

4 GROUNDWATER

4.1 Introduction

4.1.1 Focus

This section predicts and evaluates the potential effects of the project on groundwater, including:

- groundwater in aquifers, i.e., saturated geological materials capable of providing a supply of water
- groundwater-fed waterbodies

Changes in groundwater can affect biophysical components, such as:

- aquifers that are used for potable water
- springs and seeps that affect winter fish habitat
- groundwater discharge areas that provide an environment for rare or uncommon plant species

Pipeline or all-weather access road construction, removal of borrow material, or facilities production and infrastructure activities can cause changes in groundwater flow patterns. These changes can result in the following effects:

- creation of groundwater-fed wetlands in some areas
- drying up of wetland areas
- formation of icings, i.e., accumulations of ice formed by continuous freezing of slowly discharging water
- formation of frost bulbs, i.e., a frozen zone formed around a chilled pipeline passing through unfrozen ground
- change in slope stability
- change in spring or seep outflow rates

4.1.2 Summary of Findings

The groundwater, i.e., hydrogeological, assessment investigated the effects of the project on the following:

- groundwater quantity and flow patterns
- groundwater quality

SECTION 4: GROUNDWATER

The following key indicators (KIs) were used to understand the project effects on hydrogeological valued components (VCs):

- groundwater discharge rates
- groundwater discharge locations
- groundwater chemical parameters

Pathways through which the project could affect groundwater quantity and flow patterns include:

- changes in recharge and discharge, specifically through:
 - changes in groundwater discharge areas, e.g., pipeline construction near springs
 - changes in recharge from surface water
 - extraction of materials from borrow sites
- flow obstruction, specifically from:
 - drainage being blocked
 - shallow groundwater flow being deflected
 - frost bulbs forming
- changes in permafrost patterns, such as thaw settlement and frost heave
- sedimentation

Pathways through which the project could affect groundwater quality include:

- changes in surface water quality
- changes in permafrost patterns, such as thaw settlement and frost heave

All effects on groundwater from project-related activities are expected to be of local extent. Most effects will be initiated by construction activities and will result in changes that will persist through, or occur during, the remainder of the project. Some effects would persist into the far future, specifically those related to:

- sedimentation
- flow obstruction, e.g., in areas where the pipeline is abandoned in place
- changes in permafrost at Niglintgak and Taglu
- changes in recharge and discharge related to removing materials from the borrow sites

All residual effects are expected to cause a small adverse change in groundwater, i.e., a change that is within the normal range of variation. Because all effects were evaluated as having a low magnitude, the effects of project activities on groundwater were determined to be not significant.

4.1.3 Traditional Knowledge

Volume 1, Section 3, Traditional Knowledge, outlines the status of the traditional knowledge studies that communities near the project are undertaking. Because those studies are ongoing, the proponents used existing published traditional knowledge in this EIS. Little traditional knowledge related to groundwater was identified. The lack of groundwater information available is because most published traditional knowledge is related to resource use, e.g., fisheries and drinking water.

However, traditional knowledge does refer to groundwater. A traditional legend, as told by an Elder from Fort Good Hope (SHPSJWG 2000) refers to an underground river that flows into the Hare Indian River, from the side of a cliff. This probably refers to the relationship between karst in the Colville Lake area and groundwater flow from this area into the Hare Indian River. Although this connection has not been demonstrated by field studies, it is consistent with scientific understanding of karst systems. The biophysical baseline provides a further discussion of karst systems (see Volume 3, Section 4, Groundwater).

4.2 Assessment Approach

Volume 1, Section 2, Assessment Method, provides information about the general assessment approach. The assessment approach for groundwater included the following steps:

1. Identify project-related activities and associated physical and chemical changes that might affect groundwater, i.e., key issues.
2. Identify VCs and KIs for measuring potential changes in VCs, resulting from project activities. In this assessment, groundwater quantity and flow patterns and groundwater quality are the VCs.
3. Identify the potential effects and illustrate in the form of an effect pathway diagram, the linkages between project activities and effects.
4. Identify mitigation measures that will be implemented to reduce or prevent potential effects.
5. Evaluate the applicability of each pathway, after accounting for mitigation measures.
6. Predict changes in groundwater quantity and flow patterns and groundwater quality, for the applicable pathways.
7. Evaluate and classify the predicted effects based on weight of evidence, comparison with regulatory guidelines or relation to site-specific benchmarks.
8. Identify a monitoring program to verify effects predicted and to comply with commitments in Volume 7, Environmental Management.

4.2.1 Key Issues

Key issues included in this assessment were identified through:

- community input, including regional technical workshops and community-level meetings
- review of other environmental assessments in the region
- professional experience

Issues relating to groundwater include:

- obstruction of groundwater flow, e.g., by frost bulb formation, could affect winter baseflow in streams. A reduction in winter groundwater flow in surface waterbodies could affect overwintering habitat for fish.
- slope instability could result from the blockage of groundwater flow in areas of groundwater discharge and cross-slope pipeline crossings
- alteration of recharge to the groundwater flow system or changes in groundwater flow patterns could result in changes in:
 - available groundwater supply
 - distribution of groundwater-fed wetland areas
 - hydrology
 - groundwater quality
- alteration of groundwater discharge points could result in the loss of rare or uncommon plant habitats
- potential spills or leaks into the hydrologic system, i.e., surface water and groundwater

4.2.2 Valued Components and Key Indicators

4.2.2.1 Valued Component Selection Process

As part of the hydrologic cycle, changes in groundwater storage, movement and quality could result in alterations to the biophysical environment. Communities have raised concerns regarding the quality of groundwater and potential on fish and wildlife (Gartner Lee Ltd. 2003). Stakeholders have identified the need to characterize near-surface groundwater flow, i.e., quality and quantity, and to identify the effects of changes in permafrost on groundwater flow along the pipeline corridor and at watercourse crossings (Gartner Lee Ltd. 2003).

Groundwater VCs for the project include:

- groundwater quantity and flow patterns
- groundwater quality

Table 4-1 lists selected VCs and the selection criteria for each. The VCs are described in the following discussion.

Table 4-1: Selection Criteria for Valued Components

Valued Component	Regulatory Status	Stakeholder Concerns	Ecological Vulnerability	Importance to Local Communities	Precedence in Other Assessments
Groundwater quantity and flow patterns	•	•	•	•	•
Groundwater quality	•	•	•	•	•

4.2.2.2 Valued Components

Groundwater Quantity and Flow Patterns

Many of the identified issues concerning groundwater relate to possible changes in shallow groundwater flow or groundwater discharge, i.e., springs, seeps or recharge into surface waterbodies. These features are components of the groundwater flow system, i.e., groundwater flow from an area of recharge through the subsurface to a point or area of discharge. For this reason, they are evaluated as a single valued component, comprising groundwater quantity and flow patterns. This single valued component considers the amount of groundwater in the flow system and the rate and pattern of groundwater flow in the subsurface.

Groundwater Quality

Groundwater quality is another valued component. Groundwater is used as a potable water supply in only one community, Wrigley. Groundwater quality also requires protection because it provides the recharge to surface waterbodies, and some seeps and springs are of ecological importance.

4.2.2.3 Key Indicators

Key indicators (KIs) are measured to determine the effects on valued components (VCs). For example, changes in groundwater discharge rates and locations, as observed in the distribution and flow rates of springs and seeps, can be used as KIs for groundwater quantity and flow patterns. Changes in chemical parameters in groundwater can be used as a KI for groundwater quality.

Project components could cause changes in the VCs, which can be determined by observing changes in a KI. The following discussion describes identified KIs that could be used to measure changes in groundwater conditions in the project area, including:

- groundwater discharge rates
- groundwater discharge locations
- groundwater chemical parameters

Groundwater Discharge Rates

Groundwater quantity and flow patterns can be reflected in the flow rate of springs and seeps. Winter baseflow in watercourses could partly indicate groundwater discharge. The size of groundwater-fed wetlands can also indicate the quantity of groundwater discharge.

Groundwater Discharge Locations

The locations of springs, seeps or groundwater-fed wetlands reflect groundwater flow patterns. Changes in groundwater flow patterns can be observed by a change in the location of groundwater discharge. This could include the development of new discharge areas or the alteration of existing ones.

Groundwater Chemical Parameters

Groundwater quality can be evaluated by analysis of ion concentrations and other parameters, e.g., pH and dissolved oxygen. Groundwater quality indicates the groundwater flow path, as chemical interactions between the groundwater and the sediments or rocks of the aquifer can alter the groundwater quality. Also, groundwater quality can change because of the introduction of foreign substances into the groundwater flow system or alterations in the flow path.

4.2.3 Key Question and Effect Pathway Diagram

The issues discussed in Section 4.2.1, Key Issues, have been incorporated in a single key question for the hydrogeological component of the assessment:

- How will the project affect groundwater?

Table 4-2 shows the relationship between the key question, the related issues and the VCs.

Table 4-2: Key Question, Related Issues and Valued Components

Key Question	Related Key Issue	Potentially Affected Valued Component
How will the project affect groundwater?	<ul style="list-style-type: none"> • Change in recharge and discharge • Flow obstruction • Change in permafrost patterns • Subsidence • Sedimentation 	Groundwater quantity and flow patterns
	<ul style="list-style-type: none"> • Change in surface water quality • Spills and leaks • Change in permafrost patterns • Deep well disposal 	Groundwater quality

An effect pathway diagram was developed to show various paths by which project activities could affect VCs. The effect pathway diagram is provided in Section 4.3.1, Effect Pathways.

4.2.4 Effect Descriptions

Effects of project activities on the hydrogeological regime are classified in terms of four attributes (see Table 4-3):

- direction
- magnitude
- geographic extent
- duration

The combination of these effect attributes is used to determine if an effect is significant.

Table 4-3: Definitions of Effect Attributes for Groundwater Quantity, Flow Patterns and Quality

Attribute	Definition
Direction	
Adverse	Effect leads to a change in groundwater quantity, flow patterns or quality
Neutral	No change in groundwater quantity, flow patterns or quality
Positive	Not applicable
Magnitude	
No effect	No effect on groundwater quantity, flow patterns or quality
Low	Effect on groundwater quantity, flow patterns or quality is expected to be within the normal range of variation
Moderate	Effect on groundwater quantity, flow patterns or quality is predicted to be outside the normal range of variation, but unlikely to pose a serious concern or management challenge
High	Effect on groundwater quantity, flow patterns or quality is predicted and likely to pose a serious concern or management challenge
Geographic Extent	
Local	Effect on groundwater is restricted to the local study area
Regional	Effect on groundwater is restricted to the regional study area
Beyond regional	Effect extends beyond the regional study area
Duration	
Short term	Effect on groundwater continues for less than one year
Medium term	Effect on groundwater continues for a period of one to four years
Long term	Effect on groundwater continues for more than four years but not more than 30 years after decommissioning and abandonment
Far future	Effect on groundwater continues for more than 30 years after decommissioning and abandonment

4.2.4.1 Direction

The direction of an effect is identified as:

- adverse
- neutral
- positive

An adverse effect is one that is expected to produce a negative change in the VC. With aquifers and groundwater systems, any change outside the normal range of variation is considered an adverse effect. Therefore, there can be no positive effects. Natural systems are adapted to the existing flow directions, flow rates and water quality, so any alterations will result in changes to the natural system.

4.2.4.2 Magnitude

Magnitude describes the severity or intensity of an effect, i.e., the extent and degree to which the groundwater flow system is affected, following mitigation. For springs or seeps, typical measurements would include a change in the number of discharge points or the extent of a discharge area and a change in the flow rate or quality of spring or seep water. Magnitude is identified as:

- no effect
- low
- moderate
- high

4.2.4.3 Geographic Extent

The geographic extent describes the area within which an effect occurs. There are three geographic extent classifications:

- local – within the local study area (LSA)
- regional – within the regional study area (RSA)
- beyond regional – beyond the RSA

The LSA and RSA are described in Section 4.2.5, Study Areas and Boundaries.

