CHAPTER 3

AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER RESOURCES

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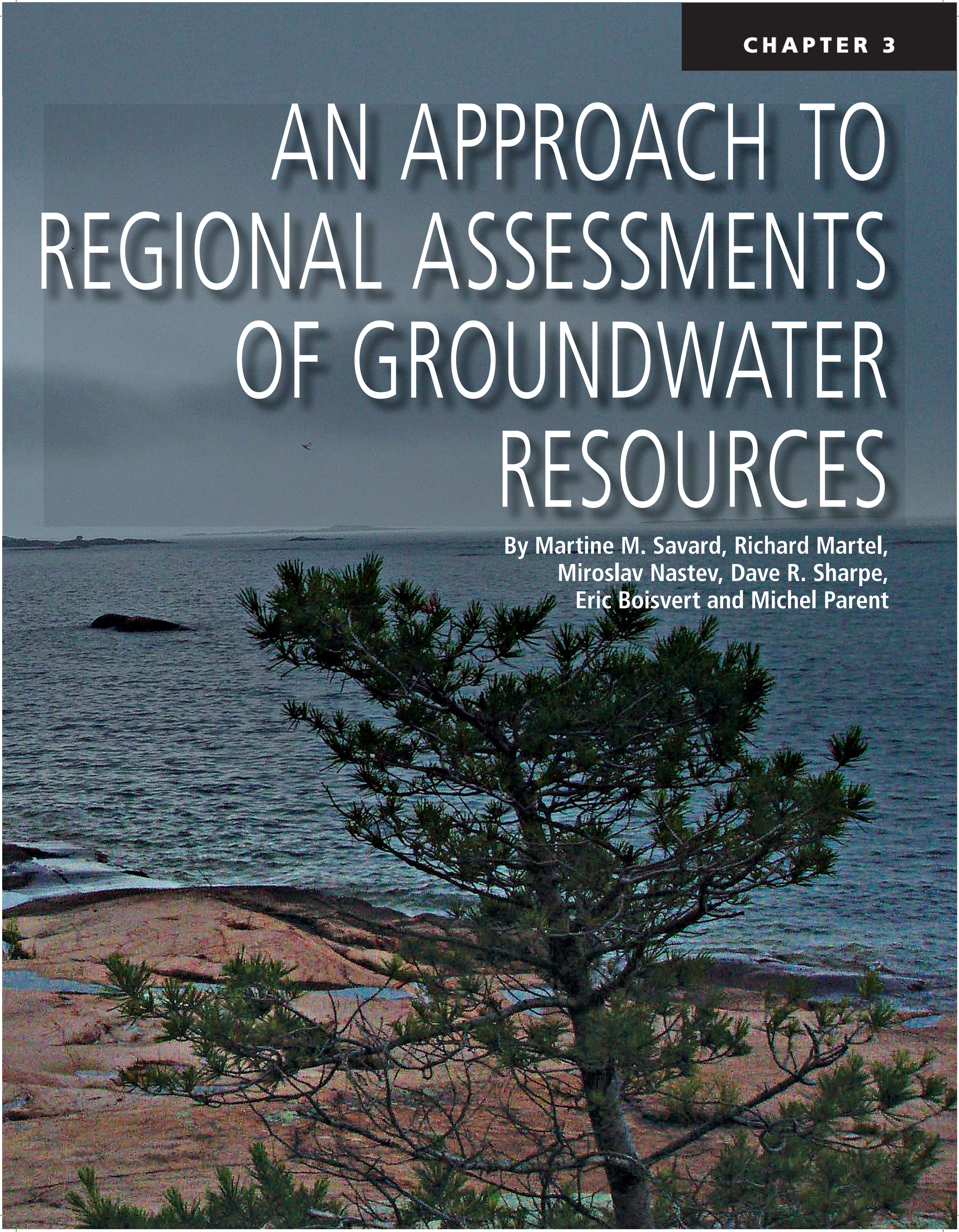


3.1 REGIONAL AQUIFER SYSTEMS: HIDDEN AND SIZEABLE! HOW DO WE ASSESS THEM?

Canada's groundwater is an important water supply source for many urban areas and industries, in addition to being a vital supply for rural areas across the country.

The extent of Canadian groundwater reserves, however, is only partially understood, even as we do know that groundwater is a basic component of the hydrological cycle, forming the base flow to rivers and streams and sustaining water levels of lakes and wetlands (those shallow aquifer systems—less than 100 m—which represent reservoirs of easily extractable water, with much of excellent quality for potable use).

To date, there has been only limited mapping and quantification of our regional groundwater resources. The Canadian population continues to grow, requiring more and more fresh water. Surface water allocation limits have already been reached in parts of the country and future water demand will place a greater reliance on groundwater. Today's water requirements call for increasing abstraction of brackish to saline water in some areas, as climate change is modifying the hydrological cycle all over North America (IPCC, 2007). These facts raise several serious questions regarding the future of Canada's groundwater reserves. How much groundwater do we actually have? How much groundwater can be extracted annually in a sustainable manner? How will groundwater reserves be affected by stresses on the system (changing land use and climate change?)

Answers can only be drawn from quantitative assessments of Canada's aquifer systems. Generating of these assessments at local and regional scales, provide key information to create methodologies which will support sustainable groundwater use and groundwater resource protection.

This chapter presents an overview of these issues based on proven practices and techniques for systematic regional groundwater assessment.

Although groundwater is out of sight, properly conducted engineering and geoscientific investigations can identify and delineate it, characterize water quality and estimate groundwater availability. A multidisciplinary approach, one which combines geophysics, geology, hydrogeology, and information technology is recommended to produce new interpretations and understanding (Figure 3.1).

Such methodology has already been used in assessing fourteen regional aquifer systems within the provincial-federal coordinated Canadian framework (Rivera et al., 2003). Such investigations usually cover large areas ranging from tens

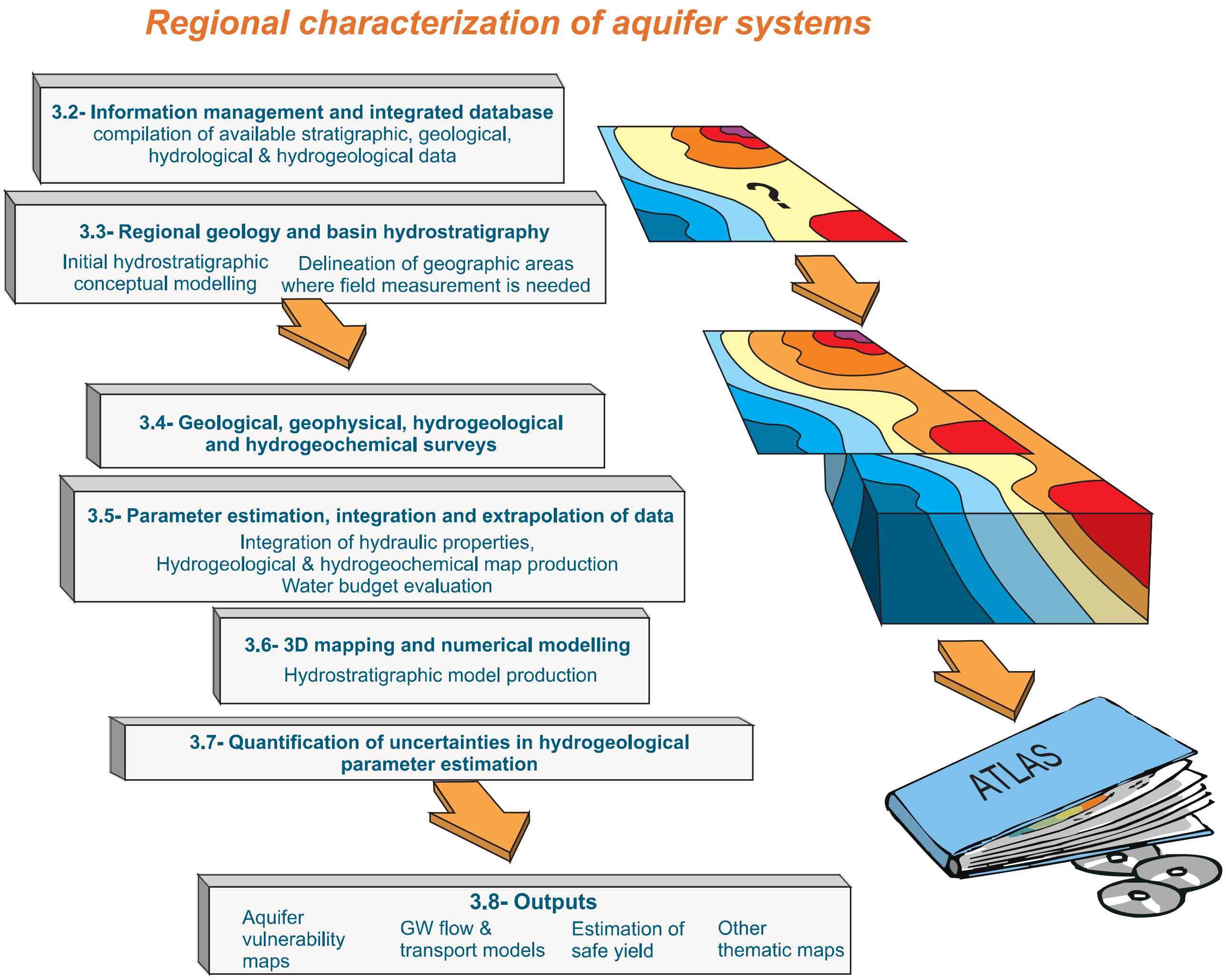


Figure 3.1 Suggested steps for regional characterization of aquifer systems.

TABLE 3.1 PRINCIPAL PARAMETERS REQUIRED FOR SYSTEMATIC REGIONAL SURVEYS OF AQUIFER SYSTEMS

(MODIFIED FROM SAVARD ET AL., 2008)

GEOLOGICAL PARAMETERS

Sedimentary Quaternary units

- Lithology
- Stratigraphy (age)
- Porosity
- Regional distribution
- Origin
- Facies types
- Landforms
- Orientation
- Sedimentary structures
- Paleoflow direction

Rock formations

- Lithology
- Nature of porosity
- Porosity volume
- Stratigraphy (age)
- Regional structures (folds, faults, fractures) and distribution

HYDROLOGICAL PARAMETERS

Climate

- Precipitation
- Temperature
- Solar radiation
- Wind

Surface waters

- Location
- Flow rate
- Hydrographs (water levels)
- Hydraulic link to aquifers

HYDROGEOLOGICAL PARAMETERS

Physical

- Water levels (depth to groundwater)
- Well hydrographs
- Groundwater flow directions
- Hydraulic gradient
- Hydraulic links between aquifer formations
- Recharge zones
- Discharge zones
- Estimation of recharge
- Estimation of discharge
- Hydraulic conductivity, transmissivity and storativity*
- Intrinsic vulnerability

Anthropogenic

- Wellhead protection areas
- Estimation of groundwater extraction
- Well yield

Hydrogeochemical

- Concentration of major and trace ions
- Concentration of total dissolved solids
- Electrical conductivity, temperature, pH, Eh
- Dissolved oxygen
- Water quality (e.g., relative to drinking criteria)
- Water type distribution
- Water age
- Source of contaminants

*Consider also specific storage or specific yield.

to thousands of square kilometres. The main challenges to regional characterization include selecting the proper amount of reliable coverage data to allow finding, at reasonable cost, the right quantity of groundwater to extract while protecting the aquifer's groundwater quality. Regional studies also need to overcome the problem of aquifer variability, and produce methodologies that allow extrapolation or "scale-up" parameters measured at local scales (tens of metres) to watershed scales (tens of kilometres).

Studies of Canadian groundwater began during the 1870s. Historical information about these research projects, and details on provincial and federal contributions to the first aquifer inventories may be found in Brown, 1967. More recent developments are covered in Chapter 16 of this book.

The assessment approach presented in this chapter was developed by the Geological Survey of Canada and, as mentioned above, its partners, and has been applied to a number of studies over the past 15 years. Variations of this approach are also being used by other agencies.

Within this chapter, we will describe state-of-the-art methodologies used to characterize regional aquifer systems through multidisciplinary assessments coupled with federal and provincial collaborative projects. These procedures provide the input required to properly characterize aquifers and understand groundwater flow systems described in Part IV of this book. This approach integrates field geophysical, geological, geochemical and hydrogeological surveys to produce a 3D hydrostratigraphic model within a linked database management system. Importantly, an estimate of regional hydraulic parameters as well as an estimation of the uncertainty of acquired information is crucial to reliable groundwater assessment (Figure 3.1; Table 3.1).

Regional aquifer systems should also be described in terms of hydrostratigraphy (rock reservoirs and layers of low permeability), hydrogeology (aquifer characteristics, hydraulic conductivity, recharge, etc.) and numerical modelling (potential drawdown). Quantitative assessment (water availability) and hydrogeochemistry (water quality; e.g., Cloutier, 2004) are two other vital elements of regional surveys, because reliable yield and water quality data are always included in any aquifer system assessment (Table 3.1). Chapters 4 through 7 address these elements in greater detail. The goal is to produce regional assessments that contribute to a national inventory

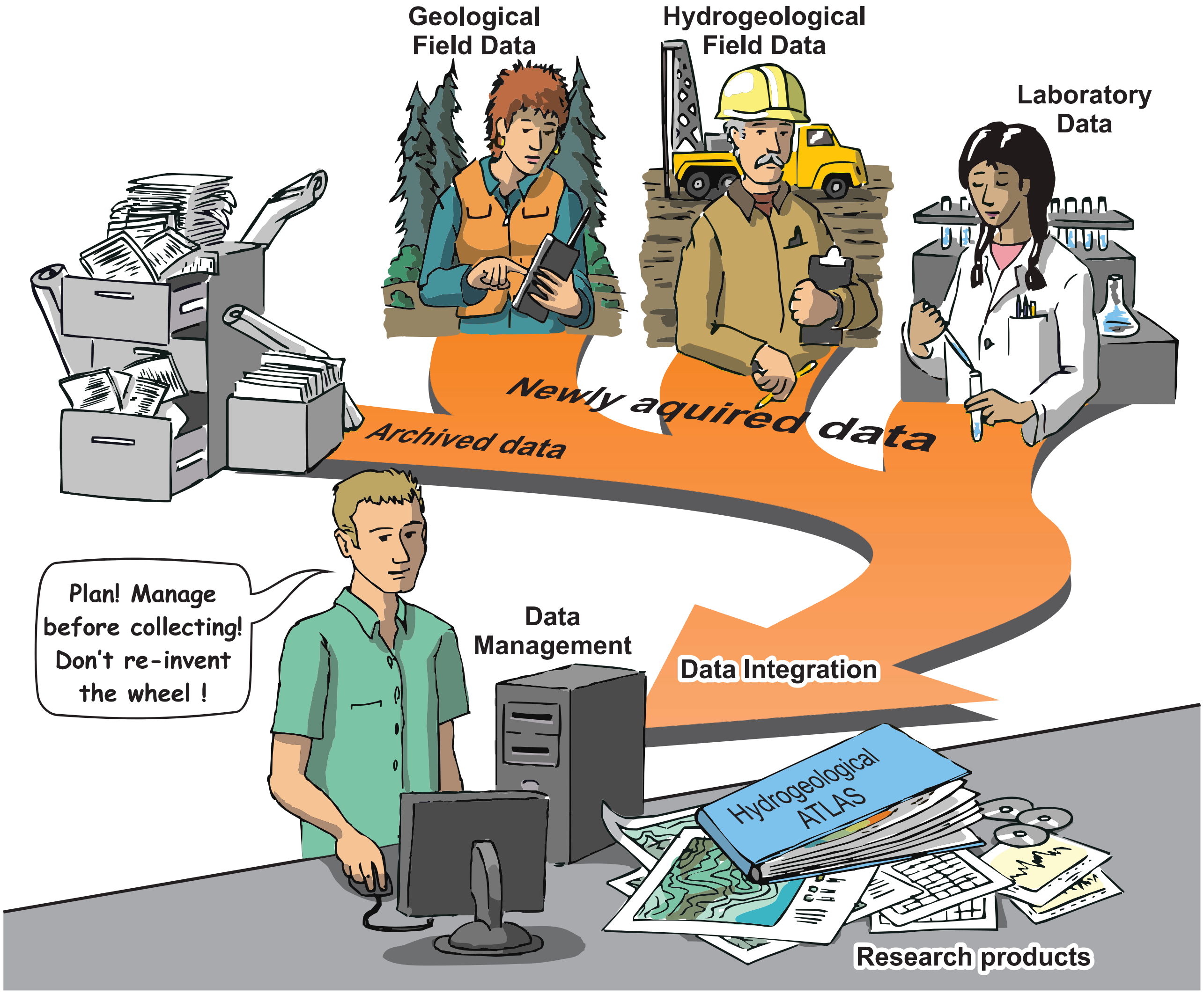


Figure 3.2 Importance of database organization and management for regional aquifer-system assessments.

used for sustainable development and protection of Canadian groundwater resources.

