversified geology and contrasting climate conditions, thus influencing the hydrogeology of the studied regions. The projects cover three hydrogeolocal regions of Canada described by Rivera (2014): 1) the Precambrian Shield, 2) the St. Lawrence Lowlands, and 3) the Appalachian. These hydrogeological regions correspond to important geological domains of Québec, i.e. the Superior and Grenville provinces, the St. Lawrence Platform, and the Appalachian Province (MRN 2012). The last glaciation/deglaciation cycle, with the deposition of unconsolidated sediments, the formation of proglacial lakes and marine invasions, had major impacts on the shaping of the landscape, as well as on the hydrogeology and hydrogeochemistry of the aquifer systems. Details of these geological contexts are presented in the ten articles. The papers focus on three main components of aquifer characterization, i.e. aquifer geometry (Légaré-Couture et al. 2018; Nadeau et al. 2018; Walter et al. 2018), hydrogeochemistry and isotope tracers (Beaudry et al. 2018; Chaillou et al. 2018; Rey et al. 2018), as well as groundwater flow modeling and particle tracking (Gagné et al. 2018; Janos et al. 2018; Montcoudiol et al. 2018; Turgeon et al. 2018). The paper by Walter et al. (2018) combines the topics of geometry and hydrogeochemistry.

In their characterization of the major aquifer systems in the Saguenay – Lac-Saint-Jean region (SLSJ), Walter et al. (2018) provide a comprehensive overview of the three phases of a PACES project and of their outcomes, including defining the aquifer systems, quantifying the hydrogeological properties, and characterizing groundwater quality in a complex graben environment. The authors used their results to develop a conceptual model of regional hydrostratigraphic features and groundwater quality of the major

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aquifers in support of sustainable management of regional groundwater ressources. Légaré-Couture et al. (2017) propose a methodology for building a three-dimensional (3D) hydrostratigraphical model of the Quaternary deposits to define the main hydrogeological contexts of granular aquifers that provide important water supplies for most municipalities of the Mauricie region (MAUR). Based on this model, the authors identified four main hydrostratigraphic units for the study area. This refines the understanding of regional aquifers and contibuted to the identification of unexploited aquifers around the Saint-Narcisse morainic complex and along the Saint-Cuthbert Fault. Also focusing on groundwater resources within unconsolidated aquifers, Nadeau et al. (2018) describe a newly developed GIS-based approach facilitating the development of a stratigraphic sequence map for representing the architecture of aquifer– aquitard systems at the regional scale in Abitibi-Témiscamingue regions 1 and 2 (AT1 and AT2). The resulting stratigraphic sequence map was used to document the extent and volume of regional aquifers, as well to build a conceptual model of regional groundwater flow paths. The authors also dicussed the potential contibutions of the stratigraphic sequence map as a tool to support political decision makers facing issues related to groundwater resource protection and sustainable development.

Chaillou et al. (2018) present a regional groundwater hydrogeochemical portrait of the Bas-Saint-Laurent region (BSL). The contrasting geology of this region comprises the Appalachians and glacial Quaternary deposits set in close proximity to the coastal environment of the St. Lawrence estuary. The authors used major and trace ions, as well as stable isotopes of water and inorganic carbon to identify seven water facies. They proposed a conceptual model of groundwater flow to explain the hydrogeochemical evolution at the regional scale. Interestingly, their results suggest the absence of modern seawater in the samples despite the proximity of the St. Lawrence estuary. Different geological formations were studied by Beaudry et al. (2018) in the Montérégie region including the St. Lawrence Lowlands, the Appalachian Piedmont and Uplands, and the Monteregian Hills (MONT). Similarly to Chaillou et al. (2018), the authors used major and trace ions, stable isotopes of water and carbon, as well as ^{14}C and ^{3}H to identify the mechanisms controlling groundwater composition and to support the understanding of the aquifer hydrodynamics. Their results provided indications of recharge zones,

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groundwater flow zones, and discharge zones. They have also identified an extensive zone of brakish water originating from the Champlain Sea and located in the lower portion of the study area. Rey et al. (2018) have focused on the Barlow-Ojibway Clay Belt of the Abitibi-Témiscamingue region which includes many esker and moraine aquifers (AT1 and AT2). They have used stable isotopes of water and ^{3}H to improve the understanding of the regional groundwater flow system. The results were used to build a regional-scale conceptual model which describes recharge, evaporation, mixing and discharge processes.

