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March 24, 2011
P10008(16). 29

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15th Floor - 360 Portage Avenue
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Attention: M. St. Laurent, P.Eng
Section Head
Keeyask & Burntwood River Planning Section
Hydro Power Planning Department

Dear Mr. St. Laurent:

Keeyask Generating Station
Stage IV Studies
Existing Environment Ice Processes
Memorandum GN-9.1.6, Rev 0
Manitoba Hydro File 00195-11100-0141_02

Enclosed please find two copies of Revision 0 of the above noted memorandum as well as two sign-off sheets containing the relevant KGS Acres signatures.

Please add a Manitoba Hydro signature to the sign-off sheets and return one copy for our files.

Yours very truly,

N.J. Smith, P.Eng
Project Manager

RMDA:spa
Encl

cc G.P. Schick
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Manitoba Hydro
Hydro Power Planning Department
Power Projects Development Division

Keeyask Generating Station
Stage IV Studies - Axis GR-4

Design Memorandum GN-9.1.6

Rev. 0, March 24, 2011

Existing Environment Ice Processes

Manitoba Hydro File 00195-11100-0141_02

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KGS Acres Ltd.
Winnipeg, Manitoba

KEEYASK GENERATION PROJECT

STAGE IV STUDIES - PHYSICAL ENVIRONMENT

EXISTING ENVIRONMENT ICE PROCESSES

REV 0

DELIVERABLE GN 9.1.6

MANITOBA HYDRO FILE: 00195-11100-00141_02

2011/03/24

PREPARED FOR:
HYDRO POWER PLANNING DEPARTMENT
POWER PROJECTS DEVELOPMENT DIVISION
POWER SUPPLY

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Keeyask Hydropower Limited Partnership

EXECUTIVE SUMMARY

This memorandum provides an overview of the ice processes typically encountered on northern rivers and provides a detailed description of the existing environment ice regime along the Nelson River between Split Lake and Stephens Lake. Also discussed are the long term winter field observation program and the development and calibration of numerical ice models which were used to simulate winter conditions along the study reach. A characterization of the ice regime in terms of water levels at key locations along the study reach is provided, as derived through numerical modeling efforts, for both existing environment and future environment without the Project conditions.

Within the study area, two distinct ice covers typically develop over the course of a winter season; a large **hanging ice dam** forms downstream of Gull Rapids and a mechanically thickened cover forms upstream of these rapids. A thermal cover usually develops first on Split Lake and Stephens Lake. The steeper gradient, and therefore higher velocities in the main river channel between these two lakes precludes formation of a similar thermal cover, and this reach remains open initially. As temperatures drop, frazil ice is produced in these open water reaches and this ice passes downstream until it reaches the solid ice cover developing on Stephens Lake. Ice begins to collect in this area over the course of the winter, leading to the formation of a large **hanging ice dam** and considerable staging at the foot of Gull Rapids.

In the reach above Gull Rapids, border ice begins to grow from each bank (where velocities are low enough) gradually reducing the open water width of the river. As the open water width narrows and generated ice pans become larger and larger, these pans eventually jam at a narrow section of the river, creating an ice bridge. This bridge typically forms within the vicinity of Gull Lake and permits the advancement of an upstream ice cover through juxtaposition. The cover frequently shoves and thickens as it progresses upstream in response to the hydraulic forces applied to it.

The cover stalls at the foot of Birthday Rapids owing to the high velocities at that location, leading to the formation of another **hanging ice dam** downstream of these rapids. This leads to staging of the river in this area and in most winters, once stages have increased sufficiently to drown out Birthday Rapids, the cover is able to continue advancing upstream. The upstream progression of the ice cover eventually stops downstream of Clark Lake.

Anchor ice typically forms on the invert of the channel at the outlet of Clark Lake and Split Lake each winter. The build-up of this ice results in an increase in winter water levels on Split Lake that can range from 0.3 m to 1.2 m above equivalent open water levels with the average increase being approximately 0.6 m.

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1 INTRODUCTION

Developing a good understanding of ice processes is an important part of any hydro power planning study for a development located within a northern climate. Ice processes along the Nelson River were studied to:

- estimate environmental impact associated with the Project,
- assist in setting winter plant operation policies;
- assist in developing construction management strategies; and
- predict winter power production.

Ice processes have been studied in detail along the lower Nelson River since the mid 1970's. These studies have included the development of:

i) a comprehensive field observation program, and

ii) detailed numerical models, which have been successfully used to simulate the complex ice conditions along the river.

This memorandum discusses the current ice regime of the Nelson River between Split Lake and Stephens Lake as well as the ice regime expected for the future environment without the Project. Findings are based on the observations gathered and results of the numerical modeling efforts. The sections for this memorandum are organized in the following manner:

- Section 2 provides a general overview of the **ice processes** typically encountered on a northern river like the Nelson River.
- Section 3 provides a brief overview of the approach adopted in these ice studies, and summarizes the observed data available for use in this study.
- Section 4 provides a detailed description of existing **ice processes** on the river, on a reach by reach basis.
- Section 5 describes the numerical models which have been developed to simulate winter conditions on this reach of the Nelson River.
- Sections 6 and 7 provide a summary of expected water levels along the reach, as derived through the numerical modeling efforts for the existing environment and

future environment without the Project respectively. Water levels presented relate to key locations along the river reach.

2 General Overview of Ice Processes

In a typical northern river, an ice cover begins to form with the onset of cool winter temperatures. The nature of the cover varies with location and water velocity, but generally can be described as either smooth "lake ice" or rougher more dynamic "river ice".

Lake ice usually forms in areas of very low velocity, such as lakes, or deep, slow-moving river sections. It forms when cold air temperatures cool the water surface to freezing at the beginning of the winter. This type of ice cover forms very quickly, often within the span of a single night, and grows steadily in thickness with time. The thickness of lake ice is primarily governed by air temperature and the depth of snow cover on the ice. If the snow cover becomes excessively deep, it can weigh the ice cover down causing it to sink below the water surface. This can cause cracks to form in the ice, allowing water to flood over the ice surface creating "slush" on the lake.

In more swiftly moving sections of a river, the nature of the ice cover is significantly different than that in the lake portions. In these areas, the cover evolves based on five basic processes, namely:

- **ice generation**,
- **ice front** progression and formation of large **hanging ice dams**,
- ice cover consolidation/**shoving**,
- **border ice** formation, and
- **anchor ice** formation.

Figure 1 illustrates these typical river **ice processes**.

Ice generation takes place in open water sections of a river reach. With the onset of winter, water temperatures within the river begin to fall, and eventually drop to near freezing. When the temperature drops below freezing, small ice crystals begin to form in the river. These small crystals, known as **frazil ice**, resemble fine snow crystals and are highly attracted to solid objects and each other. They gather together (or agglomerate), and eventually rise to the surface to form **ice pans**. These pans drift along the water surface, and in turn join together forming larger ice sheets.

Where **ice pans** and ice sheets encounter an existing ice cover, such as at a lake, they accumulate, and the cover advances upstream. The upstream end of an advancing ice cover is called the **ice front**. If flow velocities at the **ice front** are low enough, the ice cover continues to advance upstream through the accumulation of these sheets and pans, a process known as **juxtaposition**. However, if the advancing cover reaches a section of high velocity, the cover "stalls", and the **ice pans** begin to be drawn down under the cover and accumulate there. This formation is referred to as a **hanging ice dam**, and can result in a substantial rise in water level as the ice dam grows and thickens. Figure 2 illustrates a typical **hanging ice dam** formation.

In particularly steep or high velocity reaches, the advancing ice cover may frequently adjust and thicken as it grows. This "shoving" mechanism is a response to the internal pressures which will gradually mount within the cover due to the collection of ice on the leading edge, the weight of the growing cover, and the hydrodynamic drag forces applied to the underside of the cover by the moving water. Each time this occurs, the ice front retreats and the cover thickens. The thickening of the cover strengthens it, and provides it with a greater ability to resist these applied forces. Figure 3 shows the typical profile generated by such a mechanically thickened ice cover. As shown on the diagram, the toe (downstream limit) of the mechanically thickened portion of the cover is generally located at a section of a river with a stronger thermally grown ice cover (i.e. at a lake or reservoir), or at an ice bridging point in the river. The toe of the cover is generally the thickest region, and upstream of this toe, the ice cover exhibits a relatively constant thickness i.e. the minimum thickness required to generate sufficient strength to resist externally applied forces.

Border ice forms along the shoreline of a river, where velocities are low. The overall process by which **border ice** forms is similar to that described for lake ice. Lateral growth rates are sometimes augmented as drifting **ice pans** attach to the **shorefast ice**. Throughout the winter, the **border ice** continues to grow by these processes, gradually reducing the area of open water. In particularly low velocity locations, the **border ice** forming along each shore may eventually grow together, creating an **ice bridge** and hence an **ice front** against which drifting **ice floes** can begin to accumulate. The extent of **border ice** formation is governed by the flow velocity, river geometry, and winter temperatures. Figure 4 illustrates a typical **border ice** growth formation.

Anchor ice typically forms on the river bed at locations that are shallow and flowing rapidly, such as at the brink of a set of rapids or a waterfall. At these locations, the turbulent, high velocity flow causes mixing of the newly formed **frazil ice**. The **frazil ice** comes into contact with the river bed and attaches to the material on the river bottom. As this ice mass slowly grows, it begins to constrict or block the river channel, and can result in a substantial rise in upstream water levels. Figure 5 illustrates a typical **anchor ice** accumulation.

3 APPROACH AND METHODS

To understand and document ice formation processes on the Nelson River, a comprehensive hydrometric monitoring program was established, with data collected during the winter months from November through to April. The winter program was initiated in the mid 1970's. Data collected each winter as part of the hydrometric monitoring program includes:

- photographic/video records of ice cover development and advancement. These videos and photos are taken periodically during the winter during helicopter reconnaissance flights,
- satellite imagery,
- periodic observations of ice cover progression and **anchor ice** formation along the reach,
- periodic survey measurements of water surface profiles,
- ice thickness measurements,
- collection of daily air temperatures (recorded at the Gillam Airport MSC meteorological station [Station No. 5061001]), and
- Split Lake outflow data (back-calculated from flows and levels recorded at the downstream Kettle Generating Station [G.S.]).

Based on this information, detailed numerical ice models were developed and calibrated to simulate the formation of the ice cover and its growth throughout the winter [Ref 1, Ref 2 and Ref 3]. Using actual daily air temperature and flow data, the models were calibrated to match observed field conditions. Once calibrated, the models were used to assess how the nature of the cover may vary depending on the severity of the winter air temperatures, and winter flow scenarios.

4 EXISTING ENVIRONMENT

The lower Nelson River within the Keeyask G.S. study area, which for the purposes of this memorandum is defined to start at the outlet of Split Lake and end at the inlet to Stephens Lake, is a fast flowing river with reaches separated by rock controls, rapids, and lakes. This reach of the river contains some lakes which are shallow and narrow (simple widenings of the river) such as Clark Lake and Gull Lake. The river drops approximately 26 m along its 56 km course between Split Lake and Stephens Lake.

Ice formation on the lower Nelson River within the study area is a relatively complex process, and has been studied for many years by Manitoba Hydro. The following sections summarize major observations that have been gathered on the existing ice regime for the lower Nelson River in the study area.

4.1 ICE FORMATION ON THE NELSON RIVER

Under the present winter regime, a thermal cover usually develops first on the reach's bounding lakes (Split Lake and Stephens Lake), while other faster sections of the river remain open, generating large volumes of **frazil ice**. As a result, two distinct ice covers typically develop over the course of a winter season in this reach:

i) a large **hanging ice dam** forms immediately downstream of Gull Rapids, and

ii) a mechanically thickened cover forms in the reach between Gull Rapids and Split Lake. In addition, **anchor ice** growth at the outlets to both Clark Lake and Split Lake results in winter staging on these lakes.

Major **ice processes** observed along the river, from Split Lake to the Inlet of Stephens Lake, are briefly described below for each of these reaches.

4.1.1 SPLIT LAKE TO GULL RAPIDS

In this reach, the Nelson River drops 13 m, from an elevation of approximately 166 m on Split Lake, down to an elevation of approximately 153 m on Gull Lake. The majority of this head drop occurs over a relatively steep section of the river located between the outlet of Clark Lake down to a point which is approximately 15 km upstream of Gull Rapids. The higher velocities in this reach have a significant impact on overall ice formation processes.

Figure 6 provides an overview of the **ice processes** observed along this section of the lower Nelson River. The following bullets provide additional explanation:

- Each year, a competent ice cover forms on Split Lake relatively quickly, usually beginning sometime between mid-October and mid-November. This cover then gradually thickens over the winter period, depending on the air temperature, and the snow cover. The thickness of ice on the lake can range from 0.8 m to 1.2 m depending on the meteorological conditions.

- Downstream of Split Lake, ice initially forms as a thin strip of **border ice** along each bank. Where velocities are relatively low, such as in Clark Lake, **border ice** growth is significant, and can cover a large portion of the lake. In other areas, like the relatively steep reach between the outlet of Clark Lake and Birthday Rapids, velocities are considerably higher. These higher velocities typically limit the growth of **border ice** to thin strips along the shoreline that are generally 20 m in width or less, as shown in Figure 7.

- At the same time, **frazil ice** is generated in the open water sections of the river, and these generated flocs agglomerate into **ice floes** and eventually, into larger **ice pans** and sheets. These pans gradually grow in size with time of exposure, and distance travelled downstream. Figure 8 shows a reach of the river near Gull Rapids, and gives an indication of the density and size of some of these pans.

- As the generated **ice pans** become larger and larger, they normally begin to jam at a narrow section of the river, creating an **ice bridge**. This bridge typically forms within the vicinity of Gull Lake, and thus permits the progression or advancement of an upstream ice cover. As shown on Figure 6, the **ice bridge** typically occurs at one of three locations in the vicinity of Gull Lake. Figure 9 shows the ice cover at a bridging point located near Gull Lake. The date at which this **ice bridge** may form is quite variable. Typically, bridging occurs by mid-December, but it has been known to occur as early as mid-November, and in other years, has not been observed to occur at all.

- Once initiated, this cover advances upstream through a **juxtaposition** process, as shown in Figure 10. The typical cover in the downstream reach of the lake (i.e. up to 10 km upstream of Gull Rapids) is relatively thin, and smooth, as the cover is able to advance fairly quickly and easily against the lower velocities in this area. However, the cover in the upstream reach of the lake is considerably thicker and rougher, as it must periodically **shove** and thicken. Each time this occurs, the ice cover collapses and consolidates, and ice may move downstream along the shore of each bank. This can expose sections of the shoreline to possible abrasion if they are in direct contact with this **pack ice**. Figure 11, taken at a section near the upper end of Gull Lake in mid-January, illustrates the roughness of this **pack ice**. The cover typically grows to be between 5 m and 8 m thick in this area of the river.

- If sufficient **border ice** exists in a river reach, the **border ice** acts as a buffer between the **pack ice** and the shore, and the interaction of the **pack ice** with the shorezone is reduced. However, the hydraulic forces exerted on the river ice cover in the streamwise direction also create stresses in the **pack ice** which are partially spread laterally towards the riverbanks. Therefore it is also possible for **pack ice** in the river reach to be pushed laterally into the banks in response to this lateral pressure, or to push the **border ice** sections into the bank. The thicker the accumulation, the greater the developed lateral pressures will be. This can sometimes cause portions of the ice cover to buckle against the bank, or even be pushed up over the bank. Figure 12, taken in mid-January shows this bulldozing action at a location near the upstream end of Gull Lake. This action may also strip the shoreline of vegetation over large reaches.

- The advancing ice cover typically stalls either temporarily or for the season at the foot of Birthday Rapids, owing to the higher velocities present at this location. These high velocities causes **ice pans** to submerge and be carried under the leading edge, leading to the formation of a **hanging ice dam** downstream of the rapids. The formation of the **hanging ice dam** can result in a considerable accumulation of ice in a very local area. This congestion restricts the conveyance capacity of the channel below Birthday Rapids, and can lead to significant local staging. As the cover grows over the winter, significant internal stresses/pressures develop, and the cover can shift often as the matrix of ice fragments/floes grows. A portion of these loads can be transferred to the banks, due to lateral pressure exerted by the accumulation. If the accumulation of ice in the **hanging ice dam** is large enough, it can also result in some redirection of flow along the river banks as the main channel conveyance capacity drops. Figure 13 shows an ice dam which formed downstream of Birthday Rapids during one winter.

