BC Ministry of Forests, Lands and Natural Resource Operations

Fraser River June 2012, Looking East from Carey Point

Fraser River Design Flood Level Update – Hope to Mission FINAL REPORT

Flood Safety Section, March 2014

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FINAL REPORT

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March 2014

DISCLAIMER

This document was prepared to help the Inspector of Dikes establish dike design levels along Fraser River. However, there are many sources of uncertainty in both flood model inputs and the modelling process. Flood levels higher than the indicated design levels can occur and freeboard allowances may be insufficient to prevent dike overtopping. Floodproofing elevations for buildings and other development in the floodplain are established by and are the responsibility of local government and other development approval officials. These floodproofing elevations may vary from the flood profile plus freeboard elevations provided in this report.

EXECUTIVE SUMMARY

The first Fraser River MIKE 11 hydraulic model was developed by UMA consultants for the gravel reach (Laidlaw to Mission) in 2000/2001. The model was based on the LiDAR and bathymetry data collected in 1999. From 2006 to 2008, Northwest Hydraulic Consultants (NHC) was hired to develop the hydraulic model in the sand reach (Mission to ocean) of the Fraser River. The two models were used to establish the design profiles in the gravel reach and the sand reach respectively. Later, both models were merged to create a single integrated model which has been used as the freshet forecasting model since 2007.

The gravel reach of the Fraser River is very dynamic compared to many rivers in North America. The channel geometry keeps changing due to sedimentation, erosion, channel alignment shifts (avulsions) and ongoing river engineering works such as bridges, river training structures, dredging and gravel removal etc. These changes can result in both increases and decreases in design flood levels, so it is necessary to re-survey and update the hydraulic model at least every ten years. In 2008, the floodplain and the bathymetry of Fraser River were resurveyed from Hope to Mission. A completely new model was developed in-house by FLNRO staff based on the new datasets. NHC provided guidance and technical review of the model development work (Appendix 2).

The raw survey data included bathymetry data in the channel and LiDAR coverage of the floodplain. The raw survey data was then processed in ArcGIS to create a surface model (TIN) to extract x-sections at the most desired locations. The x-sections and channel network were then exported to create the new MIKE 11 one-dimensional model, which extended the full reach from Mission to Hope.

In the first phase, the model was calibrated and validated for 2007 and 2011 data respectively. The validation showed differences near Herrling Island. It was suspected that the major channel shift (avulsion) that took place near Herrling Island in 2009 likely triggered a significant channel geometry change in this area. To verify this hypothesis, the reach near the avulsion was re-surveyed in 2010. Subsequently, the surface model and the x-sections were revised in this area. The revised model showed some improvements but the results were still not satisfactory. It was then decided to collect bathymetry data for a longer reach to capture more of the channel changes related to the avulsion.

In 2012, the bathymetry was collected again from Big Bar to Tranmer Bar. Since the 2012 freshet was the 5th largest freshet in the known history of Fraser River, the bathymetry data was collected after the freshet to capture the most recent changes that may have resulted during the freshet. In addition to the bathymetry data, an extensive set of water level and flow data was also collected. This data included a continuous longitudinal water level profile from Hope to Mission at near the peak flow, observed water levels at approximately 44 gauges (including seven new continuous gauges), three sets of flow split measurements at approximately 34 locations at varying flows and ortho-photos from Hope to the ocean during the high flow period.

To take advantage of the data collected during a high freshet, the model was re-calibrated for the extensive 2012 dataset. The flows used for calibration were taken from Water Survey of Canada (WSC) gauges at Hope and Harrison River. Observed WSC flows were not yet finalised at the time of calibration and preliminary values were used. The model was validated for 2011 and 2007 data. Based on the differences between the observed and simulated water levels at peak flows, the model accuracy is estimated to be +0.1 m on average. Some local differences of up to 0.43 m were observed for hydraulically complex areas such as on the left (south) bank of the river just downstream of the Agassiz Rosedale Bridge. These differences are mainly due to the 1-D limitations of the model for areas where the flow patterns are strongly 2 and 3 dimensional. However, overall, the model performance was satisfactory.

The new upper (Hope to Mission gravel reach) model was merged with the existing lower (Mission to ocean sand reach) model to establish the new design profile. Comparison of the new profile was then made with the old design profile. Even though the new model was created with entirely new survey data and had a different layout than previous model, the differences between the two profiles, with a few exceptions, were within ± 0.2 m. The new profile is lower by about 0.35m near Harrison Knob (just downstream of the confluence of the Harrison River), about 0.5m lower from Big Bar to Agassiz Rosedale Bridge(just downstream of the bridge), about 0.2 m lower near Herrling Island, 0.2-0.3 m lower near Wahleach and about 0.2 m higher near Peters Island.

Harrison Lake was added to the merged model to be used as the freshet forecasting model. The flow data from a new gauge at Tenas Narrows on the Lillooet River upstream of Harrison Lake were used as boundary conditions for testing the merged and extended model.

The new dike design profile for the Hope to Mission reach is primarily based on the new model flood level profile. However, for short reaches where the new model profile is lower than the old model profile and the differences are considered to be caused by changes in channel geometry, the old (higher) water levels were adopted as the dike design level. This approach is necessary to cover the possibility of future channel change and higher flood levels.

There are 15 dikes totalling 146 km in the Hope to Mission reach. A dike crest elevation assessment was conducted by comparing the existing dike crest profiles with the new design profile. To ensure that dike crest elevation data was up to date, the ministry hired a contractor in March 2014 to complete a survey of many of the dikes in the gravel reach. This survey excluded the City of Chilliwack dikes as the City had updated their survey in 2013.

Most of the dikes were found to have inadequate freeboard and are at high risk of over topping during a design flood event. Within the study area, only the Matsqui B dike generally meets design level and freeboard requirements.

CREDITS AND ACKNOWLEDGEMENTS

This project was conducted under the leadership and guidance of Neil Peters, P.Eng. of the BC Ministry of FLNRO. John Pattle, P.Eng. of FLNRO also provided support, information and guidance on the project. Hydraulic modeling along with processing of its GIS components was carried out by Khalid Wasey Khan P.Eng. of Flood Safety Section, FLNRO. Other staff from FLNRO, who contributed to the model development and quality assurance from time to time between 2010 and 2013 include: Lotte Flint-Petersen P.Eng., Sandra Jensen, Jim Ziemba, Ashfaque Ahmed, P.Eng., Khaled Akhtar, P.Eng. and Abdullah Mamun E.I.T. The cooperation of all gauge operators during 2011 and 2012 freshet for collecting water level data was also highly appreciated.

The model development was conducted under the technical supervision of Northwest Hydraulic Consultants (NHC). Key staff involved were Monica Mannerstrom P.Eng., Vanessa O'Connor P.Eng., Tamsin Lyle P.Eng., who provided technical guidance and reviewed the model development; Darren Ham, PhD, Geomorphologist, who provided guidance and reviewed the surface model development; and Sarah North GISP, who helped with the GIS component of the project. The Final Report was prepared by Khalid W Khan P.Eng. of FLNRO.

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1. INTRODUCTION

Fraser River is the largest river flowing to the west coast of British Columbia. It starts at Mount Robson and drains a catchment of around 235,000 km^2 (almost one quarter of the province) to the west of the Rocky Mountains. It travels more than 1,100 km before reaching the ocean at Georgia Strait. The river follows a steep course through the mountains and plateau where it picks up gravel and finer sediment. The river slope abruptly declines near Sumas Mountain greatly reducing the river's gravel transport capacity. Most of the gravel is deposited in islands and gravel bars in the 82 km long Hope to Mission reach, known as the "gravel reach".

UMA (2000) summarized the hydrology of four main tributaries to Fraser River from Hope to Mission. These are Harrison River, Chilliwack River, Chehalis River and Silverhope River with catchment sizes of 7,870 km^2, 1,230 km^2, 383 km^2 and 350 km^2 respectively. With Harrison River being the most significant contributor, these tributaries all together can typically contribute from 5% to 15% of the summer freshet flows. Peak flows of Fraser River are usually snow generated but sometimes can be a combination of snowmelt and rainfall. It always peaks during summer generally during the period from May to mid July. The peak flows of Harrison River are mainly generated from snowmelt but it generally peaks after Fraser River has seen its peak at Hope. Harrison River is back-watered from Fraser River at its high flows and thus Harrison Lake comprises an important storage component during large floods. The Chilliwack and Chehalis rivers generally peak in the fall/winter, however, Chilliwack River's peak is sometimes related to snowmelt in summer.

The first Fraser River MIKE 11 hydraulic model was developed by UMA consultants for the gravel reach (Laidlaw to Mission) in 2000/2001. The estimated flow of the 1894 flood event was used as the design discharge. The model was based on 1999 survey data. From 2006 to 2008, Northwest Hydraulic Consultants (NHC) was hired to develop the hydraulic model in the sand reach of the Fraser River. Both the models were independently used to establish the design profile in the gravel, and sand reaches, respectively. Later, the sand reach model was merged with the gravel reach model to create a single integrated model as a forecasting tool which is used every year to predict 5-day water levels during the freshet.

Fraser River is very dynamic in nature. Its channel geometry keeps changing due to sedimentation, erosion and ongoing river engineering works such as bridges, river training structures, dredging and gravel removal. The dynamic nature of the river demands that the model be kept up-to-date over time. In 2008, the floodplain and the bathymetry of Fraser River were resurveyed from Hope to Mission. Starting in 2010, a new gravel reach model was developed and merged with the existing sand reach model. The new model was extended all the way up to Hope Bridge and was calibrated for 2012 data. A large set of water level and flow data was collected during 2012 freshet which was used in the calibration process. After calibration, the model was successfully validated with 2011 and 2007 data. For the design run, the same flows at Hope and the gravel reach tributaries were used as those used in 2000 and 2008 model.

In order to meet the long term goal of MFLNRO to develop expertise in developing and maintaining the Fraser River Hydraulic Model, the Flood Safety Section undertook the task to develop the new model in-house. Throughout the project, NHC played the role of a mentor and provided guidance and technical review of the model development work from the start to the final phase of generating the new design profile. NHC's letter of endorsement is attached as Appendix 2.

1.1 SCOPE OF WORK

The Fraser River reach modelled in this study extended from Hope Bridge to Mission – a river length of approximately 82 km. The model also includes Harrison River and lower reaches of Sumas and Vedder River for calibration and design flow scenarios. Harrison Lake was added for the forecasting model only. The project's scope of work was as follows:

1. Process raw LiDAR and bathymetry data in ArcGIS to create a surface model in order to extract the x-sections at appropriate locations.
2. Export Channel network and x-sections from ArcGIS to MIKE 11 format.
3. Set up 1-D MIKE 11 hydrodynamic model.
4. Compile water level and flow data for 2011 and 2012 freshet.
5. Calibrate the model with 2012 data.
6. Validate the model with 2011 and 2007 data.
7. Merge the new upper model with the lower (sand reach) model and run it for the design flow of 17000 m^3/s at Hope.
8. Update the design profile in gravel reach and compare it with the old design profile.
9. Add Harrison Lake to the merged model to create the forecasting model.
10. Compare existing dike crest elevation data with the new dike design profile.

1.2 REPORT OUTLINE

This report presents the process for updating the Fraser River Hydraulic model in the gravel reach. It discusses model calibration and validation and the limitations of the 1-D nature of the model. The updated design flood profile in the gravel reach is presented and compared with the old design profile. Dike crest elevation data are compared to the updated profile.

Section 2 describes the methodology of processing the LIDAR and bathymetry data in GIS and transforming them into MIKE 11 modeling environment. Section 3 summarizes the data collected during 2012 freshet. Section 4 describes model calibration and validation. The model results and the dike crest comparison are discussed in section 4 followed by a discussion of the forecasting model in Section 5. Conclusions and recommendations are presented in section 6.

2. SURVEY DATA PROCESSING

In 2008, the channel and floodplain of the Fraser River were surveyed again. The LiDAR data was collected from Hope to Mission for the floodplain, islands and gravel bars above the water level. Since, the LiDAR technology used was not advanced enough to penetrate through water surface, bathymetry transects were conducted to capture the channel bed levels. The two datasets were integrated together into a more useable format using techniques described later. Colour orthophotos having a resolution of 20 cm were also collected.

The bathymetry data was collected by Public Works and Government Services Canada at the request of the Ministry of Public Safety and Solicitor General, Emergency Management BC. The sounding data was collected in June 2008. Echo soundings were performed along the cross lines every 100m to 200m on the Fraser River and its navigable side channels from Hope to Mission. In the side channels which were too narrow to run the cross lines, long lines were run. The echo sounder used was a Knudsen 320M which operated on 200 kHz transducer. The final data was delivered as a digital XYZ in ASCII format with soundings thinned to 1m apart. The expected horizontal accuracy, relative vertical accuracy and absolute vertical accuracy were less than 2m, 0.2m and 0.5m respectively (PWGC 2008).

The LiDAR survey was undertaken by Fraser Basin Council through Terra Remote Sensing Inc. The survey was conducted in the fall (October to November) of 2008 to take advantage of leaf-off season and to cover maximum area across the channel as gravel bars are exposed due to low flow season. For quality control, an independent third party survey was carried out by Parallel Geo-Services to confirm LiDAR positions and elevations in different cover types. The project area covered 62,500 ha on the Lower Fraser floodplain. The LiDAR data achieved horizontal and vertical accuracies of 0.5m and 0.15-0.25 m respectively (TRSI 2009). The final LiDAR data was delivered as 1 m grid with X,Y,Z in ASCII format.

2.1 PRE-PROCESSING

The size of the LiDAR data was huge – around 1TB and it was a challenge to process such a huge dataset. To make it more manageable, a few steps were taken. First, the LiDAR was trimmed such as to keep only the data lying within the full width of the floodplain. To define the floodplain width, left and right levees along the river were marked using the existing dikes. Where there were no dikes, highways or railway tracks were used to mark the x-section extents. Using the design flood profile from NHC 2008 Fraser Model, W.L was estimated at Hope and other areas. These water levels were then used roughly to fix the left/right x-section boundaries i.e. picking the ground level or highway/railway which was at least as high as the estimated W.L.

Secondly, the LiDAR was thinned from 1m grid to 3m grid. This further reduced the data size by one ninth. The size of 3m grid was decided to ensure that the dike crest elevations are not missed – note that the dike crests are generally about 4m wide.

Furthermore, the data was divided in sub-groups for processing. Data Blocks were created by grouping 6-12 csv files (LiDAR data was stored as csv files). This resulted into 17 blocks in total (see Figure 1 – Blocking Scheme). Both LiDAR and bathymetry data were clipped for each block and were processed independently block-wise. Afterwards, the processed data from all the blocks were merged together in to a single surface model.

2.2 CONTOUR CREATION

The bathymetry data was collected along transects spaced every 100m to 200m. It was important to estimate the gap in-between the bathymetry transects with reasonable elevation information rather than allowing the surface model interpolation algorithm to execute blindly. To estimate these gaps, contours were created manually using the bathymetry point elevations. Engineering judgement was applied with the help of orthophotos. Though the contour creation process was grueling and time consuming, it was worth the effort as it significantly improved the quality of the surface model.

The contours were used as one of the inputs to the surface model, therefore, it was important that the quality of the data was maintained. A two level review process was adopted. After contour creation, they were peer reviewed in-house and then sent to NHC for review by a fluvial geomorphologist. This ensured a good quality surface model which was going to form the basis of the hydraulic model.

2.3 PROCESSING IN ArcGIS

The LiDAR, bathymetry and contours were used as primary input for the surface model. The LiDAR and bathymetry data were trimmed for each block and the contours were created. The LiDAR returns from the water surface are not valid so this data was clipped off and was replaced with the bathymetry and contours in the channel. Each block was processed independently. Since this process was repeatable for every block, tools were developed in ArcGIS Model Builder to automate the process. This significantly saved the development time. Later, the surface models from all the blocks were merged together into a single surface model which was used for cutting x-sections and deciding on channel network.

Fraser River is heavily braided in the gravel reach which makes it quite challenging to model using a one dimensional hydrodynamic model. The complexity of flow in braided channel areas was simplified by treating side channels as independent branches such that they formed a channel network with the main stem of the river. To distinguish main channel from the side channels, a thalweg was created using the merged surface model. The channel network developed included a total of 21 branches.

After deciding on the channel network, the x-sections for each branch were drawn perpendicular to the channel flow. Consideration was given to consider the conveyance of the whole Fraser River at high flows when the islands are possibly submerged. Chainages for each x-section were calculated using ArcGIS tools. In order to transfer roughness information from the channel and floodplain to the x-sections, three types of land-use polygons were created: forests, agriculture and channel. Values of relative roughness (forest=4, agriculture=1.5 and channel=1), were stored as attributes on these polygons. Tools were developed in ArcGIS Model Builder to transfer these values to the x-sections.

Again, for quality assurance, the channel network and the x-sections were sent to NHC for review before exporting to MIKE 11. The MIKE 11 utility was used to import channel network from ArcGIS Shape files whereas code was written to export the x-sections to MIKE 11 format.

Because no new bathymetry data were collected for Harrison and Vedder Rivers, x-sections from the 2008 model were used for these key tributaries.

3. 2012 DATA COLLECTION AND ANALYSIS

The 2012 freshet was the 5th largest flood in the known history of Fraser River. The Fraser peaked at Hope on June 22nd, 2012 with an instantaneous discharge of 11,874 m^3/s (11,714 m^3/s daily average). With funds provided by Emergency Management BC, an exceptionally valuable set of data was collected during this freshet. This included:

1. In the gravel reach, water level data was collected at 44 gauges (18 continuous and 26 staff). This included 7 new gauges – 3 installed by FLNRO and City of Chilliwack and 4 by WSC.
2. Discharge measurements conducted by WSC at Hope, Harrison River and Mission.
3. Three sets of flow split measurements at key locations where the river branched into major side channels. The three sets of data were collected for daily average of approximately 9000 m^3/s, peak flow of 11,714 m^3/s and 6687 m^3/s at Hope. The idea was to capture the impact of different flow rates on the flow splits between the main channel and side channels .
4. Continuous longitudinal water surface profile along centerline of main stem of the river from Hope to Mission. This data was collected on June 24th – two days after the peak occurred but the flows were still higher than 11,000 m^3/s.
5. Bathymetry data was collected from Big bar to Tranmer bar to capture the impact of Herrling avulsion that initiated in 2009. The data was collected on the falling limb of the freshet hydrograph.
6. Orthophotos from Mission to ocean during the high flow period.

3.1 WATER LEVEL GAUGES

It is very important to have a good coverage by the gauge network not only for flood monitoring but also for model development and maintenance. Due to the three dimensional nature of the flow in the gravel reach and because individual cross-sections can be up to 2 km wide, the water level at the left and right bank of the river can vary by 0.5 m or more. To capture that, a well planned network of the gauges is required. Unfortunately, before 2012, the Fraser River did not have a good coverage by the gauges upstream of Mission. Before 2012, there were only 10 continuous gauges and 25 staff gauges in the 82 km reach.

FLNRO, in collaboration with Ministry of Environment, WSC, EMBC and City of Chilliwack, successfully installed eight new continuous reading gauges prior to 2012 freshet. Five of the gauges which were installed through WSC were:

- Fraser River at Cannor - 08MF038
- Fraser River near Harrison Mills - 08MF073
- Fraser River near Agassiz - 08MF035
- Fraser River at Laidlaw - 08MF072
- Tenas Narrows at Lillooet River – 08MG027

The other three continuous gauges were installed through a contract administered by City of Chilliwack. The contractor was Northwest Hydraulic Consultants (NHC).

- Lower Kent
- North of Herrling Island
- North of Hunter Creek

The water level data from Hope to Mission was collected at 44 gauge locations (18 continuous and 26 staff) in total. An effort is being made to get more gauges installed in future.

3.1.1 Tenas Narrows Flow Gauge on the Lillooet River/Harrison Lake System

Harrison River constitutes the biggest tributary to Fraser River in the Lower Fraser Valley. Unfortunately, since the Harrison is back-watered by Fraser River at high flows, the discharge calculated at WSC gauge "Harrison R. near Harrison Springs - 08MG013" does not give reliable flows in real time. While this issue does not impact the reliability of the model calibration and design flow runs, the gauging of the Harrison system is very important for the forecasting model.

During freshet, the forecasting version of Fraser Model is run in real time to produce a 5-day prediction report. The 5-day predicted flows from River Forecast Centre (RFC) are used as input to the model daily runs. One of the predicted flows is given at Harrison Lake inlet – flows contributed by Lillooet River. However, since there had been no gauge near the inlet to Harrison Lake, it was not possible to validate the RFC flow forecast.

In 2012, at the request of FLNRO and MoE, WSC installed a flow gauge in Lillooet River at Tenas Narrows Bridge. This gauge is located in Lillooet River 52 km upstream of the lake inlet. The gauge location is at a wide section of the river, which is not hydraulically ideal. Despite a lot of effort, no feasible location could be found nearer the Harrison Lake inlet. Because of the gauging challenges, WSC took several measurements during the 2012 freshet to ensure the reliability of the new gauge. A summary of the tests conducted by WSC are given in Appendix 1.

Since this gauge was under investigation during 2012 freshet, it was not possible to use its data in real time. However, this gauge became operational in real time starting freshet of 2013. This will help to improve the quality of the freshet forecasting in future.

Based on the fact that this gauge is located 52 km upstream of Harrison Lake inlet, to take care of the travel time and contribution from the catchment between Tenas Narrows and the lake inlet, NHC ran a quick calculation and recommended to increase the flows by 10% and add 5 hours to the time of measurement. An NHC calculation on the gauge transposition is also included in Appendix 1. It is recommended that the above correction be applied to the Tenas Narrows time series at the time of using this data during freshet forecasting.

3.2 DISCHARGE MEASUREMENTS

Having accurate flow inputs to the model is crucial for computing correct water levels. Unfortunately, 2012 WSC verified flow data were not available at the time of calibration and the preliminary data were used. However, WSC took several flow measurements during the entire freshet of 2012. A comparison of the WSC field measured flows with the rated flows at Hope and Mission are presented in Table 1 and Table 2. For the month of June, the rated flows at Hope overestimated the measured flows by up to 2.77%. WSC updates their rating curves only when the differences are greater than 5%, therefore, the rating curves were not updated. Since the differences were not large, it was considered reasonable to use the WSC rated flows for model calibration. For 2011 and 2007, the WSC verified flows were used.

3.3 FLOW SPLIT DATA

The model must calculate the flow splits correctly at the bifurcations and trifurcations to compute water levels accurately in the main channel and in the side channels. To verify that the model is splitting the flows correctly at the islands and the sand bars, several flow split measurements were conducted by FLNRO through contractor CRA Canada Inc. Flow splits can be sensitive to discharge in the parent channel, therefore 3 sets of flow split measurements were conducted at varying flows; one on the rising limb, one near the peak and the last one on the falling limb of the hydrograph at Hope.

The surveyor was provided with the geo-referenced locations (Figure 2) in the gravel reach - approximately 34 in total. The first set of measurements was taken from June 12 to 14 for an average flow of around 9000 m^3/sec at Hope. Based on some practical limitations of data collection, some locations were adjusted. Still, despite all efforts, there were places where it was not possible to capture the discharge of the whole channel. Also, where the water was running over the banks due to high flows, it was not possible for the boat to access treed areas along the banks. This resulted in a general trend of under-estimation of the measured discharge compared to the actual. Notes were prepared for all such locations and consideration was given at the time of comparisons. The second and third set were conducted on June 22-23 (daily average flows of approximately 11,794 m^3/sec) and July 25-26 (average flows of around 6687 m^3/sec at Hope) respectively.

At every flow measurement location, the average flow was calculated by measuring velocities and depths for each water column while moving in the survey vessel in real time. Current flow velocities of each water column were measured using the RDI Teledyne 1200 khz ADCP. The transducer was mounted on a specially constructed side mount on the survey vessel. The corresponding water column depths were measured using the Odom Hydro-trac digital survey Fathometer - a single frequency unit operating at 200 khz via a narrow beam transducer. To ensure data was collected in correct datum, Trimble GNSS R8 RTK GPS was used to tie can-net correction systems to local geodetic monuments. For each set of measurement, the contractor provided FLNRO with the average flow and average velocity at every x-section.

An attempt was also made to collect flow splits at some key locations downstream of Mission (sand reach of Fraser River). However, extensive bed load movement due to high flows made it difficult to track the channel bed and take reliable readings. After a few unsuccessful attempts, it was decided to abandon these measurements.

3.4 CONTINUOUS LONGITUDINAL WATER SURFACE PROFILE

A continuous longitudinal water surface profile was collected along the main stem of Fraser River from Hope to Mission and in Minto Channel. The data was collected on 24th June, 2012 with the average discharge of 11,360 m^3/s at Hope. Note that the freshet peak occurred on June 22nd with the daily average flow of 11,714 m^3/s. The water levels were collected along the centerline of the channel.

The original data was too dense (around 0.4 m interval) therefore it was thinned to around 40 m interval by taking an average of every 100 values. The survey data was collected starting from Hope whereas the chainage of the MIKE 11 x-sections proceeds from Mission to Hope. Therefore, the order of survey data had to be inverted. This was easily achieved by sorting on the time stamp. Chainage for each data point was then calculated using Linear Referencing tools in ArcGIS to synchronize it with the chainage of MIKE 11 x-sections. This profile was extensively used for the model calibration.

3.5 BATHYMETRY SURVEYS AT HERRLING

Subsequent to the completion of 2008 bathymetry surveys, Fraser River at Lower Herrling underwent a major channel shift near Lower Herrling. PWGC was contracted to do the bathymetry survey in 2010 (Figure 3). The surface model and x-sections were updated accordingly. But, during the first iteration of calibration, very little change was observed due to the new bathymetry. It was presumed that the full extent of the impacted area was probably not captured in the first attempt; therefore, it was decided to re-survey it in 2012 for a longer reach - from Big Bar to Tranmer Bar (Figure 4).

The bathymetry data was collected on the falling limb of the 2012 freshet – July 27th, with a discharge of around 6500 m^3/s at Hope. The data was acquired using a single beam automated hydrographic acquisition system. The acquisition software used was Hypack Max. The x,y,z data files were supplied for approximately 100 x-sections in UTM coordinates referenced to geodetic datum.

During the processing of 2008 bathymetry data, it was realized that manual contour creation was a very time consuming process. Therefore, the contractor was asked to supply 1 m contours of the bathymetry data. Contours were created using AutoCAD Civil 3D. However, at the time of creating the surface model, it was realized that the auto-generated contours from software may not work very well for irregular shape channels. The software can easily introduce errors if it does not have enough information of the channel layout. For example, for areas where the channel is extremely irregular or has sharp curves, auto-generated contours may not follow the embankments properly and can easily cut through higher ground. Therefore, the auto-generated contours were discarded and a new set of contours were created manually and were used in updating the surface model.

4. MODEL DEVELOPMENT

4.1 MODEL SET UP

The accuracy and reliability of the model depends on several factors which include: accuracy of the survey data and how it has been processed, setting up of the channel network schematics, and the quality and quantity of the observed water level data. Fortunately, for this project, all of these components could be achieved. The LIDAR and bathymetry data were processed to create a surface model which allowed cutting the x-sections at desired locations perpendicular to flow. The orthophotos in conjunction with the surface model were very helpful in dealing with the islands and gravel bars while setting up the channel network. They also helped in deciding to provide link channels to handle lateral flows back and forth from the main stem and the side channel. And as documented above, extensive calibration data was available.

MIKE 11 hydrodynamic modelling software, developed by Danish Hydraulic Institute (DHI), was used as the development platform. MIKE 11 performs one dimensional simulation solving St. Venant equations for the conservation of mass and momentum. These equations can account for storage, routing, friction, flood attenuation and wave propagation. To solve the continuity and momentum equations, MIKE 11 uses a 6-Point Abbot implicit finite differencing scheme. Detailed information on the governing equations and the solution scheme can be found in MIKE by DHI, 2011.

MIKE 11 provides options to choose from three different flow descriptions: High Order Fully Dynamic approach, Diffusive Wave approach and Kinematic Wave approach. The fully dynamic approach uses the full momentum equation whereas the latter approaches are the equation’s simplified versions. More information on the three approaches can be found in NHC 2008 report and MIKE by DHI 2011 reference manual. Based on the recommendation in the DHI reference manual (DHI 2011), the model was set to use the High Order Fully Dynamic approach.

Model development involved setting up of the MIKE 11 network file, preparation of x-section data, compilation of flow and water level data and estimation of hydrodynamic modelling parameters. As discussed in the earlier chapter, ArcGIS was extensively used for creating the channel network, x-sections and deciding on junctions and roughness etc. The orthophotos, surface model, channel network, x-sections and water level gauge locations were added as layers in the ArcMap file. This file was heavily used back and forth with the MIKE 11 model in its course of development, calibration and validation.

To be consistent with the lower model (sand reach), the x-sections were assigned chainages increasing from downstream to upstream. Since this is opposite to the default setting of MIKE 11, the flow direction for all the branches and link channels in the network editor were set as negative. Also, the chainage of the first x-section of Fraser River branch in the upper model was set as 85400 to allow continuity of the chainage at the time of merging of the new model with the existing lower model. The model was extended all the way up to Hope making the total thalweg length from Mission to Hope to be

81,735 m. Once fully developed, the model ended up having 21 branches, 10 link channels and 561 x-sections in total. A summary of all the branches are provided in Table 4.

In order to compute channel conveyance of the x-sections, the option for “Radius Type” was chosen as “Resistance Radius” as this provides a smoother transition of conveyance from a channel flow situation to an overbank flow situation (DHI reference manual 2011). In the real world, the roughness varies as we go along an x-section from, say, a channel to a grassy island to a treed floodplain. To allow taking care of transverse variation of the roughness, the option of “Transversal Distribution” was chosen as “Distributed”. This option is better than the other available options of “Uniform” or “High/Low Flow Zones” as it provides a more realistic way of applying the actual roughness values. To capture all possible roughness values, three land use areas were defined – channel, agriculture and forest. Their relative resistance with respect to channel were defined as 1, 1.5 and 4 respectively. These resistances were incorporated in the x-sections by setting Resistance Type as “Relative Resistance” in the x-section editor. The channel roughness of all the branches were defined in the MIKE 11 HD Parameter file under the tab “Bed Resist”.

The gravel reach is heavily braided consisting of lots of islands and gravel bars making the flow highly complex and almost impossible for a 1-D model to simulate accurately. To mimic the 2-D nature of the flow, link channels were provided at locations where significant lateral flows were expected between the main stem and the side channels. However, an attempt was made to keep the number of link channels small to avoid un-necessary complexity of the model and an increase in the run time. The values of the head loss coefficients for all the link channels were kept as the suggested default values by MIKE 11.

Following bridges were added to the model:

- Highway #17 bridge over Fraser River between Agassiz and Rosedale
- Highway #7 bridge over Harrison River
- CPR bridge over Harrison River

Bridges over Sumas and Maria slough were ignored. It was assumed that their impact on the Fraser River flood profile would be negligible because these channels are back-watered from Fraser River at high flows.

Weirs at Greyell Slough, Peters Island and Bristol Island were added to the model. At Bristol Island, high ground exists between Fraser River and the upstream end of the side channel. Due to this, the side channel becomes active only at very high flows. This situation was modelled by treating the high ground upstream of the channel as a weir. All the weirs were defined as broad crested weirs and the values for their head loss factors were kept as per the default settings in the software.

Due to the 1-D limitation of the model to simulate flows at sharp bends and at sudden expansions and contractions, energy losses were provided at the following locations in the model:

- Harrison River – at several locations to take care of expansion, contraction and sharp bends.

- Fraser River at Harrison Knob – to allow for the sharp bend just downstream of the confluence of Harrison River with the Fraser River.
- Minto Channel – Minto channel "off-takes" from Fraser River at a very sharp angle. Energy losses were added at the upstream end of the channel.

In the first iteration of the model, Hope slough was not made part of the model network and the area in-between Wing Dike and Young Road to Chilliwack Mountain Dike was modelled as part of the main stem. Later, it was observed that the water level in the area between the two dikes is controlled by the water level at the junction of Hope slough with Fraser River at the location where Wing Dike is not overtopped. Therefore, it was more realistic to treat Hope slough as a branch and let it be back watered from Fraser River. This allowed flexibility of the model to be used for normal freshet flows. For the flows of the order of 1894 (design) flood, the last 1400 m of the Wing Dike is very likely to overtop. This overtopping was simulated by providing link channels to allow overflow from Fraser into Hope Slough once the water level became higher than 11 m geodetic (taken from surface model). It was assumed that the Wing Dike did not breach and withstood the design flood. Upon analysis for the design flows, it was found that very little flow overtopped the Wing Dike (around 1.4% of the design flow), making a negligible difference in the water levels (less than 1 cm) near this area. However, it was decided to keep these link channels in the model.

Once the model was initially set up, it was run for the first few days of the freshet period to create hot start files. Hot start files are MIKE 11 result files which can be used as initial conditions. This allows defining hydraulic parameters, such as discharge, depth and velocity etc, at every node at the beginning of the simulation period. Using these values as the starting point, the model can then proceed with the subsequent numerical computations. A time step of 15 seconds was used for the general model runs, whereas, hot start files were created using a much smaller time step. In the beginning, test runs were conducted for a few days to ensure that no instabilities occurred. Later, the model was run for the entire freshet period.

The results were copied from MIKE View to Excel where they were processed for comparison with the observed water level data.

4.2 BOUNDARY CONDITIONS

For the calibration and validation runs (2012, 2011 and 2007), the upstream boundary conditions of the MIKE 11 model were provided at Hope and Harrison River. Time series (hydrographs) of flows at Hope and Harrison River were used. The flow data was taken from the WSC gauges 08MF005 (Hope) and 08MG013 (Harrison River near Harrison Springs). Though the WSC flow estimation method at WSC gauge 08MG013 is not very reliable, (UMA 2000), there was no alternative method available. The downstream boundary condition was provided at Mission as a time series of water level data taken from WSC Mission Gauge (08MH028). Since Vedder / Chilliwack River and Hope Slough were added to the channel network as branches, they were defined as open boundaries. Whereas, the other tributaries

(Chehalis River, Silverhope creek, Sumas River, Ruby and Wahleach creek) were treated as point source boundaries. The estimated flows of all the tributaries were taken from the monthly average flow estimates from NHC's 2007 freshet forecasting report (NHC 2007). These flows were based on reported flows and estimations based on relative drainage areas of the tributaries (NHC 2008). A summary of all boundary conditions for 2012, 2011 and 2007 are provided in Table 5. For the time series of the boundary conditions used, refer to Figure 5 to 16.

For the design run, a constant discharge equivalent to 1894 flood event (17,000 m^3/s) was assigned at Hope and 1,300 m^3/s at Harrison River upstream end (NHC 2008). At Mission, a time series of water levels was taken from the 2008 model (NHC 2008) which corresponds to a constant boundary of 8.9 m. However, since the final design profile was generated using the merged model (new upper model was merged with the lower model), no boundary condition was required at Mission. Instead, tidal time series having 1.89 m high tide (occurred on 28 May 2002) was used as downstream boundary condition at the four outlet arms (Fraser, North Arm, Middle Arm and Canoe) – refer to Figure 17. For all other tributary inflows, the flows used were the same as in the 2008 model (NHC 2008).

WSC verified data was available for 2011 and 2007 only. The 2012 data was still under the process of verification by WSC.

4.3 MODEL CALIBRATION AND VERIFICATION

The model was calibrated and validated using the network which did not include Harrison Lake. The Harrison Lake was added afterwards to enable the model run in real time forecasting mode during the freshet.

