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Caractérisation environnementale et hydrogéologique de l'écoulement à la base des forces canadiennes (BFC) Shilo, Manitoba, Canada

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SUMMARY

The Assiniboine Delta Aquifer (ADA), a major regional aquifer in southwestern Manitoba, supplies water for irrigation and for the domestic needs of Canadian Forces Base (CFB) Shilo and surrounding communities. Canadian and German troops trained intensively at CFB Shilo over the past decades and following the departure of the later, Defense Research and Development Canada (DRDC) in Valcartier undertook a research project in collaboration with INRS to assess the impacts of military training on the environment. With an average thickness of 18 m, the ADA sand aquifer is unconfined and thus vulnerable to potential sources of contamination. It is underlain by silty clay and till layers. Groundwater drains in the most part towards the Assiniboine river (south) but also towards Epinette Creek (north). Three training areas were investigated: the rifle ranges (~0,4 km^2), the grenade range (~0,0025 km^2, or 2500 m^2) and battleruns (~8 km^2). The objectives were to describe the geological and hydrogeological context, to identify potential sources of contamination of soils and groundwater and to assess their potential impact on the aquifer using a numerical model.

A characterization campaign was conducted over a three year period (2000-2002) and involved the analysis of metals, energetic materials, thorium-232 and other potential contaminants in the soils and groundwater of CFB Shilo. ^{232}Th is a radioactive isotope found in the guiding system of some MILAN missiles fired at CFB Shilo. Geological and hydrogeological investigations were conducted by INRS-ETE, the Geological Survey of Canada (GSC-Quebec) and Defence Construction Canada (DCC): deep borehole drilling, installation of 78 observation wells, slug tests, flowmeter survey and water level measurements, etc.

Measured concentrations of metals, energetic materials and ^{232}Th were compared against background concentrations plus 2 times the standard deviation (BG+2STD) and Canadian Council of Ministers of the Environment (CCME) guidelines, when available.

- Heavy metals, including As, Cu, Cd, Ni, Pb and U, were detected in concentrations exceeding CCME guidelines for agricultural use and/or BG+2STD mostly in rifle and grenade ranges. Cu and Pb in rifle ranges and Zn in the grenade range were even exceeding CCME guidelines for industrial use. Metals concentrations in groundwater however were below CCME Drinking Water Quality Guidelines, except for high, naturally occurring iron and manganese concentrations.

- Energetic materials such as HMX and RDX were detected in low concentrations (<5 ppb) in the soils of grenade ranges and in some battleruns (<1 ppb), but not in groundwater.

- ^{232}Th concentrations in CFB Shilo soils were equivalent to natural background concentrations. Concentrations in groundwater were higher than background levels but always below the CCME guideline for drinking water (24.5 ppb). ^{232}Th distribution pattern suggests an anthropogenic contribution (MILAN missile) although some high ^{232}Th concentrations in the northen section of the base could not be explained. Available data are thus insufficient to establish a clear relationship between Th^{232} concentrations in groundwater and military training activities. MILAN missiles are no longer in use at CFB Shilo.

A groundwater numerical, finite element flow model for the area covered by CFB Shilo was developed with Feflow to define the flow dynamics in this section of the aquifer. Calibrated recharge was 58 mm/y compared to initial estimates varying from 22 to 68 mm/y. Three zones of different hydraulic conductivities were defined in the calibrated model: 3×10^{-4} m/s, $3{,}5 \times 10^{-4}$ m/s and 7×10^{-5} m/s, generally higher than the average hydraulic conductivity estimated from slug tests and grain-size analysis (1×10^{-4} m/s). The calibration was adequate except for hydraulic conductivities lower than expected in the eastern section of the model and groundwater velocities lower than those measured using a flowmeter (100 to 300 m/y with the flowmeter compared to 25 to 100 m/y in the calibrated model). Flowmeter measurements should however be considered with caution. The capture area of the CFB Shilo supply well was defined and found to overlap with some of the rifle ranges.

In summary, although no major environmental concerns were identified, the characterization campaign revealed localized problems of metal contamination in soils. Preventive measures were identified and shared with base authorities, including the avoidance of any activities that could change soil pH in contaminated areas, in order to prevent leakage towards the aquifer, groundwater quality monitoring and the delineation of a wellhead protection area (WHPA) to manage activities that could potentially threaten groundwater quality of base supply wells. This study is part of a wider research program on the potential environmental impact of training activities on Canadian Forces bases.

Catherine Gauthier, student

René Lefebvre, Research Director

RÉSUMÉ COURT

L'aquifère du delta de l'Assiniboine (ADA), un important aquifère situé dans le sud-ouest du Manitoba, sert de source d'approvisionnement pour l'irrigation et pour combler les besoins domestiques de la Base des Forces Canadiennes (BFC) Shilo et des villages environnants. Des troupes canadiennes et allemandes se sont entraînées de façon intensive à Shilo au cours des dernières décennies. À la suite du départ des troupes allemandes, Recherche et développement pour la défense Canada (RDDC) à Valcartier a entrepris un projet de recherche en collaboration avec l'INRS-ÉTÉ afin d'évaluer l'impact des activités d'entraînement militaire sur l'environnement. D'une épaisseur moyenne de 18 m, l'aquifère de sable de l'Assiniboine est de type non-confiné et est donc vulnérable aux sources potentielles de contamination. Il repose sur des unités d'argile silteuse et de till. L'eau souterraine s'écoule de façon générale vers la rivière Assiniboine (sud) mais également vers le ruisseau Épinette (nord). Trois zones d'entraînement ont été examinées : les champs de tir de petit calibre (~0,4 km^2), le champ de tir de grenades (~0,0025 km^2, or 2500 m^2) et les champs de bataille (~8 km^2). Les objectifs du projet étaient de décrire le contexte géologique et hydrogéologique, d'identifier les sources potentielles de contamination des sols et de l'eau souterraine et d'évaluer l'impact potentiel de ces dernières sur l'aquifère à l'aide d'un modèle numérique.

Une campagne de caractérisation a été réalisée sur une période de 3 ans (2000-2002) au cours de laquelle des analyses de métaux, de matériaux énergétiques, de thorium-232 et autres contaminants potentiels ont été réalisées dans les sols et dans l'eau souterraine de la BFC Shilo. Le ^{232}Th est un isotope radioactif présent dans le système de guidage de certains missiles MILAN utilisés à la BFC Shilo. Des études géologiques et hydrogéologiques ont également été réalisées par l'INRS-ÉTÉ, la Commission géologique du Canada (CGC-Québec) et Construction pour la défense Canada (CDC) : forage de puits profonds, installation de 78 puits d'observation, essais de perméabilité, mesures d'écoulement à l'aide d'un tachymètre, mesures de niveau d'eau, etc.

Les concentrations mesurées de métaux, de matériaux énergétiques et de ^{232}Th ont été comparées avec le bruit de fond plus 2 fois l'écart-type (BF+2ET) et avec les recommandations du Conseil canadien des ministres de l'environnement (CCME), lorsque disponibles.

- Des concentrations de métaux lourds, notamment As, Cu, Cd, Ni, Pb et U, excédant les recommandations du CCME pour usage agricole et/ou BF+2ET ont été mesurées principalement dans les champs de tir de petit calibre et de tir de grenade. Les concentrations de Cu et Pb dans les champs de tir de petit calibre et celles de zinc dans le champ de tir de grenade excédaient même

les recommandations du CCME pour usage industriel. Les concentrations de métaux dans l'eau souterraines se sont toutefois avérées inférieures aux recommandations du CCME pour l'eau potable, sauf pour le fer et le manganèse qui sont naturellement présents en concentration élevée dans l'aquifère.

- Des matériaux énergétiques tels que le HMX et le RDX ont été détectés en faible concentration (<5 ppb) dans les sols du champ de tir de grenade et ceux de certains champs de bataille (<1 ppb), mais pas dans l'eau souterraine.

- Les concentrations de ^{232}Th mesurées dans les sols de la BFC Shilo étaient équivalentes aux concentrations naturelles de fond. Les concentrations mesurées dans l'eau souterraine étaient en revanche plus élevées que le bruit de fond mais se situaient toujours en deça des recommandations du CCME pour l'eau potable (24.5 ppb). La distribution des concentrations de ^{232}Th dans l'eau souterraine suggère une contribution anthropogénique (missiles MILAN) aux concentrations mesurées sur la base, bien que quelques concentrations élevées dans la section nord de la base ne puissent être expliquées. Les données disponibles ne permettent pas d'établir une relation claire entre les concentrations de Th^{232} dans l'eau souterraine et les activités d'entraînement militaire. Les missiles MILAN ne sont plus utilisés à la BFC Shilo.

Un modèle numérique d'écoulement de l'eau souterraine par éléments finis couvrant le territoire de la BFC Shilo a été développé avec le logiciel Feflow afin de définir la dynamique de l'écoulement de cette section de l'aquifère. La recharge calée a été établie 58 mm/an alors que les estimés initiaux variaient entre 22 et 68 mm/an. Trois zones de conductivité hydraulique distincte ont été définies dans le modèle calé (3×10^{-4} m/s, $3,5 \times 10^{-4}$ m/s et 7×10^{-5} m/s), soit des valeurs généralement plus élevées que la conductivité hydraulique moyenne estimée à partir de tests de perméabilités et d'analyses granulométriques (1×10^{-4} m/s). Le calage du modèle s'est révélé adéquat mis à part une conductivité hydraulique inférieure à la valeur attendue dans la section est du modèle et des vitesses d'écoulement de l'eau souterraine inférieures à celles mesurées avec le tachymètre (100 to 300 m/an avec le tachymètre comparativement à 25 to 100 m/an dans le modèle calé). Les résultats obtenus avec le tachymètre doivent toutefois être considérés avec prudence. La zone de captage des puits d'approvisionnement de la BFC Shilo a été définie; elle recoupe une partie des champs de tir de petit calibre

En conclusion, bien qu'aucun problème environnemental majeur n'ait été identifié, la campagne de caractérisation a révélé l'existence de problèmes localisés de contmaination des sols par les métaux. Des mesures préventives ont été identifiées et présentées aux autorités de la base, incluant l'évitement

de toute activité susceptible de modifier le pH du sol dans les champs d'entraînement contaminés afin de prévenir la lixiviation de métaux vers l'aquifère, la surveillance de la qualité de l'eau souterraine et l'identification d'un périmètre de protection pour assurer une gestion adéquate des activités qui pourraient potentiellement affecter la qualité de l'eau des puits d'approvisionnement de la base. Cette étude fait partie d'un programme de recherche élargi sur l'impact potentiel des activités d'entraînement militaire sur des bases des forces canadiennes.

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René Lefebvre, Directeur de recherche

RÉSUMÉ LONG

CONTEXTE ET OBJECTIFS

La Base des forces canadiennes de Shilo (BFC Shilo), située dans la portion sud-ouest de la province du Manitoba (figure 2.1, p 10), a été utilisée comme site d'entraînement par les militaires canadiens et allemands au cours des dernières décennies. L'Allemagne et le Canada avaient en effet signé un accord de coopération qui a pris fin en 2000. À la suite du départ des troupes allemandes, un projet de recherche a été entrepris afin d'évaluer l'impact des activités militaires passées sur l'environnement de la base. Recherche et Développement pour la Défense Canada (RDDC-Valcartier) a coordonné ce projet auquel ont notamment collaboré l'INRS-ETE et la Commission Géologique du Canada (CGC-Québec).

La base de Shilo, d'environ 30 km de long et de large, compte plusieurs sites d'entraînement (figure 2.3, p 14). Quatre champs de tir de petit calibre et un champ de tir de grenades sont situés dans la section nord de la base, à quelques kilomètres de la zone habitée par les militaires. Ces champs de tir occupent une superficie minime: 400 x 100 m environ pour un champ de tir de petit calibre et 50 x 50 m pour le champ de tir de grenade. Le reste de la base compte cinq champs de bataille principaux. Ces derniers s'étendent sur plusieurs kilomètres de long. Différentes activités s'y déroulent, telles que l'entraînement avec des chars d'assaut et le tir de divers missiles.

Les activités d'entraînement militaire peuvent engendrer divers impacts sur l'environnement. Le présent projet de recherche s'attardera aux rejets et émissions de contaminants dans les sols, les eaux souterraines et de surface. Le tir de petit calibre et l'explosion de grenades dans les champs de tir sont susceptibles d'occasionner des rejets de différents métaux dans l'environnement. Les grenades peuvent libérer des matériaux énergétiques, également appelés explosifs. Les métaux et les explosifs peuvent aussi se retrouver au sein des champs de bataille étant donné la variété des activités d'entraînement qui s'y déroulent. Par ailleurs, les troupes allemandes ont utilisé dans certains champs de bataille des missiles de type MILAN dont le système de guidage contenait du thorium-232, une substance radioactive de très longue demi-vie. Les échantillons de sol et d'eau souterraine récoltés sur ces sites d'entraînement ont donc été analysés en vue de détecter les substances qui pouvaient avoir été rejetées dans l'environnement lors des activités d'entraînement militaires identifiées plus haut: métaux, explosifs et thorium-232.

Une telle analyse de la situation environnementale est particulièrement importante dans le cas de Shilo étant donné que la base occupe une certaine portion de l'aquifère régional de l'Assiniboine (ADA). Ce dernier couvre une superficie de 3885 km^2 et constitue la principale source d'approvisionnement en eau potable de la BFC Shilo et des communautés environnantes; il est également utilisé par les agriculteurs pour l'irrigation et par l'industrie. L'ADA est un aquifère de sable non-confiné formé lors de la dernière déglaciation il y a environ 12 000 ans alors que les eaux de fonte glaciaires de la rivière Assiniboine se déversaient dans l'ancien lac Agassiz à la hauteur de l'actuelle ville de Brandon (30 km à l'ouest de Shilo). Ces eaux de fonte charriaient des sédiments qui se sont déposées à l'embouchure de la rivière Assiniboine, formant ainsi un delta qui constitue aujourd'hui l'aquifère du delta de l'Assiniboine (ADA).

Les objectifs spécifiques du projet de recherche (figure 1.1, p 5) peuvent être résumés ainsi:

1. Décrire le contexte géologique et hydrogéologique du site d'étude;

2. Identifier les sources potentielles de contamination des sols, de l'eau de surface et de l'eau souterraine;

3. Déterminer de quelle façon les sources potentielles de contamination pourraient affecter l'aquifère et ses utilisateurs à l'aide d'un modèle numérique d'écoulement.

Le développement d'un modèle numérique d'écoulement a été jugé utile afin d'intégrer la grande quantité d'information recueillie lors des campagnes de terrain, de mieux comprendre le système d'écoulement et de définir la zone de captage des puits d'approvisionnement de la base de Shilo.

Dans la suite de ce résumé, nous présenterons les travaux de terrain réalisés à Shilo, le contexte géologique et hydrogéologique du site d'étude tel que défini à partir des données recueillies sur le terrain, les résultats de la caractérisation environnementale et une description du modèle numérique d'écoulement. La contribution de ce projet de recherche à l'avancement des connaissances sera également mise en évidence dans le texte.

L'auteure a participé activement à deux des campagnes de terrain réalisées à la BFC Shilo. Les activités réalisées incluent l'installation de puits d'observation, la prise de mesure de données physico-chimiques avec des sondes portatives, l'échantillonnage des sols, de l'eau souterraine et de l'eau de surface, la prise de mesures de vitesse et de direction d'écoulement de l'eau souterraine à l'aide d'un tachymètre, la prise de mesures de niveau d'eau et la réalisation d'essais de perméabilité. Elle a également participé à la rédaction de deux rapports de recherche présentés par DRDC-Valcartier à la Défense nationale (Ampleman et al., 2003a, Ampleman et al. 2003b) et effectué deux présentations dans le cadre du Congrès de l'Association canadienne française pour l'avancement de la science (ACFAS) (Gauthier et al., 2003a) et de la 4^{e} conférence conjointe sur l'eau souterraine AIH-SCG (Gauthier et al., 2003b). Un article a également été publié dans le compte-rendu de cette dernière conférence (Gauthier et al., octobre 2003). L'auteure a produit la majorité des cartes présentées dans ce mémoire, incluant la carte piézométrique du site. Les travaux réalisés incluent également l'analyse et la mise en forme des données géochimiques sur l'eau souterraine et le développement d'un modèle numérique d'écoulement. Tel que mentionné dans l'introduction de ce mémoire, de nombreuses personnes ont joué un rôle clé dans ce projet par le partage de leur expertise et par leurs conseils.

CONTEXTE GÉOLOGIQUE

Étant donné son importance pour l'approvisionnement en eau de la région, plusieurs études géologiques et hydrogéologiques de l'ADA ont été réalisées au cours des dernières décennies. La géologie de surface a tout d'abord été étudiée par Johnston (1934), Erlich et al. (1957) et Halsted (1959). Des forages réalisés dans les années '60 et '70 par l'ancien *Manitoba Natural Resources Department* (maintenant *Manitoba Conservation*) ont permis de définir le contexte hydrogéologique régional (Pedersen, 1968, Province of Manitoba, 1976, November 1970, April 1977, November 1978). Une étude détaillée réalisée entre 1980 et 1986 dans le cadre d'un accord entre la province et le gouvernement fédéral (Render, 1986), suivie d'un programme de forage réalisé en 1993, ont conduit à une définition plus précise de la géologie de la région et des ressources en eau (Frost and Render, 2002).

L'INRS-ETE et la CGC disposaient donc de données de base permettant de savoir que l'ADA reposait sur une couche de silt argileux de faible conductivité hydraulique. Cette dernière recouvre un till d'origine glaciaire qui repose sur la roche-mère, soit des shales du Crétacé et du Jurassique. La presque totalité des données de forage disponibles, particulièrement les forages profonds, était toutefois concentrée dans les régions de l'aquifère situées hors de la base de Shilo. Il devenait donc nécessaire d'effectuer des travaux de terrain pour mieux caractériser cette région moins connue de l'aquifère.

Ces derniers ont été réalisés au cours de l'automne des années 2000, 2001 et 2002. En ce qui a trait à la géologie, deux forages profonds, des relevés Géoradar et des observations de terrain ont permis de produire une carte des dépôts superficiels et une coupe stratigraphique (appendices E et F, p 133 et 137). Cette dernière confirme que la succession géologique connue de l'ADA est la même sous la base de Shilo que dans le reste de l'aquifère et que l'épaisseur moyenne de ce dernier est de 18 m. L'épaisseur est plus grande sous la zone habitée de la base (où se trouvent les puits d'approvisionnement), où elle peut atteindre 35 m.

La couche de sable deltaïque est recouverte à plusieurs endroits par une couche de sable éolien; des dunes de sables sont présentes dans les parties nord et est de la base. Très peu de végétation forestière se retrouve sur la base, mis à part quelques bosquets d'arbres épars. On retrouve toutefois en abondance des plantes herbacées typiques de la région des Prairies. Le sable est directement exposé par endroits, d'où une infiltration presque immédiate des précipitations. La topographie est généralement plane, avec une légère pente en direction sud. Des dunes de sable stabilisées se trouvent au sud du ruisseau Épinette et dans la partie ouest de la base.

CONTEXTE HYDROGÉOLOGIQUE

Des études antérieures ont permis de connaître le niveau piézométrique général de l'ADA et de diviser ce dernier en sous-bassins (Render, 1986). Rappelons que la BFC Shilo est bordée par la rivière Assiniboine au sud, qui coule en direction est, et par une zone marécageuse au nord où serpente le ruisseau Épinette. Ce ruisseau se jette dans la rivière Assiniboine à l'est de la base.

L'eau souterraine s'écoule généralement en direction sud sur la plus grande partie de la base, vers la rivière Assiniboine, dans le sous-bassin Assiniboine ouest (appendice H, p 148). Par ailleurs, la crête de dunes de sable au sud du ruisseau Épinette crée une ligne de partage des eaux entre celles qui se dirigent vers ce ruisseau et celles qui s'écoulent vers la rivière Assiniboine. Une partie de l'écoulement se fait donc en direction nord-nord-est vers le ruisseau Épinette, au sein du sous-bassin Epinette Creek South. Ce dernier n'occupe cependant qu'une partie très limitée de la base.

Des travaux de terrain ont été réalisés afin de mieux définir le contexte hydrogéologique de la portion de l'aquifère située sous la BFC Shilo. Un réseau de 78 puits d'observation a donc été mis en place en 2000 et 2001 (appendice B, p 119). Ces puits ont été positionnés en tenant compte des zones d'entraînement militaire, de la couverture globale de la zone d'étude et de la facilité d'accès aux sites de forage. Des puits d'observation déjà en place sur la base et des puits d'approvisionnement privés ont également été utilisés.

Des échantillons de sol ont été recueillis lors du forage afin de réaliser des tests granulométriques et d'estimer la conductivité hydraulique de l'aquifère. Des essais de perméabilité ont également été réalisés dans chaque puits dans le même objectif. Le sable de l'ADA à Shilo est généralement un sable moyen dans la zone deltaïque et un sable fin dans les dunes de sable. La conductivité hydraulique médiane a été estimée 1 x 10^{-4} m/s avec les deux méthodes (figure 3.4, p 32). La variabilité des résultats était toutefois plus importante avec les tests granulométriques (1 x 10^{-3} à 7 x 10^{-9} m/s) qu'avec les essais de perméabilité (7 x 10^{-4} à 3 x 10^{-5} m/s). Un degré de confiance plus élevé est accordé aux essais de perméabilité étant donné que le volume d'aquifère qu'ils représentent est plus important que celui des échantillons utilisés dans les tests granulométriques. La présence d'hétérogénéités locales est donc plus susceptible d'influencer les résultats des tests granulométriques que ceux des essais de perméabilité.

Les conductivités hydrauliques estimées ont été interpolées afin de produire une carte de conductivité hydraulique pour la région de Shilo (figure 3.6, p 34). Cette dernière indique que la conductivité hydraulique est plus élevée vers l'ouest et tend à décroître en direction est. Cette interprétation est compatible avec le mode de formation de l'aquifère. Les sédiments les plus grossiers ont été déposés à l'apex du delta (ouest) tandis que les sédiments plus fins ont été charriés plus loin vers l'est, d'où une conductivité plus faible dans cette direction.

Des mesures de niveau d'eau ont également été prises dans les puits d'observation et ont été interpolées pour produire une carte piézométrique. L'écoulement souterrain est influencé par la topographie du terrain: une très faible pente en direction sud se terminant abruptement par brusque dénivellé dans la vallée creusée par la rivière Assiniboine. Cette dernière a creusé son cours au travers des dépôts sablonneux jusqu'à la couche de silt argileux sous-jacente, ce qui explique la présence de résurgences le long de la rivière. L'ADA contribue d'ailleurs de façon importante au débit de base de la rivière.

Les niveaux d'eau mesurés varient entre 371 m au nord de la base et 332 m à proximité du brusque dénivellé menant à la rivière Assiniboine. Le niveau moyen de l'aquifère au moment des prises de mesures a varié comme suit: baisse de 3 cm de 2000 à 2001, suivie d'une baisse de 32 cm entre 2001 et 2002 (figure 3.8, p 36). La surface piézométrique révèle une pente à faible gradient en direction de la rivière Assiniboine. Le gradient hydraulique augmente subitement à l'approche du dénivellé le long de la rivière Assiniboine. Un haut piézométrique a également pu être observé dans le champs de bataille Essen près de la rivière Assiniboine et donne naissance à une ligne de partage des eaux près du ruisseau Épinette. La présence possible d'un écoulement régional en direction sud sous le ruisseau Épinette a été évoquée dans des études précédentes mais n'a pu être vérifiée au cours de cette étude.

Des mesures prises avec un tachymètre (Geoflo 40) ont été utilisées pour déterminer les directions et les vitesses d'écoulement de l'eau souterraine. Ces mesures confirment la présence d'une ligne de partage des eaux et sont généralement en accord avec la carte piézométrique établie à partir des mesures de niveau d'eau. Selon les mesures Geoflo, la vitesse d'écoulement de l'eau souterraine varie de 111 à 986 m/an, avec une vitesse médiane de 183 m/an. Les vitesses les plus élevées ont été mesurées près des zones de résurgence. La vitesse varie généralement entre 100 et 250 m/an sur la plus grande partie de la base (appendice L, p 167). Ces vitesses sont cependant plus élevées que celles esitmées à partir du modèle d'écoulement, lequelles se situent plutôt autour de 25 à 100 m/an.

Les analyses granulométriques effectuées sur des échantillons provenant de la couche de silt argileux sous-jacente ou de lentilles de silt contenues dans la couche de sable ont révélé une conductivité hydraulique de 10^{-8} à 10^{-9} m/s. L'écoulement vertical entre l'ADA et la couche d'argile sous-jacente est donc considéré négligeable puisque les données stratigraphiques suggèrent que la couche d'argile est continue.

CARACTÉRISATION ENVIRONNEMENTALE

Des échantillons de sol de surface, d'eau souterraine et d'eau de surface ont été récoltés et analysés au cours des trois campagnes de terrain. Les échantillons d'eau souterraine ont été tirés des puits d'observation et d'autres puits de la région et filtrés avant analyse, sauf pour les analyses de routine telles que le pH et la conductivité. Les échantillons d'eau de surface n'ont pas été filtrés. Les résultats d'analyse des échantillons recueillis sur les sites d'entraînement ont été comparés avec ceux provenant de l'extérieur de la base, censés représenter le bruit de fond (bruit de fond plus deux fois l'écart-type - BF2ET). Ils ont également été comparés aux recommandations canadiennes pour la qualité des sols ou de l'eau du Conseil canadien des ministres de l'environnement (CCME) lorsque disponibles (CCME, 2003). Certaines caractéristiques de l'eau souterraine ou de surface ont aussi été mesurées *in situ* à l'aide de sondes portables.

En ce qui a trait aux métaux, les analyses suivantes ont été effectuées dans les sols et l'eau souterraine: Al, Sb, As, Ba, Bs, Br, Cd, Cs, Cr, Co, Cu, Fe, Pb, Li, Mn, Mo, Ni, Rb, Se, Ag, Sn, Sr, Te, Ti, U, V, Zn and Zr. Les concentrations de métaux mesurées dans les champs de tir de petit calibre indiquent un impact évident des activités de tir sur la composition du sol de surface. Quatre-vingt-dix-sept pourcent (97%), 91% et 41% des échantillons contenaient des concentrations de plomb, de cuivre et de zinc excédant le BF2ET et les recommandations du CCME pour l'usage agricole des sols. Les concentrations de plomb et de cuivre excédaient même les recommandations du CCME pour l'usage industriel. Par exemple, la concentration maximale de plomb s'élevait à 45 000 mg/kg, soit 2381 fois le bruit de fond.

Du côté des champs de tir de grenade, 100%, 94%, 94% et 76% des échantillons excédaient le BF2ET et les recommandations du CCME pour l'usage agricole pour le zinc, le cadmium, le cuivre et le plomb. Ces deux derniers métaux étaient toutefois présents en quantités inférieures à celles mesurées dans le champs de tir de petit calibre. Les concentrations de chrome et de magnésium excédaient également fréquemment le bruit de fond tandis que celles de zinc excédaient même les recommandations du CCME pour l'usage industriel (figure 4.5, p 58).

Peu de dépassements significatifs du bruit de fond ou des recommandations du CCME ont été observés dans les sols des champs de bataille. Les concentrations de métaux les plus élevées étaient généralement situées près des cibles de tir. La grande superficie de ces sites d'entraînement semble ainsi permettre d'éviter une accumulation de métaux dans les sols de surface, malgré le nombre important d'activités d'entraînement qui s'y déroulent.

Bien que des concentrations élevées de certains métaux aient été détectées dans les sols de surface de quelques sites d'entraînement, les analyses de l'eau souterraine ont clairement indiqué que les problèmes de contamination étaient limités aux sols. En effet, aucune concentration de métaux lourds dans l'eau souterraine ne dépassait les recommandations du CCME pour l'eau potable ni le bruit de fond de façon significative.

La qualité de l'eau souterraine à la BFC Shilo est généralement très bonne. La température se situe autour de 9 °C, le pH à 7,5, la conductivité autour de 275 et la salinité à 0,2 ppt. La dureté est d'environ 220 mg/L, les solides dissous de 220 mg/L tandis que les concentrations de nitrates sont généralement peu élevées (médiane de 0,35 mg/L). Quelques échantillons indiquaient des concentrations de nitrates de 2 à 6,5 mg/L mais ils étaient situés pour la plupart hors de la base de Shilo, en zone agricole. Plusieurs échantillons contenaient également des concentrations de fer et de manganèse excédant les recommandations du CCME pour l'eau potable, tant sur la base de Shilo qu'à l'extérieur. Cette caractéristique de l'eau de la région avait été relevée précédemment dans d'autres études et par la station de pompage de Shilo. Une analyse des ions majeurs a démontré que l'eau est généralement de type Ca-HCO_3.

La présence d'explosifs tels que le RDX, le TNT et le HMX a également fait l'objet d'analyses. Dans les champs de bataille, des explosifs ont pu être quantifiés dans seulement 30% des échantillons de sol. Il s ont également été détectés, mais sous la limite de quantification, dans 39% des échantillons. Les concentrations étaient toutefois inférieures à celles mesurées dans le champ de tir de grenade et se situaient sous la barre du 1 mg/kg, sauf une exception à 2 mg/kg. Par ailleurs, tous les échantillons de sol du champs de tir de grenade contenaient des quantités mesurables de plusieurs explosifs, bien qu'en concentration minime (le maximum était de 4 mg/kg pour le RDX). Leur présence a pu être associée aux grenades M-67 présentement en usage au Canada. Ces concentrations sont considérées comme étant peu élevées et similaires, quoiqu'un peu inférieures, à celles qui ont été rapportées dans une autre base aux États-Unis (Jenkins et al, 1998). Aucun explosif n'a été détecté au-delà de la limite de quantification de 0,01 µg/L dans l'eau souterraine ou de surface.

Le thorium-232, dont la demi-vie est de 14 milliards d'années, a également fait l'objet d'analyses. Le ^{232}Th est naturellement présent dans l'environnement et une des premières étapes a d'abord été d'établir les concentrations de fond. La concentration moyenne de ^{232}Th dans les sols situés hors de la base était de 3,04 mg/kg, contre 2,87 mg/kg sur la base. Aucune distribution particulière des concentrations en relation avec les sites de tir de missiles MILAN n'a pu être établie.

Selon plusieurs auteurs, les concentrations naturelles de ^{232}Th dans les eaux souterraines sont difficiles à évaluer étant donné le peu d'analyses réalisées; elles sont toutefois faibles et généralement de l'ordre de quelques dizaines à centaines de pg/L. Dans le cadre de ce projet de recherche, la présence de ^{232}Th n'a pu être détectée dans les 4 échantillons recueillis de 5 à 40 km de la base, la limite de détection étant de 0,01 μg/L. Sur la BFC Shilo même, les concentrations varient de sous la limite de détection à 2,35 μg/L. De façon générale, les concentrations de thorium les plus élevées ont été détectées en aval des sites de tir de missiles MILAN selon la direction de l'écoulement souterrain, laissant supposer une relation possible entre l'utilisation de ces missiles et la présence de thorium dans l'eau souterraine. Cependant, un certain nombre d'échantillons d'eau souterraine contenant des concentrations de ^{232}Th parmi les plus élevées provenaient de puits d'observation situés en amont des zones de tir de missiles MILAN (principalement près de la zone habitée) et l'un d'entre eux provenait même de l'extérieur des limites de la base (3 km au nord) (figure 4.7, p 63).

Ces résultats ne permettent donc pas de déterminer avec certitude l'origine naturelle ou anthropique des concentrations de ^{232}Th dans l'eau souterraine. Des recherches plus poussées seraient nécessaires pour statuer sur ce point. La recommandation du CCME pour l'eau potable pour le ^{232}Th est de 24,5 μg/L alors que la concentration maximale mesurée est 2,35 μg/L. La plupart des concentrations mesurées se situaient de 2 à 4 ordres de grandeur sous la recommandation du CCME, indiquant ainsi l'absence de problème de qualité de l'eau associé au ^{232}Th. Le ^{232}Th étant une substance radioactive, il convient toutefois d'appliquer le principe de précaution et d'éviter à l'avenir d'utiliser des équipements d'entraînement pouvant libérer ce type de substance dans l'environnement. Cette mesure préventive a d'ailleurs déjà été appliquée à la BFC Shilo depuis plusieurs années.

L'ensemble des données sur la composition de l'eau souterraine qui ont été recueillies en cours de projet a permis de dresser un portrait plus détaillé de la qualité de l'eau de l'aquifère Assiniboine. Bien que plusieurs analyses de qualité de l'eau aient été effectuées par le passé dans chacun des sous-bassins de l'aquifère, ces dernières se limitaient pour la plupart aux paramètres de routine communément retenus pour déterminer la qualité de l'eau potable et n'incluaient pas une liste de métaux aussi complète ni de substances spécifiques telles que celles qui ont fait l'objet d'analyses lors de la présente étude.

SIMULATION NUMÉRIQUE DE L'ÉCOULEMENT SOUTERRAIN

Un modèle numérique de l'écoulement a été développé pour trois principales raisons:

1. intégrer l'importante quantité de données recueillies durant les campagnes de terrain;
2. améliorer la compréhension du système d'écoulement de la zone d'étude;
3. délimiter l'aire d'alimentation des puits d'approvisionnement de la base de Shilo.

Les informations géologiques et hydrogéologiques recueillies durant les campagnes de terrain ont tout d'abord été utilisées pour développer un modèle conceptuel de l'aquifère. Le protocole de modélisation décrit dans Anderson et Woessner (1982) a ensuite été utilisé pour concevoir le modèle numérique d'écoulement.

MODÈLE CONCEPTUEL

Les unités de sable deltaïque et éolien constituent l'aquifère de l'Assiniboine; ce dernier constitue la seule unité hydrostratigraphique représentée dans le modèle numérique (figure 5.1, p 68). La couche de silt argileux sous-jacente, dont la conductivité hydraulique a été établie à 10^{-8} - 10^{-9} m/s, a été représentée par une limite imperméable inférieure dans le modèle. L'importante différence de conductivité entre le silt et le sable indique en effet que le flux entre les deux unités géologiques est probablement négligeable.

L'infiltration des précipitations constitue la seule source de recharge du système. Il tombe en moyenne de 450-480 mm de pluie par an, dont 5 à 15% sont disponibles pour la recharge (table 5.4, p 81). La plus grande partie des précipitations est en effet perdue par évapotranspiration. Il convient de noter que l'eau souterraine peut également entrer dans le système par la limite hydraulique nord du modèle, qui sera décrite plus loin. L'eau sort du système par les limites hydrauliques nord et sud du modèle, qui correspondent respectivement au ruisseau Épinette et à la rivière Assiniboine (limite parallèle à cette dernière).

Certaines simplifications du système réel ont été nécessaires étant donné la complexité de ce dernier et le manque de certaines données. Par exemple, le gradient hydraulique est considéré égal à la pente de la surface libre, le milieu poreux est supposé anisotrope ($K_x = K_y \neq K_z$) et la quantité d'eau pompée pour l'irrigation est considérée négligeable dans le domaine modélisé. Le développement du modèle numérique est décrit dans la section suivante.

MODÈLE NUMÉRIQUE D'ÉCOULEMENT

Un modèle numérique en trois dimensions a été développé à l'aide du logiciel Feflow, conçu en Allemagne (Diersch, 1998). Ce dernier utilise des éléments finis et a été testé et amélioré depuis une vingtaine d'années. Sa facilité d'utilisation et la présence de spécialistes de son fonctionnement à l'INRS-ETE comptent parmi les facteurs ayant influencé le choix de ce logiciel.

Les limites du modèle ont été tracées en prenant en compte les limites de la base de Shilo, la disponibilité des données hydrogéologiques, la présence de limites physiques pour l'écoulement et la localisation des puits de pompage de la BFC Shilo (figure 5.2, p 73). La plus grande partie de la base est donc couverte par le modèle. Les limites de ce modèle ont été situées suffisamment loin des puits de pompage de façon à ce que ces derniers ne viennent pas les affecter. Le modèle couvre une superficie de 400 km^2. Le maillage a été généré avec un nœud tous les 350-400 m sur la plus grande partie du modèle, cet espacement ayant été jugé adéquat étant donné le faible gradient hydraulique. Ce maillage a cependant été raffiné à un nœud tous les 30 m autour des puits de pompage de Shilo de façon à représenter plus adéquatement la courbure élevée du niveau piézométrique autour des puits; le maillage devient ensuite de plus en plus grossier à mesure que l'on s'éloigne du puits (figure 5.3, p 73).

Le modèle a été divisé en 15 couches de 2-3 m d'épaisseur en moyenne, générant un maillage comportant 176 144 nœuds et 317 805 éléments triangulaires (figure 5.4, p 74). Les données d'élévation représentant l'interface silt-sable ont été interpolées sur la couche inférieure du modèle. Il convient d'attirer l'attention sur le peu de données disponibles sur cette surface, ce qui introduit des incertitudes quant à la localisation exacte de la base de l'aquifère. Les élévations d'un modèle numérique de terrain ont été interpolées pour créer la couche supérieure du modèle. Ce dernier a ensuite été divisé en 15 couches de 2-3 mètres d'épaisseur en moyenne.

Les élévations de niveau d'eau mesurées ont ensuite été interpolées pour créer la couche supérieure du modèle de façon à créer une limite supérieure de surface libre. Une fonction de Feflow fait en sorte que l'élévation de cette dernière peut varier verticalement selon la position de la nappe libre.

L'attribution des limites s'est faite de la façon suivante. Une limite à charge imposée a été sélectionnée au nord du modèle; il s'agit du ruisseau Épinette. Au sud, une ligne piézométrique suivant la rivière Assiniboine constitue une limite imposée à charge constante. L'utilisation d'une ligne piézométrique plutôt que la rivière Assiniboine permet de simplifier le modèle en évitant de représenter des surfaces de suintement et des résurgences, d'autant plus que les données piézométriques étaient limitées dans cette région du modèle. Deux limites à flux nul représentant des lignes d'écoulement complètent le modèle à l'est et à l'ouest (figure 5.7, p 77). Quant aux trois puits de pompage de la BFC Shilo, ils ont été représentés par un seul puits avec un taux de pompage moyen de 1650 m^3/j. Les trois puits sont situés à moins de 200 m l'un de l'autre et fonctionnent en alternance.

Des valeurs de conductivité hydraulique et de recharge ont ensuite été imposées avant d'entamer le processus de calage du modèle. Deux scénarios ont été testés en ce qui a trait à la conductivité: une valeur uniforme variant entre 3×10^{-5} et 7×10^{-4} m/s, et trois zones de conductivité variable définies à partir de l'analyse de l'interpolation des conductivités estimées sur le terrain (figure 5.13, p 94). Étant donné le peu d'information disponible au sujet de la variabilité de la recharge dans la zone d'étude, une valeur uniforme variant entre 20-70 mm/an a été utilisée.

Plusieurs objectifs de calage ont été définis. Ils sont décrits ci-dessous et accompagnés d'une analyse des résultats obtenus avec le modèle calé.

1. **Valeurs de niveau d'eau réalistes.** La cible retenue est 5 % de la variation du niveau d'eau sur le site d'étude, soit 5 % de 31 m (341 à 372 m) = 1,5 m (figures 5.9 et 5.11, p 88, 89 et 91).

   Afin de vérifier l'atteinte de cet objectif, les valeurs mesurées dans 83 puits d'observation ont été comparées aux valeurs de niveau d'eau simulées. La carte piézométrique simulée est très similaire à celle qui a été produite avec les niveaux d'eau mesurés. Les plus grandes différences se situent dans les secteurs où le gradient hydraulique est le plus élevé (près de la rivière Assiniboine) et près du ruisseau Épinette. Seulement 5 mesures de niveau d'eau sur 83 se situent hors de l'intervalle cible de 1,5 m. L'erreur résiduelle est de moins de 1 m pour 84% des données.

2. **Directions et vitesses d'écoulement réalistes.** Les mesures réalisées avec le tachymètre Géoflo servent de base de comparaison.

   La distribution des vitesses et des directions d'écoulement dans le domaine d'étude est conforme à celle établie à partir des mesures Géoflo. Les vitesses d'écoulement sont faibles sur la plus grande partie de modèle et s'accélèrent à mesure que l'on s'approche de la limite sud, et donc de la rivière Assiniboine. La ligne de partage des eaux près du ruisseau Épinette est clairement visible sur une coupe du modèle.

Les vitesses d'écoulement de l'eau souterraine tirées du modèle numérique sont cependant inférieures à celles issues des mesures Géoflo, soit 25-100 m/an comparativement à 100-250 m/an dans la portion centrale du modèle. Il est possible qu'une sous-estimation de la conductivité hydraulique et/ou de la recharge lors de la calage soit responsable de cette différence. Une surestimation de la vitesse mesurée sur le terrain avec le Géoflo pourrait également expliquer cette situation.

3. **Reproduire le haut piézométrique dans la section nord du modèle, à la limite de partage des eaux.**

   Ce haut piézométrique a été reproduit en imposant une conductivité hydraulique plus faible dans cette région du modèle. Cette démarche est justifiée par le fait que les analyses de terrain ont démontré la présence de sables à granulométrie plus fine dans cette région et la présence de lentilles de silt et de matière organique.

4. **Erreur dans le bilan d'eau inférieure à 1%.** Une erreur minime indique qu'il y a convergence vers une solution et que les erreurs numériques sont minimes (table 5.10, p 96).

   L'erreur dans le bilan d'eau est de 4 m^3/j ou 0,004%.

5. **Flux vers la rivière Assiniboine réaliste.**

   La contribution de la section de l'aquifère Assiniboine comprise dans le modèle au débit de base de la rivière Assiniboine a été estimée à partir de valeurs rapportées dans différentes études. Selon ces estimations, cette contribution se situerait autour de 52 000 à 94 000 m^3/j. La quantité d'eau quittant la modèle par la limite sud (parallèle à la rivière Assiniboine) s'élève à 65 000 m^3/j, une valeur comprise dans l'intervalle estimé.

6. **Valeurs de conductivité et de recharge réalistes.**

   La valeur calée pour la recharge est de 58 mm/an; elle se situe donc parmi les plus hauts estimés (intervalle 20-70 mm/an). Le calage du modèle donnait de meilleurs résultats lorsque différentes zones de conductivité hydraulique étaient générées plutôt qu'avec une valeur uniforme. Trois zones ont donc été définies. Du côté ouest, la conductivité a été établie à 3,5 x

10^{-4} m/s, comparativement à une moyenne estimée initialement à 1 x 10^{-4} m/s. Toutefois, il n'a pas été possible de caler le modèle en imposant une conductivité plus élevée à l'extrême ouest du modèle puisque les charges hydrauliques devenaient trop basses. Les estimés de terrain indiquaient pourtant une conductivité de l'ordre de 10^{-3}. Un taux de recharge plus élevé aurait pu être attribué dans cette zone, ce qui aurait permis de caler le modèle avec une conductivité plus élevée.

Une seconde zone de conductivité de 3 x 10^{-4} m/s a été établie au sud du modèle, soit une conductivité supérieure à celle établie à l'aide des mesures de terrain (8 x 10^{-5} m/s). Finalement, une conductivité de 6 x 10^{-5} m/s a été attribuée à la zone 3 située près du ruisseau Épinette, une valeur semblable aux mesures de terrain (7 x 10^{-5} m/s).

Une étude de sensibilité a été réalisée afin d'examiner l'effet de variations de la recharge et de la conductivité hydraulique sur le modèle et de déterminer si les paramètres de calage permettent de minimiser l'erreur sur les charges hydrauliques. Une variation de 10, 20, 30 et 40% de chacun de ces deux paramètres a été imposée. Toutes choses étant égales par ailleurs, une augmentation de la recharge provoque une augmentation des charges hydrauliques et de la quantité d'eau fournie par le modèle à la rivière Assiniboine. Une augmentation de la conductivité hydraulique induit au contraire une diminution des charges hydrauliques mais produit le même effet sur la quantité d'eau se dirigeant vers la rivière Assiniboine qu'une hausse de la recharge. L'influence de la recharge sur la quantité d'eau qui sort du modèle est toutefois plus grande que celle de la conductivité hydraulique.

Les erreurs RMS (Root Mean Square), moyenne et absolue sont minimisées avec les valeurs de calage utilisées. Il convient toutefois de mentionner que plusieurs combinaisons de valeurs de recharge et de conductivité permettaient de reproduire adéquatement la surface piézométrique de l'aquifère. Les valeurs présentées précédemment ont été retenues car elles permettent d'utiliser une valeur de recharge élevée mais demeurant dans l'intervalle estimé, tout en générant une quantité d'eau s'écoulant vers la rivière Assiniboine réaliste. Il est à noter que le choix d'une valeur de recharge plus élevée aurait permis d'attribuer des valeurs de conductivité plus élevées et donc d'obtenir des vitesses d'écoulement de l'eau souterraine plus proches des mesures de terrain.

Des critères de convergence plus stricts ont été imposés au modèle lors de l'étude de sensibilité sans que cette modification n'affecte les résultats du modèle (charges hydrauliques, bilan d'eau). Il en va de même pour le raffinement du maillage, mis à part le fait qu'un maillage plus fin près de la limite sud du modèle provoquait une légère augmentation de la quantité d'eau sortant de ce dernier.

L'aire d'alimentation du puits de pompage de la BFC Shilo a été estimée à partir du modèle calé en utilisant la fonction de traçage inverse de particules (figure 5.15, p 99). Cette zone de captage de forme ellipsoïdale s'étend au-delà de la limite nord du modèle. L'eau située à la limite du modèle prendrait plus de 100 ans pour atteindre le puits de pompage. Mentionnons toutefois qu'une sous-estimation possible de la conductivité hydraulique, et donc de la vitesse d'écoulement, dans cette zone du modèle, pourrait faire en sorte que les temps de trajet réels soient plus élevés. Rappelons également que l'aire d'alimentation du modèle est approximative puisqu'en réalité ce sont trois puits de pompages qui sont en activité à la BFC Shilo.

Un exercice a été réalisé afin de déterminer si des zones d'entraînement se situaient à l'intérieur du périmètre de captage du puits de pompage (figure 5.17, p 102). Les champs de tir au de petit calibre no 1 et 2, ainsi qu'une partie des champs no 3 et 4, se situeraient à l'intérieur du périmètre. Une particule provenant des champs de tir 1 ou 2 prendrait respectivement entre 25-50 ans et 50-100 ans pour atteindre le puits de pompage. Ces temps de parcours sont bien sûr approximatifs. Ils ne tiennent compte que du mouvement advectif, alors que les processus de dispersion, d'adsorption et de dégradation retarderaient la migration d'éventuels contaminants sur le terrain. Une sous-estimation possible de la conductivité hydraulique dans cette zone a en revanche pu conduire à une sous-estimation des temps de parcours.

Les analyses d'eau souterraine décrites précédemment ont toutefois indiqué que la contamination par les métaux dans les champs de tir de petit calibre était limitée aux sols et n'avait pas atteint l'aquifère; un bon programme de surveillance de la qualité de l'eau devrait donc permettre de détecter toute contamination éventuelle de l'aquifère qui pourrait affecter la qualité de l'eau captée par les puits de la base.

Le champ de tir de grenades et les dépotoirs de la base seraient situés hors du périmètre de captage du puits de la base. Aucun périmètre de protection n'a été établi pour les puits de captage de la base puisqu'aucun règlement manitobain ne spécifie les distances ou temps de parcours à prendre en compte. De plus, un tel exercice bénéficierait d'un raffinement du modèle numérique.

CONCLUSION

Le projet de recherche décrit dans ce résumé a permis s'atteindre les résultats suivants:

- une meilleure caractérisation d'une partie de l'aquifère de l'Assiniboine qui avait fait l'objet de recherches moins poussées que le reste de l'aquifère, particulièrement en ce qui a trait à la conductivité hydraulique et au système d'écoulement;

- une grande quantité de données géochimiques et hydrogéologiques ont été rassemblées et rendues disponibles dans un format simple qui facilitera leur utilisation future par d'autres chercheurs ou personnes impliquées dans la gestion de l'aquifère;

- certains risques potentiels pour la qualité de l'eau souterraine ont été identifiés;

- des recommandations ont été faites aux responsables de la base en ce qui a trait à la protection de l'aquifère.

Ces recommandations peuvent être résumées ainsi:

<u>Pour les sols contaminés</u>:

- Étant donné que les sols de certaines zones d'entraînement (champs de tir de petit calibre ou de grenades) sont contaminés par des métaux tels que le plomb, le cuivre et le zinc, aucun amendement (tel que les applications de chaux) pouvant modifier le pH du sol ne doit être autorisé. De tels amendements pourraient en effet accroître la solubilité des métaux et entraîner leur lixiviation vers les eaux souterraines. Bien que le taux de lixiviation des métaux en fonction de variations du pH ne soit pas connu de façon précise pour le type de sols retrouvé à Shilo, il convient d'appliquer le principe de précaution et d'éviter toute manipulation des sols qui pourrait en faire varier le pH.

- Des tests de lixiviation pourraient être réalisés avec les sols des champs de tir de petit calibre et de tir de grenades afin d'évaluer leur potentiel de contamination de l'eau souterraine. Le potentiel de lixiviation pourrait être établi en fonction de différents pH, et la possibilité que de tels pH soient atteints en contexte réel pourrait ensuite être déterminée dans une évaluation de risque.

<u>Pour le thorium-232:</u>

- Les missiles MILAN contenant du thorium-232 ne sont plus utilisés à la BFC Shilo et ne devraient plus l'être dans le futur.

- Les débris de missiles MILAN retrouvés dans les champs de bataille devraient continuer d'être ramassés et gérés de façon appropriée et sécuritaire.

<u>Pour la qualité de l'eau souterraine</u>:

- La qualité de l'eau souterraine à la base de Shilo devrait faire l'objet d'un suivi régulier. La BFC Shilo dispose maintenant d'un excellent réseau de puits d'observation mis en place par l'INRS-ETE, en plus des autres puits mis en place au cours des deux dernières décennies dans la partie nord de la base. Un suivi régulier de la qualité de l'eau fera en sorte que toute dégradation de la qualité de l'eau serait rapidement détecté. Les zones d'entraînement dont les sols sont contaminés par les métaux devraient faire l'objet d'une attention particulière. Un programme de suivi à long terme de la qualité de l'eau pourrait être établi en prenant en compte des éléments tels que la localisation des sites d'entraînement, les priorités environnementales de la base et les coûts économiques.