- As the **hanging ice dam** grows downstream of Birthday Rapids, it initially leads to increases in water levels at the foot of Birthday Rapids. Eventually, water levels may rise to a point that is high enough to “drown out” the rapids, lowering flow velocities, and allows the cover to begin advancing upstream again. This does not occur every year, but if it does, the cover eventually stalls at a location which is approximately 5 km upstream of Birthday Rapids. The cover advancement stalls at this point due in part to the steepness of the reach, in part due to the warming of air temperatures and increased solar radiation in late winter, and in part due to a reduction in the upstream open water area (in which **frazil ice** is generated) as the cover advances.

- The ice cover in the reach upstream of Birthday Rapids is mechanically thickened in order to provide sufficient strength to resist forces created by the flowing water and the weight of the upstream ice pack. Figure 14 shows the leading edge of this cover after it has progressed upstream of Birthday Rapids. The typical end of winter thickness of the cover is 2 m to 3 m in this area.

- The **hanging ice dams** and the mechanically thickened potions of the ice cover are hydraulically very rough when they are first formed. However, over the course of the winter, the rough underside of the ice will slowly become smoother due to the erosion of ice protrusions by the flowing water, and the infilling of gaps and holes within the cover by smaller **frazil ice** pieces. This smoothing effect can lead to a drop in water levels later in the winter.

- **Anchor ice** also typically forms just downstream of the outlet of Clark Lake, and also at the immediate outlet of Split Lake, as shown in Figure 6. These accumulations slowly restrict the conveyance of the channel in this area, leading to staging upstream along both Clark Lake and Split Lake. Historical records on Split Lake have shown that this increase in stage may range from as little as 0.3 m to as much as 1.2 m over the course of a winter. The average winter increase in level on Spilt Lake is approximately 0.6 m. Figure 15 shows **anchor ice** growth observed immediately downstream of Clark Lake. Figure 16 illustrates historical staging patterns observed on Split Lake due to this **anchor ice** growth. Also shown on this figure is an average winter staging pattern for the lake. As shown, on average, water levels begin to exceed open water stages at the beginning of November, when air temperatures begin to fall. These stages typically reach a maximum in late January/early February, and begin to fall again to open water levels later in the winter as these **anchor ice** accumulations begin to detach and release from the streambed. Over the course of the winter, the **anchor ice** may release due to thermal gain from the sun, and then subsequently reform later at night resulting in fluctuations in upstream water levels.

4.1.2 GULL RAPIDS TO STEPHENS LAKE

In this reach, the Nelson River drops 13 m, from an elevation of approximately 153 m on Gull Lake to an elevation of 140 m (typical) on Stephens Lake. The majority of this head drop occurs within Gull Rapids over a distance of approximately 4 km. Although the rapids contain three separate channels (north, centre, and south) the majority of flow remains in the south channel of the river. Velocities in this branch are high, as flows cascade downstream over a series of rock controlled shelves. These high velocities have a significant impact on ice formation processes. Ice formation processes within this reach are described below:

- In this reach of the river, an ice cover initially forms on Stephens Lake in the early fall, typically by November 1st, although these formation dates may vary somewhat depending on the fall air temperatures. Historical observations have shown ice formation dates on Stephens Lake falls within a window between mid-October and mid-November.

- Once Stephens Lake freezes over, and before the upstream cover can bridge at one of the three locations on Gull Lake shown in Figure 6, all ice generated in the upstream reach pass through Gull Rapids, collect on the leading edge of the cover, and cause the cover to begin to advance upstream. However, the opportunity for upstream progression is limited and the **ice front** typically stalls at the site of the proposed Keeyask G.S. due to the high velocities. Any incoming ice is submerged and deposited under the ice cover resulting in the formation of a large **hanging ice dam** downstream of Gull Rapids. The growth of this ice dam is initially very rapid, but slows considerably when and if an **ice bridge** forms upstream in Gull Lake.

- The **hanging ice dam** continues to grow throughout the winter. However, the ice cover does not progress through Gull Rapids even under an extremely cold winter. The formation of the **hanging ice dam** can result in a considerable accumulation of ice in a very local area, as shown in Figure 17, which was taken just downstream of Gull Rapids one winter. This congestion restricts the conveyance capacity of the channel below the rapids, and can lead to significant local staging (7 m to 8 m above open water levels have been observed). As the cover grows over the winter, significant internal stresses/pressures develop, and the cover can shift often as the matrix of ice fragments/floes grows. A portion of these loads can be transferred to the banks, due to lateral pressure exerted by the accumulation. In this environment, the banks become susceptible to erosion when ice is pushed up against the bank, or moves directly along the shoreline, abrading the river bank. Figure 18 illustrates a typical example of this at a section immediately downstream of Gull Rapids.

- If the accumulation of ice in the **hanging ice dam** is large enough, it can also result in some re-direction of flow along the river banks as the main channel conveyance capacity drops. This has been observed to occur on a number of occasions in the reach within and downstream of Gull Rapids. Figure 19 illustrates flow through a new channel that was formed during the 2000/2001 winter, a year in which ice dam formation was particularly severe in this area because an **ice bridge**, and thus an ice cover, did not form upstream of Gull Rapids. It should be noted that there have been at least three winters over the past 15 years in which formation of an ice cover in the upstream reach was delayed, leading to the formation of a massive **hanging ice dam** downstream of Gull Rapids.

- The **hanging ice dam** typically extends approximately 5 km into Stephens Lake, and can lead to significant **shoving** of ice onto downstream islands within this area.

- As noted previously, typically at some point in the winter, the ice cover bridges in the vicinity of Gull Lake. This greatly reduces the amount of ice being passed through Gull Rapids and deposited in the **hanging ice dam**.

4.2 SPRING BREAKUP ON THE NELSON RIVER

In the spring, breakup of the river ice in this area is preceded by the release of **anchor ice** at the outlet of Split Lake and Clark Lake. This usually begins to occur in late February, and as a result, water levels on Clark Lake and Split Lake begin to drop in these latter winter months. The river ice then begins to deteriorate in late March and throughout April, as the sun's stronger solar radiation begins to weaken the ice, and snowmelt runoff begins. Open water leads begin to form throughout the main cover, as shown in Figure 20. In tandem with this, rising flows cause stages along the river to increase, and with this rise in water level, the cover eventually loses its bank resistance against the **shorefast ice**. The leading edge of the cover then begins to retreat down river as the cover progressively breaks, and reforms, at times possibly resulting in an **ice jam**. In areas where the **pack ice** is contained by wider **border ice** reaches, the **border ice** tends to remain in place slightly longer, and the **pack ice** retreats in the center of the river. Eventually, the leading edge will retreat to the location of the stronger lake ice, leaving open water in upstream areas. Figure 21 illustrates a section of the existing river (located just downstream of Birthday Rapids) at a point late in the breakup process. The de-staging of water levels in the reach typically begins in March, and continues through until mid-May, at which time levels return to open water levels throughout most of the reach.

Ice remnants located along the shore zone downstream of Birthday Rapids continue to melt and deteriorate, typically into June. Figures 22 and 23 illustrate typical remnants of **shorefast ice** that have become grounded along the river reach, and are melting in situ. In Figure 22, the ice remnants shown are the remains of a thinner **border ice** cover which has collapsed onto the existing shoreline following retreat of the main ice cover. Figure 23 illustrates ice remnants along the shore in an area of heavy **pack ice**.

Downstream of Gull Rapids, the large **hanging ice dam** also begins to deteriorate, leading to the development of open leads within the cover. The cover begins to melt, and with the onset of higher flows associated with the spring freshet, flush out into Stephens Lake.

5 MODELING

Sophisticated numerical models have been developed over the years to help better understand and predict ice conditions on river reaches. Prior to this study, a robust and comprehensive model, ICESIM, had been developed and calibrated to represent the steady growth of the ice cover over a typical winter period [Ref 3]. This model was used to predict ice conditions in the vicinity of the proposed Keeyask G.S. for use in the design and construction of the Project. For this study, this past work has been augmented with the development of a hydrodynamic ice model, ICEDYN, which is capable of dynamically routing projected daily discharge and/or forebay level variations through the study reach.

5.1 ICEDYN MODEL

The ICEDYN model is a powerful ice simulation program derived from the earlier ICESIM model developed for use on the Nelson River. Like its predecessor, the ICEDYN model is fully capable of simulating typical ice formation processes, including **ice generation**, deposition, advancement, **shoving** and thickening. In addition, the program is also capable of dynamically routing river flows and/or forebay water level variations through the study reach. It does so through a solution of the St. Venant equations of unsteady fluid flow. The model also has the ability to represent staging due to **anchor ice** formation along a river reach by way of a time dependent staging factor.

One of the weaknesses of both the ICESIM and the ICEDYN models are that they tend to over estimate water levels for winter dates beyond when peak staging occurs (after the **ice front** has stalled). **Ice processes** are difficult to simulate when this occurs due to the longer days (increased exposure to sunlight) and smoothing of the ice surface (reduction in ice roughness). These factors tend to result in an **ice front** recession and a reduction in water levels which these models cannot predict. As a result, the ICEDYN model cannot simulate the de-staging of water levels and the subsequent return to open water levels in the spring. For these reasons, the use of the ICEDYN model to predict winter water levels throughout the entire winter period must not be viewed as an absolute, but rather as an indicator of the trend.

5.2 MODEL SETUP

Due to the two separate ice covers which occur over the study area, modeling of the entire river reach with one model was not possible. To overcome this complication, two separate ICEDYN models were set up. One model was set up to simulate the reach upstream of Gull Rapids (between Split Lake and Gull Rapids) which will be referred to as the upstream model reach, and the other to simulate the reach downstream of Gull Rapids (between Gull Rapids and Stephens Lake) which will be referred to as the downstream model reach. A map showing these modelled reaches along with the location of the key sites along the reach where water levels have been characterized is provided on Figure 24.

Cross sections for the simulation were derived directly from existing backwater datasets of the reach. In total 58 cross sections were utilized in the reach from Split Lake to Gull Rapids, and 11 cross sections were utilized to model the reach from Gull Rapids to Stephens Lake. These cross sections were surveyed as a part of earlier hydrometric surveys, and are consistent with those sections utilized in concurrent open water studies. Additional interpolated cross sections were added to the two models to ensure stability of the dynamic model.

When user specified air temperatures fall below 0^{o}C, the simulation of **ice processes** on the river reach begins including:

- the generation of **frazil ice**,
- the initiation of **border ice** growth, and
- the advancement of the ice cover by **juxtaposition**, and where velocities are high, the deposition of ice in a **hanging ice dam** downstream of the higher velocity area.

5.3 CALIBRATION

Following its initial setup, the models were calibrated to match open water rating curves previously derived at a number of specific locations along the river reach using an open water backwater model. After obtaining a suitable match under open water conditions, the models were then used to simulate the development of an ice cover on the two study reaches for particular winters in which ice observation data was available. Ice parameters for the models were initially selected based on the parameter sets identified in earlier studies undertaken with the ICESIM model. These parameters were then adjusted as necessary to obtain a good match between the ICEDYN modelled levels and those measured in the field for a number of past winters. The variation in the ice parameters used in the models are attributed to the differences in the two model algorithms, as well as the collection of additional low flow water level data since the ICESIM model was developed.

Anchor ice staging was incorporated at two locations, at the outlet of Clark Lake, and at the outlet of Split Lake. This staging is incorporated into the model using a user defined **anchor ice** pattern applied to specific cross sections. The timing and magnitude of the **anchor ice** adjustment was derived based on past experience and measured water level data. For all simulations undertaken, these patterns were assumed to be constant. While it is recognized that the timing and amount of **anchor ice** formation is variable from year to year, there is no adequate way to simulate its development and growth. Based on the measured data available, the staging factors incorporated are expected, on average, to adequately represent the degree of staging.

The upstream boundary condition of the models consisted of a user defined flow hydrograph, while the downstream boundary condition consisted of a user defined stage hydrograph. Air temperature sequences utilized in the models were based on meteorological data collected at the Gillam airport.

Under open-water conditions, the models were calibrated to within 0.25 m of the open-water rating curves derived at the key location in the study area. Under winter conditions, a good overall match was achieved between measured and modelled water level data. Figure 25 illustrates a sample water surface profile for the upstream reach of river between Spilt Lake and Gull Rapids. As shown in Figure 25, the first 10 km (i.e. within Gull Lake), and the ice profile consists of a relatively thin, **juxtaposed** cover. Upstream of this, the cover is considerably thicker, and consists of a much rougher, mechanically thickened profile.

The upstream model was able to reproduce winter water levels at key locations upstream of Gull Rapids to within 0.5 m, on average, of those observed during the freeze-up period. Downstream of Gull Rapids, the downstream model was able to reproduce observed freeze-up water levels to within 0.75 m on average. Differences between measured and modelled water levels of up to 2 m did however exist at certain locations in some years (Birthday Rapids and downstream of the outlet of Clark Lake). Such deviations are to be expected given the lack of available data for some years on the timing and location of the **ice bridge** which initiates the upstream winter cover. This lack of data made it necessary to assume bridging locations and dates for many years based on general trends observed in other years. An error in the selection of the timing or location of the bridging points could lead to differences in the modelled arrival of the **ice front**, which at locations more susceptible to channel blockages due to ice, can lead to these larger differences.

Figure 26 shows the results of a simulation for the 1991/1992 flow year for the reach of river downstream of the Gull Rapids. Also shown for comparison on this figure are a number of surveyed water levels that were taken for this period. As discussed in Section 4, a large **hanging ice dam** typically forms in this area, and the significant size of this **hanging ice dam** is well demonstrated in this profile plot. Again, the reasonable match obtained between observed and computed water levels demonstrates the ability of the numerical model to represent ice conditions along the reach.

5.4 SPRING DE-STAGING

As indicated earlier, the de-staging of water levels during the spring cannot be modelled with ICEDYN. Based on observed data, the de-staging of water levels generally begins at the beginning of March. To accommodate this, ICEDYN modelled water levels after March 1st had a time varying de-staging factor applied to them such that as spring progressed, the modelled water levels returned to their open water equivalents. A representative de-staging factor and the date of the return to open water levels were estimated based on historical observations and were applied to all simulations undertaken. Under the existing environment, water level staging was linearly reduced by 20% over the month of March, with the remaining 80% of the total winter staging being eliminated linearly over the months of April and May. Predicted water levels were thus returned to their open water equivalents by June 1st.

6 CHARACTERIZATION OF EXISTING WATER LEVELS

The observed winter data collected in this reach, although excellent for calibration of the numerical models, is not gathered frequently enough to be able to provide a continuous characterization of water levels over the winter period. Measurements are only gathered at specified intervals. To augment this data, and thereby provide a more continuous record of levels, numerical models were setup to simulate each winter season from 1977 through to 2007.

The ICEDYN model was given actual flow and air temperature data for each winter, and simulations were then run for each winter season. Modelled winter water levels were then extracted at key locations throughout the study reach and processed into duration curves to provide a more complete picture of the range of water levels experience along this reach in the winter. Figures 27 to 37 show these duration curves of winter water levels for the key sites located along this river reach. The duration curves for Stephens Lake and Split Lake, Figures 27 and 37 respectively, reflect measured water level data rather than modelled water levels. All of these charts represent the estimated frequency with which various winter stages are experienced at each key site between November 1st and May 1st over the period from 1977 to 2007.

7 FUTURE CONDITIONS WITHOUT THE PROJECT

It is expected that without the development of the Project, and assuming that climatic and watershed conditions remain as they currently are, that the winter regime for this reach of the Nelson River would continue to be the same as that described in this memorandum for the existing environment. The severity of **ice processes** will vary from year to year depending on specific meteorological conditions, but in general the major **ice processes** and thus the ice regime will be unchanged.