2012 freshet data was used for calibration. The 2012 freshet peak is estimated to have a return period of slightly less than 20 years at Hope. After the model was successfully calibrated, it was validated for 2011 and 2007 freshet data. The model was run for the entire freshet periods to cover a range of flows. The extensive calibration data available for 2012 included:

- Continuous longitudinal water surface profile from Hope to Mission collected near the flood peak
- Flow split measurements at 34 locations from Hope to Mission (Figure 2)
- Water level data at 44 gauging stations (18 real time continuous + 26 staff gauges) – Map 1 - Gauge Location Map
- Flow data at WSC gauges at Hope (08MF005), Mission (08MH024) and Harrison River (08MG013)

Having accurate flow and water level data is extremely important for calibration. Unfortunately, the 2012 data was preliminary and WSC was still in the process of finalising it. However, WSC conducted several flow measurements at the gauge locations of Hope (08MF005), Mission (08MH024) and Harrison River (08MG013). The differences between the measured and rated flows at Mission and Hope were less than ±5%, whereas at Harrison River (08MG013), they were significantly greater (+13% to -26%). The WSC flow estimation method at 08MG013 is not very reliable (UMA 2000), but there was no other alternative available. Overall, an uncertainty of the order of 10% of the total flows at Mission existed with the inflows from Harrison system and other minor tributaries. A summary of comparison between measured and rated flows are given in Table 1, 2 and 3.

Locations of branch junctions are critical in deciding on flow splits. Depending on the channel geometry near a junction, flow split may vary with changing flows as well. Three sets of flow split measurements were conducted during the 2012 freshet: June 12-14, June 22-23 and July 25-26. The flow split measurements are summarised in Table 7, 8 and 9.

For sub-critical flows, any change in the water level does not impact water levels downstream. Since we were dealing with sub-critical flows, calibration was done by selecting reaches starting from Mission and working upwards in the upstream direction. The roughness (Manning's n) was the main parameter to be adjusted. Typical channel roughness ranged from 0.028 to 0.036. The values in the side channels were slightly higher than the main stem. Heavily vegetated floodplain areas with trees were assigned roughness values from 0.112 to 0.144 (multiplication factor of 4) whereas the floodplain with short brush used values from 0.042 to 0.054 (multiplication factor of 1.5). A summary of values for channel roughness is provided in Table 13.

To confirm that the flow splits in the model were representative, the model flows were compared with the ADCP flow measurements. The junction locations were adjusted where necessary to achieve a better flow comparison. A summary of flow split comparison is provided in Table 10. In general, there is excellent agreement between the model and observed flows. There were some exceptions at locations near Wellington, Hamilton, Big_Bar_US and Middle Herrling (L8, L14, L20, L28). These differences could be attributed to either because the ADCP measurements could not capture the channel flow correctly due to practical limitations, or flow areas were too complex for a 1-D model.

For comparison details, see Table 10. For the locations where lateral flow was taking place in-between the main stem and the side channel, the link channels were provided. To check mass balance in the model, a comparison was made between the flows input to the model as boundary conditions at Hope and at tributaries in-between Hope and Mission (Harrison River, Chilliwack River, Chehalis River and Silverhope River), model flow and the gauged flow at Mission. The model flow matched well with the gauged flow at Mission (Table 6).

Just downstream of the confluence of Harrison River, Fraser River flows directly at an outcrop of bed rock at Harrison Knob and takes a sharp turn of almost 90 degrees introducing huge head losses. In order to simulate this flow pattern, energy losses were added to the MIKE 11 model around the bend. The continuous longitudinal water surface profile was used as guidance to decide on the locations and the amount to achieve a closely matching modelled longitudinal profile. In 2012 freshet, a new continuous gauge "Fraser River near Harrison Mills - 08MF073" was installed by WSC right at the Harrison Knob. This gauge is located on the inner side of the bend (Map 1). Because the MIKE 11 is a 1-D model and is not capable of handling curves, it was expected that the water level data at the gauge would be slightly lower than the modelled water level due to the super-elevation effect. Keeping this in mind, this reach was calibrated by keeping the modelled water level slightly higher (around 0.1 m) than the observed gauge water level.

Other energy losses were provided at the head of Minto channel due to the sharp off-taking angle and in Harrison River to allow for sharp curves and abrupt expansions and contractions.

4.3.1 Comparison with Observed Continuous Longitudinal Water Surface Profile

While comparing the model longitudinal profile with the measured continuous water surface profile, it was observed that the model introduced minor kinks and bumps at branch junctions and locations with abrupt expansions or contractions. Despite lot effort, these irregularities in the profile could not be eliminated altogether. This seemed to be a limitation of the MIKE 11 solution scheme to handle abrupt changes in flow or in channel geometry. Similar behavior was observed in the previous UMA and NHC models. These irregularities were local and dissipated spatially. However, care was taken to avoid putting junctions close to gauge locations to prevent introducing unrealistic errors.

Because braided reaches of the river were treated by creating channels artificially, there were areas where abrupt expansions or contractions could not be avoided. One such area is downstream of Agassiz Bridge where the Powerline side channel meets Fraser River main stem. Due to the large width of the right floodplain, Fraser River faces a huge expansion after it joins the Powerline branch. A visible bump can be seen at chainage Fraser 129526 (Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only)). These bumps and kinks were reflected in the design profile as well. Therefore, the final design profile was produced after smoothing these un-realistic irregularities.

4.3.2 Comparison with Observed Gauge Data (see Map 1 for gauge locations)

The model was calibrated to slightly stay on the conservative side in general. Overall, the model results showed a good agreement with the continuous longitudinal water surface profile (Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only)) as well as with the observed water levels at 44 gauge locations. The differences between the model and observed data were similar to previous modeling results. With a few exceptions, the differences are less than +0.1 m for the freshet peak flows. It should be recognized that some gauges exist in the side channels or at locations which are not representative of water levels in the main channel. Some of the issues related to specific gauges are discussed below.

CHIP (Camp-Hope) Intake (Chwk#2): This is the only gauge location where the model consistently under-estimated the observed water levels over the entire freshet period. This gauge is located in an intake channel off-taking from a side channel near Big Bar just downstream of Agassiz Bridge (Chwk #2 on Map 1). The entrance of the side channel makes a sharp angle from the main stem of the river causing turbulence near the entrance of the intake channel at high flows. The model results and water level observations indicate that the flow patterns in this area are complex.

For 2007, the model showed a difference of -0.43 m for the peak flow. The model also under-estimated the 2011 and 2012 peak levels by -0.019 m and -0.29 m respectively.

A significant observation was that, the measured water level at this gauge was 0.46 m higher than the measured continuous longitudinal water surface profile along the main channel at the same river chainage (Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only)) collected on June 24, 2012. When compared with the observed water level at Agassiz Bridge South gauge, the continuous profile was found to be lower by only 0.06 to 0.1 m, which is a much smaller difference considering the water surface slope in the main stem of the river. It appears that the flow probably “piles up” near the intake channel at high flows.

After the freshet, City of Chilliwack was asked to check the datum of the two gauges but no problems were found. It is therefore concluded that the model variances in at the CHIP intake gauge are due to the 1-D limitation of the MIKE 11 model. It is recommended that a 2-D MIKE Flood patch be applied to the existing MIKE 11 model and see if it shows any improvement in the model results. Until then, special alerts should be issued when forecasting water levels for this gauge.

It was observed that the differences between modelled and observed water levels at this gauge were more for 2007 data compared to 2011 or 2012 data. It is presumed that this could be as result of Herrling avulsion (around 5 km upstream of this gauge) that initiated in 2009 and progressed in later years, potentially causing channel geometry change near this area. Since the new model was updated with the 2012 bathymetry, it better represents the actual geometry and thus showed relatively less differences for 2011 and 2012 data.

Agassiz-Rosedale Bridge North and South Gauges (Kent #5 and 22): There are three gauges at Agassiz Bridge. The north staff gauge is located upstream of the bridge on the right (north) bank of the Powerline side channel whereas the south staff gauge is situated just downstream of the bridge at its pier nose on the left (south) bank of main stem of the river. A new continuous gauge was also installed just upstream of the bridge by WSC on the left bank of the main stem 100 m upstream of the south staff gauge.

The river makes a wide bend at the bridge with the south staff gauge and WSC gauge falling on its outer edge. The model results over-estimated not only at these two staff gauges but also the measured continuous longitudinal profile in this reach. It took a lot of effort to calibrate in this reach mainly due to the configuration of the model network with Fraser River main stem and Powerline side channel entering the Agassiz Bridge together and abrupt expansion involved in the main stem of the river just downstream of the bridge. The effects of super elevation related to the bend add to the complexity at this location. Though the comparison at the three gauges were acceptable (0.11 for south staff gauge, 0.18 for the north staff gauge and 0.03 for the continuous gauge) for the peak freshet, the modelled water levels over-estimated observed levels for the north staff gauge in particular over the most freshet period (> 0.2 m). It is recommended to try a 2-D patch to this reach as well.

Chilliwack Creek PS (Wolfe Road) (23): The model results consistently over-estimated at this location by around 0.22 m. Due to complex flow pattern between the main stem and Wellington side channel (Map 1 - Gauge Location Map), it was difficult to estimate water levels in this reach even after providing a link channel. It is recommended to apply a 2-D patch to the existing MIKE 11 model to simulate water levels in this reach.

Quaamitch Slough (41): This gauge is not located at an ideal hydraulic location. It is located in a slough and its water level is controlled by the water level at the slough mouth for flows lower than the floodplain level. However, this control point will shift upstream at higher flows when the floodplain gets submerged, and result in higher water levels at the gauge. Taking a conservative approach, this gauge was "mapped" to a x-section considering flows high enough to submerge the floodplain. Therefore, at lower flows over-estimation is expected at this gauge.

Cuthbert Road (Kent #2): This gauge has a similar situation as Quaamitch slough. Again taking a conservative approach, this gauge was also mapped to a x-section assuming flows submerge the floodplain. Over-estimation was expected at lower flows.

Maria Slough and Bell Dam (21 and 16): The water levels measures at these gauge locations are not representative of the main channel hydraulics and were not used for calibration and validation.

Herrling Island (44): The Herrling Island staff gauge consists of two parts – lower gauge and upper gauge. The lower Herrling Island gauge is at a poor hydraulic location and was eliminated from the calibration and validation.

Johnson slough (43): Flow entry into Wahleach side channel is impacted by debris which makes it difficult to model actual flow getting into this channel. Therefore, more stress was given to basing the calibrating on "Wahleach (Jones) Creek" gauge which exists right across on the main stem of the river (Map 1).

Wahleach Powerhouse (1): The data from this gauge is unreliable when the power house is in operation.

Calibration and Validation results for the peak freshet flows are summarized in Table 11 and Table 12. In addition, a comparison of time series of the modelled and observed water levels over the entire freshet periods of 2007, 2011 and 2012 for individual gauges is also provided from Figure 18 to Figure 96.

4.4 MODEL RUN FOR DESIGN FLOW

After successful model calibration and validation, the model was set up for the design flow conditions. In 2008, the lower and upper models were run separately to generate the design profiles in the sand reach and gravel reach respectively. In order to compare the new upper model results with the previous profile in the gravel reach, the new upper model was run alone first i.e. without merging it with the 2008 lower model. Later, the new upper model was merged with the 2008 lower model to allow more realistic computation of the water levels at Mission that take into account flood routing and attenuation in the upper model reach.

Comparisons of profiles developed by the new upper model and the 2008 model requires extra care because the channel network and chainages of the two models are different, which is due to the changes in channel alignment over the period from 1999 to 2008. The new model's chainage was adopted for the comparisons.

The design profile generated with the new merged model was assumed as the final design profile. Both the models and their results are discussed in the following sections.

4.4.1 USING NEW UPPER MODEL

Following boundary conditions were used:

- Fraser River at Hope: 17,000 m^3/s (same as 2008 upper model)
- Harrison River: 1,300 m^3/s (same as 2008 upper model)
- Local tributaries (from Hope to Mission): Same as 2008 upper model
- Fraser River at Mission: Time series of water levels taken from 2008 upper model which corresponds to the peak boundary of 8.9 m

The design flow at Hope corresponds to the 1894 flood event and is estimated to have an annual exceedence probability of about 1 in 500 years (NHC 2008a). Harrison Lake was not made part of the network and the boundary was fixed on Harrison River at its upstream end – the same as the calibration set up. All the boundary conditions, including flows at Hope and Harrison River, were identical to the 2008 upper model. This allowed comparing the results of the two models which were based on different survey data (1999 vs. 2008) and slightly different modeling approaches but same boundary conditions.

Despite different modeling approaches, the two profiles matched closely and followed similar patterns. Overall, the difference was within $\pm$0.2 m with a general trend of the new profile being on the lower side. Larger differences of the order of 0.5 to 0.8 m were found at specific locations such as Harrison Knob and downstream of Agassiz Bridge. An effort was made to determine whether these differences should be attributed to changes in channel geometry or due to improvements in the modelling approach. The comparison of the new upper model profile with the 2008 profile is provided in Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only).

The new profile in near Harrison Knob is up to 0.5 m lower than the previous design profile (see Drawing 1). When the 2008 model was calibrated in this reach, energy losses were added to the model to compensate for the large head losses occurring at the sharp bend. However, much more water level data was available from the 2012 freshet to calibrate the new model. This data included the continuous longitudinal water surface profile, and two new gauges, one right at Harrison Knob and the other just upstream. This data allowed the new model to estimate the energy losses more accurately. Therefore, the change in design profile near Harrison Knob can be attributed to the model improvement.

Another big change was observed downstream of Agassiz Bridge (Herrling Bar to Hamilton Bar) where the new profile is up to 0.8 m lower than old profile. The channel geometry of this area has been changing due to the Herrling avulsion that initiated in 2009 and progressed in later years. The spot where the avulsion occurred is just upstream of Agassiz Bridge. When the old model results for 2012 freshet input data were compared with the measured longitudinal water surface profile and the water level gauges near the bridge, they showed a trend of over-prediction. The fact that the measured continuous longitudinal profile is lower than 2008 model longitudinal profile for 2012 data, and that similar order of difference is observed for the design flow, it can be concluded that the change in this reach is due to the change in channel geometry that has taken place over the period from 1999 to 2012 (note that the bathymetry data in this area was collected post 2012 freshet).

However, the reasons for the reduction in the profile in this reach could be more complicated. Another factor which contributes to model calibration complexity is the multi-dimensional flow pattern near the CHIP Camp Hope Intake gauge and the Agassiz South staff gauge as already discussed in the previous sections. If a model is calibrated to the CHIP gauge then it has the tendency to over-estimate the Agassiz Bridge gauges whereas it could be other way round if more emphasis was given to the Agassiz Bridge gauges while calibrating. In the case of the new model, more emphasis was given to the Agassiz Bridge South staff gauge and the new WSC gauge just upstream due to the fact they exist on the main stem of the river. As previously recommended more analysis is required to simulate the flow complexity near CHIP Camp Hope area using a 2-D model.

Near Peters Island, the new profile is higher than the 2008 model profile by about 0.3 m whereas it is lower by about 0.4 m near Wahleach. These differences are localized and are likely caused by the change in channel geometry over time.

4.4.2 USING NEW MERGED MODEL

As mentioned earlier, in 2008, the design profile in the sand reach and gravel reach were generated by running the 2008 Lower Model and 2008 Upper Model separately. Later, the two models were merged and Harrison Lake was added for the forecasting model. The design water level of 8.9 m at Mission was computed by the 2008 Lower Model using a discharge of 18,900 m^3/s as boundary condition at the upstream end. This discharge corresponds to 17,000 m^3/s at Hope and was computed by adding all the flows from Hope to Mission. Subsequently, the water level of 8.9 m was set as downstream boundary condition for the 2008 Upper Model to generate the design profile in the gravel reach (NHC 2008).

In order to compute water levels at Mission more realistically, it was considered appropriate to merge the new upper model with the 2008 lower model (sand reach) and then run the merged model for design flows. Since MIKE 11 uses Saint Venant equations which are fully capable of handling flood routing and attenuation, the flows computed at Mission would be more realistic. All the other boundary conditions used were the same as were used in the 2008 Lower Model and 2008 Upper Model (NHC 2008) with one exception being the tidal data as explained in the next paragraph. A summary of the boundary conditions used is as follows:

- Hope: 17,000 m^3/s (same as 2008 upper model)
- Harrison River: 1,300 m^3/s (same as 2008 upper model)
- Tributaries from Hope to Georgia Strait: same as 2008 lower and upper models
- Downstream tidal boundary condition: 2002 May high tide of 1.89 m instead of June high tides

The 2008 Lower Model used the 2002 June high tides of 1.7 m to generate the design profile whereas a high tide of 1.89 m occurred on 28, May 2002. Therefore, the new merged model was run with the 2002 May high tide to generate the final design profile. The tide levels correspond to a roughly 1 in 2 year return period summer high tide without considering any surges (NHC2008).

As a test, the new merged model was run with 2012 data and the results were compared with the upper model results for the gravel reach. The merged model level at Mission was 0.21 m higher than the upper model (Drawing 2 - Comparison of Upper Model with Merged Model - 2012 data). For clarity, the profiles are drawn from Fraser chainage 85400 (Mission) to 120400 (just upstream of Harrison confluence). The difference tapers off upstream.

For the 2012 data, the merged model computed higher water levels than the upper model because of the following reasons:

- Due to routing and attenuation effects, the flows computed by the merged model were slightly higher than the upper model.
- In the case of upper model, the water levels at Mission are controlled by the boundary condition and had less room to react to calibration.
- The lower model from Mission to Douglas Island needs recalibration.

When the new merged model was run using the June high tides, same as the 2008 Lower and Upper Model, design water levels near Mission were found to be 0.08 m higher than the new upper model which tapers off as we go upstream (Drawing 3 - Comparison of Upper Model with Merged Model - Design Run). For clarity, the profiles are drawn from Fraser chainage 85400 to 120400. When the new merged model was run using the 2002 May high tide of 1.89 m, this difference was increased to 0.13 m.

Based on the above results, it is suggested that the lower model should be re-calibrated from Mission to Douglas Island. The re-calibration should be carried out using the new merged model for 2012 WSC verified flows. NHC's recommendation of using lower roughness values for flows higher than 12,000 m^3/s at Mission should also be taken into account (NHC 2008).

4.5 NEW DESIGN PROFILE IN GRAVEL REACH

The new merged model was used to generate the final design profile in the gravel reach. The profile showed minor computational irregularities at branch junctions and at locations of abrupt geometry change. Similar to previous work, these irregularities were smoothed in the final design profile plotted along the main stem of the Fraser River (Drawing 4 - Design Profile Smoothed). The water levels in the side channels were not smoothed though. Note that the water levels shown in the layout plan (Map 5-8) are prior to smoothing, therefore, they may differ from the smoothed profile. The water levels plotted against the dike crest profiles (Dike Design Levels) are taken as the higher of the smoothed profile, side channel or the old profile. This is discussed in more detail in the next section.

4.6 DIKE CREST COMPARISON WITH NEW DESIGN PROFILE

In the 2008 NHC report, a comparison of dike crest elevations with design water levels was done based on the most updated crest level surveys available at that time (NHC 2008). This included the partial upgrades done to the dikes in Mission, Dewdney, Abbotsford, Chilliwack and Kent - D in 2007. The dike profile comparisons located in the gravel reach are repeated again in this report.

Before plotting the comparisons, all the diking authorities (municipalities, diking districts and regional districts) were contacted asking for the most recent dike crest survey data that would document any dike upgrading after 2007. It was found that minor upgrades were done to the dikes in Mission and City of Abbotsford whereas some major upgrades were done in the City of Chilliwack. When the dike data was collected from the municipalities, it was realized that some of the dike crest elevations were based on surveys as old as 1996 or even older. Therefore, in 2014, the ministry hired a contractor to complete a dike crest survey of all the dikes in the gravel reach, but excluding the dikes in the City of Chilliwack as the City updated most of their surveys in 2013. The list of dikes surveyed in 2014 included:

- Mission - B dike
- Dewdney dike
- Matsqui – B dike
- Vedder dike (left bank, Abbotsford Section)
- Kent – A dike
- Kent – B dike
- Kent – C dike
- Kent – D dike
- Nicomen Island dike
- Hope Slough Floodwall

All the dike crest profiles were prepared using the most recent dike crest surveys and were plotted against the new design water levels (see Drawings 5 to 21).

In general, the final dike design levels were taken from the higher of the main stem smoothed design profile or the adjacent side channel profile. Smoothing was applied to the main stem only and not to the side channels. For the reaches where the old design water level was higher than the new design profile and the change was due to a shift in the channel geometry, the old design water levels were chosen. This was to allow for the potential for the channel to switch back to the old or similar geometry in future. A freeboard of 0.6 m was added to the final hybrid water levels. A summary of the dike crest survey data used and the decisions taken on the final dike design levels are provided in Table 14 and Table 16.

The dike crest levels are compared with the design water levels in Drawings 5 to 21. In general, most of the dikes were found to have inadequate freeboard and are at high risk of over topping during a design flood event. Only the Matsqui B dike generally meets design level and freeboard requirements. A qualitative assessment is provided in Table 15.

4.7 MODEL LIMITATIONS

Like any hydraulic model, the updated Fraser River Hydraulic model has inherent limitations. Some of these limitations are outlined below:

1. Reliability and accuracy of flow data used for calibration and validation. Verified data for 2012 freshet was not available at the time of calibration (and still not available as of December, 2013).
2. The design flood is 40% higher than the calibration and validation flows. At higher flows roughness values may change and significant bed movement and channel changes can occur. It is extremely difficult to predict such changes and work to attempt this was outside the scope of this project. Both factors can result in water levels different from the estimated profile.
3. At the locations where “levees” are specified in the model x-sections, the model assumes glass walls in case the water level goes higher than the levee top (or dike crest) and does not allow any spillage. In the case a dike is breached or overtopped, the actual water levels would be different from the model water levels.
4. The gravel reach of Fraser River is comprised of heavily braided channels containing a number of bars, mid-channel islands and sharp curves. Areas with complex flow patterns require a 2-D model to reasonably simulate the river hydraulics. The 1-D limitation of the model is significant at the following locations:
   a) Near Wellington branch (impacting water levels for Chilliwack Creek PS)
   b) Near CHIP Camp Hope Intake
   c) Near Agassiz Bridge
   d) At the u/s junction of Minto channel
   e) Near Harrison Knob
5. Link channels were provided at locations where significant lateral flow was taking place from main stem to the side channel or vice-versa. The x-sections for these link channels were estimated considering the range of calibration flows and making use of flow split measurements. Because it is

not possible to envision the behavior of the link channels at flows of the order of design flood, actual design flood water levels could be different than those computed.

6. During the design flood event, gravel bars are likely to shift which can cause variations in the estimated profile. Such variations cannot be predicted.
7. Topographic changes in the channel and floodplain may occur over time either due to natural ongoing changes to the channel or as a result of any activity like gravel removal, building of new dikes or bridges etc. Such morphological changes over time can also result into water levels different than the computed water levels.

Because of all of the above limitations, the dynamic character of the gravel reach, and because many of these issues can cause variances in design water levels of in excess of 0.5 m, it is recommended that the adequacy of the existing freeboard allowance of 0.6 m be reviewed.

5. NEW FORECASTING MODEL

In 2007, NHC was retained to merge the upper and lower model to predict water levels along Fraser River during the freshet (NHC 2007). Since then, the forecasting model has been used every year to provide 5-day peak water level forecasts to the public, municipalities and other agencies for their flood emergency response planning. No changes other than the boundary conditions are required for the forecasting model. The boundary conditions used are as follows:

- Downstream boundary conditions: CHS predicted tides at Point Atkinson and Sandheads
- Local tributaries: Monthly average of historical inflows
- Harrison Lake Inlet flow: From daily forecast supplied by River Forecast Center (RFC)
- Harrison Lake local flows: From daily forecast supplied by RFC
- Fraser River at Hope: From daily forecast supplied by RFC

The forecasting model is run daily during the freshet. Verification of flow inputs and validation of predicted water levels are important steps. For details, refer to the 2007 NHC report on freshet forecasting.

In order to keep the forecasting model up-to-date, the new Upper Model was merged with the 2008 Lower Model (sand reach). Harrison Lake was added and the boundary condition at Harrison River (08MG013) was replaced with the flow data at Tenas Narrows (a new gauge added in Lillooet River upstream of Harrison Lake inlet in 2012). The model was tested for 2012 and 2007 data. Since the Tenas Narrows gauge is fairly new, its flow data was available for 2012 only. To transpose to Harrison Lake, the Tenas Narrows data were adjusted by adding 10% to the data and 5 hours to the time stamp as explained in section 3.1.1. The remainder of the boundary conditions were the same as used for 2012 testing of the merged model. WSC verified data was used for 2007 testing. Note that at the time of creating the old forecasting model in 2007, the WSC verified data was not available.

Similar to previous findings as outlined in section 4.4.2, the modelled water levels at Mission were found higher in the merged model compared to the upper model for both the test cases. It is recommended that the old lower model be recalibrated near Mission using the new merged model with 2012 WSC verified data when it is available.

Caution should be taken for predicting water levels at areas where the flow complexity limits the model capacity to compute the water levels accurately. One such location is near CHIP Camp Hope gauge where the model under-predicts the water level due to 2-D nature of flow. Special alerts should be issued at the time of publishing the forecasted water levels at such locations.

In addition to the limitations as outlined in section 4.7, differences between the actual and RFC forecasted flows, and deviation of the actual from the predicted tides, can be an additional source of error and uncertainty in the model results. To minimize these sources of error, it is very important that the forecasted flows are validated for the daily forecasting runs.

For all previous freshet forecasting seasons, validating inflows to Harrison Lake has always been a big challenge. To resolve this problem, the new flow gauge was installed by WSC in Lillooet River at Tenas Narrows in 2012. It should be kept in mind that this gauge is still in its infancy and its performance should be verified in the coming years. Besides, there is currently no way to verify forecasted local inflows to Harrison Lake. The existing WSC flow gauge at Harrison River (08MG013) does not give reliable results due to back-water effects from Fraser River. In order to address the issue, WSC should be encouraged to install permanent ADCP measurement equipment at Mission and at Harrison River. This will help validate the flow inputs to the model from all tributaries upstream of Mission including Harrison Lake.

6. CONCLUSIONS AND RECOMMENDATIONS

A one dimensional hydrodynamic model was developed for the reach of the Fraser River between Hope and Mission using DHI MIKE 11 hydraulic modeling software. This was a completely new model based on the bathymetry and LiDAR data collected in 2008.

6.1 CONCLUSIONS

1. The model was calibrated and validated with an extensive set of observed flows and water level data, which showed an overall accuracy of $\pm$0.1 m for the 2007, 2011 and 2012 peak freshet floods.

2. The new design profile was found to be very similar to the old profile (based on 1999 bathymetry) showing differences of $\pm$0.2 m in general. At a few places, it showed higher differences which were attributable to improvement in the model or changes in channel geometry.

   For example, at Harrison Knob, where the new profile is up to 0.5 m lower, it could be clearly demonstrated that the differences were due to improvements in the way the energy losses were applied. So, this change can be attributed to model improvement. Downstream of Agassiz Bridge, where the new profile was found 0.3 to 0.8 m lower than the old profile, the difference is likely due to changes in channel geometry from 1999 to 2008. However, at some locations it was difficult to determine whether the differences were due to the modeling approach or channel change. The local differences at Peters Island and Wahleach of +0.3 m and -0.4 m respectively were presumed to be due to changes in channel morphology.

3. The longitudinal profile showed kinks and bumps at branch junctions and abrupt geometry change locations. These are due to the model's numerical scheme and were also observed in the previous models. These irregularities are minor and were smoothed out in the final design profile.

4. The final design profile was generated after merging the new upper model with the existing lower model (sand reach). When the results were compared for the new merged model with the new upper model, the results from the merged model were found 0.21 m higher for 2012 data and 0.08 m higher for the design flow at Mission.

5. High tides from May 2002 were used as downstream boundary conditions at the ocean to generate the design profile. This caused a further increase of around 0.05 m at Mission

compared to the old profile. The combined effect of using the new merged model and adopting 2002 May high tide of 1.89 resulted into an increase of 0.13 m at Mission compared to the results using the new upper model only. The Lower Fraser reach needs to be re-calibrated from Mission to Douglas Island using the new merged model and May 2002 high tide of 1.89.

6. At locations like CHIP Camp Hope Intake, Agassiz Bridge and Wellington Bar, the model performance was relatively less accurate. This was due to high complexity of flows in these areas and 1-D limitation of the model to simulate such flows appropriately.

7. To finalise the Dike Design Levels for each dike, an "upper envelope curve" approach was used between the old and new design profiles. First, from the new profile, the higher of the water levels of the main stem and the side channel along a dike were selected. Then, these water levels were compared with the old design water levels. If the old design water level was higher than the new design water level, the old water level was chosen as the Dike Design Level. Otherwise, the new design water levels were used.

   This approach was applied for the reaches where the differences in the profiles were attributed due to changes in channel geometry. This was to cover the possibility of future channel change. Note that the Dike Design Levels shown on dike crest profile drawings may be different from the final smoothed design profile (Drawing 4 and Maps 5 to 8 showing x-sections and water levels). Care should be taken that **Dike Design Levels** for each dike be read from the dike crest profile drawings (Drawing 5 to 21).

8. Near Harrison Knob, new design water levels were used as new Dike Design Levels for Kent-D dike (Drawing 8) even though they were lower than the old design water levels. This was because the differences in the two profiles were due to an improvement in the new model.

9. Updated dike crest survey data for the dikes protecting Kent, Chilliwack, Nicomen Island, Abbotsford, Dewdney and Mission were compared with the new dike design levels. In general, most of the dikes were found to have inadequate freeboard and are at high risk of over topping during a design flood event. Only the Matsqui dike in Abbotsford generally meets design level and freeboard requirements.

6.2 RECOMMENDATIONS

1. Due to the 1-D limitations of the model, it is strongly recommended that a 2-D "patch" be applied at the following locations to revisit the design water levels in these areas:
   a. Near Wellington branch (impacting water levels for Chilliwack Creek PS) – impacts the real time forecasting near the PS
   b. Near CHIP Camp Hope Intake – impacts Chilliwack East Dike
   c. At the upstream junction of Minto channel - impacts Chilliwack East Dike

2. The maximum difference of 0.8 m between old and new profile, found downstream of Agassiz Bridge, falls outside the bound of existing freeboard of 0.6 m. While in this case the new profile was lower, the comparison of the two modelled profiles indicates that a change in channel geometry can easily cause a change (increase or decrease) in water level greater than the existing freeboard allowance, therefore, revision of the freeboard criteria should be considered.

3. The Lower Fraser reach needs to be re-calibrated from Mission to Douglas Island using the New Merged model and 2002 May high tide of 1.89. This should be done using 2012 WSC verified data when it is available. NHC's recommendation of using lower roughness values for flows higher than 12,000 m^3/s at Mission should be taken into account (Appendix 2).

4. For future model upgrades, it is recommended that the merged model be used for calibration, validation and producing the design profile.

5. The calibration in the gravel reach should be reviewed and confirmed when 2012 verified flows and water level data are made available by WSC.

6. Over time, as the model is updated based on new channel geometries, it is suggested that the "upper envelope curve" approach, as explained earlier in the "Conclusion" section, be adopted for dike crest design. This approach, will in part help to anticipate the potential for higher water levels caused by channel alignment change.

7. Tenas Narrows gauge is still new and its performance during the freshet has yet to be verified. It is recommended that WSC continue to take flow measurements every year and monitor its performance in the upcoming freshets.

8. Dike breach modelling was not under taken in this study. However, for floods approaching the design flows modelled, it is likely that many of the dikes would breach. It is recommended that breach analyses be completed to prepare new flood hazard maps and assess flood risks. The MIKE 11 model described in this report can provide the boundary conditions for the dike breach and floodplain models for specific community risk assessments.

7. References

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TABLES

Table 1 - Comparison of WSC Measured Q vs. WSC Rated Q at Hope (08MF005)

Date	Mean Time of measurement	Q (measured by WSC) m^3/sec	Q (Rating Curve) m^3/sec	Difference (Measured Q - Rated Q)/Rated Q	Comments
2011:					
20-May-2011	11:11:00	7500	7191	4.29%	WSC approved. Rated Q is taken at 11:00:00
14-Jun-2011	15:04:48	9150	9310	-1.72%	WSC approved. Rated Q is taken at 15:00:00
05-Jul-2011	12:53:51	9320	9189	1.42%	WSC approved. Rated Q is taken at 13:00:00
13-Jul-2011	12:13:08	9790	9661	1.33%	WSC approved. Rated Q is taken at 12:00:00
2012:					
03-May-2012	15:29:57	6110	5926	3.11%	Subject to revision by WSC. Rated Q is taken at 15:00:00
08-Jun-2012	13:43:29	7330	7399	-0.94%	Subject to revision by WSC. Rated Q is taken at 14:00:00
12-Jun-2012	11:00:21	9150	9214	-0.69%	Subject to revision by WSC. Rated Q is taken at 11:00:00
21-Jun-2012	14:30:44	11300	11370	-0.61%	Subject to revision by WSC. Rated Q is taken at 14:00:00
22-Jun-2012	9:22:46	11300	11611	-2.68%	Subject to revision by WSC. Rated Q is taken at 09:00:00
29-Jun-2012	10:36:17	10700	11005	-2.77%	Subject to revision by WSC. Rated Q is taken at 11:00:00

Notes:

1. Data and Measurements are approved by WSC to the end of 2011 (ref: email from Curt Naumann (WSC) dated Feb 06, 2012)
2. Boundary conditions for 2011 validation at Hope and Mission are used from WSC approved data
3. The rating curve at Mission was last updated on 01 January 2010 (ref: email from Curt Naumann (WSC) dated Feb 06, 2012)
4. WSC had not released the final data (water level and discharge) for 2012 as of December 2013.
5. Boundary conditions at Hope (flow) and Mission (water level) for 2012 calibration were downloaded in Nov 2012 from WSC website (due to malfunction of Hope flow gauge, WSC applied an interim fix to eliminate the bad data for 20-21 June, 2012).

Table 2 - Comparison of WSC Measured Q vs. WSC Rated Q at Mission (08MH024)

Date	Mean Time of measurement	Q (Measured by WSC) m^3/sec	Q (Rating Curve) m^3/sec	Difference (Measured Q - Rated Q)/Rated Q	Comments
2011:					
25-May-2011	11:01:00	8560	8511	0.57%	WSC approved. Rated Q is taken at 11:00:00
30-May-2011	10:41:00	10100	9691	4.22%	WSC approved. Rated Q is taken at 11:00:00
14-Jun-2011	10:12:00	10900	10817	0.77%	WSC approved. Rated Q is taken at 10:00:00
04-Jul-2011	10:31:00	11000	11528	-4.58%	WSC approved. Rated Q is taken at 11:00:00
13-Jul-2011	15:26:28	10800	10839	-0.36%	WSC approved. Rated Q is taken at 15:00:00
2012:					
04-May-2012	9:38:27	6840	6826	0.20%	Subject to revision by WSC. Rated Q is taken at 10:00:00
07-Jun-2012	15:43:06	8540	8578	-0.44%	Subject to revision by WSC. Rated Q is taken at 16:00:00
13-Jun-2012	8:56:46	10000	10087	-0.87%	Subject to revision by WSC. Rated Q is taken at 09:00:00
21-Jun-2012	18:55:55	12100	12050	0.42%	Subject to revision by WSC. Rated Q is taken at 19:00:00
22-Jun-2012	14:14:34	12500	12861	-2.81%	Subject to revision by WSC. Rated Q is taken at 14:00:00

Note:

1. Data and Measurements are approved by WSC to the end of 2011 (ref: email from Curt Naumann (WSC) dated Feb 06, 2012)
2. Boundary conditions for 2011 validation at Hope and Mission are used from WSC approved data
3. The rating curve at Mission was last updated on 01 January 2010 (ref: email from Curt Naumann (WSC) dated Feb 06, 2012)
4. WSC has not released the final data (water level and discharge) for 2012 yet.
5. Boundary conditions at Hope (flow) and Mission (water level) for 2012 calibration were downloaded in Nov 2012 from WSC website (due to malfunction of Hope flow gauge, WSC applied an interim fix to eliminate the bad data for 20-21 June, 2012).

