Collapse of permafrost and failure of bridges in the community of Pangnirtung, Nunavut

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ABSTRACT
The community of Pangnirtung is situated on the west side of the Cumberland Peninsula, Baffin Island, and located within the continuous permafrost zone. During the week ending June 16, 2008, heavy rains along with flooding resulted in significant thermo-erosion of the river banks, numerous landslides and cracks in the ground surface down to a depth of 5 m to 7 m. These processes also damaged two bridges across the Duval River. Site reconnaissance and assessments were conducted to determine the causes of intensive development for thermo-erosion and landslides. A drill program was performed across the river valley to assist in determination the subsoil and permafrost conditions for abutments of a new bridge. Based on the results of field investigations and assessments, it was considered that soil erosion due to heavy rains, anomalous climate conditions in 2007/2008 and presence of ice rich materials and frost cracking were the key factors for development of thermo-erosion and landslides. Short term and long term remediation were recommended. A cost effective foundation approach for the new bridge was also provided.

RÉSUMÉ
La communauté de Pangnirtung est située du côté ouest de la péninsule Cumberland, sur l'Île de Baffin, dans une zone de pergélisol continu. Pendant la semaine se terminant le 16 juin 2008, de fortes pluies avec inondations ont causé une thermo-érosion importante des berges de la rivière, de nombreux glissements de terrain et des fissures s'étendant depuis la surface du sol jusqu'à quelque 5 m à 7 m de profondeur. Ces processus ont également endommagé deux ponts sur la rivière Duval. Une reconnaissance du site et des évaluations ont été réalisées pour déterminer les causes de cette thermo-érosion et des glissements de terrain. Un programme de forage a été effectué dans la vallée de la rivière pour déterminer les conditions du sous-sol et du pergélisol en vue de la construction des culées d'un nouveau pont. Sur la base des résultats des études de site et des évaluations associées, il est considéré que l'érosion des sols due à de fortes pluies, les conditions climatiques anormales en 2007/2008, de même que la présence de matériaux riches en glace et de fissures de gel, constituent les facteurs clés qui ont menés au développement de thermo-érosion et de glissements de terrain. Des mesures correctives à court terme et long terme ont été recommandées. Une approche économique pour les fondations du nouveau pont a également été fournie.

1. INTRODUCTION

The community of Pangnirtung is situated on the west side of the Cumberland Peninsula, Baffin Island, and located within the continuous permafrost zone. The community is divided into the north and south portions by the Duval River. Surficial soil encountered on the south and north banks of the river consisted of coarse to medium grained sand with various amounts of gravel, cobbles and boulders. Fine to coarse grained sand or silty sand with trace gravel was found below the coarse to medium sand. The permafrost temperature was measured in a range between -3°C and -5°C at depth from 10 m to 16 m. During the week ending June 16, 2008, heavy rains along with flooding resulted in significant thermo-erosion of the river banks, numerous landslides and cracks in the ground surface down to a depth of 5 m to 7 m. These processes also damaged two bridges across the Duval River. With both bridges being closed, residents had no access to municipal services such as water reservoir, sewage treatment plant and landfill. High water also knocked down a power pole in the community causing power failures in some areas. These caused a considerable impact to the social life of the community and the Hamlet of Pangnirtung declared a state of emergency after flooding.

Site reconnaissance and assessments were conducted to determine the causes of intensive development for thermo-erosion and landslides. A drill program was performed across the river valley to assist in determining the subsoil and permafrost conditions for abutments of a new bridge.

2. SITE CONDITION

Pangnirtung is located in about 350 km northeast from the town of Iqaluit and just several kilometres south of the Arctic Circle (Figure 1). The population of the community is about 1,350 people. The community is bordered by glacier-capped mountains to the northeast and Cumberland Sound to the southwest.

The Duval River divides the community into two parts. The majority of residential houses, shopping centre, police and hospital are located on the south side of the river, while the water treatment plant, water reservoir and a few commercial and residential buildings are situated on the north side of the river. The southern and northern parts of the community were connected by two bridges across the Duval River.

Figure 1: Site Location

3. GENERAL GEOLOGY

The fluvial deposits of the Duval River comprise a mix of various materials, ranging in size from boulders to fine grained sand and silt, mainly brown in colour. Thickness of the fluvial deposits within the flooding area was in a range from 2 m to about 15 m. The marine deposits encountered below the fluvial deposits were greyish and bluish silty to clayey sediments, with occasional gravel inclusions.