Gagné et al. (2017) present a 3D model of groundwater flow for the Bécancour and Nicolet watersheds in the Centre-du-Québec region (BEC and NSF). In this region, the main aquifer is located in the sedimentary fractured bedrock and is overlain by till, sand and clay from the Champlain Sea. The spatially distributed recharge was simulated independently with a surface water budget approach. The steady-state MODFLOW model (Harbaugh 2005) was calibrated using measured heads and baseflows with PEST (Doherty 2015). The authors have shown that isotope-derived groundwater travel times and major ion chemistry can be used to validate the model. Janos et al. (2018) developed a vertical 2D steady-state flow model with the FLONET/TR2 numerical code (Molson and Frind 2017), and calibrated it with PEST using measured heads for the Chaudière-Appalaches region (CHAUD-A). The model simulated groundwater ages that were used to show that the area is dominated by local scale flow systems, thus confirming the conceptual model identified using hydrogeochemical variables. The authors also investigated the role of faults in disturbing groundwater age patterns. Montcoudiol et al. (2017) have also used the FLONET/TR2 numerical code to simulate 2D steady-state groundwater flow in the fractured bedrock of the Canadian Shield overlain by sand, gravel and clay in the Outaouais region (OUT). Their model was calibrated using heads and measured ^{3}H values and helped to validate and update a conceptual model of geochemical evolution. Turgeon et al. (2018) used the integrated the MikeSHE flow model (DHI 2007) to simulate transient-state groundwater and surface water interactions in the Raquette River watershed of the Vaudreuil-soulanges region (VS). The complex geology of the watershed is composed of sedimentary bedrock and of the Rigaud Monteregian Hill, with till and thick sand and clay deposits. The model was calibrated

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using river flowates and heads and provided a good insight into the watershed surface and groundwater flow. The authors identified areas of possible improvements in the model, notably the explicit simulation of infiltration processes in the unsaturated zone.

The topics covered by this Special Issue do not address all the topics covered in the PACES projects. Many other papers have been published in different journals on a wide array of groundwater-related issues derived directly from the PACES projects or closely linked to them. In terms of physical hydrogeology, the PACES related studies allowed the development of methods to assess groundwater recharge (e.g. Gosselin et al. 2016; Huet et al. 2016), to estimate transmissivity from specific capacity data (e.g. Richard et al. 2014; Laurencelle and Lefebvre 2018) and to improve the spatial analysis of piezometric data (e.g. Tremblay et al. 2015). Other studies allowed better highlighting the role of groundwater in river flow or peatland-aquifer interactions (e.g. Ferlatte et al. 2015; Rosa et al. 2018). The use of groundwater geochemistry further allowed assessment of chemical evolution of groundwater along flowpaths (e.g. Ghesquière et al. 2015; Montcoudiol et al 2015) and deciphering the processes influencing the occurrence of geogenic arsenic in fractured bedrock aquifers (e.g. Bondu et al. 2017). Other studies examining groundwater geochemistry focused on evaluating groundwater vulnerability (e.g. Meyzonnat et al. 2016) and documenting the concentrations of emerging contaminants such as pesticides and pharmaceutically active compounds in groundwater (e.g. Saby et al. 2016). Studies focusing on the use of GIS further allowed the development of a method for supporting groundwater protection in unconfined granular aquifers (e.g. Nadeau et al. 2015), as well the development of sustainable groundwater resource indicators to support knowledge transfer initiatives (Lefebvre et al. 2016). Moreover, the PACES projects have provided large databases and new knowledge about Québec aquifers. Many challenges now arise including, for example, how to maintain up-to-date databases, how to monitor groundwater quality and quantity over the long-term, or how changing climate conditions and changing land use will impact groundwater resources. The research is ongoing in many of these domains.

We believe that this Special Issue provides a valuable snapshot of the current, state-of-the-art knowledge on groundwater resources in the Province of Quebec. It summarizes

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new knowledge on groundwater availability, groundwater flow conditions, aquifer recharge and groundwater quality that occur in this part of Canada. It also presents a portrait of state-of-the art methods for aquifer characterization and how they can be used in different geological settings. It is our hope that this Special Issue will be a reference for hydrogeologists across the country and motivate the initiation of new research for a better understanding of our groundwater resources.

