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Evaluating Bank-Filtration Occurrence in the Province of Quebec (Canada) with a GIS Approach

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Received: 20 November 2019; Accepted: 20 February 2020; Published: 1 March 2020

Abstract: Due to the abundance of surface water in the province of Quebec, Canada, it is suspected that many groundwater wells are pumping a mixture of groundwater and surface water via induced bank filtration (IBF). The regulatory framework in Quebec provides comprehensive guidelines for the development and monitoring of surface water and groundwater drinking water production systems. However, the regulations do not specifically address hybrid groundwater-surface water production systems such as IBF sites. More knowledge on the use of IBF in the province is needed to adjust the regulations with respect to the particularities of these systems. In order to provide a first evaluation of municipal wells potentially using IBF and the corresponding population served by these wells, a Geographic Information Science framework (GISc) was used to implement an IBF spatial database and calculate the distance from each well to the nearest surface water body. GISc is based on open source GIS programs and openly available data, to facilitate the reproducibility of the work. From this provincial scale approach, we show that nearly one million people are supplied by groundwater from municipal wells located <500 m from a surface water body, and half a million have a significant probability to be supplied by IBF wells. A more focused look at the watershed scale distribution of wells allows us to improve our interpretations by considering the aquifer type and other regional factors. This approach reveals strong spatial variability in the distribution of wells in proximity to surface water. Of the three selected regions, one has a high potential for IBF (Laurentides), one requires additional information do draw precise conclusions (Nicolet), and the third region (Vaudreuil-Soulanges) is unlikely to have widespread use of IBF. With this study, we demonstrate that extensive use of IBF is likely and that there is a need for improved understanding and management of these sites in order to properly protect the drinking water supply.

Keywords: managed aquifer recharge (MAR); induced bank filtration (IBF); geographic information science (GISc); geographic information systems (GIS); drinking water supply; guidelines

1. Introduction

Induced bank filtration (IBF) is a widely used method of managed aquifer recharge (MAR) [1]. In an IBF system, surface water is drawn through the banks and bed of a lake or river towards a pumping well by an induced hydraulic gradient. This results in a pumped mixture of both groundwater and infiltrated surface water. This process reduces the risk of intensive use [2] of the aquifer and improves water quality relative to surface water [3]. The drawback of this method, however, is that there is a higher risk of contamination from certain sources in comparison to standard groundwater exploitations [4–7],

which makes it important to develop a specific regulatory framework adapted to this type of drinking water supply system.

In recent reviews of the international use of bank filtration [8–11], it is clear that IBF has been used worldwide and, in particular, in Europe for more than 100 years. In the last decades, the use of IBF also became relatively popular in the USA [3 and references therein]. More recently, few IBF systems have also been implemented in developing countries [3 and references therein]). The use of this technology is, however, completely overlooked in Canada and the province of Quebec in particular. As of this point in time, no inventory of IBF sites exists for the province, and the extent of its use throughout the province remains unknown. There is, however, a high probability that IBF is widely used. Indeed, Quebec is a province rich in both surface water and groundwater, with 22% of its surface covered by water either in the form of lakes, rivers, or wetlands [12]. It is estimated that Quebec contains 3% of the Earth's renewable freshwater resources [13]. In addition, Quebec was settled through its waterways, which has had long-term effects on its population distribution. The abundance of water and the distribution of the population mean that there is a high probability that pumping wells are located in close proximity to surface water. The process of unintentional IBF is thus likely to be occurring in many municipalities throughout the province.

In addition to the number of IBF sites throughout Quebec being unknown, the current regulations and guidelines in Quebec do not specifically address wells that pump a mixture of surface water and groundwater. In Quebec, the *Règlement sur le prélèvement des eaux et leur protection* (RPEP) provides comprehensive guidelines for protecting surface water and groundwater extractions from contamination [14]. This regulation provides a framework for monitoring contaminants that allows for appropriate intervention when groundwater resources contain surface microbiological contaminants, which ensures that the population is not likely to be affected by changes in water quality. Additionally, drinking water production systems that are considered Groundwater under the Direct Influence of Surface Water (GWUDI) are subjected to the same regulations as surface water, which are more stringent than for all groundwater wells. For instance, in such a case, the raw pumped water is tested weekly for microbiological parameters, whereas groundwater can be tested monthly [15]. Despite its name, the GWUDI classification does not aim at characterizing infiltration from surface water bodies. Rather, what is referred to as "surface water" within this classification system is in reference to any source of contamination from the surface (including septic tanks) that might provide recurrent microbial or viral contamination to a well. There is, therefore, no correlation with surface water bodies that are hydraulically connected to an aquifer unless said surface water bodies is considered a potential source of contamination or if there is persistent bacteriologic or virologic presence in the pumping well during initial characterization. Existing non-GWUDI IBF sites are therefore necessarily treated as standard groundwater extractions. This means that even if the groundwater wells are located within a few meters of a water body, and there is a hydraulic connection between them, there is a lack of protection guidelines for the nearby surface water.

Due to the lack of regulations specific to hybrid groundwater-surface water systems, many problems common to IBF sites may be overlooked or unanticipated during the planning and operation of these sites. IBF sites are sensitive to changes in surface water quality [6,16], changing redox conditions [17], and changes in the hydraulic conditions of the site [18]. Additionally, there are many undesirable chemical components and contaminants that can be found at pumping wells in IBF sites including Mn [19–21], Fe [22,23], NO^{-3-} [24], organic micropollutants [25–28], cyanobacteria [29–31], coliforms [32]. In order to have a more resilient water supply, the risk posed by these contaminants should be identified as early on in the development of the site as possible in order to minimize unforeseen costs and develop plans to reduce the risk. By identifying the potential contaminants at the sites related to changing hydraulic and chemical conditions, the risks associated with them would be reduced by allowing for strategic planning to avoid the conditions associated with poorer water quality. For example, well configuration and pumping schemes could be modified to increase transit times from surface water to pumping wells producing a more consistent water quality.

Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) approaches are being developed for site suitability mapping for the development of MAR ([33] and references therein) and IBF [34,35]. As an example, Jamarillo Uribe [36] has studied the impact of stream morphology on bank filtration sites. Nonetheless, to our knowledge, this is the first study that uses a GISc approach to identify the number of existing IBF sites. The objective of this study is to provide a first overview of the potential extent of IBF in the province of Quebec. The framework is based on the concept of Geographic Information Science (GISc), described in [37] and [38]. GISc is based on the use of open-source GIS programs and openly available data. This concept facilitates reproducible research to other areas of study and data sets and could improve the transparency of research using GIS. First, we have processed and homogenized the sources of information from three different agencies. Secondly, we have carried out a pre-quantification of municipal wells with a higher likelihood of providing drinking water through IBF using easily available government data. Following this pre-selection, zones with varying characteristics are considered in greater detail, and the likelihood of IBF taking place in these areas is discussed.

2. Materials and Methods

2.1. Data Set

2.1.1. Well Data

The well data in the province of Quebec is contained in a variety of databases. All private wells require that various information is reported following drilling, such as coordinates, ownership, well design (i.e., type of tubing and depth of well), and stratigraphic sequence. This data is compiled in the *Système d'Information Hydrogeologique* (SIH) database [39], which has previously been described by Sterckx [40]. The SIH database consists of information largely provided by well-drilling companies. This can lead to inconsistencies in the geological descriptions and the precision of the coordinates. This database is, however, considered a reliable source of information concerning the depth of the contact between overburden and bedrock [41].

The database with the most extensive information is available through a series of studies entitled "*Programme d'Acquisition de Connaissances sur les Eaux Souterraines*" (PACES) [42]. These projects were initiated in 2008 and aimed at improving knowledge of groundwater resources in the southern regions of the province of Quebec in order to protect them and ensure their sustainability. These studies have led to a number of subsequent publications [43–46]. As of today, the PACES studies have been completed on a total of 13 regions throughout the province and led to the compilation of varied information (i.e., depth of well, depth of screen, depth of water table, type of aquifer, type of well and coordinates) on a total of roughly 180,000 wells. Supplemental information, including geochemistry, geology, and hydrogeological data (e.g., hydraulic conductivity), was also compiled for a small subset of wells (n = 15,162). The PACES database contains significant overlap with the SIH database, and therefore, some issues with the reliability of the coordinates and geological descriptions also affect this database.

The third database is comprised of municipal wells and surface water extraction points [47]. This database is typically used by decision-makers for public health and land-use planning. The version of the database used in this study was acquired in 2017 (i.e., prior to the most recent update in November 2018). The information contained in this database is centered on geographic coordinates, population served, and types of potabilization treatment. It contains information on 2116 individual wells and surface water extraction points. The geographic coordinates are generally more recently acquired and derived from official declaration documents, resulting in a better precision of the localization of the wells than the two other databases.

The municipal database formed the basis of this study with complementary information pulled from the other sources. The decision to focus on the municipal well database was made since (i) IBF requires sufficiently high pumping rates to induce a hydraulic gradient from the surface water to the well, (ii) the localization of the wells is precise and (iii) all these wells are supplying drinking water to

the population. The PACES database was used to extract complementary information and draw some general conclusions about the distribution of wells within the province. Table 1 summarizes the data sets and the variables used in this study.

Table 1. Summary of data available in the databases.

Information	SIH	PACES *	Municipal *
Number of wells	~216,000	~180,000	~2000
Depth of well	X	X	
Depth of screen		X	
Geology	(X)	(X)	
Chemistry		(X)	
Population Served			X
Type of aquifer	(X)	X	
Type of well		X	X
Type of treatment			X
Coordinates	X	X	X

* Databases used for subsequent calculations; (X) not systematically compiled.

2.1.2. Surface Water Bodies and Other Data

Natural Resources Canada's (NRCAN) website contains a variety of vector data in the Canvec portion of the site [48]. The surface water files are subdivided into two categories, "watercourses" and "water bodies". Many of the features in the "watercourses" files are drainage ditches and ephemeral streams that are not likely to be supplying bank filtrate to wells throughout the year. The features in the "water bodies" files correspond to water bodies of larger size and more permanent nature, which are more likely to contain a sufficient volume of water to support a municipal water supply. Considering the above, it was decided to conduct our province-wide study with the "waterbodies" files only. The named rivers from the "watercourses" files were added to the regional studies. These files contain two types of data, i.e., polygons and polylines, respectively representing the water bodies and shorelines.

2.2. Description of the GISc Framework

In this study, we used a GISc framework in order to calculate the minimal distance between each municipal pumping well and the nearest surface water body (i.e., lake or river). Throughout this study, the distance to surface water is calculated with respect to the "waterbodies" files retrieved from the NRCAN website, as mentioned above. The work process has been carried out with the Quantum GIS program (QGIS) [49]. In this subsection, we list a number of steps that were taken in order to perform the spatial analysis.

2.2.1. Processing and Homogenization of Spatial Data Sets

- Removal of duplicate wells

The work process is initialized with spatial data debugging. The database of municipal wells contained a number of duplicated geometries, i.e., wells with identical coordinates, which caused issues when performing the calculations. The duplicate data most often resulted when wells were supplying water to multiple municipalities. In order to remedy this, duplicate geometries were automatically identified and removed from the spatial database. In cases where discrepancies were found in the attribute table, the correct points were identified and retained.

- Homogenization of the spatial reference system

Coordinates needed to be converted into a common projected coordinate system in order to do subsequent distances calculations. Spatial data were reprojected from the original coordinate system

(i.e., NAD 83) to Lambert EPSG: 32,198. The Quebec Lambert was selected since it is suitable for use in Quebec (Canada) and for applications with an accuracy of <2 m [50].

- Conversion of geometries

First, the geometries were converted from multipart to single part. This step was necessary in order to ensure that the conversion to lines in the following step inserted all the necessary points. Without this step, only the existing nodes of the polyline file were converted to points, which led to an uneven and wide-ranging spread of points along the shorelines.

Second, waterbody files were converted from lines to points with 2 m spacing with the function *Convert lines to points* in the SAGA [51] toolbox. This function was run as a batch process for all of the 1:50,000 National Topographic System (NTS) zones individually.

2.2.2. Performing Distance Calculation

- Calculate the distance from each well to the nearest point

Using the smaller 1:50,000 zones allowed for the direct calculation from each well to the nearest point in each of the NTS zones. This calculation was completed using the *Distance to nearest hub* function. This algorithm identifies the nearest feature to each point and the Euclidean distance between all points. This, however, led to the creation of roughly 220 different files, each containing one distance value for each well. This avoided some problems that occurred when the calculation was done in the reverse order, but it created extremely large files that were not easy to work with in QGIS, especially for the larger PACES files.