4.2.4.4 Duration

Duration refers to how long an effect occurs, i.e., the length of time for groundwater to return to pre-project conditions. Values assessed for duration of an effect are:

- short term – less than one year
- medium term – one to four years

- long term – from four years to 30 years after decommissioning and abandonment
- far future – more than 30 years after decommissioning and abandonment

4.2.5 Study Areas and Boundaries

Two types of study area were defined to assess the geographic extent of project effects:

- local study area (LSA)
- regional study area (RSA)

4.2.5.1 Local Study Areas

The groundwater assessment uses seven LSAs, one for each project component, or group of components, for which project effects are separately assessed. These LSAs are:

- Niglintgak
- Taglu
- Parsons Lake
- gathering pipelines and associated facilities
- pipeline corridor
- production area infrastructure
- pipeline corridor infrastructure

The geographic extent of these LSAs includes a 1-km-wide buffer surrounding the anchor fields and a 1-km-wide strip centred along the gathering pipelines and pipeline corridor. The LSAs for the infrastructure sites that are outside these LSAs, such as the barge landing sites, include the infrastructure footprint plus a surrounding 500-m buffer.

4.2.5.2 Regional Study Area

The RSA was selected to include groundwater-related features that could be affected by the project. The groundwater RSA boundary is a 30-km buffer surrounding the anchor fields and a 60-km-wide strip centred on the gathering system and pipeline corridor, i.e., 30 km on either side of the centre line. Figure 4-1 shows the RSA boundaries for the north area. Figure 4-2 shows the RSA boundaries for the central area. Figure 4-3 shows the RSA boundaries for the south area.

Figure 4.1 has been removed for the purposes of reducing file size and can be viewed as a graphic separately. This document can be accessed through the link in the Table of Contents reference web page.

Figure 4.2 has been removed for the purposes of reducing file size and can be viewed as a graphic separately. This document can be accessed through the link in the Table of Contents reference web page.

Figure 4.3 has been removed for the purposes of reducing file size and can be viewed as a graphic separately. This document can be accessed through the link in the Table of Contents reference web page.

Groundwater features are most pronounced in the Franklin Mountains and Mackenzie Plain physiographic region, between Fort Good Hope and Willowlake River. In this region, groundwater flow systems that might be affected by the project are expected to extend from the ridgeline or crest of the Franklin Mountains to the Mackenzie River. This area lies entirely within the RSA boundaries. Groundwater effects in other regions are more localized because the length of groundwater flow paths is reduced where there is less topographic variation. The effects are well within the RSA boundaries. A detailed description of these physiographic regions is provided in the biophysical baseline, Volume 3, Section 4, Groundwater.

4.2.6 Analytical Approach

Baseline information (see Volume 3, Section 4, Groundwater), including literature searches and field studies done in 2002 and 2003 on groundwater inflow to surface waterbodies and groundwater-related surface features, was used to identify:

- areas of groundwater recharge and discharge
- groundwater flow patterns
- presence of aquifers

Information about the groundwater flow systems and aquifers from field studies and available literature was used to assess the potential impacts from specific project components.

The literature provides background information on groundwater in the area. However, the information is general and rarely site-specific. Where site-specific information is available, it is seldom georeferenced, so the historical information cannot be easily mapped or linked to the proposed crossing locations.

The 2002 and 2003 field studies provided information on:

- groundwater-related features, including:
 - areas of open water in winter
 - polynas, i.e., patches of open water along a stream
 - icings
 - springs
- flow rates
- chemistry, i.e., pH, dissolved oxygen, conductivity and temperature, and major ions
- the geological setting of springs and seeps

4.3 Effects on Groundwater

4.3.1 Effect Pathways

The effect pathway diagram, Figure 4-4, illustrates the pathways by which the project could affect groundwater. Changes in groundwater quantity, flow patterns and quality are the key pathways that result in a change in groundwater. Effects related to a pathway are determined by changes in the KIs, i.e., groundwater quantity and flow patterns, and groundwater quality. Pathway descriptions related to specific project components are discussed following.

4.3.1.1 Change in Groundwater Quantity and Flow Patterns

Change in Recharge and Discharge

Recharge and discharge areas are locations where water enters or leaves the groundwater system. Effects on recharge areas might occur through extracting borrow material from borrow sites, which are frequently important recharge areas. These changes would reduce infiltration into the groundwater aquifers and could result in alterations to groundwater storage and flow patterns in these areas. Changes in surface water flow patterns and quantities can be caused by land disturbance, surface water withdrawals and other activities. These changes can alter the recharge of surface water into the groundwater system and result in changes in groundwater quantity and flow patterns.

The presence of project facilities in areas of discharge might disrupt groundwater discharge or result in the formation of new discharge areas. These changes could result in:

- alterations to groundwater quantity and flow patterns
- changed water table levels
- changes in the distribution of wetlands frequently associated with the discharge areas

Extracting Borrow Material

Removing borrow material from borrow sites might alter local groundwater flow. Most of the borrow sites are on ground that is higher than the surrounding terrain and the borrow material usually has greater permeability than the surrounding material. In areas of permafrost, the active layer is thicker than at locations where finer materials are found at the surface. Rain and runoff can infiltrate unfrozen borrow material, where the water can be stored before being released into the groundwater flow system. These sites are locations of recharge for local groundwater flow systems. Seasonal springs or seeps might be present at the edges of the borrow sites.

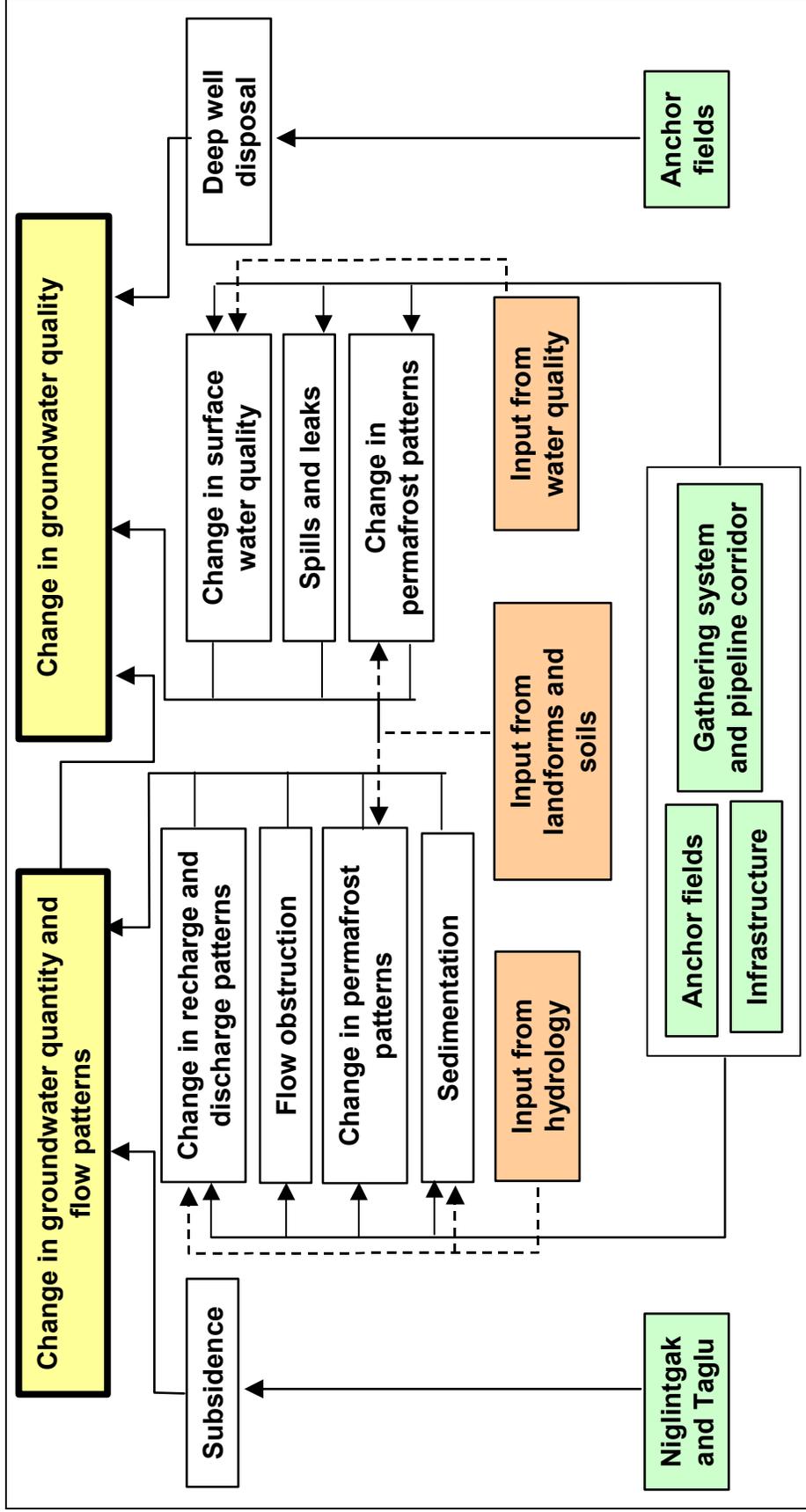


Figure 4-4: Effect Pathways – Groundwater

The extent of borrow material removed can affect groundwater flow in different ways. Complete removal of all the borrow material could result in:

- removing an area of groundwater storage or recharge
- drying seasonal springs and seeps
- increasing overland runoff.

Groundwater Discharge

Groundwater discharge to surface waterbodies might be derived from one or more of the following sources:

- winter flow
- karstic inflow
- drainage from unfrozen granular materials
- drainage from wetlands

Winter flow, identified in some rivers, is interpreted as drainage from lake storage within the drainage basin. Perennial groundwater contribution to streams in winter results in areas of open flowing water, polynas and many icing buildups along the streams.

Karstic features, such as sinkholes, caves and underground drainage develop from a combination of mechanical and water dissolution processes in areas of carbonate and evaporitic rock, such as limestone, dolomite and gypsum. Many karstic flow systems in the area are local, although some of the larger karstic springs might be fed in part from sources within and to the east of the Franklin Mountains, i.e., beyond the limits of the RSA. Spring flow rates, spring water temperature and chemistry can vary considerably. The flow rates are influenced by the nature, length and depth of the flow path, the type of geological materials encountered along the flow path, flow velocity and length of time in the ground. Many springs are located on regional faults.

Specific potential groundwater discharge effects resulting from project activities include the following:

- effects of construction on temporary flow – in locations downslope and close to perennial springs, construction could temporarily divert spring flow. Ditch dewatering might be required and upslope ponding is possible. Some means of channelling spring outflow might be necessary in some places.
- effects of construction on spring outflow – in locations upslope and close to perennial springs, construction activities could affect spring outflow. If pipeline ditching encounters the spring's source aquifer, an inadvertent diversion of spring flow into the pipeline ditch is possible. The likelihood of

this occurring will decrease as the elevation difference between the pipeline location and the point of spring outflow increases.

- effects of karst terrain on groundwater flow – in areas of karst terrain, groundwater might be diverted. Sinkholes could occur in areas of proposed activities. Spring water might flow into excavations downslope of sinkholes, although this is considered a remote possibility, unless sinkholes are close. This effect would occur during construction only.
- effects of faults on water flow – groundwater or surface water could flow into the pipeline ditch in locations where the pipeline route crosses fault zones. Effects would be restricted to areas where the bedrock surface is near the surface.
- borrow sites – on glacially formed eskers, some borrow sites might form areas of groundwater storage. The active layer could be thicker beneath these features or under areas of ponded water at their base. A chilled pipeline crossing a borrow site, for example, could result in the development of a frost bulb around the pipeline (see under Frost Bulb Formation in this section). Dewatering borrow site areas might be required during construction. This could temporarily alter local groundwater flow.