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This Special Issue has brought together hydrogeologists that were involved in the recent Groundwater Knowledge Acquisition Program. We wish to thank the authors who have contributed to advancing knowledge about groundwater resources in the Province of Quebec. We acknowledge the financial contribution of the Quebec Ministry of the Environment (*Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques*) through the Groundwater Knowledge Acquisition Program (PACES), as well as the contribution of all the regional partners that were involved in the projects. We also thank the reviewers who have contributed to the high scientific level achieved by this Special Issue and all its comprising articles.

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Figure Caption

Figure 1. Location of completed and current groundwater characterization projects in the Province of Quebec. The map illustrates the pre-PACES projects (PORT (dark grey)/Portneuf; AFSOQ/Basses-Laurentides; CHAT/Châteauguay, and CHAUD-A (dark grey)/Basse-Chaudière), the PACES projects from 2009-2015 (AT1 and AT2/Abitibi-Témiscamingue–1 and 2, BEC/Bécancour, BSL/Bas-Saint-Laurent, CN/Charlevoix–Haute-Côte-Nord, CHAUD-A (light grey)/Chaudière-Appalaches, CMQ/Communauté métropolitaine de Québec, MAUR/Mauricie, MONT/Montérégie-Est, NSF/Nicolet–Saint-François, OUT/Outaouais, SLSJ/Saguenay–Lac-Saint-Jean, Vs/Vaudreuil-Soulanges), and the ACES projects that started in 2018 (KRT/Bas-Saint-Laurent-Témiscouata, ESTR/Estrie, LAUR-M/Laurentides, LANAU/Lanaudière, MAUR-E/Mauricie-Est, and PORT (hatched)/Portneuf).

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PREFACE TO THE SPECIAL ISSUE

Results from the Quebec Groundwater Knowledge Acquisition Program

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Groundwater is a crucial supply of freshwater worldwide. It is estimated that groundwater represents more than one third of water withdrawals used for irrigation, domestic, and manufacturing purposes (Döll et al. 2012). In Canada, about 30% of the population (nearly 10 million inhabitants) depends on groundwater for their water supply (CCA 2009). In the Province of Quebec, 20% of the population relies on groundwater for its drinking water over 90% of the inhabited territory (MDDELCC 2018).

Globally, several pressures impact the state of groundwater ressources, including urbanization, land and water uses, pollution and climate variability (WWAP 2009). The intensification of industrial and agricultural activities, that can lead to contamination and overexploitation, as well as natural climate variability and climate change, are threats to Canada’s groundwater (CCA 2009; Rivera et al. 2004). It has been recognized at different levels of organizations that the lack of knowledge on groundwater resources and aquifers, as well as the difficulty in accessing water related data, are major obtacles to the implementation of sustainable management of groundwater resources (Government of Québec 2002; CCA 2009; WWAP 2009).

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To face this challenge in the Province of Quebec, a unique and systematic program of regional hydrogeological mapping, the Groundwater Knowledge Acquisition Program (*Programme d’acquisition de connaissances sur les eaux souterraines* - PACES), was implemented in 2008 by the Québec Ministry of the Environment (*Ministère du Développement durable, de l’Environnement et de la Lutte contre les changements climatiques - MDDELCC*) to ensure the protection and long-term sustainability of groundwater resources (MDDELCC 2018). The proposed methodology for the PACES program was based on the experience developed during previous hydrogeological mapping projects in Quebec (pre-PACES projects; Figure 1), including the Portneuf granular aquifers (Fagnan at al. 1999), the Basses-Laurentides fractured aquifer system (Savard et al. 2013), the Châteauguay River Watershed (Nastev and Lamontagne 2010), as well as the Basse and moyenne-Chaudière agricultural region (Tecsult 2008).