- Calculate the minimum value for each well

The subsequent step was to merge all of these roughly 220 files and calculate the minimum value for each well. This was done in QGIS using the *merge* function, and the minimum selection was made using the *Select by expression* dialogue box and the following line of code HubDist = minimum (HubDist, Well ID). This could only be done in QGIS for the smaller municipal well files. For the larger PACES files, the merge and distance calculations were completed using R [52] programming language.

Once the distance was calculated, manipulation of the data was done manually using filters in QGIS, and R. Additional data was also joined to the well files either manually, or using common fields or spatial relationships using a variety of functions in QGIS.

This process was repeated for the regional studies with named rivers from the watercourse file and the water bodies used in the province-wide study.

3. Results and Discussion

There are two main conditions that will determine whether a well is pumping a mixture of surface water and groundwater. First, a hydraulic connection between the surface water and the aquifer is necessary. Second, assuming groundwater typically discharges into surface water bodies in the study region [53], it is necessary to pump a sufficient volume to reverse that natural gradient and draw surface water toward the pumping well. In order to conduct a study at the scale of the province, we used the municipal well database (description available in Section 2.1.1), which reports the geographical coordinates and the population served by each of the 2075 municipal wells and surface water extraction points. Since the type of aquifer is not reported within this database, the distance from the surface water bodies was deemed to be the most important criterion for estimating the number of IBF sites available for a province-wide scale. Then, we selected three areas with distinct characteristics in order to conduct regional analyses, including integrating the type of aquifer and other hydrogeological information. The results of both province and regional scale approaches are presented and discussed in the next subsections.

Bank filtration sites can be located at various distances from surface water bodies [32,54] from a few meters to greater than one kilometer. In this study, as a starting point, distances >500 m are

considered less likely to be performing IBF, as wells were located <500 m from surface water in several studies on IBF [32,54,55]. Groundwater will discharge from aquifers towards rivers and lakes in most of Quebec for the majority of the year, especially during drier months [53]; therefore, wells must be able to reverse that natural gradient in order to perform IBF. In addition, most of the sites have been operational for at most a few decades, are not likely to have experienced intensive use [2], and therefore, large scale flow regime reversals, as seen in the Netherlands [54], are not likely. These combined factors make it unlikely that wells at a distance >500 m are performing IBF since reversal of a gradient over those distances would be more difficult. This choice for the cut-off could potentially omit some bank filtration sites from the province; however, this is considered to have minimal impact on the overall conclusions of this study.

3.1. Overview of the Province

3.1.1. Municipal Drinking Water Supply: Surface Water vs. Groundwater

Municipal drinking water sources can be classified into three categories, i.e., groundwater, surface water, and groundwater considered surface water, as shown in Figure 1. The first category (in red) includes all municipal drinking water sources which rely on one or multiple groundwater wells. Contrastingly, the second category (in blue) refers to municipal drinking water sources supplied by surface water. The third category (in green) corresponds to the few municipal drinking water sources relying on groundwater wells, which are documented as GWUDI according to the protocol detailed in the *Guide de conception des installations de production d'eau potable* described in Section 1 [15]. Of the 2075 municipal extraction points, 87% (n = 1799) are groundwater pumping wells, whereas 13% (n = 276) are directly extracting surface waters. This results in approximately 15% of the population of Quebec relying on groundwater resources for drinking water, representing roughly 1,260,000 citizens. A similar estimate (i.e., 20%) was also reported by the *Ministère de l'environnement et lutte contre les changements climatiques* [42]. The discrepancy between these two estimates is likely due to the proportion of the population supplied by private wells rather than a municipal distribution network.

In the more densely populated areas, surface water is the main water source for drinking water supply systems. This is likely a consequence of the greater drinking water demand in the cities, and the larger population's ability to support the more costly water treatment required for surface water. In smaller municipalities, groundwater sources are preferred as they are less costly to operate. In fact, in rural areas of the province, 90% of the population is served by groundwater sources [56]. As explained above, the important number of surface water bodies and the population's distribution results in a high likelihood of having groundwater wells near a surface water body, suggesting that many municipal drinking water systems may be benefiting from IBF processes.