Table 3 – Comparison of WSC Measured Q vs. WSC Rated Q at Harrison River near Harrison Springs (08MG013)

Harrison River near Harrison Springs (08MG013)					
Date	**Mean Time/Time**	**Q (Measured by WSC) m^3/sec**	**Q (Rating Curve) m^3/sec**	**Difference (Measured Q - Rated Q)/Rated Q**	**Comments**
2012:					
04-May-2012	13:22:00	574	494	13.94%	Subject to revision by WSC. Rated Q is taken at 13:00:00
08-Jun-2012	8:51:00	769	762	0.91%	Subject to revision by WSC. Rated Q is taken at 13:00:00
12-Jun-2012	16:00:00	509	644	-26.52%	Subject to revision by WSC. Rated Q is taken at 21:00:00

Note:

1. Data and Measurements are approved by WSC to the end of 2011 (ref: email from Curt Naumann (WSC) dated Feb 06, 2012)

2. Boundary conditions for 2011 validation at Hope and Mission are used from WSC approved data

3. The rating curve at Mission was last updated on 01 January 2010 (ref: email from Curt Naumann n(WSC) dated Feb 06, 2012)

4. WSC has not released the final data (water level and discharge) for 2012 yet.

5. Boundary conditions at Hope (flow) and Mission (water level) for 2012 calibration were downloaded in Nov 2012 from WSC website (due to malfunction of Hope flow gauge, WSC applied an interim fix to eliminate the bad data for 20-21 June, 2012).

Table 4 - Summary of Branches in Upper Model

Branch Name	Upstream Chainage	Downstream Chainage	Flow Direction	Branch Type
Fraser_R	85400	167135	Negative	Regular
Minto	-316	5526	Negative	Regular
Wellington	-528	3631	Negative	Regular
Greyell_S	-442	4782	Negative	Regular
Lower_Herrling	-271	7024	Negative	Regular
Peters	528	4125	Negative	Regular
Spring_Bar	-437	3757	Negative	Regular
Wahleach	-331	2287	Negative	Regular
Hamilton	-443	4390	Negative	Regular
Big_Bar_US	-320	1598	Negative	Regular
Tranmer	-59	3332	Negative	Regular
Queens	-636	3212	Negative	Regular
Middle_Herrling	36	2653	Negative	Regular
Bristol	-425	1394	Negative	Regular
Vedder_R	0	6727	Negative	Regular
Link_Fraser_Well	0	642	Negative	Link Channel
Hope_S	-636	2985	Negative	Regular
Link_Fraser_Hamilton	0	1059	Negative	Link Channel
Harrison_R	0	17845	Negative	Regular
Link_Fraser_Hope_WingDike_US	0	300	Negative	Link Channel
Link_Fraser_Hope_WingDike_DS	0	300	Negative	Link Channel
Greenwood	143	1993	Negative	Regular
Sumas	0	3370	Negative	Regular
Link_Fraser_Queens1	0	414.84937	Negative	Link Channel
Link_Fraser_Queens2	0	526.307895	Negative	Link Channel
Link_Fraser_Hamilton_2	0	740.405294	Negative	Link Channel
Link_Fraser_Wah	0	359.504663	Negative	Link Channel
Big_Bar_DS	-682	1478	Negative	Regular
Link_Fraser_Hamilton_3	0	575.847202	Negative	Link Channel
Link_Fraser_Powerline	0	414.366987	Negative	Link Channel
Powerline	-703	2135	Negative	Regular

Table 5 - Summary of Boundary Conditions in the Upper Model

Location	2007 Peak Flows (m^3/sec) / W.L (m)		2011 Peak Flows (m^3/sec) / W.L (m)		2012 Peak Flows (m^3/sec) / W.L (m)		Boundary Description
	Model Flows / W.L		Model Flows / W.L		Model Flows / W.L		
	Time of Peak	Peak Flow (m^3/sec) / W.L (m)	Time of Peak	Peak Flow (m^3/sec / W.L (m)	Time of Peak	Peak Flow (m^3/sec / W.L (m)	
Fraser River at Hope	10-06-2007 00:00	11125	03-07-2011	9780	22-06-2012 12:00	11870	Used as Model u/s boundary. Time series of inflows for 2012 & 2007 were input as hourly whereas 2011 as daily average
Harrison River - 08MG013	24-07-2007 16:00	1460	03-07-2011	1050	22-06-2012 00:00	990	Time series of inflows was input as daily average
Chehalis (Harrison River local inflows)		40		40		40	Constant boundary
Vedder (Chilliwack River)	21-05-2007	267	03-07-2011	156	22-06-2012 08:00	190	Time series of inflows for 2012 as hourly whereas 2007 & 2011 as daily average
Silverhope		34		34		34	Constant boundary
Sumas		2		2		2	Constant boundary
Ruby +Wahleach		7		7		7	Constant boundary
Hope Slough		0		0		0	Constant boundary
Fraser River at Mission	11-06-2007 5:00	6.08	04-07-2011 11:00	5.88	23-06-2012 11:00	6.42	Used as Model d/s boundary. Time series of water levels was input as hourly data

Note: For hydrographs of all boundary conditions, refer to Figures 5 to 16

Table 6 – Flow Comparison (sanity check) at Mission

Location	2011			2012			Comments
	Time of Peak	**Peak Flow (m^3/s)**	**Diff (Model Less Actual)**	**Time of Peak**	**Peak Flow (m^3/s)**	**Diff (Model Less Actual)**	
Discharge at Mission (sum of tributary flows input to the model)		11,062			13,126		
Discharge at Mission (from MIKE 11 result file)	03-07-2011 23:00	10,891	-1.57%	22-06-2012 23:00	12,936	-1.47%	
Discharge at Mission (from WSC rating curve)	03-07-2011 23:00	11,213	2.95%		12,810	0.97%	2011 flows are WSC approved. 2012 flows are preliminary.

Table 7 - Flow Split Measured Data (Set #1)

Section	Date	Time	Measured Q (m^3/s)
L1	2012-06-14	7:42 AM	8295
L2	2012-06-14	8:00 AM	974
L3	2012-06-14	8:15 AM	7386
L4	2012-06-14	8:33 AM	5916
L5	2012-06-14	8:55 AM	269
L6	2012-06-14	9:45 AM	7966
L7	2012-06-14	10:15 AM	4895
L8	2012-06-14	1:09 PM	3594
L9	2012-06-14	11:58 AM	5223
L10	2012-06-14	11:43 AM	7817
L11	2012-06-14	11:15 AM	6335
L12	2012-06-14	12:09 PM	534
L13	2012-06-14	12:33 PM	4403
L15	2012-06-14	1:31 PM	7353
L15a/L14	2012-06-14	1:58 PM	1328
L16	2012-06-14	2:20 PM	6205
L17	2012-06-13	11:14 AM	5617
L18	2012-06-13	10:58 AM	535
L19	2012-06-13	12:18 PM	291
L20	2012-06-13	11:22 AM	1957
L21	2012-06-12	9:44 AM	7530
L22	2012-06-12	4:36 PM	4757
L23	2012-06-12	5:03 PM	5526
L24	2012-06-12	5:23 PM	695
L25	2012-06-12	5:53 PM	1450
L26	2012-06-13	9:39 AM	1482
L27	2012-06-13	7:19 AM	5065
L28	2012-06-13	7:41 AM	4101
L29	2012-06-13	8:14 AM	9250
L30	2012-06-13	8:49 AM	1618
L31	2012-06-13	9:08 AM	3176
L32	2012-06-13	2:46 PM	8047
L33	2012-06-13	11:38 AM	3674
L34	2012-06-14	3:45 PM	3008
Carey Point	2012-06-14	2:58 PM	8765

Notes:

1. Date of Measurement: June 12-14/2012. Q at Hope 9,370 to 8,933 m^3/s
2. See **Figure 2** for measurement locations.

Table 8 - Flow Split Measured Data (Set #2)

Section	Date	Time	Measured Q (m^3/s)
L1	2012-06-22	8:59 AM	10963
L2	2012-06-22	9:34 AM	1437
L3	2012-06-22	9:48 AM	9447
L4	2012-06-22	10:08 AM	7257
L5	2012-06-22	11:11 AM	586
L6	2012-06-22	11:36 AM	10682
L7	2012-06-22	12:07 PM	6396
L8	2012-06-22	1:42 PM	5637
L9	2012-06-22	4:37 PM	6003
L10	2012-06-22	12:27 PM	9672
L11	2012-06-22	12:42 PM	7832
L12	2012-06-22	1:11 PM	883
L13	2012-06-22	2:01 PM	5300
L14	2012-06-22	2:51 PM	2246
L15	2012-06-22	2:28 PM	8814
L16	2012-06-22	3:06 PM	7865
L17	2012-06-22	3:28 PM	5880
L18	2012-06-22	3:47 PM	637
L19	2012-06-22	5:07 PM	504
L20	2012-06-22	4:01 PM	2572
L21	2012-06-23	7:54 AM	10645
L22	2012-06-23	8:13 AM	6569
L23	2012-06-23	8:37 AM	7701
L24	2012-06-23	9:50 AM	870
L25	2012-06-23	10:01 AM	2174
L26	2012-06-23	10:11 AM	2644
L27	2012-06-23	10:27 AM	6211
L28	2012-06-23	10:44 AM	4906
L29	2012-06-23	11:09 AM	11754
L30	2012-06-23	11:47 AM	2078
L31	2012-06-23	12:07 PM	4203
L32	2012-06-23	9:29 AM	9560
L33	2012-06-22	4:17 PM	4879
L34	2012-06-23	9:11 AM	3963

Notes:

1. Date of Measurement: June 22-23/2012. Q at Hope 11,794 to 11,710 m^3/s
2. See **Figure 2** for measurement locations.

Table 9 - Flow Split Measured Data (Set #3)

Section	Date	Time	Measured Q (m^3/s)
L1	2012-07-25	8:36 AM	6424
L2	2012-07-25	8:58 AM	694
L3	2012-07-25	9:10 AM	5649
L4	2012-07-25	9:31 AM	4676
L5	2012-07-25	10:01 AM	129
L6	2012-07-25	10:33 AM	6510
L7	2012-07-25	10:50 AM	3447
L8	2012-07-25	1:24 AM	3156
L9	2012-07-25	4:00 AM	4444
L10	2012-07-25	11:11 AM	6032
L11	2012-07-25	11:28 AM	4868
L12	2012-07-25	12:31 PM	263
L13	2012-07-25	1:30 PM	3185
L14	2012-07-25	2:14 AM	450
L15	2012-07-25	2:25 AM	5934
L16	2012-07-25	2:38 AM	4432
L17	2012-07-25	2:58 AM	4106
L18	2012-07-25	3:27 AM	296
L19	2012-07-25	3:51 AM	182
L20	2012-07-25	3:38 AM	1180
L21	2012-07-26	7:34 AM	6392
L22	2012-07-26	8:06 AM	3749
L23	2012-07-26	8:26 AM	5045
L24	2012-07-26	8:43 AM	561
L25	2012-07-26	8:57 AM	825
L26	2012-07-26	9:10 AM	896
L27	2012-07-26	9:24 AM	3981
L28	2012-07-26	9:56 AM	3624
L29	2012-07-26	10:15 AM	7626
L30	2012-07-26	10:34 AM	1648
L31	2012-07-26	11:08 AM	2312
L32	2012-07-26	11:38 AM	6685
L33	2012-07-25	4:21 AM	2269
L34	2012-07-26	12:03 PM	2446

Notes:

1. Date of Measurement: July 25-26/2012. Q at Hope 6,687 to 6,628 m^3/s
2. See **Figure 2** for measurement locations.

Table 10 - Flow Split Measurement Analysis

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	**Q (Set 1) cms (12-14 Jun/12)**	**% split Set 1**	**Q (Set 2) cms (22-23 Jun/12)**	**% split Set 2**	**Model XS**	**Model Flows for Set#1 cms**	**% split**	**Model Flows for Set#2 cms**	**% split**	**Comments**
Wahleach											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Wahleach	L1	8295		10963		Fraser_151864	8870		11715		
Fraser flow d/s of Wahleach	L3	7386		9447		Fraser_151064	7883		10192		
Wahleach flow	L2	974	11.74%	1437	13.11%	Wahleach_1490	985	11.11%	1515	12.93%	
Fraser flow u/s of Link Channel	L3	7386		9447		Fraser_151064	7883		10192		
Fraser flow d/s of Link Channel	L4	5916		7257		Fraser_149848	6152		7852		
Flow in Link Channel	L3-L4	1470	19.91%	2189	23.18%		1731	21.96%	2340	22.96%	
						LINK_FRASER_WAH 0.00	1729		2334		
Peters											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Peters	L4	5916		7257		Fraser_149848	6152		7852		
Peters flow	L5	269	4.55%	586	8.07%	Peters_1991	241	3.91%	474	6.04%	
Spring_Bar (Seabird Island)											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Spring_bar	L6	7966		10682		Fraser_144102	8865		11677		
Fraser flow d/s of Spring_bar	L7	4895		6396		Fraser_141439	4941		6517		

Table 10 – Flow Split Measurement Analysis (cont.)

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	**Q (Set 1) cms (12-14 Jun/12)**	**% split Set 1**	**Q (Set 2) cms (22-23 Jun/12)**	**% split Set 2**	**Model XS**	**Model Flows for Set#1 cms**	**% split**	**Model Flows for Set#2 cms**	**% split**	**Comments**
Spring_bar flow	L6-L7	3071	38.56%	4286	40.13%		3923	44.26%	5160	44.19%	
						Spring_bar_2923	3925	44.28%	5158	44.17%	
Lower Herrling											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Lower Herrling	L7	4895		6396		Fraser_141439	4941		6517		
Lower Herrling flow	L12	534	10.91%	883	13.81%	Lower_Herrling_5861	511	10.34%	801	12.29%	
Tranmer											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Tranmer	L10	7817		9672		Fraser_138766	8360		10872		
Fraser flow d/s of Tranmer	L11	6335		7832		Fraser_137374	6727		8550		
Tranmer flow	L10-L11	1482	18.96%	1839	19.02%		1633	19.54%	2322	21.36%	
						TRANMER_ 2521.00	1635	19.55%	2321	21.35%	
Middle Herrling											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Powerline	L11	6335		7832		Fraser_137374	6727		8550		
Flow in Middle Herrling	L8	3594	56.73%	5637	71.97%	Middle_Herrling_1731	4287	63.72%	5956	69.66%	Note that surveyor (CRA) had trouble getting L8 measurement in set #1

Table 10 – Flow Split Measurement Analysis (cont.)

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	**Q (Set 1) cms (12-14 Jun/12)**	**% split Set 1**	**Q (Set 2) cms (22-23 Jun/12)**	**% split Set 2**	**Model XS**	**Model Flows for Set#1 cms**	**% split**	**Model Flows for Set#2 cms**	**% split**	**Comments**
Powerline											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s of Powerline	L13	4403		5300		Fraser_133558	4584		5711		
Powerline flow (at exit)	L14	1328	30.17%	2246	42.39%	Powerline_823	1309	28.56%	2200	38.53%	Note that L14 measurement was problematic for set#1
Big_Bar_US											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s Big_Bar_US	L14+L15	8681		11060		Fraser_130256 +Powerline_0	8868		11761		Note that L14 measurement was problematic for set#1
Fraser flow d/s Big_Bar_US	L16	6205		7865		Fraser_129148	6734		9001		
Big_Bar_US flow		2476	28.53%	3196	28.89%	Big_Bar_US_641	2132	24.05%	2762	23.48%	
Big_Bar_DS											model data is from: Set #1 = June 14, Set #2 =June 22
Fraser flow u/s Big_Bar_DS	L16	6205		7865		Fraser_129148	6734		9001		
Fraser flow d/s Big_Bar_DS	L17	5617	64.71%	5880	53.17%	Fraser_127666	5069	57.16%	6515	55.39%	Note: %age is with respect to total Fraser flow i.e. L14+L15
Big_Bar_DS flow	L33	3674	42.33%	4879	44.11%	Big_Bar_DS_833	3796	42.81%	5250	44.63%	
Hamilton Branch											model data is from: Set #1 = June 13, Set #2 =June 22
Fraser flow u/s of Hamilton	L17+L33	9292		10759		Fraser_127666 + BigBarDS_833	9053		11662		

Table 10 – Flow Split Measurement Analysis (cont.)

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	Q (Set 1) cms (12-14 Jun/12)	% split Set 1	Q (Set 2) cms (22-23 Jun/12)	% split Set 2	Model XS	Model Flows for Set#1 cms	% split	Model Flows for Set#2 cms	% split	Comments
Hamilton flow (at entrance)	L18	535	5.76	637	5.92	Hamilton_3748	712	7.87	908	7.79	
Hamilton flow d/s of link channels (at exit)	L20	1957		2572		Hamilton_0	2946		3498		Complex flow area. Measured L20 is not reliable as it under-estimated. Flow in Link channel should be more than the measured. Also, L20 is u/s of Link_3 and has not captured the flow coming from this link channel
Flow in Link Channel		1422	15.31	1935	17.98		2234	24.67	2590	22.21	
						Link_Fraser_Hamilton 0	1557		2133		
						Link_Fraser_Hamilton_2 0	180		327		
						Link_Fraser_Hamilton_3 0	496		131		
						Flow in Link channel	2233		2591		
Fraser flow at L9	L9	5223	56.21	6003	55.79	Fraser_124720	6206	68.55	7612	65.27	Complex flow area
Greyell_S Branch											
Fraser flow u/s of Hamilton and Greyell_S	L17+L33	9292		10759		Fraser_130256	9053		11662		
Greyell_S flow	L19	291	3.13	504	4.68	Greyell_S_3760	398	4.40	680	5.83	

Table 10 – Flow Split Measurement Analysis (cont.)

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	**Q (Set 1) cms (12-14 Jun/12)**	**% split Set 1**	**Q (Set 2) cms (22-23 Jun/12)**	**% split Set 2**	**Model XS**	**Model Flows for Set#1 cms**	**% split**	**Model Flows for Set#2 cms**	**% split**	**Comments**
Minto Branch											model data is from: Set #1 = June 12, Set #2 =June 23
Fraser flow u/s of Minto	L21	7530		10645		Fraser_120109	9404		11771		
Fraser flow (u/s of Harrison confluence)	L22	4757		6569		Fraser_118629	5774		7066		
Fraser flow (d/s of Harrison confluence)	L23	5526		7701		Fraser_116277	6505		8213		
Minto flow	L34	3008	39.94	3963	37.23	Minto_4830	3634	38.64	4705	39.97	
	or L21-L22	2773	36.83	4076	38.29						
Queens Branch											model data is from: Set #1 = June 12, Set #2 =June 23
Fraser flow u/s of Queens	L23	5526		7701		Fraser_114403	6507		8212		
Queens Flow	L24	695	12.57	870	11.29	Queens_2714	539	8.28	832	10.14	
Queens flow u/s of Link_1	L24	695		870		Queens_2714	539		832		
Queens flow d/s of Link_1	L25	1450		2174		Queens_1163	1279		2084		
Queens flow d/s of Link_2	L26	1482		2644		Queens_0	1395		2634		
Flow in Link_1	L25-L24	756		1304			740		1252		
Flow in Link_2	L26-L25	32		470			115		550		
Flow through both link channels		787	14.24	1775	23.04	Or LINK_FRASER_QUEENS1 0.00 +LINK_FRASER_QUEENS2 0.00	856	13.15	1802	21.94	Calculated %age with L23 just for comparison

Table 10 – Flow Split Measurement Analysis (cont.)

	Measured during freshet 2012					Modelled Flow Data					
	Measurement Location	**Q (Set 1) cms (12-14 Jun/12)**	**% split Set 1**	**Q (Set 2) cms (22-23 Jun/12)**	**% split Set 2**	**Model XS**	**Model Flows for Set#1 cms**	**% split**	**Model Flows for Set#2 cms**	**% split**	**Comments**
Wellington Branch											model data is from: Set #1 = June 12, Set #2 =June 23
Fraser flow u/s of Wellington	L32+L25	9498		11734		Fraser_111192 +Queens_0	10151		12914		
Wellington flow	(L32+L25)-L27	4433	46.67	5523	47.07	Wellington_2734	4750	46.79	6393	49.51	
Fraser flow u/s of Link channel	L27	5064		6210		Fraser_110180	5407		6518		
Fraser flow d/s of Link channel	L28	4100	43.17	4906	41.81	Fraser_108822	4687	46.18	5917	45.82	Complex flow area – model flows are over-estimated
Flow getting into Link Channel	L27-L28	964	19.04	1304	21.00		720	13.31	601	10.15	Complex flow area – 1-D limitation of the model can be seen here
Fraser flow d/s of Wellington jnc	L29	9250		11754		Fraser_106506	10168		12906		
Wellington flow d/s of Link channel	L29-L28	5150	55.67	6848	58.26		5480	53.90	6989	54.15	Complex flow area

Table 11 - Calibration / Validation Summary (Continuous Gauges)

Gauge Name (Downstream to Upstream)	Located far from main channel	**2007 (Peak - 10 June 2007)** Obs Time (10 June 2007)	Obs WL (m GSC)	Modelled Time (10 June 2007)	Modelled WL (m GSC)	Diff (Modelled less Obs) m	**2011 (Peak - 03 July 2011)** Obs Time (03 July 2011)	Obs WL (m GSC)	Modelled Time (03 July 2011)	Modelled WL (m GSC)	Diff (Modelled less Obs) m	**2012 (Peak - 22 June 2012)** Obs Time (22 June 2012)	Obs WL (m GSC)	Modelled Time (22 June 2012)	Modelled WL (m GSC)	Diff (Modelled less Obs) m	Comments
Dewdney PS	x	7:00	6.47	6:00	6.43	-0.04	23:00	6.09	23:00	6.10	0.01						
McGillivray Slough PS	x						23:00	6.92	23:00	6.96	0.04	7:00	7.52	15:00	7.74	0.22	Obs Data not reliable from 22-25 June, 2012. Instead peak is taken on June 21st
Fraser River at Cannor - 08MF038	x											15:00	8.05	23:00	8.13	0.08	
Chilliwack Creek PS (Wolfe Road)							23:00	8.14	23:00	8.36	0.22	15:00	8.79	23:00	9.04	0.25	
Hope Slough at Young Road							22:00	8.67	23:00	8.63	-0.04	16:00	9.25	23:00	9.27	0.02	
Fraser River at Bell Slough	x											16:00	11.21	23:00	11.13	-0.08	
Fraser River near Harrison Mills - 08MF073	x											18:00	10.94	23:00	11.13	0.19	
Harrison R. at Harrison Mills - 08MG014																	
Harrison R. below Morris Creek - 08MG022		19:00	11.77	23:00	11.66	-0.11	23:00	11.39	23:00	11.32	-0.07	23:00	11.97	23:00	11.95	-0.02	
Lower Kent	x											22:00	12.45	23:00	12.65	0.20	
Fraser River near Agassiz - 08MF035	x											12:00	17.21	23:00	17.24	0.03	
North of Herrling Island - Cont	x											7:00	21.87	16:00	21.98	0.11	
North of Hunter Creek - Cont	x											9:00	31.25	15:00	31.37	0.12	
Fraser R. at Hope Bridge - 08MF005	x	0:00	37.35	0:00	37.36	0.01	15:00	36.88	23:00	36.88	0.00	14:00	37.67	14:00	37.71	0.04	

Table 12 - Calibration / Validation Summary (Staff Gauges)

		2007 (Peak 10 June 2007)				2011 (Peak 03 July 2011)				2012 (Peak 22 June 2012)				
Gauge Name (Downstream to Upstream)	Located far from main channel	Obs Time (10 June 2007)	Obs WL (m GSC)	Modelled WL (m GSC)	Diff (Modelled less Obs) m	Obs Time (03 July 2011)	Obs WL (m GSC)	Modelled WL (m GSC)	Diff (Modelled less Observed) m	Obs Time (22 June 2012)	Obs WL (m GSC)	Modelled (m GSC)	Diff (Modelled less Observed) m	Comments
Mission CPR Bridge		7:30	5.90	6.00	0.09					8:18	6.28	6.31	0.03	
Robson PS	x	13:40	6.90	6.88	-0.02	10:00	6.45	6.49	0.04					
McGillivray Slough PS	x	8:00	7.37	7.36	-0.01									
Collinson PS	x	8:00	7.33	7.37	0.04									
Quaamitch Slough	x	14:10	7.74	7.90	0.16					8:30	8.02	8.25	0.23	
Chilliwack Creek PS (Wolfe Road)	x	8:00	8.49	8.71	0.22									
Hope Slough at Young St.	x	8:00	8.95	8.96	0.01									
Minto Landing Area (Bell Slough)		8:00	10.79	10.80	0.01	8:00	10.35	10.41	0.06					
Harrison Mills (Kilby)		8:14	11.58	11.52	-0.06					9:48	11.82	11.78	-0.04	
Duncan Bateson PS		7:53	11.68	11.61	-0.07					9:21	11.89	11.86	-0.03	
Scowlitz		8:05	11.61	11.73	0.12					6:30	12.01	12.03	0.02	We started reading Scowlitz from June 24th, therefore added the comparison from June 24th instead of June 22nd
Carey Point		8:00	13.21	13.13	-0.08	8:00	12.75	12.76	0.01	8:00	13.52	13.48	-0.04	Data missing for June 22nd. Therefore added comparison for June 23rd for Carey Point
Hammersley PS	x	7:44	13.91	14.03	0.12					8:55	14.25	14.30	0.05	
Chip (Camp-Hope) Intake		8:00	16.74	16.30	-0.44	8:00	16.19	16.00	-0.19	7:00	16.87	16.58	-0.29	
Tuyttens Road at Cutler	x													
Agassiz-Rosedale Bridge South		10:18	16.97	16.81	-0.16	8:00	16.32	16.53	0.21	7:00	16.97	17.08	0.11	Data missing for June 22nd. Therefore added comparison for June 23rd for Agassiz Bridge South
Agassiz-Rosedale Bridge North		9:44	16.87	16.81	-0.06					11:57	16.92	17.10	0.18	
Cuthbert Road		10:08	19.08	18.91	-0.17					11:49	19.19	19.15	-0.04	

Table 12 – Calibration / Validation Summary (Staff Gauges) – cont.

		2007 (Peak 10 June 2007)				2011 (Peak 03 July 2011)				2012 (Peak 22 June 2012)				
Gauge Name (Downstream to Upstream)	Located far from main channel	**Obs Time (10 June 2007)**	**Obs WL (m GSC)**	**Modelled WL (m GSC)**	**Diff (Modelled less Obs) m**	**Obs Time (03 July 2011)**	**Obs WL (m GSC)**	**Modelled WL (m GSC)**	**Diff (Modelled less Observed) m**	**Obs Time (22 June 2012)**	**Obs WL (m GSC)**	**Modelled (m GSC)**	**Diff (Modelled less Observed) m**	Comments
Herrling Island	x	10:00	20.65	20.40	-0.25					7:12	20.67	20.64	-0.03	
Seabird Island										8:19	21.89	22.01	0.12	
Johnson Slough		7:50	26.83	26.85	0.02					8:07	26.95	27.14	0.19	
Wahleach (Jones) Creek		9:35	26.95	26.80	-0.15					7:24	27.14	27.07	-0.07	
Hunter Creek - Staff										7:33	31.05	31.08	0.03	

Table 13 - Summary of Roughness Values

Branch name	Chainage	Manning's "n"
Harrison_R	0	0.032
Harrison_R	9000	0.032
Harrison_R	11700	0.035
Harrison_R	14800	0.035
Harrison_R	17844.6	0.035
Fraser_R	85400	0.029
Fraser_R	95477	0.029
Fraser_R	101745	0.03
Fraser_R	107158	0.03
Fraser_R	108882	0.028
Fraser_R	109795	0.028
Fraser_R	110180	0.028
Fraser_R	112217	0.031
Fraser_R	112925	0.031
Fraser_R	119296	0.032
Fraser_R	122189	0.032
Fraser_R	128018	0.031
Fraser_R	129916	0.029
Fraser_R	130256	0.029
Fraser_R	132206	0.029
Fraser_R	133899	0.031
Fraser_R	134143	0.032
Fraser_R	138445	0.03
Fraser_R	142241	0.03
Fraser_R	143763	0.031
Fraser_R	147036	0.033
Fraser_R	150218	0.033
Fraser_R	151456	0.031
Fraser_R	156030	0.031
Fraser_R	158604	0.033
Fraser_R	163447	0.033
Fraser_R	167135	0.033
Sumas	0	0.032
Sumas	1146	0.032
Vedder_R	0	0.032
Vedder_R	6340	0.032
WELLINGTON	0	0.03
WELLINGTON	3930	0.03

Table 13 – Summary of Roughness Values (cont.)

Branch name	Chainage	Manning's "n"
Queens	0	0.032
Queens	2714	0.032
MINTO	0	0.031
MINTO	5141	0.031
HAMILTON	0	0.034
HAMILTON	3748	0.034
Greyell_S	0	0.036
Greyell_S	4424	0.036
HARRISONLAKE	0	0.02
HARRISONLAKE	56000	0.02
Big_Bar_DS	0	0.031
Big_Bar_DS	1103	0.031
Big_Bar_US	0	0.031
Big_Bar_US	1039	0.031
Powerline	0	0.03
Powerline	823	0.03
Powerline	1207	0.031
Powerline	1788	0.031
Middle_Herrling	0	0.032
Middle_Herrling	2360	0.032
Lower_Herrling	-271	0.036
Lower_Herrling	7024	0.036
Tranmer	-494	0.032
Tranmer	3332	0.032
Spring_Bar	0	0.03
Spring_Bar	3307	0.03
Peters	528	0.036
Peters	4125	0.036
Wahleach	-331	0.033
Wahleach	2287	0.034
Bristol	0	0.036
Bristol	1013	0.036
Greenwood	0	0.034
Greenwood	1848	0.034

Table 14 - Summary of Dike Crest Data

Diking Authority	Dike Name	Reference Drawing	Comments
District of Mission	Mission A	Outside project scope	Mission A Dike is d/s of CPR bridge and is outside the project scope
	Mission B	Drawing 20	Upgrades were done to the dike along Harbour Ave in 2011. Crest elevation data from 2014 MFLNR survey.
Dewdney Area Improvement District	Dewdney Dike	Drawing 19	No upgrading since 2007. Crest elevation data from 2014 MFLNR survey.
City of Abbotsford	Matsqui A		Outside project limits (Located d/s of CPR bridge)
	Matsqui B	Drawing 18	Crest elevation data from 2014 MFLNR survey. In 2010 4'' road mulch was added from chainage 178 to 2181 (from CPR Railway bridge going upstream) and, from chainage 4181 to 6435 in 2008
	Vedder River Left Bank (chainage 3744 to 8487) - North of Keith Wilson Rd	Drawing 14	No upgrade since 2007. Crest elevation data from 2014 MFLNR survey.
	Sumas River Dike	Outside project scope	Outside project limits
City of Chilliwack	Vedder River Right Bank, Left bank (chainage 0 to 3744) – up to Keith Wilson Rd	Drawing 13 and 14	Crest elevation data from City of Chilliwack 2013 and 2011 surveys.
	Chilliwack East Dike	Drawing 9	City of Chilliwack 2011 survey
	Island 22 Wing Dike	Drawing 10	City of Chilliwack 2013 LiDAR survey
	Young Road to Chilliwack Mountain Dike	Drawing 11	City of Chilliwack 2013 LiDAR survey
	Young Road Dike	Drawing 11	City of Chilliwack 2013 LiDAR survey
	Cattermole Dike	Drawing 12	City of Chilliwack 2013 survey
District of Kent	Kent A	Drawing 5	No upgrade since 2007. Crest elevation data from 2014 MFLNR survey.
	Kent B	Drawing 6	No upgrade since 2007. Crest elevation data from 2014 MFLNR survey.
	Kent C	Drawing 7	No upgrade since 2007. Crest elevation data from 2014 MFLNR survey.
	Kent D	Drawing 8	No upgrade since 2007. Crest elevation data from 2014 MFLNR survey.
Nicomen Island Improvement District	Nicomen Island Dike	Drawing 15, 16 & 17	Crest elevation data from 2014 MFLNR survey.

Table 15 - Qualitative Dike Elevation Assessment (see Drawings 5 to 21)

Dike Name	Dike at or above Design Crest Level	Dike Crest below Design Crest Level (Design WL + 0.6 Freeboard)		Dike Crest below Design Water Level	
		Some low sections	Extensive Sections of Dike	Some low sections	Extensive Sections of Dike
Mission B					
Dewdney Dike					
Matsqui B					
Vedder River Left Bank (chainage 3744 to 8487) - North of Keith Wilson Rd (Abbotsford) and Left bank (chainage 0 to 3744)south of Keith Wilson Rd (Chilliwack)					
Vedder River Right Bank					
Chilliwack East Dike					
Island 22 Wing Dike					
Young Road to Chilliwack Mountain Dike (Young Road + Town Dike)					
Cattermole Dike					
Hope Slough Floodwall					
Kent A					
Kent B					
Kent C					
Kent D					
Nicomen Island Dike					

Legend

	Dike generally at or above Design Crest Level (Design WL + Freeboard)
	Dike partially below Design Crest Level (Design WL + Freeboard)
	Extensive sections of Dike below Design Crest Level (Design WL + Freeboard)
	Dike Crest below Design Water Level

Table 16- Summary of Decisions Made to Determine Specific Dike Design WLs*

Dike name	Decisions/Comments
Mission Dike A	*Outside project limits*
Mission Dike B	Used new design water levels as "Dike Design Level" all along
Dewdney Dike	Used new design water levels as "Dike Design Level" all along
Matsqui A Dike	*Outside project limits*
Matsqui B Dike	Used new design water levels as "Dike Design Level" all along
Vedder River Left Bank (chainage 3744 to 8487) - North of Keith Wilson Rd	Used new design water levels as "Dike Design Level" all along
Sumas River Dike	*Outside project limits*
Vedder River Right Bank, Left bank (chainage 0 to 3744) – up to Keith Wilson Rd	Used new design water levels as "Dike Design Level" all along
Chilliwack Dike (East Dike)	Used old design water levels as "Dike Design Level" all along
Island 22 Wing Dike	Used old design water levels as "Dike Design Level" all along
Young Road to Chilliwack Mountain Dike (Young Road + Town Dike)	Dike chainage 0 to 913: used new Fraser WLs as they were higher than old WLs. Dike chainage 913 to 3089: used new WLs of Fraser as they were higher than both Hope_S and old WLs. Dike chainage 3089 to 5612: Dike design WL will be controlled by Minto 0 chainage which is closest to the boat ramp. For design purposes, it is assumed (after consultation with city of Chilliwack), that Wing Dike stays intact upstream of the boat ramp. Design WL of 12.1 is taken from old model at Minto_C 0 chainage which is also close to the boat ramp and higher than the new WL at Minto 0.
Cattermole Dike	New dike - used new design water levels as "Dike Design Level" all along
Hope Slough Floodwall	This dike is outside model boundary. However, design WL at Young Road is used as the "Dike Design Level" for this dike as well. For rationale, see comment for Young Road.
Kent A Dike	Dike chainage 0 to 2180: used new WLs of the main stem as Fraser WLs were higher than Tranmer branch Dike chainage 2377 to 5342: used new WLs of the channels along the dike Dike chainage 5482 to 5890: used old WLs as they were the highest
Kent B Dike	Used old WLs all along the dike as they were the highest
Kent C Dike	Dike chainage 0 to 2444: used old WLs as they were the highest Dike chainage 3356 to 4180: used new WLs of Hamilton branch
Kent D Dike	Used the new design profile even though it is lower than old profile. This difference was not due to the change in channel geometry but was due to the difference in Harrison Knob energy losses. This was an improvement to the model and therefore the new profile was used as the dike design water levels
Nicomen Island Dike	Dike chainage 0 to 18,000: used new WLs along the dike as they were higher (differences <= 0.06m were ignored) the old WLs. Dike chainage 18,000 to 35,000: New WL of Fraser 96277 was used as dike design WL assuming the dike does not breach upstream. This was due to the fact that if the dikes does not breach then the WL in Nicomen Slough is controlled by the Fraser WL at the slough's mouth due to back water effect.