- Le seul moyen utilisé pour identifier visuellement sur le terrain la plupart des 78 puits d'observation mis en place par l'INRS-ETE est un bâton de bois peint de couleur orange planté dans le sol. L'expérience a démontré qu'il était difficile de retrouver ces puits un an après le dernier échantillonnage, même lorsque les gens envoyés sur le terrain étaient familiers avec leur emplacement et disposaient d'un GPS. Les puits sont en effet très rapidement recouverts par le sable. Il serait donc nécessaire de prendre rapidement les mesurer nécessaires afin d'identifier les puits de façon plus permanente.

- La vulnérabilité de l'aquifère dans la zone d'étude pourrait être évaluée par la méthode DRASTIC.

- Un périmètre de protection devrait être délimité pour les puits d'approvisionnement de la BFC Shilo. Toute activité pouvant affecter la qualité de l'eau souterraine devrait être examinée et des mesures préventives instaurées.

- Une modélisation du transport de masse pourrait eventuellement ête réalisée si des problèmes de contmaination de l'eau souterrain étaient découverts.

Les travaux de terrain et l'analyse des données réalisés au cours de ce projet ont permis à l'équipe de recherche d'acquérir de l'expérience sur la façon de réaliser des caractérisations environnementales sur des sites militaires. D'autres projets de recherche similaires sont en cours sur d'autres bases à travers le Canada et l'expérience de Shilo (et d'autres études réalisées antérieurement, à Valcartier notamment) est riche en leçons qui serviront à améliorer les projets actuels et futurs. Par exemple, une méthodologie plus performante pour l'échantillonnage de l'eau souterraine sera testée à Shilo et dans d'autres conditions hydrogéologiques et pourrait être utilisée dans de futurs projets si les résultats s'avéraient concluants.

Les données recueillies à Shilo et sur d'autres bases militaires à travers le Canada ont permis de mieux comprendre les impacts des activités d'entraînement militaire sur l'environnement. Ce bagage de connaissance sera utile pour caractériser d'autres sites au Canada et dans d'autres pays et pour développer des programmes d'entraînement avec des impacts environnementaux moindres.

REMERCIEMENTS ET QUELQUES MOTS DE RÉFLEXION

Ainsi s'achève une odyssée de trois ans qui m'aura permis de découvrir un monde fascinant, celui de l'hydrogéologie. Je tiens tout d'abord à remercier René Lefebvre, mon directeur de recherche, pour son appui tout au long de cette aventure. Sa rigueur intellectuelle et sa connaissance approfondie de l'hydrogéologie ont su maintenir mon intérêt et m'insuffler un dynamisme renouvelé lorsque des embûches se présentaient lors du parcours. Richard Martel, co-directeur, a également participé de près aux travaux qui font l'objet de ce mémoire, notamment lors des campagnes de terrain et du suivi du projet auprès des autorités de la base de Shilo. Sa vaste expérience du travail de terrain m'a communiqué un intérêt particulier pour la caractérisation de sites et les méthodes d'échantillonnage. Merci également à Guy Ampleman et à Sonia Thiboutot de *Recherche et développement pour la Défense Canada* (RDDC) à Valcartier pour les échanges et les commentaires lors de la rédaction des rapports de recherche destinés à la Défense nationale. Des remerciements particuliers sont adressés Jean-Marc Ballard et Jeff Lewis, avec qui j'ai partagé de très bons moments lors des longues journées passées à échantillonner les puits de Shilo. Les précieux conseils de Miroslav Nastev de la Commission géologique du Canada (CGC-Québec) lors des travaux de modélisation ont également été très appréciés. Merci également à tous ceux et celles qui ont participé de près ou de loin aux nombreux travaux de terrain, de cartographie et de laboratoire, ainsi qu'à Bob Betcher de Manitoba Conservation qui a pu m'orienter vers de précieuses sources d'information.

L'hydrogéologie n'est pas d'une discipline facile pour quelqu'un qui possède une formation de base en biologie. Je tiens donc à remercier les différents professeurs qui ont su expliquer des concepts parfois arides et complexes de façon intéressante grâce à leur passion pour la matière enseignée et à leur vaste expérience, notamment Pierre Gélinas, René Thérien et René Lefebvre.

J'aimerais également remercier le Conseil de recherche scientifique en science naturelle et en génie (CRSNG) qui m'a octroyé une bourse d'étude, me permettant ainsi de me concentrer sur mes études. J'aimerais aussi mentionner mon employeur actuel, le ministère de l'Environnement du Québec, et particulièrement à Marcel Gaucher, qui a su faire preuve de flexibilité de façon à ce que je puisse mener à bien ce projet de recherche tout en travaillant à temps plein au cours de la dernière année et demi. Mes derniers remerciements s'adressent au plus merveilleux Réunionnais de la planète, Florent, qui a su me soutenir au cours de ces deux dernières années si chargées.

La fin de cette maîtrise n'annonce en réalité que le début d'un apprentissage continu qui se poursuivra au cours des prochaines décennies. Nous avons le choix de nous laisser entraîner passivement dans le tourbillon du monde professionnel et de la vie, d'agir en tant que simples exécutants. Nous avons également l'alternative de mettre en pratique ce que nous avons appris tout en cherchant continuellement à apprendre et à se dépasser, dans l'optique d'améliorer ce qui nous semble perfectible. C'est dans cette seconde voie que je choisis de m'engager. Ma crainte? En arriver à un point où s'éteint la volonté d'agir face à un monde où les intérêts collectifs sont bafoués au profit de ceux de quelques privilégiés, où les politicailleries plutôt qu'une vision à long terme guident les décideurs. L'espoir? Qu'en prenant conscience et en acceptant la nature ambivalente, parfois digne d'émerveillement parfois noire et répugnante, de l'être humain, nous puissions tous éloigner les menaces environnementales qui pèsent sur l'humanité.

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S2	S2-PresentationAIH2003	Power Point	Présentation orale lors de la 4e conférence conjointe sur l'eau souterraine AIH-SCG (Winnipeg, 29 septembre au 1er octobre 2003)
S3	S3-PresentationACFAS2003	Power Point	Présentation orale lors du Congrès de l'Association canadienne française pour l'avancement de la science (ACFAS) (Rimouski, 10 au 14 mai 2003)
S4	S4 – Poster Americana 2003	Corel	Poster présenté lors du Salon des technologies environnementales des Amériques (Américana 2003) (Montréal, 19 au 21 mars 2003)
S5	S5-WellLog	PDF	Relevés de forage des puits d'observation de l'INRS installés en 2000 et 2001
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S11	S11-SamplingSchedule	Excel	Cédule d'échantillonnage pour les années 2000, 2001 et 2002
S12	S12-ResultatsAnalyseGWInorganique	Excel	Résultats des analyses des échantillons d'eau souterraine – Inorganique
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S14	S14-ConcentrationsMétauxGWExcedantCCME	Excel	Identification des concentrations de métaux dans l'eau souterraine excédant les recommandations du CCME pour l'eau potable
S15	S15-ConcentrationsMétauxSWExcedantCCME	Excel	Identification des concentrations de métaux dans l'eau de surface excédant les recommandations du CCME pour l'eau potable
S16	S16-ConcentrationsThoriumGW	Excel	Résultats des analyses de thorium dans l'eau souterraine
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INTRODUCTION

1.1 Contexte

L'avancement continu des connaissances scientifiques, l'édiction de lois et de normes de plus en plus sévères, la mobilisation des groupes environnementaux et de la population et les questions de responsabilité sont autant d'éléments qui ont engendré une prise de conscience de l'importance de prendre en compte les impacts environnementaux d'un projet avant sa mise en œuvre. Il est en effet reconnu qu'il est moins onéreux de prendre des mesures préventives que de tenter de réparer les dégâts par la suite. La Table ronde nationale sur l'environnement et l'économie (TRNEE) a d'ailleurs récemment attiré l'attention sur les coûts astronomiques que devront assumer les générations futures afin de gérer l'héritage des sites contaminés au Canada (TRNEE, 2003). Il devient de plus en plus clair qu'une approche de prévention de la pollution est infiniment préférable à une de réhabilitation.

Dans les domaines d'activités traditionnels que sont l'agriculture et l'industrie, les risques environnementaux sont maintenant bien connus et continuent de faire l'objet d'études de plus en plus approfondies. Ces secteurs d'activité sont en outre encadrés au Canada par des législations environnementales fédérale et provinciales de façon à assurer un certain niveau de protection des écosystèmes et de la santé humaine. Les impacts des activités militaires, en revanche, sont beaucoup moins connus. Les exigences croissantes des législateurs et du public, qui demandent la protection du milieu naturel et l'application du principe de pollueur-payeur, ont cependant contribué à générer un intérêt grandissant envers ce créneau de la recherche environnementale, tant au sein des agences militaires que des milieux de la recherche.

1.2 Problématique

C'est dans ce contexte que le ministère de la Défense nationale a investi des ressources afin de mieux comprendre les impacts potentiels des activités d'entraînement militaire sur l'environnement. Recherche et développement pour la Défense Canada (RDDC) – Valcartier, un centre de recherche ayant pour principal client les Forces armées canadiennes, a donc reçu le mandat de caractériser plusieurs sites d'entraînement militaire canadiens et d'évaluer les risques environnementaux qui découlent de certaines activités qui s'y déroulent. Plusieurs bases militaires canadiennes ont fait l'objet de tels travaux, notamment Valcartier (Québec), Gagetown (Nouveau-

Brunswick), Cold Lake (Alberta) et Shilo (Manitoba). Le présent travail de maîtrise portera sur les travaux effectués à la Base des forces canadiennes de Shilo (BFC Shilo).

D'assez grande étendue, cette base militaire est située sur un important aquifère du sud du Manitoba, l'*Assiniboine Delta Aquifer* (ADA). Il s'agit d'un aquifère de sable non-confiné qui constitue une source importante d'approvisionnement en eau pour l'agriculture, pour l'industrie et pour la consommation résidentielle, incluant celle de la base. Deux cours d'eau, la rivière Assiniboine (Assiniboine River) et le ruisseau Epinette (Epinette Creek), coulent respectivement au sud et au nord de la base. Cette dernière a servi de terrain d'entraînement militaire depuis le début du siècle, particulièrement depuis la seconde guerre mondiale. Des milliers de soldats allemands s'y sont même exercés au cours des deux dernières décennies. C'est d'ailleurs à la suite du départ des troupes allemandes en l'an 2000 qu'un mandat a été confié à RDDC-Valcartier par le Directeur Général Environnement du ministère de la Défense nationale afin de déterminer quels ont pu être les impacts des activités d'entraînement antérieures sur les sols, les eaux de surface et les eaux souterraines.

RDDC-Valcartier a donc effectué une campagne de caractérisation des sols, des eaux de surface et des eaux souterraines s'échelonnant de 2000 à 2002 (3 périodes de 3-4 semaines). Les travaux hydrogéologiques ont été réalisés en collaboration avec l'Institut national de la recherche scientifique (INRS- Eau, Terre et Environnement). Il a également été jugé utile de développer un modèle numérique d'écoulement pour compléter la caractérisation et mieux comprendre le contexte hydrogéologique de l'aquifère.

1.3 Objectifs visés

Tel que mentionné précédemment, le but fondamental des travaux présentés dans le cadre de ce mémoire est de déterminer l'impact des activités d'entraînement militaire sur les sols, les cours d'eau et l'aquifère de la base de Shilo. Il a été traduit en trois objectifs plus spécifiques, que différents travaux de forage, de caractérisation et de modélisation ont permis d'atteindre:

1. Décrire le contexte géologique et hydrogéologique du site d'étude;
2. Identifier les sources potentielles de contamination des sols, de l'eau de surface et de l'eau souterraine;
3. Déterminer de quelle façon les sources potentielles de contamination pourraient affecter l'aquifère et ses utilisateurs.

La démarche qui a guidé la réalisation de ce travail et les liens entre ses diverses composantes sont décrits de façon plus détaillée dans la section qui suit.

1.4 Cadre conceptuel et méthodologie

Un cadre conceptuel a été développé afin de montrer de quelle façon s'articulent les éléments du projet de recherche. Il est illustré à la figure 1.1.

En plus des sections traditionnelles que sont l'introduction (chapitre 1) et la conclusion (chapitre 6), la présent mémoire de maîtrise est divisé en quatre chapitres. **Le second chapitre** (Description du site) présente des informations générales sur le site d'étude. Ces informations permettront au lecteur de situer l'endroit, de se familiariser avec son histoire, d'identifier les principaux éléments physiques et hydrographiques, et de relever les principales activités d'entraînement qui s'y déroulent.

Plusieurs informations contenues dans ce chapitre sont issues de divers rapports de consultants, d'articles scientifiques et d'observations sur le terrain. Des recherches dans les archives de la bibliothèque de la base de Shilo et des discussions avec des officiers lors des campagnes de terrain ont fourni des données sur l'évolution de l'entraînement militaire sur la base de Shilo au cours des dernières décennies.

Le troisième chapitre (Caractérisation géologique et hydrogéologique) présente les interprétations des contextes géologique et hydrogéologique qui découlent des données recueillies lors des campagnes de caractérisation et lors de recherches dans la littérature. Il permet de bien décrire le contexte dans lequel la caractérisation environnementale (chapitre 4) a été effectuée et a servi de base à la réalisation du modèle conceptuel lors de la modélisation de l'écoulement (chapitre 5).

La description de la géologie du site est issue de travaux réalisés sur le terrain, notamment des relevés visuels, des mesures de Géoradar et des forages profonds. Une carte géologique et une coupe stratigraphique ont été produites. Les données hydrogéologiques proviennent d'observations prises lors du forage de puits d'observation sur la base, de mesures prises avec des sondes portatives dans les puits d'observation, d'essais de perméabilité et de mesures de la vitesse et de la direction de l'écoulement à l'aide d'un tachymètre. Des mesures de niveau d'eau dans les puits d'observation ont servi de base à la production d'une carte piézométrique.

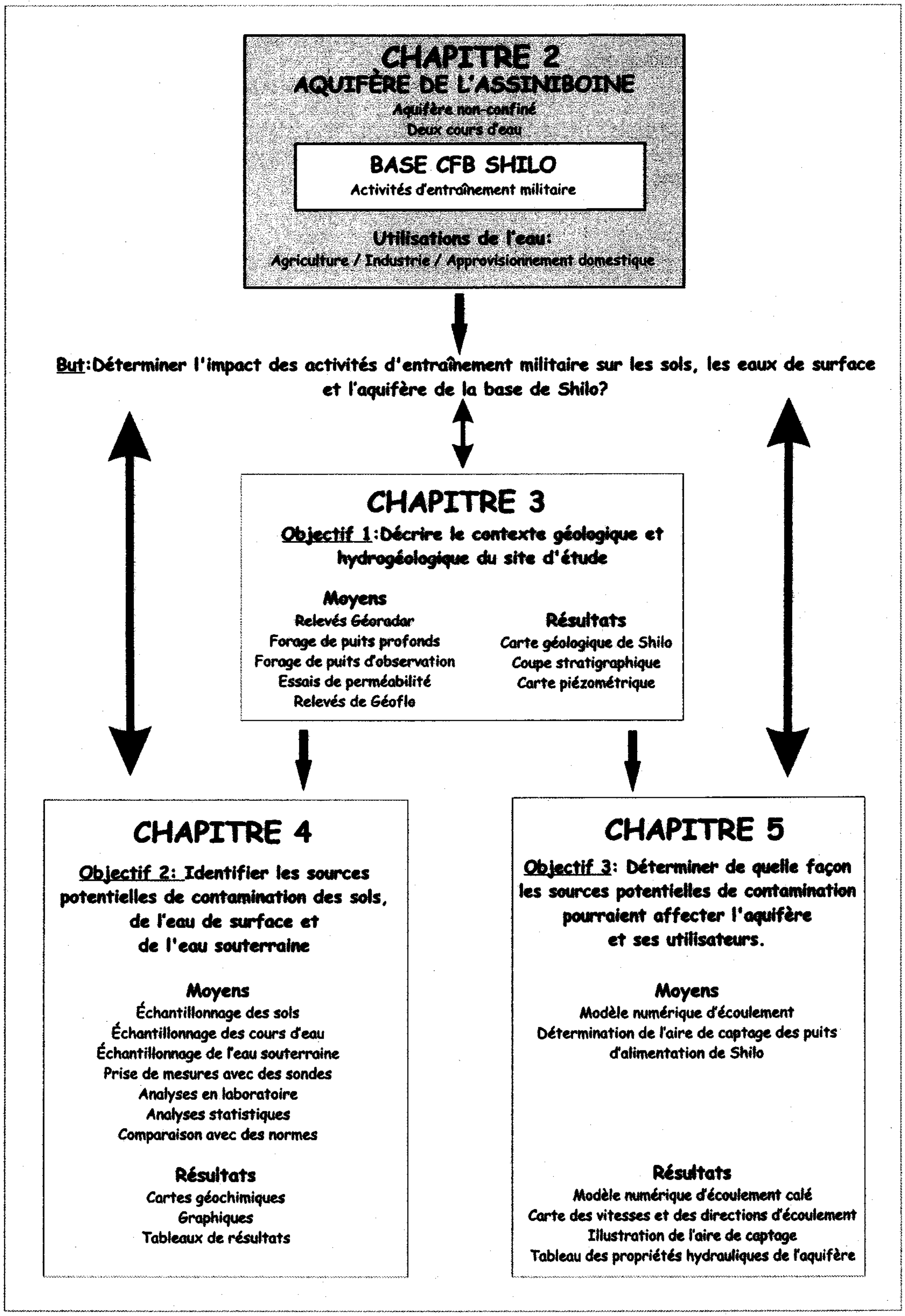


Figure 1.1 : Cadre conceptuel du projet de maîtrise.

Le chapitre quatre présente les résultats d'analyse d'échantillons de sols, d'eau de surface et d'eau souterraine issus de trois campagnes d'échantillonnage (2000 à 2002). Les analyses ont porté sur les paramètres suivants : métaux, matériaux énergétiques, thorium-232 et ions majeurs pour l'eau. Les concentrations mesurées sur la base ont été comparées aux concentrations de fond et aux normes existantes (lorsque disponibles) afin de déterminer la présence et l'ampleur d'une éventuelle contamination.

L'échantillonnage des sols a été réalisé selon une méthodologie développée par RDDC et décrite en détail dans Ampleman et al. (2003 : 11). Un réseau de quelque 80 puits d'observation forés pour les besoins de l'étude a été utilisé pour l'échantillonnage de l'eau souterraine. L'analyse des échantillons de sols et d'eau a été réalisée par un laboratoire privé du Manitoba (métaux), par la Commission géologique du Canada à Ottawa (thorium) et par RDDC (matériaux énergétiques). Les données ont été analysées conjointement par RDDC et l'INRS. Les résultats de ces analyses sont présentés sous forme de cartes, de graphiques et de tableaux.

Le chapitre cinq est axé sur l'étude de l'aquifère. La réalisation de simulations à partir d'un modèle numérique développé à l'aide du logiciel Feflow a permis d'estimer de façon plus précise le contexte hydrogéologique de l'aquifère élaboré à partir des observations de terrain (chapitre 2). Le modèle calé d'écoulement a finalement été utilisé pour déterminer la zone de captage des puits d'alimentation de la base de Shilo.

Les résultats conjugués des trois chapitres ont donc permis de caractériser la zone d'étude (chapitre 3), d'identifier les zones contaminées sur la base de Shilo (chapitre 4) et d'évaluer les risques que ces dernières, ainsi que les activités d'entraînement, puissent affecter les usages de l'aquifère (chapitre 5).

Le lecteur prendra note que la méthodologie utilisée pour réaliser les travaux présentés dans ce mémoire est présentée en association avec les résultats qui en découlent, de façon à ce que chaque thématique (géologie, hydrogéologie, caractérisation environnementale et modélisation numérique) forme un tout.

1.5 Contribution de l'auteure

Il va sans dire que la réalisation d'un projet de caractérisation géologique, hydrogéologique et environnementale de l'ampleur de celui réalisé à la base de Shilo n'a pu être accompli sans l'implication soutenue d'un nombre important de collaborateurs.

RDDC-Valcartier est le porteur du mandat de caractérisation de la base de Shilo et le récipiendaire des subventions de la Défense nationale ayant permis la réalisation de ce projet. L'INRS-ETE a été associé de près à l'ensemble des travaux.

L'auteure a activement participé aux deux dernières campagnes de terrain (2001-2002) en compagnie d'autres partenaires et a réalisé la planification et le suivi des travaux sur le terrain en 2002 en collaboration avec Jeff Lewis de RDDC-Valcartier et des équipes de consultants. Les tâches réalisées sur le terrain ont été les suivantes :

- Installation de puits d'observation
- Prise d'échantillons d'eau souterraine, d'eau de surface et de sols
- Prises de mesures dans l'eau à l'aide de sondes portatives (pH, salinité, etc.)
- Prises de mesures de direction et de vitesse de l'écoulement souterrain (Geoflo)
- Réalisation d'essais de perméabilité

L'auteure a également effectué les analyses granulométriques des sols en laboratoire. Elle a joué un rôle lors de la rédaction de deux rapports (Ampleman et al., 2003 a et Amplean et al, 2003b) soumis à la Défense nationale par RDDC : préparation des tableaux de données relatifs à la section hydrogéologie et rédaction d'une partie du texte sur l'hydrogéologie (Ampleman et al., 2003). Les mêmes résultats ont également été publiés dans Pennington et al, 2003. Par ailleurs, bien que les données relatives aux sols aient été traitées par RDDC dans leurs rapports, elles ont également été utilisées par l'auteure et sont présentées sous une forme quelque peu différente dans ce mémoire.

Finalement, la modélisation de l'écoulement a été réalisée par l'auteure, non sans bénéficier des précieux conseils de plusieurs spécialistes de la modélisation, notamment Miroslav Nastev, René Lefebvre, Richard Martel et Daniel Paradis.

1.6 Précisions sur la structure et la forme du mémoire

Le présent mémoire de maîtrise a été rédigé sous une forme intermédiaire entre le mémoire traditionnel et le mémoire par article. Cette forme de présentation a été retenue puisqu'une partie importante des résultats (description du site, caractérisation géologique et hydrogéologique, caractérisation environnementale) avait déjà fait l'objet d'un article (voir document S1) et d'une présentation (voir document S2) dans le cadre de la 4^{e} conférence conjointe sur l'eau souterraine AIH-SCG, tenue à Winnipeg du 29 septembre au 1er octobre 2003 (Gauthier et al., 2003b). L'article, intitulé *Assessment of the Impacts of Live Training on Soil and Groundwater at Canadian Forces Base Shilo, Manitoba*, est présenté au chapitre 4. Par ailleurs, le rapport final du projet présenté à la Défense Nationale *Evaluation of the Impacts of Live Training at CFB Shilo* (Ampleman et al., 2003) a servi de base à la rédaction d'une bonne partie des chapitres II et III. Ce matériel a également fait l'objet d'une présentation au Congrès de l'Association canadienne française pour l'avancement de la science (ACFAS) qui s'est tenu du 10 au 14 mai 2003 à Rimouski, dont le titre est *L'impact des activités militaires sur l'environnement : perspectives de développement durable* (voir document S3) (Gauthier et al., 2003a). Enfin, un poster présentant les principales conclusions de la caractérisation environnementale de la base a été exposé lors du Salon des technologies environnementales de Amériques tenu du 19 au 21 mars 2003 à Montréal (voir document S4).

Par ailleurs, l'anglais a été choisi comme langue de rédaction pour deux principales raisons. Nous voulions tout d'abord nous assurer que les intervenants responsables de la gestion environnementale de la base de Shilo ainsi que les personnes impliquées dans la recherche et la gestion des ressources hydriques de l'aquifère de l'Assiniboine, des Manitobains anglophones, puissent avoir accès aux données et aux résultats de ce projet de recherche. Ensuite, une partie importante des résultats présentés dans ce mémoire a été publiée dans une série de rapports de la Défense Nationale, tous rédigés en anglais uniquement; il devenait alors logique d'utiliser le texte déjà rédigé et ayant fait l'objet de révisions détaillées.

Un dernier point mérite d'être soulevé. La réalisation d'un projet de caractérisation environnementale et hydrogéologique de l'ampleur de celui réalisé de 2000 à 2002 à la base militaire de Shilo a demandé l'investissement de ressources financières et humaines importantes. Il a permis de recueillir une quantité impressionnante de données de terrain qui, si rendues accessibles aux divers intervenants travaillant à la préservation des ressources de la région, pourraient permettre le développement d'outils de gestion plus puissants que ceux qui sont actuellement disponibles, ou à tout le moins fournir un portrait plus détaillé de la situation. Les données brutes ont donc été compilées sous une forme simple et accessible à tous (tableaux Excel) et sont disponibles sur le CD qui accompagne le mémoire. Il convient de préciser que les mesures de terrain erronées ont été omises de façon à éviter toute confusion. D'autre matériel, tel que les exposés Power Point présentés dans le cadre de congrès, sont également disponibles en format CD. La plupart des figures et tableaux du mémoire, les cartes et annexes et le mémoire lui-même ont aussi été enregistrés sur le CD de façon à colliger l'ensemble des données du projet Shilo en un seul endroit.

II SITE DESCRIPTION

2.1 Location

CFB Shilo is located in southwestern Manitoba, approximately 185 km west of Winnipeg and 25 km southeast of Brandon, Manitoba (Figure 2.1). Brandon, with its 43 000 inhabitants, is the most important city in the region and lies on the western limit of the aquifer (Figure 2.1). Fields and some forests account for most of the territory associated with the aquifer, along with a number of small towns and settlements such as Carberry, Glenboro and Cypress River.

The base is overlying a major unconfined, sand and gravel aquifer called the Assiniboine Delta Aquifer (ADA). This regional aquifer covers a 3885 km^2 area. As can be seen in Figure 2.1, CFB Shilo occupies a major portion of the southwestern corner of the ADA.

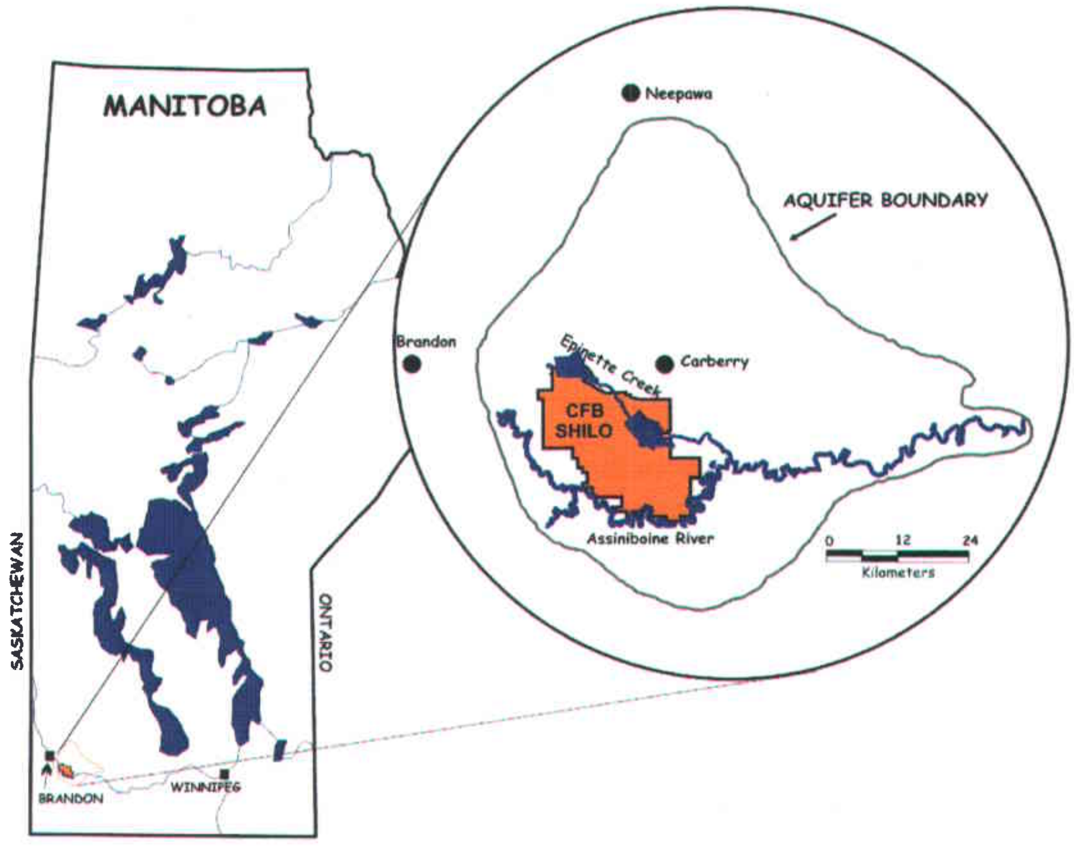


Figure 2.1: Location of CFB Shilo and the Assiniboine Delta Aquifer, Manitoba. ADA boundaries are shown. CFB Shilo overlies the southwestern corner of the aquifer. (Drawing in circle adapted from Render, 1988).

The 28 000 hectare base borders consist mostly of rivers and parks; the Assiniboine River to the south, Epinette Creek to the north and Spruce Woods Provincial Park to the East. This conservation park features some forests, mixed-grass prairies and active and stabilized sand dunes. The farmlands of Cornwallis Rural Municipality serve as CFB Shilo's western limit.

2.2 History

Settlers established in the Carberry-Shilo area at the end of the 19th century benefited from a period of abundant moisture that allowed agricultural activities to take place until the return to normal dry conditions (Stevens and Carreiro, 1973 : 2). Farms were abandoned in the beginning of the 20th century and some lands were converted to forestry.

Military training in the area has its origin at the turn of the century. Military training started with the opening of a first camp (Sewell Camp) in 1910 some 5 miles north of CFB Shilo's current location. This came about when the continued influx of population into the west directed the attention of the Militia Department to the importance of securing areas of the prairie provinces as military reservations. This camp was used by as many as 30 000 troops during World War I, and for summer training only thereafter (Ampleman et al., 2003 : 4).

Army engineers carried out their first survey of part of what is now CFB Shilo in 1931. Army training started in 1934 with mounted artillery and machine gun units, with infantry units joining in the following year. After seasonal use in the summer, the current base area became a permanent year-round establishment around 1942. After World War II, Shilo became the permanent home of the Royal Canadian Artillery, except for the coast and aircraft elements (Ampleman et al, 2003 : 4).

In 1974, the Federal Republic of Germany and Canada signed an agreement allowing German military troops to conduct training and perform manoeuvres at CFB Shilo. This exchange program was named GATES for German Army Training Exchange Shilo. Following the departure of German troops in 2000 after 23 years of training, the German and Canadian governments agreed to share unexploded ordnances (UXO) clean up and field remediation costs. A three-year characterization campaign was thus undertaken to evaluate the environmental impacts of military training activities.

2.3 Physical environment

Agriculture is one of the major economic activities in southwestern Manitoba and the Brandon-Shilo region is no exception. Groundwater from the aquifer is widely used for crop irrigation, domestic needs and as a drinking water source for the base. Coarse-textured surface deposits make the aquifer vulnerable to contamination, thus strengthening the need for environmental monitoring.

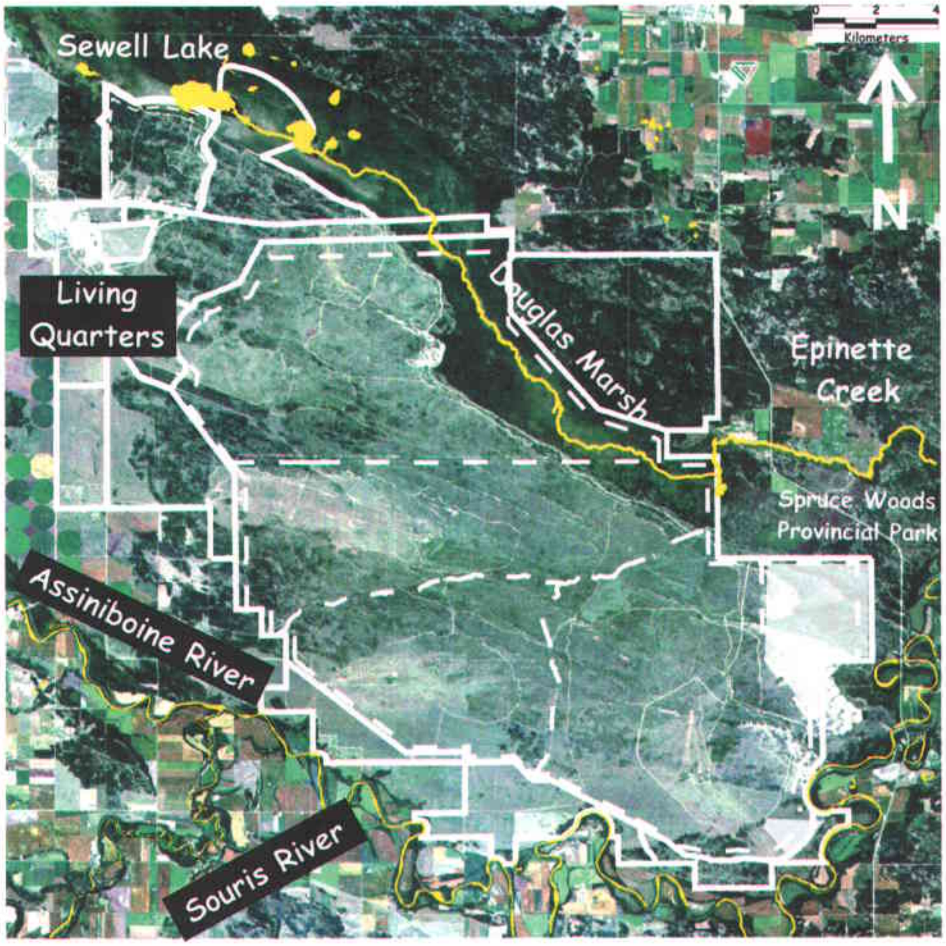


Figure 2.2: Aerial photograph of Canadian Forces Base Shilo and surrounding areas. Rivers and lakes are shown in yellow. Base limits are highlighted in white.

The aerial photograph of CFB Shilo on Figure 2.2 clearly shows the presence of irrigated fields to the west, southwest and northeast of the base. Douglas marsh and forests are visible to the north, as well as Spruce Woods Provincial Park. Scattered trees can be found on CFB Shilo but the area is treeless for the most part. Bare sand is often covered with prairie grass. The topography is generally flat, with sand dunes in the western portion of the study area. The relatively level plain slopes gently south, leading to the steep shores of the U-shaped valley incised by the Assiniboine River. Almost all of the water in this area drains towards the Assiniboine. Base living quarters and administrative buildings are located in the northwestern part of the base.

CFB Shilo's climate is continental, with hot summers and cold winters. The mean daily temperature ranges from a high of 18,7 °C in July to -18,4 °C in January. The annual mean precipitation is 453 mm; most of which falls as rain from April to September. Wind is a constant factor at CFB Shilo.

2.4 Hydrography

Few watercourses or waterbodies are found on the Assiniboine Delta Aquifer. This can be attributed to the high porosity of earth material. Only two water courses flow in the Shilo area: the Assiniboine River and Epinette Creek.

The Assiniboine River takes its origins in Saskatchewan where it flows from north to south and then from west to east after joining the Qu'Appelle River near the Manitoban border. Flow in the river is controlled by the Shellmouth Reservoir (near the Saskatchewan-Manitoba border) for flood control purposes and for securing surplus to meet water demands along the course of the river. Flow in the river from 1974 to 1990 have ranged from 4 m^3/s to 335 m^3/s (CFB Shilo Natural Resources Management Plan : 31). The river erodes a broad and deep valley along CFB Shilo's southern border, where it is joined by an important south-bank tributary, the Souris River (Figure 2.2). These two rivers incised their course in the deltaic sand deposits as glacial Lake Agassiz receded, establishing a much lower base level (Kerr & Welsted, 1978 : 409). In the north, drainage from the Douglas marsh gives rise to a few ponds and lakes, the biggest being Sewell Lake, which constitutes Epinette Creek headwaters. This low-flow creek meanders through Douglas marsh, a flat and poorly drained area until it meets the Assiniboine River.

2.5 Military Training Activities

CFB Shilo counts several training ranges dedicated to different types of training activities (Figure 2.3); a brief description of those ranges and associated activities will assist in identifying potential sources of contamination. Three types of ranges will be investigated in this study: the rifle ranges, the grenade range and the battleruns. Most of the land (85%) used by the base is the property of the government of Manitoba and has been leased to the government of Canada since 1913. The remaining portion (15%) is owned by the federal government.

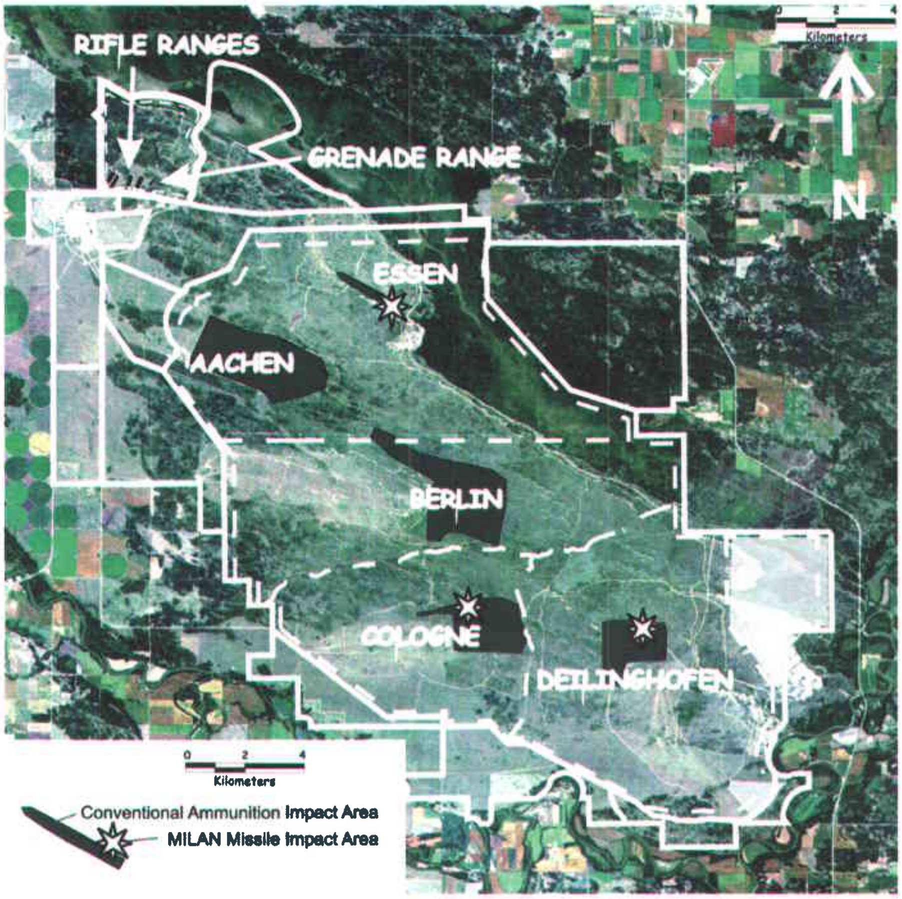


Figure 2.3: Aerial photograph of Canadian Forces Base Shilo and surrounding areas. CFB Shilo boundaries are shown. Danger areas are identified with a dotted line. Conventional ammunitions and main MILAN missile impact areas are shown.

CFB Shilo boundaries are illustrated in figure 2.3. Some base areas are classified as danger areas because of the nature of military activities taking place in these areas or because of the possible occurrence of unexploded ordnances. Three areas (shaded) were declared out-of-bounds to preserve rare plant species: the golf course next to the administrative buildings (northwest of the map) and two active dune areas near Spruce Woods Provincial Park (southeast corner).

Shilo's four rifle ranges (Figure 2.3) are located in the northern part of the base, northeast of the administrative buildings and living quarters. They are used for small arm shooting exercises. Each range is rectangular in shape (Figure 2.4), with a length of about 500 m and a width of 100 m. Fixed targets are installed side by side on an earth butt at the end of the range. Soldiers fire ammunitions from various distances, usually from firing positions located behind small sand butts spreaded every hundred meters or so and covered with sand bags. High panels installed behind the targets stop the flying bullets for security purposes. Ammunition debris can therefore be found behind the targets or at various distances in the shooting zone, mainly in the back stop.

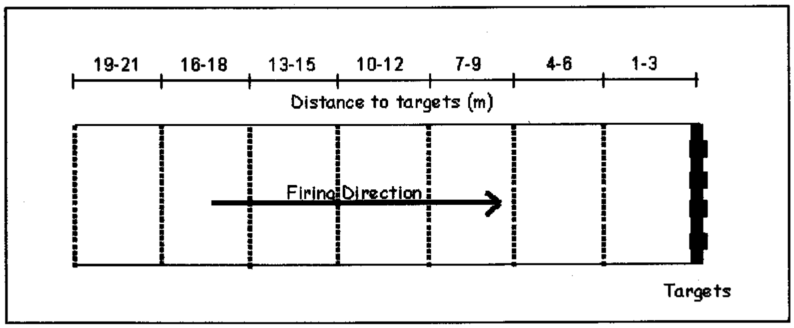


Figure 2.4: Schematic drawing of a rifle range.

Another small-size training range examined in this study is the grenade range (Figure 2.5), located one km east of the rifle ranges. This range consists in a concrete bunker from which soldiers hand fire grenade on a small plot of land (150 m long by 100 m wide); disturbance is thus limited to a small area. The grenade range is almost completely void of vegetation due to the frequent explosion of grenades, exposing the topsoil layer and the underlying sand.

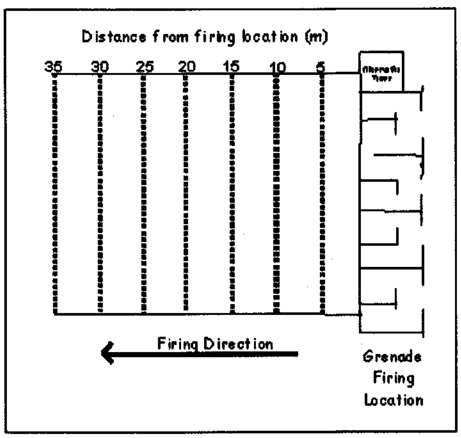


Figure 2.5: Schematic drawing of a grenade range

The other training areas investigated are the battleruns. Contrary to the rifle and grenade ranges, battleruns cover extensive areas of 800 000 to 1 000 000 m^2 in size. CFB Shilo includes five major battleruns (Aachen, Berlin, Cologne, Deilinghofen and Essen) scattered throughout the base. They were used primarily by German troops between 1978 and 2000, thus their German names. In addition to the ongoing Canadian Forces training, the battleruns were used by the Germans for leopard tank, mobile artillery training and other training activities (Shoesmith, 1982). Most of the targets found in the battleruns are pop-up targets instead of static targets as in the rifle ranges. All training ranges are illustrated on Plate 1 (Appendix A).

A particular training activity carried out by the Germans in three of the battleruns (Cologne, Deilinghofen and Essen) is the firing of MILAN missiles. Manufactured in Europe, MILAN (*Missile d'Infanterie Léger Antichar*) missiles are portable, medium-range (max 2 km), antitank weapons with a warhead penetration depth of up to one meter. They were developped for the French and German armies and are in service in about 40 countries. Some models of MILAN missile contain small amounts of an isotope of thorium in their guiding system, ^{232}Th, a metal with a very long half live (1,41 x 10^{10} years). The main MILAN missile impact areas are shown in figure 2.3.

The precise number of ammunitions fired at CFB Shilo over the years is unknown, However, starting in 1971, the base established an ammunition expenditure record that provides an idea of the number and location of rounds fired. This record (Ampleman et al. 2003: 190-191) reports the firing of some 6 000 to 20 000 ammunitions every year.

III Geological and Hydrogeological Characterisation

3.1 Introduction

This chapter will present major geological and hydrogeological features of the Assiniboine Delta Aquifer (ADA). General information about the ADA was first derived from previous studies and reports (section 3.2). Field investigations carried out at CFB Shilo by the *Institut national de la recherche scientifique – Eau, Terre et Environnement* (INRS-ETE) and the Geological Survey of Canada (Quebec Division) (GSC) from 2000 to 2002 allowed for a more precise geological and hydrogeological description of the section of the aquifer underlying the study area. Methodology for this work is described in section 3.3. Geological information is summarized in maps of surface sediments and cross-sections (section 3.4). Finally, a detailed description of the aquifer is presented in section 3.5, including hydraulic conductivity estimates, groundwater flow direction and velocity, and groundwater chemistry. Section 3.6 briefly highlights physico-chemical characteristics of surface water.

General information about the ADA collected from existing reports was helpful in preparing the first field characterization campaign performed in 2000. Data specific to the study area gathered during this period were then used to orient the work of the subsequent campaigns. For example, knowledge of aquifer thickness, depth to the groundwater table or groundwater flow direction was helpful in designing and positioning additional observation wells for groundwater geochemical characterization (chapter 4). Also, the conceptual model of the aquifer used as a basis for the modeling work (chapter 5) relies upon the geological and hydrogeological interpretations presented in this chapter.

3.2 Previous studies

Given its utmost importance as the main supply of high-quality water for the region, the Assiniboine Delta Aquifer has been extensively studied over the past 40 years, mainly for groundwater availability.

Surficial geology was studied by Johnston (1934), Ehrlich et al. (1957) and Halstead (1959). Test drilling of the aquifer was first carried out in the '60s by Arnold Pedersen (IAH, 2003 : 25). This led to the first definition of the general hydrogeological framework of the ADA (Render, 1988 : 18). In the following decade ('70s), several groundwater availability investigations were completed by Manitoba Natural Resources Department (now Manitoba Conservation) in several

Rural Municipalities. They provided background information about geological units and groundwater resources in the ADA, including an assessment of the suitability of various sections of the aquifer for groundwater exploitation. Deep oil exploration drilling logs also provided useful information on the extent of stratigraphic units.

A detailed and extensive study of the aquifer, conducted from 1980 to 1986 under a federal-provincial water supply evaluation agreement (*Canada-Manitoba Interim Subsidiary Agreement on Water Development for Regional Economic Expansion and Drought Proofing*), provided further hydrological and hydrogeological data. The study included detailed core drilling, hydraulic testing and water level, as well as other measurements. Thirteen aquifer sub-bassins were defined. This work was published in a report by Render in 1986. Data from this study, along with maps and cross-sections of the aquifer, were also summarized in a report published in 1987 by the same author (Render, 1987). A model of a portion of the aquifer underlying CFB Shilo was developed from these data by Render (1988) and was used to estimate the potential for future groundwater development in this section of the aquifer.

A well-drilling program carried out in 1993 (Frost and Render, 2002) allowed for the collection of further data and for a more detailed mapping of the potentiometric surface of the aquifer. This work confirmed sustainable yield estimates for the aquifer calculated by Render in 1988. Finally, a modeling project of the entire ADA is currently ongoing at the University of Manitoba as well as a study of dissolved oxygen in groundwater at the University of Saskatchewan (personal communication).

All these investigation projects allowed for a good characterization of the ADA on a regional scale. Summary reports and maps of several characteristics of the aquifer (soil type, vegetation cover, hydraulic conductivity, etc.) produced by Manitoba Conservation and its partners are available and are currently being used by researchers, public agencies and communities to improve the management of groundwater resources in the region. Detailed information is lacking however at the local scale in parts of the aquifer, including the Shilo area.

3.3 Fieldwork – methods of investigation

Investigations were undertaken by INRS-ETE and the GSC within the limits of CFB Shilo with the collaboration of Base Authorities. A limited number of observations wells were drilled outside the base and groundwater samples collected with the agreement of private landowners.

3.3.1 Geology

Field observations during the 2000 characterization campaign were helpful in understanding the general layout of the aquifer. The steep banks along the Assiniboine River, where the sand unit was deeply incised by the river down to the silt-sand interface, count with several good observation sites.

More detailed investigations were carried out in September 2001 by the CGS and two consultants from Cogeo Consultants inc. Because of the shallow depth of most boreholes located within the training areas, two deep boreholes were drilled to evaluate the sequence of sediment formations and the thickness of the aquifer. Ground penetrating radar surveys were also made by the GSC to obtain further information on sediment structures. Surface and subsurface soil samples were analyzed for their composition. These data were used to draw the stratigraphic section presented in Appendix E.

3.3.2 Hydrogeology

Field investigations for the hydrogeological characterization of the aquifer were performed in 2000, 2001 and 2002 and included the drilling, installation and development of 78 observation wells. These wells, as well as a number of wells from other monitoring networks, were used for groundwater sampling, measurement of physicochemical parameters of groundwater with portable probes, and measurement of groundwater level, flow direction and velocity. Slug tests were also performed. The location of all wells used in this study is shown on Plate 2, Appendix B.

3.3.2.1 Borehole drilling and well installation

Well locations were selected according to several criteria, including site safety, ease of access, proximity to potential contamination sources, and adequate site coverage. In order to allow the safe drilling of boreholes in UXO (Unexploded Ordnances) impacted training ranges, a safety proofing of all sites was performed prior to drilling. The drilling sites were surveyed to a depth of 9 m to detect surface-laid and buried metallic objects, thus ensuring the absence of unexploded ordnances.

Drilling and installation of groundwater monitoring wells was conducted in October 2000 (42 wells) and September 2001 (36 wells). They were drilled by Paddock drilling Ltd (Brandon, MB) in 2000 and 2001 and installed under INRS guidance by Cochrane Engineering Ltd (Winnipeg, MB) in 2000 and by Defence Construction Canada in 2001. Drilling logs are available in document S6 on the CD. The majority of boreholes were drilled with a Caterra rig. A Nodwell-Brat 22 caterpillar was required for a few boreholes located in difficult access areas. Both rigs were equipped with a hollow-stem auger. For each site location, a probe hole was first drilled with a 125-mm stem auger to determine the depth to the water table and then backfilled with bentonite. This was to ensure that all observation wells would be drilled to at least 2 m below the water table.

All wells were installed with PVC tubing according to standard methods. Most wells were cased with a flush-mount protective metal casing and a locking cap as requested by CFB Shilo Range personnel. Stick-up casings could not be used in training areas as they could be in the way of army vehicules. A more detailed description of wells structure, installation and development is available in Appendix C. Figure 3.1 below is a schematic representation of well structure.