4. CLIMATE & PERMAFROST

Environment Canada provides records of the mean monthly air temperatures for the Pangnirtung weather station between 1996 and 2008. The mean annual air temperature within this period was calculated to be about -5 °C. The average freezing and thawing indexes for the same period of time were 2,860 degree-days, and 1,050 degrees-days, respectively.

The mean winter (October through April) and spring (May and June) air temperatures were also calculated from 1996 to 2008. Figure 2 presents the results of calculations. It can be seen that the 2007/2008 winter and 2008 spring had extremely cold (-18 °C) and extremely warm (2.5 °C) air temperatures, respectively.

Based on published data (Maxwell 1980), the mean annual permafrost temperature in the community is in a range from -8 °C to -9 °C, and the active layer thickness varies from 0.8 m to 1.6 m depending on soil moisture content and type/thickness of ground vegetation.

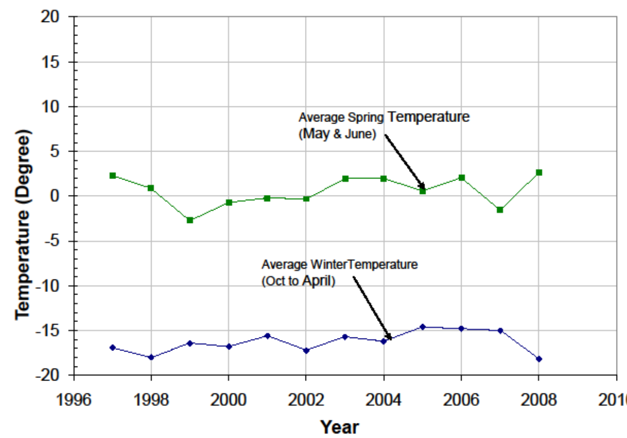


Figure 2: Mean Winter and Spring Air Temperature

5. FIELD RECONNAISSANCE

A field reconnaissance was conducted in June, 2008, a few days after the flooding. The findings of the field reconnaissance are summarized below.

5.1 General Site Conditions

The flooding occurred along the Duval River valley, starting from the bridge locations and extending upstream to about 350 m, where the valley is generally narrow and entrenched in bedrock. The floodplain of the river is asymmetrical: the north side of the valley is up to 200 m wide, while the south side is about 20 m to 30 m wide. The slope at the north side of the valley is gentle to moderate, about 5 degrees to 10 degrees, while the south slope is up to 20 degrees steep.

The valley within the flooding area was rugged and strewn with boulders, up to 500 mm in size. There were numerous permanent and intermittent watercourses mainly parallel to the river channel, which converged to a single channel near the bridge locations. Dry channels, generally parallel to the main river channel and outlined by numerous boulders, were also observed in the floodplain.

5.2 Erosion and Landslides

It was observed that large amount of water undermining the river banks and causing severe erosion and landslides along both sides of the river. The depths of landslides could exceed 8 m, and landslide escarps were in the order of several metres (Photograph 1). Flowing water, greyish to bluish in color, was observed in all of the cracks (Photograph 2). The color of the water suggests that erosion of the marine deposits was occurred. It was also observed that the fines and sand particles in the fluvial deposits were being washed out, leaving a cobble-boulder matrix with large voids between the particles.

Photograph 1: Landslide Escarp

Photograph 2: Water Flowing from River Bank

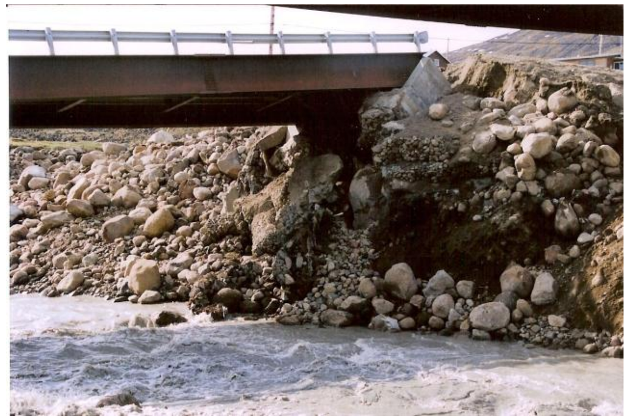
5.3 Damage of Existing Bridges and Location of New Bridge

Two existing bridges across the Duval River, located approximately 15 m apart, were damaged by the flooding. The older bridge (upstream) was built about 30 years ago and was expected to be replaced by the new bridge (downstream). The downstream new bridge had just recently been built, but was not yet commissioned when the flooding occurred.