With this in mind, Figures 38 to 41 illustrate representative hydrographs for the key sites on this river reach under the 5th, 50th, and 95th percentile average seasonal winter flows (November to March). Note that hydrographs for the Keeyask Tailrace site (Figure 41) reflect typical ice bridging dates on Gull Lake. Thus, water levels will be higher than illustrated at this site in years when the bridging of Gull Lake is delayed or does not occur. The 5^{th}, 50^{th}, and 95^{th} percentile Stephens Lake levels are assumed to occur with the 5^{th}, 50^{th}, and 95^{th} percentile average seasonal winter flows.

REFERENCES

REFERENCES

1. Crippen Acres, "Birthday/Gull Stage II Studies – Winter Ice Staging Pre and Post Downstream Development", File Number 2180.25/2180.29, November 1988.

2. Acres Wardrop, "Birthday/Gull Ice Studies – 1994 Update", File Number 10008.19.03.02, September 1994.

3. KGS ACRES Ltd., Memorandum GN-2.2 "Keeyask Generating Station, Stage IV Studies – Axis GR-4 – Updated Backwater Study Winter Conditions" Rev. 1, Manitoba Hydro File 00195-11410-0028_02, July 2009.

4. Ashton, G.D., *River and Lake Ice Engineering*, Water Resources Publications, Littleton Colorado, USA, 1986.

FIGURES

Figure 1: Typical river ice processes (after Ashton 1986) [Ref 4]

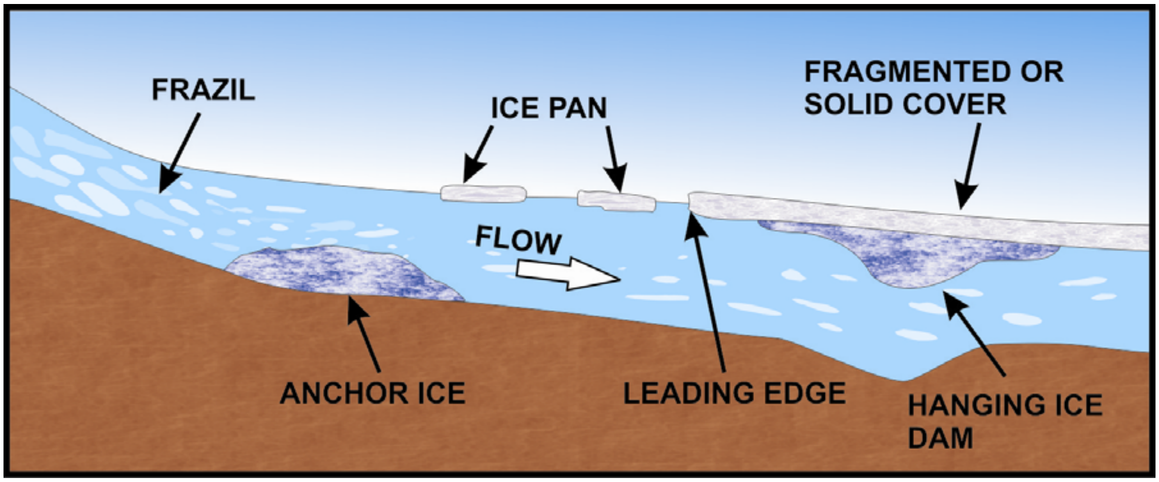


Figure 2: Typical hanging ice dam (after Ashton 1986) [Ref 4]

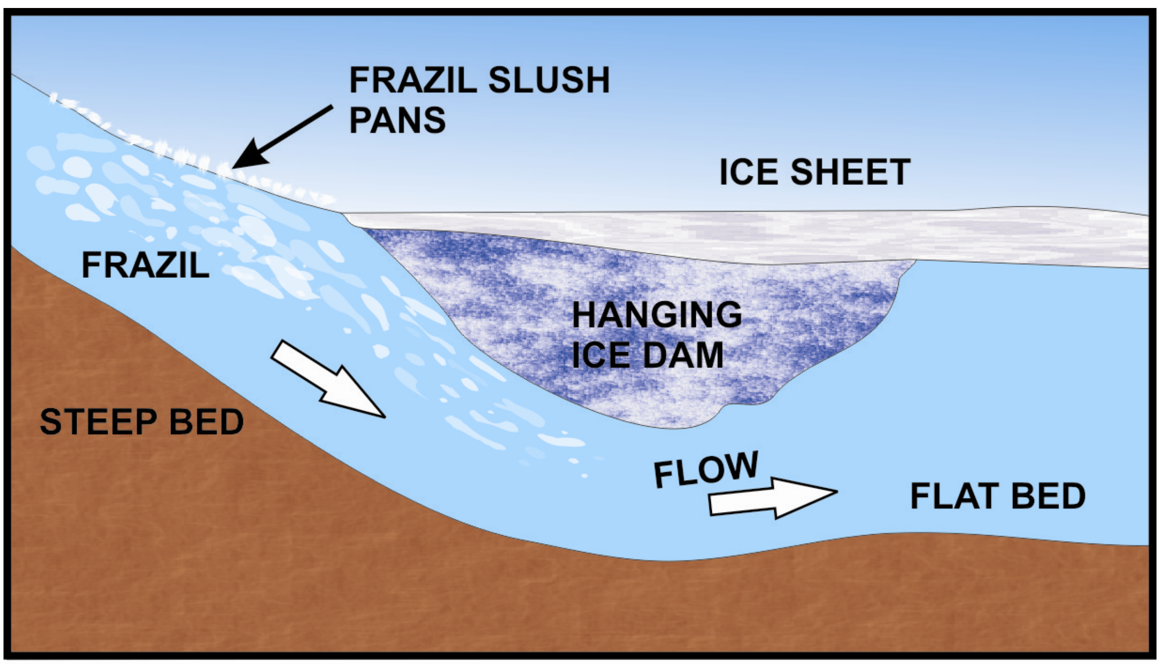


Figure 3: Typical mechanically thickened ice profile (after Ashton 1986) [Ref 4]

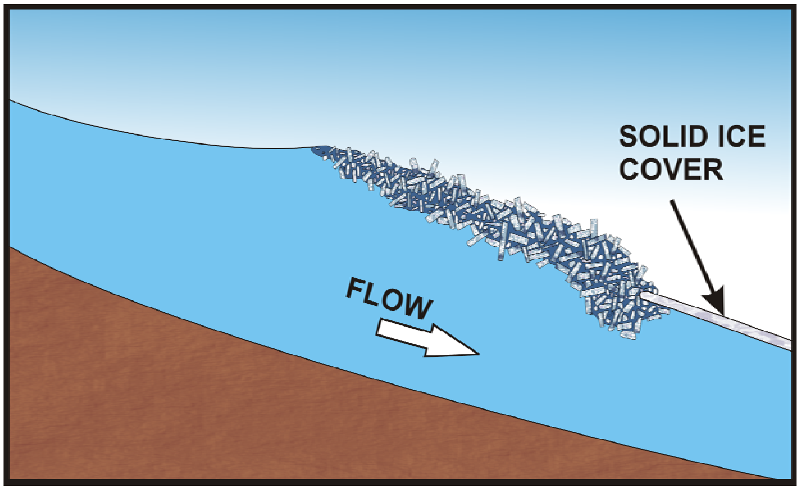


Figure 4: Typical border ice growth (after Ashton 1986) [Ref 4]

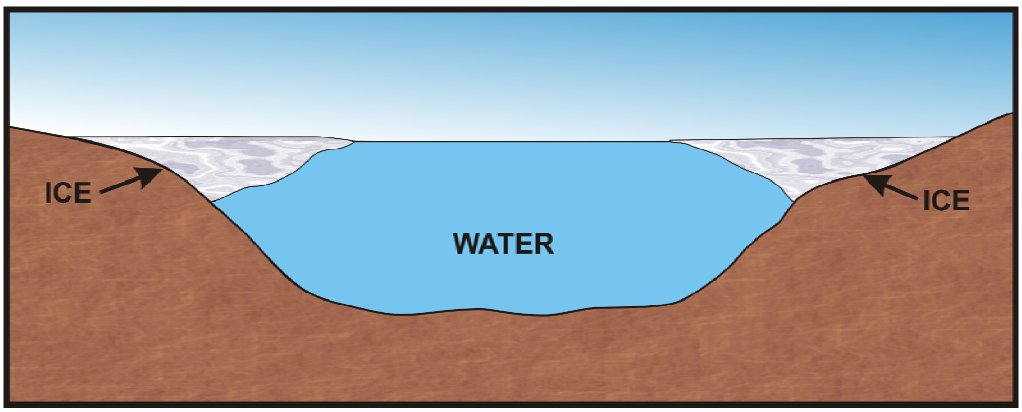
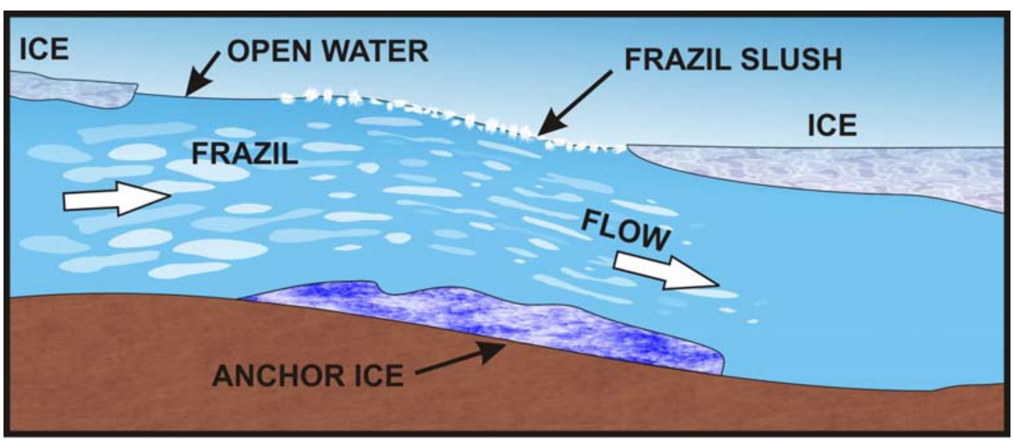


Figure 5: Typical anchor ice accumulation (after Ashton 1986) [Ref 4]



KEEYASK

0 1,500 3,000 6,000 Meters
0 7,500 15,000 30,000 Feet

Projection: Universal Transverse Mercator Zone 15N, NAD 83

Data Source: Baseline lakes, rivers, roads, railway and transmission line, taken from NTDB maps 64A and 54D, 2005.

Mapping grade, for general reference only.

Ice Processes from Split Lake to Stephens Lake

Figure 6

Created By:
KGS ACRES

Date Created:
March 13, 2009

Figure 7: Outlet of Clark Lake (looking downstream)

Figure 8: Typical ice pan density, just upstream of Gull Rapids (looking downstream)

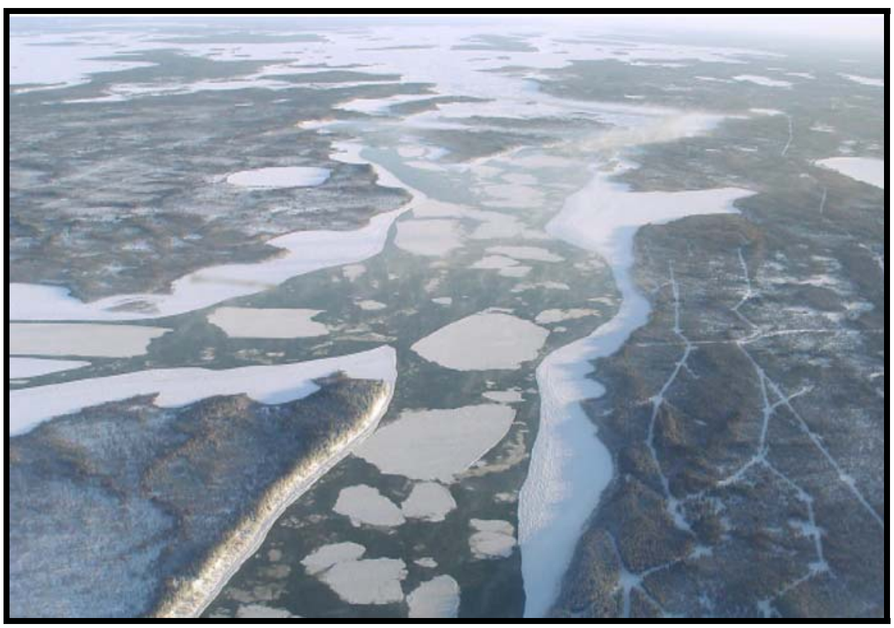


Figure 9: Typical bridging point near Gull Lake
(looking downstream)

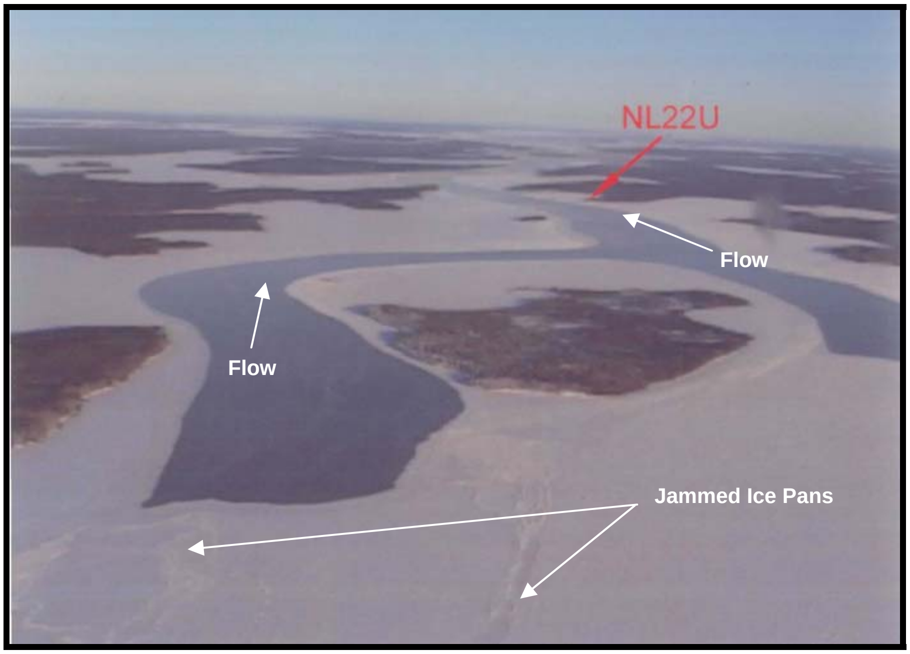


Figure 10: Leading edge of advancing ice cover

Figure 11: Pack ice surface at upstream end of Gull Lake
(looking downstream)

Figure 12: Lateral push of border ice near upstream end of Gull Lake

Figure 13: Ice dam downstream of Birthday Rapids (looking downstream)

Figure 14: Leading edge of cover upstream of Birthday Rapids (looking downstream)

Figure 15: Anchor ice at outlet of Clark Lake
(looking downstream)

Figure 16
Historical Winter Staging Patterns on Split Lake
(for the years of 1997 to 2006)

