Desktop Study - Sinkhole Site Characterization, Dempster Highway, Yukon Territory

Prepared for

Government of Yukon

Prepared by

SRK Consulting (Canada) Inc.
1CG023.002
November 2014

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Executive Summary

SRK Consulting (Canada) Inc. has performed a desktop study to characterize eleven highway sections where sinkholes have been identified or could reasonably be expected to occur. This study represents the first phase of more extensive investigations to understand sinkhole development along the Dempster Highway, Yukon Territory.

Highway sections were characterized using existing airphotos, LiDAR data, ground temperature measurements, and surficial and bedrock geology maps. The information provided in this report supports the understanding of site conditions which may contribute to sinkhole development. Review of the available literature indicates that sinkholes defined by rapid collapse of the surface have been documented in other permafrost environments. In most cases, these sinkholes develop as a result of hydro-thermal erosion of massive ground ice caused by flowing water.

The highway sections characterized in this study extend across varying terrain with extensive discontinuous to continuous permafrost. Degrading ice wedges are present at some locations. Surficial geology units for these sites include fluvial, morainal till, and colluvium deposits consisting of varying amounts of silt, sand, or gravel. Improper drainage of surface water was identified along some sections of highway which may contribute to permafrost degradation.

Sinkholes reported by Highway and Public Works are spatially distributed along the Dempster Highway. Reoccurrence of these features at some locations suggest they form under unique ground conditions which promote development of subsurface voids. The available data does not provide direct evidence for the formation of sinkholes; however the hydro-thermal erosion of ground ice is highly plausible for the investigated highway sections. The local geology across most highway sections does not favor sinkhole formation caused by potential dissolution of carbonate rocks. Highway as-built reports were not available for review and should be examined to determine if construction material and practices contribute to sinkhole development.

Multi-offset ground penetrating radar (GPR) and capacitively-coupled resistivity (C-CERI) may prove to be the most effective geophysical techniques available for operational mapping of shallow subsurface voids within the highway embankment. These geophysical instruments can be pulled along the highway surface using a vehicle at a rate of 5-10 km per hour. Two dimensional velocity sections generated from multi-offset GPR are expected to indicate high velocity anomalies at the location of air-filled voids. Single-fold GPR measurement may also result in distinct radar signatures that are associated with voids. Additional recommendations are provided within this report to further advance the investigation of sinkholes and to test geophysical techniques which may be suited to detecting these road hazards.

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1 Introduction

1.1 Background

The Dempster Highway is a vital all-weather transportation route which connects southern Canada with the Yukon and Northwest Territories. The highway extends approximately 738 km across complex mountainous and lowland terrain with ice-rich permafrost. The Government of Yukon Highways and Public Works (HPW) maintains approximately 465 km of the Dempster Highway in the Yukon.

Of immediate concern to highway safety is the formation of “sinkholes” that have been observed along some sections of the highway (Appendix A). Presently, there is little documentation on the location and frequency of these features, or the processes which contribute to their development. HPW has initiated a study to determine the cause of sinkhole formation and to assess geophysical methods suited to the detection of these road hazards.

HPW has retained SRK Consulting (Canada) Inc. (SRK) to perform a desktop study to characterize eleven (11) highway sections where sinkholes have been identified or could reasonably be expected to occur. This study represents the first phase (Phase 1) of more extensive investigations. The scope of this study was to:

- Review scientific and engineering literature relevant to sinkhole formation in similar environments;
- Characterize geomorphology, surficial geology, surface hydrology, permafrost/ground ice features, and infrastructure using existing data;
- Determine historical change in surface conditions, if present;
- Evaluate the findings in the context of geophysical techniques suitable for detecting sinkhole features; and
- Provide recommendations related to testing of geophysical techniques and the undertaking of future field investigations.

1.2 Study Approach

This study provides the initial framework for understanding site conditions which may contribute to sinkhole formation and provides the basis for future geotechnical and geophysical investigations at the sites.

A literature review was performed to determine if sinkholes have been documented in similar environments. Historical and present-day surface conditions were then characterized at eleven (11) highway sections where sinkholes have been identified or could be reasonably expected to occur (Figure 1). Table 1 summarizes the location of each highway section.

Site characterization was based on available aerial photographs, high-resolution Light Detection and Ranging (LiDAR), and supporting spatial datasets (Refer to Section 2). This information was evaluated in the context of geophysical methods that are suited for detecting sinkholes. Recommendations are provided for undertaking future field investigations and geophysical surveys.

Table 1: Location of Highway Sections

Site #	Highway Reference	Easting	Northing	UTM Zone	NTS Index	NTS Mapsheet
1	km 71-73 (Tombstone Park)	633639.00	7156867.00	7	116B 09	North Fork Pass
2	km 80 -85	631171.00	7164284.00	7	116B 09	North Fork Pass
3	km 92-98	624114.00	7175140.00	7	116B 09	North Fork Pass
4	km 99-103 (Two Moose Lake)	625553.56	7181294.26	7	116B 09	North Fork Pass
5	km 115-117 (Chapman Lake)	626033.35	7193409.54	7	116B 16	Lomond Lake
6	km 141-143	633548.48	7216182.20	7	116G 01	Engineer Creek
7	km 185-187	629620.00	7244025.00	7	116G 08	Mount Jeckell
8	km 191-193	627851.12	7249567.55	7	116G 08	Mount Jeckell
9	km 246-248	364259.38	7292640.44	8	116H 12	Mount Cronkhite
10	km 373-375	423176.47	7366663.36	8	116I 07	Corbett Hill
11	km 424-426	440226.23	7402145.71	8	116I 09	Mount Hare

2 Data Sources and Analysis

The following section describes the data and analysis used in this study. All dataset were provided by HPW or represent publicly available sources of information.

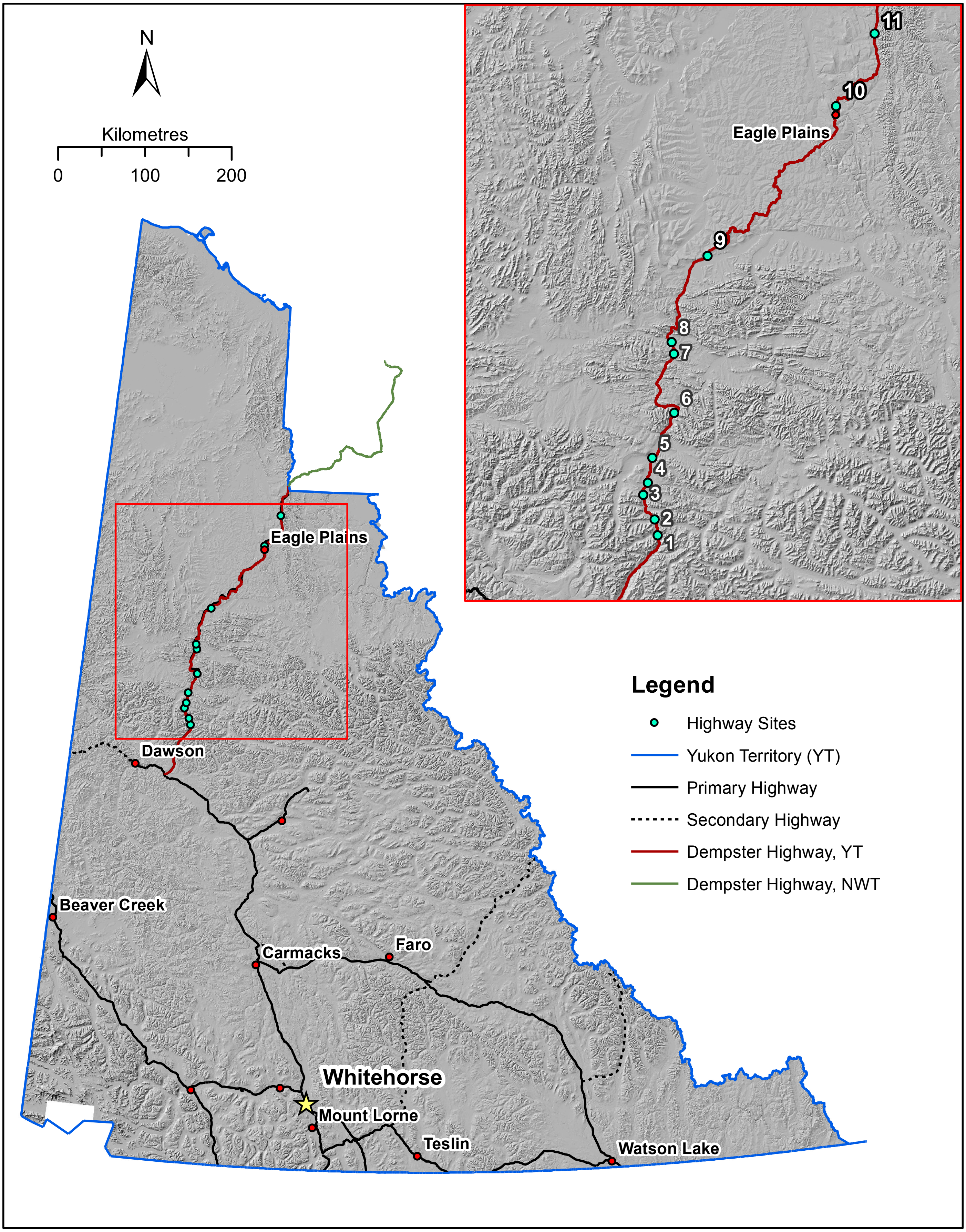
2.1 Airphotos

Historical monochromatic airphotos and modern colour airphotos were examined to determine changes to permafrost features, surface hydrology, and highway infrastructure. Historical airphotos were collected from a low flying aircraft during the following periods: August 12, 1963 (photo series A27489) and July 29, 1989 (photo series A18137). Airphoto interpretation of surface features was based photo tone, texture, and 3-D topographic effects observed in stereo view. Modern colour airphotos were also examined to determine current conditions at the sites. The colour airphotos were acquired using a Leica RCD105 to produce 15 cm resolution RGB photos.

2.2 Light Detection and Ranging

LiDAR data collected along the highway corridor was used to generate hillshade models and intensity maps which supported site characterization. The data were collected using a Leica AKS70-HP. The average vertical accuracy of the measurements is reported to be ±7 cm (Allnorth 2013).

LIDAR has become a widely accepted tool used for generating accurate terrain models along northern highway corridors. Among the many uses of LiDAR data, elevation models and derivative data products aid in hazard mapping, vegetation classification (Chasmer et al. 2011), infrastructure characterization (Stevens et al. 2012a), and permafrost feature identification (Stevens and Wolfe 2012; Stevens et al. 2012b; Wolfe et al. 2014).



srk consulting

Albers Conic Equal Area

DESIGN: cws	DRAWN: cws	REVIEWED:
SCALE: 1 centimeter = 60 kilometers		DATE: 9/13/2014
FILE: Study_Area_Map_Rev01_cws.mxd		

Yukon Territory - Sinkhole Study Sites, Dempster Highway

DRAWING TITLE: **Location Map**

ISSUED FOR: **Government of Yukon**

DRAWING NO. **Figure 1**

REVISION NO. **1**

SRK JOB NO. **1CG023.002**

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LiDAR intensity maps generated for this study indicate the amount of energy returned to the sensor relative to the amount of energy initially transmitted. LiDAR signal intensity measurements have only recently been used for terrain characterisation (Hopkinson, 2007; Mazzarini et al. 2007; Antonarakis et al. 2008) and moisture mapping in low-latitude environments (Garroway et al. 2011; Stevens and Wolfe 2012).

Intensity measurements presented in this report were not normalised for range bias and atmospheric effects (Hopkinson 2007), owing to:

- Short acquisition period for each highway section;
- Relatively flat surface conditions within the survey footprint;
- Narrow scan width within the footprint; and
- Consistency in system parameters.

Normalisation of LiDAR data for the above factors reduces intensity variation spatially across the laser scan and where multiple swaths are merged and classified (Hofle and Pfeifer 2007; Gatziolis, 2009).

2.3 Ground Temperature Data

Ground temperature measurements were supplied by HPW to examine the ground thermal regime beneath and adjacent to the highway embankment at km 124 (Latitude 64.903N, Longitude 138.278W). Data available for this study were collected between February 21 and May 13 of 2014. Site names described in the text of this report follows the naming convention used by HPW (S1-Road, S2-Toe, and S3-Field). For comparison, all ground temperature measurements have been referenced to LiDAR surface elevations. Analysis of the data focused on differences in near-surface ground temperature at the onset of the thawing season due to its potential impact on the movement of water.

2.4 Other Data

Highway kilometre post markers were provided by HPW. Graphical display of the highway network and streams and rivers were based on CanVec data from Natural Resources Canada at a scale of 1:50 000. Digital surficial geology maps were downloaded from the Yukon Geological Survey (Lipovsky and Bond 2014). The digital surficial geology maps represent a compilation product based on original maps published by the Geological Survey of Canada and Yukon Geological Survey. The original surficial geology mapsheets for the investigated highway sections include: Ricker (1967) and Thomas and Rampton (1982a; 1982b; 1982c; 1982d; 1982e; 1982f). Digital bedrock maps were provided by the Yukon Geomatics Department (original maps complied by Gordey and Makepeace [1999]).

All site photographs were taken by HPW personnel during daily operations and inspections. HPW field notes provided to SRK are also included in Appendix A.

3 Literature Review

3.1 Sinkhole Formation and Morphology

Sinkholes are naturally occurring geological features formed when the overlying ground (rock or soil) collapses into a subsurface void, resulting in surface subsidence. Sinkholes have been extensively studied for many decades (Ford 1963; Jennings 1985; Sweeting 1973; Williams 1971; Gao 2002) and represent a world-wide hazard to infrastructure (buildings, roads, pipelines) and a risk to human safety (Quinlan 1986; USGS 2007).

Three main morphological types of sinkholes are described in the literature; bowl-shaped, funnel-shaped, or well-shaped (Sweeting 1973). The size of the features typically ranges from a metre to several hundred metres in surface distance. Jennings (1985) further classifies sinkholes into five major types based on the processes which contribute to their development; solution, subsidence, collapse, alluvial stream sink, and subjacent karst collapse sinkholes. These sinkhole types were originally described for non-permafrost environments, but may also occur in cold climate environments. Review of the literature indicates that sinkholes are often caused by more than one mechanism and thus are often polygenetic in origin.

Ritter et al (1995) describes cover-collapse and cover-subsidence sinkholes. A cover-collapse sinkhole develops abruptly as the bearing strength of the overlying material is rapidly lost. In contrast, cover-subsidence sinkholes develop over a longer period of time as sediment gradually fills the underlying voids and the ground subsides to form a depression.

Sinkholes commonly form in carbonate bedrock (limestone and dolostones) and evaporate deposits (halite, gypsum, calcite mineral accumulations) where groundwater movement and chemistry result in physical and chemical weathering. Chemical weathering may occur when acidic groundwater causes dissolution of minerals within the rock, forming voids ranging in size from small vugs to large cavities and caverns (Ritter et al. 1995).

Terrain characterized by sinkholes typically exhibits undulating topography described as karst terrain (Jennings 1985). Karst terrain can be an indication that an area is susceptible to future sinkhole development.

In the presences of unconsolidated soils, flowing water may act to erode material and form a void in the ground which eventually forms a sinkhole. In most cases, the physical transport of soil by water results from winnow and downwash of fine-grained soil particles. Chemical weathering of minerals in the soil is also possible. Where the soils are cohesive, the excavation of the material and formation of a subsurface void may occur without surface expression of the feature until collapse of the cover. Soil cohesion may be due to frozen soil conditions. In non-cohesive soils, the silt and clay fractions are often observed to be transported from the coarser-grained material.

Locally, the subsurface voids responsible for sinkholes may be connected to form a more extensive conduit system which permits for groundwater flow and perpetual weathering and erosion. As a result, the change in groundwater may contribute to increased frequency of sinkholes. Newton (1984) observed increased sinkhole development caused by drawdown of the groundwater table. Under these conditions, the strength of the overlying material bridging the void is removed as the water table is lowered and failure occurs.

3.2 Sinkholes in Permafrost Environments

In permafrost environments sinkholes may form under a unique set of conditions due to the interaction between permafrost, ground ice, groundwater, and other cold climate processes. However, the mechanisms responsible for sinkhole development in more temperate climates can also be the cause of sinkholes in northern regions.

Seasonal and long-term thaw-settlement is commonly observed along northern highways as continual surface subsidence. This form of settlement is due to thaw-consolidation caused by the melting of ground ice and consolidation of the material under the applied load (Andersland and Ladanyi 2004; Smith and Burgess 2004). Surface depressions are commonly observed at these sites (Romanovsky and Osterkamp 2001; Jorgenson et al. 2010) due to continual consolidation of the material over time.

In the case of sinkholes recently observed along the Dempster Highway, rapid collapse of a subsurface void occurs (see Section 4). This form of subsidence is significantly different from more common forms of thaw-settlement. In this report the term sinkholes is reserved for ground subsidence caused by the development of subsurface voids which rapidly collapse to form a hole at the surface.

Surface-collapse sinkholes have been documented to occur within permafrost environments. Leffingwell (1915) describes formation of voids in ground ice due to drainage of surface water and the melting of an ice wedge. Voids in permafrost are also mentioned by Mackay (1974, 1981, 1988, 1997), Hyatt (1992), and Seppala (1997). Evidence of former voids in permafrost is also supported by observations of thermokarst-cave ice or pool ice which form by the freezing of water in pre-existing voids and tunnels (Shumskiy 1964; Mackay 1997; Kotler and Burn 2000; Shur et al. 2004; Bray et al. 2006).

Frozen or partially frozen soils may contribute to this process by increasing the strength of soils which temporary bridge the voids. Once the material strength is exceeded and/or thaw occurs, the subsurface void may rapidly collapse and form a sinkhole. The capacity of the frozen soil to bridge the void depends in part on the thickness and width of material spanning the void, the thermal conditions and unfrozen water content, and the load applied to the material, among other factors. The change in these conditions and subsequent growth of the void may cause sudden surface collapse.

Fortier et al. (2007) documents both the formation and collapse of subsurface voids caused by rapid development of a drainage system on Bylot Island located in the Arctic Archipelago. In this case, hydro-thermal erosion of an ice wedge system caused formation of subterranean tunnels which acted as conduits for flowing water. The process was initiated by erosion of ice wedges by surface runoff which flowed into open frost cracks. Heat transported by the water leads to perpetual thaw which expanded cracks and subsurface flow pathways.

The tunnels described by Fortier et al. (2007) were located less than 4 m below the ground surface; with a maximum tunnel height of 1.75 m and maximum width of 9.7 m. Individual tunnels were measured to be up to 25 m in length. Several of the tunnels were discovered to be dry due to a change in the routing of water. Fortier et al. (2007) describes surface gullies formed by the collapse of the overlying material into the tunnels. The gully systems mimic the overall pattern of the ice wedge system.

Several sinkholes have been recently reported near Fairbanks, Alaska. In some cases, these holes have formed near infrastructure and in association with ice-rich permafrost. Reported cases include a sinkhole discovered at the University of Alaska Fairbanks (UAF) which was approximately 3 m deep and 1.2 m in width at the surface.

Review of the literature revealed several studies that have been performed to investigate the use of geotextiles to reinforce road embankments and bridge voids or depressions (Shannon and Wilson 1981; Shannon and Wilson 1985). These studies indicated that geotextile fabrics with a high tensile strength installed at the bottom of the embankment could theoretically be used to bridge voids and depression.

4 Dempster Highway Sinkholes

4.1 Photographic Observations

The following section describes several sinkholes encountered along the Dempster Highway using photographic evidence and a limited number of field descriptions provided by HPW (Appendix A). Table 2 summarizes the location of sinkholes observed by HPW.

Table 2: Location of Sinkholes

Highway Location	Date Observed	Reference[1]
km 36	August 14, 2014	-
km 72	August 14, 2014	Figure A-4
km 77.6	August 14, 2014	-
km 81.8	August 14, 2014	-
km 82	June 22, 2014	Figure A-1
km 82	August 14, 2014	Figure A-2
km 82	Date unknown	Figure A-4
km 87.6	August 14, 2014	-
km 92	August --, 2008	Figure A-8
km 95.2	August 14, 2014	-
km 95.7	August 14, 2014	-
km 95.8	August 14, 2014	-
km 95.0	August 14, 2014	-
km 101.2	August 14, 2014	-

1. Reference to photographs provided in Appendix A.

Figure A-1 shows a sinkhole discovered by HPW maintenance crews on June 22 of 2014. During the excavation of the void, the sinkhole was estimated to be 7.5 m long, 4.5 m wide, and several metres deep. The surface opening of the sinkhole is estimated from the photographs to be approximately 0.4-0.6 m wide at the surface (Figure A-1). The elongated dome-shaped void was located within the embankment is reported to be filled with dry to moist soil. Water was not observed in any of the photographs taken on June 22nd. Shallow surface collapse of the embankment was observed several metres from the sinkhole adjacent to a drainage ditch (Figure A-1).

Highways and Public Works maintenance crews estimate the sinkhole shown in Figure A-1 was filled with approximately 32 m^3 of “pit run” material and 16 m^3 of “crush” material during a temporary repair of this site.

Appendix A-2 shows a sinkhole discovered on August 14 of 2014 during field inspections conducted by HPW. It can be inferred from photographs that the sinkholes observed in June (Figure A-1) and August (Figure A-2) formed within very close proximity of each other. The location is observed to be adjacent to the highway drainage ditch. Figure A-3 also shows evidence of highway instability near km 82 that dates back to August of 2009.

Figure A-4 shows an additional sinkhole discovered near highway km 82. The date of the photograph is unknown, but pre-dates sinkholes shown in Figures A-1 and A-2. Vegetation surrounding the site suggests the photograph was taken sometime between June and August. The surface opening of the hole is estimated from the photograph to be 1.5-2.0 m long, 0.4-0.5 m wide, and 1.2-1.5 m deep. The extent of the void in the subsurface may be greater than the observed surface opening.

Sinkholes have been encountered near highway km 82 for at least two years (Figures A-1 to A-4). These holes appear to have formed at the same location, suggesting sinkholes do not randomly develop but instead occur in response to specific conditions which contribute to their formation.

Figure A-5 shows evidence of several sinkholes observed on August 14 of 2014 near highway km 72. Surface erosion of the embankment is also observed in the photograph, suggesting surface water runoff and erosion occurred at the site.

Sinkholes were also observed south of Chapman Lake (Figure A-6) and near Two Moose Lake (Figure A-7). The sinkhole identified near Two Moose Lake is located along a section of highway with ice wedge polygons. The sinkhole discovered at this location is within metres of a culvert. Water may have contributed to development of the hole at this site.

Over the course of this study, SRK identified photographic evidence of a sinkhole near highway km 92 (UTM Zone7N, 624724.0 E, 7172583.0 N) using GoogleEarth Street View (Figure A-8). The street view image was taken in August of 2009.

4.2 Ground Temperature Data

Ground temperature measured beneath and adjacent to the highway embankment at km 124 (Latitude 64.903N, Longitude 138.278W) are provided in Appendix B. The temperature cable at site S1-Road is installed within the highway embankment (Figure B-1). At site S2-Toe, the temperature cable is installed beneath the toe of the embankment. Site S3-Field is located approximate 15 m from the toe of the embankment within vegetated terrain. Temperature measurements are recorded to 10 m below the surface at S1-Road and to 8 m below the surface at S1-Toe and S1-Field. All depths have been referenced to LiDAR surface elevations.

Ground temperature profiles from the three locations indicate permafrost is present beneath the highway embankment and the surrounding vegetated terrain. Ground temperatures measured beneath the toe of the embankment (S2-Toe) were considerably warmer than those measured beneath the embankment (S1-Road) and the vegetated terrain (S3-Field) (Appendix B). The consistently warmer ground temperature measured at S2-Toe is likely related to increased snow accumulation at the toe of the embankment during the winter and the presence of water during the thawing season.