The general objective of the PACES was to provide an integrated portrait of the groundwater resources of Quebec's municipal regions, both in terms of groundwater quantity and quality, to better protect and sustainably manage groundwater resources. A total of thirteen regional hydrogeological mapping projects of PACES were completed during the 2009-2015 period (Abitibi-Témiscamingue-1 and -2, Bécancour, Bas-Saint-Laurent, Charlevoix–Haute-Côte-Nord, Chaudière-Appalaches, Communauté métropolitaine de Québec, Mauricie, Montérégie-Est, Nicolet–Saint-François, Outaouais, Saguenay–Lac-Saint-Jean, Vaudreuil-Soulanges; Figure 1). These projects were led by research teams from seven Quebec universities (Institut national de la recherche scientifique centre Eau Terre Environnement - INRS-ETE, Université Laval, Université du Québec à Chicoutimi-UQAC, Université du Québec à Montréal-UQAM, Université du Québec à Rimouski-UQAR, Université du Québec en Abitibi-Témiscamingue-UQAT, and Université du Québec à Trois-Rivières-UQTR), in collaboration with regional stakeholders (e.g. Regional Conference of Elected Officials, *Conférence régionale des élus* – CRÉ); Regional County Municipalities, *Municipalités regionals de comtés* – MRC; Watershed Organizations, *Organismes de bassins versants* – OBV), provincial (Ministry of Ariculture, *Ministère de l'Agriculture, des Pêcheries et de l'Alimentation* – MAPAQ; Ministry of Energy and Natural Ressources, *Ministère de l'Énergie et des Ressources naturelles* – MERN) and federal (Natural Resources Canada) partners. A unique and efficient inter-university collaborative approach was developed to share equipment and services, co-supervise graduated students, and develop common protocols, from field data acquisition to map production (Palmer et al. 2011). All the PACES projects thus used uniform databases and similair methodologies for development of thematic maps, allowing comparisons between regions. Four new projects were initiated in 2018, with funding from the MDDELCC, and will use the same methodology, thus completing the territory coverage in many regions of the Quebec Province (Figure 1; the new projects are named ACES for *Acquisition de connaissances sur les eaux souterraines*).

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Figure 1. Location of completed and current groundwater characterization projects in the Province of Quebec. The map illustrates the pre-PACES projects (PORT (dark grey)/Portneuf; AFSOQ/Basses-Laurentides; CHAT/Châteauguay, and CHAUD-A (dark grey)/Basse-Chaudière), the PACES projects from 2009-2015 (AT1 and AT2/Abitibi-Témiscamingue−1 and 2, BEC/Bécancour, BSL/Bas-Saint-Laurent, CN/Charlevoix−Haute-Côte-Nord, CHAUD-A (light grey)/Chaudière-Appalaches, CMQ/Communauté métropolitaine de Québec, MAUR/Mauricie, MONT/Montérégie-Est, NSF/Nicolet−Saint-François, OUT/Outaouais, SLSJ/Saguenay−Lac-Saint-Jean, Vs/Vaudreuil-Soulanges), and the ACES projects that started in 2018 (KRT/Bas-Saint-Laurent-Témiscouata, ESTR/Estrie, LAUR-M/Laurentides, LANAU/Lanaudière, MAUR-E/Mauricie-Est, and PORT (hatched)/Portneuf).

The collaborative approach between university researchers lead to the creation in 2011 of the Quebec Groundwater Network (*Réseau Québécois sur les Eaux Souterraines* – RQES; www.rqes.ca). The mission of the RQES is to consolidate and extend collaborations between university researchers and the Québec Ministry of the Environment, and other governmental and non-governmental organizations, consultants, educational institutions and additional organizations interested in groundwater, with the objective of facilitating groundwater knowledge transfer to water managers. The PACES projects allowed an unprecedented regional scale groundwater characterization of southern Quebec. Nevertheless, despite this major advance, the adequate integration and use of the hydrogeological information in land management remains a challenge, due to the complexity related to data and map interpretation and to the lack of dedicated knowledge transfer initiatives. To face this critical issue, the RQES developed a knowledge exchange strategy that is based on a series of interactive workshops undertaken in all the PACES regions. These workshops helped to optimize the adequate use of quantitative hydrogeological data in land management with the objective of better protecting groundwater resources (Ruiz 2016).

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The purpose of this Special Issue was to bring together a sample of the vast new knowledge that was created by the PACES projects across the Province of Quebec between 2009 and 2015. Many of the scientists who were involved in these projects have responded positively to the invitation. This Special Issue contains ten contributions from university researchers and private consultants on relevant topics such as aquifer geometry and hydraulic properties, hydrogeochemistry and isotopic tracers, residence times, and groundwater flow modelling.