The upstream bridge experienced the most severe damage. Photograph 3 shows that failure of the abutment on the south bank of the river resulted in significant tilting of the bridge substructure. Two major cracks and significant displacement developed in the approach embankment behind the north abutment as well as failure of north bank occurred, resulting in considerable settling of the bridge steel structure (Photograph 4 and 5)

The damage to the downstream bridge was less and tilting the bridge substructure was slight. However due to differential settlement, some damage occurred in steel abutment bins. A considerable amount of fill was placed in front of the abutments to stabilize the abutment slopes and prevent collapse of the bridge.

In general, abutment foundation soils were in an unfrozen state during the reconnaissance, and water was flowing out underside of the bridge abutments (Photograph 6), resulting in significant ground loss and lateral/vertical movements of the bridge substructures.



Photograph 3: Failure of South Abutment

Photograph 4: Failure of North Approach Fill

Photograph 5: Failure of North Bank

During the site reconnaissance, the new bridge was determined to be located at approximately 20 m downstream from the damaged bridges. The span of the new bridge is 81 m with both abutments to be located on gentle terrace slopes beyond the river floodplain. Additional fill is required to bring the existing grade up to the designed bridge elevation.

Photograph 6: Water Flowing Underside of Bridge Foundation

5.4 Structures on North Bank

The potential impact of the flooding to the commercial and residential structures located on the north bank of the river was assessed. A review of the terrain features near the structures and the findings from field investigation suggested that the structures on the north bank were located beyond the Duval River valley, and founded on a gentle rock slope which was covered with moraine deposits. There was no evidence of cracks on the ground surface near the structures which would indicate pre-failure zones or tension cracks due to flooding and erosion. In addition, the absence of frost cracks on the ground surface, and the absence of free water inside the advanced boreholes lead to a conclusion that the flooding would not present an immediate danger to the commercial and residential buildings on the north bank of the Duval River.

6. SITE INVESTIGATION

6.1 Drill Program

Eight Boreholes (BH-1 to BH-8) were advanced at the terraces of the Duval River close to the new bridge abutments. Additional two boreholes were drilled at the flood plain close to areas where water seepage was observed on the river bank, about 20 m downstream from the new bridge crossing. The purpose of these two boreholes was to assess the potential for water seeping in the active layer. All boreholes were advanced using an air track (down hammer) drill rig operated by Canadrill.

The drill program was carried out between July 1 and July 2, 2008. Boreholes located near the abutments were drilled to a depth of 19 m to 20 m, while BH-9 and BH-10 were advanced to 9 m and 6 m depth, respectively. Thermistor cables were installed in five boreholes (three on north bank and two on south bank) for permafrost temperature measurements.

All boreholes were logged continually during the drilling operation based on examination of materials returned to the ground surface.

A laboratory test program was conducted on selected borehole samples to determine the moisture content, Atterberg Limits and grain size distribution. In order to evaluate the potential for sulphate attack on the bridge concrete foundations, two samples were derived from a nearby borrow source for water soluble sulphate tests.

6.2 Geophysical Investigation

Associated Geosciences Ltd. was retained to carry out a geophysical investigation. The primary objectives of the investigation were to provide additional soil information in the vicinity of the bridge foundations and to determine if any substantial voids exist in the subsurface. The Ground Penetrating Radar (GPR), a radio-frequency electromagnetic technique, was utilized. A total of 14 survey lines were conducted near the south and north abutments.

Time-Domain Electromagnetic Soundings was also used to obtain information on soil and permafrost conditions of the crossing. The field geophysical investigation was undertaken in July 2008.

7. SUBSURFACE CONDITIONS

7.1 Subsoil Conditions

The surficial soil layer at the north abutment consisted of fluvial coarse sand with inclusions of gravel, cobbles, boulders and rock fragments up to 2 m in size. This layer was underlain by fine to coarse grained sand with some silt to silty sand and trace gravel, which extended to a depth of 14.5 m. Laboratory tests indicated that the moisture content of the sand was in a range from 7 percent to 10 percent. Below the sand was clayey silt with moisture content ranging from 11 percent to 17 percent, Liquid Limit varying between 19 percent and 21 percent and Plastic Index of about 3.

