Nested groundwater flow systems in Wood Buffalo National Park, Alberta-Northwest Territories, Canada

by

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Abstract

Water chemistry, numerical simulation and groundwater-related surface phenomena were combined into one integrated model to confirm the different scales and segments of flow systems in Wood Buffalo National Park (WBNP).

Total Dissolved Solid (TDS) concentrations in surface waters and springs in WBNP range from less than 1,000 mg/L to more than 300,000 mg/L. Hydrochemical facies of the waters form four distinct groups: 1) sodium- and chloride -dominated waters, 2) “mixed”-type of waters, 3) calcium- and sulphate-dominated waters, and 4) calcium- and bicarbonate-dominated waters. The origin of waters in WBNP is meteoric water rather than formation fluids of the Alberta Basin. The geochemical character of waters resulted from three main rock-water interactions: dissolution of halite, dissolution of sulphate minerals (gypsum, anhydrite), and dissolution of carbonates. The water chemical characteristics reflect different scales and segments of flow systems in the study area.

The flow regime in WBNP exhibits hierarchically nested regional, intermediate and local scale flow systems. Simulation results demonstrate that the Caribou Mountains create an isolated flow regime in the park which prevents formation fluids from basin-scale flow systems entering the WBNP region. The decreasing thickness of the basin and the topographic elevations of the Caribou Mountains induce a regional-scale flow system in the deep part of the domain that limits deep, basin-scale fluid-flow.

Surface-related phenomena related to groundwater discharge include water chemical characteristics, as well as presence of wetlands, springs, saline soils,

phreatophyte/halophyte vegetation, karstic features and geothermal anomalies. These phenomena indicate discharge from different scales of groundwater flow systems.

Wetlands, fresh water springs and phreatophyte vegetation indicate groundwater discharge of short flow systems near the Caribou Mountains and in the Salt Plains. Wetlands accompanied by springs with elevated TDS and Ca-SO_4-type water, hypogene karstification and thermal anomalies signify ascent of groundwaters from intermediate-scale flow systems in the central lowlands. Saline/brine springs, salt crusts, phreatophyte/halophyte vegetation and positive thermal anomalies indicate ascending regional groundwater flow in the Salt Plains area.

The results and interpretations presented here advance the knowledge on the hydrogeological processes and interactions of groundwaters and surface waters in WBNP. This improved knowledge of hydrogeological conditions provides can be used for management decisions to protect the unique ecological values of WBNP.

Preface

A version of Chapter 2, 3 and 4 of this thesis will be submitted for publication co-authored by B.J. Rostron and C. Mendoza. The structure and format of these chapters follow that of a paper manuscript ready to be submitted for publication. I was responsible for the data collection and analyses as well as the composition of the manuscripts. B.J. Rostron and C. Mendoza were supervisory authors and were involved with concept formation and manuscript edits.

“Tamdiu discendum est, quemadmodum vivas, quamdiu vivas“

– As long as you live, keep learning to live

(Lucius Annaeus Seneca)

Dedication

To my husband without whom I would not be the person who I am today. This triumph is just as yours as it is mine. Thank you for everything.

Ajánlás

Férjemnek, aki nélkül nem lennék az, aki ma vagyok. Ez a győzelem legalább annyira a Tiéd, mint amennyire az enyém. Köszönök mindent!

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Köszönetnyílvánítás

Köszönettel tartozom magyarországi barátaimnak, akik támogattak és mindvégig hittek bennem. Külön köszönet Babikámnak, aki a legnehezebb helyzetekben is segített meglátni a jót.

Örökké hálás leszek szüleimnek, akik a taníttatásomat mindenek fölé helyezték, és megtanítottak a tanulás szeretetére. Nélkülük nem lennék ott, ahol ma vagyok.

Végül, de nem utolsósorban, köszönöm a férjemnek, hogy mindig és mindenben támogatott, amiben az emberileg lehetséges volt, és aki kitartott mellettem jóban, rosszban. Köszönök mindent.

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Chapter 1 Introduction

1.1. Rationale

Wood Buffalo National Park (WBNP), located in Alberta and Northwest Territories, is Canada's largest national park, with an area of 44,807 km^2. It includes boreal forests, extensive wetlands and prairie, and exhibits outstanding examples of karstic landforms, saline springs and salt plains, and unique ecosystems. The area represents outstanding ecological and biological values, and as such, it became a designated UNESCO World Heritage site (UNESCO World Heritage Committee 1983). It sustains one of the world's largest free-roaming and self-regulating bison herds. It is the last remaining natural nesting area of the highly endangered whooping cranes (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). The park also contains one of the world's largest inland deltas, the Peace-Athabasca Delta (PAD). The PAD region and the northern wetlands of the whooping cranes' nesting area were declared as Wetlands of International Importance under the Ramsar Convention in 1982 (Ramsar List 2018). Further significant characteristics of the area that gained international recognition are its gypsum karst landforms that represent some of the finest examples of such features in North America, its unique salt plains and vast areas of boreal plains unaffected by human activities.

Despite its protected status and multiple international recognitions, WBNP faces several challenges. As part of a high-latitude, wetland-dominated environment, WBNP, especially the wetlands of the Peace-Athabasca Delta, is extremely vulnerable to climate change that will have direct effect on the conservation values of the area (Beltaos et al 2006; Peters et al 2006; Prowse et al 2006; Toth et al 2006; Timoney 2009).

Several concerns have recently been raised about human activities endangering the park's world heritage values: 1) upstream flow regulation on Peace River associated with the operations of W.A.C Bennett Dam and Peace Canyon Dam; 2) potential effects of planned Site C Hydroelectric Dam project; 3) impacts of planned and existing oil sands developments in the Athabasca Oil Sands Region (AOS) (WHC-IUCN, 2017).

The PAD is a highly productive and hydrologically driven wetland system where the perched basins and the water-dependent ecosystems are sustained by ice jams and seasonal flooding (Prowse and Conly 2000; Prowse et al 2006). Flow regulations by hydroelectric dams may affect the timing and magnitude of flow on Piece River and reduce recharge and hydration of the basins in the PAD impacting its biodiversity and productivity.

The rapid growth of oil sand-related projects in the AOS-region brought the mining activities in close proximity of the southern boundary of WBNP. Some of the main concerns regarding the potential effects of oil sands development on WBNP are atmospheric deposition of contaminants in the PAD, transport of water-borne contaminant such as mercury, or incorporation of contaminants into the food-web (WHC-IUCN, 2017).

Due to raising concerns over the effects of human activities on the ecological values of WBNP, there is a pressing need for better understanding of ecological, hydrological and hydrogeological processes in the area. Understanding the governing subsurface processes, hydraulic connections and relationship between groundwater and surface water is a vital factor in a successful strategy to protect ecological values such as the nesting area of the whooping cranes, the water-dependent ecosystems of the PAD, or the unique ecosystems of the Salt Plains.

Despite the outstanding ecological importance and global recognition of WBNP there is currently no regional hydrogeological compilation available of WBNP, and it remains one of the few areas in Alberta that was not mapped by the Alberta Research Council (ARC) in their hydrogelogical mapping program (Lemay and Guha 2009) (Figure 1.1). This gap is partly due to the protected status of the area, i.e. lack of detailed subsurface geological information and hydraulic data, and partly due to its remote nature that makes the access to most of the area extremely difficult and expensive.

Foresaid factors, such as the outstanding and globally-recognized ecological importance of the area, already existing and anticipated effects of human activities on the area's natural habitats, as well as the lack of available hydrogeological information, created interest in a regional hydrogeological characterization in WBNP.

1.2. Wood Buffalo National Park: an overview

1.2.1. *Geography*

The study area is located in northeastern Alberta and southern Northwest Territories (Figure 1.2). The landscape of the area is characterized by boreal uplands of the Caribou Mountains in the east and the Birch Mountains in the south, and by lowlands of the boreal plains (Figure 1.2). Much of the area within the national park's boundary is part of the boreal lowlands with flat or slightly rolling terrains that gradually decrease in elevation northeastward (Natural Regions Committee 2006). The plateau of the Caribou Mountains rises above the lowlands by 700 m and exhibit rolling to gently rolling terrains and occasionally large depressions.

The climate of the study area is characterized by long, cold winters and relatively short, cool-to-warm summers. The majority of the annual precipitation (62-70%) falls during the growing season (April to August), and ranges from 375 to 512 mm in the driest and most humid regions of the area, respectively (Natural Regions Committee 2006). The climate favours accumulation of organic material. More than 75% of the area is covered by peatlands with more than 40 cm peat accumulation (Turchenek and Pigot 1988). The peat plateaus are often covered by wetlands with fens and bogs. Low temperatures and the insulating effect of peat layers contribute to sporadic, discontinuous permafrost formation with less than 10% ice content in the upper 10-20 m of the ground (Heginbottom et al 1995).

Significant portions of the area are covered by wetlands. Two of the wetlands regions, i.e., the Peace-Athabasca Delta (PAD) in south and the whooping cranes' nesting area in northeast, are declared Wetlands of International Importance under the Ramsar Convention due to their outstanding ecological value (Ramsar List 2018) (Figure 1.3).

Karstification and related landforms are widely-known features in WBNP (Soper 1939; Drake 1970; Ford 1997). Its gypsum karst landforms are one of the finest examples of covered evaporite karst in Canada (Ford 1997). Northeastern WBNP was previously described as "a land of underground streams" referring to their relation to sinkholes and connection to underground cavities (Soper 1941). Drake (1970) estimated the number of sinkholes to be in the order of thousands. Both solution and collapse sinks are present in the area (Drake 1970; Tsui 1982; Ford 1997). The first type of sinks is attributed to dissolution of exposed evaporites on the surface by infiltrating precipitation, while the second one is associated with dissolution of evaporites in the subsurface that leads to formation of cavities/caves and collapse of the weakened top layers resulting in depressions on the land surface (White 1988; Ford and Williams 2007).

The Salt Plains region exhibits several of the most outstanding features in WBNP, such as salt flats, brine springs and thick salt deposits (Figure 1.2). The salt flats are separated from the upland region by a steep escarpment extending southwards from the Slave River. Brine springs discharge at the base of a steep escarpment and deposit tens of centimetres of salt.

1.2.2. *Geology*

WBNP is situated in the northeastern corner of the Alberta Basin. As part of the Western Canadian Sedimentary Basin, regional characterizations of the Phanerozoic strata were given by Meijer Drees (1994), Oldale and Munday (1994) and Switzer et al (1994), as well as Prior et al (2013). Stratigraphic nomenclature and generalized lithology are shown in Figure 1.4 and Figure 1.5.

The geology of the area is represented by four major geologic packages:

1) The igneous and metamorphic rocks of the southwesterly dipping, wedge-shaped Precambrian basement is overlain by conformably deposited Phanerozoic sediments with a thickness ranging from 1,700 m in the west to 0 m in the east along the outcrop of the Canadian Shield.

2) Devonian strata directly overlie the Precambrian basement and represent the most important bedrock sediments in WBNP. They are composed of carbonates, evaporites and shales. They contain two regional aquifers, the Keg River (Winnipegosis) and Slave Point formations.

3) Cretaceous deposits are limited to the Caribou Mountains and Birch Mountains, as well as to an approximately 2,500 km^2 tongue-shaped remnant in the central region. Due to extensive pre-Cretaceous erosion, Devonian strata are unconformably overlain by the sandstone of the McMurray and Bluesky formations that represent a local aquifer in the area. The Devonian-Cretaceous unconformity zone is overlain by thick shales, sandstones and siltstones of Lower and Upper Cretaceous age.

4) The unconsolidated sediments of Quaternary age are composed of unconsolidated non-glacial (eolian, fluvial and lacustrine sediments) and glacial deposits (glaciolacustrine and moraine sediments), and directly overlie Mesozoic sediments (Mougeot and Fenton 2010; Lemmen 1998a,b; Bayrock 1972a,b,c) (Figure 1.6). The thickness of the unconsolidated materials overlying the bedrock varies between less than 1 m and 45 m in the plains but locally reaches more than 50 m in the Caribou Mountains and Birch Mountains (Pawlowicz and Fenton 1995; Fenton et al 2013). Organic material is present in a large portion of the area and often underlain by fine-grained lacustrine or glaciolacustrine deposits, or in some places by till.

1.3. Hydrogeology of the northern Alberta Basin

Regional hydrogeological characterization of WBNP has not been published so far. Its hydrostratigraphy and hydrodynamics can be described as part of the northern Alberta Basin based on studies by Hitchon (1969, 1984), Tóth (1978), Garven (1985, 1989), Bachu and Underschultz (1993) and Bachu (1997). A local study was carried out in the Caribou Mountains region by Ozoray (1980).

1.3.1. *Hydrostratigraphy*

The generalized hydrostratigraphy of WBNP can be characterized by three major aquifer systems: Middle Devonian, a Middle-Upper Devonian and a Lower Cretaceous aquifer system (Figure 1.4).

Middle Devonian aquifer system

The deepest Middle Devonian aquifer consists of the Keg River (Winnipegosis) and – when present - the Contact Rapid formations (Figure 1.4, Figure 1.5). Hydraulic head decreases from 500 m asl at the Rocky Mountains Fold Belt to around 250 m asl at the northeastern edge of the basin (Bachu 1997). Salinity of formation waters in this aquifer ranges from 50,000 mg/L to 250,000 mg/L in northern Alberta with the lowest salinities observed in the northeast due to direct inflow and mixing with fresh meteoric water in the outcrop area (Bachu 1997).

Middle-Upper Devonian aquifer

The second regional aquifer is the Beaverhill Lake Aquifer and consists of the Slave Point Formation (Bachu 1997) (Figure 1.4, Figure 1.5). The overall flow direction is from southwest to northeast, however high hydraulic heads under the Caribou Mountains indicate the influence of major topographic features on the basin-scale flow character of the formation (Bachu 1997). The salinity of the formation water ranges from less than 50,000 mg/L to 150,000 mg/L in northern Alberta and less than 50,000 mg/L in the northeast (Bachu 1997).

Lower Cretaceous aquifer system

The third aquifer consists of the McMurray and Bluesky formations and is locally restricted to the Caribou Mountains region and central portion of WBNP (Figure 1.4, Figure 1.5). It is situated directly above the sub-Cretaceous unconformity zone. The hydraulic head distribution in this aquifer is controlled by "local" topographic features in northeastern Alberta Basin, i.e., the Caribou Mountains, where the aquifer is characterized by high hydraulic head values associated with groundwater recharge (Bachu and Underschultz 1993). The salinity of these formation waters is less than 10,000 mg/L (Bachu and Underschultz 1993).

1.3.2. *Hydrodynamics in the Alberta Basin*

Groundwater in this topography-driven, basin-scale flow system is thought to recharge at the fold belt at the Rocky Mountains and at the Bovie Lake Fault and discharge at the major lowlands in the northeastern corner of the Alberta Basin (Hitchon 1969, 1984; Bachu 1997). For this thesis, "basin-scale" flow system refers to that component of the flow regime. Major topographic features, such as large uplands, however, can modify the basin-scale flow pattern by breaking up the flow systems and changing the flow regime into a more regional-intermediate-scale flow domain (Hitchon 1969; Bachu 1997). In places of high salinities, topography-driven groundwater flow is modified by the driving force of high-density fluids by enhancing or retarding the flow intensity (Hitchon 1969; Bachu and Underschultz 1993; Bachu 1997).

Tóth (1978) and Hitchon et al (1990) identified three major hydrodynamic zones in central-northern Alberta (Red Earth region, Peace River Arch): a deep Paleozoic zone characterized by flow systems in a transient state that are still adjusting to present-day topography, a Paleozoic-Mesozoic zone under steady-state conditions characterized by intermediate-regional-scale flow systems; and a Mesozoic-Cenozoic zone in equilibrium with present-day topography with local-scale flow systems. Similar conclusions were made by Bachu and Underschultz (1993) who divided the Northeastern Alberta Basin into a regional, an intermediate and a local flow regime. Aquifers below the Prairie Evaporite (Muskeg) Formation (e.g. Keg River Aquifer) show regional flow-regime characteristics with a northeastward flow direction. Paleozoic aquifers above the Prairie Evaporite (e.g. Slave Point Aquifer) exhibit intermediate-scale flow characteristics with an up-dip flow to the northeast; and Cretaceous aquifers (e.g. McMurray-Bluesky Aquifer) show local flow-regime characteristics (Bachu and Underschultz, 1993). Ozoray (1980) identified the same hydrodynamic zones in the Caribou Mountains and vicinity (59°N-60°N and 114°W-118°W) and concluded that only the upper hydrodynamic zone (drift and Cretaceous formations) discharges groundwater to the surface. The groundwater has low TDS contents and dominantly Ca-HCO_3-type facies.

1.4. Theoretical background - Regional groundwater flow and nested flow systems

1.4.1. *Definitions*

Gravity-driven groundwater flow is governed by elevation differences in the water table and may result in hierarchically superimposed flow systems of different orders, i.e. local, intermediate and regional flow systems (Tóth 1963). The pattern of gravity-driven flow is controlled by the relief of the water table and modified by heterogeneities of the rock framework, i.e. geometry and geology of the medium (Tóth 1963; Freeze and Witherspoon 1967). Local flow systems recharge at topographic highs and discharge at topographic lows that are immediately adjacent to the recharge area (Tóth 1963). An intermediate flow system recharges at a topographic high and discharges at a topographic low that is not immediately adjacent to the recharge area, and may encompass one or more local-scale flow systems. A regional flow system recharges at the regional groundwater divide and discharges at the lowest topographic elevation of the basin (Tóth 1963). Segments of groundwater flow systems are characterized by three distinctly different flow regimes: the recharge, midline and discharge, with distinct physical, chemical and hydrokinetic conditions. Many processes and surface phenomena are associated with the different orders and segments of groundwater flow systems and can be considered manifestations of gravity-driven groundwater flow (Tóth 1999). These phenomena include hydrologic and hydraulic, chemical and mineralogical, vegetal, soil and rock mechanical, geomorphologic, as well as transport and accumulation phenomena.

1.4.2. *Examples of nested flow systems*

There are many examples of regional-scale hydrogeological studies that focus on gravity-driven groundwater flow and nested flow systems and their applicability in groundwater management. A few examples of the sedimentary basins characterized by nested flow systems are the Great Basin (U.S), the Great Artesian Basin (Australia), the Ordos Basin (China), and the Pannonian Basin (Hungary).

Great Artesian Basin, Australia

The Great Artesian Basin (GAB) is Australia's largest groundwater basin where groundwater resources are used to support agricultural and industrial sectors as well as to support domestic water use. Increasing groundwater use contributed to extended inland soil salinization that is one of the main groundwater issues in the region. To better manage salinity a Groundwater Flow Systems (GFS) Framework was developed (Coram 1998; Walker et al 2003). The framework uses topographic, geologic and geomorphologic features to identify areas of local, intermediate and regional scale flow systems that helps to determine where salinity risk is the greatest and where management activities are needed (Walker et al 2003).

Great Basin, U.S.

As part of the Great Basin Regional Aquifer Analysis project in the U.S., several conceptual and numerical regional groundwater flow models were developed to study aquifer systems in the Great Basin (NV, UT, CA, ID, AZ, OR) to gain a better understanding and provide more accurate quantitative estimations for the water supplies (Brooks et al 2014; Heilweil and Brooks 2011; Prudic et al 1995). The underground nuclear test site in Nevada (NTS) and nuclear waste repository at Yucca Mountain also initiated numerous regional groundwater modeling studies to understand flow paths and travel times, as well as to characterize groundwater flow systems in the region (Belcher et al 2004; Bredehoeft et al 2005; D'Agnese et al 2002).

Ordos Basin, China

The Ordos Basin represents one of the most important areas for China's natural resources, such as coal, petroleum and natural gas. The increasing industrial need for water has driven several regional-scale hydrogeological studies to characterize the flow regime, groundwater flow system circulation and recharge in the area (Hou et al 2008; Yin et al 2010, 2011). Groundwater flow systems of different scales were identified using hydrochemical indicators and numerous surface features related to regional groundwater flow (Jing et al 2018; Wang et al 2015).

Buda Thermal Karst, Pannonian Basin, Hungary

The Buda Thermal Karst System in Hungary represents the discharge area of Europe's largest naturally flowing thermal water system. The hierarchically nested local and regional flow systems manifest in several discharge phenomena, such as adjacent springs with highly distinct chemical compositions and temperatures, caves, mineral precipitates (e.g. Alföldi 1982, Erőss et al 2008, Erőss et al 2012, Déri-Takács 2015, Mádl-Szőnyi and Tóth 2015, Erhardt et al 2017).

1.5. Objectives of the thesis

The overall objective of this thesis is to advance understanding of regional- intermediate- and local-flow systems within WBNP by integrating hydrogeochemical characteristics of surface waters and springs, modelling the groundwater flow numerically, and analyzing of groundwater-related surface phenomena. The general working hypothesis of the project is that groundwater in the park is dominantly controlled by elevation differences of the water table, and that hydrochemical characteristics of springs and surface waters, as well as the observed surface phenomena reflect the different scales and segments of groundwater flow systems.

The study is composed of three main components: geochemical characterization of waters (Chapter 2), numerical simulation of conceptual models of groundwater flow in WBNP (Chapter 3), and identification and interpretation of groundwater-related surface phenomena (Chapter 4) (Figure 1.7). The final result of the research is an integrated conceptual model that combines results of the three separate components and elucidates the nested nature of groundwater flow systems in the park.

1.5.1. *Chapter 2 - Geochemistry of groundwaters and surface waters of Wood Buffalo National Park, Canada*

The objective of Chapter 2 is to provide a geochemical characterization of groundwaters and surface waters in Wood Buffalo National Park (WBNP), using total dissolved solids (TDS) and hydrochemical facies. Rock-water interactions and their effects on the geochemical character of waters are evaluated to examine possible sources of solutes. Possible connection of the groundwaters in WBNP with deep Devonian formation waters in the Alberta Basin is also analyzed and results are used to elucidate the origin of salt in brine waters discharging at the Salt Plains.

The geochemical characteristics of waters in WBNP reflect the three hydrogeological zones of the area, i.e., regional recharge in the Caribou Mountains; local flow paths in the central plains; and local recharge and discharge, as well as regional and intermediate discharge along the eastern edge of the basin in the Salt Plains region. Groundwaters and surface waters in WBNP show significant variability in total dissolved solids concentrations ranging from less than 1000 mg/L to more than 300,000 mg/L. Hydrochemical facies of the waters form four distinct groups: 1) sodium- and chloride -dominated waters, 2) “mixed”-type of waters, 3) calcium- and sulphate-dominated waters, and 4) calcium- and bicarbonate-dominated waters. The origin of water is meteoric. Solutes in the waters are from three main rock-water interactions: 1) dissolution of halite; 2) dissolution of sulphate minerals; and 3) dissolution of carbonates. The solute sources are

Devonian evaporites, halite and carbonates that represent most of the bedrock sediments in the area.

1.5.2. *Chapter 3 - Numerical simulation of the isolating effect of the Caribou Mountains on flow systems in Wood Buffalo National Park, Alberta, Canada*

Chapter 3 analyzes how a major topographic feature, specifically the Caribou Mountains, affects the flow pattern of formation fluids in the northern Alberta Basin. The impact of the Caribou Mountains on the flow domain of the WBNP is examined through numerical simulation of two conceptual models of groundwater flow in the area. The study demonstrated that the Caribou Mountains blocks the flow of basinal fluids from the west, and that the flow regime in central WBNP remains isolated from the rest of the Alberta Basin. The results support the findings of Chapter 2, i.e., brine springs discharging in the Salt Plains region are not related to deep formation waters of the Alberta Basin but rather originate from modern meteoric water.

1.5.3. *Chapter 4 - Geochemistry, surface phenomena and numerical simulations demonstrates effects of gravity-driven groundwater flow*

Chapter 4 synthesizes the results of previous chapters into one fully-integrated conceptual model by combining water chemistry, numerical simulation and groundwater-related surface phenomena. Results of numerical simulations (Chapter 3) are compared with the geochemical characteristics of waters (Chapter 2) to evaluate their diagnostic value in identifying different scales and segments of groundwater flow systems. Subsequently, groundwater-related surface phenomena, such as wetlands, springs, saline soils, phreatophyte/halophyte vegetation, karstic features and geothermal anomalies, are added to the model to further validate the flow patterns conceptualized earlier in the study area. The study demonstrated a good correlation between the salinity and hydrochemical facies of waters and the simulated flow systems. The presence of groundwater-diagnostic features, such as saline springs and soils, salt deposits, phreatophyte and halophyte vegetation and positive thermal anomalies are also consistent with the different scales and segments of the simulated flow systems.

1.6. Summary

This research used an integrated approach utilizing surface-based data to characterize the hydrogeological conditions of Wood Buffalo National Park, Canada's largest national park. The research was solely based on data accessible on the surface; i.e., chemical analyses of springs and surface waters, observations of surface phenomena. The combined application of geochemistry, numerical modelling and field-based and remote observation of surface features led to a regional-scale hydrogeological characterization of remote areas with limited access and data availability, such as WBNP.

The study contributes to a more detailed understanding in northeastern Alberta's hydrogeology and to expanding our knowledge on regional- intermediate- and local-flow systems within a basin setting.

The results and interpretations presented here advance the knowledge on the hydrogeological processes and interactions of groundwaters and surface waters in the area, and will lead to an improved understanding on ecological, hydrological and hydrogeological processes in WBNP. The study provides a basis for further studies in the area and helps to formulate a successful strategy to protect the unique ecological values of the area.

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Figure 1.1: Areas with mapped and unmapped hydrogeology in Alberta (modified after Lemay and Guha, 2009)

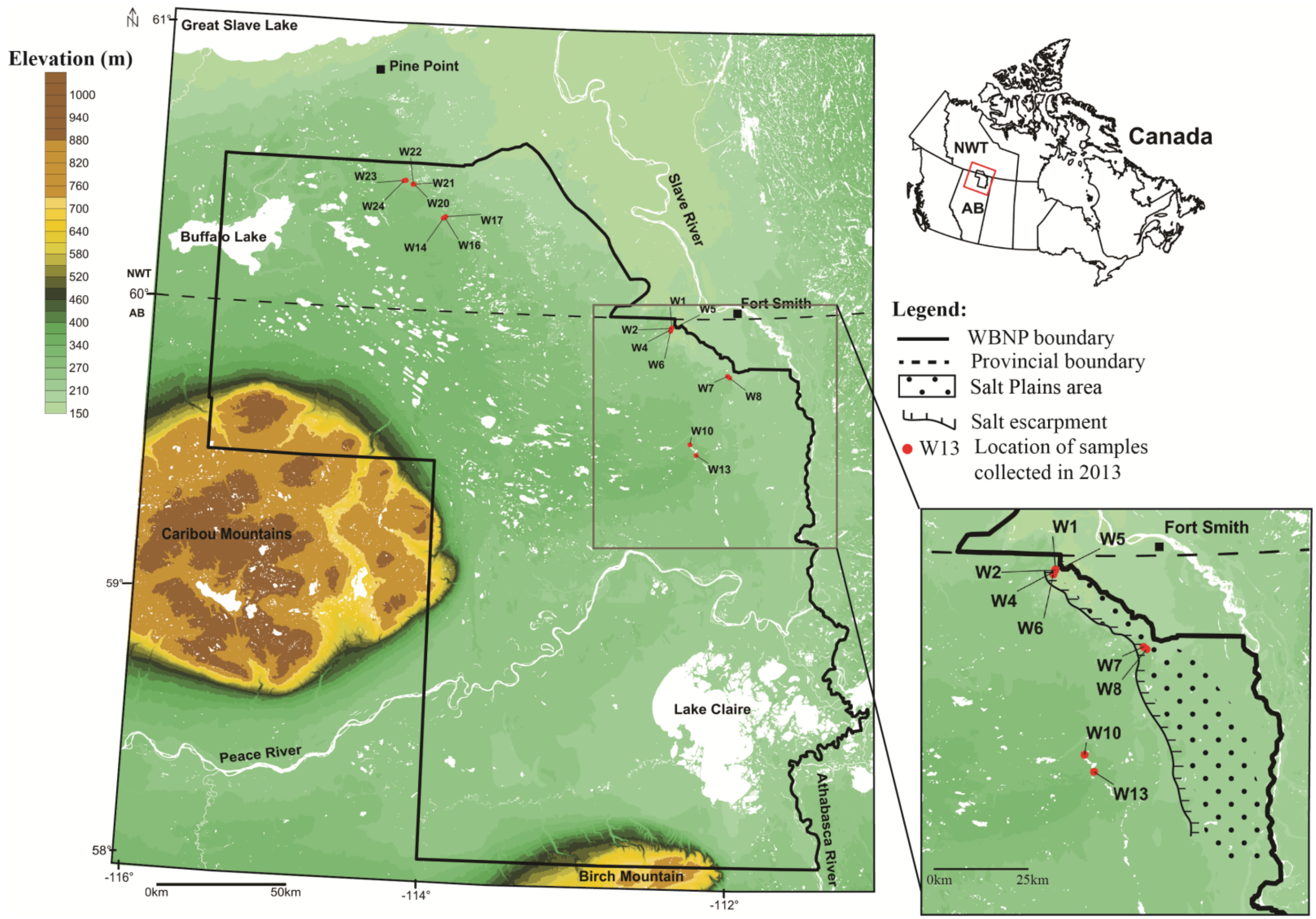

Figure 1.2: Topography of the Wood Buffalo National Park, Alberta-Northwest Territories, Canada and location of samples collected in 2013.

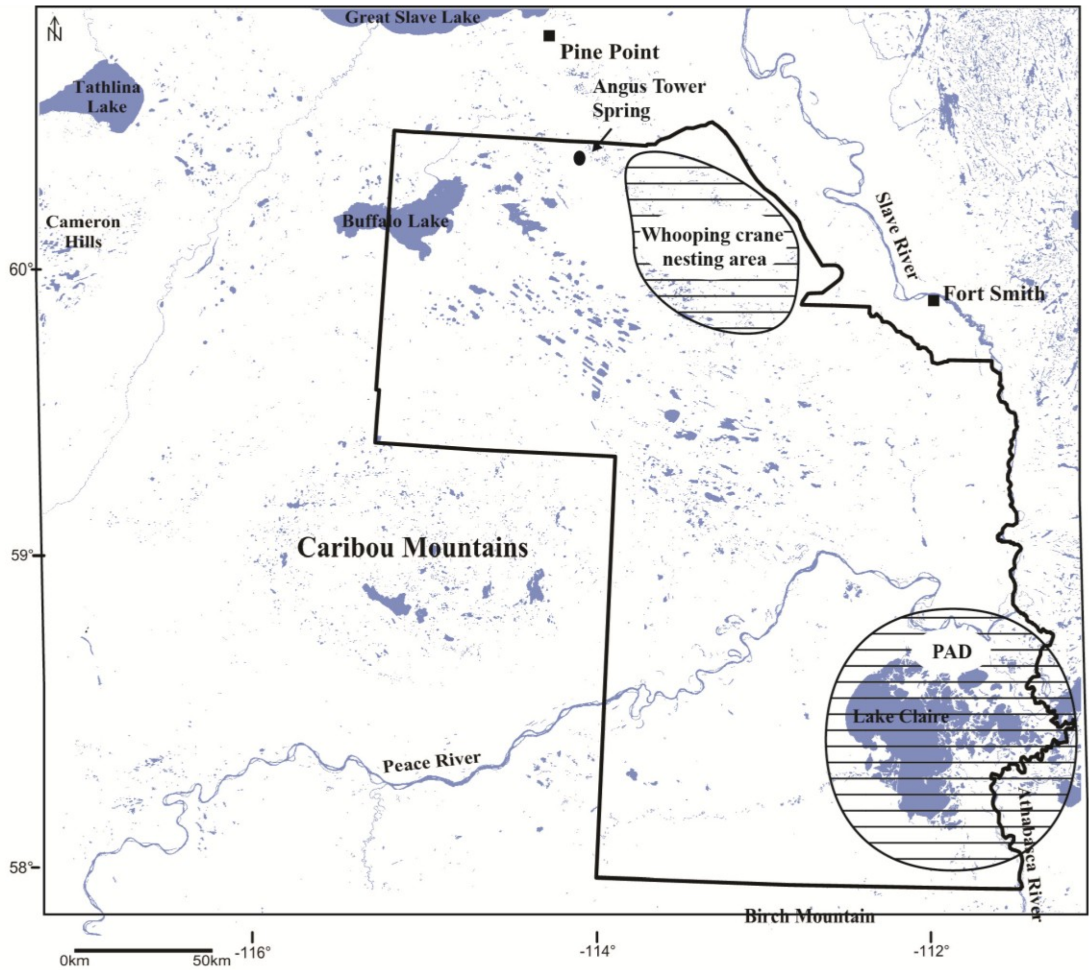

Figure 1.3: Location of the Peace-Athabasca Delta (PAD) and the whooping crane nesting area in Wood Buffalo National Park

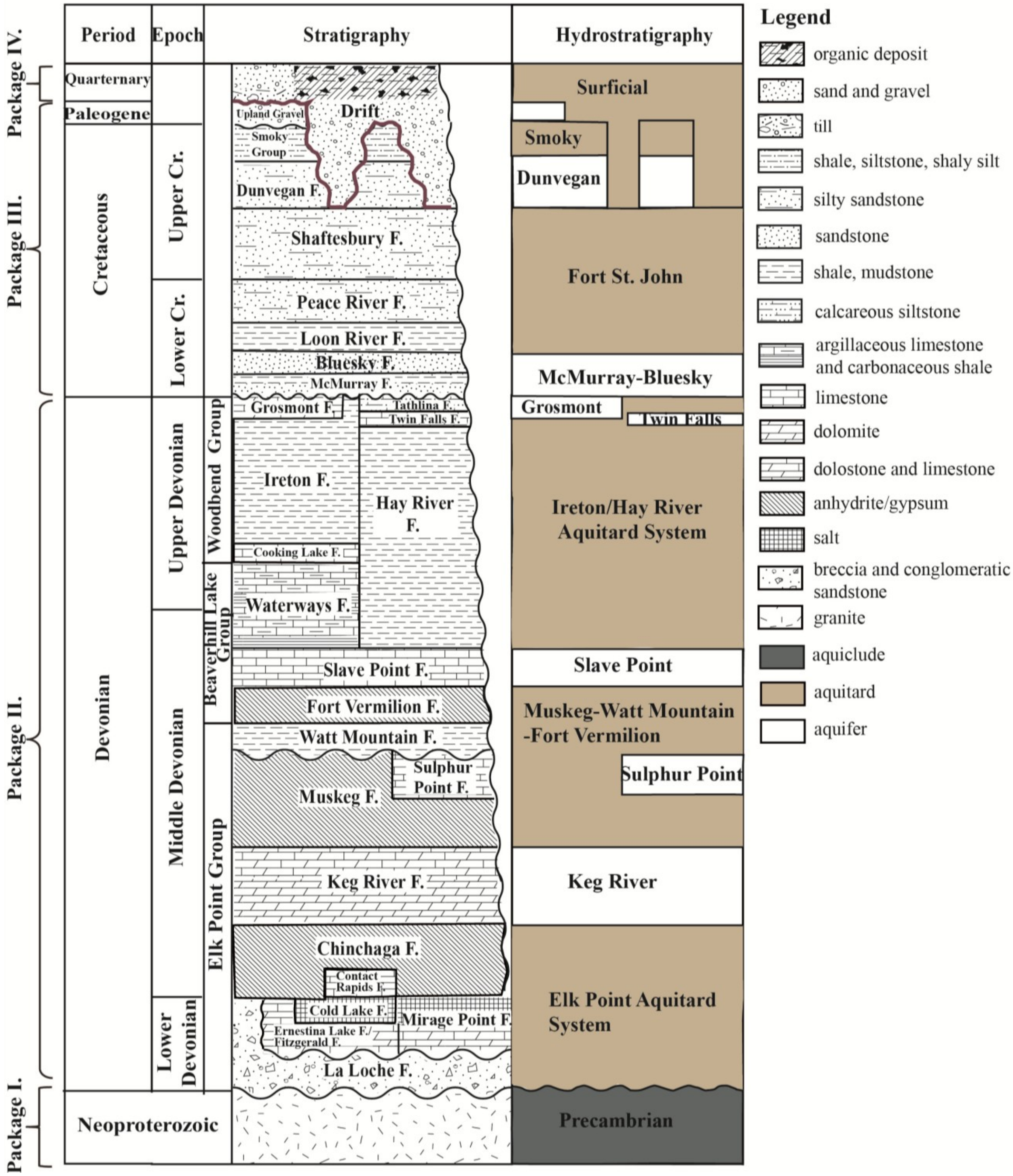

Figure 1.4: Generalized stratigraphy of Wood Buffalo National Park region (adapted from Norris, 1973; Meijer Drees, 1994; Oldale and Munday, 1994; Switzer et al, 1994; Prior et al, 2013; AER/AER, 2015) and hydrostratigraphy (modified after Bachu and Underschultz, 1993 and Bachu, 1997)

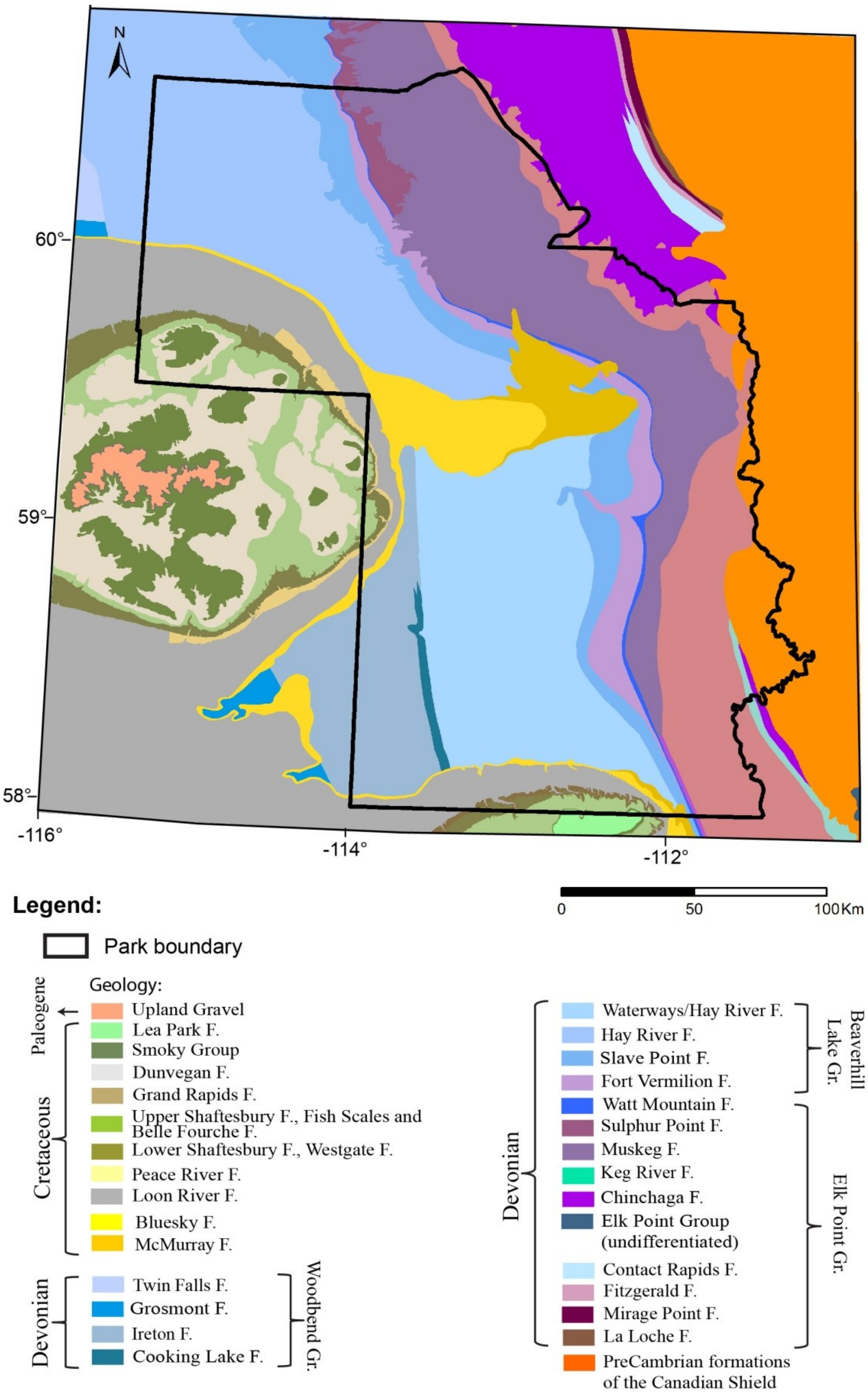

Figure 1.5: Bedrock geology of Wood Buffalo National Park (modified after Prior et al. 2013 and Okulitch and Fallas 2007).

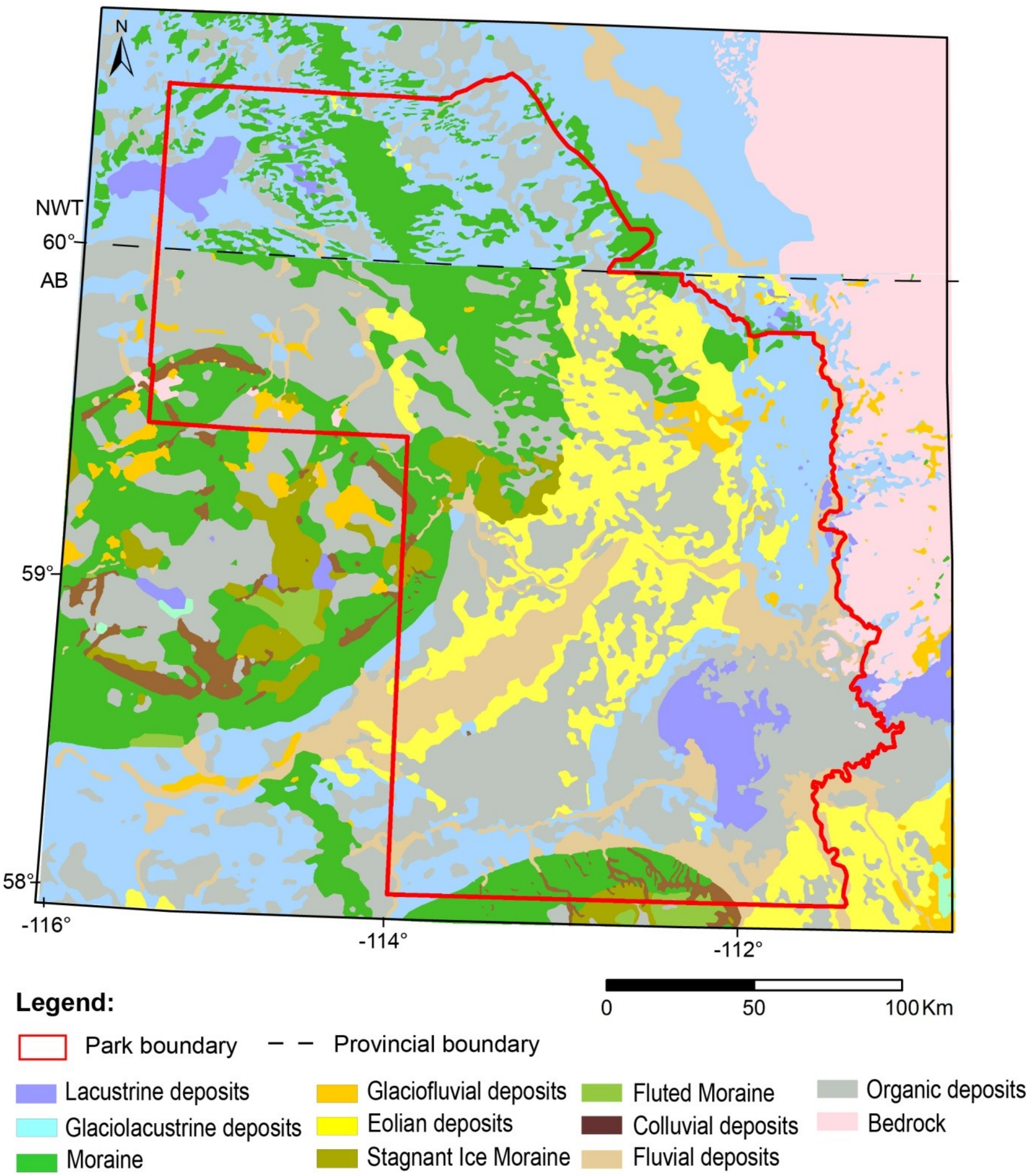

Figure 1.6: Surficial geology of Wood Buffalo National Park (modified after Lemmen 1998a, b and Fenton et al. 2013).