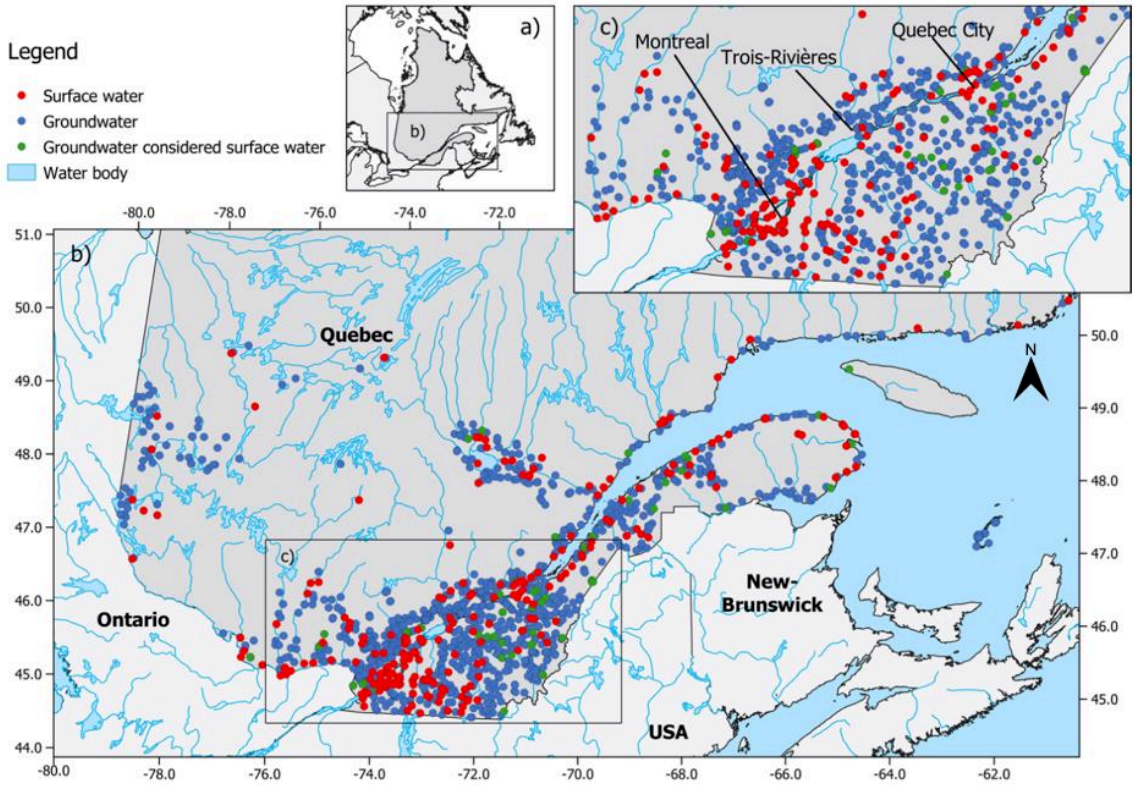

Figure 1. Spatial distribution of municipal drinking water sources. The water sources are classified into three categories, i.e., groundwater (in blue), surface water (in red), and groundwater considered surface water (in green). (**a**) overview of the study area; (**b**) view of the distribution of all wells throughout the province; (**c**) view of the most densely populated area of the province along the Saint-Lawrence River

3.1.2. Water Bodies Distribution around Wells

Among the municipal wells, almost all (97% of the cases; n = 1749) are located at <2000 m from a surface water body. As illustrated in Figure 2a, it is evident that the closest water body to most municipal wells is lakes (72%; n = 1262). This is likely due to the extremely high number of lakes in Quebec, which means that there is likely always a lake within a reasonable distance from any given point in the province, resulting in a geographically homogeneous distribution of municipal wells near lakes. The distribution of wells in close proximity to rivers (28%; n = 487) is less homogenously distributed throughout the province compared to those in proximity to lakes (see Figure 2). Many municipalities are located in close proximity to a river due to the settlement of the province through its waterways. Secondly, the area around rivers can often have more favorable properties for larger-scale water extraction due to the higher likelihood of containing sandy granular deposits compared to the more common glacial-marine deposits that cover the rest of the province [57].

Figure 2b also reveals the same trend of homogenous distribution of wells in proximity to lakes for each bin of 10 m width. In fact, 14% (n = 245) of the municipal wells are located at <200 m from a river. The overall distribution of wells shows a significant decrease in the density of wells at around the 120 m marks. Since the number of wells in proximity to lakes remains relatively constant in all 10 m bins, and the distribution of wells near rivers decreases around the 120 m marks, the overall trend in this graph of more wells in the first 120 m is controlled mostly by the greater number of wells in proximity to rivers.

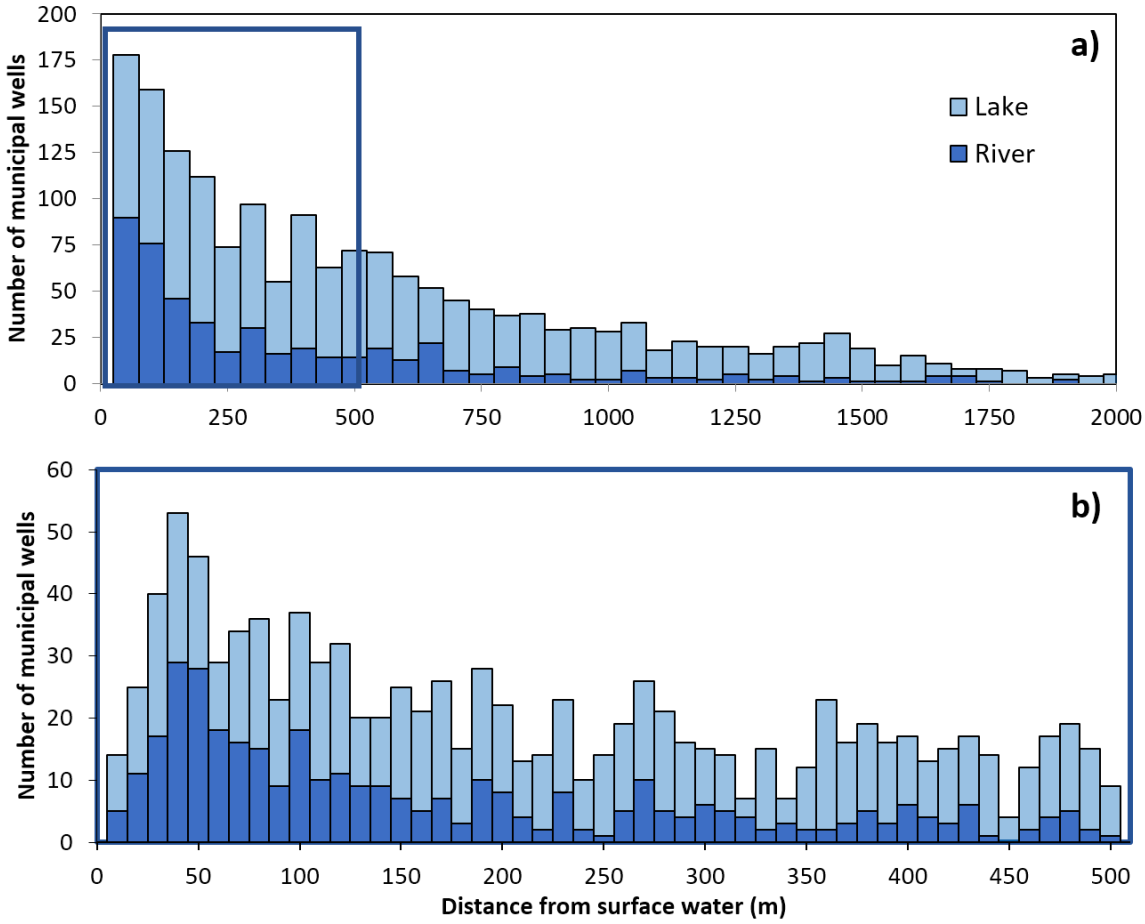

Figure 2. The distance of municipal wells from water surfaces for (**a**) 0 to 2000 m and (**b**) 0 to 500 m.