The studied PACES regions are distributed over a large area of the meridional portion of the Province of Quebec (Figure 1). The territory has highly diversified geology and contrasting climate conditions, thus influencing the hydrogeology of the studied regions. The projects cover three hydrogeolocal regions of Canada described by Rivera (2014): 1) the Precambrian Shield, 2) the St. Lawrence Lowlands, and 3) the Appalachian. These hydrogeological regions correspond to important geological domains of Québec, i.e. the Superior and Grenville provinces, the St. Lawrence Platform, and the Appalachian Province (MRN 2012). The last glaciation/deglaciation cycle, with the deposition of unconsolidated sediments, the formation of proglacial lakes and marine invasions, had major impacts on the shaping of the landscape, as well as on the hydrogeology and hydrogeochemistry of the aquifer systems. Details of these geological contexts are presented in the ten articles. The papers focus on three main components of aquifer characterization, i.e. aquifer geometry (Légaré-Couture et al. 2018; Nadeau et al. 2018; Walter et al. 2018), hydrogeochemistry and isotope tracers (Beaudry et al. 2018; Chaillou et al. 2018; Rey et al. 2018), as well as groundwater flow modeling and particle tracking (Gagné et al. 2018; Janos et al. 2018; Montcoudiol et al. 2018; Turgeon et al. 2018). The paper by Walter et al. (2018) combines the topics of geometry and hydrogeochemistry.

In their characterization of the major aquifer systems in the Saguenay – Lac-Saint-Jean region (SLSJ), Walter et al. (2018) provide a comprehensive overview of the three phases of a PACES project and of their outcomes, including defining the aquifer systems, quantifying the hydrogeological properties, and characterizing groundwater quality in a complex graben environment. The authors used their results to develop a conceptual model of regional hydrostratigraphic features and groundwater quality of the major

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aquifers in support of sustainable management of regional groundwater ressources. Légaré-Couture et al. (2017) propose a methodology for building a three-dimensional (3D) hydrostratigraphical model of the Quaternary deposits to define the main hydrogeological contexts of granular aquifers that provide important water supplies for most municipalities of the Mauricie region (MAUR). Based on this model, the authors identified four main hydrostratigraphic units for the study area. This refines the understanding of regional aquifers and contibuted to the identification of unexploited aquifers around the Saint-Narcisse morainic complex and along the Saint-Cuthbert Fault. Also focusing on groundwater resources within unconsolidated aquifers, Nadeau et al. (2018) describe a newly developed GIS-based approach facilitating the development of a stratigraphic sequence map for representing the architecture of aquifer– aquitard systems at the regional scale in Abitibi-Témiscamingue regions 1 and 2 (AT1 and AT2). The resulting stratigraphic sequence map was used to document the extent and volume of regional aquifers, as well to build a conceptual model of regional groundwater flow paths. The authors also dicussed the potential contibutions of the stratigraphic sequence map as a tool to support political decision makers facing issues related to groundwater resource protection and sustainable development.

Chaillou et al. (2018) present a regional groundwater hydrogeochemical portrait of the Bas-Saint-Laurent region (BSL). The contrasting geology of this region comprises the Appalachians and glacial Quaternary deposits set in close proximity to the coastal environment of the St. Lawrence estuary. The authors used major and trace ions, as well as stable isotopes of water and inorganic carbon to identify seven water facies. They proposed a conceptual model of groundwater flow to explain the hydrogeochemical evolution at the regional scale. Interestingly, their results suggest the absence of modern seawater in the samples despite the proximity of the St. Lawrence estuary. Different geological formations were studied by Beaudry et al. (2018) in the Montérégie region including the St. Lawrence Lowlands, the Appalachian Piedmont and Uplands, and the Monteregian Hills (MONT). Similarly to Chaillou et al. (2018), the authors used major and trace ions, stable isotopes of water and carbon, as well as ^{14}C and ^{3}H to identify the mechanisms controlling groundwater composition and to support the understanding of the aquifer hydrodynamics. Their results provided indications of recharge zones, groundwater flow zones, and discharge zones. They have also identified an extensive zone of brakish water originating from the Champlain Sea and located in the lower portion of the study area. Rey et al. (2018) have focused on the Barlow-Ojibway Clay Belt of the Abitibi-Témiscamingue region which includes many esker and moraine aquifers (AT1 and AT2). They have used stable isotopes of water and ^{3}H to improve the understanding of the regional groundwater flow system. The results were used to build a regional-scale conceptual model which describes recharge, evaporation, mixing and discharge processes.