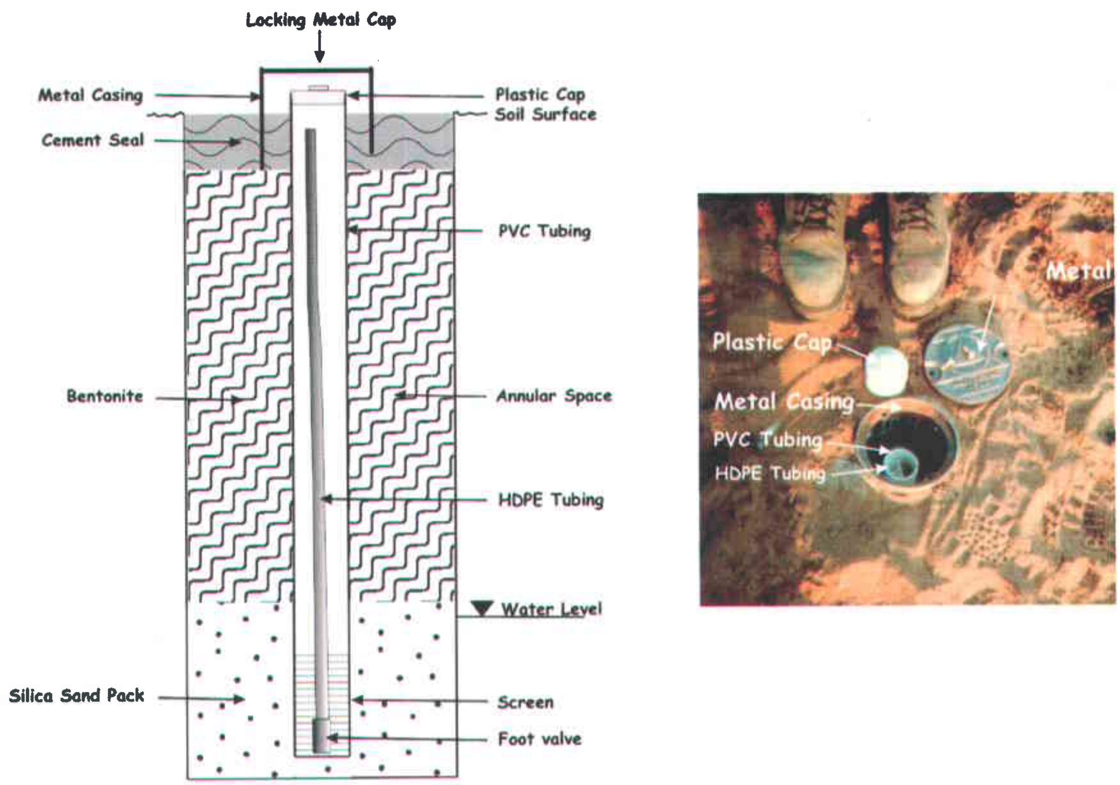


Figure 3.1 Schematic representation of INRS-drilled observation wells installed at CFB Shilo. The picture to the right shows apparent well structures.

All wells were GPS surveyed by Wardrop Engineering Inc. (Winnipeg, MB) in 2000 and by Lennon surveys (Brandon, MB) in 2001 with a precision on location of ± 2 m and on elevation of

± 0.01 m. The point of reference for elevation was the metal casing. Since the point of reference for measuring the water level was the top of the PVC tubing, adjustments were made to calculate the elevation of this datum using the elevation of the metal casing provided by the GPS surveys and manual measurements of the distance between the top of the PVC tubing and the metal casing. GPS coordinates for all wells drilled or used in this study are presented in Appendix D, as well as well depth and screen length.

3.3.2.2 Water-level measurements

The first step in the elaboration of a piezometric map of the aquifer was to obtain field measurements of the depth to the water table. This was done by introducing an electric water-level probe in a total of 80 piezometers, or observation wells, installed at or near CFB Shilo. This instrument consists in a graduated cable with two electric conducers; one end of the cable is linked to an electrode, the other to a battery. When the electrode gets in contact with water in the well, the electric circuit is closed, turning on a lamp and a whistle. The depth to the water table from a specific datum (top of PVC tubing) is then recorded and subsequently substracted from the elevation of this datum to obtain the elevation of the water table at a given location. The water-level probe has a precision of ± 0.5 cm.

The second step in designing the water table map was to interpolate the available water table elevation data, along with estimated elevations of the water levels of Sewell Lake, Epinette Creek and the Assiniboine River using the software Surfer 7.0.

3.3.2.3 Groundwater velocity and direction

Measurements of the horizontal component of groundwater velocity and direction were made *in situ* with a flowmeter (Geoflo 40L) in the developed observation wells. The Geoflo 40L is a probe with eight thermistors placed around a heat source (Ampleman et al., 2003 : 19). The probe is introduced in a well below the water level; a heat pulse is generated after enough time is elapsed for the water to become still. The instrument measures the propagation and the deformation of the heat pulse in groundwater. In dynamic systems like an aquifer, the heat pulse propagates with an elliptic shape, and the long-axis is oriented in the groundwater flow direction. The length and the orientation of this axis can be calculated with usual trigonometric formulas. The resultant vector is fitted on a calibration curve made in the laboratory using sand from the aquifer to obtain the groundwater velocity. Geoflo measurements were also performed in studies similar to this one (Boutin, 2003). However, recent investigations with the Geoflo on other military bases suggest that the instrument performance in terms of velocity and direction measurements may not be as accurated as previously thought, at least not under all hydrogeological conditions (René Lefebvre, personal communication, 2005). Geoflo performance thus needs to be further investigated.

Interpretation curves and calculations are available in document S5 on the CD. Results were compared with the piezometric map.

3.3.2.4 Hydraulic conductivity determination

Hydraulic conductivity was estimated with two different methods: grain-size analysis and slug tests.

Subsurface soil samples used for grain-size analysis were collected with a 51-mm split spoon (60 cm long) at a depth corresponding to the middle of the screen interval. Samples were collected in 73 well locations throughout CFB Shilo and dried in an oven at 45 °C. The grain size of the sand fraction was determined in three steps : sieving, laser particle analysis and calculation.

The soil fraction was shaken through a series of eight woven wire cloth sieves of decreasing size (ASTM E-11-70 standard sieves: 8 mm, 4 mm, 2 mm, 1 mm, 0.50 mm, 0.25 mm, 0.125 mm and 0.063 mm) with a high speed mechanical stirrer. Some of the samples were divided in quarts with a sample splitter (Quart Carpco Inc, model SS-16-13) when sand fractions were too big for the sieves.

The resulting fine fraction (below 63 μm) was then analysed with a laser particle size analyser (Analysette 22 by Fritsch). The measuring range selected was 0.44 *u*m to 63.31 *u*m. The technique consists in adding a small quantity of fines to a flow cell filled with water and targeted with a laser beam. The diffraction and the diffusion pattern of the laser beam provides information about the size of particles. Data obtained from sieving and laser analysis were analyzed with the software Gran V 1.01 created by Eric Boisvert at the GSC-Québec. Grain-size distribution was plotted on semi logarithmic paper. Interpretation curves are presented in document S7 on the CD.

Finally, the Hazen formula was used to estimate the hydraulic conductivity of the sand samples. This formula uses the effective diameter d_{10} (corresponding to the granulometric fraction for which 10% of particules are finer) according the following relationship (Freeze & Cherry, 1979) :

$$K=A(d_{10})^2 \qquad \text{(equation 3.1)}$$

Where d_{10} is measured in mm, A is 1 and K is expressed in cm/s.

This formula was established using linear regression and its validity is limited only to a range of sediments type (Gélinas and Therrien, 2001). The criteria are a) 0.1mm < d_{10} < 3mm and b) uniformity coefficient ($Cu = d_{60}/d_{10}$) < 5. All samples are very similar to one another and a representative sand sample (ATR-1) is used to illustrate that the two validity criteria are met. For this sample, d_{10} is equal to 0.18 mm and the uniformity coefficient is equal to 2.24. Grain-size curves and calculations results are presented in document S7 on the CD.

Air injection slug tests were also performed in 71 observation wells in 2000 and 2001 to estimate the hydraulic conductivity of the sand formation; 2-3 tests were usually performed in each well to verify the reproductivility of test results, for a total of 152 tests. This pneumatic method is described by Levy and Pannell (1991). During the tests, compressed air is injected in the well casing with an injection device equipped with a pressure gauge. Air injection artifically creates a loss in hydraulic head, lowering the water table some 30-70 cm below its static water level. Pressure is then released instantaneously through a release valve. A pressure gauge (Level Logger from Solinst) previously installed well below the water table records the drawdown and rate of recovery of the water table. A different method involving the removal of water from the well with a bailer was used in a limited number of wells. The Bouwer & Rice method (1976) was used to analyze the recorded data and estimate hydraulic conductivity. The same method was used to evaluate hydraulic conductivity in a sand aquifer at Canadian Forces Base Valcartier in Québec and is described in Boutin (2003 : 22-24). Interpretation results for slug tests are provided in document S8 on the CD.

Hydraulic conductivity estimates from grain-size analysis and slug tests are presented in section 3.5.2. Upper and higher values are presented, as well as the geometric mean. The use of the geometric mean is more appropriate than the arithmetic mean in this case because hydraulic conductivity distribution is skewed to the right. Geometric mean is less affected by extreme values than arithmetic mean and is therefore more useful as a measure of central tendency for skewed values.

3.4 Geology

CFB Shilo is located in the Western upland physiographic division of Manitoba, in the Upper Assiniboine Delta sub-division (Province of Manitoba, 1976). Stratigraphic information from boreholes revealed that geological units underlying the military base, from bottom to top, are as follows: bedrock, dense, matrix-dominated till, glaciolacustrine silty clays and silts, deltaic sands, aeolian sands. A stratigraphic cross-section schematically showing the geological layers overlying the bedrock is presented in Plate 3 (Appendix E) and the surficial geology map is presented in Plate 4 (Appendix F).

The bedrock underlying CFB Shilo is composed of Mesozoic shales of the Cretaceous and Jurassic periods (Burton et Ryan, 2000). These soft clay shale formations are of very low permeability (Province of Manitoba, 1978 : 2). They are almost entirely part of the Vermillon River formation, which comprises the Pempina and Gammon Ferruginous Members, the Boyne Member and the Morden Member (Province of Manitoba, 1976). Some are part of the Favel formation. Hard, fractured shale can also be found in the southwest corner of the aquifer, south of the study area (Province of Manitoba, 1978 : 2). A bedrock channel is found in the north of the area and is filled mainly with till and some sand and gravel (Province of Manitoba, 1977).

Surficial sediments overlying the bedrock vary in thickness from 55 to 115 m under CFB Shilo (Province of Manitoba, 1976). Glacial grey till forms the lowest layer of surficial deposits, resting directly on the bedrock. It was deposited during the Wisconsin glaciation. Sand and gravel layers and lenses may be found within this unit, whose thickness vary from 0 to 75 m under the ADA (Province of Manitoba, 1977 : 2). An extensive and thick glacialocustrine clay and silt layer of proteltaic origin, rests over the till. Its thickness varies from a few cm to 25 m thick or more under the aquifer. Lenses of sand and gravel deposits may also occur in this layer. The silt and clay layers may be missing in some locations due to erosion prior to the deposition of the topset layer (Province of Manitoba, 1977).

The silt and clay deposits are overlain by a thick surficial fine to coarse sand layer that varies in thickness from a few meters to 30 m in the area overlying CFB Shilo. This layer forms the Assiniboine Delta Aquifer, an extensive sand and gravel deposit extending over a 3885 km^2 area. The deltaic sands covering most of the base belong to the Stockton sand formation; they are finely-textured, loamy sands, where sand dunes have developed. Miniota sands found to the south and east of the base are coarser and derived from glacio-fluvial outwash (Anonymous, 1984).

CFB Shilo is located over the southwestern portion of the Assiniboine Delta Aquifer. ADA sediments were deposited during the last deglaciation at an elevation of about 375 m above sea level (ASL). During this period some 12 000 years ago, ancient post-glacial Lake Agassiz lied in a depression in the glacial till that overlay the shale bedrock. A large portion of Manitoba Lowlands were covered by Lake Agassiz as the retreating ice sheets formed a barrier to drainage into the Hudson Bay. The old Assiniboine River, then a large glacial river, drained in a large bay of post-glacial Lake Agassiz just south of present day Brandon and is responsible for the deposition of the sediments which now form the Assiniboine Delta Aquifer. The sand fanned out eastward at a point located just east of Brandon. A meltwater delta that extends almost to Portage la Prairie was formed, with its apex at the eastern edge of Brandon (Figure 3.2). The depositional history of sediments in the ADA explains the presence of coarse gravel deposits near Brandon, with sediments generally turning into coarse, medium and fine sand in a general eastward direction as distance from the apex of the delta increases. However, the frequent rearrangement of the distributory channels of the old Assiniboine river and changes in river flow resulted in heterogeneity in the grain-size and thickness of deposits.

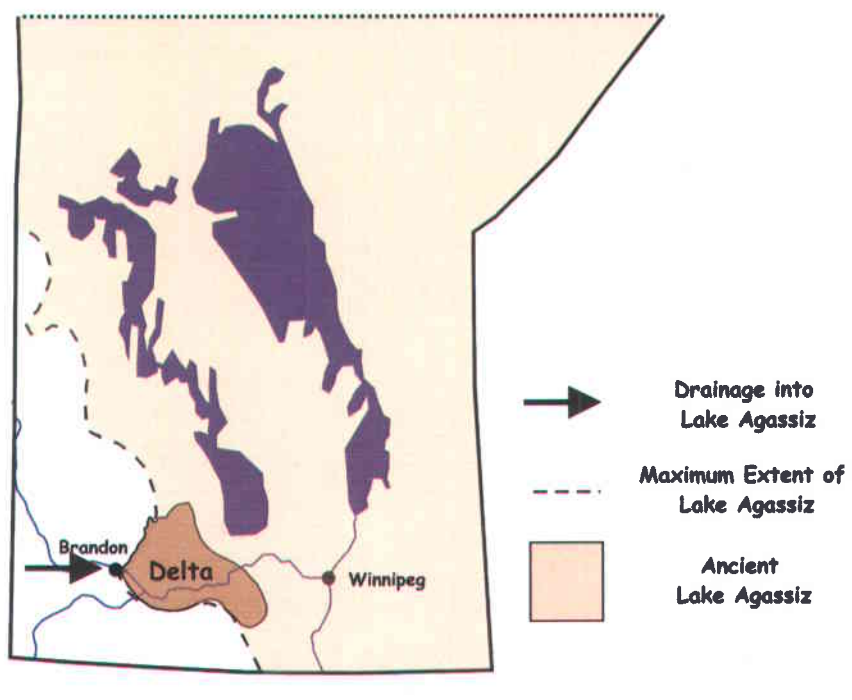


Figure 3.2 Schematic representation of the formation of the Assiniboine Delta Aquifer. The figure was inspired from the Community Atlas of Brandon. (http://www.brandonsd.mb.ca/CCATLAS/default.HTM)

Surficial geologic mapping surveys carried out at CFB Shilo showed that the base is entirely underlain by thick sandy sediments (Plate 4, Appendix F). This deltaic sand is medium to coarse-grained with an observed thickness ranging from 15 m in natural sections on the banks of the Assiniboine River to as much as 36 m in the built-up area of the base. Interbedded and intermixed clay, silt, sand and gravel deposited as alluvium can be found along the banks of the Assiniboine River.

Most of the surface of the deltaic sands has been reworked extensively by wind activity and exhibits aeolian features such as composite parabolic dunes. Prevailing northwest winds structured the dunes in a series of north-west-southeast trending dune ridges (Kerr and Welsted, 1978). Active sand dunes are found in Spruce Woods Provincial Park, a protected area adjacent to CFB Shilo. These medium to fine-grained sands are hence commonly finer-grained than the underlying deltaic sands. Composite subsurface samples collected with a split-spoon during borehole drilling reveal an average composition for soils of 88% sand, 6% silt, 6% clay and 1% organic carbon (Ampleman et al. 2003). The sand percentage is consistent with Render's estimate (Render, 1988 : 20), who reports percentages of silica ranging from 75% in the west of the aquifer to 95% or more in the east. Subsurface investigations also revealed the presence of several discontinuous organic layers, which form paleosols or buried peats of Holocene age. Peat and other organic deposits overlay the sand unit in the vicinity of Douglas Marsh, Sewell Lake and Epinette Creek

3.5 Hydrogeology

3.5.1 Aquifer Description

With an area of 3885 square kilometres, the sand and gravel drop-shape ADA constitutes the most important aquifer feature in the area. Given the strong agricultural vocation of the region, it is widely used for irrigation. It also meets domestic needs of CFB Shilo and a number of small towns and settlements, as well as local industrial needs (mainly potato processing).

The ADA is developed within the combined aeolian and deltaic sand layers, which form a single hydrogeological unit. As previously mentioned, the thickness of the sand layer under CFB Shilo varies generally from 15 to 36 m, the thickest portions being near the residential part of the base. Saturated aquifer thickness generally follows a similar trend. The thickest portions of the aquifer are found between Aachen and Essen battleruns while the aquifer becomes very thin near the

Assiniboine River. Render (1988) reported aquifer thickness of 6 to 27 m in the Assiniboine West sub-basin, with a mean saturated thickness of 18 m.

The vadose zone follows an opposite pattern: it generally increases from a few meters in the northern part of the base to 25 m under the plateau leading to the abrupt cliffs of the Assiniboine River valley.

The aquifer is almost entirely unconfined except for thin silt and clay layers overlying limited areas of the aquifer out of CFB Shilo (mostly in northern portion of the aquifer) and for swampy areas in the vicinity of Epinette Creek. Because of its direct exposure to the surface environment and its low content in organic material resulting in a low retardation factor, the ADA can be considered as vulnerable to groundwater pollution. In the past few years, increasing water demand for irrigation and economic development have led to concerns about potential contamination and overuse of the resource. These concerns led to the development of a management plan for the Assiniboine Delta Aquifer by the Manitoba Ministry for Natural Resources (now Manitoba Conservation) and local stakeholders. Principles to protect and allocate water supply were defined and are a key component of a sustainable management strategy for the aquifer. This process was overseen by an Advisory Board under the responsibility of the Manitoba Minister for Natural Resources and integrated by representatives from public institutions, the private sector and public interest groups. The Advisory Board was assisted by a Technical Steering Committee and consultation with stakeholders and the public were held at various moments during the process (Assiniboine River Management Advisory Board, 1997).

Previous hydrogeological investigations allowed for the division of the Assiniboine delta aquifer into 13 sub-basins (Figure 3.3). Most of CFB Shilo's territory is located within the Assiniboine West, with its northern part lying in the Epinette Creek sub-basin. Total development yield for the Assiniboine West sub-basin is 8256 acre-ft/y (10 184 760 m^3/y), with an allocation limit of 4128 acre-ft/y (5 092 380 m^3/y). One hundred percent (100%) of this limit is already allocated (Little and Bodnaruk, 2001).

Characteristics of the aquifer such as transmissivity, specific yield and storage were estimated in previous investigations. Render (1988) presented estimates for transmissivity varying from 0.03 m^2/s in the southwestern segment of the aquifer to 0,0007 m^2/s along its eastern edge. For specific yield, reported values are 0.1 to 0.29 (Render, 1988) and 0.11 to 0.39 (Frost and Render,

2002) Storage coefficient estimates are in the range of 0.0007 to 0.01 (Render 1988) and 0.0006 to 0.001 (Frost and Render, 2002).

In the overall aquifer, well yields range from 1 to 75 L/s, which is considered adequate for high capacity wells (Province of Manitoba, 1978 : 6, 9). Isolated sand and gravel lenses interbedded in the alluvium of the Assiniboine River may also yield moderate amounts of water, from 1 to 10 L/s, or more when they are recharged by the river (Province of Manitoba, 1978 : 6).

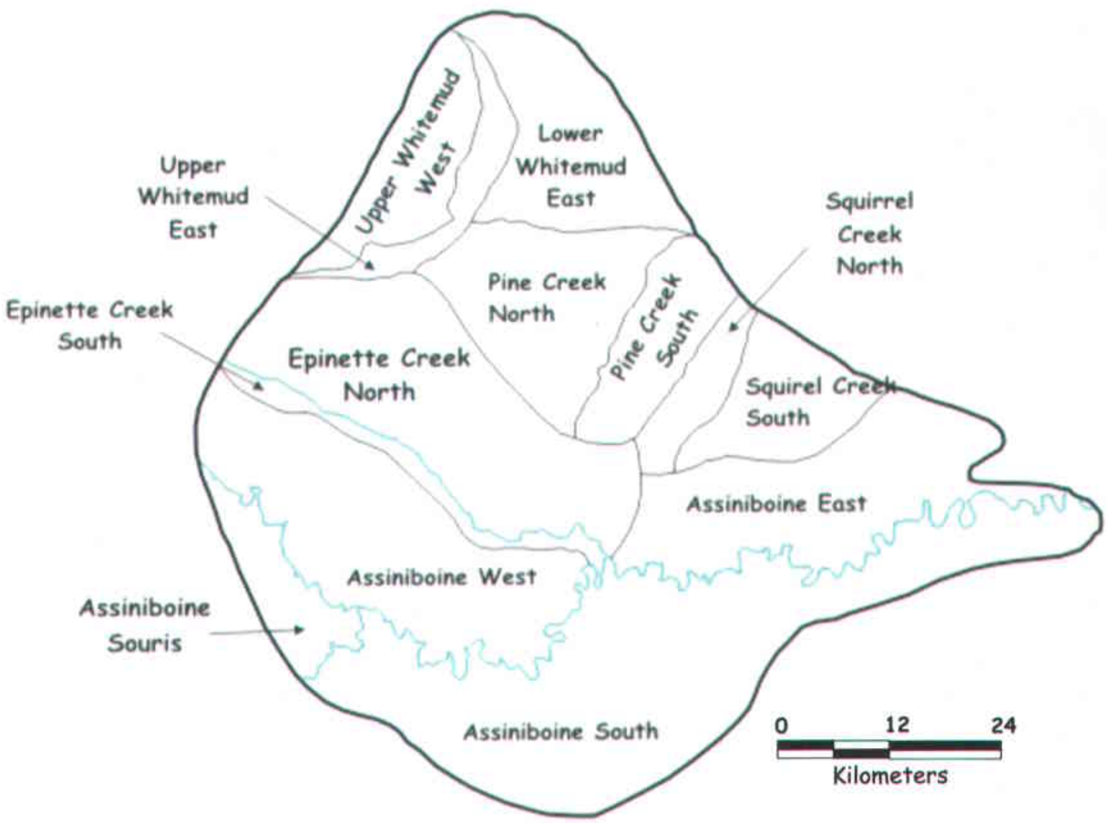


Figure 3.3 Assiniboine Delta Aquifer sub-basins. Figure derived from Manitoba Conservation figures published in various reports and articles.

The important contribution of the aquifer to the base flow of the Assiniboine River should be mentioned. Groundwater discharge areas are common along the river banks. The aquifer is recharged mainly through precipitation.

3.5.2 Hydraulic conductivity

Hydraulic conductivity (K) can be defined as "a coefficient of proportionality describing the rate at which water can move through a permeable medium" (Fetter, 1994 : 641). In other words, it measures the ability of a medium to transmit water. It is a function of both the porous medium and the fluid flowing through this medium, as indicated by equation :

$$K = \frac{\mu k}{\rho g} \qquad \text{(Equation 3.2)}$$

where μ is the water dynamic viscosity (Pa.s), k is the intrinsic permeability (m^2), ρ is the water density (kg/m^3) and g is the acceleration of gravity (m/s). The intrinsic permeability is affected by physical characteristics of the medium such as the size and shape of the pores and their interconnections.

Estimating hydraulic conductivity is an important aspect of any hydrogeological study because of the influence of this aquifer property on groundwater movement. As previously mentioned, hydraulic conductivity was estimated from field data using two different methods: grain-size analysis and slug tests.

Grain-size analysis performed on subsurface soil samples indicated a grain size diameter that varied from 0.4 μm to 8 mm, although particles smaller that 1 μm or larger than 1 mm typically represented respectively less than 1% of the samples. A typical grain-size distribution for sand samples collected at CFB Shilo (ZONE – 5S) is as follows:

- Clay and silt (< 63 μm) 2 %
- Very fine sand (63 – 125 μm) 2 %
- Fine Sand (125 –250 μm) 12 %
- Medium Sand (250 – 500 μm) 65 %
- Coarse Sand (500 μm – 1 mm) 19 %
- Very Coarse Sand (1 – 2 mm) > 1 %
- Pebbles (> 2mm) > 1 %

The median grain-size diameter of the majority of soil samples is generally between 250 and 500 μm, which corresponds to medium sand, although a number of samples reveal the presence of fine and coarse sand in some locations. Table 3.1 presents hydraulic conductivity estimates for CFB Shilo based on grain-size analysis and slug tests.

Table 3.1 Hydraulic conductivity estimates for the sand layer at CFB Shilo

Methodology	Number of samples / tests	Highest Value (m/s)	Lower Value (m/s)	Geometric Mean (m/s)
Grain-size Analysis	74	$1.35x10^{-3}$	$7.31x10^{-9}$	$1.37x10^{-4}$
Slug Tests	152	7.38×10^{-4}	2.56×10^{-5}	1.36×10^{-4}

The estimated geometric mean hydraulic conductivity of the sand formation, established from 74 subsurface samples with the Hazen formula based on the d_{10} of the grain-size curves, was 1.37×10^{-4} m/s (1.35×10^{-3} m/s to 7.31×10^{-9} m/s). Estimated hydraulic conductivity obtained from slug tests (152 tests performed in 71 wells) varied between 7.38×10^{-4} m/s and 2.56×10^{-5} m/s, with of a geometric mean of 1.36×10^{-4} m/s. Tests performed successively in the same wells yielded similar results. Slug test results are thus in agreement with those established with the Hazen formula based on the d_{10} of the grain-size curves. A summary table of all grain-size analysis and slug test results is presented in Appendix G.

A higher level of confidence is associated with slug test values because it is a direct measurement and also because the zone influenced by a slug test is much larger than the size of a sample collected for grain-size analysis. Laboratory-size samples collected for grain-size analysis may reflect local heterogeneities, such as clay or gravel lenses known to occur in the aquifer, as indicated by drilling logs, whereas the slug test would encompass a larger area, thus limiting the odds that the test be influenced only by local heterogeneities. This could explain the broader range of K values obtained from grain-size analysis as opposed to those measured from slug tests, as illustrated in Figure 3.4 below.

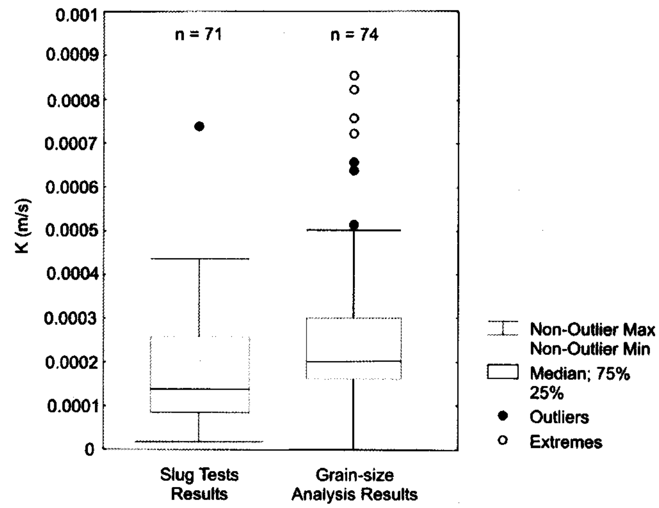


Figure 3.4 Box plot illustrating the broader range of values estimated using grain-size analysis as opposed to measurements with slug tests. However, in spite of these differences, the bulk of samples fall within the same range and the median value is similar (0.00014 for slug tests and 0.0002 for grain-size analysis). The geometric mean value is almost the same for the two methods: 1.36×10^{-4} m/s for slug tests and 1.37×10^{-4} m/s for grain-size analysis.

An attempt was made to correlate hydraulic conductivity values calculated with the two methods presented above (Figure 3.5).

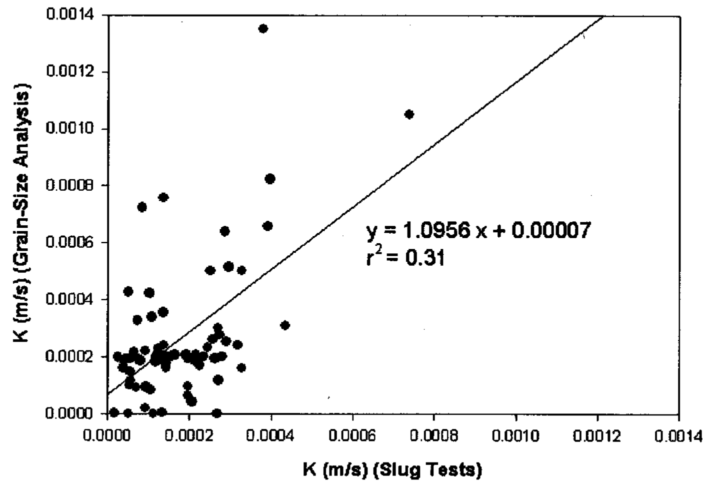


Figure 3.5 Correlation between K measurements obtained with two different methods. There is poor correlation between hydraulic conductivity values obtained from two different methods: slug tests and grain-size analysis. The soil material collected or affected by the tests always originated from the same location: the depth of the screen interval.

However, no significant correlation was found (r^2 = 0.31). This is an indication of the heterogeneity of the sand material at a small scale and reinforces the conclusion that slug tests results should be more reliable as they provide a direct measurement of K and capture a bigger volume of sand material than grain-size samples.

Hydraulic conductivity values estimated from field data fall in the range of values quoted in the literature. For example, Anderson and Woesner (1992 : 40) estimated the ranges of values for the hydraulic conductivity of fine to coarse sand at 5,8 x 10^{-6} m/s to 1.1 x 10^{-3} m/s. Estimates by Freeze & Cherry (1979) vary from 1 x 10^{-7} m/s to 0.02 m/s. K values estimated from field data may thus adequately represent field conditions. Field estimates are also similar to hydraulic conductivity values previously measured on the Assiniboine Delta Aquifer. Frost and Render (2002) reported values ranging from 2.3 x 10^{-3} m/s to 1.4 x 10^{-3} m/s (205 to 123 m/d) in the Shilo area. Render had previously reported hydraulic conductivity values of 3.8 x 10^{-3} m/s to 1.4 x 10^{-3} m/s (328 to 123 m/d) in the Shilo area and of less than 4.6 x 10^{-5} m/s (4 m/d) along the eastern fringes of the aquifer (Render, 1988).

The distribution of hydraulic conductivity values obtained from slug tests is represented below (Figure 3.6). The mean hydraulic conductivity of 1.4 x10^{-4} m/s indicates that the aquifer is highly permeable. However, hydraulic conductivity is not homogeneous throughout the aquifer but tends to decrease in an eastward direction. This eastward trend can be associated with the finer grain size of sand particles as the distance from the mouth of the postglacial deltaic delta increases (see Figure 3.2). The first map of hydraulic conductivity distribution was obtained by kriging using a linear variogram model and a small nugget effect. This model yielded the most realistic representation of hydraulic conductivity at a regional scale with the fewest bull-eyes (caused by the high variability of some adjacent samples). An exponential variogram model was used to generate the second hydraulic conductivity distribution.

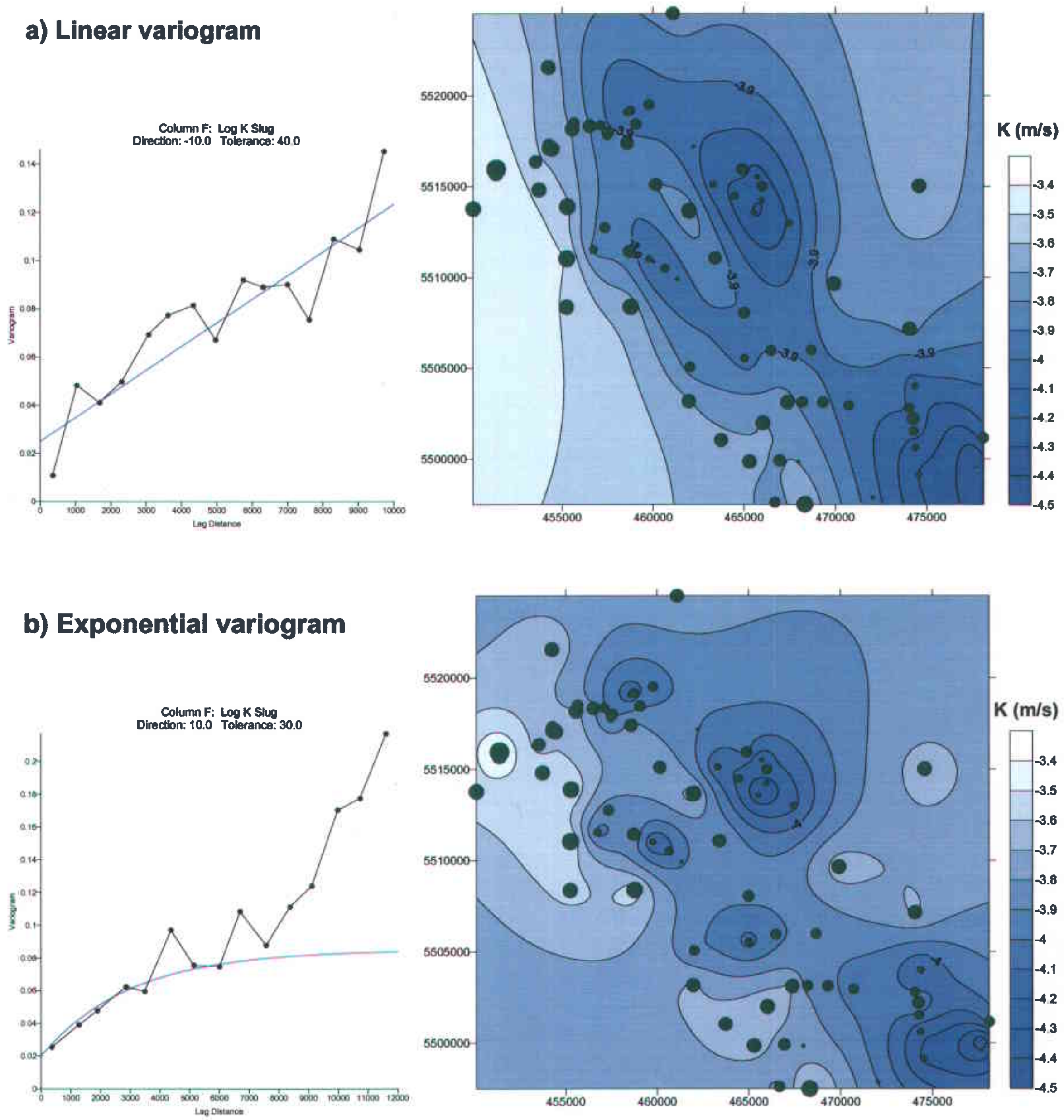


Figure 3.6. Hydraulic conductivity log distribution: linear and exponential interpretations. Slug tests results were used to produce this map. The software Surfer 7.0 was used. Circles represent slug tests locations and are proportional to log K.

Finally, hydraulic conductivity was also estimated for the glacio-lacustrine formation (sandy clay) from grain-size analysis using 8 samples collected in silt lenses during borehole drilling. Estimated K values vary from 8.9×10^{-9} m/s to 8.0×10^{-8} m/s, with a geometric mean of 8.7×10^{-9} m/s. These low values are an indication that the silt/clay layer can be legitimately considered an impermeable barrier to groundwater flow in the model developed in chapter 5.

3.5.3 Groundwater flow

Water level measurements were performed in a total of 79 observation wells over a three-year period. These data were converted to water table elevations and were used to produce a water table map of the portion of the unconfined aquifer underlying CFB Shilo.

Figure 3.7 illustrates the distribution of water table elevation measurements from 2000 to 2002. These elevations range from 332 to 377 m. Water level elevation measurements are presented in Appendix D. As can be observed on Figure 3.8, the difference between water level measurements performed over a one year interval is relatively constant for all wells. This is an indication that water level measurements were done adequately every year. When the difference in water level between two years for a well was significantly different than the average difference for the other wells, the data was circled in figure 3.8 and was used with caution in the preparation of the water table map presented in figure 3.9.

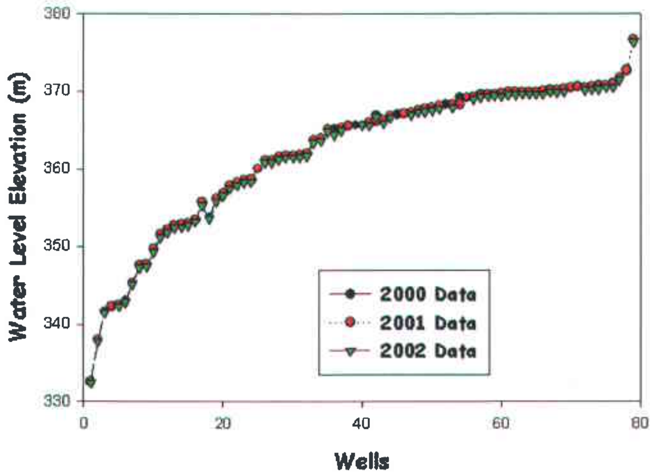


Figure 3.7 Distribution of water table elevation measurements in observation wells at CFB Shilo from 2000 to 2002. This figure also shows that observation wells were located in such a way that water level measurements were available regularly over the entire hydraulic gradient in the study area.

As illustrated in figure 3.8, the water table remained relatively stable between September 2000 and September 2001, showing a slight average decrease of 0.03 m. A more pronounced decrease in the level of the water table was observed between September 2001 and September 2002 with an average of - 0.32 m. The summer of 2002 was particularly dry in the Prairies region.

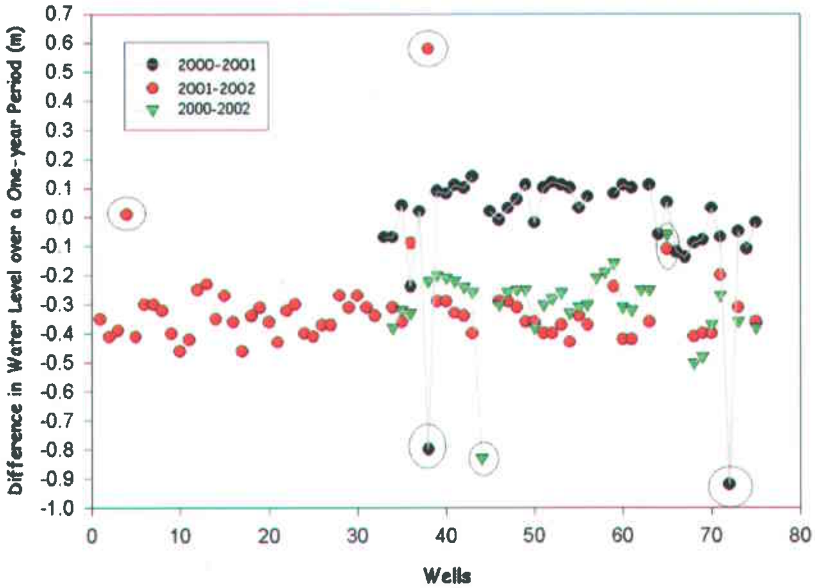


Figure 3.8 Difference in water level between yearly measurements

The topography at CFB Shilo is generally flat, with a gentle southward slope towards the Assiniboine River. This slope ends abruptly on the northern banks of the Assiniboine river as it reaches the drainage valley of the river, leading to a cliff. Sand dunes are an important feature in the eastern portion of CFB Shilo as well as in the neighbouring Spruce Woods Provincial Park eastward of the base.

A detailed water table map of the aquifer is presented on Plate 5 (Appendix H). Each line represents a constant hydraulic head, in the same way as contour lines on a map represents surfaces of constant elevations. Piezometric contours were drawn using water level elevations measured in observation wells. Elevations of surface water bodies and rivers were estimated from a topographic map. A small number of manual control points were added in areas void of measurements based on best judgement in order to obtain a more realistic representation of the water table surface. For example, wells installed in the southeastern portion of the base indicated that the hydraulic gradient increases slowly as groundwater flows towards the Assiniboine River , until a "breaking point" where the water table drops abruptly as the aquifer gives rise to seepage faces along the Assiniboine cliffs. Water levels measurements were not available near the southwestern border of the modeled area and were estimated based on the similarity of topography and hydraulic gradient between this area of the model and that located to the southeast. Elevation data were interpolated by kriging. A linear interpolatin scheme provided the most realistic representation of piezometric lines (Figure 5.9) . A contour map of the portion of the aquifer represented in the groundwater flow model (chapter 5) is presented in figure 3.9 below.

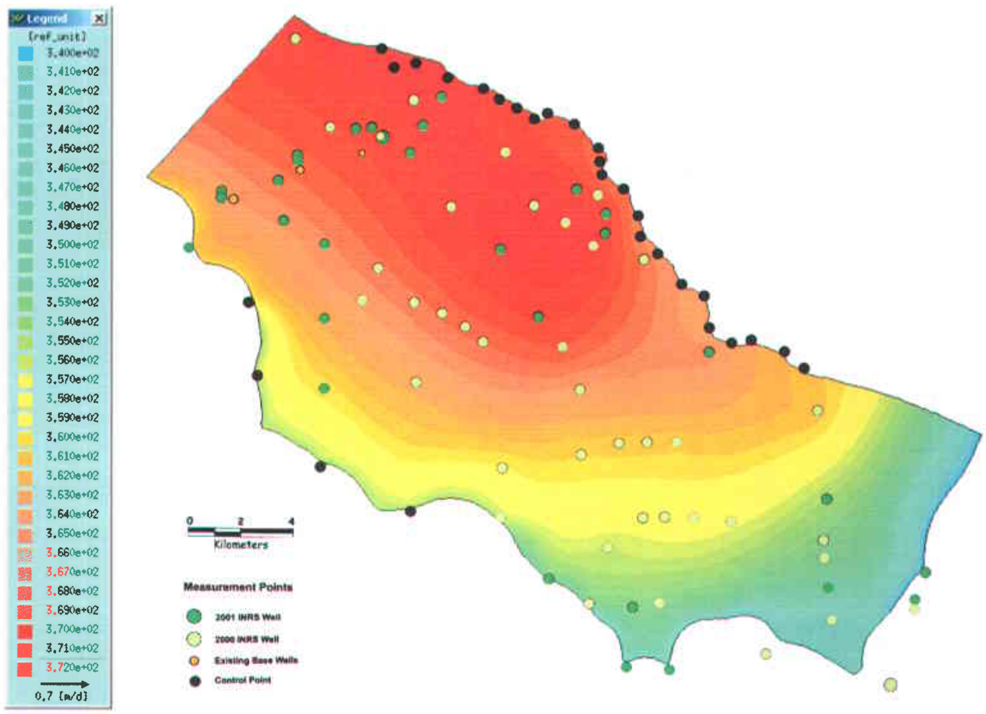


Figure 3.9. Water table map of the unconfined sand aquifer over the modeled area (2002 data). See also Plate 5 (Appendix H). The water table map on figure 3.9 was drawn with Feflow and covers only the modeled area; the only data used were those collected by the INRS-ETE team (consistent methodology for all wells and precision up to 0,01), except for 4 control points. The INRS-ETE data are the only data that were used to compare measured versus simulated water elevations in chapter 5. On the other hand, the water table map presented on Plate 5 was drawn with Surfer 7.0 and covers a slightly bigger area extending to the Assiniboine River. A few more control points were thus used in Plate 5 in the southeastern section of the map. It should be noted that Manitoba Conservation water elevation data (from a Manitoba Conservation database) were also used to draw the map on Plate 5 as the objective of this map is to give a general idea of the water elevation distribution in this section of the aquifer.

As observed on Plate 5 and on figure 3.10, the groundwater drainage pattern is generally consistent with surface topography and is influenced by the surface drainage system that includes two watersheds: Assiniboine and Epinette. Most of the groundwater at CFB Shilo flows in a radial pattern, to the southwest, south and southeast and discharges into the Assiniboine River. The hydraulic gradient increases abruptly as the water table reaches the cliffs on the north banks of the Assiniboine River, creating seepage faces.

A notable feature of the water table map is the presence of a local high to the south of Epinette Creek (groundwater divide). The fact that two wells seem to give rise to this elevation in the groundwater table suggests that this feature may not be due to measurement errors, although this possibility is not discarded. As will be seen in chapter 5, an elevation in the till and silt layers underlying the aquifer may influence the patters of groundwater flow in this area.

Another interesting characteristic of drainage in this area is the presence of a groundwater divide. A small portion of the aquifer thus drains into Epinette Creek. The groundwater divide is probably due to the presence of a high sand ridge that extends a few hundred of meters to the south of Epinette Creek along most of its course. This groundwater divide appears at the mouth of Epinette Creek but does not seem to extend further north near Sewell Lake, where regional flow aims directly at the Assiniboine River. It is not clear indeed whether the drainage towards Epinette Creek consists in a surficial local drainage system overlying a regional system that drains towards the Assiniboine River.

Groundwater flow velocity and direction are influenced by several factors, including hydraulic conductivity, porosity and hydraulic gradients. They were measured at various observation well locations with a Geoflo and were overlaid on a water table map on Plate 6 (Appendix I). Results are presented in document S9 on the CD. Two measurements were made in each observation well and the mean value was reported on the map. However, when the difference in flow direction between the two measurements exceeded 65°, the mean result was not considered reliable enough and is represented by a red arrow. All other results are represented with black arrows. Generally speaking, most groundwater flow directions measured with a flowmeter are consistent with the piezometric map.

Arrow lengths on Plate 6 are proportional to groundwater flow velocity. According to Geoflo measurements, groundwater velocities range from 111 to 986 m/y, with a mean velocity of 255 m/y (average) or 217 m/y (geometric) and a median velocity of 183 m/y. These values were compiled using only validated results (black arrows). Average linear groundwater velocity can also be calculated using Darcy's law (Gorelick et al., 2000 : 83). The following parameters were used: average hydraulic conductivity estimated from slug tests (1.4×10^{-4} m/s), the horizontal hydraulic gradient from the water table map (0.0006 to 0.009 in the model, with 0.00145 as a typical value) and an estimated effective porosity (n_e) of 0.25 (typical of medium sand). These values were introduced in equation 3.2

$$V = \frac{K\,i}{n_e} = \frac{K\,dh}{n\,dl} \qquad \text{(equation 3.2)}$$

Groundwater velocities calculated with this method are smaller than those measured with the Geoflo. Estimated velocities vary between 10 to 159 m/y and a typical value would be 26 m/y. It should be noted that Geoflo results should be considered with caution. Although most flow directions estimated from Geoflo measurements at CFB Shilo are generally consistent with those derived from the piezometric map, various recent experimentations in different field conditions by INRS-ETE researchers indicate that the Geoflo may not be as accurate as previously thought (for both groundwater velocity and direction).

Groundwater flow velocities tend to increase with proximity to the Assiniboine River. The steep banks along the northern shore of the river create an abrupt topographical slope that results in a sudden increase in the hydraulic gradient, and consequently in groundwater flow velocity.

3.5.4 Groundwater chemistry

General physico-chemical characteristics of groundwater were measured *in situ* with a portable probe. These include: temperature, pH, conductivity, specific conductivity, salinity, redox potential and dissolved oxygen. Document S10 presents results for year 2000 to 2002. The discussion below relies only on 2002 data given the broader coverage of measurements compared to 2000 data and the increased confidence in the data as opposed to year 2001 where some problems were experienced with the probes. Nevertheless, mean values and ranges of values are presented for all three years in Table 3.2. All measurements (2000 to 2002) were performed in the month of September.

Table 3.2 Mean values and ranges for various groundwater parameters measured *in situ* with a portable probe in 2000, 2001 and 2002.

Parameter	Temperature (°C)			Salinity (ppt)		
Year / Statistic	Mean	Range	n	Mean	Range	n
2000	9,44	4,90 – 12,60	43	0.2	0,1 – 0,4	42
2001	10,46	7 – 15,39	79	0.2	0 – 2.8	80
2002	8,87	7,05 - 13,10	76	0.19	0.10 – 0.38	76
Parameter	pH			Redox Potential (mv)		
Year / Statistic	Mean	Range	n	Mean	Range	n
2000	7,83	7,40-8,37	42	242	-331	42
2001	7,45	4,49 – 8,42	80	204	-288	79
2002	7,58	7,02 - 8,51	70	111	-345	70
Parameter	Conductivity (µS/cm)			Dissolved Oxygen (%)		
Year / Statistic	Mean	Range	n	Mean	Range	n
2000	291	227 - 536	41	73,10	14,70 – 126, 30	42
2001	277	19 - 652	77	67	1 - 127	81
2002	266	166 - 540	75	45	1 - 188	75
Parameter	Specific Conductivity (µS/cm)			Dissolved Oxygen (mg/L)		
Year / Statistic	Mean	Range	n	Mean	Range	n
2000	414	310 - 839	41	8,48	2,81 – 15,07	42
2001	432	163 - 958	35	8,46	0,17 – 49,20	80
2002	382	241 - 772	75	6,89	0,12 – 103,10	78

Shilo groundwater is characterized by a mean temperature of 8,87 °C, a neutral pH (mean 7,58), a low conductivity (mean 266 µS/cm) and a low salinity (mean 0.2 ppt). The redox potential averages of 111 mV, indicates an oxidizing environment.

A number of other parameters related to water quality were also analyzed in a laboratory: hardness, dissolved solids, sodium, nitrates, phosphates, iron and manganese. Results of laboratory analysis performed on groundwater samples collected in 2002 are presented in table 3.3 below.