The change in ground temperature from late-February to mid-May is shown in Figures B-2 to B-7. Shallow ground temperatures are observed to warm from February to May at a depth of 0.3 m below the surface. On April 14 of 2014, rapid warming was measured at the toe of the embankment, with temperatures increasing from -9°C to -3°C. Following this period of warming, temperatures continue to warm to 0.2°C by May 13 of 2014 (Figure B-8).

At S1-Road, the upper 0.3 m of the highway embankment remained frozen until April 28th. The thawing front at this site increased to 1 m by May 11th. At this time, the elevations of the thawing front are similar at S1-Road and S2-Toe. A slower progression of active layer thaw was measured at site S3-Field (Figure B-8).

4.3 Highway Sections

Appendix C provides aerial colour orthophotos, LiDAR derived hillshade models, surficial geology, local hydrology networks, and interpreted permafrost features for each of the eleven (11) highway sections. Hydrological networks and surficial geology boundaries provide approximate position based on the scale at which these products were generated. Maps provided in Appendix C are not suitable for engineering design.

Section 1 (km 71-73)

Highway Section 1 is located within the North Fork Pass mapsheet (NTS 116 B09) and extends from km 71 to km 73 (Figure C-1). The highway section parallels the North Klondike River located directly to the west of the highway. Local surface hydrology generally flows from higher mountainous terrain east of the highway to the North Klondike River Valley to the west (Figure C-1).

Local surficial geology is characterized by fluvial sands and gravel from km 71-72 and coarse-grained till veneer and bedrock from km 72-73. Bedrock is regionally mapped as clastic sedimentary rocks consisting of argillites and low-grade metamorphic slate, phyllite, and quartzite. Extensive discontinuous permafrost has been regionally mapped for this area. Ice wedges are not identified from aerial imagery or LiDAR measurement. Ground temperature data is not available for this location.

Surface disturbance along the highway includes several areas where aggregate has been removed for purposes of highway construction. Disturbance sites are delineated in Figure C-1. Surface disturbance also includes locations with infrastructure related to the Tombstone Campground.

Sinkholes were observed by HPW near highway km 72 on August 14 of 2014. A large area has been disturbed by construction activity surrounding this site which may impact permafrost and groundwater movement.

Section 2 (km 80-85)

Highway Section 2 is located within the North Fork Pass mapsheet (NTS 116 B09) and extends from km 80 to km 85 (Figure C-2). Figures C-2.1 and C-2.2 provide two sub-set maps of the highway section at a scale of 1:7 500. Local surface water flow is from the northeast to the southwest which is perpendicular to the orientation of the highway.

Local surficial geology is characterized by morainal till consisting of sand, silt, and gravel. Bedrock is regionally mapped as Upper Cambrian and Ordovician age volcanic rocks consisting of mafic basalt and tuff.

Former road alignments and disturbance from past road activities are observed within Section 2. Extensive discontinuous permafrost has been regionally mapped for this area. Ground temperature data is not available for this section of highway.

Sinkholes were observed by HPW near highway km 82 and km 81.8 on August 14 of 2014. Ice wedges and other permafrost-related features are not observed at these locations. However, several pits (depressions) of unknown origin occur along this section of highway. A sinkhole was also observed further north at km 87.6 on August 14 of 2014.

Section 3 (km 92-98)

Highway Section 3 is located within the North Fork Pass mapsheet (NTS 116 B09) and extends from km 92 to km 98 (Figure C-3). Two sub-set maps at a scale of 1:7 500 are provided in Figures C-3.1 and C-3.2. The highway parallels the East Blackstone River and is located at an elevation above the modern river floodplain. Local surface water along the highway corridor generally flows from the west to the east towards the river which is perpendicular to the orientation of the highway.

Local surficial geology is characterized by glaciofluvial, morainal till, and fluvial sediments consisting mainly of sand, gravel, and silt. Bedrock is regionally mapped as Upper Proterozoic to Lower Cambrian age slate. Bedrock outcrops are not observed within the 300 m of the highway embankment.

Areas of major surface disturbance are delineated in (Figures C-3.1 and C-3.2). Material borrow pits are located on the east and west side of the highway near km 94.5. Evidence of a former highway alignment is located to the east between the current highway embankment and the East Blackstone River.

Extensive discontinuous permafrost has been regionally mapped for this area. However, local observations suggest continuous permafrost exist along this section of the highway corridor, with exception of beneath major water courses and areas of surface disturbance. Ground temperature data is not available for this section of highway.

Ice wedge polygons are spatially extensive from highway km 92 to km 93.9 and from km 94.7 to km 98. Ice-rich terrain extends beyond highway km 98. Historical airphotos indicate that ice wedges are degraded at a number of locations, such as locations near km 92.7 and km 96.7. Figure C-3.2 indicates one location where the extent of degrading ice wedges has expanded since 1989.

Sinkholes were observed by HPW near highway km 95.0, km 95.2, km 95.7, and km 95.8 on August 14, 2014. Ice wedge polygons occur at each of these locations (Figures C-3, C-3.1, and C-3.2).

Section 4 (km 99-103)

Highway Section 4 is located within the North Fork Pass mapsheet (NTS 116 B09) and extends from highway km 99 to km 103 (Figure C-4). Two sub-set maps at a scale of 1:7 500 are provided in Figures C-4.1 and C-4.2. The highway is located directly to the west of the East Blackstone River. The highway is above the elevation of the modern river valley from km 99 to 102, as evident by its position relative to the escarpment (Figure C-4.1). Near highway km 102.5, the highway is located adjacent to Two Moose Lake (Figure C-4.2).

The highway extends across both fluvial, glaciofluvial, and morainal till. The surficial geology within the modern East Blackstone River valley consists of fluvial silt, sand, and gravel. Bedrock is regionally mapped as Ordovician to Lower Devonian age sedimentary rocks consisting of shale, chert, siltstone, limestone, and conglomerate.

Local surface water generally flows from the hillslopes on the western side of the highway to lower elevations within the East Blackstone River. From highway km 100 to km 102, surface diversion ditches have been constructed to capture hillslope runoff. Surface disturbance for this section highway include former highway alignments and material borrow pits (Figures C-4.1 and C-4.2).

Historical airphotos indicate an increase in the extent of the eastern shoreline of Two Moose Lake since 1963. Progressive change in shoreline is also observed in airphotos acquired in 1989. The change in extent of the lake may relate to rising water levels, shoreline erosion, or subsidence. The proximity of the shoreline to the highway embankment has also decreased at some locations. Terrain to the east and to the south of Two Moose Lake shows widespread surface disturbance from past excavation of sand and gravel.

Continuous permafrost has been regionally mapped for this area. Ice wedge polygons are widespread for terrain located above the elevation of the modern river valley (Figures C-4.1 and C-4.2). Ice wedges are locally degrading and form the preferred pathway for surface water to flow. The degrading ice wedge polygons are observed to be incised at some locations due to melting of the ice wedge. These features are evident directly upgradient of the hillslope diversion channel between km 100 and km 102. Ground temperature data is not available for this section of highway.

Sinkholes were observed by HPW near highway km 101.2 on August 14, 2014. Ice wedges are observed at this location (Figures C-4 and C-4.1).

Section 5 (km 115-117)

Highway Section 5 is located within the within the Lomond Lake mapsheet (NTS 116 B16) and extends from highway km 115 to km 117 (Figure C-5). This section of highway parallels the Blackstone River located to the southeast of the highway embankment. Chapman Lake is located near highway km 116. The embankment is above the elevation of the modern Blackstone River floodplain and closely borders the valley escarpment from km 115.4 to km 116.4.

Local surface water generally flows from the northwest to the southeast towards the Blackstone River. The highway embankment is orientated perpendicular to the main direction of surface water flow. Drained lake basins form the dominate terrain for 2-3 km north of the highway embankment.

The local surficial geology along this section of highway is predominately morainal till. Bedrock is regionally mapped as Ordovician to Lower Devonian age sedimentary rocks consisting of shale, chert, siltstone, limestone, and conglomerate. Bedrock is not observed to outcrop along this section of highway.

Continuous permafrost has been regionally mapped for this area. Ice wedges are prevalent in drained lake basins and across other low lying terrain. Figure C-5 shows the locations where standing water and degraded ice wedges are observed.

HPW has indicated the development of tension cracks and instability of the embankment south of Chapman Lake. At this location, the escarpment is approximately 20 m high and slopes at approximately 30 degrees. Active erosion from the Blackstone River is expected along this section as it forms the cut-bank side of the river. The instability of the embankment likely relates to the over-steepened escarpment due to removal of material by the river and possible creep of the adjacent terrain. Groundwater and permafrost extent are not known at this location.

Historical airphotos indicate surface water adjacent to the embankment near highway km 115.6 has increased in extent since 1989. This section of highway extends across degrading ice wedges which form surface depressions. Improper drainage of surface water also exists to near km 117.4 (Figure C-5).

Section 6 (km 141-143)

Highway Section 6 is located within the within the Engineer Creek mapsheet (NTS 116 G01) and extends from highway km 141 to km 143 (Figure C-6). This highway section was constructed sometime after 1963.

The northwest slope includes boulder rich colluvium deposits. Fluvial gravel, sand, and silt occupy the modern Blackstone River floodplain. Bedrock is regionally mapped as Lower Proterozoic age sedimentary rocks consisting of shale, siltstone, and sandstone. Continuous permafrost has been regionally mapped within this area.

The highway borders steep terrain from highway km 141.6 to km 144.1. South of km 141.6 the highway extends across the low-gradient floodplain of the Blackstone River. Ground temperature data is not available. Surface disturbance included two material borrow pits located at highway km 141.2 (Figure C-6).

Section 7 (km 185-187)

Highway Section 7 is located within the within the Mount Jeckell mapsheet (NTS 116 G08) and extends from highway km 185 to km 187 (Figure C-7). This highway section was constructed sometime after 1963. The highway parallels Engineer Creek and is located across the modern fluvial floodplain. Local surface water in the vicinity of the highway generally flows from west to east towards Engineer Creek. The highway is orientated perpendicular to this local direction of flow.

Local surficial geology consists of fluvial fan and colluvium deposits to the west of the highway and modern fluvial gravel, sand, and silt with the floodplain of Engineer Creek. Bedrock is regionally mapped as Lower and Middle Devonian age sedimentary rocks consisting of limestone and shale. Bedrock outcrops along higher elevation terrain surrounding the highway corridor.

Continuous permafrost has been regionally mapped for this area. There is limited evidence for ice rich ground, with the exception of ice wedges which possibly occur within several low-lying sites with surface organics (Figure C-7). Ground temperature data is not available.

Section 8 (km 191-193)

Highway Section 8 is located within the within the Mount Jeckell mapsheet (NTS 116 G08) and extends from highway km 191 to km 193 (Figure C-8). The highway section is parallels Engineering Creek and crosses low-lying wet terrain. The Engineering Creek Campground is located near highway km 193.2.

Local surficial geology consists of fluvial fan and colluvium deposits. Bedrock is regionally mapped as Lower and Middle Devonian age sedimentary rocks consisting of limestone and shale. Continuous permafrost has been regionally mapped for this area. Ground temperature data is not available for this highway section.

Section 9 (km 246-248)

Highway Section 9 is located within the within the Mount Cronkhite mapsheet (NTS 116 H12) and extends from highway km 246 to km 248 (Figure C-9). Local surface water in the vicinity of the highway generally flows from the north to the south towards the Ogilvie River valley.

The highway extends across modern fluvial gravel, sand, and silts from the start of Section 9 to approximately km 245.7. The local relief increases as the highway transects organic terrain underlain by colluvial sand and silt. Bedrock is regionally mapped as Upper Cretaceous age sedimentary rocks consisting of mudstone and sandstone.

Continuous permafrost has been regionally mapped for this area. There is limited visible evidence of permafrost features associated with ice-rich ground. However, organic deposits underlain by silt-rich colluvium may be susceptible to ground ice formation. Ground temperature data is not available for this highway section.

Section 10 (km 373-375)

Highway Section 10 is located within the within the Corbett Hill mapsheet (NTS 116 I07) and extends from highway km 373 to km 375 (Figure C-10). Section 10 is located approximately 5 km north of Eagle Plains. Local surficial geology consists of colluvium deposits consisting of sand and silt. Bedrock is regionally mapped as Upper Devonian siltstone and sandstone.

Local surface water generally flows from east to west which is opposing the dominate orientation of the highway. Surface water is observed on the west side of the highway from km 374 to at least km 375. LiDAR intensity measurements near km 375 show surface water adjacent to both sides of the embankment (Figure C-10.1). Historical airphotos indicate the spatial extent of surface water at this site was less in 1989.

Continuous permafrost has been regionally mapped for this area. Surface features commonly associated with ground ice were not identified for this highway section. However, silt in this area may be susceptible to ground ice formation. Ground temperature data is not available for this highway section.

Section 11 (km 424-426)

Highway Section 11 is located within the within the Mount Hare mapsheet (NTS 116 I09) and extends from highway km 424 to km 426 (Figure C-11). Local surface hydrology flows from west to east and opposes the north-south orientation of the highway. Surface water pathways are identified by distinct changes in vegetation.

The highway section extends across colluvium deposits consisting of sand, silt, and gravel. At highway km 246, surficial sediments transition to fluvial gravel, sand, and silt. Bedrock is regionally mapped as Upper Devonian siltstone and sandstone.

Continuous permafrost has been regionally mapped for this area. Surface features commonly associated with ground ice were not identified for this highway section. Ground temperature data is not available for this highway section.

5 Future Investigations

The following section provides recommendations for future field investigations which may advance the understanding of sinkholes along the Dempster Highway.

5.1 Data Collection

It is recommended that maintenance crews be trained to collect field observations which document these road hazards. Highway maintenance crews have the opportunity to observe both highway infrastructure and environmental conditions which may lead to sinkhole development. Information gathered by HPW could be compiled into a spatial database which documents field observations and measurements. This database would support future efforts to understand sinkholes and potentially assist in assessing terrain susceptible to sinkhole formation. The latter would narrow highway monitoring efforts.

Appendix D provides an example field datasheet template to assist highway maintenance crews with proper documentation of sinkholes. The field datasheet should be used to guide the collection of field observations and measurements. A key component of this datasheet is the ability to record both the km marker and a more exacting location using a Global Positioning System (GPS). The datasheet also provides space for recording additional observations.

The Government of Yukon Health and Safety Program should be followed prior to collecting any field measurements to ensure safe workplace conditions exist.

5.2 Site Investigations and Instrumentation

Field investigations could be performed along key highway section where sinkholes have been observed. These investigations should focus on both highway infrastructure and the surrounding environment which may contribute to sinkhole development, such as natural drainage and degrading ice wedges that occur beyond the embankment. Useful information could be obtained from field inspections conducted during the spring freshet and throughout the thawing season. Site descriptions provided in Section 4 and Appendix C should be used to support these field investigations.

The reoccurring nature of some sinkholes suggests that field instrumentation could be used to document site conditions. The abovementioned field investigations should be performed prior to installing field instruments to ensure proper design of the monitoring system at each site.

The hydrological interaction with seasonal frost and permafrost may be an important component of sinkhole development. Several instruments to document these interactions include; time-lapse cameras, shallow piezometer wells, and ground temperature cables. Information collected from time-lapse cameras may include the timing and location of surface water runoff and ponding, surface erosion, and the formation of road potholes and cracks. Shallow piezometer wells and ground temperature cables may provide useful information relevant to the timing and location of nearsurface groundwater in relation to seasonal frost and permafrost at the site.

5.3 Geophysical Investigations

Geophysical surveys could be performed to characterize subsurface conditions and to test the effectiveness of the techniques to detect and map subsurface voids which contribute to sinkhole development. The following section focuses on geophysical techniques suited to detecting and mapping of subsurface voids. Geophysics may also be used to characterize other site conditions, such as massive ground ice, permafrost extent, and shallow groundwater.

The development of a successful sinkhole detection method requires an understanding of the geophysical target (i.e. the subsurface voids), the survey environment, and the general expectation of the end-user.

The following items were considered in the context of the information presented in this report:

- Survey objective(s);
- Subsurface material (attenuation of energy source);
- Surface limitations (logistical, surface obstructions, etc.);
- Target to background contrast;
- Vertical and lateral resolution of geophysical technique;
- Overburden material properties between surface and target;
- Existing data sources useful to pre-survey assessment;
- Potential usefulness of multiple geophysical techniques;
- Survey platform / rate of data acquisition;
- Ground limitations (vegetation, local terrain, etc.);
- Performance of equipment in all-weather conditions;
- Survey positioning (global positioning systems); and
- Survey line spacing and orientation.

Additional considerations for conducting geophysical surveys in permafrost environments include:

- Active layer thickness and moisture content
- Soil salinity
- Unfrozen water content

- Cryostratigraphy (ice content and ice type)
- Taliks (target or limitation to geophysical technique)
- Survey period (early or late in the freezing season, early or late in the thaw season)

Section 4 provides site-specific information useful to the design and implementation of geophysical surveys which aim to characterize subsurface conditions and detect subsurface voids within the road embankment.

5.3.1 Survey Objectives

The geophysical survey objectives specific to the detection of sinkholes may include, but is not limited to:

- Identification of air or water filled voids within and beneath the highway embankment;
- Mapping of frozen ground and unfrozen saturated material within and beneath the embankment; and
- Subsurface characterization of native ground surrounding embankment.

The detection of subsurface voids with geophysics would only be effective for operational monitoring if the technique meets the following criteria:

- Geophysical surveys and data processing and analysis are cost effective;
- Surveys over large areas can be conducted in relatedly short periods of time; and
- Geophysical anomalies caused by voids can be positivity discriminated from other physical changes in the subsurface.

HPW may wish to further develop survey objectives to meet internal requirements and ensure highway safety.

5.3.2 Geophysical Target

Subsurface voids may vary in size from small cracks and vugs to large cavities within and beneath the road embankment. Sinkholes observed by HPW along the Dempster Highway are provided in Section 4. Sinkholes observed to date have been air-filled voids either directly formed in the highway embankment fill or due to subsidence of fill cause by ground ice melt occurring within the native soil.

The observational data suggests the voids are air-filled prior to collapse of the highway surface. As such, the main geophysical target would be an air-filled void or crack. Water-filled voids, tunnels, and cracks should also be considered as these conditions may exist prior to drainage and collapse of the surface.

5.3.3 Survey Location and Design

Geophysical surveys should include the collection of geophysical information from the highway embankment surface and along the adjacent right-of-way. Data collected along the right-of-way may provide valuable information about the subsurface stratigraphy at the site and other environmental factors contributing to sinkhole formations, such as improper drainage of water and permafrost and ground ice distribution. The testing of some geophysical techniques may not be suitable for off highway surveys.

Surveys conducted from the highway embankment surface will require proper traffic control measures are in place. If the subsurface feature is identified prior to the survey, additional safety procedures should be followed by survey crews.

5.3.4 Validation

It is recommended that validation of the geophysical anomalies be performed soon after completion of the surveys. This may include drilling, cone penetrometer probing, or excavation of pits. Validation must be performed under the assumption that a void exists at the site to ensure safety of all field personnel and equipment. It is recommended that the validation technique meet HPW Health and Safety Program, and if necessary additional safety procedures should be developed. If sinkholes are positively confirmed, highway repairs should be conducted immediately to ensure highway safety.

5.4 Geophysical Techniques

Based on review of the available literature, the most commonly used and recommended geophysical techniques for the investigation of sinkhole voids include ground penetrating radar (GPR), electrical resistivity tomography (ERT), and seismic methods (refraction tomography and reflection). Most applications take place in non-permafrost environments and some focus on deep void detection in carbonate rock.

5.4.1 Multi-offset Ground Penetrating Radar

GPR is a non-invasive geophysical technique that operates by transmitting short pulses of electromagnetic energy. This energy is partially reflected from subsurface features with different electrical properties. GPR profiling is commonly applied to map road conditions. GPR offers high-resolution data with the capability for quick data acquisition and processing at a relatively low cost.

Most GPR surveys are acquired with a constant transmitter-receiver offset; i.e. two antennas are pulled across the ground surface with a constant offset. An alternative survey configuration is called multi-offset GPR which deploys one transmitting antenna and multiple receiving antennas. This survey configure allows for multiple radar gathers (multiple travel time measurement) at different antenna offsets. Data acquired with multi-offset GPR is analogous to a common mid-point (CMP) survey.

The processed CMP and multi-offset GPR data can be processed to derive a vertical 1D velocity profile. Variations in velocity can be attributed to major difference in material type, moisture, air, and ice content (Davis and Annan 1989). The 1D velocity profile for laterally continues reflectors is based on normal moveout (NMO) analysis (Campbell et al. 1995; Bradford et al. 1996; Young and Sun 1996) and Dix inversion (Dix 1955). Bradford and Harper (2005) demonstrate the use of migration velocity analysis (MVA) for datasets dominated by hyperbolic reflections. These calculations applied to multi-offset GPR data provide 2D velocity sections; i.e. vertical and horizontal changes in radar velocity.

It is anticipated that the velocity structure from both CMP and multi-offset GPR surveys would be effective in detecting high velocity zones associated with air-filled voids or low velocity water-filled voids. The surrounding soil, rock, or ice would be expected to have a lower velocity (velocity ranging from 0.07-0.16 m ns^{-1}) compared to an air-filled void (0.3 m ns^{-1}).

GPR frequencies suited for testing may include 100 MHz, 250 MHz, and 500 MHz antennas. The CMP and multi-offset surveys would also provide single-fold data used to produce traditional 2D geophysical sections. Single-fold surveys may resolve high amplitude reflection from air and water filled voids. Smaller voids close to the wavelength of the transmitted EM energy may also be observed as hyperbolic point source reflections. Gravel and culverts within the embankment would also be expected to produce point source.

It is recommended that single fold and multi-offset GPR surveys be tested along highway sections where sinkholes are reasonably expected to occur. At a minimum both traffic lanes should be surveyed with GPR. Multi-offset GPR data could be collected along the road at a rate of 5-10 km per hour. Geophysical testing could also coincide with the discovery of future sinkholes, assuming complete collapse of the hole has not occurred. Such surveys would allow for more detailed collection of data and positive confirmation of the technique. If a void is detected, caution should be used at the sinkhole site as the ground may be unstable and subject to surface collapse. Highway safety measures would also be required to control vehicle traffic and to ensure field crews can safely operate at the site.

5.4.2 Capacitively-Coupled Electrical Resistivity Imaging

Capacitively-coupled electrical resistivity imaging (C-CERI) is a geophysical method that measures the apparent electrical resistivity using an alternating electrical current that is coupled to the ground via a transmitter. The change in voltage is measured by one or more receivers, which is proportional to the apparent resistivity of the ground. C-CERI systems are designed to be pulled long the ground surface, allowing for time effective surveys over large areas. This technique is different from direct current (DC) resistivity which requires temporary installation of galvanized rods at the surface to couple direct electrical current with the ground. Both DC resistivity and C-CERI have been successfully used to identify permafrost features (Kneisel et al. 2008) and detect subsurface voids.

C-CERI surveys conducted over subsurface air-filled voids are expected to result in high resistive zones. Water-filled voids are expected to result in low-resistivity (conductive) zones. These geophysical responses, however, commonly occur in association with other subsurface conditions. For example, frozen ground and ground ice would be expected to exhibit high resistivity which may be similar to the geophysical response of air-filled voids. Feature resolution may also prove to be below the detection limit of the technique.

C-CERI testing should be tested over small areas to determine its effectiveness in detecting air-filled and water-filled voids. At a minimum, both lanes of traffic should be surveyed with C-CERI. Surveys may be conducted in conjunction with multi-offset GPR surveys to provide direct comparison of data acquired from both techniques.