3.1.3. Insights into the Potential Population Supplied by IBF

Figure 3 illustrates the cumulative population served by municipal wells that are located at a distance of 0 m to 2000 m from a surface water body. It shows that approximately 1,200,000 people are served by those municipal wells. It also reveals that outside of the major cities, wells located at less than 500 m from a surface water body account for 74% of the population (n = 920,000) whose drinking water is supplied by groundwater from municipal wells. In fact, there is a rapid increase in the population served by wells within the first few hundred meters of a water body. Wells within 250 m and 100 m account for 57% (n = 720,000) and 34% (n = 410,000) of the population served by municipal wells respectively. Although many of these sites may not be using IBF due to various factors, these results reveal a significant probability that half of the groundwater-fed population connected to a municipal drinking water supply in Quebec, i.e., more than half a million citizens, might depend on IBF. This initial overview demonstrates the great opportunity of a better assessment of IBF occurrence in the province of Quebec in order to better protect our resources. This high proportion of close-to surface water wells is likely an indication that planners and developers are, in fact, selecting pumping sites in close proximity to surface water. Still, as aforementioned, the existing knowledge of IBF is not fully integrated into the planning process when developing and managing water abstraction plants.

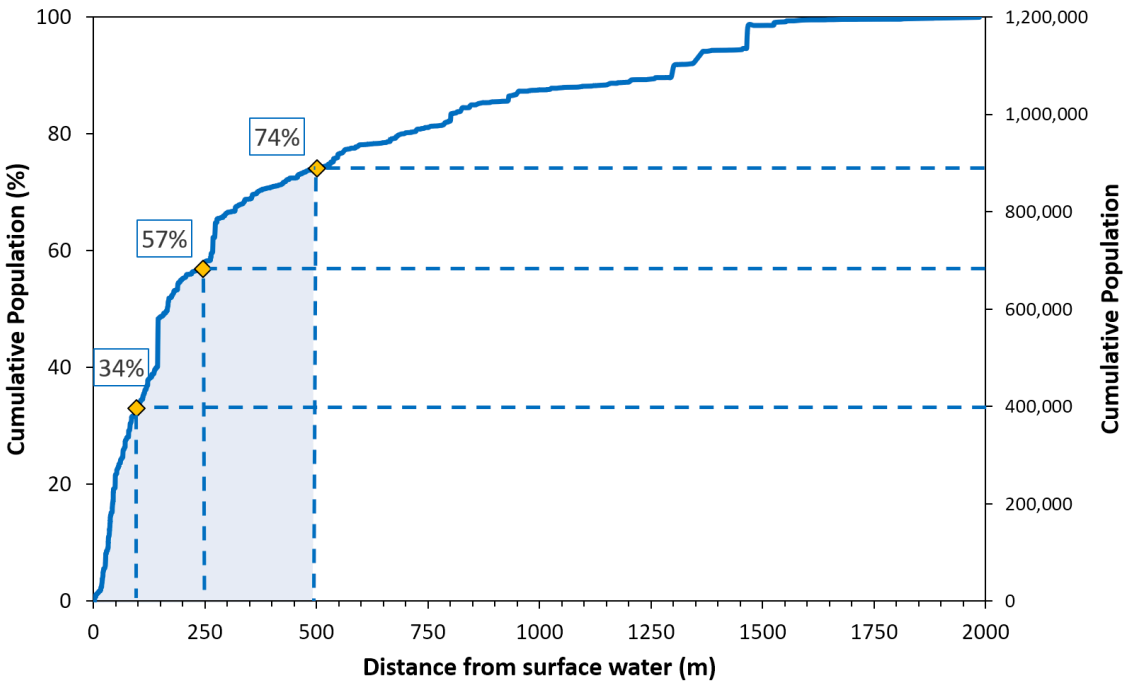

Figure 3. Cumulative population supplied by municipal groundwater wells with respect to the distance from the surface water body.

3.2. Insights on Selected Sub-Basins

In light of the results presented in the previous subsection, it was determined that making widespread generalizations about the province would not be straightforward. We opted to focus on a selection of areas with diverse population sizes, diverse geological settings, a variety of distances from surface water, a variety of surface water body types, and a variety of land cover types. By cross-checking the ID and localization of wells in the available databases, it was possible to manually assign the type of aquifer (fractured bedrock, unconfined granular, confined granular) to 101 municipal wells within the three areas, namely Laurentides (area #1), Nicolet (area #2) and Vaudreuil-Soulanges (area #3). These areas correspond to watersheds "du Nord", "Nicolet", and "Vaudreuil-Soulanges"respectively. It is important to note that the "Vaudreuil–Soulanges" watershed also extends into the neighboring province of Ontario to the West, but the investigation is limited to the portion within the Quebec border. The localization and the extent of each area are illustrated in Figure 4. The main geological contexts are also reported in this figure. The Grenville Province (area #1) is mainly composed of Archean autochthonous rocks dominated by highly metamorphosed gneissic complexes. The Appalachian Province (area #2) is composed of various types of strongly deformed rocks (i.e., sedimentary, volcanic, and ophiolitic rocks), whereas the St-Lawrence Platform (area #3) corresponds to sedimentary rocks. The criteria used to evaluate each region are the nature of quaternary deposits, the type of nearest water body in proximity, the population of the municipalities, the distance of wells, as well as certain qualitative factors that are mentioned in the PACES reports for each region [58–61].