Table 3.3 Mean and median values for various parameters obtained from laboratory analysis performed on groundwater samples collected in 2002. (1) CCME - GDW: Canadian Council of Ministers of the Environment Guidelines for Drinking Water

Location/ Parameter		Hardness as CaCo3 (mg/L)	Solids (TDS) (mg/L)	Sodium (mg/L)	NitrateNitrite-N (mg/L)	Phosphorus (mg/L)	Iron (mg/L)	Manganese (mg/L)
	CCME – GDW[1]	500	500	200	10	None	0.30	0,05
Background	Mean	278	272	4.63	1.95	0.02	0.46	0.33
	Median	280	250	4.07	0.48	0.02	0.17	0.14
	N	7	7	7	7	7	7	7
CFB Shilo	Mean	217	219	3.29	1.05	0.03	0.36	0.10
	Median	213	210	1.11	0.35	0.02	0.12	0.01
	N	65	68	69	68	69	69	69

Generally speaking, most of the mean parameter values presented in Table 3.3 are slightly higher in the background areas as opposed to CFB Shilo, except for phosphorus, whose concentration is similar in both areas. Higher values in background areas are probably due to the influence of agricultural activities on groundwater quality.

In the Shilo area, the average water hardness ranges from 149 to 310, with a median value of 213. Values under 500 mg/L are considered acceptable for domestic use. Dissolved solids concentrations vary from 150 to 490, with a median value of 210, well under the CCME aesthetic objective of 500 mg/L. Dissolved sodium concentrations are also low at CFB Shilo with a median value of 1.11 mg/L, as opposed to 4.07 mg/L in background areas. Irrigation may be responsible for the increased sodium concentrations in background areas.

CCME guidelines for drinking water state that nitrate-nitrogen concentrations should be below 10 mg/L. None of the samples collected during the entire project length showed concentrations exceeding this guideline. However, a limited number of samples showed concentrations in the 2-6,5 mg/L range, indicating a potential impact of human activities on the aquifer. Samples with higher nitrate concentrations were located both in background areas and on Shilo base, although it should be noted that high-nitrate content samples on CFB Shilo were almost all collected near the base residential area and agricultural fields.

Several samples showed iron and manganese concentrations exceeding CCME guidelines for drinking water. These results are consistent with the findings of several other groundwater monitoring studies carried out during the last decade (Canadian Forces, 1994 : 5) as well as with water analysis regularly carried out at the CFB Shilo treatment plant. Finally, anion concentrations are very low (usually below detection limits for carbonate, chloride and sulphate).

These data indicate that water is generally suitable for domestic and farm use, although iron and manganese concentrations may sometimes exceed guidelines for drinking water. Hydrogeological reports consulted for this project qualify groundwater quality in most of the aquifer, including CFB Shilo, as good to excellent.

As groundwater flows through aquifers, its composition is changed due to the interaction with different lithologic facies. An analysis of the proportion of major ions in groundwater samples was thus performed in order to determine the water type of the Assiniboine aquifer.

According to Fetter (1994 : 420), more than 90% of the dissolved solids in groundwater can be attributed to the eight following ions: Na^+, Ca^{2+}, K^+, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^- and CO_3^{-2}, and are usually present at concentrations exceeding 1 mg/L. At CFB Shilo, the major cations are Ca, Mg, Na and major anions are HCO_3, SO_4 and Cl.

A Piper diagram was used to represent the major ions and illustrate the water type. A Piper diagram is a trilinear figure in which major ion concentrations are plotted on the basis of the percent of each ion. Cations are plotted on the left triangle, anions to the one on the right. The apex of each triangle represent a concentration of 100% in one of the three ions (cations or anions). Relative cation and anion concentrations are plotted on the diamond-shaped figure between the triangles.

The following water types were established when taking into account all ions whose concentration exceeded 10% of molar ion concentration. A limit of 10% was chosen instead of the typical 20% value in order to identify minor variations in water quality in this relatively homogeneous aquifer.

Ca-HCO_3	29 samples
Ca-Mg-HCO_3	69 samples
Ca-Na-HCO_3-Cl	1 sample

The Piper diagram presented in Figure 3.10 indicates that the water type is predominantly Ca-HCO_3, with a small increase in Mg as groundwater flows towards the Assiniboine river. The only sample with a Ca-Na-HCO_3-Cl water type was collected in well MW-111, just downgradient of the active dump area at CFB Shilo. The high sodium and chloride concentrations are probably due to leacheates from the dump.

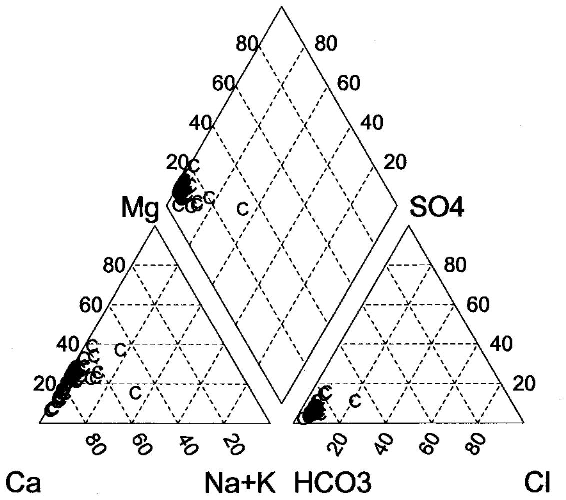


Figure 3.10 Piper diagram for groundwater at CFB Shilo

Metal concentrations in groundwater were analyzed; general statistics such as arithmetic and geometric mean, minimum and maximum values, number of samples exceeding CCME guidelines for drinking water of the background value + 2 times STD are presented in Appendix J.

Figure 3.11 below illustrates the distribution of concentrations for various metals in CFB Shilo groundwater. Trace elements found in concentrations below 0,016 mg/L are represented in the first graph. Other metals were found in higher concentrations and are represented in the second graph. Arsenic, barium and lithium concentrations are all below 0.1 mg/L. The same pattern is observed for aluminium, boron, strontium and zinc, although a number of samples showed concentrations up to 0.6 mg/L. The last graph includes the same metals as graph no 2, plus iron and manganese. It clearly illustrates that these two metals are predominant in CFB Shilo groundwater, with concentrations sometimes exceeding 1 mg/L.

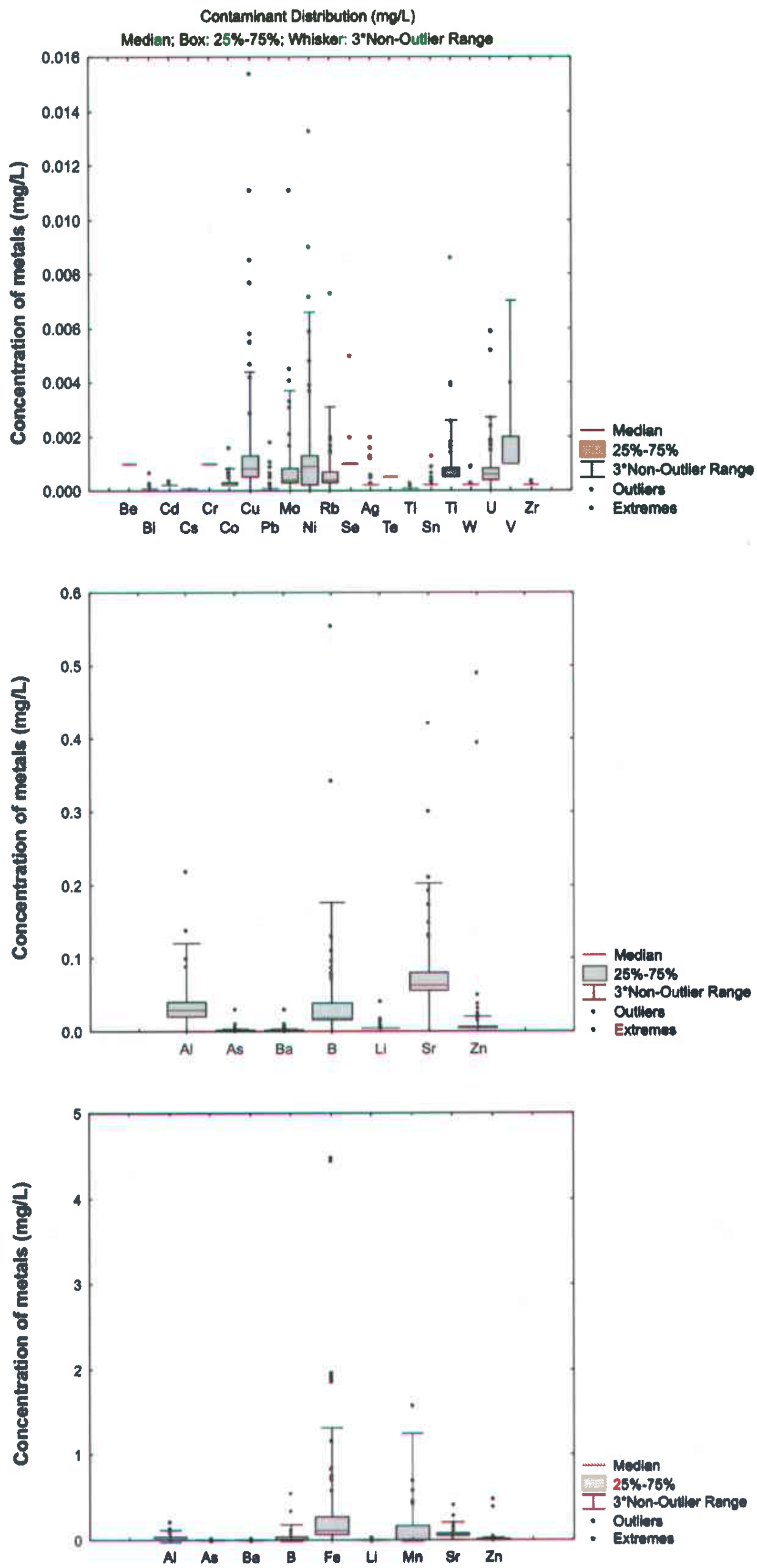


Figure 3.11 Distribution of metal concentrations in CFB Shilo groundwater

3.6 Surface water chemistry

The same physico-chemical characteristics as for groundwater were measured *in situ* with a portable probe in the three watercourses surrounding CFB Shilo: the Assiniboine River, the Souris River and Epinette Creek. Results are presented in document S10 on CD

The pH and salinity of surface water were higher than those of groundwater and varied respectively from 7.10 to 8.80 and from 0.2 to 0.6 ppt. Water temperature varied between 15 and 18 °C in September (except for a few measurements taken in October when T = 5 °C). Other parameters showed values higher than in ground water, including alkalinity, conductivity and total dissolved solids concentration. For the Assiniboine River, no tendency along the river course could be observed, and mean values for years 2000, 2001 and 2002 were respectively: alkalinity as HCO_3^- (289 mg/L, 298 mg/L, and 275 mg/L), lab conductivity (910 μohms/cm, 956 μohms/cm, 1016 μohms/cm), and total dissolved solids concentration (587 mg/L, 650 mg/L, 637 mg/L). The same parameters showed an increase along the course of Epinette Creek, starting from Sewell Lake, for all three years: alkalinity as HCO_3^- (195 to 410 mg/L, 211 to 395 mg/L, and 197 to 411 mg/L), lab conductivity (338 to 609 μohms/cm, 318 to 584 μohms/cm, and 329 to 603 μohms/cm) and total dissolved solids concentration (180 to 340 mg/L, 160 to 370 mg/L and 160 to 330 mg/L).

An analysis of water types was also performed on surface water. Only ions exceeding 20% of the total major ions molar concentration were taken into account. Samples whose cations concentrations were below 20% and more or less equal were considered of mixed type. Water types are as follows:

Assiniboine River	Mixed-SO_4/HCO_3
Sewell Lake	Mg-HCO_3
Epinette Creek	Ca-HCO_3
Souris River	Na-SO_4/HCO_3

These different water types reflect the different geological environments and human activities affecting the water courses. These water types are represented in a Piper diagram in figure 3.12 below.

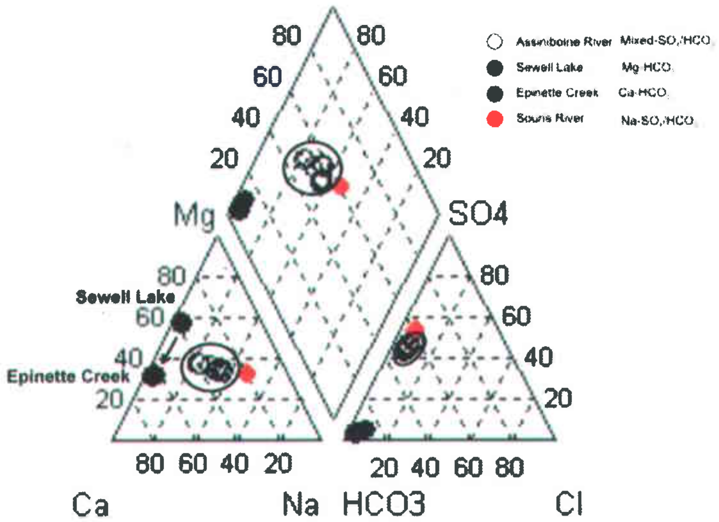


Figure 3.12. Piper diagram illustrating the water types of rivers and streams surrounding CFB Shilo.

The presence of chloride, an ion that was not detected in measurable concentration in groundwater, was detected every year in the Assiniboine River (25 to 39 mg/L) and in the Souris River (29 to 35 mg/L). The same is true for sulphate, detected every year in both rivers: Assiniboine (200 to 260 mg/L) and Souris (279 to 359 mg/L). However, chloride and sulphate were neither detected in Sewell Lake nor Epinette Creek, except for low sulphate concentrations at the southernmost sampling points on Epinette Creek in 2001 and 2002 (12 and 11 mg/L respectively). The presence of chloride and sulphate in the Assiniboine and Souris River could be linked to industrial and agricultural activities upstream. Sewell Lake and Epinette Creek, on the other hand, are taking their source in an extended marsh area north of the base which acts as a buffer zone.

IV ENVIRONMENTAL CHARACTERIZATION

4.1 Overview

This chapter presents the content of an article presented at the 4th Joint IAH-CNC/CGS Conference held in Winnipeg from 29 September to 1er October 2003 and published in its proceedings (Gauthier et al., 2003b). The article is entitled *Assessment of the impacts of live training on soil and groundwater at Canadian Forces Base Shilo, Manitoba.* Its main purpose is to analyse the results of the geochemical characterization of soils and groundwater at CFB Shilo.

For those who would like to consult the raw geochemical data, a number of Excel tables are available in the CD accompanying this thesis. These include:

S11 – Sampling schedule for years 2000, 2001, 2002
S12 – Results of groundwater analysis – Inorganics
S13 – Results of groundwater analysis – Organics
S14 – Identification of metal concentrations in groundwater exceeding CCME guidelines for drinking water
S15 - Identification of metal concentrations in surface water exceeding CCME guidelines for drinking water
S16 – Thorium analysis in groundwater
S17 – Thorium analysis in surface water
S18 – VOCs detected in groundwater

4.2 Abstract/Résumé

The environmental impacts of military training activities on soil and groundwater were evaluated during a 3-year characterization campaign at Canadian Forces Base Shilo, Manitoba. Geological and hydrogeological investigations highlighted the vulnerability to potential contamination of the underlying unconfined sand aquifer. High metal concentrations (Bi, Cd, Cr, Co, Pb, Mg, Ni, Zn) were detected in the soils of rifle and grenade ranges, as well as low concentrations of energetic materials in the grenade range and in battleruns. Groundwater analyses revealed no indication of aquifer contamination with metals or energetic materials. Finally, low thorium-232 concentrations

(below 2.5 μg/L) were found in groundwater in training areas. The presence of thorium-232 outside and upgradient hydrogeologically from some training areas remains difficult to explain.

L'impact des activités d'entraînement militaire sur les sols et l'eau souterraine a été évalué au cours d'une campagne de caractérisation de trois ans à la base de Shilo au Manitoba. Les travaux géologiques et hydrogéologiques réalisés ont mis en évidence la vulnérabilité à une contamination potentielle de l'aquifère libre sous-jacent. Des concentrations élevées de métaux ont été mesurées dans les sols des champs de tir d'artillerie et de grenade, de même que de faibles concentrations de matériaux énergétiques dans le champ de tir de grenade et les champs de bataille. Les analyses d'eau souterraine ne révèlent aucune évidence de contamination de l'aquifère par les métaux ou les matériaux énergétiques. Finalement, de faibles concentrations de thorium-232 (moins de 2.5 μg/L) ont été mesurées dans l'eau souterraine dans les sites d'entraînement. Cependant, la présence de thorium-232 en dehors et en amont hydrogéologique de certains de ces sites demeure difficile à expliquer.

4.3 Introduction

Environmental stewardship is a growing issue in Canada as the health consequences and environmental hazards associated with contaminated sites, and the costs for their remediation, become better known. The government of Canada has undertaken a major challenge consisting in the identification of the contaminated sites located on its properties. The efforts of the Ministry of National Defence were highlighted in the last reports of the Auditor General of Canada (2003) and of the Commissioner of the Environment and Sustainable Development (2002). In recent years, DRDC-Valcartier, in collaboration with INRS-ETE, has conducted several studies on various Canadian Forces Bases (Valcartier, Gagetown, Cold Lake, Shilo) to better understand the impacts of military training on the environment.

The objective of this study is to evaluate the potential environmental impacts of more than 60 years of Canadian troops training, including 20 years of joint training with German troops, at Canadian Forces Base Shilo (CFB Shilo), Manitoba. The approach used includes a geological study of the area, the characterization aquifer properties, the geochemical analysis of soils and groundwater and the modelling of groundwater and contaminant transport in the subsurface. This paper presents the results of a three-year characterization campaign carried out between 2000 and 2002. Descriptive maps and geochemical statistics describe the influence of military training activities on contamination patterns on training ranges. Results are presented by contaminant type (metals, energetic materials, thorium-232) and are associated with specific training activities that took place at CFB Shilo.

4.4 Site description and history

CFB Shilo is located 25 km southeast of Brandon, Manitoba (Figure 4.1). The 38 000 hectare base is located on a flat and predominantly treeless terrain covered by sand dunes in its eastern portion. Boundaries of CFB Shilo consist mostly of rivers and parks. The Assiniboine River erodes a broad deep valley along CFB Shilo's southern border. In the north, Epinette Creek rises from Sewell Lake and runs through a marsh until it meets the Assiniboine River. The fields of Cornwallis Rural Municipality serve as CFB Shilo's western limit and Spruce Woods Provincial Park borders its eastern portion.

The base is located on the Assiniboine Delta Aquifer (figure 1), a major regional unconfined aquifer covering 3885 km^2.

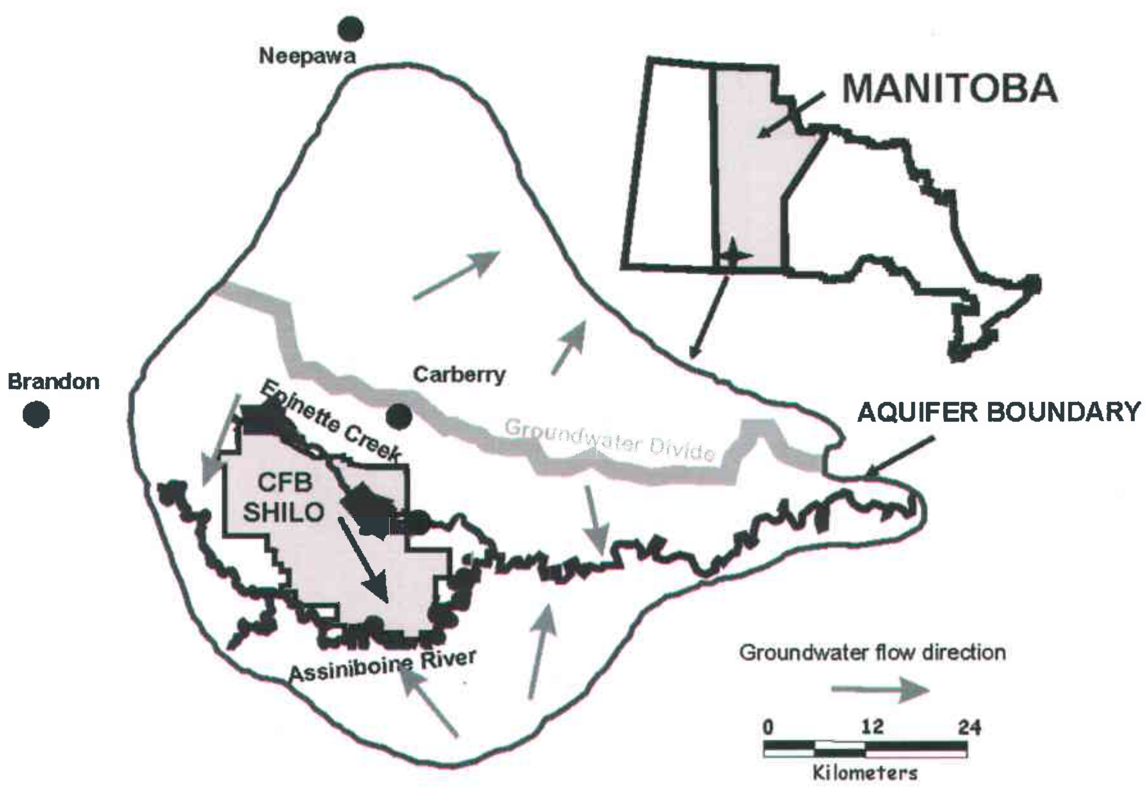


Figure 4.1: Location of the study area (Adapted from Render, 1988)

Groundwater from the aquifer is widely used for crop irrigation, domestic needs and as a drinking water source for the base. Coarse-textured surface deposits makes the aquifer vulnerable to contamination, thus strengthening the need for environmental monitoring.

CFB Shilo comprises several training areas (Figure 4.2). Rifle and grenade ranges are located in the northern part of the base, northeast of the administrative buildings and living quarters. Five major battleruns (Aachen, Berlin, Cologne, Deilinghofen and Essen) scattered throughout the area were used primarily by German troops between 1978 and 2000.

Military training in the area has its origin at the turn of the century. The first camp opened in 1910 some 5 miles north of CFB Shilo's current location. It was used by as many as 30 000 troops during World War I, and for summer training only thereafter. The current base area became a permanent year-round establishment around 1942. In the 1970's, Germany and Canada signed an agreement allowing German military troops to conduct training and perform manoeuvres at CFB Shilo. This exchange program was named GATES for German Army Training Exchange Shilo. Following the departure of German troops in 2000 after 23 years of training, the German and Canadian government agreed to share unexploded ordnances (UXO) clean up and field remediation costs. A three-year characterization campaign was thus undertaken to evaluate the environmental impacts of military training activities.

Military training can affect the environment in several ways, from vegetation trampling to releases of hydrocarbons in the groundwater. This study will focus on the release in the environment of targeted contaminants associated with specific military activities; these are heavy metals, energetic materials and thorium-232 (^{232}Th).

Heavy metals are common components of bullets, missiles and rockets, and are therefore expected to be present in all training locations: rifle ranges, grenade ranges and battleruns. Energetic materials, also called explosives, are the main component of gunpowder, explosive warheads and solid rocket propellants and may be found on grenade ranges and battleruns. ^{232}Th is a radioactive metal present in small amounts in certain types of MILAN missiles fired at CFB Shilo. Manufactured in Europe, MILAN (*Missile d'Infanterie Léger Antichar*) missiles are portable, medium-range, antitank weapons. They were fired in specific locations in three battleruns: Cologne, Deilinghofen and Essen.

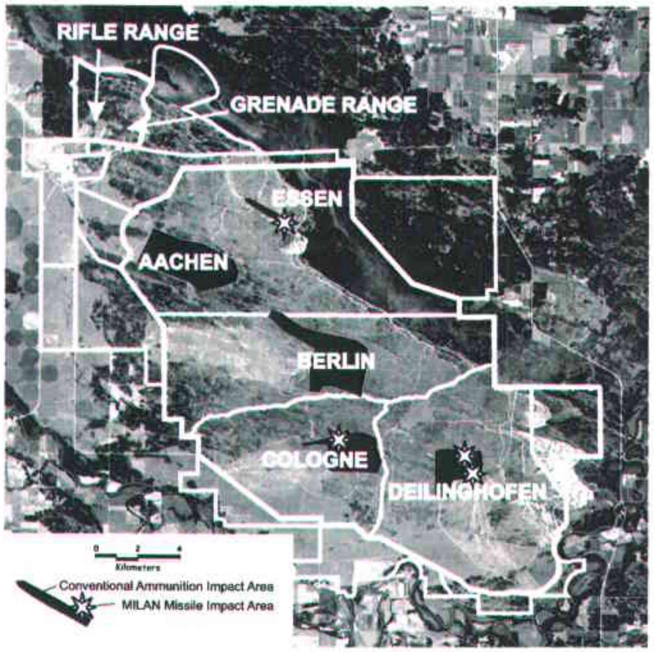


Figure 4.2: CFB Shilo boundaries. Conventional ammunitions and MILAN missile impact areas are shown.

4.5 Geological and hydrogeological characterization

4.5.1 Methods of investigation

Geological information was collected in 2001. Because of the shallow depth of most boreholes located within the training area, two deep boreholes were drilled to evaluate the sequence of sediment formations and the depth of the aquifer. Ground penetrating radar surveys were also made to obtain further information on sediment structures. Surface and subsurface soil samples were collected and analyzed for their grain-size.

Field investigations for the hydrogeological characterization of the aquifer were performed in 2000 and 2001 and included the drilling, development and installation of 78 observation wells. A safety proofing of all sites was performed prior to drilling to ensure the absence of UXO. All wells were installed with PVC tubing according to standard methods. All wells were GPS surveyed with a precision on elevation of ± 0.01 m. Slug tests were performed with a pneumatic method described by Levy and Pannell (1991). Data interpretation for the evaluation of hydraulic conductivity was done with the Bower and Rice method. A total of 152 slug tests were performed in 71 wells in 2000 and 2001.

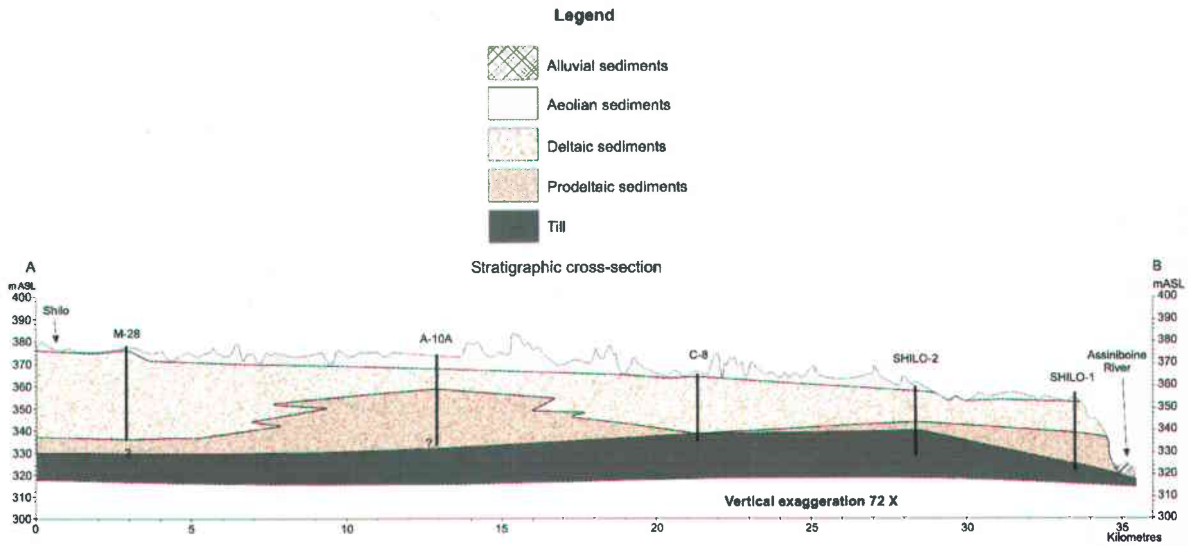


Figure 4.3: Stratigraphic cross-section (NW - SE) of CFB Shilo (from Cloutier and Parent, *in* Ampleman *et al.* 2003)

Water-level measurements were made and used to draw a water table elevation map. The horizontal component of groundwater velocity and direction was measured with a flowmeter in the observation wells.

4.5.2 Geology

Surficial geologic mapping surveys showed that CFB Shilo is entirely underlain by thick sandy sediments (Figure 4.3). These sediments were deposited at an elevation of about 375 m above sea level (ASL) by the large meltwater-fed Assiniboine delta in Lake Agassiz during the last deglaciation (Ampleman et al. 2003). This deltaic sand is medium to coarse-grained with an observed thickness ranging from 15 m in natural sections on the banks of the Assiniboine River to as much as 36 m in the built-up area of the base.

Most of the surface of the deltaic sands has been reworked extensively by wind activity and exhibits aeolian features such as composite parabolic dunes. These medium to fine-grained sands are hence commonly finer-grained than the underlying deltaic sands. Composite subsurface samples collected with a split-spoon during borehole drilling reveal an average composition for soils of 88% sand, 6% silt, 6% clay and 1% organic carbon (Ampleman et al. 2003). Subsurface investigations also revealed the presence of several discontinuous organic layers, which form paleosols or buried peats of Holocene age. Surficial organic sediments were also found near Epinette Creek.

Stratigraphic information from the boreholes revealed that the deltaic sands are generally underlain by glaciolacustrine silts a few cm to 25 m thick or more, which are in turn underlain by dense, matrix-dominated grey till (Figure 4.3). This glacial till was deposited during the Wisconsin glaciation and rests directly on the bedrock, composed of Mesozoic shales of the Cretaceous and Jurassic periods (Burton 2000).

4.5.3 Hydrogeology

The Assiniboine Delta Aquifer is developed within the combined aeolian and deltaic sand layers, which form a single hydrogeological unit. The water table is at the soil surface in certain areas and can reach a depth of more than 20 m in others. The saturated thickness of the aquifer ranges from 0 to 60 m, with an average of 18 m under CFB Shilo. Aquifer transmissivity estimates range from 0.0007 to 0.03 m^2/s (Burton et Ryan, 2000) Specific yield estimates vary from 0.1 to 0.29 (Render 1988). The aquifer is recharged mainly through precipitation. The annual mean precipitation is 453 mm. Mean recharge in Shilo was estimated from well hydrographs at 50 mm/y over a 17-year period (Ampleman *et al.* 2003).

As observed in Figure 4.4, groundwater at CFB Shilo flows in a radial pattern, to the southwest, south and southeast. Groundwater flow is influenced by the surface drainage system that includes two watersheds: Assiniboine and Epinette. Most of the groundwater discharges into the Assiniboine River while a small portion of the aquifer drains into Epinettre Creek. Most of the groundwater is thought to discharge to surface water as no vertical leakage to underlying and less permeable formation has been reported (Burton et Ryan, 2000).

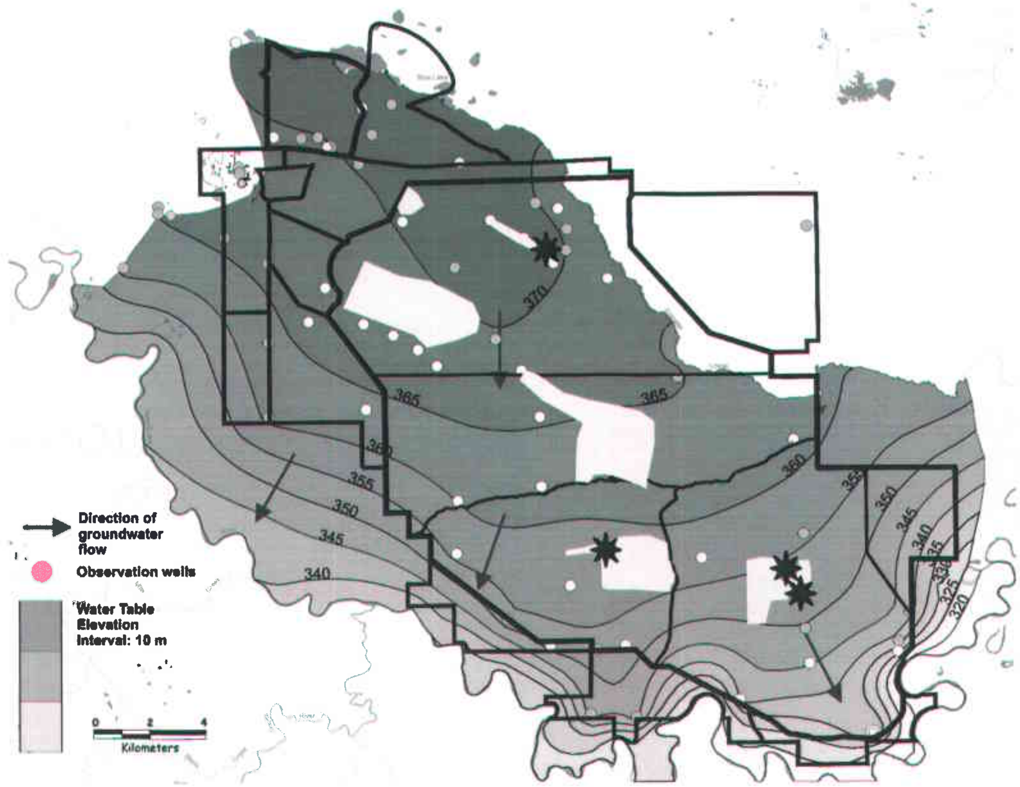


Figure 4.4: Water table elevation map of CFB Shilo

Most groundwater flow directions measured with a flowmeter are consistent with the piezometric map. Groundwater velocities range from 70 to 700 m/y, with an average of 350 m/y. Calculated groundwater velocities are based on the average hydraulic conductivity estimated from slug tests ($1x10^{-4}$ m/s), the horizontal hydraulic gradient from the water table map (0.002 to 0.02 with a mean of 0.01) and an estimated effective porosity of 0.3. *(Note: An effective porosity of 0.3 was used for these calculations to be consistent with Geoflo calculations already completed (year 1 results) before the author started her project. However, an effective porosity of 0.25 was used for calculating groundwater velocity with Darcy's law on p39, for determining CFB Shilo supply well capture area in chapter 5 and for particle tracking exercices also in chapter 5)*

Grain-size analysis performed on subsurface soil samples indicated a grain size diameter that varied from 0.5 μm to 1 mm with a mean of 350 μm. The estimated hydraulic conductivity of the sand formation, established from 72 subsurface samples with the Hazen formula based on the d_{10} of the grain-size curves, was $2x10^{-4}$ m/s ($1.4x10^{-3}$ m/s to $2.2x10^{-6}$ m/s). These results are in agreement with the value $1x10^{-4}$ m/s obtained from 152 slug tests performed in 71 wells. Five samples collected in the sandy clay formation below the sand aquifer indicate a hydraulic conductivity of 8.66 x 10^{-9} m/s based on grain size.

An analysis of the proportion of major ions in groundwater samples indicate that the water type is predominantly Ca-HCO_3, with a steady increase in Mg as groundwater flows towards the Assiniboine river.

Conceptual and numerical models of the aquifer will be developed to illustrate groundwater flow and transport mechanisms of potential contaminants in soils and groundwater. This model will use information collected during the characterization campaign such as hydraulic heads, hydraulic conductivity, recharge, the pumping rate of CFB Shilo drinking water supply and nearby farm irrigation wells and will be used to delineate well head protection areas for the water supply wells of the base.

4.6 Environmental Characterization

4.6.1 Methods of investigation

Groundwater and surface water

Surface water and groundwater were sampled in 2000 and 2002 for major ions, metals, energetic materials, and ^{232}Th with standard sampling methods. A total of 109 groundwater samples and 37 surface water samples were collected and analyzed. Also, several physicochemical parameters were measured *in situ* with portable probes: temperature, pH, conductivity, salinity, dissolved oxygen and redox potential.

Soils

Background soil samples are critical for establishing the anthropogenic contribution versus the natural contribution for all chemicals. Background samples were thus collected in different locations outside training areas. Given the varying types and characteristics of firing exercises conducted at Shilo, specific sampling strategies were adopted for the different ranges, including a linear sampling pattern in the ranges and a circular pattern around the targets and hotspots, as described in Ampleman et al. (2003). All strategies were based on the collection of composite samples in order to decrease the high level of heterogeneity usually observed with explosives residues in previous studies (Thiboutot et al. 1998). Soil sampling sites are shown on Plate 7 (appendix K)

Metals and ^{232}Th were analysed by Inductively Coupled Plasma Mass Spectrometry (ICP/MS). A gas chromatography-electron capture detector (GC-ECD) method was used to analyze samples for explosive contamination.

Measured concentrations of metals, energetic materials and ^{232}Th were compared against background concentrations and Canadian Council of Ministers of the Environment (CCME) guidelines, for available parameters.

4.6.2 Heavy Metals in Training Areas

Soil and groundwater samples were analysed for several metals: Al, Sb, As, Ba, Be, Bs, Br, Cd, Cs, Cr, Co, Cu, Fe, Pb, Li, Mn, Mo, Ni, Rb, Se, Ag, Sn, Sr, Te, Ti, Tl, U, V, W, Zn, Zr. Metal concentrations in soil samples collected in training areas were compared both to the most stringent CCME Soil Quality Guidelines (Agricultural Use) and to a value corresponding to the background concentration plus two times the standard deviation (BC2SD). A detailed description of metal concentration in soils is available in Ampleman et al, 2003.

Metal concentrations in soil samples collected in rifle ranges indicate a clear impact of firing activities with small arms (Figure 4.5). In rifle ranges, respectively 97%, 91% and 41% of all sample concentrations for lead, copper and zinc were over both CCME guidelines and the BC2SD. Lead and copper concentrations were particularly high, with maximum values of 45 000 mg/kg for lead (2381 times background) and of 7620 mg/kg for copper (259 times background). Significant concentrations of bismuth, arsenic and nickel were also found over background concentrations (59%, 26% and 26% of samples), as well as titanium, strontium, selenium and vanadium in a number of sampling locations.

The hand grenade range also revealed high metal concentrations over the entire surface of the range (Figure 4.5). Zinc, copper, cadmium, and lead were found in concentrations exceeding both CCME guidelines and the BC2SD in respectively 100%, 94%, 94% and 76 % of samples. However, although present on the entire range, lead and copper concentrations are not as high as those observed in rifle ranges, with a maximum concentration of 404 mg/kg (21 times background) for lead and 779 mg/kg (26 times background) for copper. Other metals, not detected in significant concentrations in rifle ranges, were found in concentrations exceeding background levels in the grenade range: chromium (94% of samples) and magnesium (71%). Nickel and titanium were also found exceeding the BC2SD and/or CCME guidelines.

The situation was different in battleruns. Analysis results from samples collected over the length of the battleruns revealed very few locations (mainly around targets) where metal concentrations were exceeding CCME guidelines or the BC2SD, thereby indicating that general training activities in battleruns do not lead to detectable soil contamination by metals.

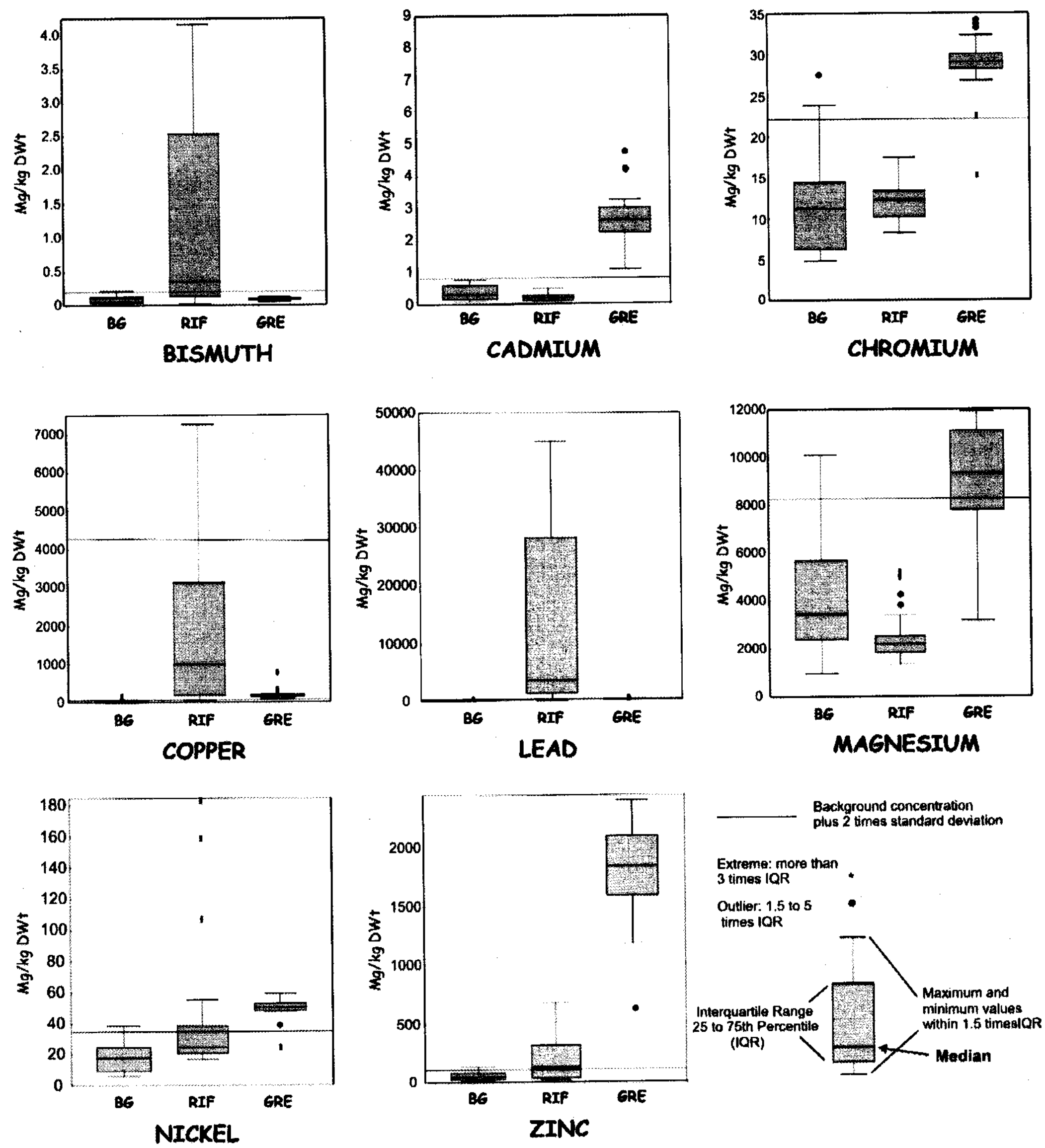


Figure 4.5: Concentrations for selected metals in soil samples BG = Background, RIF = Rifle Range, GRE = Grenade Range

Circular sampling in a 5 m radius around targets and hotspots (small calibre shells, melted flares, mortar, intact or broken shells) allowed the identification of patterns of metal accumulation around a few targets, mostly in Deilinghofen and Essen ranges. Targets with clear contamination patterns from Co, Cu and Pb, and to a lesser extent Mg and Sr, were identified in the Deilinghofen battlerun. However, Cu and Pb are characteristic of small arms ranges. CFB Shilo range control confirmed the use of these targets for small arm and large calibre rounds exercises. Tank manoeuvres in the range often included the firing of small calibre ammunition with mounted machine guns. High Cu and Pb concentrations up to 6.7 times the background and exceeding CCME guidelines were also measured around targets in Essen. Overall, Cu and Pb concentrations found around targets in battleruns were lower than those detected in rifle and grenade ranges.

Groundwater analyses clearly indicate that contamination problems with metals are limited to surface soils. Except for Mn, Fe and Al concentrations that were found above CCME guidelines for drinking water in respectively 31%, 22% and 4% of groundwater sampling locations, no other metals were detected in significant concentrations in training areas. Measured concentrations in groundwater varied from 0.05 to 1.59 mg/L for Mn, 0.3 to 2.0 mg/L (with one sample reaching 4.5 mg/L) for Fe and 0.10 to 0.27 mg/L for Al. Mean Fe, Mn and Al concentrations measured in training areas were not higher than those measured in background locations. Measured concentration levels are not uncommon in groundwater and may be linked to local geological conditions. No relation between metal concentrations in groundwater with training activities can be established.

4.6.3 Energetic Materials in Training Areas

Stabilized energetic materials (EM) are widely used in various types of warheads and other ammunitions. Grenades and rockets used in Shilo grenade range and battleruns also contain energetic materials. EM do not occur naturally in the environment. The most common ones are RDX, TNT and HMX. These molecules can be found in a granular state on the soil surface in training areas, where precipitations contribute to their dissolution. They can migrate through the soil surface to the groundwater table. Several studies suggest that EM such as RDX, TNT and HMX are not very soluble in water but once dissolved can migrate relatively easily (Selim et al. 1995).

Background locations, the hand grenade range and the battleruns were sampled for EM, where 17, 15 and 70 samples were collected respectively. The background samples collected outside of the training areas showed no quantifiable traces of EM. However, traces of TNT, TNB and RDX were detected below the limit of quantification. This could be an indication that dust transport by wind contributes to very low levels of explosives outside the designated training areas.

All soil samples collected in the grenade range contained measurable amounts of several explosive residues, including RDX, TNT and HMX: maximum concentrations were 4058 μg/kg for RDX, 725 μg/kg for TNT and 191 μg/kg for HMX. The contamination was present on the entire surface of the grenade range but showed no distinctive pattern of concentration from the grenade-firing zone to the end of the detonation zone. Contamination from energetic materials in this range can be linked to the M 67 hand grenades currently in use in Canada, which contain 186 g of a melt-cast explosive (60% RDX, 39% TNT) and HMX as an impurity in military-grade RDX (Ampleman 2003).

The situation is different in battleruns, where no EM were detected in 31% of the soil samples. Traces were detected below quantification limits in 39% of samples and quantified in another 30%. Several residues were detected and quantified, mostly RDX and TNT but also nitroglycerine (NG), various forms of DNT and TNB. Measured concentrations in battleruns were low and all below 1 mg/kg except for one sample, with concentrations reaching 44 μg/kg for RDX, 55 μg/kg for TNT (with a hit of 2068 μg/kg) and 406 μg/kg for NG. There is no clear distribution of EM concentrations in the battleruns, where samples where no EM were detected are interspaced with others containing varying, but always low, EM concentrations. The situation is the same both in the battleruns themselves and around targets, except for the Essen battlerun where clear accumulations of NG were identified around targets.

The levels of EM contamination in the hand grenade range are thus higher than those found in the battleruns. However, the maximum level measured was under 5 mg/kg, which is not considered a high level of contamination. Similar, although somewhat higher, results for explosives in soils were obtained in US hand grenade ranges at Fort Lewis and Fort Richardson (Jenkins et al. 1998).

More than 140 groundwater and 26 surface water samples were collected and analyzed for EM over a three-year period, with none of these substances detected over the quantification limit of 0.01 μg/L.

Other recent investigations on several Canadian Forces site have demonstrated that EM are not common contaminants, since they exhibit limited aqueous solubility and are dispersed in a heterogeneous pattern of contamination (Ampleman et al. 2003, Pennington et al., 2003). The same conclusion can be drawn from the results obtained at CFB Shilo, where EM were heterogeneously dispersed on the soils of the training areas and not detected in groundwater.

4.6.4 Thorium-232 in Training Areas

^{232}Th is a radioactive element which occurs naturally in low concentrations in the environment. Essentially all thorium in nature (99.99%) occurs as ^{232}Th. This isotope has a half-life of 14 billion years and thus decays very slowly (ATSDR 1990). The guiding system of some types of MILAN missiles contain ^{232}Th. The first step in assessing the influence of MILAN missile firing on ^{232}Th concentrations in the environment was to establish background concentrations for this radionuclide in the Shilo area.

^{232}Th normally occurs in soils in concentrations in the order of 10 mg/kg, although higher concentrations can be found in certain geological materials. In a study of a contaminated site in South Carolina, ^{232}Th concentrations in a loamy sand soil reached 7 mg/kg in background areas and 270 mg/kg in contaminated areas (Kaplan et al. 2002).

At CFB Shilo, soil samples were collected in background locations and in training areas. ^{232}Th concentrations in soils varied between 0.11 and 9.1 mg/kg, with a mean concentration of 2.87 mg/kg in training ranges and 3.04 mg/kg in background areas. These values are typical of natural concentrations in soils. Plotting of ^{232}Th values on a map indicates no correlation between ^{232}Th concentration and soil type or proximity to MILAN target areas.

Hem (1989) reports that typical natural ^{232}Th concentrations in groundwater are low but are not known with certainty because of the low number of analyses for this element. Roger and Adams (1969a) and Turekian (1969), quoted in Hem (1989) reported an analysis suggesting concentrations in groundwater of no more than a few tens or hundredths of μg/L. Other studies estimate ^{232}Th concentrations in natural fresh water do not exceed 1 μg/L (Langmuir and Herman 1980) and 0.01 ug/L (Kaplan et al. 2002). CCME Maximum Acceptable Concentrations (MAC) for ^{232}Th and ^{210}Pb in drinking water are the most stringent among radionuclides and were established at 0.1 Bq/L, which is equivalent to 24.5 μg/L for ^{232}Th.

To determine background ^{232}Th concentration, several groundwater samples were collected in four wells located far from CFB Shilo (5 to 40 km away) in the same geological unit. No ^{232}Th was detected in those wells. Three other samples were collected closer to the base (1-3 km) but still out of training ranges. ^{232}Th was undetected in one location and found in low concentration in another (0.04 and 0.09 μg/L) but in higher concentration (0.25 and 0.84 μg/L) in the last location 3 km north of the base. Aside from this last result, which will be discussed more extensively, the absence or low concentrations of ^{232}Th in locations far from CFB Shilo provides a strong indication that the background ^{232}Th concentration in the Assiniboine aquifer is below 0.01 μg/L (detection limit), as expected in natural environments. Groundwater with detectable concentrations of ^{232}Th may therefore have been impacted by anthropogenic sources.