DC resistivity would not be effective for operation monitoring of the highway over large distances due to the slow rates of data acquisition. However, DC resistivity surveys should be considered for short highway sections (500 m or less) where an understanding of deep ground conditions (up to 20-30 m below surface) is warranted.

5.4.3 Other Techniques

Several other geophysical techniques were considered during the course of this study. Vehicle-mounted LiDAR has been used to map road surface conditions. Repeat road surveys can be used to produce change detection maps indicating the difference in road surface elevation. Applying this mapping technique to map sinkholes would require the ability to detect gradual collapse of the road surface. As, such vehicle-mounted LiDAR was determined to be ineffective due to the rapid collapse of these features and continual modification of the highway surface by vehicle traffic and surface grading.

Satellite Interferometric synthetic aperture radar (InSAR) was considered as a technique which could offer wide-area mapping. The relatively small size of the sinkholes and the high-level of seasonal and long-term subsidence that naturally occurs along the highway would suggest this technique would be ineffective for this application.

Micro-gravity surveys have been used to map sinkholes and karst terrain under highways. The technique measures small changes in the gravity field. A high level of quality control in the field and rigorous data processing is required. Micro-gravity surveys would not be cost effective for operational monitoring of the highway.

Seismic refraction tomography is a method commonly utilized to detect sinkholes. Tomographic processing of the data provides lateral variability in velocity as a function of changes in material density. Shallow seismic techniques could be useful for site investigations; however, surveys would prove to be costly over large areas. The technique would also have limited ability to resolve small voids.

5.5 Geotechnical Site Investigation

Geotechnical drilling should be performed to verify geophysical interpretations and to provide subsurface information which supports an understanding of sinkhole development. Geotechnical drilling should be reserved for sites where the exact location of the sinkhole is known. Geotechnical investigations should include description and identification material composition and stratigraphy, moisture content and density of the material, and cryostratigraphy.

Excavation pits and cone penetrometer probing may also contribute information about the vertical and lateral extent of materials beneath and surrounding sinkholes. HPW may wish to restrict pit excavation to the extent of the sinkhole, as further excavation could potentially cause disturbance to the highway embankment and the underlying permafrost.

6 Conclusions and Recommendations

This study provides the initial framework for understanding site conditions which may contribute to sinkhole development and provides the basis for future field investigations. The following conclusions are reached based on the available data:

- Sinkholes are spatially distributed along the Dempster Highway; however, reoccurrence of these features at some locations suggest they form under unique ground conditions;
- Rapidly forming sinkholes in permafrost environments are typically attributed to hydro-thermal erosion of massive ice by water which creates a subsurface voids;
- Improper drainage of surface water and degrading ice wedges may lead to formation of subsurface voids which develop into sinkhole;
- Sinkholes observed to date have been air-filled voids either directly formed in the highway embankment fill or due to subsidence of fill cause by ground ice melt occurring within the native soil;
- The increased frequency of intense hydrological events, such as rainfall, may increase the likelihood of sinkholes in permafrost environments;
- Local geology across most highway sections does not favor sinkhole formation caused by dissolution of carbonate rocks;
- Multi-offset GPR and C-CERI techniques may prove to be the most effective geophysical techniques available for mapping shallow subsurface voids that contribute to sinkhole development; and
- LiDAR hillshade models and intensity maps provide useful information for identifying ice wedge polygons and hydrologic pathways which are otherwise indiscernible from field observations. These datasets could support water management and improve highway engineering and maintenance along the Dempster Highway.

SRK recommends the following activities to further the understanding of sinkholes and to test geophysical techniques which effectively detect these road hazards:

- Development of sinkhole-related safety and highway repair procedures given the hazard to field personnel and highway traffic;
- Field inspections and monitoring of sites where sinkholes have been previous identified due to the potential for reoccurrence of these hazards. HPW may wish to increase monitoring and field inspections during the spring freshet and significant rainfall events and following repair of highway sections with prior sinkhole damage.

- Training of HPW maintenance crews to safely collect observations and measurements which support an understanding of sinkhole formation;
- Geophysical testing of multi-offset GPR and C-CERI to detect sinkholes at sites where these features are known or suspected to occur. These surveys may coincide with the discovery of a sinkhole along the highway. Safety control measures would be required to perform test surveys and ensure safe conditions exist for road users and field personnel;
- Geotechnical evaluations at the location of an existing sinkhole to characterize soil stratigraphy and type, texture, moisture content and density, and the phase state (frozen or unfrozen condition) of the material. Detailed drill logs and field observations should be made in addition to the description of ground ice encountered by the borehole; and
- Review of highway as-built reports to determine if construction materials and practices contribute to sinkhole development.

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All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.

7 References

Allnorth Land Surveyors. 2013. Dempster Highway LiDAR Accuracy Report. Submitted to Government of the Yukon.

Andersland, O.B., and Ladanyi, B. 2004. Frozen ground engineering, 2nd ed. Hoboken, New Jersey: John Wiley & Sons.

Antonarakis, A.S., Richards, K.S., and Brasinton, J. 2008. Object-based land cover classification using airborne lidar. Remote Sensing of Environment. 112: 2988–2998.

Bradford, J., Ramaswami, M., and Peddy, C. 1996. Imaging PVC gas pipes using 3-D GPR: Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP), Environmental and Engineering Geophysical Society, Proceedings, 519-524.

Bradford, J., Harper, J.T. 2005. Wave field migration as a tool for estimating spatially continuous radar velocity and water content in glaciers. Geophysical Research Letters. 32: L08502.

Bray, M.T., French, H.M., and Shur, Y., 2006. Further cryostratigraphic observations in the CRREL permafrost tunnel, Fox, Alaska. Permafrost and Periglacial Processes 17, 233-243.

Campbell, D.L., Lucious, J. E., Ellefson, K. J., and Deszcz-Pan M. 1995. Monitoring of a controlled LNAPL spill using groundpenetrating radar: Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP). Environmental and Engineering Geophysical Society. Proceedings. 511-517.

Chasmer, L. Quinton, W. Hopkinson C. Petrone, R. and Whittington, P. 2011. Vegetation canopy and radiation controls on permafrost plateau evolution within the discontinuous permafrost zone, Northwest Territories, Canada. Permafrost and Periglacial Processes. vol. 22. 199-213.

Davis, J., and Annan A.P. 1989. Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophysical prospecting vol. 37. 531-551.

Dix, C.H. 1955. Seismic velocities from surface measurements. Geophysics 20: 68-86.

Ford, D. 1963. Aspects of the geomorphology of the Mendip Hills. PhD. Thesis. Oxford University.

Fortier, D., Allard, M., and Shur, Y. 2007. Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. Permafrost and Periglacial Processes. 18: 229-243.

Gao, Y. 2002. Karst feature distribution in southeastern Minnesota: Extending GIS-based database for special analysis and resource management. PhD. Thesis. University of Minnesota.

Garroway, K., Hopkinson, C., and Jamieson, R. 2011. Surface moisture and vegetation influences on lidar intensity data in an agricultural watershed. Canadian Journal of Remote Sensing 37: 275–284.

Gordey, S.P., and Makepeace, A.J. (compiled) 1999: Yukon bedrock geology in Yukon digital geology. Geological Survey of Canada Open File D3826 and Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada. Open File 1999-1(D). Scale 1:250 000.

Hopkinson, C., Crasto, N., Marsh, P., Forbes, D., Lesack, L. 2011. Investigating the spatial distribution of water levels in the Mackenzie Delta using airborne LiDAR. Hydrological Processes 25: 2995-3011.

Hyatt J.A. 1992. Cavity development in ice-rich permafrost, Pangnirtung, Baffin Island, Northwest Territories. Permafrost and Periglacial Processes 3: 293–313.Jennings, J.N. 1985. Karst Geomorphology. Basil Black Well, Ltd. Oxford. pp. 293.

Jennings, J.N., 1985: Karst Geomorphology. Basil Blackwell, Ltd., pp. 293, Oxford.

Jorgenson, M.T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E.A.G., Kanevskiy, M., and Marchenko, S. 2010. Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research 40:1219-1236.

Kneisel, C., Hauck, C., Fortier, R., and Moorman, B. 2008. Advances in geophysical methods for permafrost investigations. Permafrost and Periglacial Processes 19: 157-178.

Kotler, E., and Burn, C.R., 2000. Cryostratigraphy of the Klondike 'muck' deposits, westcentral Yukon Territory. Canadian Journal of Earth Sciences 37, 849-861.

Leffingwell, E.K. 1915. Ground-ice wedges, the dominant form of ground-ice on the north coast of Alaska. Journal of Geology 23: 635–654.

Mackay, J.R. 1974. The rapidity of tundra polygon growth and destruction, Tuktoyaktuk Peninsula-Richards Island area, N.W.T. In Current Research, Part A. Geological survey of Canada: Ottawa, Paper 74-1A: 391–392.

Mackay, J.R. 1981. An experiment in lake drainage, Richards Island, Northwest Territories: a progress report. In Current Research, Part A. Geological Survey of Canada: Ottawa, Paper 81-1A: 63–68.

Mackay, J.R. 1988. Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie. In Current Research, Part D. Geological Survey of Canada: Ottawa, Paper 88-1D: 83–90.

Mackay, J.R., 1997. A full-scale field experiment (1978–1995) on the growth of permafrost by means of lake drainage, western Arctic coast: a discussion of the method and some results. Canadian Journal of Earth Sciences 34, 17–33.

Mazzarini F., Pareschi, M.T., Favalli, M., Isola, I., Tarquini, S., and Boschi, E. 2007. Lava flow identification and aging by means of LiDAR intensity: Mount Etna case. Journal of Geophysical Research 112: B02201.

Newton, J. 1984. Sinkholes resulting from ground-water withdrawls in carbonate terranes-an overview. Reviews in Engineering Geology. Geological Society of America.

Quinlan, J.F. 1986. Legal aspects of sinkhole development and flooding in karst terranes: Review and synthesis. Environmental Geology and Water Sciences. vol. 8. 41-61

Ricker, K.E. 1967, North Klondike and Upper Blackstone River, University of British Columbia unpublished map. Scale 1:50 000.

Romanovsky, V.E., and Osterkamp, T.E. 2001. Permafrost: changes and impacts. In: Paepe, R., and Melnikov, V., eds. Permafrost response on economic development, environmental security and natural resources. Dordrecht, Netherlands: Kluwer Academic Publishers. 297-315.

Seppala, M. 1997. Piping causing thermokarst in permafrost, Ungava Peninsula, Que´bec, Canada. Geomorphology 20: 313-319.

Shannon and Wilson Inc. 1981. Use of Geotextiles to bridge thermokarst theoretical analysis and Report submitted to the State of Alaska Department of Transportation and Public Facilities Division of Planning and Programming Research Section, Fairbanks, Alaska.

Shannon and Wilson Inc. 1985. Field and Laboratory Study on the use of geotextiles and related products to bridge thermokarst. Report submitted to the State of Alaska Department of Transportation and Public Facilities Division of Planning and Programming Research Section, Fairbanks, Alaska.

Shur, Y., French, H.M., Bray, M.T., and Anderson, D.A., 2004. Syngenetic permafrost growth: cryostratigraphic observations from the CRREL Tunnel near Fairbanks, Alaska. Permafrost and Periglacial Processes 15, 339-347.

Smith, S.L., and Burgess, M.M. 2004. Sensitivity of permafrost to climate warming in Canada. Bulletin 579. Ottawa: Geological Survey of Canada, Natural Resources Canada.

Stevens, C.W. and Wolfe S.A. 2012. High-resolution mapping of wet terrain within discontinuous permafrost using LiDAR intensity. Permafrost and Periglacial Processes. 23: 334-341.

Stevens, C.W. Short, N. and Wolfe, S.A. 2012a. Seasonal surface displacement and highway embankment grade derived from InSAR and LiDAR, Highway 3 west of Yellowknife, Northwest Territories. Geological Survey of Canada. Open File 7087.

Stevens, C.W., Wolfe, S.A., Gaanderse, A.J.R., 2012b. Lithalsa Distribution, Morphology and Landscape Associations in the Great Slave Lowlands, Northwest Territories. Geological Survey of Canada, Open File 7255

Sweeting, M.M. 1973. Karst Landforms. Columbia University Press, New York. pp. 362.

Thomas, R.D., and Rampton, V.N. 1982a. North Klondike River. Geological Survey of Canada. Preliminary Map 6-1982. Scale 1:50 000.

Thomas, R.D., and Rampton, V.N. 1982b. Upper Blackstone River. Geological Survey of Canada. Preliminary Map 7-1982. Scale 1:100 000.

Thomas, R.D., and Rampton, V.N. 1982c. Engineer Creek. Geological Survey of Canada. Preliminary Map 8-1982. Scale 1:100 000.

Thomas, R.D., and Rampton, V.N. 1982d. Lower Ogilvie River. Geological Survey of Canada. Preliminary Map 9-1982. Scale 1:100 000.

Thomas, R.D., and Rampton, V.N. 1982e. Moose Lake. Geological Survey of Canada. Preliminary Map 10-1982. Scale 1:100 000.

Thomas, R.D., and Rampton, V.N. 1982f. Rock River. Geological Survey of Canada. Preliminary Map 11-1982. Scale 1:100 000.

USGS. 2007. Sinkholes. Fact Sheet 2007-3060. U.S. Department of Interior, U.S. Geological Survey.

Williams, P.W. 1971. Illustrating morphometric analyses of karst with examples from new Guinea Zeitschrift fur Geomophologie. 15: 40-61.

Wolfe, S.A., Stevens, C.W., Gaanderse, A.J., and Oldenborger, G.A. 2014. Lithalsa distribution, morphology and landscape associations in the Great Slave Lowland, Northwest Territories, Canada. Geomorphology. vol. 204. 302-313.

Young, R.A., and Sun, J. 1996. 3D ground penetrating radar imaging of a shallow aquifer at Hill Air Force Base. Utah: Journal of Environmental and Engineering Geophysics. 1: 97-108.

Appendix A – Sinkhole Photographs

Notes provided by Government of Yukon, Highways and Public Works:

1. Photographs taken on June 22, 2014 near km 82 of the Dempster Highway, Yukon Territory
2. Sinkhole was measured by maintenance crews to be approximately 7.5 m long, 4.5 m wide, and several metres deep
3. Sinkhole was filled with 32 cubic metres of pit run and 16 cubic metres of crush during a temporary repair

srk consulting	**Government of Yukon** **Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Highway km 82**
Job No: 1CG023.002 Filename: Sinkhole Photographs_June22_2014_km 82	Yukon Government	Date: Sept. 12, 2014 — Approved: — Figure: **A-1**

Notes:

1. Photographs taken on August 14, 2014 near km 82 of the Dempster Highway, Yukon Territory

srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Highway km 82**
Job No: 1CG023.002 Filename: Sinkhole Photographs_Aug 14_2014_km82	Yukon Government	Date: Sept. 12, 2014 · Approved: · Figure: **A-2**

Notes:

1. Photographs taken on August 14, 2014 and August of 2009 near km 82 of the Dempster Highway, Yukon Territory
2. Photographs from August of 2009 taken from Google Earth Street View
3. Blue arrows indicate direction of surface water flow within drainage ditch

srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Highway km 82**
Job No: 1CG023.002 Filename: Sinkhole Photographs_Aug 14_2014_km82	Yukon Government	Date: Sept. 12, 2014 · Approved: · Figure: **A-3**

Notes:
1. Photographs taken near km 82 of the Dempster Highway, Yukon Territory
2. Date of photograph is unknown
3. Vegetation surrounding the site suggests the photograph was taken sometime between June and August
4. Direct field measurement of sinkhole size are not available
5. Sinkhole is estimated from the photograph to be 1.5-2.0 m long, 0.4-0.5 m wide, and 1.2-1.5 m deep near the surface opening

srk consulting	**Government of Yukon** **Highways and Public Works** **Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway,** **Highway km 82**
Job No: 1CG023.002 Filename: Sinkhole Photographs_Unknown Date_km 82	Yukon Government	Date: July 15, 2014 · Approved: · Figure: **A-4**

Notes:

1. Photographs taken on August 14, 2014 near km 72 of the Dempster Highway, Yukon Territory
2. Red arrows indicate location of sinkholes

srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Highway km 72**		
Job No: 1CG023.002 Filename: Sinkhole Photographs_Aug 14_2014_km72	Yukon Government	Date: Sept. 12, 2014	Approved:	Figure: **A-5**

Notes:
1. Photographs taken on August 14, 2014, South of Chapman Lake along the Dempster Highway, Yukon Territory
2. Red arrows indicate location of sinkholes

srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, South of Chapman Lake**		
Job No: 1CG023.002 Filename: Sinkhole Photographs_Aug 14_2014_km72	Yukon Government	Date: Sept. 12, 2014	Approved:	Figure: **A-6**

Notes:
1. Photographs taken on August 14, 2014 near Two Moose Lake along the Dempster Highway, Yukon Territory
2. Red arrows indicate location of sinkholes

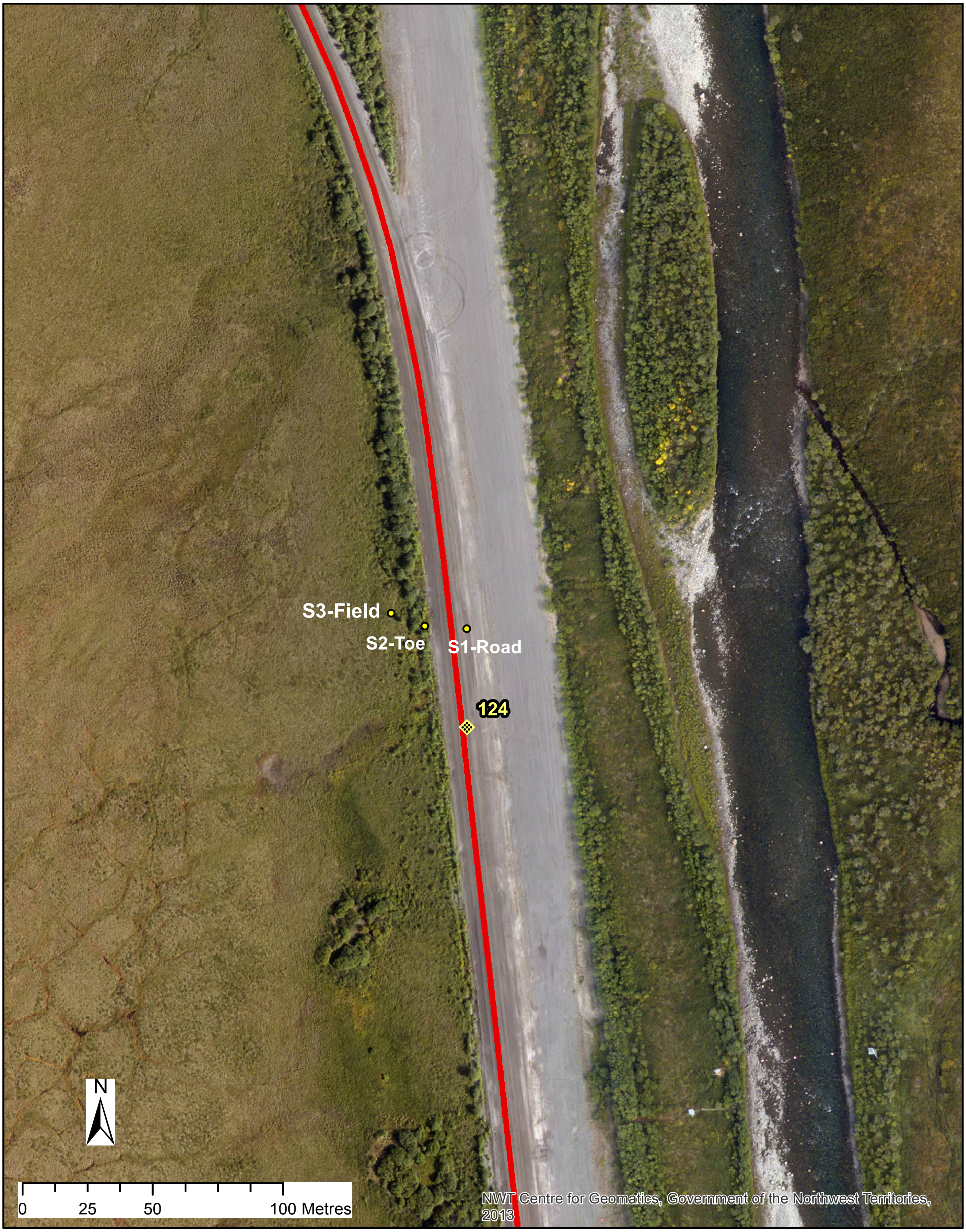
srk consulting	Government of Yukon Highways and Public Works, Engineering Transportation	Sinkhole Site Characterization Study **Dempster Highway,** **Two Moose Lake**		
Job No: 1CG023.002 Filename: Sinkhole Photographs_Aug 14_2014_km72	Yukon Government	Date: Sept. 12, 2014	Approved:	Figure: **A-7**

Notes:

1. Dark circular hole (indicated with red arrow) is interpreted to be the surface opening of a sinkhole near highway km 92
2. Photographs acquired from Google Earth Street View
3. Photograph data reported to be August of 2009
4. Sinkhole location: UTM Zone7N, 624724.0 E, 7172583.0 N

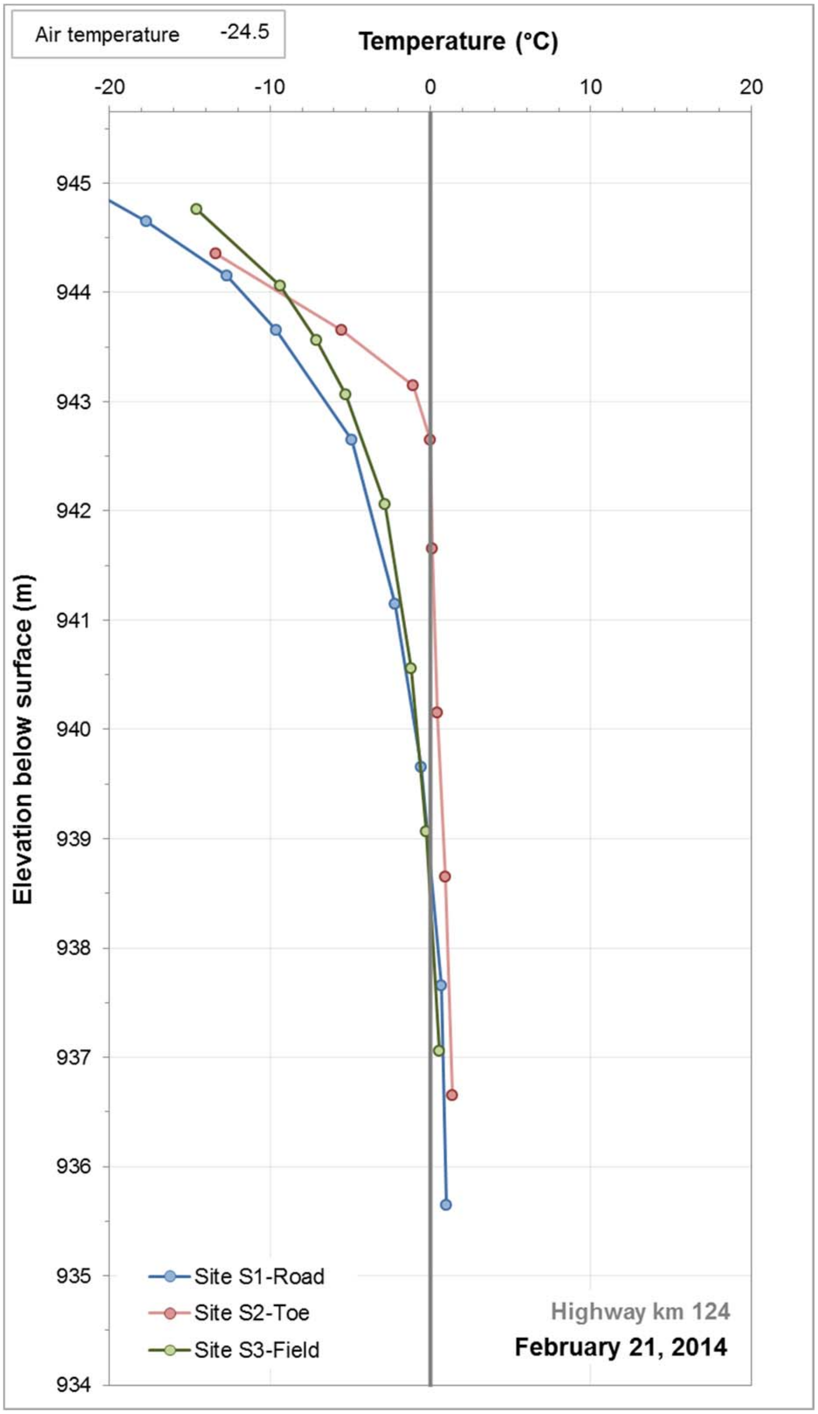
srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Highway km 92**
Job No: 1CG023.002 Filename: Sinkhole GoogleEarth_StreetView_km 92	Yukon Government	Date: July 15, 2014 | Approved: | Figure: **A-8**