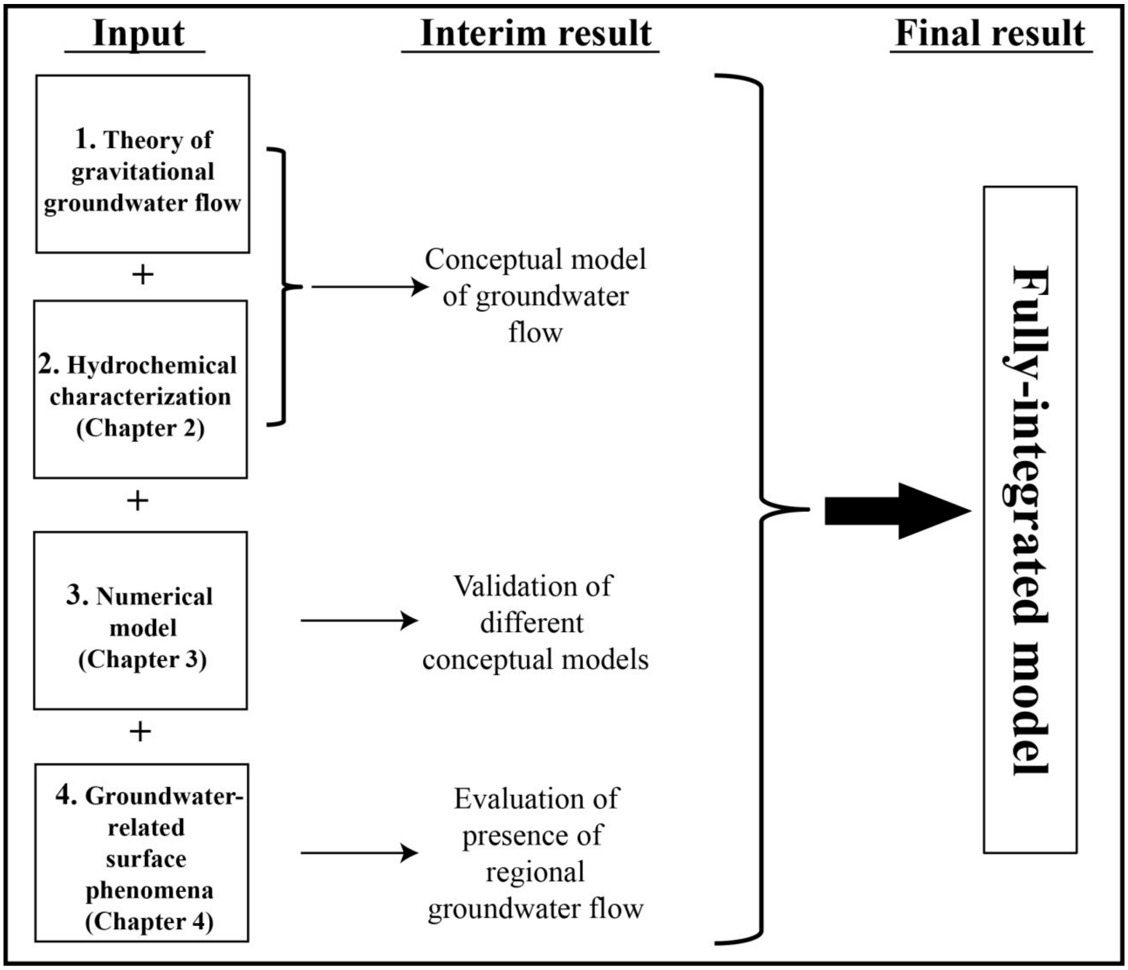

Figure 1.7: Workflow

Chapter 2 Geochemistry of groundwaters and surface waters of Wood Buffalo National Park, Canada

2.1. Abstract

The geochemistry of groundwaters and surface waters in Wood Buffalo National Park (Canada) were characterized and the dominant rock-water interactions that affected the chemical composition of the waters were determined. The geochemical characteristics of waters reflect the three hydrogeological zones of the area, i.e., regional recharge in the Caribou Mountains; local flow paths in the central plains; and local recharge and discharge, as well as regional discharge along the eastern edge of the basin in the Salt Plains region. Total Dissolved Solid (TDS) concentrations range from less than 1,000 mg/L to more than 300,000 mg/L. Hydrochemical facies of the waters form four distinct groups: 1) sodium- and chloride -dominated waters, 2) "mixed"-type of waters, 3) calcium- and sulphate-dominated waters, and 4) calcium- and bicarbonate-dominated waters. The highest variability in both TDS content and water type were found along the eastern edge of the study area. Isotopic compositions indicate two different water origins: 1) recharge from local precipitation, and 2) recharge from precipitation in a colder climate.

Analysis of sodium-chloride-bromide relations, calcium-excess, sodium-deficit, and major element ratios suggest solutes in the waters originate from three main processes: 1) dissolution of halite; 2) dissolution of sulphate minerals; and 3) dissolution of carbonates. The solute sources are expected to be Devonian evaporites, halite and carbonates that represent most of the bedrock sediments in the area.

2.2. Introduction

Wood Buffalo National Park (WBNP) located in Alberta and Northwest Territories is Canada's largest national park, with an area of 44,807 km^2 (Figure 2.1). It includes boreal forests, extensive wetlands and prairie, and exhibits outstanding examples of karstic landforms, saline springs and salt plains, and unique ecosystems. It sustains the world's largest herd of bison, and is the only remaining natural nesting area of the highly endangered whooping cranes (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). The park also contains one of the world's largest inland deltas, the Peace-Athabasca Delta (PAD), and is a UNESCO World Heritage site (UNESCO World Heritage Committee 1983). Both the PAD and the nesting area of the whooping cranes are declared Wetlands of International Importance under the Ramsar Convention (Ramsar 2018).

The physiography of the national park is characterized by two highland areas with topographic elevations over 1030 m asl: the Caribou Mountains in the west, and the Birch Mountains along the southern boundary (Figure 2.1). The largest rivers are the Slave River, which flows south to north along the eastern boundary, and the Peace River which separates the northern areas from the mostly wetland-dominated southern part of the region (Figure 2.1). Topographic elevations gradually decline from the foot of the Caribou Mountains to a steep escarpment near the eastern boundary, approximately 30 km west of Fort Smith (Figure 2.1). The escarpment extends southwards from the Slave River and separates the Salt Plains and the Slave River lowlands from the upland region of WBNP.

There is currently no regional hydrogeological compilation of WBNP. It remains one of the few areas in Alberta that was not mapped by the Alberta Research Council (ARC) in its province-wide hydrogeological mapping program conducted in 1970s-1980s (ERCB/AGS

2009). Hydrogeological characterization by the ARC with an accompanying map exists only for a small portion in the western region of WBNP, e.g. Ozoray (1980) as shown in Figure 2.2.

The objective of this study is to provide a geochemical characterization of groundwaters and surface waters in WBNP, using total dissolved solids (TDS) and hydrochemical facies. Geochemical data are used to characterize rock-water interactions and their effects on the geochemical composition of waters. Possible connection of the groundwaters in WBNP with deep Devonian formation waters in the Alberta Basin is examined and results are used to elucidate the origin of salt in saline and brine waters discharging at the Salt Plains. The geochemical characterization of the area is used to reinforce the conceptual model of groundwater flow in WBNP.

2.2.1. *Geology*

Wood Buffalo National Park sits on the northeastern edge of the Western Canadian Sedimentary Basin (WCSB) and as such its geological description can be found in regional characterizations of the strata of the WCSB (e.g. Meijer Drees 1994; Oldale and Munday 1994 and Switzer et al. 1994). The current bedrock and surficial geology maps were published by the Alberta Geological Survey (AGS) and Geological Survey of Canada (GSC) as part of regional 1:1,000,000 scale bedrock and surficial geology mapping (Okulitch 2006; Okulitch and Fallas 2007; Fenton et al. 2013; Prior et al. 2013). Higher resolution characterization of surficial materials (1:250,000 scale) are also available (Bayrock 1972a, b, c; Lemmen 1998a, b; Mougeot and Fenton 2010).

Local-scale geological mapping in WBNP was initiated by Camsell (1917) who studied gypsum and salt bedrock deposits in the area and covered the area east of 113°W and west of Slave River northward to 60°N. Later, Devonian stratigraphy of the Slave River region and the Caribou Mountains-Fort Smith area north of Peace River was described by Norris (1963) and Richmond (1965), respectively. More recently, Park and Jones (1982), Tsui (1982) and Tsui and Cruden (1984) investigated processes leading to deformations and brecciation in the Devonian Keg River and Chinchaga formations in the Salt River region (Figure 2.3).

Combining the regional and local-scale mapping conducted to date, the overall geology of the area (Figure 2.3, Figure 2.4) can be characterized by four major geologic packages:
Package I consists of crystalline Precambrian rocks of the Canadian Shield. These dip to the southwest and are composed of igneous and metamorphic rocks of the Canadian Shield. The outcrop area of the Precambrian basement in the eastern margin of WBNP is shown in Figure 2.3.

Package II consists of Devonian-aged strata and represents the most widespread sedimentary bedrock in WBNP (Figure 2.3, Figure 2.4). The southwesterly-dipping Devonian sediments are composed of carbonates, evaporites and shales, and are divided into three geological groups: Elk Point, Beaverhill Lake and Woodbend groups. Outcrop areas of are shown in Figure 2.3. Stratigraphic nomenclature and generalized lithology are shown in Figure 2.4. Three significant evaporite strata are present in the area. The Chinchaga Formation consisting of mostly anhydrite and gypsum underlies the Salt Plains (Figure 2.1). The Muskeg Formation is composed of mostly gypsum and is stratigraphically equivalent with the Prairie Evaporite Formation that is present south of the area and characterized by variable halite content ranging from 5-10% in north to >40% in south Alberta (Grobe 2000). The third evaporite stratum is the Fort Vermilion Formation that consists mostly of anhydrite. The Devonian package also includes two regionally extensive carbonate formations, i.e., the Keg River and Slave Point formations, and three shale layers, i.e., Watt Mountain, Hay River and Ireton formations.

Package III consists of Cretaceous siliciclastic deposits that unconformably overlay the Devonian strata. They only occur in the Caribou and Birch Mountains regions with the exception of a tongue-shaped remnant of Bluesky and McMurray formations in the central portion of WBNP (Figure 2.3). Cretaceous stratigraphic nomenclature and generalized lithology are shown in Figure 2.4.

Package IV includes unconsolidated surficial material of Quaternary and/or recent age with thickness varying from 1 to 45 m over most of the lowlands, but locally reaching 50 to 150 m in the upland areas (Pawlowicz and Fenton 1995; Fenton et al. 2013). Quaternary/recent materials across WBNP are dominantly glaciolacustrine and moraine sediments, but there are areas of aeolian, fluvial and lacustrine sediments. Fine-grained deposits are often overlain by organic material (peat).

2.2.2. *Previous hydrogeological investigations in WBNP*

There is no regional hydrogeological compilation published for WBNP. As part of the ARC mapping program, Ozoray (1980) presented a regional picture of groundwater conditions including groundwater flow directions, hydrochemical characterization and groundwater discharge features in the western region of WBNP (Figure 2.2). Study of groundwater-related phenomena initiated by the ARC was conducted by Stein (1979) in the Peace Point – Fitzgerald region, however the results were never published (Figure 2.2).

There have been several local studies of the hydrogeology/hydrochemistry of WBNP. Areas of coverage are shown in Figure 2.2. A brief description of each of these studies and their conclusions follow.

Groundwater flow

The earliest hydrogeologic study in the WBNP appears to be by Drake (1970) who proposed three "hydrologic zones" within WBNP: 1) the Caribou Mountains with good surface drainage (*zone 1*); 2) a waterlogged muskeg zone between the Caribou Mountains and the escarpment with poor surface drainage (*zone 2*); and 3) a drier drift zone in the vicinity of the escarpment with a proposed discharge area of local and regional/intermediate groundwater flow systems at the base of the escarpment (*zone 3*) (Figure 2.2).

Later work supported these three zones. For example, Tsui (1982) and Tsui and Cruden (1984) concluded that the fresh and salt springs discharging near the salt escarpment are controlled by local, intermediate and regional flow systems recharging in *zone 1*, *zone 2* and *zone 3*.

Peripheral to WBNP, Weyer (1983) studied groundwater flow in the Pine Point region on a local and regional scale and argued that the Caribou Mountains (*zone 1*) act as a regional recharge area where water penetrates the Devonian strata and discharges at regional discharge areas, such as Salt River and the Slave River along the eastern edge of WBNP (Figure 2.2).

Nielsen (1972) concluded that the Peace-Athabasca Delta area is dominated by local flow systems and that the existing regional flow systems from the Caribou and Birch Mountains have little to no effect on the local flow regime at the land surface due to the low-permeability shale layer covering the area (Figure 2.2).

Origin of chemistry

Weyer et al. (1979) studied groundwater flow and water chemistry in the Pine Point-area on a local and regional scale and indicated that the chemistry of discharging groundwater between Hay River and Slave River could be derived from three types of water: calcium-bicarbonate, calcium-sulphate-bicarbonate, and sodium-chloride. Tsui (1982) proposed that groundwater recharging at Caribou Mountains flows through the halite in Cold Lake Formation; it becomes brine and discharges between the escarpment and the Slave River (Figure 2.2). Most recently, Grasby and Chen (2005) and Grasby (2006) used oxygen and hydrogen stable isotopes and Br/Cl ratios to argue that brine waters in WBNP originate from halite dissolution by present-day processes rather than from deep-basin brines.

Surface water – groundwater interactions

The National Hydrology Research Institute studied surface water – groundwater interactions around the northeastern wetlands between 1985 and 1990 to examine the potential effects of dewatering operations at Pine Point Mine, as well as possible effects of climate change on the whooping cranes' only remaining natural nesting ground (Nobert and Barrie 1986; McNaughton 1991) (Figure 2.2). Nobert and Barrie (1986) concluded that there is a significant groundwater influx to the studied ponds in the northern wetland area. Nielsen (1972) concluded that groundwater interaction between water bodies in the PAD region is negligible. This is supported by Peters (2006) who reported insignificant groundwater flux in perched basins in PAD.

2.2.3. *Conceptual model of groundwater flow in the WBNP*

Synthesis of the previous works along with fieldwork (described below) has led to the development of a conceptual model of groundwater flow in WBNP. The conceptual model presented in this study integrates early hypotheses on groundwater flow with geochemical characteristics of waters observed in WBNP (Figure 2.5). The working hypothesis is that the flow regime is dominated by nested flow systems: local-scale, with shallow flow paths near the surface, superimposed on intermediate to regional-scale flow paths in the deeper parts of the basin (Figure 2.5). Groundwater is recharged by precipitation. The area can be characterized by three zones are: *Zone 1*: the Caribou Mountains, the main recharge area of the deep flow paths where precipitation penetrates down through Cretaceous sand and shale and Devonian carbonates and evaporites, and evolves from Ca-HCO_3-type, low TDS waters to Ca-SO_4, Na-Cl type waters (Figure 2.5). *Zone 2* is the flat lowlands where, in the absence of large topographic relief, infiltrating water cannot penetrate deep in the basin, and, therefore, the area is dominated by shallow, local-scale flow paths represented by fresh waters with low TDS concentrations and Ca-HCO_3 water type (Figure 2.5). *Zone 3* is in the vicinity of the escarpment along the eastern edge of the basin. It is characterized by flow paths of different scales. The presence of the escarpment generates local flow paths with recharge on the top of the escarpment and discharge at the base. These local flow systems are associated with fresh waters and Ca-HCO_3 water type (Figure 2.5). In the same area, regional-scale flow systems recharged at the Caribou Mountains discharge at the base of the escarpment and on the Salt Plains. Waters discharging at the base of the escarpment are associated with wide range of TDS concentrations (brackish, saline, brine) and more evolved, Ca-SO_4, Na-Cl and “mixed” water types due to discharge of groundwater from different flow paths and their potential mixing.

This conceptual model will be tested through geochemical characterization of the area by analyzing the spatial distribution of TDS and hydrochemical facies in the study area as well as by characterization of possible rock-water interactions and their effects on the water chemistry in WBNP.

2.3. Data and methods

Samples of surface waters and groundwaters were collected within the park to determine the hydrochemical characteristics (e.g., TDS) of waters in WBNP and to develop a hydrochemical facies classification. Two sources of data were used: 1) archive water chemistry data were provided by Alberta Geological Survey (AGS) based on sampling conducted in the 1970s (AGS 2009a,b; AER/AGS 2014), and 2) seventeen targeted samples collected in 2013. The type and number of the water samples are listed in Table 2.1. Newly collected samples are shown in Figure 2.1 labeled by “W”. Measured and calculated chemical parameters are shown in Table 2.2.

Samples were collected by hand, either directly or using a telescopic water sampling tool. Springs were sampled as close to the source as possible to minimize dilution effects from precipitation or shallow groundwater influx. Samples from surface-water bodies were sampled as far from shore as practical.

Sample bottles were pre-rinsed three times with sample water before filling. Samples were split for geochemical analysis and, where needed, were filtered through 0.45 μm filters and stored in 50 mL polypropylene centrifuge tubes with plug seal caps in cool, dark conditions until transported to the laboratory. Potentially unstable parameters (i.e., pH, temperature and electrical conductivity) were measured in the field at the sampling sites using a portable Oakton pH/CON 300 meter, which was calibrated with pH buffers 7, 10 and 14, and a conductivity standard of 1413 μS/cm. Samples collected for analysis of major cations were acidified to pH<2 with ultra pure nitric acid. Samples for analysis of stable isotopes were collected in 50 mL polypropylene centrifuge tubes that were tightly capped and stored unpreserved.

All samples were collected for analysis of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, $SO4^{2-}$, HCO^{3-}, and $CO3^{2-}$). In addition, the 17 samples collected in 2013 were analyzed for minor elements and stable isotopes of hydrogen and oxygen in water. Samples collected for analysis of major dissolved metals were analyzed by Inductively Coupled Plasma/Mass Spectrometry method (APHA 3125B/USEPA 200.8). Alkalinity (HCO_3^-) was measured by Titration Method (2320B) (APHA 1999). Concentrations of dissolved Cl, Br and SO_4 were analyzed by a Dionex ICS-2010 Ion Chromatograph equipped with IonPack AS18 column, an AS18 guard column and AS-DV autosampler. Reproducibility for dissolved Cl, Br, and SO_4 is better or equal to ± 5% (± 1σ). The charge balance of major ion analyses was better than +/-5% for 14 samples and had positive charge balance excesses from 6 to 9 % in case of 3 samples (Table 2.2). Trace dissolved metals were analyzed by Inductively Coupled Plasma (ICP) Method (3120B) (APHA 1999). Standard analytical error is equal to or better than 10% (±1σ) for the trace elements and can be higher (e.g., >20%) when close to the detection limits of the trace elements. Stable isotope compositions of hydrogen and oxygen were performed on a Cavity Ring Down Spectroscope (CRDS) Picarro L2130-i. Measurement uncertainty was +/-0.15‰ for $\delta^{18}O$ and 0.7‰ for $\delta^{2}H$.

2.4. Results and discussion

In the following section chemical characteristics of surface and groundwaters in WBNP are defined by determining TDS and hydrochemical facies based on major ions. The classification of the water samples mostly follows Back's (1966) classifications criteria. To yield a clearer representation of the data, waters with mixed ion composition, i.e., waters containing less than 80% of each major cation (Ca+Mg, Na+K) and anion (HCO_3+CO_3), were merged into the group of "mixed" water type. In the case of Ca-HCO_3-, Ca-SO_4- and Na-Cl-type waters, Ca+Mg or Na and HCO_3, SO_4 or Cl dominate the ionic composition, respectively; their normalized ratio is ≥80% relative to the rest of the ions.

Stable isotopes of oxygen and hydrogen are used to characterize the origin of recharge; and the nature of rock-water interactions affecting the waters are evaluated by ion relations. Results are compared to, and discussed in light of, previous findings to develop an integrated conceptual model of the water origin and factors influencing the water chemical composition within WBNP.

2.4.1. *Total dissolved solids (TDS) content and hydrochemical type of waters in WBNP*

Total dissolved solids (TDS) content shows significant variability in WBNP. Groundwaters range from 35 mg/L to 331,000 mg/L (Figure 2.6). Surface waters range from 4 mg/L to 319,000 mg/L. Most water samples have TDS content less than 1,000 mg/L, which spatially dominate much of the central region and the entire southern part of WBNP

(Figure 2.6). Highest TDS concentrations (>300,000 mg/L) are found in the Salt Plains region, along the eastern boundary of the area (Figure 2.6).

Water types in WBNP form four groups: Na-Cl-type (*Type I*) waters, "mixed" (*Type II*) waters, Ca-SO_4-type (*Type III*) waters, and Ca-HCO_3-type (Type IV) waters.

The spatial distribution of water types reveals that most of the study area is dominated by Ca-HCO_3-type waters (Figure 2.7). A distinct cluster of Ca- and SO_4-dominated waters can be seen in the northern area, near 60°N. These samples coincide with members of a similarly distinct group of waters with TDS concentrations between 1,000 and 5,000 mg/L (Figure 2.6). The spatial variability of the hydrochemical facies is greatest along the eastern edge of the area, similarly to the TDS distribution. This is where Na- and Cl-dominated waters are found and where Ca- and HCO_3-dominated waters and more evolved Na- and Cl-dominated waters occur next to each other. This area coincides with the lowest topographic elevations of the region (Figure 2.1, Figure 2.7).

Sodium-chloride-type waters form two separate groups based on their TDS concentrations (Figure 2.7). The first group is dominated by Na-Cl-type waters with TDS values less than 100,000 mg/L (Group 1), while the second one contains Na-Cl-type waters with TDS values higher than 300,000 mg/l (Group 2). Waters from Group 1 can be found across the entire Salt Plains. Two samples with Group 1 chemistry were located to the west and south, respectively, of the main Group 1 cluster. Waters of Group 2 are only present in the northern Salt Plain area.

There is a correlation between spatial distribution of the waters with low TDS values (<1000 mg/L) and samples with Ca-HCO_3-type hydrochemical facies (Figure 2.6, Figure 2.7). Both the low TDS and the predominance of Ca and HCO_3 ions in the water indicate fresh water fed directly by precipitation or "young" waters with short flow paths (Chebotarev 1955a, b, c). The more evolved Ca-SO_4 and Na-Cl-type of waters correspond to elevated TDS values and suggest longer flow path and effects of different rock-water interactions.

Group 2 Na-Cl-waters correspond to the outcrop area of Chinchaga Formation in the WBNP, while Group 1 waters show no apparent relation to one specific formation or lithology (Figure 2.7). The cluster of Ca-SO_4-type waters in the northern region corresponds with the outcrop area of Devonian evaporites. The remainder of the water types do not appear to be related to bedrock lithology.

The hydrochemical facies observed in WBNP correspond to the water types south of Great Slave Lake observed by Weyer (1983) and Weyer et al. (1979). These authors also postulate that Na-Cl- and Ca-SO_4-type waters are manifestations of regional groundwater discharge. This supports the hypothesis that water types in WBNP reflect the regional flow patterns. Water recharges in the Caribou Mountains, penetrates the Devonian strata and discharges as Na-Cl- and Ca-SO_4-type springs at regional discharge areas, such as the Salt Plains area.

There is a relationship between the sample source type and its hydrochemical facies (Figure 2.8a). Sinkhole samples have two different hydrochemical facies: 1) Ca(Mg)-HCO_3-type waters, and 2) Ca(Mg)-SO_4-type waters. Groundwaters have a range in chemical facies including all four identified water types, i.e., Ca(Mg)-HCO_3, Ca(Mg)-SO_4, Na-Cl and "mixed" water types (Figure 2.8b). In contrast, still, flowing surface waters, and wetlands show no apparent correlation between source type and hydrochemical facies.

The two distinct water types for sinkhole samples indicates that these waters originate from two different water sources and/or have different rock-water interaction histories (Figure 2.8a). The Ca(Mg)-HCO_3-type waters with low TDS values indicate recharge by precipitation and represent proximity to a recharge area. An alternative explanation is that they are fed by groundwater and located near the discharge area of short, shallow flow paths. Sinkholes with Ca(Mg)-SO_4-type water appear to be fed by groundwater. The presence of sulphate in these waters indicates different scale of flow path and rock-water interactions compared to the Ca(Mg)-HCO_3-type waters.

2.4.2. *Isotopic composition of waters in WBNP*

Isotopic compositions of the 17 new samples ranged from -23.1‰ to -7.1‰ for $\delta^{18}O$ and from -179‰ to -102‰ for $\delta^{2}H$. The lowest value was found in one spring sample (W21) at -23.1 and -179‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively; while the highest values -7.1‰ and -102‰ were found in lake W13 (Figure 2.1, Table 2.2).

Samples in WBNP exhibited a typical near-linear relationship between $\delta^{18}O$ and $\delta^{2}H$ (Figure 2.9). Figure 2.9 shows the measured $\delta^{18}O$ and $\delta^{2}H$ values of water in comparison with the local meteoric water line (LMWL) and the local evaporation line (LEL) (after Wolfe et al. 2007).

Since isotopic compositions behave in different ways in surface and groundwaters, the water samples were divided into two separate classes based on the type of the sample; i.e., surface waters and groundwaters.

Surface waters form two separate groups. The first group of surface waters, including W8, W14, W16, W17, W20 and W23, clusters near the LMWL and plots close to the average isotopic composition of local precipitation (Figure 2.9a). A second group of surface water samples, including W7, W22, W10 and W13, has significantly higher $\delta^{18}O$ and $\delta^{2}H$ values than that of the average isotopic composition of local precipitation and has a broad range of values, from -7.1‰ to -14.6‰ and from -102‰ to -158‰ for $\delta^{18}O$ and $\delta^{2}H$ respectively (Figure 2.9a). These samples do not plot on or near LMWL, but rather follow the LEL and have a similar isotopic composition to surface waters in the PAD region.

The isotopic composition of groundwaters in WBNP follows the trend of the LMWL (Figure 2.9b). Most of the groundwater samples, including W1, W2, W4, W5, W6, cluster tightly around the average isotopic composition of local precipitation (Figure 2.9b). Groundwater sample W21 has considerably lower $\delta^{18}O$ and $\delta^{2}H$ values than the rest of the groundwater samples.

Groundwater samples have significantly lower $\delta^{18}O$ and $\delta^{2}H$ values than that of the Devonian and Jurassic-Cretaceous brine waters (Figure 2.9b). The $\delta^{18}O$ and $\delta^{2}H$ values in the Devonian and Jurassic-Cretaceous brines range from -15.8‰ to 2.4‰ and from -127‰ to -69‰, respectively; and the isotopic composition of the brackish and saline Cretaceous and the mostly fresh Quaternary groundwater samples varies between -21.4‰ and -17.1‰ for $\delta^{18}O$ and -157‰ and -134‰ for $\delta^{2}H$ (Connolly et al. 1990; Lemay 2002) (Figure 2.9b). Although the $\delta^{18}O$ values of WBNP's groundwaters have a range similar to the Quaternary groundwater samples, they show lower deuterium contents with $\delta^{2}H$ values ranging from -154‰ to -179‰. Groundwater samples from WBNP have depleted isotopic compositions compared to the seeps in the Athabasca Oil Sands (AOS) region. Although groundwater samples in WBNP fall within the range of springs in the AOS region (-23.5‰ and -16.5‰ for $\delta^{18}O$ and -178‰ and -130‰ for $\delta^{2}H$), most of the AOS springs exhibit a more depleted isotopic composition that that of the springs in WBNP (Figure 2.9b).

2.4.2.1. Origin of surface waters

The first group of surface water samples in WBNP (W8, W14, W16, W17, W23 and W24) has a meteoric origin and its isotopic composition shows little or no enrichment due to evaporation (Figure 2.9a). The samples do not show correlation with the surface-water bodies in the PAD. They belong to the same cluster as most of the groundwater samples suggesting that 1) these surface water bodies are fed (partially or fully) by groundwater and 2) these surface waters and the isotopically similar groundwaters have similar water source, i.e. isotopically altered meteoric water.

The isotopic composition of the second group (W7, W22, W10 and W13) reflects recharge from direct precipitation that was subsequently altered by varying degrees of evaporation. Samples W10 and W13 are affected the most by evaporation, while samples W22 and W7 are the least evaporated (Figure 2.9a). The high salinity and elevated Br content of sample W7 (Table 2.2) compared to the other samples within the group indicates that it is also fed by groundwater, in addition to direct precipitation.

2.4.2.2. Origin of groundwaters

Results presented above suggest that the original source of the groundwaters in WBNP is meteoric water. The majority of groundwaters cluster along the local meteoric water line and suggest the same water source. Sample W21, however, appears to have anomalously low $\delta^{18}O$ and $\delta^{2}H$ compositions (Figure 2.9b). Factors resulting in decreased $\delta^{18}O$ and $\delta^{2}H$ values are generally related to temperature, altitude and seasonality (Sharp 2007).

Precipitation in colder regions will be depleted in heavy isotopes compared to warmer regions resulting in more negative $\delta^{18}O$ and $\delta^{2}H$ values because cold air masses cannot hold as much water as they can in warmer areas. Infiltration at higher latitudes can explain the lower than average $\delta^{18}O$ and $\delta^{2}H$ values in sample W21. This sample is the only one collected in NWT, and it represents the northernmost sampling site. This makes cold climate a plausible explanation for the observed low $\delta^{18}O$ and $\delta^{2}H$ values of sample W21. The rest of the above mentioned samples were collected in the Salt Plains located near Fort Smith.

The isotopic composition of precipitation is also affected by seasonal variations in temperature (Sharp 2007). This results in precipitation with higher $\delta^{18}O$ and $\delta^{2}H$ values in the summer and lower ones in the winter. Recharge on the Prairies happens after snowmelt and results in depletion of heavy oxygen and hydrogen isotopes in groundwater (Hayashi et al. 2003; Grasby et al. 2010). In the Boreal Plains, however, the storage capacity of soil materials is high relative to the moisture surpluses or deficits (Redding and Devito 2008). In fine-textured soils the larger storage capacity of the vadose zone leads to decreased or an insignificant amount of groundwater recharge from snowmelt (Redding and Devito 2005, 2008). Ferone and Devito (2004) demonstrated that the contribution of snowmelt to the recharge of shallow groundwater in the Boreal Plains is not significant due to the storage effect of peat material. Although the area of WBNP is significantly larger than the sites in the studies above, WBNP is located in a similar ecoregion and dominated by peat and other fine-grained surficial material with a relatively high water-retaining capacity that is expected to prevent significant contribution of direct snowmelt to the recharge of shallow groundwater. Since sampling location of groundwater sample W21 is located in such environment, it can be assumed that its lower than average isotope value is not the result of recharge from snowmelt.

Recharge during a colder climate period than present (e.g., from meltwater during glacial epoch) might also cause depleted isotopic composition. The $\delta^{18}O$ value of glacial meltwater is estimated to be -28‰ for the Yellowknife region (Clark et al. 2000). The lower than average isotopic composition of brine and saline springs along the eastern and northern erosional edge of the Western Canadian Sedimentary Basin has been attributed to Pleistocene subglacial meltwater (Grasby and Chen 2005), and it was found that some of the saline springs in AOS region contain up to 75% Laurentide glacial meltwater (Gue, 2012; Gue et al. 2015). Sample W21 in WBNP shows similarly low isotope values as some of the samples in the AOS region that are thought to be partially recharged from glacial meltwater. The significantly lower salinity of sample W21, however, indicates shallower, shorter groundwater flow path than that of brine springs studied by Grasby and Chen (2005) and Gue et al. (2015), making contribution from Laurentide glacial meltwater as an explanation for the observed low $\delta^{18}O$ and $\delta^{2}H$ values unlikely (Table 2.2).

Groundwater samples W1, W5, W6 and W2, W4 exhibit similar isotopic compositions; however their TDS concentrations are significantly different (Table 2.2). The considerably lower TDS contents in samples W2 and W4 indicate a shorter flow path than that of samples W1, W5 and W6 with significantly higher salinity. The “mixed” water type of samples W4 and W2 as opposed to the Na- and Cl-dominated waters of samples W1, W5 and W6 also indicates either a different water origin (flow path of different length and depth) or potential mixing between deep and relatively shallow groundwaters. A longer flow path is associated by prolonged rock-water interactions. Longer rock-water interaction is expected to cause enrichment in heavy oxygen isotopes and a shift from the LMWL (Land and Prezbindowski 1981; Spencer 1987; Clayton et al. 1966; Hitchon and Friedman 1969). It is plausible, therefore, that isotopic compositions of samples W1, W5 and W6 represent compositions that have evolved due to rock-water interactions along their flow paths from originally more depleted meteoric water. This theory is in line with the hypothesis that regional-scale flow paths discharging in the Salt Plains area originate from the Caribou Mountains where the predicted $\delta^{18}O$ and $\delta^{2}H$ values of precipitation should be 1 to 3 ‰ and 6 to 24 ‰ lower, respectively, than that at Fort Smith due to the higher altitude (Clark and Fritz 1997) (Figure 2.5).

2.4.3. *Rock-water interactions and their effects on groundwater in WBNP*

Waters in WBNP have four water types: Na-Cl (*Type I*), "mixed" (*Type II*); Ca-SO_4 (*Type III*) and Ca-HCO_3 (*Type IV*). The highest spatial variability in the water type was observed in the Salt Plains region where waters with different TDS concentrations and water types can be found next to each other (Figure 2.6, Figure 2.7). Oxygen and hydrogen isotope values show that the waters have a meteoric origin. In the following section rock-water interactions will be analyzed to elucidate the source of solutes in the four different water types found in the study area.

Considering the lithology of the bedrock, the three possible sources of solutes in the waters in WBNP are: a) dissolution of halite, b) dissolution of sulphate minerals (gypsum/anhydrite), and c) dissolution of carbonates.

2.4.3.1. Source of sodium and chloride in Type I and Type II waters

Na-Cl-Br log-ratios were used to elucidate the possible sources of Na and Cl in groundwaters and surface waters in the study area (Figure 2.10). Na-Cl-Br relations are represented by z_1 and z_2 orthonormal coordinates and intend to indicate whether the water is related to halite dissolution or seawater evaporation (Engle and Rowan 2013). Only samples obtained in 2013 were used in the analysis because Br measurements are only available for the recently collected samples. All Na-Cl-type waters (W1, W5, W6 and W8) (*Type I*) exhibit elevated Na and Cl ratios relative to Br and plot along the halite dissolution trend above the halite saturation point (Figure 2.10). Therefore they indicate that Na, Cl and Br solutes in these waters originate from halite dissolution. Their location relative to the halite saturation point in the diagram can be explained by progressive cycles of halite dissolution followed by dilution (Engle and Rowan 2013). Halite dissolution is also supported by the predominance of Na and Cl relative to other ions in these samples (Table 2.2). The Na-Cl-Br relations of samples W1, W5, W6 and W8 show good correlation with springs in the AOS-region that are also thought to be derived from halite dissolution (Grasby 2006; Gue 2012) (Figure 2.10). In WBNP, halite is the main constituent of the Cold Lake Formation; it can reach up to 80 m in the Caribou Mountains area and gradually becomes thinner eastward due to subsurface dissolution (Grobe 2000). The Muskeg/Prairie Evaporite Formation contain variable amounts of halite ranging from 5-10% in central WBNP up to more than 40% in the southern areas (Grobe 2000).

“Mixed” type waters (*Type II*) are of three origins. The first group (W2 and W4) (*Type IIa*) plots on the halite dissolution trend. The second (W7) (*Type IIb*) and third type (W13) (*Type IIc*) do not follow either the halite or the seawater dissolution line (Figure 2.10).

The sodium and chloride content of *Type IIa* "mixed" groundwaters (W2, W4) originate from halite dissolution. The equal dominance of Ca, SO_4, Na and Cl in their ionic composition, however, suggests that halite is not the only and predominant source of solutes in these waters.

Type IIb "mixed" water (W7) does not appear to be related to halite dissolution. Its isotopic composition indicated that it originates from local precipitation and it is affected by moderate level of evaporation (Figure 2.9a). Its elevated Br/Cl ratio relative to other precipitation-fed surface waters (W10, W13 and W22) suggests that precipitation is not the sole water source (Table 2.2). It appears to be partially fed by groundwater with elevated Br content that is diluted by local precipitation and affected by moderate degree of evaporation.

Type IIc "mixed" waters (e.g. W13) indicate that the water chemical characteristic was not affected by halite dissolution. The ionic composition of *Type IIc* is dominated by Ca(+Mg) and HCO_3 with a low amount of SO_4 and only insignificant amounts of Na and Cl showing no evidence of halite dissolution. This is consistent with its isotopic composition that showed it is primarily fed by local precipitation and affected by evaporation (Figure 2.9a).

Most of the Ca-SO_4-type waters (W14, W16, W17, W20, W22, W23 and W24) (*Type III*) and the only Ca-HCO_3-type water (W10) (*Type IV*) plot away from both trend lines and do not indicate any halite dissolution. Although surface-water samples W16 and W23 fall near the trend line of halite dissolution, they have insignificant amounts of Na and Cl and their chemical composition is dominated by Ca and SO_4 suggesting that they were not affected by either halite dissolution or seawater evaporation.

2.4.3.2. Source of calcium in Type II and Type III waters

Ca-excess and Na-deficit correlations help to understand the nature of other rock-water interactions that might have affected the waters in the study area, and elucidate the origin of excess Ca in the waters (Davisson et al. 1994; Davisson and Chris 1996). Trend lines 1 and 2 in Figure 2.11 indicate Ca_{excess} due to gypsum dissolution/dolomitization and albitization, respectively. Halite dissolution (Trend line 3) and seawater evaporation (Trend line 4) are represented by decreased Ca_{excess} and $Na_{deficit}$. Figure 2.11 shows the Ca-excess and Na-deficit of *Type II* ("mixed") and *Type III* (Ca-SO_4) groundwaters and surface waters in WBNP.

Calcium-sulphate-type and "mixed" groundwaters (e.g., W2, W4 and W21) do not exhibit $Na_{deficit}$ compared to seawater, but they do indicate increased Ca_{excess} and plot along trend line 1 (Figure 2.11a). The same trend can be seen in surface waters, except for a few of "mixed" water samples showing slightly more or less $Na_{deficit}$ than the rest of the samples in the group. In both groundwaters and surface waters, Ca-HCO_3-type waters plot near seawater and show zero or close to zero $Na_{deficit}$ and Ca_{excess} (Figure 2.11a,b).

Calcium-sulphate-type and "mixed" waters indicate additional calcium and suggest that the extra calcium in these waters is related to dissolution of calcium-bearing minerals, such as gypsum or/and anhydrite.

Although the extra calcium indicated in Figure 2.11 could also be derived from replacive dolomitization and albitization, these are highly unlikely in the study area. Although albitization is known to affect sodium and calcium ions in formation waters, the process is not extensive in the Alberta Basin (Connolly et al. 1990). Groundwater samples in WBNP do not show the distinct 2:1 correlation between Ca and Na that would confirm the presence of albitization process (Spencer 1987; Connolly et al. 1990; Michael et al. 2003). Replacive dolomitization should cause a negative correlation between Ca and Mg concentrations in the fluid as a result of ion exchange between the Mg-bearing fluid and the Ca-rich limestone (Michael and Bachu 2002). In case of the groundwaters in WBNP, however, there is a pronounced positive correlation between these ions (Figure 2.12). Therefore replacive dolomitization as an explanation for the extra calcium in the WBNP-waters is unlikely.

Results suggest that calcium in *Type II* and *Type III* waters originate from dissolution of gypsum.

2.4.3.3. Source of calcium and bicarbonate in Type IV waters

Type IV (Ca-HCO_3-type) waters did not show correlation with any of the rock-water interactions presented in the diagrams of Ca-Na and Na-Br-Cl relations and originate neither from halite nor from gypsum dissolution.

Carbonate minerals, such as calcite and dolomite are abundant in the study area and therefore it is likely that dissolution of carbonate strata influenced the chemistry of the waters. The dissolution of these minerals is described by the following reactions (Ford and Williams 2007):

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \text{ (calcite)} \tag{2.1}$$

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \text{ (dolomite)} \tag{2.2}$$

The dissolution of calcite and dolomite releases equal concentrations in meq/L of Ca and HCO_3 or Ca+Mg and HCO_3 ions, respectively, and results in a 1:1 ratio of Ca (or Ca+Mg) and HCO_3 ions (Eqs. 2.1, 2.2).

Calcium-bicarbonate-type waters in WBNP fall on the 1:1 line where the total Ca+Mg concentration is balanced by that of HCO_3 (Figure 2.13). The 1:1 correlation of Ca+Mg and HCO_3 ion concentrations in the Ca-HCO_3-type waters indicates that carbonates are the main sources of solutes in these waters.

The elevated Ca+Mg content in *Type II* (Ca-SO_4) and *Type III* ("mixed") waters indicate addition of extra calcium plus magnesium to the water that is in line with the results of previous section (Section 2.4.3.2). Gypsum/anhydrite is an important source of solutes in groundwaters in WBNP and affects most of water types in addition to carbonate dissolution (Figure 2.14). When dissolution of both carbonate and sulphate minerals is occurring, additional Ca and SO_4 ions are added to the solution:

$$CaSO_4{\bullet}2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \tag{3}$$

In the case of dissolution of carbonates and gypsum, the concentration in meq/L of Ca+Mg should be equal to that of HCO_3+SO_4 and the samples should plot along a 1:1 linear trend (Gue et al. 2015). When gypsum dissolution is included in the ion ratios *Type II* and *Type III* waters show good correlation with the 1:1 slope suggesting that these waters have been affected by dissolution of both carbonates and sulphate minerals (Figure 2.14). *Type I* waters (Na-Cl) also indicate contribution of gypsum dissolution to the solutes in these waters.

2.5. Summary and Conclusions

The geochemical characteristics of waters in Wood Buffalo National Park reflect the conceptual model of groundwater flow in the area and show evidences of the three hydrogeological zones introduced in Section 2.2.3. The brines of the Salt Plains are thought to be derived from the Caribou Mountains that represents the regional recharge area (*Zone 1*). The Ca-HCO_3-dominated central region (*Zone 2*) is characterized by recharge and discharge areas of shallow, local flow systems, low TDS contents and Ca-HCO_3-type water. The highly distinctive geochemical characteristic of the waters in the Salt Plains region represents *(Zone 3)* recharge and discharge of local- and discharge area of regional-scale flow systems.

The chemistry of groundwaters and surface waters in Wood Buffalo National Park is complex. The chemical composition of waters are highly variable, with total dissolved solids concentrations ranging from less than 1,000 mg/L to more than 300,000 mg/L. Waters form four separate hydrochemical groups: *Type I*) Na-Cl-type waters; *Type II)* "mixed" waters; *Type III)* Ca-SO_4-type waters; *Type IV)* Ca-HCO_3-type waters.

The greatest variability in the TDS concentrations and the water types occurs in the Salt Plains area along the eastern edge of the sedimentary basin.

The spatial distribution of Na-Cl-type waters is limited to the Salt Plains. These waters are associated with elevated TDS concentrations (10,000 to >331,000 mg/L) forming two distinct families, one with TDS< 100,000 mg/L (Group 1) and one with TDS>300,000 mg/L (Group 2). Both the elevated TDS content and the Na-Cl water type are manifestations of discharge of regional groundwater flow and indicate regional-scale flow paths along which waters reached their current chemical compositions through prolonged rock-water interactions. This agrees well with the conceptual model of groundwater flow in WBNP that argued that the Salt Plains area represents discharge area of a regional-scale flow system that recharged in the Caribou Mountains.

"Mixed" water types can be found across the entire WBNP with TDS contents ranging from fresh (TDS<1,000 mg/L) to saline (10,000<TDS<100,000 mg/L). They represent mixtures between the other three water types.

$Ca-SO_4$-type waters are typically associated with salinity ranging from 1,000 to 5,000 mg/L. They occur in multiple, separate clusters across the area and appear to coincide with the outcrop areas of Devonian evaporites.

Accompanied by elevated salinity and evolved water type, "mixed" and $Ca-SO_4$-type waters may indicate intermediate-scale groundwater flow paths.

The southern and central part of WBNP is dominated by $Ca-HCO_3$-type waters. They are attributed to either presence of extended wetlands (e.g. PAD region) fed by direct precipitation or influence of shallow, local groundwater flow paths.

The isotopic composition of groundwaters suggests they originate from meteoric water, rather than formation waters of the Alberta Basin. They are mostly recharged from local, "modern" precipitation.

Surface waters are fed by direct precipitation and/or by groundwaters, and as such, their solutes originate from these two sources.

Solutes in groundwaters originate from three main rock-water interactions: 1) dissolution of halite; 2) dissolution of sulphate minerals; and 3) dissolution of carbonates.

Sodium and chloride in Na-Cl (*Type I*) waters are not related to seawater evaporation, but rather to dissolution of halite. Halite can be found in the Cold Lake Formation that can reach thicknesses up to 80 m in the study area and gradually becomes thinner eastward due to subsurface dissolution (Grobe 2000). The Chinchaga and Muskeg/Prairie Evaporite formations are regionally extensive evaporite units that may contain halite in variable amounts.

Calcium-sulphate (*Type III*) waters predominantly originate from dissolution of sulphate minerals and are not affected by halite dissolution. The possible source of sulphate minerals are the anhydrite and gypsum of Chinchaga, Fort Vermilion and Muskeg formations.

Solutes in Ca-HCO_3 (*Type IV*) groundwaters originate from carbonate minerals, such as calcite and dolomite that are abundant in the area. Regional carbonate units are the Keg River and Slave Point formations. Evaporite units (Chinchaga, Muskeg and Fort Vermilion formations) and the Waterways Formation also contain some amount of carbonates.

"Mixed" (*Type II*) waters reflect geochemical characteristics affected by multiple solute sources, e.g. mixture of halite and gypsum dissolution, mixture of carbonate and gypsum dissolution.

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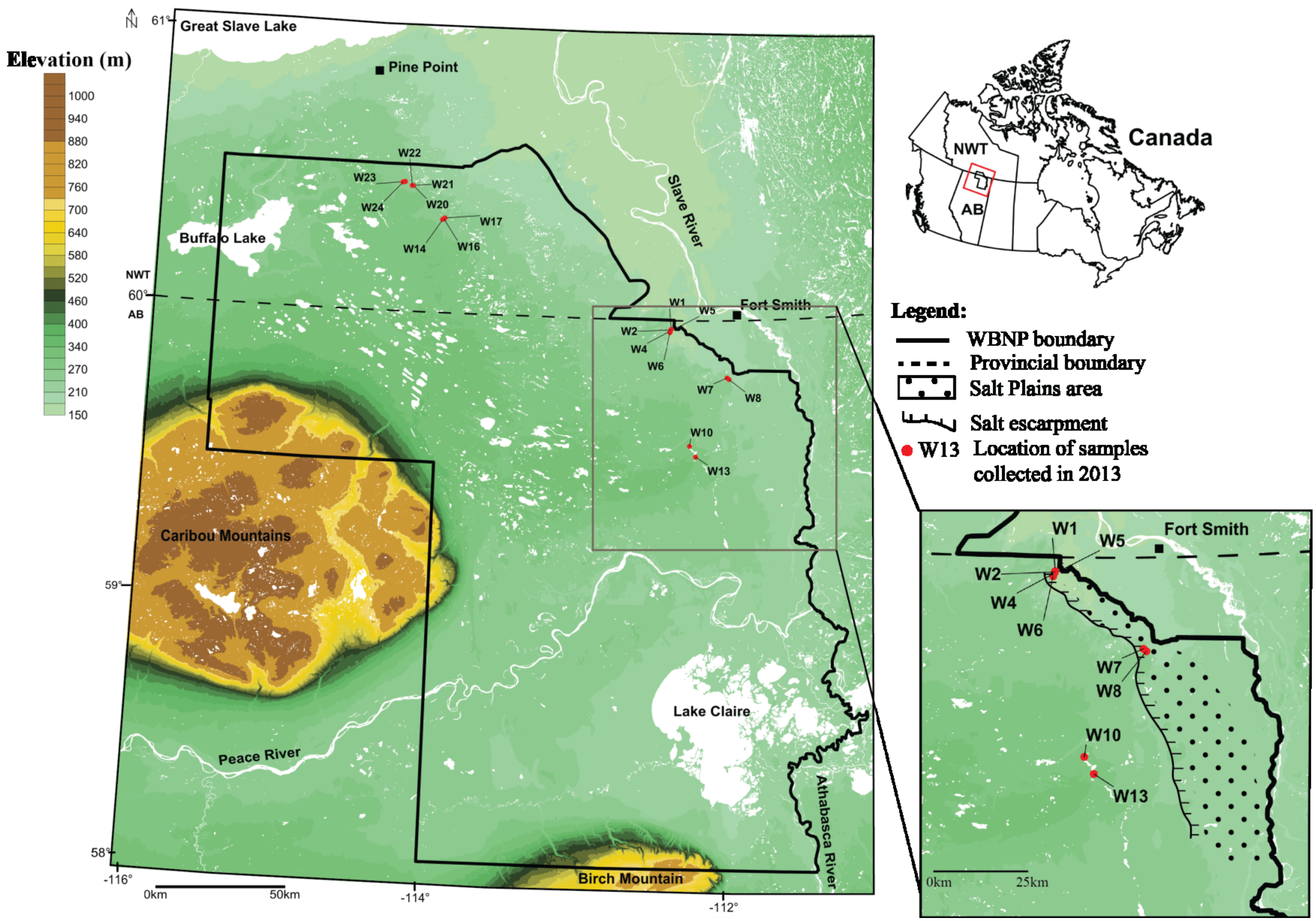

Figure 2.1: Topography of the Wood Buffalo National Park, Alberta-Northwest Territories, Canada and location of samples collected in 2013.