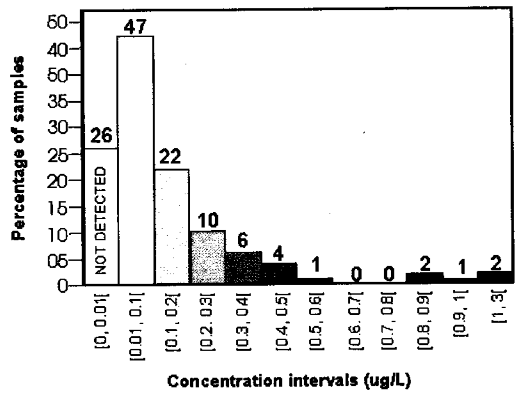


Figure 4.6: Distribution of ^{232}Th in groundwater

Measured ^{232}Th concentrations in groundwater collected in training ranges varied by three orders of magnitude, ranging from below detection limit to 2.35 μg/L. Most concentrations were below 0.5 μg/L (Figure 4.6). These results suggests the absence of health concerns associated with the presence of ^{232}Th in groundwater, the highest measured concentration being one order of magnitude below the CCME guideline for drinking water. Moreover, no traces of ^{232}Th were detected in the three wells used for supplying water to the base nor in any of the privately owned supply wells sampled in the area.

The pattern of ^{232}Th concentration in the vicinity of two of the MILAN target areas (Cologne and Deilinghofen) reveals that the highest concentrations (including 2.35 μg/L) were measured close to MILAN target areas and downgradient in the direction of groundwater flow (Figure 4.7 and Plate 8, Appendix L). The same observation can be made about the Essen target area. The uncertainty associated with the exact location of firing sites should be kept in mind; the firing of missiles slightly northwest of the Milan target area identified on Figure 4.7 (and on Plate 8, Appendix L) could explain the presence of relatively high ^{232}Th concentrations southwest of Essen range.

However, unexpected results were obtained in sampling locations north and northwest of Essen target area. As mentioned earlier, relatively high ^{232}Th concentrations in groundwater were measured out of the training ranges, but also in rifle and grenade ranges. These results are not consistent with the general direction of ground water flow as they were measured in wells located hydrogeologicaly *upgradient* of MILAN target areas. Moreover, the presence of relatively high ^{232}Th concentrations in groundwater in a well some 3 km out and northwest of the training ranges is also hard to explain as the possibility for a lost missile to have landed there is unlikely.

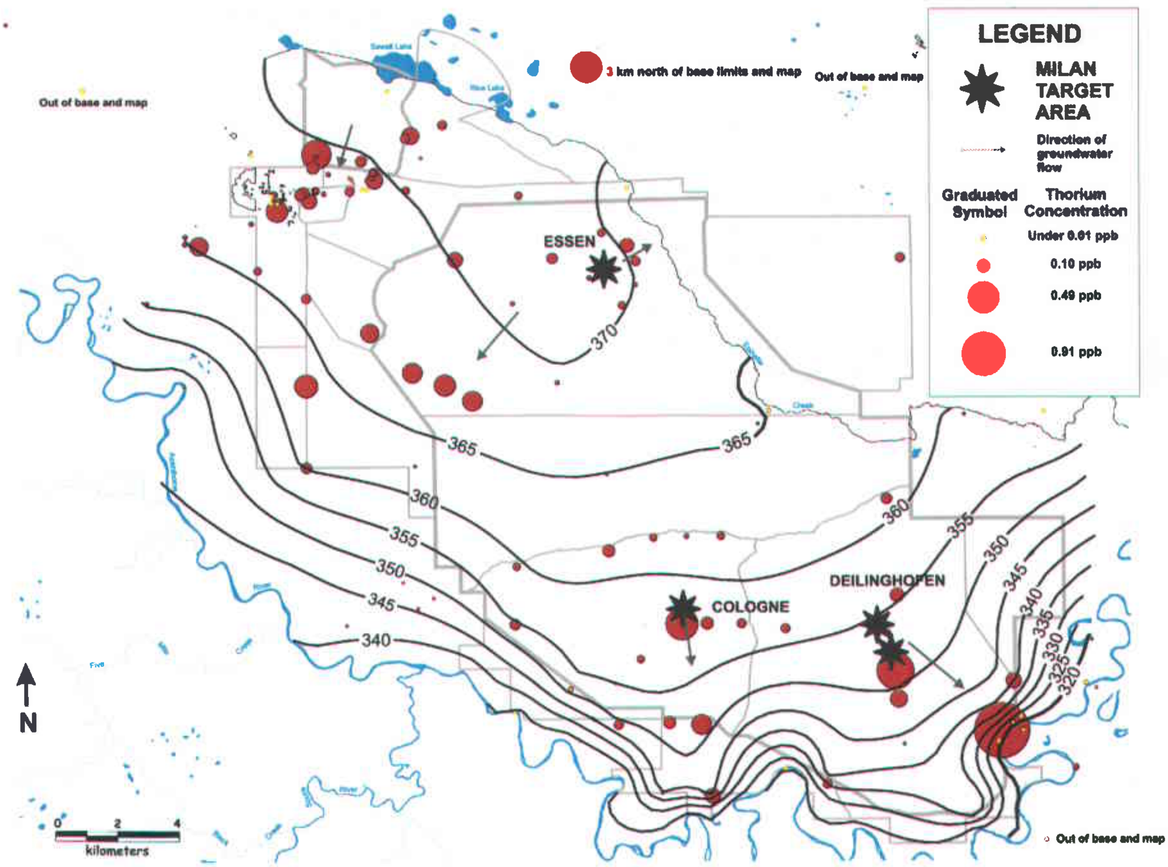


Figure 4.7 : ^{232}Th concentration in groundwater. Circles proportional to thorium concentration. When a location was sampled more than one time, circle size corresponds to the highest concentration measured. Thorium in groundwater is also illustrated on Plate 8 in Appendix L.

Measured thorium concentrations in groundwater may be attributed either entirely to local geological conditions or partly to anthropogenic activities. Should the last option prevail, a possible explanation for the high ^{232}Th concentrations observed in groundwater outside the general flow path could be transport and deposition by wind prior to percolation to the water table. This transport could happen either during the firing exercises or by dust transport. Wind has been identified as a major contributor to soil erosion in Manitoba, particularly in large unprotected fields such as those commonly found in southwestern Manitoba. The high erosion rate of surficial soil may also explain the low thorium concentrations measured in soils of training ranges.

The short distance between sampling locations with high ^{232}Th concentrations in groundwater and others with values under detection limits in training areas, may also suggest the possible presence of ''hotspots''. Hotspots in training ranges are created by the deposition of missile debris following its explosion or by wind transport. Unless missile debris are apparent, hotspots may be difficult to locate. They could provide a reasonable explanation both for the great variability in ^{232}Th levels found in groundwater and for the presence for ^{232}Th upgradient from MILAN target areas and also explain the absence of a ^{232}Th concentration pattern in soils. It should be noted that highly heterogenous concentrations for energetic materials in soils were also observed near targets and seem to be associated with hot spots. Further research would be needed in order to better understand the concentration pattern of ^{232}Th in groundwater at CFB Shilo. Although the absence of detectable ^{232}Th concentrations in groundwater far from the base as opposed to the highest concentrations measured in training areas suggest a possible link with MILAN firing activities, the ^{232}Th concentration pattern in some areas of the base remains difficult to explain. No final conclusions can be drawn at this stage.

^{232}Th concentrations in surface water were lower than those observed in groundwater, ranging from below detection limit to 0.08 μg/L. These results are an indication that MILAN missile firing or other anthropogenic activities did not contribute to significant ^{232}Th concentrations in lakes and rivers in the area.

4.7 Summary and conclusion

This paper presented the results from the characterization of CFB Shilo whose objective was to evaluate the potential impact of military training activities on the environment. Geological and hydrogeological investigations confirmed the high vulnerability of the unconfined sand aquifer to potential contamination. The distribution of heavy metals and energetic materials concentrations in soils and groundwater demonstrate a relationship between military training activities and contaminant concentrations. Soil concentrations significantly above background and/or exceeding CCME guidelines were detected in various training areas for both metals and energetic materials. Specifically, firing activities lead to significant accumulations of several metals in grenade and rifle ranges (Bi, Cd, Cr, Cu, Pb, Mn, Ni and Zn). Results also indicate that firing activities conducted in the battleruns did not lead to significant accumulations of metals in soils, except around specific targets. Energetic materials were detected in relatively low concentrations in soils in the hand grenade range (below 5 mg/kg) and in the battleruns (below 1 mg/L). Contamination by metals and energetic materials was limited to soils; significant concentrations were not detected in groundwater or nearby lakes and rivers. The pattern of ^{232}Th concentration in groundwater may also suggests a link with military training.

^{232}Th distribution at CFB Shilo is more difficult to interpret. Although no specific pattern of ^{232}Th concentration was detected in soils, concentrations in groundwater, although generally low (below 0.1 μg/L), were highest in groundwater downgradient from some firing areas. However, relatively high concentrations were also detected upgradient from these areas and further investigations would be needed to better understand the results of the characterization.

In general, CFB Shilo does not represent a high-risk situation that would justify recommending a halt to training activities. Nevertheless, some points are still of concern and lead to a series of recommendations to base authorities. These include avoiding the use of soil amendments (such as lime application) that might change the pH of soils on metal-contaminated areas since it may allow their leaching towards the groundwater table. Also, even if ^{232}Th concentrations in groundwater are below levels of concerns, a recommendation was made to stop firing MILAN missiles with ^{232}Th in their guiding system at CFB Shilo.

Although improvements are still needed, the militaries have also already instigated best practices to limit the potential of contamination as well as health and security hazards from their activities. One example is the sieving of metal debris from the sand butts in rifle ranges in order to decrease the potential for soil and groundwater contamination. CFB Shilo also maintains an ongoing annual monitoring program at sites where there is potential for groundwater to become contaminated by operational activities. Considering the need for Canadian Forces to train its personnel and test equipment and munitions in conditions that are as realistic as possible, assessing and mitigating environmental impacts of these activities will allow for a safer use of training areas in the long term.

4.8 Acknowledgement

The authors would like to thank CFB Shilo personnel for providing access to the training grounds and base equipments, and for the information provided on previous military and environmental activities. Thanks are also extended to INRS, especially Jean-Marc Ballard, and DRDC personnel, for their assistance during field work. NSERC provided financial support to the first author through a postgraduate scholarship.

V – NUMERICAL SIMULATION OF GROUNDWATER FLOW

5.1 Introduction

A numerical model of groundwater flow at CFB Shilo was developed for three main purposes:

1. to integrate the important amount of field data collected during the characterization campaigns;
2. to improve the understanding of the flow system underlying the study area;
3. to delineate the capture zone and well head protection areas for CFB Shilo groundwater supply wells.

The methodology used for developing both the conceptual and the numerical flow model will first be presented in section 5.2. A brief description of the conceptual model will follow in section 5.3. The three-dimensional (3-D) numerical model and its calibration process will be the focus of sections 5.4 and 5.5, respectively. Flow model results and a sensitivity analysis will be outlined in section 5.6. Finally, the calibrated flow model will be used to delineate the capture zone of CFB Shilo's supply wells (section 5.7). Concluding thoughts (section 5.8) will close this chapter.

5.2 Methodology

Physical and hydrogeological information collected during the characterization campaign (chapter 3) such as stratigraphic data, field observations, water levels, hydraulic conductivity estimates and water well pumping rates were used to develop the conceptual model and to provide input data in the numerical model.

The modeling protocol described in Anderson and Woessner (1982) was used to build the numerical model. The process involves the following stages: establishing the purpose of the model, developing a conceptual model of the system, selecting a governing equation and a computer code, designing the model, establishing convergence criteria, model calibration, calibration sensitivity analysis, and presentation of modeling results. Each of these stages is outlined in this chapter. Finally, well head protection areas for CFB Shilo water supply wells were derived from the calibrated numerical model.

5.3 Conceptual Model

A conceptual model of the groundwater flow system was developed and used as a framework for building the numerical flow model. Developing this conceptual model involved the definition of hydrostratigraphic units, a description of the water budget and the identification of input parameters and simplifying assumptions.

5.3.1 Definition of hydrostratigraphic units

Chapter 3 presented an interpretation of fundamental geological and hydrogeological features of the study area. This interpretation relied on data assembled from various sources: drilling logs (oil exploration drill holes, supply and observation wells), geological and hydrogeological reports from the Manitoba Ministries of Natural Resources and the Environment and from consulting firms, ground-penetrating radar surveys and soil samples collected during field work.

The conceptual model used for modeling groundwater flow in the aquifer underlying CFB Shilo is presented in figure 5.1 below. Hydrostratigraphic units in the conceptual model were derived from the interpretation of stratigraphic and hydraulic conductivity data presented in chapter 3. Hydrostratigraphic information was in turn used to define equivalent units in the numerical model.

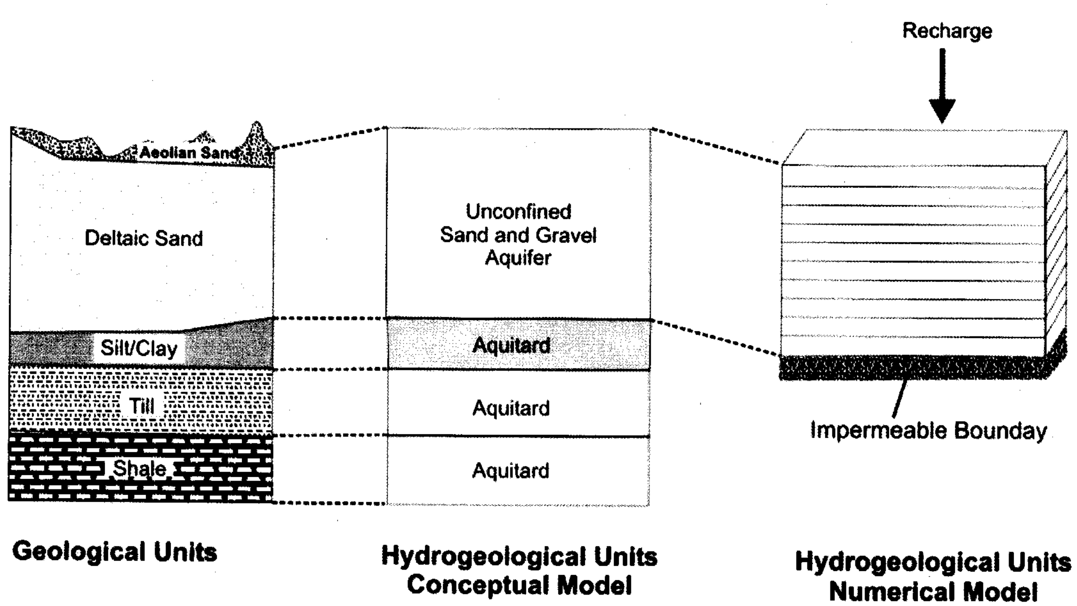


Figure 5.1 Relationship between geological and hydrogeological units, the conceptual and the numerical models.

As can be seen on figure 5.1, the two upper geological units (deltaic and aeolian sand) represent a single hydrogeological unit: the unconfined Assiniboine Delta Aquifer. This hydrogeological unit is the only one represented in the numerical model.

Available information regarding the hydraulic conductivity of the various layers underlying the sand units was scarce. The hydraulic conductivity of the silt/clay layer was estimated using grain-size analyses from samples collected either directly in the unit or in silt/clay lenses encountered while drilling in the sand layer. Estimated hydraulic conductivity was in the range of 10^{-7} to 10^{-9} m/s, as opposed to 10^{-3} to 10^{-5} m/s for the sand layer. Anderson and Woessner (1992 : 100) estimate that "a two order of magnitude contrast in hydraulic conductivity may be sufficient to justify placement of an impermeable boundary". With a hydraulic conductivity difference of this magnitude, flow lines are refracted in such a way that flow in the higher conductivity unit is essentially horizontal. This tangential flow at the layers interface acts as an impermeable barrier. The difference of 2 – 6 orders of magnitude between the hydraulic conductivity of the sand and silt/clay layers justifies considering the latter as an impermeable boundary to flow from the upper sand aquifer and as the lower confining unit of the conceptual model. Moreover, according to Province of Manitoba (1970 : 14,19), groundwater observation stations indicate that vertical movement of groundwater between the Assiniboine Delta aquifer and underlying formations is not a significant factor in the Carberry area located north of CFB Shilo. Canadian Forces (1994 : 3) also report no vertical component to the groundwater flow field in two wells installed side by side at 7 and 16 m deep within the limits of CFB Shilo. The bottom shale unit is also known to be of very low permeability.

5.3.2 Water Budget

The water budget of an aquifer is established by comparing recharge and discharge. The general equation for the water budget can be written as (Fetter, 1994):

$$\text{Inflows} = \text{Outflows} +/- \text{Change in Storage}$$

Or, in more details:

$$\text{Precipitation (P)} = (\text{Evapotranspiration (ET)} + \text{Discharge to rivers/springs (F)} + \text{Consumptive Use (C)}) \pm (\Delta\ \text{Soil moisture (Ss)} + \Delta\ \text{Groundwater Storage (Sg)})$$

and

$$\text{Infiltration (I)} = P - ET$$

Generally speaking, inflows may include precipitation, inflows from surface water bodies and imported water (such as irrigation water coming from outside the system). Outflow may include evapotranspitation, base flow, spring flow and exported water. Changes in storage may occur in the surface water or the groundwater reservoirs.

The previous equation will be written as follows for the portion of the Assiniboine aquifer located in the study area:

$$R + EF = F + C \text{ (base water supply wells)} \pm \Delta Sg$$

where EF is groundwater flow entering the system through a hydraulic boundary and R is the groundwater recharge (P-ET $\pm \Delta S_s$).

Recharge occurs only through infiltration of part of precipitation. As will be explained in more details in section 5.4.7, a very high proportion of precipitation is lost to evapotranspiration and other processes (surface runoff, interflow) are considered negligible. From 5-15 % of precipitations is thus available for groundwater recharge. Groundwater may also enter the system through a hydraulic boundary set parallel to a piezometric line.

Water is lost to the system mainly through base flow and spring flow discharge along the banks of the Assiniboine River. The water table also outcrops in the swamps in the vicinity of Epinette Creek, which appears to be a groundwater discharge area (Province of Manitoba, 1978 : 8). Finally, three CFB Shilo supply wells (represented as a single well in the model since they are located very close to one another – 200 m) and a number of irrigation wells in the southwestern portion of the study area contribute to the consumptive use of the aquifer. A portion of this water is used for irrigation or domestic needs and may eventually return to the aquifer.

5.3.3 Identification of simplifying assumptions

A numerical model was selected over other types of models (analytical, mathematical) given the significant number of field data and the complexity of the geometry and boundary conditions of the study area. As such, simplification of the real-world system was necessary due to the limited knowledge and understanding of the flow system and to ensure a balance between model accuracy and computational speed. Simplifying assumptions (including Dupuits') were used in the development of the conceptual and numerical models:

- The hydraulic gradient is equal to the slope of the water table;
- The porous media is homogeneous but anisotropic ($K_x = K_y \neq K_z$)
- Water pumping for irrigation is negligible

5.3.4 Identification of input parameters

The following properties were specified in the numerical saturated model: datum elevation for the topographic surface (z_1) and the silty clay/sand interface (z_2), water table elevation (z_3), boundaries, hydraulic conductivity (K), recharge (R) and water supply wells pumping rates. Field data and geological reports were used to build contour maps for K, z_1 and z_2.

Table 5.1 Properties specified in the saturated numerical flow model.

Array/Model Type	**Saturated Flow**
	Hydrostratigraphy
Top of layer (z_3) (z_1)	Water table elevation
Bottom of layer (z_2)	Datum Elevation for silty clay / sand interface
	Boundaries
Northern and Southern boundaries	Specified Head
Western and eastern Boundaries	No flow
Material properties	Hydraulic Conductivity (K)
	Recharge (R)
Stress to the system	CFB Shilo Supply Wells

5.4 Flow Model

A three dimensional model was built to represent groundwater flow in the aquifer. The various steps leading to the development of this numerical model are outlined in this section.

5.4.1 Flow Model Simulator

The code used to run the simulations of groundwater flow is called Feflow (Diersch, 1998) and is described as an interactive, graphics-based finite element simulation system for subsurface flow and transport processes. This simulator thus combines integrated hydrologic and water quality capabilities; however, only the first module was used in this project. Feflow was developed by the Water Resources Planning Systems Research ltd. in Germany.

Feflow development was initiated in 1979. Since then, the code has been modified, improved and tested for different practical tasks and theoretical studies, compared with analytical and numerical solutions and benchmarked with experimental data (www.wasy.com). Examples of practical applications as well as a more detailed description of Feflow capabilities is available in Diersch (1998a, 1998b, 2000).

This code was selected for several reasons. First, a finite element code allows more flexibility than finite difference codes in designing the grid, particularly in areas where the boundary is complex and where the grid needs to be refined. Second, Feflow is a well-known code that has been tested extensively. The fact that several researchers at the Geological Survey of Canada in Québec are using this code regularly combined with their willingness to share their expertise was also an important factor in the decision. Finally, the user-friendliness of the simulation interface allows the user to concentrate on the actual problem as opposed to computational issues.

5.4.2 Model Domain

A number of factors were considered for the delineation of the model domain:

- Need to represent most of the area covered by CFB Shilo;
- Availability of hydrogeological data;
- Presence of natural physical boundaries;
- Presence of water supply wells at CFB Shilo.

The model domain is represented in Figure 5.2 (black line). The model encompasses most of CFB Shilo, except for a little used area to the northeast. Hydrogeological data were available over most of the model domain, as most of the fieldwork was performed within CFB Shilo limits. Physical boundaries could not be used extensively for setting boundaries for a number of reasons set out in section 5.4.5. The only physical boundary is the northern one (Epinette Creek). The western limit of the model domain was set westward of CFB Shilo's boundaries in order to ensure it would not be affected by CFB Shilo supply wells. The modelled area covers 400 km^2.

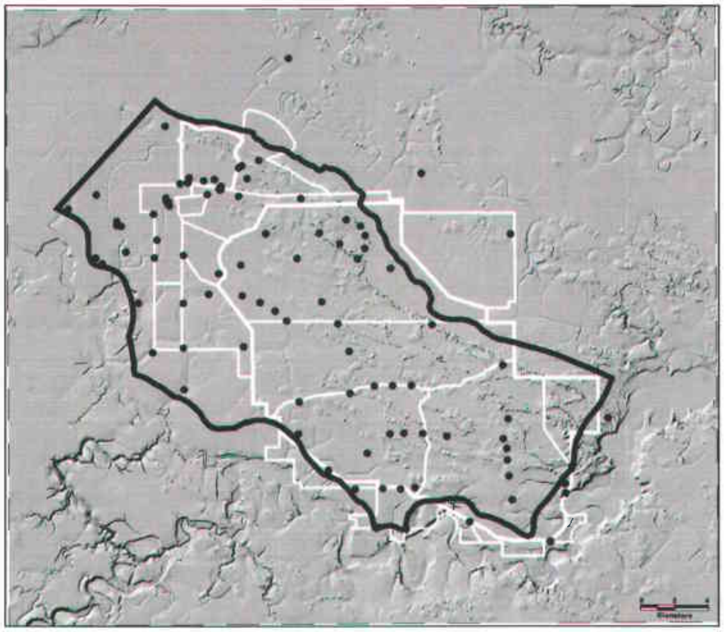


Figure 5.2 Groundwater flow model domain (black line). CFB Shilo boundaries are shown in white. Observation wells are shown as black circles.

5.4.3 Grid Design

The nodal spacing selected varies but is generally set at one node every 350-400 m over most of the study area (Figure 5.3). This spacing was deemed adequate to represent groundwater flow given the small hydraulic gradient over most of the study area.

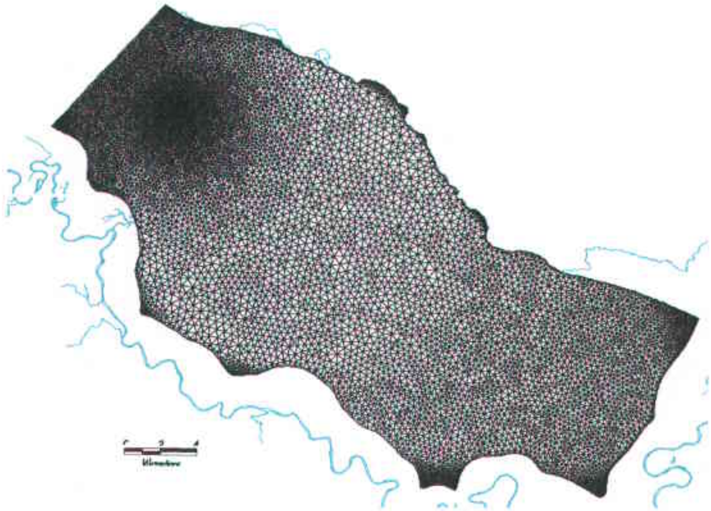


Figure 5.3 2-D model representation. The grid was refined around CFB Shilo's water supply wells. Feflow automatically refines the grid in areas where model boundaries are of irregular shape in order to facilitate convergence. Water courses are shown in blue.

The grid was refined to one node every 30 m around CFB Shilo supply wells to represent more accurately the highly curved water table (drawdown) around those wells. The grid spacing was progressively expanded from the supply wells to the remainder of the grid domain in order to maintain the aspect ratio (ratio of maximum to minimum element dimensions) as low as possible, as the dimensions of adjacent elements should more or less similar. This ratio should be close to unity in order to minimize numerical errors, and a ratio greater than five should be avoided (Anderson and Woessner, 1992 : 68). Therefore, the grid was refined progressively around the well. The grid comprises 176 144 nodes and 317 805 linear triangular elements (cells). External nodes fall directly on the boundaries.

5.4.4. Definition of hydrostratigraphic units

A third dimension was introduced into the 2-D model following mesh generation. First, two sets of elevation data were interpolated to the bottom and top of the initial model layer. The layer was then divided into a number of thinner layers.

The bottom of the first layer represents the silty clay/sand interface. As illustrated in figure 5.4, stratigraphic information was scarce within the limits of CFB Shilo and a number of control points based on best judgement had to be used to guide the interpolation process.

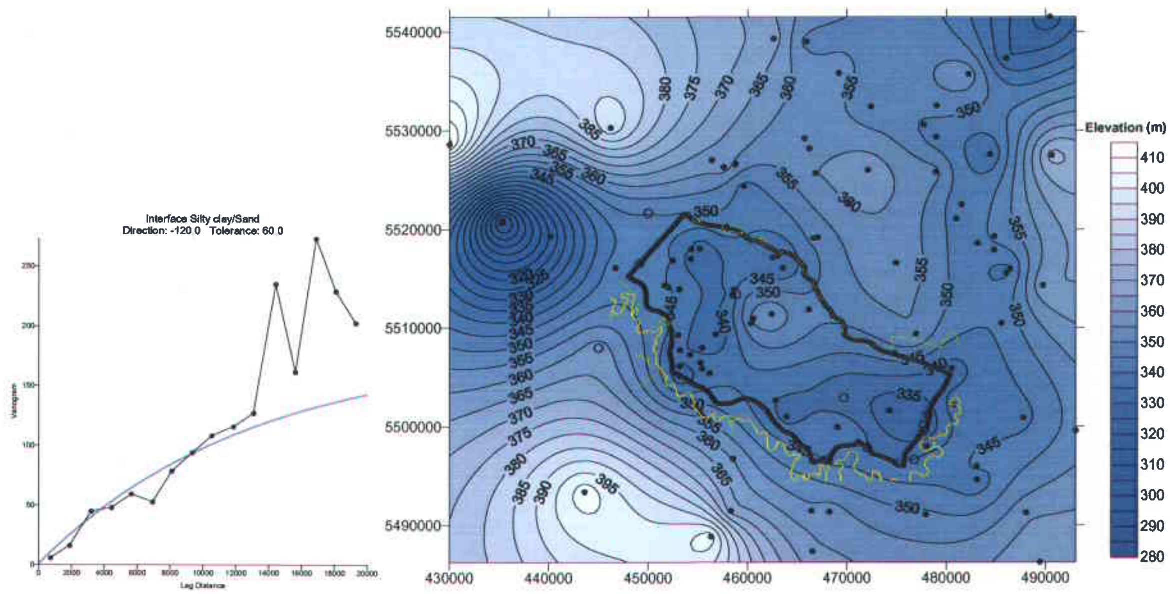


Figure 5.4 Interpolated silty clay/sand layers interface and associated variogram. Bottom sand layers measured elevations are shown as full black circles. Estimated elevations are represented as empty circles.

Kriging was used to define the bottom of the aquifer with this dataset as it preserves field values at measurement points and considers the structure of the variable, giving more weight to the values closest to the measurement point.

Topographic and water table elevations were then successively assigned to the top layer. Topographic elevations were established with a digital elevation model (DEM) developed by the geological Survey of Canada (figure 5.5). A natural neighbour interpolation scheme was used; elevation data were available every 100 m. These elevations were then replaced with water table elevations in order to allow the use of a movable top layer. More details about this model feature are provided in section 5.4.5.

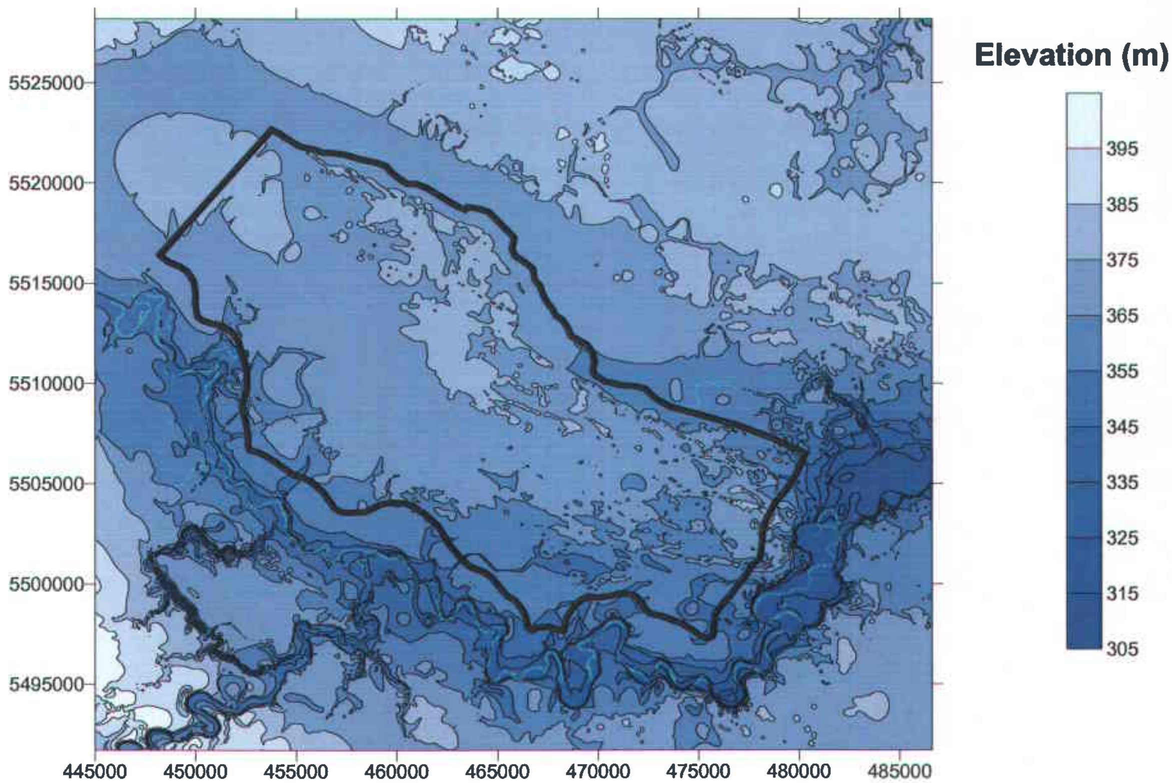


Figure 5.5 Interpolated digital elevation model (DEM) for CFB Shilo

The 2-D model was transformed into a 3-D model following the assignment of the model bottom and top elevations. As can be seen in figure 5.6, the saturated flow model consists in 15 layers representing the Assiniboine Delta Aquifer. This division of the aquifer in several layers is helpful in representing adequately water supply wells in the flow model as well. Layers were set at equal distance to one another and all have the same thickness at a given location, averaging of 2-3 m. Layer thicknees vary, however, across the model domain. The model top and base elevations reaches 371 and 330 m above sea level respectively, for an average model thickness of 30 m.

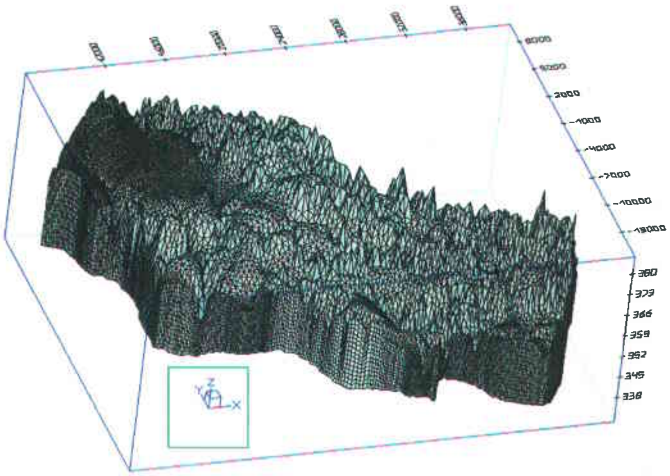


Figure 5.6 3-D model representation. The Assiniboine Delta Aquifer is represented by a 15-layer grid.

5.4.5 Boundary conditions

The Assiniboine delta aquifer is the only aquifer represented in the numerical model. The portion of this aquifer located in the study area in completely unconfined.

The top of the silty clay layer overlying the glacial till was set as the lower, no-flow boundary of the model. According to Burton and Ryan (2000), most of the groundwater is thought to discharge to surface water as no vertical leakage to underlying and less permeable formation has been reported. The surface of the sand aquifer was considered a free-surface (water-table) upper boundary condition. In the numerical model, the top layer was set as "free and movable", a feature available in Feflow in which the top slice of the model simulates a free water table and changes its vertical position. A new free surface location is determined following computation of hydraulic heads; the location of intermediate slices located between the bottom slice (fixed slice) and the top slice (movable) is then adjusted accordingly. Measured hydraulic heads were initially assigned to this upper layer prior to initiating simulations.

The four lateral boundaries of the model represented on Figure 5.7 are described below. The true hydrogeologic boundaries of the system were not used because almost all of our data (water level measurements, hydraulic conductivity estimates) were collected only within CFB Shilo and did not cover the entire sub-basin.

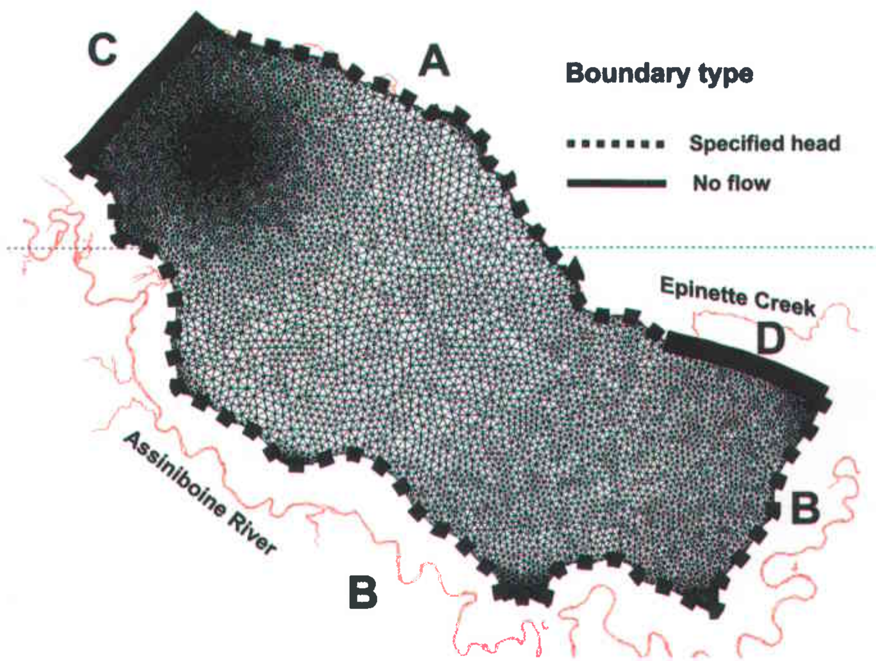


Figure 5.7 Model boundaries

A physical feature, Epinette Creek, was chosen as the northern model boundary (A). This stream is in contact with the aquifer, allowing for the imposition of specified head boundary conditions (Dirichlet conditions). Constant head conditions were set for Sewell Lake, with the head varying linearly along Epinette Creek. Stream heads were estimated from the linear interpolation from heads derived from the water table map of the area and topographic maps. This method was deemed precise and realistic enough due to the adequate number of water level data in this area and the very low hydraulic gradient.

Epinette Creek would thus act as a drain to water coming from its northern side, located outside the boundaries of the model. As such, Frost and Render (2002) noted that surface evidence indicate that Epinette Creek could be a boundary to flow from north to south in the aquifer. The situation is not clear however, and water flow may occur under Epinette Creek. Local flow systems overlying deeper regional flow systems are not uncommon in the Canadian prairies.

Therefore, the specified head condition on Epinette Creek may not extend throughout the entire thickness of the aquifer. A regional streamline may be forming a hydraulic boundary under which regional groundwater flows towards the Assiniboine River. However, the model developed by Render (Render, 1988) used a specified head condition for Epinette Creek and provided a realistic representation of groundwater flow in the Assiniboine South sub-basin. Specified head conditions were selected with the above-mentioned uncertainties about groundwater flow in the Epinette Creek region in mind. Finally, according to Frost and Render (2002), a hydraulic boundary may occur along the south side of Epinette Creek during snowmelt and periods of heavy precipitations. This boundary would disappear afterwards due to the strong drainage to the south.

The Assiniboine river running to the south of CFB Shilo could have constituted an ideal specified head boundary as this watercourse fully penetrates the aquifer. In the past, the Assiniboine River dug its way through the entire thickness of the sand layer along most of its course within the study area. CFB Shilo training ranges stand several meters above the level of the Assiniboine River, leading to an abrupt cliff near the river banks. Several springs and seeps discharging groundwater into the river can be observed along its shores. This occurs because the interface between the sand and the silt-clay layers is exposed on the banks of the Assiniboine river above stream level.

Representation of seepage faces would have added increased complexity to the model. It was thus decided for simplification purposes to use piezometric lines (B) (specified head, hydraulic boundary) as the southern boundary. The fact that the main area of interest lies near the supply wells in the northern portion of the model also supported this decision, along with the scarcity of stratigraphic and hydraulic head data near the shores of the Assiniboine River.

The use of specified head boundaries means that these head values are constant during the steady-state simulation. The groundwater system may thus pull or discharge water from these boundaries. This approach is realistic in the vicinity of Epinette Creek, which drains most of the water coming from the north of the aquifer. Water must be discharged from the southern boundary as it is flowing towards the Assiniboine River.

Finally, no flow hydraulic boundaries were selected along the streamlines based on the knowledge of the flow system and the water table map (C and D). Precautions were taken to ensure that CFB Shilo supply wells (represented as a single well in the model) were located far enough from hydraulic boundaries not to affect them. According to Canadian Forces (1994 : 2), groundwater in the Shilo area is pumped from three water supply wells used by the base as well as from a number of irrigation wells located in the southwestern portion of the study area, and these wells cause very little drawdown under the base. The hydraulic-head drawdown induced by pumping from the base supply wells was estimated for various distances from these wells using the Theis solution (Appendix M). According to these estimates, if wells were pumped full time at full capacity, the drawdown would become small to negligible (less than 3 cm) at a distance of about 3 km. The hydraulic boundaries of the model were therefore drawn in such a way that a minimal distance of 3 km after a year of pumping is always kept between model boundaries and the CFB Shilo supply wells.

5.4.6 Hydraulic Conductivity

Hydraulic conductivity distribution for CFB Shilo was presented in section 3.5.2. Table 5.2 below summarizes information collected from a number of sources, including field tests results, scientific reports and textbooks.

According to generic data, hydraulic conductivity may vary from 1×10^{-7} to 2×10^{-2} m/s in a sand aquifer. Slug tests performed at CFB Shilo yielded hydraulic conductivity measurements varying from 2.6×10^{-5} to 7.4×10^{-4}, compared with estimates in the range 7.3×10^{-9} to 1.4×10^{-3} m/s using grain-size analysis. Provided that the study area is underlain mostly by medium sand, the range of hydraulic conductivity values to be used as input to the model was set at 3×10^{-5} to 7×10^{-4} m/s. K was considered isotropic in the horizontal plane (K_x=K_y). A vertical anisotropy (K_x/K_z) in hydraulic conductivity is to be expected given the depositional history of the aquifer and the presence of bedding planes and silt lenses. Anderson and Woessner (1992 : 70) report vertical anisotropy ratios typically varying from 1 to 1000 in model applications. A vertical anisotropy ratio was selected for the model application: $K_z = 0,1K_x$ or K_x/K_z=10.

Two hydraulic conductivity patterns will be tested in the modeling process. In the first one, a homogeneous hydraulic conductivity value will be set across the modelled area based on a range of realistic values identified in table 5.2.

Table 5.2 Hydraulic conductivity estimates for CFB Shilo and the Assiniboine Delta Aquifer.

Reference	K (m/s)	Location
	Estimates	
Ampleman et al. (2003) (slug tests)	2.56×10^{-5} to 7.38×10^{-4}	Shilo area
Ampleman et al. (2003) (grain-size analysis)	7.31×10^{-9} to 1.35×10^{-3}	Shilo area
Frost and Render (2002)	2.3×10^{-3} to 1.4×10^{-3}	Shilo area
Render (1988)	$3{,}8 \times 10^{-3}$ to 1.4×10^{-3}	Shilo area
	Generic	
Freeze and Cherry (1979)	1×10^{-7} to 2×10^{-2}	--
Anderson and Woesner (1992 : 40)	$5{,}8 \times 10^{-6}$ to $1{,}1 \times 10^{-3}$	--
Range of input values for the numerical model	3×10^{-5} to 7×10^{-4}	CFB Shilo

Zones of different hydraulic conductivities established based on the hydraulic conductivity map presented in figure 3.6 will be defined in the second scenario. Indeed, the analysis of our data indicates that hydraulic conductivity generally decreases in an eastward direction. This trend is consistent with regional scale measurements reported by Render (1988). The depositional history, whereby sediments carried by the glacial Assiniboine river to the west created an alluvial fan, also supports this interpretation. Smaller particles such as fine sand would have been carried further than medium sand or gravel, thus resulting in a decrease in hydraulic conductivity in an eastward direction. Therefore, zones of different hydraulic conductivity will be defined based on figure 3.6.

5.4.7 Recharge

Recharge can be defined as the amount of water reaching the saturated zone of the aquifer. It is an important component in the understanding of groundwater systems, and one of the most difficult to evaluate precisely. Natural recharge in an unconfined aquifer may be determined by several factors: the amount of precipitation available for infiltration (precipitation minus evapotranspiration and runoff), the vertical hydraulic conductivity of surficial deposits and other strata above the aquifer (which determine how much water can move downward to the aquifer - infiltration in the saturated zone), and the transmissivity of the aquifer and its potentiometric gradient (Fetter, 1994 : 512).

Precipitation will be considered the only source of groundwater recharge for the modeled area. Several authors estimated the distribution of precipitation in the ADA aquifer system among the various pathways available to inflow to the system. A number of estimates are presented in table 5.3.

Table 5.3 Parameters controlling recharge in the Assiniboine Delta Aquifer.

Pathway / Author	Harrison & Kelin, 2003	Kelin, 2002	Frost & Render, 2003	Render, 1988
IN – Precipitation	100 %	100 %	100 %	100 %
OUT - Evapotranspiration	85 %	85 %	90 %	95 %
OUT – Streamflow	13 %	10 %	8 %	5 %
OUT – Consumptive Use	2 %	2 %	2 %	
OUT – Interflow		2 %		
OUT – Surface Runoff		1 %		

Recharge can be expressed in various ways: as a percentage of total annual precipitation, as a height of rainfall (product of total water level change during the recharge period and effective porosity, in mm) or as an increase in the level of the water table (mm). Groundwater recharge values for the Assiniboine aquifer were drawn from two major sources: a) estimates from three authors (first four rows, Table 5.4) and b) estimates from a water table hydrograph from a well located in CFB Shilo (last row, Table 5.4). This well is located in the middle of the base, in an area where the water level is not influenced by irrigation wells or base water supply wells. It should be noted that the low recharge rate for an unconfined aquifer may be explained by the fact that more than half of precipitations occur during summer months in brief rain episodes, when the climate is particularly warm (high evapotranspiration and low infiltration). Recharge occur almost exclusively in the spring during snowmelt

Table 5.4 Recharge estimates for the Assiniboine Delta Aquifer.

Reference /Parameter	Annual precipitation (mm)	Increase in water table level (mm)	Recharge (mm/an)	Recharge (% of precipitation)	Study period	Location
Province of Manitoba (1970)	483	143,5	23	5%	1921-1967	Northeast of Shilo (Carberry)
Render (1988)	--	--	25	5 %	1983-1986	Pine Creek watershed, north east of Shilo
Frost and Render (2002)	--	--	47	10%	--	ADA
Kelin 2002	--	--	56	12%	--	ADA
Harrison and Kelin (2003)	--	--	68 (max)	15% (max)	--	ADA
Ampleman et al. (2003)	453	--	50	11 %	1981-2001	Shilo area

As can be seen in Table 5.4, estimated recharge values vary from 5 % to 15% of precipitation, or 23 mm to 68 mm if expressed in equivalent height of rainfall. The recharge value of 50 mm (11% of precipitation) calculated from a CFB Shilo well falls within the range of the three last values and is twice as high as the two first reported values. The presence of patches of surficial clay in the area where these two first values (5%) were measured may account in part for the lower recharge rates in this zone as opposed to that of the overall aquifer or Shilo area. Differences in vegetation cover and in study periods may also explain the discrepancy in estimated recharge values.

In the model, recharge inflow is equal to $R\Delta x\Delta y$ (L^3/T) for each surface cell element. A constant recharge value was assumed over the entire study area given the similar prevalent soil and vegetation characteristics (sandy soils with sparse vegetation). Based on the values reported in table 5.4, recharge was allowed to vary over the entire range of estimated recharge values (20 to 70 mm/y) during the calibration process.

According to several authors (Table 5.4), precipitation contributes to recharge mostly during the spring period following snowmelt. In summer and autumn, rainfall is almost entirely lost to evapotranspiration. However, rare periods of excess rainfall may induce some recharge in periods other than spring (Province of Manitoba, 1977 : 5). This interpretation of recharge behaviour is supported by the well hydrographs presented in figure 5.8, which illustrates the general trend in water levels in the portion of the aquifer underlying CFB Shilo over the long term. Spring recharge results in a steep rise in water level, followed by a gradual decline in summer and winter until the following spring recharge event. Water levels were also recorded in two observation wells over a one year period in 2001; well hydrographs and methodology are presented in appendix N. Calculation files are available in document S19 on the CD-ROM.

The hydrograph presented in figure 5.8 was used to assess the average long term water level in the ADA (black line).

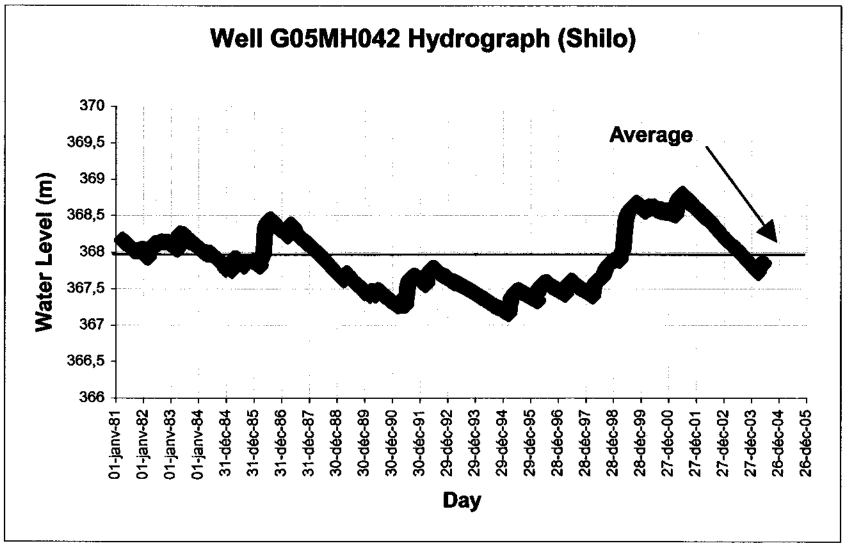


Figure 5.8 Well hydrographs for a well located within CFB Shilo, outside the influence of pumping wells.

This evaluation was useful to determine which of the available water level data sets (year 2001 or 2002) should be used for model calibration. The dataset whose average level is closer to the average long term water level in the aquifer should be used. Year 2000 data set was not considered because of the small number of water measurements for that year. The hydrograph clearly shows that water levels were generally fairly high between 1999 and 2002 and above the long term average. Therefore, water level measurements from year 2002 will be used for model calibration, as they are lower than those from year 2001 (30 cm below) and not too far from the long-term average.

5.4.8 Pumping Wells

Pumping wells are a source of hydrologic stress to the system. Three categories of pumping wells were identified within the study area:

- CFB Shilo supply wells. According to CFB Shilo Natural Resources Management Plan, citing Environnement Canada (1994 : 44), CFB Shilo is one of the single largest users of the aquifer. Three wells are used on a daily basis to supply water for both domestic and operational purposes: GW-SUP-5, GW-SUP-16 and GW-SUP-27. These wells account for most of the water withdrawal within the study area and were therefore included in the model. The heaviest use is in the summer period and in early fall. Metered consumption records for the past years are as follows: 775 300 m^3 in 1994 (Environment Canada, 1994 cited by CFB Shilo Natural Resources Management Plan), 830 000 m^3 in 1997 (Kelin 2002), 701 888 m^3 in 1998-1999, 509 900 m^3 for 1999-2000 and 426 737 m^3 for 2000-2001 (Frost and Render 2002).

Wells GW-SUP-5 and GW-SUP-16 have a lower supply capacity. According to the operator of the pumping station, these two wells are usually operated simultaneously in rotation with well GW-SUP-27. Maximum operating levels and other well characteristics are reported in Table 5.5 below.

Table 5.5 CFB Shilo water supply well characteristics.