Appendix B - Ground Temperature Measurements



srk consulting	**Yukon Territory - Sinkhole Study, Ground temperature sites**	DRAWING TITLE:	**Location of Ground Temperature Cables**
UTM Zone 7 Northern Hemisphere		ISSUED FOR:	**Highway and Public Works**
DESIGN: cws; DRAWN: cws; REVIEWED:		DRAWING NO.	**FIGURE B-1**
SCALE: 1 centimeter = 20 meters; DATE: 9/15/2014		SRK JOB NO.	**1CG023.002**
FILE: GroundTemperatureSite_rev01_cws.mxd		REVISION NO.	1

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\GroundTemperatureSite_rev01_cws.mxd



Notes:

1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on February 21, 2014
3. Elevation below surface determined from LiDAR measurements

srk consulting

Government of Yukon
Highways and Public Works, Engineering Transportation

Sinkhole Site Characterization Study

Dempster Highway, Ground Temperature (km 124)

Job No: 1CG023.002

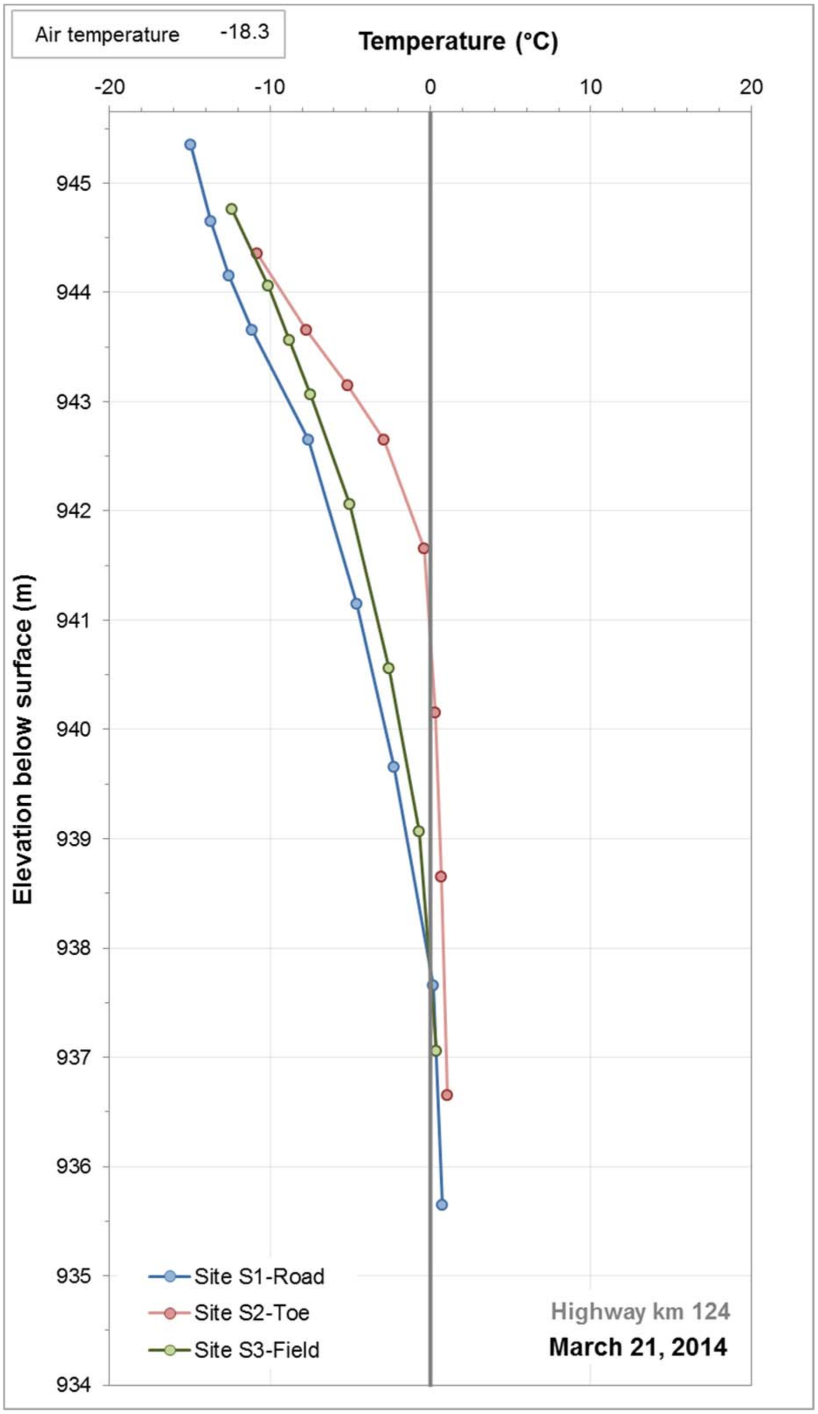
Filename: Ground Temperature_km 124

Yukon Government

Date: Sept. 15, 2014

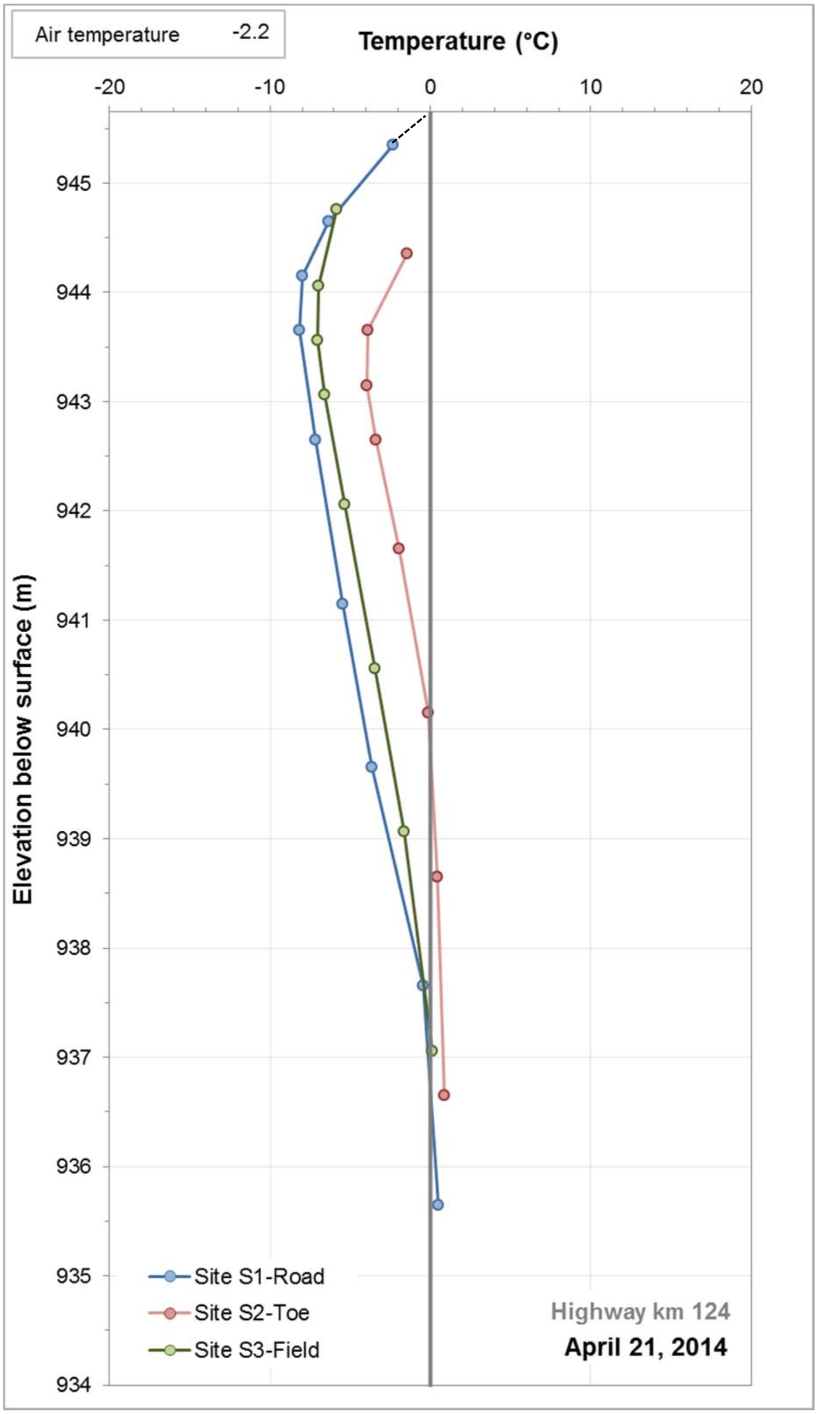
Approved:

Figure: **B-2**



Notes:
1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on March 21, 2014
3. Elevation below surface determined from LiDAR measurements

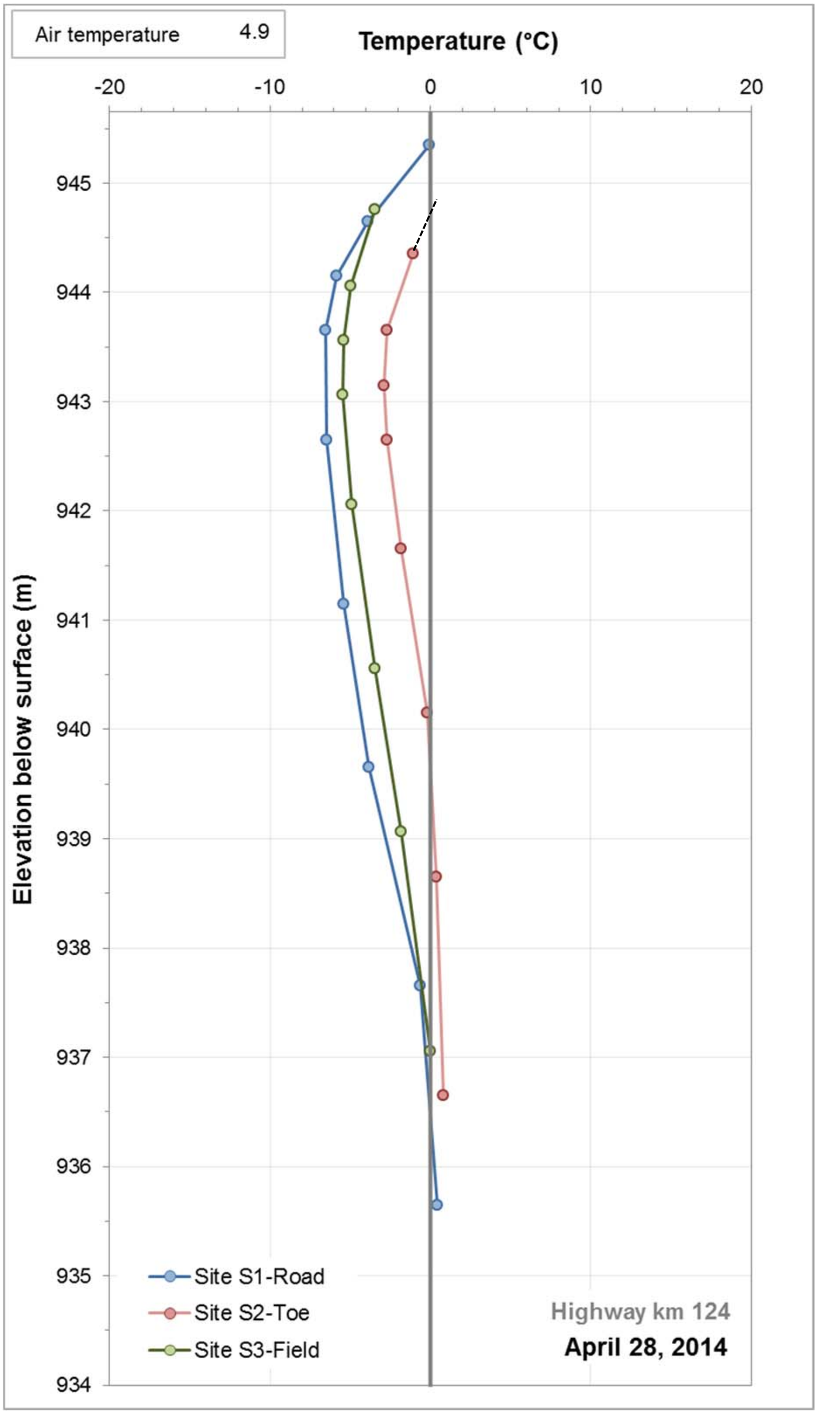
srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Ground Temperature (km 124)**
Job No: 1CG023.002 Filename: Ground Temperature_km 124	Yukon Government	Date: Sept. 15, 2014 · Approved: · Figure: **B-3**



Notes:

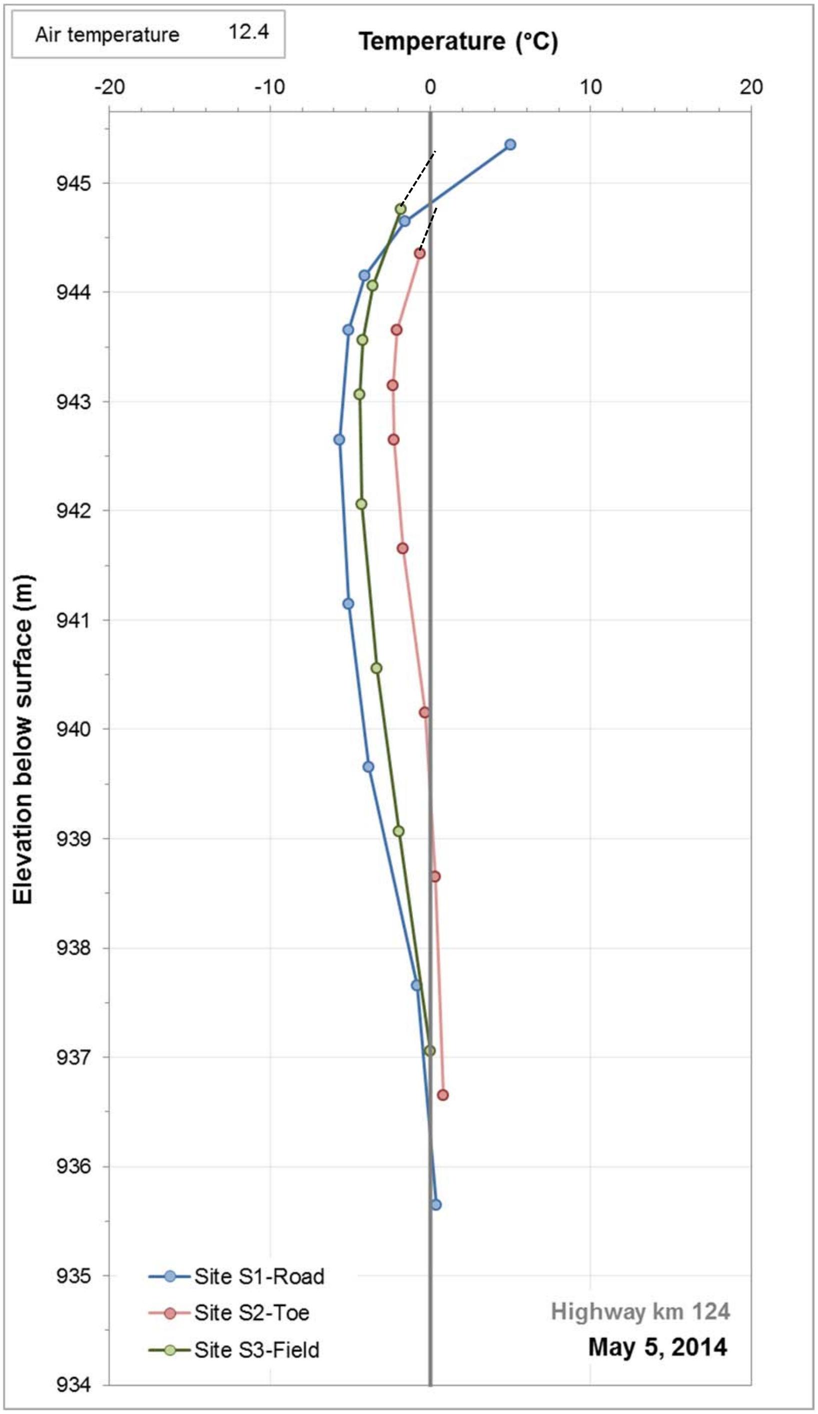
1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on April 21, 2014
3. Elevation below surface determined from LiDAR measurements

srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Ground Temperature (km 124)**
Job No: 1CG023.002 Filename: Ground Temperature_km 124	Yukon Government	Date: Sept. 15, 2014 · Approved: · Figure: **B-4**



Notes:
1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on April 28, 2014
3. Elevation below surface determined from LiDAR measurements

srk consulting	**Government of Yukon** **Highways and Public Works,** **Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway,** **Ground Temperature (km 124)**
Job No: 1CG023.002 Filename: Ground Temperature_km 124	Yukon Government	Date: Sept. 15, 2014 · Approved: · Figure: **B-5**



Notes:

1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on May 5, 2014

srk consulting

Government of Yukon
Highways and Public Works,
Engineering Transportation

Sinkhole Site Characterization Study

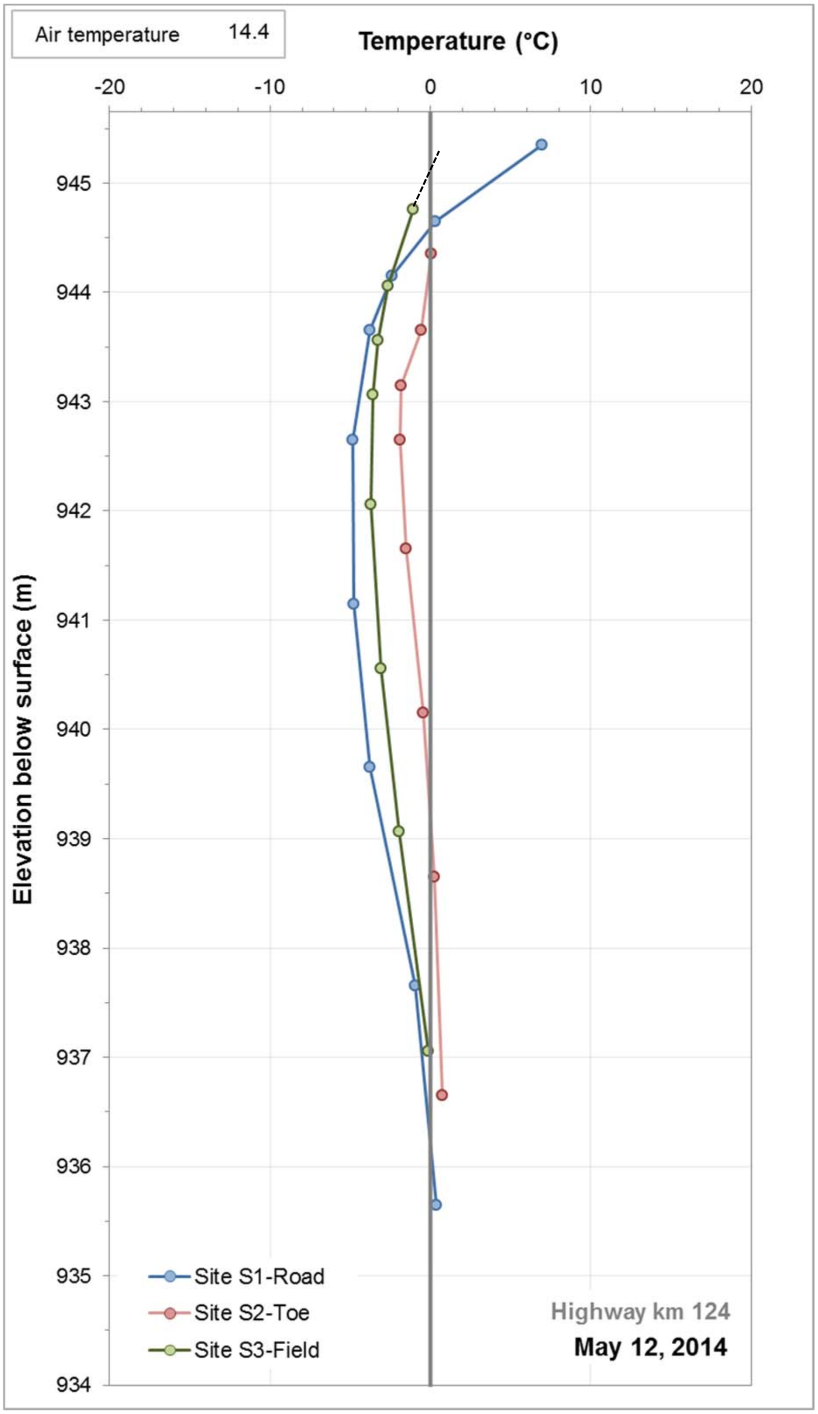
Dempster Highway,
Ground Temperature (km 124)