3.2 INFORMATION MANAGEMENT — INTEGRATED DATABASES

Once an area is selected for regional hydrogeological assessment, the first step of the process is to develop a regional database, compiled from reports, studies and data sets held by various agencies. Regional assessments inevitably generate large data sets which must be integrated and manipulated to be easily accessible for interpretation and hydrogeological modelling. Traditional sources of groundwater data, such as provincial water well records and geological maps are useful, particularly when combined with other data collections. Federal departments such as Environment Canada, Agriculture Canada and Statistics Canada hold a wealth of information, as do provincial agencies like Geological Surveys. Large information banks are held locally by municipalities, industries, consultants and community groups. All data collected should be stored in a properly structured relational database.

Given the abundance of sources, types and entries of information, establishment of a sound metadata strategy is important before the situation becomes unmanageable (Figure 3.2). Metadata records increase efficiency, and help the end user understand the assessment limits.

A sound analysis of user requirements, wherein the real assessment needs are known and weighed, must be done before studies start. The project needst must not overshadow responsibilities for post-project data management by other groups. When all requirements are understood, a scan of available datasets should be initiated to identify relevant material and potential gaps. This analysis will be used to construct a data acquisition plan where major gaps (according to project requirement) are addressed and prioritized. Computer systems owned by government departments, and staff resources already assigned to these systems should be considered as part of new regional projects.

A sound data model can guide the construction of a relational database for all geological, hydrogeological and geotechnical data. Do not forget that verification is a key step when populating databases. Location and elevation of all data should be checked before applying a standard elevation from a digital elevation model. It is helpful to use a standardization technique like a rock/sediment coding protocol based on unit descriptions from geological maps. A geologist with field experience in the study area must recode lithological descriptions of all input

data to new standardized classes.

Large regional assessments are generally conducted through partnerships involving scientists from multiple organizations; this leads to questions of data ownership, database management and database format (i.e., software), legal constraints, and accessibility, issues which may lead to the possibility of using several systems in a network. The standard procedures then shift from common database software to common data exchange protocols.

The Open Geospatial Consortium proposes a series of standards (http://www.opengeospatial.org) which can be used to exchange data over distributed systems. These standards are being implemented by software editors (such as ArcInfo or MapInfo). Governments, as well, are active participants in developing these standards and using them (GeoConnections, 2005). Several database management projects such as the National Groundwater Database of Natural Resources Canada (http://ess.nrcan.gc.ca/2002_2006/gwp/p2/index_e.php) take advantage of such standards to manage their data. Recently, the Groundwater Information Network (GIN, http://gw-info.net) began using a groundwater data encoding standard named GWML (Groundwater Markup Language) based on GML (Geographic Markup Language) to access a network of heterogeneous data stores (http://ngwd-bdnes.cits.nrcan.gc.ca/service/apingwds/en/gwml.html). GIN allows access to all data stores using a common interface and a common data format as if it was a seamless database. The data can be downloaded in a variety of popular formats (ESRI SHP file, Geodatabase, Microsoft Excel, Google Earth KML, etc.), although users should be aware that the quality of the dataset is quite variable (with, for instance, outdated stratigraphic units or erroneous lithological descriptions). As GIN is being implemented in Canada, other countries have also embarked in developing similar infrastructure, most notably the United States, with U.S. GIN (http://usgin.org/, which has an unfortunate identical acronym), Morocco HydrIS (http://www.springerlink.com/content/a646n54t002552m5/) and IUGS (International Union of Geological Science) One Geology (http://www.onegeology.org/).

A complete database system not only comprises software and hardware, it also includes database management procedures and experts who maintain, feed and use it. Database design and implementation requires qualified information technology professionals such as data modellers, database managers and programmers.

3.3 REGIONAL GEOLOGY AND BASIN HYDROSTRATIGRAPHY

3.3.1 Basin study

Developing a comprehensive model and understanding the geological setting of a region is a critical first step towards understanding its groundwater systems. Scientists undertaking regional studies of sedimentary rock or multi-layered unconsolidated aquifer systems often use basin analysis to delineate depositional environment and basin evolution, which, in turn, can be employed to develop geological and hydrostratigraphic conceptual models. Basin analysis reveals its history by analyzing of lithology, composition, structure and architecture of its sediment fill. Basin analysis specifically characterizes textural, stratigraphic and structural controls on groundwater flow systems at regional scales, including a characterization of fluids in the basin.

Consider surface water drainage in two drainage

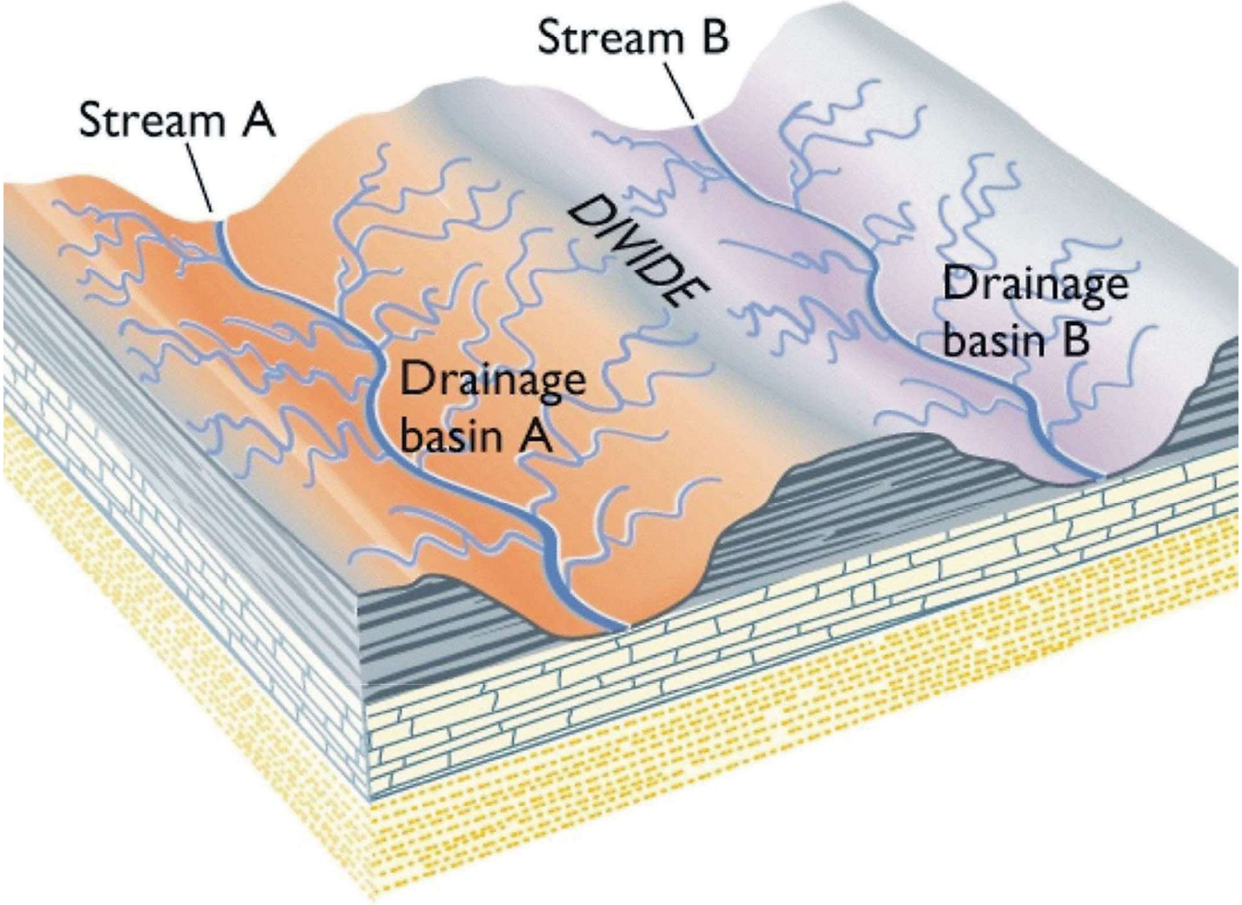


Figure 3.3 How a surface basin serves to define overland and stream flow based on topography (meandering light blue tributary lines). Regional groundwater flow provides a different conceptual model as infiltration at a topographic high may take a short flow path to the stream within the basin (light blue arrows). In areas where basins are tilted, some groundwater flow will take a longer path and flow, for example, from the basin A divide to discharge in the stream located in basin B (Czech Geological Survey, 2011).

basins. If the study region is characterized by surface flow which operates independently in the upper part of each basin (A, B in Figure 3.3), groundwater flow in layer-cake subsurface strata allows for inter-watershed flow in the underlying sedimentary basin strata (Figure 3.3). Variations on the simple surface and groundwater flow pattern may occur if the basin is folded, tilted, fractured or covered by glacial deposits.

Basin analysis in a more complex aquifer system can be illustrated with bowl-shaped sedimentary strata, like the Michigan Basin in Ontario and mid-western United States (Figure 3.4). The underground reservoir systems available for groundwater recharge, storage and flow can be thousands of kilometres across. Geological mapping and conceptual hydrogeological modelling of the bowl-shaped basins allows reservoir pathways (aquifers) and low-permeability layers (aquitards) to be portrayed with relatively sparse data, and derived, perhaps, from just a few wells and subsurface information from geophysical transects. Developing conceptual models, even for models of simple basins however (Figure 3.4), requires an organized set of steps.

3.3.2 Conceptual geological models

Conceptual geological models serve as schematic explanations of specific scientific principles and/

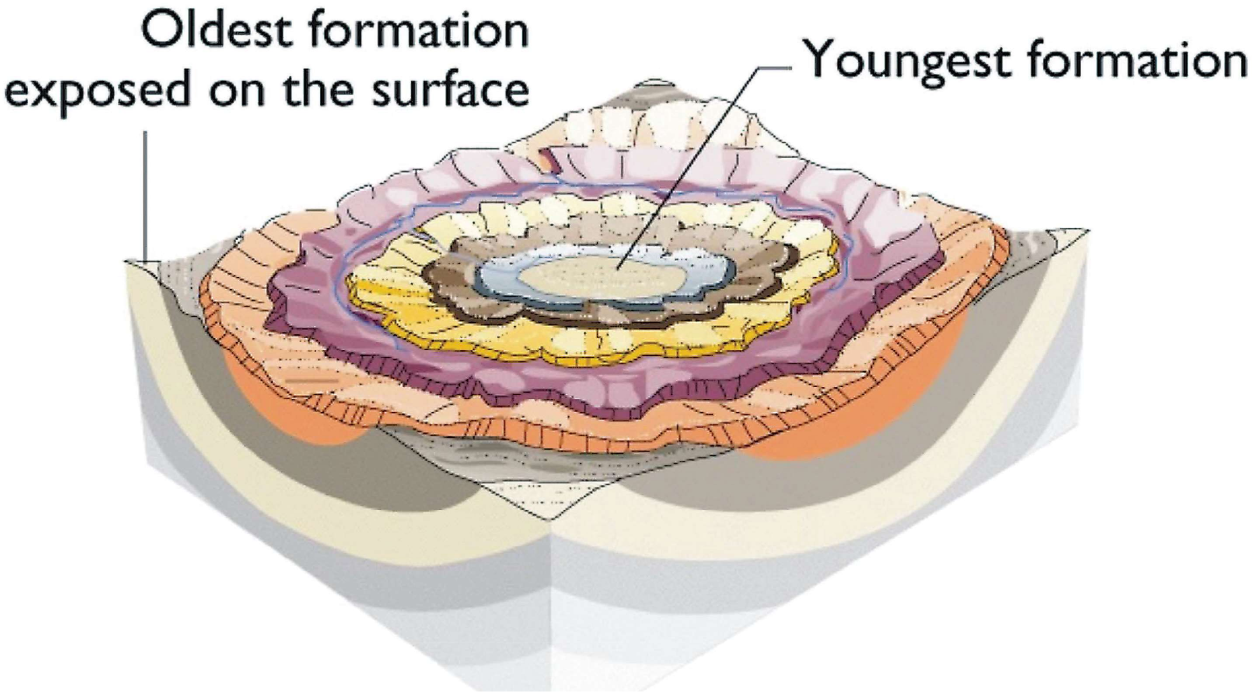


Figure 3.4 An illustration of how basin architecture (saucer shape) controls regional aquifer-system flow. Aquifers are depicted in light tones while aquitards (there is always flow in aquitards) are shown in darker tones. Bold blue arrows identify points of recharge (modified from Grotzinger et al., 2007).

or understandings. Canadian researchers need to refine the understanding of subsurface flow systems and to integrate more geological data at regional scales for groundwater flow modelling (Sharpe et al., 2002; Russell et al., 2006). It is crucial to extend our understanding beyond scarce data points, and to develop sound and physically credible conceptual models.

Conceptual geological modelling begins with a review of the geological and geotechnical literature reports, maps, sections, high-quality boreholes and other subsurface data. The resulting conceptual models should describe all relevant strata and their relative 3D geometries. These models are built from first principles in a four-step process (see also Figure 3.1): (1) development of conceptual understanding, (2) model preparation, (3) model construction, and (4) model testing and documentation. Systematics for conceptual modelling involves assignment of stratigraphic codes (organized rock sequence) based on the stratigraphic framework, and applying these codes to primary data within the stratigraphic framework. It is practical to use the stratigraphic framework and its geological rules to guide and constrain interpretation and coding of secondary data (e.g., water well data) and, where needed, to develop interpretive elements to infer plausible geometries. The stratigraphic framework of a region or basin is linked to its geometry, or the architectural relationships of its structural/ stratigraphic units. A robust geological model incorporates current understanding of geological processes related to the basin under study. A basin subject to marine processes, for example, may be affected by poor water quality and other attributes of its environmental setting. Thus understanding earth processes allows researchers using the conceptual model to make informed predictions about areas where data is not currently available. The conceptual model can be portrayed in a schematic drawing which elucidates salient details of the basin's geological system. Examples of conceptual models representing regional geology are presented in section 3.6 (Russell et al., 2006).

3.3.3 Model testing and documentation

Geological models must be tested and documented, usingvery reliable data (e.g., geophysical profiles with core) for model refinement as time and data quality allow. The modeller must document all procedures in an accessible format with pertinent examples, along with identifying and explaining protocols used. Our experience in developing conceptual geological understanding and 3D modelling suggests that it may be appropriate to form 3D model peer review teams.