***Design Criteria: The higher of the new design WL on the main stem, the side channel or the old design WL, plus 0.6m freeboard . The old design WL was used only where the change could be attributed to changes in channel geometry.**

FIGURES

Figure 1 - Blocking Scheme

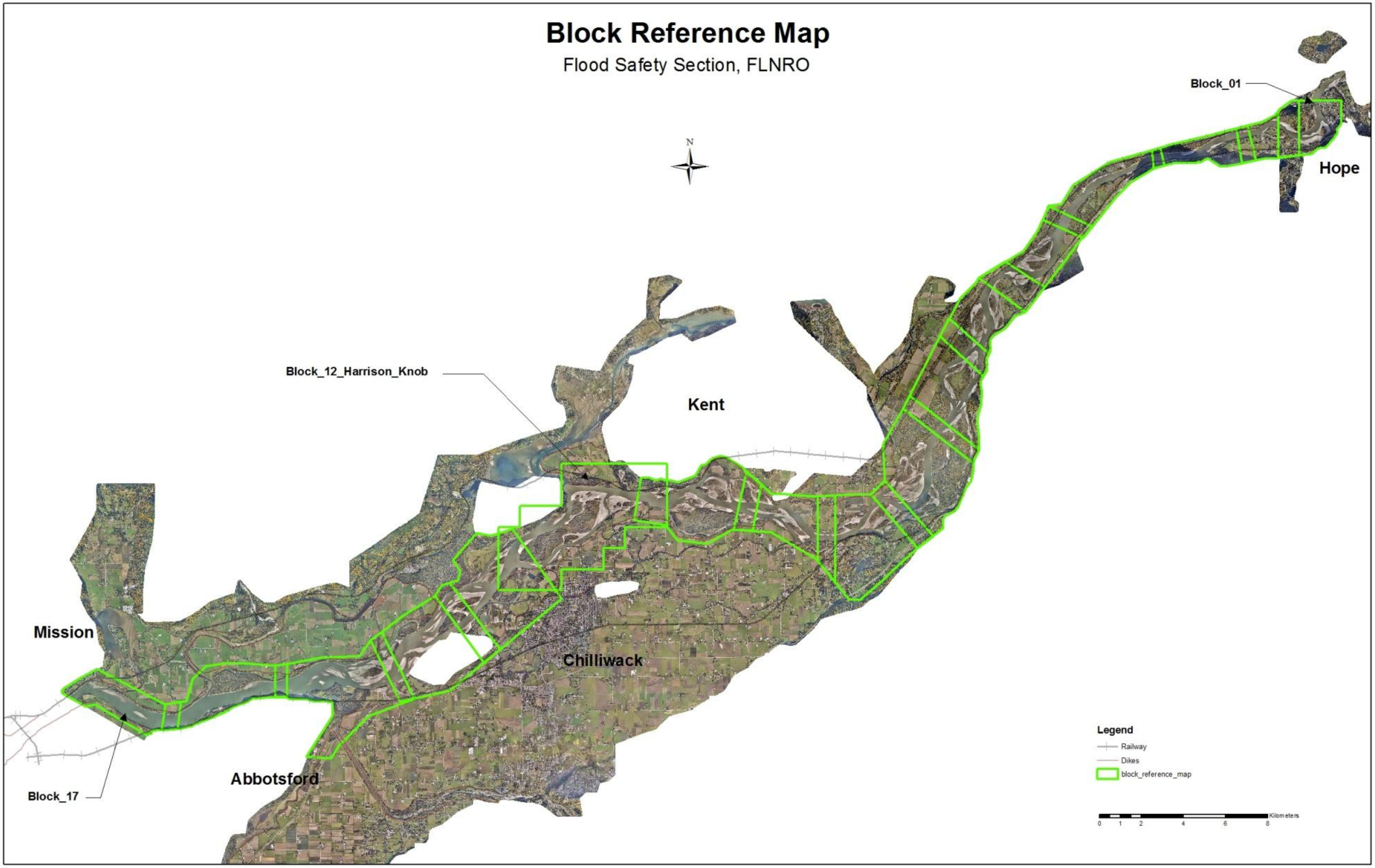


Figure 2 - Flow Split Measurement Locations

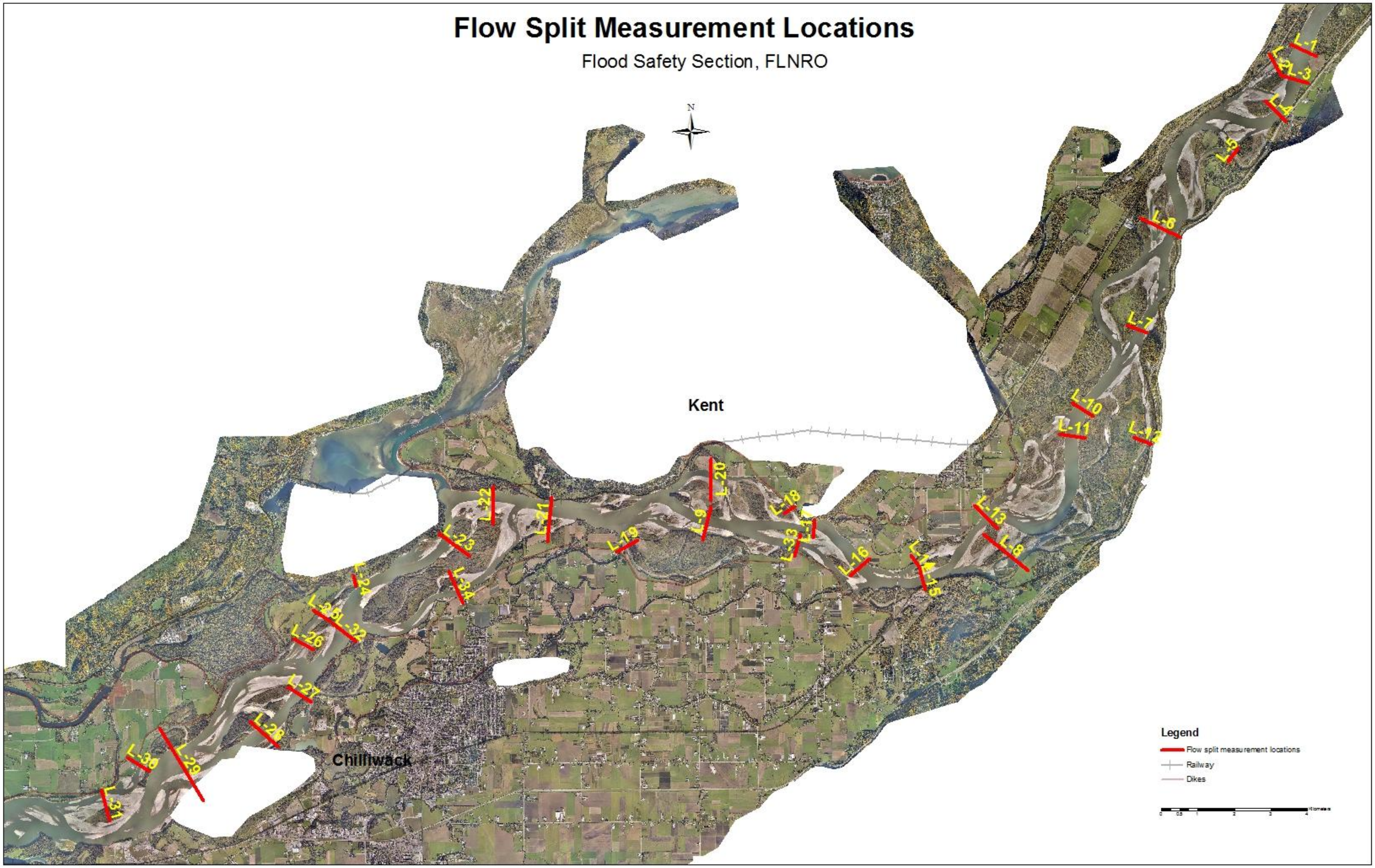


Figure 3 - Bathymetry data collected in 2010

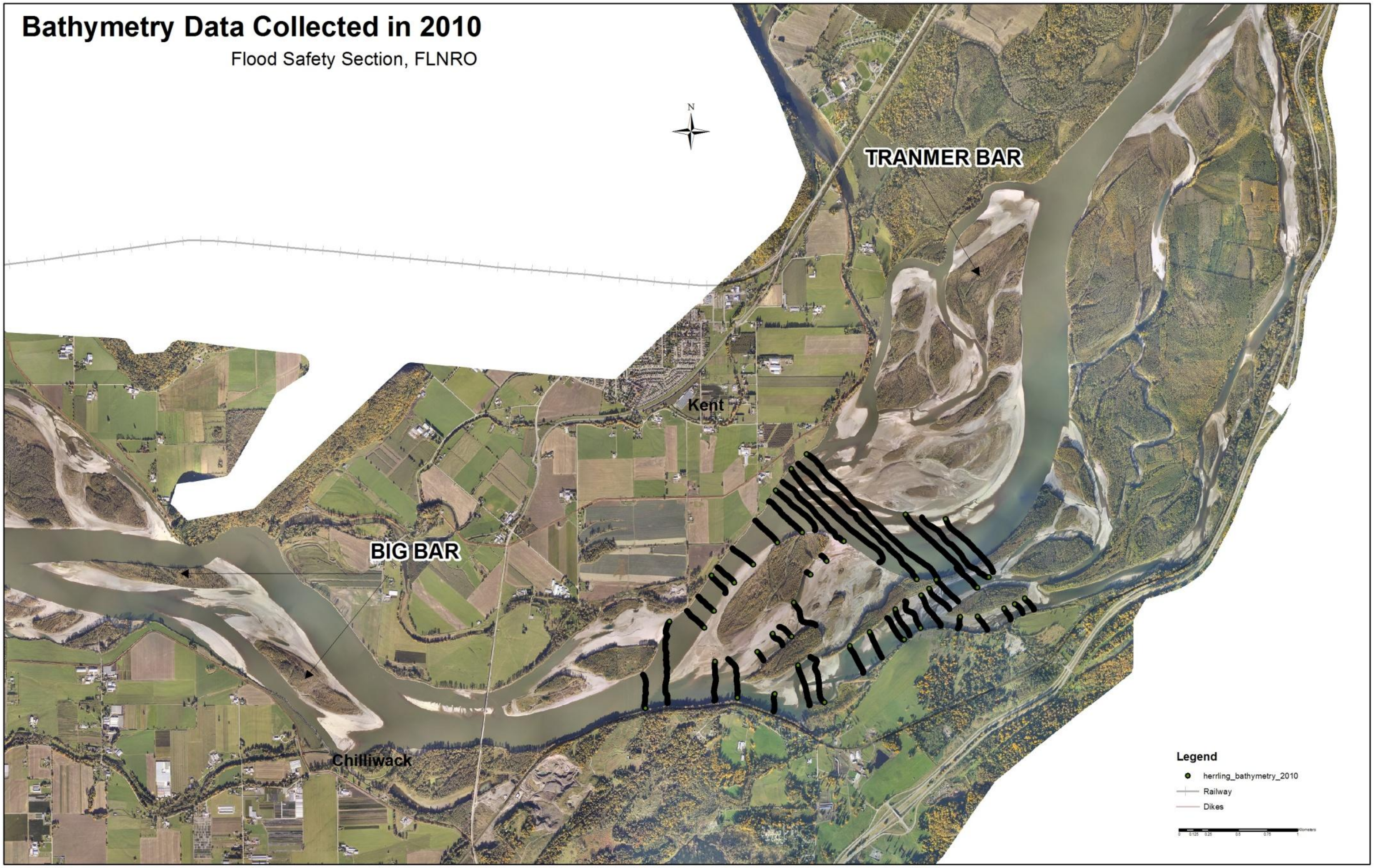


Figure 4 - Bathymetry data collected in 2012

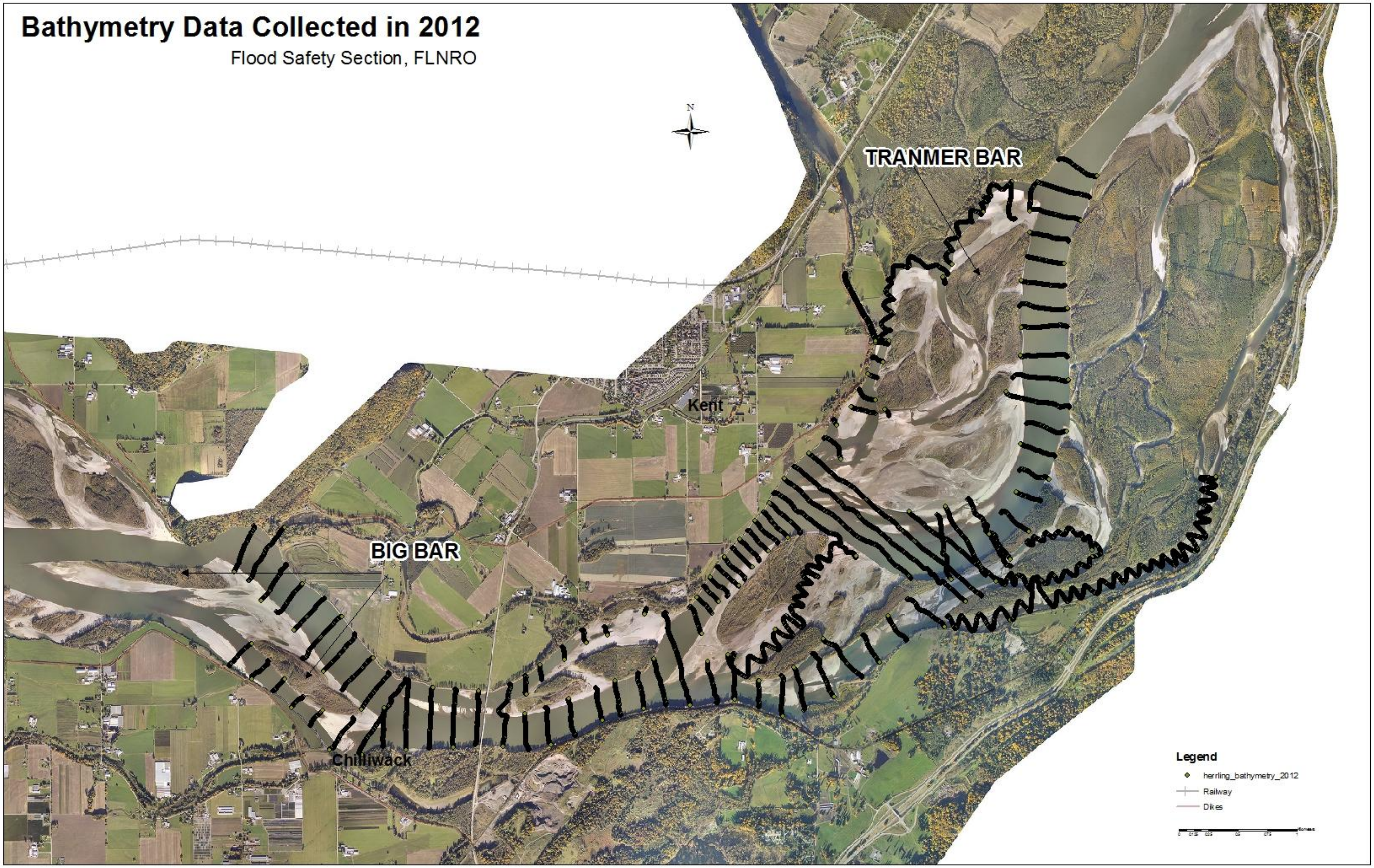


Figure 5

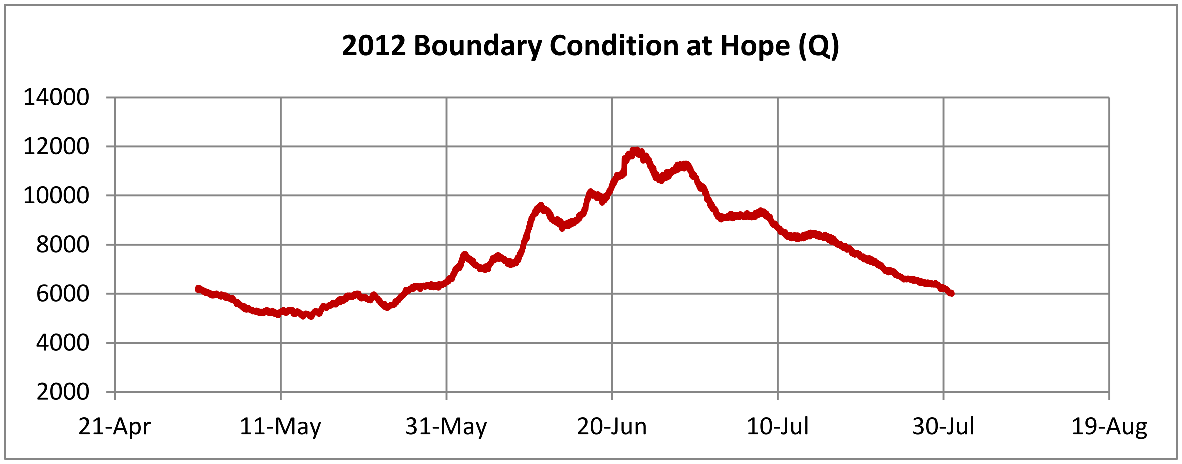


Figure 6

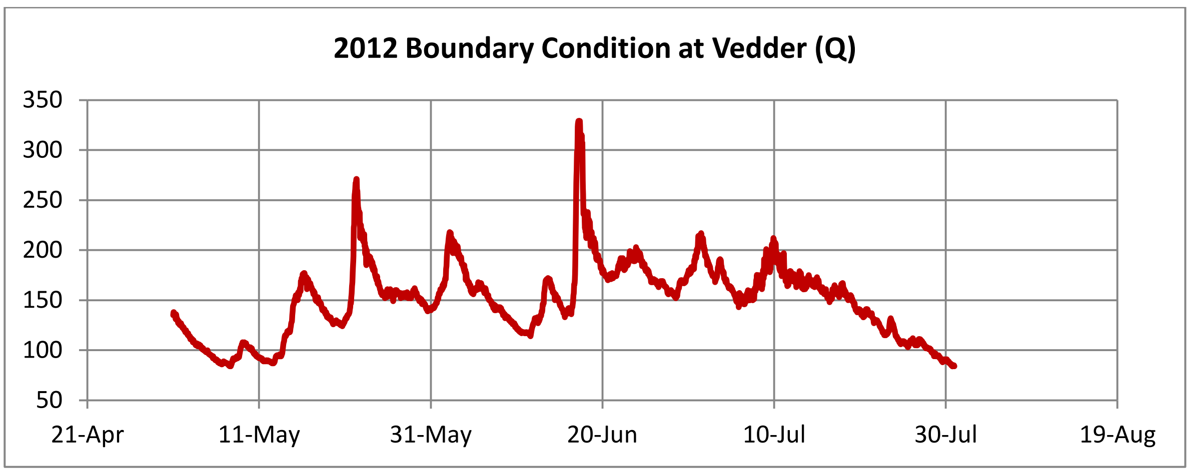


Figure 7

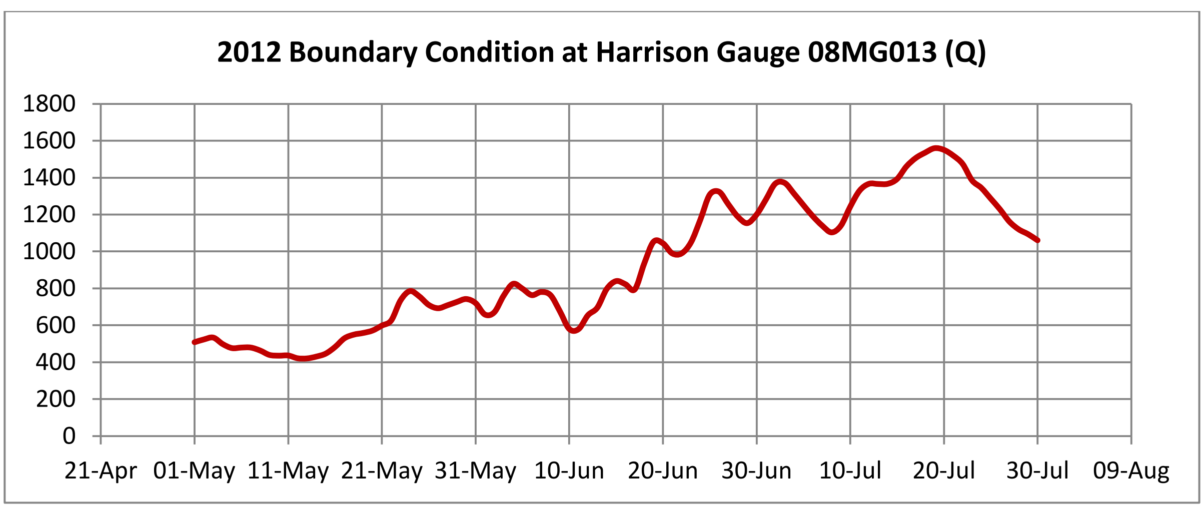


Figure 8

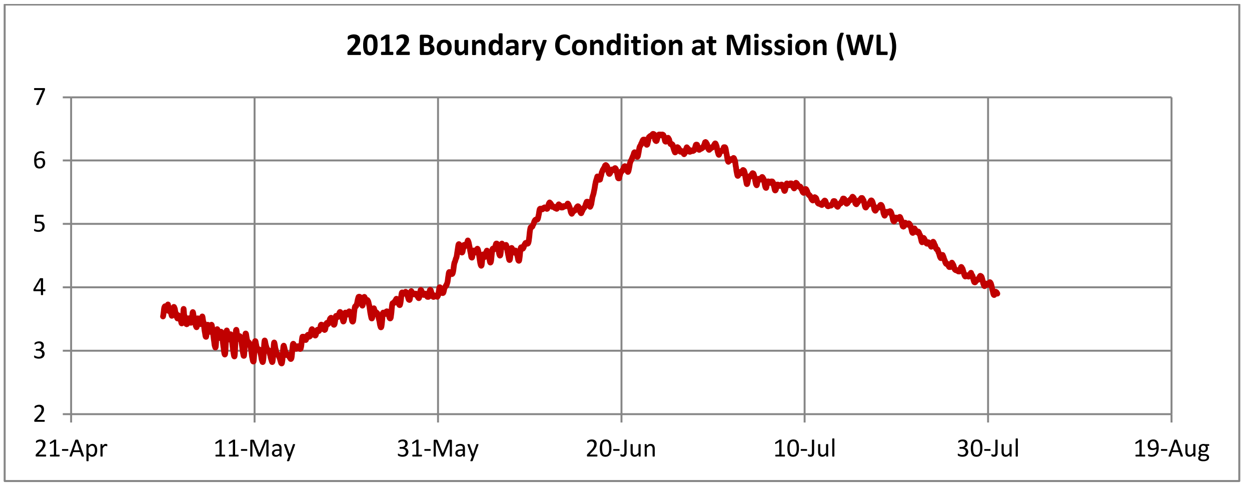


Figure 9

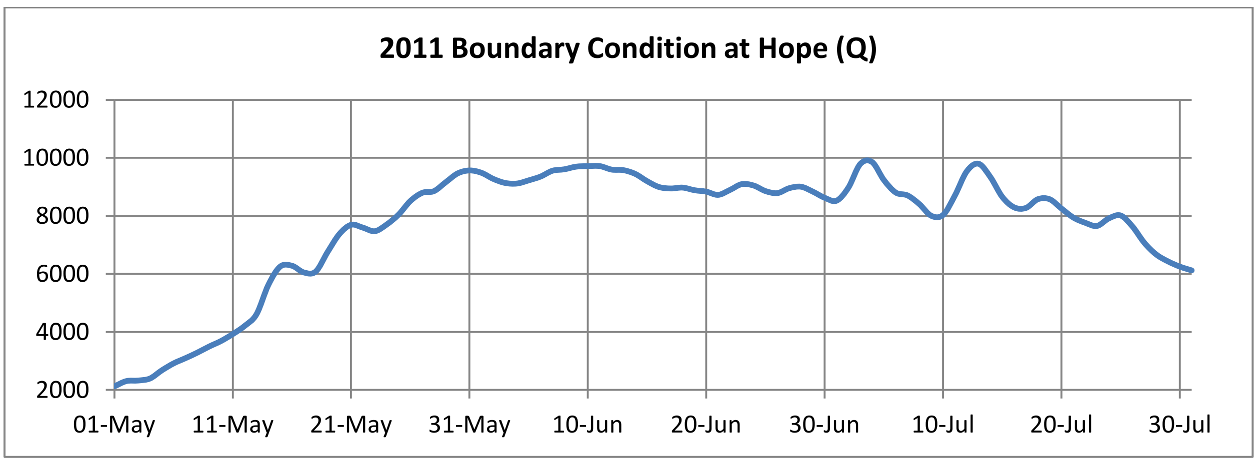


Figure 10

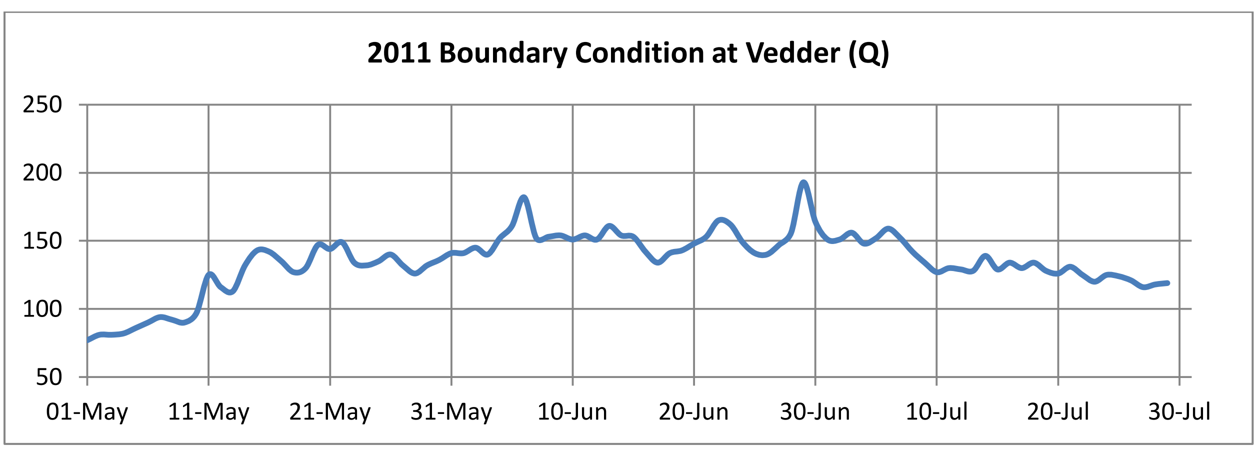


Figure 11

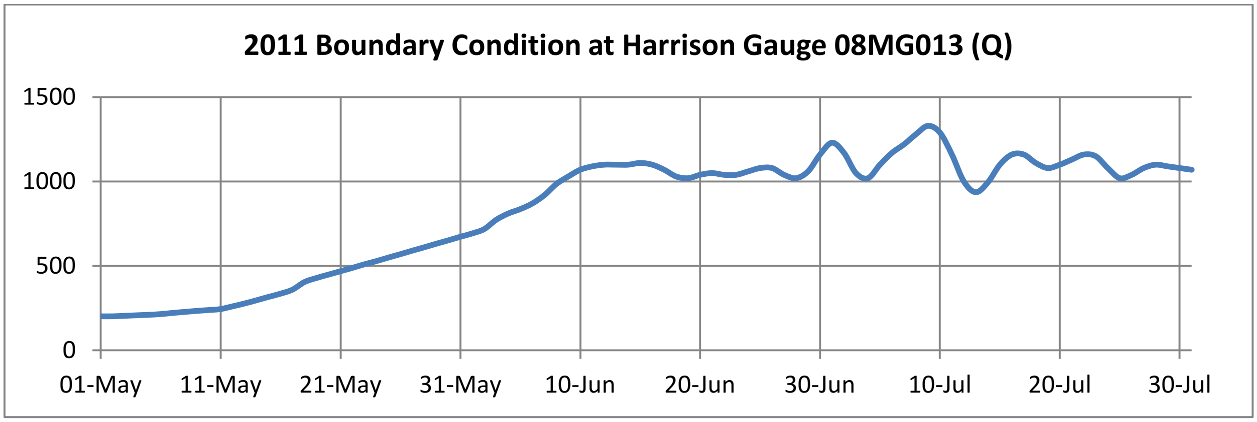


Figure 12

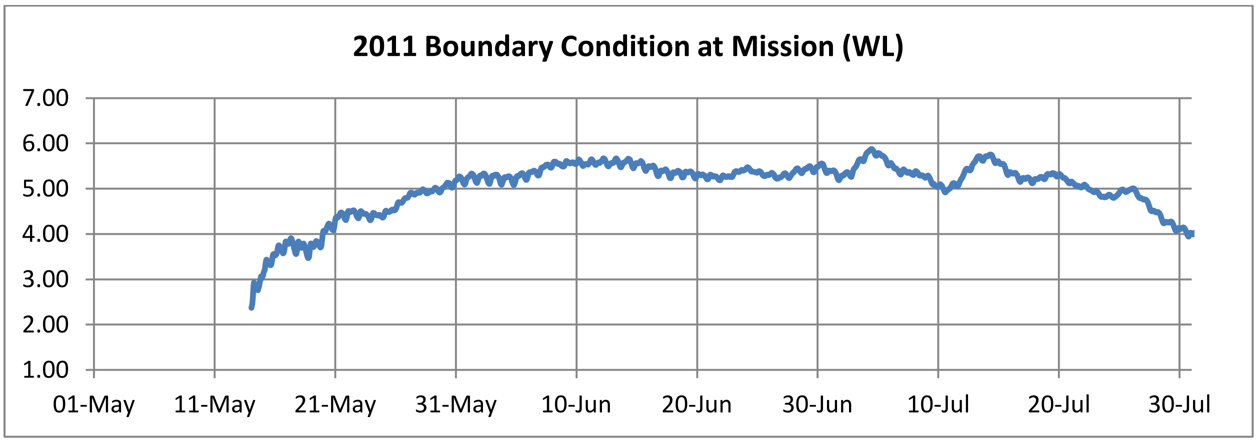
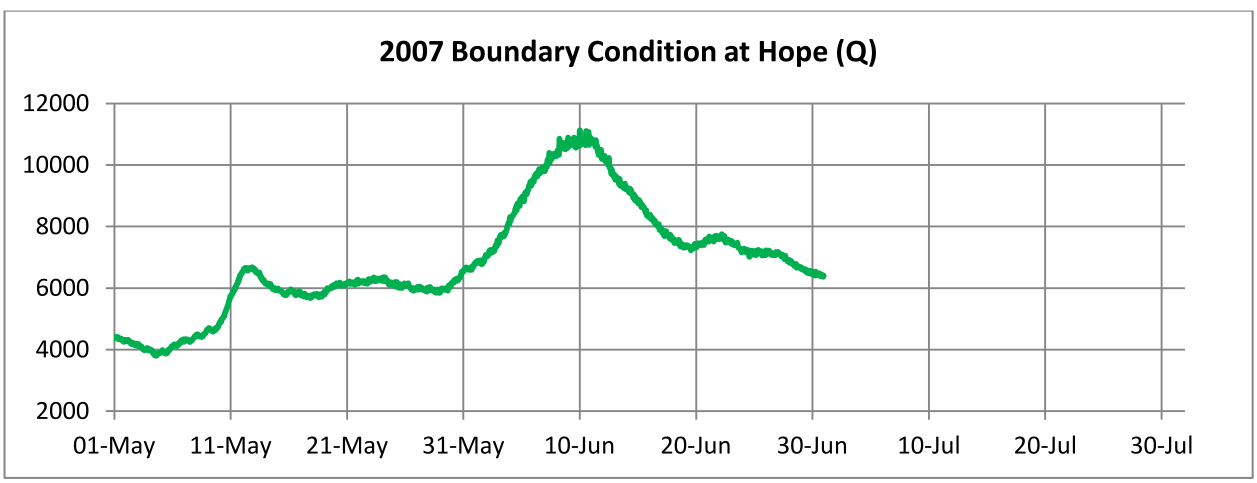


Figure 13



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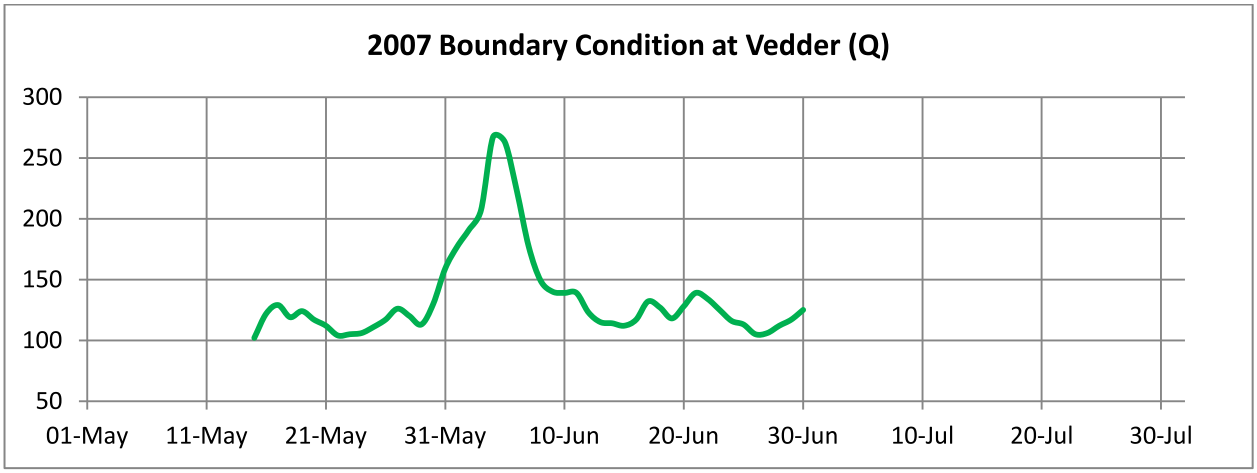