Groundwater Discharge – Slides

Groundwater outflow related to slides was observed at two types of slides in the LSA:

- retrogressive thaw–flow slides, where the outflow is formed by melting permafrost exposed by the slide
- active layer detachment slides, also called skin slides, which occur along the base of the active layer

Only retrogressive thaw–flow slides were identified in the production area.

Retrogressive thaw–flow slides occur mainly along the edges of lakes, and form when permafrost melts at an exposed headwall, causing slope instability. This instability results in a gravity-driven debris flow of thawed sediment and ice.

Skin slides occur mainly on hillsides and along streambanks when the active layer melts, detaches from the permafrost surface and moves downslope along this failure surface. Both types of slides will add small amounts of water to lakes, streams and seasonal stream flow, but are not expected to add to winter baseflow. Flow debris from some skin slides might reach the pipeline route at some locations. Icings could form at some retrogressive thaw–flow slides.

Pipeline construction activities, such as ditching, could create zones of weakness, especially where the pipeline is located at an upslope location close to an active or inactive retrogressive thaw–flow slide or to a high bank of a lake, pond or stream. This could trigger further slide retrogression and concentrate shallow groundwater flow, resulting in local changes in groundwater flow patterns.

Groundwater Discharge – Recharge from Surface Water

Surface water and groundwater interact through areas of recharge and discharge. Changes in surface water flow are reflected in similar changes in flow patterns in the groundwater system, specifically in flow rate, water level and direction of flow. Some project components might cause changes to surface water runoff amount, drainage patterns, water levels and flow volumes, resulting in changes to groundwater quantity or flow patterns. Potential changes in surface water relating to project activities are discussed in detail in Section 5, Hydrology. In general, changes in groundwater quantity and flow patterns in response to changes in surface water recharge are expected to be somewhat attenuated, i.e., more subdued in magnitude and potentially of longer duration.

Groundwater Withdrawal

A supply of water will be required for many purposes including:

- drilling
- industrial supply
- pressure testing
- potable water for camps
- winter road construction

Surface waterbodies or transported supplies have been identified as the primary water sources for potable water. The sources of water supplies for other purposes have not been identified. The groundwater withdrawal pathway is not considered applicable because no groundwater withdrawals are currently planned or likely.

Flow Obstruction

Subsurface project components, particularly the pipeline, could affect shallow groundwater flow by blocking existing flow paths. A blockage usually results in upslope ponding and a change in the shallow groundwater flow direction. Specific types of settings and the effects of this pathway are described in the following discussion.

Blockage of Drainage

Possible blockage of downslope drainage within fens might result in:

- changes in shallow groundwater flow direction
- ponding of water in upslope locations

Fens in southern areas do not freeze to the bottom and icings can develop in these areas. Icings are not expected in fens within continuous permafrost, as the shallow fens are expected to freeze to the bottom in winter. However, some fens, located on gentle sidehill slopes in areas of a thin active layer, are likely to be affected during construction.

Deflection

Deflection of shallow groundwater flow and water ponding could occur in areas where the pipeline crosses a sidehill slope of permeable granular materials, e.g., alluvial fans, kames and eskers. Icings could form where deflection occurs in the active layer.

Frost Bulb Formation

The presence of a chilled pipeline in an area of unfrozen ground could result in a frost bulb developing around the pipe. Based on the project design specifications, the temperature of the natural gas pipeline north of Little Chicago will be below freezing. South of Little Chicago, the natural gas pipeline temperature will vary with location and time of year. The pipeline temperature will average above zero south of Little Chicago. However, the pipe temperature could locally be below freezing in areas of discontinuous permafrost.

Complete or partial blockage of groundwater flow could result from the presence of a frost bulb around the pipeline. Complete obstruction of groundwater flow could only occur in areas where groundwater flow is restricted to a zone thin enough that it could be completely blocked by a frost bulb, e.g., in a shallow talik underlying a watercourse, or seasonally within the active layer.

In other areas, groundwater flow could be locally diverted around a frost bulb, but would not be noticeably obstructed. Obstruction of groundwater flow will also be related to the rate of groundwater movement and permeability of the subsurface materials. Larger flow rates might offset the thermal effects, and coarse subsurface materials could restrict the growth of the frost bulb. These factors could result in a smaller frost bulb than in other areas with finer subsurface materials or moderate rates of groundwater movement.

In areas with lower permeability materials and low groundwater flow rates, the area would likely freeze in winter and effects related to obstruction would be relatively low. Effects related to frost bulb development might be most noticeable in areas with moderate rates of perennial groundwater flow. If most of the groundwater flow is obstructed by a frost bulb, groundwater flow might be stored in the subsurface upgradient of the frost bulb or redirected to surface, where it could pond at surface or flow downslope. Icings might develop where groundwater is redirected to the surface during winter conditions. Slope instability could result in areas where substantial subsurface storage occurs upslope of the frost bulb.

Following is a summary of the potential for groundwater obstruction related to watercourse crossings:

- Vegetated Channels, i.e., ephemeral drainage courses that do not include measurable groundwater contributions – a vertical separation typically exists between the groundwater table and channel bottom in these watercourses. Therefore, no interaction between a frost bulb, if one were to develop, and groundwater is expected.
- Active II Channels, i.e., channels with no significant groundwater contributions and no active flow in the winter – because of the limited groundwater flow contributions to these channels, a frost bulb would have a low potential effect on groundwater movement
- Active I Channels, i.e., channels with perennial groundwater contributions – the development of a frost bulb around the pipeline at one of these watercourse crossings has the potential to affect groundwater flow during the winter. The rate of groundwater or stream flow might be sufficient to reduce the growth of the frost bulb and limit the effects of flow obstruction. The magnitude of effects will vary depending on the hydrological and geological setting at a particular crossing.
- Large River Channels – groundwater flow in the subsurface below the streambed will not be substantially obstructed because the thermal effects of the stream flow are expected to sufficiently limit the growth of a frost bulb
- watercourse crossings where horizontal directional drilling is used, i.e., identified Active I and Large River Channels – the burial depth will be sufficient to maintain a thaw zone under the channel bottom and prevent groundwater flow from becoming completely obstructed

Frost bulbs would begin to develop in areas where conditions are favourable, when the pipeline is operational. Once the pipeline is decommissioned, the frost bulbs would begin to thaw and are expected to disappear.

Flow obstruction related only to the physical presence of the pipeline in the subsurface is possible, but would occur only in areas where the pipeline blocks most, or all, of a high permeability unit through which the groundwater flows. These conditions are expected to be few and would be readily identified during the pipeline emplacement. Installing subdrains or ditch breakers could prevent flow obstruction.

Change in Permafrost Patterns

The presence of project components, changes in vegetation cover, ground disturbance and other mechanisms can cause thermal changes that might affect the lateral distribution and vertical extent of permafrost. The distribution of

permafrost controls the movement and defines the flow paths available for groundwater flow. Effects such as ground settlement, ground heave and ponding can be triggered by changes in the thermal regime, possibly resulting in changes in groundwater flow patterns. See Section 8, Soils, Landforms and Permafrost, for details on potential changes in permafrost resulting from project activities.

Subsidence

Land subsidence is expected to occur at both Niglintgak and Taglu because of project construction and operations. The extraction of natural gas and natural gas liquids (NGLs) will reduce reservoir volumes and pressures, leading to compression of the reservoir and subsequent subsidence of the overlying land. This subsidence will combine with the relative sea-level increase that is currently occurring in the delta at an average rate of 1 mm/a. The total subsidence from production is estimated as 0.4 m at Niglintgak and 0.3 to 0.5 m at Taglu.

Subsidence and flooding could raise an already high water table and increase groundwater salinity. The extent of the saltwater intrusion depends on tides, river flow and bathymetry of the channel bed. Because saltwater is denser than fresh water, a saltwater wedge tends to form along the bottom of channels in a transition zone. The extent of a saltwater wedge would be greatest at high tide during low river flow. Land subsidence, and the associated lowering of channel beds, might allow the saltwater influences to extend farther upstream, leading to saltwater infiltration of the shallow groundwater system, with subsequent effects on underlying, freshwater taliks.

Given the dynamic physical system that operates within the delta area, the localized extent and relatively low amount of subsidence predicted, it is expected that any changes in groundwater quantity and flow patterns or groundwater quality will not be detectable at Niglintgak or Taglu.

Sedimentation

The construction of project components, runoff from facilities, and activities related to all-weather roads and other infrastructure might increase the amount of sediment in surface water runoff and mobilize sediment into aquifers. Fine sediment particles, mainly silt-sized, can be transported by water and become lodged in the pore spaces of the aquifer material, thereby reducing the aquifer's storage capacity and ability to transmit water. These particles would remain in place and therefore any effects related to siltation would persist into the far future.

Siltation, referred to here as sedimentation, is most likely to occur where disturbance is located in or near areas of high water table or near shallow, highly permeable materials, e.g., sands and gravels, and fractured or karstic bedrock. Construction activities at borrow sites are the most likely pathway by which sedimentation of an aquifer could occur. Screening and crushing activities

produce sediment that can be carried directly into the ground and underlying aquifers by runoff or precipitation.

Mitigation measures to control the release of sediment into surface water (see Section 5, Hydrology), combined with trapping sediment in surface water runoff, via vegetation and deposition on the land surface, are sufficient to render the possibility of sedimentation from most project disturbances remote. Therefore, this pathway is not considered applicable. The potential for sedimentation is considered applicable and included as part of this assessment only with respect to activities at the borrow sites.

4.3.1.2 Change in Groundwater Quality

Change in Surface Water Quality

Changes in surface water quality caused by wastewater discharge or other processes could result in changes in groundwater quality through recharge of surface water to groundwater.

Spills and Leaks

Small spills that can occur during normal construction, operations and decommissioning activities have the potential to affect groundwater quality in wetland areas, where the water table is near or above the ground surface. Management practices and mitigation plans, as described in Volume 7, Environmental Management, will reduce the potential for spills and leaks so this pathway is not considered applicable.

A remote sump is to be used for disposing drilling fluids and cuttings from Niglintgak. Potential changes in groundwater quality could occur from the development of leachate if precipitation percolates through the waste and seeps into the groundwater system.

Deep Well Disposal

Produced water, drill cuttings and other fluids and cuttings from the gas field development will be either injected into a disposal well at each of the fields or transported off site for disposal. Deep well disposal could directly affect the groundwater of the receiving formation and could affect other formations and aquifers through seepage out of the receiving formation.

Effects of deep well disposal on groundwater quality have not been evaluated for the following reasons:

- disposal will be into formations more than 1 km deep that do not contain potable water
- formation isolation and wellbore integrity will be confirmed during well development

Currently, no other use of wells or landfills for waste disposal is indicated.

Change in Permafrost Patterns

Permafrost melting affects groundwater quality. Ice in the permafrost is usually fresh in quality. Therefore, permafrost melting and this water being added to the groundwater system has a diluting effect on groundwater chemistry. Similarly, as groundwater freezes and becomes permafrost, the chemistry of the remaining liquid tends to become more concentrated.

Change in Groundwater Quantity and Flow Patterns

Groundwater quality is affected by changes in the flow path along which the groundwater moves. Because groundwater makes contact with different geological materials, changes occur in the chemical interactions between the groundwater and the aquifer sediments or rocks. These changes can result in alterations to the groundwater quality. Because this assessment has not identified significant changes in groundwater quantity or flow patterns, this pathway is not considered applicable.

4.3.2 Overview of Project Design and Mitigation

An overview of the mitigation strategies for each of the potential effects on groundwater from project components is provided in Table 4-4, and was discussed previously in Section 4.3.1, Effect Pathways. Most effects will be initiated during construction and some will result in changes that will persist or develop during the remainder of the project. Decommissioning will remove many project components that generate effects. For example, effects related to the chilled natural gas pipeline would not be permanent. Some effects, such as those related to project components abandoned in place or to removing materials from borrow sites, are expected to persist into the far future.