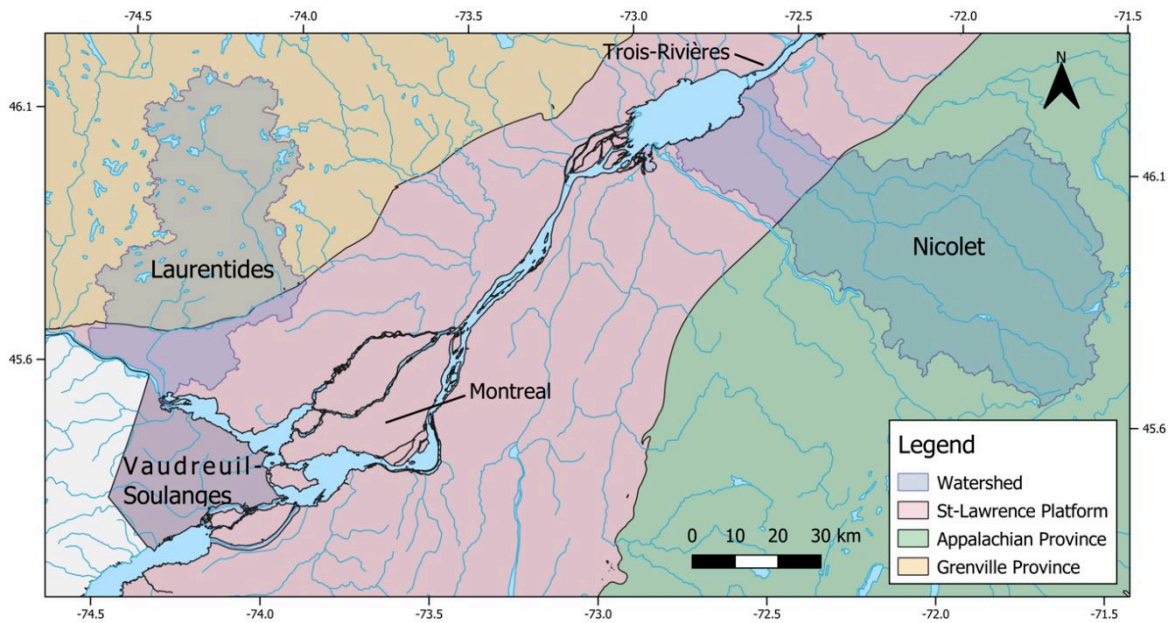

Figure 4. Location of the three selected watersheds (area#1: Laurentides, area #2 Nicolet, and area #3 Vaudreuil–Soulanges).

3.2.1. Area #1: Laurentides

The area of Laurentides has a mixture of forested areas and urban areas and is underlain by the hilly Grenville Province. It has not been covered by regional PACES studies at this time, and therefore, a detailed description of the surficial deposits underlying the region is somewhat dated. Portions of the area along the Saint Lawrence and Ottawa Rivers were described by Lajoie [58]. Bedrock in this area is overlain by till that varies in thickness from 7 to 12 m. Deposits of sand and gravel can also be found within this region, that were deposited by glacial rivers. Along existing rivers, including the Rivière-du-Nord, recent fluvial deposits composed mainly of loam are present [59]. Supplemental Materials containing the map of the quaternary geology and well distribution for each area is provided with this paper (Figure S1, Tabel S1).

In this area, 31 municipalities (of a total of 58) rely on groundwater to produce drinking water from a total of 136 municipal wells, and 91% (n = 124) are located <500 m from a surface water body. A total of 63 municipal wells (51%) are located at <500 m from a lake, the remaining part (49%; n = 61) being at <500 m from a river. As shown in Figure 5, a significant number (31%; n = 39) of municipal wells are found along the main river (i.e., Rivière-du-Nord). These wells are often serving municipalities with a population of >1000 people and are typically found in unconfined granular aquifers. There are three other rivers and a lake with wells in close proximity, namely, Red River with four wells serving two municipalities, Ottawa River with four wells serving three municipalities, Lac de Deux Montagnes with 12 wells serving one municipality, Achigan River with two wells serving one municipality. Further from the Rivière-du-Nord, the population generally decreases, and the wells are more frequently found in proximity to lakes and in fractured bedrock aquifers. The type of aquifer could be compiled for a total of 56 wells. Of these wells, 73% (n = 41) are found in an unconfined granular aquifer, with the majority located <100 m from a surface water body. Since the largest municipalities are more likely to be pumping sufficiently to induce a hydraulic gradient forcing the surface water to infiltrate the aquifer, the municipalities with the highest likelihood of performing IBF are the more populated ones in proximity to the Rivière-du-Nord. Meanwhile, wells located further from surface water and installed in fractured bedrock present a lower confidence level in the probability that IBF is taking place. It is important to note that the above-mentioned results include some wells outside of the selected watershed, as they shared a similar geological setting.

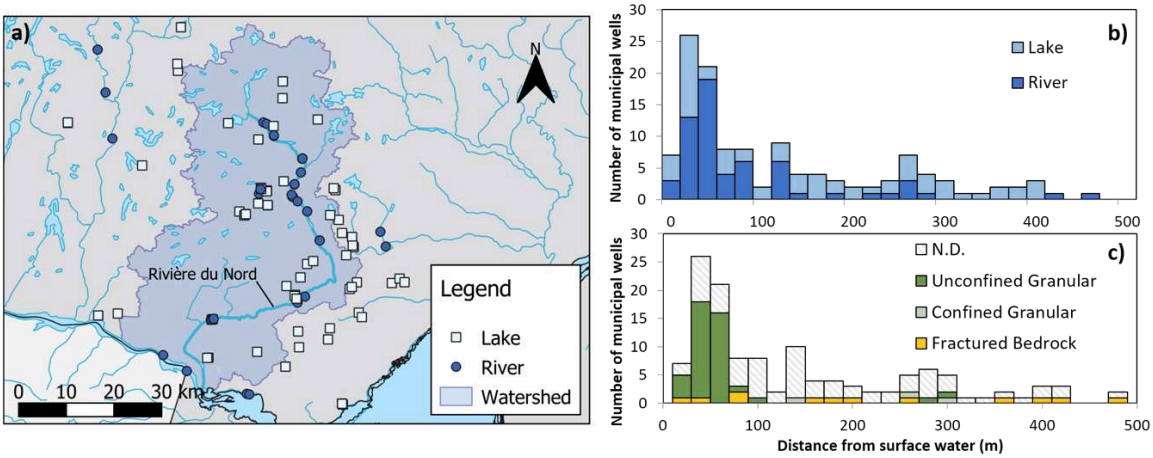

Figure 5. (**a**) The spatial distribution of municipal wells located at less than 500 m from lakes and rivers in area #1 and the distribution of wells according to (**b**) the type of surface water and (**c**) the type of aquifer.