Job No: 1CG023.002

Filename: Ground Temperature_km 124

Yukon Government

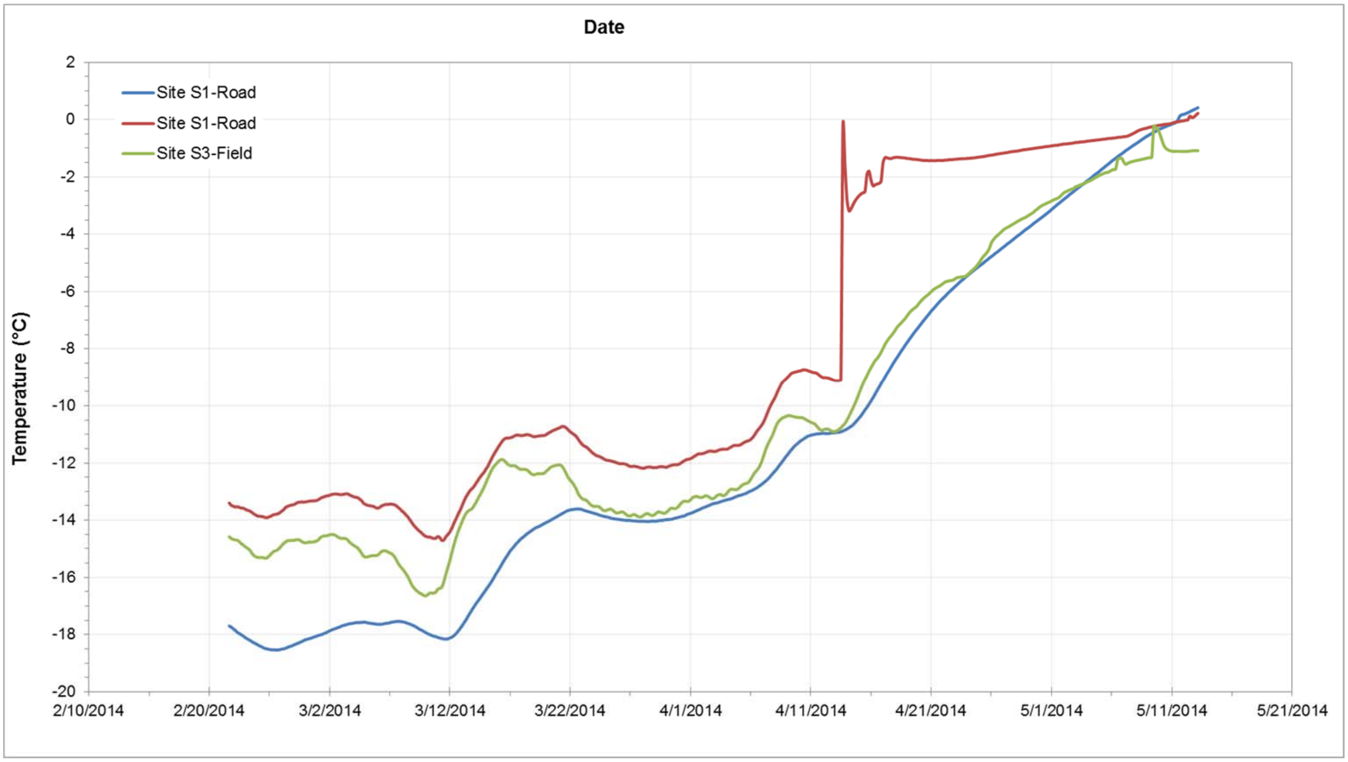
Date:	Approved:	Figure:
Sept. 15, 2014		**B-6**



Notes:

1. Ground temperature sites S1-Road, S2-Toe, and S3-Field
2. Temperatures measured on May 12, 2014

srk consulting	Government of Yukon Highways and Public Works, Engineering Transportation	Sinkhole Site Characterization Study **Dempster Highway, Ground Temperature (km 124)**		
Job No: 1CG023.002 Filename: Ground Temperature_km 124	Yukon Government	Date: Sept. 15, 2014	Approved:	Figure: **B-7**



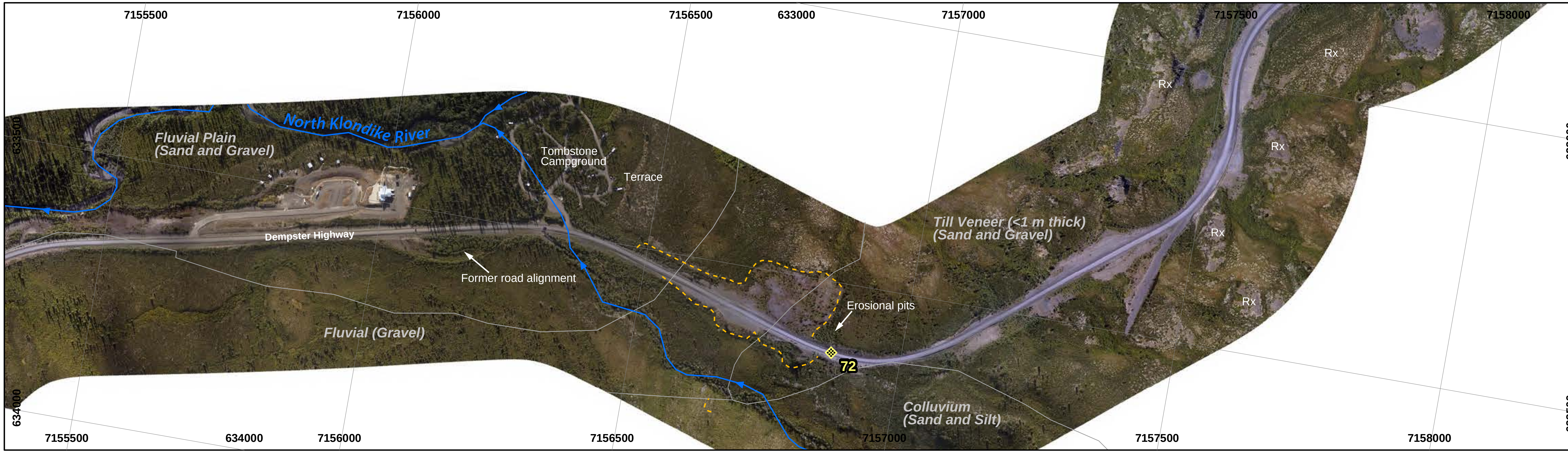
Notes:

1. Time-series temperature plot for sites S1-Road, S2-Toe, and S3-Field
2. Sensor elevations shown include: S1-Road (944.65 masl), S2-Toe (944.35 masl), and S3-Field (944.76 masl)
3. Elevation determined from LiDAR measurements

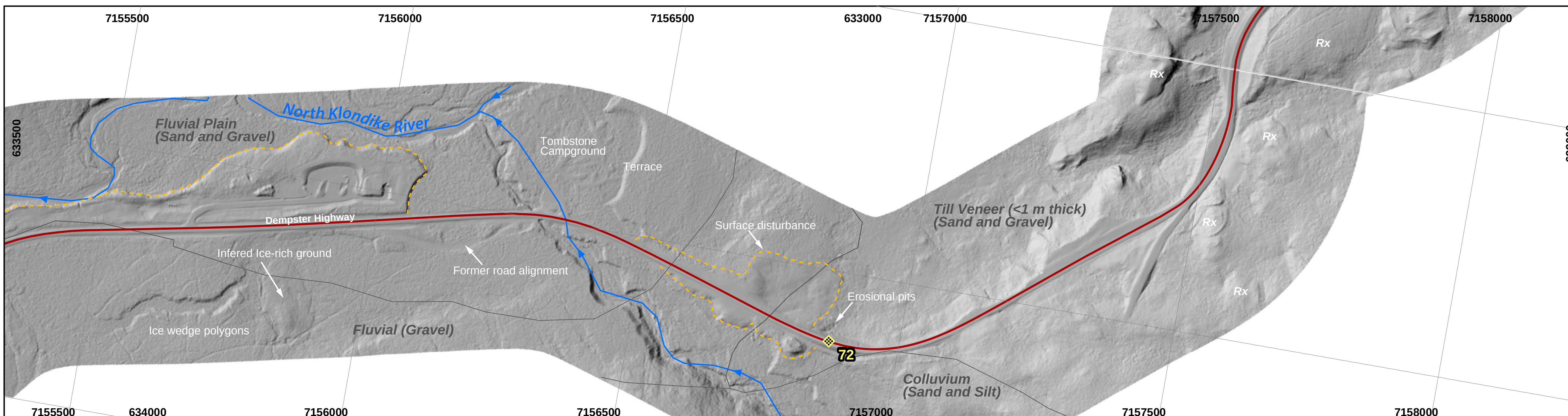
srk consulting	**Government of Yukon Highways and Public Works, Engineering Transportation**	Sinkhole Site Characterization Study **Dempster Highway, Ground Temperature (km 124)**		
Job No: 1CG023.002 Filename: Ground Temperature_km 124	Yukon Government	Date: Sept. 15, 2014	Approved:	Figure: **B-8**

Appendix C - Highway Sections

Colour Orthophoto



LiDAR Hillshade Model



N

0 100 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression

Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/16/2014
FILE: Highway Section 2.mxd		

Highway Section 1 (km 71-73)
Dempster Highway, YT

DRAWING TITLE: **Site Map**

ISSUED FOR: **Government of Yukon**

DRAWING NO. **Figure C-1**

SRK JOB NO. **1CG023.002**

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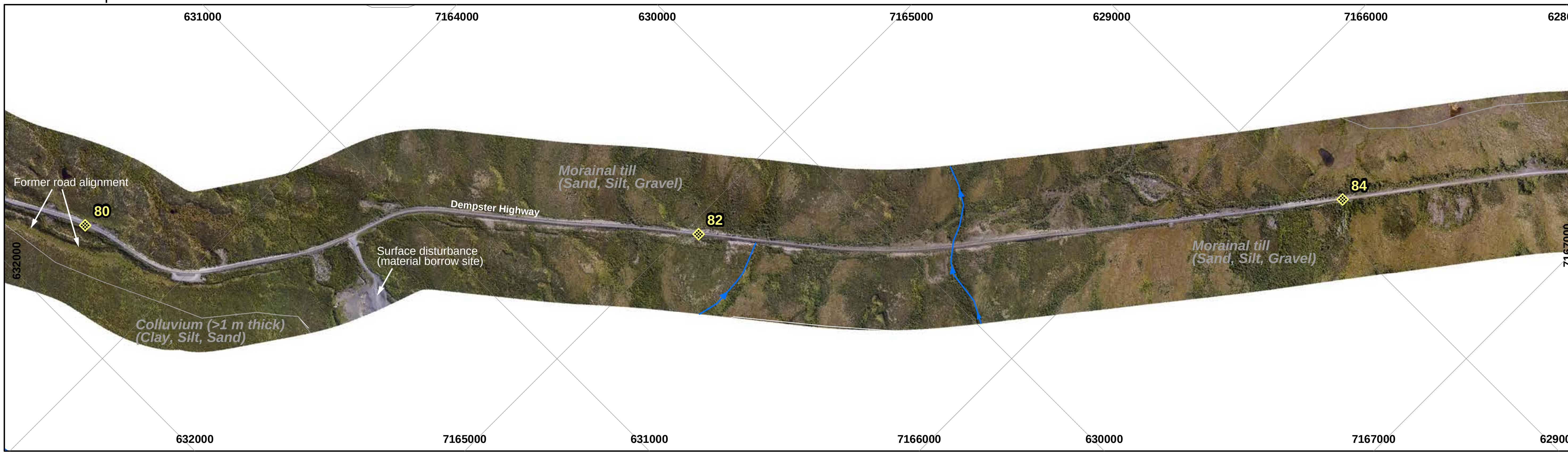
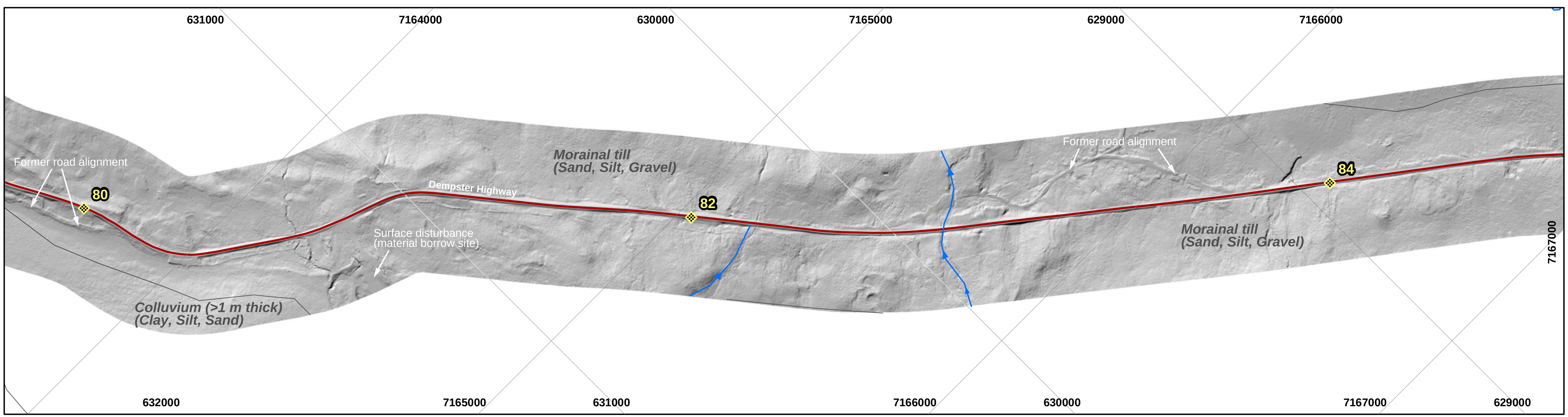
Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
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FILE: Highway Section 2.mxd		

Highway Section 2 (km 80-85)
Dempster Highway, YT

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ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-2
SRK JOB NO.	1CG023.002

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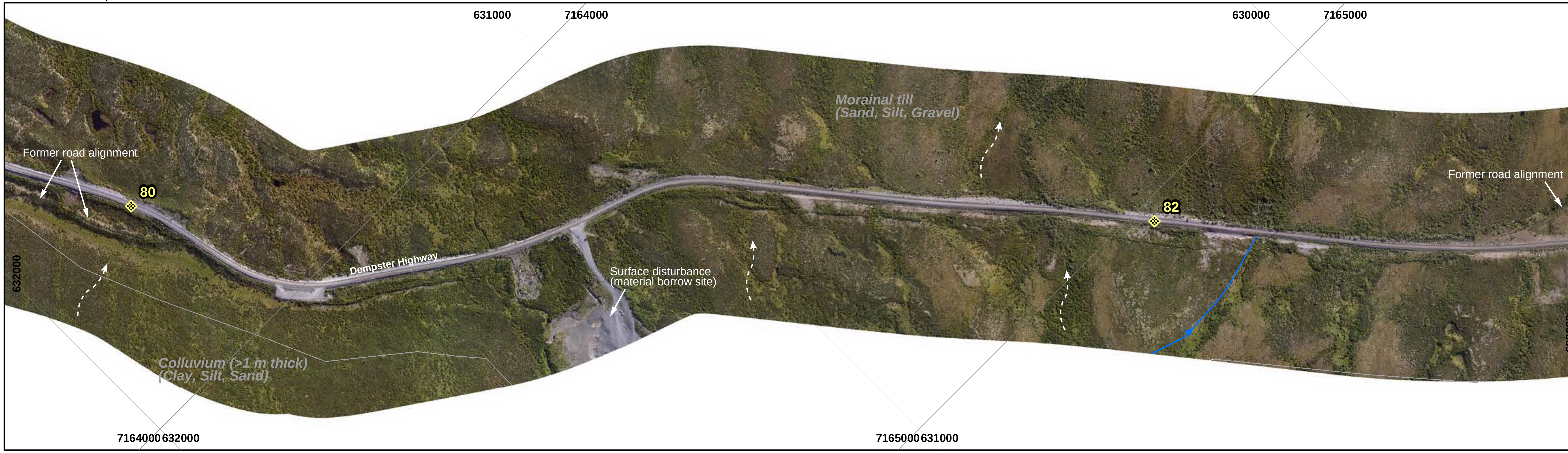
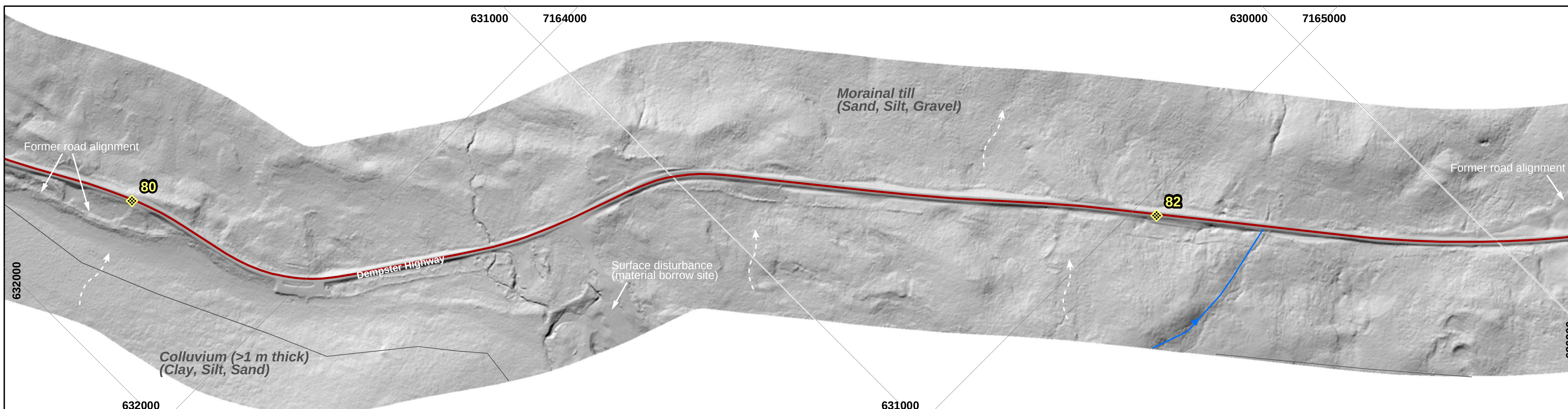
Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N			
DESIGN: CWS	DRAWN: CWS	REVIEWED:	
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014	
FILE: Highway Section 2A.mxd			

Highway Section 2
Dempster Highway, YT

DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-2.1**
SRK JOB NO.	**1CG023.002**

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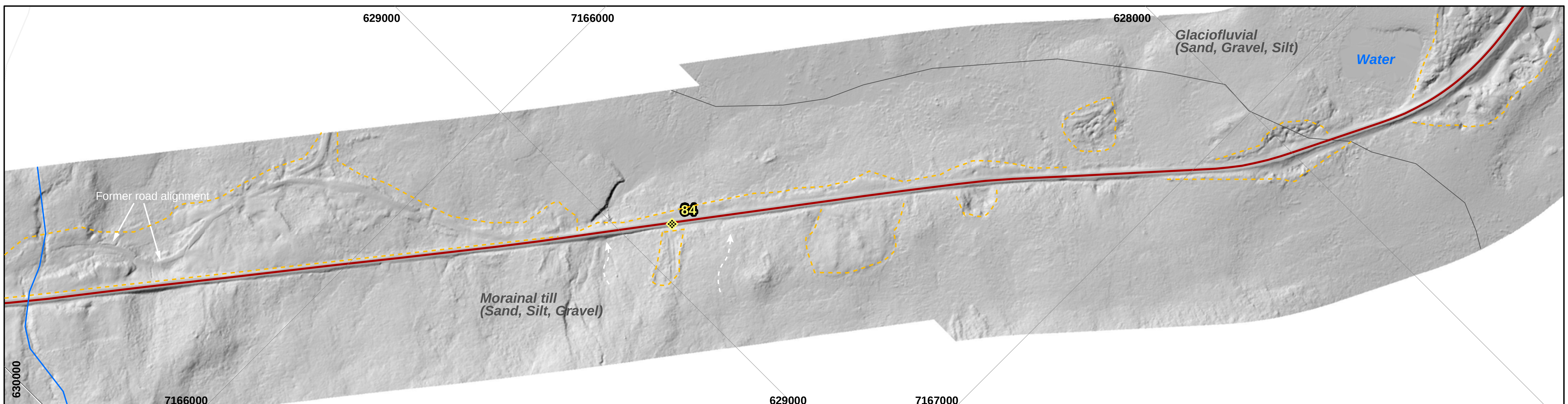
Colour Orthophoto

LiDAR Hillshade Model



0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014
FILE: Highway Section 2B.mxd		

Highway Section 2
Dempster Highway, YT

DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-2.2**
SRK JOB NO.	**1CG023.002**

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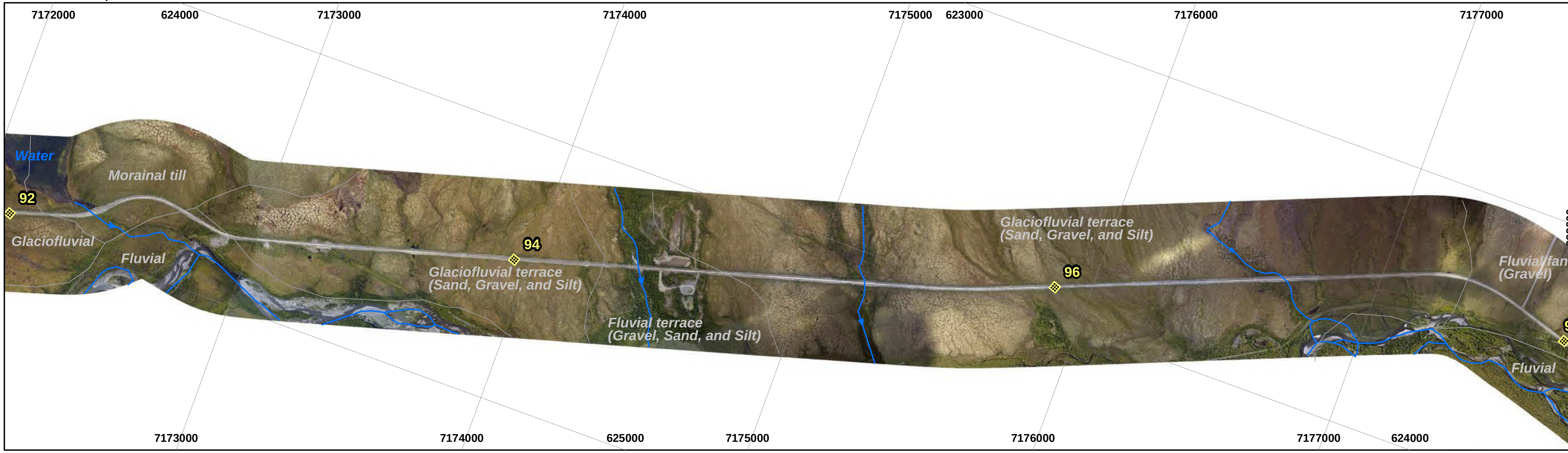
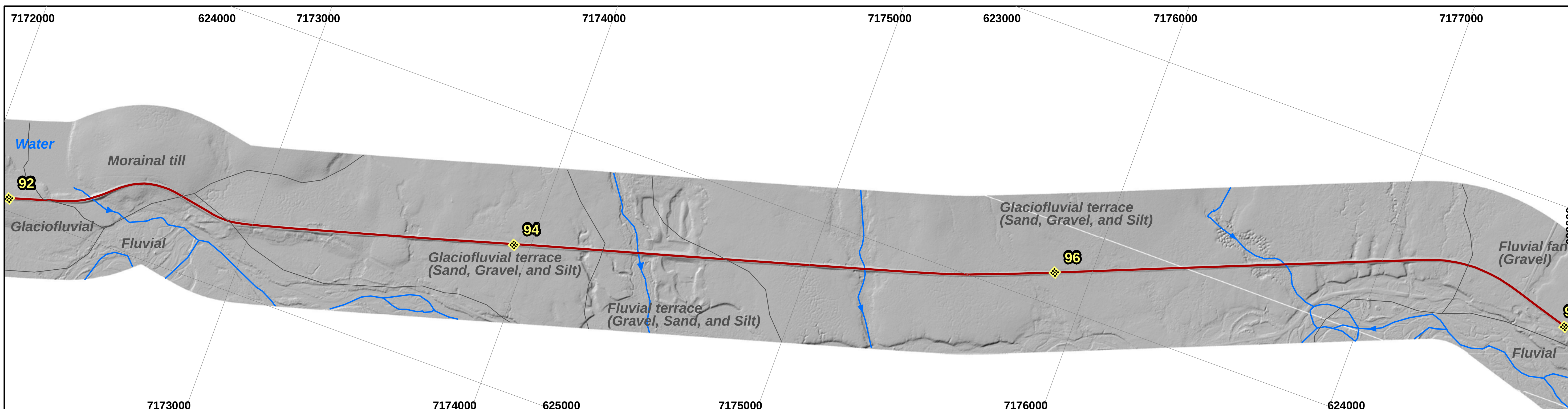
Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N			
DESIGN: CWS	DRAWN: CWS	REVIEWED:	
SCALE: 1 centimeter = 150 meters		DATE: 7/16/2014	
FILE: Highway Section 3.mxd			