Figure 15

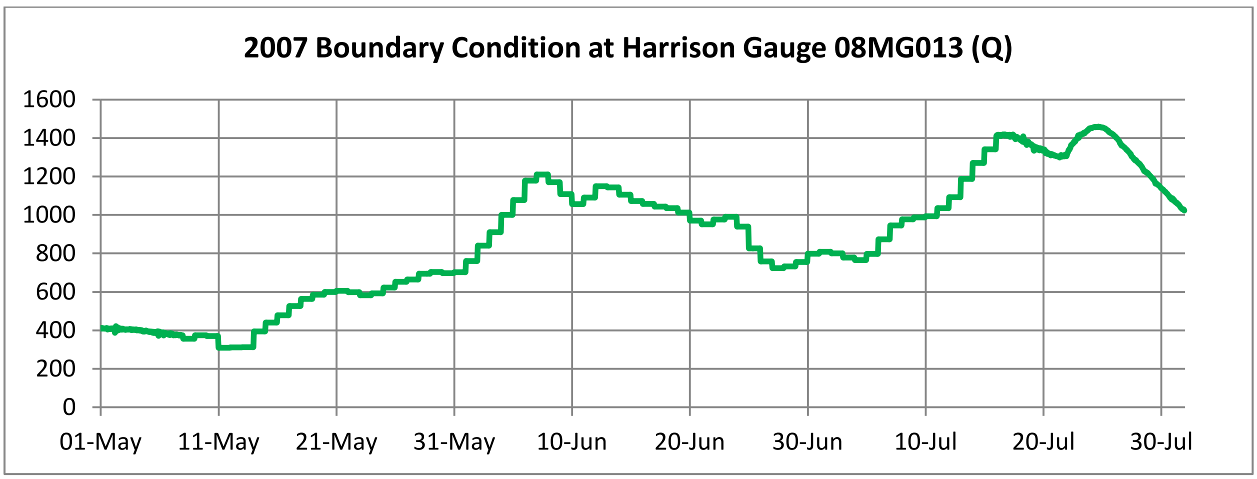


Figure 16

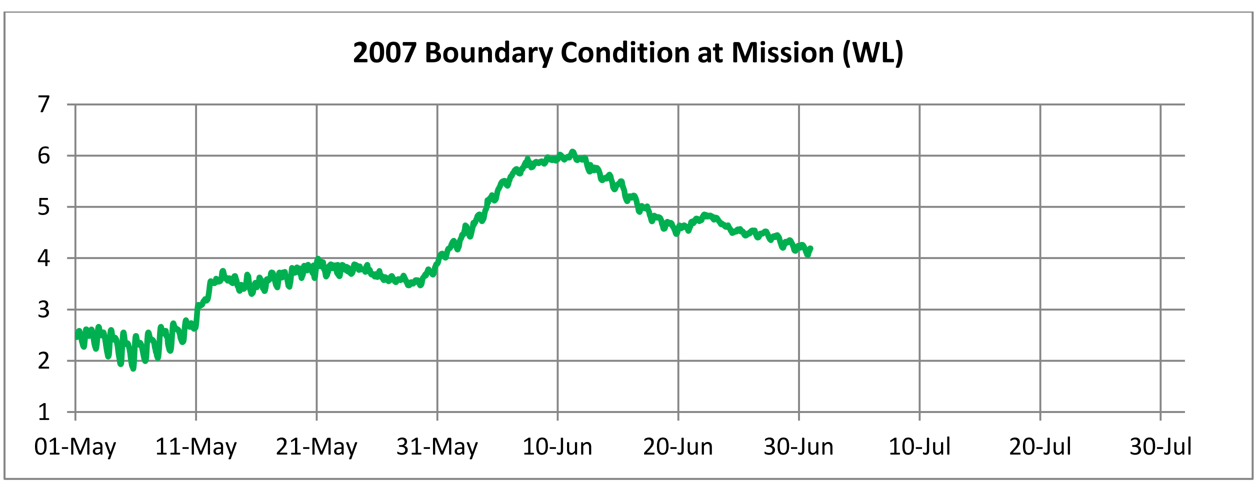
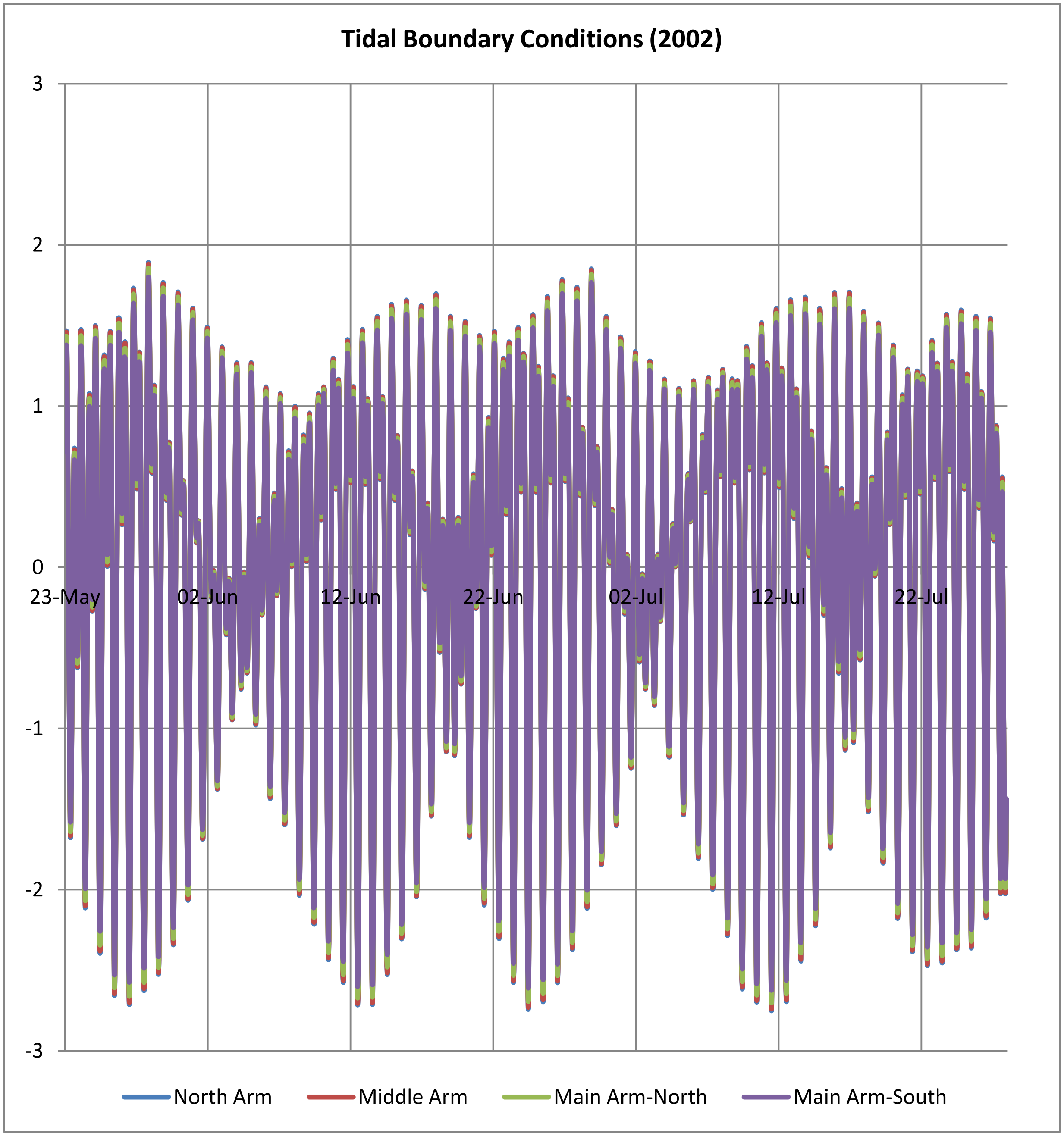


Figure 17



Tidal Boundary Conditions (2002)
3
2
1
0
-1
-2
-3
23-May
02-Jun
12-Jun
22-Jun
02-Jul
12-Jul
22-Jul
North Arm
Middle Arm
Main Arm-North
Main Arm-South

Figure 18

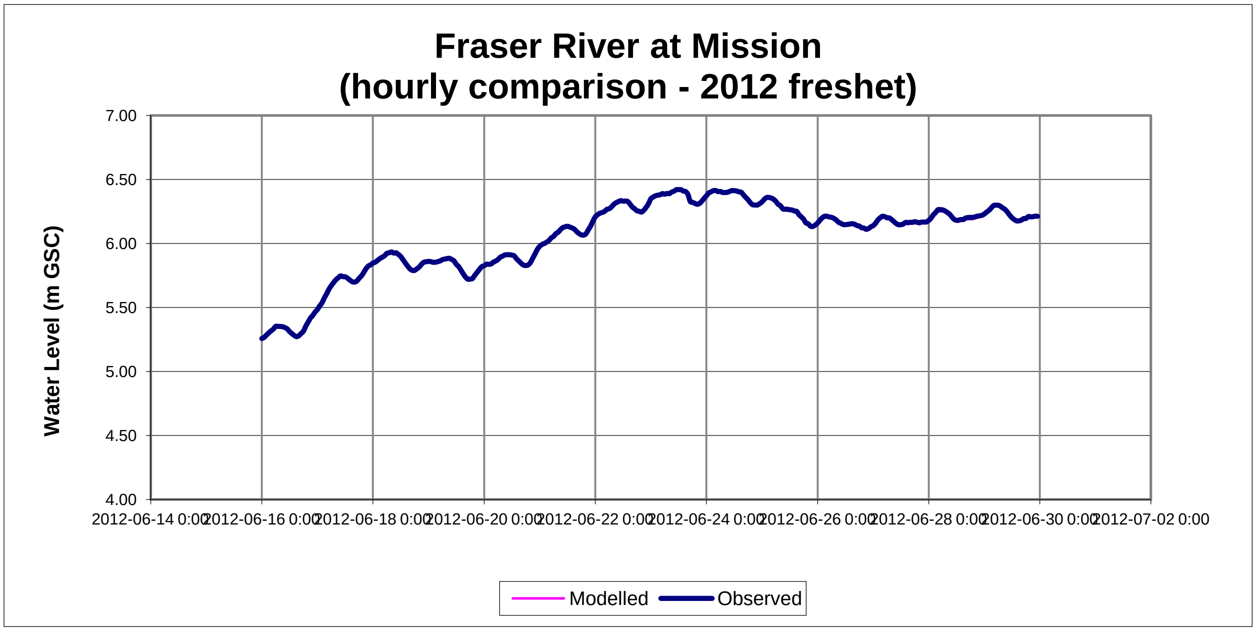


Figure 19

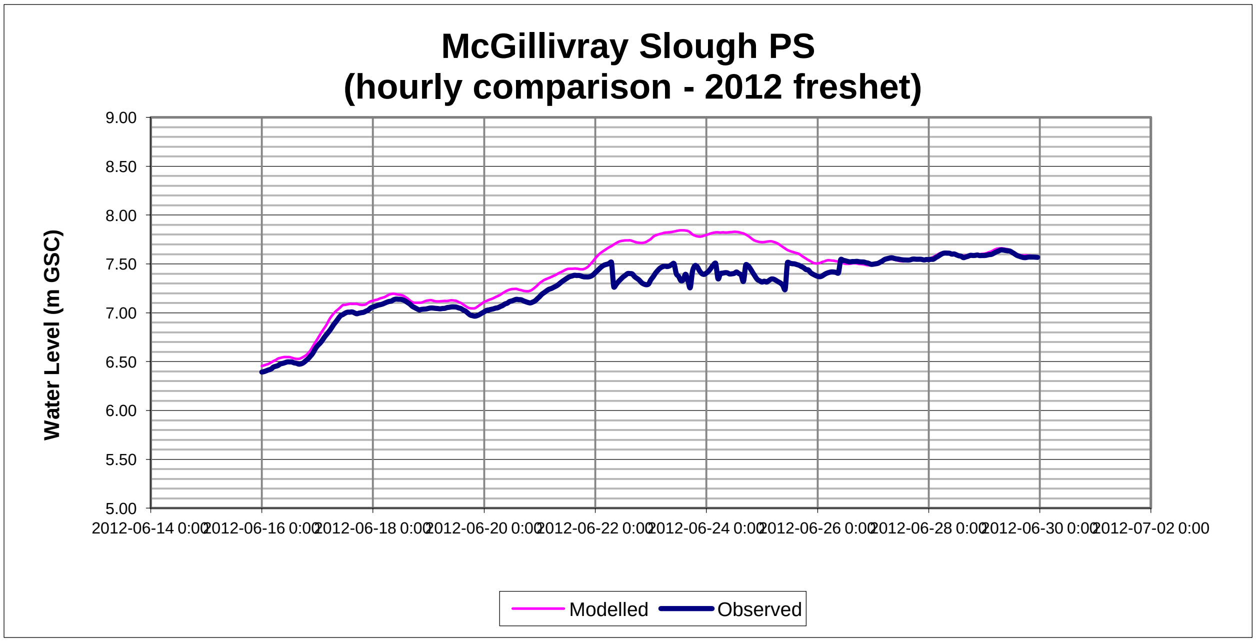


Figure 20

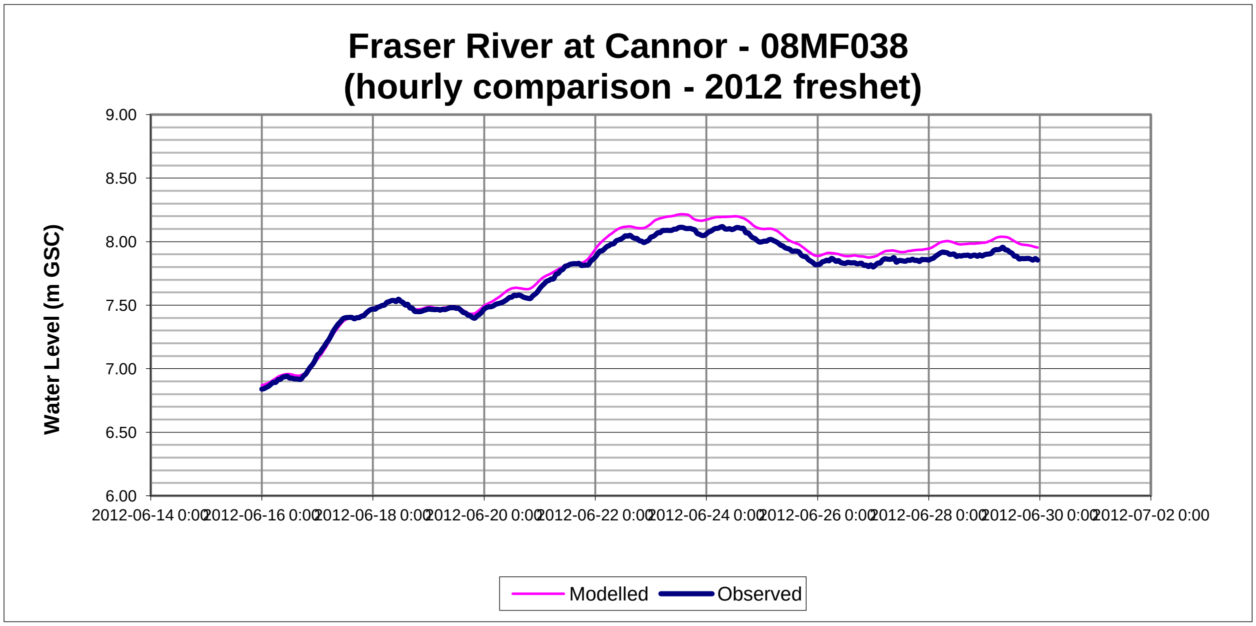


Figure 21

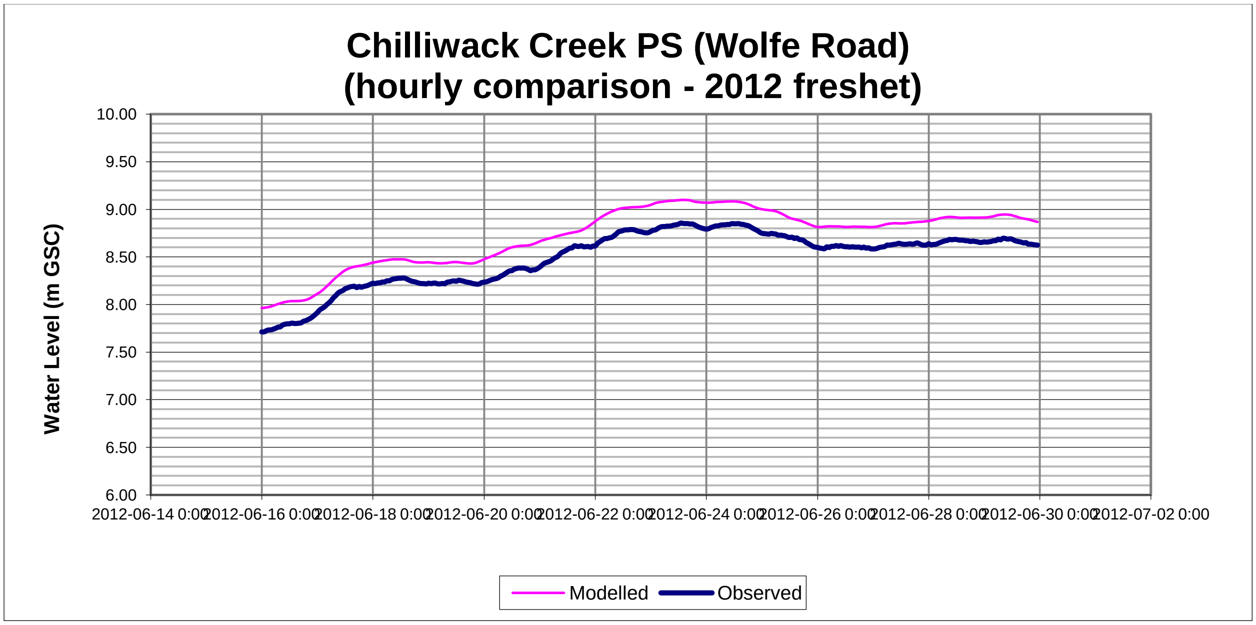
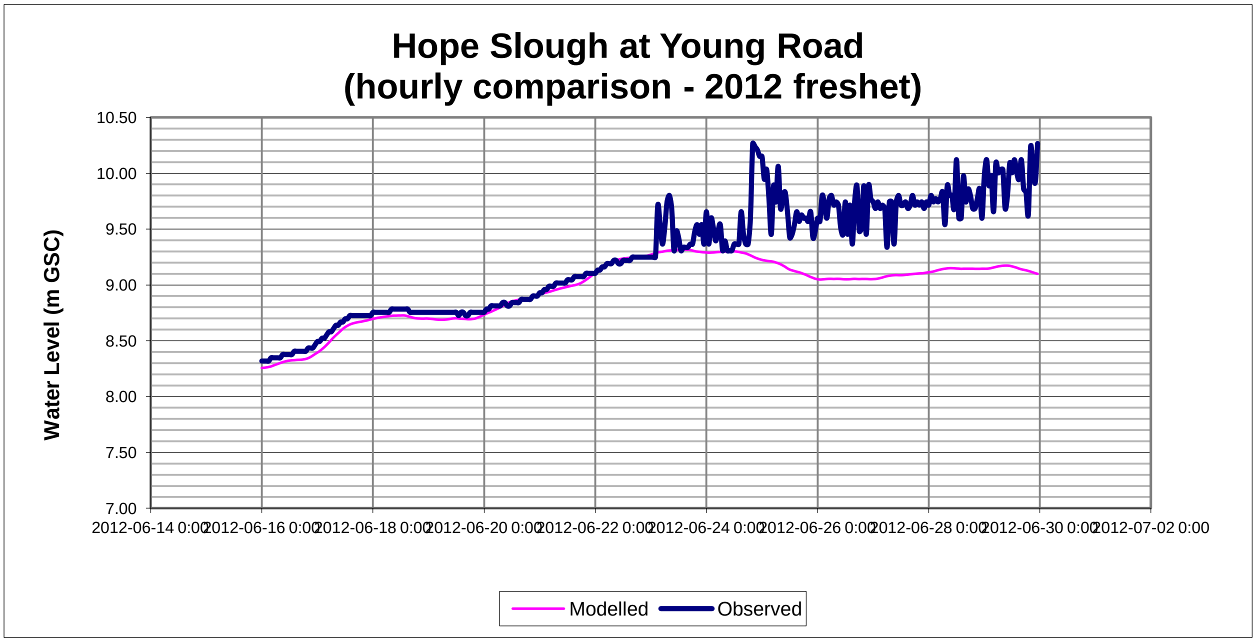


Figure 22



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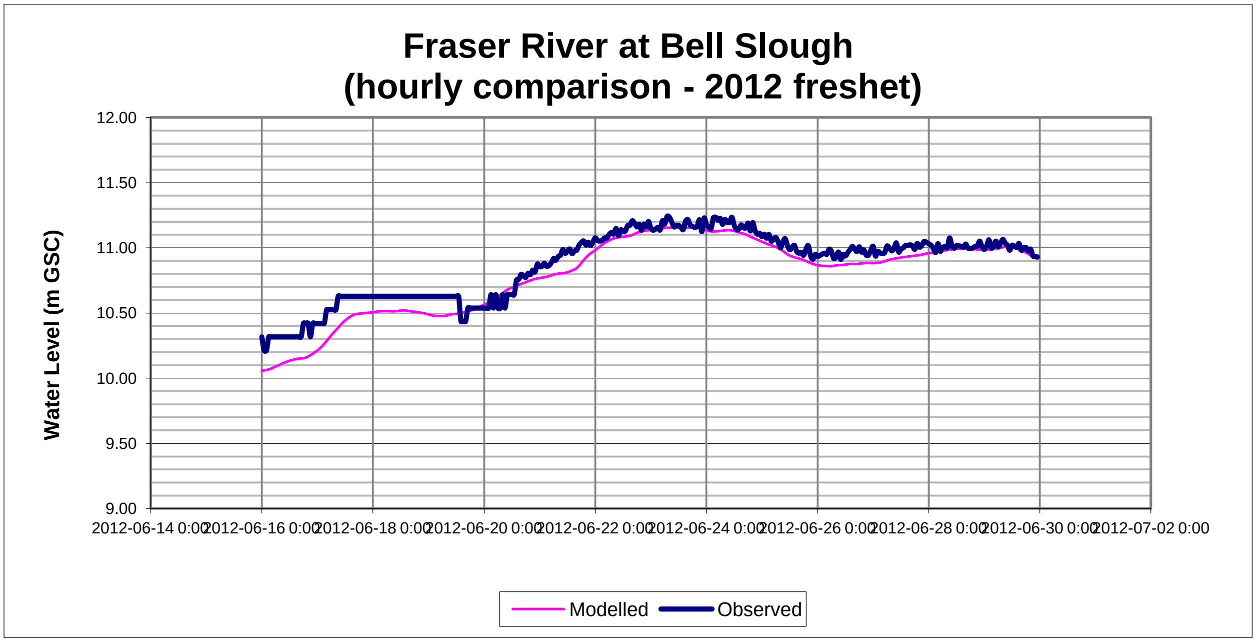
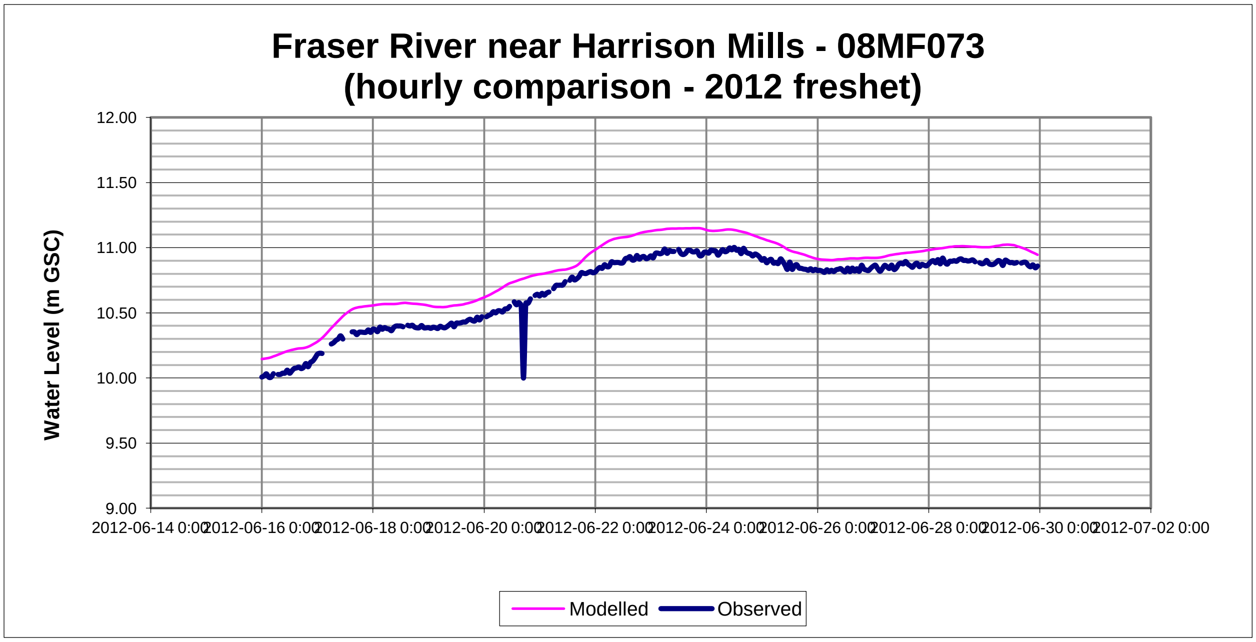


Figure 24



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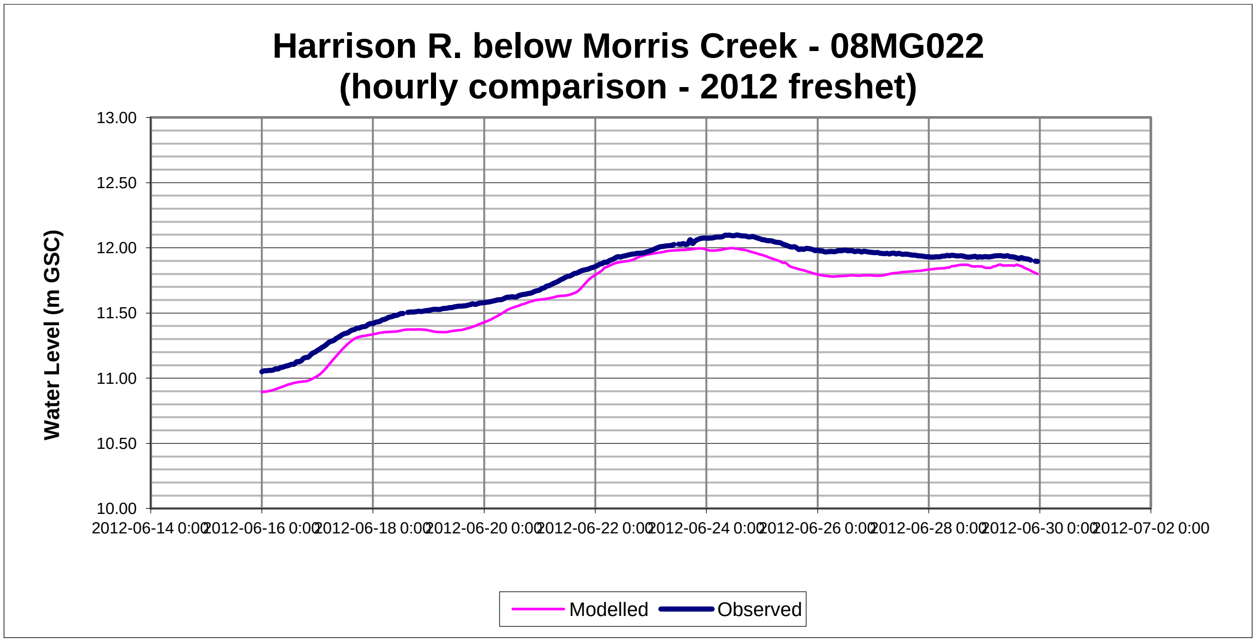


Figure 26

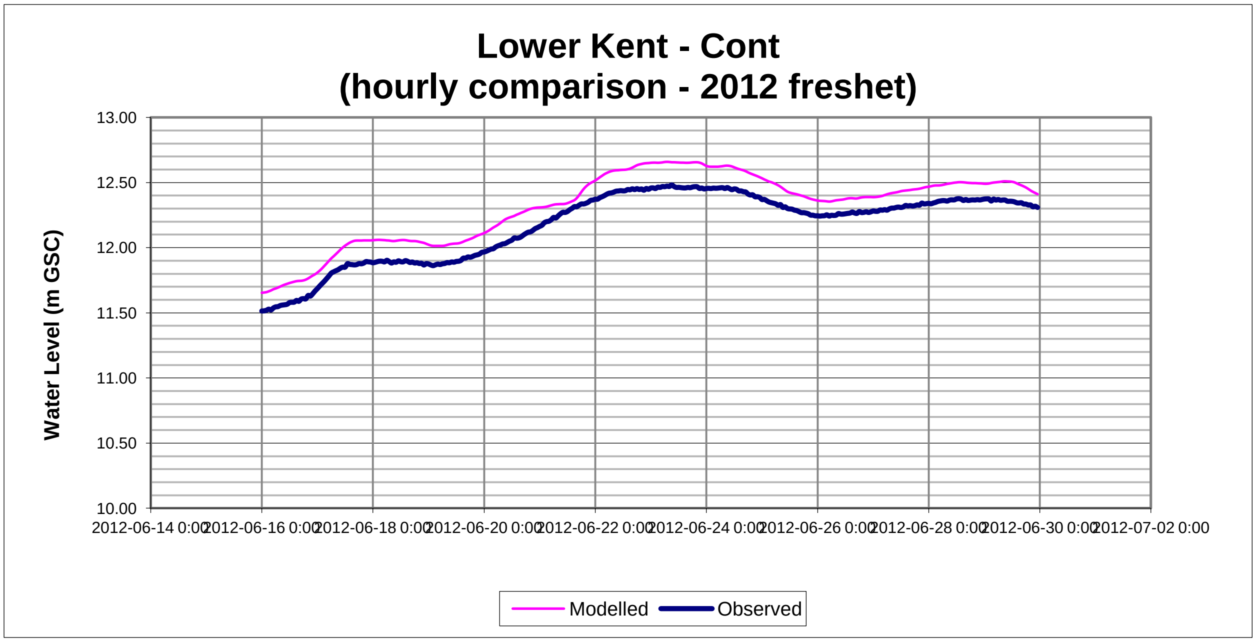
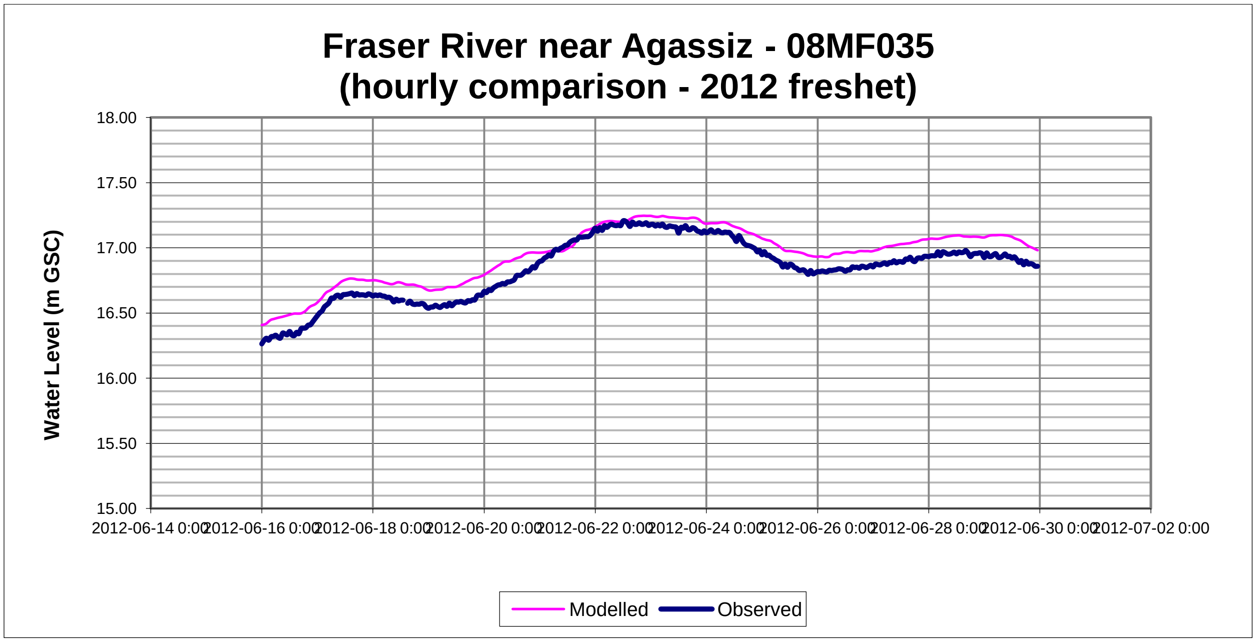


Figure 27



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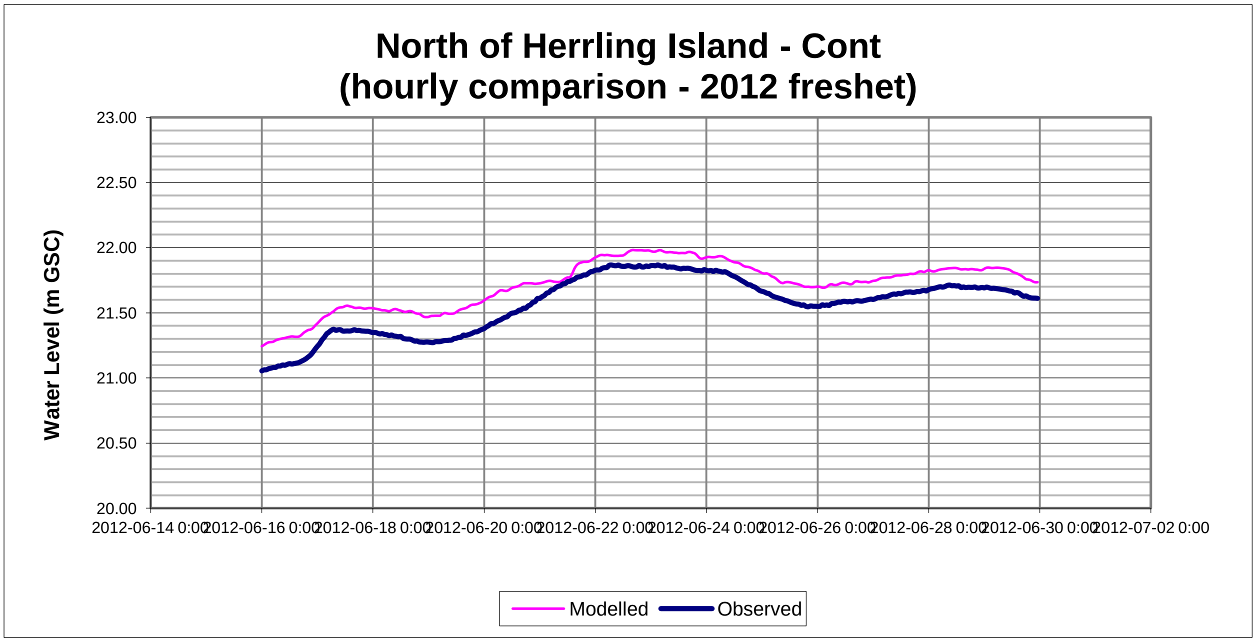