Table 4-4: Primary Mitigation Strategies for Potential Effects on Groundwater

Effect Pathway	Primary Mitigation Strategy
Obstruction of groundwater flow related to frost bulbs during construction and operations	Increase burial depth of pipeline or use insulation at Active I crossing locations susceptible to heave or frost bulb growth where fall spawning or overwintering fish habitat is present (locations to be identified based on pipe temperature, soil characteristics and fish habitat).
Obstruction of groundwater flow related to blockage from pipeline construction	Install drainage controls in areas of substantive groundwater flow encountered during ditching, before the ditch is backfilled. Crown gas pipeline and gathering system ditches, and place breaks at intervals to maintain natural flow paths.

Table 4-4: Primary Mitigation Strategies for Potential Effects on Groundwater (cont'd)

Effect Pathway	Primary Mitigation Strategy
Change in recharge and discharge related to slides during construction activities	Avoid unstable slopes where practical. Reclaim, stabilize and armour slopes and banks as necessary.
Change in recharge and discharge related to surface water recharge from facility construction and operation	Install drainage diversions around facility sites, such as compressor stations, where required. Install culverts or bridges where access roads cross a defined watercourse, where required. Stabilize any ford crossings at low points along access roads. Ensure adequate cross drainage occurs in the corduroy that is left in place. Use geotextile to limit the depth of corduroy on the reclaimed right-of-way if necessary. Incorporate drainage culverts in all-weather roads, as required. Re-establish drainage where it is blocked and where ponding occurs along the right-of-way and roads, when conditions are appropriate.
Change in natural recharge from development of borrow sites	Maintain sufficient permeable surface area at borrow sites to ensure recharge, as necessary.
Increased sedimentation from development of borrow sites	Implement drainage, erosion and sediment controls such as grading and ditching to direct runoff through silt fences, sediment traps, vegetation, berms or isolation areas, as appropriate for the location. Monitor effectiveness of controls through routine inspection.
Change in groundwater quality from spills and leaks during construction and operations	Implement management practices, contingency plans, and emergency response plans to prevent and address leaks and spills.
Change in groundwater quality related to seepage from remote sump at Niglintgak	Ensure material at the Niglintgak remote sump remains frozen and that the cap is stable.
Change in areas of discharge related to construction activities	Monitor, by aerial inspection, visual changes in location or extent of groundwater discharge areas.
Change in groundwater discharge and quality from construction activities	Monitor thaw settlement and frost heave, pond formation and drainage, and erosion at selected sites.
Change in groundwater quantity and flow patterns and groundwater quality from subsidence at Niglintgak and Taglu	Visually monitor effects of land subsidence from gas extraction at Niglintgak and Taglu, e.g., Kumak and Kuluarpak channels.

Construction

Frost bulb formation could occur during pipeline operations. The formation of these features and obstruction of groundwater flow can be reduced by engineering design, through deep burial or insulating the pipeline at selected vulnerable watercourse crossings.

In areas where groundwater flow is encountered during ditching and pipeline emplacement, drainage controls will be installed before the ditch is backfilled. Installing subdrains will enable groundwater flow to be redirected around the pipeline. This is expected to effectively reduce effects related to the obstruction of groundwater flow.

Constructing the pipeline ditch could create localized zones of weakness resulting in slide formation. These factors were considered in the route selection process (see Volume 2, Section 2, Route and Site Selection). Areas of concern were identified and addressed during the design process, or selected for ongoing monitoring. Monitoring of pipeline integrity during operations (see Volume 2, Section 4, Pipelines), including aerial inspections, will help identify areas of ground instability and enable appropriate response actions to be taken.

A freeze, cover and bury method will be used at the remote sump for disposing drilling fluids and cuttings from well development at Niglintgak. A monitoring program will be implemented to ensure that this material remains frozen and the cap is stable.

Changes in groundwater flow resulting from alterations of surface water flow patterns could occur at any surface or subsurface project component site. Appropriate mitigation strategies for effects on surface water flow are described in Section 5, Hydrology. Similar strategies will be effective for road construction or at surface facilities where required in areas of high water table.

Removing materials from borrow sites can affect recharge to shallow groundwater. Leaving an area of permeable materials will enable some groundwater recharge to continue from the infiltration of precipitation or runoff. The thickness or extent of borrow material to be left in place at each borrow site will be considered in preparing the pit development plans (see Volume 2, Section 7, Borrow Sites).

Crushing or screening activities related to the development or operation of the borrow sites have the potential to mobilize fine sediment into nearby aquifers. Most of the activities related to borrow site operations would occur in the winter, resulting in an attenuated dispersal of fine sediment particles that melt out from frozen excavated material or are released by crushing. Operating practices to reduce mobilization of fine sediment particles will be developed, where necessary, as part of the detailed borrow site development plans.

Small surface spills that could occur during construction, operations or decommissioning will be addressed through a spill response plan. These spills could occur at the facilities, infrastructure sites, or along the gathering pipelines or pipeline corridor.

Operations

Frost bulbs could form during pipeline operations. Appropriate engineering solutions will be developed as required to reduce the effects of frost bulbs, particularly in areas where upslope ponding of groundwater is possible.

Surface facilities constructed in permafrost areas will be designed to prevent thermal transfer to the ground and to limit changes in the local permafrost regime, which could result in changes in the groundwater quantity and flow patterns, or groundwater quality. Monitoring for areas experiencing thaw settlement along the pipeline corridor will be completed. Additional fill materials will be used in these areas to provide insulation and restore ground stability where necessary.

During operations, spills along the pipeline corridor and gathering pipelines will be identified during regular aerial inspections. A leak detection system (see Volume 2, Section 4, Pipelines) will be used to identify pipeline leaks in the NGL pipeline and these will be addressed according to the spill contingency plan described in Volume 7, Section 5, Contingency Plans.

Subsidence is expected to occur at Niglintgak and Taglu because of gas and NGL extraction. The amount of subsidence will be monitored annually.

4.3.3 Niglintgak

As described in Volume 2, Project Description, Niglintgak will include:

- three proposed well pads (north, central and south)
- six to 12 production wells
- a gas-conditioning facility
- associated above-ground flow lines
- a disposal well
- a remote drilling sump
- supporting infrastructure

Two options are being considered for the Niglintgak gas conditioning facility:

- a proposed barge-based facility in the Mackenzie River (preferred option)
- an alternative land-based facility on the east bank of Kumak Channel

4.3.3.1 Baseline Conditions

The Niglintgak field is within the Mackenzie Delta in the area of intermediate discontinuous permafrost (Heginbottom 2000). The surficial materials at

Niglintgak comprise an assemblage of deltaic fluvial, i.e., river-deposited, silt, sand and gravel, covered in places with organic deposits. The geology is complex, as a result of the many changes in streambed alignment that have taken place during the formation of the Mackenzie Delta.

The terrain at Niglintgak is low lying and subject to annual flooding. Niglintgak straddles the wide expanse of the Mackenzie River. Middle Channel and Kumak Channel lead off the Mackenzie River along the east side of Niglintgak Island (see Figure 4-5). The depth to the base of the active layer at Niglintgak ranges from 0.25 to 1.3 m. Movement of groundwater in this area is expected to be slow because of the flat terrain. The active layer is expected to become thinner away from the larger bodies of water and their associated taliks. Permafrost thickness below the active layer at Niglintgak ranges from 146 to 275 m (Burgess et al. 1982; Taylor et al. 2000).

Extensive or through taliks, i.e., taliks that extend completely through the permafrost, are likely to occur beneath the larger lakes and river channels in this lease area and the surrounding delta. Burn (2002) estimated that on Richards Island, which is the lake-dominated area located between Harry and East channels of the Mackenzie River, 23% of the lakes and 10 to 15% of the surface area of the island are underlain by through taliks.

Detailed groundwater quality information is not available at Niglintgak. Formation water, i.e., water within the gas reservoir, at Niglintgak is fresh, which suggests that groundwater in shallower zones will also be fresh. This could indicate active water movement from surface sources into and through the groundwater flow system.

4.3.3.2 Niglintgak Effects

Table 4-5 summarizes project-related pathways that could affect groundwater quantity and flow patterns at Niglintgak. Table 4-6 summarizes pathways related to groundwater quality.

The relative difference in effects on groundwater between the barge-based and land-based gas conditioning facility options is small. The area of surface disturbance is larger for the land-based option. However, this is not expected to make a detectable difference with respect to effects on groundwater, and project effects are the same for either development option.

Figure 4.5 has been removed for the purposes of reducing file size and can be viewed as a graphic separately. This document can be accessed through the link in the Table of Contents reference web page.

Table 4-5: Effects on Groundwater Quantity and Flow Patterns – Niglintgak

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Neutral	No effect	N/A	N/A
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Far future
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Table 4-6: Residual Effects on Groundwater Quality – Niglintgak

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Far future
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

The effect attributes are for the residual effects following implementation of mitigation (see Section 4.3.2, Overview of Project Design and Mitigation, and Volume 7, Environmental Management). The effects relating to each of the applicable pathways are described by project phase in the following discussion.

Groundwater Quantity and Flow Patterns

Potential effects relating to the recharge and discharge pathway are limited to changes in recharge from surface water. Groundwater flow patterns usually mirror

surface water flow patterns. Local alterations to the surface drainage patterns will result in minor changes in the seasonal groundwater flow patterns in the active layer (see Section 5, Hydrology). Similarly, changes in surface water levels could affect recharge to groundwater in the active layer, and groundwater quantity. Effects on surface water drainage patterns and water levels at Niglintgak are expected to be low magnitude through all project phases.

Low- to moderate-magnitude changes could be expected because of surface water withdrawals during construction and potential flow obstruction during construction and operations. Changes in groundwater quantity and flow patterns in response to these changes in surface water recharge are expected to be similar, but somewhat attenuated, i.e., more subdued in magnitude and potentially of longer duration. The changes in groundwater quantity and flow patterns are expected to be low magnitude. Changes would occur during construction, operations and decommissioning, and effects related to these activities would persist into the long term, i.e., for some time after the removal of surface facilities and reclamation of the land.

The presence of subsurface structures could result in effects on groundwater quantity and flow patterns through obstruction of groundwater flow. Subsurface disturbance will occur during construction when the piles are driven and wells are drilled. The installation and ongoing presence of these project components will result in a minor local change to groundwater flow patterns that is not expected to be detectable. This minor change will persist into the far future because these subsurface structures might be abandoned in place and related effects will persist as long as the structures are in place.

Surface facilities will be elevated, or thermally separated, from the ground so changes in permafrost conditions are expected to be low magnitude. Minor, undetectable effects on groundwater quantity and flow patterns are expected in response to any changes in permafrost distribution. Changes in permafrost because of subsidence caused by resource extraction would persist into the far future. Related changes in groundwater quantity and flow patterns would also persist into the far future.

Groundwater Quality

Changes in surface water quality are expected to be low magnitude for all effects during construction and operations (see Section 6, Water Quality). Any effect on groundwater quality from surface water recharge is therefore expected to be low magnitude. Given the slow rates of groundwater movement expected in this area, it is possible that changes in groundwater quality could persist in the groundwater system in the long term. Once operations cease, it is expected that surface water quality, and subsequently groundwater quality, will return to near baseline conditions.

SECTION 4: GROUNDWATER

Drilling fluids and cuttings will be transported to an area about 30 km southeast of the field for disposal in a sump, using a freeze, bury and cover method. The sump is located on high ground above the floodplain. A monitoring program will be implemented to ensure that this material remains frozen and the cap is stable. As long as the cuttings and fluids stay frozen, no seepage from this material into the groundwater system is expected and there would be no effect on groundwater quality.

Effects on permafrost from project activities at Niglintgak are expected to be low magnitude. Therefore, any changes in groundwater quality through this pathway are expected to be undetectable. These changes would be initiated during construction and operations. Changes in permafrost because of subsidence caused by resource extraction would persist into the far future. Related changes in groundwater quality would also persist into the far future.