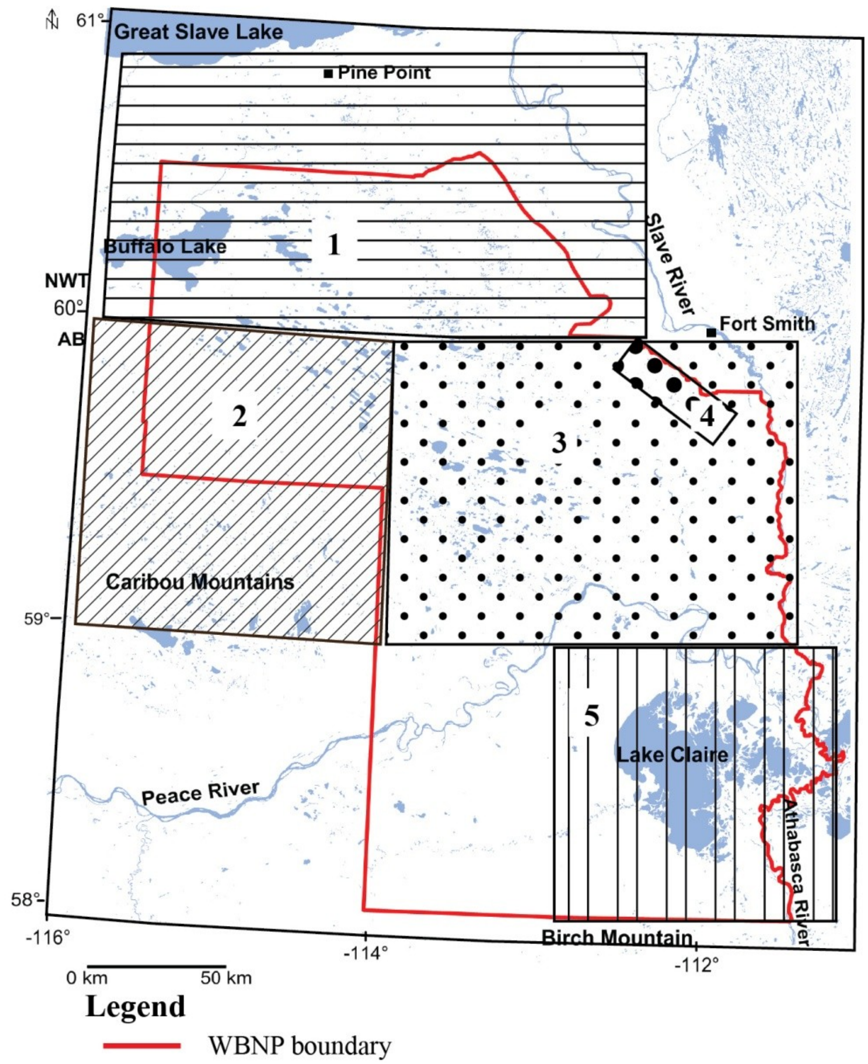

Figure 2.2: Locations of previous studies in Wood Buffalo National Park. 1: Northwest Territories region (Nobert and Barrie 1986; McNaughton 1991; Weyer et al. 1979; Weyer 1983), 2: Caribou Mountains region (Ozoray 1980; Weyer 1983), 3: Central region (Stein, 1979), 4: Salt River, salt escarpment region (Drake 1970; Tsui 1982; Tsui and Cruden 1984), 5: Peace-Athabasca Delta (Nielsen 1972; Peters 2006)

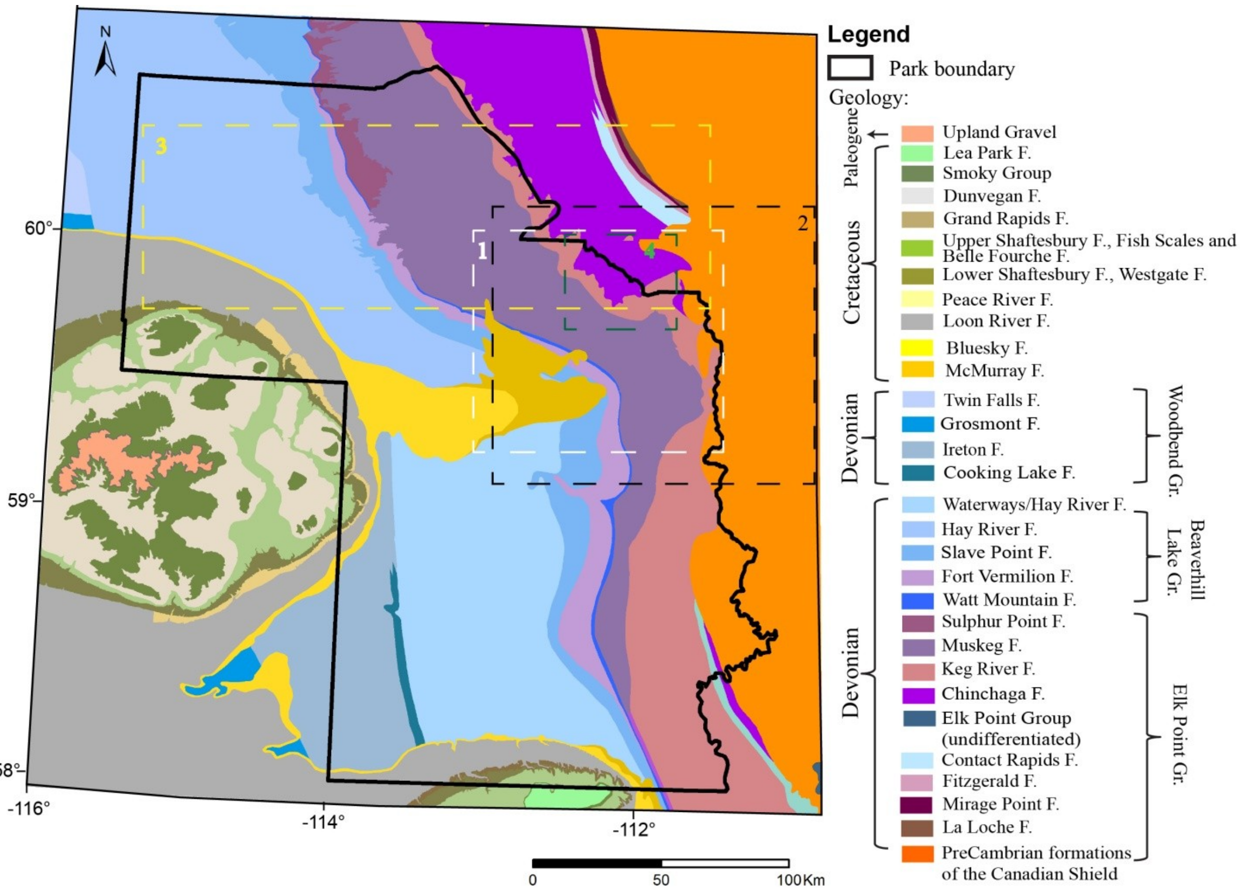

Figure 2.3: Bedrock geology of the Wood Buffalo National Park (modified after Prior et al. 2013 and Okulitch and Fallas 2007). Previous study areas are also shown (1: Camsell 1917; 2: Norris 1963; 3: Richmond 1965; 4: Park and Jones 1982; Tsui 1982 and Tsui and Cruden 1984)

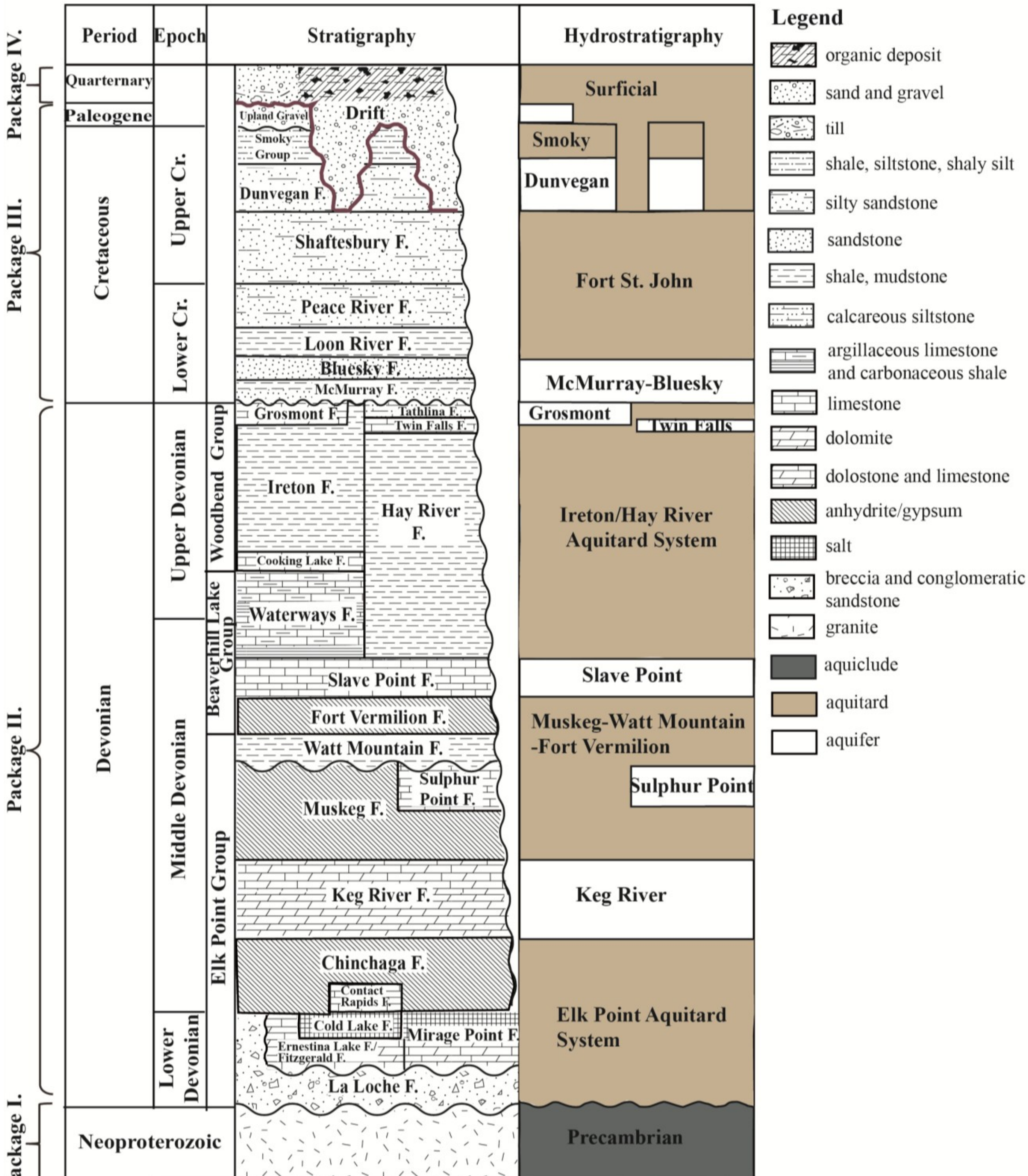

Figure 2.4: Generalized stratigraphy (adapted from Norris 1973; Meijer Drees 1994; Oldale and Munday 1994; Switzer et al. 1994; Prior et al. 2013; AGS, 2015) and hydrostratigraphy (modified after Bachu and Underschultz 1993 and Bachu 1997) of WBNP

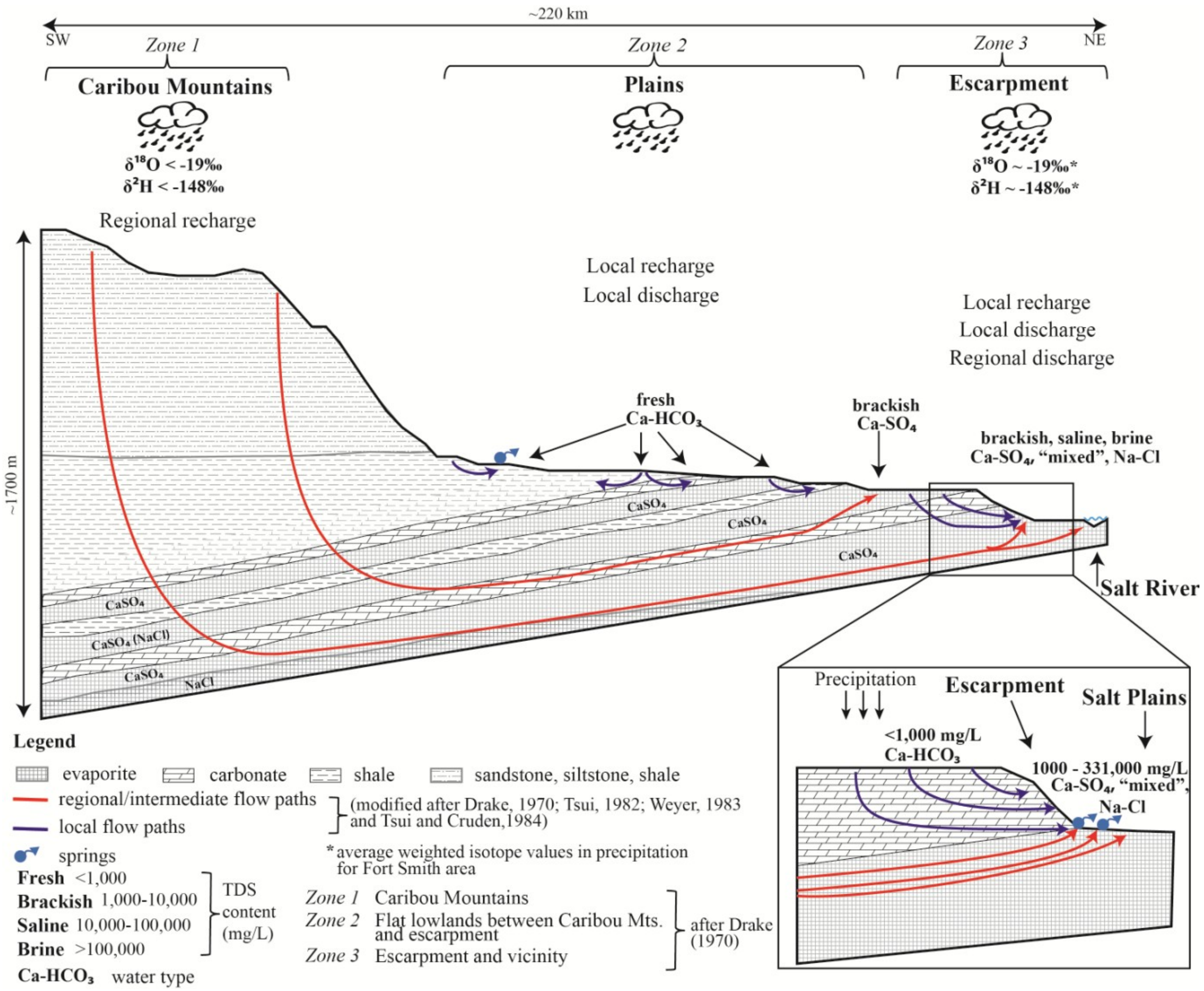

Figure 2.5: Conceptual model of groundwater flow in WBNP showing groundwater flow paths (based on Drake 1970; Tsui 1982; Tsui and Cruden 1984 and Weyer 1983) with associated water type and TDS content. *Zones 1*, *2* and *3* correspond with the hydrological zones of Drake (1970). Average isotopic composition of precipitation measured in Fort Smith region (Escarpment zone) is also shown.

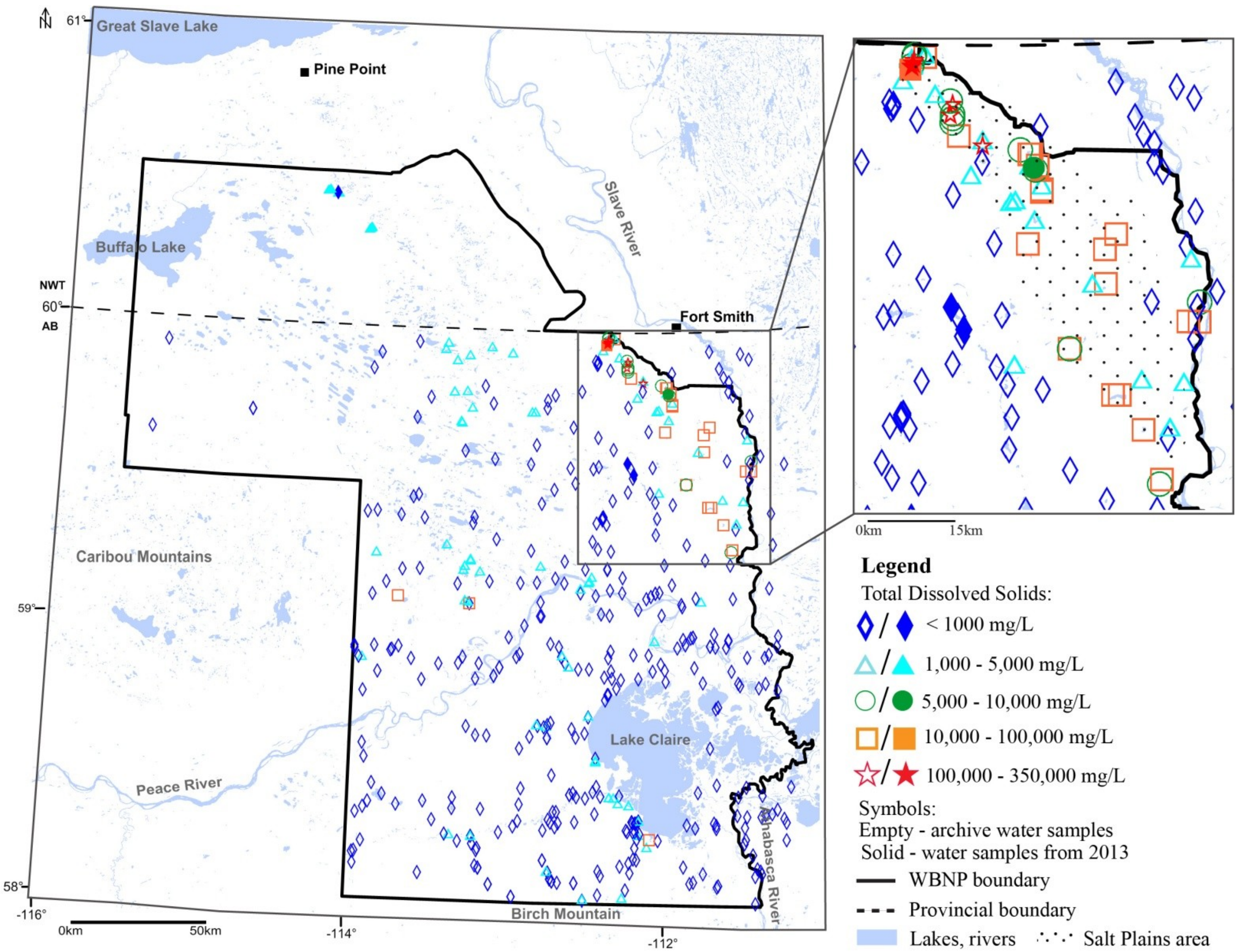

Figure 2.6: Spatial distribution of total dissolved solids (TDS) concentrations of water samples in WBNP. Empty symbols: samples from archive dataset, Solid symbols: samples from 2013. Inset map shows the Salt Plains area.

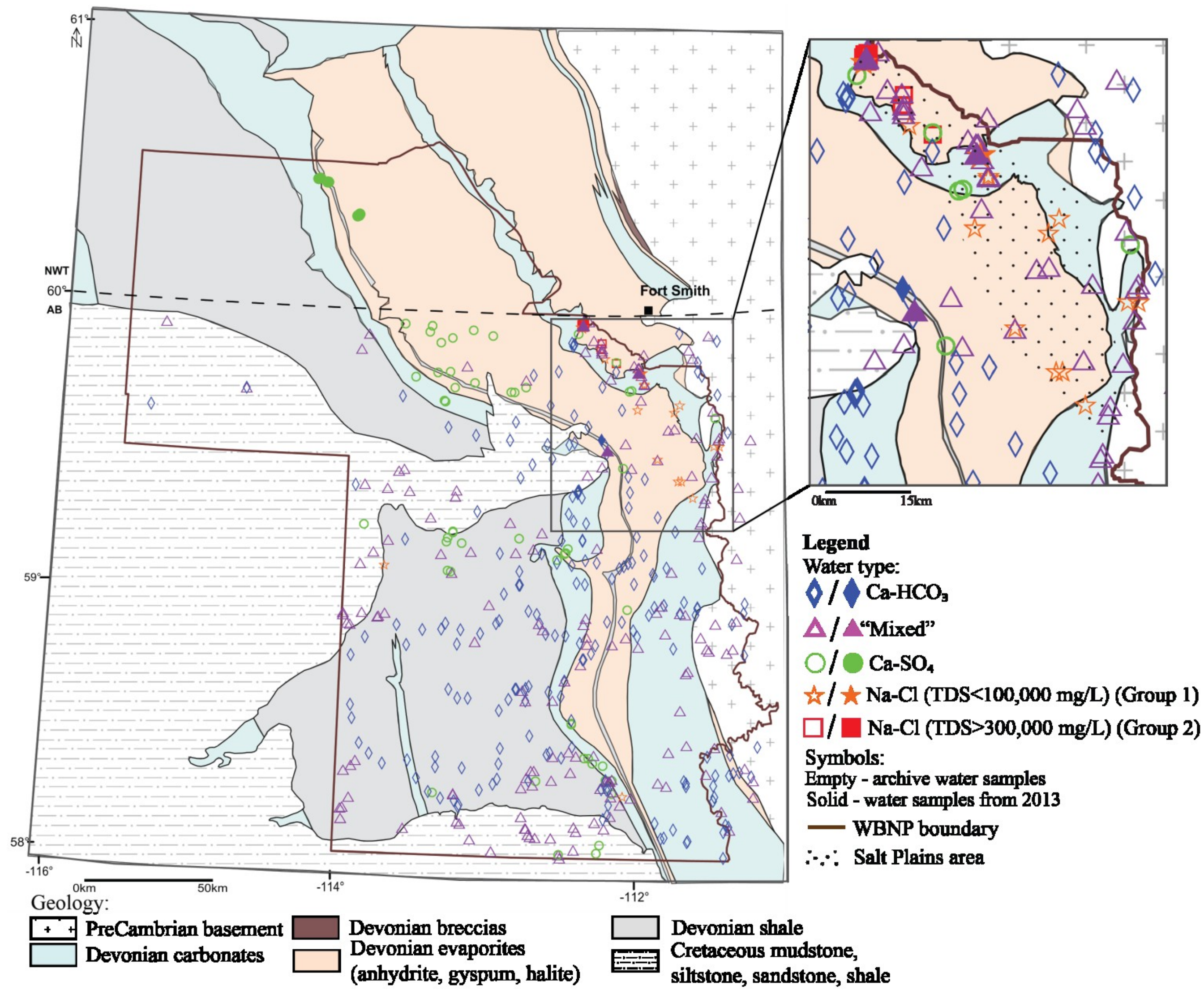

Figure 2.7: Hydrochemical facies of water samples in WBNP. Empty symbols: samples from archive dataset, Solid symbols: samples from 2013. Inset map shows the Salt Plains area. Bedrock geology is also shown (modified after Prior et al. 2013 and Okulitch and Fallas 2007)

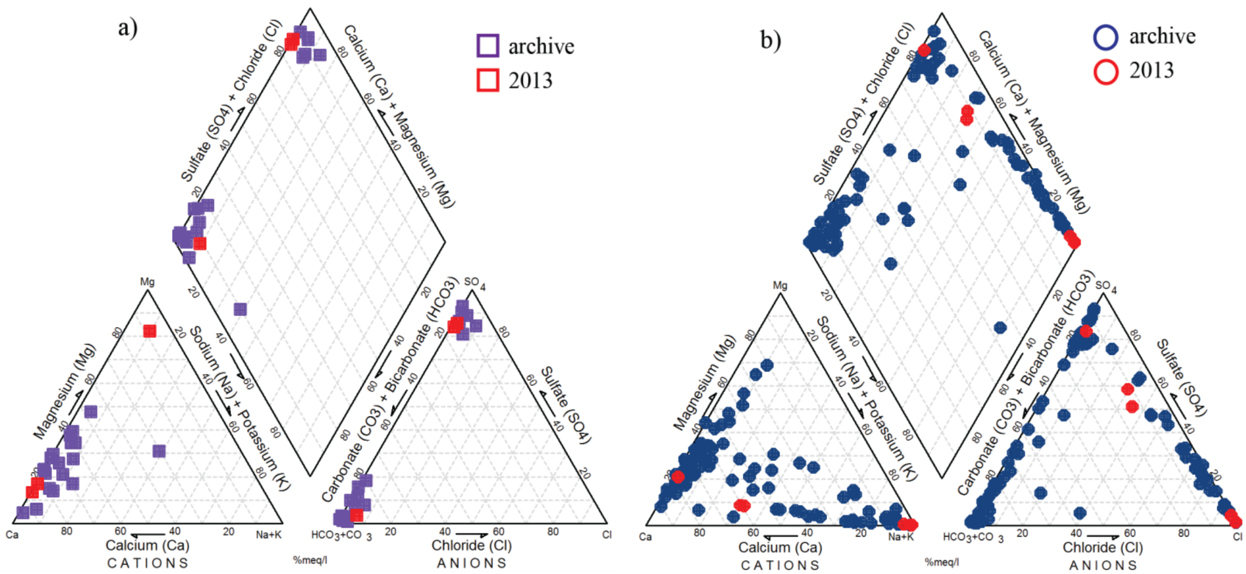

Figure 2.8: Piper plot of waters in the Wood Buffalo National Park by sample source a) sinkhole lakes b) groundwaters

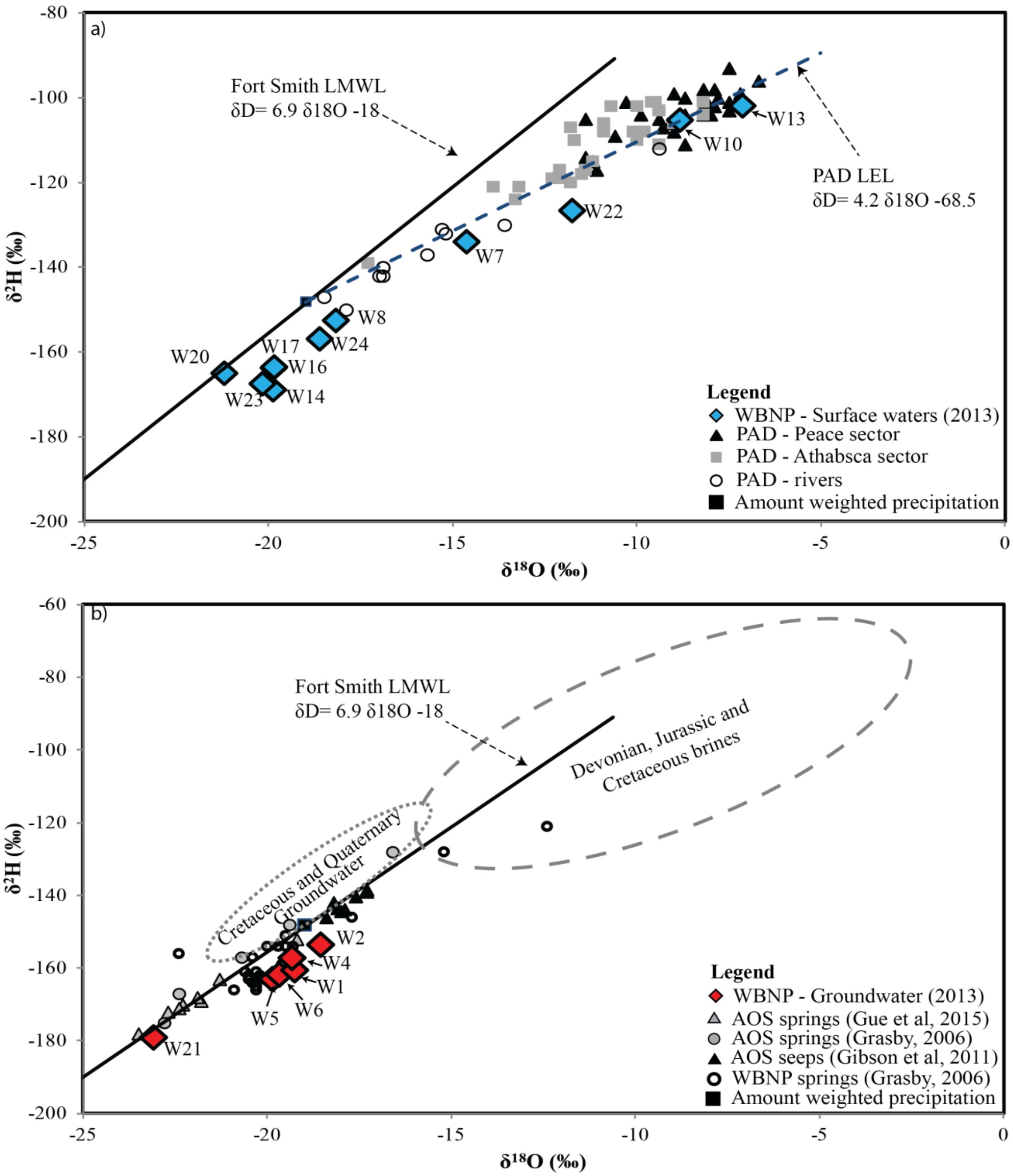

Figure 2.9: Isotopic composition of springs and surface waters from WBNP. Local Meteoric Water Line (LMWL) was constructed from the isotopic composition of precipitation measured for Fort Smith, NWT (IAEA/WMO 2015). Predicted Local Evaporation Line (LEL) for PAD (Wolfe et al 2007) is also shown. The average weighted δ^{18}O and δ^{2}H values in precipitation for Fort Smith is -19.0‰ and -148‰, respectively (Birks et al. 2003). a) Comparison of isotopic composition of surface waters in WBNP and in the PAD (Wolfe et al. 2007) b) Comparison of isotopic composition of groundwaters in WBNP with Devonian (Connolly et al. 1990), Jurassic (Connolly et al. 1990), Cretaceous (Connolly et al. 1990 and Lemay 2002) and Quaternary (Lemay 2002) groundwaters from the Alberta Basin, as well as springs and seeps from the AOS (Grasby 2006; Gue et al. 2015; Gibson et al. 2011)

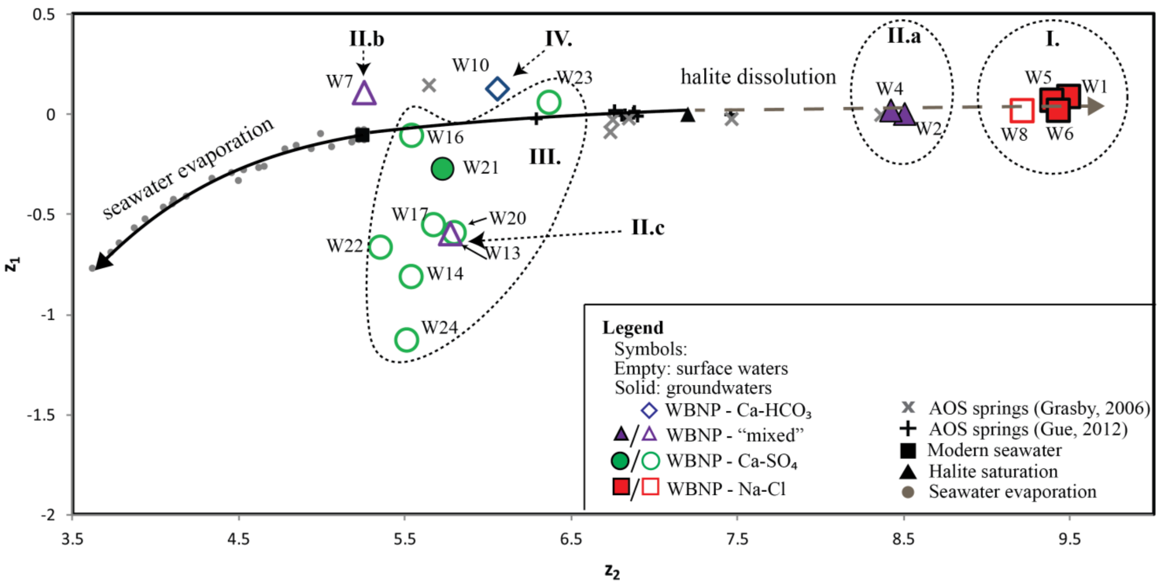

Figure 2.10: Na-Cl-Br isometric log-ratio diagrams of springs and surface waters from WBNP. Springs from AOS area (Grasby 2006; Gue 2012; Gue et al. 2015) are showed for comparison. The solid line represents the seawater evaporation and halite dissolution trends. Data for seawater evaporation line is from McCaffrey et al. 1987. The dashed line represents progressive cycles of halite dissolution by either diluted seawater or meteoric water followed by dilution. Latin numerals indicate types of waters.

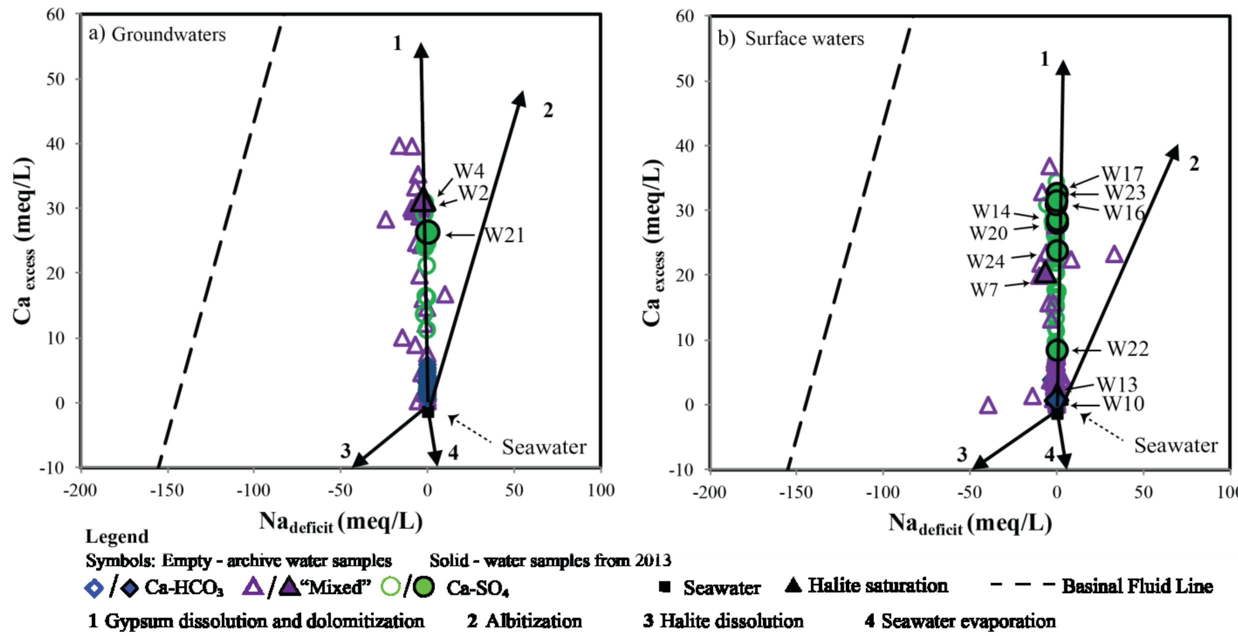

Figure 2.11: a) Na deficit and Ca excess diagram of groundwater samples in WBNP. b) Na deficit and Ca excess diagram of surface water samples in WBNP. Solid lines represent trends for various processes that may affect the composition of the fluids. Dashed line represents the Basinal Fluid Line from Davisson and Criss (1996).

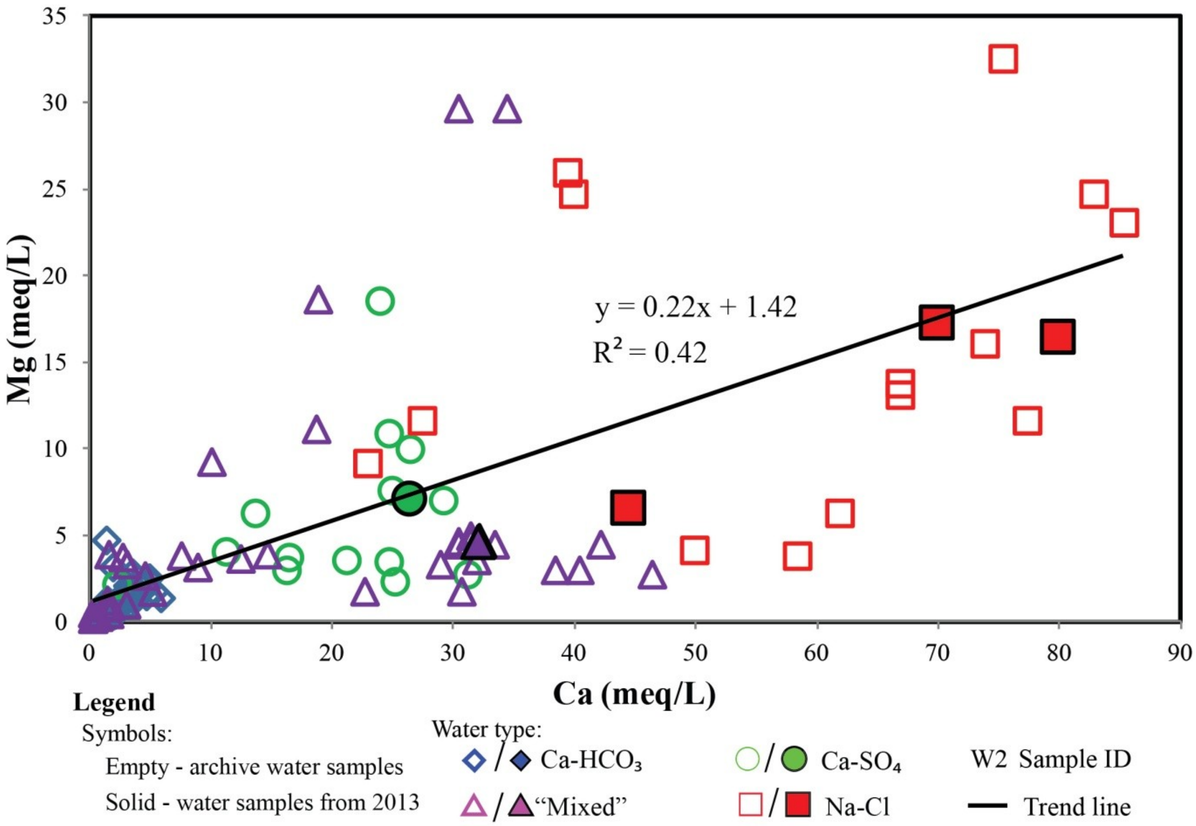

Figure 2.12: Correlation between Ca versus Mg in groundwaters in WBNP

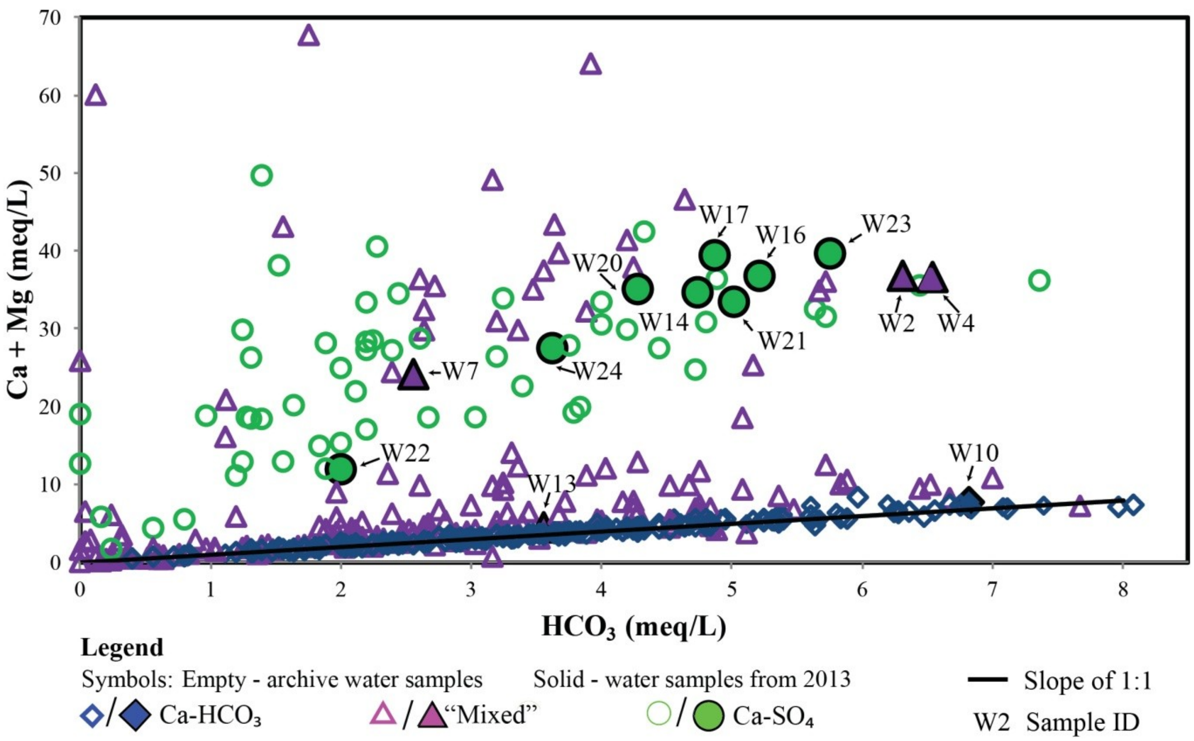

Figure 2.13: Concentrations of Ca plus Mg versus HCO_3. Slope of 1:1 represents the trend of Ca+Mg and HCO_3 concentrations in meq/L and indicates dissolution of carbonates composed of calcite and dolomite.

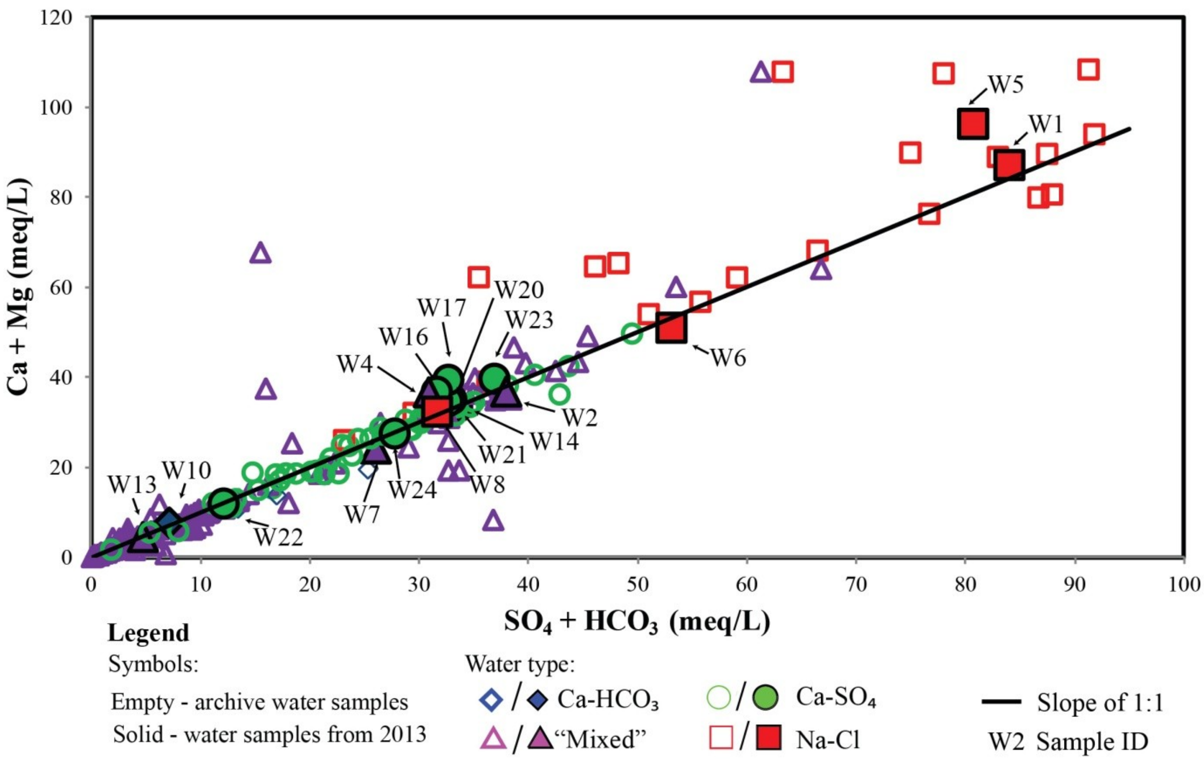

Figure 2.14: Concentrations of Ca plus Mg versus SO_4 plus HCO_3 in waters from WBNP. Slope of 1:1 represents the trend in Ca+Mg and SO_4+HCO_3 concentrations when carbonate and gypsum dissolution both contribute to the ion composition.

Table 2.1: Type of water sampling locations, and number of samples (SW= Surface water; GW= Groundwater)

Type of water sample	Sampling location	Number of samples	
		Archive	**2013**
flowing surface water (SW)	stream, river, creek, ditch, channel	67	-
still surface water (SW)	lake, pond, pool, hole, wallow	229	8
wetland (SW)	muskeg, oxbow, cutoff, slough	46	-
sinkhole lake (SW)	sinkhole	19	3
groundwater (GW)	spring, seep, cave, auger, well	92	6
N/D	not defined	4	-
Total		457	17

Table 2.2: Location, type, field measurements of samples collected in 2013 in WBNP. Results of stable isotope analyses for $\delta^{18}O$ and $\delta^{2}H$; and water types are also listed.