Gagné et al. (2017) present a 3D model of groundwater flow for the Bécancour and Nicolet watersheds in the Centre-du-Québec region (BEC and NSF). In this region, the main aquifer is located in the sedimentary fractured bedrock and is overlain by till, sand and clay from the Champlain Sea. The spatially distributed recharge was simulated independently with a surface water budget approach. The steady-state MODFLOW model (Harbaugh 2005) was calibrated using measured heads and baseflows with PEST (Doherty 2015). The authors have shown that isotope-derived groundwater travel times and major ion chemistry can be used to validate the model. Janos et al. (2018) developed a vertical 2D steady-state flow model with the FLONET/TR2 numerical code (Molson and Frind 2017), and calibrated it with PEST using measured heads for the Chaudière-Appalaches region (CHAUD-A). The model simulated groundwater ages that were used to show that the area is dominated by local scale flow systems, thus confirming the conceptual model identified using hydrogeochemical variables. The authors also investigated the role of faults in disturbing groundwater age patterns. Montcoudiol et al. (2017) have also used the FLONET/TR2 numerical code to simulate 2D steady-state groundwater flow in the fractured bedrock of the Canadian Shield overlain by sand, gravel and clay in the Outaouais region (OUT). Their model was calibrated using heads and measured ^{3}H values and helped to validate and update a conceptual model of geochemical evolution. Turgeon et al. (2018) used the integrated the MikeSHE flow model (DHI 2007) to simulate transient-state groundwater and surface water interactions in the Raquette River watershed of the Vaudreuil-soulanges region (VS). The complex geology of the watershed is composed of sedimentary bedrock and of the Rigaud Monteregian Hill, with till and thick sand and clay deposits. The model was calibrated

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using river flowates and heads and provided a good insight into the watershed surface and groundwater flow. The authors identified areas of possible improvements in the model, notably the explicit simulation of infiltration processes in the unsaturated zone.

The topics covered by this Special Issue do not address all the topics covered in the PACES projects. Many other papers have been published in different journals on a wide array of groundwater-related issues derived directly from the PACES projects or closely linked to them. In terms of physical hydrogeology, the PACES related studies allowed the development of methods to assess groundwater recharge (e.g. Gosselin et al. 2016; Huet et al. 2016), to estimate transmissivity from specific capacity data (e.g. Richard et al. 2014; Laurencelle and Lefebvre 2018) and to improve the spatial analysis of piezometric data (e.g. Tremblay et al. 2015). Other studies allowed better highlighting the role of groundwater in river flow or peatland-aquifer interactions (e.g. Ferlatte et al. 2015; Rosa et al. 2018). The use of groundwater geochemistry further allowed assessment of chemical evolution of groundwater along flowpaths (e.g. Ghesquière et al. 2015; Montcoudiol et al 2015) and deciphering the processes influencing the occurrence of geogenic arsenic in fractured bedrock aquifers (e.g. Bondu et al. 2017). Other studies examining groundwater geochemistry focused on evaluating groundwater vulnerability (e.g. Meyzonnat et al. 2016) and documenting the concentrations of emerging contaminants such as pesticides and pharmaceutically active compounds in groundwater (e.g. Saby et al. 2016). Studies focusing on the use of GIS further allowed the development of a method for supporting groundwater protection in unconfined granular aquifers (e.g. Nadeau et al. 2015), as well the development of sustainable groundwater resource indicators to support knowledge transfer initiatives (Lefebvre et al. 2016). Moreover, the PACES projects have provided large databases and new knowledge about Québec aquifers. Many challenges now arise including, for example, how to maintain up-to-date databases, how to monitor groundwater quality and quantity over the long-term, or how changing climate conditions and changing land use will impact groundwater resources. The research is ongoing in many of these domains.

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We believe that this Special Issue provides a valuable snapshot of the current, state-of-the-art knowledge on groundwater resources in the Province of Quebec. It summarizes new knowledge on groundwater availability, groundwater flow conditions, aquifer recharge and groundwater quality that occur in this part of Canada. It also presents a portrait of state-of-the art methods for aquifer characterization and how they can be used in different geological settings. It is our hope that this Special Issue will be a reference for hydrogeologists across the country and motivate the initiation of new research for a better understanding of our groundwater resources.

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This Special Issue has brought together hydrogeologists that were involved in the recent Groundwater Knowledge Acquisition Program. We wish to thank the authors who have contributed to advancing knowledge about groundwater resources in the Province of Quebec. We acknowledge the financial contribution of the Quebec Ministry of the Environment (*Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques*) through the Groundwater Knowledge Acquisition Program (PACES), as well as the contribution of all the regional partners that were involved in the projects. We also thank the reviewers who have contributed to the high scientific level achieved by this Special Issue and all its comprising articles.