Characteristic/Well	GW-SUP-5	GW-SUP-16	GW-SUP-27
Construction Year	1965	1978	1982
Casing (m)	0 - 27,7	0 - 26,2	0 - 29,1
Perforations (m)	27,7 - 38,4	26,2 – 30,8	29,1 – 35,3
Pumping rate capacity (m^3/min)	1,84	1,84	3,40
Pumping rate capacity (m^3/day)	2642	2642	4896
Pumping rate (reported/model) (m^3/day)	825	825	1650

Reported consumption levels indicate that CFB Shilo supply wells are probably not used to full capacity during most of the year. If well GW-SUP-27 were used at its full capacity (4896 m^3/day) 24 hours per day, the total consumption would be 1 787 040 m^3 over a year. This is more than 4 times the metered consumption reported in 2000-2001. An average consumption of 600 000 m^3/year will be assumed in the model, as well as corresponding average pumping rates for the three supply wells (Table 5.5, row 6). Moreover, the three pumping wells will be represented in the model as a single well with a pumping rate of 1650 m^3/d. This representation is realistic as the three wells are used in rotation and are located close to each other (200 m). Supply wells were located directly on a node and the pumping rate assigned to the layers corresponding to the well screened interval.

- Private domestic wells. A small number of private houses located to the northwest and west of CFB Shilo residential area use private wells or sand points. These pumping devices will be ignored provided their low consumption rates compared to aquifer capacity.

- Irrigation wells and pivots: A number of irrigation wells and pivots are located to the west and southwest of the study area. Render (1988 : 31) estimated that in the mid-1980's, about 30 pivots were pumping an average of 4 934 000 m^3/year from the Assiniboine West sub-bassin, which amounts to an average of 450 m^3/d per pivot. Pivots are pumping water only during a limited number of days during summer time (40-60 days in average). According to a 2001 survey carried out by water licensing staff of Manitoba Conservation, 32 irrigation wells were identified in the Assiniboine West sub-basin. About 17 of those wells are located within the western portion of the study area.

  Render (1988) simulated a massive pumping using 86 pivots and a total pumping of 16 037 000 m^3 over a 83 day-period. Drawdown was up to 1.9 m under the pivots and less than 30 cm under CFB Shilo residential area. These results suggest that water pumping for irrigation probably has little effect on the water table under CFB Shilo. Irrigation pivots were therefore not represented in the model.

5.5 Flow Model Calibration Targets

A number of parameters, such as stratigraphic data, mesh design and boundary conditions were assumed to be known and were kept constant throughout the calibration process. Therefore, hydraulic conductivity and recharge were the only two parameters to be adjusted in the model.

Six calibration targets were established prior to initiating simulations:

1. Realistic hydraulic heads

   The calibration target is expressed as a percentage (5%) of the range of measured hydraulic head values. Head values range from 341 to 372 m; the calibration target is therefore set at 5% of this range, or +/- 1,55 m. In other words, simulated head should range between the measured head value plus or minus 1.55 m, or about 1.5 m. Another objective of the calibration process is to minimize the root mean square, mean and absolute mean errors for simulated hydraulic heads compared to heads measured in observation wells.

2. Realistic groundwater flow directions and velocities

   Flow directions derived from water level measurements and Geoflo testing were illustrated on plate 6. Velocities vary between 100 m/y to the north of the study area to 600 m/y near the Assiniboine River. Since model boundaries do not reach the river banks, velocities should all be well below 500 m/y. Average velocities should be around 150 m/y over most of the modeled area.

3. Reproduce higher piezometric contours in the northern section of the study area (Plate 5, Appendix H)

   As shown on Plate 5, a piezometric high appears on the water level contour map in the Essen battlerun. It is located in the sand dune area and the intent is to reproduce this feature in the model.

4. Water budget deviation below 1%

   A small deviation in water budget (mass balance) is an indication that the model converges towards a solution and that numerical errors are minimal. Error and convergence criteria are set to define the precision required in the solution of non-linear flow equations. A small error criterion requires a greater accuracy in model design and data input, as well as increased numerical efforts (number of iterations). Therefore, an equilibrium must be established between model precision and computational time when selecting an error criteria. The error criteria was set at 10^{-5} (relative number) in order to minimize numerical errors and the maximum number of iteration established at 12. These errors can be due to truncation or round-off during the iteration process. The relatively high number of elements minimized discretization errors.

5. Realistic outflow (baseflow) towards the Assiniboine River.

   Groundwater represents a significant contribution to streamflow in the Assiniboine River, particularly during dry periods. The discharge rate to the river is also relatively constant (Harrison and Kelin, 2003 : 2). According to estimates by Harrison and Kelin (2003 : 4), the Assiniboine Delta Aquifer contributes on average 10% of flow upstream of Winnipeg. This contribution increases to 16% in dry years (1:10 year conditions) and 25% in drought years (1:50 year conditions). Discharge from the Assiniboine Delta Aquifer is estimated to be distributed with a proportion 65:35 respectively in the two river systems (Assiniboine and Whitemud) of the aquifer (Frost and Render, 2002 : 10).

A number of authors estimated the ADA discharge rate into the Assiniboine River. These estimates were used to evaluate the amount of discharge that could be attributed to the portion of the ADA comprised in the model area. Table 5.6 presents those estimates; a more detailed description is available in Appendix O. Average daily discharge vary from 52 000 m^3/d under dry conditions to 94 000 m^3/d in normal years. Sporadic discharge rate in springtime may reach 400 000 m^3/d. Provided that the model is run under steady-state conditions, an average annual long term discharge rate from the model between 50 000 and 95 000 m^3/d will be considered realistic for calibration purposes.

Table 5.6: Estimated discharge rates in the Assiniboine river from the ADA section included in the modeled area.

Reference	**Discharge rate to the Assiniboine from the model area**	**Estimated annual discharge to the Assiniboine (m^3/y)**
Frost and Render (2002)	At least 52 000 m^3/d	18 980 000
Render (1988)	94 000 m^3/d	34 310 000
Harrison (1986) in Render (1988)	65 500 m^3/d	23 725 000
Harrison (1985)	90 000 m^3/d	32 850 000
Harrison and Kelin (2003) in Render (1988)	69 000 m^3/d (52 000 m^3/d in drier years)	21 185 000 (18 980 000 in drier years)
Kelin (2002)	73 000 m^3/d	26 645 000
Mattick and Wagner (1968)	73 000 m^3/d (400 000 m^3/d in the spring)	26 645 000

6. Realistic hydraulic conductivity and recharge values

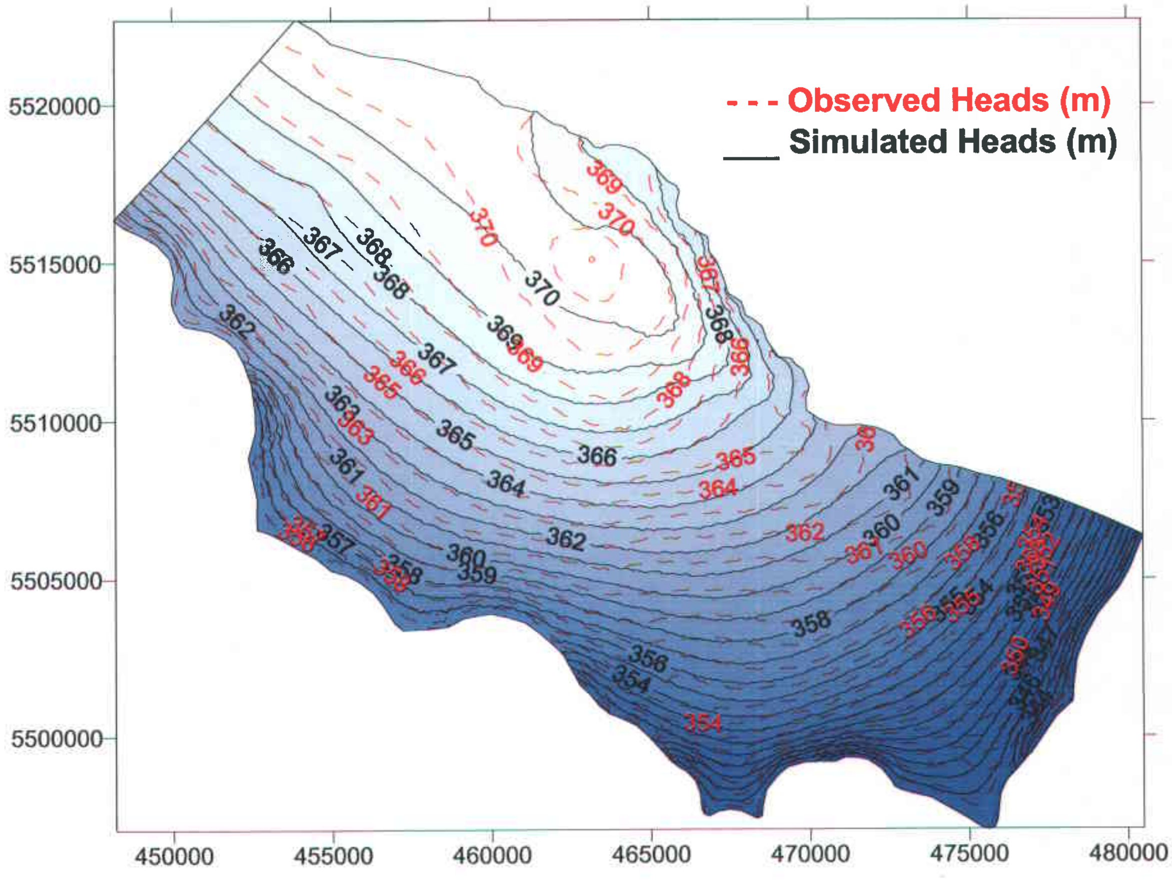
As commented in sections 5.4.6 and 5.4.7, hydraulic conductivity and recharge values will be allowed to vary respectively between 3×10^{-5} and 7×10^{-4} m/s and 20-70 mm/y. A sensitivity analysis will determine whether selected model parameters result in an optimal calibration.

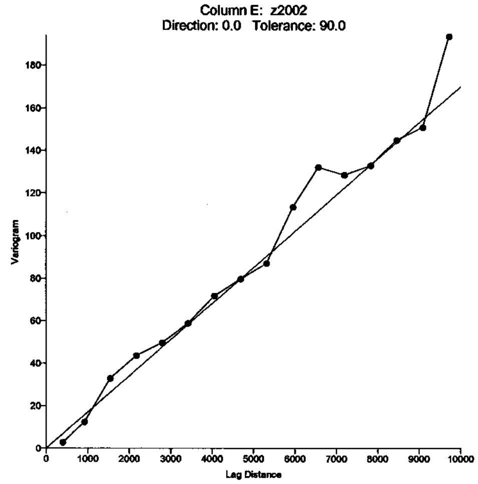
5.6 Model Results

The numerical groundwater flow model was calibrated under steady-state conditions only. The calibration process was carried out using a combination of manual trial-and-error and systematic approach based on a realistic range of hydraulic conductivity and recharge values (see calibration target #6). Model results are presented in this section. Input and output files are available on CD (S20).

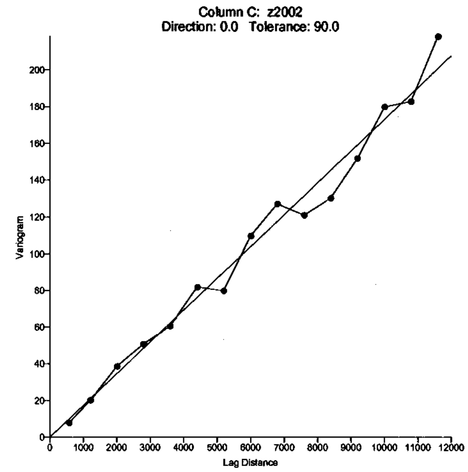
5.6.1 Groundwater Flow – Simulated heads and velocity

Figure 5.9 illustrates the simulated heads overlain with the interpolation of observed head contours. The calibrated model represents adequately the groundwater flow system over most of the study area. Model precision is lower in sectors with high hydraulic gradients (near the southern border), as well as near the Epinette Creek border. CFB Shilo water supply well has a very limited influence on the regional water table.





Linear variogram - Interpolation of measured groundwater elevations
Figure 3.10 (2002 water elevation data) and Figure 5.9 dotted red lines



Linear variogram - Interpolation of simulated groundwater elevations
Figure 5.9 plain black lines

Figure 5.9 Comparison between the simulated and observed groundwater flow patterns. Simulated heads are represented with black lines and a blue background. The red dotted lines are observed head contours. Linear variograms for both the simulated and observed (measured) groundwater flow paterns are also shown.

Two cross-sections of simulated hydraulic heads are shown in figure 5.10. The increase in hydraulic gradient from the Epinette Creek border (A, B) to the southern border (A', B') is obvious on both cross-section. The influence of CFB Shilo supply well on the water table (drawdown) is illustrated in cross-section AA'. Cross-section BB' clearly shows the groundwater divide between the Epinette Creek South and Assiniboine West sub-bassins.

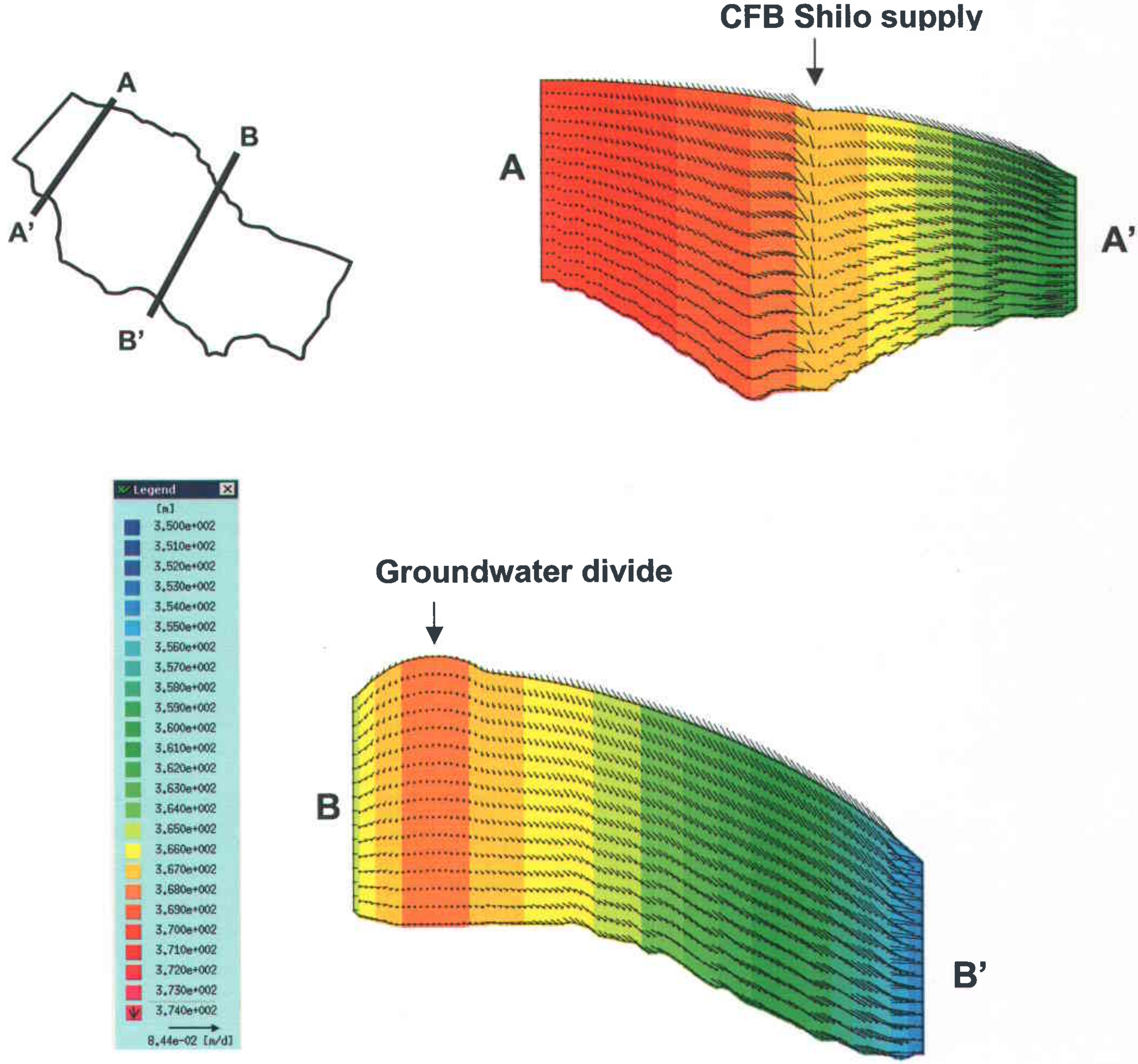


Figure 5.10 Cross-section showing simulated heads (colours) as well as velocity vectors (arrows).

The relationship between simulated and observed heads is shown in figure 5.11. A total of 83 observation wells scattered over the entire study area (figure 5.12) were used as a reference for calibration. The 1:1 line in figure 5.11 represents a perfect match between simulated and observed heads. Simulated heads generally follow the trend of the 1:1 line and are scattered on both of its sides, indicating an adequate match of simulated and observed head values.

The model error can be further assessed by looking at the difference between simulated and observed heads. As mentioned in the previous section, the calibration target was set at +/- 1.55 m from the 1:1 line. Only five calibrated head values (6%) fall out of this target, one exceeding the target and four falling below. Eighty-four (84%) of calibrated head values have residual error below +/- 1.00 m and 61% below +/- 0.50 m. Not surprisingly, the highest discrepancies between observed and simulated head values occur near the southern border of the model, where the hydraulic gradient is the highest. Since observation wells do not fall directly on the nodes, the distance between the location of observation wells and the nodes closest to these wells (where the simulated head values were retrieved) may also explain part of the discrepancies between observed and simulated head values.

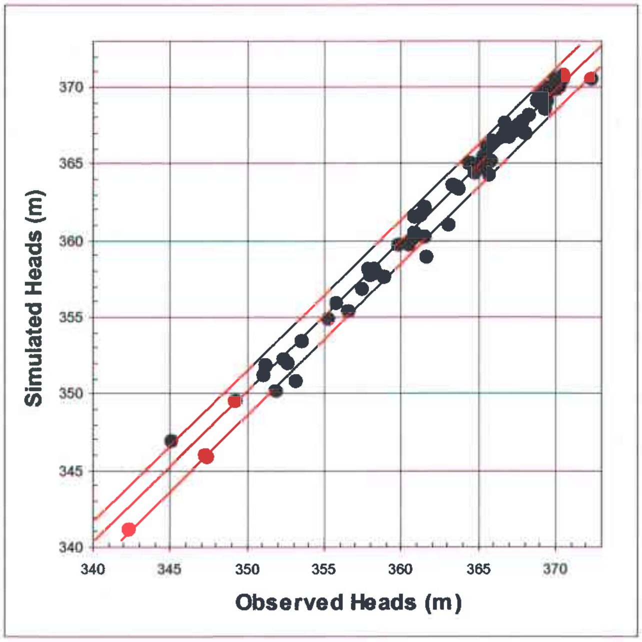


Figure 5.11 Simulated versus Observed Hydraulic Heads

Simulated groundwater velocities were retrieved using Feflow postprocessor. An effective porosity of n = 0,25 was selected to calculate groundwater velocity based on de Marsily (1986, p. 36) assessment of total porosity in sand aquifers (15-48%). Velocity vectors shown in figure 5.12 clearly indicate an increased velocity near the southern model limit as well as near the supply well. Results also show that almost all the model groundwater drains towards the Assiniboine River.

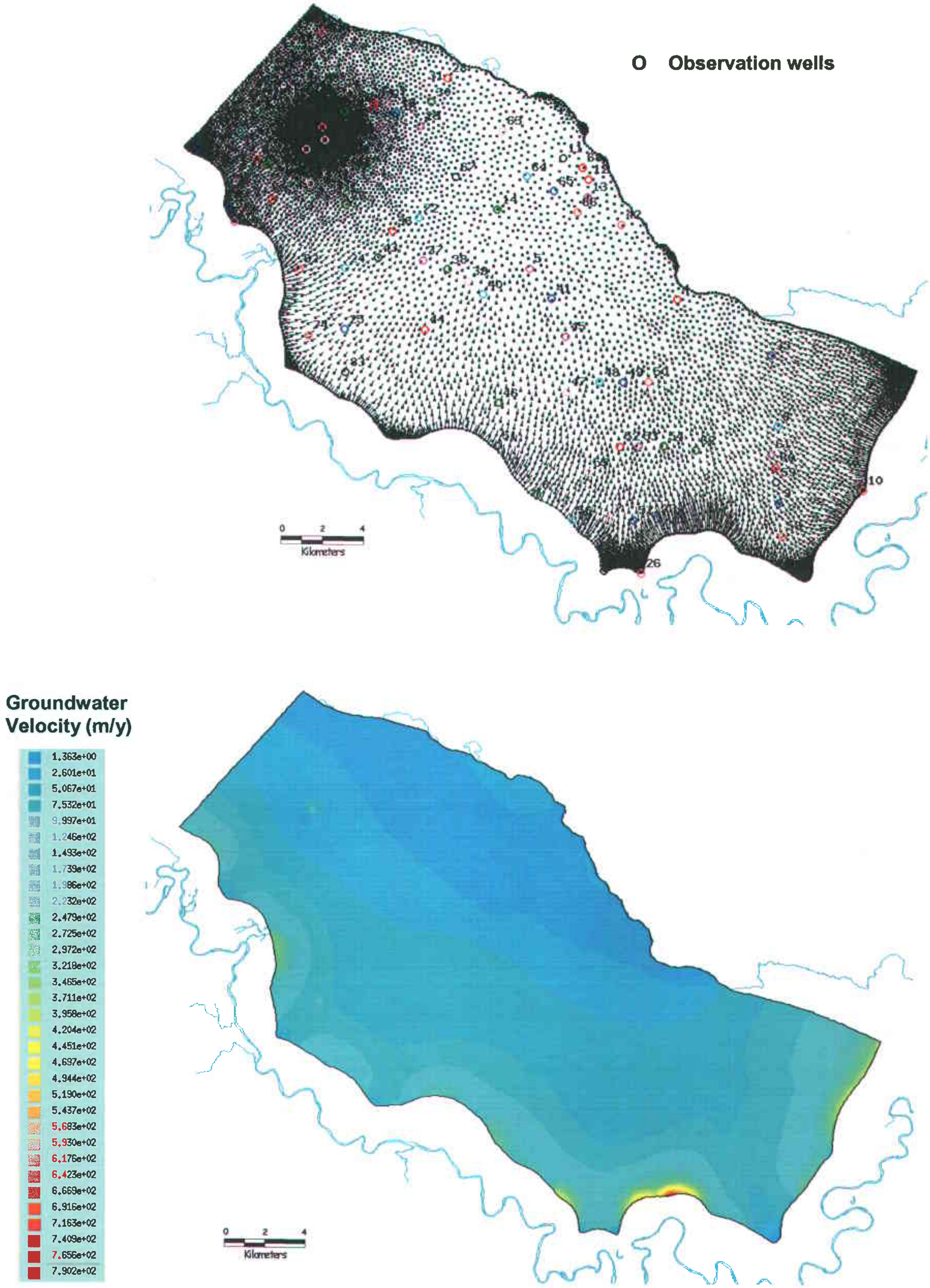


Figure 5.12 Groundwater velocities in m/y. Velocity vectors are shown as black arrows in the upper section, indicating an increase in groundwater velocity near the southern limit of the model. Groundwater velocity distribution pattern is shown in colour in the bottom part of the figure.

The bottom section of figure 5.12 illustrates the distribution of groundwater velocities in the model. Velocities vary between 26 and 100 m/y in the central section of the model and increase rapidly to several hundreds of m/y close to the southern limit of the model. This model limit is located near the seepage faces of the steep Assiniboine River banks.

Simulated velocities in the central part of the model (26-100 m/y) are lower than those measured with the Geoflo (100-250 m/y in the same section). Geoflo inaccuracies, misestimation of effective porosity, underestimation of K or R values may account for this discrepancy. Feflow calculation process based on simulation results (Feflow Darcy fluxes used in the calculation of groundwater velocity are secondary results of the simulation run) may also account for the difference in velocities.

5.6.2 Calibrated Parametric values

Ranges of hydraulic conductivity and recharge values used as input in the model are summarized in table 5.7 below.

Table 5.7 Hydraulic conductivity and recharge values: estimates, model input and simulated values.

Array	**Reported or Measured values**	**Feflow input**	**Calibrated Model**
Hydraulic conductivity (m/s)	10^{-7} to 3×10^{-3}	3×10^{-5} to 7×10^{-4}	Three zones: 3.5×10^{-4}, 5×10^{-5} and 3×10^{-4}.
Recharge (mm/y)	23-68	20-70	58

The effect of variations in each of these two parameters were evaluated through successive runs of the model (Table 5.8). All things being equal, an increase in the recharge rate results in a higher water table and greater amounts of water flowing through the aquifer. A decrease in hydraulic conductivity also results in higher hydraulic heads but tends to also decrease the amount of water flowing through the aquifer. Since the amount of water discharging to the Assiniboine river was used as a guidance in the calibration process, an adequate combination of hydraulic conductivity and recharge values resulting in realistic discharges to the river had to be identified.

Table 5.8 Effect on the model of modifications to hydraulic conductivity and recharge values

Parameter	Action	Influence on Hydraulic Heads	Influence on Discharge to the Assiniboine River
Hydraulic conductivity	Decrease	Increase	Decrease
Hydraulic Conductivity	Increase	Decrease	Increase
Recharge	Decrease	Decrease	Decrease
Recharge	Increase	Increase	Increase

The simulated calibrated parameters are 58 mm/y for the recharge and a hydraulic conductivity varying from 3×10^{-4} to 5×10^{-5} m/s. Recharge thus represents about 11% of precipitation, a value in the upper range of reported recharge values (Table 5.4). A homogeneous recharge was applied over the entire study area given the lack of precise information to justify recharge zoning. Two different scenarios were tested for hydraulic conductivity. In the first one, a homogeneous hydraulic conductivity was applied over the entire study area. In the second, three zones of varying hydraulic conductivity were established as shown in Figure 5.13. The error associated with simulated heads was minimized with the second scenario. Various combinations of recharge and hydraulic conductivity were tested until the error was minimized.

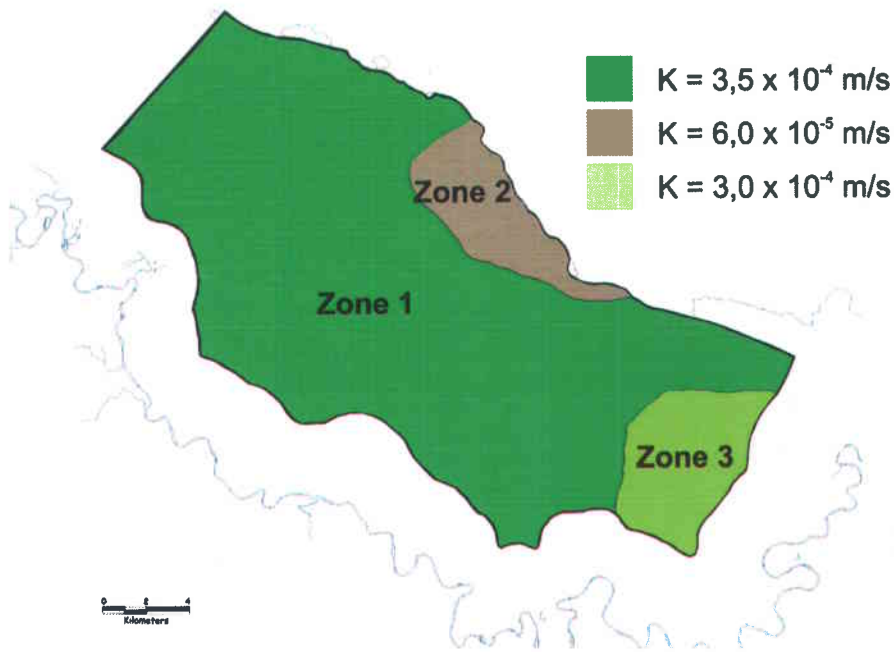


Figure 5.13: Hydraulic conductivity values in the calibrated model

Hydraulic conductivity values averaged for each zone from slug tests data are compared to calibrated values in table 5.9. In the model, hydraulic conductivity in zone 1, which covers most of the study area, is slightly greater than the value estimated from slug tests and is indicative of the important amount of water flowing through the aquifer. It should be noted that higher hydraulic conductivity values similar to those obtained from slug tests in the western part of the study area ($K=10^{-3}$ m/s) did not produce coherent head values when introduced in the model, resulting in simulated heads lower than observed heads. The same K value was thus used over the western and central parts of the model (zone 1) even if calibrated K values in the eastern part of that zone are smaller than estimated values. Errors in the model stratigraphy may explain the systematically lower hydraulic head values obtained in this area .

Head values in zone no 2 could be reproduced with a hydraulic conductivity lower than that of zone 1 and similar to that estimated from slug tests. Lower conductivities in this area are supported by the presence of fine sand and the finding of organic lenses in drilling cores in this area. The piezometric high identified in Plate 4 appears in the model. Finally, the calibrated K value in zone no 3, although slightly lower than that in zone no 1, remains significantly higher than the estimated value. Stratigraphic uncertainties as well as an underestimation of measured hydraulic conductivity due to the presence of heterogeneities could account for this difference. Although hydraulic conductivity in zone 3 is very similar to that in zone 1, a lower K value was attributed in zone 3 since slug tests performed in zone 3 suggest a lower K value than in other parts of the model domain. For each zone, K_x was deemed equal to K_y. It was estimated that K_z was one order of magnitude lower than K_x or K_y ($K_z = 0{,}1K_x = 0{,}1K_y$).

Table 5.9 Comparison between estimated and calibrated hydraulic conductivity.

Zone	Estimated Hydraulic conductivity (slug test) (m/s)	Calibrated Hydraulic conductivity Kx=Ky (model) (m/s)	Calibrated Hydraulic conductivity Kz (model) (m/s)
Zone 1	$2{,}0 \times 10^{-4}$	$3{,}5 \times 10^{-4}$	$3{,}5 \times 10^{-5}$
Zone 2	$7{,}0 \times 10^{-5}$	$6{,}0 \times 10^{-5}$	$6{,}0 \times 10^{-6}$
Zone 3	$8{,}0 \times 10^{-5}$	$3{,}0 \times 10^{-4}$	$3{,}0 \times 10^{-5}$

Finally, it is worth noting that a number of combinations of hydraulic conductivity and recharge values yielded plausible model results, including head values. The most adequate calibration values for K and R were therefore selected based on the amount of outflow to the Assiniboine River as well as based on the recharge, whose value was reaching the upper limit of the estimated interval.

5.6.3 Water Balance

Components of the groundwater balance in the calibrated model are presented in table 5.10. These values were retrieved using the budget analyser tool in Feflow, whose function is to compute fluxes which enter or leave the model domain. Inputs include recharge and constant head cells from the northern boundary (Epinette Creek and Sewell Lake). This input represents groundwater coming from upgradient aquifer portions north of the modelled area and flowing under Epinette Creek, mostly under Sewell Lake and its discharge area. Outputs from the model include base water supply well as well as constant head cells along the southern boundary (near the Assiniboine River) and along the northern boundary (Epinette Creek). Discharge along Epinette Creek is indicative of a contribution of the Epinette Creek South sub-bassin to Epinette Creek baseflow.

Discharge along the southern border (65 000 m^3/d) is consistent with estimates of the contribution of this section of the aquifer to the Assiniboine river (52 000 – 94 000 m^3/d). The steady state water balance discrepancy is 4 m^3/d, or 0,004%. A discrepancy of 0.01% is generally considered adequate.

Table 5.10 Groundwater balance for the calibrated model

Source/Water Balance		**IN (m^3/day)**	**OUT (m^3/day)**
Recharge		**64047**	**0**
Flux through boundaries		**1266**	**63667**
	Northern boundary	1214	5959
	Southern boundary	52	57708
	No flow boundary West	0	0
	No flow boundary East	0	0
Pumping Well		**0**	**1650**
Total		**65313**	**65 317**
Discrepancy : 4 m^3/d or 0.004%			

The fluid flux analyser tool was also used to evaluate the amounts of water entering or leaving the model at boundaries. Flow through sections is estimated as follows: velocities (specific Darcy fluxes) for each node are projected onto the sections and multiplied with the flow through area. According to Feflow help program, inaccuracies may occur because velocities are secondary results of the simulation run and the velocity vectors from nodes are projected onto the sections.

The fact that a 2,25% discrepancy occur between inflow and outflow into the model when analysed with this tool supports this statement. The fluid flux analyser indicates an outflow of 51 299 m^3/d along the southern border, less than with the budget analyser. Small volumes of water are also entering or leaving the model from no flow boundaries according to the fluid flux analyser. This could be an indication that these boundaries are not totally perpendicular to groundwater flow. These amounts of water, however, are negligible.

5.6.4 Sensitivity Analysis

The sensitivity of the model to changes in hydraulic conductivity and recharge was estimated. An analysis was carried out by varying each of these parameters independently. Hydraulic conductivity and recharge rates were modified by 10, 20, 30 and 40% both above and under the calibration values as shown in Table 5.11. These modified values and rates fall within the range of measured and reported hydraulic conductivity and recharge values.

Table 5.11 Effect of variations of hydraulic conductivity and recharge on the calibrated groundwater flow model. Errors apply to measured piezometric values.

RECHARGE							
Variation	**Recharge (mm/y)**			**RMS Error (m)**	**Mean Error (m)**	**Absolute Mean Error (m)**	**Discharge to Assiniboine River (m^3/d)**
-40%	35			1,92	-1,69	1,71	36 003
-30%	41			1,53	-1,31	1,34	39 810
-20%	46			1,21	-0,97	1,01	43 362
-10%	52			0,92	-0,58	0,68	47 371
0%	58			0,77	-0,21	0,55	51 299
+10%	64			0,82	0,11	0,63	54 806
+20%	70			1,03	0,47	0,89	58 716
+30%	76			1,30	0,80	1,17	62 370
+40%	82			1,60	1,12	1,45	66 006
HYDRAULIC CONDUCTIVITY							
Variation	**K Zone 1 (m/s)**	**K Zone 2 (m/s)**	**K Zone 3 (m/s)**	**RMS Error (m)**	**Mean Error (m)**	**Absolute Mean Error (m)**	**Discharge to Assiniboine River (m^3/d)**
-40%	$2,10 \times 10^{-4}$	$3,6 \times 10^{-5}$	$1,8 \times 10^{-4}$	2,38	1,86	2,14	45 029
-30%	$2,45 \times 10^{-4}$	$4,2 \times 10^{-5}$	$3,1 \times 10^{-4}$	1,64	1,15	1,47	46 614
-20%	$2,80 \times 10^{-4}$	$4,8 \times 10^{-5}$	$2,4 \times 10^{-4}$	1,13	0,60	0,99	48 284
-10%	$3,15 \times 10^{-4}$	$5,4 \times 10^{-5}$	$2,7 \times 10^{-4}$	0,84	0,15	0,66	49 732
0%	$3,50 \times 10^{-4}$	$6,0 \times 10^{-5}$	$3,0 \times 10^{-4}$	0,77	-0,21	0,55	51 299
+10%	$3,85 \times 10^{-4}$	$6,6 \times 10^{-5}$	$3,3 \times 10^{-4}$	0,88	-0.52	0,64	52 712
+20%	$4,20 \times 10^{-4}$	$7,2 \times 10^{-5}$	$3,6 \times 10^{-4}$	1,06	-0,77	0,84	54166
+30%	$4,55 \times 10^{-4}$	$7,8 \times 10^{-5}$	$3,9 \times 10^{-4}$	1,25	-1,00	1,04	55 603
+40%	$4,90 \times 10^{-4}$	$8,4 \times 10^{-5}$	$4,2 \times 10^{-4}$	1,43	-1,19	1,22	57138

The evolution of the RMS error depicted in figure 5.14 indicates that RSM, mean and absolute mean errors are minimized with the chosen recharge and hydraulic conductivity calibration values. Therefore, the sensitivity analysis indicates that the model is adequately calibrated.

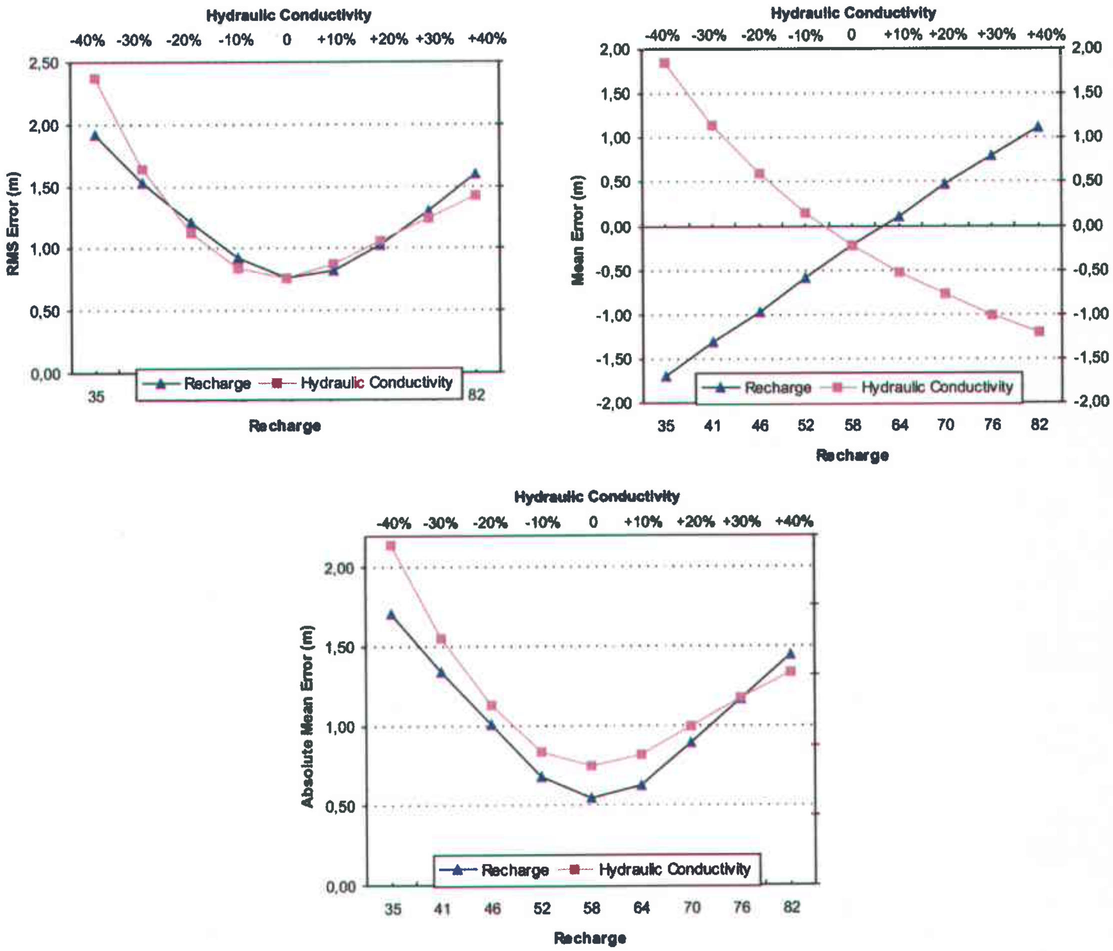


Figure 5.14 Effect of variations of hydraulic conductivity and recharge on the calibrated groundwater flow model

Figure 5.14 also indicates that the model is equally sensitive to both recharge and hydraulic conductivity in terms of head variations. The amount of discharge to the Assiniboine river, however, is more affected by variations in recharge than in hydraulic conductivity (Table 5.11).

Finally, the effect of grid design on error and convergence criteria was tested by refining the grid and increasing the criteria. Both head values and discharge rates were not affected by these operations. However, grid refinement at the southern border increases discharge through that border by some 2000 m^3/d. Grid refinement in this section of the model, where the hydraulic gradient is higher than in the rest of the model domain, thus provides a better representation of groundwater flow.

5.7 CFB Shilo supply wells capture zone

Inverse particle tracking was performed in Feflow in order to determine the extent of the CFB Shilo base supply well capture area as well as to evaluate whether CFB Shilo supply wells draw water from areas containing potentially hazardous substances such as the rifle ranges, the grenade range or dumps.

The maximum extent of CFB Shilo base supply wells capture area is illustrated in 2-D in figure 5.15. The capture area was established at a depth of 33 m, corresponding to the bottom of the screened interval. The capture zone reaches the model upper limit, indicating that some well water may ultimately be drawn from outside the modelled area.

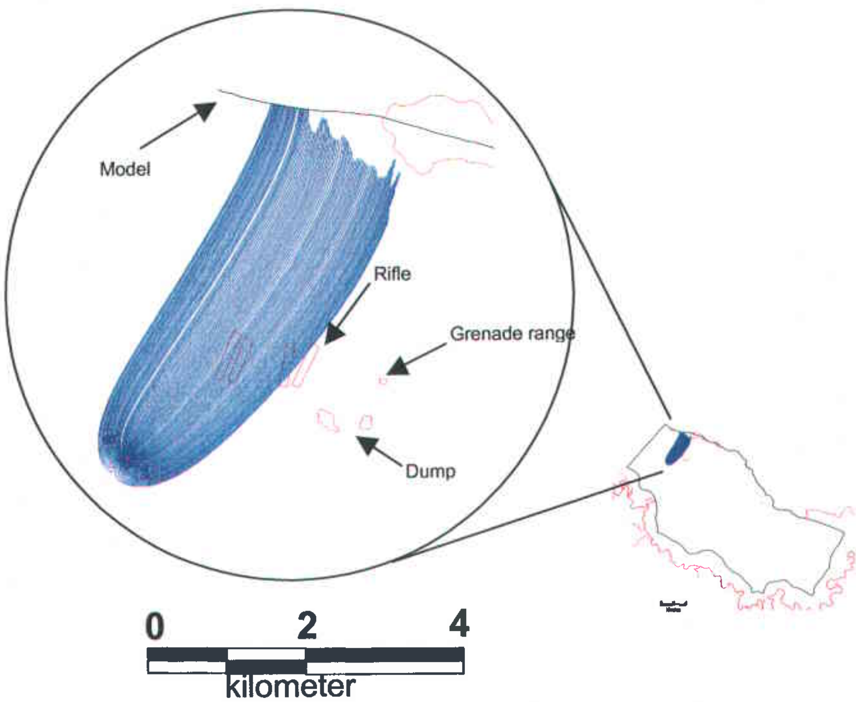


Figure 5.15 CFB Shilo supply wells capture zone.

As shown on the close-up section of figure 5.15, the capture area does not overlap CFB Shilo dump areas nor the grenade range. It does however encompass rifle ranges no 1 and 2 as well as part of rifle ranges no 3 and 4. A note of caution should be introduced at this time to recall that

CFB Shilo uses 3 supply wells located close to each other while the model uses only one. Figure 5.15 is thus only an approximation of the real capture zone of CFB Shilo supply wells. Moreover, this capture zone may vary according to effective pumping rates at CFB Shilo pumping station.

The three CFB Shilo pumping wells were represented as a single well in this regional model. However, representing each of the three wells individually would be preferable in a local model. Provided the other sources of uncertainty in the regional model, representing the three wells individually instead of as a single well would probably have had little influence on the capture zone, except in the immediate vicinity of the wells.

Inverse particle tracking with isochrone markers was performed to evaluate the travel time of groundwater to CFB Shilo supply wells (represented as a single well in the model). Resulting pathlines with time markers are illustrated in 2-D and 3-D in figure 5.16. The ellipsoidal shape of the capture zone of the supply well is clearly visible in the bottom illustration. Near the model border, pathlines follow the general direction of the regional groundwater system and then converge towards the well as the distance to the well decreases.

According to figure 5.16, water leaving the northern border of the model would take more than 100 years to reach the supply wells. Modeled velocity in this area is low (26 m/y), about 4 times lower than that measured with the Geoflo. However, the uncertainties associated with these measurements should be kept in mind. One reason that may explain the low modeled velocity near CFB Shilo supply well is the fact that model was calibrated in the western section with a K value lower than that estimated from field data (slug tests). Therefore, water velocities around CFB Shilo supply wells may be underestimated and travel time overestimated when performing inverse particle tracking. The use of a higher hydraulic conductivity value more representative of slug tests measurements, associated with a higher recharge, would have led to increased water velocities and lower travel times in this section of the model.

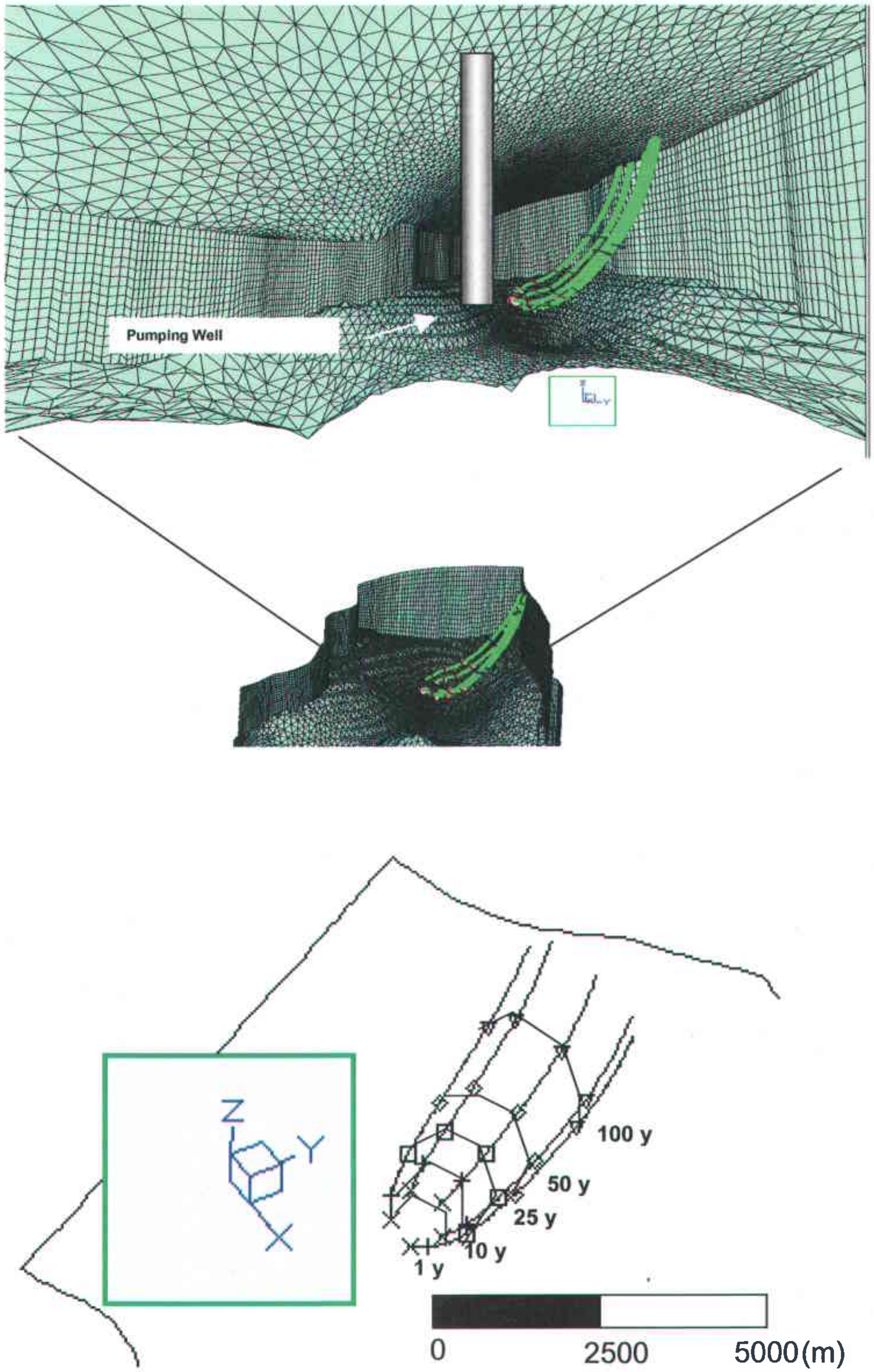


Figure 5.16 3-D and 2-D pathlines with isochrone markers illustrating the travel time within the well capture zone. Isochrones are represented as follows: blue & triangle = 100 y, orange & lozange = 50 y, red & square = 25 y, pink & x, = 10 y, purple & cross = 1 y.

Another exercise was performed to illustrate the travel path of hypothetical particles leaving rifle and grenade ranges as well as their time of travel (figure 5.17).