Sample ID[a]	Sample type	Latitude (°)	Longitude (°)	pH[b]	T (°C)[b]	TDS (mg/L)	CBE (%)[c]	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	HCO_3 (mg/L)
W1	spring	59.96381	112.40172	5.6	8.9	331,000	6.2	138000	0	210	1400	198
W2	spring	59.96216	112.40348	6.57	5.3	3,550	-1.0	373	0	57	644	385
W4	spring	59.95954	112.40430	7.22	7.1	3,260	6.2	399	0	56	642	399
W5	spring	59.95806	112.40656	5.89	10.6	324,000	5.0	133000	0	200	1600	209
W6	spring	59.95220	112.41127	-	4.7	66,800	1.2	25300	0	80	890	250
W7	pond	59.79718	112.01135	7.36	18	3,110	1.8	588	0	34	428	156
W8	lake	59.79177	111.99855	7.7	20.1	9,450	1.2	2900	0	30	599	175
W10	sinkhole	59.55707	112.25985	8.45	17.3	619	-4.0	14	9	85	13.8	416
W13	lake	59.51972	112.21765	8.02	20.1	370	-3.3	5	8	34	33.2	217
W14	lake	60.32058	114.01690	6.9	9.9	2,300	2.5	4	2	75	572	289
W16	lake	60.32280	114.00708	7.1	13.7	2,300	7.5	5	2	64	631	318
W17	sinkhole	60.32647	114.00212	7.2	15.9	2,390	9.0	5	2	83	654	297
W20	lake	60.43442	114.23298	6.78	12.1	2,320	2.6	8	2	86	562	261
W21	spring	60.43467	114.24110	6.66	5.5	2,320	-0.3	10	2	86	528	306
W22	lake	60.43452	114.24084	7.5	15.3	840	-1.7	4	2	43	169	122
W23	lake	60.44697	114.29075	6.41	6	2,660	3.7	36	3	106	620	351
W24	sinkhole	60.44441	114.30522	7.26	14.6	1,920	-1.2	2	1	45	477	221

Sample ID[a]	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	Br (mg/L)	$\delta^{18}O$ (‰)[d]	$\delta^{2}H$ (‰)[d]	Br/Cl	z_1[e]	z_2[e]	Ca_{excess} (meq/L)[f]	$Na_{deficit}$ (meq/L)[f]	Water type
W1	0	3879	188000	4.0	-19.3	-161	0.00002	0.09	9.5	-141.3	-1410.0	NaCl
W2	0	1521	571	0.0	-18.5	-154	0.00007	0.00	8.5	31.5	-2.2	"mixed"
W4	0	1170	596	0.0	-19.3	-157	0.00008	0.02	8.4	31.4	-2.8	"mixed"
W5	0	3712	186000	4.5	-19.9	-163	0.00002	0.07	9.4	-129.1	-1239.9	NaCl
W6	0	2353	37900	0.8	-19.7	-162	0.00002	0.02	9.4	1.7	-172.0	NaCl
W7	0	1129	778	3.0	-14.6	-134	0.004	0.11	5.3	20.5	-6.5	"mixed"
W8	0	1383	4360	0.1	-18.2	-153	0.00003	0.02	9.2	25.0	-19.4	NaCl
W10	48	16	18	0.0	-8.8	-105	0.001	0.13	6.1	0.7	-0.2	$CaHCO_3$
W13	0	57	17	0.0	-7.1	-102	0.001	-0.60	5.8	1.6	0.2	"mixed"
W14	0	1340	19	0.0	-19.9	-169	0.001	-0.81	5.5	28.5	0.3	$CaSO_4$
W16	0	1269	9	0.0	-19.8	-164	0.002	-0.11	5.5	31.5	0.0	$CaSO_4$
W17	0	1336	16	0.0	-19.9	-164	0.001	-0.55	5.7	32.6	0.2	$CaSO_4$
W20	0	1377	27	0.0	-21.2	-165	0.001	-0.59	5.8	28.0	0.3	$CaSO_4$
W21	0	1367	23	0.0	-23.1	-179	0.002	-0.27	5.7	26.3	0.1	$CaSO_4$
W22	0	486	15	0.0	-11.8	-127	0.002	-0.66	5.4	8.4	0.2	$CaSO_4$
W23	0	1496	51	0.0	-20.2	-167	0.001	0.06	6.4	30.9	-0.3	$CaSO_4$
W24	0	1160	17	0.0	-18.6	-157	0.001	-1.13	5.5	23.8	0.3	$CaSO_4$

[a] Samples W3, W9, W11, W12, W15, W18, W19 were not analyzed
[b] Measured in the field
[c] Charge Balance Error (cut-off 10%)
[d] V-SMOW
[e] $z_1 = \frac{1}{\sqrt{2}} ln \frac{[Na]}{[Cl]}$; $z_2 = \frac{\sqrt{2}}{\sqrt{3}} ln \frac{([Na][Cl])^{0.5}}{[Br]}$ (Engle and Rowan, 2013)
[g] $Ca_{excess} = [\mathrm{Ca_{meas}} - (\mathrm{Ca/Cl})_{\mathrm{sw}}\mathrm{Cl_{meas}}]\, 2/40.08$; $Na_{deficit} = [(\mathrm{Na/Cl})_{\mathrm{sw}}\mathrm{Cl_{meas}} - \mathrm{Na_{meas}}]\, 1/22.99$ (Davisson and Criss, 1996)

Chapter 3 Isolating effect of the Caribou Mountains on flow systems in Wood Buffalo National Park, Alberta, Canada

3.1. Abstract

Topography is the main driving force of regional groundwater flow systems, especially in the Alberta Basin. However, variations in the topography can break up regional groundwater flow systems into local and intermediate systems.

The Caribou Mountains are one of the largest topographic features in the northern Alberta Basin. They are bounded by the protected lowlands of WBNP in north and east and considered a major regional recharge area in the region.

Basin-scale flow of formation fluids in the northern Alberta Basin is driven by topography. This paper illuminates the isolating effect of the Caribou Mountains on the flow regime of WBNP and elucidates how the mountains affect the connection between the fluids in WBNP and the basin-scale formation waters in the rest of the Alberta Basin.

Simulations of flow systems show no connection between the flow regime in WBNP and basin-scale fluids migrating from the western part of the Alberta Basin. The Caribou Mountains are important controlling factor of the flow regime in WBNP that block basin-scale formation fluids from entering the central region of WBNP.

3.2. Topography-driven groundwater flow and nested flow systems in the Alberta Basin

Flow of basin-scale formation fluids in large sedimentary basins is most commonly driven by hydraulic gradients induced by elevation differences in the water table (topographic relief) with lesser amounts driven by buoyancy effects due to differences in density of formation fluids (Garven 1995).

Topography-driven regional groundwater flow is generated by variations in fluid potential (i.e. hydraulic head) caused by differences in the water table elevation where the water table is considered to be a subdued replica of the topography (Tóth 1962, 1963). Undulation in the topography generates hierarchically superimposed, nested flow systems on local, intermediate and regional (or basin) scale (Tóth 1963). Local flow systems are defined as systems where recharge and discharge areas are adjacent to each other; whereas regional flow systems have recharge at the region's major divide and discharge at the major valley. Intermediate flow systems have recharge and discharge areas separated by one or more local flow systems (Tóth 1963).

A well-studied example of topography-driven flow is the Alberta Basin. Basin-scale flow of formation fluids in the northern Alberta Basin is driven by topography- and, in places, modified by the driving force of high-density fluids by enhancing or retarding the flow intensity (Hitchon 1969; Bachu and Underschultz 1993; Bachu 1997).

The basin-scale flow direction in the northern Alberta Basin is northeastward. The general flow is from the fold belt in the southwest and the Bovie Lake Fault (Bachu 1997). Basin-scale formation fluids discharge at the major lowlands in the northeastern corner of Alberta and south Northwest Territories (Hitchon 1969, 1984; Bachu 1997). Three major hydrodynamic zones have been identified in northern Alberta. Aquifers below the Prairie Evaporite (Muskeg) Formation (e.g. Keg River Aquifer) show regional flow-regime characteristics with a northeastward flow direction. Paleozoic aquifers above the Prairie Evaporite (e.g. Slave Point Aquifer) exhibit intermediate-scale flow characteristics with an up-dip flow to the northeast; and Cretaceous aquifers (e.g. McMurray-Bluesky Aquifer) show local flow-regime characteristics (Tóth 1978; Ozoray 1980; Hitchon et al. 1990; Bachu and Underschultz 1993). While the regional flow systems of the Paleozoic zone are in a transient state still adjusting to present-day topography, the intermediate-regional-scale flow systems in the Paleozoic-Mesozoic zone; and the local-scale flow systems of the Mesozoic-Cenozoic zone are in equilibrium with present-day topography and show steady-state conditions (Tóth 1978; Hitchon et al. 1990).

3.3. Influence of elevated topography on regional groundwater flow

The Caribou Mountains are the largest topographic feature in the northern Alberta Basin attaining elevations of 1000 m above sea level. They are surrounded by extensive boreal and taiga plains and bounded by the protected lowlands of the Wood Buffalo National Park (WBNP) in north and east (Figure 3.1). The uplands of the Caribou Mountains are considered a major regional recharge area (Hitchon 1969, 1984).

It has been demonstrated that major topographic features, such as large uplands can modify the basin-scale flow pattern changing it into a more regional-intermediate-scale flow domain (Hitchon 1969; Bachu 1997). The effect of these topographic features on the potentiometric surface is the most dominant in the intermediate and local flow regimes. The deep, regional flow regimes remain isolated from these local topographic effects (Bachu 1997; Bachu and Underschultz 1993).

This paper analyzes how major topographic features, such as the Caribou Mountains, affect the flow pattern of formation fluids in the Alberta Basin. The main question is: Do the Caribou Mountains effectively block up-dip movement of "basinal" fluids from the Alberta

Basin in the west? The hypothesis is that the Caribou Mountains represent a groundwater divide that impedes entry of basin-scale fluids from the west in the northeastern corner of the Alberta Basin. Numerical simulations and sensitivity analyses of two conceptual models of groundwater flow are used to show lack of connection of central WBNP to the rest of the Alberta Basin and to see how the different conceptualizations of groundwater flow influence the flow patterns in central WBNP (Figure 3.2). The two scenarios considered were: *Case 1* represents a system where fluids can enter the region from the western Alberta Basin and flow up-dip towards the eastern edge of the basin, i.e. there is no vertical "no-flow" boundary beneath the Caribou Mountains (Figure 3.2a). In *Case 2*, up-dip flow from the west is not allowed. The Caribou Mountains are considered a groundwater divide that breaks up flow systems and prevent fluids entering the region from the west, i.e., there is a vertical "no-flow" boundary beneath the mountains (Figure 3.2b).

3.4. Study area

3.4.1. *Topography*

The area considered in this study encompasses the uplands of the Caribou Mountains in the west and the lowlands of WBNP located at the northeastern edge of the basin (Figure 3.1).

The Caribou Mountains are a large plateau with an area of 14,222 km^2, characterized by undulating to rolling highlands and large low-lying, poorly-drained depressions. The plateau is covered by extended peatlands and moraine sediments (Figure 1.6). The top of the plateau lies in the Boreal Subarctic Natural Subregion while the slopes and some of the deeper valleys belong to the Lower Boreal Highlands Natural Subregion (Allen et al. 2006). The Caribou Mountains rise 600-700 m above the surrounding lowlands and represent the highest elevations in northern Alberta reaching to a maximum of 1030 m asl (Figure 3.1). The low temperatures and the insulating effect of peat layers contribute to sporadic, discontinuous permafrost formation (Heginbottom et al 1995). Seasonal frost in the subarctic region reduces infiltration of water from snowmelt and early spring rains and promotes overland flow (Woo and Winter 1993).

To the east of the Caribou Mountains is the area of WBNP. WBNP occupies the largest portion of the studied region (Figure 3.1) hosting extensive boreal forests, wetlands and prairie with unique ecosystems, as well as outstanding examples of karstic landform, saline springs and salt deposits (Figure 3.1). The land surface of the park gradually declines from the foot of the Caribou Mountains to a steep escarpment near the eastern boundary separating the Salt Plains and the Slave River-area from the rest of the lowlands of the national park (Figure 3.1).

3.4.2. *Geology and hydrostratigraphy*

The study area sits on the northeastern edge of the Alberta Basin. Strata in the northeastern Alberta Basin are from Devonian to recent age (Figure 3.3, Figure 3.4). Their geological description can be found in regional characterizations of the strata of the Western Canadian Sedimentary Basin (Meijer Drees 1994; Oldale and Munday 1994 and Switzer et al. 1994).

The overall geology of the area can be characterized by four major geologic packages (Figure 3.3). The simplified geology and hydrostratigraphy of typical cross-section through the area is shown in Figure 3.3, Figure 3.4 and Figure 3.5.

Package I - Crystalline basement

Package I consists of crystalline Precambrian basement dipping to the southwest and composed of igneous and metamorphic rocks (Figure 3.3, Figure 3.4). The Precambrian crystalline basement is considered an aquiclude (e.g. Hitchon et al. 1989) since its hydraulic conductivity is orders of magnitudes lower than that of sedimentary rocks (Unit I) (Figure 3.3, Figure 3.5)

Package II - Devonian strata

Package II contains Devonian strata and represents the most important bedrock units in WBNP. The southwesterly-dipping Devonian rocks are composed of carbonates, evaporites and shales, and divided into three geological groups, the Elk Point, the Beaverhill Lake and the Woodbend groups (Figure 3.3). The low-permeability successions of carbonates, halite and anhydrite are considered aquitards and form the Elk Point Aquitard system (Unit G) (Bachu 1995a, 1997) (Figure 3.3, Figure 3.4, Figure 3.5). Above that is the first regionally extensive aquifer unit, which is the carbonate-dominated Keg River Formation with hydraulic conductivity values ranging from 10^{-10} to 10^{-4} m/s (Unit F) (Bachu 1997) (Figure 3.5). The Keg River Aquifer is overlain by the low-permeability geological units of the Muskeg-Watt Mountain-Fort Vermilion Aquitard System with an average hydraulic conductivity of 10^{-10}-10^{-9} m/s forming the second regionally extensive aquitard in the area (Unit E) (Bachu and Underschultz 1992) (Figure 3.5). Over top of that is the Slave Point Formation, which forms the second regional aquifer. The Slave Point Aquifer has hydraulic conductivity values ranging from 10^{-9} to 10^{-5} m/s in Northeastern Alberta (Unit D) (Bachu 1997).

The Ireton/Hay River Aquitard System comprises of the low-permeability shales, calcareous shales and argillaceous limestones of the Waterways, Hay River and Ireton formations with hydraulic conductivity values ranging from 10^{-11} to 10^{-9} m/s (Unit C) (Tóth and Millar 1983). The edge of the Grosmont Formation is included in the Ireton/Hay River Aquitard System, but this formation was not differentiated as a separate hydrostratigraphic unit in this study due to lack of detailed distribution data of the formation.

Package III - Cretaceous strata

Package III consists of Cretaceous siliciclastic deposits that unconformably overlay the Devonian strata and only occur in the Caribou and Birch Mountains regions (Figure 3.3). The Devonian-Cretaceous unconformity zone is characterized by the sandstone of the McMurray and Bluesky formations, which are considered aquifers with an average hydraulic conductivity of 10^{-7}-10^{-6} m/s measured from drill stem tests and on cores (Unit B) (Tóth 1978; Tóth and Millar 1983). The occurrence of the McMurray-Bluesky Aquifer is limited mostly to the area of the Caribou Mountains.

Overlaying the McMurray-Bluesky aquifers are the thick shales of the Cretaceous Fort St. John Group and Smoky Group with the imbedded sandstone of the Dunvegan Formation that are considered to be aquitard units. These units are part of the Cretaceous Aquitard System with an average hydraulic conductivity of 10^{-9}-10^{-11} m/s determined on core samples (Tóth 1978; Tóth and Millar 1983) (Unit A).

Package IV - Quaternary deposits

Package IV includes unconsolidated surficial material of Quaternary age. The thickness varies from 1 to 45 m in most of the study area but locally it can reach up to 150 m in the upland areas (Pawlowicz and Fenton 1995; Fenton et al. 2013). It contains glaciolacustrine and moraine sediments as well as aeolian, fluvial and lacustrine sediments that are often overlain by organic (peat) material. Extended peatlands cover the uplands of the Caribou Mountains where the low temperatures and the insulation effect of the peat layer promote discontinuous, sporadic permafrost formation (Heginbottom et al 1995). The hydraulic conductivity of the surficial material can range from 10^{-8} m/s or lower to 10^{-3} m/s depending on the clay, silt, sand and peat content of the sample (Nobert and Barrie 1986). Permafrost is generally considered aquitard or aquiclude (Woo 2012). Considering their limited vertical thickness in most of the study area Quaternary deposits were not incorporated in the model structure.

The latest bedrock and surficial geology maps of the area were published by the Alberta Geological Survey and Geological Survey of Canada as part of regional bedrock and surficial geology mapping at a 1:1,000,000 scale (Prior et al. 2013; Okulitch 2006; Okulitch and Fallas 2007; Fenton et al. 2013). Surficial geology maps at a scale of 1:250,000 are also available (Bayrock 1972a, b, c; Lemmen 1998a, b; Mougeot and Fenton 2010).

3.5. Methods and data

Numerical simulations of nested flow systems were concluded with Visual MODFLOW, a Graphical User Interface for MODFLOW-2005 (Harbaugh 2005).

3.5.1. *Conceptual models*

Two two-dimensional (2D) groundwater flow models were created. In *Case 1*, flow is allowed into the domain from the Alberta Basin west of the study area (Figure 3.2a). In *Case 2*, the western boundary of the domain is represented by no flow boundaries and flow is isolated from the rest of the Alberta Basin (Figure 3.2b).

3.5.2. *Domain design*

The models represent cross-section A-A' running from the highest peak of the Caribou Mountains in the southwest (SW) to the Salt Plains in the northeast (NE) (cross section A-A', Figure 3.1). The starting point of cross-section A-A' was determined based on results of numerical simulation of groundwater flow along an extended version (A**-A') of cross-section A-A'. Details of cross-section A**-A' and the result of the numerical modeling are shown in Appendix I. The starting point of the cross-section (A) represents the surface water divide (SWD) in the area. The direction of the cross-section A-A' follows the preferential, northeastward flow direction of formation fluids in the northern Alberta Basin.

The two-dimensional model grid contains 303 columns and 1 row with grid spacing of 750 m. Number of layers in the grid is 24 with finer spacing in the aquifers and coarser in the aquitard units (Figure 3.6).

The top of the model was created from 90 m (1:250 000) resolution digital elevation models (CDED 1997-1999). Topographic elevation data were exported from DEM files using GIS resources and then imported as surface elevation into Visual MODFLOW. The bottom elevation of the model follows the top of the Precambrian basement. The depth of the basement was obtained from literature data (Green 1958; Burwash et al. 1994; Prior et al. 2013) and interpolated.

The thickness of the domain is 1,700 m in the west and decreases towards the basement outcrop in the east.

The geology was simplified by grouping the geologic formations based on their ability to conduct (aquifer) or retard (aquitard) water as shown by the modelled hydrostratigraphy (Figure 3.3). The hydrostratigraphic units of the modelled cross-sections are shown in Figure 3.5. In addition to the previously discussed aquifers and aquitards, a separate unit (Unit H) was introduced at the eastern edge of the modelled area to represent the weathered zone in the Chinchaga Formation in its outcrop area (Figure 3.5).

Hydraulic conductivity values were first assumed based on published data for hydrostratigraphic units in northern Alberta (Tóth 1978; Bachu and Underschultz 1992; Bachu 1997), and later were calibrated to match the simulated hydraulic head values to measured values in observation wells (Figure 3.6, Table 3.1, Table 3.2).

3.5.3. *Boundary conditions*

The model is bounded by three types of boundary conditions: no flow/impermeable, specified head, and general head boundaries.

A no-flow boundary is used at the bottom of the domain to represent the very low-permeability geologic units of the Precambrian basement (e.g. Hitchon et al. 1989). The water table was represented as a specified head boundary with hydraulic head values specified at the topographic surface elevations based on the assumption that the water table is a subdued replica of the topography (Tóth 1963).

For *Case 1*, a head-dependent flux boundary was used within the aquifer units (Keg River, Slave Point, McMurray aquifers) along the left side of the domain (Figure 3.2a). General-head boundaries allow groundwater to move either into or out of the model domain as a function of the hydraulic head changes along the boundary. In practice, hydraulic head values were assigned at distance of 8.3 km in Keg River and Slave Point aquifers and 13 km in the case of the McMurray-Bluesky Aquifer east of the cross-section. Head values assigned to these nodes were calculated from formation pressure data measured from drill-stem tests in the Caribou Mountains (Table 3.3). The calculated head values are consistent with previously published literature data on hydraulic head distribution in the aquifers of the northern Alberta Basin (Bachu 1997).

For *Case 2*, a vertical no-flow boundary was assigned across the aquifer and the aquitard units. This representation does not allow groundwater to leave or enter the model domain across this boundary and assumes that the simulated flow regime is isolated from the remainder of the Alberta Basin (Figure 3.2b).

3.5.4. *Model calibration, particle tracking*

The simulations were calibrated to minimize the difference between observed and simulated hydraulic head values. Subsurface data are scarce and the number of observations available for calibration was limited due to the protected and remote status of the study area. For calibration, hydraulic head values were calculated from fluid-pressure measurements in 7 wells (3 in Keg River Formation, 4 in Slave Point Formation), all located in the west side of the domain, in the Caribou Mountains region (Figure 3.6).

The difference between observed and calculated values was measured by root mean squared error (RMSE). RMSE is the residual standard deviation divided by the range of observed hydraulic head values over the domain. Recommended RMSE values should be less than 10% for a good calibration (Wels et al. 2012). The calibration criterion in the current study was set at 10%, and hydraulic conductivity values were adjusted through trial-and-error method to meet the calibration target.

Once calibrated, pathlines were computed using the MODPATH particle tracking program (Pollock 2012). Particles were placed at the top of the first layer along the entire domain and tracked forward to their discharge location. Results of particle tracking were used to identify groundwater flow paths of different scales; i.e. local, intermediate and regional flow systems, and to qualitatively characterize the flow domain in the study area.

3.5.5. *Further assumptions*

The model implementation deliberately neglects the effects of variable density flow caused by changes in fluid properties such as salinity or temperature. Effects of variable-density formation waters in the post-Muskeg aquifers, i.e., Slave Point and Bluesky-McMurray aquifers, are not significant and can be neglected (Bachu and Underschultz 1993). Although high fluid densities in the Keg River Formation could cause deviations in the magnitude and local flow direction of fresh water (Bachu and Underschultz 1993), it is assumed that it would not significantly affect the regional northeastward flow direction that characterizes the basin.

3.6. Results and discussion

3.6.1. *Cases of different conceptualizations of the Caribou Mountains*

Case 1 -Connection to the Alberta Basin to the west

In *Case 1*, simulated hydraulic heads range from 977 m above sea level in the Caribou Mountains to 180 m above sea level in the Salt Plains region with the steepest hydraulic gradients at the foot of the mountain, and the lowest gradients in the lowlands (Figure 3.7). Simulated heads were compared to observed heads that showed reasonable agreement after calibration with field observations (RMSE=10%) (Figure 3.8a).

Diverging flow paths indicate that there is a regional groundwater divide (RGD) 46 km east of southwestern domain boundary that penetrates the deepest aquifer (Keg River Aquifer, Unit F). The RGD falls to the east of the surface water divide (SWD) and does not coincide with the highest topographic elevation of the section (Figure 3.7).

The main recharge area of the intermediate/regional-scale flow systems is in the Caribou Mountains (Zone 1) (Figure 3.7); whereas local-scale flow systems are induced by local topographic relief in the Caribou Mountains and in the shallowest parts of the domain. The main discharge area is at the NE boundary of the domain (A'), in the Salt Plains region, where groundwaters discharge both from regional and local flow systems (Zone 3) (Figure 3.7). Regional-scale flow occurs only in the Keg River Aquifer. Intermediate-scale flow systems are associated with the Slave Point and Keg River aquifers in the middle of the domain (Zone 2) (Figure 3.7), and local flow systems are related to the McMurray-Bluesky Aquifer and at near-surface depths in the Keg River and Slave Point aquifers.

Case 2 –Caribou Mountains as regional groundwater divide

In Case 2, a no-flow boundary was assigned to the aquifers in the southwest representing the Caribou Mountains as regional groundwater divide (Figure 3.9). The simulation with adjusted hydraulic conductivities resulted in a good agreement between the simulated and observed hydraulic heads (RMSE=9%) (Table 3.1, Figure 3.8b). The highest topographic elevation coincides with the RGD, as a natural consequence of the model structure and implemented boundary conditions.

The Caribou Mountains act as the main recharge area in the region (Zone 1) (Figure 3.9). The lowlands (Zone 2), similarly to *Case 1*, are characterized by local flow systems in shallow depths generated by local topographic reliefs and by discharge of intermediate-scale flow systems (Figure 3.9). The discharge area of regional-scale flow systems occurs in the right side of the domain, in the Salt Plains region (Zone 3) (Figure 3.9). The regional-scale flow system is only present in the deepest aquifer, the Keg River Aquifer; intermediate flow systems are characteristic of the Slave Point and Keg River aquifers; while the shallowest McMurray-Bluesky Aquifer and outcrop areas of deeper aquifers are dominated by local flow regime.

Summary

Case 1 and *Case 2* show similar characteristics in the flow field, i.e., regional-scale flow in the Keg River Aquifer, intermediate-scale flow systems in the Slave Point and Keg River aquifers and local flow systems in the McMurray-Bluesky Aquifer and at near-surface depths. In both cases, there is a groundwater divide under the Caribou Mountains. The only difference between the two scenarios is a northeastward shift of the groundwater divide in

Case 1 resulting in lesser amount of flow in aquifers towards WBNP as shown by the water balance calculation (Table 3.4).

3.6.2. *Sensitivity analysis*

The sensitivity of the models to two parameters was assessed: hydraulic conductivity and hydraulic head values assigned to the general head boundary. A sensitivity analysis was also carried out to evaluate uncertainty in the location of the regional groundwater divide.

Sensitivity to hydraulic conductivity

The sensitivity of the models to hydraulic conductivity was tested by increasing and decreasing the hydraulic conductivity by variable K'/K ratios (K'/K= 0.5; 0.2; 0.1; and 2; 5; 10) (Table 3.1), where *K* is the calibrated value and *K'* is the increased or decreased value (Figure 3.10). In both cases, the McMurray-Bluesky aquifers and Cretaceous aquitard units were shown to be the least sensitive to the change in the hydraulic conductivity values by not yielding an appreciable change in RMSE values. Among the aquitards, change in K of the Ireton/Hay River and Muskeg-Watt Mountain-Fort Vermilion units resulted in the highest increase in the RMSE values, reaching 60% in case of Ireton/Hay River, and 45% in case of Muskeg-Watt Mountain-Fort Vermilion aquitards. In case of the aquifers, change in hydraulic conductivity of Slave Point and Keg River aquifers had the largest impact on the model. The impact of changing hydraulic conductivity in Slave Point Aquifer is less significant in the case of simulation using general-head boundaries (*Case 1*) than that in the case of using no-flow boundary conditions (*Case 2*).

Comparing the magnitude of perturbation of hydraulic heads for both cases, the RMSE values show a much larger range with a higher maximum (9-61%) in *Case 2* than that of the head-dependent simulations (9-47%) in *Case 1* (Figure 3.10).

Sensitivity to hydraulic head

Case 1 was also tested for sensitivity to variable head values (deep basin heads) assigned to the general-head boundary in the three aquifers (Table 3.3). The tested h'/h ratios change between 0.1 and 2 (0.1, 0.4, 0.7 and 1.1, 1.3, 1.6, 2) where *h* is the hydraulic head used in the base case simulation and *h'* is increased/decreased head value. It can be seen in Figure 3.11 that the RMS error is essentially unaffected by the change in the boundary head value in the McMurray-Bluesky Aquifer. The model indicates the highest sensitivity to the change in boundary value in the Keg River Aquifer.

Uncertainty in location of the RGD

The sensitivity of the location of the groundwater divide to variable K'/K ratios in *Case 1* is demonstrated in Figure 3.12a. The original distance of the RGD in the base case was 46 km from the left domain boundary (Figure 3.7). This distance was prone to change when hydraulic conductivities of Keg River and Slave Point aquifers were increased or that of Muskeg and Ireton aquitards were decreased. In both cases the groundwater divide shifted towards the SWD or outside of the domain in case of K'/K=5 and 10 for Keg River Aquifer, and K'/K=0.1 for the Muskeg and Ireton aquitards.

As a result of change in the deep basin heads (values for general head boundaries) in *Case 1*, the original location of the RGD also changes. The RGD shifts closer to the left when the head is increased and to the right when it is decreased (Figure 3.12b). Similarly to hydraulic conductivities, change in head values at the boundary of Keg River Formation resulted in the highest impact on the system indicating significant variations in the location of RGD. Change in the h'/h ratios in McMurray-Bluesky and Slave Point aquifers has little to no effect on RGD location resulting in a maximum shift of 15 km to the left and 5 km to the right. Increasing head values in the Keg River Aquifer, however, cause significant changes in RGD location resulting in a maximum shift of 195 km to the right when head decreased (h'/h=0.1), and pushing the RGD outside of the domain when head increased (h'/h=1.6 and 2) (Figure 3.12).

Uncertainty in the location of the groundwater divide was also tested by applying various water table elevations in the main recharge area (i.e., the Caribou Mountains region) to see how the decreasing water table influences the location of the groundwater divide (Figure 3.13). In the base case (*Case 1*) the water table is approximated with the topographic surface elevation along the cross-section A-A' (Figure 3.7). The groundwater divide is located at 46 km east of the left domain boundary in the base case scenario. Decrease in the water table elevation causes the groundwater divide to shift to the west, towards the left side of the domain (Table 3.5). There is no significant change in the first two cases when the water table elevation is decreased by about 100 and 200 m, respectively. In the most extreme case, when the water table was decreased by 400 m, the groundwater divide moves outside of the domain, west of the left domain boundary (Table 3.5).

3.6.3. *Evaluation of validity of simulated models in Case 1 and Case 2*

Simulations for both conceptualizations met the calibration target (RMS error ≤ 10%), and the adjusted hydraulic conductivity values fall into the range of measured hydraulic conductivities previously reported in literature (Bachu 1997; Bachu and Underschultz 1992; Tóth 1978; Tóth and Millar 1983). However, in both cases higher hydraulic conductivities were necessary in order to meet the calibration target than the average hydraulic conductivity values reported in literature.

The sensitivity analyses revealed that, in both cases, the behaviour of the system is highly sensitive to changes in hydraulic conductivity and, in *Case 1*, to changes in deep basin head value in Keg River Aquifer (Figure 3.10, Figure 3.11). The calculated head value used as the general-head boundary in the simulation is similar to head values calculated from adjacent DST for the area. It is also consistent with previously published results on hydraulic head distribution in the Winnipegosis Aquifer in northern Alberta (Bachu 1997). These observations indicate that the values used in the base case simulations are reasonable and representative of the system.

Hydraulic head distributions in the aquifers along the cross-section are demonstrated for the two different cases in Figure 3.14. The hydraulic head distributions in the two base cases are very similar in the McMurray-Bluesky Aquifer (Figure 3.14). The potentiometric surfaces closely follow the surface topography in both cases and exhibit the highest head values in the mountains and the lowest in the lowland region (Figure 3.14). For the Slave Point Aquifer the potentiometric surface exhibits the highest head values in the mountain region and the hydraulic heads decline towards the lowlands presenting a more subdued replica of the topography than that in the McMurray-Bluesky Aquifer. While the hydraulic heads in the first two aquifers mimic fairly well the topography, the heads in the Keg River Aquifer do not or only slightly reflect the water table-relief. The hydraulic heads show a relatively flat potentiometric surface along the aquifer in both cases (Figure 3.14).

The lower than water table-elevation and downwards-decreasing hydraulic head values in the Caribou Mountains-area indicate a downward flow between the aquifers which supports that the uplands of the Caribou Mountains is a major recharge area of the basin. The subdued nature of the potentiometric surface in the Slave Point Aquifer indicates energy loss through the confining, low-permeability aquitards. This is more accentuated in the Keg River Formation.

A large-scale underpressure is a known phenomenon in the Keg River Aquifer, which is explained by presence of low upgradient and high downgradient permeabilities that allow the upgradient propagation of low hydraulic heads characterizing the discharge area (Belitz and Bredehoeft 1988; Bachu 1997). The phenomenon is explained in detail with the "tensiometer effect" by Tóth (1981).

Both models represent a regional-scale fluid flow in the northeastward direction. The Caribou Mountains isolate WBNP from the rest of the Alberta Basin. They serve a major recharge area in the region, while the regional topographic low in the northeast is considered a major discharge area.

The relation of regional, intermediate and local flow regimes to hydrostratigraphic units is also similar in the two different conceptualizations and is in good agreement with previously identified hydrodynamic zones (Tóth 1978). The regional-scale flow system only occurs in the deepest aquifer (Keg River Aquifer) and groundwater discharges at the regional topographic low. Intermediate flow systems dominate the Keg River and Slave Point formations with groundwater discharging along the second half of the domain. Local flow systems are related to the shallowest part of the domain.

It is demonstrated that the basin-scale flow in the Alberta Basin recharging at the foothills of the Rocky Mountains and discharging in the northeastern corner of the basin is modified by the major topographic feature of the Caribou Mountains. The models show that the basin-scale flow does not reach the northeastern corner of the basin along the cross-section, and that the Caribou Mountains become a dominant controlling factor in the subsurface flow-pattern as a groundwater divide.

In both cases, the Caribou Mountains isolate the flow domain in central WBNP from the remainder of the northern Alberta Basin. The groundwater divide coincides, naturally, with the highest topographic elevation (i.e., SWD) in *Case 2* when no-flow boundary is used. In *Case 1*, however, when flow from west into the domain is not restricted by no-flow boundary conditions, the RGD shifts to the east of the SWD. The change in the location of the RGD is the most extreme when hydraulic conductivity is increased in Keg River Aquifer or decreased in Muskeg and Ireton aquitards which push the RGD to the left side of the SWD (outside of the domain). In any other scenario, the RGD can be found to the east of the SWD. The significant change in the RGD location due to changing general-head boundary value would require unrealistically large increase or decrease in the deep basin heads. Such a great change in heads is highly unlikely considering the similar magnitude of other hydraulic heads calculated in the area and the general distribution of hydraulic heads in the northern Alberta Basin (Bachu 1997). The location of the groundwater divide moves outside of the domain when the water table elevation is decreased by about 400 m. Water table in the area is thought to be located relatively close to the surface as it is indicated by extended muskegs and wet soils on the top of the Caribou Mountains (Ozoray 1980). Although the shallow water table may locally represent perched water body (Ozoray 1980), it is unlikely that the unsaturated zone under the perched water body is 400 m thick. Springs with elevated TDS content discharging on the Caribou Mountains (AER/AGS 2014) indicate that the water table intercepting the surface is not a perched water body but rather represents the actual water table.

In *Case 2*, the setup of the model structure does not allow for the groundwater to enter or leave the domain and all of the water infiltrating in the mountains has to discharge inside of the domain. The RGD falls at the same location where the SWD is located providing a larger recharge area than that in *Case 1*. The larger recharge area is expected to cause quantitative differences in water budget between the two conceptual models. The qualitative interpretation of the flow domains, however, does not differ significantly.

3.7. Summary and conclusions

The Caribou Mountains form a regional groundwater divide in the Alberta Basin that blocks the basin-scale formation fluids from entering the region of WBNP, and creates an isolated flow regime in the northeastern corner of the basin.

The two different conceptualizations of the flow systems, i.e., one where up-dip flow from the Alberta Basin in the west is allowed and one where the Caribou Mountains are considered a regional groundwater divide impeding fluids entering the region, showed that the Caribou Mountains have considerable impact by isolating the flow regime in WBNP from the rest of the Alberta Basin.

The two models do not reveal significant qualitative differences in the pattern of the groundwater flow field in WBNP. In both proposed conceptual models the Caribou Mountains are important controlling factor in the regional- and intermediate-scale flow regime in WBNP. The decreasing thickness of the basin and the topographic elevations of the Caribou Mountains induce regional-scale flow systems in the deep part of the domain that changes the basin-scale character of the deep fluid-flow into a more regional-intermediate one in the WBNP region.

The deepest aquifer, the Keg River Aquifer is characterized by a deep, regional flow regime recharging at the Caribou Mountains and discharging at the lowest elevations of the basin, in the Salt Plain region. The Slave Point Aquifer is associated with intermediate flow regime when the overlying Ireton Aquitard is present and changes into local character when the aquitard becomes thinner and the Slave Point Aquifer outcrops. Local flow systems are limited to the shallowest aquifer (McMurray Aquifer) and the outcrop areas of deeper aquifers where the bottom of the wedge-shaped basin approaches the surface. The nature and relation to hydrodynamic zones of the simulated groundwater flow systems are consistent with findings previously reported in literature.

The flow paths, as shown by simulations, can be divided into three hydrogeological zones: Zone 1) Caribou Mountains, Zone 2) central plains of WBNP and Zone 3) the Salt Plains and vicinity along the central eastern edge of the basin (Figure 3.7 and Figure 3.9). While Zone 1 is mostly found outside of WBNP, Zone 2 and Zone 3 are fully located within the park. The Caribou Mountains (Zone 1) are characterized primarily by downward fluid flow and represents the recharge area of regional and intermediate flow systems. Its local topographic relief also induces local flow paths that penetrate the subsurface at various depths. The central lowlands (Zone 2) of WBNP are characterized by recharge and discharge from shallow local flow systems as well as discharge from intermediate flow systems. The Salt Plains (Zone 3) area is dominated by regional groundwater discharge, as well as local-scale flow systems that occur in shallower depths superimposed on the regional flow system.

The numerical simulations of this study are in agreement with the main findings of Chapter 2 that concludes brine springs of the Salt Plains region are manifestations of regional groundwater flow that recharged at the Caribou Mountains and gained their geochemical characteristics through prolonged rock-water interactions along their flow path.

The isolating effect of the Caribou Mountains is consistent with findings of Chapter 2 where it was concluded that saline and brine waters of the Salt Plains region are not related to other Devonian formation waters in the Alberta Basin but rather originate from meteoric water.

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Table 3.1: Hydrostratigraphic units and calibrated hydraulic conductivity (K) values in base case models in *Case 1* (General-head Boundary Conditions) and Case 2 (No-flow Boundary Conditions). Values of Root Mean Squared (RMS) error and normalized RMS are also shown.

Hydrostratigraphic zone	**K (m/s)**		**K' (m/s) in sensitivity analyses, K'<K**			**K' (m/s) in sensitivity analyses, K'>K**		
	Case 1	**Case 2**	**K'/K=0.5**	**K'/K=0.2**	**K'/K=0.1**	**K'/K=2**	**K'/K=5**	**K'/K=10**
Cretaceous Aquitard (*zone A*) (Case 1, 2)	4.0E-09	4.0E-09	2.0E-09	8.0E-10	4.0E-10	8.0E-09	2.0E-08	4.0E-08
McMurray-Bluesky Aquifer (*zone B*)(Case 1, 2)	1.0E-06	1.0E-06	5.0E-07	2.0E-07	1.0E-07	2.0E-06	5.0E-06	1.0E-05
Ireton/Hay River Aquitard system (*zone C*) (Case 1, 2)	1.0E-10	1.0E-10	5.0E-11	2.0E-11	1.0E-11	2.0E-10	5.0E-10	1.0E-09
Slave Point Aquifer (*zone D*) (Case 1)	5.0E-06	_	2.5E-06	1.0E-06	5.0E-07	1.0E-05	2.5E-05	5.0E-05
Slave Point Aquifer (*zone D*) (Case 2)	_	2.5E-05	1.3E-05	5.0E-06	2.5E-06	5.0E-05	1.3E-04	5.0E-04
Muskeg-Watt Mountain-Fort Vermilion Aquitard system (*zone E*) (Case 1)	1.0E-10	_	5.0E-11	2.0E-11	1.0E-11	2.0E-10	5.0E-10	1.0E-09
Muskeg-Watt Mountain-Fort Vermilion Aquitard system (*zone E*) (Case 2)	_	5.0E-11	2.5E-11	1.0E-11	5.0E-12	1.0E-10	2.5E-10	5.0E-10
Keg River Aquifer (*zone F*)(Case 1, 2)	7.0E-05	7.0E-05	3.5E-05	1.4E-05	7.0E-06	1.4E-04	3.5E-04	7.0E-04
Elk Point Aquitard system (*zone G*)	5.0E-10	5.0E-10	_	_	_	_	_	_
wheathered zone (*zone H*)	3.1E-05	3.1E-05	_	_	_	_	_	_
RMS (m):	32	29						
Normalized RMS (%):	10	9						

Table 3.2 Calibration data, well location and hydraulic head values calculated from measured fluid pressures used in numerical simulations

UWI	Well #	Tested formation	Recorder depth (m)	Latitude (°)	Longitude (°)	Calculated hydraulic head (m)
00/07-25-120-10W5/0	KR1	Keg River	1249	59.451750	-115.566748	340
00/11-22-117-06W5/0	KR2	Keg River	1234	59.178687	-114.930039	351
00/08-17-120-01W5/0	KR3	Keg River	588	59.420863	-114.117413	285
100/02-10-118-08W5/0	SP1	Slave Point	1042	59.228874	-115.263352	589
100/11-18-118-07W5/0	SP2	Slave Point	967	59.251790	-115.186954	546
100/10-15-120-08W5/0	SP3	Slave Point	975	59.425130	-115.275512	574
100/10-24-120-08W5/0	SP4	Slave Point	879	59.440608	-115.217038	601

Table 3.3 Hydraulic head values assigned to general head boundaries. Hydraulic head values used in sensitivity analysis are also shown.

Hydrostratigraphic units	Base case	Sensitivity analysis - h'>h				Sensitivity analysis - h'<h			
	Head (m)	h'/h=1.1	h'/h=1.3	h'/h=1.6	h'/h=2	h'/h=0.1	h'/h=0.4	h'/h=0.7	h'/h=0.9
McMurray-Bluesky Aquifer	341	375	443	546	682	307	239	136	32
Slave Point Aquifer	625	688	813	1000	1250	563	438	250	63
Keg River Aquifer	321	353	417	514	642	289	225	128	34
RMS (m):	32								
Normalized RMS (%):	10								

Table 3.4 Volumetric flow rates of recharge and discharge in Case 1(general head BC) and Case 2 (no-flow BC). Total amount of inflow entering the Wood Buffalo National Park from the western part of the domain (Caribou Mountains, CM) is also shown in both cases.

Volumetric flow rates	Case 1	Case 2
Total In (m^3/d)	11,150	9,560
Total Out (m^3/d)	11,150	9,560
From CM to WBNP (m^3/d)	2,097	3,393

Table 3.5: Location of groundwater divide relative to the left side of the domain (0km) with decreasing water table elevation in *Case 1.* The groundwater divide -originally located at 46 km east of the left domain boundary- shifts closer to the left boundary.

Water table position	**RGD location (km)**
1	41.2
2	41.2
3	25.2
4	7.3
5	west of left domain boundary

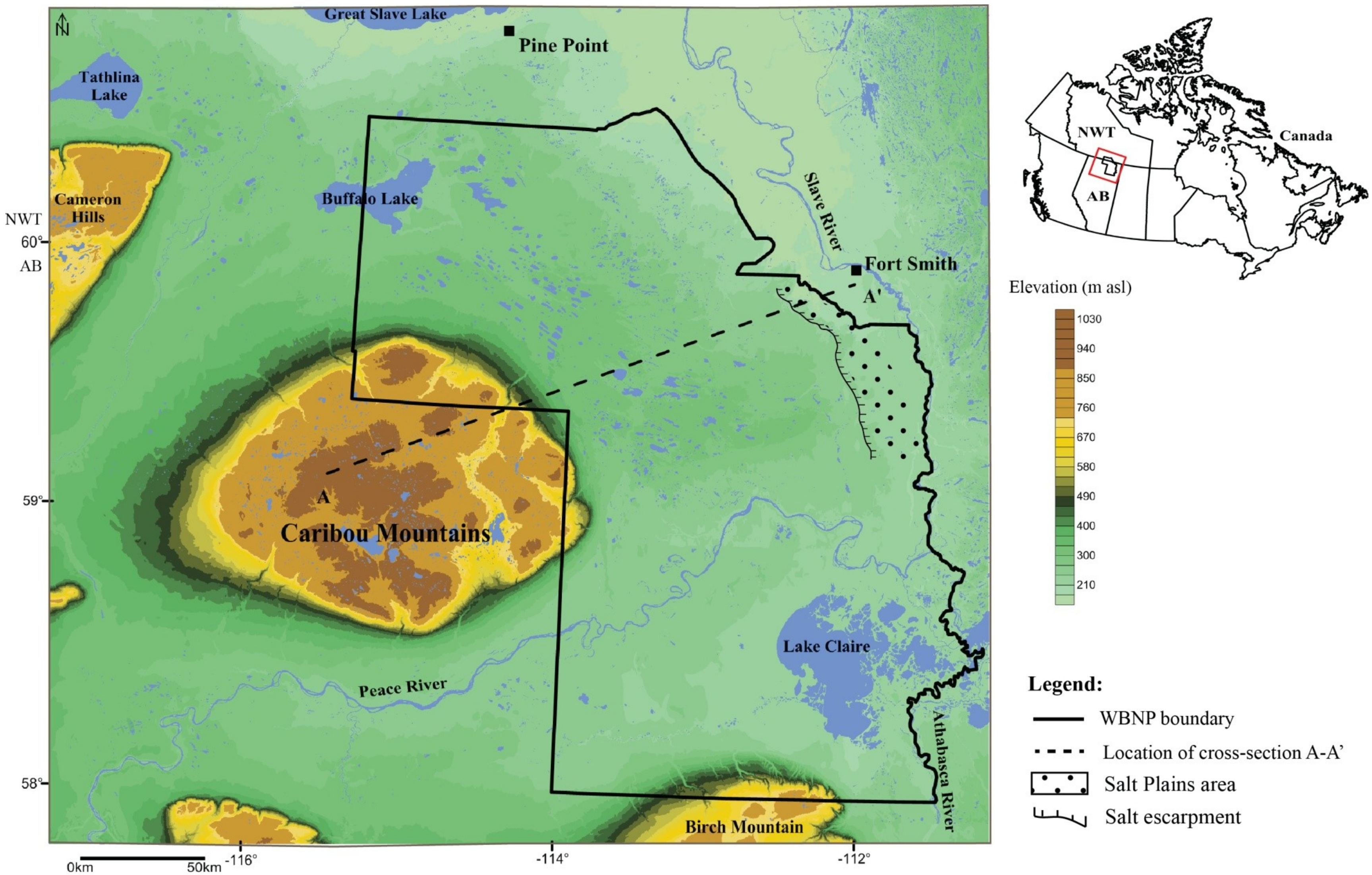


Figure 3.1: Geographic location and topography of the study area with location of cross-section A-A' shown in Figure 3.4

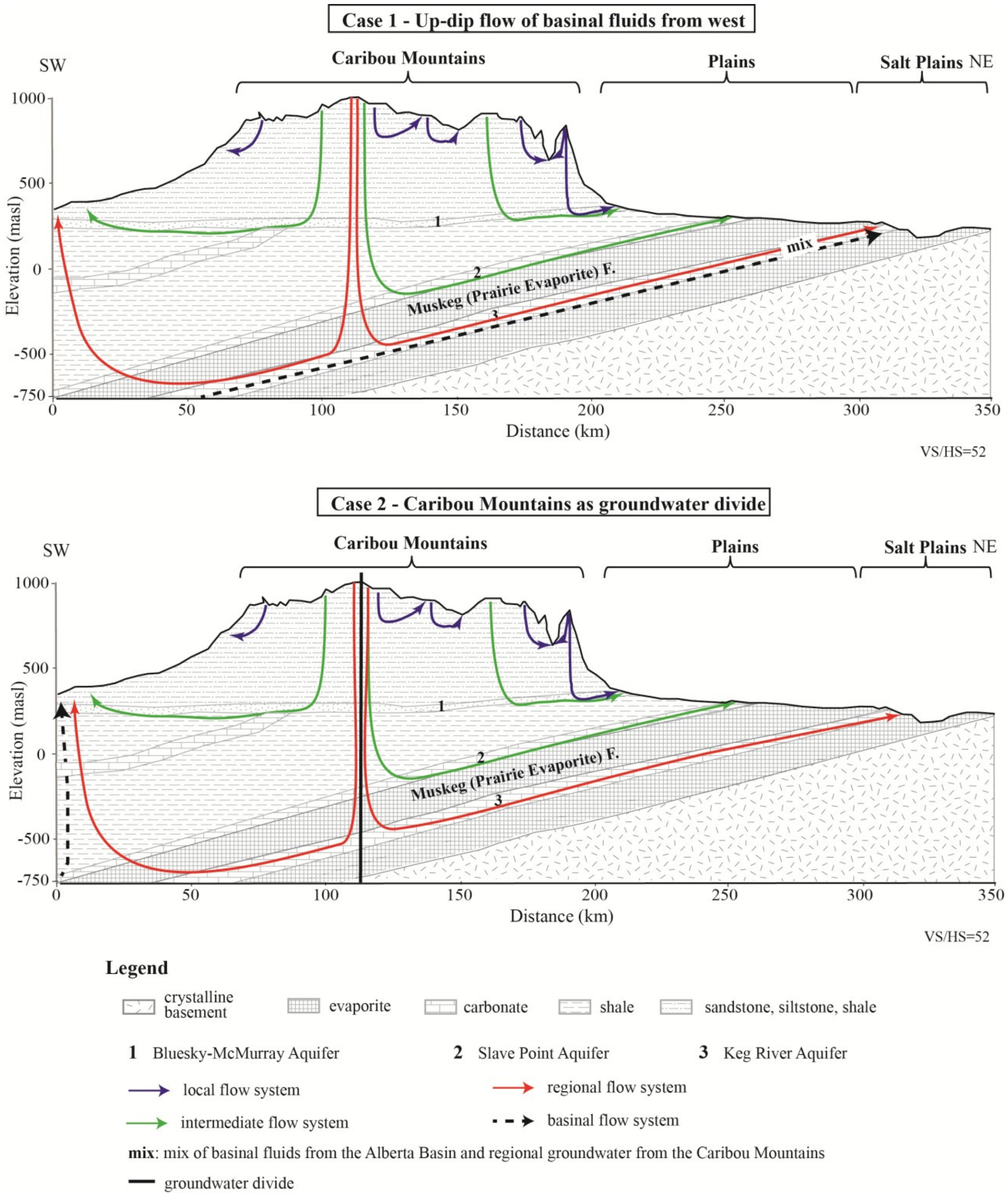


Figure 3.2: Conceptual model of groundwater flow in two different scenarios simulated in *Case 1* and *Case 2*. Location of cross-section is shown in Figure AI.1. In *Case 1*, flow is allowed into the domain from the Alberta Basin west of the study area. In *Case 2*, the western boundary of the domain is represented by no-flow boundaries and flow is isolated from the rest of the Alberta Basin.