Highway Section 3 (km 92-98)
Dempster Highway, YT

DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-3
SRK JOB NO.	1CG023.002

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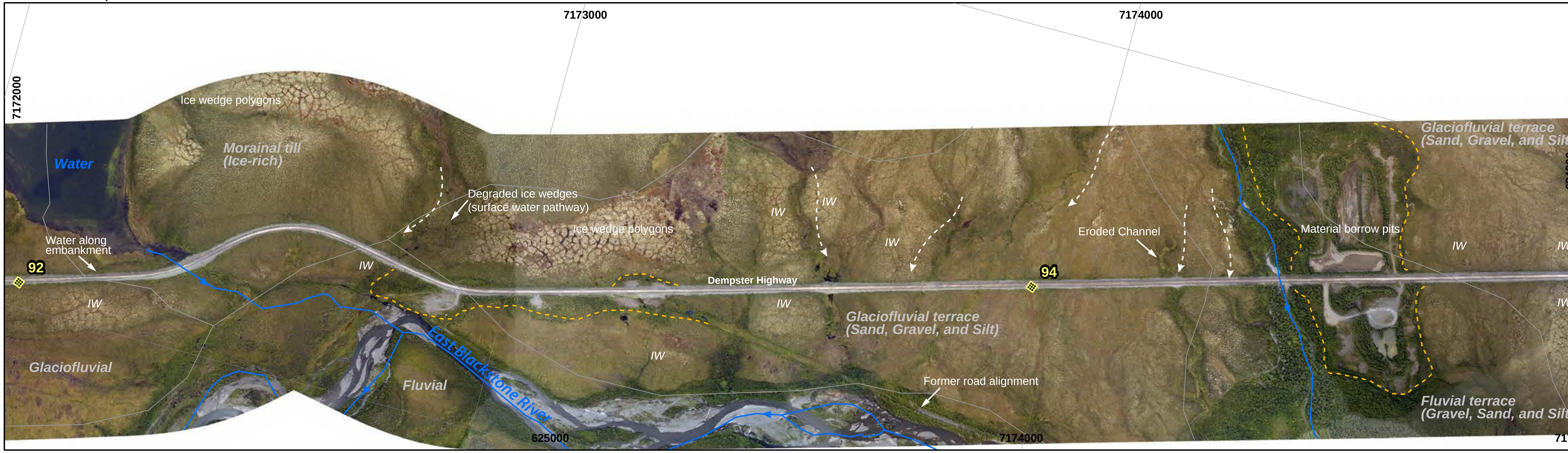
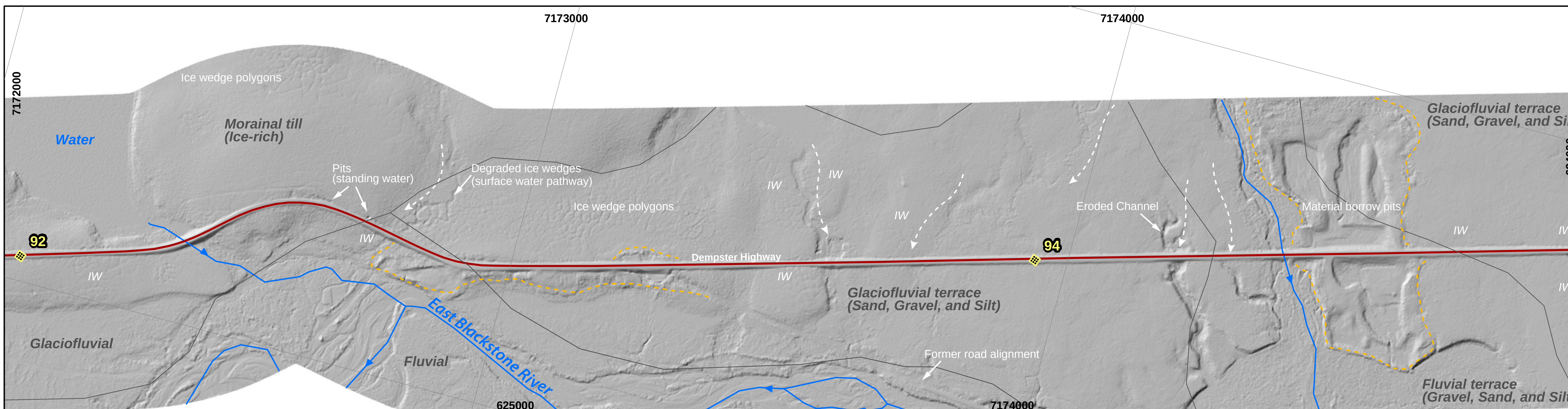
Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N			
DESIGN: CWS	DRAWN: CWS	REVIEWED:	
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014	
FILE: Highway Section 3A.mxd			

Highway Section 3
Dempster Highway, YT

DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-3.1
SRK JOB NO.	1CG023.002

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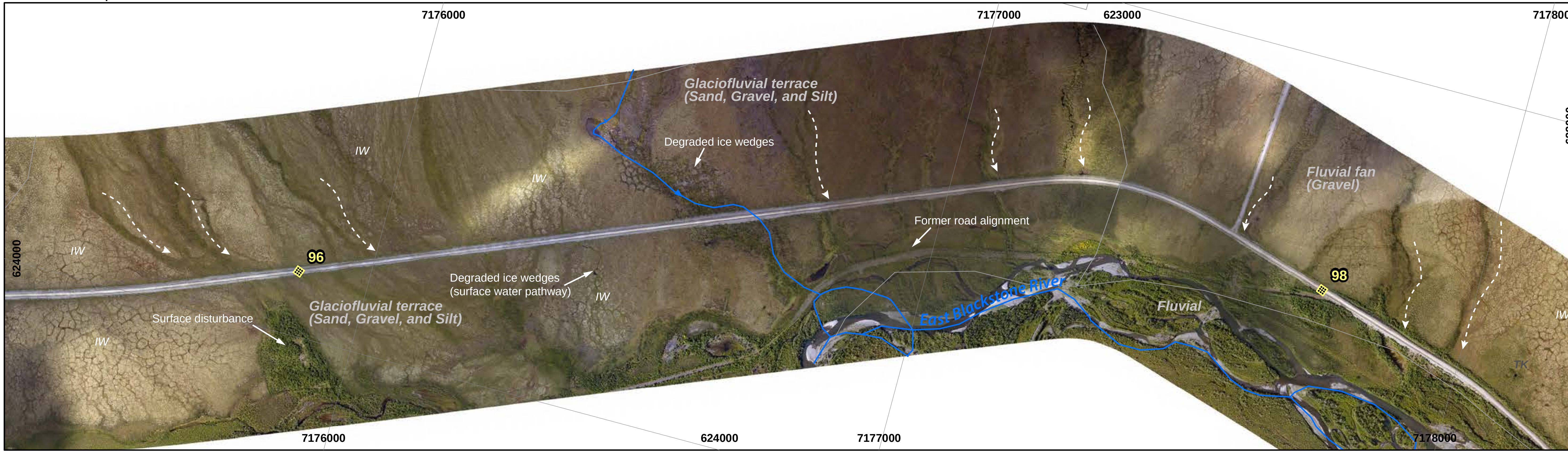
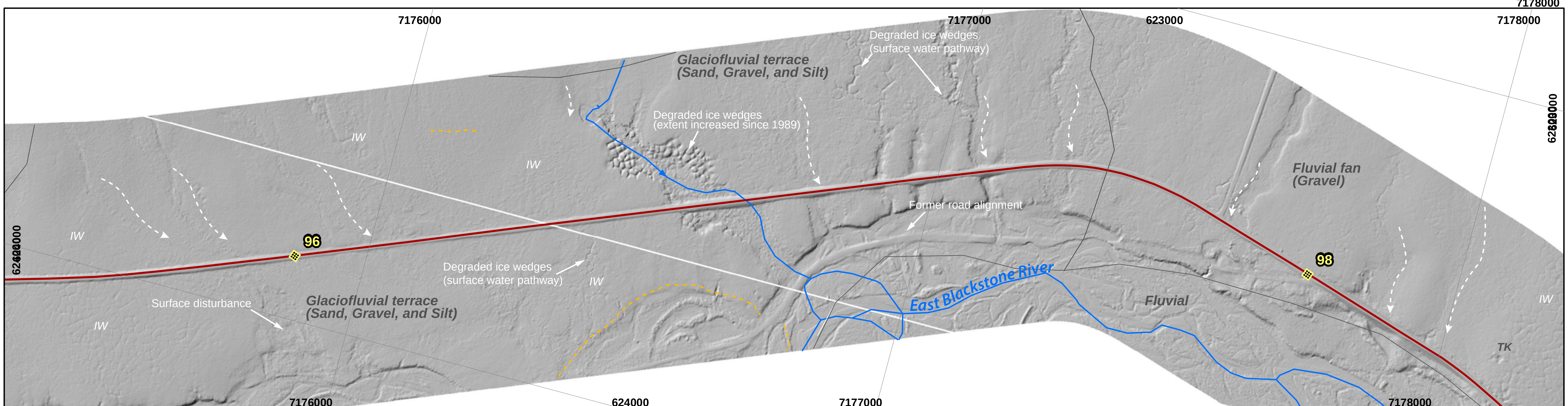
Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression

Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014
FILE: Highway Section 3B.mxd		

Highway Section 3
Dempster Highway, YT

DRAWING TITLE: **Site Map**

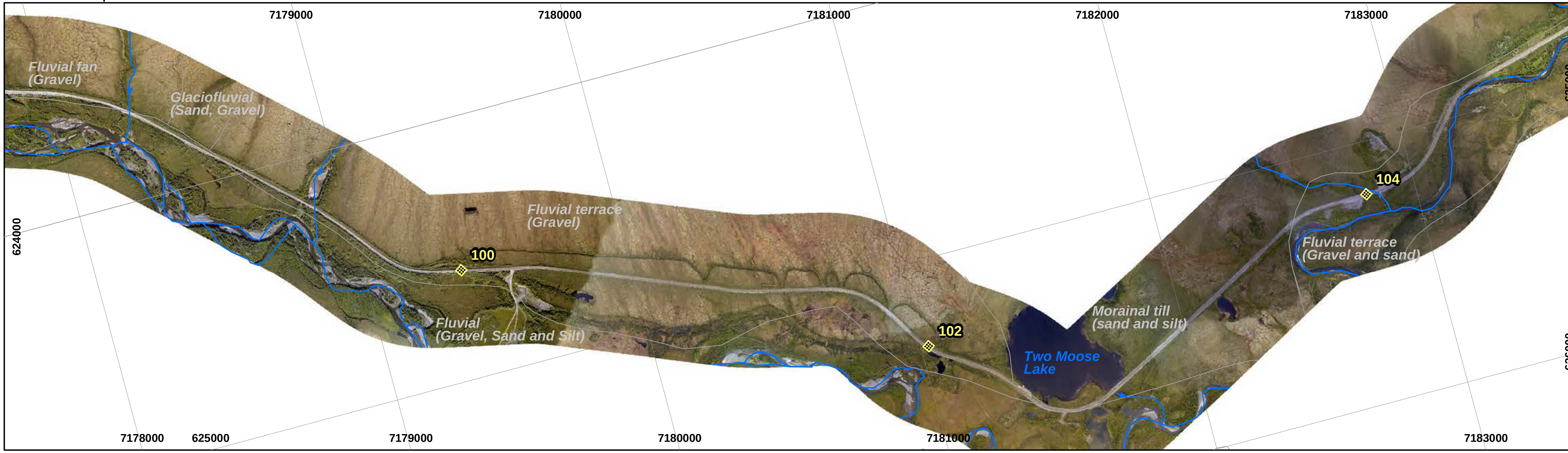
ISSUED FOR: **Government of Yukon**

DRAWING NO. **Figure C-3.2**

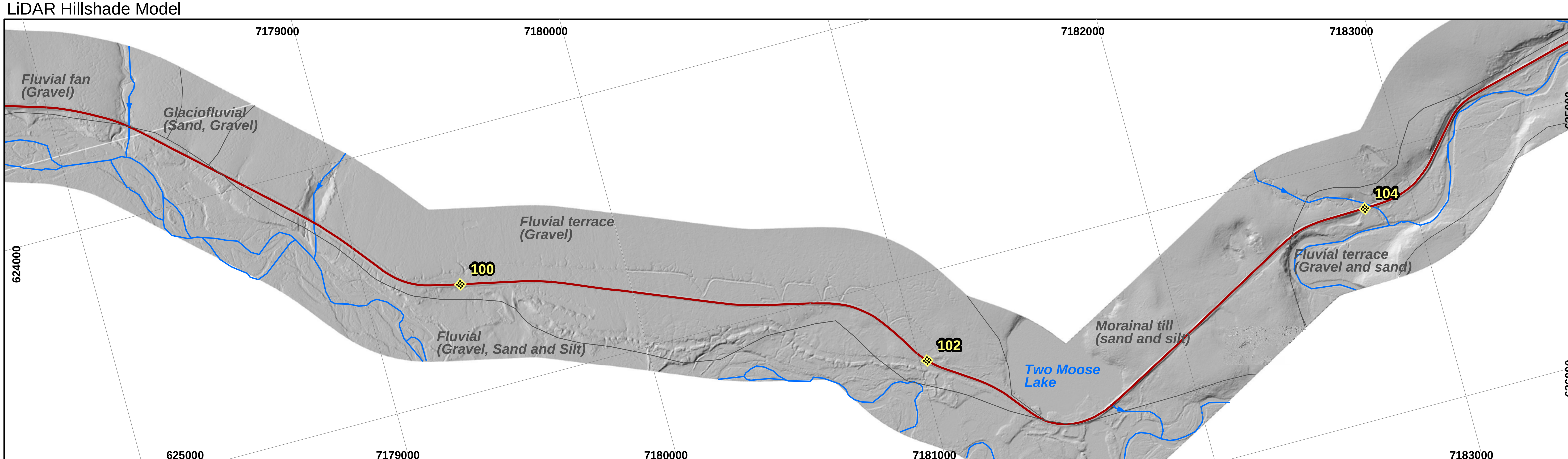
SRK JOB NO. **1CG023.002**

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 3B.mxd

Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

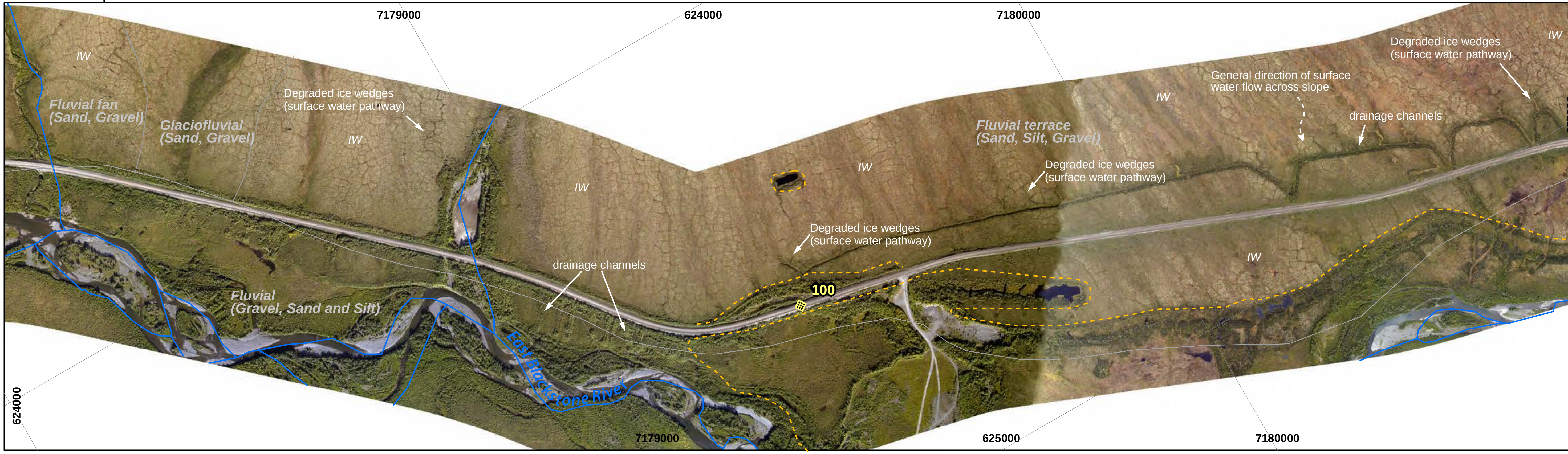
NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 155 meters		DATE: 7/16/2014
FILE: Highway Section 4.mxd		

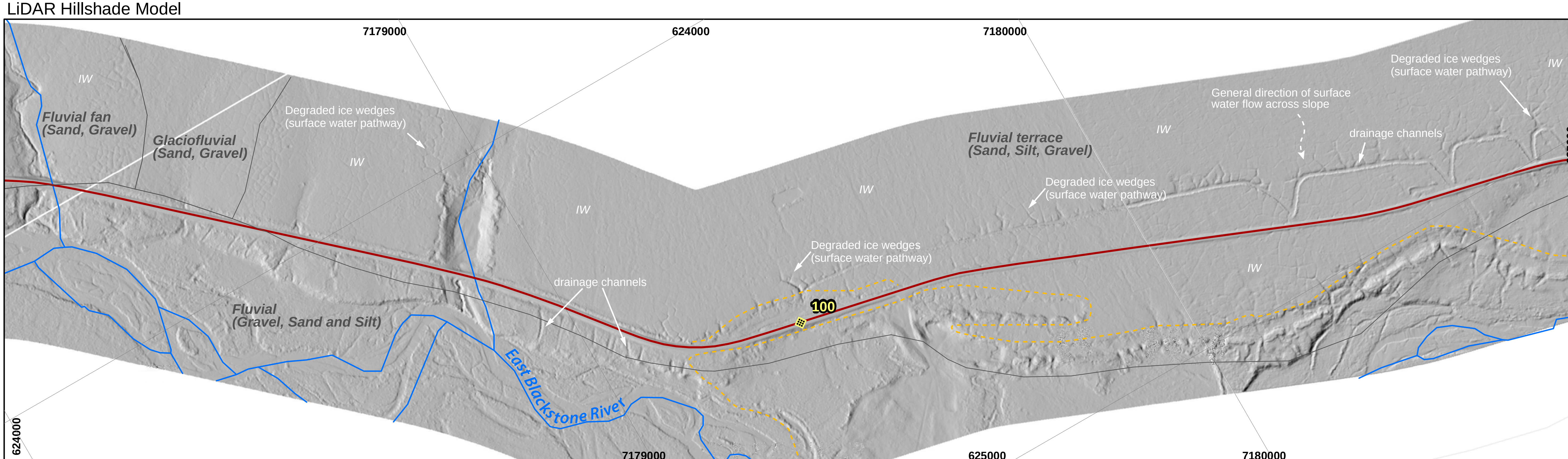
Highway Section 4 (km 99-103)
Dempster Highway, YT

DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-4
SRK JOB NO.	1CG023.002

Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

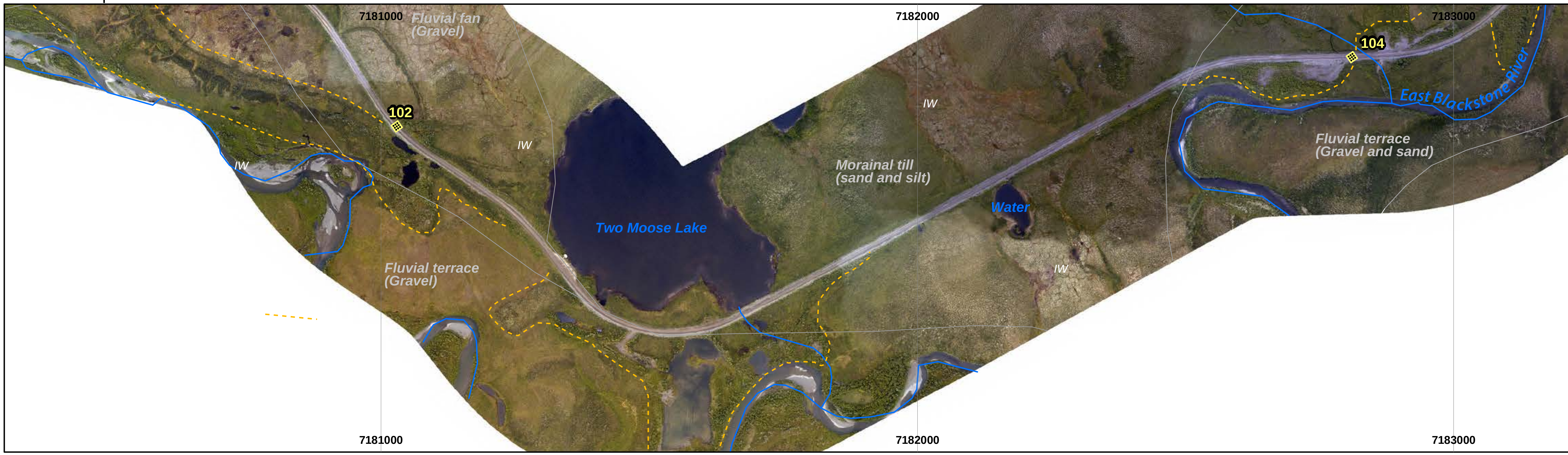
DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014
FILE: Highway Section 4A.mxd		

Highway Section 4 (km 99-103)
Dempster Highway, YT

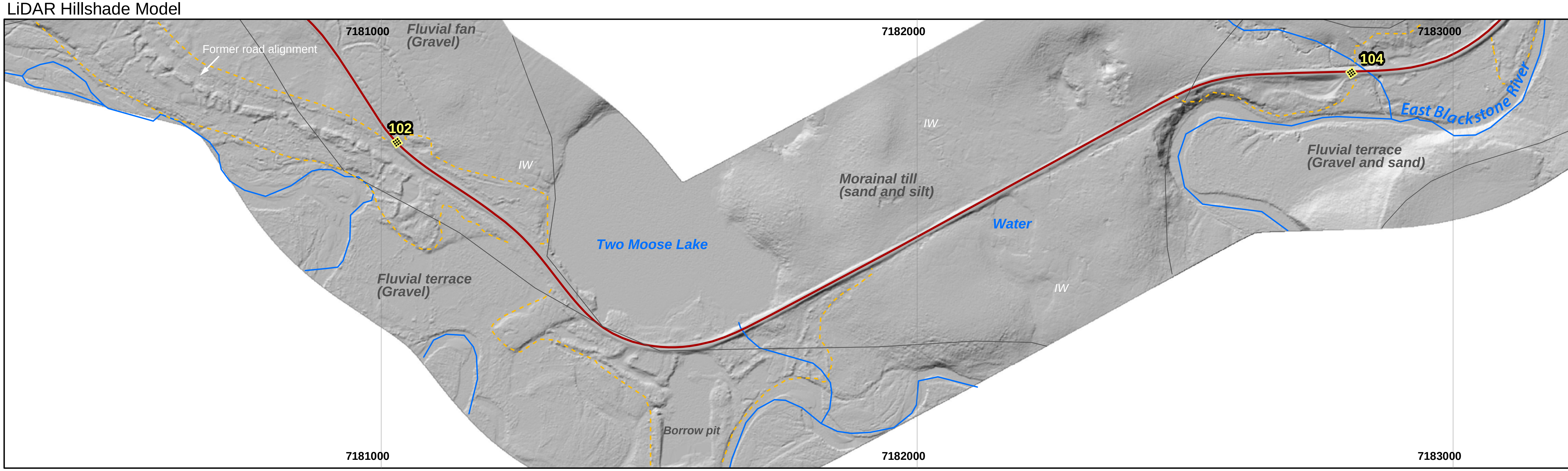
DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-4.1
SRK JOB NO.	1CG023.002