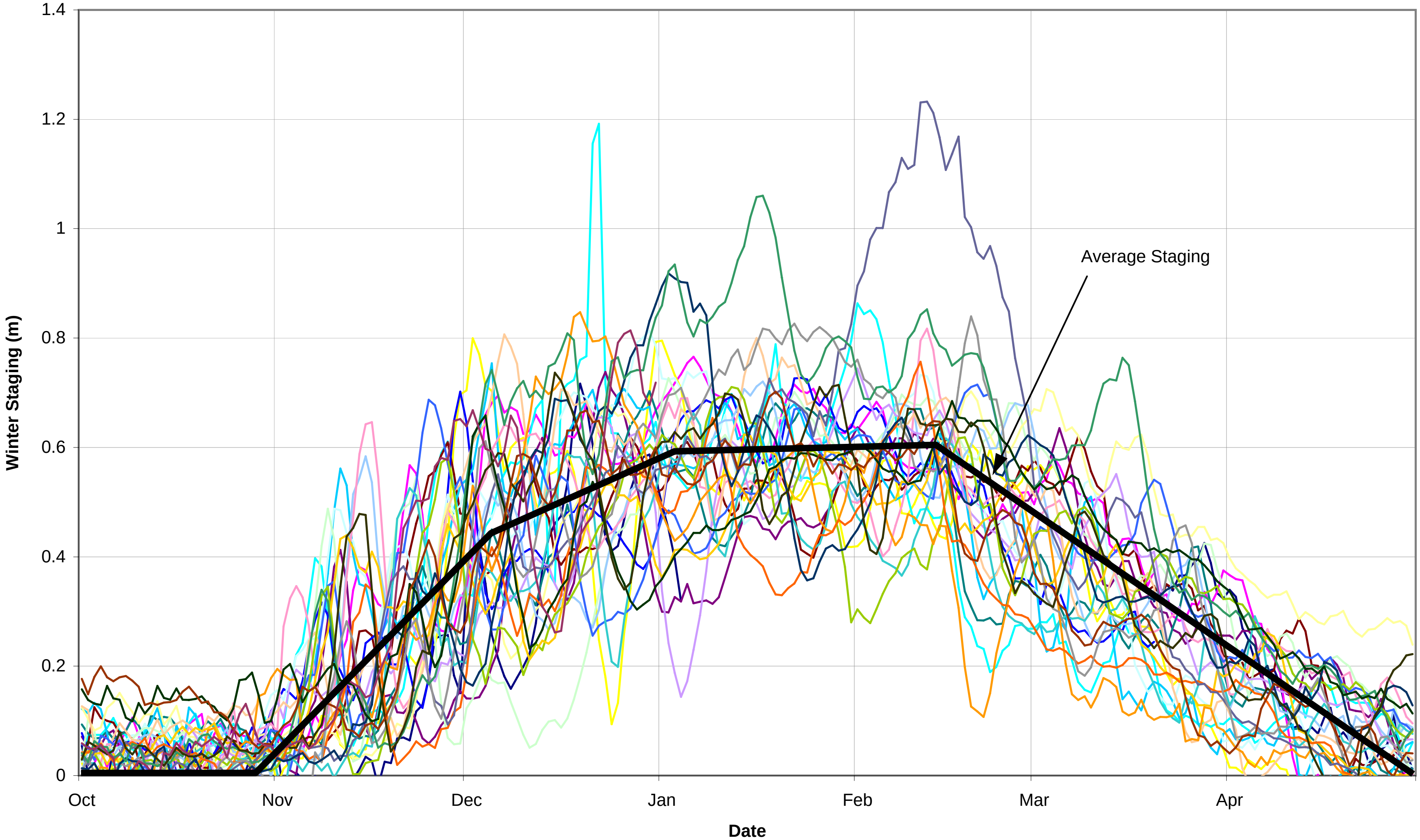
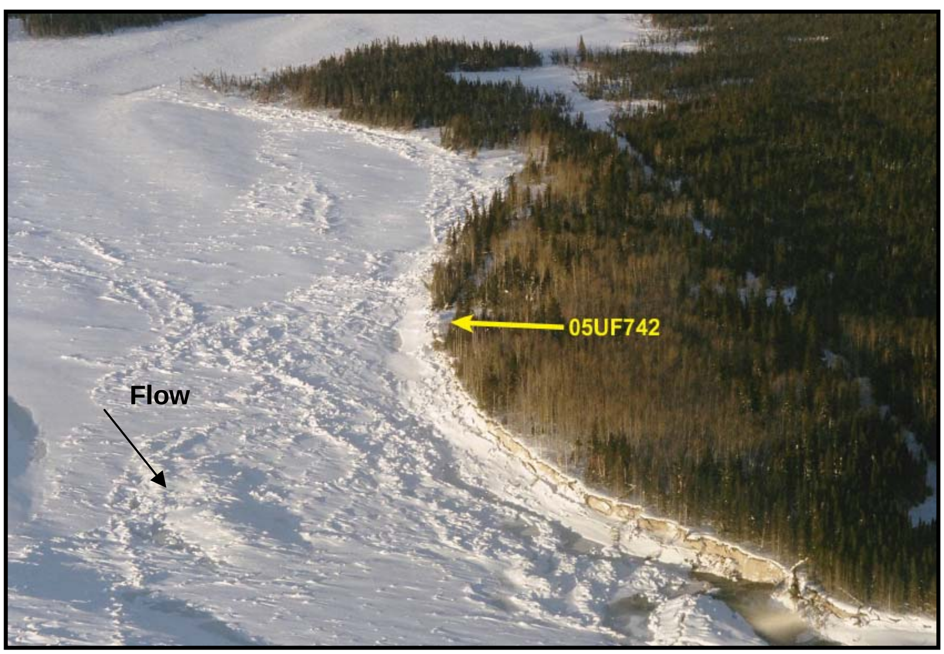
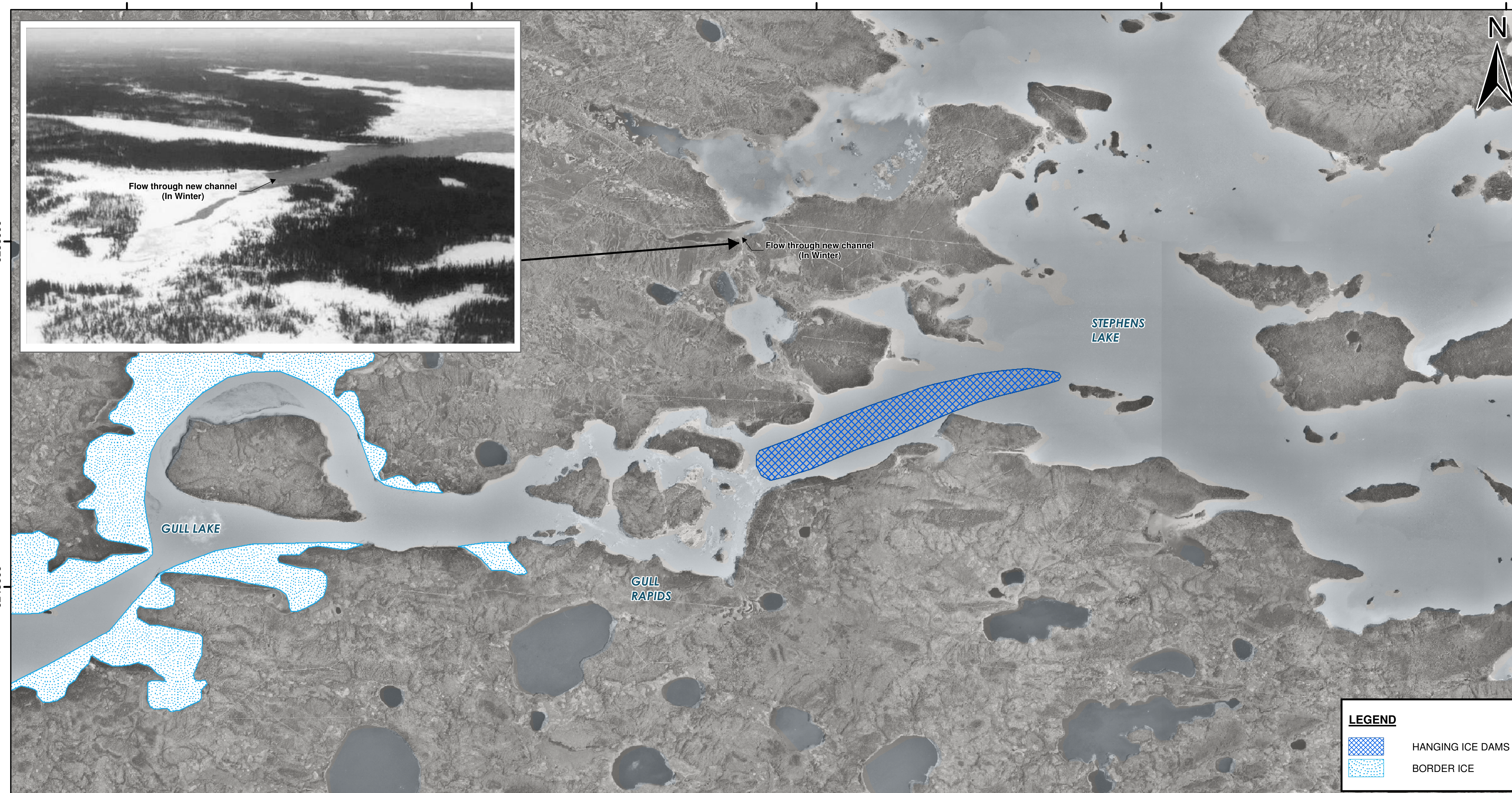


Figure 17: Hanging dam downstream of Gull Rapids (looking upstream)

Figure 18: Abrasion of ice along shoreline





KEEYASK

0 500 1,000 2,000 Meters
0 2,500 5,000 10,000 Feet

Projection: Universal Transverse Mercator Zone 15N, NAD 83

Data Source: Air Photos Provided by Manitoba Hydro 2006

Mapping grade, for general reference only.

Hanging Ice Dam Downstream of Gull Rapids Leads to Erosion of New Channel

Figure 19

Created By:
KGS ACRES

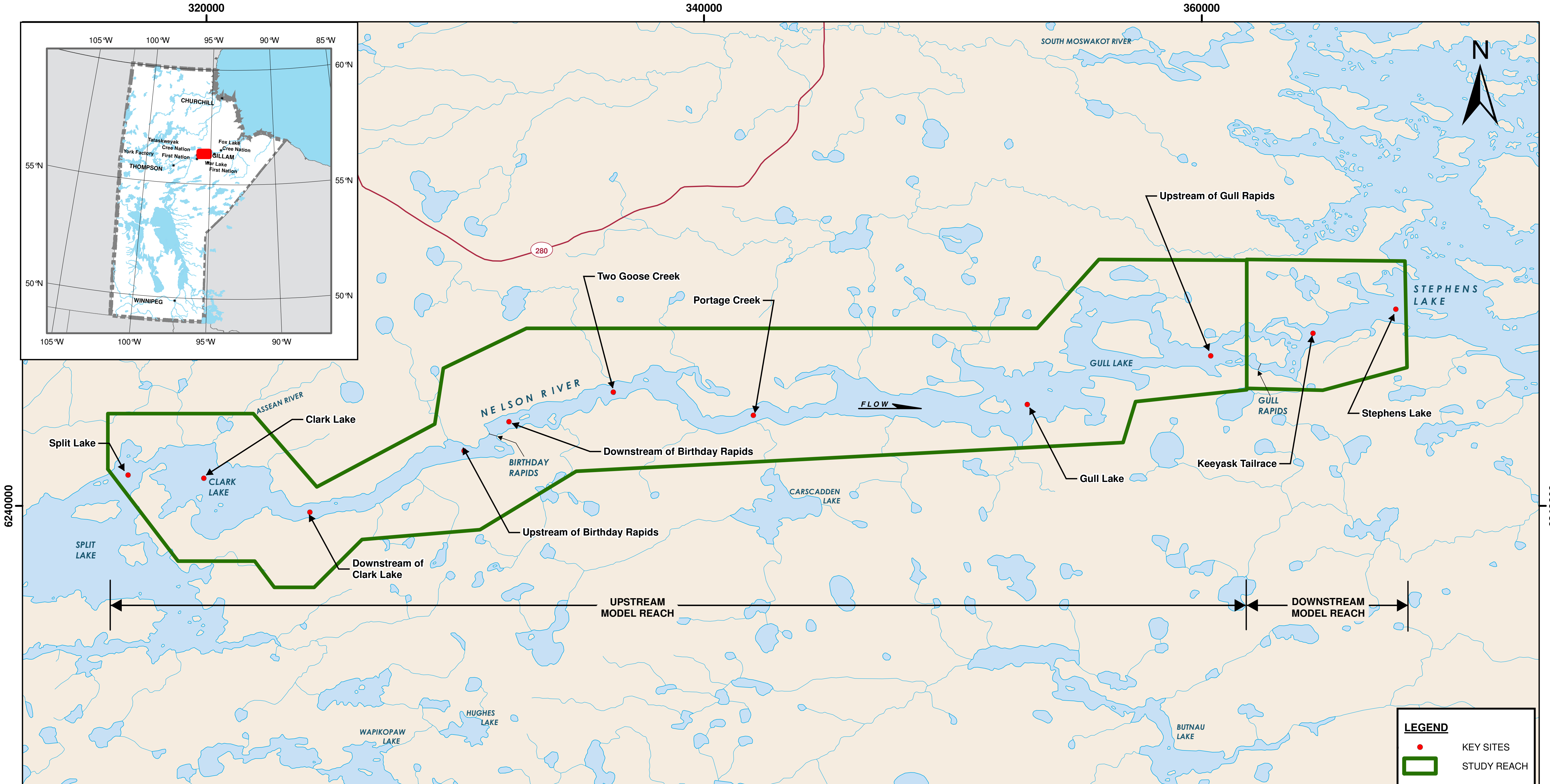
Date Created:
April 04, 2009

Figure 20: Initial breakup of river ice cover downstream of Birthday Rapids (looking downstream)

Figure 21: Movement of pack ice from reach downstream of Birthday Rapids (looking downstream)

Figure 22: Collapse of border ice onto shorezone

Figure 23: Remnant of pack ice on shore



KEEYASK

0 1,500 3,000 6,000 Meters

0 7,500 15,000 30,000 Feet

Projection: Universal Transverse Mercator Zone 15N, NAD 83

Data Source: Baseline lakes, rivers, roads, railway and transmission line, taken from NTDB maps 64A and 54D, 2005.

Mapping grade, for general reference only.

Key Sites Along Study Reach

Figure 24

Created By:
KGS ACRES

Date Created:
March 13, 2008

Figure 25
Nelson River Above Gull Rapids
Modeled Water Surface Profiles - Winter 2003/2004

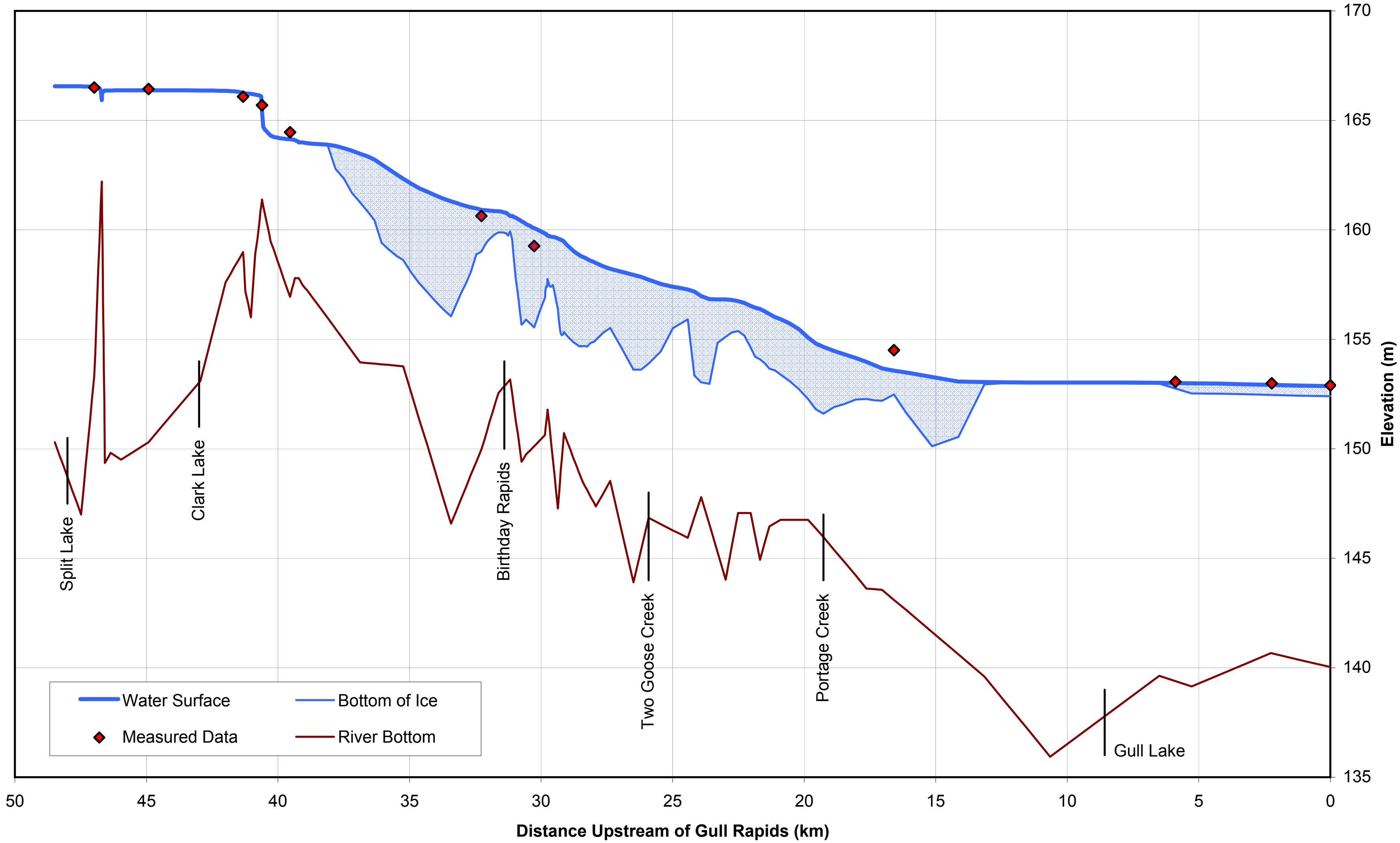


Figure 26
Nelson River Below Gull Rapids
Modeled Water Surface Profiles - Winter 1991/1992