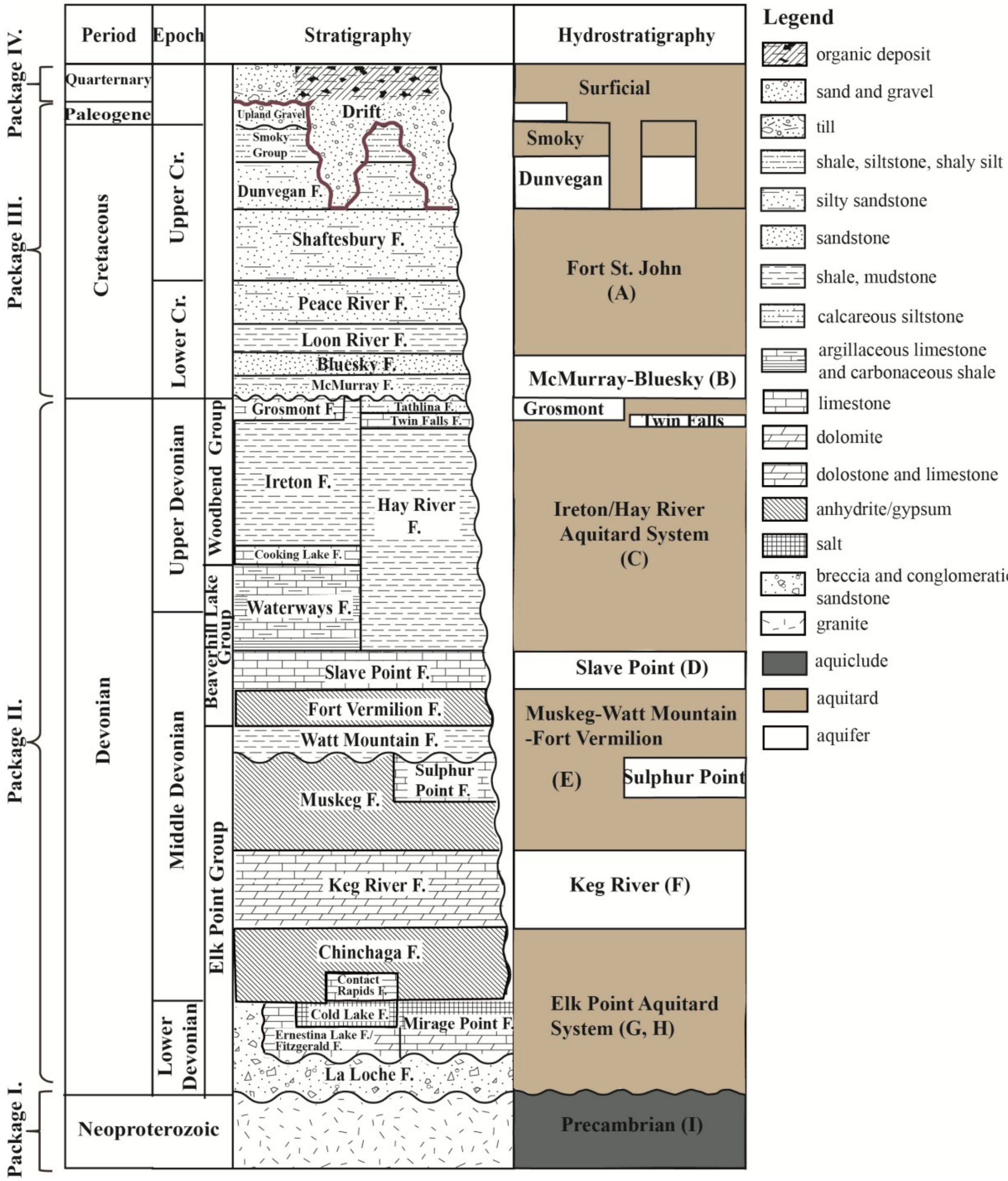


Figure 3.3: Generalized stratigraphy and hydrostratigraphy of the Wood Buffalo National Park (modified from Figure 4, Chapter 2) Geology is adapted from Norris 1973; Bachu and Underschultz 1993; Bachu 1997; Tóth 1978; Meijer Drees 1994; Oldale and Munday 1994; Schwitzer et al. 1994; Morrow et al. 2002; Prior et al. 2013; AGS 2015).

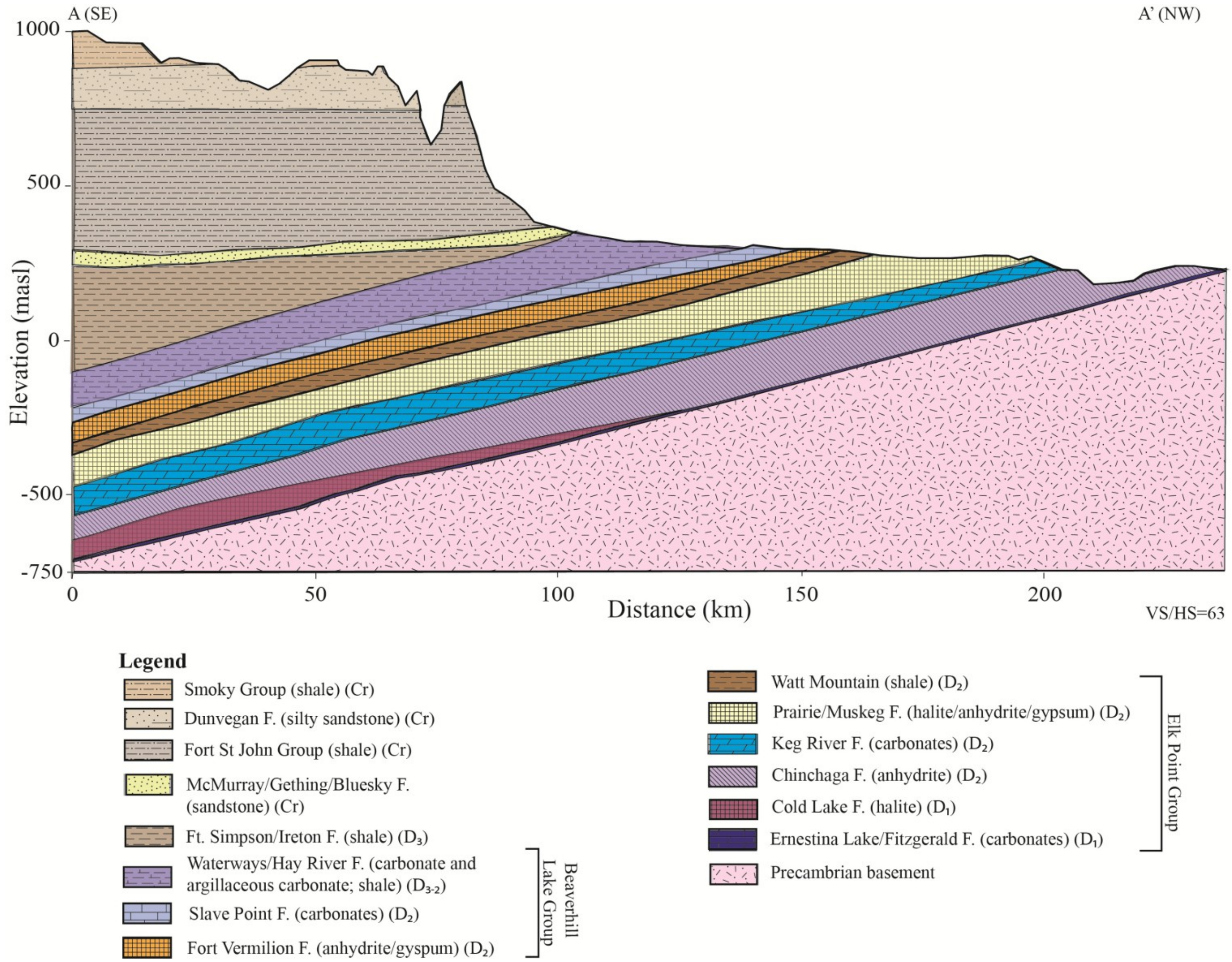


Figure 3.4: Geologic cross-section along the line A-A' as shown in Figure 3.1.

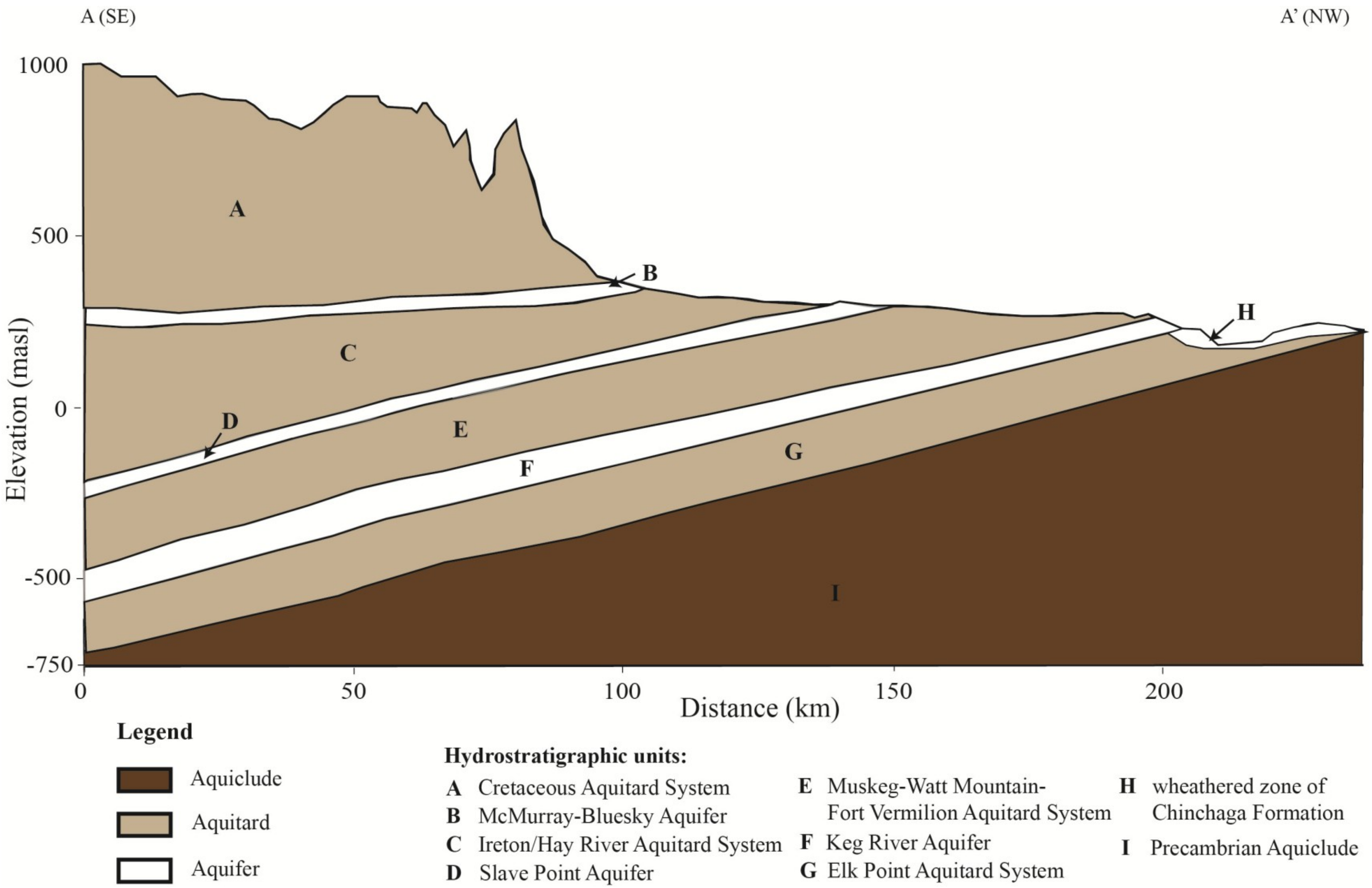


Figure 3.5: Hydrostratigraphy and conductivity zones used in model

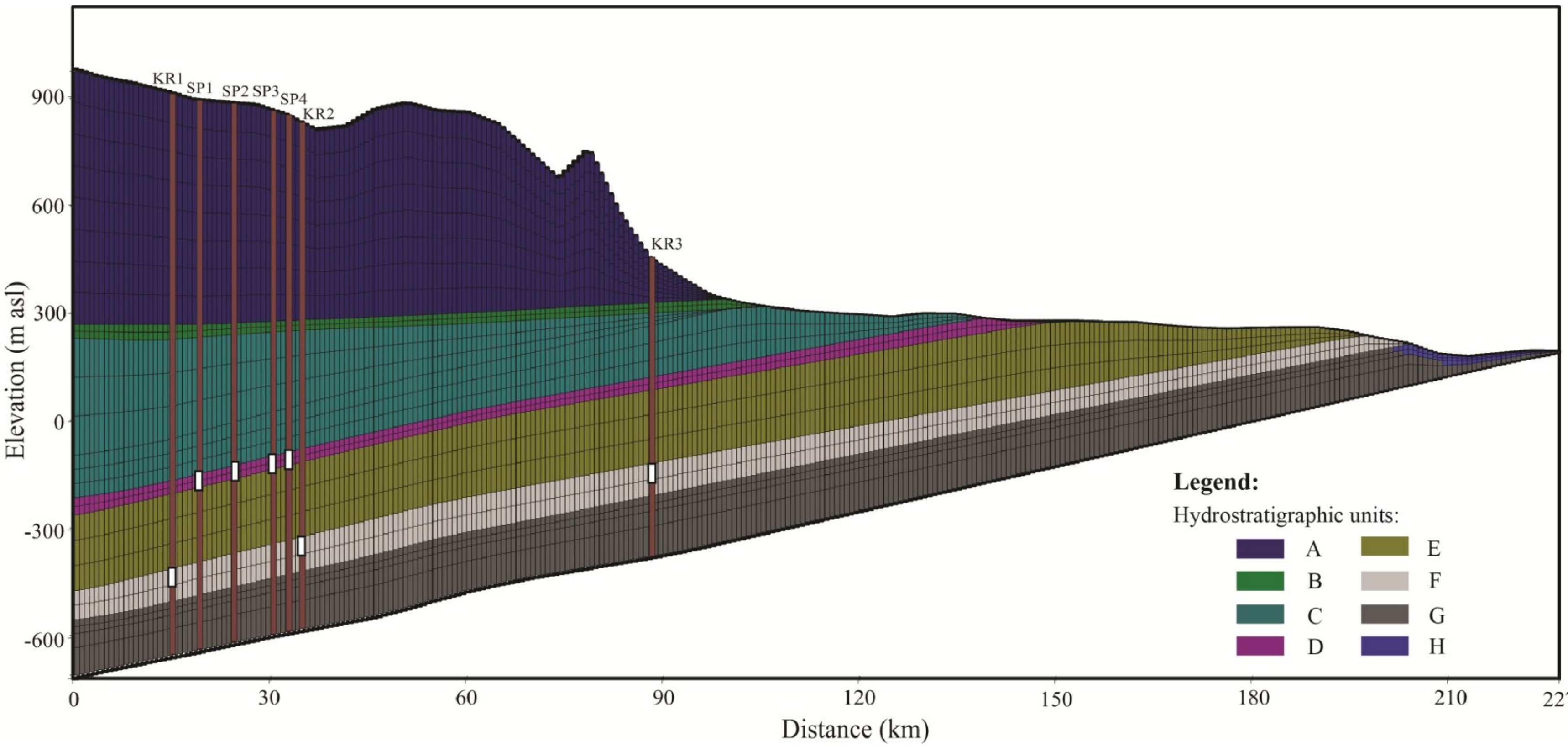


Figure 3.6: Grid refinement of the model domain. Colors show hydrostratigraphic units as shown and labeled in Figure 3.5. Location of observation wells is also shown. White rectangles indicate depths tested by DSTs. Details of the wells are shown in Table 3.2.

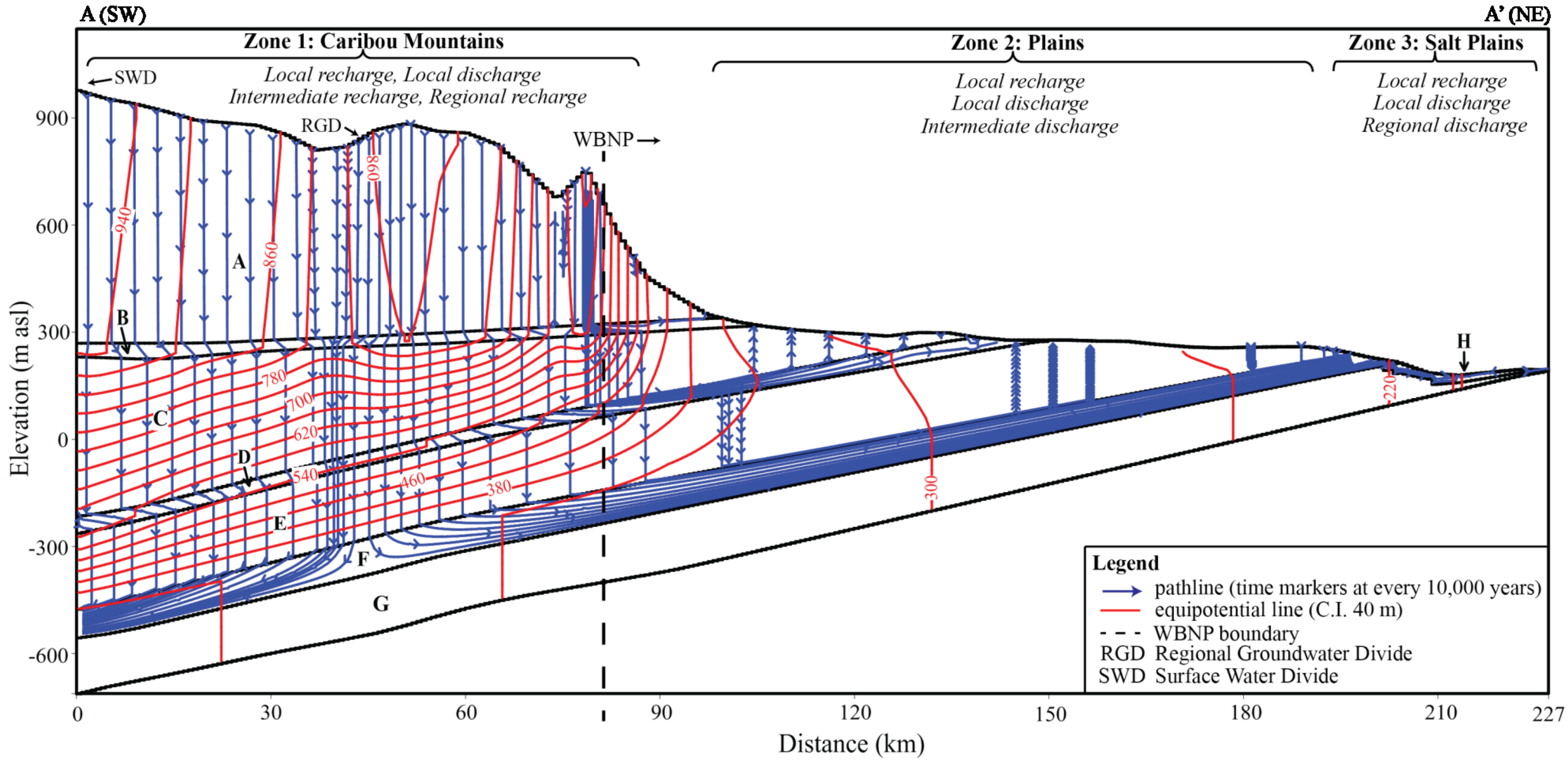
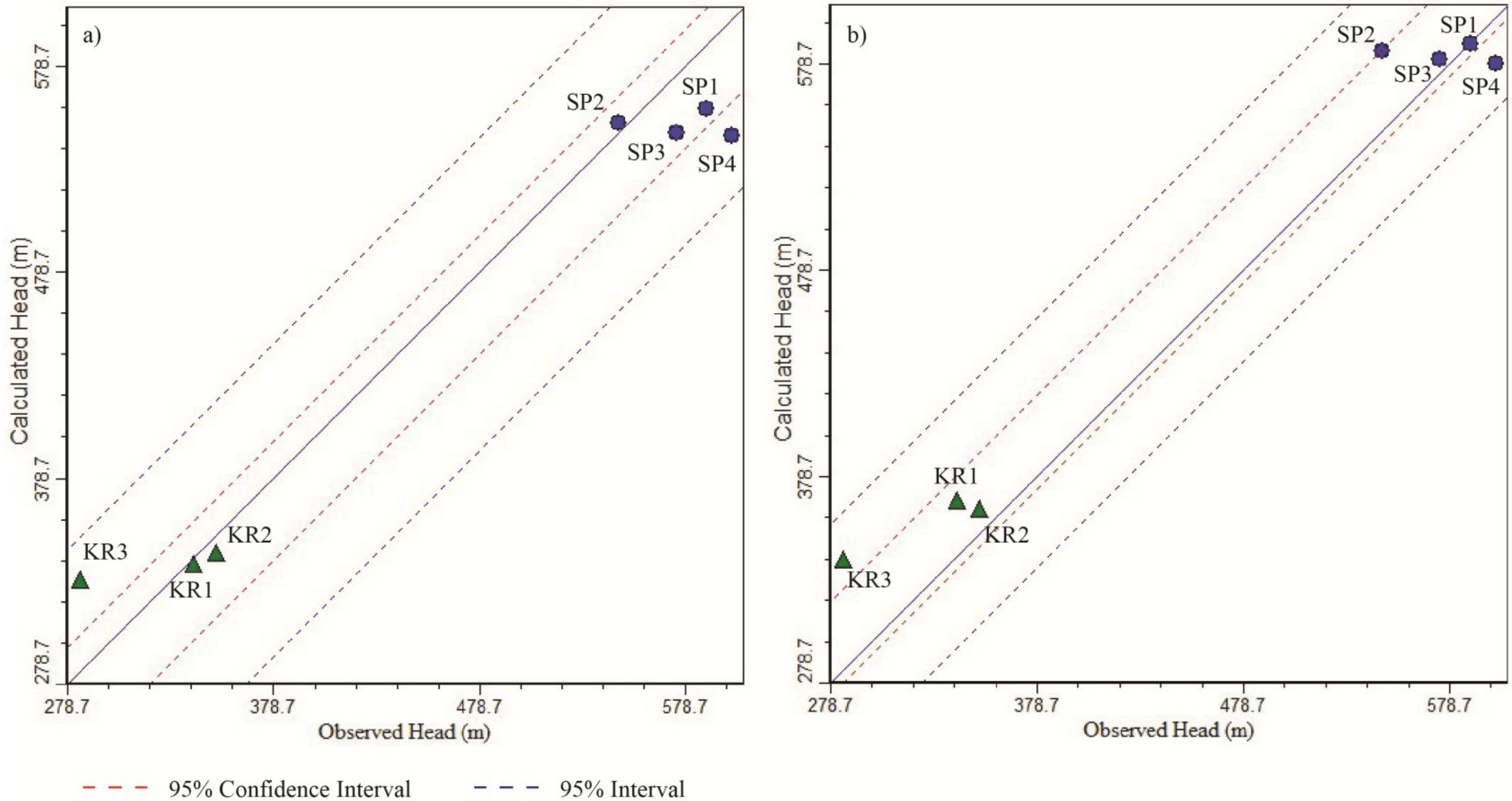


Figure 3.7: Simulated hydraulic head distribution and flowpaths in *Case 1* (Up-dip flow from basin is possible)



	a)	b)
Number of data points	7	7
Standard Error of the Estimate (m)	12.141	9.683
Root Mean Squared (m)	31.663	28.862
Normalized RMS (%)	10.02	9.134
Correlation Coefficient	0.984	0.988

	a)	b)
Max. Residual (m)	-56.159	53.719
Min. Residual (m)	-2.701	-0.719
Residual Mean (m)	-10.87	16.444
Abs. Residual Mean (m)	25.159	23.071

Figure 3.8 Scatter plots of observed vs. calculated hydraulic heads for Case 1 (a) and Case 2 (b). Calculated calibration statistics are also shown.

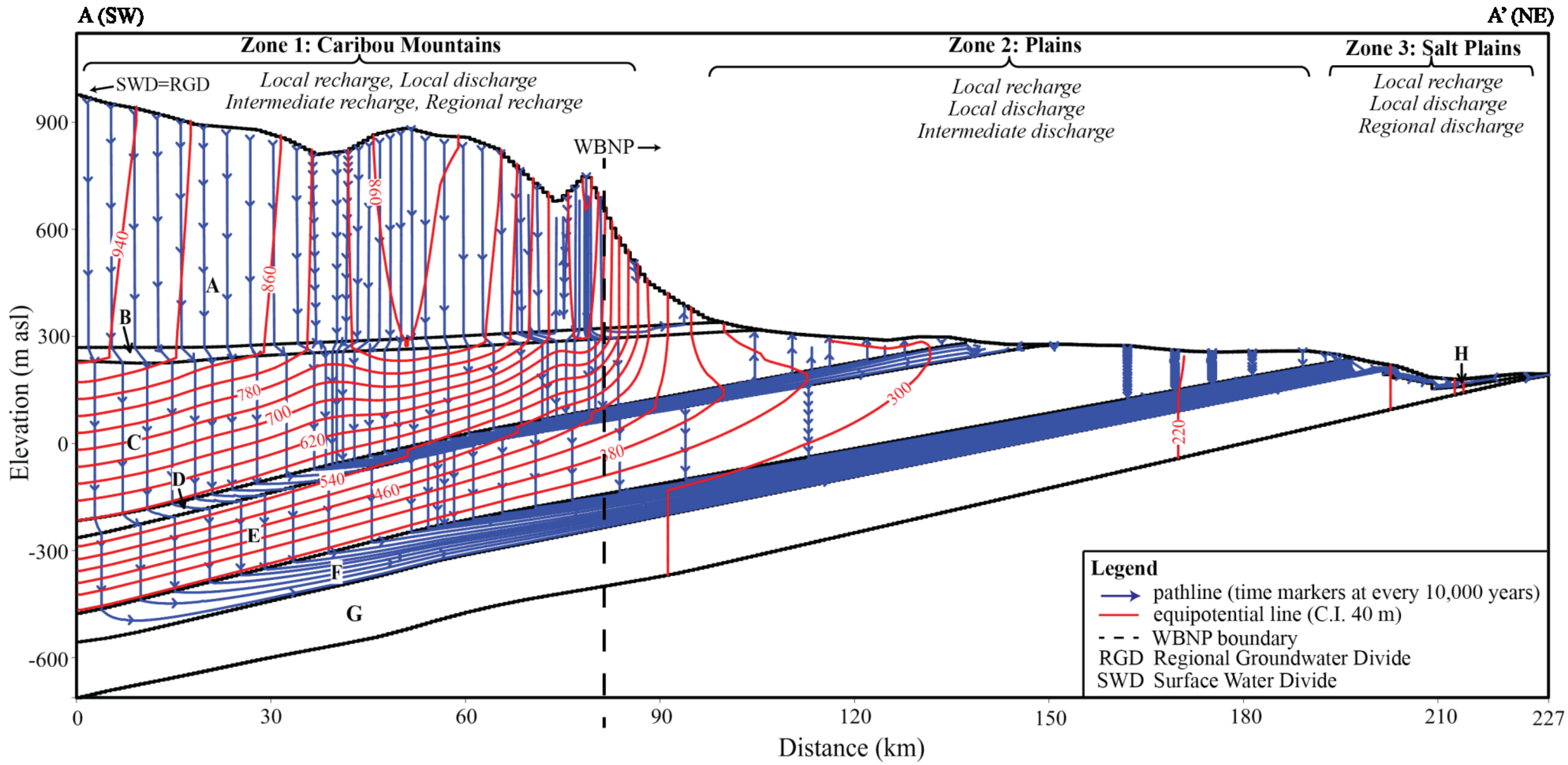


Figure 3.9: Simulated hydraulic head distribution and flowpaths in *Case 2* (Caribou Mountains as groundwater divide)

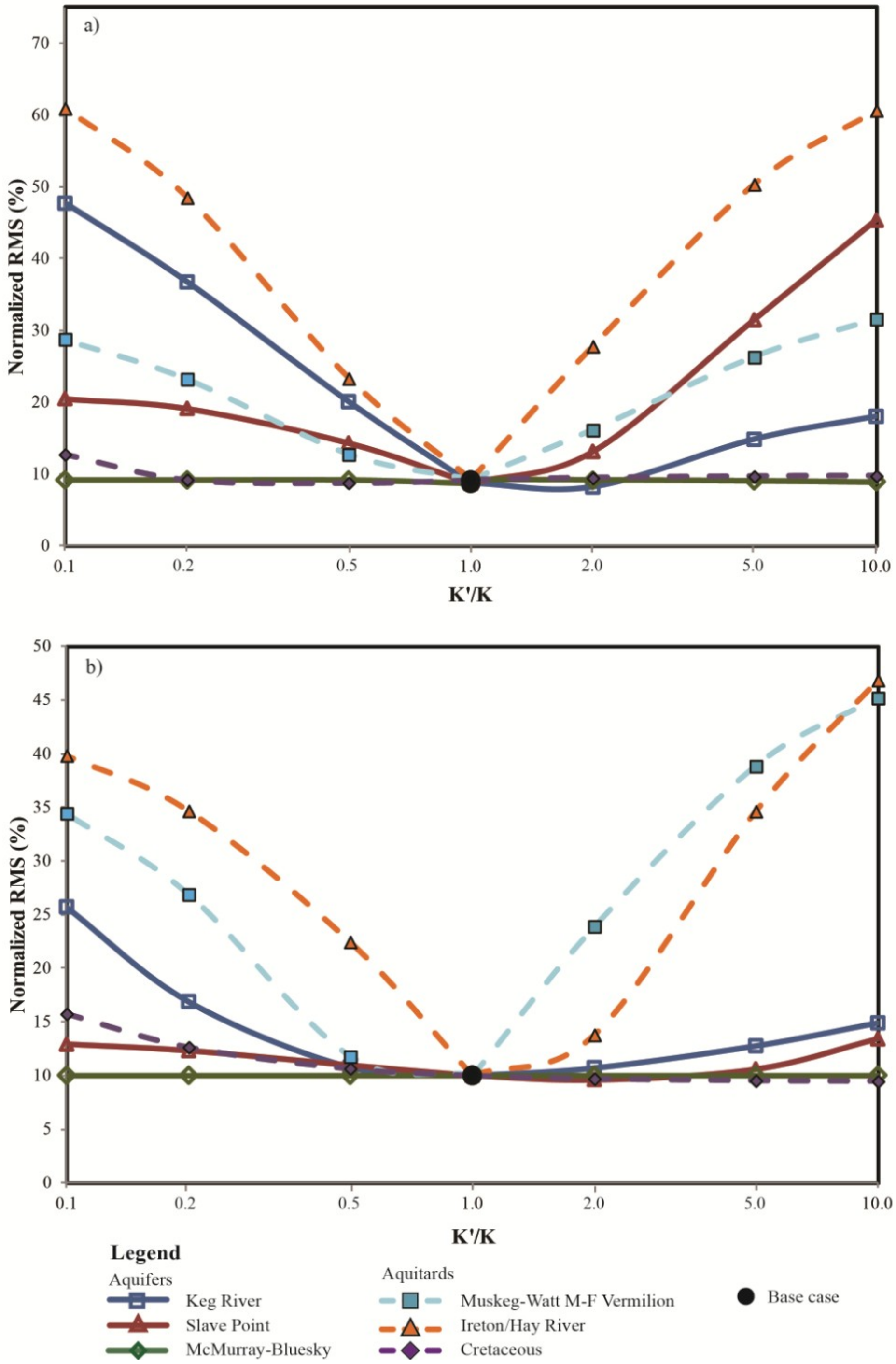


Figure 3.10: Change in normalized RMS (%) with increasing and decreasing K'/K ratios, where K is the hydraulic conductivity in the calibrated base case models using a) no-flow and b) general-head boundary conditions, and K' is increased or decreased value of hydraulic conductivity for the tested unit. Solid lines represent aquifers, dashed lines represent aquitards.

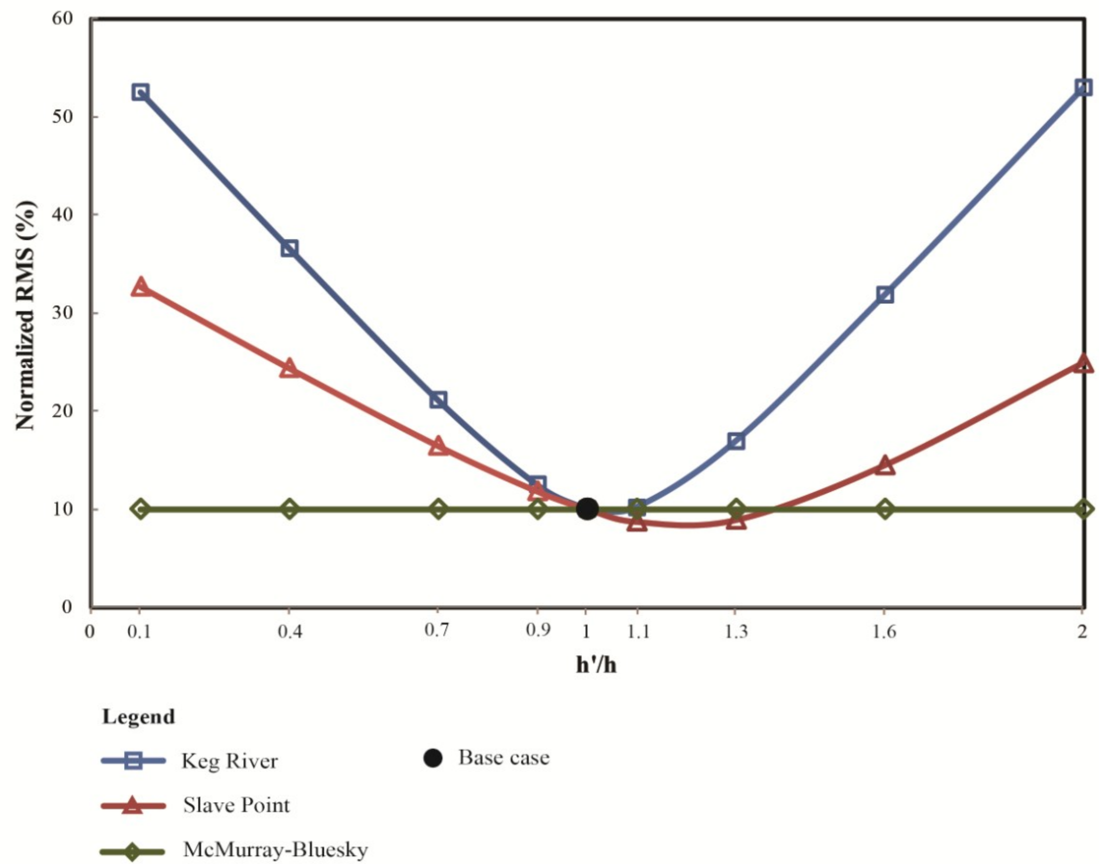


Figure 3.11: Normalized RMS (%) versus hydraulic head values used as general-head boundary condition in the aquifers. Solid lines represent increase, dashed lines represent decrease of head values (h') relative to the original head values (h) used in the base case model.

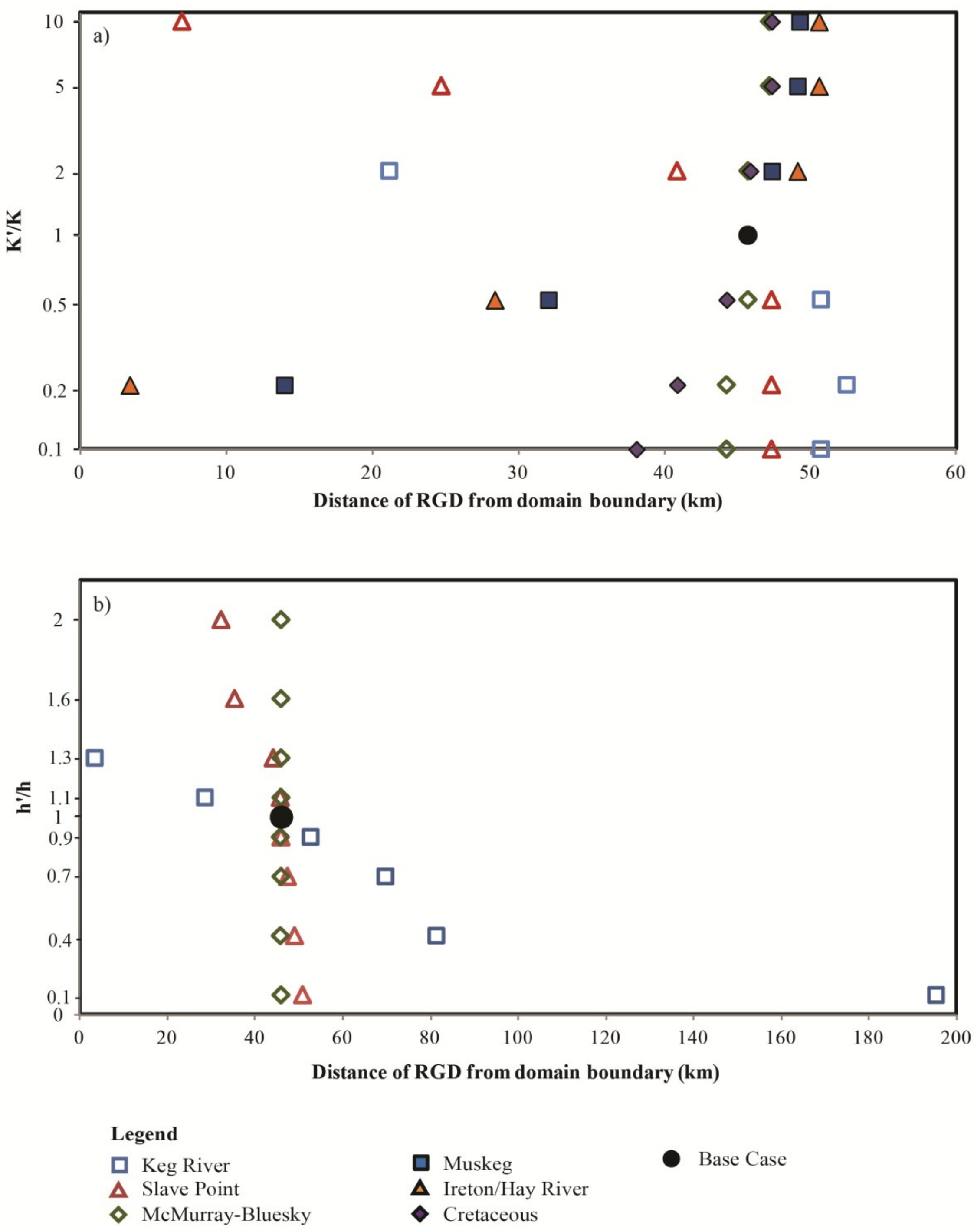


Figure 3.12: Location of Regional Groundwater Divide (RGD) as a function of changing general head boundary value

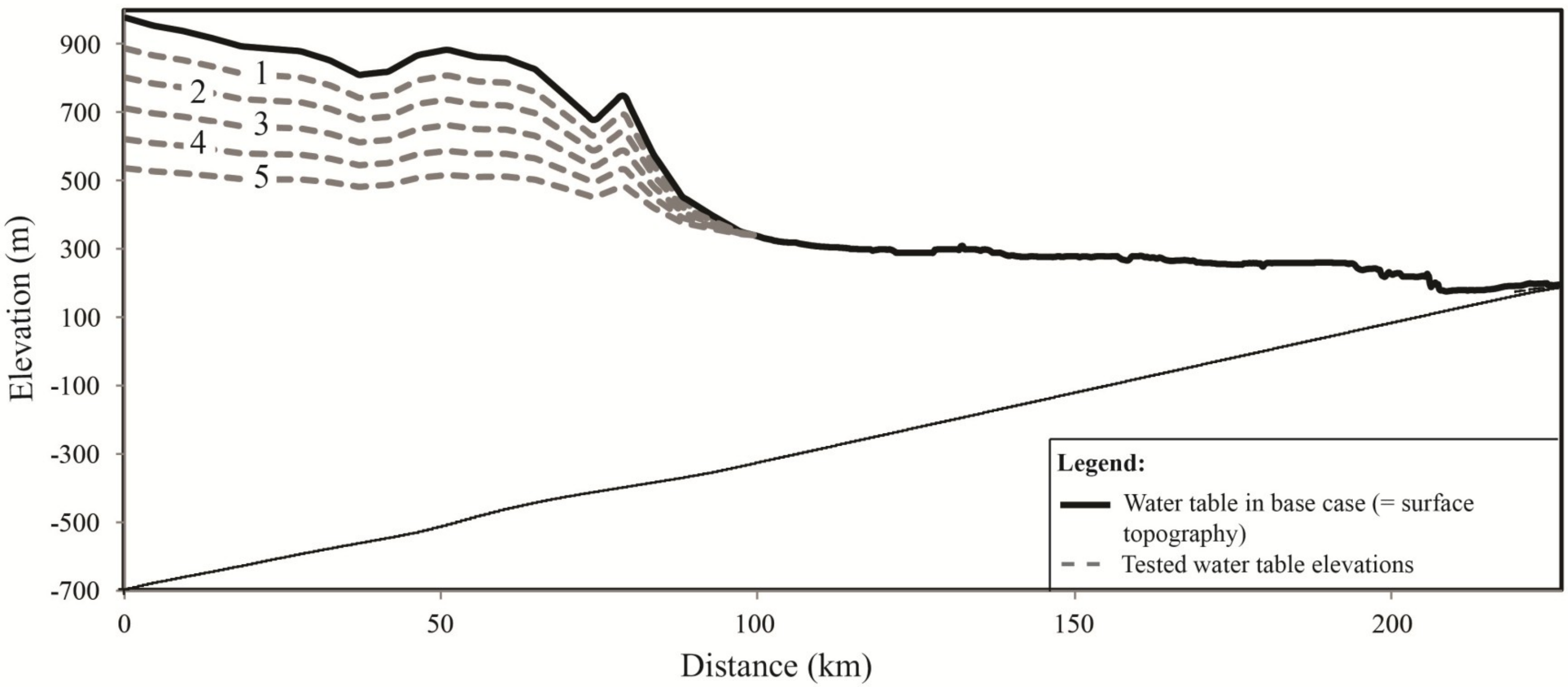


Figure 3.13: Tested water table elevations in the Caribou Mountains region along cross-section A-A'.