4.3.4 Taglu

As described in Volume 2, Project Description, Taglu will include:

- a gas conditioning facility
- 10 to 15 production wells on a single well pad
- associated above-ground flow lines
- one or two disposal wells
- supporting infrastructure

4.3.4.1 Baseline Conditions

Taglu is within the Mackenzie Delta in the area of intermediate discontinuous permafrost (Heginbottom 2000). Surficial materials at Taglu, in the area west of Harry Channel, are similar to those at Niglintgak, i.e., an assemblage of deltaic fluvial silt, sand and gravel, covered in places with organic deposits. East of Harry Channel, Taglu is mantled by sediments described as *mainly hummocky or ridged moraine and lacustrine deposits with extensive organic cover* (Norris 1975).

The terrain at Taglu is low lying and subject to annual flooding. The Harry, Kuluarpak and Kanguk channels of the river cut across the Taglu lease (see Figure 4-5, shown previously). The depth to the base of the active layer at Taglu is expected to be similar to that at Niglintgak, i.e., ranging from 0.25 to 1.3 m. The active layer is expected to become thinner away from the larger bodies of water and their associated taliks. Permafrost thickness below the active layer ranges from 500 to 670 m (Burgess et al. 1982; Taylor et al. 2000).

Extensive or through taliks are likely to occur beneath the larger lakes, e.g., Big Lake and river channels at Taglu and in the surrounding delta.

At Taglu, groundwater is present within closed, or intra-permafrost taliks. Across part of the Taglu lease is a laterally continuous, shallow, unfrozen zone, 20 to 60 m thick, which forms a closed talik beneath a 35- to 90-m thick permafrost cap. This closed talik overlies the main permafrost body below it. Water was produced from a depth of 67 m in a well drilled into this talik (Bowerman and Coffman 1975).

The base of the permafrost at Taglu is within the Miocene Beaufort Formation, which is made up of gravel, sand and sandy mud (Young and McNeil 1984). The coarse granular nature of this formation suggests that subpermafrost water might be abundant within the lease area. Interconnections and groundwater flow directions between surface waterbodies, through taliks beneath waterbodies, and subpermafrost and intrapermafrost taliks are unknown.

Detailed information on groundwater quality is not available at Taglu. Formation water at Niglintgak is fresh, which suggests that groundwater in shallower zones at Taglu will also be fresh. This could indicate active water movement from surface sources into and through the groundwater flow system.

4.3.4.2 Taglu Effects

Table 4-7 summarizes project-related pathways that could affect groundwater quantity and flow patterns at Taglu. Table 4-8 summarizes pathways related to groundwater quality. The effects relating to each of the applicable pathways at Taglu are expected to be similar to those at Niglintgak (see Section 4.3.3.2, Niglintgak Effects, for details).

4.3.5 Parsons Lake

As described in Volume 2, Project Description, Parsons Lake will include:

- a gas conditioning facility
- north and south well pads
- above-ground flow lines
- two disposal wells
- supporting infrastructure

The site will be developed in two stages. The north pad, including a single well pad with nine to 19 production wells, flow lines, two disposal wells and gas conditioning facility, will be developed first. The south pad will follow about five to 10 years after development of the north pad, and will consist of a single well pad with three to seven wells. An above-ground flow line will transport produced hydrocarbons from the south pad to the north pad for conditioning.

SECTION 4: GROUNDWATER

Table 4-7: Effects on Groundwater Quantity and Flow Patterns – Taglu

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Neutral	No effect	N/A	N/A
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Far future
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Table 4-8: Residual Effects on Groundwater Quality – Taglu

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Far future
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

4.3.5.1 Baseline Conditions

The Parsons Lake field is within the zone of continuous permafrost (see Figure 4-6). Permafrost thickness to the north and east of the Parsons Lake field is consistently about 354 to 378 m (Taylor et al. 2000). The active layer is less than 0.30 m thick in organic peats and silts, and up to 1 m thick in the sparsely vegetated glaciofluvial gravel and sand that cover much of this area (Hardy and Associates 1976).

Geotechnical test holes have been drilled east and southeast of Parsons Lake to depths of 11.3 m (Hardy and Associates 1976). Earth material in all holes was frozen. Some zones, most often at the base of the deeper holes, were logged during drilling as poorly bonded or friable frozen soil with nonvisible ice. It is possible that some of these zones could pass into unfrozen strata at depth, where groundwater might be present.

The drilling program included test holes on the north shore of Hans Bay about 6 km southeast of Parsons Lake. These test holes identified a maximum depth to the top of permafrost of 19 m in offshore test holes. The depth to the top of permafrost varied with depth of water in the lake. Although the test holes on Hans Bay encountered permafrost, it is likely that deep or through taliks exist beneath the central parts of Husky Lakes and of Parsons Lake.

An unusual feature in the area is a small, unnamed lake that is reported to stay unfrozen in winter (Canadian Helicopters personnel 2002, personal communication). This lake is located immediately southeast of Parsons Lake. Gas is reported to bubble up through the water. This lake had open water on June 5, 2002 when other lakes nearby were still frozen over. The lake differs from nearby lakes of similar size by having patches of vegetation within it and a broad fringe of aquatic vegetation along its shoreline. Patches of open water in winter have also been reported at Parsons Lake (Canadian Helicopters personnel 2002, personal communication). A water sample collected from the unnamed lake indicates that the water has low ionic strength, as reflected by a low specific conductance and total dissolved solids concentration. The major ion chemistry of this lake does not appear to be affected by the nearby bubbling gas.

4.3.5.2 Parsons Lake Effects

Table 4-9 summarizes project-related pathways that have the potential to affect groundwater quantity and flow patterns at the Parsons Lake lease. Table 4-10 summarizes pathways related to groundwater quality. Although there will be no subsidence at Parsons Lake, the effects relating to each of the applicable pathways at Parsons Lake are expected to be similar to those at Niglintgak (see Section 4.3.3.2, Niglintgak Effects, for details).

4.3.6 Gathering Pipelines and Associated Facilities

The gathering pipelines connect the three production fields to the Inuvik area facility (see Volume 2, Project Description). The gathering pipelines and associated facilities will include the Niglintgak lateral, Taglu lateral, Parsons Lake lateral, Storm Hills lateral, the Inuvik area facility, Storm Hills pigging facility and two intermediate block valves.

Figure 4.6 has been removed for the purposes of reducing file size and can be viewed as a graphic separately. This document can be accessed through the link in the Table of Contents reference web page.

Table 4-9: Effects on Groundwater Quantity and Flow Patterns – Parsons Lake

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Neutral	No effect	N/A	N/A
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Table 4-10: Effects on Groundwater Quality – Parsons Lake

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Far future
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

4.3.6.1 Baseline Conditions

The gathering pipelines and associated facilities in the production area traverse two main kinds of terrain:

- low-lying areas within the present-day Mackenzie Delta, consisting of alluvial plain sediments with intermediate discontinuous permafrost
- higher land comprising various surficial materials with continuous permafrost

Substantial winter flow is present beneath ice cover in channels of the Mackenzie River (Brooks 2000; McCart 1973; Water Survey of Canada 1992). Taliks occur below the main channels, some of which might extend through to the base of the permafrost (Burn 2002; Smith and Hwang 1973). The lateral extent of taliks away from the channels is unknown. The role of taliks, if any, in maintaining or adding to the stream flow in this area is not known.

Groundwater-related surficial features along the gathering pipeline route include pingos and retrogressive thaw–flow slides. Pingos are common north of North Storm Hills. Retrogressive thaw–flow slides occur mainly along the edges of lakes. At these sites, groundwater outflow is expected to occur because permafrost, exposed by the slide, will melt. Flow is expected only during the warmer months. At other times, icings are likely to form at these slides.

Winter open water and icings occur infrequently along the gathering pipeline route. Winter open water has been observed at the outlet from Noell Lake, and a 2-km long icing was noted downstream of the outlet from Noell Lake. These features are both attributed to flow derived from lake storage rather than to groundwater inflow. Springs in this area are seasonal and related to the active layer thawing.

4.3.6.2 Gathering Pipelines Effects

The gathering system includes buried pipelines that will transport gas and NGLs from Niglintgak to Taglu, and laterals from Taglu and Parsons Lake to the Storm Hills pigging facility. The Storm Hills lateral will transport gas and NGLs south to the Inuvik area facility. The pipeline routes were selected to avoid lakes and ponds, so taliks are unlikely to be encountered during ditching, except at major river crossings. Drained lake basins, including those that contain pingos, have also been avoided.

Table 4-11 summarizes project-related pathways that have the potential to affect groundwater quantity and flow patterns within the gathering pipelines. Table 4-12 summarizes pathways related to groundwater quality.

Groundwater Quantity and Flow Patterns

Construction

The potential effects of construction of the gathering pipelines are the same as those described for Niglintgak in Section 4.3.3.2, Niglintgak Effects.

Table 4-11: Effects on Groundwater Quantity and Flow – Gathering Pipelines

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Flow obstruction	Construction	Adverse	Low	Local	Far future ¹
	Operations	Adverse	Low (Moderate possible)	Local	Long term ²
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A

NOTE:
N/A = not applicable
1 Related to the physical disruption of flow
2 Related to frost bulb formation

Table 4-12: Effects on Groundwater Quality – Gathering Pipelines

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A

NOTE:
N/A = not applicable

Effects through the recharge and discharge pathway could also occur through the development of slides. Ditching and other intrusive activities upslope and close to a retrogressive thaw-flow slide or high bank of a lake, pond or stream have the potential to create a zone of weakness, which could trigger further slide retrogression and concentrate shallow groundwater flow. The route selection

process tried to avoid these areas wherever practical (see Volume 2, Section 2, Route and Site Selection) and no particular areas of concern are expected along the gathering pipelines route. Monitoring pipeline integrity during operations, including aerial inspections, would identify the development of any slides and enable the correct response.

The presence of subsurface project components, in particular the gathering pipeline sections, have the potential to block and deflect groundwater flow. Ditching through the active layer, pipe placement and replacement of cover will be done during frozen conditions, which will reduce effects on shallow groundwater in the active layer. Replacing surficial material with the original soil, in many areas, will reduce potential adverse effects on the shallow groundwater flow system, such as blocked flow and water ponding along the route. Precautions will be taken when crossing sidehill slopes and areas of granular materials.

The potential for effects related to blockage is considered low because of the low relief of the production area. However, areas where blockages could occur include locations of granular materials and the region of greater relief at Storm Hills. Potential effects in areas of groundwater flow encountered during ditching can be adequately addressed by installing subdrains or ditch breakers, where required, to enable groundwater flow to continue without substantial impediment. Effects of flow obstruction related to the physical presence of the pipeline within the subsurface would continue into the far future, unless these pipelines are removed during decommissioning and abandonment. Effects related to flow obstruction are expected to be low magnitude.

Surface facilities will be elevated or thermally separated from the ground so changes in permafrost conditions are expected to be low magnitude. Minor, undetectable effects on groundwater quantity and flow patterns are expected during construction and operations.

Operations

Frost bulbs might develop in areas of unfrozen ground during operations. The frost bulb could form a barrier to downgradient movement of groundwater and, in some cases, this obstruction could be substantial enough to result in upgradient ponding of groundwater or rerouting of groundwater flow. The proportion of unfrozen ground within the production area is small, and rates of shallow groundwater flow are expected to be low because of the gentle topography. Some Active I watercourse crossings and some slope areas could experience moderate-magnitude effects, whereas all other areas are expected to have low-magnitude effects. The pipeline will return to ambient temperatures following decommissioning and abandonment. Therefore, effects would be long term.

Groundwater Quality

Changes in surface water quality are expected to be low magnitude during construction and operations. Any effects on groundwater quality via this pathway are therefore expected to be low magnitude. Given the slow rates of groundwater movement expected in the production area, it is possible that changes in groundwater quality could persist for a long time in the groundwater system. After operations cease, it is expected that surface water quality, and subsequently groundwater quality, will return to near baseline conditions.