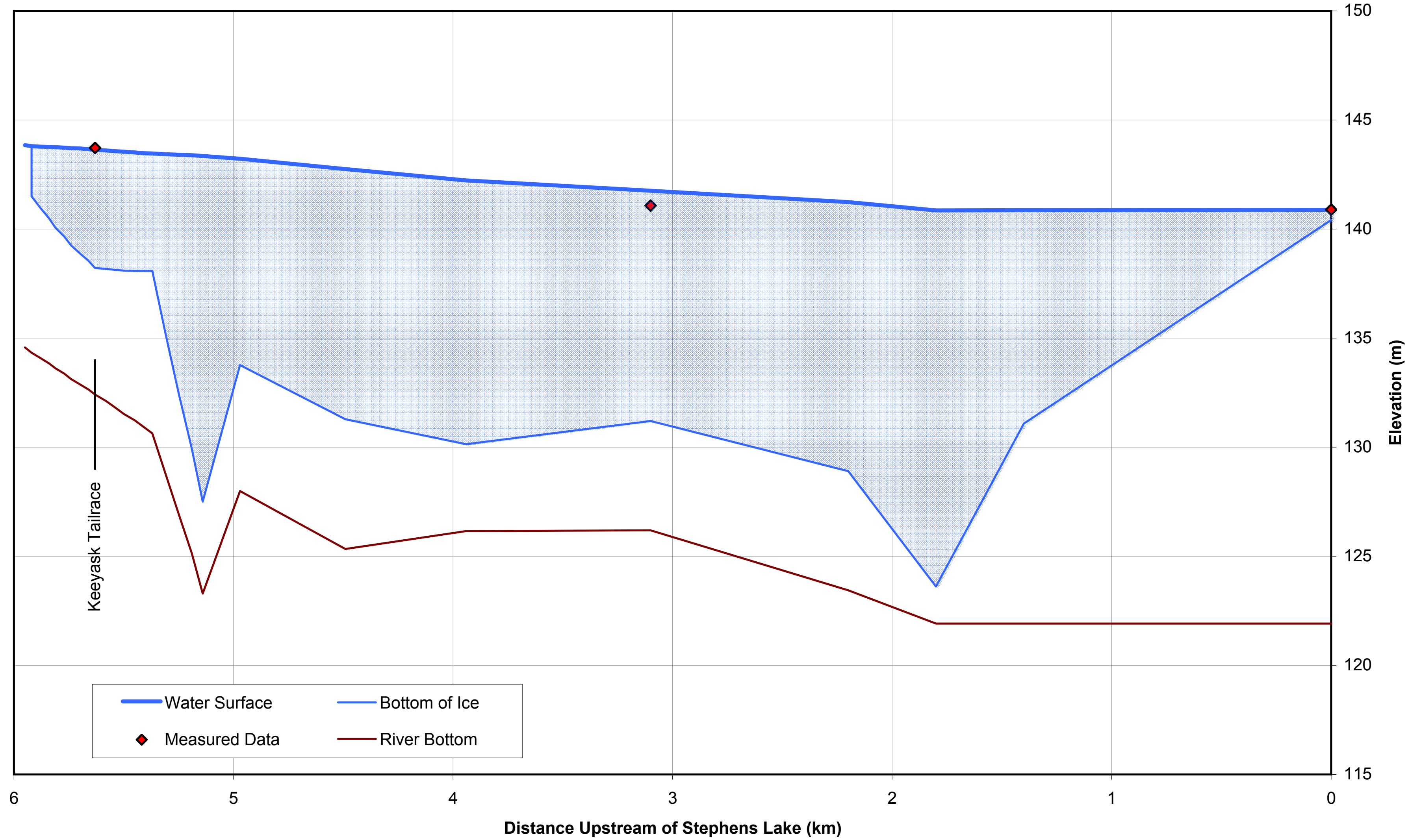
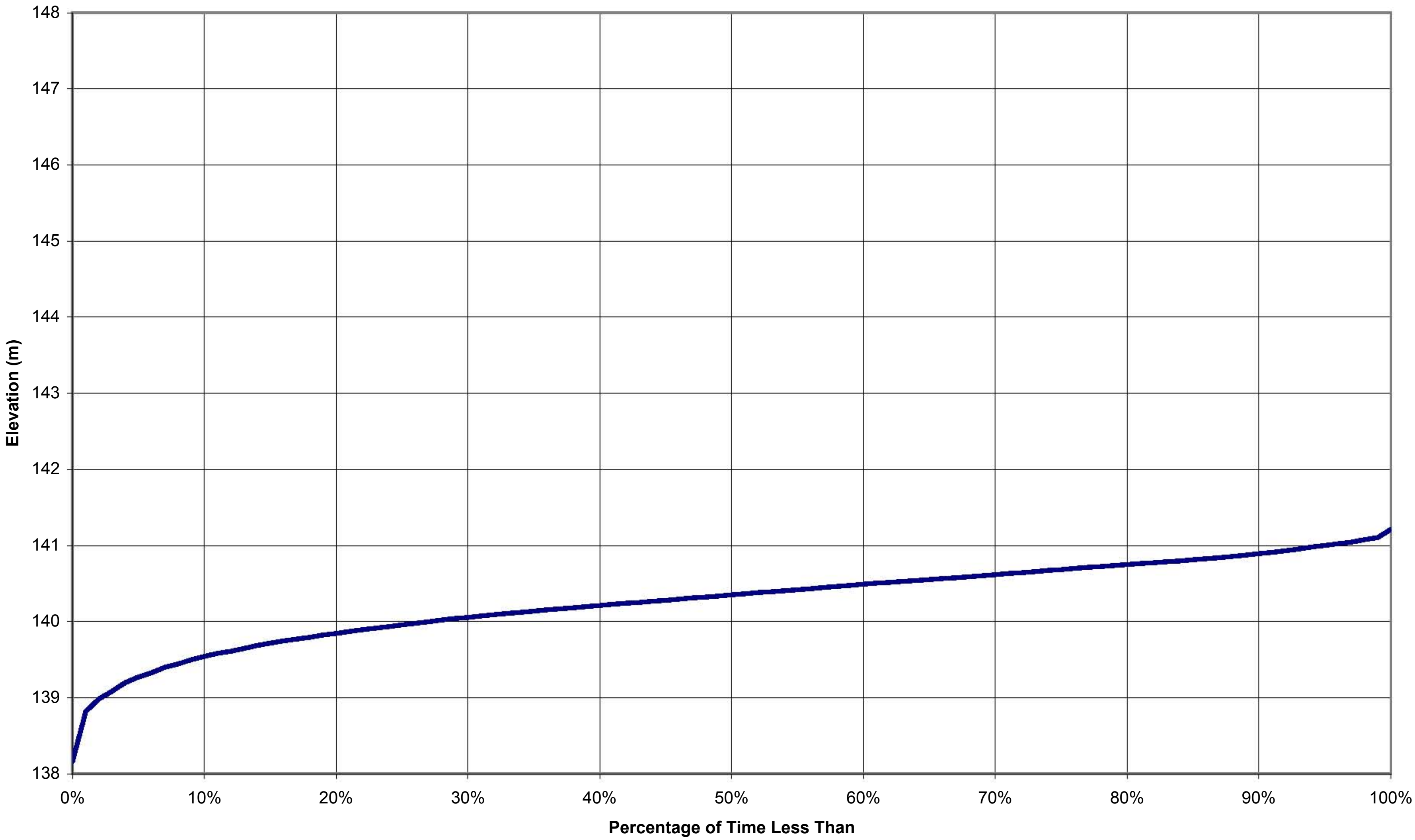
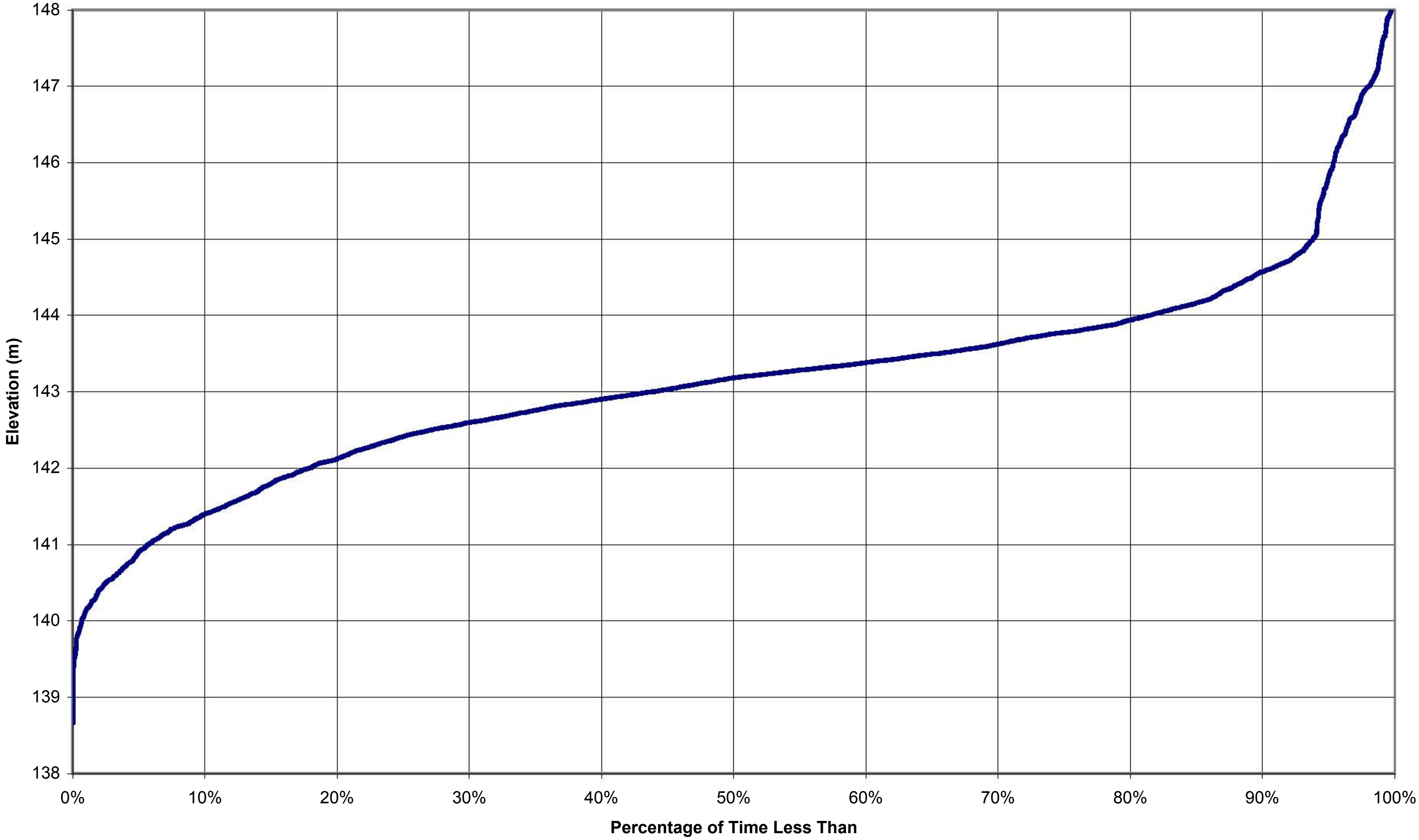


Figure 27
Nelson River at Stephens Lake - Existing Environment Winter Stage Duration Curve



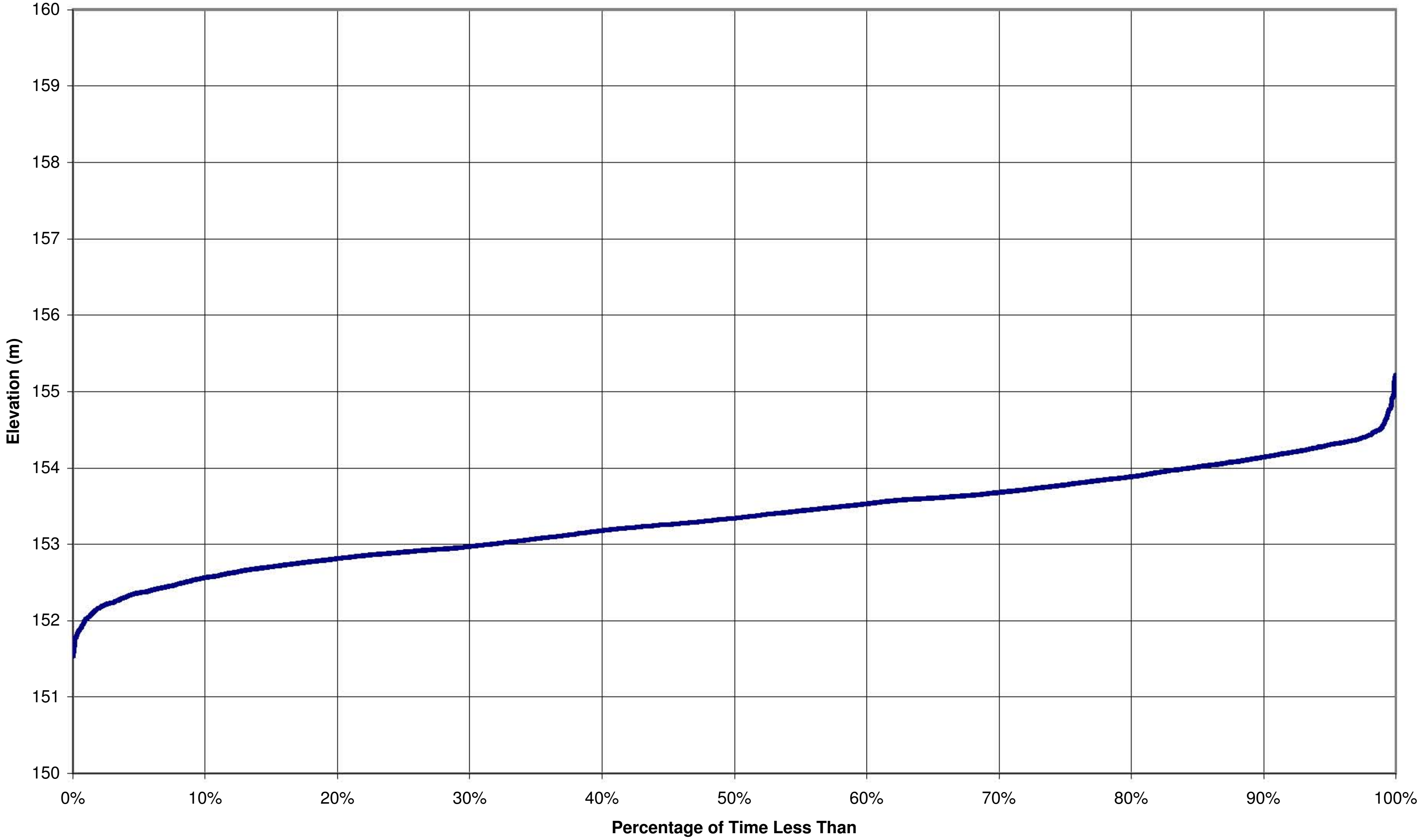
Note: Curve based on measured winter water levels between November 1 and May 1