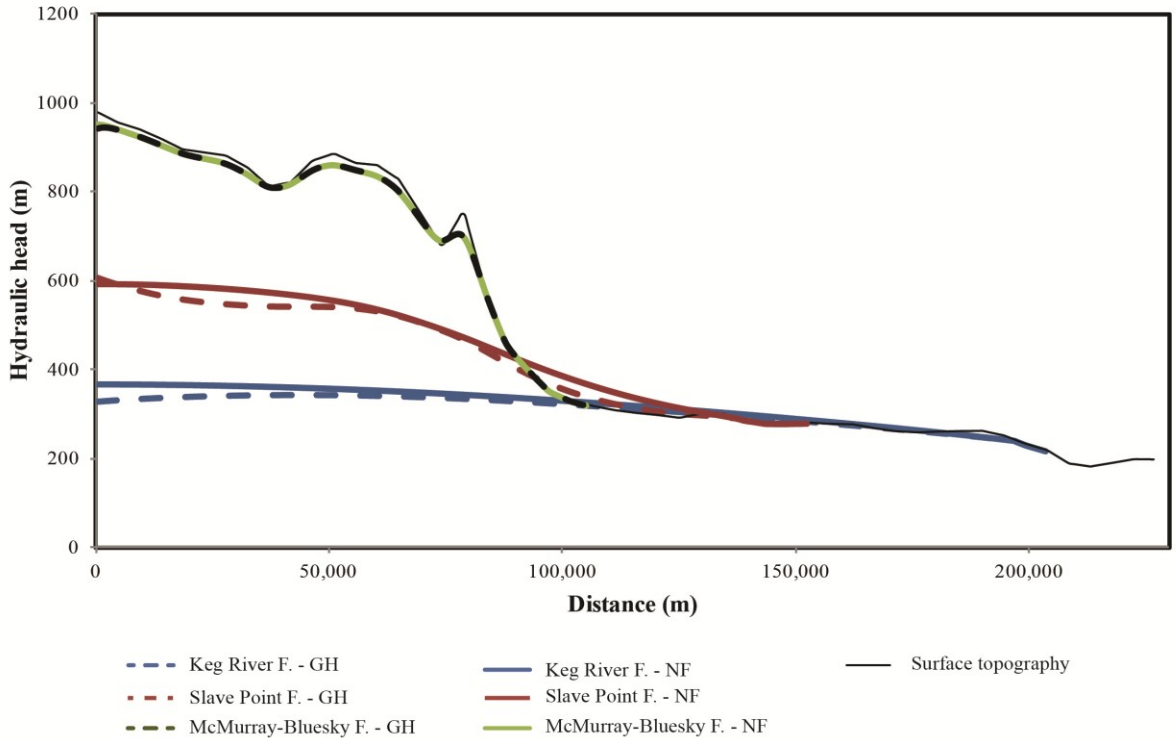


Figure 3.14: Hydraulic head distribution in aquifers along cross-section A-A' in different conceptualizations. Dashed and solid lines represent simulated heads using general-head (GH) and no-flow (NF) boundaries, respectively.

Chapter 4 Geochemistry, surface phenomena and numerical simulations demonstrate effects of gravity-driven groundwater flow

4.1. Abstract

Wood Buffalo National Park (WBNP) is Canada's largest national park and a designated UNESCO World Heritage Site. Understanding the governing subsurface processes, hydraulic connections and relationship between groundwater and surface water is one of the key aspects leading to the successful protection of its ecological values. The objective of this study is to provide a general characterization of hydrogeological conditions in WBNP by integrating surface and spring water chemistry, numerical simulation and analyses of groundwater-related surface phenomena. The study provides a combined method to map hydrogeological conditions in remote, hard-to-access areas that lack information on the subsurface environment (e.g. geology, structure, hydraulic head measurements, hydraulic conductivity, etc).

Previous results showed good correlation between the salinity and hydrochemical facies of waters and the numerical simulation of groundwater flow in WBNP. Accordingly, Ca-HCO_3-type, low salinity waters occur at local discharge areas, whereas Ca-SO_4-type, brackish waters are found in the central region where groundwater from intermediate-scale flow paths discharge. Na-Cl-type, saline-brine waters correspond with discharge area of groundwaters from regional–scale flow system and indicate regional groundwater discharge. The high variability in TDS concentrations and hydrochemical facies found in the Salt Plains area are consistent with the simulated flow field that indicate a terminal

zone of various flow systems. The presence of groundwater-diagnostic features, such as wetlands, springs, saline soils and salt accumulations, vegetation, karstic features agree with the previously determined conceptual model of groundwater flow in WBNP reinforced by geochemical characteristics of surface and spring waters and with the numerically simulated flow regime in the area. The study shows that the simulated flow field is representative of the system, and that gravity-driven groundwater flow theory is applicable for describing the flow regime in WBNP.

4.2. Introduction

Gravity-driven groundwater flow is generated by elevation differences in the water table which, in general, is a subdued replica of the land surface in humid climates. The overall gravity-driven flow pattern is modified by heterogeneities in geology and by the climate (Tóth 1963, 2009; Freeze and Witherspoon 1966, 1967). Flow systems induced by topography have three different segments, i.e., recharge, midline and discharge areas and potentially different scales. Topographic highs are characterized by downward flow and considered recharge areas while topographic lows are characterized by upward flow and are discharge areas. Depending on the general slope and local relief of the topography, hierarchically nested local, intermediate and regional flow systems may be generated (Tóth 1962, 1963). By definition, local flow systems recharge at topographic highs and discharge at topographic lows that are immediately adjacent to the recharge area (Tóth 1963). An intermediate flow system recharges at a topographic high and discharges at a topographic low that is not immediately adjacent to the recharge area, and may encompass one or more local-scale flow systems. A regional flow system recharges at the regional groundwater divide and discharges at the lowest topographic elevation of the basin (Tóth 1963).

Flowing groundwater interacts with its environment through various chemical, physical and kinetic processes and produces numerous in-situ effects, such as dry surface conditions in recharge areas and water excess in discharge areas; changes in water chemistry (e.g., concentration, anion-cation composition); saline soils; geothermal anomalies; and, different types of vegetation in recharge and discharge areas that reflect the characteristic soil-moisture content or water chemistry (Tóth 1999).

Gravity-driven groundwater flow dominates the flow regime of Wood Buffalo National Park (WBNP) (Chapter 3). It was also shown that the Caribou Mountains isolate the flow regime in WBNP and impedes the northeastward flowing basin-scale fluids of the western Alberta Basin from entering the region of central WBNP. Existence of three (i.e., local, intermediate, regional) hydrodynamic flow regimes were also demonstrated in the area.

Regional geochemical characterization of springs and surface waters of WBNP was presented in Chapter 2. It was concluded that the spatial distribution of the four main water types identified in the area reflect the different orders and segments of the conceptualized groundwater flow systems.

Several surface phenomena, such as springs, soil salinization, vegetation and thermal anomalies, are indicative of and associated with different segments and scales of groundwater flow systems (Tóth 1971, 1999).

Groundwater-related surface phenomena and their relation to groundwater recharge and discharge in the central-eastern region of WBNP (59°N - 60°N, and 111°30’W and 114°W) were previously studied by the Alberta Research Council (Stein, 1979). The Salt Plains region located along the central eastern boundary of the park is one of the most studied areas of WBNP due to its easy accessibility and diverse surface features (Figure 4.1). Fresh and saline springs at the base of the escarpment have been thought to be discharge areas of groundwaters from local and regional/intermediate flow systems (Drake 1970; Tsui 1982; Weyer 1983; Tsui and Cruden 1986) (Figure 4.2).

The objective of this study is to synthesize existing results of previous chapters and to integrate them into a conceptual model that combines water chemistry, numerical simulation and groundwater-related surface phenomena. The simulated flow field is associated with the geochemical characteristics of waters to evaluate their diagnostic value in identifying different scales and segments of groundwater flow systems. Subsequently, groundwater-related surface phenomena, such as wetlands, springs, saline soils, phreatophyte and halophyte vegetation, karstic features and geothermal anomalies, are coupled with the different scales and segments of flow systems to validate previous results and create an integrated model of groundwater flow in WBNP.

4.3. Physiography, geology and hydrostratigraphy of the study area

4.3.1. *Physiography*

WBNP is located in northeastern Alberta and south Northwest Territories, Canada (Figure 4.1). It is Canada's largest national park with an area of 44,807 km^2. It is the home of one of the world's largest inland deltas, the Peace-Athabasca delta, and it is a UNESCO World Heritage site (World Heritage Committee UNESCO 1983). It encompasses extensive boreal forests, wetlands and prairie, and exhibits outstanding examples of karstic landform, saline springs and salt plains (Soper 1939; Drake 1970).

From west to east, the topography within the park gradually declines from the Caribou Mountains to a steep escarpment near the eastern boundary (Figure 4.1). The Salt Plains region along the central eastern edge of WBNP covers more than 300 km^2. It is separated from the central plains by the escarpment and includes several salt flats (Photo 4.1a). It also exhibits numerous surface features, such as springs with variable chemical composition, thick salt accumulations, and karst geomorphology.

4.3.2. *Geology and hydrostratigraphy*

WBNP sits on the northeastern edge of the Western Canadian Sedimentary Basin (WCSB) and as such its geological description can be found in regional characterizations of the strata of the WCSB (e.g. Meijer Drees 1994; Oldale and Munday 1994 and Switzer et al. 1994).

The overall geology of the area (Figure 4.3, Figure 4.4) can be characterized by four major geologic packages:

Package I consists of crystalline Precambrian basement. The basement dips to the southwest and is composed of igneous and metamorphic rocks of the Canadian Shield. The outcrop area of the Precambrian Basement in the eastern margin of WBNP is shown in Figure 4.3.

Package II consists of Devonian strata and represents the most widespread sedimentary bedrock in WBNP (Figure 4.3, Figure 4.4). The southwesterly-dipping sediments are composed of carbonates, evaporites and shales. Three significant evaporite strata are present: 1) the Chinchaga Formation consists of mostly anhydrite and gypsum and underlies the Salt Plains, 2) the Muskeg Formation is composed of mostly gypsum and is stratigraphically equivalent with the Prairie Evaporite Formation, and 3) the Fort Vermilion Formation consists mostly of anhydrite. The Devonian package also includes two regionally extensive carbonate formations, the Keg River and Slave Point formations, and three shale layers, the Watt Mountain, Hay River and Ireton formations.

Package III consists of Cretaceous siliciclastic deposits that unconformably overlie the Devonian strata (Figure 4.3, Figure 4.4).

Package IV includes unconsolidated Quaternary or recent surficial materials consisting dominantly of glaciolacustrine and moraine sediments with aeolian, fluvial and lacustrine sediments often overlain by organic material (peat) (Bayrock 1972a,b,c; Lemmen 1998a,b; Mougeot and Fenton 2010; Fenton et al. 2013).

Local-scale geological mapping in WBNP was conducted by Camsell (1917), Norris (1963) and Richmond (1965), Park and Jones (1982), Tsui (1982) and Tsui and Cruden (1984).

The interpreted hydrostratigraphy of WBNP is shown in Figure 4.4. Detailed description of the units with measured hydraulic conductivity values is provided in Chapter 3. The overall hydrostratigraphy is characterized by four aquitard systems (A, C, E, G), and by two regionally extensive aquifers in the Devonian succession (D, F) and one with limited occurrence above the Devonian-Cretaceous unconformity (B) (Figure 4.4, Figure 4.5). Unit I represents the weathered outcrop-zone section of the Chinchaga Formation (Elk Point aquitard system).

4.4. Data and methods

4.4.1. *Data*

Details of the water chemical analyses, calculated TDS contents, and determinations of hydrochemical facies, as well as interpretations on rock-water interactions and their influence on the water chemical composition, are described in Chapter 2. Springs were identified using an archive data collected by the Alberta Geological Survey (Alberta Research Council) in the 1970s (AGS 2009; AER/AGS 2014), and data collected in 2013. Wetlands and disappearing streams were identified based on digital data from National Topographic Data Base (NTDB) at 1:250,000 scale (NTDB 1998a,b). Karst areas were identified during field work, from satellite images and published surface geology maps by Bayrock (1972b,c) and Lemmen (1998a,b). Types of sinkholes (solution, collapse) were distinguished based on their geomorphologic characteristics described in the literature (Drake 1970; Sweeting 1973; Tsui 1982; Ford 1997). Descriptions of surface features, such as brine springs, salt accumulations and salt flats are based on field observations and literature data (Bayrock 1972c). Digital data on spatial distribution of salt flats were generated by the author based on surficial geology map by Bayrock (1972c). Vegetation characteristics were identified based on field observations and botanical description made by others (Raup 1935; Schwarz et al. 1988). Aerial observations related to open water in winter were made by Parks Canada, at the request of the author, during a regularly-scheduled bison survey, early March to early April 2014.

4.4.2. *Methods*

First, results of the numerical simulation study investigating the validity of different conceptual models of groundwater flow in WBNP (Chapter 3) are summarized and compared to existing results on geochemical characterization of waters in WBNP (Chapter 2). Subsequently, different scales and segments of flow systems are correlated with groundwater-related surface phenomena observed in the field, such as wetlands, springs; saline soils and salt accumulations; plant communities; karst geomorphology; and, temperature anomalies.

4.4.3. *Pre-existing analyses and results*

The current study uses the end-result of the simulations of Chapter 3 and focuses only on the relevant part of the original analysis. The west side of the cross-section (A^*) represents the regional groundwater divide in the Caribou Mountains. The water table, approximated by the land surface, forms the upper boundary. The wedge-shaped model domain is bounded by an impermeable boundary on the bottom to represent the Precambrian basement. Further details on the model design and results of different conceptualizations of the modelled flow regime are described in Chapter 3.

Orders (1=local, 2=intermediate, 3=regional) and segments (R=recharge, D=discharge) of flow systems along cross-section A^*-A' are labeled in Figure 4.5 based on the results of Chapter 3. Accordingly, the Caribou Mountains represent the main recharge area for intermediate and regional flow systems (2R and 3R) that are associated with the Keg River and Slave Point formations. They discharge in the central plains (between 100 and 160 km) and in the Salt Plains region (2D and 3D). Recharge and discharge areas of local flow systems (1R and 1D) generated by local topographic relief are superimposed on larger-scale flow systems. Local flow systems typically extend only to shallow depths in the plains and occur in permeable units that outcrop. Exceptions are the local flow systems generated by the local peaks of the Caribou Mountains. These flow paths penetrate deeper, reaching the McMurray-Bluesky aquifer. The Salt Plains region represents discharge areas of local and regional flow systems.

Geochemical characterization of study area along cross-section A*-A’ is based on the results of Chapter 2 (Figure 4.6a,b). It was concluded that Ca-HCO_3-type fresh waters represent recharge and/or discharge from shallow, local flow systems, while the Na-Cl-type saline-brine waters are associated with regional-scale flow paths. The highly distinctive geochemical characteristics of waters in the Salt Plains area represent a discharge from both regional and local flow systems. Along cross-section A*-A’, waters in the central plains can be largely divided into two groups: 1) Ca-HCO_3-type fresh waters with TDS content <1000 mg/L; and 2) Ca-SO_4-type brackish waters typically associated with TDS content of 1,000 to 5,000 mg/L. Water samples with low TDS concentrations (<1,000 mg/L) and Ca-HCO_3-type facies at 130 to 160 km (1R-1D, Figure 4.6) correspond with the occurrence of local flow systems (1R-1D) at 145 to 157 km in Figure 4.5. The Ca-SO_4-type, brackish waters separate into a distinct cluster in the central part of the study area. Their occurrence at 92 to 125 km (2D, Figure 4.6) overlaps with the discharge area of intermediate flow system between 100 and 135 km (2D, Figure 4.5). In the Salt Plains, samples become more saline and highly variable in TDS (Figure 4.6a). Sodium-chloride-type waters are typically limited to this area and have TDS concentrations >10,000 mg/L. The simulated discharge area of regional flow systems at 160 to 168 km (3D, Figure 4.5) coincides with the occurrence of Ca-SO_4, “mixed” and Na-Cl-type waters with brackish, saline and brine water salinity observed between 160 and 167 km in the Salt Plains region in Figure 4.6 (Insets).

4.5. Groundwater-related surface features – Observations

The analysis focuses on phenomena that are commonly found to be surface manifestations of different orders and segments of the flow systems. These phenomena are wetlands, springs, soil salinization and accumulation of salt deposits, salt tolerant and phreatophyte plant species, karst landforms, and temperature anomalies.

4.5.1. *Wetlands*

The study area exhibits extensive wetlands along cross-section A*-A’. Wetlands are present in the uplands of the Caribou Mountains between 0 and 10 km (3R, Figure 4.7). Large wetland areas also occur in the central lowland between 50 and 80 km (1D, Figure 4.7) and 95 and 135 km (2D, Figure 4.7).

4.5.2. *Springs*

Springs with diffuse discharge (seepage) as well as with focused discharge through an orifice are both present in WBNP (Figure 4.6, Figure 4.7, Figure 4.8). Their discharge elevations and interpreted distances from the Caribou Mountains, as regional recharge area, were compared to their hydrochemical characteristics (Figure 4.9). Higher elevations in the central region of WBNP are dominated by lower TDS contents (<5,000 mg/L) while the higher TDS concentrations (>5,000 mg/L) occur at lower topographic elevations (Figure 4.9a). The hydrochemical facies also appear to change as the TDS concentrations increase showing Ca-HCO_3- to Ca-SO_4-type waters at higher elevations, and "mixed" to Na-Cl-type waters at lower elevations (Figure 4.9). Springs with "mixed" and Na-Cl water types are limited to areas located farther than 160 km from the Caribou Mountains (Figure 4.9b).

4.5.3. *Salt deposits, saline soils*

Salt deposits and saline soils are most common in the Salt Plains region of WBNP (Figure 4.8, Photo 4.1). Several salt flats were identified east of the escarpment along the central eastern boundary of WBNP (Figure 4.8). Salt accumulations and salt crusts were observed around the discharge point of numerous springs and diffuse seepages (Photo 4.1). The thickness of salt crusts varies from a few millimetres with a thin salt layer covering the top of the soil to tens of centimetres thick massive salt deposits.

4.5.4. *Vegetation*

The vegetation of Salt Plains is characterized by saline grassland vegetation consisting of halophytic plant species that are associated with saline soil and a shallow water table (Figure 4.10, Photo 4.2, Photo 4.3a) (Raup 1935; Schwarz et al. 1988). The vegetation is characterized by several halophytic species, such as red samphire (*Salicornia europea ssp. rubra*) associated with alkali cordgrass (*Spartina gracilis*), Nuttall's alkaligrass (*Pucinellia nuttalliana*), sea milkweed (*Glaux maritima*), horned seablite (*Suaeda calceoliformis*), and salt grass (*Distichlis spicata*) (Photo 4.2) (Raup 1935; Schwarz et al. 1988). Occurrence of foxtail barley (*Hordeum jubatum*), Baltic rush (*Juncus balticus*) and cat-tail (*Typha latifolia*) are also among the most characteristic plants in the salt flats (Raup 1935).

West of the salt flats, towards the salt escarpment, the halophyte vegetation of the Salt Plains lowland changes abruptly to shrub and boreal forest vegetation with several upslope transitions (Figure 4.10, Photo 4.3). Immediately adjacent to the halophyte vegetation, the base of the slope is covered by shrubs, such as willow (*Salix spp*) associated with black spruce (*Picea mariana*) and tamarack (*Larix laricina*). Uphill, the forest becomes a mix of aspen poplar (*Populus tremuloides*) and black spruce, which finally transitions into a mostly aspen poplar forest (Figure 4.10). Isolated topographic highs in the salt flats are often covered by black spruce, tamarack and shrub communities (Figure 4.10, Photo 4.2).

4.5.5. *Karst geomorphology*

Karstic features, such as sinkholes and disappearing streams, are widespread in WBNP (Soper 1939; Drake 1970). Sinkholes appear to form in an arched belt along the outcrop areas of soluble rock formations (Figure 4.3) and are the most abundant on outcrops of the Chinchaga and Muskeg evaporite formations and Keg River and Slave Point carbonate formations (Figure 4.3). Several sinkholes are filled with water and were observed to remain unfrozen during the winter.

Both solution and collapse sinkholes are present in WBNP. Where the outcrop is primarily soluble gypsum and the unconsolidated surficial material is thin, formation of solution sinkholes, cracks, cavities and shafts are present. Solution sinkholes were observed on outcrops of the Chinchaga Formation in the central eastern region of WBNP (Photo 4.4a). Solution sinkholes are characterized by oval to elliptical-shaped, enclosed depressions, circular shafts or linear troughs formed by solutional enlargement of joints and fractures (Sweeting 1973; Tsui 1982; Ford 1997).

Collapse sinkholes are the most abundant karstic features in the area and represent the principal landscape features of covered evaporite karst to which most of the karstic areas of WBNP belong (Cruden et al. 1981; Tsui and Cruden 1984; Ford 1997, 2004, 2009) (Photo 4.4b). They were identified on outcrops of Chinchaga, Keg River, Muskeg and Slave Point formations. They are characterized by closed, circular or near-circular depressions with steep-cliffed sides and relatively high depth:diameter ratio (Sweeting 1973; Tsui 1982). They are often found to be aligned, suggesting preferential direction of possible underground conduits (Photo 4.4c).

4.5.6. *Temperature anomalies*

Unfrozen (open) waters, including flowing (i.e., springs and streams) and still water bodies (i.e., lakes), were registered mid-April to mid-May 2014 by Parks Canada (Figure 4.8). At the time of the survey the measured mean air temperature was -17.1°C and the average snow cover was 37 cm in Fort Smith (*http://climate.weather.gc.ca/historical_data*). Still open waters were identified as sinkhole lakes (Photo 4.5).

The highest number of unfrozen waters was found in the northern Salt Plains area where the carbonates and evaporites of the Keg River and the Chinchaga formations outcrop (Figure 4.8b). In the broader study area, occurrence of unfrozen sinkhole lakes coincides with karstic areas covering the carbonates of Slave Point and Keg River formations, and the evaporites of the Muskeg formations (Figure 4.8a). Farther away, SE and NW, from cross-section A*-A', outcrops of Slave Point and Muskeg formations indicate several more sinkholes with unfrozen water in them (Figure 4.3, Figure 4.8a).

4.6. Groundwater-diagnostic surface features and their relations to groundwater

4.6.1. *Wetlands*

Wetlands form where water-saturated conditions in the root zone or at/above the land surface are maintained either by groundwater discharge to the surface or by precipitation and poor drainage conditions (van der Kamp and Hayashi 1998; Winter et al. 1998). They do not necessarily occupy topographic lows; they can form on slopes where the water table intersects the land surface and in upland regions (Winter et al. 1998). In general, wetlands occupying topographic highs indicate recharge to groundwater; however, their hydrogeological function is also dependent on their position relative to local- and regional-scale flow systems (Winter et al. 1998). Wetlands occupying flat areas adjacent to uplands are, typically, places of groundwater discharge due to upward breaks-in-slope in water table (Winter 1999). Wetlands in topographically low areas are often fed by groundwater, and, in general, are associated with other discharge features, such as springs or seepages, salt precipitates, elevated TDS content, thermal anomalies and/or lack of contribution by overland flow (Tóth 1971). Wetlands in the upland region of WBNP coincide with the main recharge area of regional flow systems. Occurrence of large wetland areas in the central lowland of WBNP coincides with local and intermediate discharge areas in the simulated cross-section at 50 to 80 km (1D, Figure 4.5) and 100 to 135 km (2D, Figure 4.5), respectively. The apparent lack of overland flow to the wetlands found in intermediate discharge areas in WBNP suggests that they are dominantly maintained by groundwater (Figure 4.7).

4.6.2. *Springs*

Springs are natural discharge features of groundwater flow systems and represent the place where the hydraulic head reaches and/or exceeds the land surface (Tóth 1971; Tóth 1999; Kresič 2010). It has been shown that the discharge elevation of springs in carbonate regions is indicative of the flow-path length and represents the relative hierarchy of gravity-driven groundwater flow systems (Mádl-Szőnyi and Tóth 2015, 2017). Elevation of springs in WBNP is indicative of the segment and the relative scale of the flow systems feeding the spring. Springs in WBNP with lower TDS content typically discharge at higher elevations than springs with high TDS concentration suggesting that they are associated with flow systems of shorter flow paths, while springs with high salinity discharging at topographic lows are most likely associated with ascending flow systems of longer flow paths.

4.6.3. *Salt deposits, saline soils*

Salt crusts and accumulations can be manifestations of discharging regional groundwater and can be present in discharge areas of intermediate and regional groundwater flow system (Meyboom 1966; Williams 1968; Tóth 1971, 1999; Hendry and Buckland 1990; Thibodeau et al. 1998; Salama et al. 1999). The ascending groundwater, depending on flow-path length, contains significant amount of sodium, sulphate or chloride ions. These ions are dissolved along the flow path, precipitate and form salt deposits and saline soils in discharge regions. As a consequence of the ascending groundwater flow, the water table is located near or, in some places, above the land surface. This may result in increased evaporation of the discharging saline water. The water evaporates; the dissolved solids precipitate and salt deposits develop on the soil (Photo 4.1).

4.6.4. *Vegetation*

Vegetation can be important indicator of the nature of groundwater flow. Consequently, some plant communities may be used as indicators of groundwater flow conditions (Meinzer 1927; Tóth 1966, 1999; Bernáldez and Rey Benayas 1992; Klijn and Vitte 1999, Batelaan et al. 2003; Harvey et al. 2007). The vegetation of an area reflects the soil moisture conditions and the chemical characteristics of groundwater. Recharge areas, where the water table is deep, are typically associated with vegetation that prefers low moisture conditions (xerophytes). Discharge areas are characterized by the water table situated at or near the land surface and, thus, are associated with vegetation that is tolerant to high moisture conditions (i.e., phreatophytes). Discharge areas of longer flow paths are typically accompanied by high TDS contents in the groundwater resulting in plant communities that are tolerant to high salinity in the soil (i.e., halophytes).

Red samphire is a groundwater-dependent, halophytic species and generally indicates a shallow water table, i.e., water supply available during the whole growing season, and saline conditions (Meinzer 1927; Ungar 1974; Mitsch et al. 2009). Cattail and Baltic rush are typical species of phreatophyte plant communities and are less tolerant of saline conditions; however, they grow in brackish marshes and can tolerate moderately saline conditions (Shay and Shay 1986; Millar 1976). Black spruce and tamarack are common species of wetlands in northern Alberta. They are groundwater-dependent phreatophyte plants that prefer shallow water table and fresh water supply (Meinzer 1927). Willows also represent phreatophyte vegetation. They are associated with moist conditions with water of good quality, low salinity and low alkalinity. They usually grow where the water table is less than 4.5-5 m deep (Robinson 1958).

4.6.5. *Karst geomorphology*

Karstic features can be indicative of descending and ascending groundwater. They can be place of focused recharge where water, precipitation and/or surface stream, enters the system and becomes a part of the subsurface flow regime (Ford and Williams 2007). They can also be related to subsurface dissolution by upwelling, deep flow systems (Klimchouk 2012, 2015, 2017).

Solution sinkholes (Type 1) form where infiltrating precipitation dissolves soluble minerals on the surface as it percolates downward while creating fissures and cavities, and often develops in upland regions (White 1988; Ford and Williams 2007) (*1*, Figure 4.11) (Photo 4.4a). Solution cavities and sinks, in general, indicate focused recharge for shallow groundwater (Ford and Williams 2007).

Subsidence/collapse sinks (Type 2) are attributed to dissolution of soluble minerals in the subsurface that eventually undermines the overlying strata and leads to collapsing of the weakened top layers resulting in depressions on the land surface. Dissolution of soluble geologic media in the subsurface can be by either descending or ascending groundwater (Drake 1970; Tsui 1982; Ford 1997). The infiltrating precipitation percolates through the medium, dissolves the most soluble material and forms underground dissolution zones, voids and cavities (2A, Figure 4.11). Karstification due to ascending groundwater is defined as hypogene karstification and occurs when dissolution of subsurface material is related to ascending, deep groundwater. Development of collapse sinkholes in WBNP are related to dissolution of gypsum/anhydrite and halite minerals that have solubility orders of magnitude higher than carbonates. The dissolving solvent is often a mix between the infiltrating fresh water percolating downward and the deep brines that are moving upward towards the edge of the basin (Type 2B, Figure 4.11). It has been shown that the hypogene karstification created several collapse sinkholes in the Athabasca Oil Sands (AOS) region south of the WBNP via large-scale halite removal process from the Prairie Evaporite Formation by upward moving groundwater (Broughton 2017). The halite-bearing Prairie Evaporite Formation of the AOS area transforms into the anhydrite-dolostone dominated Muskeg Formation under the WBNP (Grobe 2000). Considering the presence of highly soluble material in the formation and the similar, edge-of-the-basin geologic setting of both regions, it is postulated by the author that several of the sinkholes associated with the Muskeg Formation are formed by the same process that formed the hypogene evaporite karst features in the AOS area.

4.6.6. *Thermal anomalies*

Moving groundwater exchanges heat with its ambient environment and modifies heat distributions in the subsurface by convection. With increasing depth of penetration, moving groundwater can result in a subdued temperature gradient in recharge areas and enhanced temperature gradient in discharge areas, relative to the ambient geothermal gradient (Domenico and Palciauskas 1973). Sustained discharge of deep, relatively warm groundwater into surface water bodies can result in these waters remaining unfrozen during winter (Prowse and Belatos 2002; Rautio and Korkka-Niemi 2011). Occurrences of unfrozen waters in WBNP at 82 km (1D, Figure 4.8a) and 125 and 141 km (2D, Figure

4.8a) along cross-section A^*-A' correspond to the numerically calculated local discharge area at 80 km (1D, Figure 4.5) and the intermediate discharge area between 100 and 160 km (2D, Figure 4.5). Thermal anomalies on groundwater discharge areas suggest hydraulic connection between surface waters and groundwaters and that these waters are fed by variable amount of groundwater that prevents the water from freezing by having higher temperature than the ambient environment.

4.7. Combining surface features and groundwater flow systems in WBNP

The interpretation of different surface features and their relation to flow systems follows the natural path of water on different spatial and temporal scales and moves from recharge to discharge areas on local to regional scale.

4.7.1. *Groundwater recharge*

Since recharge areas of local, intermediate and regional flow systems lack distinguishing characteristics, the different scales of flow systems will not be differentiated in recharge areas.

Wetlands occupying uplands in the Caribou Mountains and karstic features observed on the salt escarpment represent the most important surface manifestations of groundwater recharge observed in the area. Wetlands on the top of the Caribou Mountains are consistent with simulated recharge area of regional groundwater systems. Their interaction with groundwater, however, is dependent on their relative position to local-scale flow systems present in the uplands but not shown by the numerical simulation.

Recharge from local flow systems on the salt escarpment adjacent to the Salt Plains is indicated by solution sinkholes and cavities that suggest focused recharge of shallow flow systems and are consistent with the results of the numerical simulation (Figure 4.5).

Presence of “micro-recharge” areas is suggested by Black spruce and shrub communities on isolated topographic mounds on the salt flats (Figure 4.10). The hummocky landscape of the Salt Plains can be described as saline, grassy flats and wetlands alternating with elevated forest-covered hills. The small change in the topography between the salt flat and the hummock results in abrupt transition from the saline grassland into the black spruce- and shrub-dominated vegetation (Figure 4.10). Although the exact hydraulic connection between the saline depressions and the black spruce-dominated hills cannot be quantified and adequately interpreted due to lack of data, a hypothesized model is proposed and shown in Figure 4.10. The Salt Plains were shown to be discharge area of regional-scale, deep flow system (Figure 4.5) (Chapter 3). The topographically slightly elevated hills are in the area of ascending regional groundwater, however, they also represent “micro-recharge” areas where precipitation can enter the soil and superimpose on the ascending deep flow system. The entering fresh water sits on the saline groundwater and provides fresh water supply for the vegetation. In form of sub-local-scale flow systems it can move towards lower areas as it is shown by the conceptual model (Figure 4.10). The sudden change in vegetation on the hummocks relative to the saline flats reflects the entry of fresh water into the system which enables the growth of fresh water tolerant plant species, such as black spruce and the associating plant communities.

4.7.2. *Local groundwater discharge*

Local groundwater discharge characterizes the western lowlands and the salt escarpment which are are associated with wetlands and phreatophyte vegetation, respectively. A local discharge area is indicated by wetlands occupying the eastern foreground of the uplands of the Caribou Mountains and is consistent with the results of the numerical simulation. These wetlands are associated with low TDS waters (Figure 4.6a, Figure 4.7). Since water chemistry of surface waters in local recharge and discharge areas often lacks distinguishing characteristics, the low TDS content only indicates the local nature of flow systems in the area, not necessarily the segment of it.

The local discharge area identified in the Salt Plains region is also indicated by phreatophyte plant species, such as black spruce, tamarack and willow, that are characteristic of fresh groundwater and shallow water table, i.e., discharge area of short flow paths.

4.7.3. *Intermediate groundwater discharge*

The eastern part of the central lowlands of WBNP is characterized by discharge areas of intermediate-scale flow systems. Intermediate discharge areas in the central lowlands coincide with large wetland areas (Figure 4.5, Figure 4.7). They are also associated with several other manifestations of groundwater discharge, such as elevated TDS, “mixed” and Ca-SO_4-type water, springs/seepages, unfrozen waters, and lack of contribution by overland flow. The occurrence of sulphate in these waters associated with elevated TDS concentration is evidence of intermediate-scale flow paths. However, the hydrochemical characteristics of these waters reflects also the effect of the lithology of the area as most of these Ca-SO_4-type waters are found in the outcrop area of the anhydrite-dominated formations (Chapter 2). Hypogene karstic features spanning across the central lowlands coincide with simulated upward movement of deep flow systems and is in agreement with discharge of groundwater from intermediate-scale flow systems simulated in the area (Figure 4.5).

4.7.4. *Regional groundwater discharge*

The Salt Plains region, based on the numerically calculated flow field, was identified as a discharge area of regional flow systems (Figure 4.5).

Springs and seepages identified in the area represent terminal zones of groundwater flow systems. The high salinity, Na-Cl-type waters, the saline soils and salt accumulations all indicate discharge from regional groundwater flow systems. Na-Cl-type brine springs are limited to the lowest topographic elevations of the basin, i.e., the Salt Plains region, and are manifestations of regional-scale groundwater discharge (Figure 4.8b). To maintain the necessary conditions for a long-term salt accumulation process, a sufficiently long period of time is necessary. In gravity-driven flow systems only regional-scale groundwater flow can maintain such conditions and be a source of such a large amount of dissolved material (Tóth 1999). Halophyte plant species, such as the Red samphire, and phreatophyte species, such as Cattail and Baltic Rush, signify discharge from moderately saline to saline flow systems associated with long groundwater flow paths of intermediate/regional flow systems. The high density of unfrozen waters in the Salt Plains region is evidence of discharge of deep, large-scale groundwaters simulated in the region. The unfrozen waters coincide with other surface manifestations of regional groundwater discharge, such as springs with elevated TDS and Na-Cl-type hydrochemical facies, salt accumulations and halophyte vegetation (Figure 4.5, Figure 4.6, Figure 4.8, Figure 4.10).

4.8. Conclusions

Groundwater-diagnostic surface features, such as wetlands, springs, saline soils and salt deposits, vegetation, karst geomorphology and positive thermal anomalies are indicative of the different scales and segments of flow systems in WBNP and are in agreement with the simulated groundwater flow field in the area. The strong correlation between the results of the numerical model and interpretations of field observations supports the hypothesis that the groundwater regime is dominantly controlled by elevation differences in water table in central WBNP and that the flow field is characterized by hierarchically superimposed flow systems. Wetlands, fresh water springs and phreatophyte vegetation indicate groundwater discharge of short flow systems near the Caribou Mountains and in the Salt Plains. Wetlands accompanied by springs with elevated TDS and Ca-SO_4-type water, hypogene karstification and thermal anomalies signify ascent of groundwaters from intermediate-scale flow systems in the central lowlands. Saline/brine springs, salt crusts, phreatophyte/halophyte vegetation and positive thermal anomalies indicate ascending regional groundwater flow in the Salt Plains area.

Although this study focuses on the area of the previously simulated cross-section in central WBNP (A^*-A), field and satellite observations indicate the identified patterns of hydrogeological conditions may be extrapolated to the rest of WBNP. The strong agreement between water chemical characteristics, numerical simulation and groundwater-related surface phenomena suggests that the integrated conceptual model introduced in this study represents well the groundwater flow regime in the park. The general characterization of the hydrogeological conditions in WBNP presented in this study provides a solid understanding on the flow regime and provide framework for further studies in the area.

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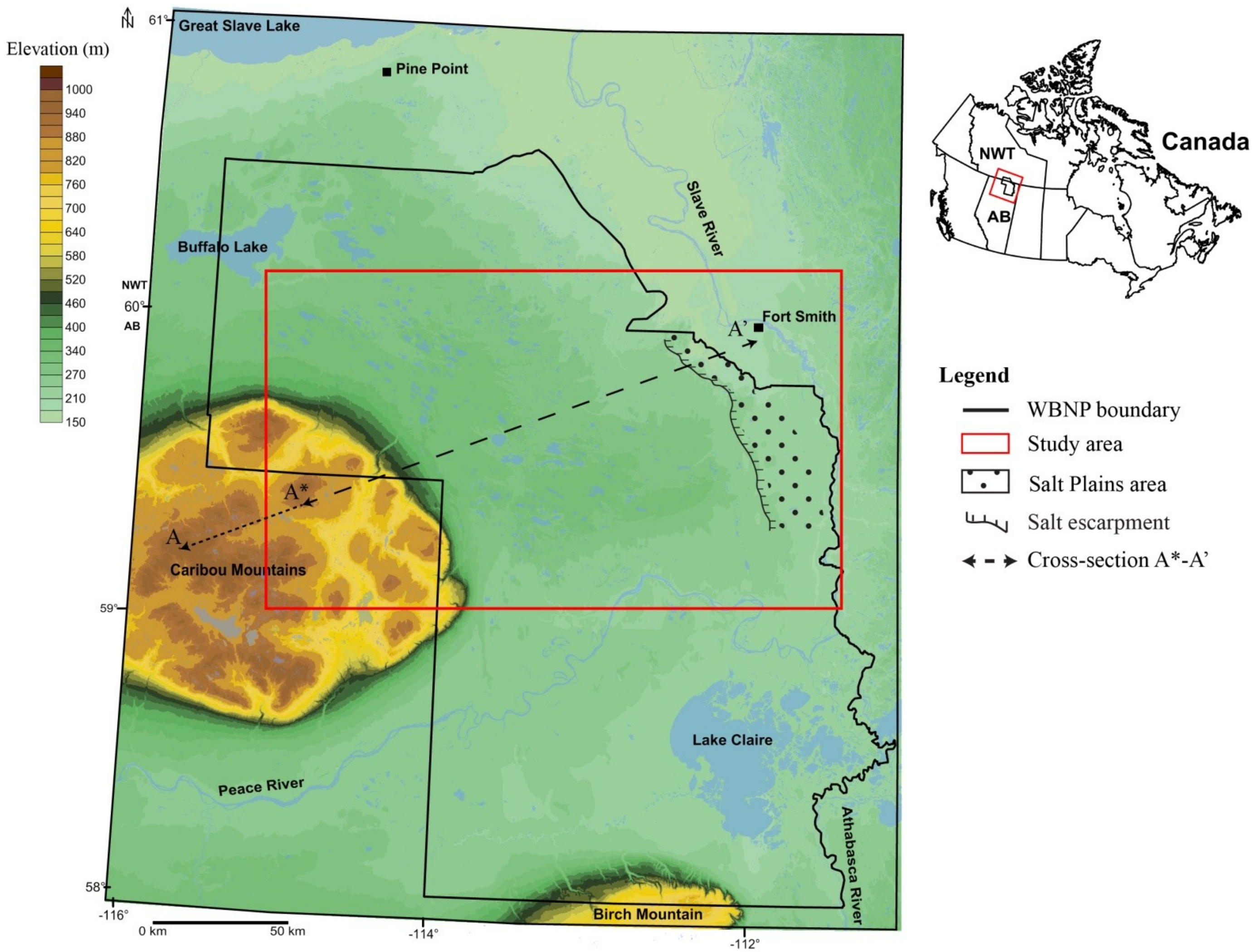

Figure 4.1: Topography of Wood Buffalo National Park. Cross-section A*-A’ is a truncated section of cross-section A-A’ simulated in Chapter 3. Location of A* represents the regional groundwater divide identified by numerical simulations in Chapter 3. The Salt Plains are also shown.

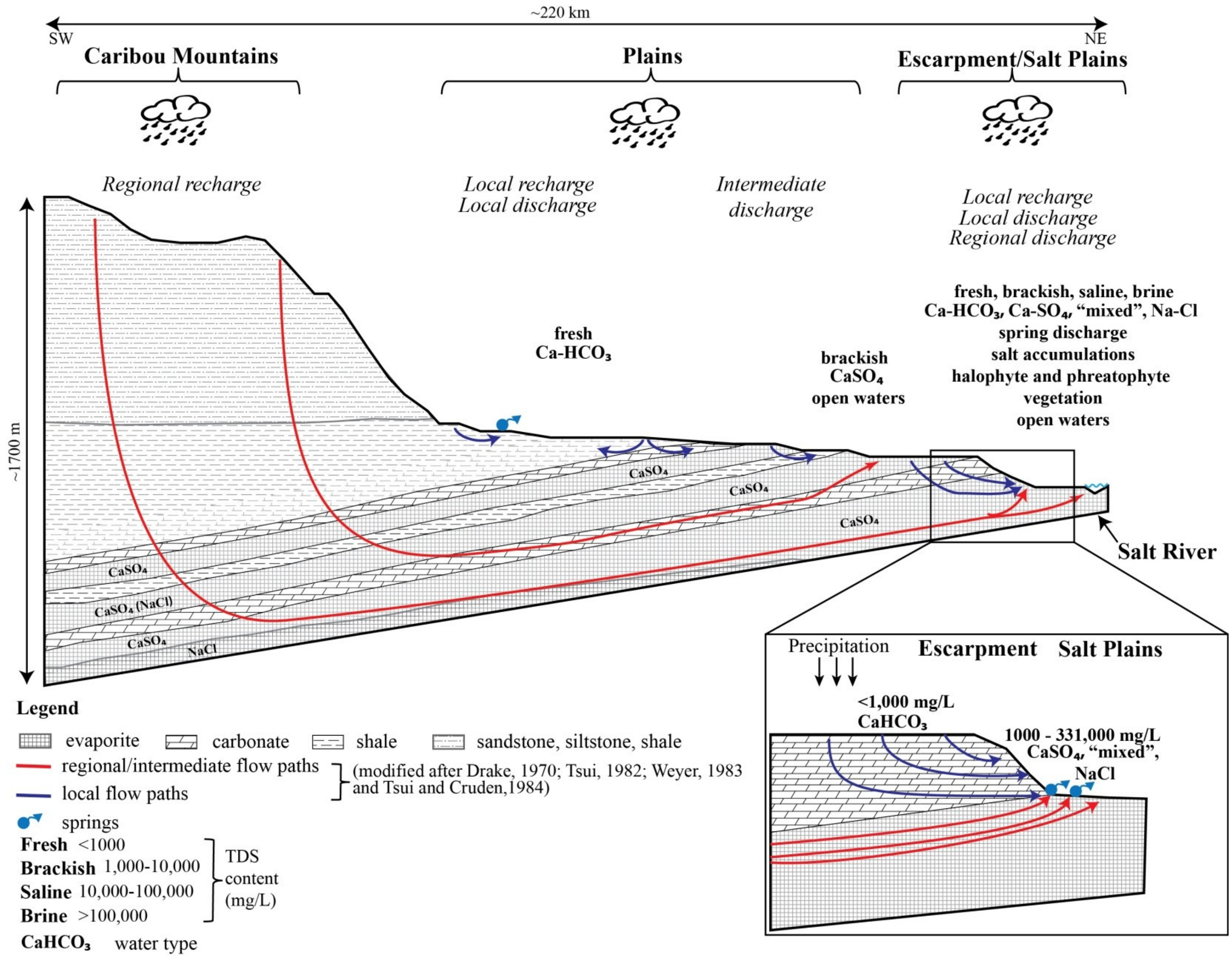

Figure 4.2: Conceptual model of groundwater flow in Wood Buffalo National Park (modified from Figure 5, Chapter 2)

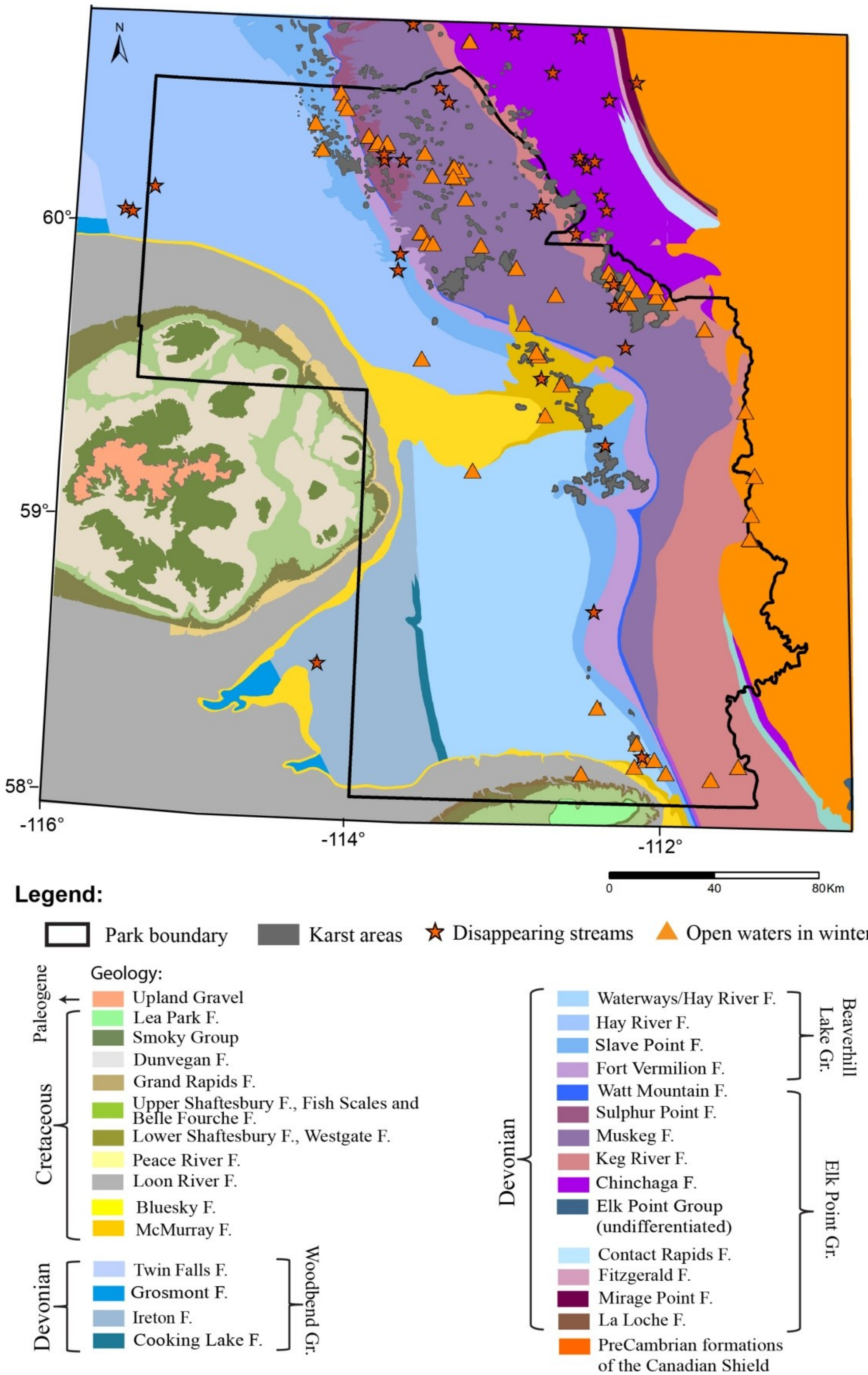

Figure 4.3: Bedrock geology of Wood Buffalo National Park (modified after Prior et al. 2013 and Okulitch and Fallas 2007). Karst areas and disappearing streams are also shown.