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Figure Caption

Figure 1. Location of completed and current groundwater characterization projects in the Province of Quebec. The map illustrates the pre-PACES projects (PORT (dark grey)/Portneuf; AFSOQ/Basses-Laurentides; CHAT/Châteauguay, and CHAUD-A (dark grey)/Basse-Chaudière), the PACES projects from 2009-2015 (AT1 and AT2/Abitibi-Témiscamingue–1 and 2, BEC/Bécancour, BSL/Bas-Saint-Laurent, CN/Charlevoix–Haute-Côte-Nord, CHAUD-A (light grey)/Chaudière-Appalaches, CMQ/Communauté métropolitaine de Québec, MAUR/Mauricie, MONT/Montérégie-Est, NSF/Nicolet–Saint-François, OUT/Outaouais, SLSJ/Saguenay–Lac-Saint-Jean, Vs/Vaudreuil-Soulanges), and the ACES projects that started in 2018 (KRT/Bas-Saint-Laurent-Témiscouata, ESTR/Estrie, LAUR-M/Laurentides, LANAU/Lanaudière, MAUR-E/Mauricie-Est, and PORT (hatched)/Portneuf).

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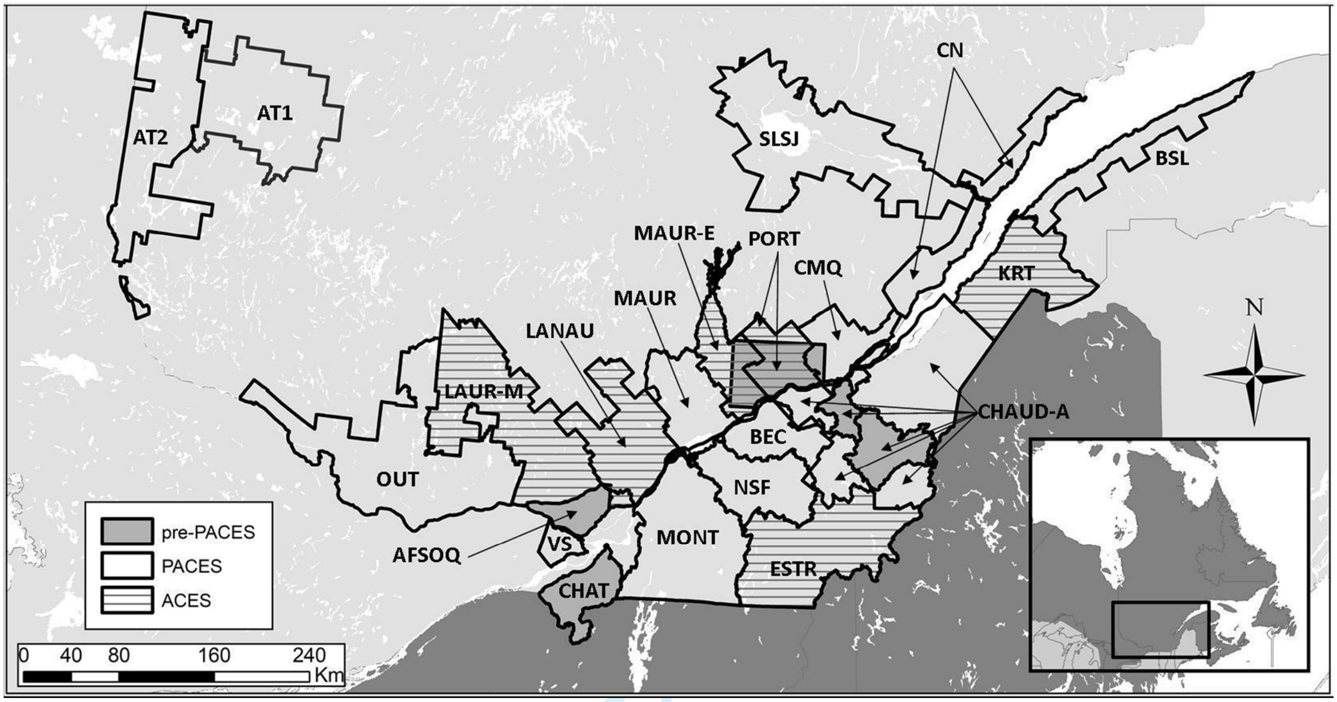

Figure 1.
Larocque et al 2018
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