Figure 28
Nelson River at Keeyask G.S. Tailrace - Existing Environment Winter Stage Duration Curve



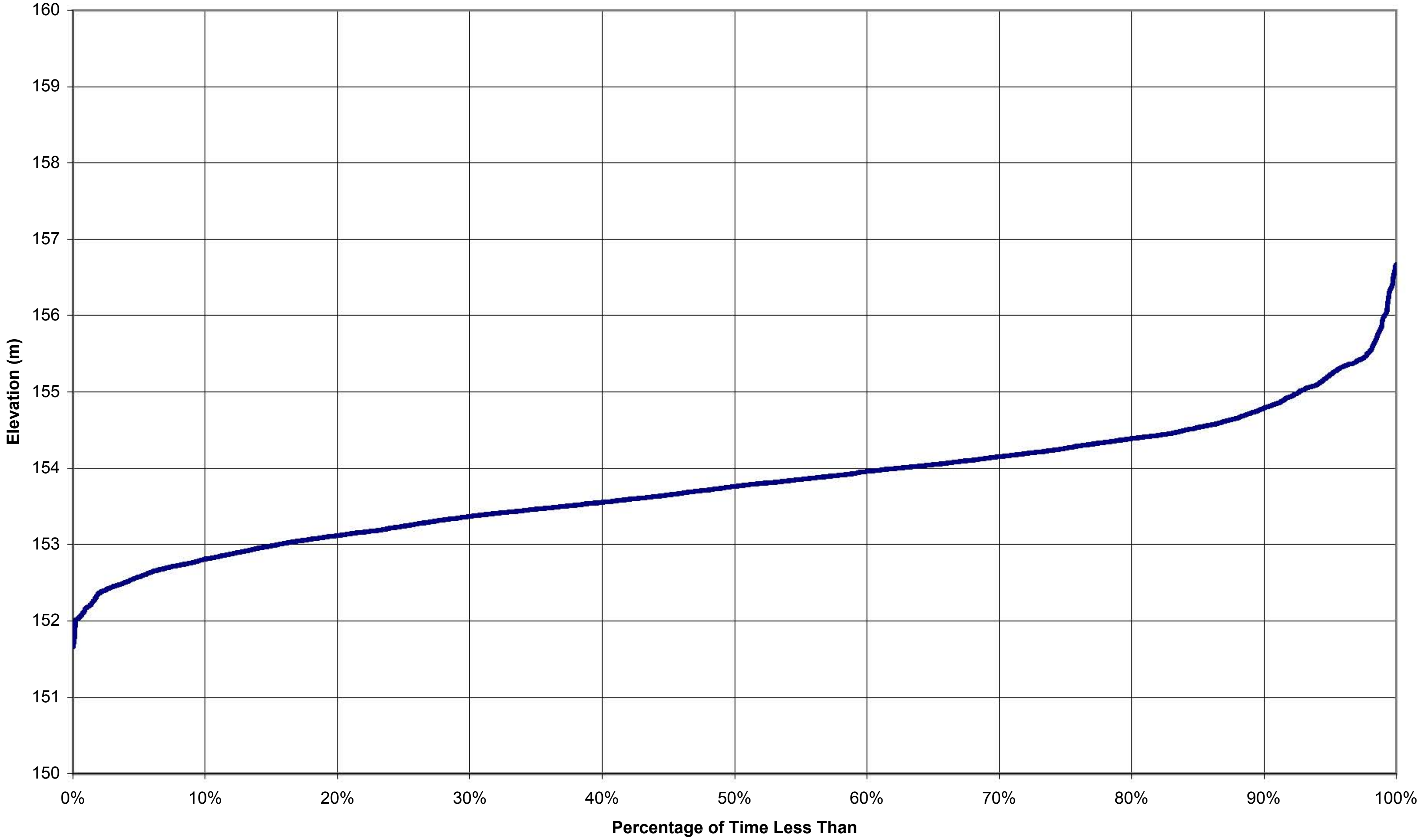
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 29
Nelson River above Gull Rapids - Existing Environment Winter Stage Duration Curve



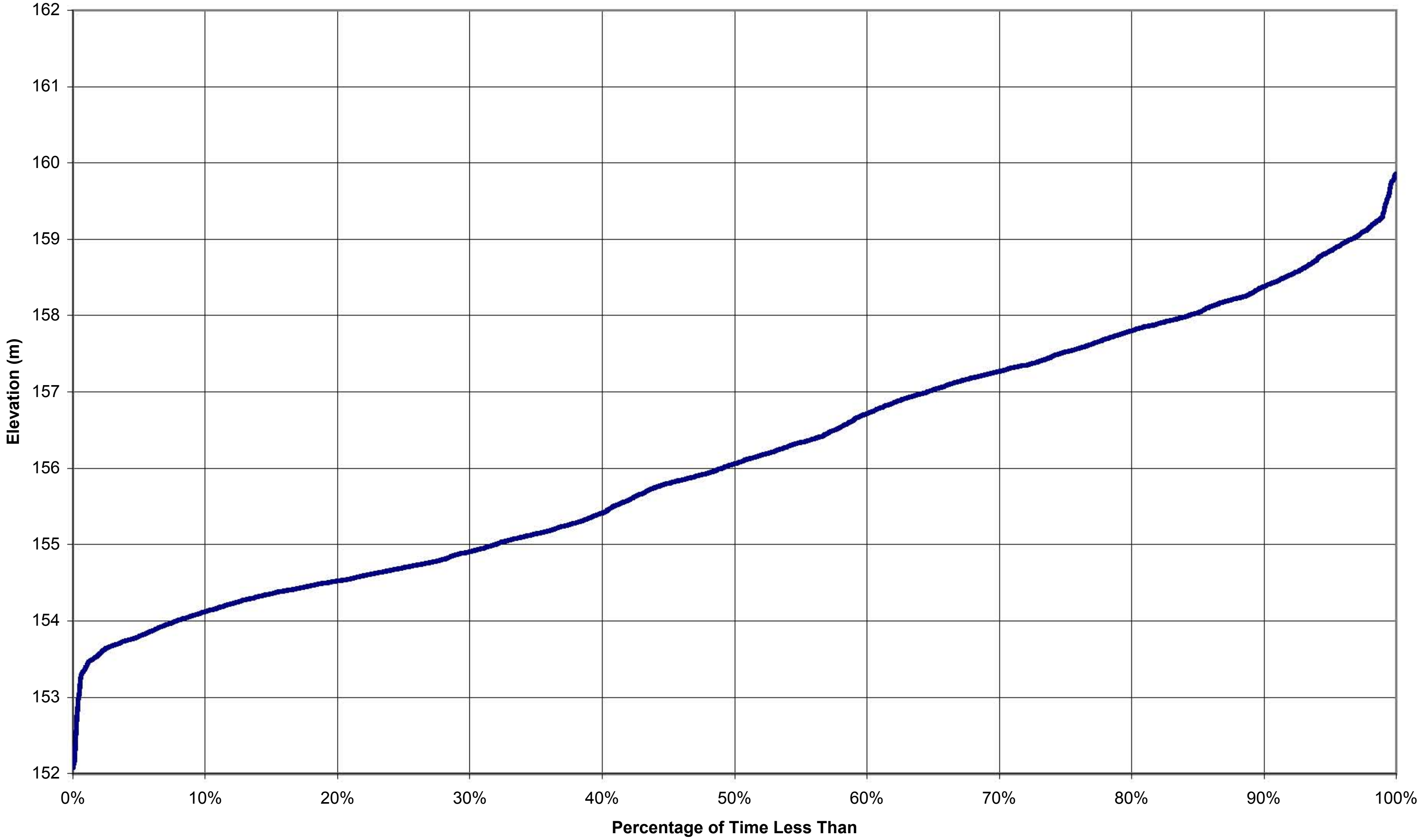
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 30
Nelson River at Gull Lake - Existing Environment Winter Stage Duration Curve



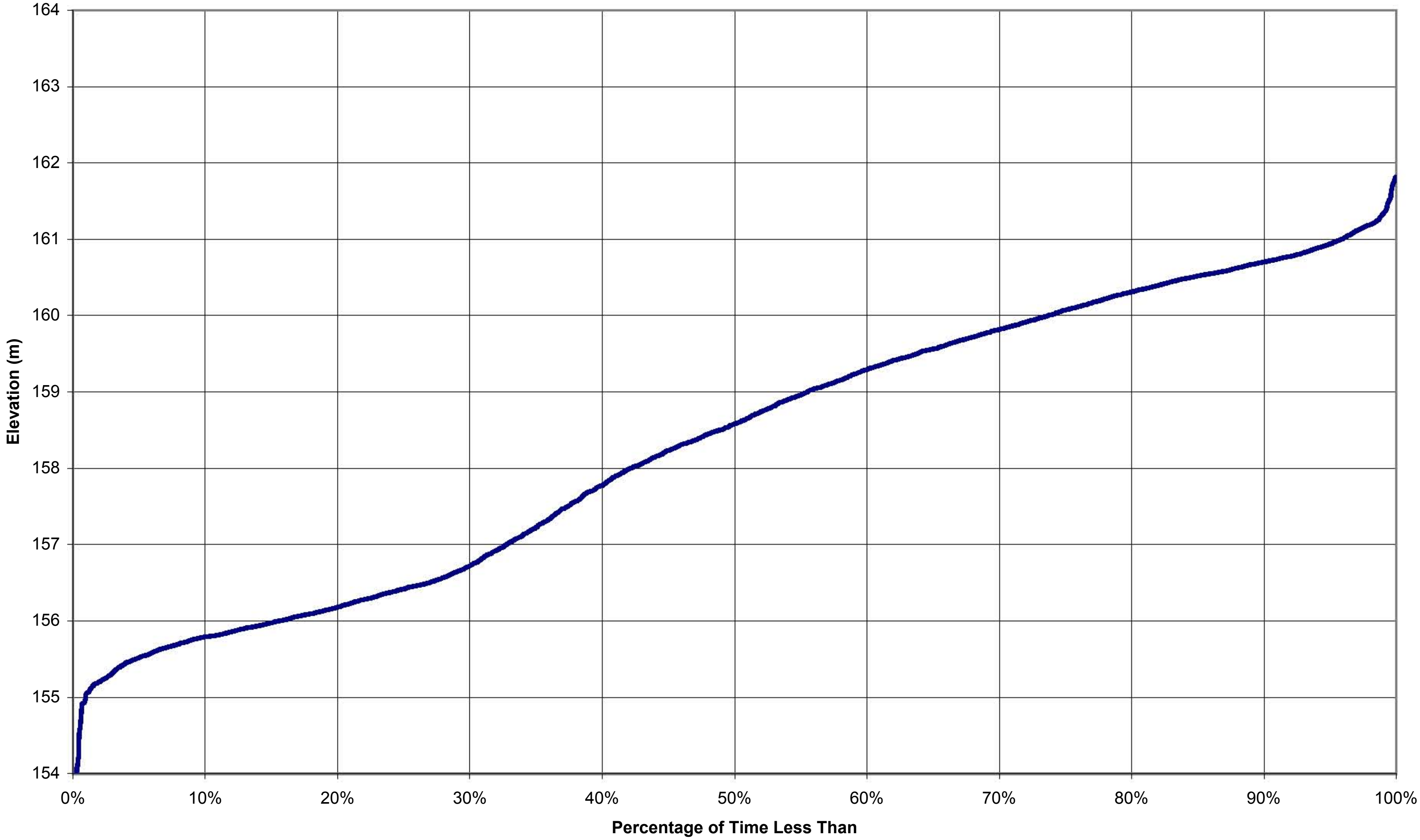
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 31
Nelson River at Portage Creek - Existing Environment Winter Stage Duration Curve



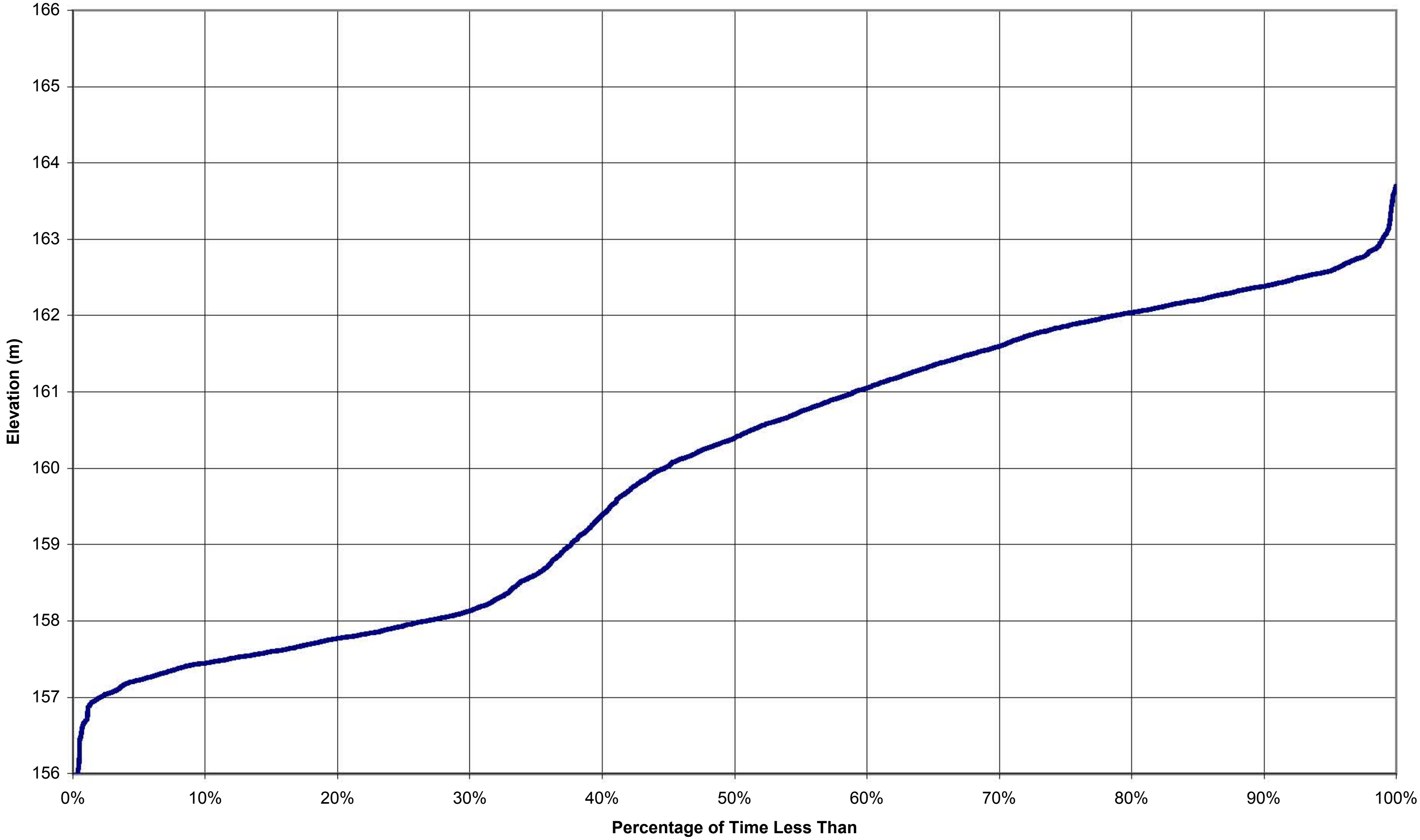
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 32
Nelson River at Two Goose Creek - Existing Environment Winter Stage Duration Curve