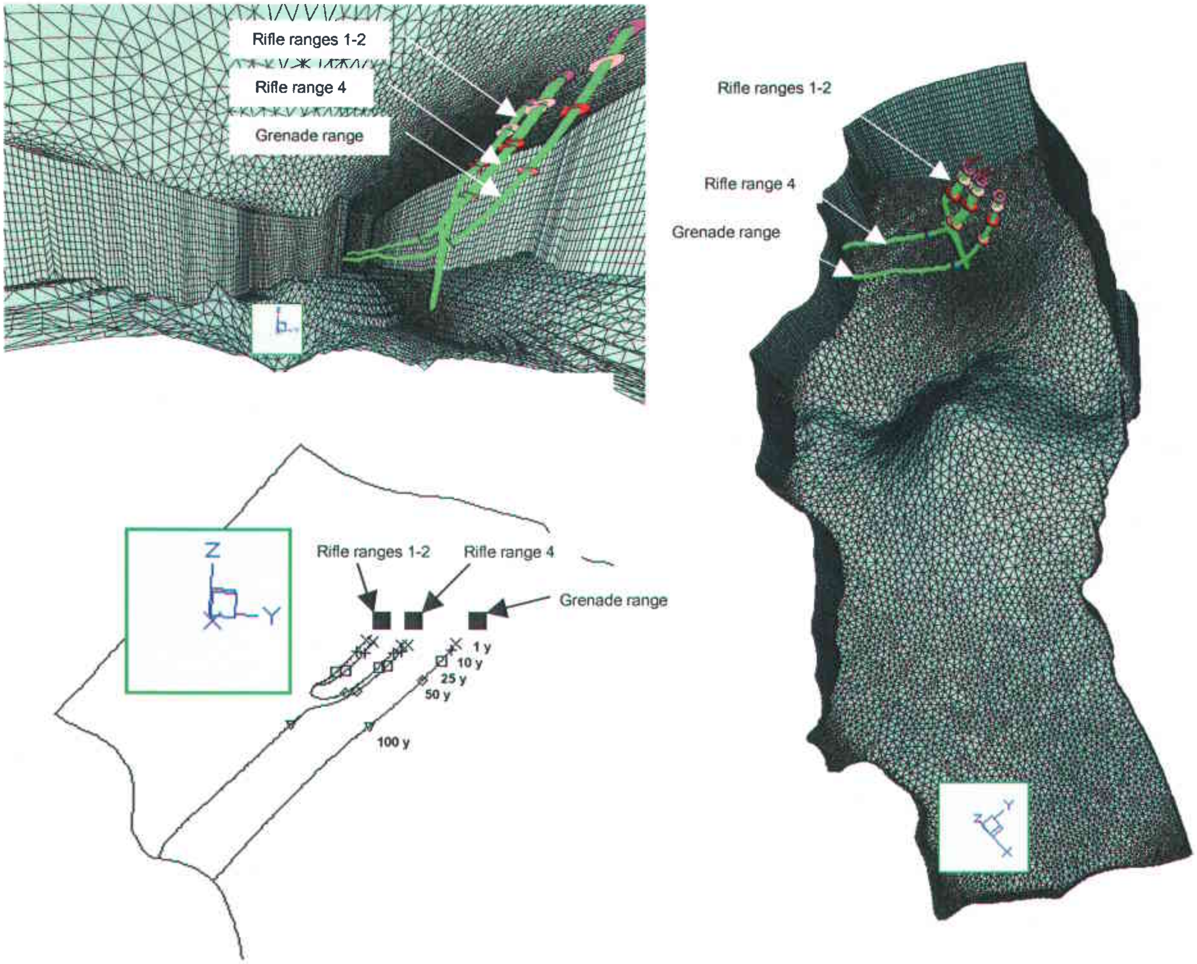


Figure 5.17. 3-D and 2-D pathline with isochrone markers illustrate the maximum travel itinerary and time of particles leaving the rifle ranges as well as adjacent areas. Legend: blue & triangle = 100 y, orange & square = 50 y, red & lozange = 25 y, pink & x, = 10 y, purple & cross = 1 y.

This exercise indicates that the potential for contamination of base water supply wells from contaminants leaching from training ranges is low. First, it should be recalled that none of the substances analysed in groundwater near the training ranges was found in concentrations exceeding CCME guidelines for drinking water or background levels. For the aquifer and eventually base supply wells to be eventually tainted by training activities, contaminants would first need to reach the water table. The unsaturated zone under rifle and grenade ranges vary from

3 to 8 m. Should potential contaminants eventually reach the water table, travel time to the base supply well was estimated at 25-50 y and at 50-100 y respectively for rifle ranges 1 and 2. This significant period leaves enough time for detecting potential contaminants through groundwater monitoring activities. Particles leaving part of rifle range 4 or the grenade range are heading towards the Assiniboine River.

As previously mentioned, a potential underestimation of hydraulic conductivity in this section of the model may lead to travel times estimates lower than field values. It should also be noted that travel times were calculated without consideration of adsorption effects and with only advective transport. Real travel times for contaminants would be longer should degradation processes, dispersion and retardation be taken into account.

Well head protection areas were not established as there are currently no regulations or guidelines defining well-head protection areas in Manitoba. However, set-back distances are specified in some regulations between wells and potential sources of contamination such as sewage lagoon, septic systems, manure stockpiles or confined livestock areas (Bob Betcher, Manitoba Conservation, personal communication, September 2004). It would be interesting to calculate well head protection areas using different values of effective porosity.

5.8 Concluding Thoughts

A conceptual model of the section of the ADA underlying CFB Shilo was developed using geological and hydrogeological data described in chapter 3. The groundwater flow pattern, hydraulic conductivity and recharge were then estimated using a numerical model of the aquifer. This model includes two specified and two no flow boundaries. The CFB Shilo's three supply wells were represented as a single pumping well. The calibrated model yielded a realistic pattern of hydraulic conductivity distribution and groundwater velocities. However, the later were lower than those estimated from field measurements with Geoflo.

Calibrated K and R values are close to field estimates, except for calibrated K values in the eastern section of the model, where they are lower than anticipated. This could explain the lower calibrated velocities in this area. Estimated outflow from the southern border (near the Assiniboine River) is consistent with estimates of the contribution of this section of the model to the Assiniboine River. Negligible discrepancies in the water balance indicate that numerical errors are minimal. A sensitivity analysis was performed to verify the calibration results.

Finally, CFB Shilo supply wells capture zone was defined using particle tracking. This tool was also useful in illustrating that should potential contaminants reach the water table under some training areas, their travel time would be long enough for an early detection. The modeling exercise presented in this chapter is based on a number of simplifying assumptions that may influence the results. For example, the exact thickness of the aquifer in not known precisely due to the very limited number of deep boreholes in this area. Also, the three base supply wells were represented as a single pumping well and irrigation wells were ignored. Both the uncertainties associated with the location of the bottom limit of the aquifer and the simplified pumping pattern may have affected the groundwater flow pattern. It would be useful to refine the model should a well head protection area be eventually defined around CFB Shilo supply wells. Finally, mass transport simulations could be performed should groundwater contaminati on be discovered int he future.

VI CONCLUSION

Located over a major regional aquifer in southern Manitoba, the Assiniboine Delta Aquifer, Canadian Forces Base Shilo has been used extensively for military training over the past decades by both Canadian and German troops. Following the departure of the Germans in 2000 and in the context of an increased environmental awareness in the military, an extensive investigation was carried out to identify the potential impacts of military training on the environment.

DRDC-Valcartier, in collaboration with INRS-ETE, undertook three field investigation campaigns from 2000 to 2002 to sample soils, groundwater and surface water. Collected samples were analyzed for metals, explosives and thorium 232, a radioactive isotope present in small quantities in the guiding system of MILAN missiles fired at CFB Shilo. Samples were collected in training ranges - rifle ranges, grenade ranges and battleruns - as well as in background areas. Hydrogeological investigations included the installation of a network of 78 observation wells, the drilling of two deep boreholes, water level measurements, measurements of groundwater velocity and direction, slug tests and grain-size analysis.

The objectives of the study were therefore to describe the geological and hydrogeological context, to identify potential sources of contamination of soils, groundwater and surface water and to assess the potential impact of these sources of contamination on the aquifer using a numerical model.

General geological and hydrogeological information was retrieved from previous studies of the aquifer; specific information about the study area was scarce however, and field work provided most of the data needed. Geological units underlying CFB Shilo, from bottom to top, are as follows: bedrock, till, silty clays, deltaic sands and aeolian sands. The Assiniboine Delta Aquifer (ADA) comprises both the deltaic and the aeolian sand layers. Its thickness vary from 15 to 36 m under CFB Shilo. Mean hydraulic conductivity was estimated at 1×10^{-4} m/s from slug tests and grain-size analyses, with K decreasing in an eastern direction.

Soils, groundwater and surface water were sampled for various substances whose presence in the environment could be associated with military activities such as artillery training or weapon explosions. The analysis of soil samples collected in rifle and grenade ranges revealed several metal concentrations over both CCME soil quality guidelines for agricultural use and the background concentration plus two times STD. Lead, copper and zinc concentrations were particularly high in both the rifle and grenade ranges, and cadmium in the grenade range only. Bismuth, arsenic and nickel were found over background concentration in the rifle ranges. In the grenade range, background concentrations were also exceeded for chromium and magnesium. The situation was different in battleruns, where only a few samples collected around targets contained significant metal concentrations. It should be recalled that rifle and grenade ranges are very limited in size (length of hundredths m or ten m respectively) while battleruns cover a much larger surface (length of several km).

Groundwater analysis revealed that water quality is very good, although iron and manganese concentrations often exceed CCME guidelines for drinking water. No other metal was detected in significant concentrations in groundwater, even in training ranges, indicating that contamination problems with metals are limited to surface soils.

Energetic materials (explosives) such as RDX, TNT and HMX were also found in CFB Shilo soils, but only in low concentrations. Measurable amounts of explosives were found in all soil samples collected in the grenade range (maximum concentration < 5 mg/kg). In the battleruns, explosives were quantified in 30% of samples (maximum concentration < 1 mg/kg except for 1 sample) and detected below quantification limit in 39% of samples. No trace of these substances were found in groundwater.

Thorium-232 was found in soils in concentrations ranging from 0.11 to 9.1 mg/kg, with no specific concentration pattern. Natural background concentrations for this type of soils fall within this range. Concentrations in groundwater varied between < 0.01 μg/L (detection limit) to 2.35 μg/L, with several of the highest concentrations measured downgradient of MILAN missile impact areas and "clean" samples located in background areas. Typical natural ^{232}Th concentrations in groundwater are estimated to a few tenth or hundredth of μg/L. Although the distribution pattern of ^{232}Th in groundwater in the battleruns may suggest a relationship with the firing of MILAN missiles, the presence of some of the highest ^{232}Th concentrations upgradient of firing sites in the northern part of the base could not be explained. No missile storage sites are know in this part of the base. Further investigations would be needed to clarify the natural or anthropogenic origin of ^{232}Th in Shilo's groundwater.

The piezometric map of the aquifer as well as flowmeter measurements at CFB Shilo indicate that most of the groundwater flows towards the Assiniboine River (south). Some water also drains in Epinette Creek (north). Groundwater velocity generally varies from 100 to 300 m/y according to flowmeter estimates, and increases to 900 m/y close to the steep banks and seepage zones along the Assiniboine River.

The last part of the research project involved the development and calibration of a finite element model representing the unconfined Assiniboine Delta Aquifer within CFB Shilo. The clay layer underlying the ADA was represented as an impermeable bottom layer. Lateral boundaries includes two no flow boundaries parallel to flow lines and two specified head boundaries (piezometric lines). Calibrated recharge value is 58 mm/y (estimated range 22-68 mm/y). Hydraulic conductivity varies across the modeled area; 3 zones of different hydraulic conductivity were defined in the calibrated model: 3.5×10^{-4}, 3×10^{-4} and 6×10^{-5} m/s.

The calibration was adequate although groundwater velocities in the northern and central parts of the model were lower than those estimated with a flowmeter. CFB Shilo supply well capture zone was established and encompasses rifle ranges 1 and 2 as well as part of rifle range 3 and 4. The grenade range and dump areas fall outside the capture zone.

In summary, this project yielded the following results:

- A better characterization of a section of the ADA that had been less extensively investigated than other parts of the aquifer, particularly as it relates to hydraulic conductivity, water table elevations and groundwater flow velocity and direction.
- An important quantity of geochemical and hydrogeological data was collected and made available in a simple format to facilitate its future use by other investigators or managers of the aquifer.
- Potential risks for water quality were identified.
- Recommendations were made to base authorities regarding the protection of the aquifer.

These recommendations can be summarized as follows:

For contaminated soils:

- Given that some training areas (rifle and grenade ranges) are contaminated with metals such as lead, copper and zinc, no soil amendment - such as lime application – that might change the soil pH should be allowed, in order to avoid an increase in the solubility of metals and their leaching towards the water table. Although the impact of variations in soil pH on the leaching rate is not known for Shilo's soils, the precautionary principle should be applied here and activities that might change the soil pH should be avoided.
- Leacheate testing should be accomplished with rifle and grenade range soils to evaluate the risk of contaminant leaching towards the water table. The potential for leaching could be established for each of the metals found in high concentrations on these sites for various pH values. The probability that soils could reach pH values that would allow pH leaching under field conditions should be evaluated in a risk assessment.

For thorium:

- MILAN missile containing ^{232}Th are not in use anymore at CFB Shilo and should not be used in the future.
- The existing practice of collecting and disposing of MILAN debris found on site in a safe manner should continue.

For groundwater quality:

- Groundwater monitoring should be performed regularly using the observation well network put in place by INRS. Other wells previously installed in the northern portion of the CFB Shilo could also be used. This monitoring will ensure that any threat to groundwater quality will be detected promptly and appropriate actions taken. INRS-ETE staff met with CFB Shilo officials to discuss this matter. Since the location of INRS-drilled observation wells was indicated only with a painted stick in most cases, measures should be taken to better mark their locations. Observations wells can be covered quickly by sand, and experience shows that they are difficult to locate even with precise GPS coordinates.

Sampling frequency should be based on an assessment of risks and environmental priorities for CFB Shio, as well as on economic considerations. Since metals were found in high concentrations on rifle and grenade range soils, groundwater quality monitoring should focus on this area. More specifically, the following wells could be sampled once every two years, or more frequently should an increase in metal concentrations in groundwater be detected: in the rifle range, wells OW-3, GW-RIF, GW-RIF-1, GW-RIF-3 and MW-102 and in the grenade range, GW-GRE, GW-GRE-1, GW-GRE-2 and GW-ATR. Wells GW-BGR-3 and BW-BGR-4 should also be sampled to measure background concentrations.

- The vulnerability of the CFB Shilo portion of the aquifer should be defined using DRASTIC or a method based on time of travel. DRASTIC is a standardized method used to map groundwater pollution potential; factors such as depth to water, recharge, aquifer media, soil media, topography, vadose zone media and hydraulic conductivity are considered in this method.

- A wellhead protection area of 30 m should be put in place around CFB Shilo's supply wells. Any activities taking place within this perimeter that could impact groundwater quality should cease, or protective measures taken. Moreover, other restrictions should be considered within CFB Shilo supply well capture area.

Field work and data analysis performed during this project were a good opportunity for the research team to learn about various aspects of this type of investigation. Characterization of other military bases is currently taking place in Canada, and CFB Shilo's lessons are helpful in designing and improving these research projects. For example, a more efficient sampling methodology for groundwater will be tested at CFB Shilo as well as under other site conditions, and could be used in the future if found adequate.

Data collected at CFB Shilo as well as on other military bases across Canada allowed for a better understanding of the impacts of military training on the environment. This knowledge will be useful in assessing other military sites in Canada and in other countries and to develop sustainable training programs with minimal environmental impacts.

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APPENDICE A

Plate 1 - General View of Canadian Forces Base Shilo

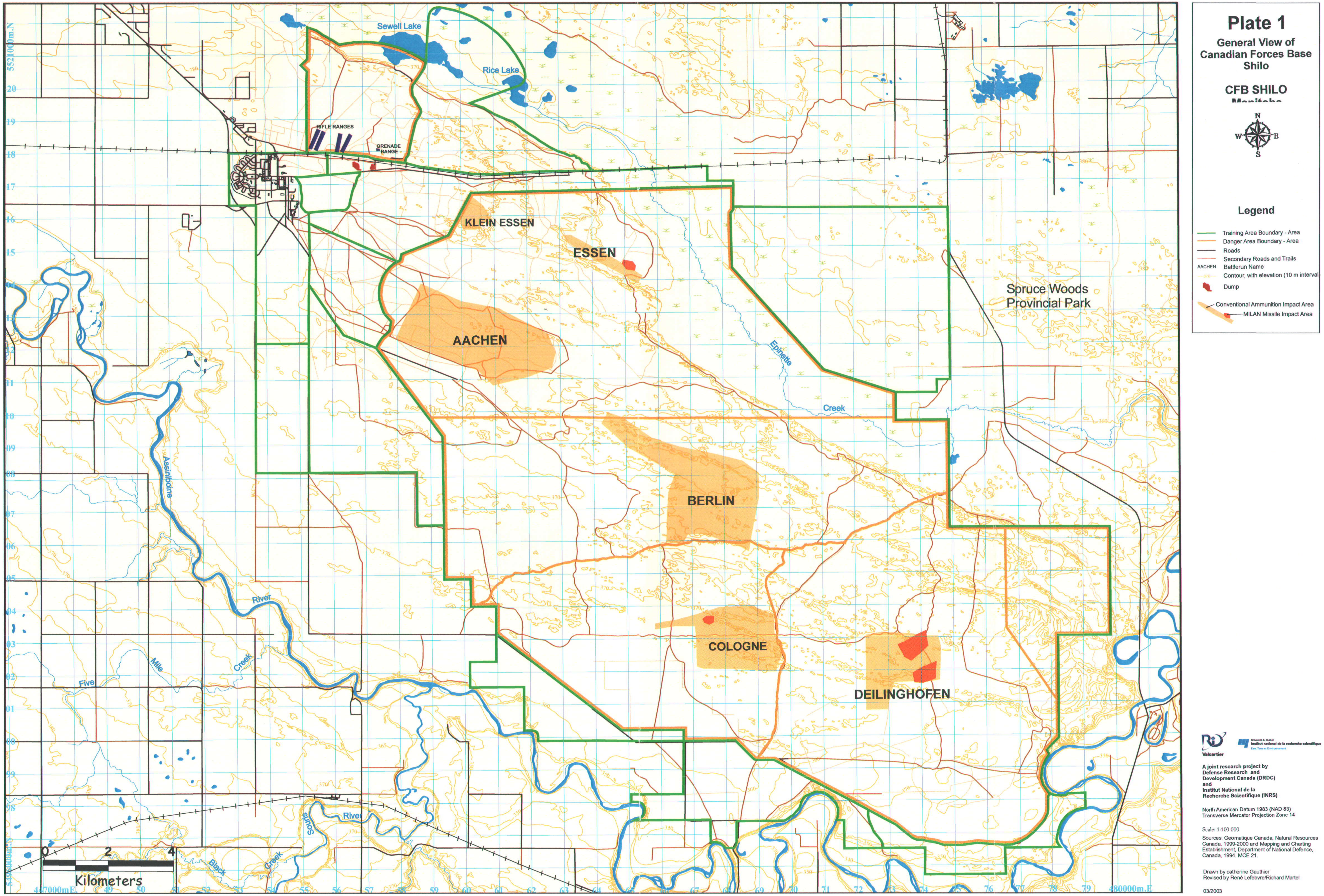


Plate 1
General View of Canadian Forces Base Shilo
CFB SHILO
Legend
Training Area Boundary - Area
Danger Area Boundary - Area
Roads
Secondary Roads and Trails
AACHEN Battlerun Name
Contour, with elevation (10 m interval)
Dump
Conventional Ammunition Impact Area
MILAN Missile Impact Area
Sewell Lake
Rice Lake
RIFLE RANGES
GRENADE RANGE
KLEIN ESSEN
ESSEN
AACHEN
BERLIN
COLOGNE
DEILINGHOFEN
Spruce Woods Provincial Park
Epinette Creek
Assiniboine River
Five Mile Creek
Souris River
Black Creek
Kilometers
0 2 4
Valcartier
Université du Québec
Institut national de la recherche scientifique
Eau, Terre et Environnement
A joint research project by Defense Research and Development Canada (DRDC) and Institut National de la Recherche Scientifique (INRS)
North American Datum 1983 (NAD 83)
Transverse Mercator Projection Zone 14
Scale: 1:100 000
Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.
Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel
03/2003

APPENDICE B

Plate 2 – Sampling Locations for Surface and Groundwater

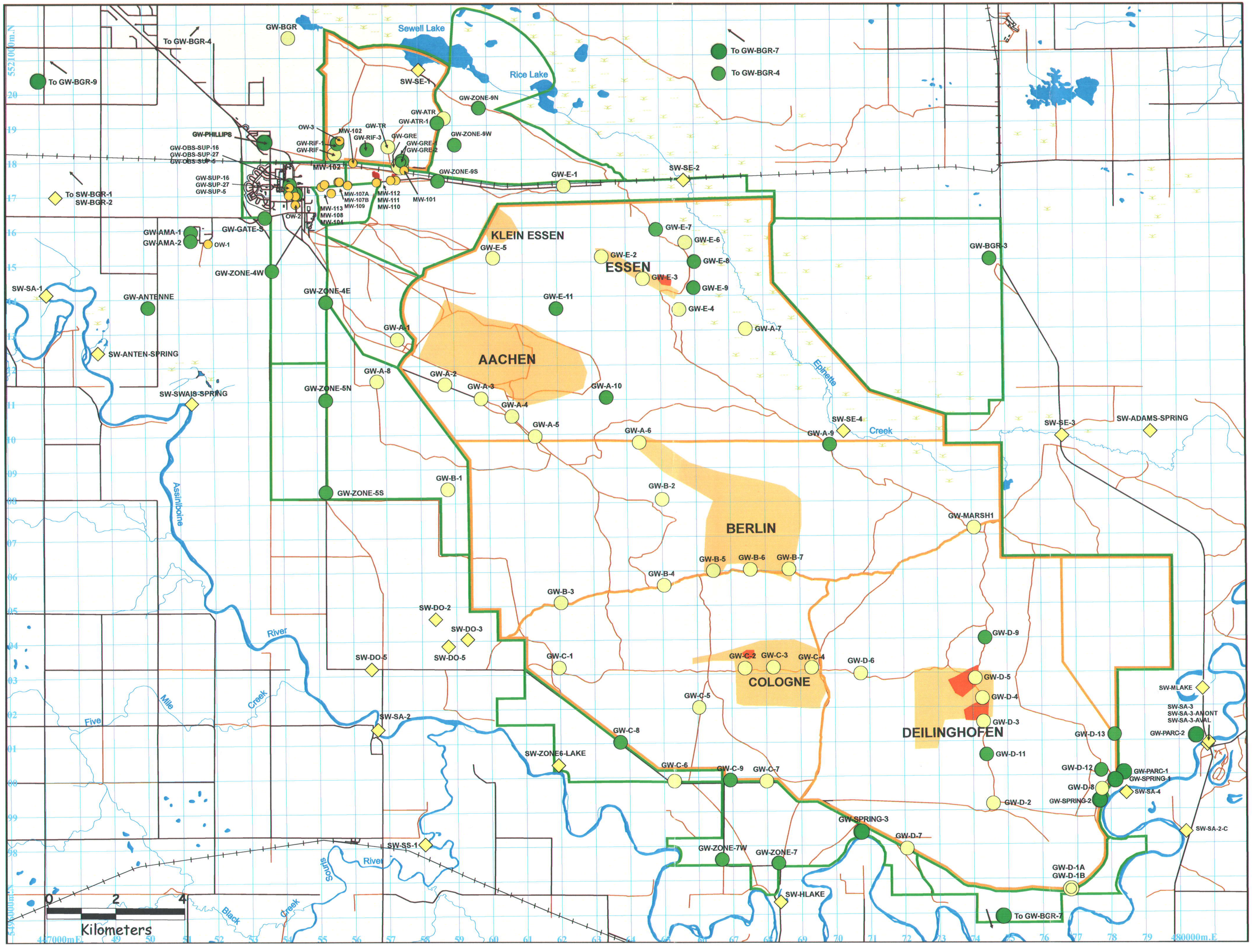


Plate 2

Sampling Locations for Surface and Ground Water

CFB SHILO Manitoba

N
W E
S

Legend

- 2001 INRS Well
- 2000 INRS Well
- Private Wells and Springs
- Existing Base Wells
- Surface Water (river, lakes or dug outs)

- Training Area Boundary - Area
- Danger Area Boundary - Area
- Roads
- Secondary Roads and Trails
- AACHEN Battlerun Name
- 370 Contour, with elevation (10 m interval)
- Dump
- Conventional Ammunition Impact Area
- MILAN Missile Impact Area

RDDC Valcartier

Université du Québec
Institut national de la recherche scientifique
Eau, Terre et Environnement

A joint research project by
Defense Research and Development Canada (DRDC)
and
Institut National de la Recherche Scientifique (INRS)

North American Datum 1983 (NAD 83)
Transverse Mercator Projection Zone 14

Scale: 1:100 000

Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.

Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel

04/2005

APPENDICE C

Description of well structure, installation and development

Description of well structure, installation and development

Monitoring wells were installed according to ASTM-D5092-90 standards. Fifty-one mm PVC tubing with a 1.5 m well screen (0.010 inch slots) was used for most of the wells. However, a 3.05 m well screen was used for a few wells such as GW-GRE and GW-RIF due to the unavailability of a sufficient number of the other well screens. A silica sand pack was placed around the screened interval of most wells to block the entry of fine particles into the well. This sand pack extended from 0.6 to 1 m above the screened interval. For a number of wells, the sand formation collapsed under the water table level, thus impeding the installation of a complete sand pack. In such cases, the *in situ* sand formation is either directly or partially in contact with the well screen.

The annular space between the PVC tubing (51 mm) and the borehole wall (200 mm) was filled above the sand pack with bentonite grount up to 0.6 to 0.9 m below the soil surface in order to prevent preferential infiltration of water from the surface. A cement seal filing the rest of the annular space up to the surface was installed. Most wells were cased with a flush-mount protective metal casing and a locking cap. A few wells located in areas prone to flooding during spring time were equipped with a stick-up of 1-m protective casing in order to facilitate their localization at all times (GW-A-7, GW-Antenne, GW-AMA-1, GW-AMA-2, GW-Zone-4E).

Thirteen-mm, high-density polyethylene (HDPE) tubing going from the bottom to the top of the well and equipped with a D-32 foot valve was placed inside the PVC tubing for use in well development and groundwater sampling. These two operations were performed with the help of an electric Waterra pump (Hydrolift II). A metallic arm attached to the HDPE tubing is powered by the pump, lifting the tubing upward and downward.

Well development involves removing fine particles in natural soil or in the sand pack around the screened interval by pumping water from each well. The purpose of well development is to obtain a representative groundwater sample (containing no sediments). Well development took longer than expected because the sand pack grain size was too large for the grain size of the sand formation and because the *in situ* sand formation was sometimes in direct contact with the screen of the well. Well development was done shortly after well installation.

A one-way foot valve and a surge block were attached to the end of the HDPE tubing. This allowed water and sediments to flow into the tubing during the downstrokes into the well. The foot valve closed the tubing as the arm moved upward, lifting the water column and fine sediments 150 mm per stoke. Groundwater was discharged a few meters away from the well downgradient from groundwater flow. When the water being pumped from the well became clear and free of sediments, the tubing was lowered to develop the next section of the screen until the entire length of the screen had been developed. This process took between 3 to 16 hours for each well and typically three wells were developed simultaneously.

Appendice D

Well location, depth and groundwater elevation

Well location, depth and groundwater elevation

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]								
GW-BGR	454238	5521554	Wardrop Engineering	370,28	370,04	369,95	5,68	5
GW-BGR-3	474578	5515026	Lennon Surveys	N/A[2]	371,77	371,47	9,74	10
GW-BGR-4	461084	5524505	Lennon Surveys	N/A	376,62	376,32	9,16	5
GW-BGR-7	480627	5527252	INRS GPS	N/A	N/A	N/A	N/A	N/A
GW-BGR-8	461522	5547413	INRS GPS	N/A	N/A	N/A	N/A	N/A
GW-BGR-9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-BGR-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
[illegible]								
GW-A-1	N/A	5512748	N/A	367,00	366,20	366,78	7,32	5
GW-A-2	458705	5511432	Wardrop Engineering	366,84	366,93	366,64	8,15	5
GW-A-3	449761	5511013	Wardrop Engineering	367,60	367,68	367,39	6,63	5
GW-A-4	460646	5510494	Wardrop Engineering	367,67	367,78	367,45	7,37	5
GW-A-5	461323	5509905	Wardrop Engineering	367,28	367,38	367,04	7,54	5
GW-A-6	464341	5509713	Wardrop Engineering	368,29	N/A	N/A	6,86	5
GW-A-8	446726	5511534	Wardrop Engineering	365,66	N/A	N/A	6,10	5
GW-A-10	463406	5511067	Lennon Surveys	N/A	369,77	369,36	5,84	10
[illegible]								
GW-B-1	458757	5508376	Wardrop Engineering	363,65	363,79	363,39	8,92	5
GW-B-2	464989	5508049	Wardrop Engineering	365,26	N/A	364,43	8,48	5
GW-B-3	462023	5505069	Wardrop Engineering	360,08	360,10	N/A	8,93	5
GW-B-4	465023	5505550	Wardrop Engineering	361,17	361,16	360,87	5,85	5
GW-B-5	466470	5505967	Wardrop Engineering	361,78	361,81	361,52	4,17	5
GW-B-6	467541	5505993	Wardrop Engineering	361,73	361,79	357,49	5,39	5
GW-B-7	468660	5506001	Wardrop Engineering	361,52	361,63	361,27	4,41	5
[illegible]								
GW-C-1	461955	5503174	Wardrop Engineering	356,92	356,90	356,54	5,45	5
GW-C-2	467365	5503126	Wardrop Engineering	358,23	358,33	357,93	5,52	5
GW-C-3	468187	5503148	Wardrop Engineering	358,53	358,65	358,25	8,30	5
GW-C-4	469302	5503132	Wardrop Engineering	358,62	358,73	358,36	6,25	5
GW-C-5	466015	5501993	Wardrop Engineering	356,07	356,17	355,74	5,42	5
GW-C-6	465284	5499858	Wardrop Engineering	352,15	352,18	351,84	13,14	5
GW-C-7	467972	5499842	Wardrop Engineering	352,73	352,80	352,43	9,53	5
GW-C-8	463729	5501035	Lennon Surveys	N/A	353,48	353,16	11,59	5
GW-C-9	466929	5499917	Lennon Surveys	N/A	353,10	352,70	8,42	5
[illegible]								
GW-D-1A	476779	5496642	Wardrop Engineering	341,66	N/A	341,45	17,89	5
GW-D-1B	476779	5496642	Wardrop Engineering	342,98	N/A	342,79	12,91	5
GW-D-2	474547	5499148	Wardrop Engineering	345,30	345,38	345,14	8,56	5
GW-D-3	474282	5501527	Wardrop Engineering	351,46	351,57	351,15	13,28	5
GW-D-4	474254	5502209	Wardrop Engineering	352,77	352,87	352,45	6,17	5
GW-D-5	474049	5502792	Wardrop Engineering	353,82	N/A	353,57	11,02	5
GW-D-6	470725	5502953	Wardrop Engineering	357,74	357,85	357,49	5,14	5
GW-D-7	472032	5497858	Wardrop Engineering	342,34	342,28	N/A	17,83	5
GW-D-8	477712	5499544	Wardrop Engineering	332,50	332,55	332,44	24,37	5
GW-D-9	474356	5504004	Lennon Surveys	N/A	355,75	355,29	7,18	5
GW-D-11	474379	5500610	Lennon Surveys	N/A	349,70	349,28	10,14	5

GW-D-12	477709	5500130	Lennon Surveys	N/A	337,99	337,74	22,16	10
GW-D-13	478113	5501165	Lennon Surveys	N/A	342,52	342,29	12,12	10
Batteries - Essex Area								
GW-E-1	462211	5517181	Wardrop Engineering	370,63	370,51	N/A	3,92	5
GW-E-2	463291	5515117	Wardrop Engineering	372,75	372,61	N/A	5,41	5
GW-E-3	464480	5514467	Wardrop Engineering	371,03	370,94	370,53	5,31	5
GW-E-4	465531	5513562	Wardrop Engineering	370,75	370,67	370,27	9,31	5
GW-E-5	460135	5515102	Wardrop Engineering	370,28	370,31	369,91	4,49	5
GW-E-6	465720	5515516	Wardrop Engineering	369,58	369,51	369,31	4,28	5
GW-E-7	464892	5515941	Lennon Surveys	N/A	370,01	369,66	5,25	5
GW-E-8	465994	5514995	Lennon Surveys	N/A	369,69	369,42	6,72	5
GW-E-9	465971	5514237	Lennon Surveys	N/A	369,98	369,62	3,68	5
GW-E-11	461977	5513661	Lennon Surveys	N/A	370,67	370,21	5,08	5
GW-A-7	467462	5512991	Wardrop Engineering	367,04	N/A	N/A	5,18	5
Ranges - Rifle Ranges								
GW-RIF	455551	5518163	Wardrop Engineering	369,20	369,22	N/A	7,34	10
GW-RIF-1	455650	5518510	Lennon Surveys	N/A	N/A	N/A	10,63	5
GW-RIF-3	456510	5518326	Lennon Surveys	N/A	369,66	369,34	7,31	5
OW-3	455669	5518600	INRS GPS	N/A	N/A	N/A	12,20	N/A
Ranges - Hand Grenade Range								
GW-GRE	457458	5517800	Wardrop Engineering	369,94	369,87	369,56	6,48	10
GW-GRE-1	457531	5517992	Lennon Surveys	N/A	370,00	369,66	6,20	5
GW-GRE-2	457485	5517962	Lennon Surveys	N/A	369,94	369,63	4,61	5
Ranges - Anti Tank Range								
GW-ATR	458734	5519174	Wardrop Engineering	370,54	370,47	N/A	4,85	5
GW-ATR-1	458557	5519084	Lennon Surveys	N/A	N/A	N/A	5,33	5
Base Water Supply & Observation								
GW-SUP-5	454380	5517000	Estimate CG (3)	N/A	N/A	N/A	N/A	N/A
GW-SUP-16	454200	5517250	Estimate CG	N/A	N/A	N/A	N/A	N/A
GW-SUP-27	454180.	5517020	Estimate CG	N/A	N/A	N/A	N/A	N/A
GW-OBS-SUP-5	454417	5517065	INRS GPS	N/A	N/A	N/A	14,30	10
GW-OBS-SUP-16	454263	5517312	Lennon Surveys	N/A	368,32	367,96	13,55	5
GW-OBS-SUP-27	454292	5517105	Lennon Surveys	N/A	368,25	367,82	12,66	10
Infantry area								
GW-GATE-S	453529	5516354	Lennon Surveys	N/A	367,15	373,74	9,03	10
GW-PHILLIPS	453586	5518592	N/A	N/A	N/A	367,61	N/A	N/A
OW-2	454369	5516746	INRS GPS	367,99	367,97	367,61	16,42	N/A
Dump & Quarry								
MW-101	457538	5517724	INRS GPS	N/A	N/A	N/A	7,71	N/A
MW-102	456050	5517950	Estimation CG	N/A	N/A	N/A	N/A	N/A
MW-104	455414	5517074	INRS GPS	N/A	N/A	N/A	6,99	N/A
MW-107-A	455621	5517404	INRS GPS	N/A	N/A	N/A	7,70	N/A
MW-107-B	455648	5517403	INRS GPS	N/A	N/A	N/A	18,43	N/A
MW-108	455127	5517261	INRS GPS	369,27	368,35	N/A	N/A	N/A
MW-109	455896	5517305	INRS GPS	N/A	N/A	N/A	N/A	N/A
MW-110	457294	5517434	INRS GPS	N/A	N/A	N/A	10,73	N/A
MW-111	457143	5517434	INRS GPS	N/A	N/A	N/A	9,24	N/A
MW-112	456734	5517376	INRS GPS	369,39	369,34	369,03	9,20	N/A
MW-113	455222	5517330	INRS GPS	N/A	N/A	N/A	7,72	N/A
Ammunition Dump								
GW-AMA-1	451371	5515945	Lennon Surveys	N/A	365,42	365,01	6,08	5
GW-AMA-2	451359	5515701	Lennon Surveys	N/A	365,21	364,82	8,38	5

OW-1	451819	5515634	INRS GPS	365,60	365,49	N/A	11,77	N/A
[illegible]									
GW-ANTENNE	450107	5513767	Lennon Surveys	N/A	361,89	361,54	14,63	10
GW-ZONE-4E	455282	5513887	Lennon Surveys	N/A	366,37	365,97	8,60	10
GW-ZONE-4W	453722	5514810	Lennon Surveys	N/A	366,02	365,61	9,17	5
GW-ZONE-5N	455251	5511039	Lennon Surveys	N/A	364,03	363,66	8,87	10
GW-ZONE-5S	455235	5508363	Lennon Surveys	N/A	361,21	360,84	9,20	10
[illegible]									
GW-ZONE-7	468312	5497496	Lennon Surveys	N/A	347,70	347,43	9,13	10(4)
GW-ZONE-7W	466672	5497613	Lennon Surveys	N/A	347,56	347,25	10,28	10
GW-SPRING-3	470678	5498362	INRS GPS	N/A	N/A	N/A	N/A	N/A
[illegible]									
GW-TR	457112	5518359	Lennon Surveys	N/A	369,87	369,57	5,13	5
GW-ZONE-9N	459767	5519509	Lennon Surveys	N/A	370,75	370,48	9,10	5
GW-ZONE-9S	458562	5517394	Lennon Surveys	N/A	370,16	369,85	3,23	5
GW-ZONE-9W	459053	5518441	Lennon Surveys	N/A	370,52	370,18	8,60	5
[illegible]									
GW-A-9	469904	5509655	Lennon Surveys	N/A	365,70	365,71	3,06	5
GW-MARSH-1	474053	5507164	Wardrop Engineering	362,00	362,04	361,68	7,48	5
[illegible]									
GW-PARC-1	478334	5500022	INRS GPS	N/A	N/A	N/A	N/A	N/A
GW-PARC-2	480450	5501075	INRS GPS	N/A	N/A	N/A	N/A	N/A

(1) GPS Locations: Universal Transverse Mercator NAD 83, Zone 14

(2) N/A: Non-available or non-applicable

(3) Estimated by Catherine Gauthier

(4) Contradictory data regarding the length of the slotted pipe. (5 or 10 feet?)

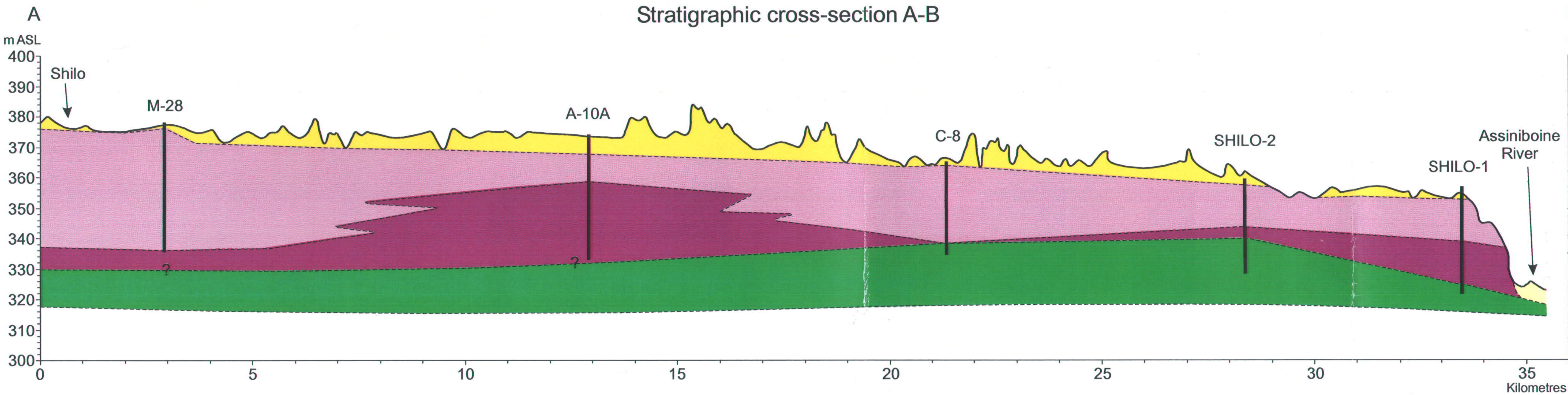
APPENDICE E

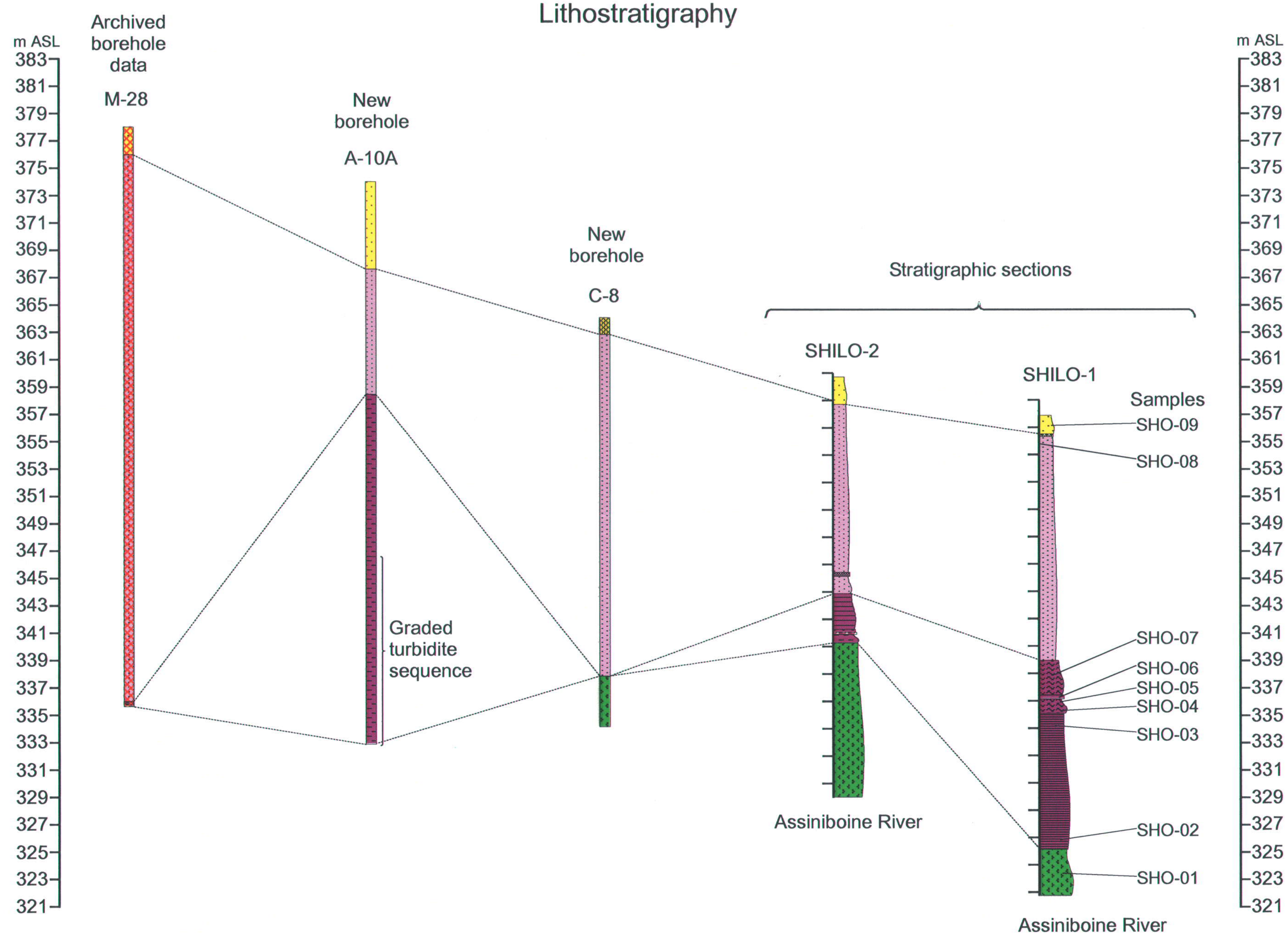
Plate 3 - Stratigraphic section and lithostratigraphy

Plate 3

Stratigraphic section and lithostratigraphy

CFB SHILO Manitoba





Legend

- Ap — Alluvial sediments
- Ed — Aeolian sediments
- Ld — Deltaic sediments
- Lp — Prodeltaic sediments
- T — Till

- Paleosol
- Gravelly horizon
- Brecciated horizon: Silty clay with clay intraclasts
- Fine sand
- Coarse to medium sand, minor gravel
- Silty sand (cross-laminated)
- Silty sand (plane-laminated)
- Clayey silt
- Silty clay
- Till: compact, Silty sandy clay matrix; < 1% boulders

Authors:
Cloutier, M. R.
(Cogeo Consultants Inc.)
Parent, M.
(Geological survey of Canada)
Natural Ressouces Canada

03/2003

Appendice F

Plate 4 – Surficial Geology

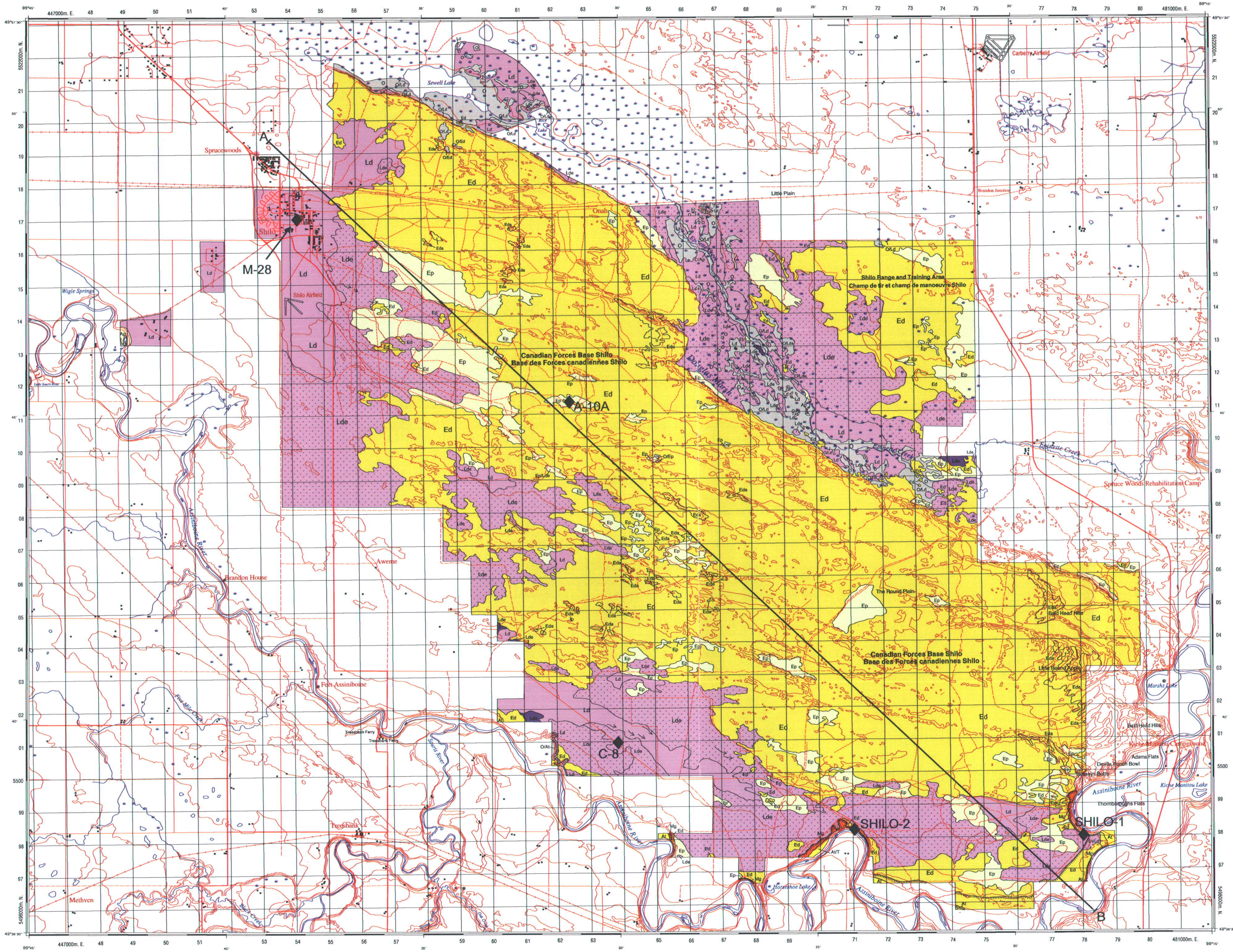


Plate 4

Surficial Geology

CFB SHILO
Manitoba

Legend
Quaterny Statigraphic Units

CENOZOIC

Slope sediments

Mg — Reworked sediments: silty clay and sand reworked by slumps along the Assiniboine River valley

Organic sediments

O — Organic and organo-detrital sediments; thickness ranging from 0.3 to 1.5 m

Alluvial sediments

Ap — Modern alluvium: poorly sorted sand, sandy silt, gravelly sand and gravel; thickness ranging from 0.5 to 3.0 m

At — Terraced alluvium: gravel and sandy silt; thickness ranging from 0.5 to 5.0 m

Aeolian sediments

Sediments deposited by wind activity, mainly derived from proximal deltaic sediments; consisting mainly of well sorted fine to medium sand, minor coarse silt; observed thickness up to 10 m but inferred to reach 30 m under some dune crests

Ep — **Ep**, flat to undulating subzone;

Ed — **Ed**, dune subzone (deflation hollows and associated parabolic dunes and crests); stabilized by vegetation or active (stippled)

Glaciolacustrine sediments

Sediments deposited in Glacial Lake Agassiz

Ld — Deltaic sediments: coarse to medium sand, minor gravel and silt, cross- and plane-stratified; thickness ranging from 10 to 30 m; flat surface generally reworked by aeolian processes (Lde)

Lp — Prodeltaic sediments: silt, clay and silty sand; plane- to cross-laminated and locally interstratified with sand or sandy gravel; observed only in boreholes; thickness up to 26 m

Glacial sediments

Till: compact, gray diamicton, with silty, carbonate-rich matrix containing some clasts and a few boulders; deposited by glacier ice

T — Till exposed at the base of scarps along the Assiniboine River; observed thickness ranging from 3 to 11 m

Well defined geological limit

Area of active dunes

Terrace scarp cut in surficial sediments

Alluvial levee

Alluvial bar

Paleochannel ; direction of flow in abandonned fluvial channels

Location of stratigraphic section or borehole

A — B *Location of surficial geologic cross-section*

1 0 1 2 3 4
Kilometres

North American Datum 1983 (NAD 83)
Transverse Mercator Projection

Authors: **Cloutier, M. R.**
(Cogeo Consultants Inc.)
Parent, M.
(Geological survey of Canada)
Natural Ressouces Canada