Chapter 8 provides conceptual models of Canada's hydrogeological regions. Each regional hydrogeological model has been developed on the basis of the physical properties of unconsolidated sediments, and their corresponding thickness over rock. The spatial extent of an aquifer is delineated by the presence of impervious physical boundaries, i.e., a low-permeability geological unit (a formation which is at least two orders of magnitude less permeable than the aquifer). No significant groundwater flows to the aquifer from such units. Note, however, that highly confined aquifers

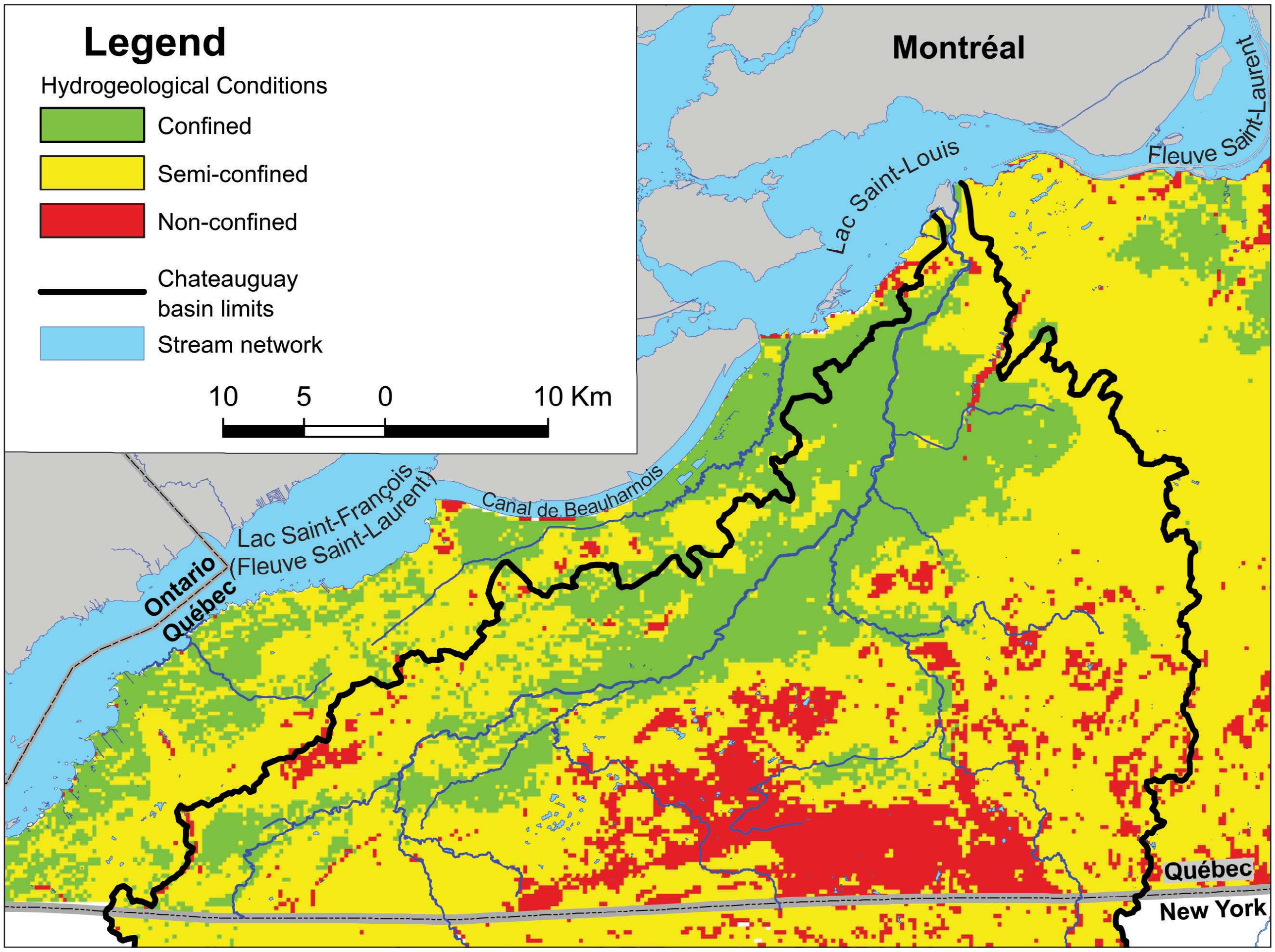


Figure 3.5 Hydrogeological conditions of the Chateauguay regional rock aquifer system defined on the basis of mapped unconsolidated sediment cover (after Croteau, 2007).

receive recharge only by slow seepage through surrounding low-permeability materials. A more detailed delineation of the aquifer systems, such as separation into sub-aquifers, can be defined through the use of hydraulic boundaries such as water divides located on topographic heights or rivers, or a line parallel to the flow (flow line). When the Chateauguay regional hydrogeological assessment was made, scientists defined confined flow conditions in areas covered with more than 5 m of marine mud characterized by low hydraulic conductivity (Croteau, 2007). Semi-confined flow was inferred for areas with marine mud less than 5 m and areas with more than 3 m of glacial sediments (till) above the aquifer. Rock outcrops or areas covered with thin till layers (<3 m), and/or by coarse, high-permeability sediments regardless of their thickness, were designated as non-confined, water-table aquifers. Based on this classification, the recharge rate was calculated to be lowest for the confined flow conditions, higher in semi-confined flow setting and highest under non-confined aquifer conditions (Figure 3.5).

Compilation of geological information through basin study and integration of the resultant data into a geological model concept constitute key steps of regional groundwater assessment. We believe that the generation of new geological information (see section 3.4) will motivate readjustment and refinement of this model, which provides the fundamental basis for planning and conducting the water quantity and quality assessments.

3.4 GEOLOGICAL, GEOPHYSICAL, HYDROGEOLOGICAL AND HYDROGEOCHEMICAL SURVEYS

Investigating the physical characteristics and properties of aquifers and groundwater is an important aspect of the regional groundwater assessment process. Field measurements are critical to verifying the assumptions inherent in conceptual and numerical models. Once the preliminary conceptual models have been determined, geological, geophysical, hydrogeological and hydrogeochemical surveys can be used to quantify the properties of the aquifer systems and groundwater, and to fill in data gaps wherever possible.

3.4.1 Geological surveys

The first steps in geological surveys include (1) interpretation of air photos to identify rock outcrops or thinly covered rock areas, in addition to the different regional settings of Quaternary sediments; (2) examination of existing geological maps; and (3) interpretation and consolidation of well logs (lithological descriptions of the material that wells intersect). Although individual Quaternary aquifers may be quite localized, they are important, and available data from geological maps or water well logs is often unable to identify the boundaries of specific sand/gravel aquifers or even indicate whether individual aquifers are present.

Most of Canada's basic geological framework has been well established by federal and provincial geological surveys and published as maps and reports commonly focusing on shallow aquifer systems (100 m deep or less) which generally contain important hydrogeological mapping information (Logan et al., 2005). Examination of existing rock and surficial-sediment geology maps provides a preliminary evaluation of the regional hydrogeological contexts, because valuable groundwater resources may be present in both lithified and unconsolidated units. Field verification of identified knowledge gaps is required prior to hydrogeological characterization of rock or surficial-sediment aquifer systems (Figure 3.1). Data gaps may occur in those areas where map units lack well support, and in such cases, it is wise to re-evaluate and update the conceptual geologic model based on assessment of new and archival data. When regional aquifers are located in sediments, however, a compilation of existing rock maps may provide sufficient characterization of the rock geology. We recommend compiling and integrating existing large scale reports and maps (e.g., 1: 20,000) to produce an intermediate scale map (e.g., 1: 100,000).

The rock characteristics which have the potential to control groundwater quality, quantity and movement are: porosity, mineralogical composition, textures and regional structures such as folds (bedding direction and dip), faults, fractures and joints (Table 3.1). The dissolution processes in carbonate rocks may result in significant alteration of primary structures such as fractures or bedding planes and produce an interconnecting network of permeable conduits which exert a major control on groundwater movement. Major structural features can be identified and located at the regional scale by using air photos and satellite images (Drury, 2001). Detailed information on characterization of rock aquifers information can be obtained from outcrops compiled, generalized and plotted on a geological map. Directional measurements of discontinuities such as strike and dip can be analyzed through a Schmidt diagram to identify families of structural features that may control groundwater flow (Ragan, 1968; Seyfert, 1987). Although usable groundwater in rock units usually resides in bedding planes and fractures, it may be necessary to estimate porosity of the bulk rock matrix (see Choquette and Pray, 1970; Friedman et al., 1992). The porosity estimation of the matrix in sedimentary rocks can be carried out in the laboratory (e.g., Hellmuth et al., 1999; Dubois et al., 1998). An analysis of rock core may be required to compile structural information, identify the lithological units in the third dimension and help develop the hydrostratigraphic conceptual model (see sections 3.3 and 3.5).

Quaternary and recent sediments commonly form a continuous to discontinuous cover over the rock units and low-permeability Quaternary units often act as seals (aquitards) for rock aquifer systems. Near-surface aquifers in Quaternary sediments are found throughout most of Canada, and scientists use surficial sediment maps to provide information on the nature and distribution of unconsolidated sediments, on their morphology (landforms), general thickness and history (origin and age). Locally, surficial sediments may reach hundreds of metres in thickness; the hydrogeological characteristics within and between units may be quite variable (there may be significant lateral facies changes over short distances or, alternatively, there may be a number of till sheets involved). Widely different descriptions of similar material often exist because geological descriptions of rock and sediments tend to be qualitative in nature. This can lead to a wide range of issues and errors when attempting to integrate various data sources into regional studies.

A simplified "geological descriptor" coding system has been developed at the Geological Survey of Canada to facilitate integration of subsurface Quaternary data from such diverse sources as well-drillers descriptions (found in thousands of provincial water-well databases) to state-of-the-art sedimentological logs (developed by expert geologists) (Sharpe et al., 2003, see Figure 3.6a; Parent et al., 2007).

It is also important to appreciate the 3D architecture of these unconsolidated sediments in order to understand the groundwater occurrence, quantity, quality and flow. Each map legend should provide information on the genesis; grain size and thickness of these sedimentary units in order to help define potential aquifer areas or zones of naturally protected aquifers (Table 3.1).

Depending on the quality of existing information, field surveys may be required to supplement existing mapping, to identify sediment types, to validate air photo interpretation and to collect samples and relevant stratigraphic data in natural (river banks) or artificial cross sections (sand pits, or auger holes). Samples should be analyzed for grain size or mineralogical or chemical composition (with clay or till content) to check the potential effect of chemical interaction between groundwater and sediments. Other specialized analyses (^{14}C dating, microflora or microfauna, etc.) can also be used for sediment identification and correlation. Borehole drilling may be required to complete the 3D mapping. A description of the geological units is made on drill cuttings or on intact sediment samples recovered from a split spoon, a Shelby tube or continuous core (Rotosonic drill), or, in the case of rock aquifers, a diamond-drilled core. Air photo interpretation takes into account observed geomorphology, field data, drilling information, existing maps and results from laboratory analyses to produce the surficial map. The resulting air photo interpretation is transferred directly to the digital base map using photogrammetric software (Paradis et al., 2001).

3.4.2 Geophysical surveys

Geophysical surveys are non-intrusive investigation techniques which allow scientists to

TABLE 3.2 CHARACTERISTICS OF MAIN GEOPHYSICAL METHODS USED IN HYDROGEOLOGY

(MODIFIED FROM MICHAUD ET AL., 2008)

A) SURFACE GEOPHYSICS

METHOD	DEPTH OF INVESTIGATION	RESOLUTION	APPLICATION
Electrical Resistivity	Tens of metres, controlled by electrode spacing	Good vertical resolution, no detection of thin beds	All types of sediments, depth to bedrock
Induced Polarization	Tens of metres, controlled by line length	Good lithologic contact resolution, no detection of thin beds	All types of sediments, depth to bedrock
Georadar	30 m, limited to fluid, high electrical conductivity soil and clay	Excellent resolution in the range of tens of centimetres	Very efficient in sandy materials, stratigraphic contact, internal structure, water table
Electromagnetic Survey (EM-31, EM-34)	1 to 60 m, depending on the electrical conductivity of the soil and the antenna spacing	Good vertical resolution (≈ 1 m), depending on the measurement station spacing	All types of sediments, depth to bedrock, water table, contaminated plume
Seismic (low depth reflection)	50–60 m, varying as a function of the power source	Metre range	Useful in fine grained sediments, depth to bedrock, internal structure
Seismic (refraction)	Vary as a function of the power source and the spreading length, always less than the seismic reflection for the same power source	Good resolution, propagation velocity increasing with depth, cannot detect thin beds	Depth to bedrock, lithologic contact, water table

B) DOWNHOLE GEOPHYSICS

LOG TYPE	MEASUREMENT	RADIUS OF INVESTIGATION	APPLICATION
Natural Gamma	Number of gamma rays (produced by decay of K, U, and Th)	0.3 m	Grain size (high counts associated with K in clay minerals)
Electrical Conductivity	Quadrature component of magnetic field induced by alternating magnetic field in transmitter coil	2-3 m	Formation conductivity (grain and/or pore water conductivity)
Magnetic Log	Magnetic Susceptibility	1-1.5 m	Presence of magnetite and other magnetic minerals (lithology)
Spectral gamma-density	Number of gamma rays returned to probe due to compton scattering	0.3 m	Water table, bulk relative soil density
Spectral gamma-ratio	Ratio of high-energy/low-energy gamma counts	0.3 m	Variation in heavy mineral content, void ration, or moisture content
Temperature	Temperature (±0.005°C) (temperature gradiant =dT/dz)	Within borehole	Thermal history (equilibrium temperature), lithology (as related to thermal conductivity), anomalies due to groundwater flow
Seismic Velocity (P-wave/S-wave)	Arrival times of seismic signal (compression/shear) from surface (determination of P-wave/S-wave velocity)	Within borehole	Variation in lithology, compaction, identification of reflecting horizons