The upper layer at the south abutment consisted of coarse to medium grained sand with various amounts of gravel, cobbles and boulders. Fine grained sand or silty sand with trace gravel was found below the coarse to medium sand. Laboratory tests indicated that the moisture content of the sand was in a range from 7 percent to 11 percent. A silt layer was encountered in localized area from 17 m depth down to the bottom of boreholes. The moisture content of the silt was less than 10 percent.

The ground was frozen at both of the abutment locations from a depth of 1.5 m to 2.7 m. Based on the moisture content data, frozen soils can be classified as ice poor sediments; however, random ice crystals or lenses were observed in various depths, especially in silt layer.

BH-9 and BH-10 revealed similar soil conditions which is composed of coarse sand with boulders and cobbles overlying fine to medium grained sand with trace of silt. The ground was frozen below 1.5 m depth. No evident of free water within the active layer was observed based on the results of drilling.

The results of geophysical investigation generally confirm the findings from boreholes, with the only exception that a significant anomaly (strong diffraction) was recorded on the south bank of the river at a depth of approximately 5.7 m. As a result, three additional boreholes were conducted on the south bank of the river in August 9, 2008 using an air track (down hammer) drill rig operated by Canadrill at the locations where "anomaly" was detected by the GPR survey. The boreholes showed fairly similar soil conditions to the other boreholes located in the vicinity of the south abutment. No evidence of anomaly was obtained by the drilling.

7.2 Permafrost

Ground temperatures were measured in five boreholes on August 9 and 10, 2008. In general, the mean annual permafrost temperatures were in a range from -3°C to -5°C at depths from 10 m to 16 m. The measured temperatures were considerably warmer than those published in literatures.

8. CAUSES FOR TERRAIN FAILURE

Based on literature review, it was understood that a similar flooding event occurred in the Duval River valley in 1984 (Hyatt, 1992). The flooding event followed a large rainstorm and undercut the bank on the south channel, creating an erosion scarp. During this event water was observed flowing through various voids (pores, cavities and cracks) below the ground surface. The erosion processes exposed numerous cavities in permafrost causing in-flowing and out-flowing streams in cavities. On this basis, it was considered that water flowing through numerous cavities was the primary mechanism that resulted in subsidence and slumps of the soil blocks along the Duval River valley. It was also stated in the paper that the cavities were formed by subsurface thermal erosion and internal piping along permeable zones in frozen soils.

Similar to the 1984 flooding event, the 2008 subsurface flooding occurred following an intensive rainstorm. According to findings from the field investigations, it was considered that the frost cracking process together with water erosion during rainstorm, anomalous climate conditions in 2007/2008 and presence of ice rich materials are the key factors for development of the landslides.

8.1 Frost Cracking

Frost cracking is a temperature-controlled process which has caused numerous pre-failure tension cracks that induced landslides within the flooding area. Lachenbruch (1962) developed a theoretical solution on the mechanics of thermal contraction cracking. Based on the results of his work, the required value of soil viscosity to induce frost cracking is reached when the air temperature falls rapidly between -20 °C to -30 °C and the temperature at the top of frozen soil also drops rapidly to about -15 °C to -20 °C. Such air and soil temperatures are being observed annually within the Pangnirtung area. A rapid drop of the temperature at the top of frozen soil is the most important triggering mechanism for frost cracking.

Grechishchev (1978) provided a method for prediction of the depth and distance between two adjacent frost cracks. Based on the Grechishchev's method, the initial depth of the frost cracks in Pangnirtung area during a single winter season was predicted to be in the order of 5 m to 6 m, and the distance between two adjacent frost cracks can be in a range from 10 m to 30 m. The initial frost cracks may extend deeper, down to 10 m to 20 m, due to freezing water in the cracks during the subsequent winter seasons. The cracks are also widened near the top due to a collapse of the crack walls and surface runoff erosion. With time, some cracks turn into watercourse channels. Such channels, dry or full with water were observed during the field reconnaissance.

In time of high water levels in the river, previously developed cracks became water channels, where intensive thermal and mechanical erosion and thawing of the permafrost would occur. Moreover, the ingress of water into cracks could induce lateral hydraulic pressure inside the cracks and cause failure of fluvial or/and marine materials.