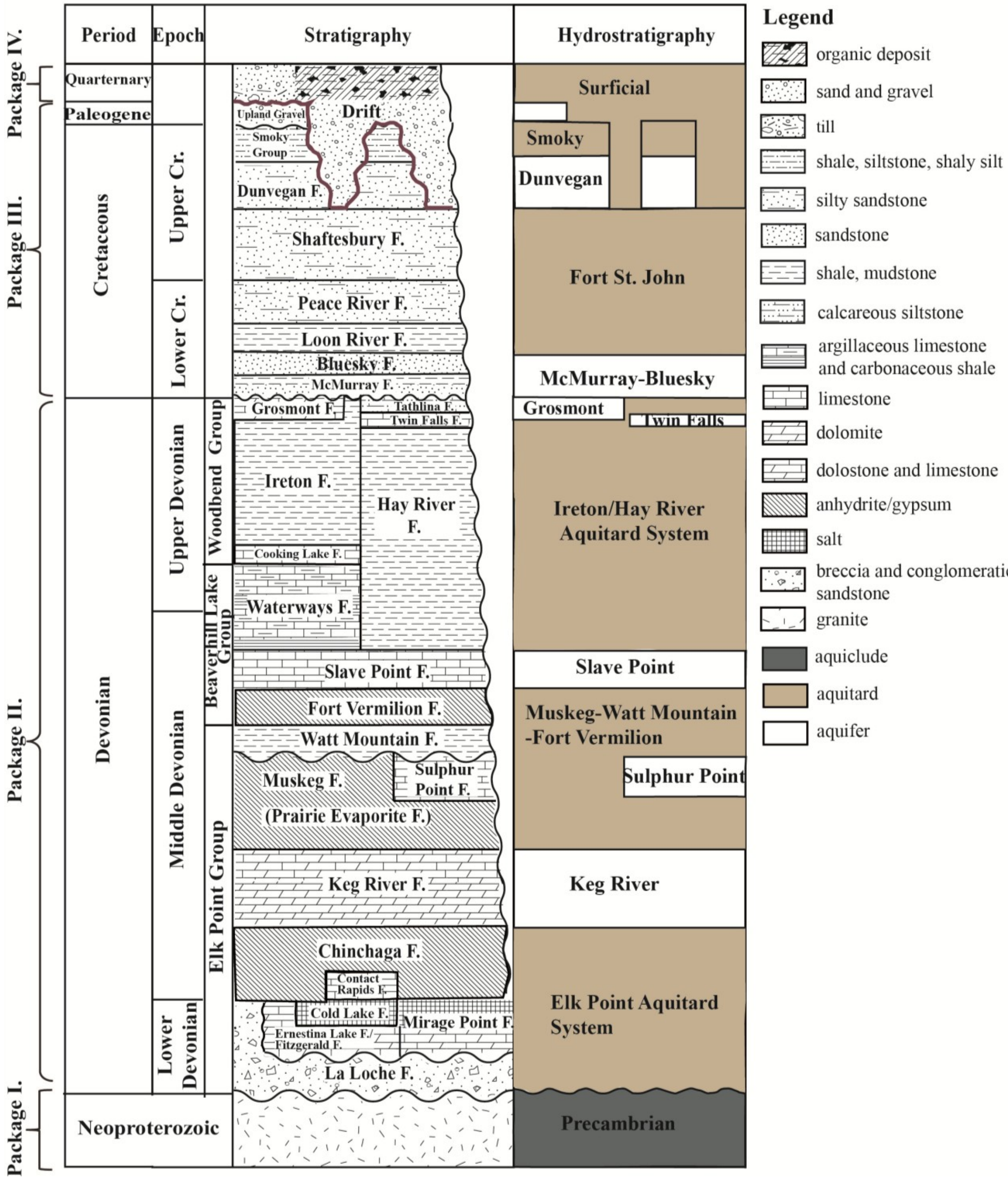

Figure 4.4: General stratigraphy and hydrostratigraphy in Wood Buffalo National Park (modified from Chapter 2)

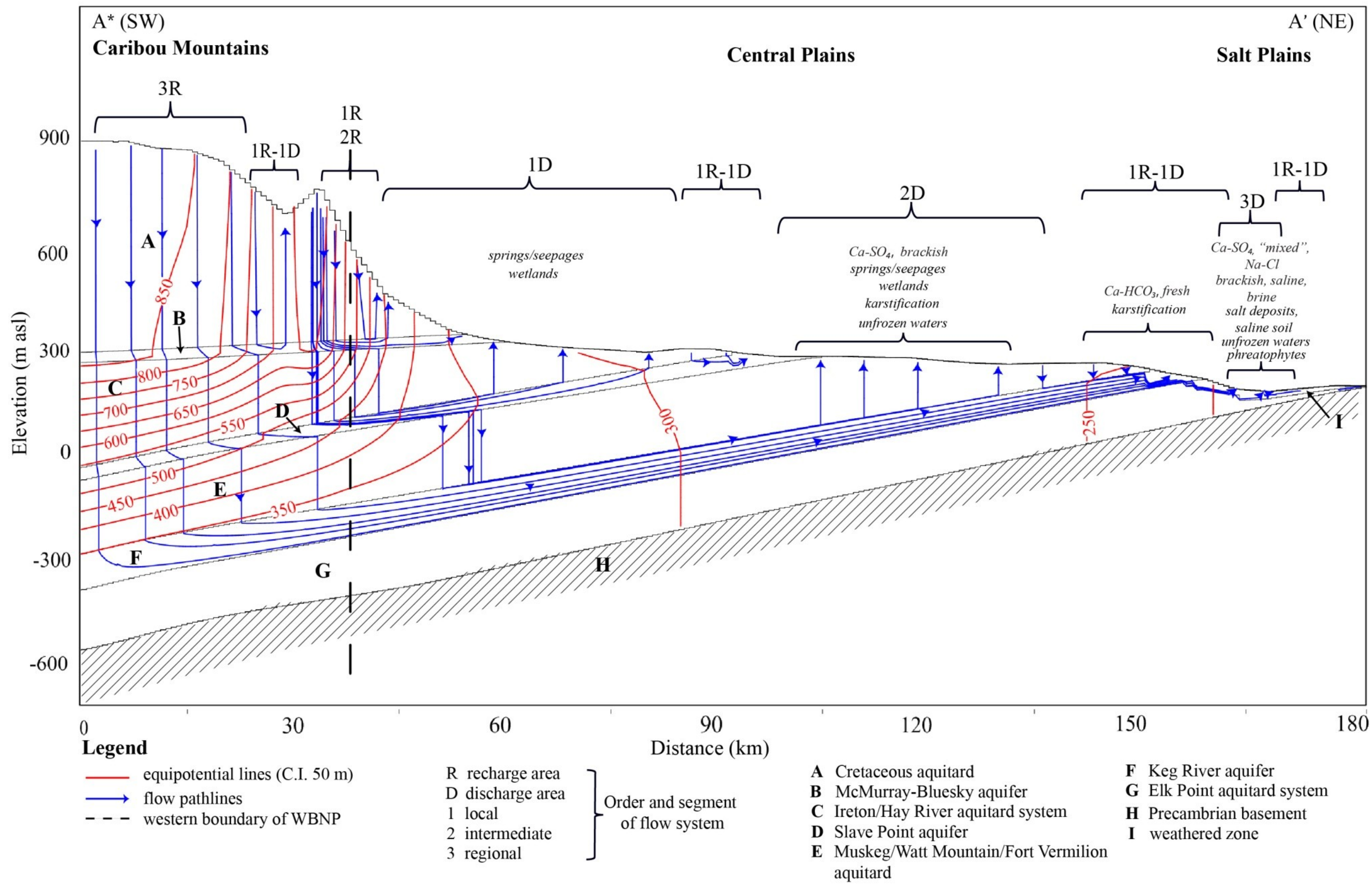

Figure 4.5 Results of groundwater flow simulation along cross-section A*-A' (modified from Figure 7 in Chapter 3). The left (west) and base are zero flux boundary conditions. The upper boundary is defined by the water table, approximated by the land surface.

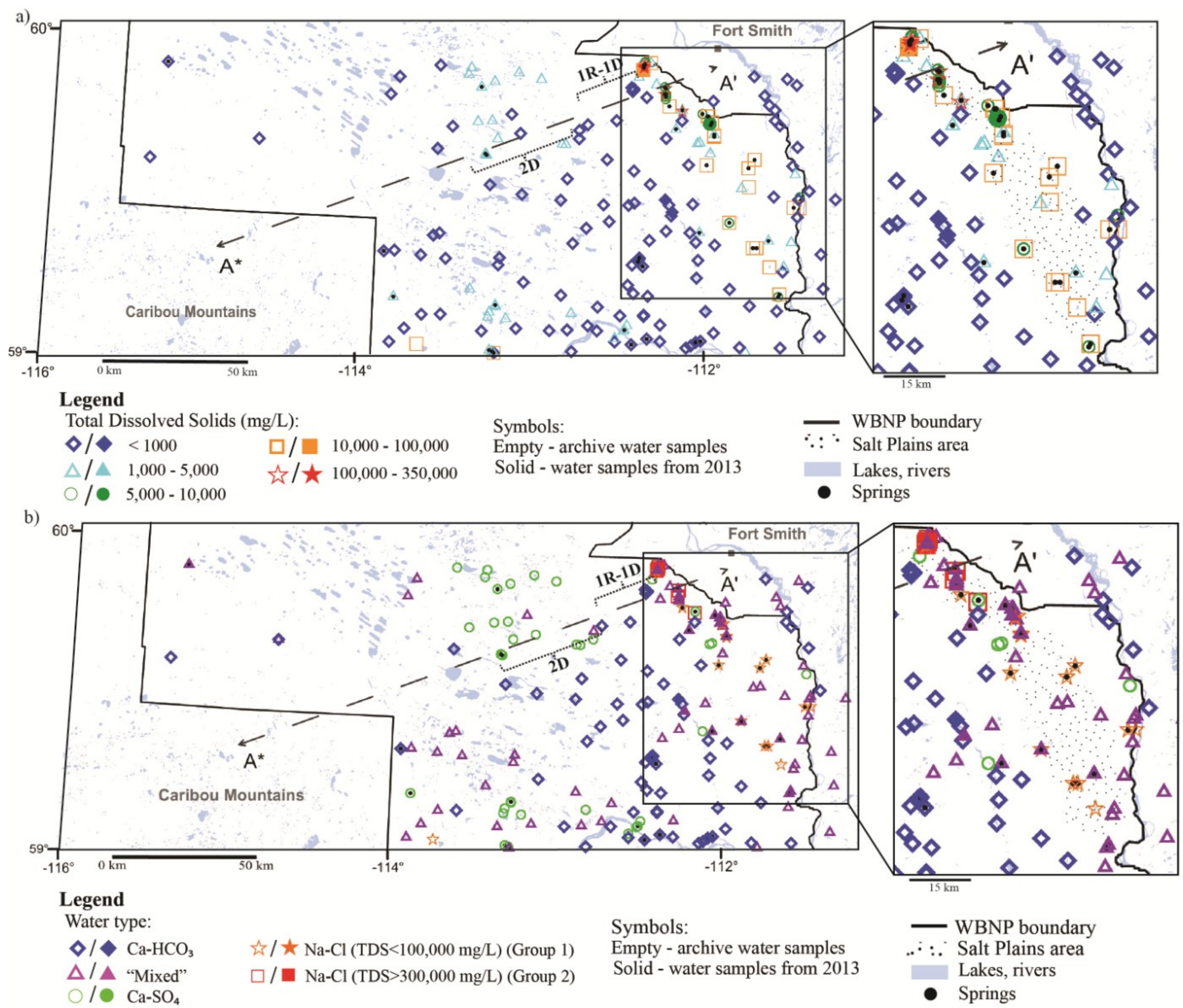

Figure 4.6: a) TDS concentration and b) hydrochemical facies in central Wood Buffalo National Park. Insets show the Salt Plains region

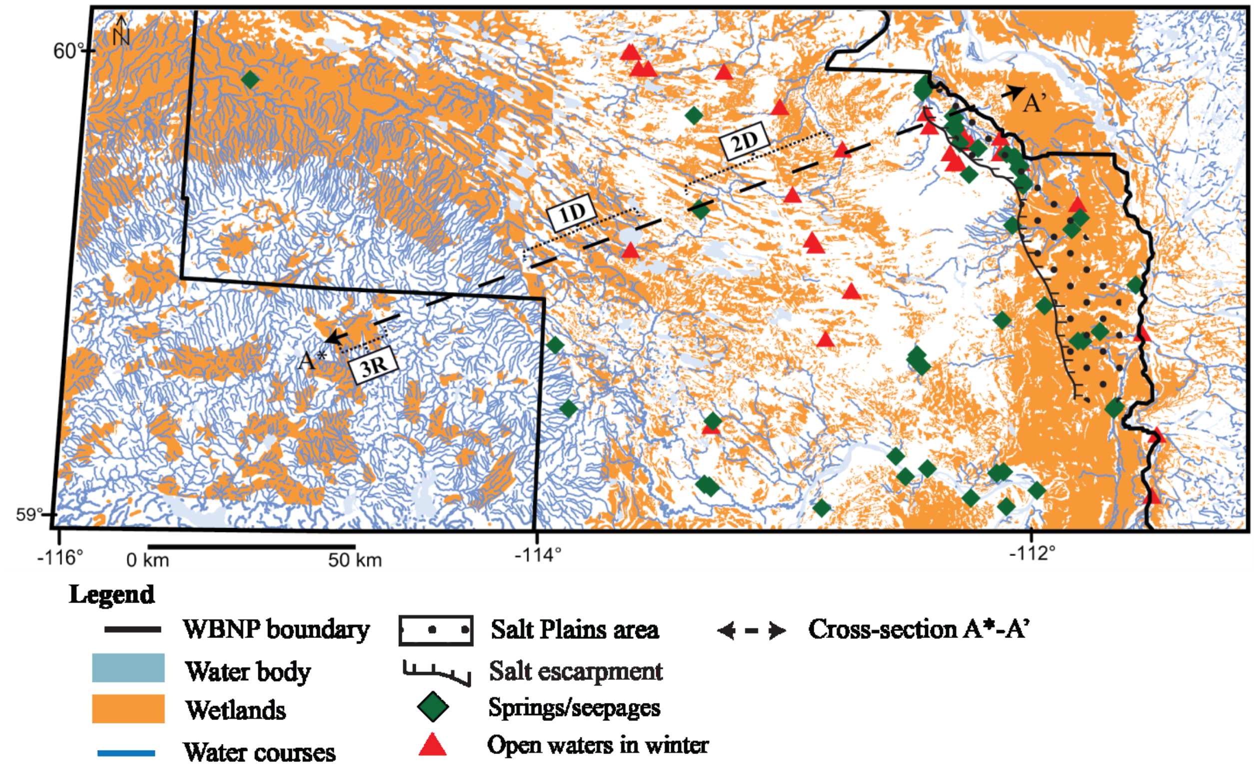

Figure 4.7: Wetlands in the Wood Buffalo National Park (modified from *wetlands.shp,* 1:250 000, National Topographic Data Base, Ministry of Natural Resources Canada Centre for Topographic Information 1998 and Mougeot and Fenton 2010). Surface water bodies and water courses are also shown.

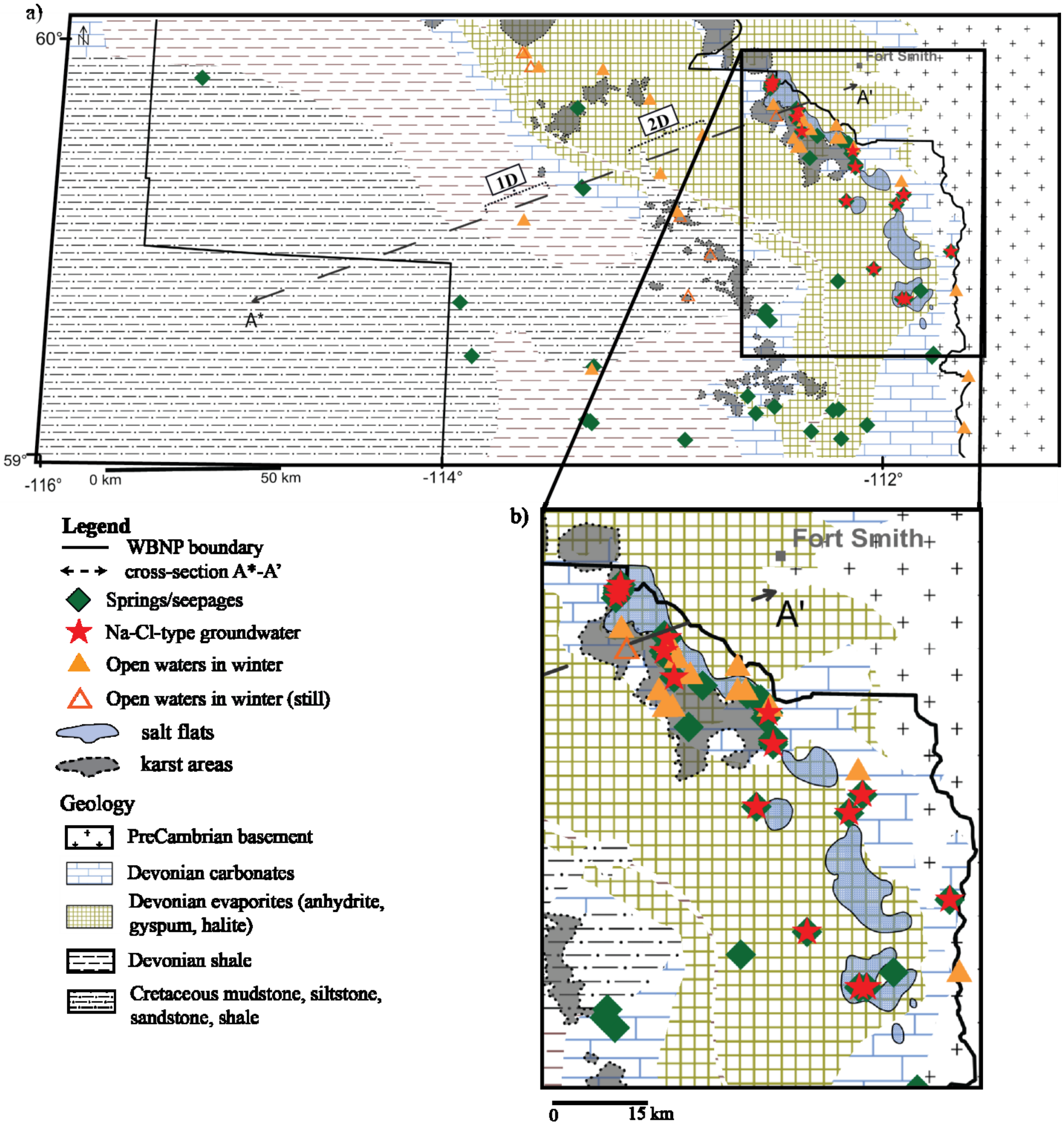

Figure 4.8 a) Location of spring discharge and Na-Cl-type groundwaters in the study area. b) Locations of spring discharge, Na-Cl-type groundwaters, temperature anomalies, salt flats and phreatophyte vegetation in the salt flats-region. Simplified bedrock lithology and karst areas are also shown.

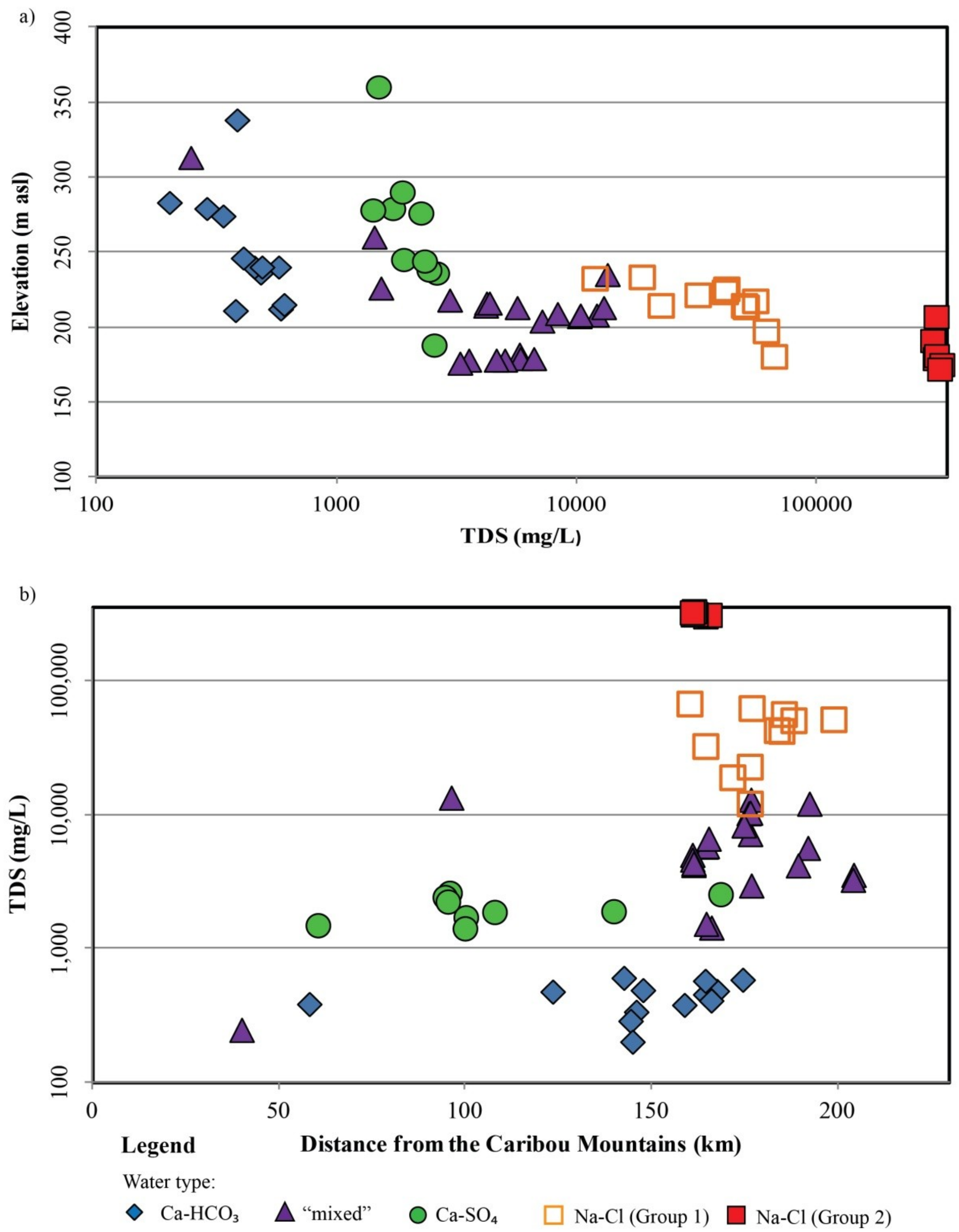

Figure 4.9 a) TDS concentration versus elevation of spring discharge in WBNP, b) Distance from the top of Caribou Mountains (km zero on cross-section A*-A') versus TDS concentration. Change in hydrochemical facies with increasing altitude and with increasing distance from the main recharge area (Caribou Mountains) is also shown.

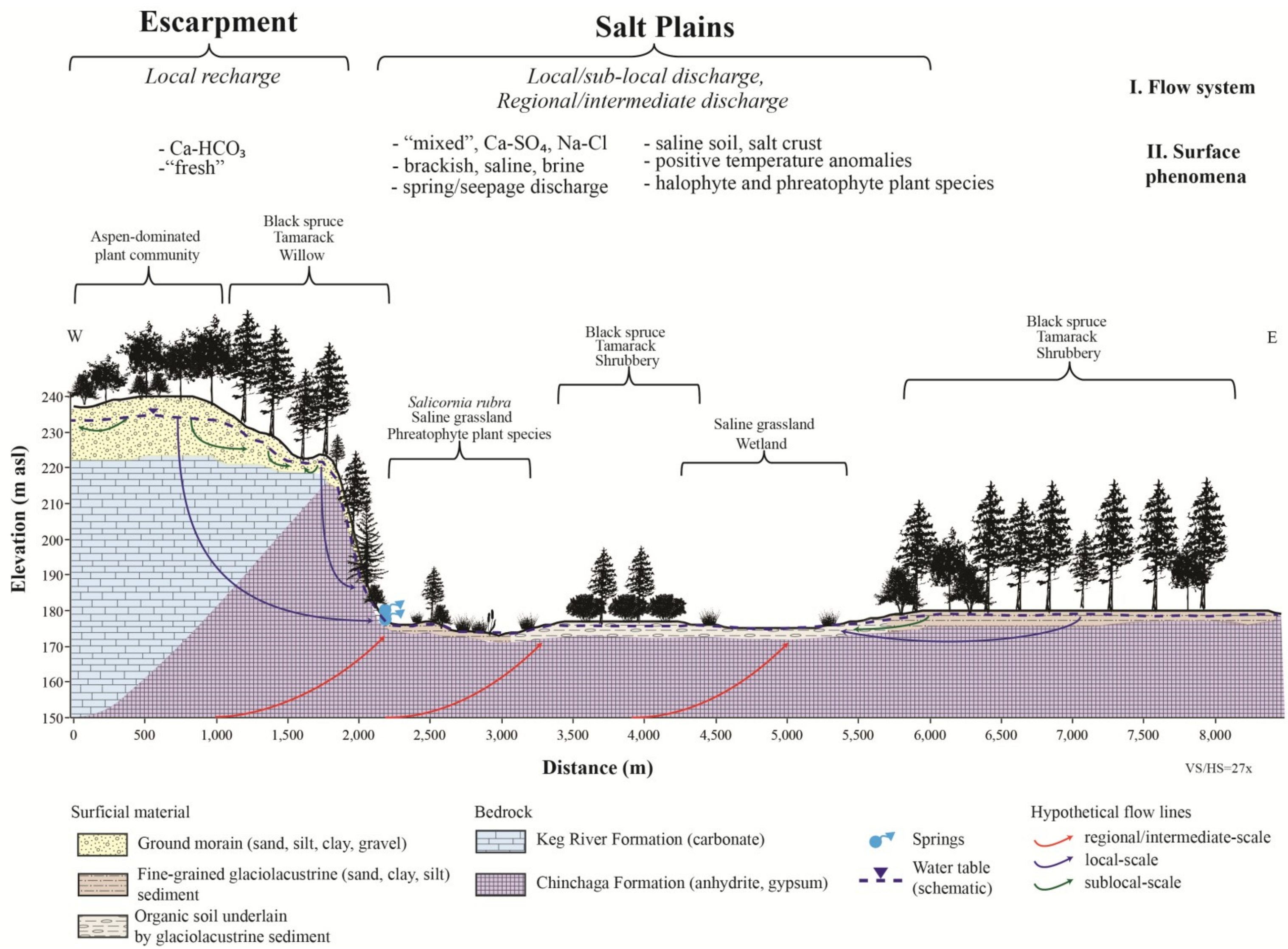

Figure 4.10: Surface phenomena and nested groundwater flow systems in the Salt Plains region. The diagram shows an arbitrary cross-section across the Salt Plains region with the salt escarpment on the left (W) and the salt flats to the right (E).

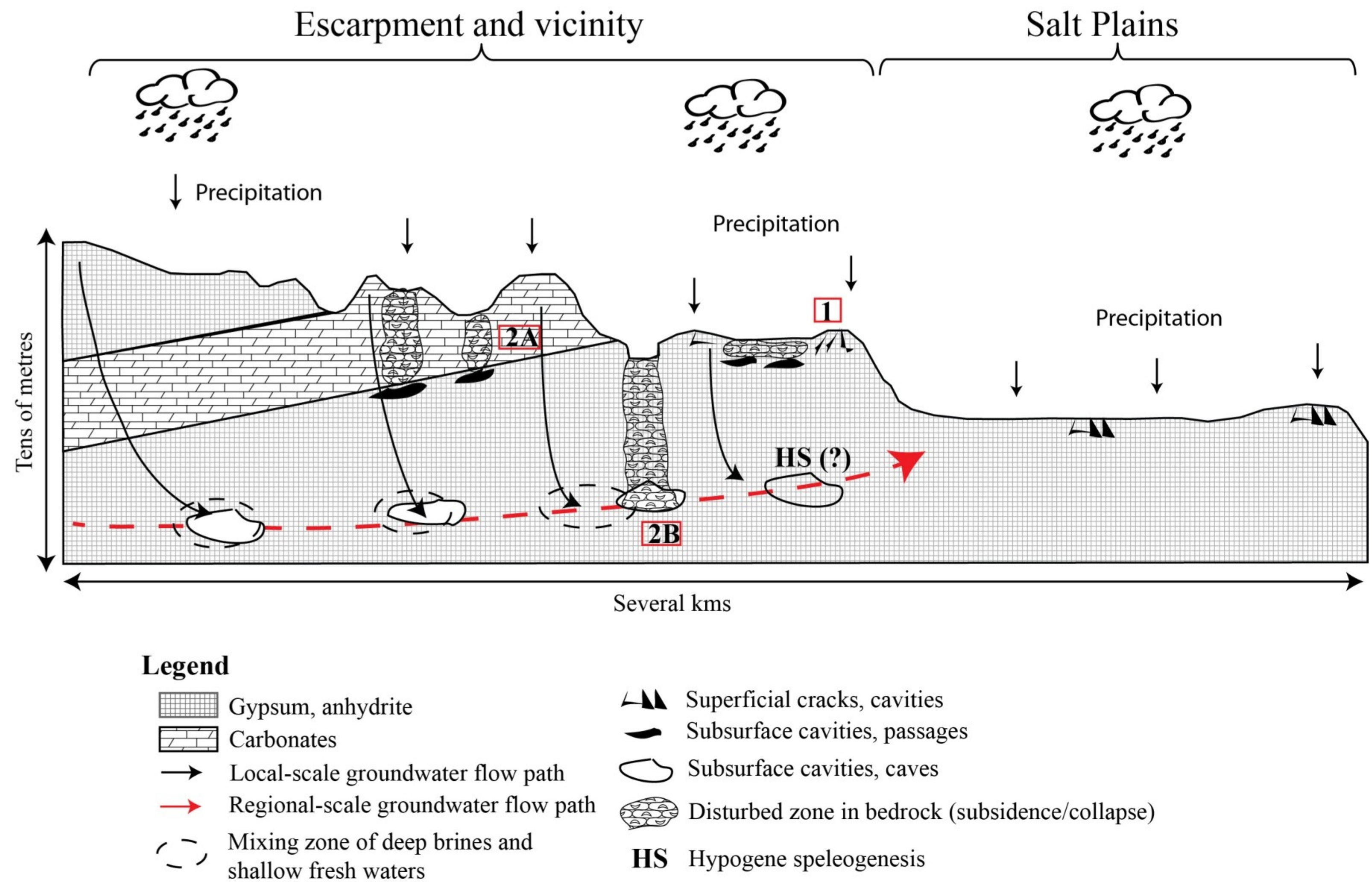

Figure 4.11: Conceptual model of karstification mechanisms in Wood Buffalo National Park. 1: Solution cavities and sinks due to dissolution by precipitation on the surface, 2A: formation of collapse sinkholes above subsurface voids and cavities dissolved by descending meteoric water, 2B: formation of collapse sinkholes due to dissolution related to ascending groundwater

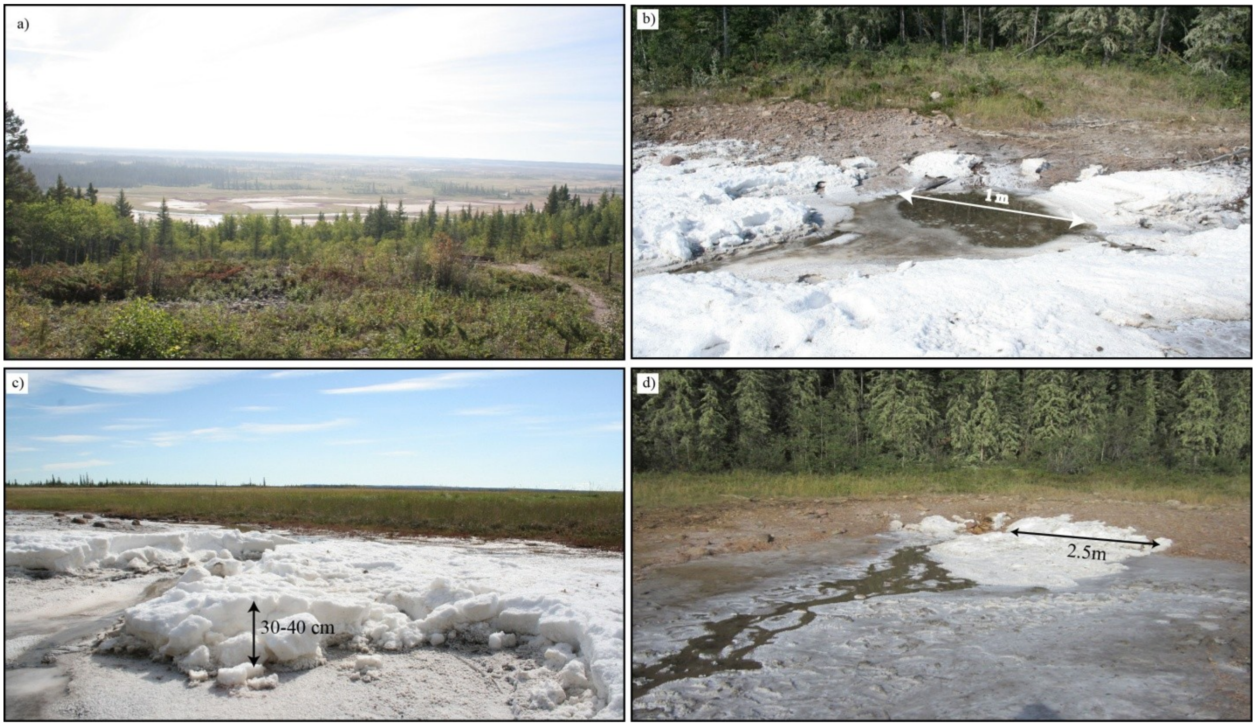

Photo 4.1: Saline features in the Salt Plains a) overlooking Salt Plains from the top of the escarpment, b) saline seepage with salt deposits around the orifice in the Salt Plains c) salt deposits adjacent to spring discharging in the Salt Plains, d) saline spring discharge with salt accumulations around the orifice and salt crusts on the topsoil (Photos by Judit Déri-Takács)

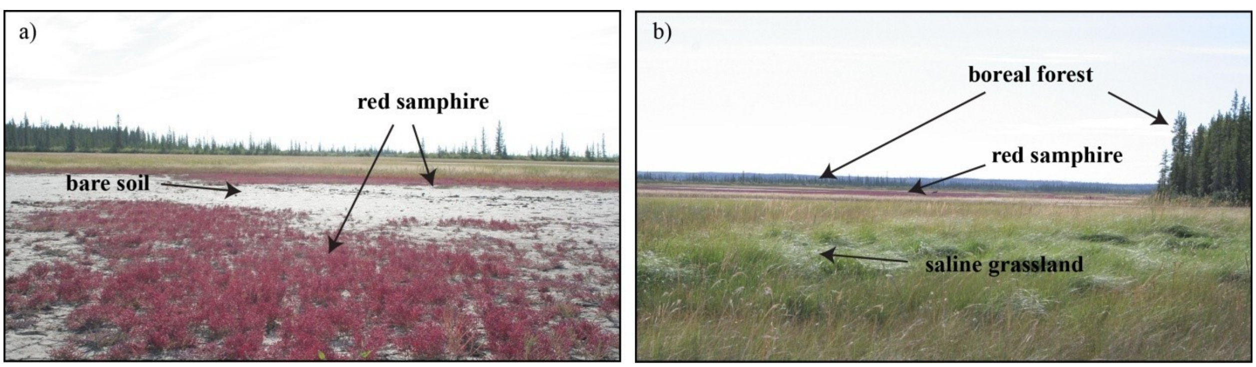

Photo 4.2: Halophyte vegetation in the Salt Plains area a) Red samphire (*Salicornia rubra*) on bare, wet soil, b) saline grassland species in the foreground and red samphire (*Salicornia rubra*) in the background with transition into boreal forest species on elevated topography (Photos by Judit Déri-Takács)

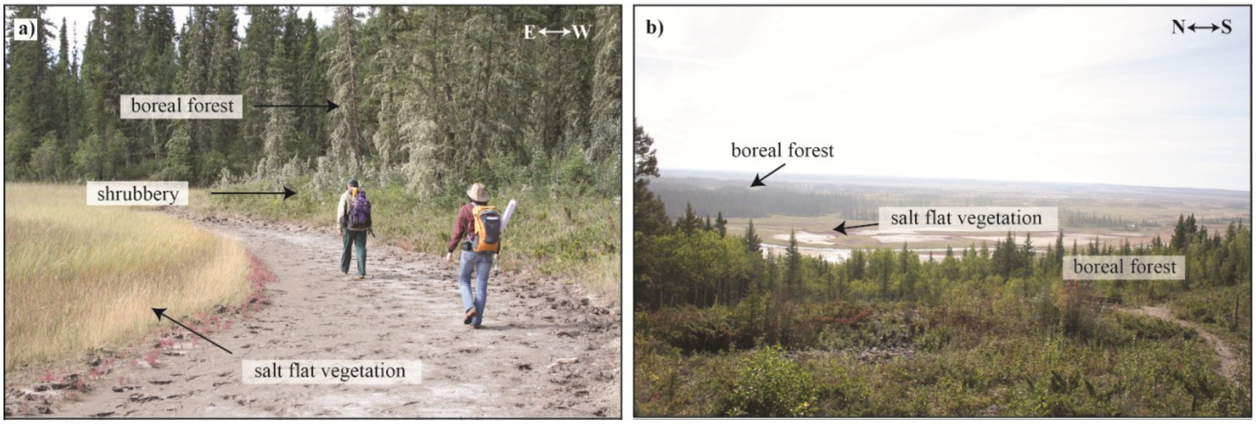

Photo 4.3: Vegetation transitions in the Salt Plains region (Photos by László Déri (a) and Judit Déri-Takács (b))

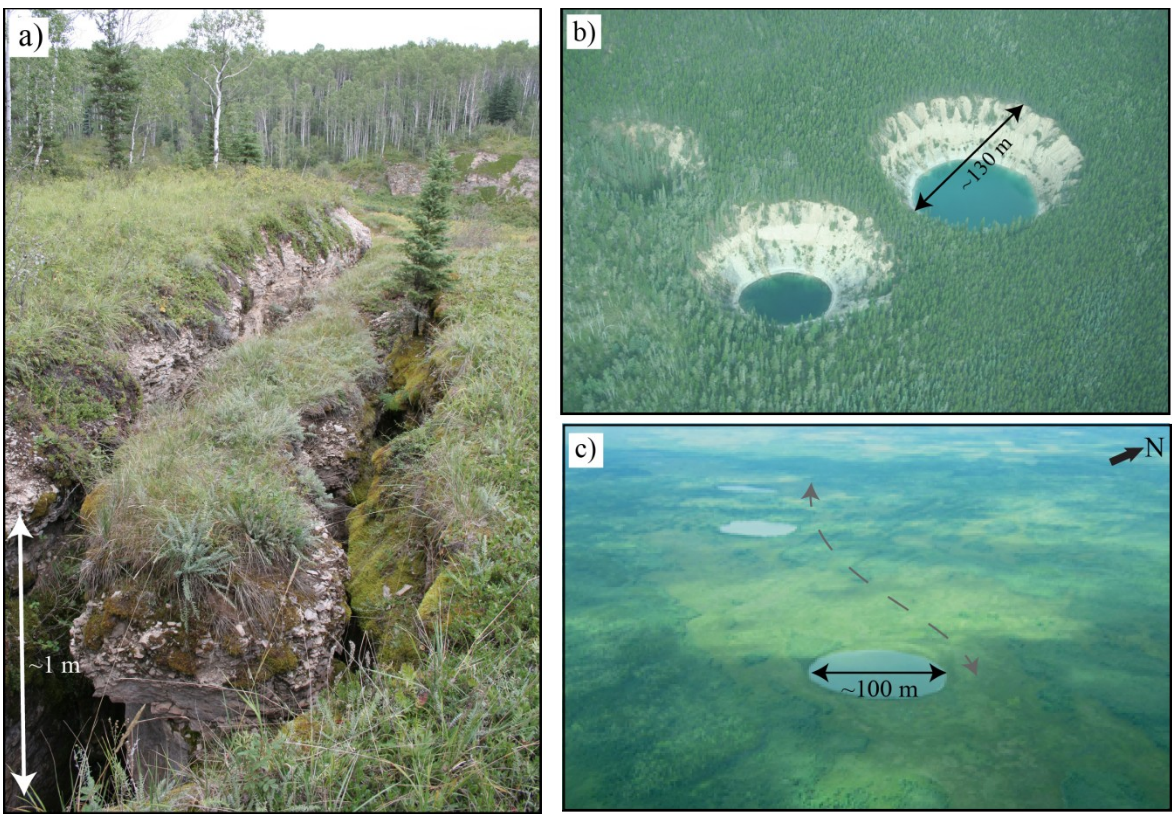

Photo 4.4: Karstic features in Wood Buffalo National Park. a) solution cavities, shafts b) collapse sinks c) aligned sinkholes (Photos by Judit Déri-Takács)

Photo 4.5: Unfrozen springs and sinkhole lakes in winter in Wood Buffalo National Park (Photos by John McKinnon, Parks Canada)

Chapter 5 Conclusions: Nested groundwater flow systems in Wood Buffalo National Park

5.1. Thesis summary

The objective of this thesis was to advance understanding of regional- intermediate- and local-flow systems within a basin setting. The following section is a summary of the major findings and conclusions of preceding chapters.

Groundwaters and surface waters in WBNP show significant variability in total dissolved solids concentrations ranging from less than 1,000 mg/L to more than 300,000 mg/L (Figure 5.1). Waters form four separate hydrochemical groups: 1) Ca-HCO_3-type waters dominating the Peace-Athabasca Delta-region in the south and most of the central region; 2) Ca-SO_4-type waters occurring in multiple, separate clusters across the area and coincide with outcrops areas of Devonian evaporites; 3) Na-Cl-type waters limited to the Salt Plains; and 4) "mixed" waters showing a mixing of the above mentioned three basic water types (Figure 5.2). The greatest variability in the TDS concentrations and the water types occurs in the Salt Plains region along the eastern edge of the study area. Na-Cl-type waters and elevated TDS content in the Salt Plains are considered manifestations of regional groundwater flow. The southern and central part of the national park is dominated by Ca-HCO_3-type waters. They are associated either with presence of extended wetlands (e.g. PAD region) fed by direct precipitation, and/or major influence of shallow, local groundwater flow paths. The isotopic composition of groundwaters suggests they originate from meteoric water, rather than formation waters of the Alberta Basin. Surface waters are fed by either direct precipitation or groundwater. It is hypothesized that NaCl-type saline and brine waters originate from precipitation that fell at higher altitude, such as the Caribou Mountains. The current enriched isotopic composition of these waters was attained through rock-water interactions on a regional-scale flow path between the Caribou Mountains and the Salt Plains region. Relations of Na-Cl-Br isometric log-ratios, Ca_{excess} and $Na_{deficit}$, and major elements (Ca+Mg vs HCO_3; Ca+Mg vs HCO_3+SO_4) suggest that solutes in the waters originate from three main processes: 1) dissolution of halite; 2) dissolution of sulphate minerals; and 3) dissolution of carbonates.

Chapter 3 explains the effect of the Caribou Mountains on the basin-scale flow regime. Numerical simulations and sensitivity analyses of two conceptual models of groundwater flow were used to show lack of connection of central WBNP to the rest of the Alberta Basin and to see how the different conceptualizations of groundwater flow influence the flow patterns in central WBNP. The two different conceptualizations of the flow system, i.e., one where up-dip flow from the Alberta basin is possible and another where the Caribou Mountains are considered a regional groundwater divide that blocks flow from the west, showed that the Caribou Mountains are an important factor controlling the flow regime of the northern Alberta Basin. The study demonstrates that the decreasing thickness of the basin and the topographic elevations of the Caribou Mountains induce regional-scale flow system in the deep part of the domain that changes the basin-scale character of the deep fluid-flow into a more regional-intermediate one in the area. The Caribou Mountains prevent the basin-scale formation fluids from entering the region of WBNP, and creates an isolated flow regime in the park. This is in line with findings of Chapter 2, i.e., saline and brine waters of the Salt Plains region are not related to other Devonian formation waters in the Alberta Basin. Variations in water table relief generate hierarchically nested flow systems on local, intermediate and regional scales in the area. Local flow systems are induced by local topographic highs across the study area. Intermediate- and regional-scale flow systems both recharge in the Caribou Mountains and discharge in the central plains and in the Salt Plains region, respectively.

Chapter 4 synthesizes the results of previous chapters by combining water chemistry, numerical simulation results and groundwater-related surface phenomena into one fully-integrated conceptual model (Figure 5.3, Figure 5.4). The simulated flow field (Chapter 3) is associated with the geochemical characteristics of waters (Chapter 2) to evaluate their diagnostic value for identifying different scales and segments of groundwater flow systems. Subsequently, groundwater-related surface phenomena, such as springs, wetlands, saline soils, phreatophyte/halophyte vegetation, karstic features and geothermal anomalies, are used to further validate the different scales and segments of flow systems in the study area. Salinity and hydrochemical facies of waters and simulated flow systems correspond well with each other. Ca-HCO_3-type, low salinity waters occurred at local discharge areas. Ca-SO_4-type, brackish waters were found in the central region where intermediate-scale flow paths discharge. Na-Cl-type, saline-brine waters correspond with discharge area of regional–scale flow system and most likely indicate regional groundwater discharge. Groundwater-diagnostic surface features, such as wetlands, springs, saline soils and salt deposits, vegetation, karst geomorphology and positive thermal anomalies are indicative of the different scales and segments of nested groundwater flow systems in WBNP. Correlation of groundwater-related surface phenomena with the numerical simulation further validated the conceptualized and numerically simulated groundwater flow systems in the area.