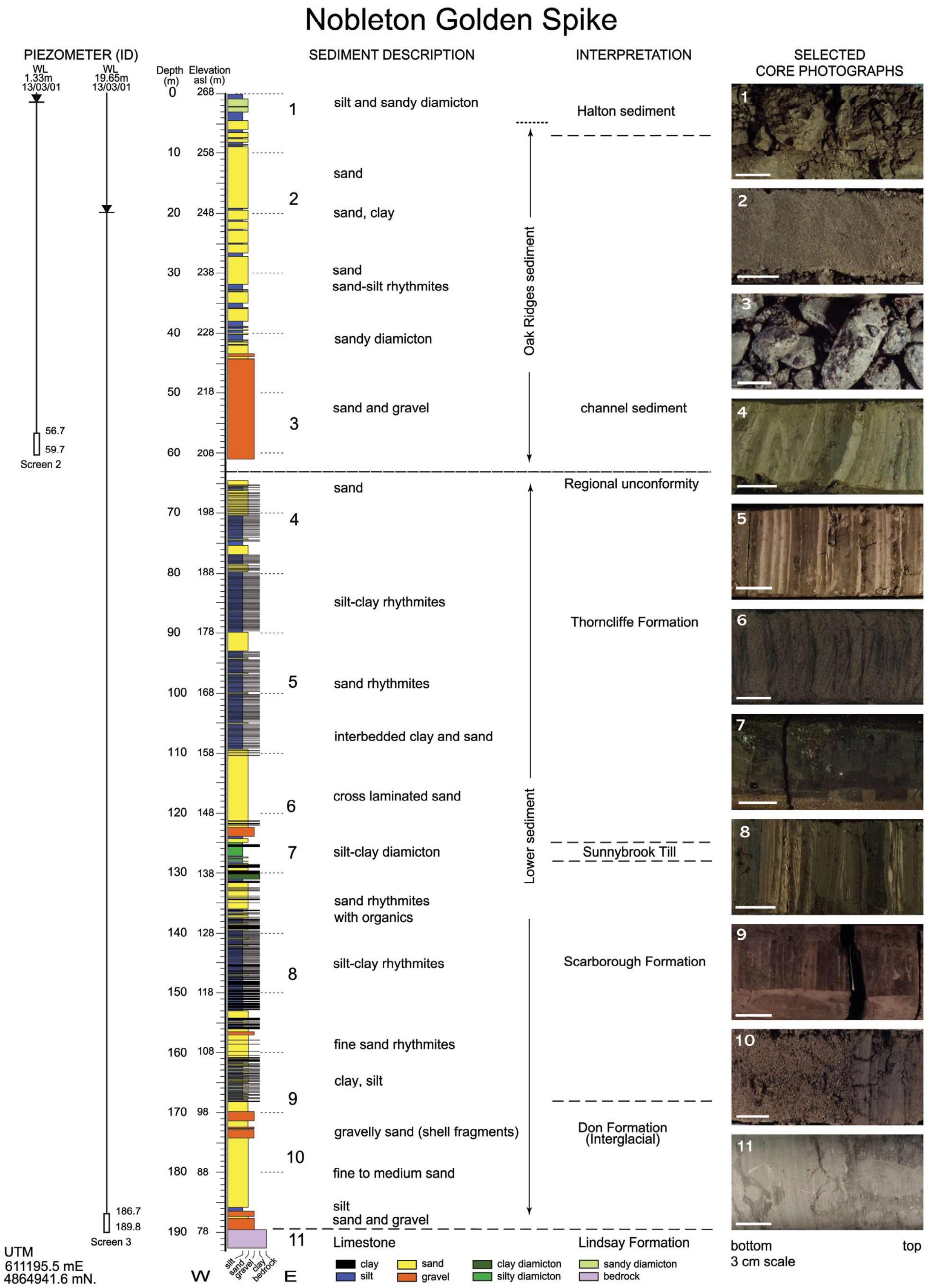
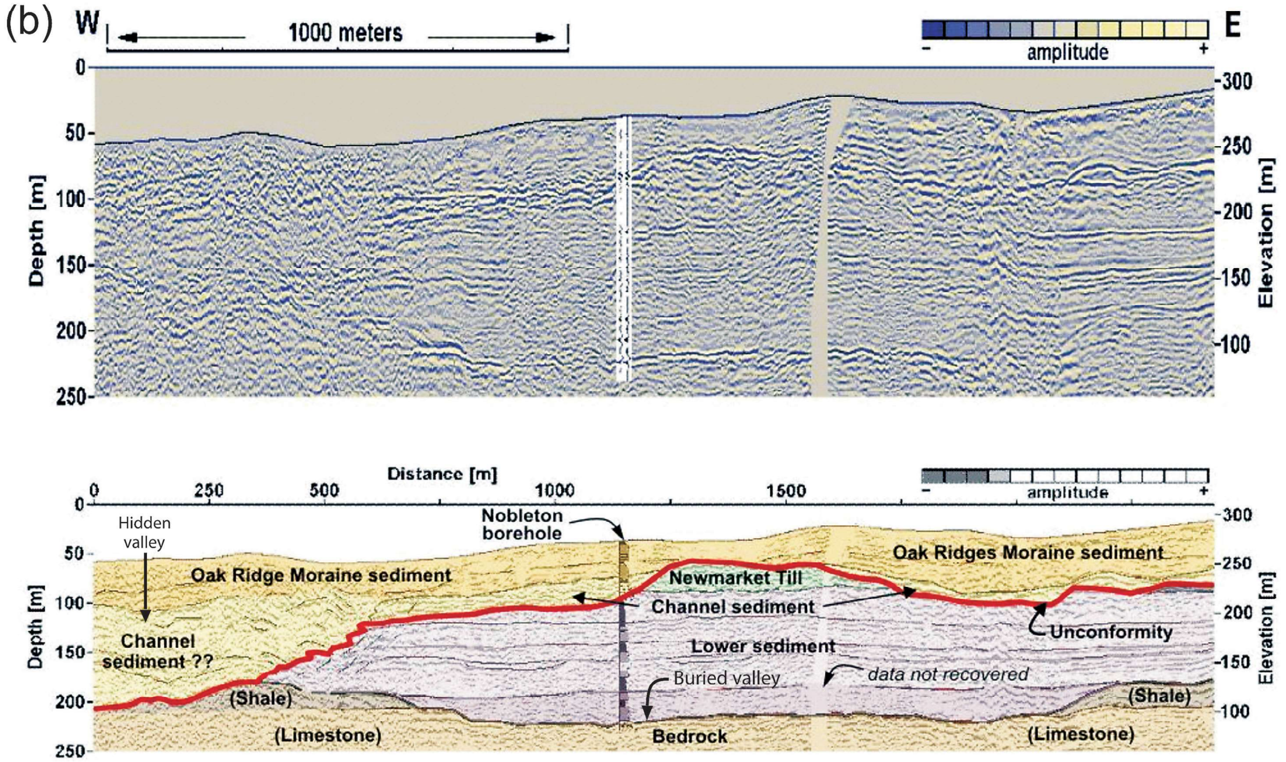


Figure 3.6 a) Continuous core sediment log (192 m) from a buried channel aquifer, Nobleton, Ontario (Sharpe et al., 2003). **b)** Seismic reflection profile (upper panel) and its interpretation (lower panel) showing the complex sediment architecture in the Oak Ridges Moraine (Pugin et al., 1999). See position of Nobleton borehole. Note buried valley on the eroded shale bedrock surface which is overlain by around 200 m thick Quaternary sediments. Red line is a regional unconformity that cuts older sediments and is filled with thick channel aquifer sediments and the Oak Ridges Moraine aquifers.



acquire additional point source or profile data such as depth to the water table, the lateral extent, the continuity, the geometry and the internal structure of subsurface geological units. These geophysical techniques are based on the fact that there are distinct and fundamental differences in how various media respond to electrical and physical *stimuli*. The geophysical survey procedure selected depends on the depth and types of geological material to be characterized (Table 3.2).

The most widely used surface geophysical methods for regional characterization are electrical resistivity, georadar and seismic reflection (Table 3.2a). The electrical resistivity procedure identifies materials according to their electrical resistance and water content. Water-saturated clay, for instance, has low resistivity, whereas dry sand shows high resistivity. Georadar helps define and position water tables, and/or subsurface sandy units along with their internal structure. Seismic reflection induces shock waves into the ground, which are captured by geophones after reflection. A seismic reflection profile can express depth to water, total thickness of the sediments, internal sedimentary structures and contacts between different geological units (Figure 3.6b). Resistivity and flow rate profiling (Table 3.2b) are the most common downhole geophysical methods. The resistivity profile is generated between two fixed spacing points on a probe moving downhole. This electrical procedure clearly detects both resistive and non-resistive material. Flow rate profiling evaluates the relative proportion of incoming water along a well as it is being pumped.

The acquisition of geophysical data minimizes regional survey costs while providing key hydrostratigraphic information. Such data can either be used in the early stage of regional work to orient the drilling program, or for completion

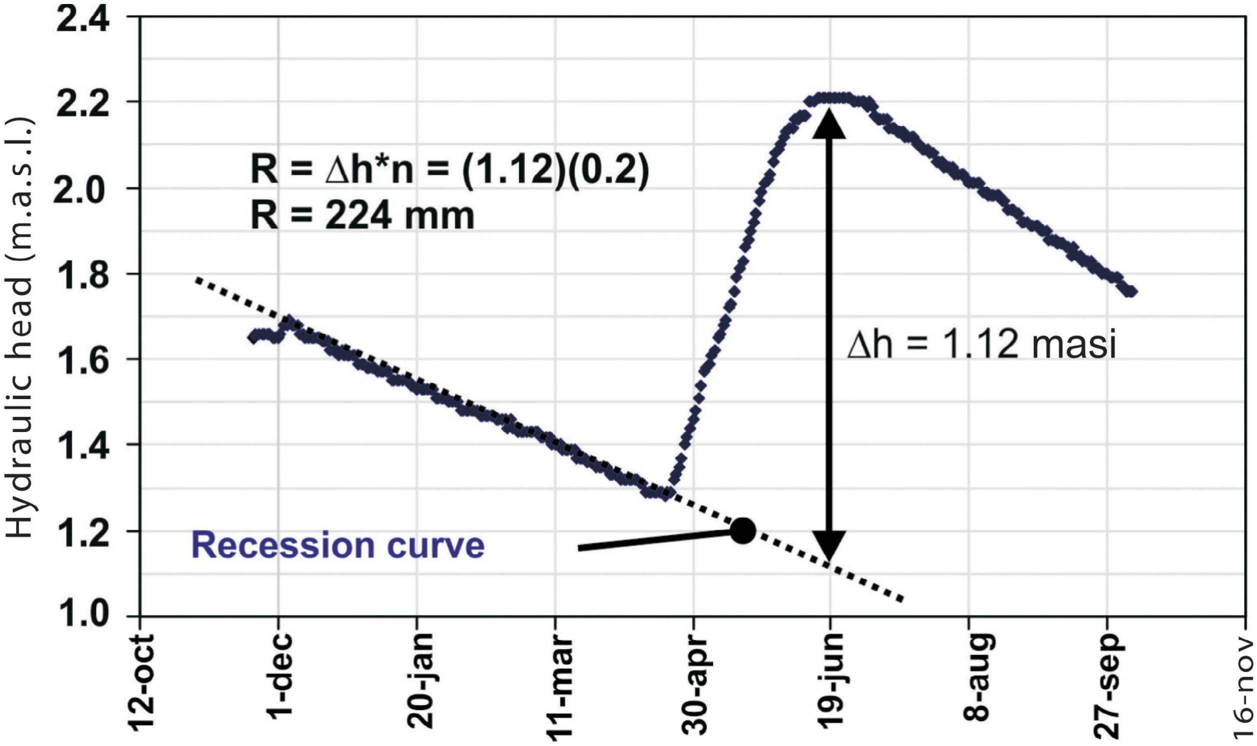


Figure 3.7 Well hydrograph illustrating how recharge (R) is estimated using porosity (n) and difference in hydraulic heads (Dh) on the recession curve, at the peak of an infiltration event (snowmelt in this case, assuming that n is air filled).

and validation of the hydrostratigraphic model when the drilling program is finished.

3.4.3 Hydrogeological surveys

At this stage of the investigation, those geological units which have been identified are classified as either permeable (aquifer) or of low-permeability (aquitard) and a hydrostratigraphic model is constructed. This model should be represented in 3D (e.g., Logan et al., 2005; see Section 3.6). Stratigraphic cross sections of rock and/or sediment sequences then allow the assembly of drilling information which, when integrated with geological and geophysical field surveys, reveals the stratigraphy and architecture of buried geological units and the connectivity of their aquifers. The use of cross sections produces depth-to-unit maps and isopach maps; these, in turn, help develop the 3D hydrostratigraphic framework (see section 3.6). Basin study is the main approach used to help infer subsurface geology and stratigraphy (Sharpe et al., 2002), and it therefore represents a key step in the development of 3D conceptual models (Smirnoff et al., 2008; see section 3.3).

Once the generalized hydrostratigraphic model has been created in 3D, hydrogeological characterization of the various conceptual units should be undertaken and other hydrogeological components of the model, recharge and discharge, for instance, added. Hydrogeological characterization at the regional scale involves (1) identification of the aquifer properties within the geological units; (2) estimation of aquifer recharge, and where recharge may be focussed; and (3) definition of the groundwater flow regime. The aquifer potential of geological units is determined by evaluating those parameters that allow quantification of these units' capacity to receive, contain and transmit groundwater (Table 3.1). These parameters include porosity, hydraulic conductivity, transmissivity, saturated thickness and storativity (for definition and methods of measurement, see Chapter 2). The permeable (aquifers) and the low-permeability units (aquitards) must all be characterized for their hydraulic properties at a spatial resolution adequate for the regional representation (e.g., Desbarats et al., 2001) and numerical modelling (see section 3.6).

Estimating the recharge of regional aquifer systems is crucial to quantify the hydrological cycle of a region, but is difficult to evaluate. Recharge (R), which is usually expressed in mm/year, depends on runoff, evapotranspiration (ET), change in storage (S) and on the transfer of water from neighbouring aquifers (and aquitards; see also Chapter 4). Recharge may be evaluated through hydrological, hydrogeological or hydrogeochmical methods (Healy and Cook, 2002; Coes et al., 2007; Bredenkamp, 2007). Hydrological methods include hydrological balance, surface water hydrograph separation, empirical correlation and hydrological modelling (Chapman, 1999; Piggott and Sharpe, 2007). The hydrological balance uses daily or monthly precipitation measurements (P), temperature (T), solar radiation, and wind speed to estimate the ET. Some of the measurement methods suggested include the Thornthwaite, the Penman, the Hargreaves, the Hamon and the Turc (Lopez-Urrea et al., 2006). Hydrological balance is the first step towards a partial resolution of the general equation to estimate recharge (Freeze and Cherry, 1979):

$$R = P\text{-}ET\text{-}Runoff \pm \Delta S \qquad (3.1)$$

To solve equation 3.1, we require data on P and runoff, an estimate of ET, and an evaluation of storage changes. If stream hydrographs are available for all or parts of the study area, these can be separated to obtain the baseflow contribution from aquifers and surface runoff on the watershed scale upstream of the gauging station (Neff et al., 2005).

Well hydrographs and hydrogeological modelling, surface water and groundwater interaction models, for example, can be used for estimating hydraulic parameters such as recharge (Purkey et al., 2006; Camporese et al., 2009). Well hydrographs are obtained via long- term (one or more years) water level monitoring in observation wells located within a chosen aquifer. A quantitative recharge estimate is determined by multiplying the water level fluctuation to the porosity of the investigated aquifer unit (Figure 3.7).

The hydraulic head (h) is the sum of hydraulic pressure (p) and elevation (z), and is usually reported in metres above sea level (masl). Hydraulic heads are calculated from water levels measured in observation wells. The water level (elevation) must be surveyed relative to a known reference, usually the mean sea level. This work commonly uses total station field measurements or the two-GPS technique. Recently, however, high quality digital elevation models (DEM; satellite imaging) and Lidar (aerial laser geophysics using light detection and ranging) have been utilized to vertically position measuring points, such as surface water and soil surface at well sites, which have been precisely located in the field,. The DEM method generally provides a metric precision, whereas the Lidar gives a centimetre precision.

Water levels and elevations should be measured in observation wells or private wells distributed over the study region in order to develop an understanding of the groundwater flow regime.