8.2 Water Erosion

Mechanical water erosion is a process of washing out soil particles by flowing water. Depending on soil physical properties, the erosion can start at water velocities ranging from several centimetres per second for fine grained sand to greater than 1 metre per second for silt and clay. The main parameter which determines the minimum water velocity is soil cohesion (for saturated conditions) together with other parameters, such as grain size, liquid limit, void ratio, and internal friction angle. The minimum water velocity near the bottom of channel was estimated using the following empirical formula developed by Tchekhovski et al. (1991) based on results of numerous experiments undertaken in Russia.

$$V=0.73+0.062c+0.0092W_L-0.0064e+0.0069d_{ave}+0.0044\phi$$

V : minimum water velocity (m/s)
c : cohesion of soil in saturated condition, kPa
W_L : liquid limit, percent
e : void ratio, percent
d_{ave} : average size of particles in soil, mm
ϕ : angle of internal friction, degree

The calculations show that the minimum water velocity required for eroding typical sandy deposits and silty deposits in the Duval River valley is about 0.6 m/sec and 2.1 m/sec, respectively. Based on field observation, the water velocity in the Duval River was considerably greater than that required value for development of the erosion.

It was also observed during the field reconnaissance that the main river channel was divided into 5 channels. Locations of the channels corresponded to locations of the landslides, and the water velocity in each of the channels could be up to about 3 m/sec. Thus, significant amount of materials had been washed out within area subjected to the subsurface flooding.

8.3 Anomalous Climate Conditions in 2007/2008

The air temperatures in the 2007/2008 winter period and in May/June 2008 spring period formed favourable conditions for accumulating considerable amount of water in the Duval River valley. Figure 2 shows that the mean air temperature for the 2007/2008 winter season was about -18°C, while the average winter temperature between 1996 and 2008 was calculated to be -16.3°C. On the contrary, the mean air temperature for May and June 2008 was about 3°C, which is the warmest temperature between 1996 and 2008. The anomalous winter and spring temperatures would to some extent intensify the impact of the rainstorm and exacerbate the consequence of the surface flooding. It is because the extremely cold 2007/2008 winter might result in freezing to a full depth of the river channel and formation of an ice berm at some distance upstream from the community. In spring time of 2008, ice berm and ponding water were observed at a distance of a few kilometres from the community. Any cracks occurred in the ice berm would cause considerable amount of water flowing through the berm and flooding the river valley.

In addition, large amount of surface runoff would occur due to a fast melting of snow during extremely warm May and June of 2008.

8.4 Presence of Ice Rich Materials

During the field investigation for the new bridge, random ice crystal, lenses or ice rich materials were observed at various depths inside boreholes. These ice rich materials are considered to be a contributing factor to the development of landslides, as thawing of ice rich materials by subsurface flooding assisted in developing slip surfaces adjacent to the Duval River.

9. GEOTECHNICAL CONSIDERATIONS

For geotechnical considerations, the key issues are foundation design for the new bridge and erosion control adjacent to the new abutments.

9.1 Foundation for the New Bridge

The thickness of the embankment fill for the new bridge placed over the existing ground surface is about 5 m to 6 m and the crest of the embankment fill is extended to 3 m beyond the foundation edges. The results of geothermal analyses indicate that the permafrost table within the footprint of the approach embankment will extend up from the current elevation (about 2 m below ground surface) to above ground surface during the first year of bridge operation. Thus, footings based on compacted granular materials (non-frost susceptible fill) contained in metal bins over the prepared subgrade were implemented. The base of metal bins was founded on about 1 m below the existing ground surface. Figure 3 illustrates the typical section for abutment foundation. An ultimate bearing resistance for the granular fill of 500 kPa was used for design.

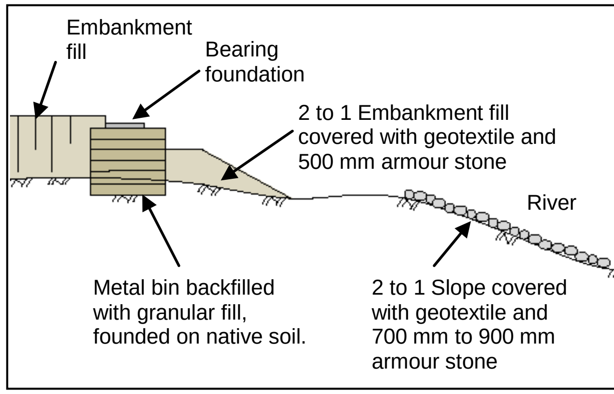


Figure 3: Typical Section for Abutment Foundation

Settlement of footings on compact granular material is influenced by a number of factors, but generally highly related to the composition and thickness of fill as well as degree of compaction and soil density. However, this settlement is considered to be elastic and should mostly occur during construction progress. Hence, settlement of footings on embankment fill should not be a major concern.