5.2. Generalization of findings

Findings suggest that the developed integrated conceptual model combining chemical characteristics of waters, numerical simulation and groundwater-related surface phenomena properly represents groundwater flow conditions in the national park. Expanding of the same relations found between groundwater flow conditions and surface phenomena described in central WBNP to the entire area is a plausible approach to advance knowledge on groundwater conditions in regions where field data are limited and/or numerical simulations are not available. Based on empirical generalization, groundwater-related surface phenomena in similar topographic and geologic settings imply similar groundwater conditions.

The central region of WBNP located between the Peace River and the 60° latitude was characterized by nested flow systems of regional, intermediate and local scales. The regional and intermediate flow systems are induced by the topographic elevations of the Caribou Mountains. Where no significant elevation differences in topography are present, e.g. in the central boreal lowlands, shallow, local flow systems dominate the flow regime.

The Peace-Athabasca Delta (PAD) is part of the southern region located south of the Peace River (Figure 5.5). Considering its topographic and geologic characteristics it is likely that most of the southern regions, including the PAD, are dominated by local, shallow flow systems, similarly to the central boreal lowlands, and regional flow systems do not play significant role in the area's hydrological processes. Water chemical characteristics introduced in Chapter 2 support this conclusion. It is also known that the PAD includes numerous perched water basins, the hydration of which depend on the regular flooding and ice jams on the Peace River (Prowse and Lalonde 1996). It can be assumed, therefore, that the PAD is much more vulnerable to changes in flooding patterns than to dewatering activities in the oil sands region south of the boundary. The karstic nature of the area, however, makes a more detailed hydrogeological investigation necessary to fully evaluate the hydraulical connection between the two regions.

The wetlands of the whooping cranes' nesting area are located in the northeastern region of the study area (Figure 5.5). The area is strongly karstified and, based on the interpretations made in preceding chapters, is hypothesized to be a discharge area of groundwater from intermediate-regional-scale flow systems entering the region from the southwest. It was concluded by Nobert and Barrie (1986) that these wetlands are fed by groundwater rather than precipitation, however, to accurately interpret the exact hydraulic connections between the wetlands of the whooping cranes and the ascending groundwater from intermediate-regional flow systems more detailed hydraulic investigations are needed. It was also shown that there is a hydraulic connection between the Pine Point-region and the Angus Tower Spring in north WBNP (Weyer 1983) (Figure 5.5). In addition to that, the intense subsurface karstification in the region increases the possibility of active hydraulic connections between the northeastern wetlands and the Pine Point-area. Although there are no current mining activities going on in the Pine Point region, it is likely that increased water withdrawal associated with mining activities would impact the wetlands of the whooping cranes.

5.3. Basinal fluids in WBNP

Results in Chapter 3 demonstrated that the Caribou Mountains significantly influence the flow regime in central WBNP. The Caribou Mountains block basin-scale fluids from entering the region from the west. This, then, implies that where the impact of the Caribou

Mountains becomes less dominant or diminishes, such as in northern or southern regions of WBNP, basin-scale fluids may be able to enter the area and reach the eastern edge of the basin. These waters are expected to show a "mixed" hydrochemical characteristic resulting from dilution of formation waters by fresh, meteoric water infiltrating the subsurface. This is in line with previous findings of Bachu (1997) who concluded salinity of formation waters decreases due dilution by and mixing with meteoric water in the northeastern part of the Alberta Basin.

Discharge of basin-scale fluids may be responsible for the elevated TDS content and increased variability in water types in some of the samples found along the southeastern shore of Lake Clair in southern WBNP (Chapter 2 Figure 2.6, Figure 2.7). The lake is situated at the edge of the basin on Devonian carbonates and evaporites, and occupies the topographically lowest elevations. The topographic and geologic setting promotes a discharge area of large-scale, deep flow systems. Springs/seepages observed in the area are definite indicators of groundwater discharge. Water with TDS content of more than 10,000 mg/L and Na-Cl water type associated with the high abundance of positive thermal anomalies (unfrozen waters in winter) detected in the area may be evidences of discharge of deep flow systems.

5.4. Limitations of the study

The research presented here was limited in several ways:

1) The objective of the current study was to provide a regional hydrogeological characterization of the area. As a consequence of the regional scale of the study, as

well as the size of the area, local patterns (e.g. local- and sub-local-scale flow systems) were often neglected or were not detectable.

2) One of the most important limitations lies in the quantity of data available from the study area. Due to its protected status and remote nature, detailed information on subsurface geology, structure, lithology or hydraulic and chemical properties of formation waters is limited. Consequently, it was often necessary to extrapolate geological, lithological and structural information known from outside of the study area and apply those to WBNP. In absence of measured hydraulic properties, such as hydraulic heads and hydraulic connectivity values, approximations (e.g. position of water table) and generalization (e.g. one permeability value over the entire formation) was necessary. This approach is appropriate to represent the system on a regional scale.

3) The uneven spatial distribution of data represents limitations in validating the conceptual model on groundwater flow in the northern region (Northwest Territories) of the study area. Out of 474 chemistry data only 8 (1.4%) were collected in the northern areas, the rest of the data were obtained from the central and southern regions (Alberta) of WBNP.

4) Due to the high data density and presence of diagnostic, groundwater-related surface features identified in the Salt Plains the numerical simulation focuses on the central part of WBNP to characterize the flow regime. The identified flow patterns, however, may be extrapolated and applied to the rest of WBNP.

5) Some of the surface phenomena (e.g. wetlands) are not exclusive indicators of the hydrogeological function of a site, and their diagnostic value cannot be generalized unless they are associated with other groundwater-diagnostic features.

6) The present study has used two-dimensional (2D) modelling approach in investigating the flow regime in the central part of WBNP. In a complex basin, the flow intensity and effect of local topography decreases with depth and its influence on the subsurface flow regime diminishes. In case of a 2D-representation, however, effects of local topographic features become more intense due to the forced nature of flow directions, and they modify the flow pattern at greater depths instead of influencing only the shallowest part of the subsurface. Consequently, 2D representation of the system causes local features to have deeper impact than they would in a 3D simulation. The 2D representation, furthermore, does not consider effects of topographic features outside of the simulated cross-section. Despite the fact that the 2D modelling approach causes limitations in representation of local flow patterns, it is believed that it is adequate to characterize the flow regime on regional scale.

5.5. Recommendations for future research

The research described in this thesis has provided insight into the hydrogeological conditions in WBNP. However the research has raised many questions in need of further investigation.

1) In general, more data is needed from the Northwest Territories region to better understand the hydrogeological processes in the area. Most of the data used in this research covered central and southern WBNP. The northern part of the national park

(north of 60°N) is characterized by sparse dataset and spatially restricted sampling locations making the general geochemical characterization of this region difficult. Substantial improvements could be made to the understanding of hydrogeological processes in northern WBNP by extending the recent datasets, and obtaining further samples for chemical and isotopic composition analyses. This would be especially important in the northeastern wetlands that encompass the last remaining natural nesting area of the highly endangered whooping cranes (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). The protection of this habitat is one of the priorities of Parks Canada. Understanding the governing subsurface processes, hydraulic connections and relationship between groundwater and surface water is a key component in the process. Design and implementation of a regional monitoring network within WBNP is recommended.

2) Considering the size, the remote nature and difficult accessibility of the area, further studies are recommended to intensely involve application of remote sensing techniques. Remote sensing allows us to observe surface features and analyze remote locations where ground proofing would be difficult or expensive. Use of satellite images to investigate hydrogeological conditions is widely known in literature (Moore 1982; Waters et al. 1990; Meijerink 1996; Becker 2006; Meijerink et al. 2007).

3) This study used 2D steady-state numerical simulation to evaluate conceptual models of groundwater flow in WBNP. Although 2D approach is helpful to investigate the adequacy of the conceptual model design, further study should implement 3D numerical simulations to be able to analyze processes that 2D simulation was not able

to capture, i.e., effect of the Caribou Mountains north and south of the uplands, or effects of local topographic highs on the shallow flow regime and dynamic flow patterns.

4) It was demonstrated in Chapter 2 that brine waters are only found in the northern area while saline waters spread across the entire Salt Plains region. It was also concluded that brine waters in the Salt Plains originate from meteoric water recharged at the Caribou Mountains which was supported by results of numerical simulation across the central region of WBNP. Further study is recommended to target saline and brine waters and their peculiar spatial distribution in the region.

5) Karstic landforms are one of the most striking features in the area. Obtaining data on the hydraulic conditions could help to validate their hydrogeological function and to improve our knowledge on the connection between groundwater flow and karstification in the area. Sinkholes are often aligned and follow a preferential direction in WBNP. Investigation of these features, as well as spring-sink relations could significantly contribute to understanding hydraulic connections in the subsurface. Improved understanding on hydraulic connections of the subsurface flow regime of WBNP could lead to a better assessment of potential impacts of human activities (e.g. Athabasca Oil Sands development) on WBNP's groundwaters and surface waters.

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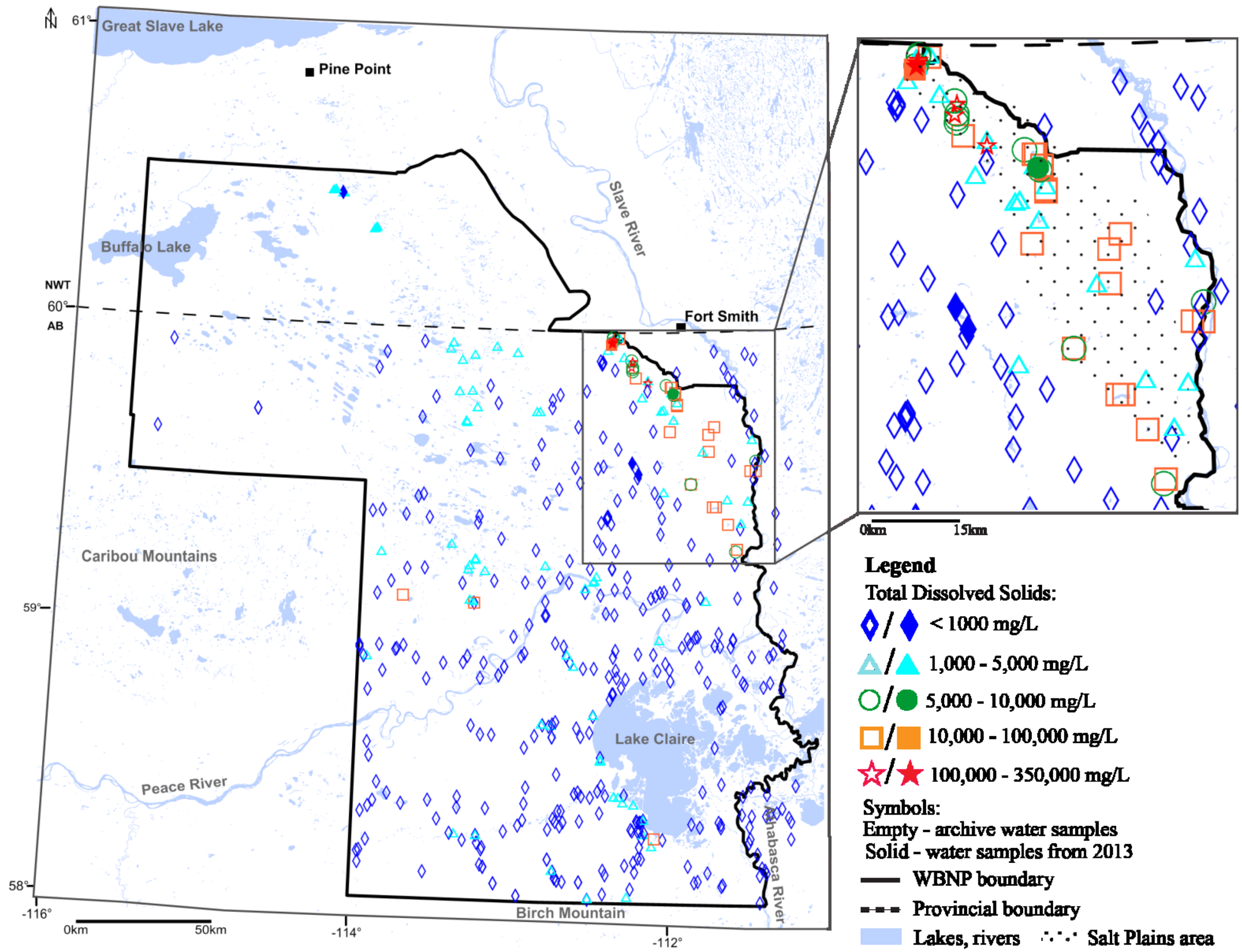

Figure 5.1: Spatial distribution of total dissolved solids (TDS) concentrations of water samples in WBNP. Empty symbols: samples from archive dataset, Solid symbols: samples from 2013. Inset map shows the Salt Plains area.

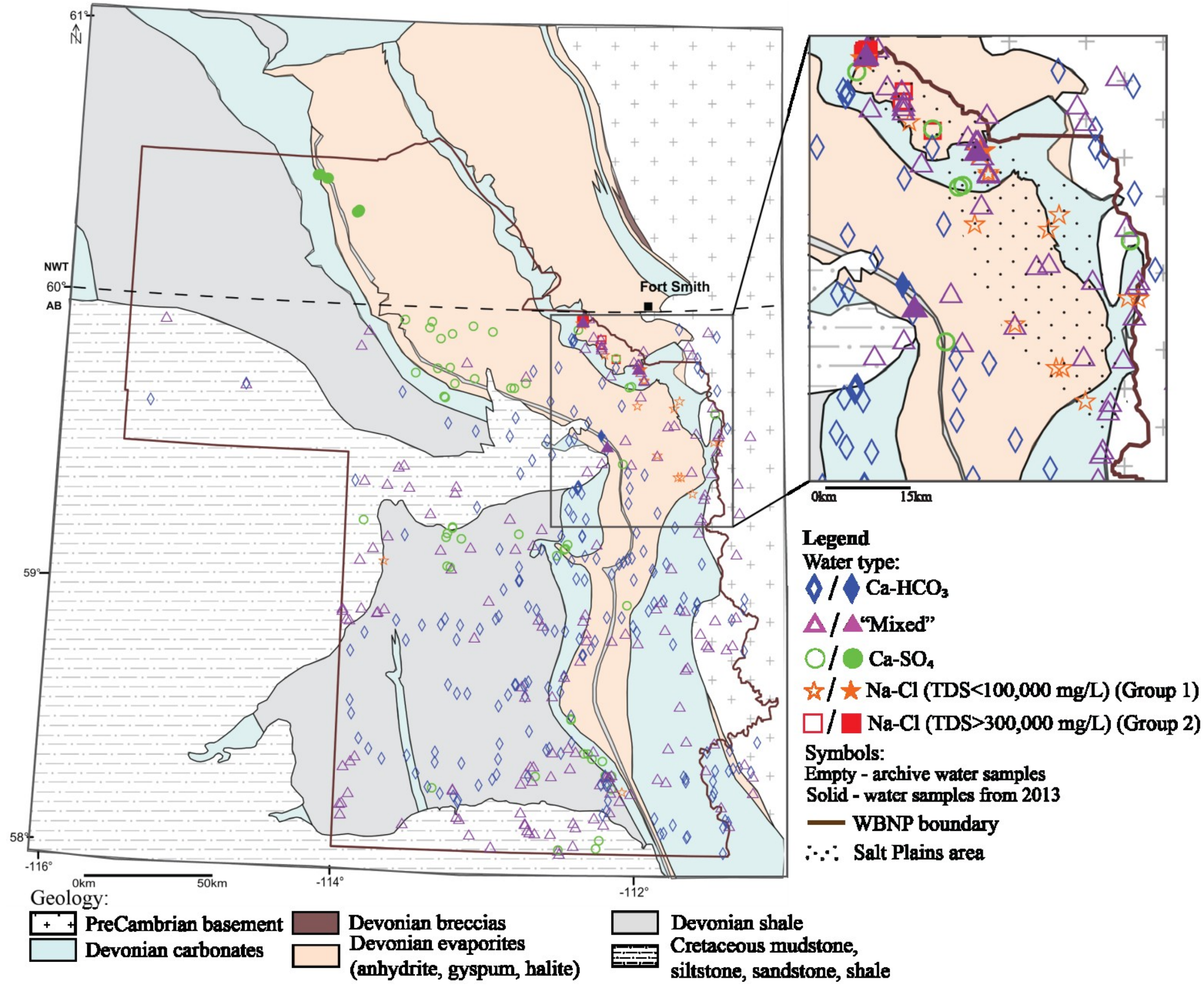

Figure 5.2: Hydrochemical facies of water samples in WBNP. Empty symbols: samples from archive dataset, Solid symbols: samples from 2013. Inset map shows the Salt Plains area. Bedrock geology is also shown (modified after Prior et al. 2013 and Okulitch and Fallas 2007)

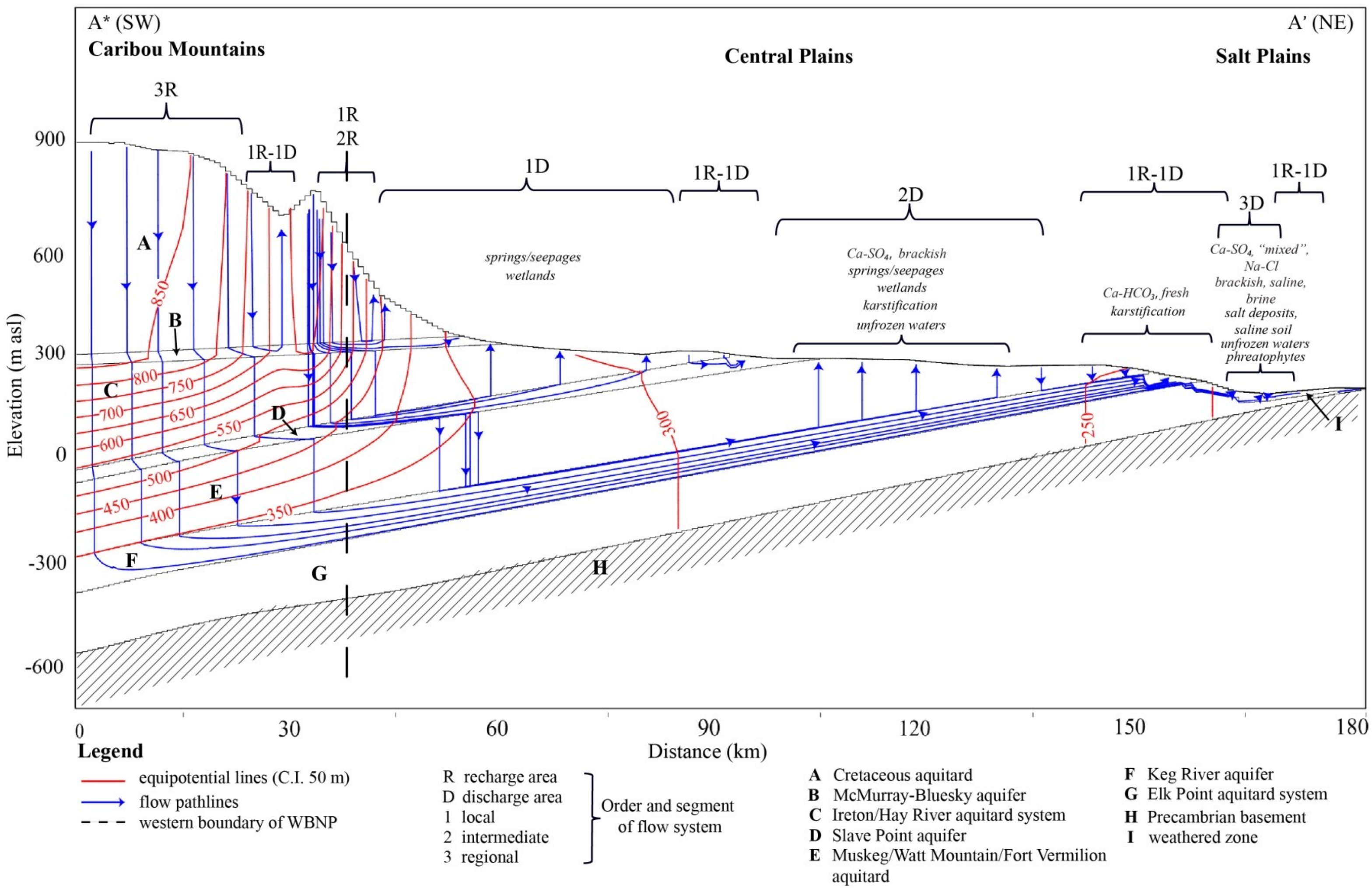

Figure 5.3: Results of groundwater flow simulation along cross-section A*-A' (modified from Figure 7 in Chapter 3). The left (west) and base are zero flux boundary conditions. The upper boundary is defined by the water table, approximated by the land surface.

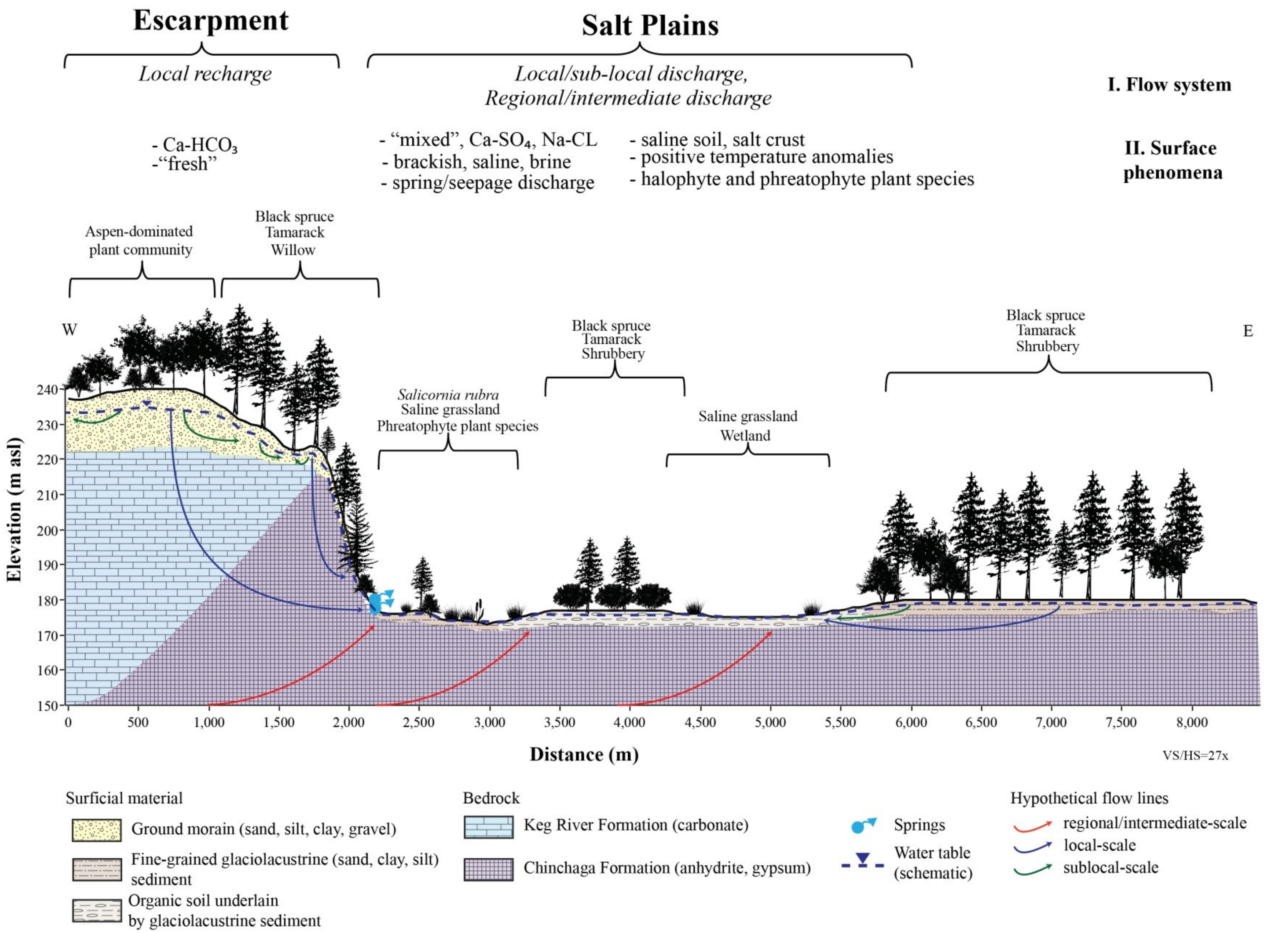

Figure 5.4: Surface phenomena and nested groundwater flow systems in the Salt Plains region. The diagram shows an arbitrary cross-section across the Salt Plains region with the salt escarpment on the left (W) and the salt flats to the right (E).

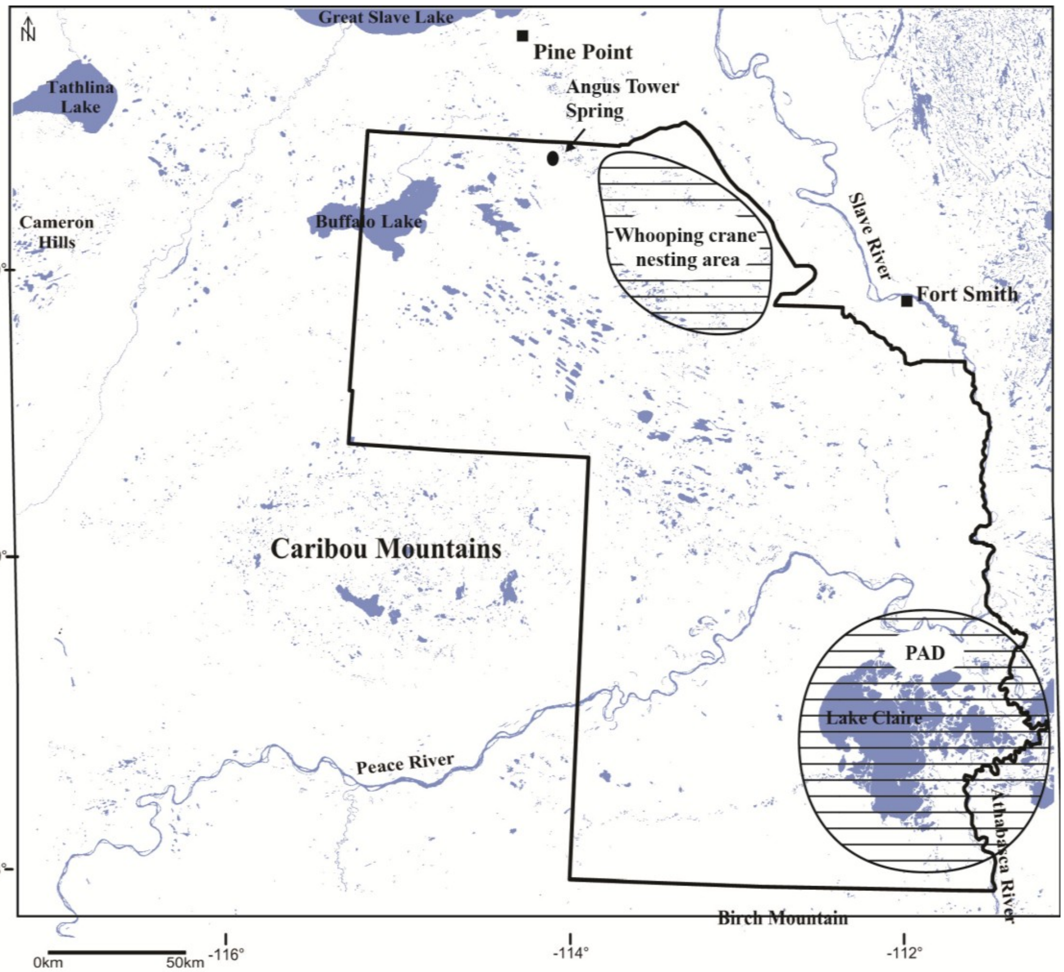

Figure 5.5: Location of the Peace-Athabasca Delta (PAD) and the whooping crane nesting area in Wood Buffalo National Park

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Appendix I.

Numerical model along cross-section A**-A'

Cross-section A**-A' represents the extended version of cross-section A-A' shown in Figure 3.1, Figure 3.7 and Figure 3.9. The model was used to test the appropriateness of the left-hand side boundary of cross-section A-A' discussed in preceding chapters of this thesis.

The model represents cross-section A**-A' running from 100 km southwest (A**) of the highest peak of the Caribou Mountains (A) to the Salt Plains in the northeast (A') (cross section A**-A', Figure AI.1). The starting point of the cross-section (A**) falls 50 km southwest of the foot of the Caribou Mountains. The direction of the cross-section A**-A' follows the preferential, northeastward flow direction of formation fluids in the northern Alberta Basin.

The geology, similarly to models A-A', was simplified by grouping the geologic formations based on their ability to conduct or retard water as shown by the modelled hydrostratigraphy (Figure 3.3). The hydrostratigraphic units of cross-section A**-A' are shown in Figure AI.2. In addition to the aquifers and aquitards introduced in cross-sections A-A' in preceding chapters, two new hydrostratigraphic units were introduced: 1) Unit J represents the carbonates of the Wabamun and Winterburn groups that are characterized as aquifers (Figure AI.2), and 2) Unit K represents the carbonates of the Grosmont Formation that was defined as aquifer (Figure AI.2) (Bachu 1997; Bachu and Underschultz 1993).

Hydraulic conductivity values were assigned to the hydrostratigraphic units based on literature data (Tóth 1978; Bachu and Underschultz 1992; Bachu 1997), and later were calibrated to match the simulated hydraulic head values to measured values in observation wells (Table AI.2).

The model is bounded by three types of boundary conditions: no flow/impermeable, specified head, and general head boundaries.

A no-flow boundary is used at the bottom of the domain to represent the very low-permeability geologic units of the Precambrian basement. The water table was represented by specified head boundary with hydraulic head values fixed at the topographic surface elevations based on the assumption that the water table is a subdued replica of the topography (Tóth 1963).

Head-dependent flux boundary was used within the Keg River, Slave Point and McMurray aquifers along the left side of the domain. Hydraulic head values were assigned at distance of 5 km in Keg River, 9.6 km in Slave Point aquifers and 7 km in the case of the McMurray-Bluesky Aquifer. Head values assigned to these nodes were calculated from formation pressure data measured from drill-stem tests in the Caribou Mountains (Table AI.3).

The simulations were calibrated to minimize the difference between observed and simulated hydraulic head values. For calibration, hydraulic head values were calculated from fluid-pressure measurements in 10 wells (4 in Keg River Formation, 6 in Slave Point Formation), mostly located in the west side of the domain (Table AI.2, Figure AI.2).

Pathlines were computed using the MODPATH particle tracking program (Pollock 2012). Particles were placed at the top of the first layer along the entire domain and tracked forward to their discharge location. Results of particle tracking were used to identify groundwater flow paths of different scales; i.e. local, intermediate and regional flow systems, and to qualitatively characterize the flow domain in the study area.

Results of the simulation showed that the Caribou Mountains represent a groundwater divide in the region that falls close to the highest topographic elevation of the mountain (Figure AI.3). The result of the simulation of the extended cross-section was used to determine the boundaries of a shorter cross-section (A-A’) that was further tested to analyze the flow patterns at different representations of the boundary conditions in the WBNP.

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Table AI.1: Hydrostratigraphic units and assigned hydraulic conductivity (K) values.

Hydrostratigraphic Unit	**Hydraulic conductivity (m/s)**
Cretaceous Aquitard System (**A**)	4.0E-09
McMurray-Bluesky Aquifer (**B**)	1.0E-06
Ireton/Hay River Aquitard System (**C**)	1.0E-10
Slave Point Aquifer (**D**)	5.0E-06
Muskeg-Watt Mountain-Fort Vermilion Aquitard System (**E**)	1.0E-10
Keg River Aquifer (**F**)	7.0E-05
Elk Point Aquitard System (**G**)	5.0E-10
Winterburn-Wabamun Aquifer (**J**)	1.0E-06
Grosmont Aquifer (**K**)	1.0E-06

Table AI.2: Calibration data, well location and hydraulic head values calculated from measured fluid pressures used in numerical simulations

UWI	Well ID	Tested formation	Recorder depth (m)	Latitude (°)	Longitude (°)	Calculated hydraulic head (m)
100/02-25-113-18W5/0	KR1	Keg River	1306	58.836315	-116.883999	371
100/01-08-117-13W5/0	KR2	Keg River	1446	59.141645	-116.166809	429
100/07-25-120-10W5/0	KR3	Keg River	1248	59.451750	-115.566748	340
100/08-17-120-01W5/0	KR4	Keg River	588	59.420863	-114.117413	285
100/04-06-115-17W5/0	SP1	Slave Point	1012	58.952770	-116.898926	460
100/13-11-117-11W5/0	SP2	Slave Point	1223	59.152488	-115.760920	601
100/02-10-118-08W5/0	SP3	Slave Point	1042	59.228874	-115.263352	589
100/11-18-118-07W5/0	SP4	Slave Point	967	59.251790	-115.186954	546
100/10-15-120-08W5/0	SP5	Slave Point	975	59.425130	-115.275512	574
100/10-24-120-08W5/0	SP6	Slave Point	879	59.440608	-115.217038	601

Table AI.3: Hydraulic head values assigned to general head boundaries in model A**-A’ shown in Figure AI.2 and Figure AI.3.

Hydrostratigraphic Unit	Hydraulic head (m)	UWI
McMurray-Bluesky Aquifer	341	100/10-30-112-21W5/0
Slave Point Aquifer	288	100/03-01-113-22W5/0
Keg River Aquifer	365	100/11-25-113-21W5/0

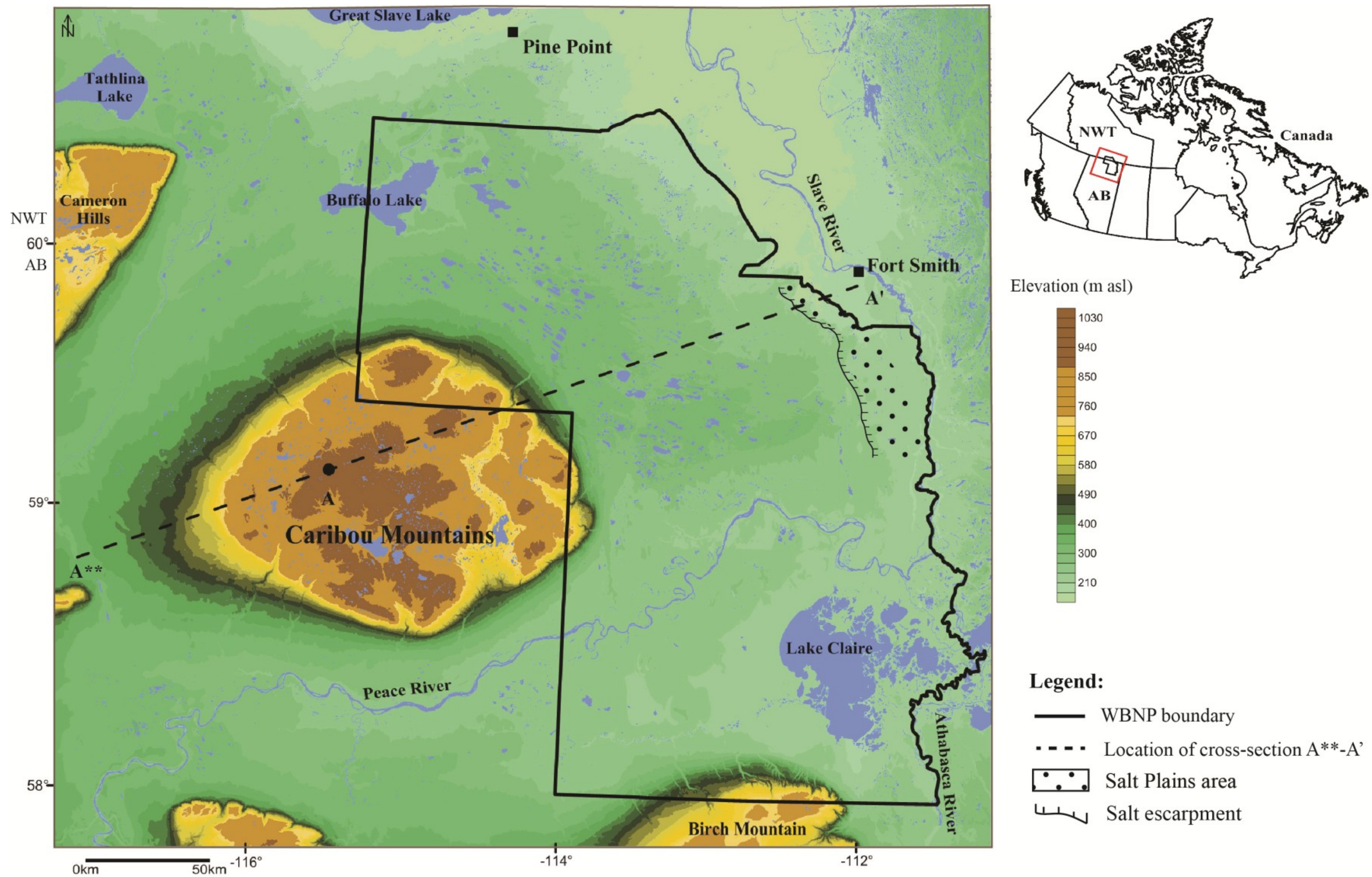

Figure AI.1 Geographic location and topography of the study area with the location of cross-section A**-A'. Location of cross-section A-A' is also shown.

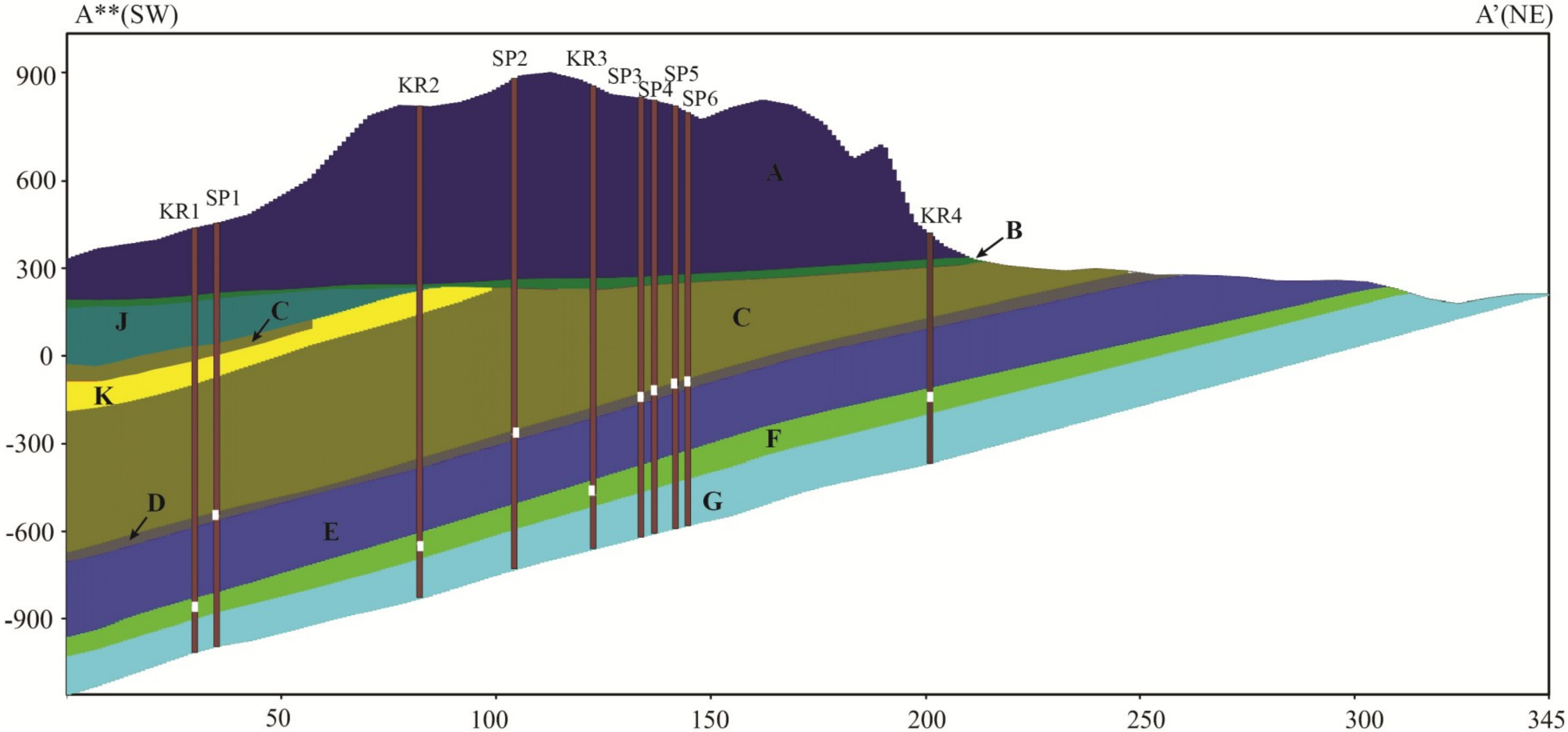

Figure AI.2: Model domain along cross-section A**-A'.

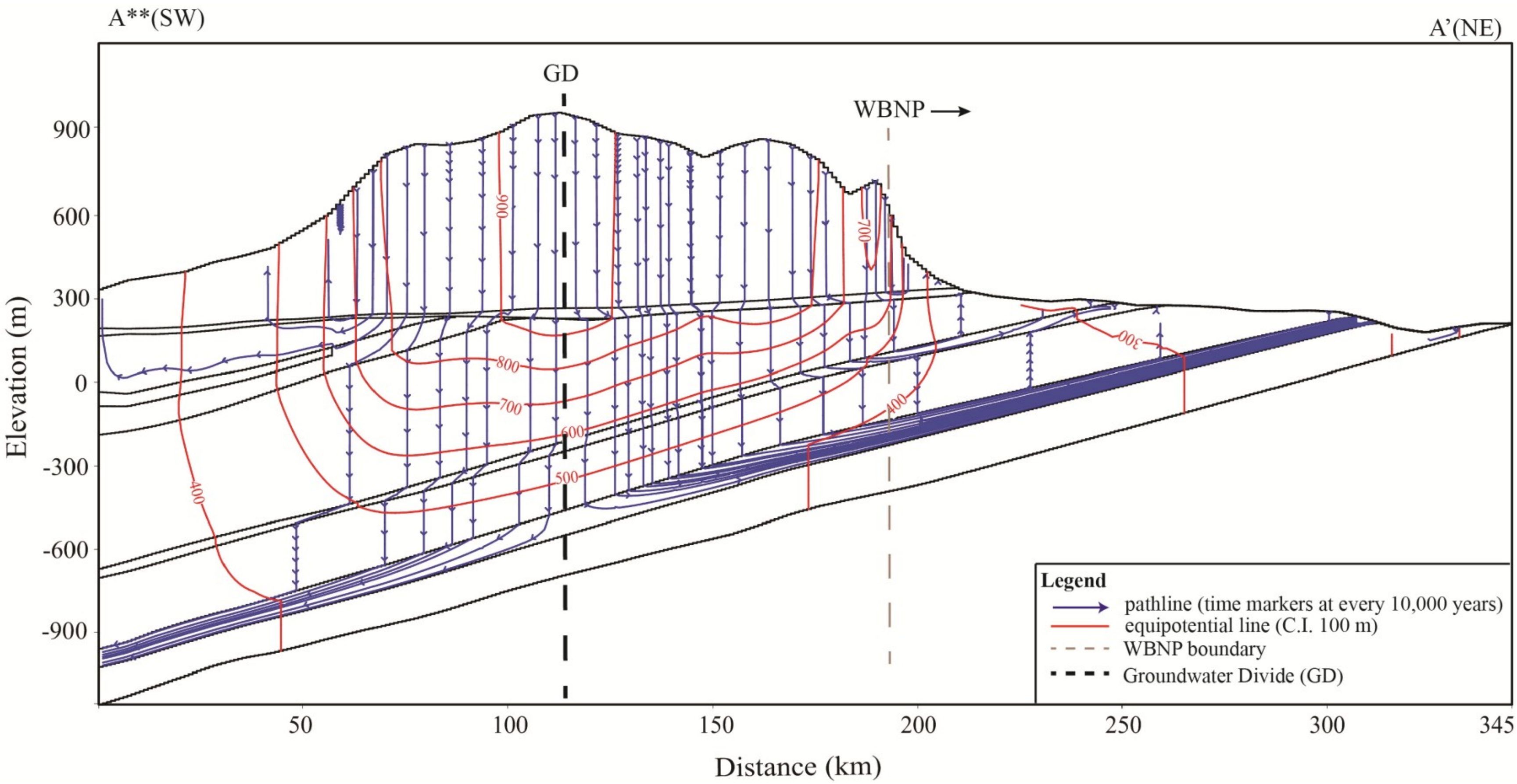

Figure AI.3: Simulated hydraulic head distribution and flowpaths along cross-section A**-A'. The groundwater divide (GD) coincide with the starting point (A) of model shown in Figure 3.1, Figure 3.7 and Figure 3.9.

Appendix II.

Comparison of water balance of numerical models (A-A') and climate conditions in Wood Buffalo National Park

An estimated recharge rate was calculated (Table AII.1) to see if the water table applied in the model is sustainable under existing climatic conditions by comparing the simulated recharge values to average recharge rates calculated for the area. Simulated recharge was calculated using the total amount of water entering the domain (Total In, Table 3.4) over the modelled area (x=227,000 m, y=5,000 m) (Table AII.1). The simulated recharge values are 4 and 3 mm in Case 1 and Case 2, respectively (Table AII.1). The estimated average recharge rate for the Peace/Slave River Basin is 38 mm (Golder Associates, 2008). The simulated recharge rates are an order of magnitude lower than the calculated recharge values for the area. Consequently, the water table applied in the model is sustainable by the groundwater recharge occurring in the study area and approximation of water table by the surface topography is representative of the system.

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Table AII.1 Estimated recharge rates for the entire model area and for each natural subregion along cross-section A-A’

Model area	x (m)	y (m)	Area (m^2)	Case 1		Case 2	
				Estimated Recharge (m/y)	Estimated Recharge (mm/y)	Estimated Recharge (m/y)	Estimated Recharge (mm/y)
Domain A-A'	227,000	5,000	1,135,000,000	0.004	4	0.003	3