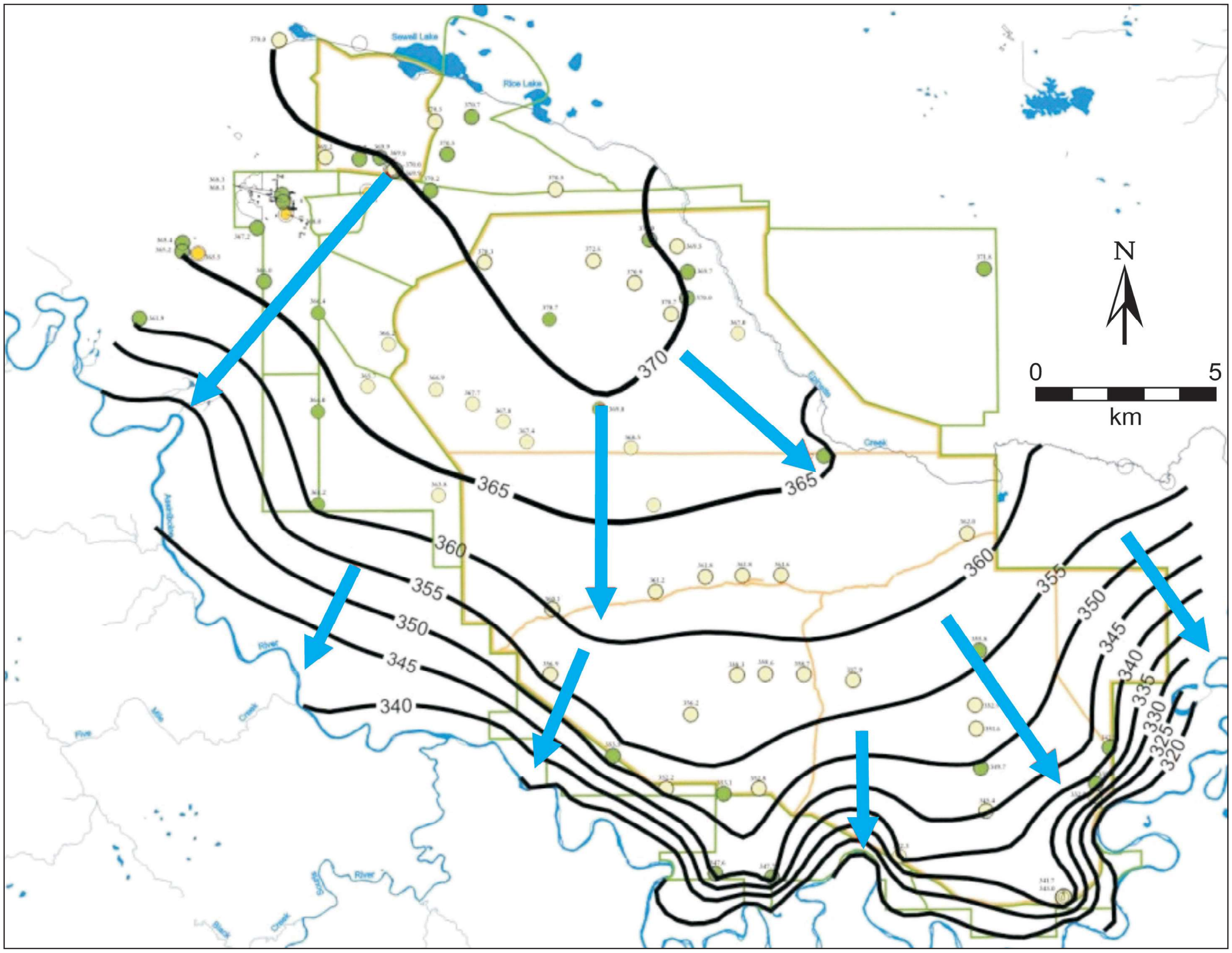


Figure 3.8 Piezometric surface map example (southern part of the Assiniboine delta aquifer). The black contours represent lines of equal hydraulic heads in metres above sea level. The arrows indicate groundwater flow directions (perpendicular to contour lines). Green circles are locations of hydraulic head measurement (adapted from Gauthier et al., 2003).

Water level measurements must be collected within a short period of time (weeks) to produce a representative snapshot of the hydraulic heads (see Chapter 2). Care must be taken to use only those wells where the completion zone is known so that the hydraulic heads can be assigned to a specific aquifer, or even to the upper or lower part of an aquifer.

Hydraulic heads gathered in this fashion can be used to develop a piezometric surface map, which represents a plan view of their distribution (Figure 3.8). This map is constructed by interpolating and contouring the measured water elevations in wells. Contour lines in the sample provided here are spaced at the metre scale (e.g., every 5 metres). The resultant surface map defines the direction and gradient of the groundwater flow regime. Groundwater flow is usually assumed to be perpendicular to the lines of equal hydraulic head, and occurs at all elevations, from high to low (Figure 3.8). However the actual direction of groundwater flow may deviate somewhat from this assumption, particularly in fractured-rock aquifers, because these aquifers are anisotropic. Piezometric surface maps usually have arrows indicating groundwater flow direction. One map is prepared for each

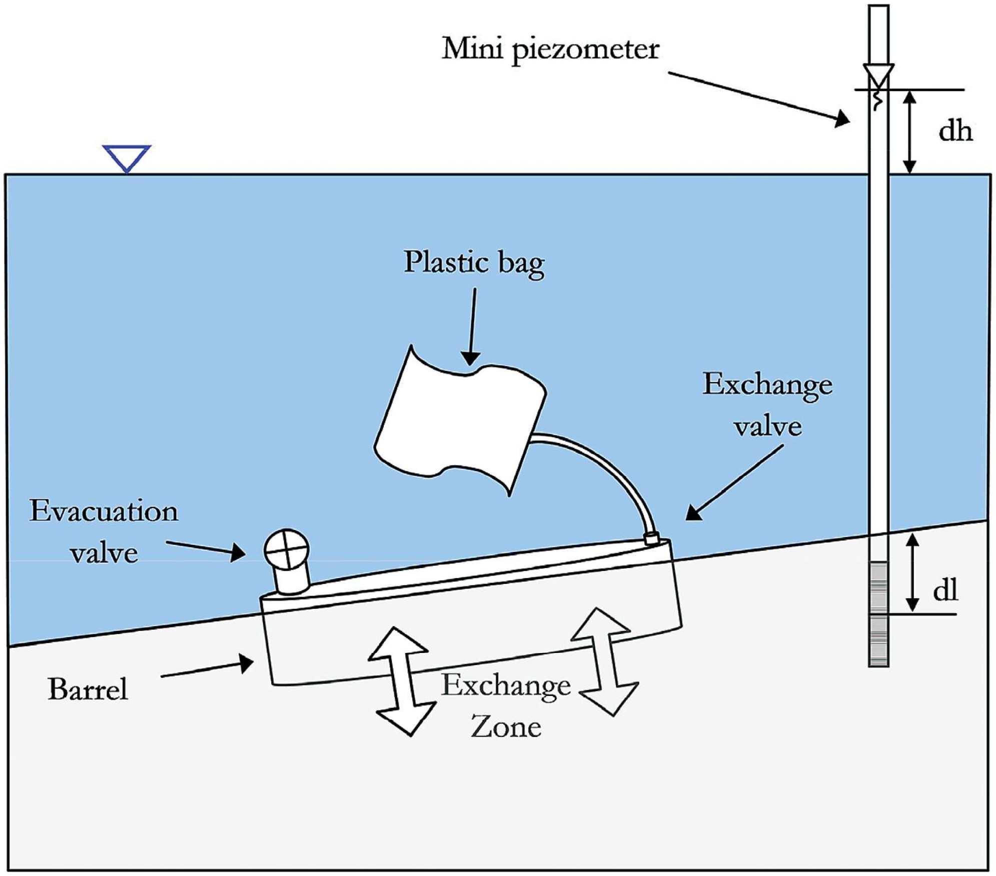


Figure 3.9 Instrumental setup for riverbed seepage tests (as per Coes et al., 2007, Purkey et al., 2006). The mini-piezometer installed into the riverbed at depth is used to measure the difference between groundwater and stream levels (denoted by dh). The barrel and plastic bag instruments are used to collect groundwater samples and to evaluate the groundwater flow rate (Q).The blue inverted triangle indicates river water level, and the black line between the blue and grey zones is riverbed. This device can also help evaluate hydraulic conductivity (K) of the river bed using Q=K × dh/dl × A, where A is the open area of the barrel.

aquifer and includes the measurement points for easier verification of interpolated levels. Other measuring points such as water elevation in dug wells, in rivers, creeks, lakes and ponds, and water outcrop elevation in sand pits or ditches, or a DEM (Desbarats et al., 2002) may also be used to create a surface map of water table aquifers, although the hydraulic link of these points with the aquifer must be confirmed before including them on the map. This can be done rapidly by visual observation of geological material on the shores or on the bottom of the water course being studied. Seepage tests and the installation of mini piezometers can also be used in river or lakebeds to determine whether groundwater is discharging into the surface water body or, conversely, whether surface water is recharging the aquifer (Figure 3.9). When surface water bodies and aquifers are hydraulically linked, the water table elevation can be extracted from a topographic map detailing those locations where topographic elevation contour and surface water bodies meet.

Regional hydrogeological studies as described above may also be supported by regional data sets obtained by remote sensing through satellite images. Hydrogeological surveys are often based on the use of spatially explicit water budget models, thus land surface surveys can be important in estimating parameters at varying detail levels. Knowledge of spatial distribution of land use and land cover (LULC) is often a required input within the algorithms for estimating interception of precipitation and surface runoff. Leaf area index (LAI), defined as the half of the all-sided green leaf area per unit of ground surface area projected on the horizontal datum, is also used mainly to compute evapotranspiration rates (Latifovic et al., 2010). The use of Earth Observation (EO) images in the hydrogeological context of Canadian populated areas is a practical solution for the estimation of the LULC and LAI because these images can cover large areas and require lower purchase and processing costs compared to traditional aerial photograph methods. Landsat Thematic Mapper (LTM) optical images are popular in this regard because they allow homogeneous mapping of the current LULC, coupled with the advantage of evolving in a numerical environment to facilitate both data management and spatial modelling (Chalifoux et al., 2006).

3.4.4 Hydrogeochemical surveys

The major goals of regional hydrogeochemistry are to characterize water quality, understand its variability, infer water origin and recognize the processes controlling quality changes be they natural or anthropogenic. One obvious objective of a regional survey is to establish whether water is drinkable and/or whether it can be used for other purposes such as irrigation, livestock needs or industrial activities. This assessment is determined by comparing analytical results with water quality guidelines (Health Canada, 2010; CCME, 2011; WHO, 2011; EPA, 2011). Water types are identified by the presence of major anions (atoms or molecules with a net negative charge: chlorides, bicarbonates and sulphates) and cations (atoms or molecules with a net positive charge: calcium, sodium, magnesium and potassium) dissolved in water. These can be illustrated graphically using Piper, Stiff or radial diagrams (e.g., Hounslow, 1995; Appelo and Postma, 1993).

Water quality is modified by natural processes as fresh water mixes with saline water, or water and rock interaction, which release natural elements such as iron, sulphur, fluorides, manganese, carbonates, arsenic, uranium, etc., or by human activities like fertilizer use, salt deicers, and underground storage tanks (Table 3.3). Potential contamination problems are identified by comparing concentrations of measured elements or dissolved chemicals with regional background values and drinking water criteria through reference to maximal acceptably safe concentrations and/or established odour and standards.

The choice of geochemical parameters to be analyzed depends on the investigated hydrogeological context and land use. These parameters usually include physicochemical characteristics (on-site temperature, pH, Eh, electrical conductivity, dissolved oxygen), and inorganic characteristics (TDS, anions, cations), coupled with organic and microbiological characteristics. Any regional study usually begins with a systematic physicochemical and inorganic survey of groundwater, followed by organic and/or microbiological analyses in selected zones as necessary, particularly those zones affected by anthropogenic activities. Additional parameters, such as the examination of stable or radiogenic isotopes, may be required for better quantitative understanding of regional water source and mixing,

TABLE 3.3 COMMON QUALITY PROBLEMS OF GROUNDWATER

(ADAPTED FROM SAVARD ET AL., 2008)

AESTHETIC PARAMETER				
TOTAL HARDNESS	**MCL[a] (MG/L)**	**AO[a] (MG/L)**	**PROBLEMS RELATED TO PARAMETERS ABOVE GUIDELINES**	**MAIN SOURCES**
Chlorides		≥250	Bad taste	Deicing salts
Iron		≥0.3	Water colouration, cloth stain, favours bacterial growth in tanks and pipes and alters taste and odour	Natural
Fluorides	1.5		Dental fluorosis	Natural
Manganese		≥0.05	Water colouration, cloth stain, favouring bacterial growth in tanks and pipes and alters taste and odour	Natural
TDS		≥500	Bad taste, drinkable potential depends man constituents	Ca and Mg salts, NaCl
NO_3+NO_2	10 (in N)		Methemoglobinemia[b], potentially carcinogen	chemical or organic fertilizers
pH		6.5 ≥ pH ≥8.5	Low pH: corrosion of metals High pH: mineral deposition	Natural
Sodium		≥200	Harmful for persons with heart problems, bad taste	Natural (rock, seawater, formation water)
Sulphides		≥0.05	Odour of rotten eggs	Natural

a AO–Aesthetic objective (taste, odour); MCL–maximum contaminant level (to protect human health). < 80 : corrosion of pipe works; >200 : poor quality but acceptable for consumption; > 500 : unacceptable for most domestic usage (deposits in pipes) (CCME, 2011)

b Decreases oxygen transport in babies' blood (Health Canada, 2010)

age dating (e.g., ^{3}H, ^{14}C, $\delta^{2}H$, $\delta^{18}O$; Clark and Fritz, 1997), and/or the fingerprinting of contaminant sources (e.g., $\delta^{15}N$, $\delta^{18}O$, Kendall and Aravena, 2000; $\delta^{37}Cl$, Vengosh et al., 2002).

For purposes of a regional survey, groundwater samples should be collected from existing private, municipal and industrial wells, springs and seeps, and newly installed observation wells or driving points. Physicochemical parameters must always be measured on site with field probes at all sampling locations, whereas the inorganic and organic parameters require water samples to be collected (using specific bottles and protocols), and shipped to analytical laboratories. Depending on the selected parameters and analytical methodology, sampling protocols may include on-site water filtration, addition of preservatives in bottles, quality assurance and control (QA/QC), and the use of particular containers, holding times, sampling equipment, sample volumes, etc.

These analytical results should be added to the regional database, and integrated in subsequent reports using various graphical and mapping formats. The dot map, wherein dot sizes are proportional to the parameter concentration, is the most practical format for regional representation, although usually only parameters with concentrations above specified guidelines, or those used to describe hydrogeological settings (confining conditions based on dissolved oxygen), or those developed to detect sources of contamination are shown on maps or graphs. The hydrogeochemical distribution can also be linked or compared with geological or land use maps to locate potential sources of natural or anthropogenic contaminants. Examples of graphs, maps with distribution of water types, and interpretation in terms of processes may be found in Cloutier et al. (2006, 2008).

Regional hydrogeochemistry studies should ultimately lead to depict a complete inventory of water quality, distribution of water types, and (when combined with groundwater quantity available), to delineate those parts of the regional aquifer system under study which require specific protective measures, and those that are favourable for human extraction. The hydrogeochemical survey allows researchers to make recommendations in terms of safe yield, and groundwater treatment needs, in addition to identifying prohibited zones of withdrawal. Hydrogeochemists working on large-scale studies may need to propose a monitoring network to check water composition over time in those areas where anthropogenic contamination occurs, as well as to assess deterioration, or improvement, of quality due to natural process (dilution, denitrification).

3.5 PARAMETER ESTIMATION, INTEGRATION AND EXTRAPOLATION OF DATA

The Chateauguay regional groundwater assessment is a classic example of recharge estimation using remote sensing. Forty-seven items, ranging from bare soil to dense forest, were selected from Latifovic et al. (2010) and adapted for hydrogeological research in order to establish guidelines for an optimal use of medium spatial resolution remote sensing imagery with LULC definition (Croteau, 2007). LAI measurements were acquired *in situ*, mainly within forested areas of variable density using a digital hemispherical photography (DHP) technique. These measurements were compared with values of the Infrared Simple Ratio vegetation index from coincident Landsat TM pixels to map LAI. The published relationships of Landsat vegetation indices with LAI were used to estimate the LAI for areas with uniform vegetation (crops, pasture and grasses). The final 250 m resolution LULC and maximum LAI maps were integrated with the other input parameters (climate data, slope, drainage distance and soil profiles) into the hydrological model HELP (see Chapter 4; Schroeder et al., 1994) to generate the regional water budget parameters. The resultant recharge estimates agreed within ±10% with independently derived estimates using hydrographs separation of recorded river flow rate. This remote sensing method estimated both the groundwater and the surface runoff contribution to river flow.