Effects on permafrost from project activities in the gathering pipelines are expected to be low magnitude, so any changes in groundwater quality through this pathway are expected to be undetectable. These changes would be initiated during construction and operations and recover to baseline conditions following decommissioning and abandonment.

4.3.7 Pipeline Corridor

For this assessment, the pipeline corridor also includes the following components of the NOVA Gas Transmission Ltd. (NGTL) ancillary project:

- the NGTL interconnect facility
- the extension of the existing NGTL pipeline in northwestern Alberta to the interconnect facility. The extension is known as the NGTL Northwest Mainline (Dickins Lake Section)
- a loop of the existing NGTL Northwest Mainline (Dickins Lake Section) north of the Thunder Creek compressor, referred to as the Vardie River Section

The pipeline corridor includes the gas pipeline, the NGL pipeline and pipeline facilities, including block valves, compressor stations and a heater station (see Volume 2, Project Description). The 1,220-km natural gas pipeline will transport sweet natural gas from the Inuvik area facility and tie in to the NGTL system. The gas pipeline and the NGL pipeline will share a common right-of-way for about 480 km from the Inuvik area facility to a point near the Norman Wells compressor station.

4.3.7.1 Baseline Conditions

The pipeline corridor spans five physiographic regions, grouped as follows for this discussion:

- Anderson Plain – from the Inuvialuit Settlement Region boundary south to just north of Chick Lake

SECTION 4: GROUNDWATER

- Franklin Mountains and Mackenzie Plain – from Chick Lake south to Willowlake River
- Great Slave Plain and Alberta Plateau – from Willowlake River to south of the Alberta boundary

Anderson Plain

Continuous permafrost is present from the northern part of the Anderson Plain to just north of Thunder River, and extensive discontinuous permafrost with a thin active layer is present to just north of Chick Lake. Morainal deposits, the dominant surficial material, are thick and form rolling terrain over most of the area. They are thin over the Ramparts Plateau between Little Chicago and Loon River, where they overlie mainly Upper Devonian shale and siltstone of the Imperial Formation. Smaller deposits of lacustrine, alluvial and glaciofluvial sediments and moraine occur in the Anderson Plain region.

Groundwater outflows were observed at a few locations only in the Anderson Plain region. Most of these were related to slides. Springs in the Gwich'in Settlement Area are believed to be seasonal flow from the active layer melting at slides, not perennial springs that would maintain winter stream flow (Thurber Engineering Ltd. 1993).

Groundwater inflow is suspected at Travaillant Lake from subpermafrost groundwater upwelling through a talik beneath the lake. Winter flow in the Loon River and Hare Indian River might be from lakes draining within their drainage basins. However, karst terrain in the Hare Indian River drainage basin might contribute groundwater to that drainage system. A spring from a gravel ridge near Fort Good Hope has been used as a source of potable water for the community. It is not used currently.

Franklin Mountains and Mackenzie Plain

Extensive discontinuous to intermediate discontinuous permafrost is present in the Franklin Mountains and Mackenzie Plain area south to about White Sand Creek, with sporadic discontinuous permafrost, i.e., 10 to 35% of land area with permafrost, south of that point. The pipeline corridor is mainly on morainal or lacustrine deposits between the mountain front and the Mackenzie River, although it crosses carbonate terrain with a thin surficial cover in places. Many sinkholes, springs and other evidence of karstic processes occur in the area.

Strata of considerable significance to karstic formation and spring flow in the Franklin Mountains are the Lower Devonian Bear Rock Formation and the Upper Cambrian Saline River Formation. Groundwater readily dissolves minerals such as halite, i.e., salt, gypsum and anhydrite in the Saline River Formation. This results in the overlying strata collapsing. The Bear Rock Formation comprises

carbonate rock, which can contain gypsum. Solution breccias and karstic features, such as sinkholes, are common in this formation, and cavernous porosity has been recorded in the subsurface. The Bear Rock Formation predominates west of the Franklin Mountains, and karstic springs are common along the mountain front. Winter flow in streams that cross the pipeline corridor is common in this area. Streams with small drainage areas or those that have headwaters in the Franklin Mountains are believed to have winter baseflow supported entirely by karstic groundwater inflow.

Karstic terrain is fairly extensive east of the Franklin Mountains, so some of the larger streams draining this area are also likely to have a proportion of their winter baseflow supported by karstic groundwater inflow. These characteristics apply particularly to the area north of White Sand Creek. During field studies to the south a greater incidence of both icings and spring outflow was observed. Streams in this region are believed to have winter baseflow supported by a combination of karstic inflow and drainage from unfrozen granular materials and possibly wetlands.

Substantial groundwater inflow is reported in eight springs or groups of springs with flow rates that vary from 0.07 m³/s to over 0.33 m³/s. These springs are located at White Sulphur Springs, Bosworth Creek, Vermilion Creek, Little Smith River and Steep Creek in the Sahtu Settlement Area, and at the Blackwater River tributary, at springs north of Willowlake River and on Willowlake River in the Deh Cho Region. Water quality in these springs varies from fresh calcium bicarbonate waters to calcium sulphate, sodium sulphate and chloride waters. The largest total outflow observed was from the Steep Creek springs. The characteristics of these springs indicate rapid flow through fractured or cavernous rock. Winter flow is sufficient to keep this creek open and flowing far downstream.

Groundwater is used as potable water in the community of Wrigley. The groundwater supply wells are likely completed in granular materials in a terrace along the Mackenzie River.

Great Slave Plain and Alberta Plateau

The Great Slave Plain and Alberta Plateau are areas of sporadic discontinuous permafrost. The terrain is relatively flat with widespread areas of bog and fen. Permafrost is usually present in bogs and absent in fens. Morainal plain is the dominant surficial material (Aylsworth et al. 2000). A large area of unfrozen ground occurs in a sandy area of fen near Manners Creek and Fort Simpson. Aeolian and lacustrine sands associated with this fen area extend along the pipeline corridor from Mackenzie River to just south of Jean-Marie Creek. Winter flow of 0.17 m³/s identified in Manners Creek and Jean-Marie Creek during a winter 2002 survey is likely drainage from the unfrozen sands.

The Upper Devonian Fort Simpson Formation includes predominantly fissile greenish grey shale, which underlies the surficial sediments south of Jean-Marie Creek. Upper Devonian limestone and calcareous shale form the bedrock between Jean-Marie Creek and Trout River. Shale of the Lower Cretaceous Fort St. John Group form the bedrock south of Trout River. Cretaceous shale is also present in the Ebbut Hills.

Springs and other karstic features could be present in the area of limestone bedrock, although none have been reported or observed near the pipeline corridor. Permafrost and bedrock shale form barriers to groundwater movement. Tills are also low permeability, except for intertill sand and gravel lenses. Sand and gravel can be present locally in:

- preglacial buried valleys below the till sheets
- interglacial valleys
- glacial meltwater channels

Groundwater contributions to stream flow in this area are usually small and seasonal.

Winter flow of 0.53 m³/s observed in the Trout and Kakisa rivers during the winter 2002 survey might be drainage from unfrozen surficial materials, with the Trout River also receiving a major contribution from lake storage.

4.3.7.2 Pipeline Corridor Effects

The pipeline corridor includes a gas pipeline from the Inuvik area facility to the Alberta boundary and an NGL pipeline from the Inuvik area facility to Norman Wells. Facilities also include four compressor stations, a heater station, an interconnect facility and block valves. The effects relating to each of the pipeline corridor pathways are expected to be similar to those related to the gathering pipelines (see Section 4.3.6.2, Gathering Pipelines Effects, for details). Differences from these expected effects are described by project phase in the following discussion. Table 4-13 shows applicable pathways that might affect groundwater quantity and flow patterns related to the pipeline corridor, and Table 4-14 shows pathways related to groundwater quality.

Groundwater Quantity and Flow Patterns

Construction

Effects through the recharge and discharge pattern pathway in the pipeline corridor could occur in areas of groundwater discharge (see Section 4.3.1.1, Change in Groundwater Quantity and Flow Patterns). Ditching and other subsurface activities near groundwater discharge areas might divert or block groundwater flow or require dewatering during construction. The route selection process has been successful in avoiding many of these areas where practical (see Volume 2, Section 2, Route and Site Selection).

Table 4-13: Effects on Groundwater Quantity and Flow Patterns – Pipeline Corridor

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low	Local	Far future
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Adverse	Low (moderate to high possible)	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Table 4-14: Effects on Groundwater Quality – Pipeline Corridor

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Groundwater discharge locations along the pipeline route that are potential areas of concern include a:

- cluster of mineralized perennially flowing springs at White Sulphur Springs just south of the Hanna River crossing in the Sahtu Settlement Area, about 400 m upgradient of the pipeline route
- spring about 5 km south of the River Between Two Mountains crossing in the Deh Cho Region, which is less than 100 m downslope of the route

SECTION 4: GROUNDWATER

Construction activities located upgradient of a spring discharge could intercept groundwater flow and divert a portion of this flow into the ditch. Installing subdrains or other appropriate measures in areas where groundwater flow is encountered during ditching, is expected to be sufficient to:

- enable groundwater flow to continue
- prevent any substantial change in groundwater flow patterns that could otherwise result in the interruption or substantial reduction of spring flow

Effects related to redirection of groundwater flow upgradient of discharge areas could persist into the far future. Effects could occur during construction and, in areas where the pipeline is removed, during decommissioning and abandonment.

Additional areas of potential concern related to the recharge and discharge pathway are:

- perennially flowing springs at Gibson Gap that emerge from the base of tree-covered slopes, upslope of the pipeline, some within 100 m of the pipeline corridor. Potential interruption of groundwater flow downgradient of a spring discharge, such as at Gibson Gap, is expected to be mitigated adequately through the use of subdrains or other appropriate measures where groundwater flow is encountered during ditching.
- at the southern end of the Gwich'in Settlement Area, a retrogressive thaw-flow slide on the bank of a small lake is located close to and upslope of the pipeline corridor. Monitoring for slope movement will identify any reactivation of slides or the development of new slide activity, and enable appropriate engineering measures.
- sinkholes in carbonate strata of the Bear Rock Formation, which occur at shallow depth near where the pipeline corridor passes Bear Rock
- a projected fault, called the Cap Fault, which has brought the limestone of the Middle Devonian Nahanni Formation to the surface at Old Fort Island to the west and at the mountains to the northeast. Thermal sulphur springs emerge from the limestone along this fault at Old Fort Island. A small circular lake, which could be a sinkhole, is about 100 m east of the route. This lake appears to be located on the projected Cap Fault, which the pipeline route crosses. If bedrock is shallow in this area and ditching intersects the fault, water flowing along the fault could possibly be redirected into the ditch and could potentially cause drainage of upgradient water storage.

Considering the shallow depth of ditching activities, the presence of surficial materials overlying bedrock and the relatively greater depths of groundwater flow expected in the karst systems, it is considered highly unlikely that karst or

geological structures, e.g., faults or sinkholes as described previously, will be encountered during ditching or that significant groundwater flow systems would be encountered at the shallow depths exposed during pipeline installation.

Examples of areas that might experience flow obstruction effects include:

- the Hill Lake area in the Gwich'in Settlement Area, where the pipeline route crosses a sidehill slope where the active layer is thin
- near Little Chicago in the Sahtu Settlement Area, where the pipeline route crosses an alluvial fan

In these areas, subsurface groundwater flow could be obstructed by ditching. Installation of subdrains in areas where groundwater flow is encountered during ditching is expected to be adequate to reduce any effects related to flow obstruction in most settings. Effects related to flow obstruction could persist into the far future, unless the pipeline is removed during decommissioning and abandonment.