Creeping of relatively ice rich sandy/silty deposits, if encountered, may induce long term settlement of the metal bin foundation. Based on our experience with other projects in similar permafrost conditions and limited published data, the bearing resistance of the native soil can be taken as 250 kPa in order to limit long term creeping deformation within acceptable criteria (1 mm per year). To minimize the potential for thaw settlement, a layer of insulation was adopted near the surface of embankment fill in front of and on both sides of the metal bin foundations.

In order to avoid potential of surface runoff seeping into embankment fill and accumulating below the ground surface, drained pipes were adopted around the metal bin at a distance of 1 m and 1.5 m below the top of the embankment fill.

9.2 Erosion Control

The approach embankment slopes (2H:1V) for the new bridge were granular materials and protected against potential run-off erosion using a sheet of geotextile covered by coarse gravel, cobbles and boulders not greater than 500 mm in size. This protective layer was implemented and extended to about 2 m beyond the toe of slopes.

The bank at the south side of the Duval River requires protection against river erosion and surface run-off. The bank slope within 10 m downstream from the new bridge alignment was flattened to 2H:1V. Geotextile was placed over the exposed material and covered with cobbles and boulders, up to 500 mm in size. The thickness of this layer was about 500 mm. Boulders, 700 mm to 900 mm in size, were placed along the toe of the slope. Such approach was also applied for the upstream slope in areas where a flattened slope could not be implemented.

The current north bank was considered to be stable against a global failure. The presence of cobbles and boulders on the slope surface also provide additional resistance to stabilize the slope and minimize river erosion. Therefore, no remediation was applied.

10. SUMMARY AND RECOMMENDATIONS

The mechanisms contributing to the 2008 flooding and landslides in Pangnirtung community could be due to a combination of intensive rainstorm, considerable river flow in June 2008 along with specific soil and permafrost conditions of the Duval River Valley including frost cracking and ice rich deposits in localized areas. The climate conditions during the 2007/2008 winter and 2008 spring might also multiply the magnitude of the subsurface flooding and assist in development of numerous landslides at various locations along the river valley and failure of two bridges.

As a result of the 2008 subsurface flooding and landslides, the Duval River valley in the vicinity of the community was substantially transformed. New water channels were created, and fines and sand particles were washed away, leaving porous stone matrix of the deposits in place. Thus, it is unlikely that a similar subsurface flooding and large scale of landslides will occur in this location in the near future because the existing channels should be able to contain a significant amount of flooding water similar to that occurred in the spring of 2008. However, as the new channels collapse with time, the majority of the channels will be filled up with surrounding soils and the risk of subsurface flooding due to an intensive rainstorm will increase over time.

For short term remediation, the following measures were recommended:

- Duval River valley should be monitored in areas a few kilometers upstream from the Pangnirtung community during the spring time. Locations of the potential ice berms with ponded water, if occur, should be identified. The ice berms should be removed prior to considerable amount of water being accumulated behind the berm.
- A detailed field reconnaissance, large scale aerial photography interpretation and survey along the Duval River valley should be conducted to determine the boundaries of potential subsidence due to the subsurface flooding, especially in areas close to the community. On this basis, a minimum setback criterion from the river should be determined. No development should be designed and constructed within the determined setback distance. Depending on results of interpretation, a field investigation (e.g. borehole drilling) may also be required to confirm the subsoil conditions.

For long term remediation measures, considerations are given to the following approaches:

- An earth dam can be built upstream from the community. A reservoir impoundment is considered to be sufficient to retain water as a result of an intensive rainstorm and snow/glacier melting. Ideally, the dam and reservoir should be built in area where the Duval River valley is narrow and in v-shaped. A gate-controlled spillway should be constructed to release water as required. Maintenance/operation of the spillway may be technically difficult in Arctic conditions and will require experienced personnel.
- Several bypass pipes can be constructed in the valley subjected to subsurface flooding. The total cross section of the pipes should be sufficient to intercept both of the river flow and surface runoff due to intensive rainstorm and fast snow/glacier melting. However, operation of the bypass pipes may be unsatisfactory due to blockage of the pipes with ice in winter period. The design of the bypass pipes should also eliminate water flow around exterior portion of the pipes as the erosion could wash out soil particles around the pipes resulting in pipe settlement.

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