Hydrogeological parameters are often measured in the field as a component of "local or site scale" investigations. A pumping test, for example, might be carried out using one water supply well and several observation wells tens to hundreds of metres away. This pumping test, however, only yields a value for hydraulic conductivity and storage, representing the aquifer portion being tested. Regional groundwater assessments, however, require the hydraulic properties of aquifers to be delineated at a scale of kilometres. Extrapolating local scale parameters to a regional scale is often referred to as up-scaling, and there are various techniques, of varying complexity and reliability, available to quantify the necessary hydrogeological parameters required for regional studies. These techniques depend on study space and time scales in addition to requiring an understanding of the physical processes leading to the heterogeneous nature of geological deposits.

Maps plotted at detailed spatial scales (1:1000, for example) cover small surfaces typical of local studies, whereas small-scale maps (such as 1:100,000), cover the thousands of square kilometres typical of watershed/regional characterization. Carrying out field work at local scales, while, at the same time, generating results and maps at the regional scale involves handling the space up-scaling problem, insofar as moving from a local to a regional scale is required for modelling of regional groundwater flow and transport. Heterogeneities of specific aquifer parameters are scale-dependent because measured attributes usually increase with the size of the investigated aquifer volume. The hydraulic conductivity values for any given unit are small when obtained over a soil sample in the laboratory (cm); they are higher when measured in field conditions with slug tests (metres), and even higher when compiled from pumping or tracer tests (>100 m; see Kruseman and de Ridder, 2000). In all cases, the parameters, which reflect an aquifer's physical properties, are assumed to be constant in time.

Other hydrogeological parameters such as groundwater recharge, runoff or evapotranspiration are all-dynamic, insofar as they can vary not only on a daily/seasonal basis but

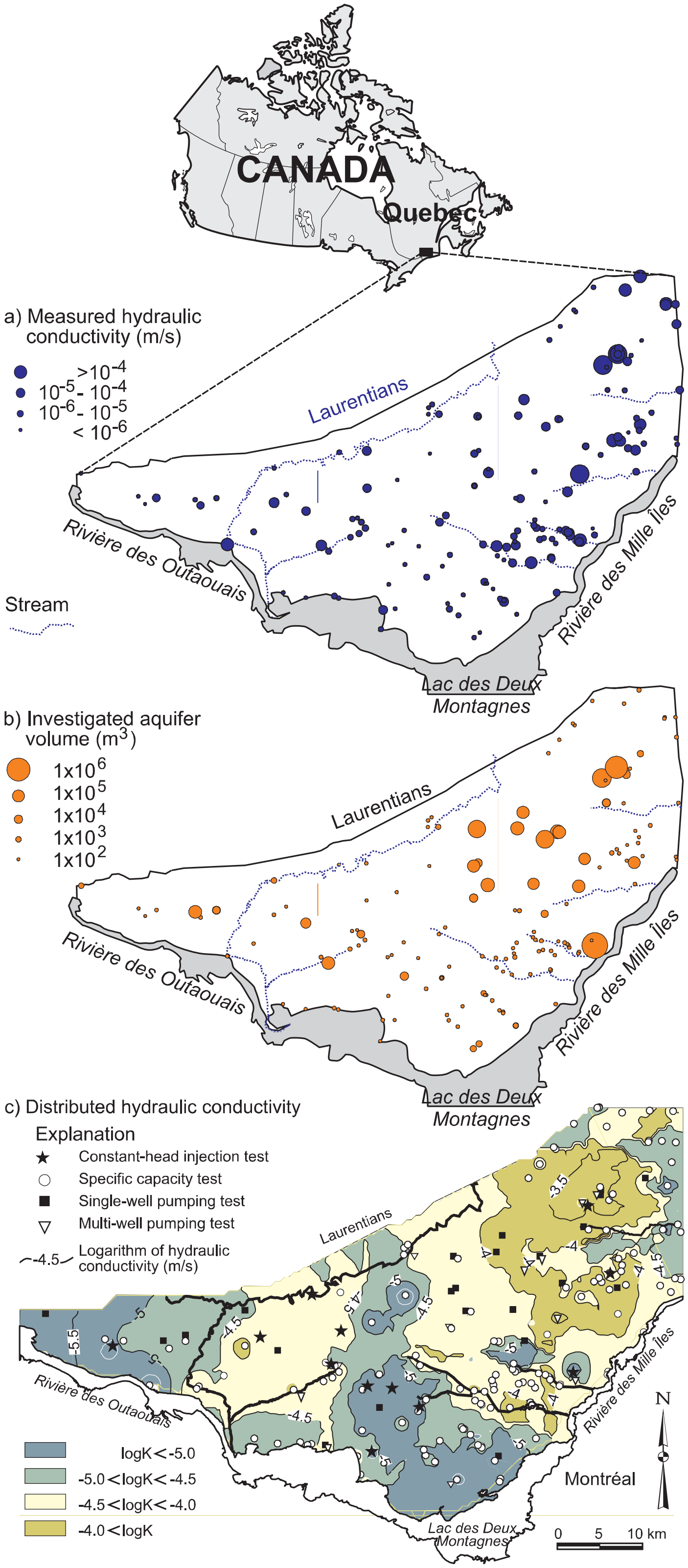


Figure 3.10 Southwestern Quebec study area showing: (a) spatial distribution of measured hydraulic conductivities; (b) interpolated horizontal log—hydraulic conductivity for the sedimentary rock aquifer system; and (c) investigated aquifer volumes (modified from Nastev et al., 2004).

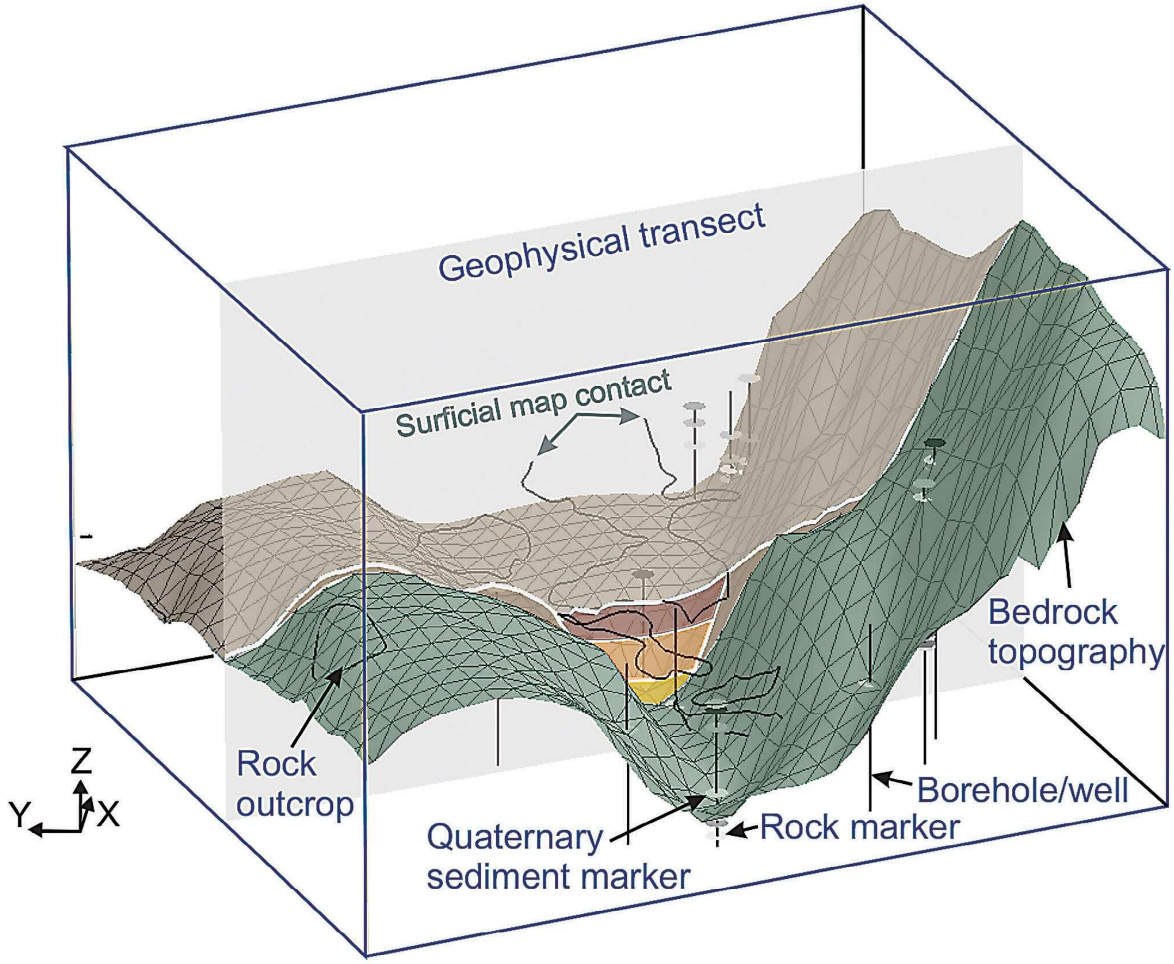


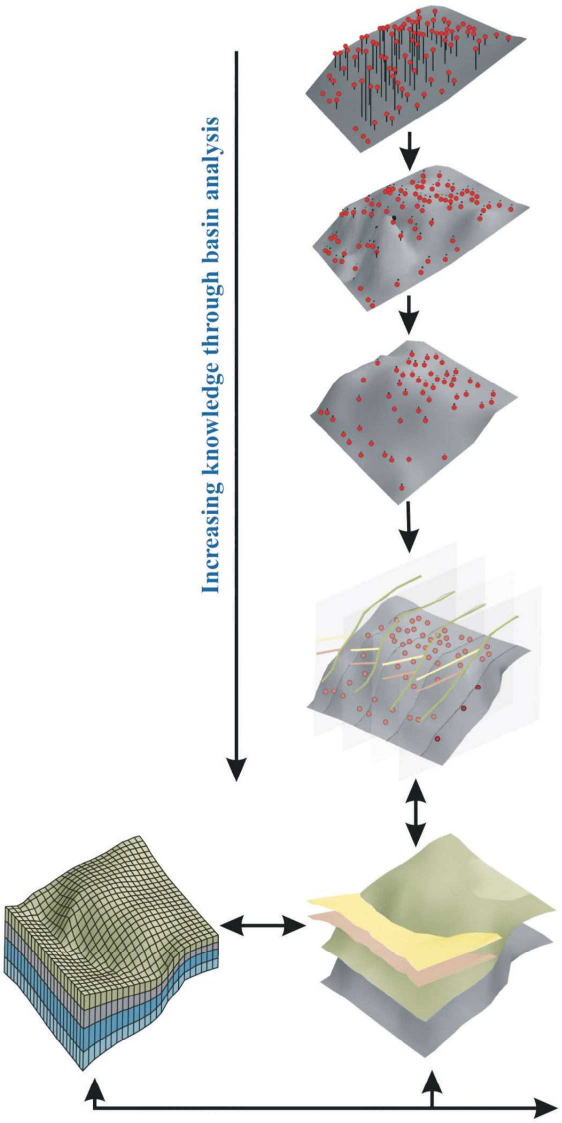
Figure 3.11 This three-dimensional representation of the bedrock surface in the southwestern Quebec aquifer system, is based on the integration of information drawn from surficial map contacts, rock outcrops, geophysical transects and well logs (after Ross et al., 2005).

also on an annual basis due to soil storage changes, land use, and climate conditions. As a result, researchers must use multiple-scale investigations to obtain representative estimates, and to refine the required knowledge because of the uncertain variability of the targeted parameters associated with each measurement technique.

One simple approach for the integration of measured field data and the interpolation of representative hydraulic conductivities (while accounting for the effects of test scales) was developed during the assessment of the St. Lawrence Lowlands sedimentary rock aquifer system (Nastev et al., 2004) as aquifer volumes were also considered in addition to measured hydraulic conductivities and distances. Hydraulic properties measurements were obtained from a number of locations and by a variety of field testing methods (packer tests, specific capacity, and single and/or multi-well pumping tests). A total of 179 hydraulic properties' measurements were made and used to generate the hydraulic conductivity field over the specified study area (Figure 3.10). These "point" hydraulic conductivity measurements were then used to generate a regional map of the whole aquifer using inverse-distance interpolation, although the method was modified to account for distance and for a second weighing function relative to the investigated aquifer volume.

The magnitude of any hydraulic conductivity at a given interpolation point is influenced both by hydraulic conductivities measured at the closest sample points and by the samples having the largest investigated volumes. Thus, small volume measurements are weighed down, whereas large volume measurements are up-weighed.

Numerical modelling of the regional groundwater flow system confirmed accuracy of the interpolation procedure by correctly reproducing the average value of hydraulic conductivity while, at the same time, largely preserving the variance of the initial data set (Anderson and Woessner, 1992).



Initial data integration from outcrops, cross sections, geological maps, geophysical surveys. Surfaces are constrained on point sets (e.g. drill-core logs, topography), curves (e.g. map polygon) and other parameters (range thickness, etc.).

Interpolation using a selected algorithm.

New surfaces are built after quality control and integration of newly-acquired data from field surveys.

Construction of regional cross sections and further quality control. Modification of surfaces at unconstrained nodes to integrate expert knowledge.

Surface borders (pinchouts) are edited to map discontinuities and to weld surfaces together. Local interpolation is done to remove remaining crossovers. Final 3D model is based on validated data only. The conceptual framework (3D grid) can be used for groundwater flow modelling.

Figure 3.12 Suggested procedure for integration of data into geological models and subsequent translation into numerical models (after Ross et al., 2005).

3.6 THREE-DIMENSIONAL MAPPING AND NUMERICAL MODELLING

Three-dimensional representation of regional aquifer systems is essential for constructing hydrogeological architecture used for groundwater flow modelling and the representation of aquifer delineation. Three-dimensional mapping of aquifer systems uses advances in GIS technologies as well as the guiding conceptual models described in section 3.3.2. A hydrostratigraphic representation can be produced through the integration of compiled data assembled within a newly generated geological model with the data set of a geo-referenced x-y-z space (Figures 3.1 and 3.11).

A basin study is used to define the various hydrogeological contexts of a region, by combining high-quality data (Pugin et al., 1999; 2009; Sharpe et al., 2003) with an understanding of the relationship between aquifers and aquitards (i.e., the regional hydrostratigraphic architecture which controls groundwater flow in the basin) operating under the influence of recharge rates related to climate and land use.

Geological maps of Quaternary sediments and rock lithologic units are essential 2D planes for modelling various spatial scales. Researchers use geological principles to integrate various subsurface data (such as drill-core logs) to produce cross sections, outcrops and 2D geophysical transects. Semi-automated or automated interpolation techniques allow scientists to generate the continuous three-dimensional subsurfaces (Figure 3.11) required for hydrogeological modelling. This approach has been successfully applied to regional systems in southwestern Quebec, the Oak Ridges Moraine and the Chateauguay aquifer systems (e.g., Savard et al., 2013; Sharpe et al., 2002; Nastev et al., 2005).

Model construction is based on available software, personnel and funds. Minimally, researchers should have a 2D GIS linked to a relational database, although 3D software which allows realistic capture and rendering of conceptual models in natural settings (Figure 3.12) is preferred. The first step is to establish a model construction protocol based on data support, data quality, available resources and goals of the modelling process. The model results should be assessed by peer review. The modeller must then repeat and refine some or all previous steps until the result is deemed plausible given the level of data support (this iterative process includes potentially rejecting the original conceptual geological model for a new one.) Model confidence is achieved by capturing and displaying the level of data support in the database (both through real and through interpolated points.) The 3D model should be portrayed graphically as a probability estimate. Both 2D and 3D products should clearly illustrate those control points which served to delineate the units of interest (e.g., permeable Quaternary formations) or specific attributes zones (e.g., distribution of hydraulic conductivities or groundwater types).

There are several methods by which scientists construct 3D representations, be they based either on expert knowledge of geological modelling (as stated above), surface delineations (Ross et al., 2005) or statistical reconstruction of volumes (Smirnoff et al., 2007). Logan et al. (2005) have provided a useful description of a rules-based approach. Subsequent steps for creating the final hydrogeological model involve the creation of a sound conceptual model, which includes predictive depositional models (Russell et al., 2006).