Operations

The chilled pipeline could create a frost bulb in areas of unfrozen ground. The frost bulb could form a barrier to downgradient movement of groundwater and in some cases this obstruction could be sufficient to force groundwater to the surface. Icing buildups are an indication of flow obstruction. Frost bulbs could develop at the Canyon Creek crossing and at other watercourse crossings between Canyon Creek and Vermilion Creek. Where moderate groundwater flow passes through a confined area of high permeability underneath the stream bed, the pipeline, with or without a frost bulb, might be a sufficient barrier to subsurface water movement and could result in the same effects. Deep burial or insulation of the pipeline at selected crossings will be sufficient to reduce the residual effect of this pathway to low magnitude, and prevent icings or substantial groundwater blockage.

Watercourse crossings where mitigation is not applied and some cross-slope areas could experience moderate to high effects. Monitoring for frost bulb development in other areas will enable an appropriate engineering response to manage effects as necessary. The pipeline will return to ambient temperatures following decommissioning and abandonment. Therefore, effects would be long term.

Groundwater Quality

Effects on groundwater quality will have variable duration in the pipeline corridor, depending on the local geology. Most surface soils are dominated by low permeability materials in which groundwater flow rates will be low and any changes in groundwater quality might persist in the groundwater system.

In some areas, shallow fractured or karstic bedrock, or highly permeable sand and gravel, are present near the surface. Rates of groundwater movement in these areas are expected to be higher, and the duration of effects related to a change in groundwater quality could be much shorter.

4.3.8 Northwestern Alberta

The proposed pipeline crosses the boundary into northwestern Alberta where it ties in to the NGTL Northwest Mainline (Dickins Lake Section). The NGTL pipeline extends from this tie-in point to about 65 km south of the Alberta–Northwest Territories boundary.

4.3.8.1 Baseline Conditions

The pipeline will cross the Alberta Plateau physiographic region, which is an area of sporadic discontinuous permafrost, with many areas of no permafrost. The terrain is flat with widespread areas of wetland. It has a thick cover of glacial till as the dominant surficial material. Sand and gravel lenses often present in the till can form aquifers, but the glacial till and the lack of topographic relief causes shallow groundwater flow to be very slow. Groundwater additions to stream flow appear mainly through seepages and small springs.

4.3.8.2 Northwestern Alberta Effects

Considering the shallow depth of ditching activities, subsurface flow is unlikely to be obstructed to any extent. However, where this does occur, installing subdrains during ditching is expected to be adequate in most settings to lessen any effects on flow obstruction. Therefore, no substantial change is expected in groundwater quantity and flow patterns.

The duration of the effects on groundwater quality will be variable, depending on the local geology (see Section 4.3.7.2, Pipeline Corridor Effects). Where the pipeline crosses areas of flat, low-permeability materials, groundwater movement is slow, so effects could persist. In the more permeable sand and gravel lenses, where groundwater movement is much faster, the effects will be of shorter duration.

The applicable pathways that might affect groundwater quantity and flow patterns and ground water quality relative to northwestern Alberta are expected to be the same as for the pipeline corridor. The effects on ground water quantity and flow patterns are listed in Table 4-13 (shown previously) and the effects on groundwater quality are listed in Table 4-14 (shown previously).

4.3.9 Infrastructure

The project infrastructure for construction and operations includes:

- barge landing sites
- pipe and material stockpile sites
- fuel storage sites
- camps
- a potable water supply
- access roads
- airstrips and helipads
- communication centres
- borrow sites

See Volume 2, Project Description, for more details about the locations, components and footprint areas of these sites. The project will require large numbers of personnel and large quantities of materials and supplies during construction. As a result, extensive transport of goods by barge, rail, aircraft, truck and other vehicles will be necessary. The transport of smaller amounts of materials and supplies will be necessary during operations.

4.3.9.1 Production Area Infrastructure

Baseline Conditions

This assessment is based on a preliminary review of the infrastructure within the production area and the potential effects on groundwater using the available regional information.

Up to seven primary and nine secondary borrow sites are planned for the production area. The area of disturbance at each site will be about 10 ha in size. No data was available on permafrost conditions and active layer thickness at the sites for the evaluation of effects of development on groundwater. Site-specific borrow site development plans are not yet finalized. See Section 4.3.1.1, Change in Groundwater Quantity and Flow Patterns, for the effects of extracting borrow material.

Production Area Infrastructure Effects

Transportation-related infrastructure, such as all-weather roads and airstrips, has the potential to cause effects on groundwater quantity and flow patterns by obstructing surface water flow. Activities at borrow sites might affect groundwater, through:

- changes in recharge and discharge patterns
- changes in surface water quality
- sedimentation

SECTION 4: GROUNDWATER

Camps and storage areas might affect groundwater in a manner similar to transportation-related infrastructure by changing surface water flow. Any effects of the camps and storage areas will be mainly limited to construction because most of these facilities will be removed after construction.

Table 4-15 shows pathways that might affect groundwater quantity and flow patterns related to production area infrastructure. Table 4-16 shows pathways affecting groundwater quality.

Table 4-15: Effects on Groundwater Quantity and Flow Patterns – Production Area Infrastructure

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low ¹	Local	Far future
	Operations	Adverse	Low ¹	Local	Far future
	Decommissioning and abandonment	Adverse	Low	Local	Long term
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Neutral	No effect	N/A	N/A
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Sedimentation	Construction	Adverse	Low ¹	Local	Far future
	Operations	Adverse	Low ¹	Local	Far future
	Decommissioning and abandonment	Adverse	Low	Local	Far future

NOTE:
N/A = not applicable
1 Rating assumes that site development plans at borrow sites will be developed to limit effects to low magnitude

Groundwater Quantity and Flow Patterns

Effects on surface water drainage, flow and level are expected to be low magnitude for all components of the production area infrastructure. Effects on groundwater through the change in groundwater recharge and discharge pathway, related to recharge from surface water, are also expected to be low magnitude for all phases of the project.

Table 4-16: Effects on Groundwater Quality – Production Area Infrastructure

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Adverse	Low	Local	Long term
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
NOTE: N/A = not applicable					

Removing materials from borrow sites also has the potential to produce effects on groundwater quantity and flow patterns through changes in groundwater recharge and discharge pathways. Removing granular materials could reduce groundwater recharge, potentially drying up springs, seeps and wetlands, and increasing overland runoff. Flow patterns would change because of these influences, and the amount of available shallow groundwater would decrease. The size and location of local wetlands could change because of reduced infiltration and increased runoff. In general, the potential magnitude of effects through this pathway within the production area is low because of the seasonal and restricted nature of groundwater flow systems in this area. The magnitude of the effects would depend on the amount of material removed. The site-specific development plans for the borrow sites will consider these concerns. Effects through changes in groundwater recharge and discharge related to removing materials at borrow sites could persist into the far future because the material is removed permanently from these sites. Changes related to activities at the borrow sites could occur during either construction or operations.

All-weather roads and possibly other surface features might affect shallow groundwater flow in the active layer. Most of the region has low relief and poor surface and subsurface drainage. Subdrains or other engineering controls might be required to prevent blocked groundwater flow. This would reduce the magnitude of any related groundwater flow obstruction to low. Effects would persist into the far future, unless these surface structures were removed during decommissioning and abandonment.

Surface structures will be elevated or thermally separated from the ground, so changes in permafrost conditions are expected to be low magnitude. Minor, undetectable effects on groundwater quantity and flow patterns are expected for all project phases related to this pathway.

Effects on sedimentation caused by borrow sites depend on site-specific pit development plans. Crushing and screening operations, where required, would increase the potential for releasing fine particles that might be carried by precipitation or surface water runoff into an aquifer. The site-specific development plans for the borrow sites will consider these concerns and be developed to limit these effects. Effects related to sedimentation are essentially permanent and would persist into the far future.

Groundwater Quality

Changes in surface water quality related to the production area infrastructure are expected to be low magnitude for all project phases, so any effects on groundwater quality via this pathway are also expected to be low magnitude throughout the project. After decommissioning and abandonment, it is expected that surface water quality, and therefore groundwater quality, will return to near baseline conditions.

Effects on permafrost from project activities related to the production area infrastructure are expected to be low magnitude, and changes in groundwater quality through this pathway are expected to be undetectable.

4.3.9.2 Pipeline Corridor Infrastructure

Baseline Conditions

This assessment is based on a preliminary review of infrastructure related to the pipeline corridor and the potential effects on groundwater using available regional information.

Up to 60 primary and 40 secondary borrow sites are planned for the pipeline corridor. The area of disturbance at each site will be about 10 ha. Most of the sites are on high points of land, some of which might form drainage divides. No data was available on permafrost conditions and active layer thickness at the sites, for the evaluation of effects of development on groundwater. Site-specific pit development plans are also not finalized. See Section 4.3.1.1, Change in Groundwater Quantity and Flow Patterns, for the effects of granular resource extraction.

Pipeline Corridor Infrastructure Effects

The potential effects on groundwater from infrastructure along the pipeline corridor are similar to those described previously for infrastructure in the production area (see Section 4.3.9.1, Production Area Infrastructure).

Table 4-17 shows applicable pathways that might affect groundwater quantity and flow patterns related to pipeline corridor infrastructure. Table 4-18 shows pathways related to groundwater quality. Effects relating to each pathway in the pipeline corridor infrastructure are expected to be similar to those related to the production area infrastructure. The following discussion discusses differences in the expected effects that could occur during construction.

Table 4-17: Effects on Groundwater Quantity and Flow Patterns – Pipeline Corridor Infrastructure

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in recharge and discharge	Construction	Adverse	Low ¹	Local	Far future
	Operations	Adverse	Low ¹	Local	Far future
	Decommissioning and abandonment	Adverse	Low	Local	Long term
Flow obstruction	Construction	Adverse	Low	Local	Far future
	Operations	Neutral	No effect	N/A	N/A
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A
Sedimentation	Construction	Adverse	Low ¹	Local	Far future
	Operations	Adverse	Low ¹	Local	Far future
	Decommissioning and abandonment	Adverse	Low	Local	Far future

NOTE:
 N/A = not applicable
 1 Rating assumes that site development plans for borrow sites will be developed to limit effects to low magnitude

Table 4-18: Residual Effects on Groundwater Quality – Pipeline Corridor Infrastructure

Pathway	Phase When Impact Occurs	Effect Attribute			
		Direction	Magnitude	Geographic Extent	Duration
Change in surface water quality	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Adverse	Low	Local	Long term
Change in permafrost patterns	Construction	Adverse	Low	Local	Long term
	Operations	Adverse	Low	Local	Long term
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A

NOTE:
 N/A = not applicable

Groundwater Quantity and Flow Patterns

Construction

Effects on surface water drainage, flow and level are expected to be low magnitude for most components of the pipeline corridor infrastructure (see Section 5, Hydrology). Effects related to changes in runoff in two basins, Little Chicago and McGill Station, are expected to be moderate magnitude, and effects related to water level and velocity are expected to be low to moderate magnitude. These effects on surface water, during construction and operations, are expected to have a low-magnitude effect on groundwater quantity and flow patterns.

The magnitude of effects of changes related to borrow site activities, via the recharge and discharge pathway or sedimentation pathways, could be greater in the pipeline corridor than in the production area. Groundwater flow systems are typically larger in the pipeline corridor RSA because permafrost is not as extensive in this area. Effects of reducing groundwater recharge could cause more extensive changes in the hydrologic system. The magnitude of these effects depends on the amount and extent of material removed at each borrow site. Site-specific development plans for the borrow sites will consider these concerns.

Effects through changes in groundwater recharge and discharge related to removing materials at the borrow sites would persist into the far future, because the material is removed permanently from these sites. Similarly, effects resulting from sedimentation would essentially be permanent and would persist into the far future.

4.3.10 Significance of Effects

In the previous discussion, the characteristics of the project's residual effects were described in terms of the effects' direction, magnitude, geographic extent and duration. These characteristics were used to determine the significance of the effects on groundwater quantity and flow patterns and groundwater quality.