3.2.2. Area #2: Nicolet

The Nicolet area straddles two geologic provinces, the Saint-Lawrence Platform in the lower altitude portion to the North and the Appalachian Orogen in the higher altitudes to the South. This area is principally covered by agricultural land. A total of 84 municipal wells are actively producing drinking water from groundwater resources to serve a total of 35 municipalities (of a total of 39). These municipalities are generally smaller than those in other regions, with many serving <500 people. As illustrated by Figure 6, in area #2, a high number of wells are in the vicinity of different rivers and tributaries, similar to area #1. In fact, a total of 48 municipal wells (57%) are in the 0–500 m range from a surface water body. Of these wells, most are located close to rivers (71%; n = 34), and the remaining 29% (n = 14) are located near lakes. However, the distance of these municipal wells varies more widely than in area #1. The Nicolet River and its tributaries are the rivers with the largest number of wells in close proximity. There are five rivers in the Nicolet river system with wells in close proximity. In addition, the Saint-Francois River has three wells in proximity serving two municipalities. Within this region, there are many more rivers whose quality could impact drinking water quality than in the other regions.

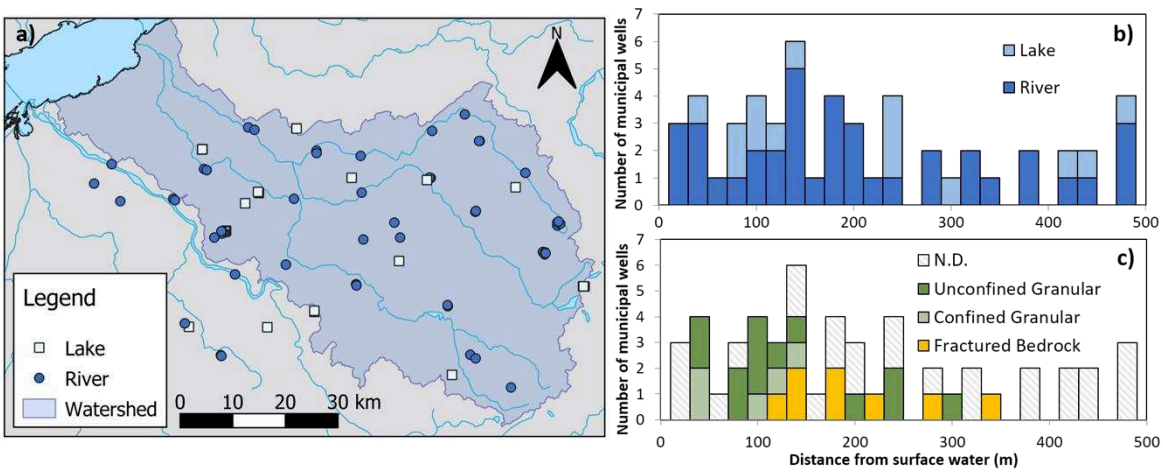

Figure 6. (**a**) The spatial distribution of municipal wells in the Nicolet area that are located at less than 500 m from lakes and rivers in area #2 and the distribution of wells according to (**b**) the type of surface water and (**c**) the type of aquifer.

The Nicolet region has a distinctly different sequence of quaternary deposits when compared to the other two zones. As reported in the PACES study [60], thick quaternary deposits exceeding 100 m in certain areas overlie the bedrock in certain parts of the region. A rough 20 km wide band along the Saint–Lawrence River is underlain by a significant thickness of marine clays, which can be partially or completely overlain by marine and lacustrine sands. The central portion of the basin located between elevations of 80 m and 120 m is dominated by aeolian and coastal sands, underlain by impermeable till around which peatlands can form. Thick glacial-fluvial sand and gravel deposits can lie directly on the bedrock in certain areas. Superficial deposit thicknesses at the municipal well locations calculated from the raster database that accompanies the PACES study [60] ranged from <5 m up to 30 m. Supplemental Materials containing the map of the quaternary geology and well distribution for each area is available (Figure S2, Table S1).

Geological information could be compiled for a total of 26 municipal wells located <500 m from a water body. In this region, 50% (n = 13) of the municipal wells procure water from unconfined granular aquifers. Of these wells, 77% (n = 10) are located <200 m from a surface water body. These results suggest that there are favorable aquifers for pumping near rivers, while the regions more distant from rivers are less favorable. This region, although it consists mostly of smaller municipalities, has a high probability of IBF taking place, especially in wells within the first few hundreds of meters from a river. More information relative to the pumping rates for these wells, combined with a geochemical and isotopic approach, would be needed to better estimate the potential use of IBF in this region.

3.2.3. Area #3: Vaudreuil–Soulanges

The area of Vaudreuil–Soulanges is located near Montreal and within the St-Lawrence Platform. The main types of land uses are agricultural and residential. This area, unlike the Nicolet area, is underlain solely by more recent quaternary deposits that were deposited uniquely during the last glacial cycle. The region is predominantly covered by marine clays (64% of the surface area). Only a small number of areas, along the Ottawa River and higher relief areas (i.e., till deposits, Mount Rigaud, "butte Saint-Lazare", and "butte de Hudson"), remain uncovered by these clays. Certain uncovered areas are composed of glacial-fluvial deposits that host productive granular aquifers. Examples of these deposits can be found along the Ottawa River in the northern portion of the zone and also in the Saint-Lazare region. Supplemental Materials containing the map of the quaternary geology and well distribution for each area is available (Figure S3, Table S1).

In this area, 36 wells are in operation and produce drinking water from groundwater resources for eight municipalities (of a total of 13) with populations typically >1000 people. As illustrated in Figure 7, the area contains a distribution of wells mostly in proximity to lakes. In fact, 66% (n = 24) of the municipal wells are located <500 m from a lake. Among these wells, 92% (n = 22) are located along a 6 km-long North-South transect near the region of Saint–Lazare. The PACES report highlights the presence of a thick and unconfined sandy deposit with a very productive aquifer in this zone [60]. Wells, in proximity to rivers, for the most part, are located along the periphery of this zone near the more major water bodies. Another zone of concentrated wells (20%; n = 10) is found in the region of Mount Rigaud, the majority of these wells are located in fractured rock or clay deposits [60], making the probability of IBF unlikely. It can also be seen in Figure 7 that there is a limited number of wells (33%; n = 16) located within the first 200 m of a water body, which sharply contrasts with the other two regions. In this region, wells are located in proximity to two rivers only. The Viviry River with four wells serving one municipality and the Saint–Lawrence River with four wells serving one municipality are the two most prominent ones with some smaller streams making up the difference. The type of aquifer could be compiled for 22 municipal wells in area #3. From these wells, the majority is found in confined granular aquifers (31%; n = 7) and fractured bedrock aquifers (40%; n = 9). The fractured bedrock aquifers are known to be confined [60], except in the regions with the highest concentrations of wells (i.e., St-Lazare, Hudson, and Rigaud).