Once the 3D geological model is completed, the numerical modelling expert creates a grid or mesh with cells or nodes, and elements representing contact surfaces between the various units of the 3D hydrostratigraphic model (Figure 3.12). Boundary conditions (e.g., no flow, constant head and imposed flux) of the numerical model are defined according to the hydraulic heads observed in the field and by their delineated hydrostratigraphic contexts.

Currently there are two major modelling approaches: deterministic and probabilistic (stochastic) (e.g., Anderson and Woessner, 1992); it should also be noted that several commercially available software programs exist for modelling based on representations using finite difference, finite element or finite volume methods. These approaches are used to subdivide the domain into smaller cells, and to numerically represent the aquifer system.

When the deterministic approach is employed,

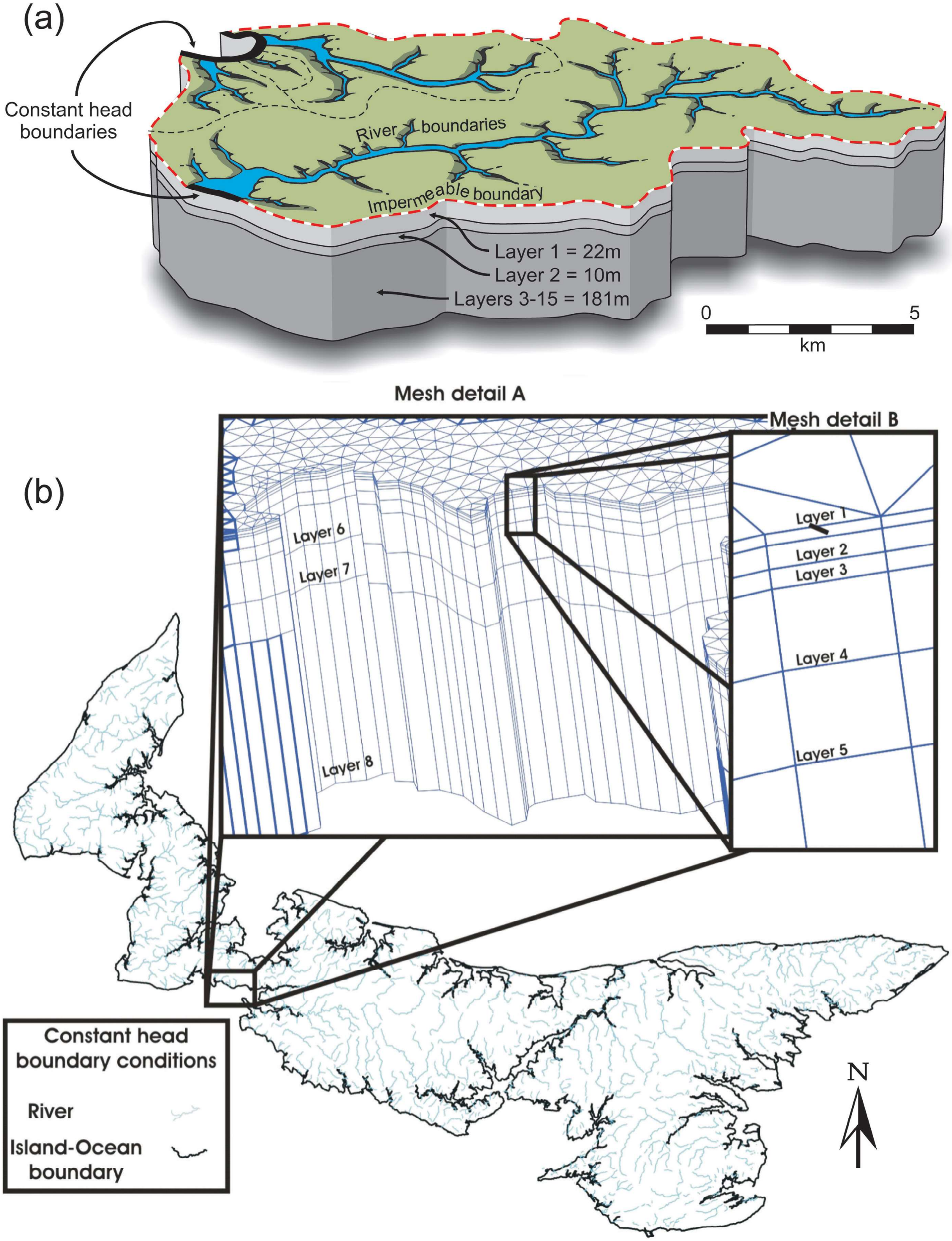


Figure 3.13 a) Conceptual model, including boundary conditions, for the aquifer of the Wilmot watershed (Prince Edward Island) which covers 87 km^2 (Jiang and Somers, 2007). **b)** Vertical discretization illustrating mesh detail (eight layers), triangular grid and boundary conditions (island map) used in the numerical flow model representing the entirety of Prince Edward Island (modified from Vigneault et al., 2007).

specific parameters (e.g., hydraulic conductivities, storage and porosity) are assigned to each unit according to field measurements and literature data. The probabilistic approach assigns ranges of values to each of the units. Aquifer recharge is generally applied over the entire study area in both approaches.

Human extraction of groundwater is taken into account either as a point source (for large users), or as uniformly imposed negative fluxes over portions of the study surface (e.g., private wells). Model calibration is performed through comparison of the observed and the modelled hydraulic heads by changing various unit parameters (such as hydraulic conductivities), or by varying the recharge rates of the aquifer system. As a general rule, the deterministic model is considered calibrated when the root means square of modelled and measured heads are within 10%. This is in contrast to probabilistic modelling, where several scenarios of hydrogeological parameters can be generated.

Basin-analysis methods in sedimentary basins, lead to a sound conceptual hydrostratigraphic model (Figure 3.13a), which is then used to finalize the digital numerical model to which hydraulic properties are attributed.

We present below two modelling examples (intermediate and regional scales) using the deterministic approach (the most frequently used in the modelling of regional groundwater flow).

The first example illustrates thicknesses of the 15 hydrostratigraphic layers used in the conceptual model representing Prince Edward Island's Wilmot watershed (Figure 3.13a; Jiang and Somers, 2007). High values of hydraulic conductivities were assigned to layers 1 and 2 to represent highly fractured sandstone; progressively decreasing hydraulic conductivities were assigned to the underlying 13 layers successively simulating the diminishing fracture aperture and connectivity associated with depth. Hydraulic conductivities used were estimated using field pumping tests and laboratory permeability tests. The boundary of the Wilmot River watershed, which is hydraulically connected to the aquifer, is included in the model, along with the constant head boundaries. Once the model was digitized and completed, modelling of the groundwater flow and nitrate transport proceeded at the local scale of the Wilmot watershed (~85 km^2; numerical model not represented here). Because the goal of this project was to understand the impact of agricultural practices and climate change on groundwater contamination by nitrate, this initial conceptual model study was adapted for all of PEI, and eventually covered approximately 5,660 km^2 (Figure 3.13b). Eight hydrostratigraphic layers were simulated; each represented by 500 m cells (close to half a million cells), with the upper layers being the most permeable (Vigneault et al., 2007). This modelling exercise predicted that, should current agricultural practices be maintained, the related nitrate input to groundwater would attain steady-state conditions at concentrations 11 % higher than present, a situation that would lead to large increases in the nitrate contamination of private domestic wells (concentrations above the recommended health threshold of 10 mg/L) For details see Vigneault et al., 2007.

Numerical models simulating regional groundwater flows are also used to delineate zones sensitive to increased human extraction of groundwater, or to study a reduction of recharge due to climatic conditions.

The groundwater flow in the southwestern Quebec's fractured-rock aquifer system (covering approximately 1,500 km^2) was simulated with seven

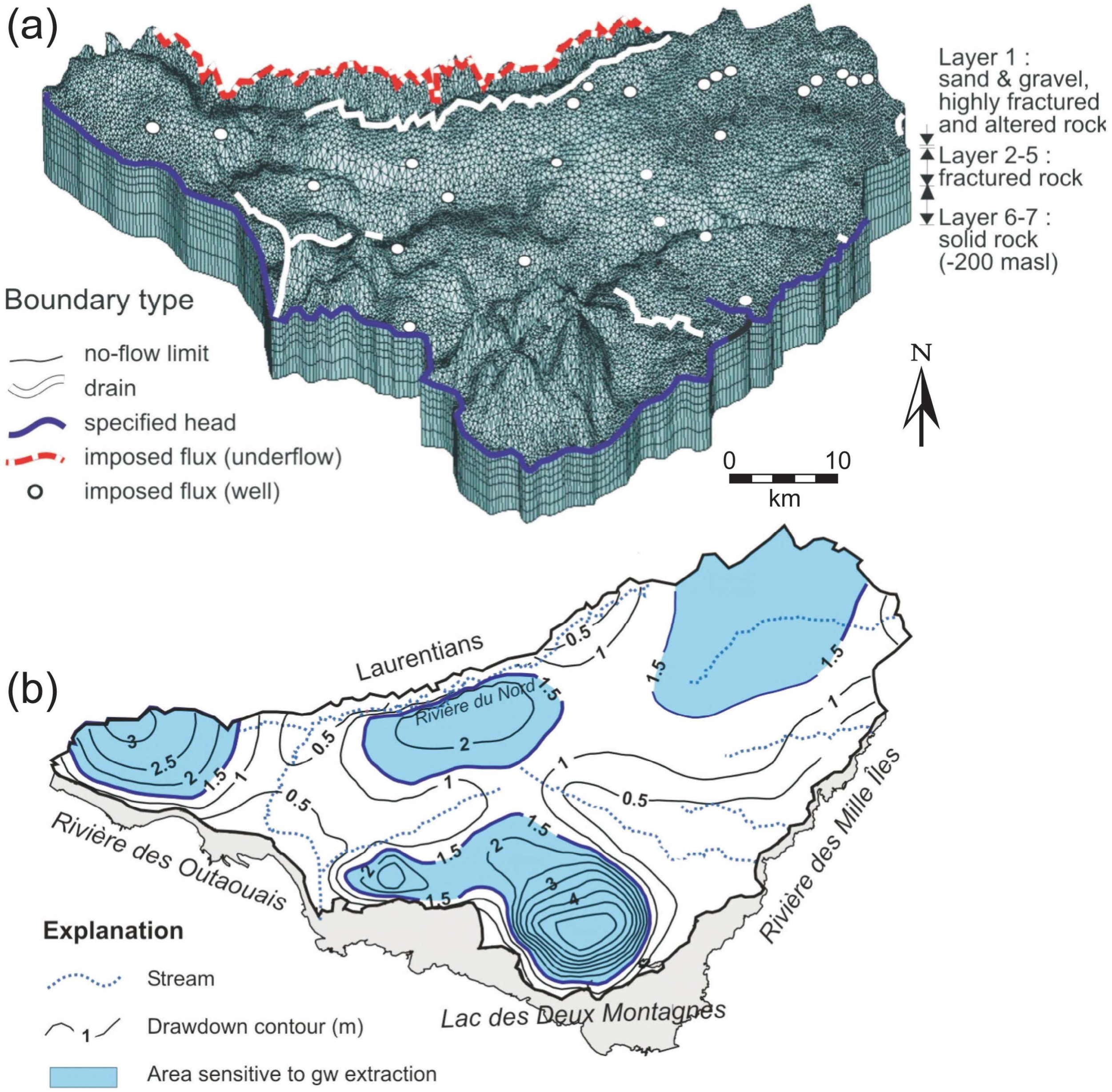


Figure 3.14 a) Numerical model with finite element grid (Nastev et al., 2005). **b)** Simulated drawdown in metres relative to currently observed hydraulic heads for the southwestern Quebec fractured rock aquifer system; gw stands for groundwater (modified from Nastev et al., 2006).

hydrostratigraphic layers (Figure 3.14a; Nastev et al., 2005). A numerical model was used to estimate impacts of increased annual extraction rates on groundwater levels (Figure 3.14b). Additional groundwater extraction (pumping) was simulated by uniformly imposing a negative flux representing a uniform pumping of $6.1 \times 10^6 m^3$/year to the finite elements of the top layer (layer 1; equivalent to 5 mm/year of water extracted for the entire surface of the layer). The resulting spatial distribution of drawdown allowed for the delineation of those zones most vulnerable to increased pumping

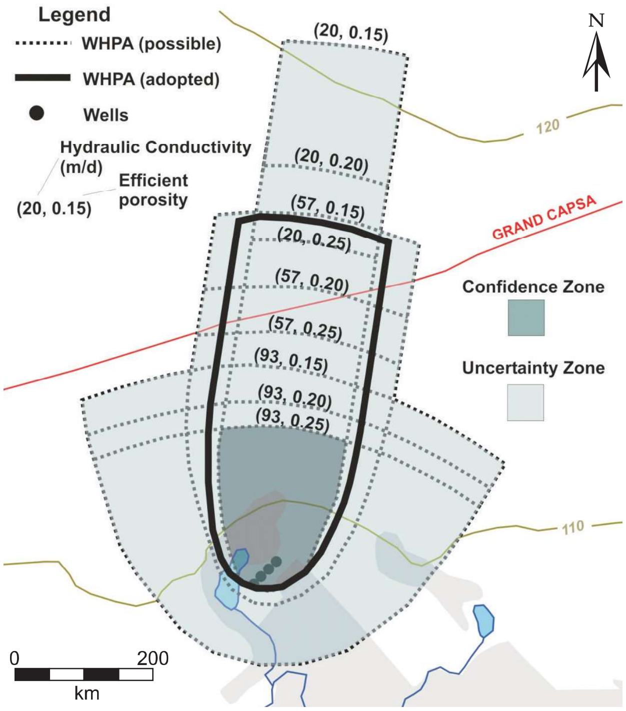


Figure 3.15 Delineation of confidence and uncertainty zones of a wellhead protection area (WHPA) based on various values of hydraulic conductivity (after Paradis, 2000).

according to the various aquifer properties and hydrostratigraphic contexts (Figure 3.14b).

The examples and text presented here constitute a very brief introduction to numerical modelling, and by no means represent a complete review on this important topic. Numerical modelling also addresses itself to several other applications not discussed here. These include the simulations of safe yield, transport of contaminants, evolution of groundwater quality, etc.