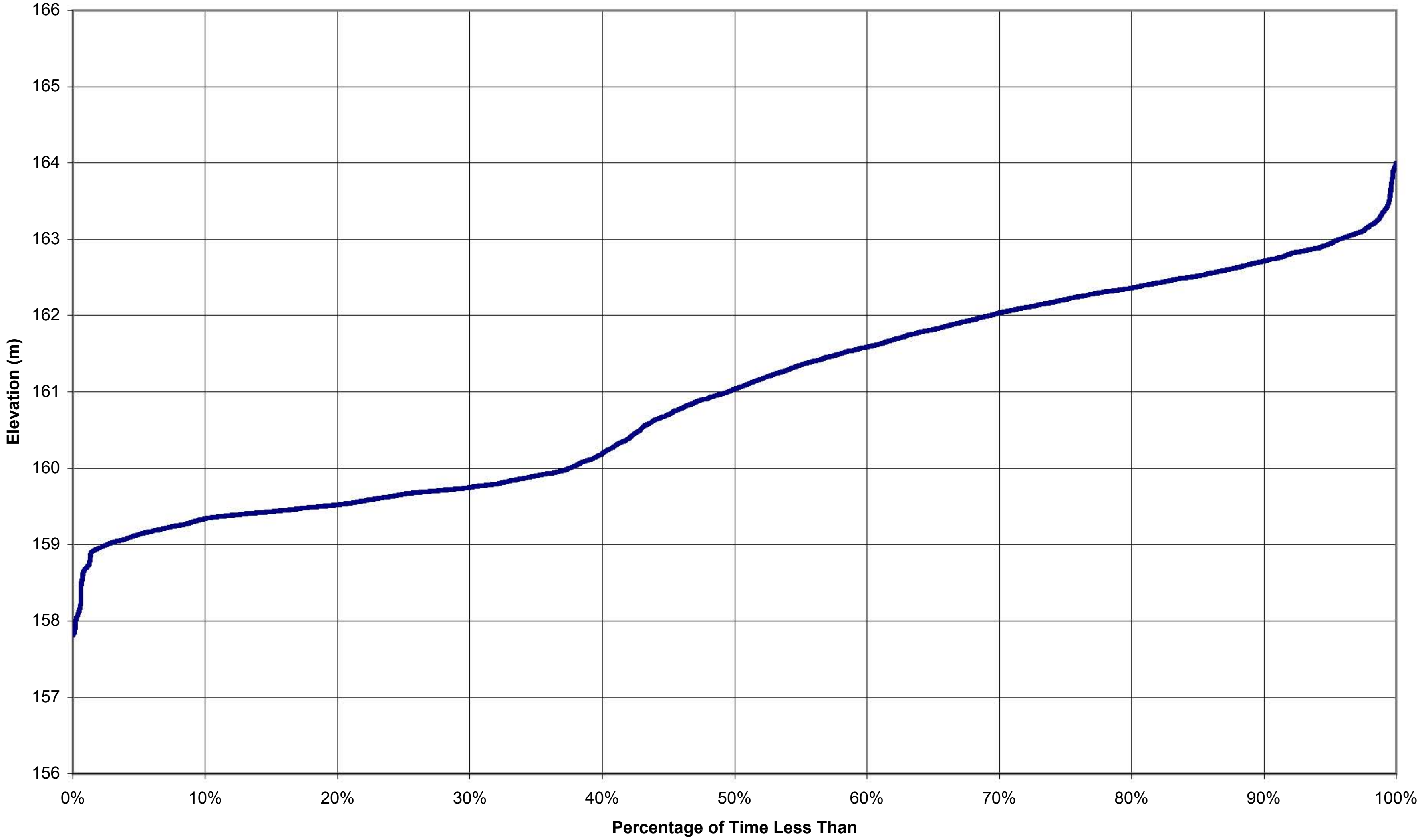
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 33
Nelson River below Birthday Rapids - Existing Environment Winter Stage Duration Curve



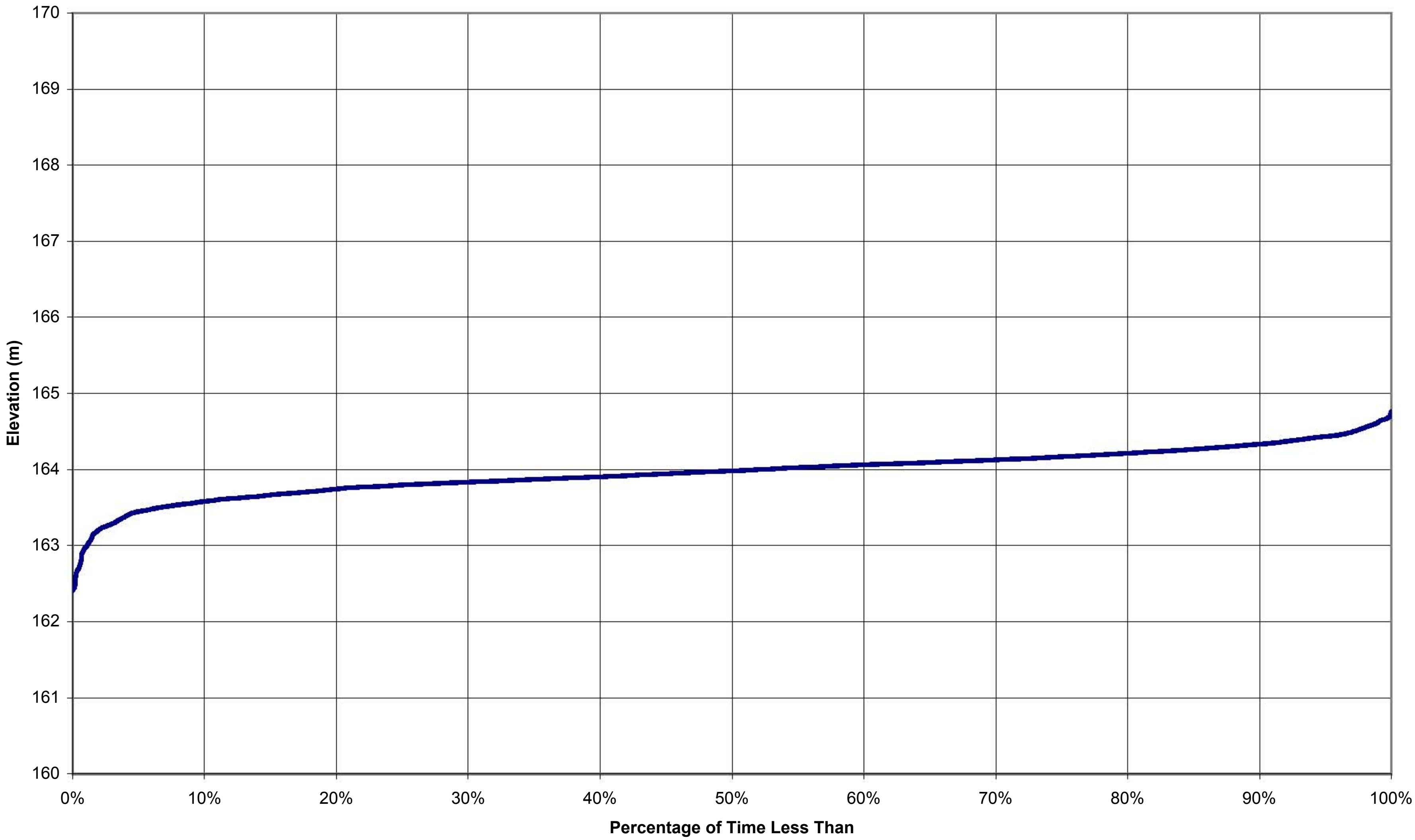
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 34
Nelson River above Birthday Rapids - Existing Environment Winter Stage Duration Curve



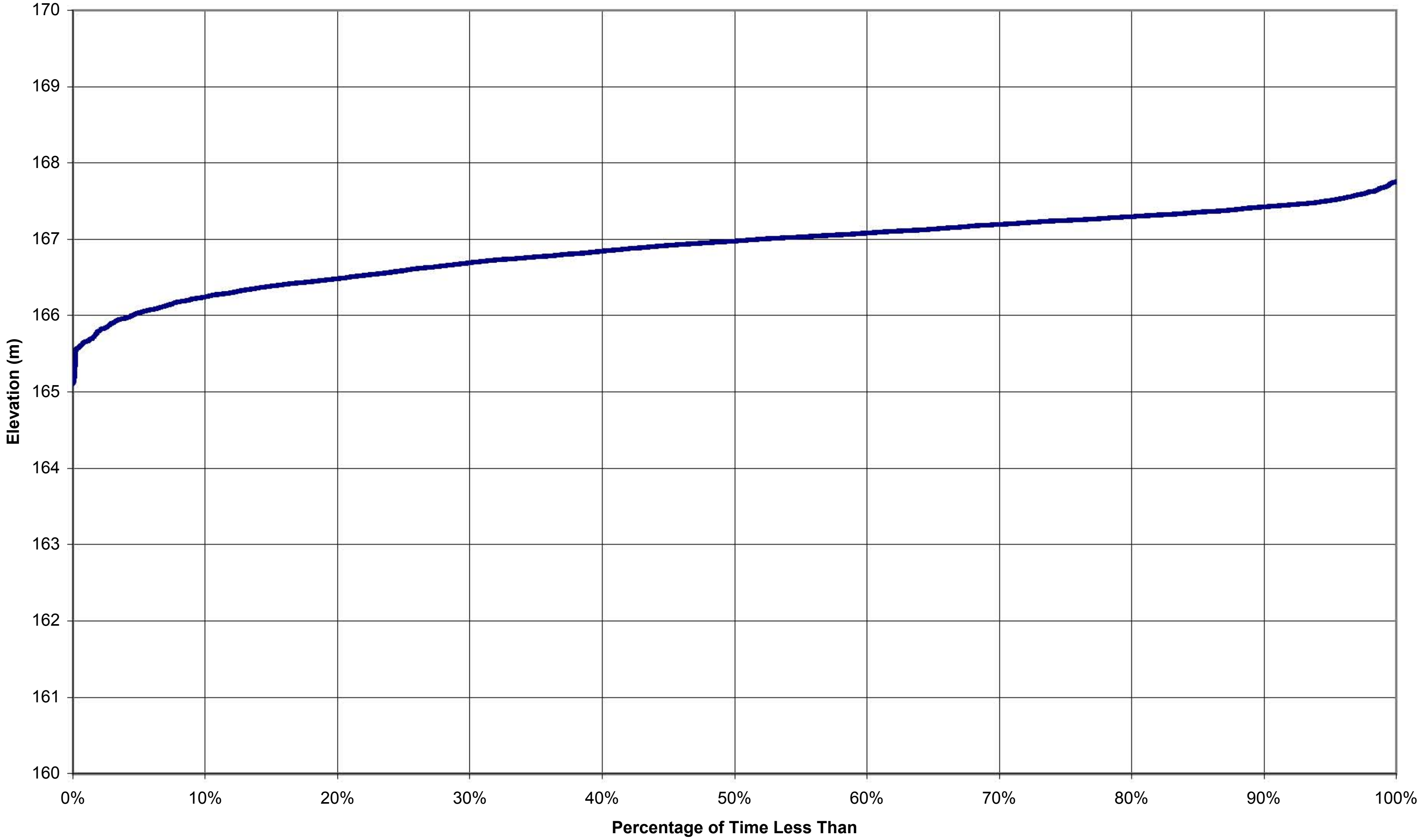
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 35
Nelson River below Clark Lake - Existing Environment Winter Stage Duration Curve



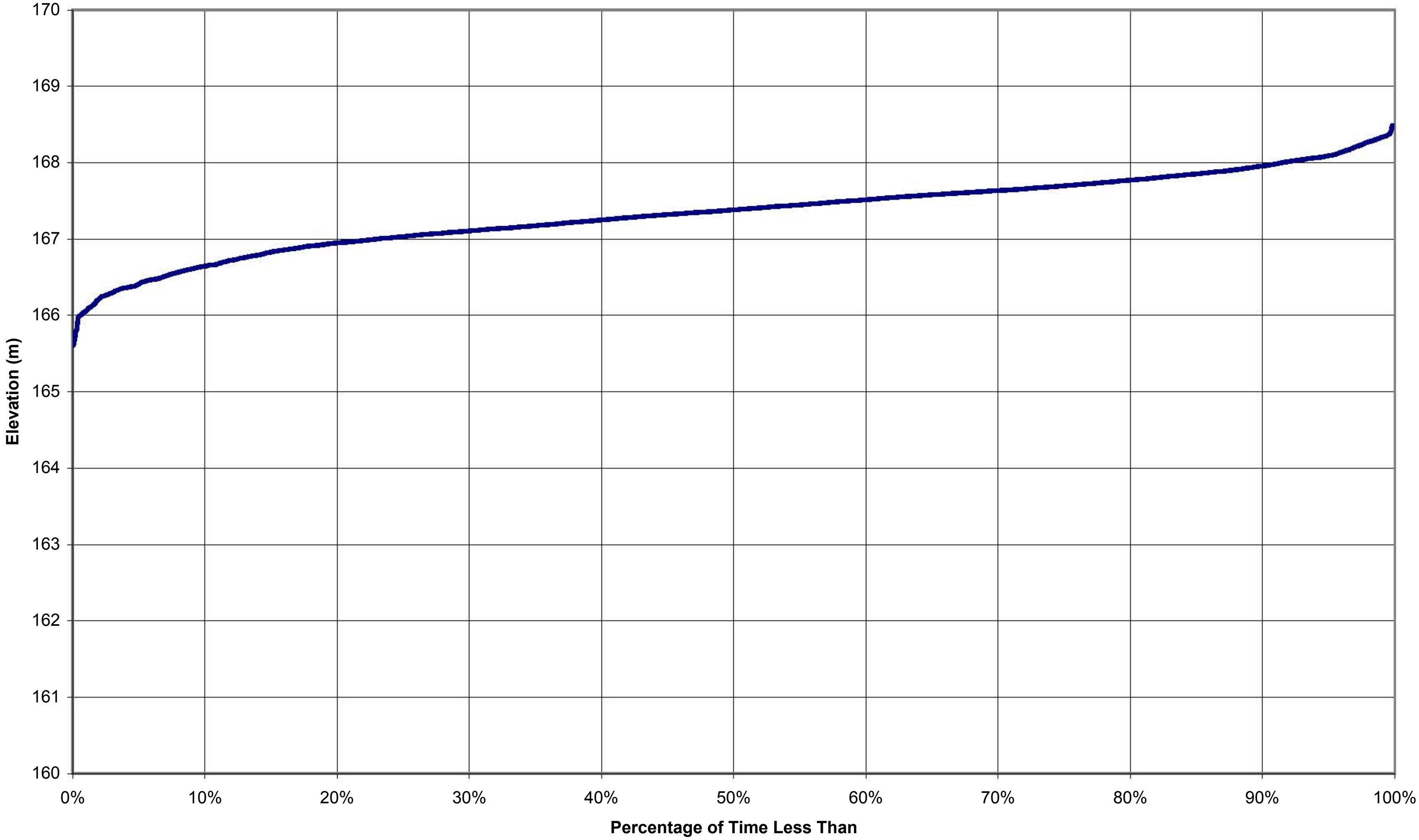
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 36
Nelson River at Clark Lake - Existing Environment Winter Stage Duration Curve