Overall, the greater distance from surface water in this area seems to indicate that IBF in most of the municipalities in this area is not likely. We identified only two municipalities with a total of 3 wells in close proximity to surface water. However, these wells are in confined granular or fractured bedrock aquifers and, thus have limited potential for IBF. Moreover, there is a strong possibility that the permeable areas of the Saint–Lazare region are influenced by infiltrating water from the spring thaw and precipitations.

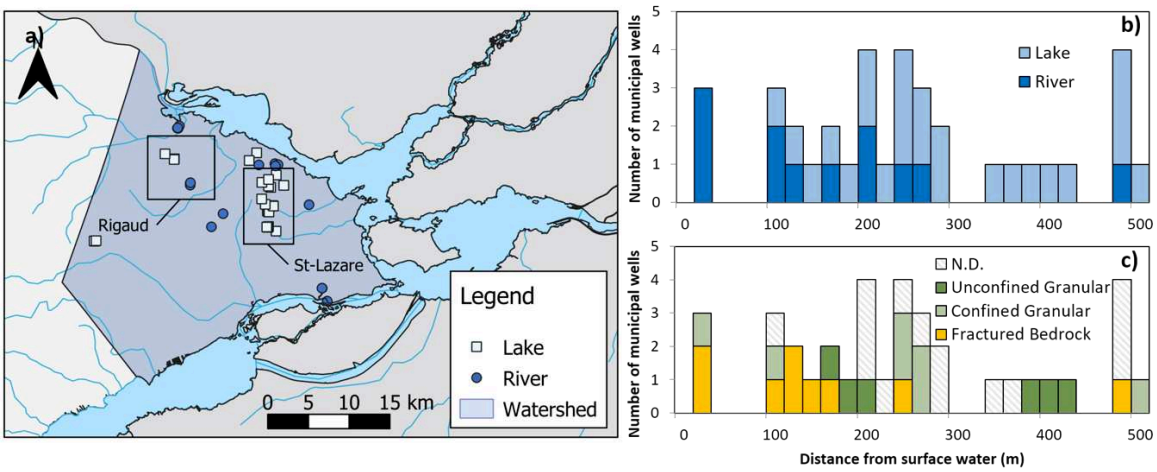

Figure 7. (**a**) The spatial distribution of municipal wells located at less than 500 m from lakes and rivers in area #3 and the distribution of wells according to (**b**) the type of surface water and (**c**) the type of aquifer.

4. Conclusions

This research has provided a reliable starting point for determining the impact of IBF on the population of Quebec. A simple process based on GISc was used by incorporating several open-source programs (QGIS, SAGA, and R) and openly available data. The initial use of distance from a surface water body as well as additional information extracted from the government database revealed that nearly one million people in the province of Quebec are supplied drinking water via wells in close proximity (i.e., <500 m) to a river or a lake. This first overview has also demonstrated that there is a high degree of regional variability with regard to the probability that IBF is being performed. One investigated area has the greatest potential use of IBF (area #1: Laurentides), a second one requires more information to draw precise conclusions (area #2: Nicolet), and the third one has the lowest probability of IBF (area #3: Vaudreuil–Soulanges).

There are a number of shortcomings that are evident in the current development, management, and understanding of hybrid groundwater-surface water extraction sites in the province of Quebec. The current regulations do not contain general insights into the protection or management of these sites. The existing GWUDI classification is not designed to assess risk at an IBF site as it does not expressly consider the contribution of surface water to a pumping well, and only under certain circumstances are IBF wells considered GWUDI. With mounting pressures on our water resources from climate change and population growth, we hope that this work demonstrates the need to better understand and improve the regulatory framework to specifically address hybrid groundwater-surface systems such as IBF in order anticipate problems common to IBF sites and ensure that our water resources are well protected and exploited sustainably.

It will be important to precisely develop guidelines for determining what municipalities should be targeted within future regulations. The policy changes would require the definition of a new category of wells for IBF sites that requires short, medium, and long-term assessment of risk related to the permanent or intermittent contribution of surface water bodies to wells.

In order to determine more precisely which wells are using IBF, a possible approach would be based on a dedicated sampling program for specific environmental tracers. These tracers would be used to quantify the spatio-temporal evolution of transit times (e.g., stable isotopes of water) and relative proportions of groundwater and surface water (e.g., electrical conductivity). A longer characterization period would allow for the minimization of unforeseen costs over the life of the water treatment plant.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/3/662/s1, Figure S1: Map of Areas #1 (Laurentides) with quaternary geology and well distribution, Figure S2: Map of Areas #2 (Nicolet) with quaternary geology and well distribution, Figure S3: Map of Areas #3 (Vaudreuil Soulanges) with quaternary geology and well distribution, Table S1: Codes for the quarternary geology units in Figures S1–S3.

Author Contributions: Conceptualization, M.P. and P.B.; Data curation, M.P.; Funding acquisition, P.B.; Investigation, M.P.; Methodology, M.P. and P.B.; Project administration, P.B.; Resources, P.B.; Supervision, P.B.; Validation, L.L. and J.M.-D.; Visualization, L.L. and J.M.-D.; Writing—original draft, M.P.; Writing—review & editing, M.P., P.B., L.L. and J.M.-D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FRQNT through grant number FQRNT 2018-NC-205703 and NSERC through grants number CRSNG—RDCPJ: 523095-17 and CRSNG-RGPIN-2016-06780.

Acknowledgments: We would like to thank the "Ministère de l'Environnement et Lutte contre les changements climatiques" for the data used in this study, Marc-André Bourgault for help during conceptualization, Guillaume Meyzonnat and Sylvain Gagné for discussions on various zones and insights into the reliability of data sources, Geneviève Boisjoly for help with the GIS calculations, and Gabriel Dion for the initial study that evolved into this one. Great thanks to Francisco Gomariz Castillo for his constructive review from a GIS expert point of view.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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