3.7 QUANTIFICATION OF UNCERTAINTIES IN HYDROGEOLOGICAL PARAMETER ESTIMATION

Construction of a sound conceptual hydrogeological model involves many participants, several sets of measurements, and various types of data interpretation, manipulation and transformation. Errors associated with data sets and data

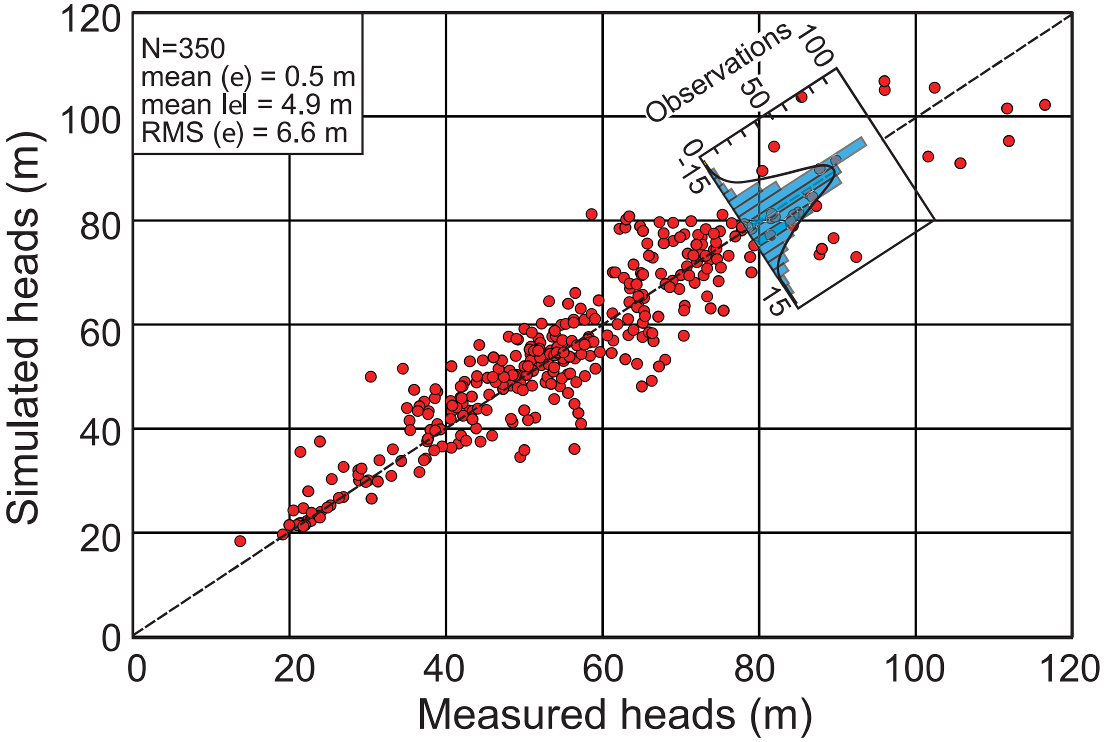


Figure 3.16 Illustration of differences between measured and simulated hydraulic heads using computer modeling of regional groundwater flow (adapted from Nastev et al., 2005).

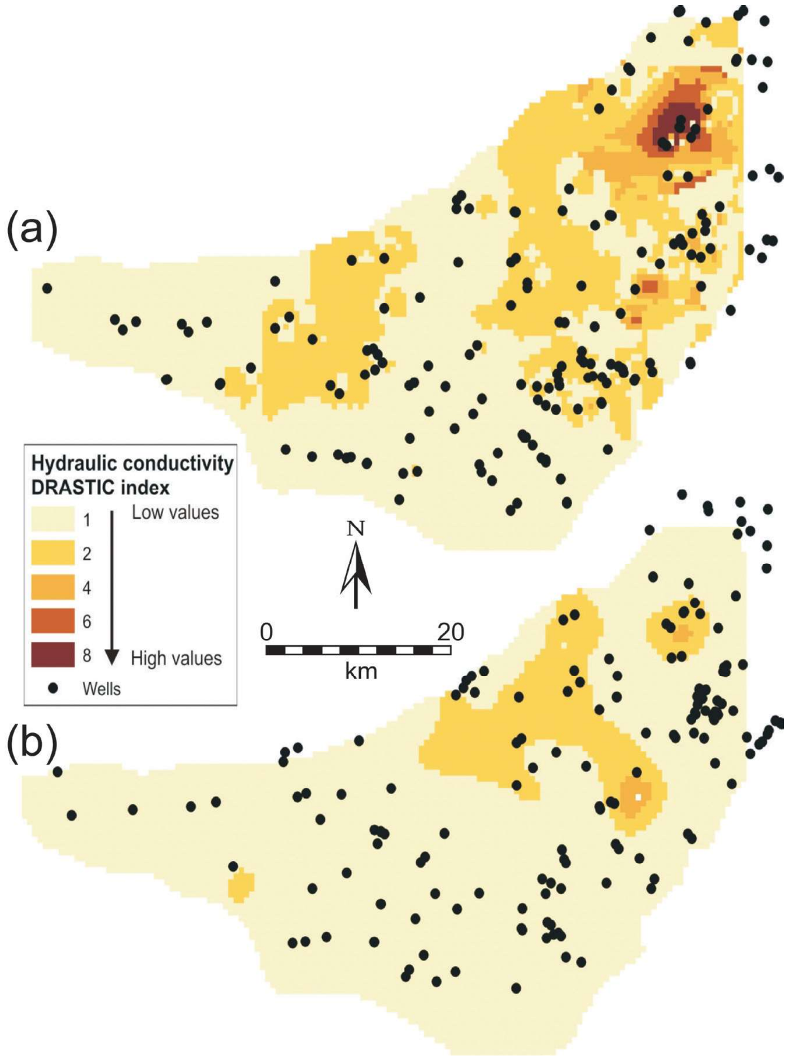


Figure 3.17 Illustration showing the distribution of hydraulic conductivity based on measurement points before (a) and after (b) correction of errors (adapted from Murat et al., 2004).

manipulation are seldom estimated, but they must be considered in order to provide a more realistic picture to users of regional characterization estimates. Hydrogeological mapping procedures contain the potential for five main sources of errors (Murat et al., 2004): in relation to conceptualization, measurement, storage media, data processing and data transformation.

Conceptual mistakes arise from differences between the reality and the reference model. For example, the groundwater flow direction in a heterogeneous aquifer (the reality) may be different than in a homogeneous aquifer (the reference model). Measurement errors, the main mistake source, are often related to instrument accuracy and calibration as well as the measurement method and individual taking the measurement. Well water level, for example, can be measured using a variety of methods ranging from probes to electronic pressure transducers. Each method has its own different accuracy level. The reference point for measurement can also often lead to error (e.g., well casing top vs. ground surface). Storage media errors relate to the media degradation for information storage and distribution. In one such case, the contact between two geological formations shown on an altered aerial photograph was not exact. Data processing error refers to mistakes in data handling, modification and transformation. Handling refers to the adaptation or movement of data from one computer system (or software) to another. Modification underlines the fact that changing a reference system or applying translation or rotation can modify database content without creating new knowledge. In fact, this can often be an important source of error, one that refers to the issue of "units". Water well record databases cover decades of data and it is not uncommon for drillers to use feet and gallons per minute (IGPM or USGPM), which measurements must then be converted to the international metric system. Data transformation error results when new knowledge

TABLE 3.4 EXPECTED MAIN PRODUCTS OF REGIONAL AQUIFER SYSTEM ASSESSMENTS

ASSESSMENTS	
COMPILED PRODUCTS	**DERIVED PRODUCTS**
NUMERICAL DATABASE	**3D REPRESENTATIONS**
	Geological model
2D REPRESENTATIONS (THEMATIC MAPS)	Hydrostratigraphic conceptual model
Geology of rock units	Hydrogeological conceptual model
Geology of Quaternary and recent sediments	**GRAPHS & MAPS PRODUCED BY 3D NUMERICAL MODELLING**
Depth to rock surface	
Quaternary sediment thickness	Compilation of hydraulic properties
Hydrogeological contexts	Estimation of errors
Hydraulic heads	Groundwater flow and transport
Hydrogeochemistry (e.g., water types)	Predicted groundwater behaviour (quality & quantity)
Hydraulic conductivity	
Land Use and Land Cover (LULC)	
Leaf Area Index (LAI)	**SCIENTIFIC REPORTS INCLUDING RECOMMENDATIONS ON SUSTAINABLE DEVELOPMENT OF GROUNDWATER**
Vulnerability	
2D REPRESENTATIONS (CROSS SECTIONS)	
Relationships between rock and Quaternary sediments Hydrostratigraphy	

is created by calculation (e.g., calculation and/or interpolation of hydraulic conductivity).

Errors can be randomly or systematically distributed over the data set, spatially (e.g., position), descriptively (e.g., soil texture) or temporally (e.g., date of collection). When using quantitative data, errors can be estimated through mathematical models, either analytically, stochastically or geostatistically. The analytical model estimates the contribution of each input parameter in single simulations.

Errors in the calculation of a well head protection area (WHPA), for example, can be estimated by assuming physically reasonable values of hydraulic conductivity and effective porosity that differ from the measured values (Figure 3.15) but still within the range of the data uncertainty. In this case, an uncertainty zone can then be determined and considered when dealing with groundwater protection at the local scale (see also Paradis et al., 2007). The difference between measured and simulated hydraulic heads with a numerical model may be illustrated and it is used to change inputs parameters in order to calibrate the groundwater flow model (Figure 3.16).

Stochastic modelling estimates result from a random sample of input parameter with a known distribution function (e.g., Monte Carlo can use thousands of simulations from which uncertainties can be estimated; Coburn et al., 2007). Geostatistical models are used to identify input errors that can be illustrated using the nugget effect on a graph; a pure nugget effect model gives equal weight to all points and hence less to the central sample and more to the peripheral ones (structured models attribute a relatively high weight to the central sample; Armstrong, 1998).

Many methods of groundwater recharge estimation have been developed because recharge is a key, albeit difficult to evaluate component of the water budget. For that reason, the variability of recharge values obtained through different evaluation methods is often very high (up to one order of magnitude). The main causes for variability relate to (1) scales of methods applied, ranging from point-source to regional scale; (2) heterogeneity and spatial distribution of geological units, their topography and geomorphology; and (3) the need to use other variables like runoff and evapotranspiration also estimated with high uncertainties (López-Urrea et al., 2006).

It is true that uncertainties associated with recharge estimation can be reduced by using a combination of several direct and indirect approaches (Scanlon et al., 2002) and by calculating a mean value (see also Chapter 4).

Scientists studying the southwestern Quebec aquifer system, quantified and illustrated the uncertainty associated with hydraulic conductivity (K) estimates as a layer of information (Murat et al., 2004). A map of hydraulic conductivity drawn from a combination of existing data and field measurements, without taking into account uncertainties (Figure 3.17a), is very different than a map of hydraulic conductivity for the same area with corrections made for uncertainties (Figure 3.17b). The corrected map of hydraulic conductivities takes into account errors due to a number of factors: (1) modifications of the initial data set due to eliminating defective values like non-indicated pumping duration; (2) well diameter too small; (3) insufficient pumping rate or short duration of the aquifer tests; (4) transformations of data such as calculation of K by applying different equations for slug, packer or pumping tests; and (5) data interpolation (Murat et al., 2004).

Looking into the future, it should be noted that potential technical problem may be generated by the rapid evolution of software used to manage numerical databases. Recently we have seen that rapid technological changes can make a-few-years-old data files out-of-date, particularly when the software that operates them becomes obsolete. Other emerging issues exist regarding climate change and its impact on future national resources. These problems will increase if an improved Canadian assessment of aquifer systems does not exist. It is important to note that forecasting future groundwater availability constitutes a real challenge, one that can be eased with comprehensive initial modeling of local climatic conditions.

Final products of regional assessments accompanied by estimated uncertainties provide a realistic picture of how decision makers and other potential users should use hydrogeological results. Values of such results cannot be employed in absolute terms but they should be regarded as broad indications and used with caution.

3.8 EXPECTED OUTPUTS AND SUMMARY

Every step in regional assessment of groundwater systems is a building block leading to an integrated understanding of large aquifers or multi-aquifer systems (Table 3.4). Data collection, the structuring of that data into a database, and the field work—gathering geological and hydrogeological information, basin analysis and 3D mapping, coupled with the numerical modelling and estimation of knowledge uncertainty—should be carried out with great care. The interactive multidisciplinary team responsible for the assessment of groundwater in any given region must deliver both compiled and derived hydrogeological products (Table 3.4). The series of maps and cross sections for a given region should be organized into a hydrogeological atlas (Rivard et al., 2007) to provide a useful integrated product, which allows for easy dissemination of information to a variety of interested groups. Transfer of data to potential users can also be facilitated directly through transmission of the complete numerical database, although only advanced users can have editorial access to perform specific queries and upgrades.

The final assessment must quantify errors in the estimation of parameters, and in the assumptions and constraints used for modelling. Currently several examples of integrated derived products exist, presented as maps and atlas components, or as graphs and maps in specific thematic reports (e.g., Savard and Somers, 2007; Savard, 2013).

The integrated approach to groundwater assessment presented in this chapter is a synthesis of current knowledge on how researchers conduct a comprehensive regional hydrogeological characterization. Issues still remain, however, relative to

- the up-scaling of the aquifer properties measured at local scales
- the simulation of extremely complex processes such as groundwater recharge or mass transport at regional scales
- the estimation of current groundwater availability
- the estimation of aquifer sustainability
- the post-project updates of generated databases
- the use of regional groundwater flow models for management purposes
- the forecasting of future groundwater use and impacts of climate change

We would like to underline the importance of coordinated efforts among interested agencies and stakeholders for the production of a comprehensive assessment of Canadian groundwater resources, in addition to the urgency of quantifying the current availability of Canadian groundwater. Other countries have recognized groundwater availability and sustainability as a priority issue, and have acted upon that recognition in order to accelerate the processes for producing national inventories (e.g., U.S. Geological Survey, 2002). Canada has begun the preliminary course of making a similar step towards speeding up this country's groundwater inventory program (e.g., Senate Canada, 2005), but we need more!

The sustainability of drinking groundwater in Canada depends on timely decisions by managers and policy makers, as well as on efficient and rigorous scientific regional assessments.

CANADA'S
GROUNDWATER
RESOURCES

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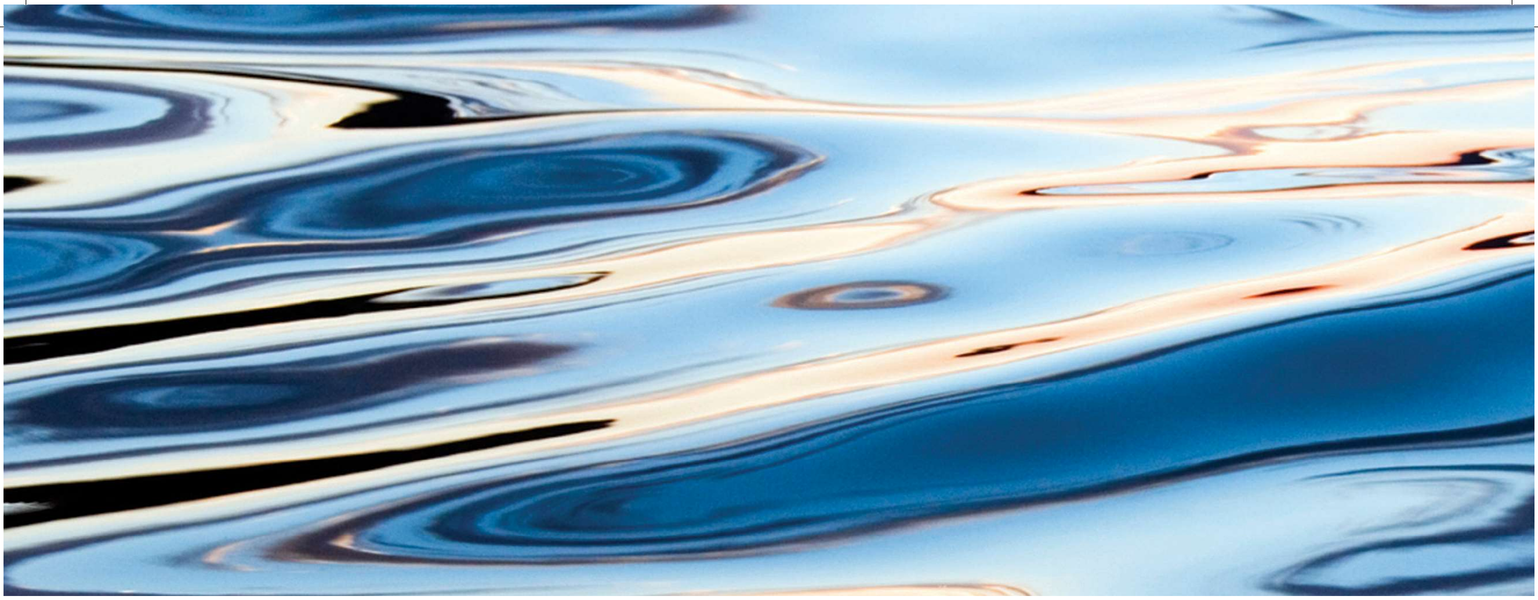

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