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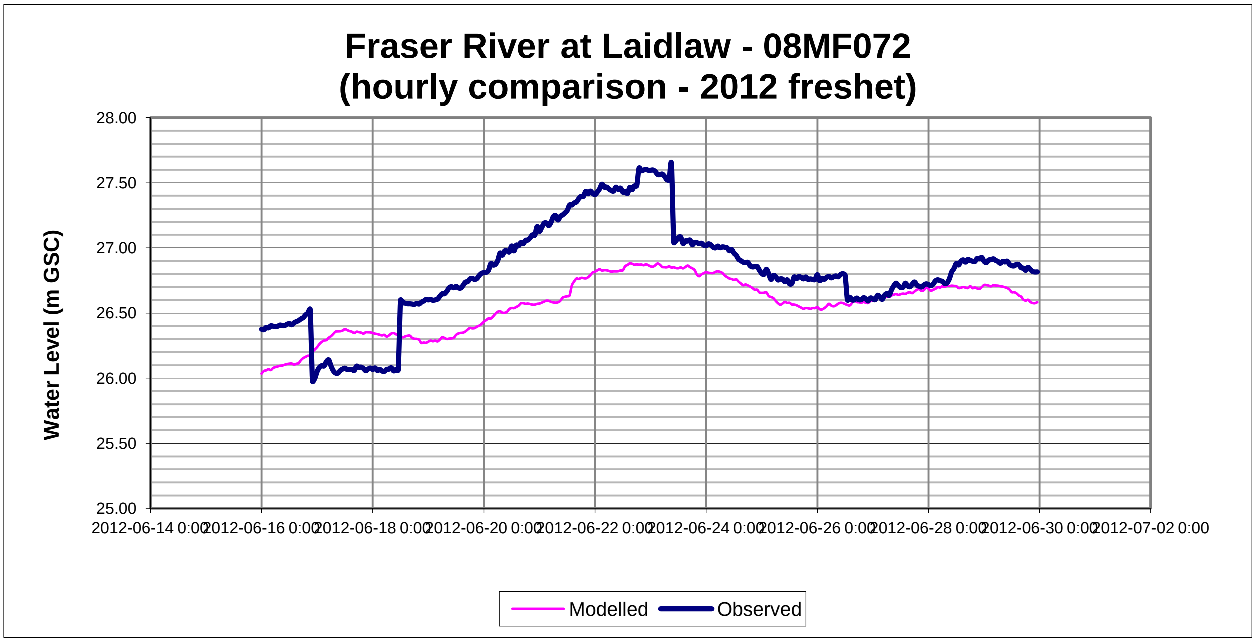


Figure 30

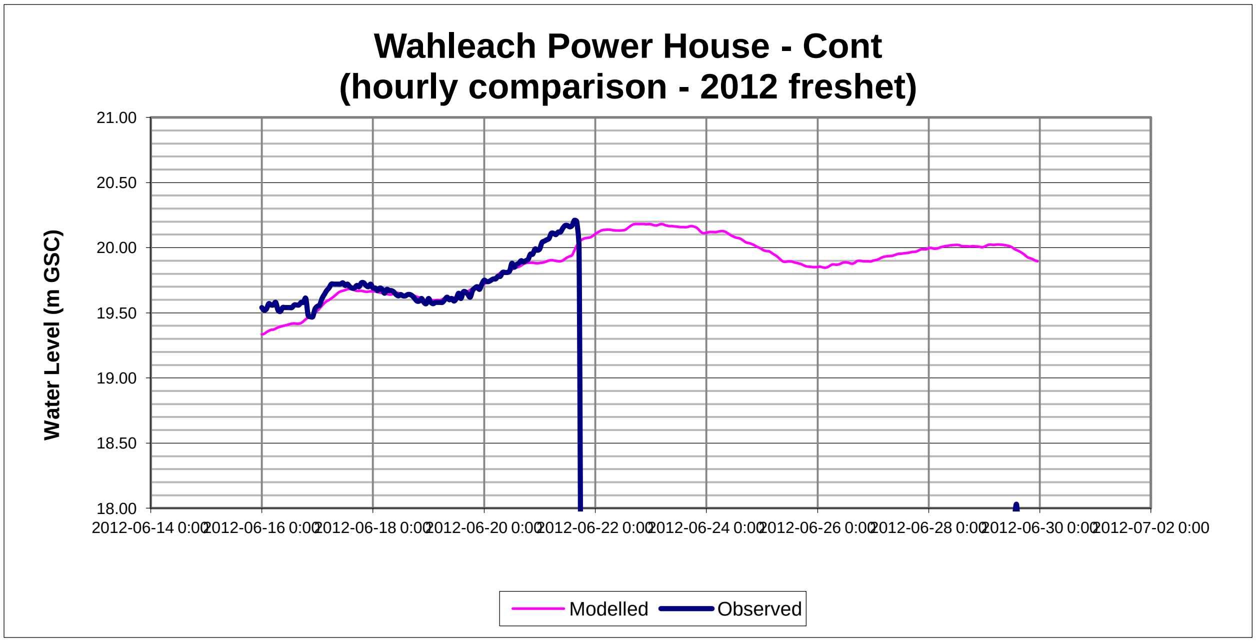


Figure 31

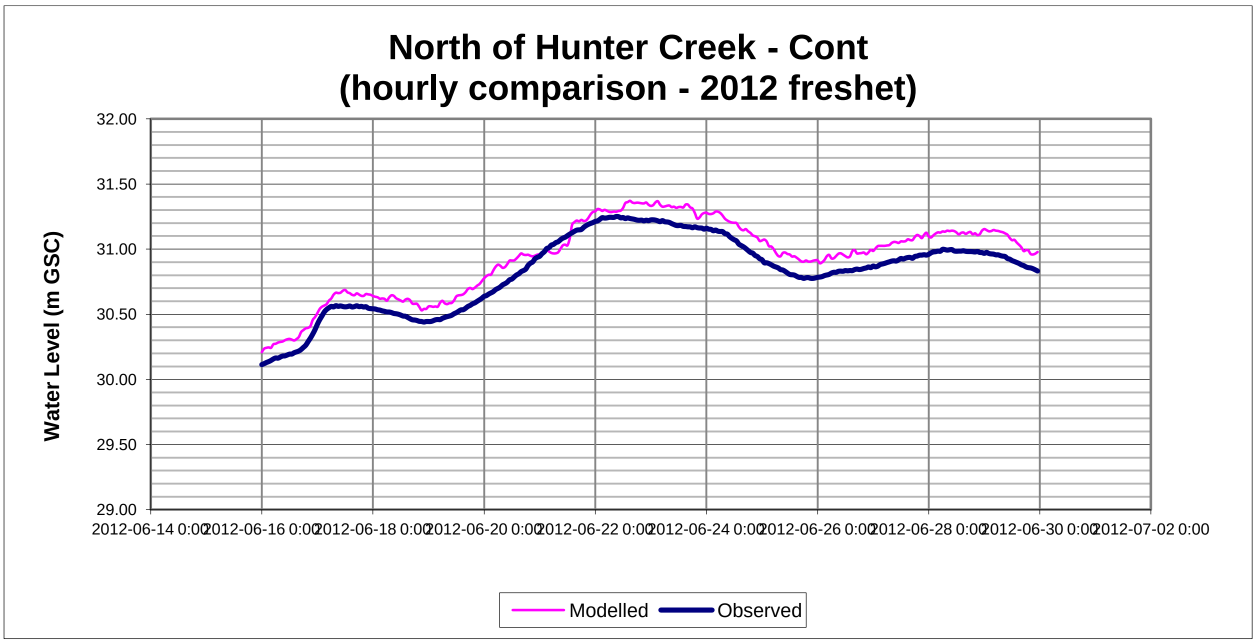


Figure 32

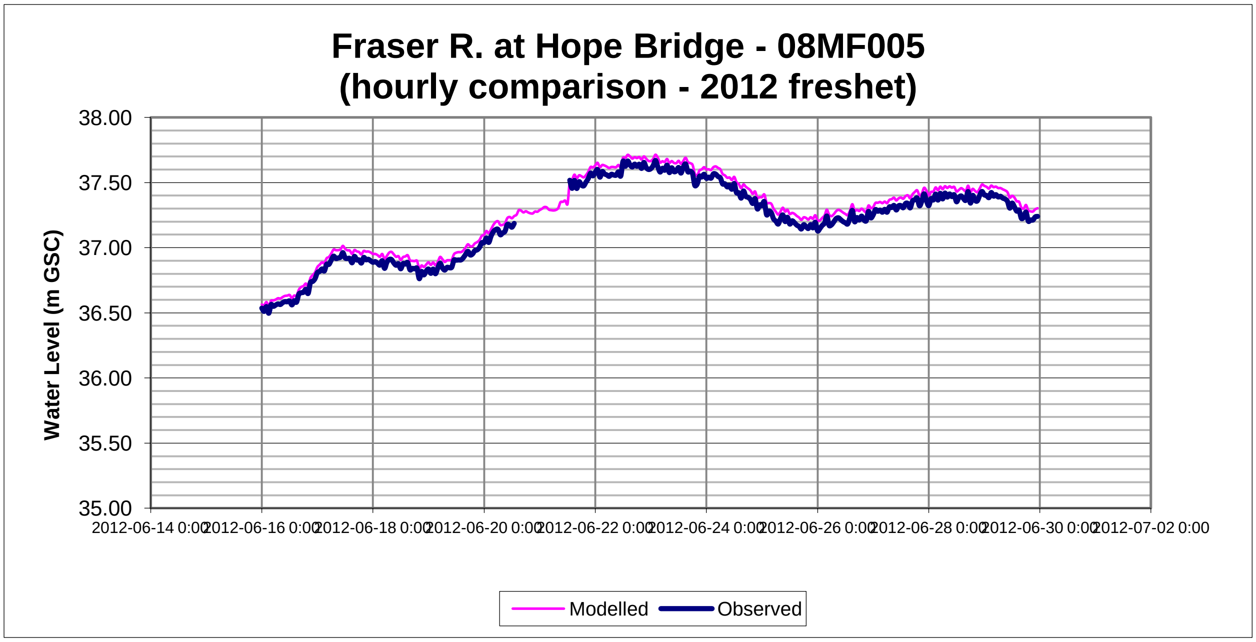

Fraser R. at Hope Bridge - 08MF005
(hourly comparison - 2012 freshet)
Water Level (m GSC)
38.00
37.50
37.00
36.50
36.00
35.50
35.00
2012-06-14 0:00
2012-06-16 0:00
2012-06-18 0:00
2012-06-20 0:00
2012-06-22 0:00
2012-06-24 0:00
2012-06-26 0:00
2012-06-28 0:00
2012-06-30 0:00
2012-07-02 0:00
Modelled
Observed

Figure 33

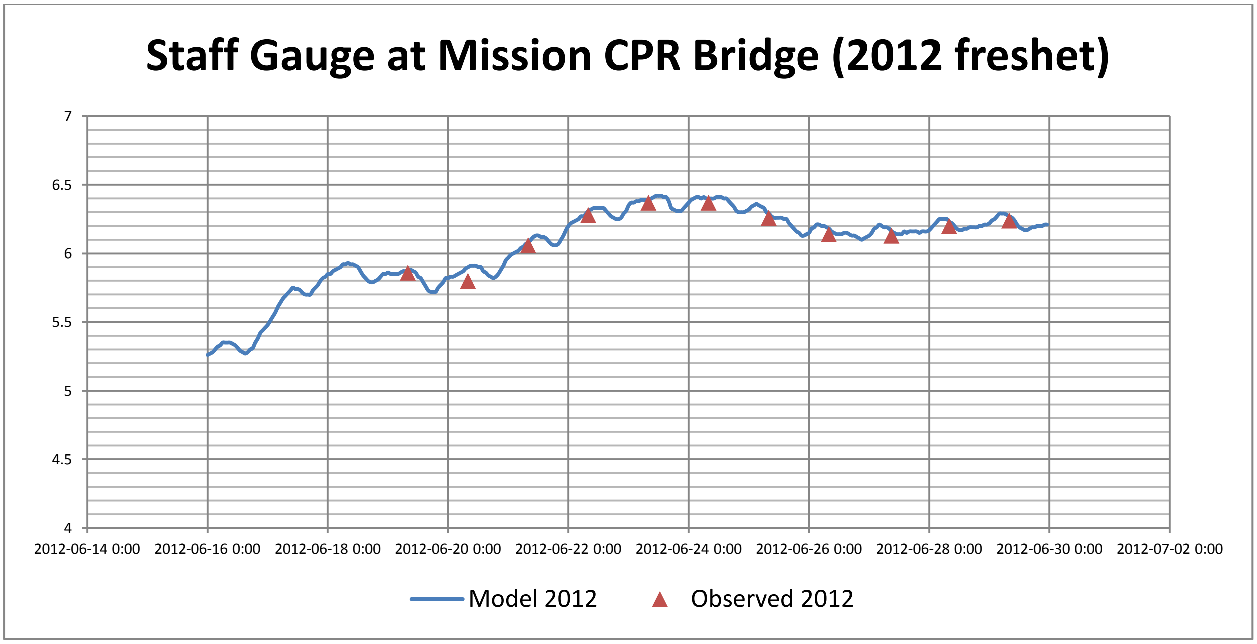


Figure 34

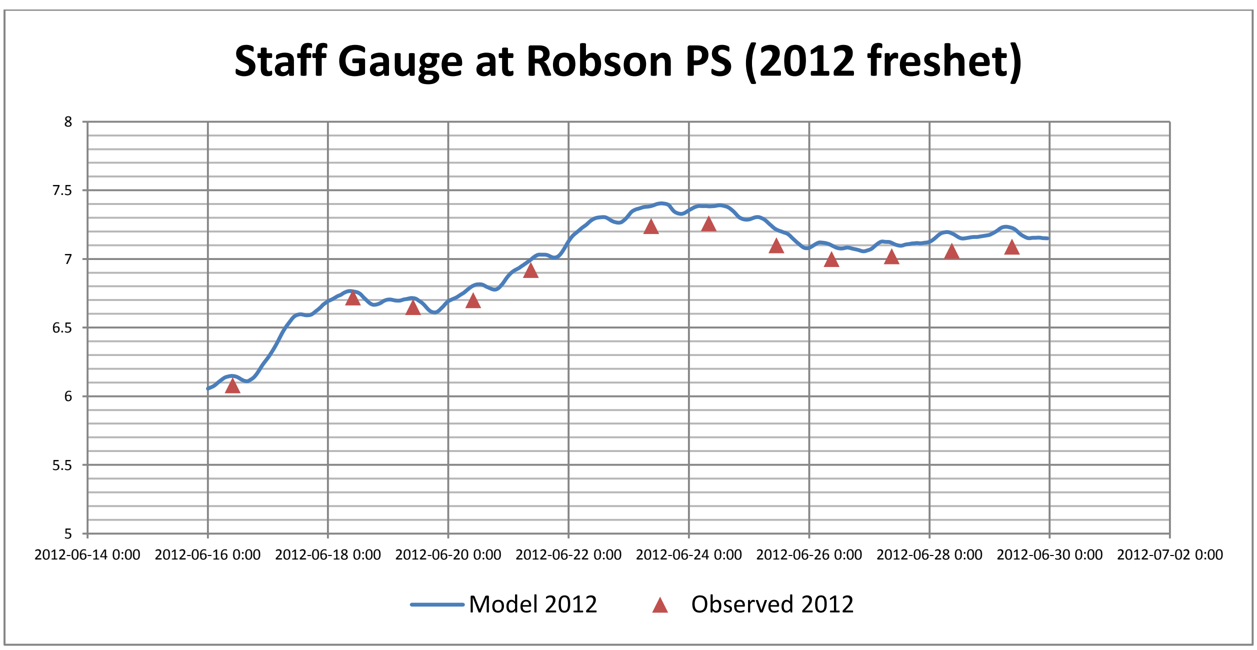


Figure 35

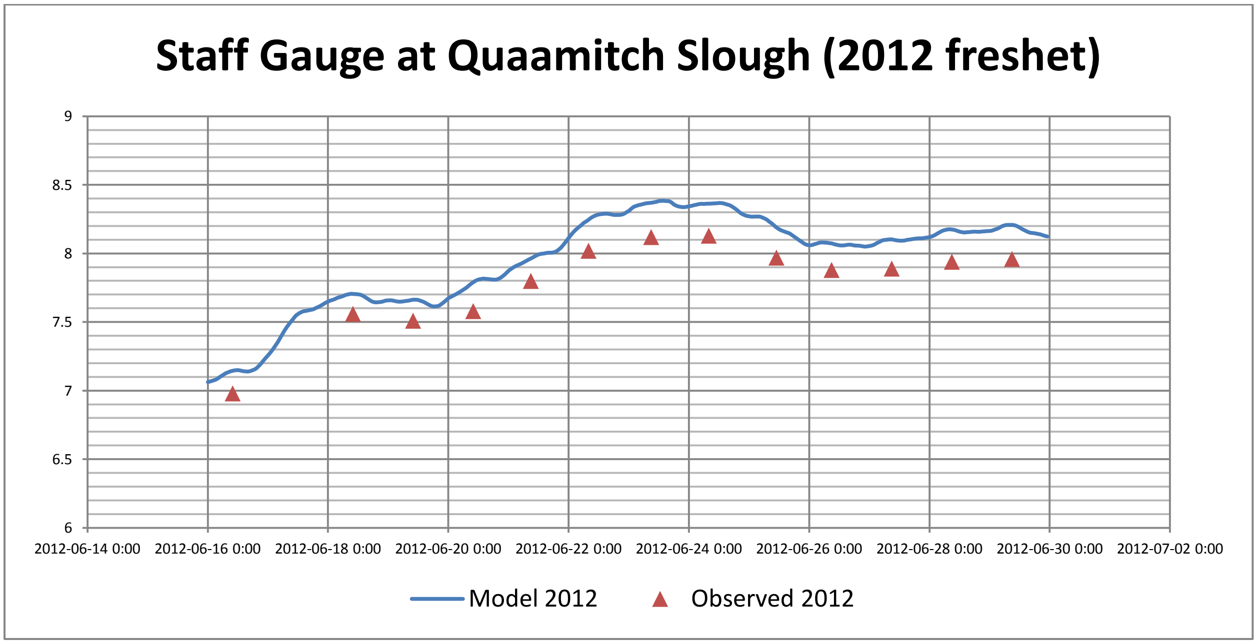
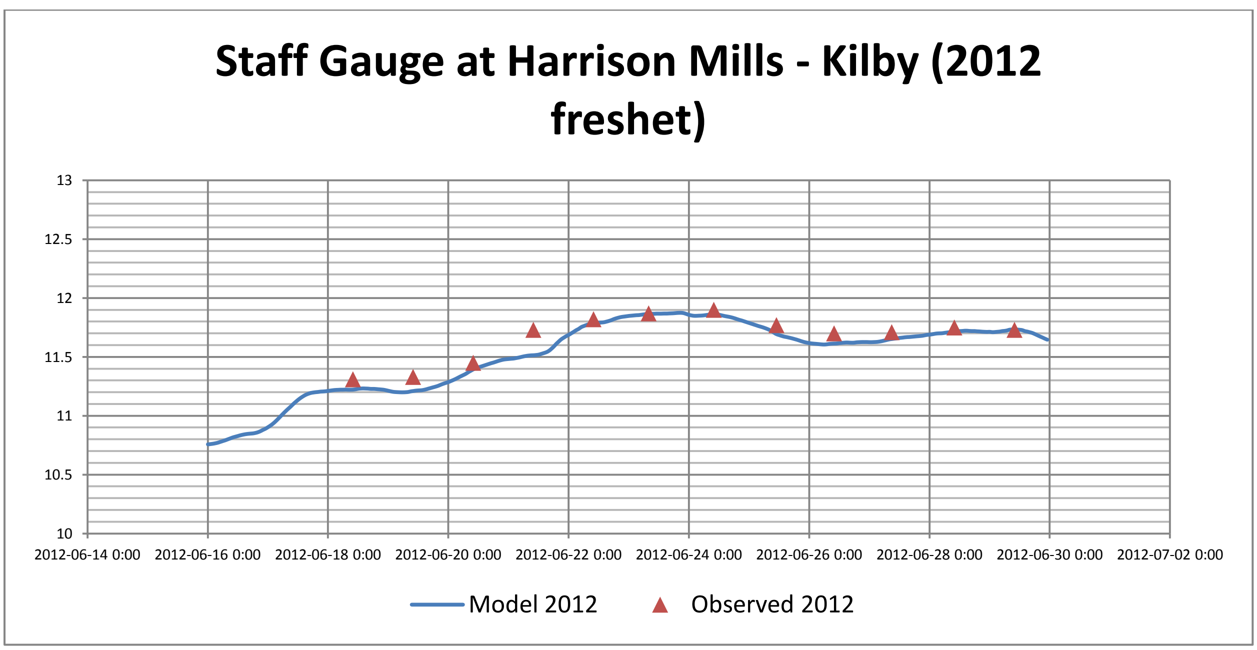


Figure 36



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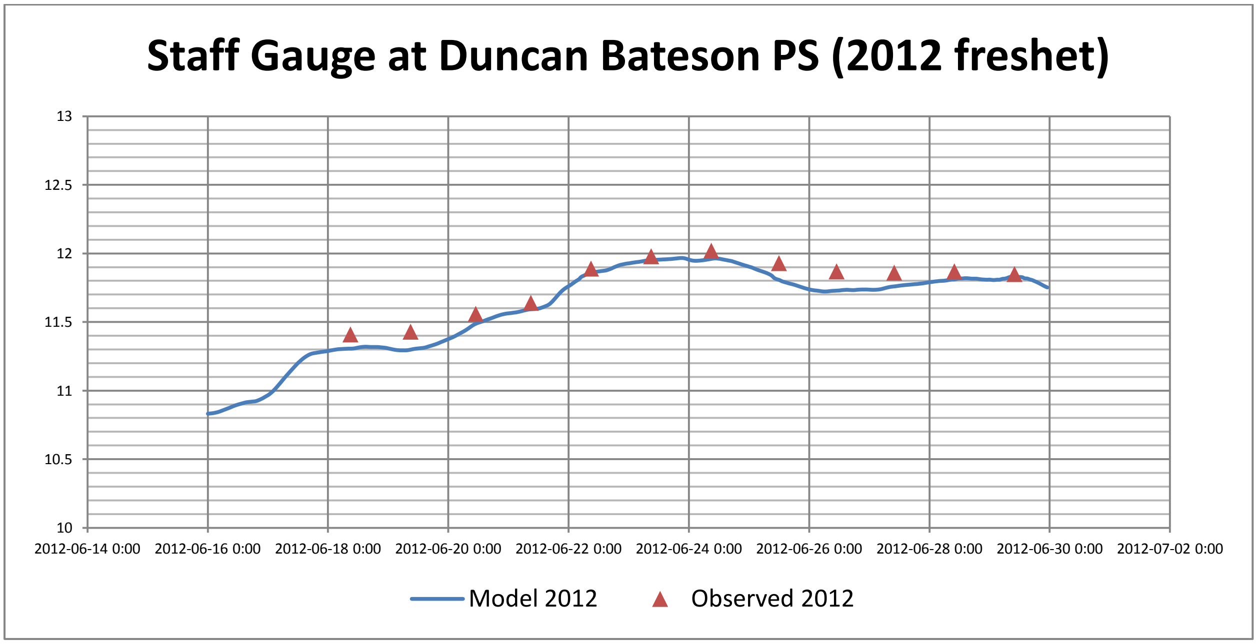