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 4A.mxd

Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression

Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N		
DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/21/2014
FILE: Highway Section 4B.mxd		

Highway Section 4
Dempster Highway, YT

DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-4.2**
SRK JOB NO.	**1CG023.002**

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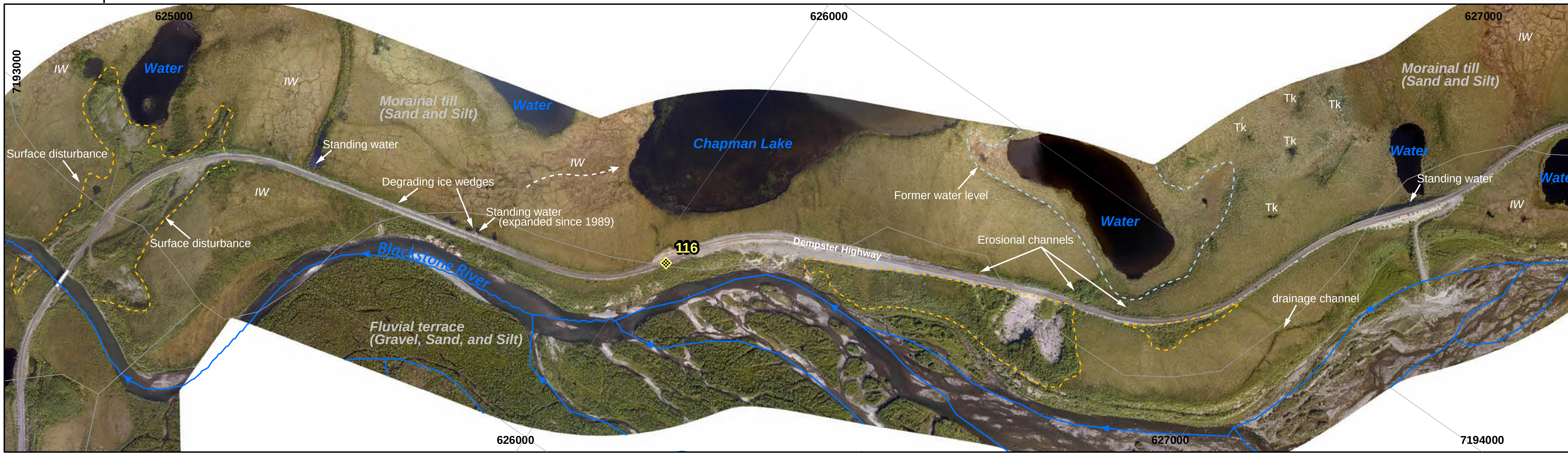
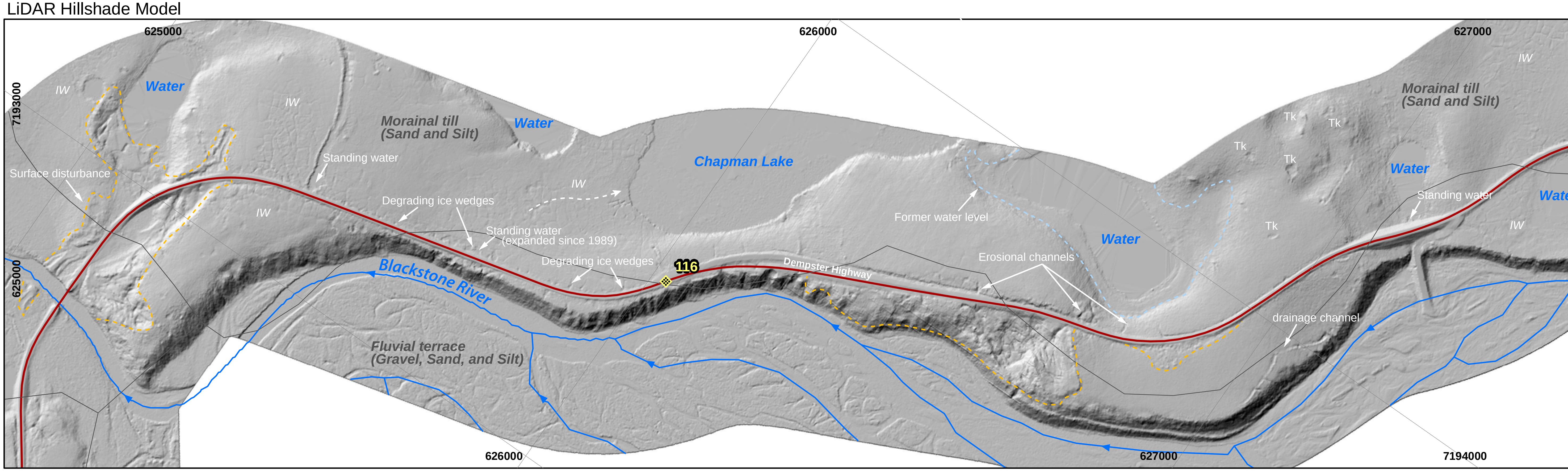
Colour Orthophoto



LiDAR Hillshade Model



N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

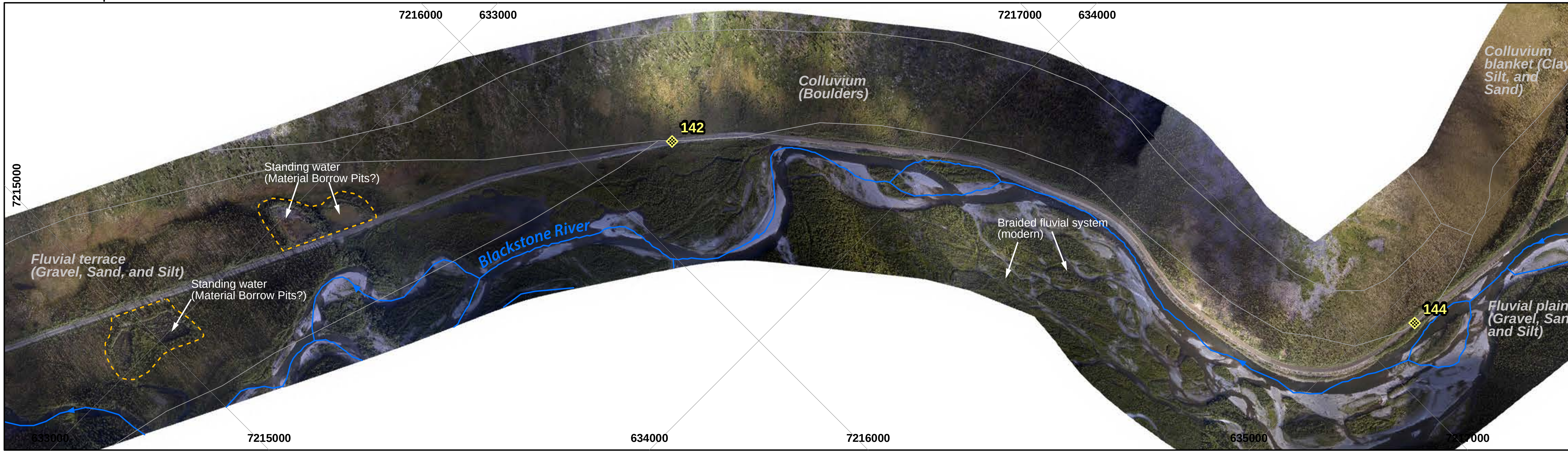
DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/16/2014
FILE: Highway Section 5.mxd		

Highway Section 5 (km 115-117)
Dempster Highway, YT

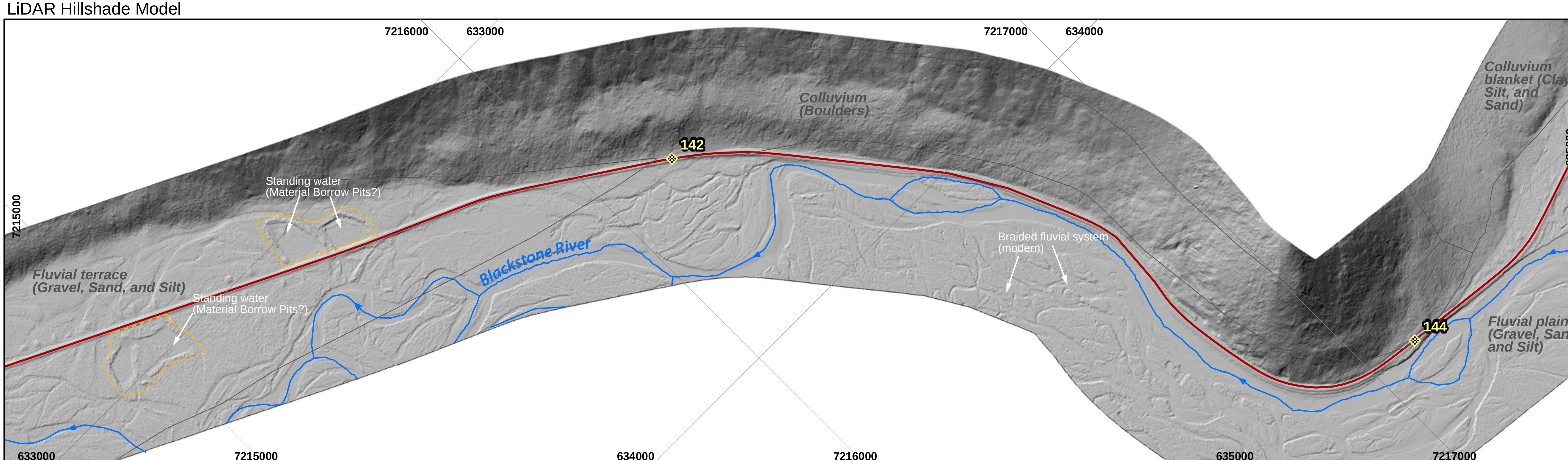
DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-5
SRK JOB NO.	1CG023.002

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 5.mxd

Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

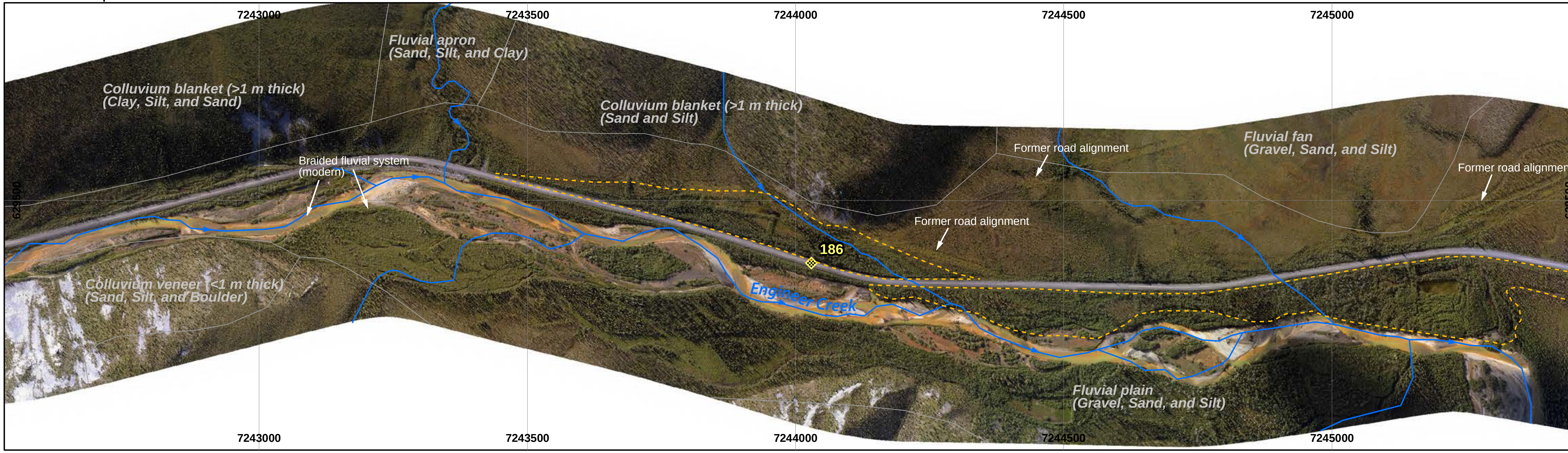
DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 95 meters		DATE: 7/16/2014
FILE: Highway Section 6.mxd		

Highway Section 6 (km 141-143)
Dempster Highway, YT

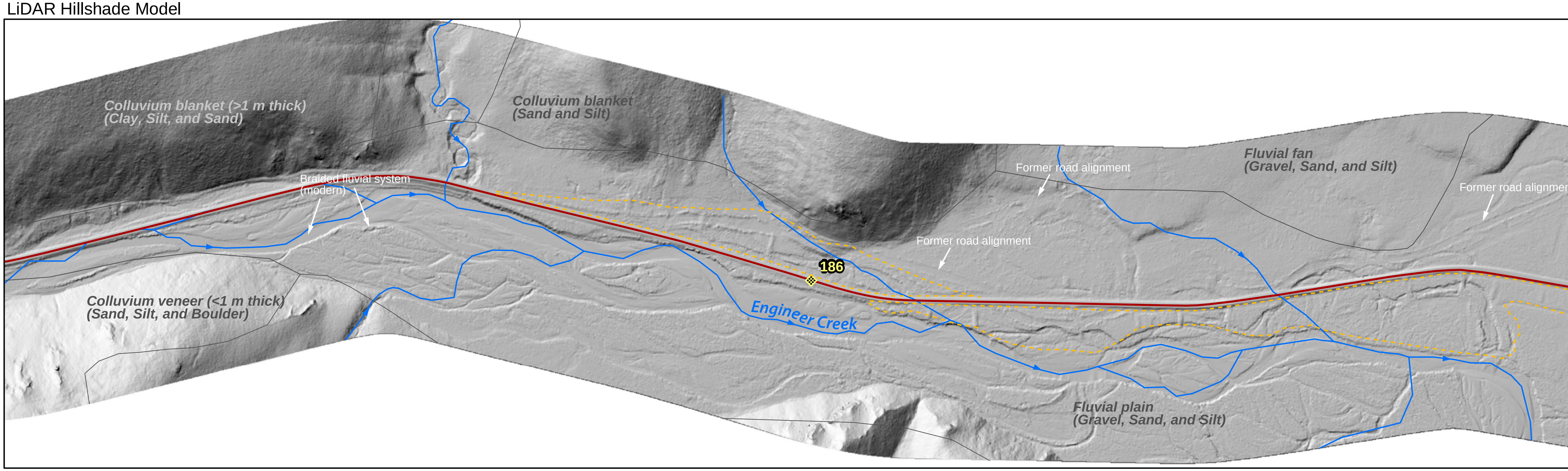
DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-6
SRK JOB NO.	1CG023.002

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 6.mxd

Colour Orthophoto



LiDAR Hillshade Model



N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

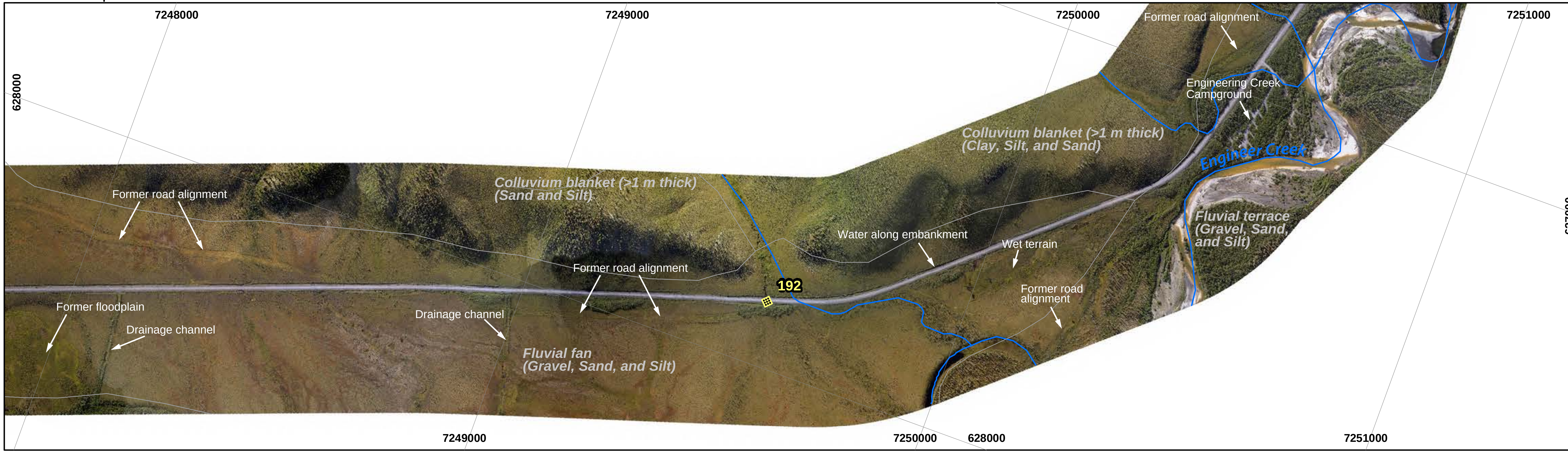
NAD83 UTM zone 7N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/16/2014
FILE: Highway Section 7.mxd		

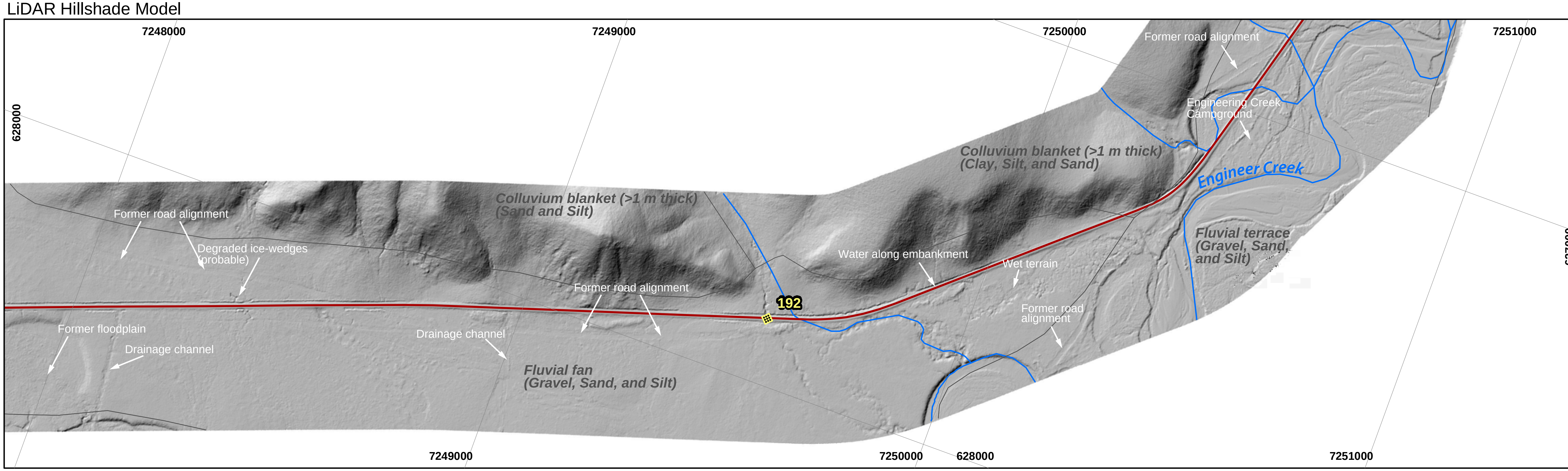
Highway Section 7 (km 185-187)
Dempster Highway, YT

DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-7
SRK JOB NO.	1CG023.002

Colour Orthophoto



LiDAR Hillshade Model



N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD83 UTM zone 7N

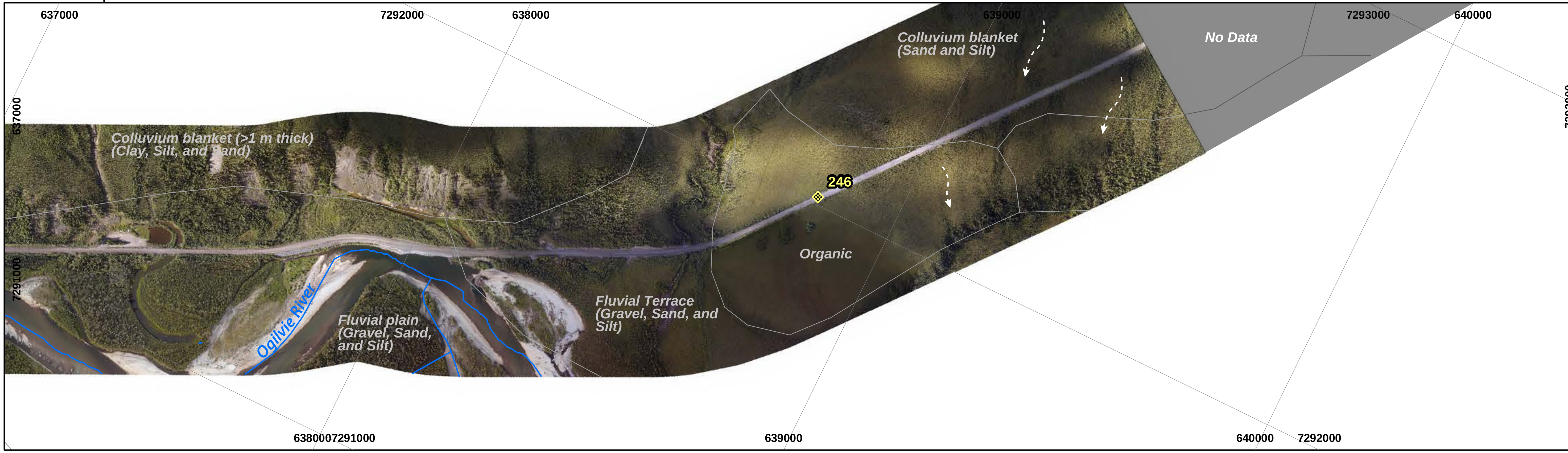
DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 95 meters		DATE: 7/16/2014
FILE: Highway Section 8.mxd		

Highway Section 8 (km 191-193)
Dempster Highway, YT

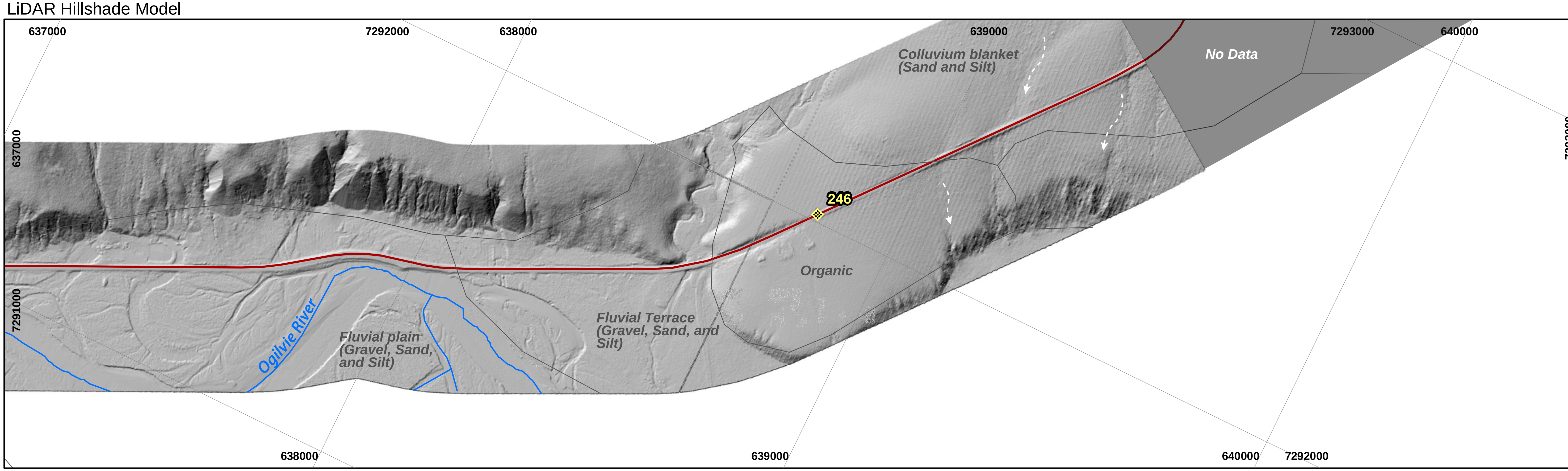
DRAWING TITLE:	Site Map
ISSUED FOR:	Government of Yukon
DRAWING NO.	Figure C-8
SRK JOB NO.	1CG023.002