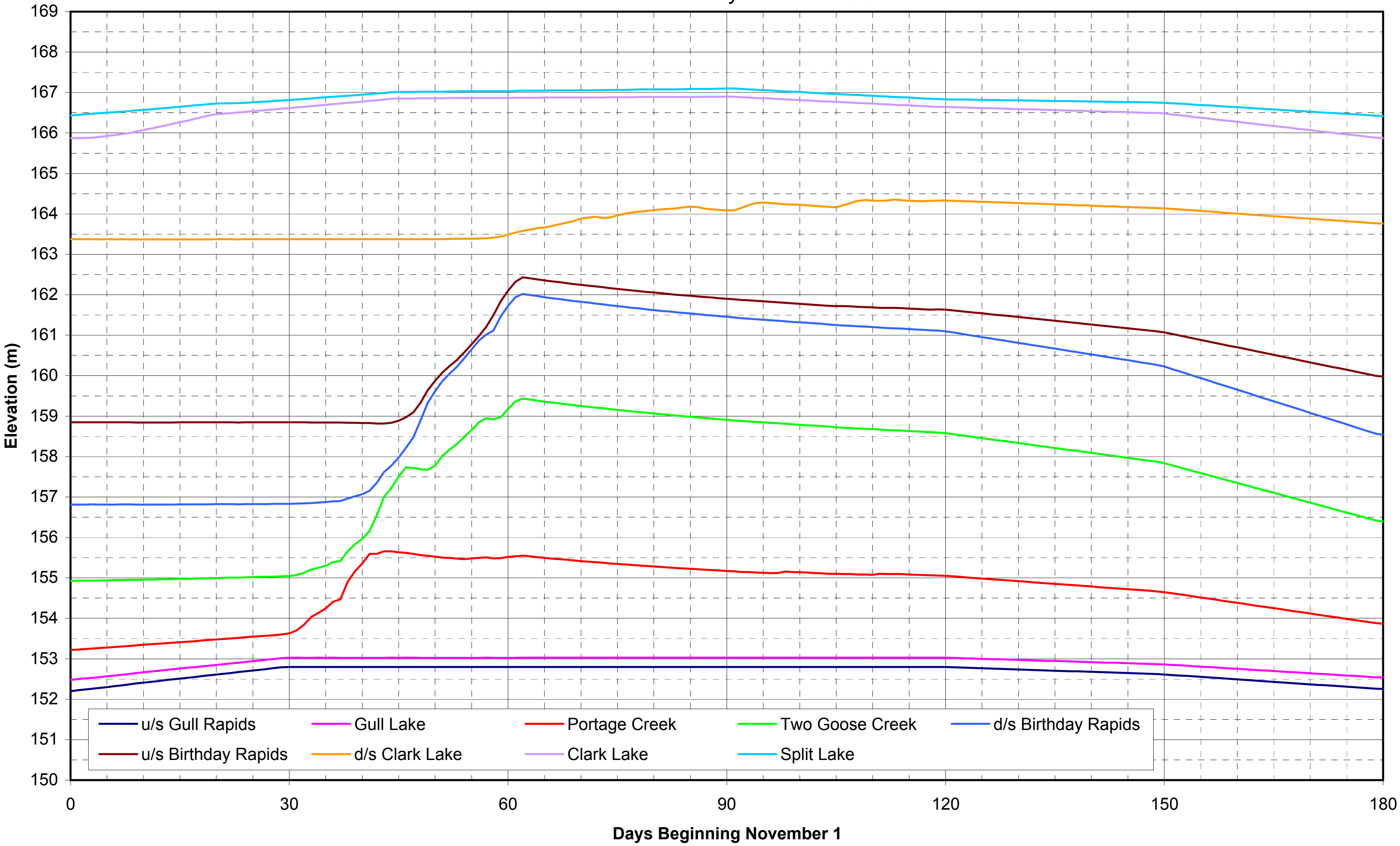
Note: Curve based on winter water level modeling between November 1 and May 1

Figure 37
Nelson River at Split Lake - Existing Environment Winter Stage Duration Curve



Note: Curve based on measured winter water levels between November 1 and May 1

Figure 38
Nelson River above Gull Rapids - Modeled Winter Stage Hydrographs
Future Environment without Keeyask G.S. - 5%tile Flow



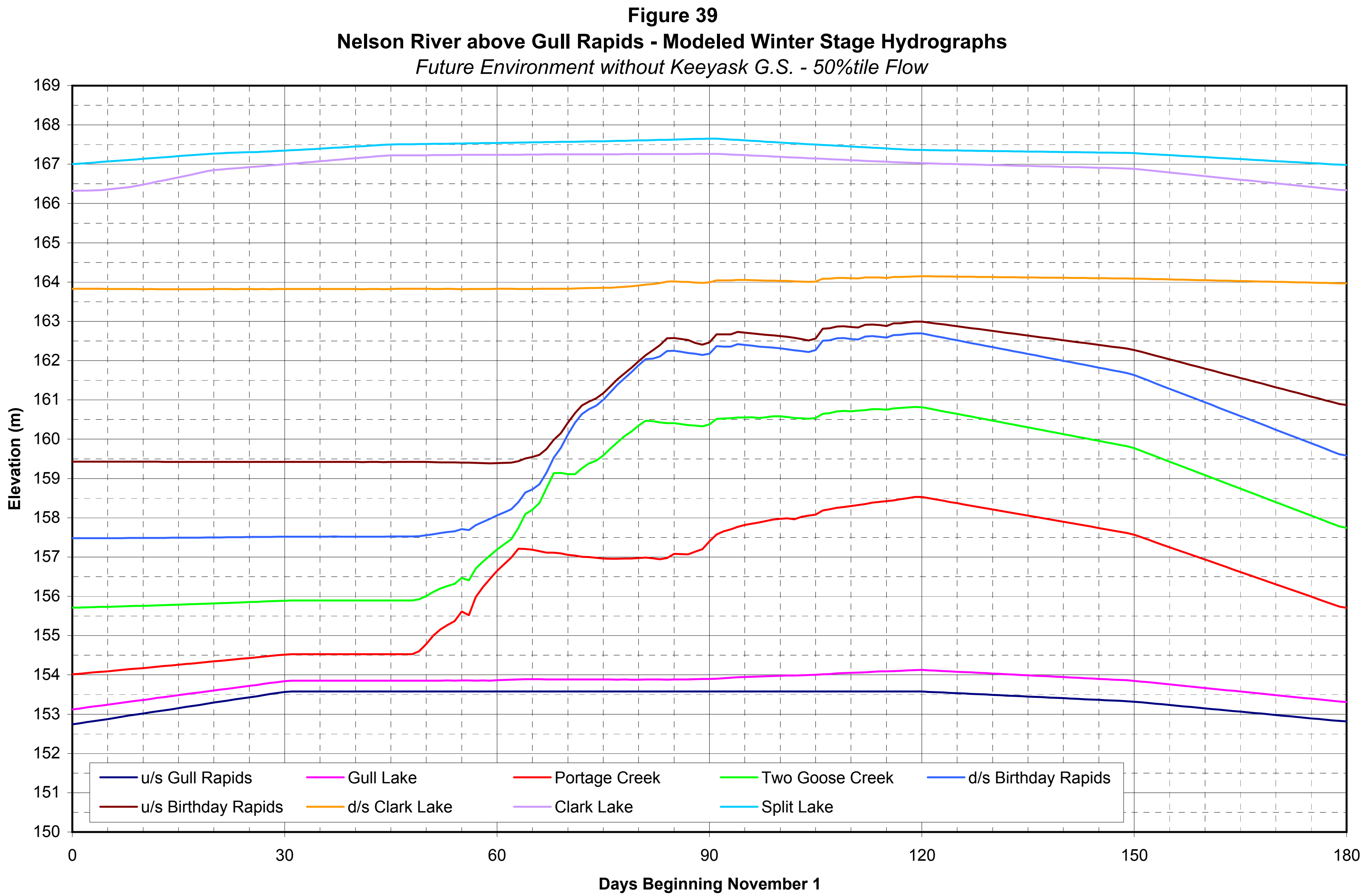


Figure 39
Nelson River above Gull Rapids - Modeled Winter Stage Hydrographs
Future Environment without Keeyask G.S. - 50%tile Flow
Elevation (m)
Days Beginning November 1
169
168
167
166
165
164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
0
30
60
90
120
150
180
u/s Gull Rapids
Gull Lake
Portage Creek
Two Goose Creek
d/s Birthday Rapids
u/s Birthday Rapids
d/s Clark Lake
Clark Lake
Split Lake

Figure 40
Nelson River above Gull Rapids - Modeled Winter Stage Hydrographs
Future Environment without Keeyask G.S. - 95%tile Flow

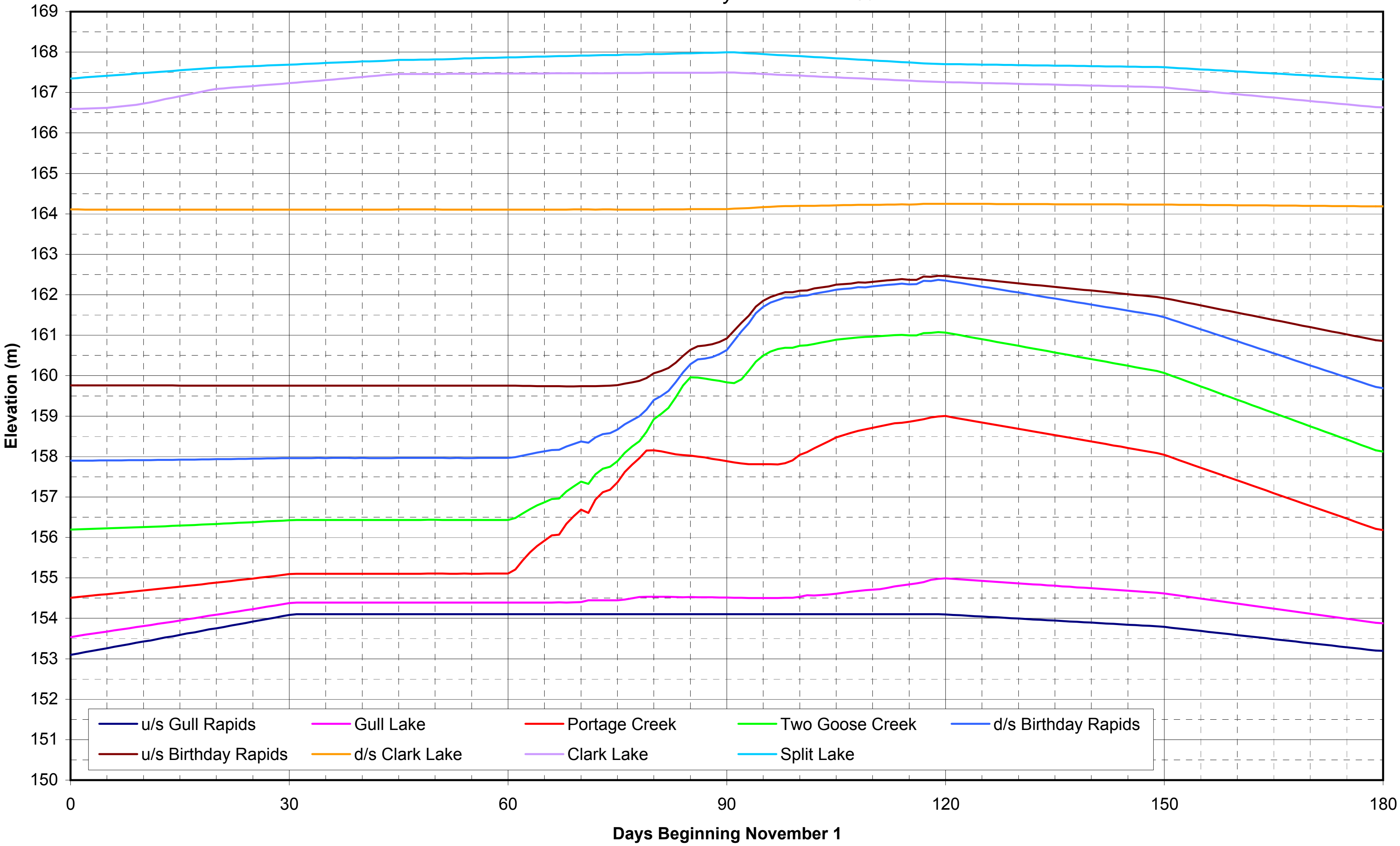
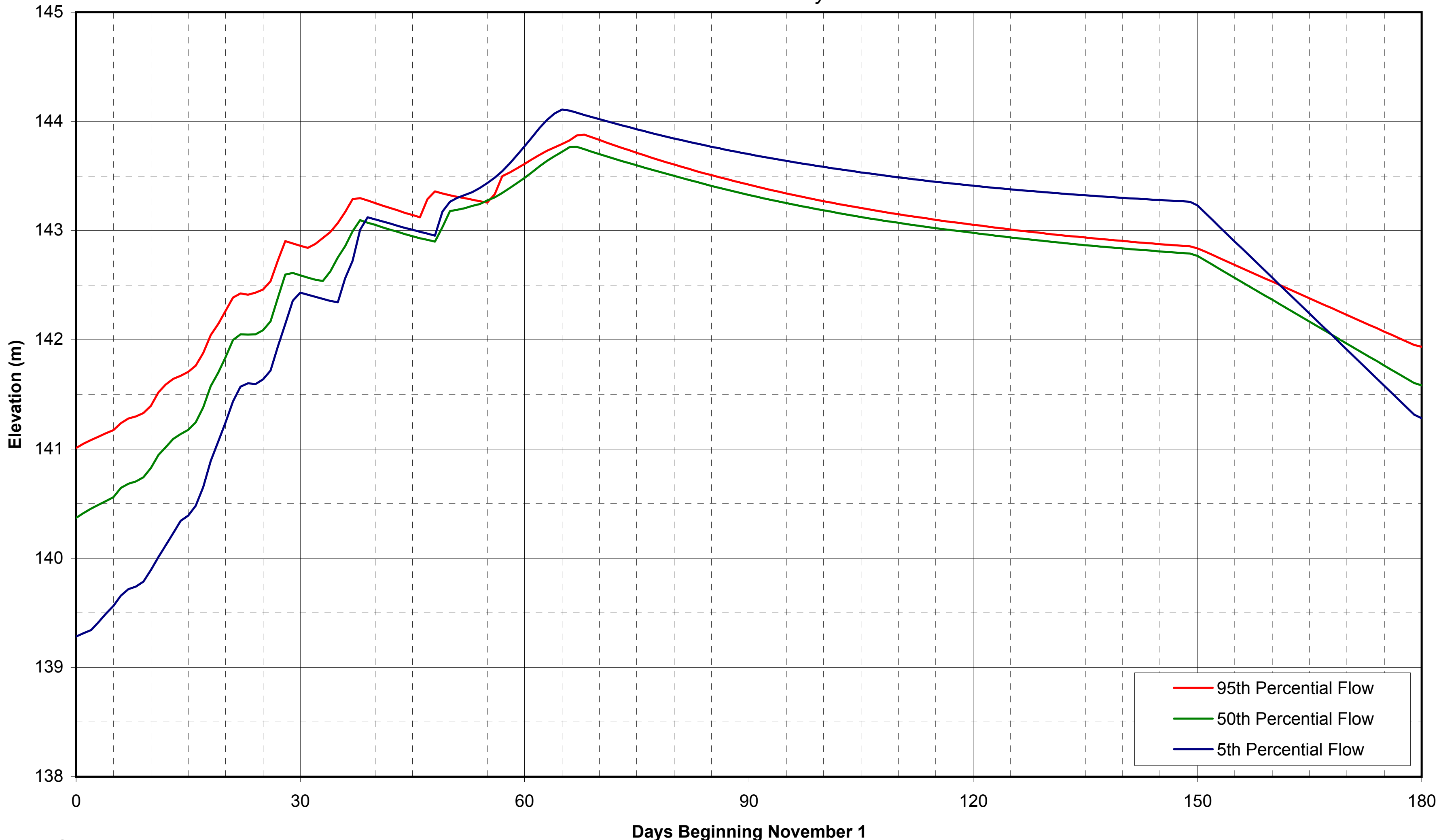


Figure 41
Keeyask G.S. Tailrace Location - Modeled Winter Stage Hydrograph
Future Environment without Keeyask G.S.



Note: 1. Stephens Lake levels assumed constant over simulation period.
2. Percentile level of Stephens Lake assumed to correspond to flow percentile under consideration (ie. 50th percentile level occurs with 50th percentile flow)

APPENDIX A - ABBREVIATIONS

ABBREVIATIONS

˚C ....degrees Celsius

D/S ....Downstream

FSL.............................full supply level

ft ....feet

ft^3/s ....cubic feet per second

G.S. ....generating station

km ....kilometre

m ....metre

m^3...cubic metre

m^3/s or cms.................cubic metres per second

U/S ....Upstream