Figure 38

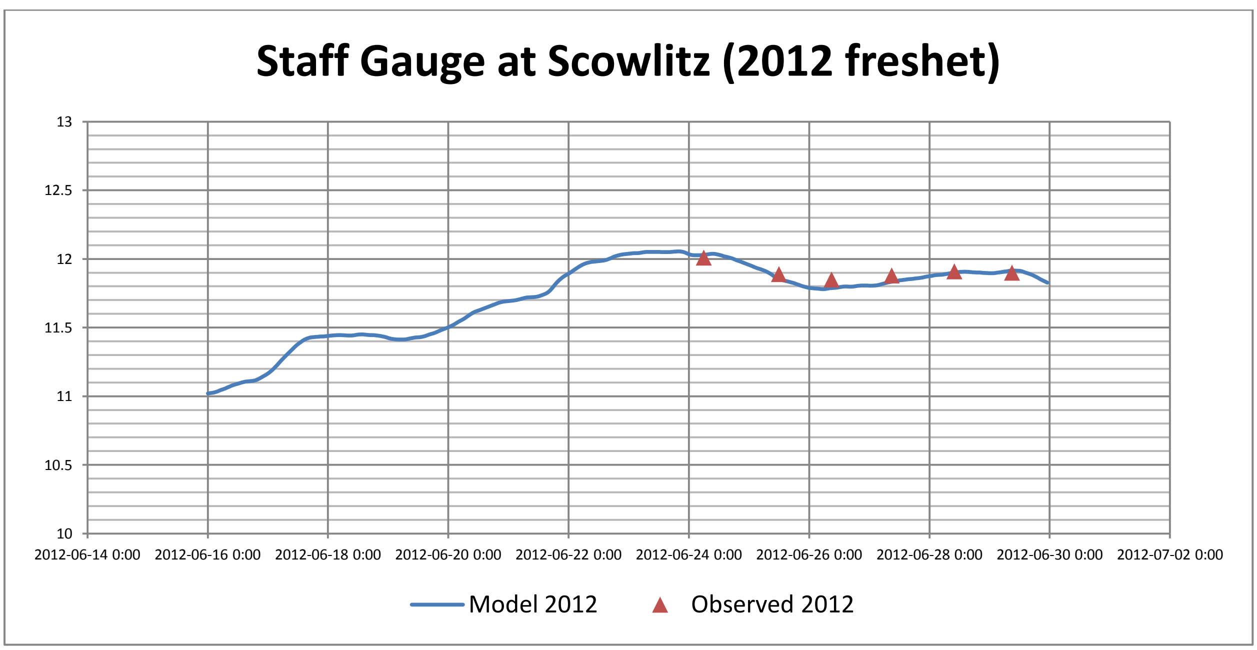


Figure 39

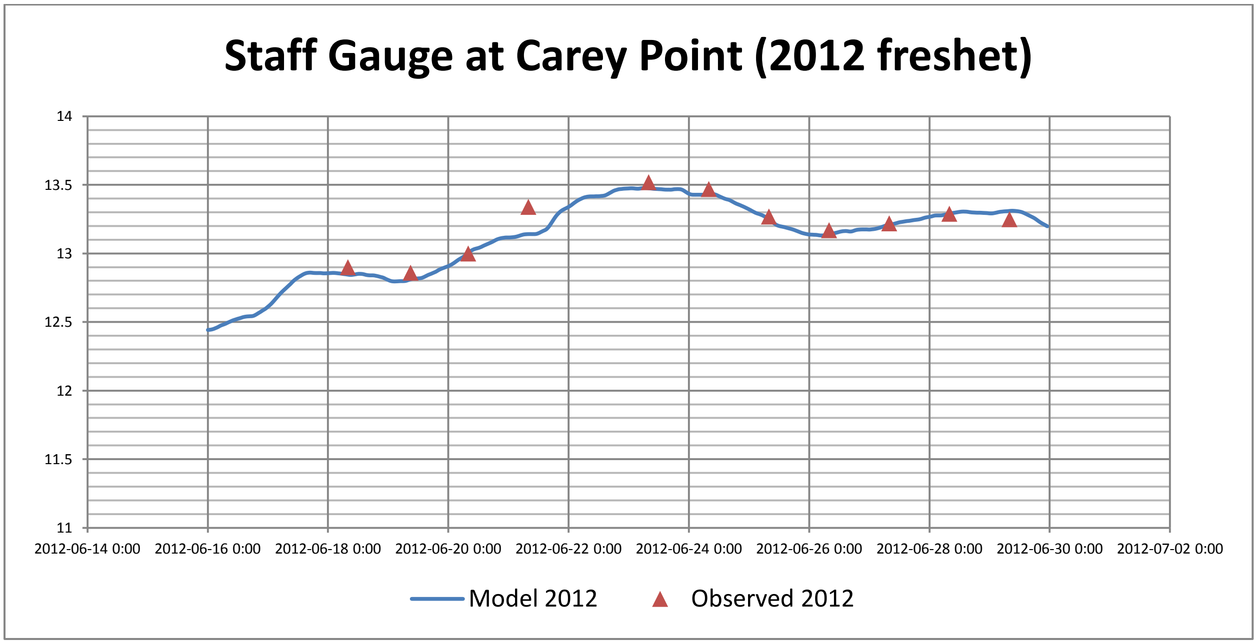


Figure 40

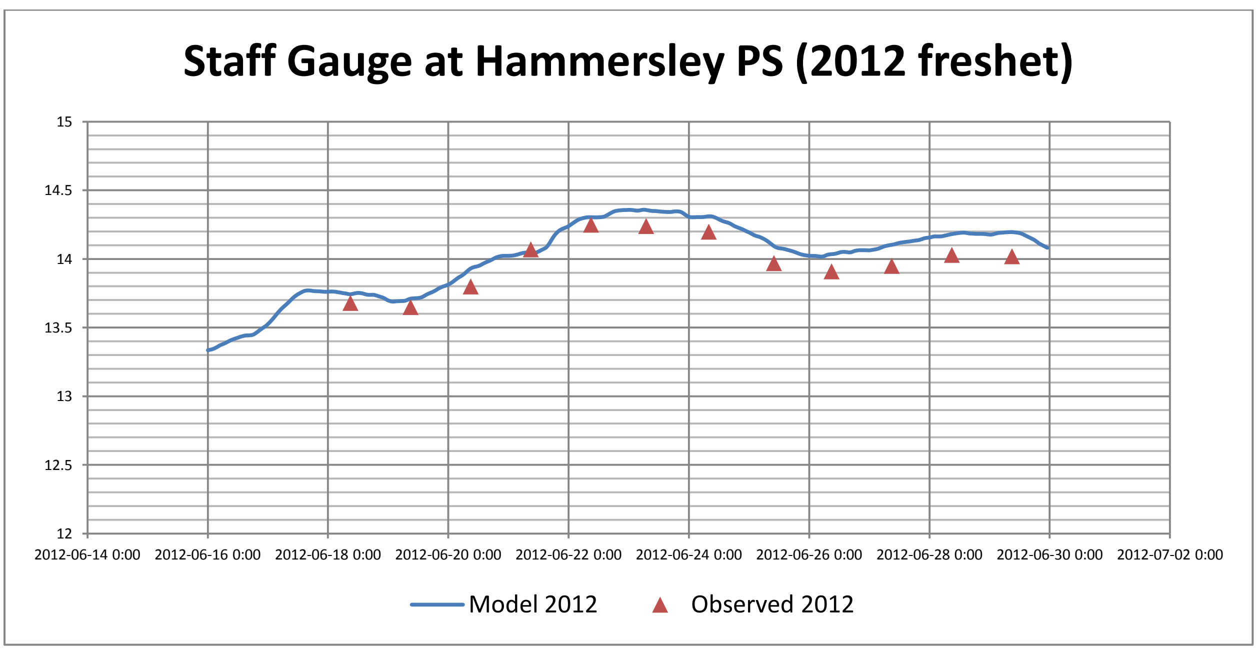


Figure 41

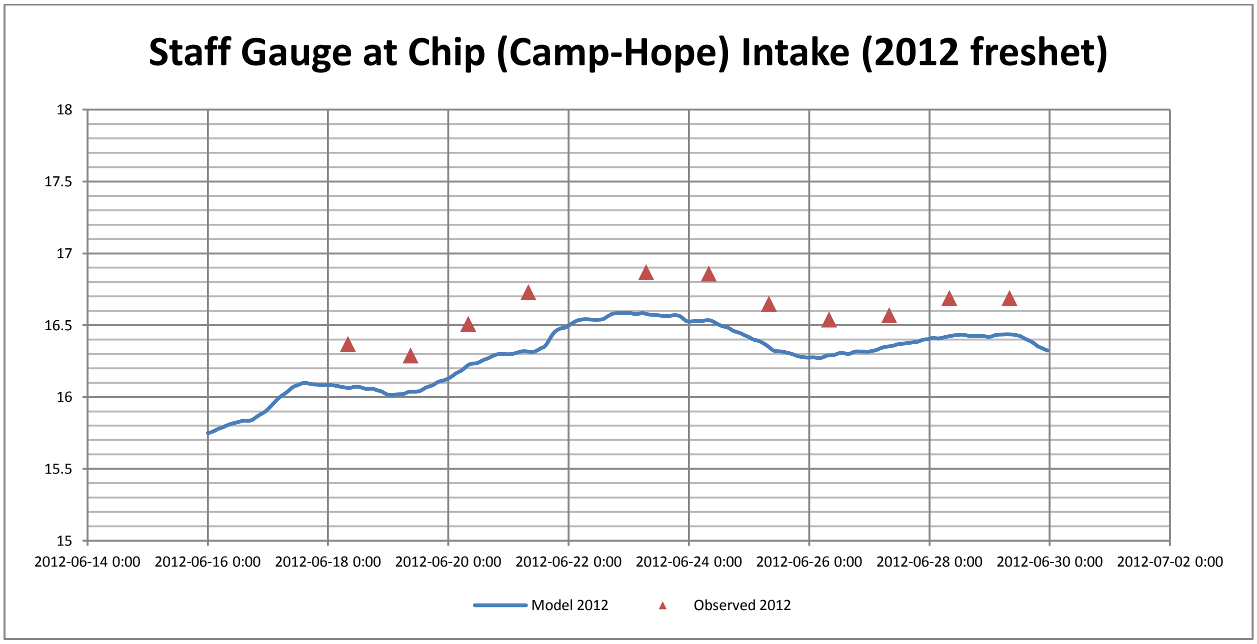


Figure 42

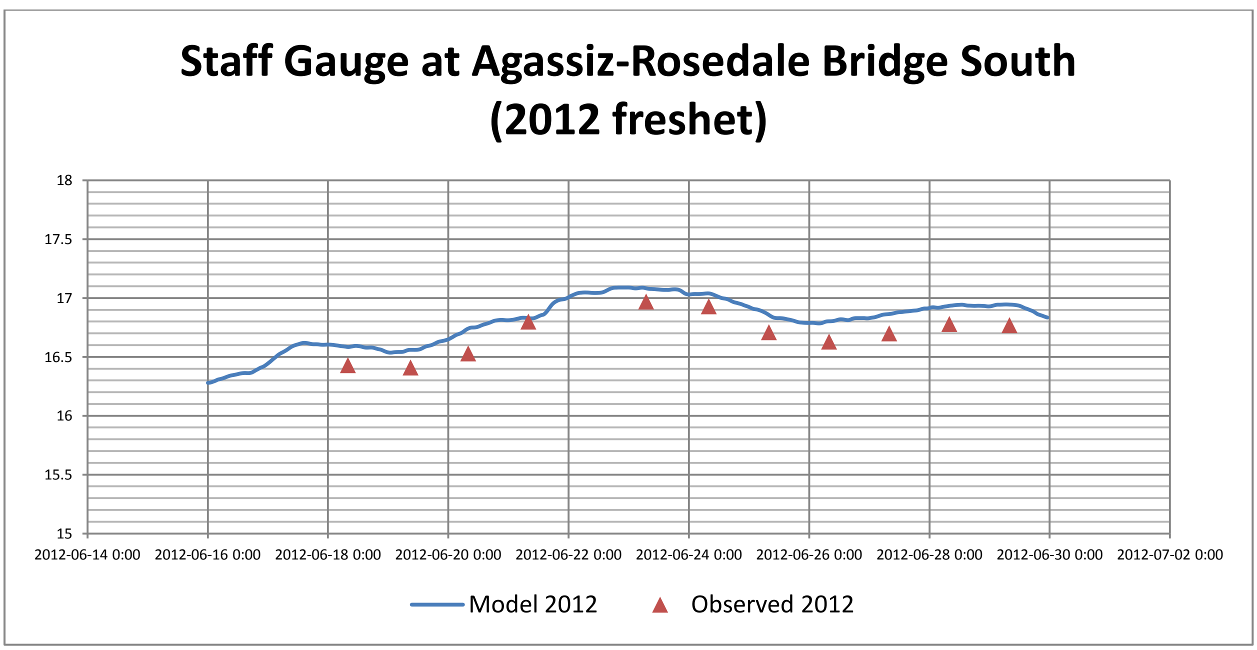


Figure 43

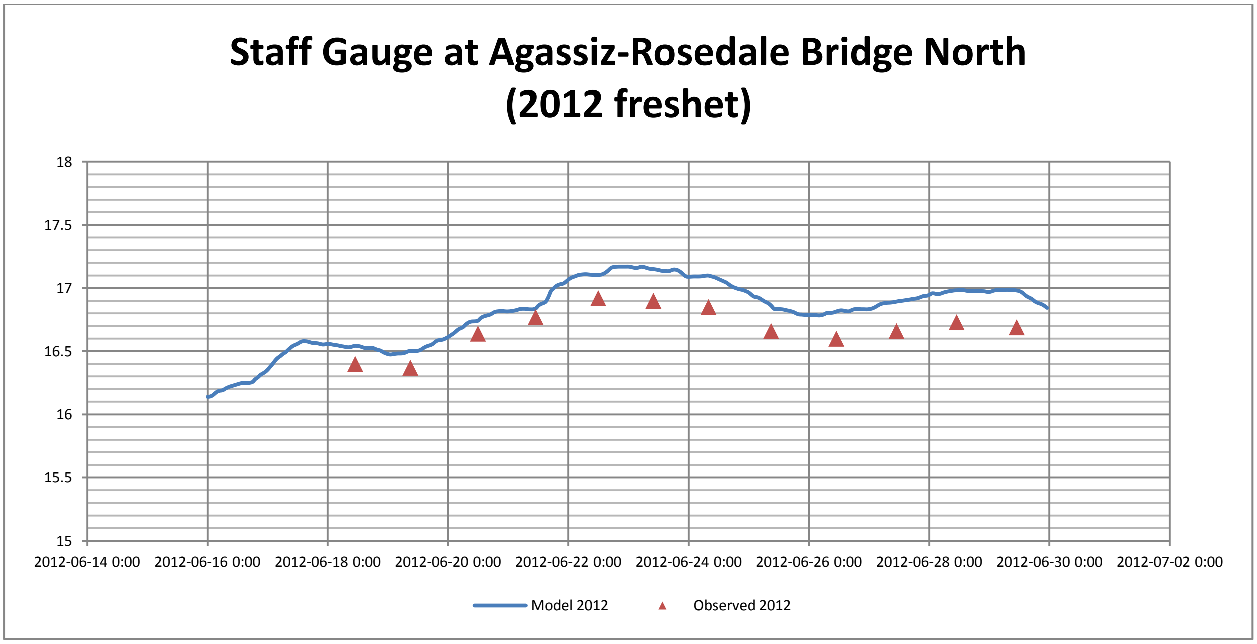


Figure 44

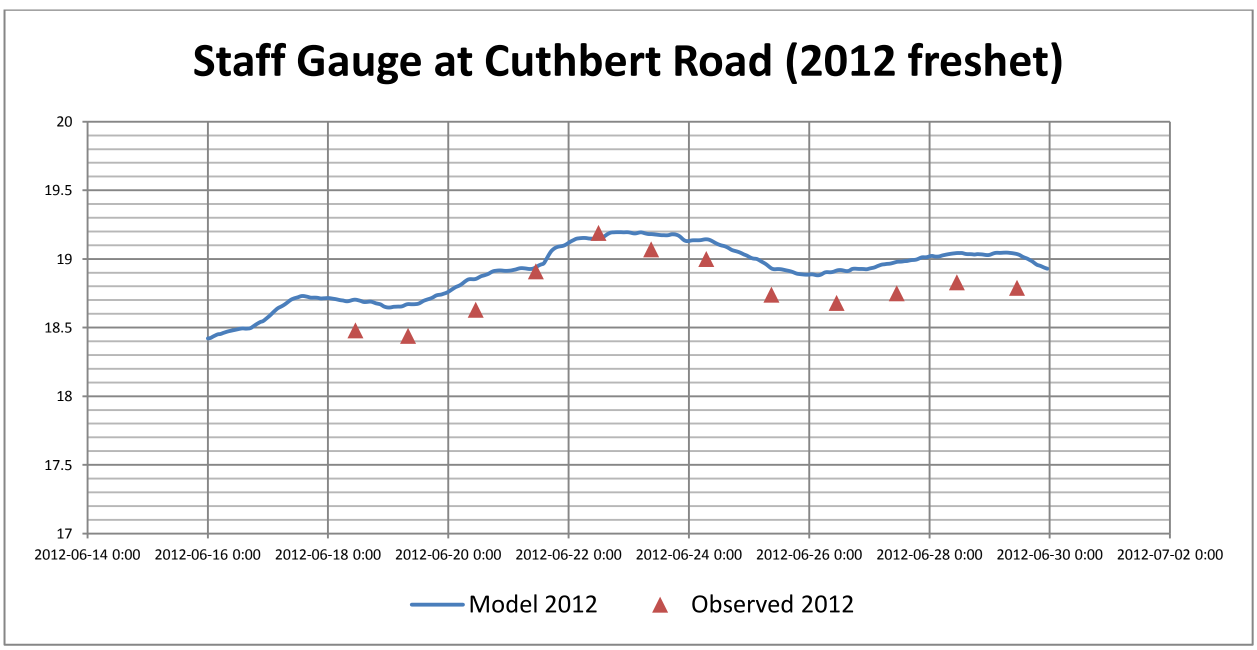


Figure 45

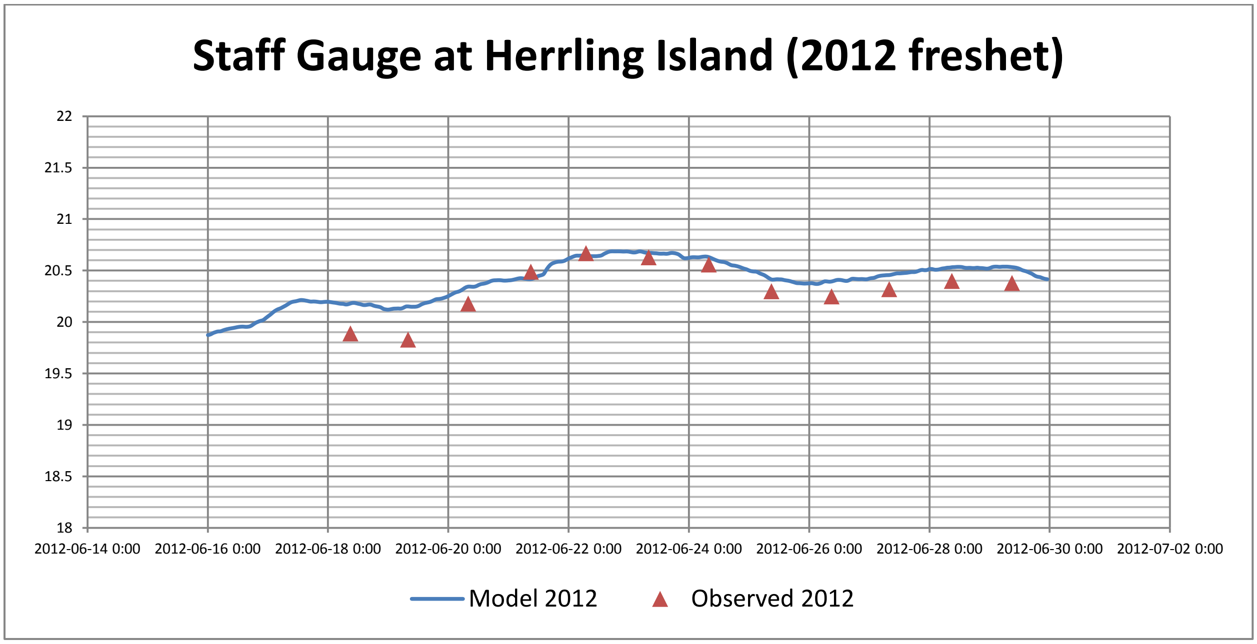


Figure 46

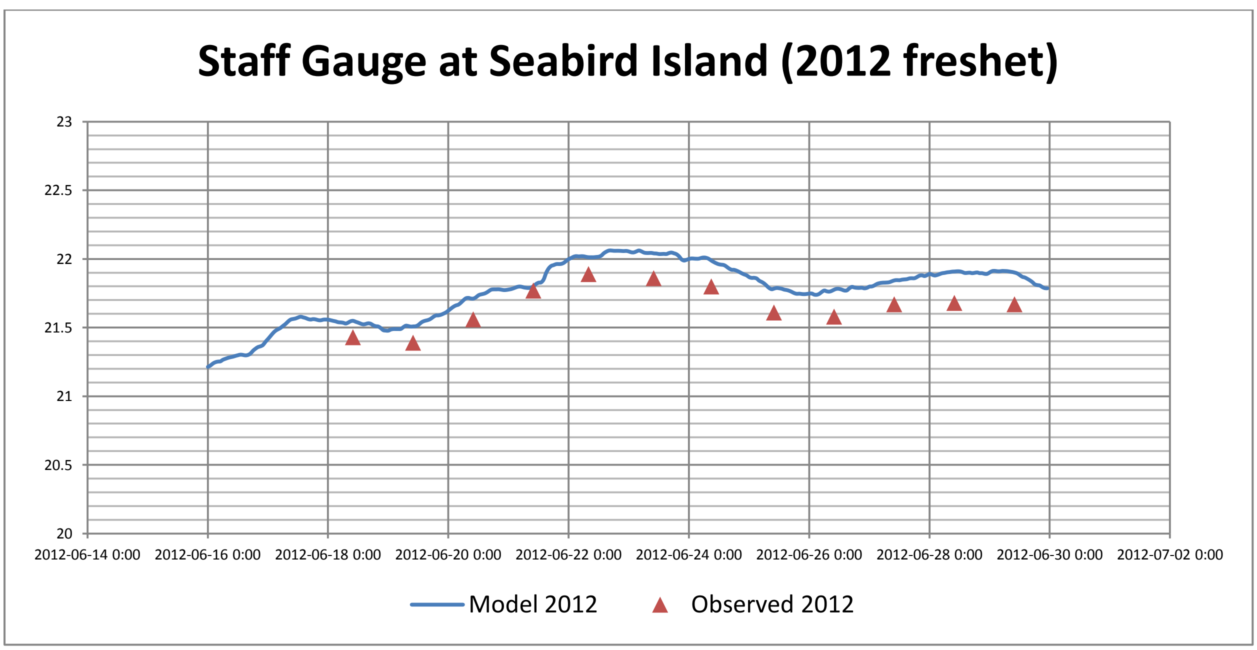


Figure 47

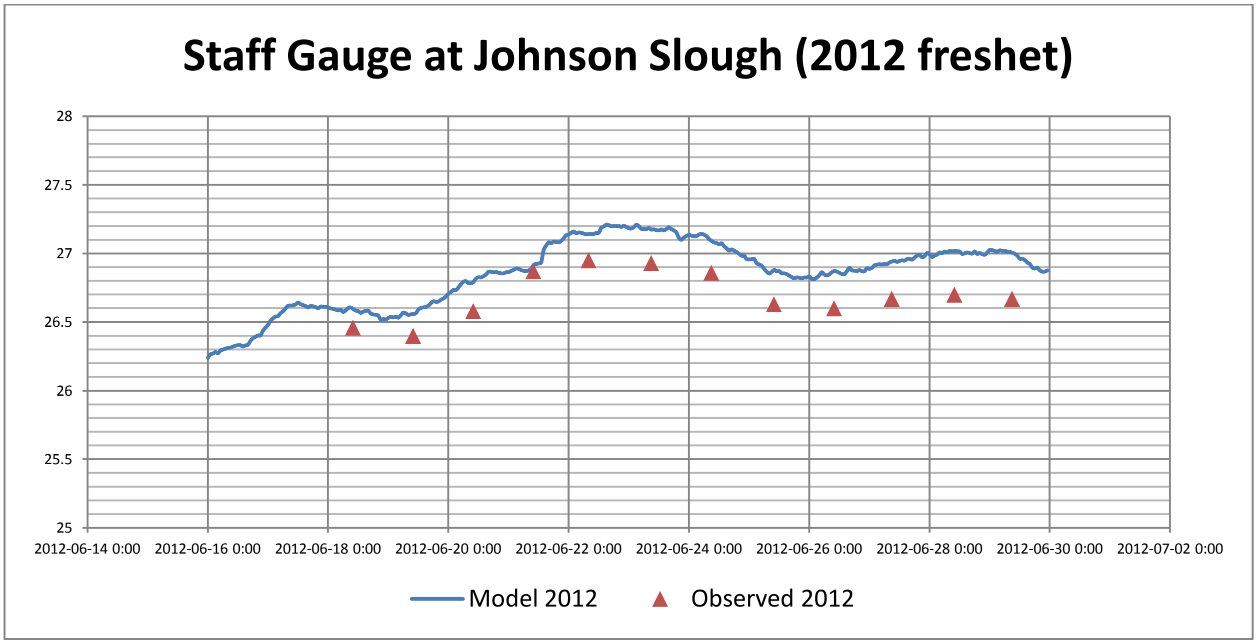


Figure 48

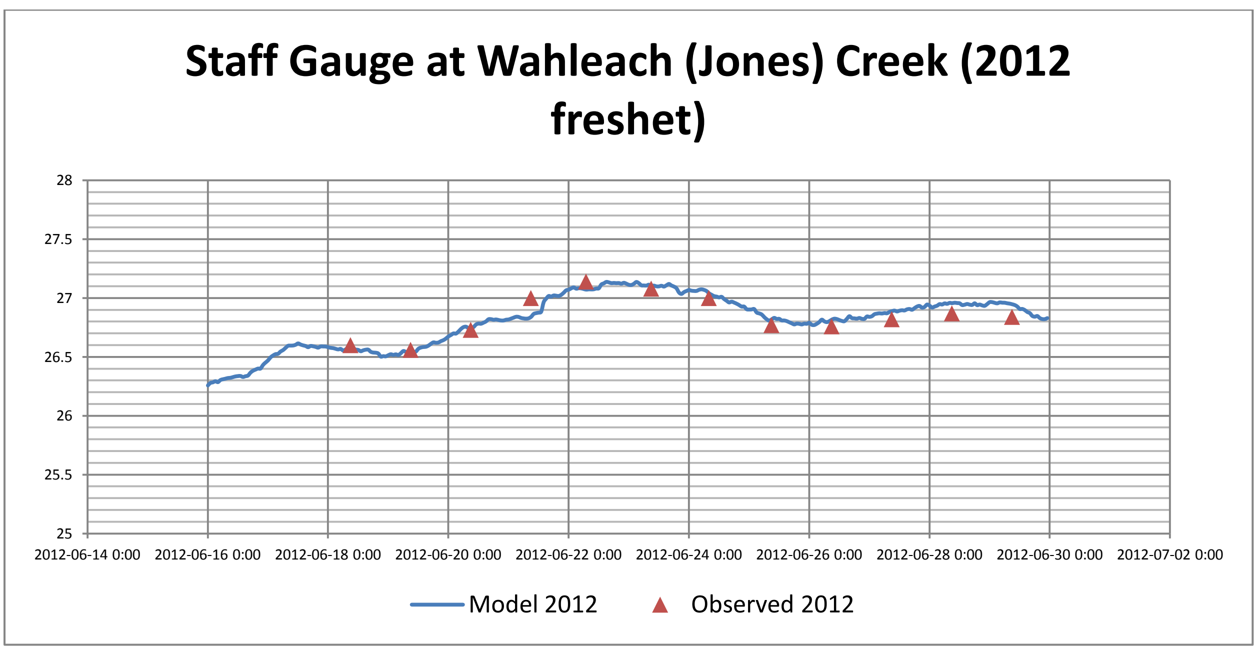
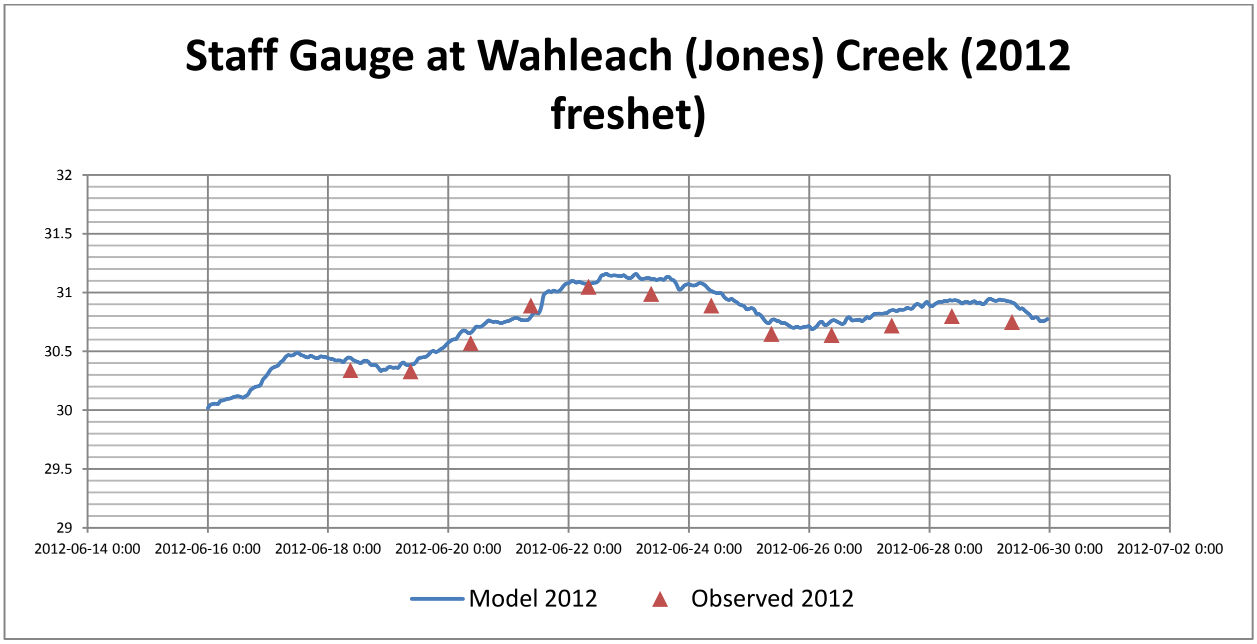
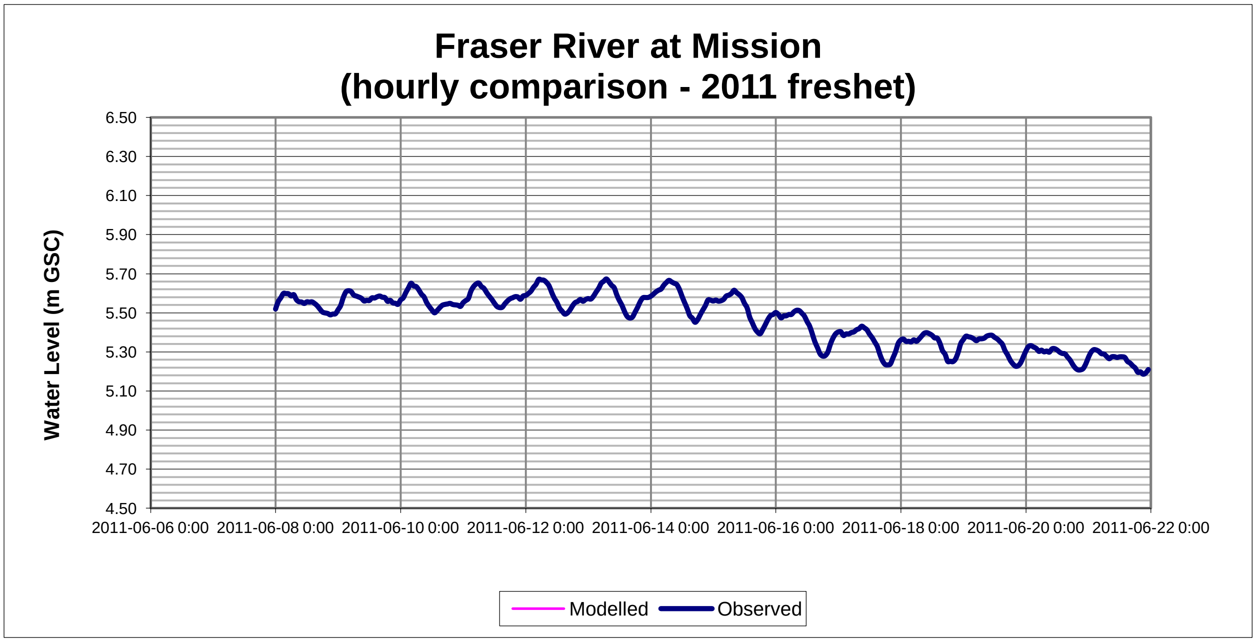


Figure 49

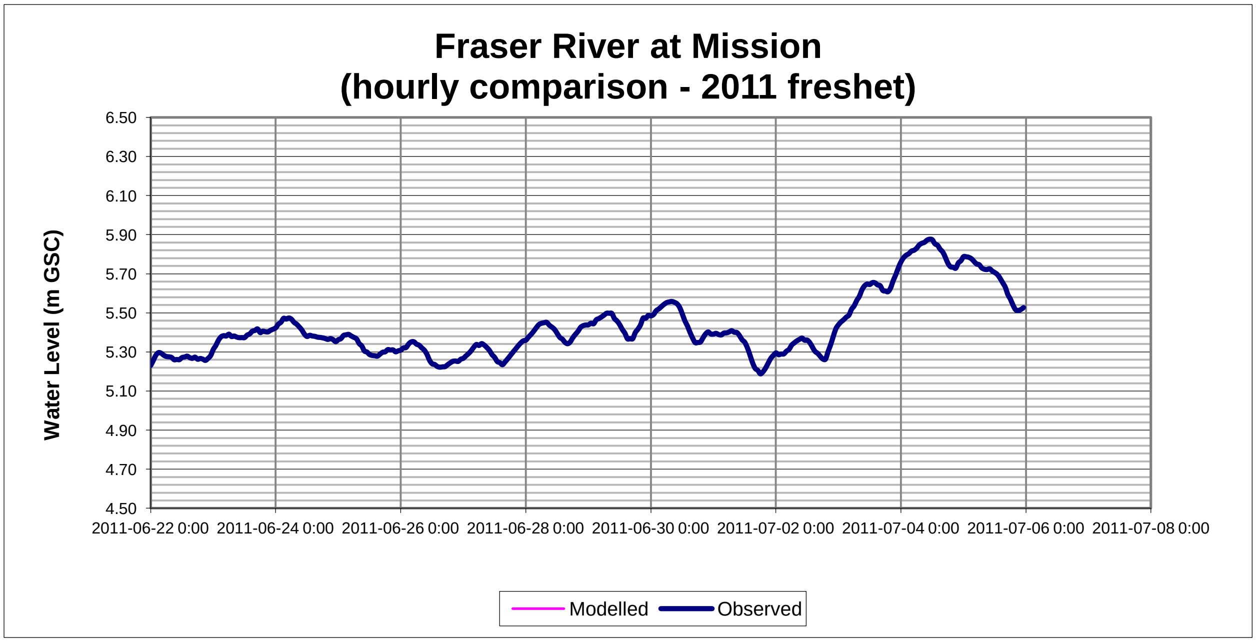


Staff Gauge at Wahleach (Jones) Creek (2012 freshet)
32
31.5
31
30.5
30
29.5
29
2012-06-14 0:00
2012-06-16 0:00
2012-06-18 0:00
2012-06-20 0:00
2012-06-22 0:00
2012-06-24 0:00
2012-06-26 0:00
2012-06-28 0:00
2012-06-30 0:00
2012-07-02 0:00
Model 2012
Observed 2012

Figure 50

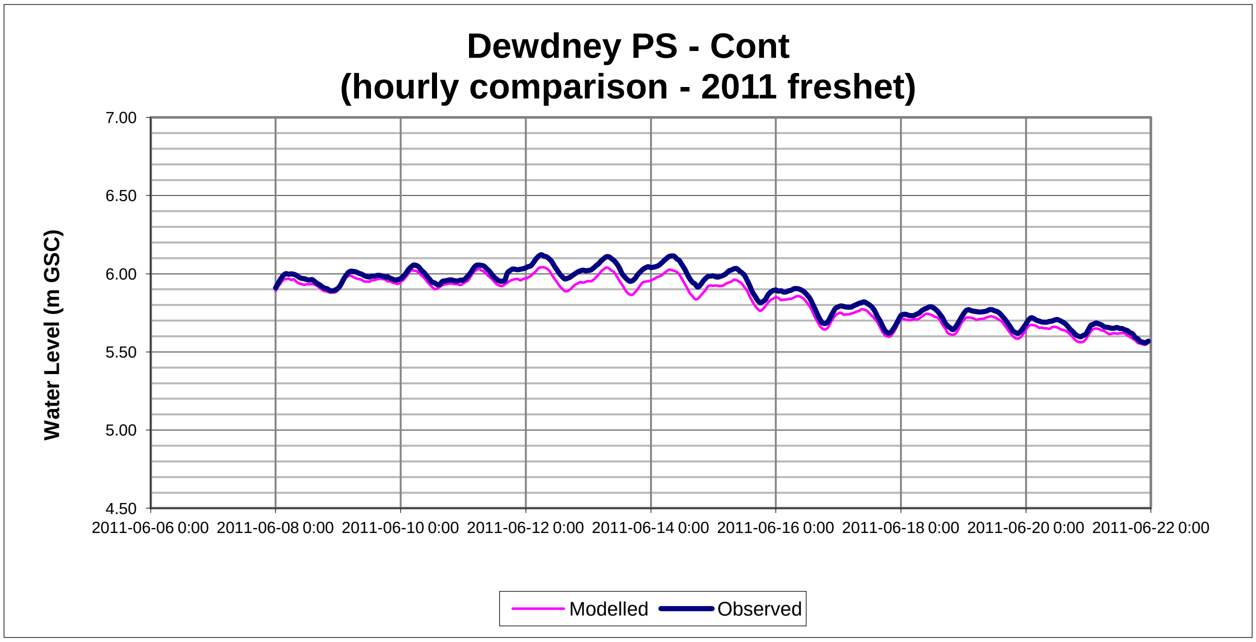


Fraser River at Mission
(hourly comparison - 2011 freshet)
Water Level (m GSC)
6.50
6.30
6.10
5.90
5.70
5.50
5.30
5.10
4.90
4.70
4.50
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed



Fraser River at Mission
(hourly comparison - 2011 freshet)
Water Level (m GSC)
6.50
6.30
6.10
5.90
5.70
5.50
5.30
5.10
4.90
4.70
4.50
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 51


Dewdney PS - Cont
(hourly comparison - 2011 freshet)
Water Level (m GSC)
7.00
6.50
6.00
5.50
5.00
4.50
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

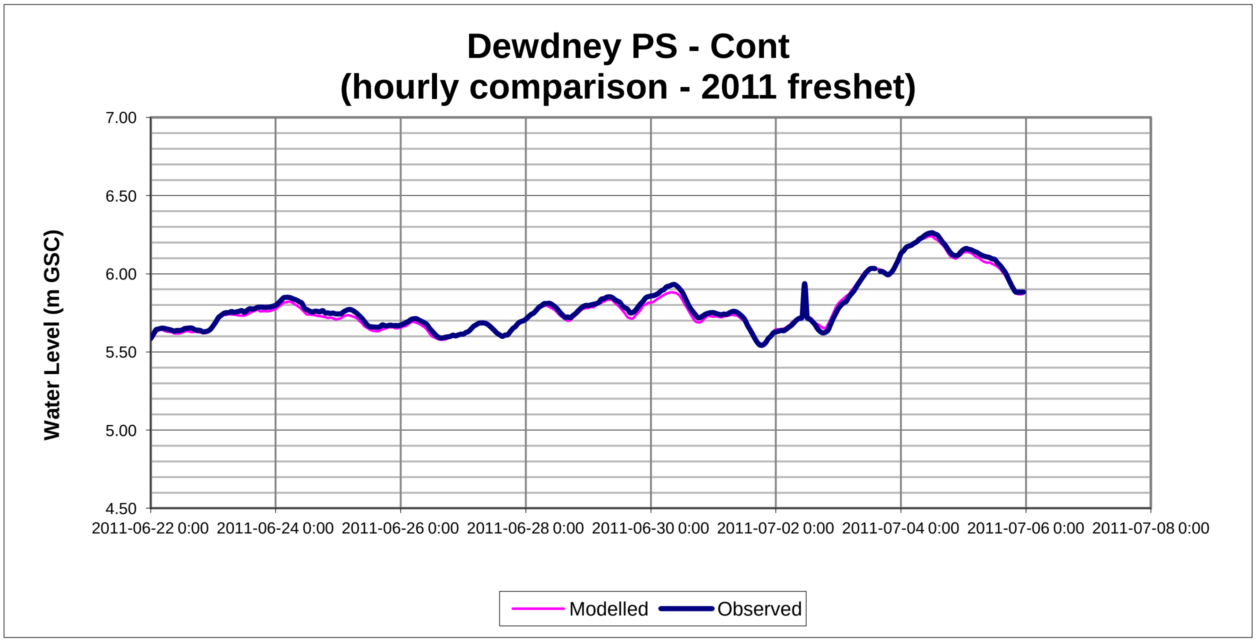
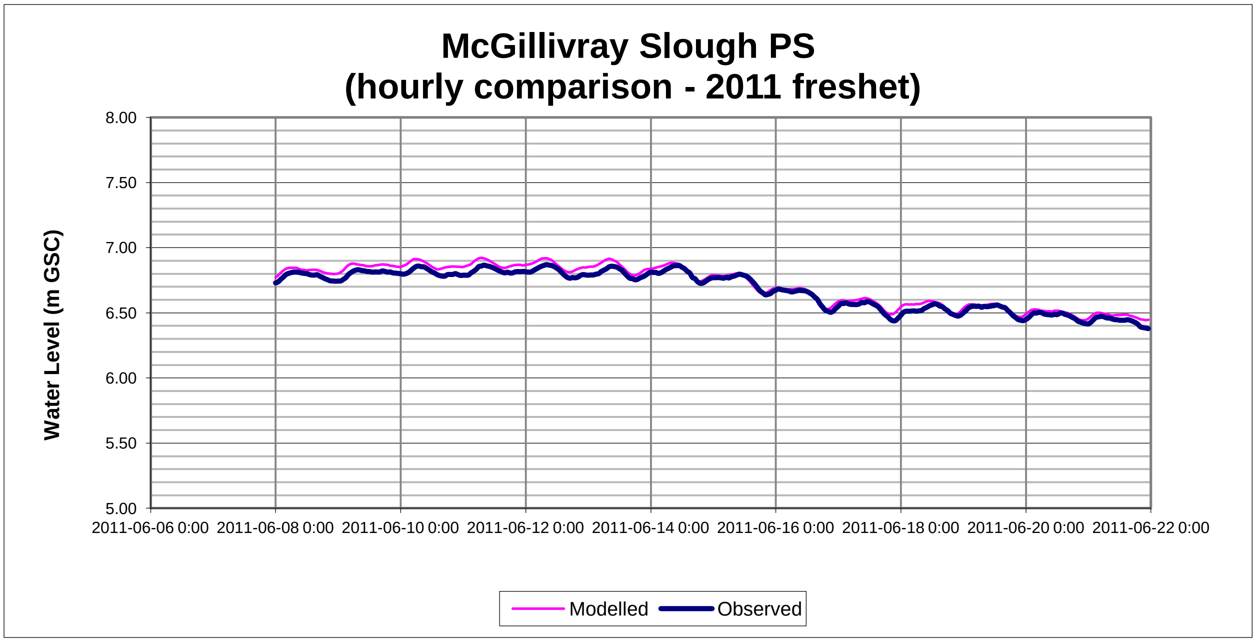
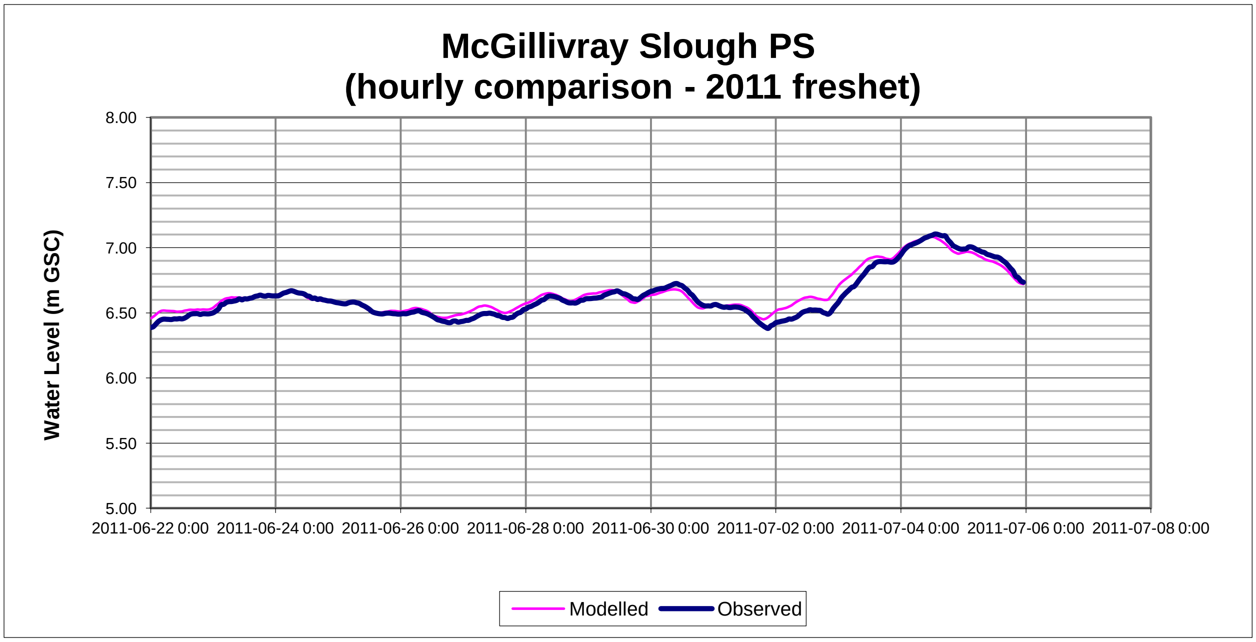

Dewdney PS - Cont
(hourly comparison - 2011 freshet)
Water Level (m GSC)
7.00
6.50
6.00
5.50
5.00
4.50
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 52

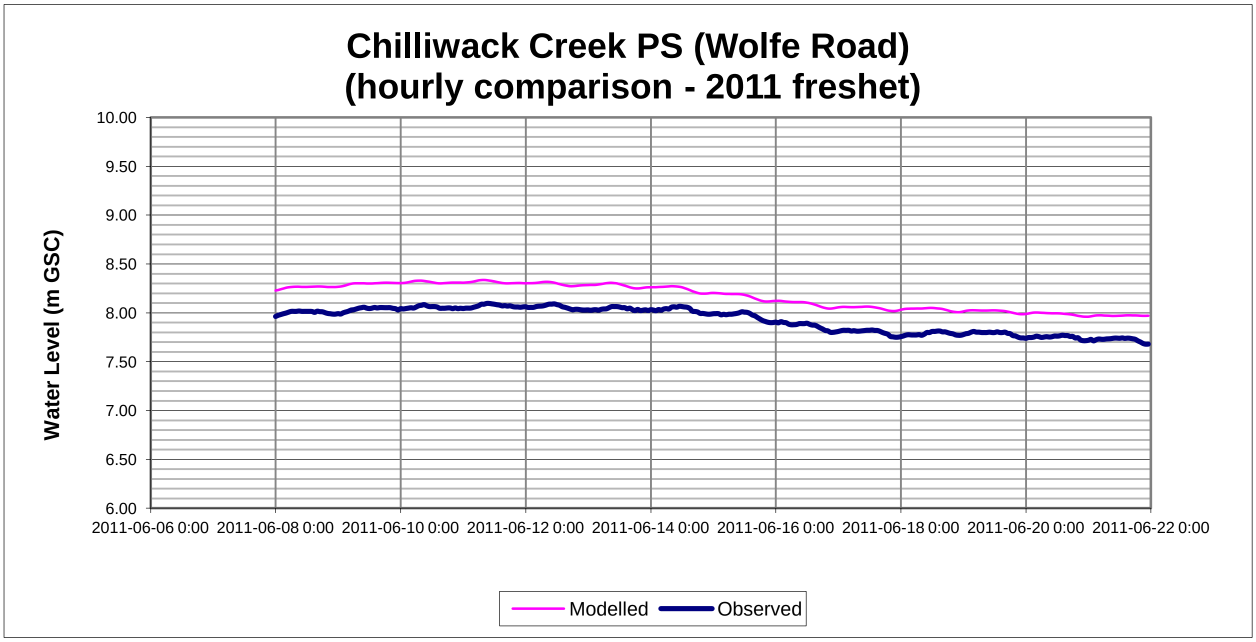


McGillivray Slough PS
(hourly comparison - 2011 freshet)
Water Level (m GSC)
8.00
7.50
7.00
6.50
6.00
5.50
5.00
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