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 8.mxd

Colour Orthophoto



LiDAR Hillshade Model



0 200 400 Meters

N

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers
- Surficial Geology

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

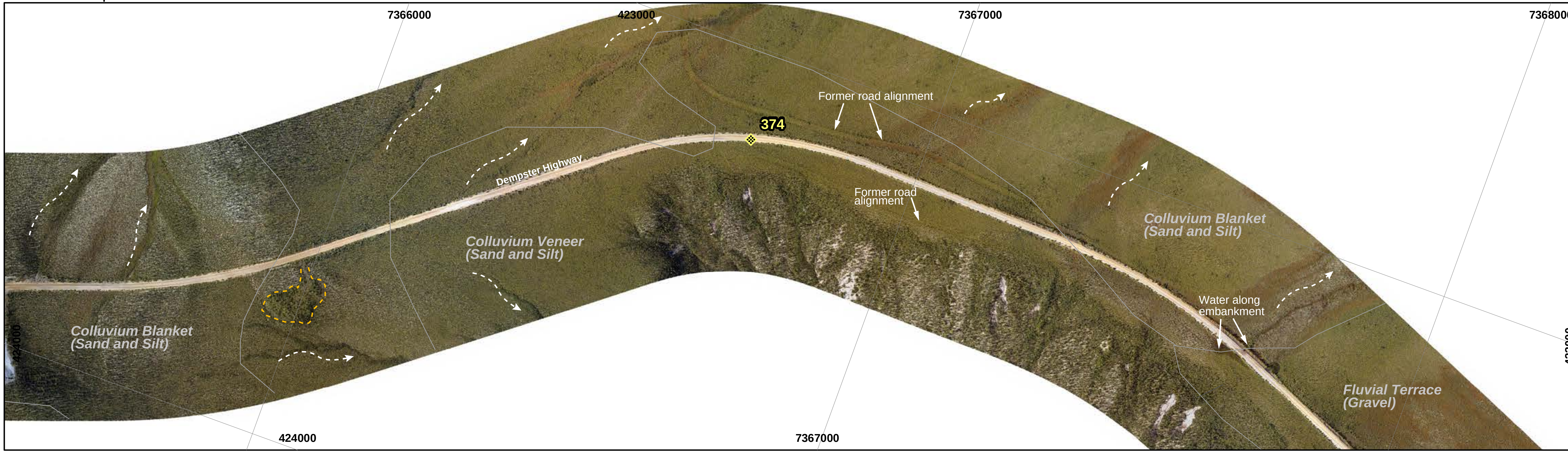
NAD83 UTM zone 7N					
DESIGN:	CWS	DRAWN:	CWS	REVIEWED:	
SCALE:	1 centimeter = 95 meters			DATE:	7/16/2014
FILE:	Highway Section 9.mxd				

Highway Section 9 (km 246-248)
Dempster Highway, YT

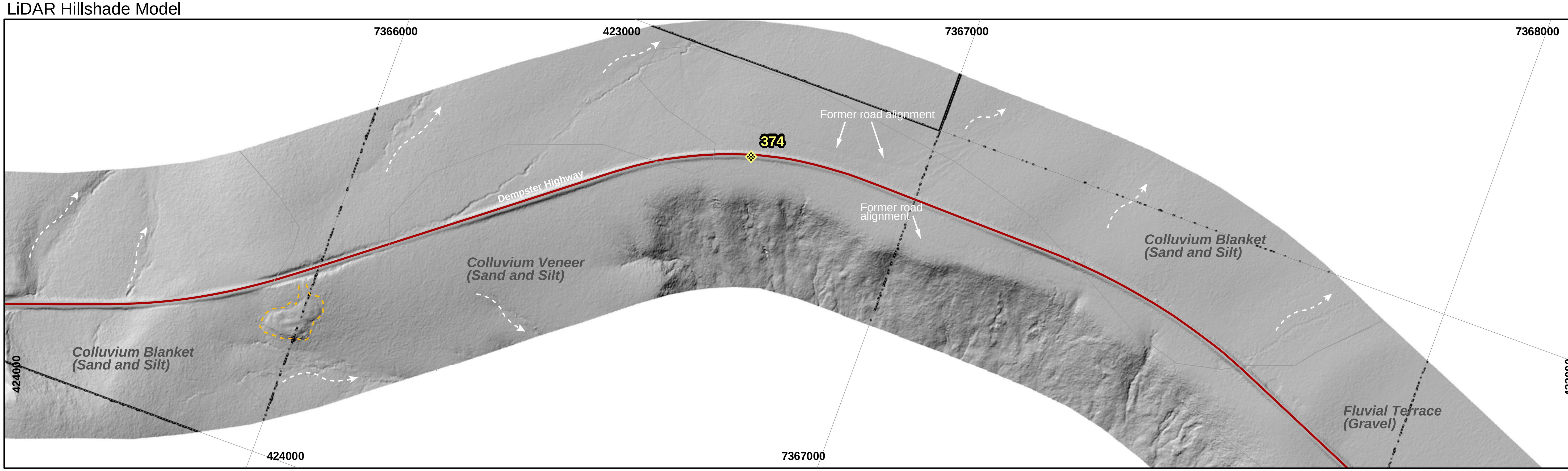
DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-9**
SRK JOB NO.	**1CG023.002**

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 9.mxd

Colour Orthophoto



LiDAR Hillshade Model



N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Surficial Geology
- Dempster Highway, YT
- Streams and Rivers

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

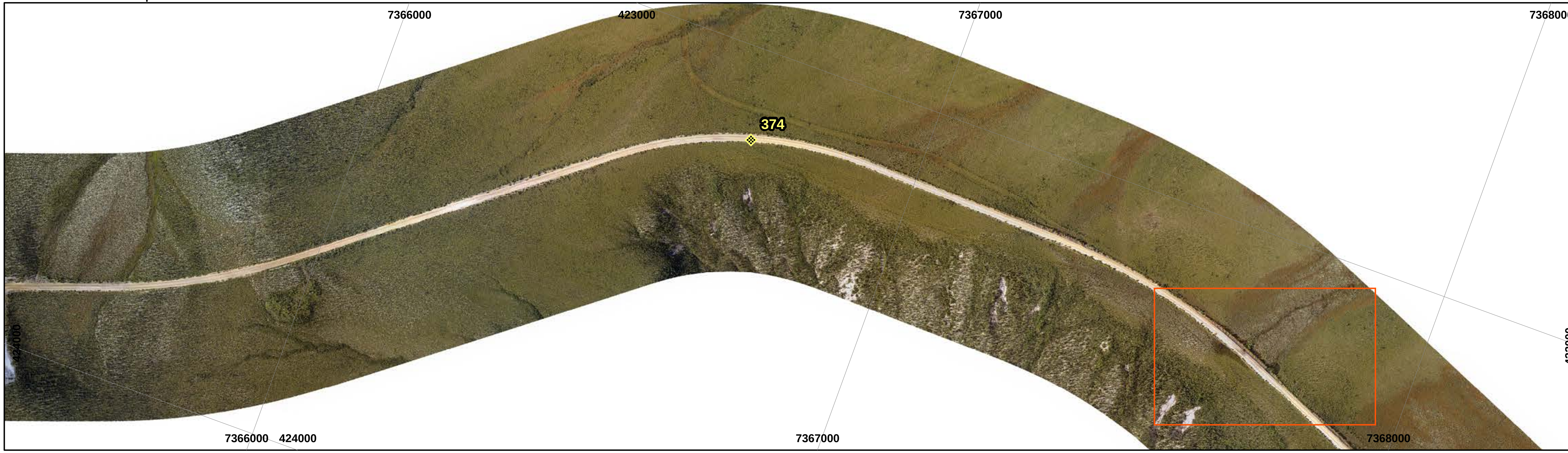
NAD 1983 UTM Zone 8N

DESIGN: CWS	DRAWN: CWS	REVIEWED:
SCALE: 1 centimeter = 75 meters		DATE: 7/24/2014
FILE: Highway Section 10z8.mxd		

Highway Section 10 (km 373-375)
Dempster Highway, YT

DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-10**
SRK JOB NO.	**1CG023.002**

2013 Colour Orthophoto



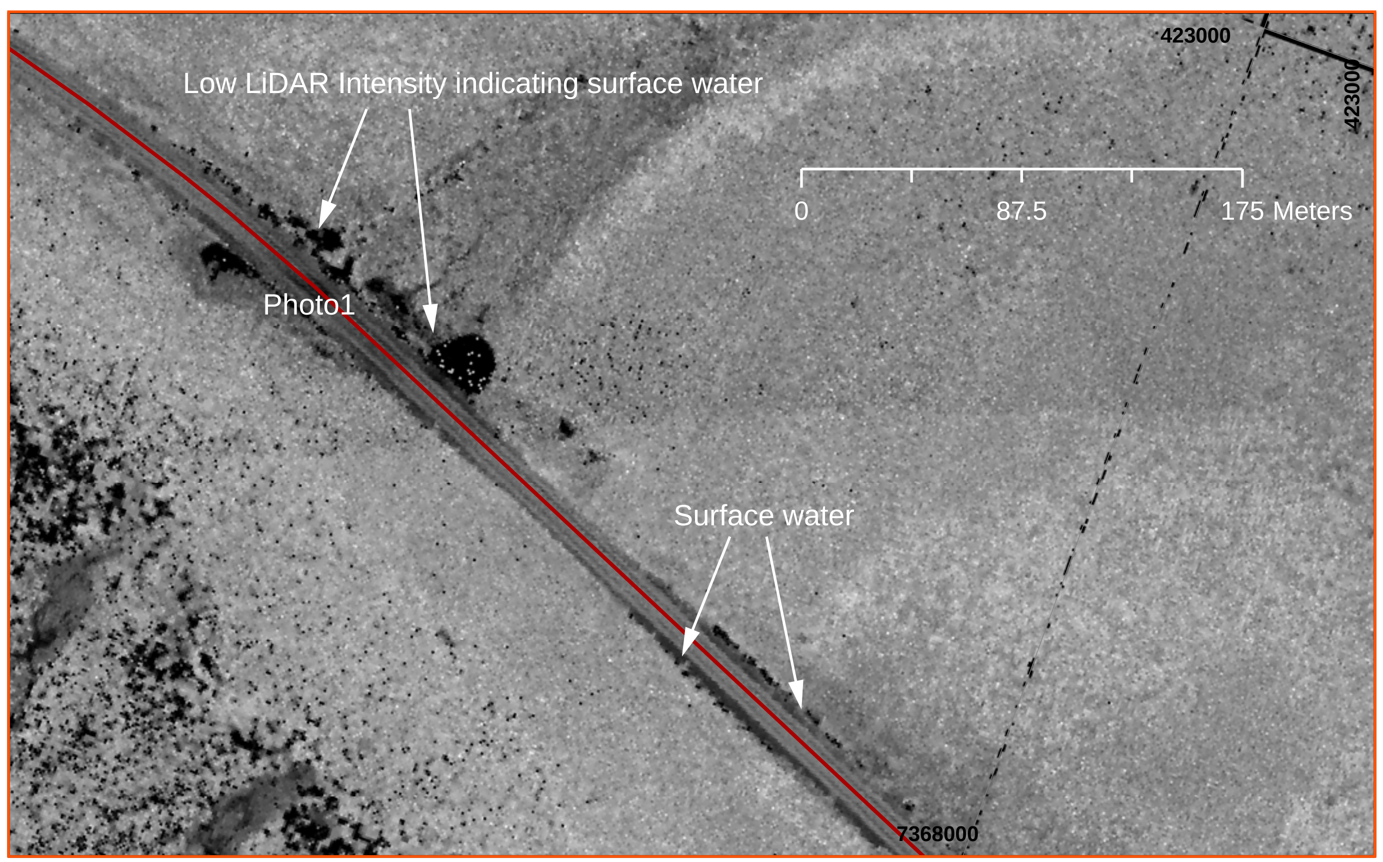
LiDAR Intensity Images

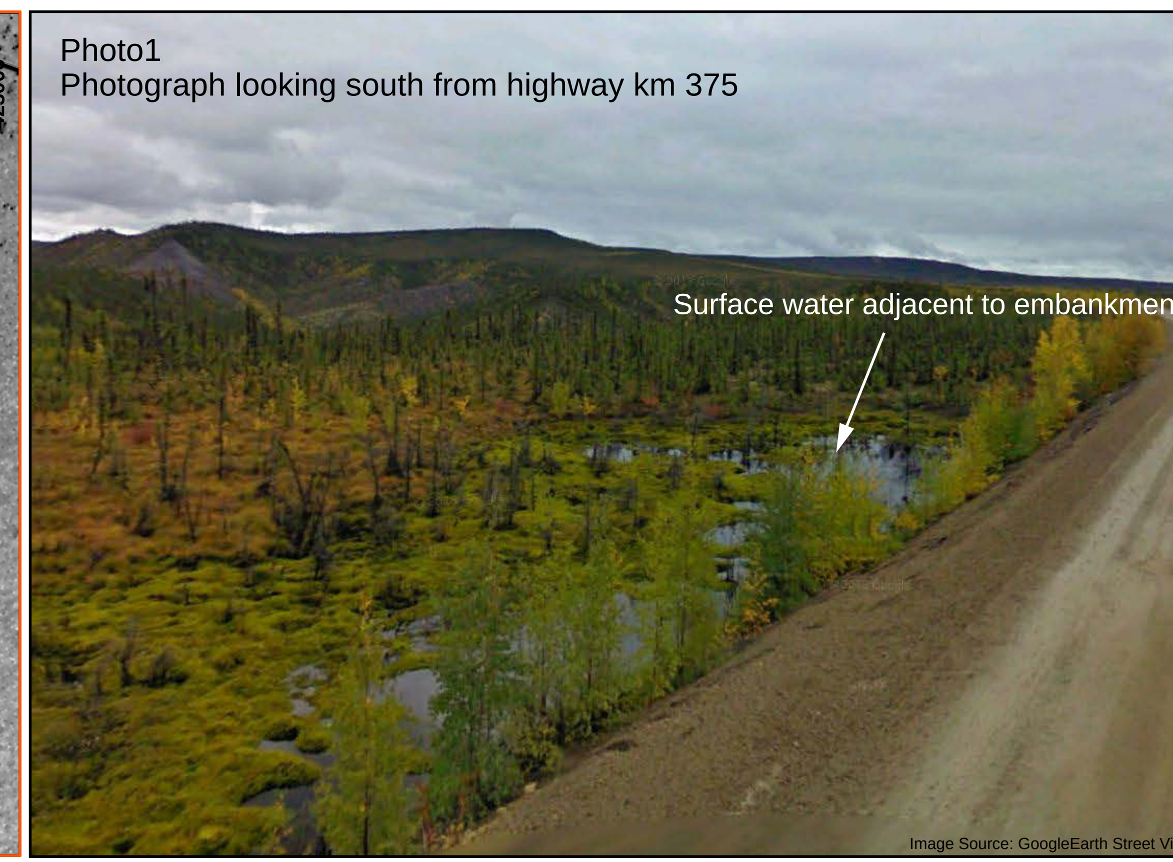
Legend

Mean Value

High : 232

Low : 0





N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Dempster Highway, YT
- Streams and Rivers

srk consulting

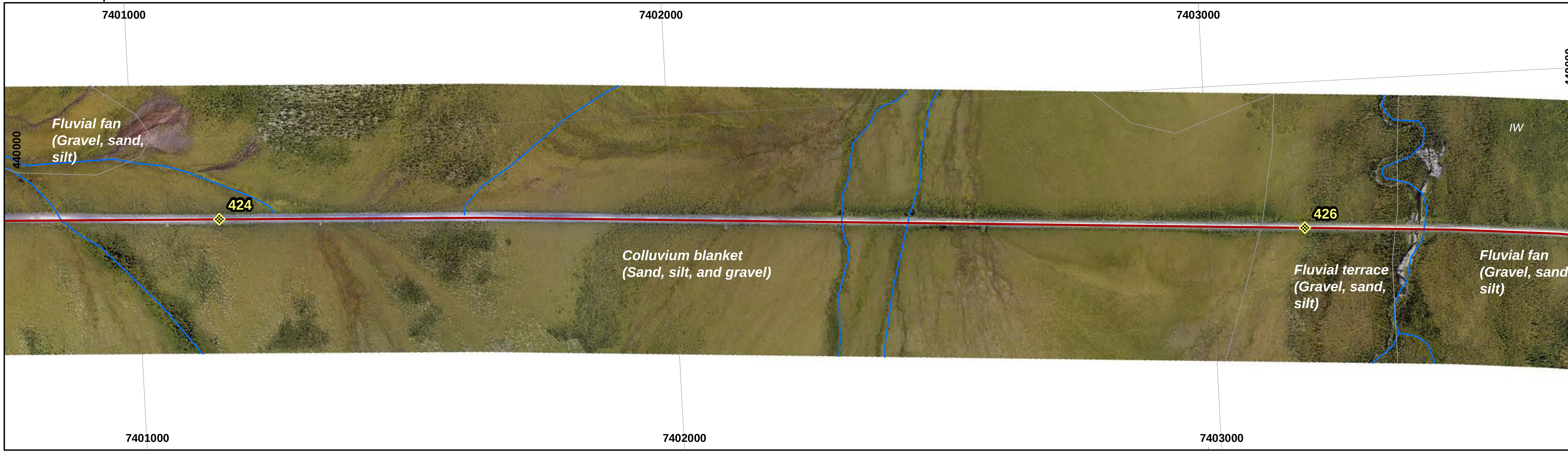
NAD 1983 UTM Zone 8N			
DESIGN: CWS	DRAWN: CWS	REVIEWED:	
SCALE: 1 centimeter = 75 meters		DATE: 9/16/2014	
FILE: Highway Section 10z8_Intensity.mxd			

Highway Section 10 (km 375)
Dempster Highway, YT

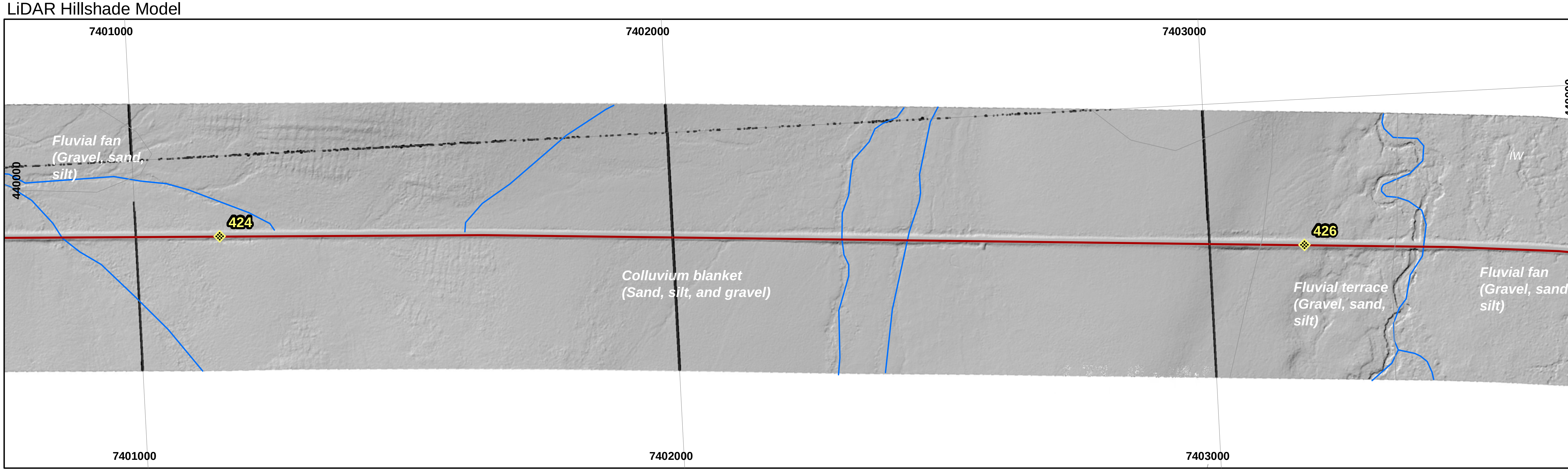
DRAWING TITLE:	**LiDAR Intensity Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-10.1**
SRK JOB NO.	**1CG023.002**

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway Section 10z8_Intensity.mxd

Colour Orthophoto



LiDAR Hillshade Model



N

0 200 400 Meters

Legend

- Highway Kilometre Post Markers
- Surficial Geology
- Dempster Highway, YT
- Streams and Rivers

IW - Ice wedge polygons
TK - Thermokarst pit / depression
Flow direction of surface water
Extent of surface disturbance

srk consulting

NAD 1983 UTM Zone 8N

DESIGN:	CWS	DRAWN:	CWS	REVIEWED:	
SCALE:	1 centimeter = 75 meters			DATE:	7/24/2014
FILE:	Highway Section 11z8.mxd				

Highway Section 11 (km 424-426)
Dempster Highway, YT

DRAWING TITLE:	**Site Map**
ISSUED FOR:	**Government of Yukon**
DRAWING NO.	**Figure C-11**
SRK JOB NO.	**1CG023.002**

PATH: P:\Dempster Highway\1CG023.002_Characterization_of_Sinkholes\040_AutoCAD_GIS\Maps\Highway_Section_Maps\Highway Section 11z8.mxd

Appendix D - Example Field Datasheet

Example Field Datasheet

The sinkhole field datasheet is designed to collect information which contributes to understanding the development and distribution of these road hazards. **The Government of Yukon Health and Saftey Program should be followed prior to undertaking sinkhole measurements.**

Instructions: Please provide as much information as possible. Datasheets and all field photographs should be sent immediately to John Smith at xxxxx@gov.yk.ca

Name:

Date:

Time:

GPS Location: Latitude Longitude

Highway Location: Kilometre marker

Location Description:

How was the Sinkhole Discovered?

Nearby Reference (material borrow pits, culverts, streams, rivers, geographic features)

Current weather conditions:

Site photographs: (email photographs to xxx@gov.yk.ca) ☐ Yes ☐ No

Site observations:

Highway conditions

Check all that apply to the site
- ☐ Potholes
- ☐ Road surface cracks
- ☐ Road surface depressions and dips

Surface water present ☐ Yes ☐ No

Culvert within 200 m of sinkhole ☐ Yes ☐ No

Other site observations:

Sinkhole Characteristics: ☐ Estimated ☐ Measured

Depth: (from base of sinkhole to highway surface)

Length: (from either side of highway)

Width:

Embankment material moisture: ☐ Wet ☐ Moist ☐ Dry

Other Visual Descriptions:

Repair Details:

Additional Observations:

Sketch of Site and Sinkhole

Sketch of Site and Sinkhole