Volume 1, Section 2, Assessment Method, provides a discussion of the rationale for determining significance. An adverse residual effect is considered significant if the effect is either:

- moderate or high magnitude and extends into the far future, i.e., more than 30 years after project decommissioning and abandonment
- high magnitude and occurs outside the LSA at any time

The significance of the effects for each project component and the combined project is presented in this discussion. Tables show the results of the effects assessment and indicate whether an effect is significant.

The magnitude of most effects on groundwater quantity and flow patterns is low and local. Effects on groundwater quality are also evaluated as low magnitude and local.

The significance of effects on groundwater is reviewed by project component in the following discussion.

4.3.10.1 Niglintgak

The pathways through which Niglintgak development might affect groundwater are changes in groundwater quantity or flow patterns caused by:

- changes in recharge from surface water
- flow obstruction from subsurface structures
- changes in permafrost patterns

Effects from changes in Niglintgak through these pathways were evaluated as having a local extent and low magnitude, i.e., they are within the normal range of variation (see Table 4-19). These changes were determined to be not significant.

Table 4-19: Significance of Effects of Niglintgak on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low	Local	Far future	No
	Operations	Adverse	Low	Local	Far future	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Far future	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No

NOTE:
 N/A = not applicable

Changes in groundwater quality might result from changes in surface water quality and changes in permafrost conditions. Effects on groundwater quality were determined to be not significant, based on their low magnitude rating.

4.3.10.2 Taglu

The applicable pathways and potential effects on groundwater at Taglu are the same as for Niglintgak (see Section 4.3.10.1, Niglintgak, and Table 4-19, cited previously). Effects at Taglu are also evaluated as not significant for groundwater quality, groundwater quantity and flow patterns because of the low magnitude of all potential effects.

SECTION 4: GROUNDWATER

4.3.10.3 Parsons Lake

The applicable pathways and potential effects on groundwater evaluated at the Parsons Lake lease (see Table 4-20) are similar to Niglintgak (see Section 4.3.10.1, Niglintgak). Effects at Parsons Lake are also evaluated as not significant for groundwater quality, groundwater quantity and flow patterns because of the low magnitude of all potential effects.

Table 4-20: Significance of Effects of Parsons Lake on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low	Local	Far future	No
	Operations	Adverse	Low	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No

NOTE:
N/A = not applicable

4.3.10.4 Gathering Pipelines and Associated Facilities

Groundwater quantity and flow patterns could be affected by the activities of the gathering pipelines and associated facilities through:

- changes in recharge from surface water
- development of slides
- flow obstruction
- changes in permafrost conditions

The magnitude of effects related to these changes is evaluated as low, so these effects are determined to be not significant. Groundwater quality could be affected by changes in surface water quality or changes in permafrost conditions resulting from gathering pipeline activities. The magnitude of effects related to these changes is also evaluated as low and these effects are also determined to be not significant (see Table 4-21).

Table 4-21: Significance of Effects of the Gathering Pipelines and Associated Facilities on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low	Local	Far future	No
	Operations	Adverse	Low (moderate possible)	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No

4.3.10.5 Pipeline Corridor

The applicable pathways and potential effects of pipeline corridor activities are similar to those of the gathering system (see Section 4.3.10.4, Gathering System). As shown in Table 4-22, the magnitude of potential effects on groundwater related to these pathways is evaluated as low, so these effects are determined to be not significant.

Table 4-22: Significance of Effects of the Pipeline Corridor on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low	Local	Far future	No
	Operations	Adverse	Low (moderate to high possible)	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Long term	No
	Decommissioning and abandonment	Neutral	No effect	N/A	N/A	No

SECTION 4: GROUNDWATER

4.3.10.6 Infrastructure

The main pathways by which infrastructure activities might cause groundwater changes are:

- change in surface water recharge
- change in permafrost patterns
- sedimentation
- change in surface water quality

Effects related to these changes are evaluated as low and are therefore determined to be not significant. Groundwater quality could be affected by changes in surface water quality or changes in permafrost conditions resulting from infrastructure activities. As shown in Table 4-23, the magnitude of effects related to these changes is also evaluated as low and these effects are determined to be not significant.

Table 4-23: Significance of Effects of Infrastructure on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low ¹	Local	Far future	No
	Operations	Adverse	Low ¹	Local	Far future	No
	Decommissioning and abandonment	Adverse	Low	Local	Far future	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Long term	No
	Decommissioning and abandonment	Adverse	Low	Local	Long term	No

NOTE:
1 Rating assumes that site development plans at borrow sites will be developed to limit effects to low magnitude

4.3.10.7 Combined Project Components

All effects of project-related activities on groundwater were evaluated as having a local extent, i.e., restricted to the LSA, as shown in Table 4-24. The magnitude of effects was generally low, with potential moderate to high effects related to flow obstruction resulting from frost bulbs. Some effects could persist into the far future, specifically those related to:

- sedimentation
- flow obstruction, e.g., in areas where the pipeline is abandoned in place

- changes in permafrost at Niglintgak and Taglu
- changes in recharge and discharge related to removing materials from borrow sites

Table 4-24: Significance of Effects of Combined Project Components on Groundwater

Valued Component	Phase When Impact Occurs	Effect Attribute				Significant
		Direction	Magnitude	Geographic Extent	Duration	
Groundwater quantity and flow patterns	Construction	Adverse	Low	Local	Far future	No
	Operations	Adverse	Low (possible moderate to high)	Local	Long term	No
	Decommissioning and abandonment	Adverse	Low	Local	Far future	No
Groundwater quality	Construction	Adverse	Low	Local	Long term	No
	Operations	Adverse	Low	Local	Far future	No
	Decommissioning and abandonment	Adverse	Low	Local	Long term	No

Effects are identified as significant where the effect is either:

- moderate or high magnitude and extends into the far future, i.e., more than 30 years after project decommissioning and abandonment
- high magnitude and occurs outside the LSA at any time

Based on this evaluation, effects of the project on groundwater are not significant.

4.3.10.8 Prediction Confidence

Available information and an understanding of hydrogeological processes were used to predict effects of the project on groundwater. As with all predictions of future conditions, the predictions in the impact assessment have a level of uncertainty.

The prediction confidence for effects on groundwater associated with the production area, gathering system and production area infrastructure is high. The effects associated with project components in these areas are local in extent and sufficient mitigation measures are available to ensure the effect magnitudes remain low. The prediction confidence for effects associated with project components in the pipeline corridor and pipeline infrastructure is moderate. Although the interaction between karst systems and project components is expected to be low because the project includes only surface structures or shallow disturbances, uncertainties related to the distribution of karst systems force a moderate rating on prediction confidence for effects in these areas.

SECTION 4: GROUNDWATER

It is likely that effects will be less than predicted because the precautionary principle has been applied in developing the effects assessment where data is uncertain (see Volume 1, Section 2, Assessment Method). Because of this precautionary approach, there is a high level of confidence in the assessment of effect significance.

4.4 Monitoring

Volume 7, Section 6, Environmental Compliance and Effects Monitoring Plan, provides an overview of the intent and purpose of the environmental monitoring program to be implemented for the project.

Two types of programs will be developed:

- compliance monitoring
- effects monitoring

4.4.1 Compliance Monitoring

Compliance monitoring will ensure that environmental mitigation, as outlined in the environmental protection plan, is implemented. Compliance monitoring will be a component of all phases of the project, from environmental inspection monitoring during construction to monitoring required for licences issued by the Mackenzie Valley Land and Water Board.

There are no compliance monitoring requirements for groundwater.

4.4.2 Effects Monitoring

Effects monitoring will be undertaken to confirm the accuracy of the prediction of effects and to determine the effectiveness of mitigation and enhancement measures. Effects monitoring is a component of the project's environmental management system, which provides a framework for adopting project practices in response to effects monitoring program results.

The effects monitoring program for groundwater will include aerial inspection of groundwater discharge areas. Aerial inspection will identify visual changes in location or extent of groundwater discharge areas. This could include changes in existing discharge or the appearance of new discharge areas.

Effects monitoring programs will be established in consultation with communities and regulations.

References

- Aylsworth, J.M., A. Duk-Rodkin, T. Robertson and J.A. Traynor. 2000. Landslides of the Mackenzie Valley and adjacent mountainous and coastal regions. In: L.D. Dyke and G.R. Brooks (ed.). *The Physical Environment of the Mackenzie Valley Northwest Territories: A Base Line for the Assessment of Environmental Change*. Geological Survey of Canada, Bulletin 547: 167–176.
- Bowerman, J. N. and R. C. Coffman. 1975. The geology of the Taglu gas field in the Beaufort Basin, N.W.T. In: C.J. Yorath, E.R. Parker and D.J. Glass (ed.). *Canada's Continental Margins and Offshore Petroleum Exploration*. Canadian Society of Petroleum Geologists, Calgary, Alberta. May 1975.
- Brooks, G.R. 2000. Streamflow in the Mackenzie Valley. In: L.D. Dyke and G.R. Brooks (ed.). *The Physical Environment of the Mackenzie Valley Northwest Territories: A Base Line for the Assessment of Environmental Change*. Geological Survey of Canada, Bulletin 547: 153–158.
- Burgess, M., A. Judge and V. Allan. 1982. Ground temperature studies of permafrost growth at a drained lake site, Mackenzie Delta. *Proceedings, 4th Canadian Permafrost Conference*, Calgary, Alberta, March 2–6, 1981. National Research Council of Canada. Ottawa, Ontario. 2-11.
- Burn, C. R. 2002. Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada. *Canadian Journal of Earth Sciences* 39: 1281–1298.
- Canadian Helicopters personnel. 2002. Personal communication.
- Gartner Lee Limited. 2003. *Identification of the Biophysical Information and Research Gaps Associated with Hydrocarbon Exploration, Development and Transmission in the Mackenzie Valley: Action Plan*. Prepared for the Department of Indian Affairs and Northern Development.
- Hardy, R. M. and Associates Ltd. 1976. *Proposed Plant, Gulf Oil Canada Limited, Parsons Lake, N.W.T.: 1976 Geotechnical Survey*. Report for Gulf Oil Canada Limited.
- Heginbottom, J.A. 2000. Permafrost distribution and ground ice in surficial materials. In: L.D. Dyke and G.R. Brooks (ed.). *The Physical Environment of the Mackenzie Valley Northwest Territories: A Base Line for the Assessment of Environmental Change*. Geological Survey of Canada, Bulletin 547: 31–39.

- McCart, P. 1973. *Late Winter Surveys of Lakes and Streams in Canada and Alaska Along the Gas Pipeline Routes Under Consideration by Canadian Arctic Gas Study Limited*. Prepared for Northern Engineering Services Co. Ltd.
- Norris, D.K. 1975. *Geology, Aklavik, District of Mackenzie*. Geological Survey of Canada, Map 1517A.
- Sahtu Heritage Places and Sites Joint Working Group (SHPSJWG). 2000. *Rakekée Gok'é Godi: Places We Take Care Of*. Report of the Sahtu Heritage Places and Sites Joint Working Group.
- Smith, M.W. and C.T. Hwang. 1973. Thermal disturbance due to channel shifting, Mackenzie Delta, Northwest Territories, Canada. In: *Permafrost, Second International Conference, North American Contribution, National Academy of Science*. 51–60.
- Taylor, A.E., M.M. Burgess, A.S. Judge and V.S. Allen. 2000. Deep ground temperatures. In: L.D. Dyke and G.R. Brooks. (ed.). *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change*. Geological Survey of Canada, Bulletin 547.
- Thurber Engineering Ltd. 1993. *Mackenzie Valley Groundwater Study*. Prepared for Indian and Northern Affairs Canada.
- Water Survey of Canada. 1992. *Historical Streamflow Summary to 1990: Yukon and Northwest Territories*. Inland Waters Directorate, Water Resources Branch, Water Survey of Canada. Ottawa, Ontario.
- Young, F. G. and D. H. McNeil. 1984. *Cenozoic Stratigraphy of the Mackenzie Delta, Northwest Territories*. Geological Survey of Canada, Bulletin 336.