03/2003

APPENDICE G

Summary of slug tests and grain-size analyses at CFB Shilo

Summary of slug tests and grain-size analyses at CFB Shilo

[illegible]							
GW-BGR	2,54E-04	2,34E-04	N/A	**2,44E-04**	**2,32E-04**	Medium	2000
GW-BGR-3	2,09E-04	1,85E-04	N/A	**1,97E-04**	**6,39E-05**	Medium	2001
GW-BGR-4	2,97E-04	2,29E-04	N/A	**2,63E-04**	**1,94E-04**	Medium	2001
GW-BGR-7	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-BGR-8	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-BGR-9	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-BGR-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A
[illegible]							
GW-A-1	2,69E-04	2,73E-04	N/A	**2,71E-04**	**1,19E-04**	Medium	2000
GW-A-2	1,20E-04	1,22E-04	1,29E-04	**1,24E-04**	**2,28E-04**	Medium	2000
GW-A-3	1,84E-04	2,14E-04	N/A	**1,98E-04**	**1,93E-04**	Medium	2000
GW-A-4	5,27E-05	4,95E-05	N/A	**5,11E-05**	**7,31E-09**	Very Fine	2000
GW-A-5	8,41E-05	N/A	N/A	**8,41E-05**	**7,23E-04**	Coarse	2000
GW-A-6	2,57E-05	2,80E-05	N/A	**2,68E-05**	N/A	N/A	2000
GW-A-8	2,79E-05	1,96E-04	N/A	**7,39E-05**	**3,27E-04**	Medium	2000
GW-A-10	3,03E-04	2,54E-04	N/A	**2,79E-04**	**2,01E-04**	Medium	2001
[illegible]							
GW-B-1	3,67E-04	4,10E-04	3,61E-04	**3,79E-04**	**1,35E-03**	Very coarse	2001
GW-B-2	N/A	N/A	N/A	N/A	**4,88E-05**	Medium	2000
GW-B-3	1,34E-04	1,45E-04	N/A	**1,39E-04**	**2,05E-04**	Medium	2000
GW-B-4	9,97E-05	1,27E-04	N/A	**1,13E-04**	**8,90E-08**	Medium	2000
GW-B-5	7,20E-05	6,78E-05	N/A	**6,99E-05**	**9,24E-05**	Medium	2000
GW-B-6	1,09E-04	1,34E-04	N/A	**1,21E-04**	N/A	N/A	2000
GW-B-7	1,18E-04	1,17E-04	N/A	**1,17E-04**	**1,84E-04**	Medium	2000
[illegible]							
GW-C-1	2,35E-04	N/A	N/A	**2,35E-04**	**2,01E-04**	Medium	2000
GW-C-2	2,73E-04	2,41E-04	N/A	**2,57E-04**	**2,62E-04**	Medium	2000
GW-C-3	1,41E-04	1,06E-04	N/A	**1,22E-04**	**2,06E-04**	Medium	2000
GW-C-4	1,46E-04	1,26E-04	N/A	**1,36E-04**	**7,58E-04**	Medium	2000
GW-C-5	2,73E-04	2,64E-04	N/A	**2,68E-04**	**7,31E-09**	Very fine	2000
GW-C-6	2,72E-04	2,31E-04	N/A	**2,51E-04**	**5,02E-04**	Medium	2000
GW-C-7	N/A	N/A	N/A	N/A	**1,87E-04**	Medium	2000
GW-C-8	2,27E-04	2,05E-04	N/A	**2,16E-04**	**2,07E-04**	Medium	2001
GW-C-9	2,13E-04	2,34E-04	2,28E-04	**2,25E-04**	**1,70E-04**	Medium	2001
[illegible]							
GW-D-1A	N/A	N/A	N/A	N/A	**3,15E-05**	Clay	N/A
GW-D-1B	N/A	N/A	N/A	N/A	**3,24E-05**	Very fine	N/A
GW-D-2	1,04E-05	2,54E-04	N/A	**5,14E-05**	**4,28E-04**	Medium	2000
GW-D-3	8,39E-05	1,06E-04	N/A	**9,43E-05**	**9,46E-05**	Medium	2000
GW-D-4	1,18E-04	1,51E-04	N/A	**1,33E-04**	**4,04E-06**	Medium	2000
GW-D-5	9,33E-05	N/A	N/A	**9,33E-05**	**2,14E-05**	Medium	2000
GW-D-6	1,16E-04	9,62E-05	N/A	**1,06E-04**	**8,48E-05**	Medium	2000
GW-D-7	N/A	N/A	N/A	N/A	**2,22E-04**	Coarse	2000

GW-D-8	N/A	N/A	N/A	N/A	**8,55E-04**	Coarse	2001
GW-D-9	1,53E-04	1,57E-04	1,83E-04	**1,64E-04**	**2,06E-04**	Medium	2001
GW-D-11	4,75E-05	5,87E-05	5,90E-05	**5,51E-05**	**9,98E-05**	Medium	2001
GW-D-12	5,73E-05	5,68E-05	5,73E-05	**5,71E-05**	**1,17E-04**	Fine	2001
GW-D-13	1,89E-05	1,10E-05	2,08E-05	**1,69E-05**	**2,15E-06**	Fine	2001
[illegible]							
GW-E-1	2,53E-05	2,60E-05	N/A	**2,56E-05**	**1,99E-04**	Medium	2000
GW-E-2	5,46E-05	5,38E-05	5,84E-05	**5,56E-05**	**1,48E-04**	Fine	2000
GW-E-3	7,41E-05	7,72E-05	N/A	**7,56E-05**	**1,90E-04**	Medium	2000
GW-E-4	4,10E-05	N/A	N/A	**4,10E-05**	**1,88E-04**	Medium	2000
GW-E-5	1,97E-04	1,90E-04	2,06E-04	**1,97E-04**	**9,69E-05**	Medium	2001
GW-E-6	4,39E-05	3,23E-05	N/A	**3,77E-05**	**1,61E-04**	Fine	2000
GW-E-7	1,30E-04	1,15E-04	N/A	**1,23E-04**	**1,84E-04**	Medium	2001
GW-E-8	1,70E-04	1,15E-04	N/A	**1,42E-04**	**1,77E-04**	Fine	2001
GW-E-9	1,14E-04	1,23E-04	N/A	**1,18E-04**	**1,80E-04**	Medium	2001
GW-E-11	3,54E-05	4,19E-05	5,43E-05	**4,39E-05**	**1,90E-04**	Medium	2001
GW-A-7	6,71E-05	6,37E-05	N/A	**6,54E-05**	**2,16E-04**	Medium	2000
[illegible]							
GW-RIF	2,73E-04	N/A	N/A	**2,73E-04**	**2,77E-04**	Coarse	2000
GW-RIF-1	3,10E-04	2,69E-04	N/A	**2,90E-04**	**2,53E-04**	Medium	2001
GW-RIF-3	1,23E-04	1,33E-04	1,38E-04	**1,31E-04**	**1,93E-04**	Medium	2001
0W-3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
[illegible]							
GW-GRE	8,49E-05	1,02E-04	N/A	**9,31E-05**	**2,21E-04**	Medium	2000
GW-GRE-1	1,93E-04	N/A	N/A	**1,93E-04**	**2,06E-04**	Medium	2001
GW-GRE-2	1,44E-04	N/A	N/A	**1,44E-04**	**1,63E-04**	Medium	2001
[illegible]							
GW-ATR	1,36E-04	N/A	N/A	**1,36E-04**	**3,56E-04**	Coarse	2000
GW-ATR-1	2,58E-04	2,81E-04	N/A	**2,70E-04**	**3,01E-04**	Medium	2001
[illegible]							
GW-SUP-5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-SUP-16	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-SUP-27	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-OBS-SUP-5	1,40E-04	1,35E-04	N/A	**1,37E-04**	**2,40E-04**	Medium	2001
GW-OBS-SUP-16	3,20E-04	2,77E-04	3,88E-04	**3,28E-04**	**1,61E-04**	Medium	2001
GW-OBS-SUP-27	1,50E-04	1,49E-04	N/A	**1,50E-04**	**1,99E-04**	Medium	2001
[illegible]							
GW-GATE-S	3,17E-04	3,39E-04	N/A	**3,28E-04**	**5,01E-04**	Coarse	2001
GW-PHILLIPS	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OW-2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
[illegible]							
MW-101	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-102	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-104	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-107-A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-107-B	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-108	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-109	7,82E-05	8,31E-05	N/A	**8,06E-05**	N/A	N/A	2000
MW-110	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-111	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-112	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MW-113	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Ammunition Dump							
GW-AMA-1	2,90E-04	3,48E-04	N/A	**3,19E-04**	**2,40E-04**	Coarse	2001
GW-AMA-2	7,35E-04	7,42E-04	N/A	**7,38E-04**	**1,05E-03**	Coarse	2001
OW-1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Agricultural Area West of the Base							
GW-ANTENNE	N/A	N/A	N/A	N/A	**1,10E-03**	Coarse	2001
GW-ZONE-4E	1,02E-04	1,10E-04	9,85E-05	**1,03E-04**	**4,24E-04**	Medium/Fine	2001
GW-ZONE-4W	4,00E-04	3,95E-04	3,97E-04	**3,97E-04**	**8,23E-04**	Coarse	2001
GW-ZONE-5N	2,69E-04	2,57E-04	3,31E-04	**2,86E-04**	**6,39E-04**	Medium	2001
GW-ZONE-5S	4,35E-04	4,49E-04	4,18E-04	**4,34E-04**	**3,09E-04**	Medium	2001
South of the Base							
GW-ZONE-7	2,96E-04	N/A	N/A	**2,96E-04**	**5,15E-04**	Medium	2001
GW-ZONE-7W	3,91E-04	N/A	N/A	**3,91E-04**	**6,58E-04**	Coarse	2001
GW-SPRING-3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
North of the Base							
GW-TR	2,33E-04	1,95E-04	N/A	**2,14E-04**	**1,84E-04**	Fine	2001
GW-ZONE-9N	9,59E-05	1,12E-04	1,53E-04	**1,20E-04**	**1,99E-04**	Medium	2001
GW-ZONE-9S	1,21E-04	9,49E-05	N/A	**1,08E-04**	**3,40E-04**	Medium	2001
GW-ZONE-9W	4,06E-05	3,73E-04	N/A	**2,07E-04**	**4,34E-05**	Fine	2001
East of the Base							
GW-A-9	6,28E-05	5,69E-05	4,89E-05	**5,62E-05**	**1,94E-04**	Medium	2001
GW-MARSH-1	7,82E-05	8,31E-05	N/A	**8,06E-05**	**1,86E-04**	Medium	2000
[illegible] Woods Provincial Park							
GW-PARC-1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GW-PARC-2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PERIMETRIC AREA							
DUPLICATES							
GW-D-4	1,18E-04	1,51E-04	N/A	**1,33E-04**		N/A	2000
GW-D-4	2,04E-04	2,32E-04	N/A	**2,18E-04**		N/A	2001

APPENDICE H

Plate 5 – Water table elevation in the unconfined Assiniboine aquifer (year 2002)

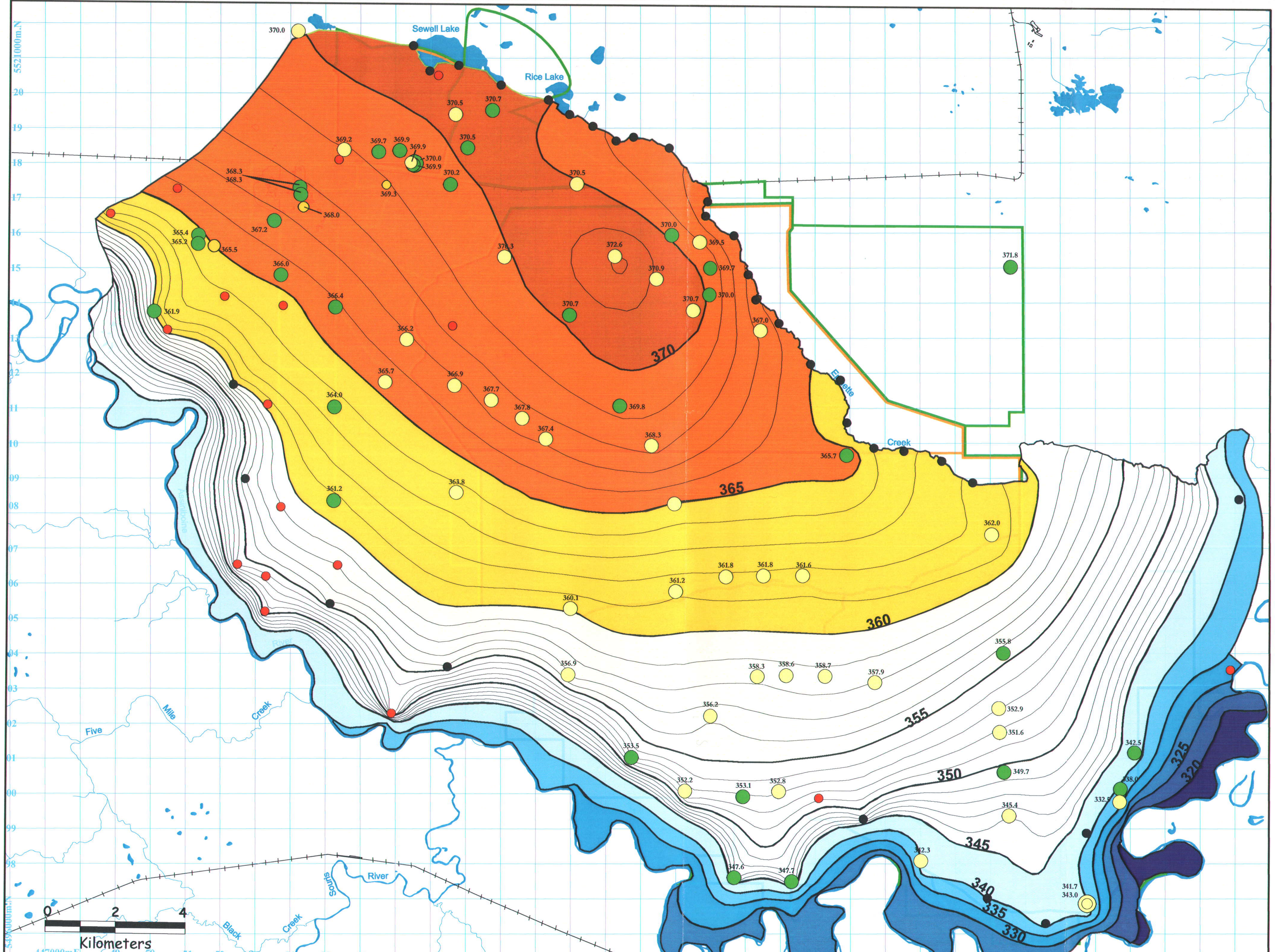


Plate 5

Water Table Elevation in the Unconfined Assiniboine Aquifer

CFB SHILO Manitoba

Legend

Water Table Elevation (m)
Interval: 5 m

Water Table Measurement Point
Measurement Date: September 2002

- 2001 INRS Well
- 2000 INRS Well
- Existing Base Well
- Manitoba Conservation Well
- Control Point

- Training Area Boundary - Area
- Danger Area Boundary - Area
- Roads
- Secondary Roads and Trails
- AACHEN Battlerun Name
- Contour, with elevation (10 m interval)
- Dump

Valcartier

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North American Datum 1983 (NAD 83)
Transverse Mercator Projection Zone 14

Scale: 1:100 000

Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.

Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel

04/2005

APPENDICE I

Plate 6 - Groundwater flow direction and velocity from Geoflo 40 in the Assiniboine Aquifer

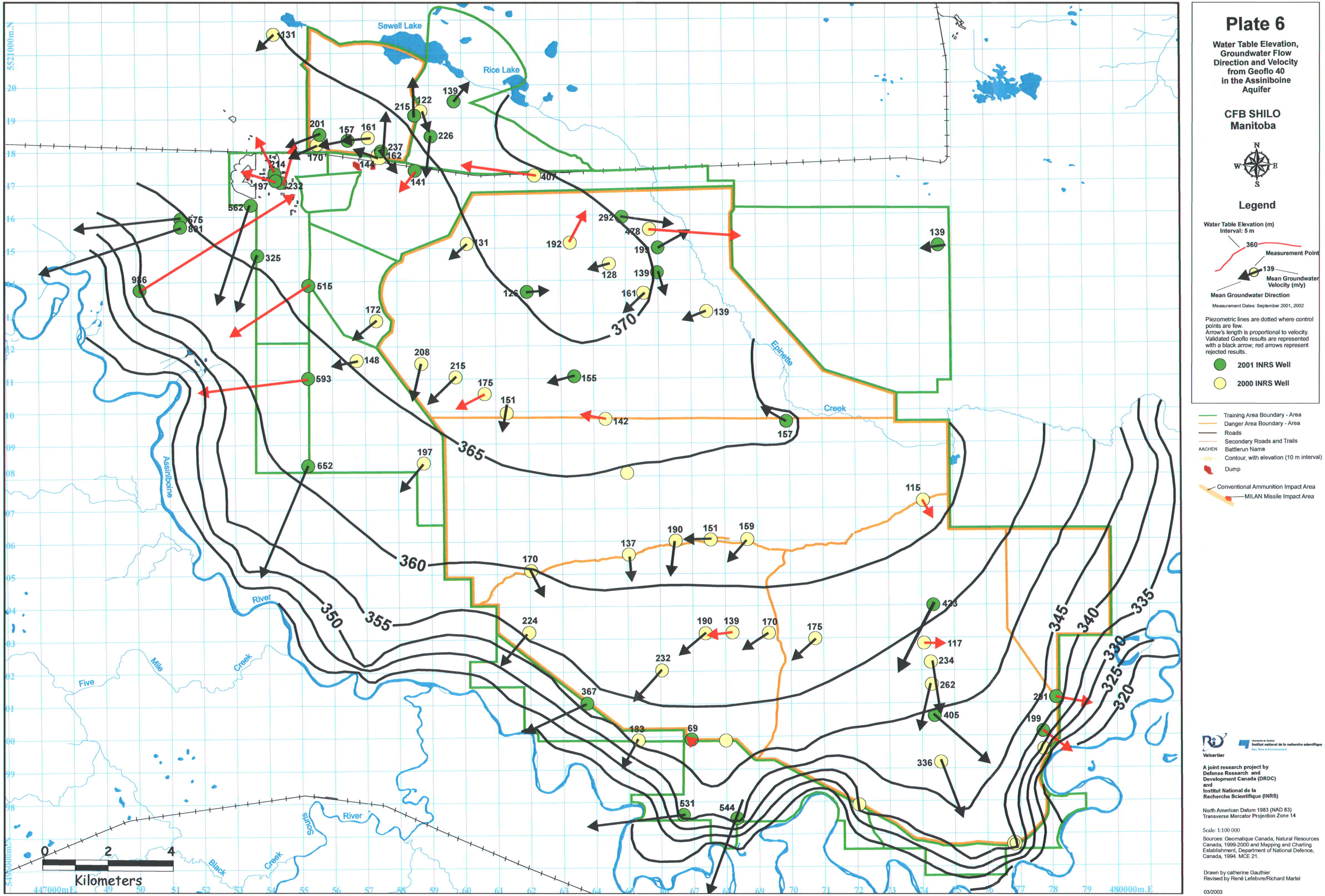
Plate 6
Water Table Elevation, Groundwater Flow Direction and Velocity from Geoflo 40 in the Assiniboine Aquifer
CFB SHILO Manitoba
Legend
Water Table Elevation (m) Interval: 5 m
Measurement Point
Mean Groundwater Velocity (m/y)
Mean Groundwater Direction
Measurement Dates: September 2001, 2002
Piezometric lines are dotted where control points are few.
Arrow's length is proportional to velocity.
Validated Geoflo results are represented with a black arrow; red arrows represent rejected results.
2001 INRS Well
2000 INRS Well
Training Area Boundary - Area
Danger Area Boundary - Area
Roads
Secondary Roads and Trails
Battlerun Name
Contour, with elevation (10 m interval)
Dump
Conventional Ammunition Impact Area
MILAN Missile Impact Area
Valcartier
A joint research project by Defense Research and Development Canada (DRDC) and Institut National de la Recherche Scientifique (INRS)
North American Datum 1983 (NAD 83) Transverse Mercator Projection Zone 14
Scale: 1:100 000
Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.
Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel
03/2003
Sewell Lake
Rice Lake
Epinette Creek
Assiniboine River
Five Mile Creek
Souris River
Black Creek
370
365
360
355
350
345
340
335
330
325
320
Kilometers
0
2
4
447000mE
480000m.E
5521000m.N

APPENDICE J

Tableau des concentrations de métaux dans l'eau souterraine (données 2002)

Tableau des concentrations de métaux dans l'eau souterraine (données 2002)

[redacted]									
Nombre de données	7	7	7	7	7	7	7	7	7
Moyenne arithmétique	0,03	0,001	0,0026	0,30	0,001	0,0001	0,11	0,0002	0,0001
Moyenne géométrique	0,03	0,001	0,0014	0,25	0,001	0,0001	0,05	0,0002	0,0001
Écart-type	0,01	0	0,0038	0,15	0	0	0,20	0,0000	0
Min	0,02	0,001	0,0005	0,05	0,001	0,0001	0,02	0,0002	0,0001
Max	0,06	0,001	0,0110	0,54	0,001	0,0001	0,56	0,0003	0,0001
Nombre de donnees inférieures ou égales a la limite de détection	0	0	0	0	0	0	0	0	0
Nombre de données	67	67	67	67	67	67	67	67	67
Moyenne arithmétique	0,03	0,001	0,0019	0,21	0,001	0,0001	0,03	0,0002	0,0001
Moyenne géométrique	0,03	0,001	0,0009	0,17	0,001	0,0001	0,02	0,0002	0,0001
Écart-type	0,03	0	0,0043	0,15	0	0,0001	0,05	0,0000	0
Min	0,01	0,001	0,0005	0,05	0,001	0,0001	0,01	0,0002	0,0001
Max	0,22	0,001	0,0307	0,69	0,001	0,0007	0,34	0,0004	0,0001
Nombre de données inférieures ou égales a la limite de détection	0	0	0	0	0	0	0	0	0

Limite de detection	0,0001	0,005	0,0002	0,0001	0,001	0,0001	-	0,0002	0,0001
Nombre de valeurs qui depassent le bruit de fond + recommendations CCME	0	0	0	0	0	0	0	0	0
Nombre de valeurs qui les recommendations CCME	1	0	1	0	0	0	0	0	0
Nombre de valeurs qui depassent le le bruit de fond + recommendations CCME	3	0	7	2	0	5	5	2	0

Metal	Chrome - Dissolved [illegible]	Cobalt - Dissolved [illegible]	Cuivre - Dissolved [illegible]	Fer - Dissolved [illegible]	Plomb - Dissolved [illegible]	Lithium - Dissolved [illegible]	Manganèse - Dissolved [illegible]	Molybdène - Dissolved [illegible]	Nickel - Dissolved (4) [illegible]
Nombre de données	7	7	7	7	7	7	7	7	7
Moyenne arithmétique	0,001	0,0005	0,0035	0,70	0,0003	0,012	0,3319	0,0022	0,0027
Moyenne géométrique	0,001	0,0004	0,0016	0,17	0,0002	0,011	0,0443	0,0016	0,0010
Écart-type	0	0,0005	0,0054	0,87	0,0004	0,005	0,5663	0,0017	0,0037
Min	0,001	0,0002	0,0004	0,01	0,0001	0,005	0,0004	0,0006	0,0002
Max	0,001	0,0016	0,0154	1,97	0,0011	0,019	1,5900	0,0045	0,0090
Nombre de donnees inférieures ou égales a la limite de détection	0	0	0	0	0	0	1	0	1
Nombre de données	67	67	67	67	67	67	67	67	67
Moyenne arithmétique	0,001	0,0003	0,0014	0,36	0,0002	0,006	0,0953	0,0008	0,0013
Moyenne géométrique	0,001	0,0003	0,0009	0,11	0,0001	0,006	0,0092	0,0005	0,0007
Écart-type	0	0,0001	0,0020	0,82	0,0002	0,005	0,1615	0,0014	0,0018
Min	0,001	0,0002	0,0004	0,01	0,0001	0,005	0,0002	0,0001	0,0002
Max	0,001	0,0008	0,0111	4,49	0,0018	0,042	0,7160	0,0111	0,0133
Nombre de données inférieures ou égales a la limite de détection	0	1	0	0	0	0	2	13	4

Limite de detection	0,001	0,0002	0,0004	0,01	0,0001	0,005	0,0002	0,0001	0,0002
Nombre de valeurs qui depassent le bruit de fond + recommendations CCME	0	0	0	2	0	0	0	0	0
Nombre de valeurs qui les recommendations CCME	0	0	0	16	0	0	27	0	0
Nombre de valeurs qui depassent le le bruit de fond + recommendations CCME	0	0	0	0	1	1	0	1	1

[redacted]

Nombre de données	7	7	7	7	7	7	7	7	7
Moyenne arithmétique	0,0004	0,001	0,0002	0,17	0,0005	0,0001	0,0002	0,0009	0,0002
Moyenne géométrique	0,0003	0,001	0,0002	0,14	0,0005	0,0001	0,0002	0,0008	0,0002
Écart-type	0,0004	0	0	0,12	0	0,0000	0	0,0005	0
Min	0,0002	0,001	0,0002	0,06	0,0005	0,0001	0,0002	0,0005	0,0002
Max	0,0012	0,001	0,0002	0,42	0,0005	0,0002	0,0002	0,0017	0,0002
Nombre de donnees inférieures ou égales a la limite de détection	0	0	0	0	0	1	0	0	0
Nombre de données	67	67	67	67	67	67	67	67	67
Moyenne arithmétique	0,0007	0,001	0,0003	0,07	0,0005	0,0001	0,0003	0,0009	0,0002
Moyenne géométrique	0,0005	0,001	0,0002	0,07	0,0005	0,0001	0,0002	0,0007	0,0002
Écart-type	0,0009	0,001	0,0003	0,04	0	0,0000	0,0002	0,0012	0,0001
Min	0,0002	0,001	0,0002	0,04	0,0005	0,0001	0,0002	0,0005	0,0002
Max	0,0073	0,005	0,0020	0,30	0,0005	0,0003	0,0013	0,0086	0,0009
Nombre de données inférieures ou égales a la limite de détection	1	0	0	0	0	0	3	0	0

Limite de detection	0,0002	0,001	0,0002	-	0,0005	0,0001	0,0002	0,0005	0,0002
Nombre de valeurs qui depassent le bruit de fond + recommendations CCME	0	0	0	0	0	0	0	0	0
Nombre de valeurs qui les recommendations CCME	0	0	0	0	0	0	0	0	0
Nombre de valeurs qui depassent le le bruit de fond + recommendations CCME	23	2	8	1	0	2	12	5	4

[redacted]

Nombre de données	7	7	7	7
Moyenne arithmétique	0,0021	0,002	0,062	0,0002
Moyenne géométrique	0,0012	0,001	0,011	0,0002
Écart-type	0,0024	0,001	0,147	0,0001
Min	0,0003	0,001	0,005	0,0002
Max	0,0059	0,004	0,396	0,0004
Nombre de donnees inférieures ou égales a la limite de détection	0	0	0	0
Nombre de données	67	67	67	67
Moyenne arithmétique	0,0007	0,001	0,015	0,0002
Moyenne géométrique	0,0005	0,001	0,007	0,0002
Écart-type	0,0005	0,000	0,060	0,0000
Min	0,0002	0,001	0,005	0,0002
Max	0,0027	0,002	0,491	0,0004
Nombre de données inférieures ou égales a la limite de détection	0	0	0	0

Limite de detection	-	0,001	0,005	0,0002
Nombre de valeurs qui depassent le bruit de fond + recommendations CCME	0	0	0	0
Nombre de valeurs qui les recommendations CCME	0	0	0	0
Nombre de valeurs qui depassent le le bruit de fond + recommendations CCME	0	0	1	6

APPENDICE K

Plate 7 – Location of soil samples and description of sampling methods

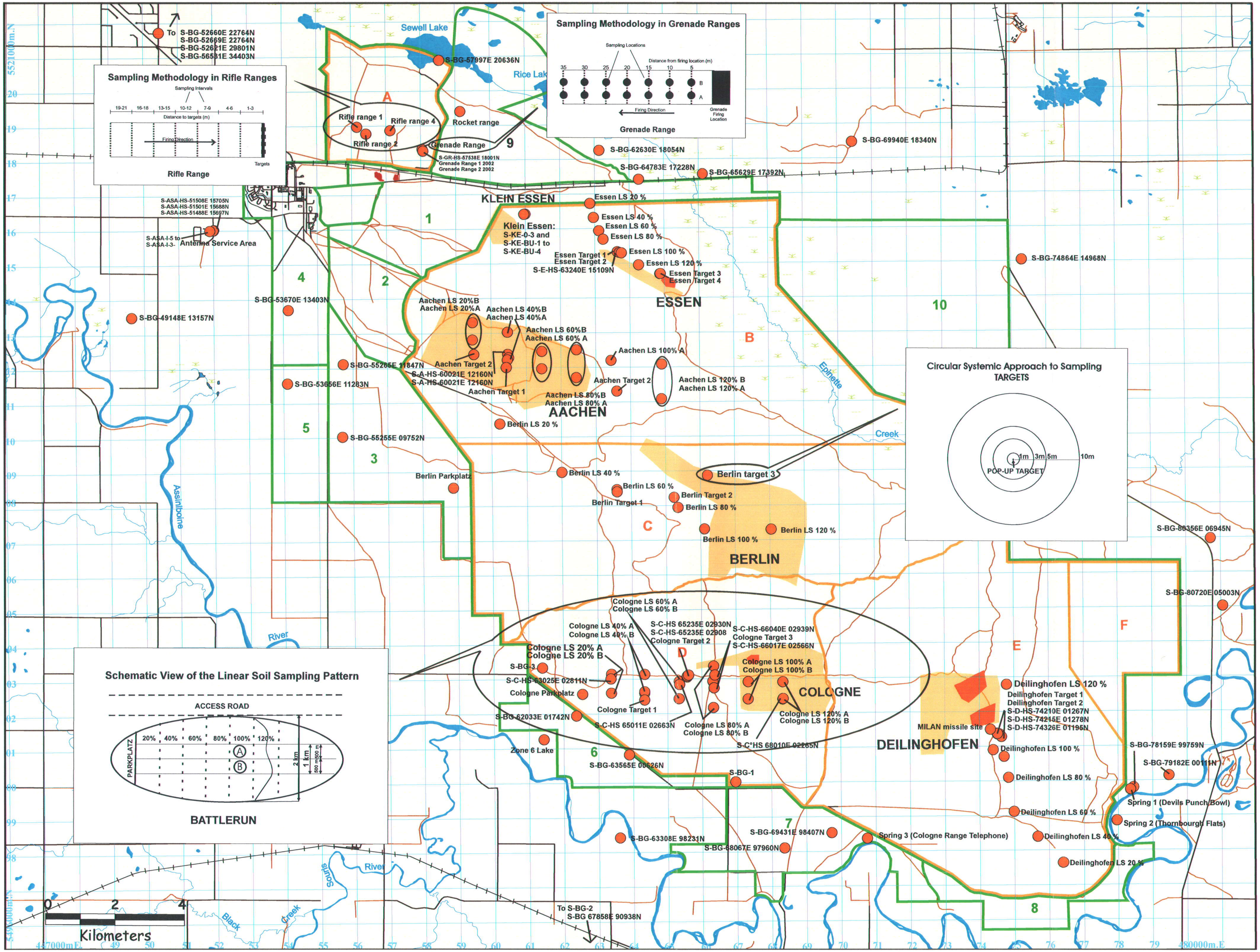

Plate 7

Location of Soil Samples and Description of Sampling Methods

CFB SHILO Manitoba

Legend

Aachen LS 100% A — Sample Location, Sample Name

- Training Area Boundary - Area
- Danger Area Boundary - Area
- Roads
- Secondary Roads and Trails
- AACHEN Battlerun Name
- Contour, with elevation (10 m interval)
- Dump
- Conventional Ammunition Impact Area
- MILAN Missile Impact Area

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North American Datum 1983 (NAD 83)
Transverse Mercator Projection Zone 14

Scale: 1:100 000

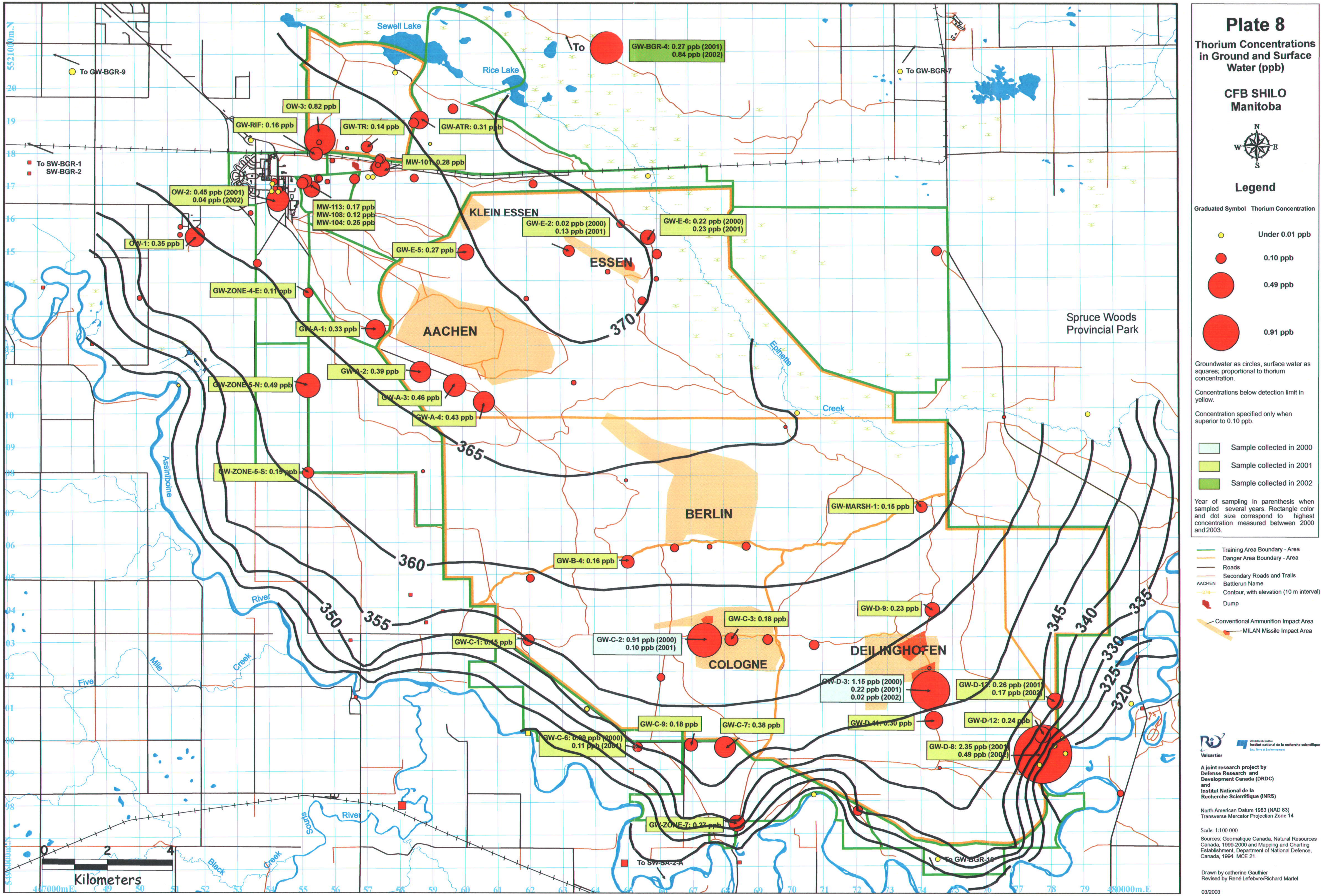
Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.

Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel

03/2003

APPENDICE L

Plate 8 – Thorium concentrations in ground and surface water



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Transverse Mercator Projection Zone 14

Scale: 1:100 000

Sources: Geomatique Canada, Natural Resources Canada, 1999-2000 and Mapping and Charting Establishment, Department of National Defence, Canada, 1994. MCE 21.

Drawn by catherine Gauthier
Revised by René Lefebvre/Richard Martel

03/2003

APPENDICE M

Calcul préliminaire du rayon d'influence des puits d'approvisionnement de BFC Shilo

Calcul préliminaire du rayon d'influence des puits d'approvisionnement de la BFC Shilo

Il est important de connaître le rayon d'influence approximatif des puits de la base de Shilo de façon à s'assurer que les limites nord (charge spécifiée) et est (flux nul) du modèle numérique d'écoulement sont situées hors de cette zone. Ces rayons d'influence ont donc été estimés pour chacun des trois puits d'approvisionnement : SUP-5, SUP-16 et SUP-27.

<u>Conditions de pompage réelles</u>

Les débits de pompage moyens de chacun des puits sont les suivants :

SUP-5	1835 L/min = 30,58 L/s = 0,03058 m^3/s
SUP-16	1835 L/min = 30,58 L/s = 0,03058 m^3/s
SUP-27	3400 L/min = 56,67 L/s = 0,05667 m^3/s

En général, les puits SUP-5 et SUP-16 sont utilisés simultanément. Leur utilisation alterne avec celle du puits SUP-27. Le calcul a donc été fait avec le débit de pompage du puits SUP-27. Il est à noter que les données disponibles sur la quantité d'eau utilisée par la base au cours des dernières années suggèrent que les débits identifiés précédemment pourraient être plus élevés que le débit de pompage réel.

L'approche utilisée pour estimer le rayon d'influence des puits de pompage de la base consiste à utiliser la solution de Theis pour résoudre l'équation décrivant l'écoulement radial dans ces puits. Le puits comportant le débit le plus élevé a été utilisé afin d'évaluer le rabattement maximal pouvant être induit par les puits de pompage de la base à différentes distances de ces derniers.

L'écoulement radial vers un puits lors du pompage dans un aquifère non-confiné crée un cône de dépression dans la surface de la nappe. L'eau produite par le puits provient des réserves dans les pores de l'aquifère, de l'expansion de l'eau dans l'aquifère sous l'effet d'une pression moindre et de la compaction de l'aquifère sous l'effet de contraintes effectives accrues. De plus, l'écoulement vers le puits comporte à la fois une composante horizontale et une composante verticale dans un tel cas.

L'approche la plus simple pour prédire le rabattement induit par un puits dans un aquifère libre consiste à utiliser la même équation que celle qui serait utilisée pour un aquifère confiné (Freeze & Cherry, 1979, p. 325). T doit être défini comme l'épaisseur initiale saturée de l'aquifère (T = Kb) et S représente la capacité d'emmagasinement spécifique. Cette approche donnerait des résultats suffisamment exacts en autant que le rabattement petit comparativement à l'épaisseur saturée, ce qui est ici le cas.

$$s = \frac{Q}{4\pi T} W(u) = \frac{Q}{4\pi Kb} W(u) \qquad u = \frac{r^2 S}{4Tt} = \frac{r^2 S}{4Kbt}$$

r = rayon d'influence du puits = 2 km = 2000m
$S = S_y = 0{,}15$
K = 0,0001 m/s
t = 1 an = 31 536 000 s
Q = 0,05667 m^3/s

$$u = \frac{(2000)^2 * 0{,}15}{4 * 0{,}0001 * 40 * 31\,536\,000} = 1{,}189$$

Unités: $\frac{m}{m/s * s}$ = Sans unités

Pour u = 1,189 W(u) = 0,18687

$$W(u) = \frac{s4\pi Kb}{Q}$$

$$s = \frac{W(u)Q}{4\pi Kb} = \frac{0{,}18687 * 0{,}05667}{4\pi 0{,}0001 * 40} = 0{,}843 \text{ m}$$

Unités: $\frac{m^3/s}{m/s * m}$ = m

Pour t = 1 an et b = 40

R (m)	s (m)	u	W(u)
5000	0,000095	7,4320	0,000084576
4000	0,001981	4,7565	0,00175745
3000	0,027827	2,6755	0,024682
2000	0,84	1,189	0,18687
1000	1,04	0,2973	0,91837
500	2,36	0,07432	2,09816
100	5,91	0,00297	5,2423
50	7,47	0,000743	6,6298
25	9,06	0,0001858	8,03798
1	14,16	0,00000198	12,5638

Pour t = 1 an et b = 27,50

R (m)	s (m)	u	W(u)
5000	0,0001387	7,4320	0,000084576
4000	0,0028819	4,7565	0,00175745
3000	0,04	2,6755	0,024682
2000	0,31	1,189	0,18687
1000	1,51	0,2973	0,91837
500	3,44	0,07432	2,09816
100	8,60	0,00297	5,2423
50	10,87	0,000743	6,6298
25	13.18	0,0001858	8,03798
1	20,60	0,00000198	12,5638

APPENDICE N

Variation du niveau d'eau dans deux puits d'observation

Variation du niveau d'eau dans deux puits d'observation

La variation du niveau d'eau dans les puits d'observation a été déterminée en soustrayant la variation de niveau d'eau due aux variations de la pression atmosphérique du niveau d'eau enregistré par le LevLogger. Les détails de ce calcul sont décrits dans les paragraphes qui suivent.

Le Levlogger mesure la hauteur du niveau d'eau dans le puits toutes les heures pendant une année. Cette mesure en cm est transformée en mm (h1).

Des données de pression atmosphérique ont été fournies par le Service météorologique d'Environnement Canada. Elles ont été prises dans la ville de Brandon à une élévation de 409 m. Les données étaient fournies en hPa et ont été converties en kPa. La formule suivante a ensuite été utilisée pour déterminer à quelle colonne d'eau correspondait la pression atmosphérique :

$$P = \rho \, g \, h_2 \quad \text{où}$$

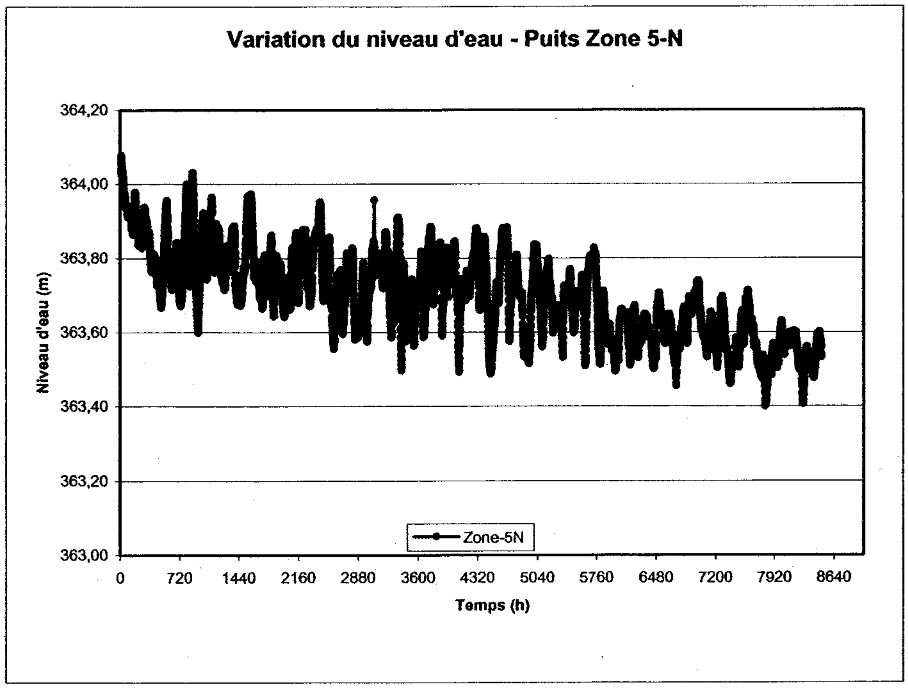
P = pression atmosphérique (kPa = kgm/s^2)
ρ = densité de l'eau (kg/m^3) pour T de 8°C = 999,849 g/L ou kg/m^3
g = accélération gravitationnelle (m/s^2) = 9,8 m/s
h_2 = équivalent en hauteur de colonne d'eau (m)

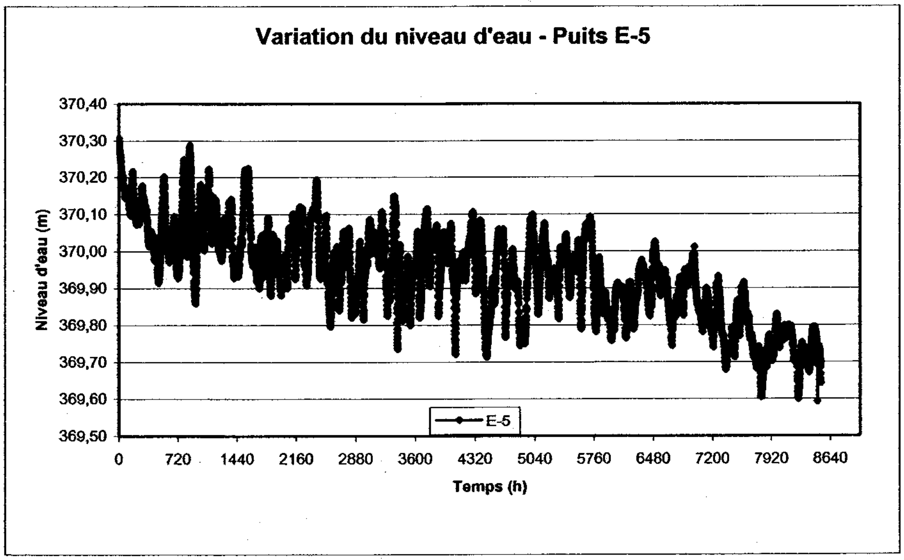
$$h_2 = \frac{P}{\rho \, g}$$

L'équivalent en colonne d'eau de la pression atmosphérique est converti en mm d'eau. (h2 exprimé en mm) et est soustrait de la hauteur de colonne d'eau mesurée par le Levlogger (h1).

Le résultat H de cette soustraction correspond à la hauteur de la colonne d'eau sans l'influence de la pression atmosphérique. Aucune correction n'a été effectuée pour l'altitude (mesures de pression atmosphérique à 409 m contre mesures de Levlogger entre 370 et 240 m) car l'influence de cette dernière est considérée négligeable.

La variation de la hauteur de la colonne d'eau entre deux intervalles de mesure (1 heure) a été calculée. Cette variation (positive ou négative) a été ajoutée au niveau d'eau réel mesuré dans le puits au début de la période de mesure. Le résultat obtenu indique la hauteur et la variation du niveau de la nappe phréatique dû uniquement à la recharge et à l'écoulement.





Les gradations sur l'axe des x représentent le temps exprimé en heures. Une gradation correspond environ à un mois, 0 corresponsant au début d'octobre 2001.

APPENDICE O

Calculation of groundwater discharge from the ADA within the study area

Calculation of groundwater discharge from the ADA within the study area

Groundwater discharge from the study area to the Assiniboine River was calculated based on the following considerations and estimates:

- Water is being discharged from two opposite banks of the river
- The discharge rate is probably higher on the river bank adjacent to CFB Shilo due to the high hydraulic gradient in this area, that is in the modelled area.
- 70-77 % of the river banks located on the AssiniboineWest sub-basin are located along the Assiniboine River (other major river: Souris river)
- 65-72 % of the river banks of the Assiniboine West sub-basin is located within the modelled area.

Groundwater discharge estimates from various authors often corresponds to only part of the river banks length included in the numerical model. Adjustments were made to provide an estimate for the entire length of the river included in the numerical model, assuming that discharge is constant over the entire river lengh, except where more specific estimates for various parts of the rivers are provided by the authors.

Thornborough flats to Brandon: 172 à 244 cm (min jusqu'à limite carte Shilo) = 86 à 122 km
Thournborough flats to longitude 82: 22 cm = 11 km
Longitude 82 to Jonction Epinette Creek : 26 cm = 13 km
Jonction Epinette Creek to the end of the aquifer: 58 km
Souris River : 65-70 cm = 32,5 – 35 km
Total Assiniboine river : 168-204

Model area : 110 km of banks
Conversion pf cfs in m3/s : divide by 35,33
Conversion from acre-feet / year to cubic feet (multiply by 43 560) to cubic meter (multiply by 0,02832)

Harrison : Brandon-Holland : 100 cfs = 2,83 m3/s
Brandon – Treebank Ferry 8,33 cfs = 0,24 m3/s
Treesbank to Stockton ferry 5,8 cfs
Stockton ferry to Provincial hughway no 5 Bridge 28,67 cfs
Provincial Trunk Highway 5 and 34 bridge, 57,8 cfs

Reference	**Methodology**	**Assiniboine River**	**Annual Discharge to the Assiniboine River from the entire ADA according to author**	**Annual Discharge to the Assiniboine River from the modeled area**
Frost and Render (2002)	Methodology not specified	100 cfs so 43% of 200 km in model 43 cfs /2 22 cfs 0,61 m3/s = 53 000 m^3/y	At least 100 cfs/year = 2,83 m^3/s	*At least 0,61 m^3/s=53 000 m3/d*
Render (1988)	pour Assiniboine west sub-bassin, 1 side 97.5 km (Western aquifer boundary to provincial highway no5) Modelling exercise	(45 cfs) 1,28 m^3/s or 110 048 m^3/j		*58 900 m3/d*
Harrison (1986) september 12-october 14, 1985 In Render (1988)	Stream Flow metering on the Assiniboine River	Brandon to Treesbank Ferry (53,75 km, including 30 km from Bandon to Wigle Springs and 23,75 km from Wigle Spring to Treesbank Ferry 8,33 cfs (0,24 m3/s or 20371 m3/d so 3,68 cfs in model section/2 1,84 cfs == 0,052 m/s= 4500 m3/d		*4500 m3/d*
		Tressbank Ferry-Stockton Ferry (24 k (0,16 m3/s ou 14 donc 2,9 cfs = 0 7100 m3/j		*7100 m3/d*
		Stockton Ferry – Provincial Trunk Highway No 5 bridge (35 km) 28,67 cfs (0,82 m3/s or 70 113 m3/d) (14,34 cfs = 0,41 m3/s = 35 000 m3/j)		*35 000 m3/d*
		Provincial Trunk Highway No 5 bridge to 34 Bridges (30,7 km) 57,8 cfs (1,6 m3/s ou 141 351 m3/jour) including 29 928 in model (4 km in model so 7,71 cfs and so 3,85 cfs = 0,11 m3/s = 9400 m3/d		*9400 m3/d*
				Total modèle : 56 000 m3/d
Harrison and Kelin (2003)	Streamflow recording	4 m^3/s (126 144 000 m^3/y) or 2,83 for drier years (89 246 880 m^3/y) so 43% of which /2 for model 74 300 à 52 600	*133 000 dam^3* = 133 000 000 m^3	*74 300 à 52 600*
Mattick and Wagner (1968) in Render (1988) 1963-1957 Brandon to highway 34: 180 km mon modèle: 83.5	Method unkonw	100 cfs in autumn to 600 cfs in spring *56 247 to (17 m3/s) 339 926 m3/d*		*56 000 to 336 000 m3/d*
Kellin (2002)		108 000 acrefeet/year		0,84 m3/s or 73 000 m3/d