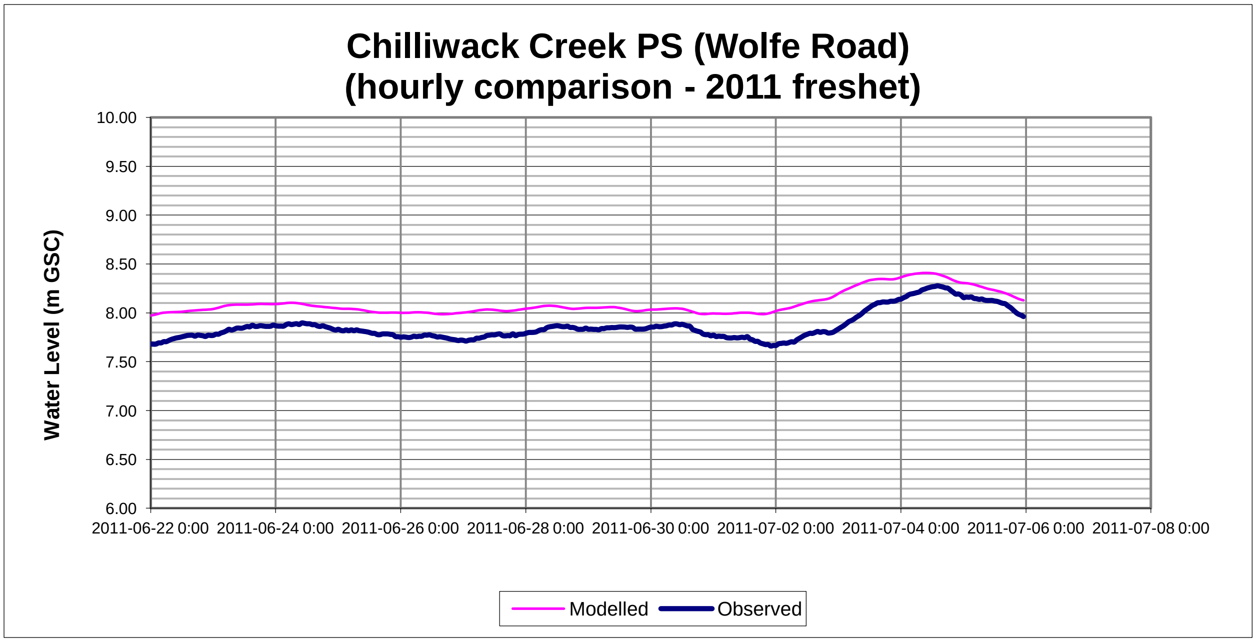


McGillivray Slough PS
(hourly comparison - 2011 freshet)
Water Level (m GSC)
8.00
7.50
7.00
6.50
6.00
5.50
5.00
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 53

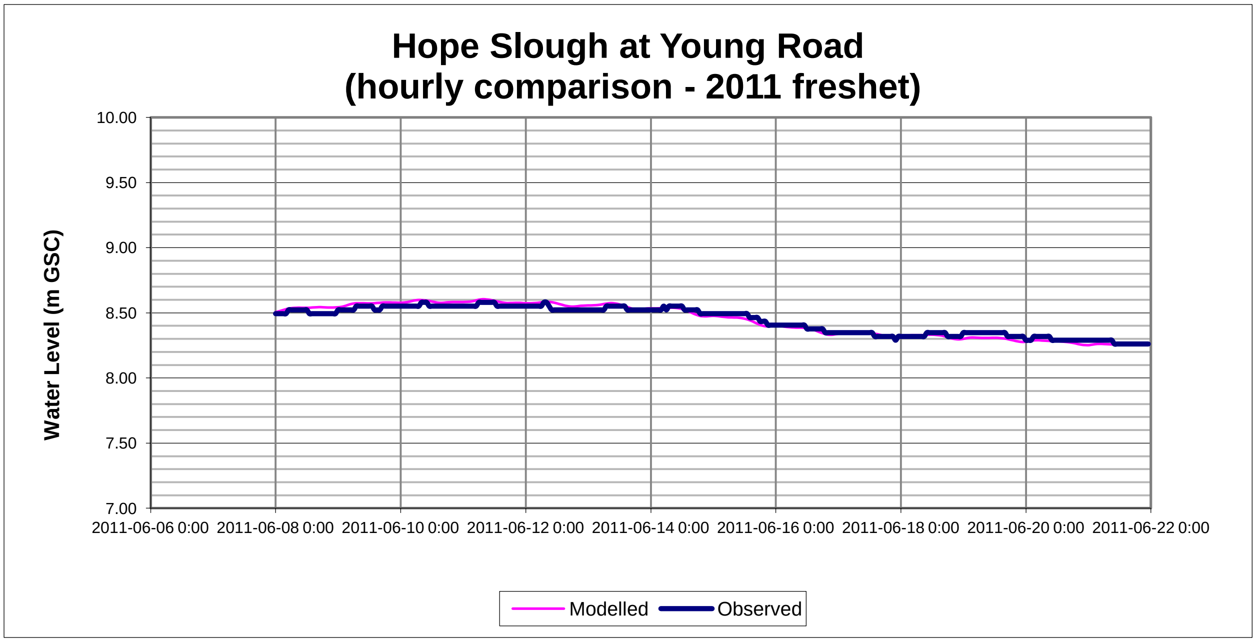


Chilliwack Creek PS (Wolfe Road)
(hourly comparison - 2011 freshet)
Water Level (m GSC)
10.00
9.50
9.00
8.50
8.00
7.50
7.00
6.50
6.00
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

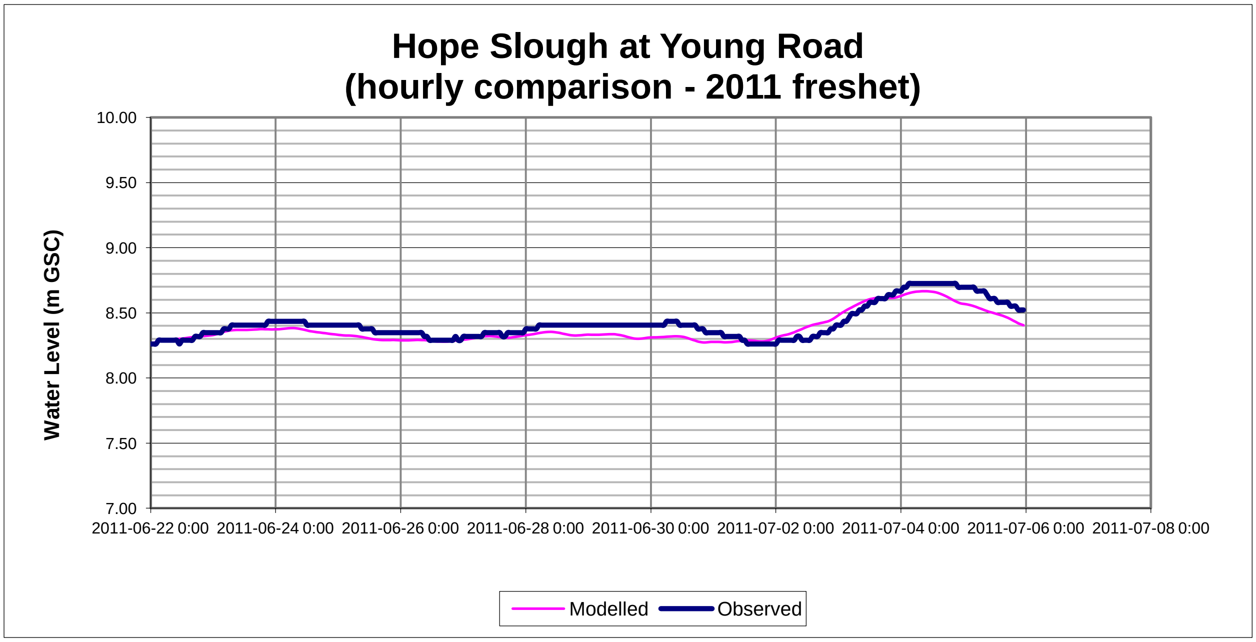


Chilliwack Creek PS (Wolfe Road)
(hourly comparison - 2011 freshet)
Water Level (m GSC)
10.00
9.50
9.00
8.50
8.00
7.50
7.00
6.50
6.00
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 54

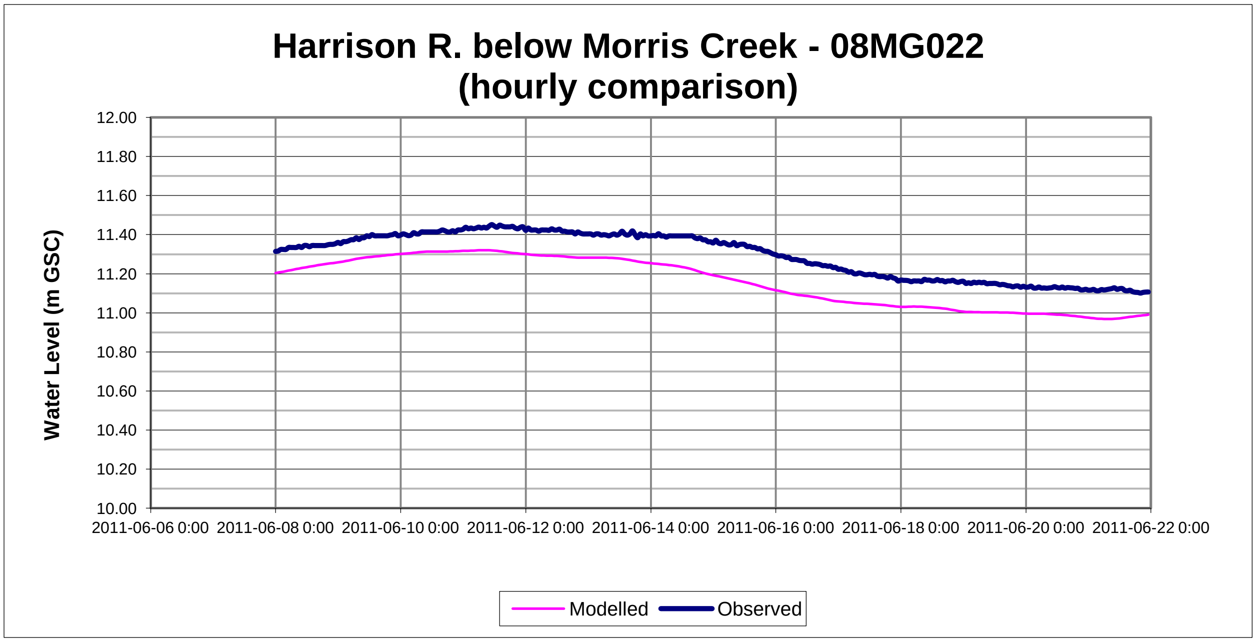


Hope Slough at Young Road
(hourly comparison - 2011 freshet)
Water Level (m GSC)
10.00
9.50
9.00
8.50
8.00
7.50
7.00
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

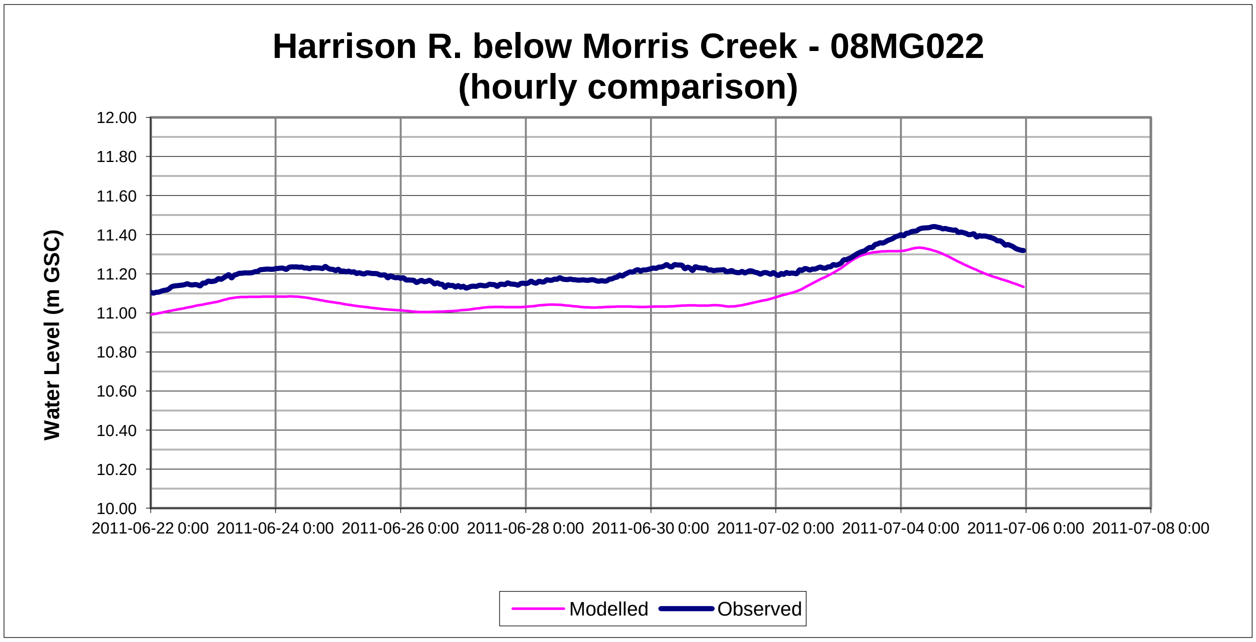


Hope Slough at Young Road
(hourly comparison - 2011 freshet)
Water Level (m GSC)
10.00
9.50
9.00
8.50
8.00
7.50
7.00
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 55

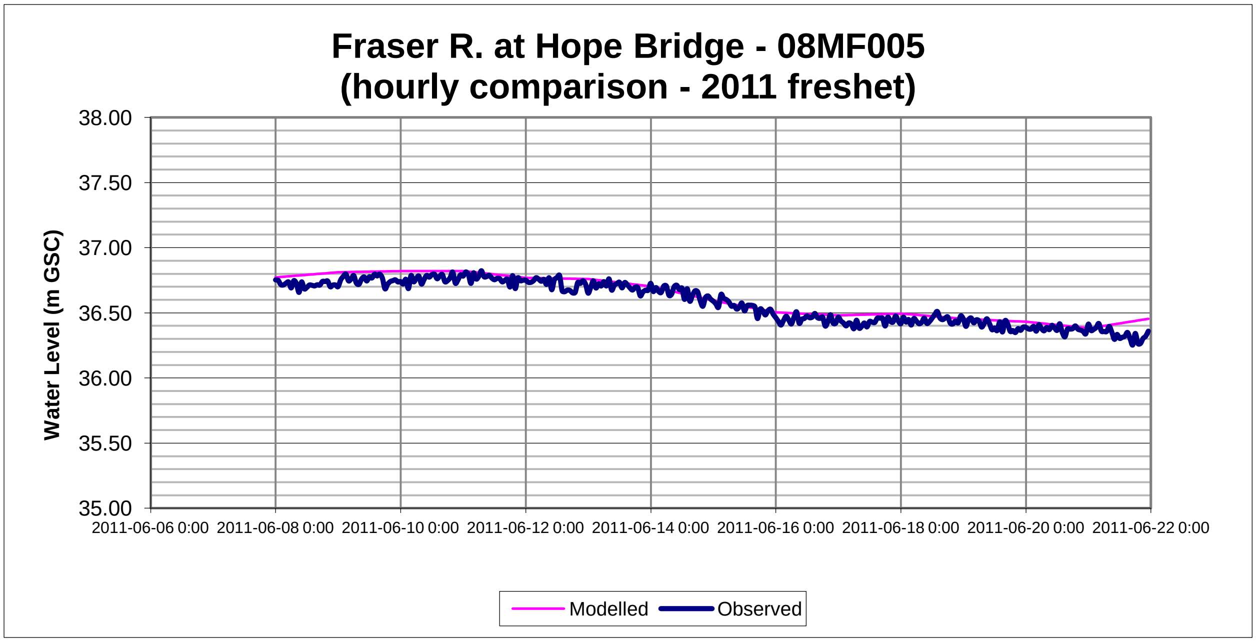


Harrison R. below Morris Creek - 08MG022
(hourly comparison)
Water Level (m GSC)
12.00
11.80
11.60
11.40
11.20
11.00
10.80
10.60
10.40
10.20
10.00
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

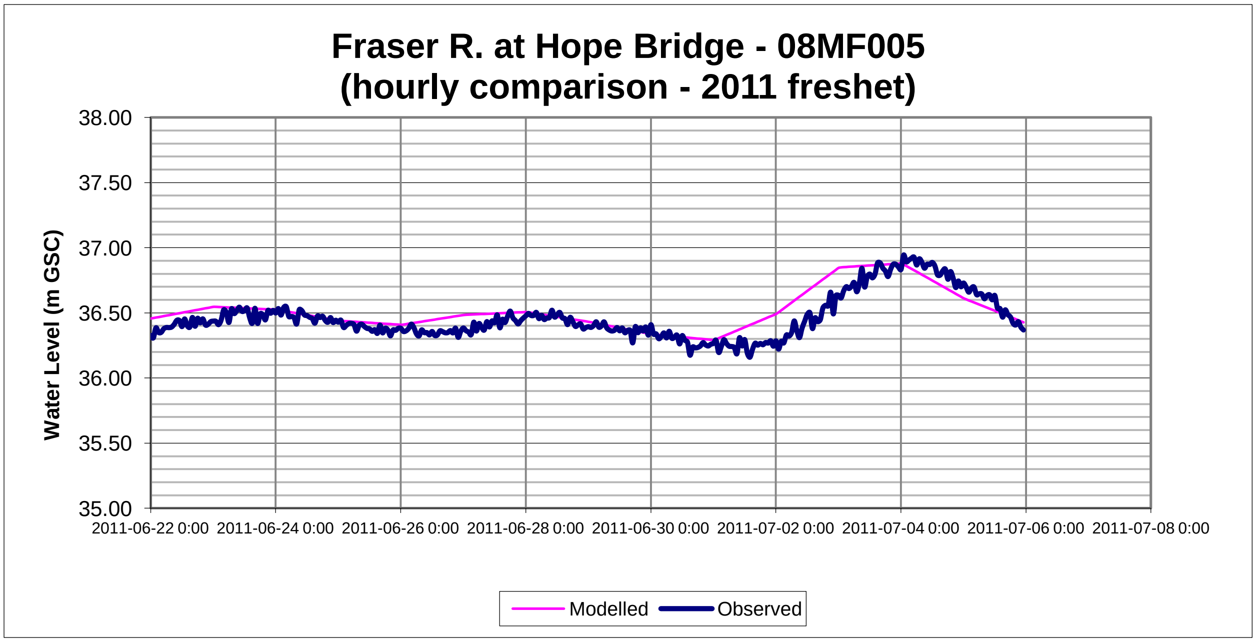


Harrison R. below Morris Creek - 08MG022
(hourly comparison)
Water Level (m GSC)
12.00
11.80
11.60
11.40
11.20
11.00
10.80
10.60
10.40
10.20
10.00
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 56

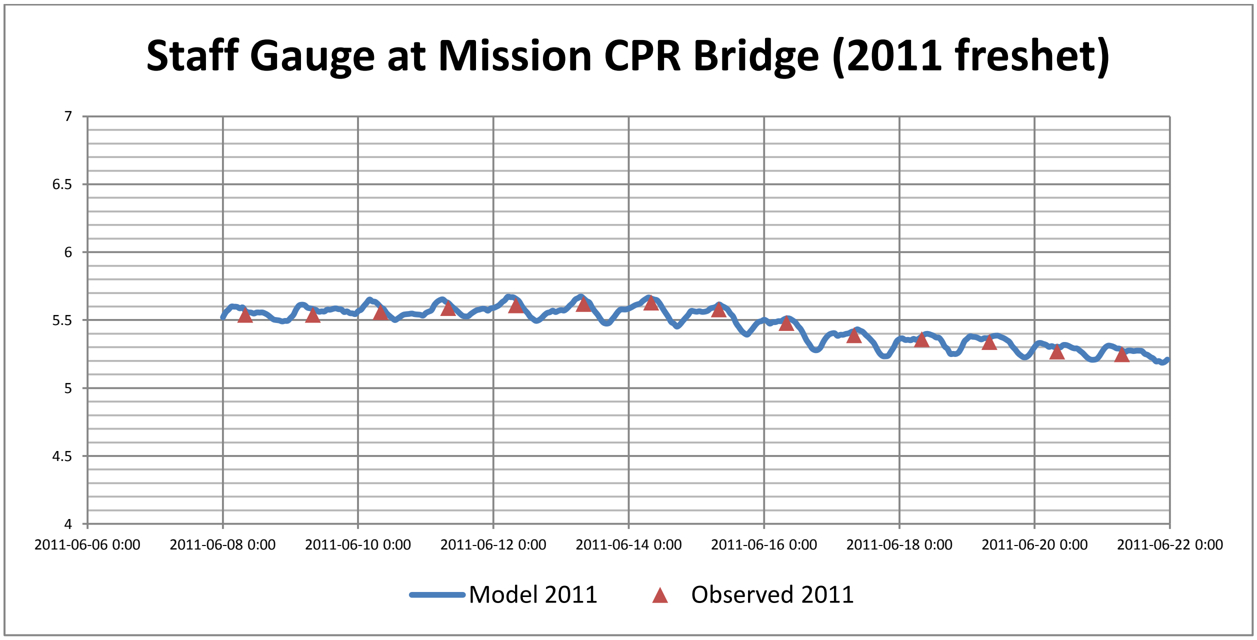


Fraser R. at Hope Bridge - 08MF005
(hourly comparison - 2011 freshet)
Water Level (m GSC)
38.00
37.50
37.00
36.50
36.00
35.50
35.00
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Modelled
Observed

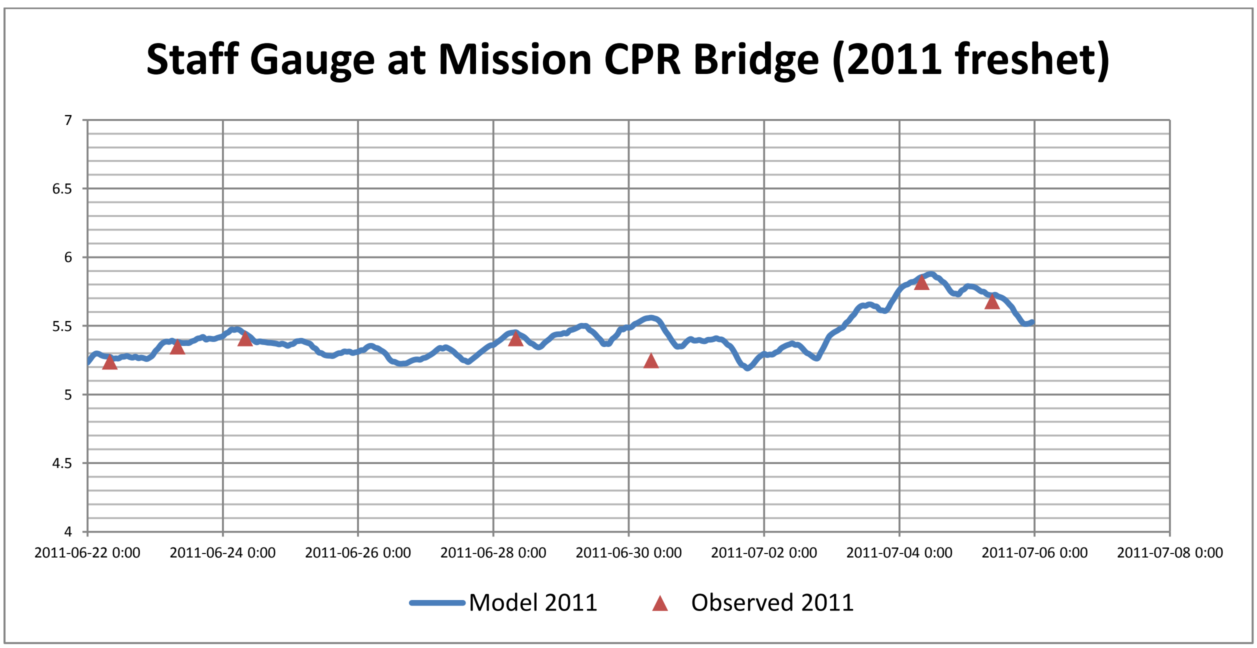


Fraser R. at Hope Bridge - 08MF005
(hourly comparison - 2011 freshet)
Water Level (m GSC)
38.00
37.50
37.00
36.50
36.00
35.50
35.00
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Modelled
Observed

Figure 57

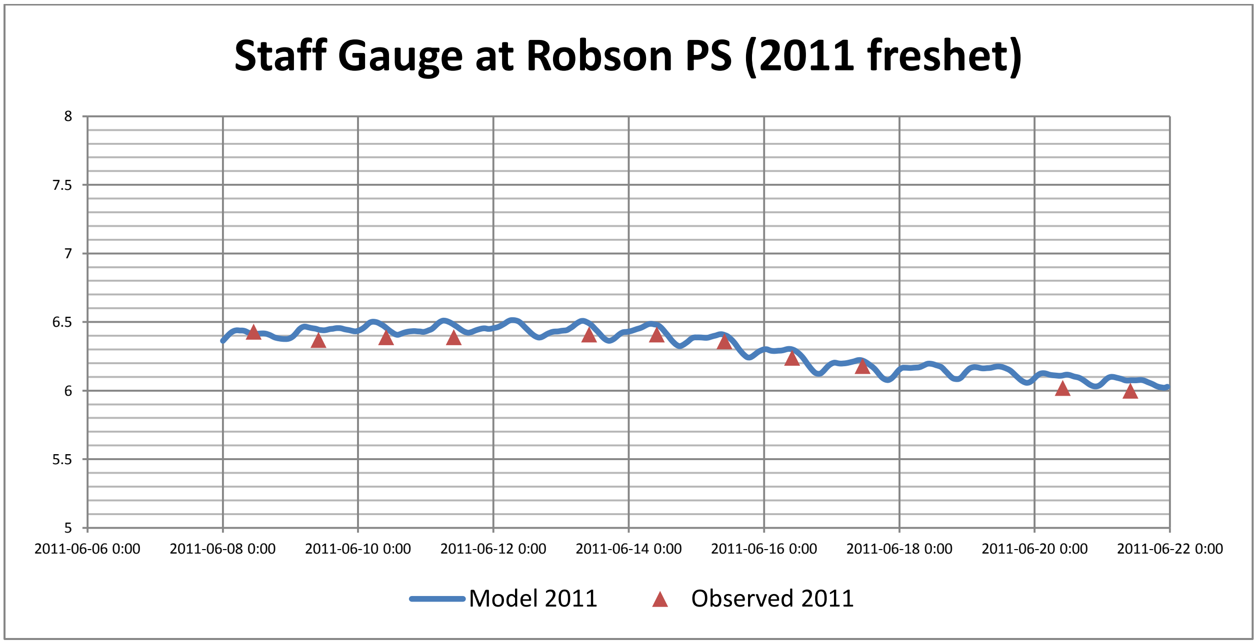


Staff Gauge at Mission CPR Bridge (2011 freshet)
7
6.5
6
5.5
5
4.5
4
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

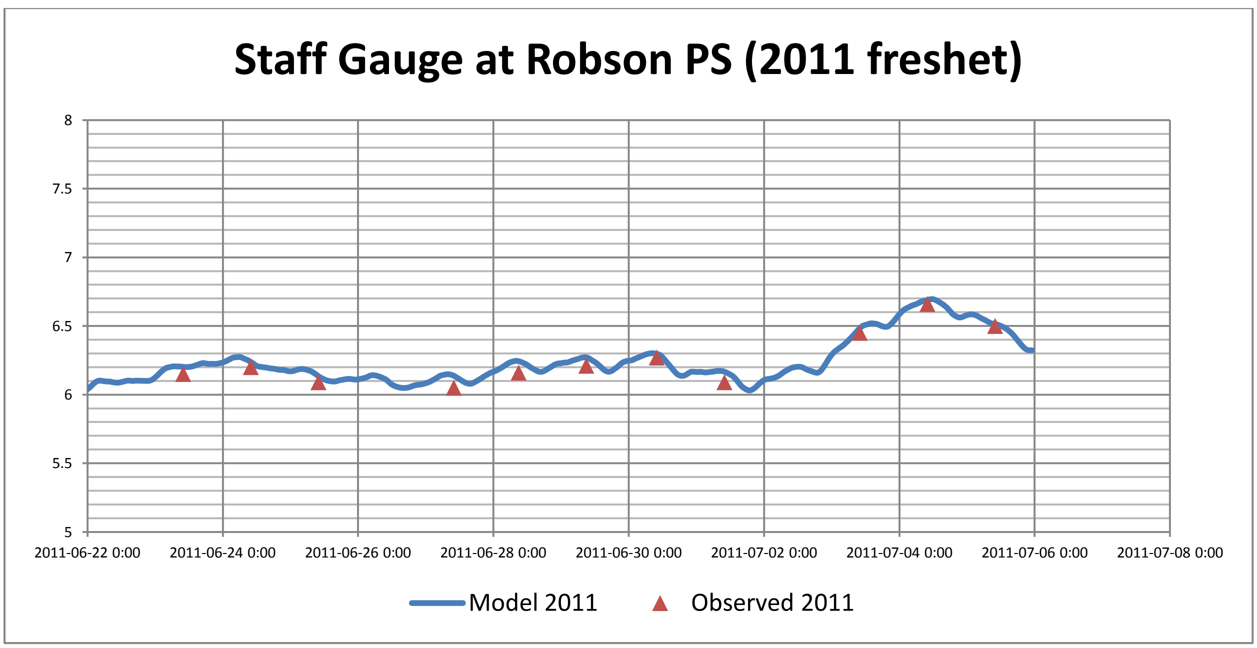


Staff Gauge at Mission CPR Bridge (2011 freshet)
7
6.5
6
5.5
5
4.5
4
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 58

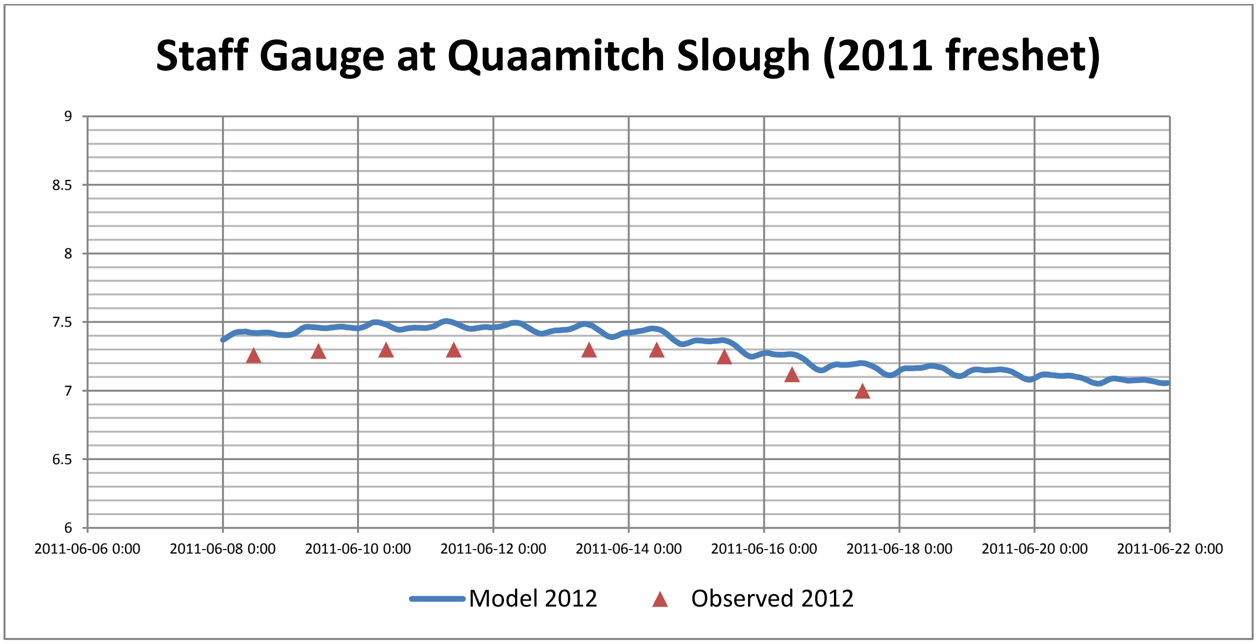


Staff Gauge at Robson PS (2011 freshet)
8
7.5
7
6.5
6
5.5
5
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

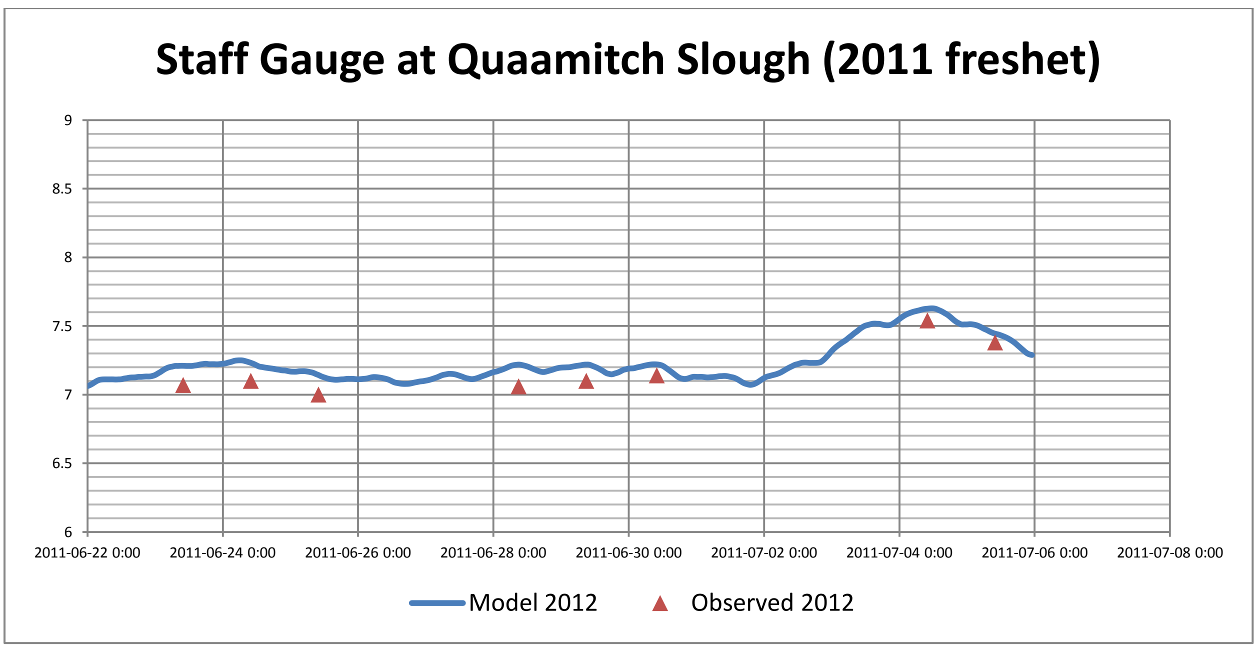


Staff Gauge at Robson PS (2011 freshet)
8
7.5
7
6.5
6
5.5
5
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 59

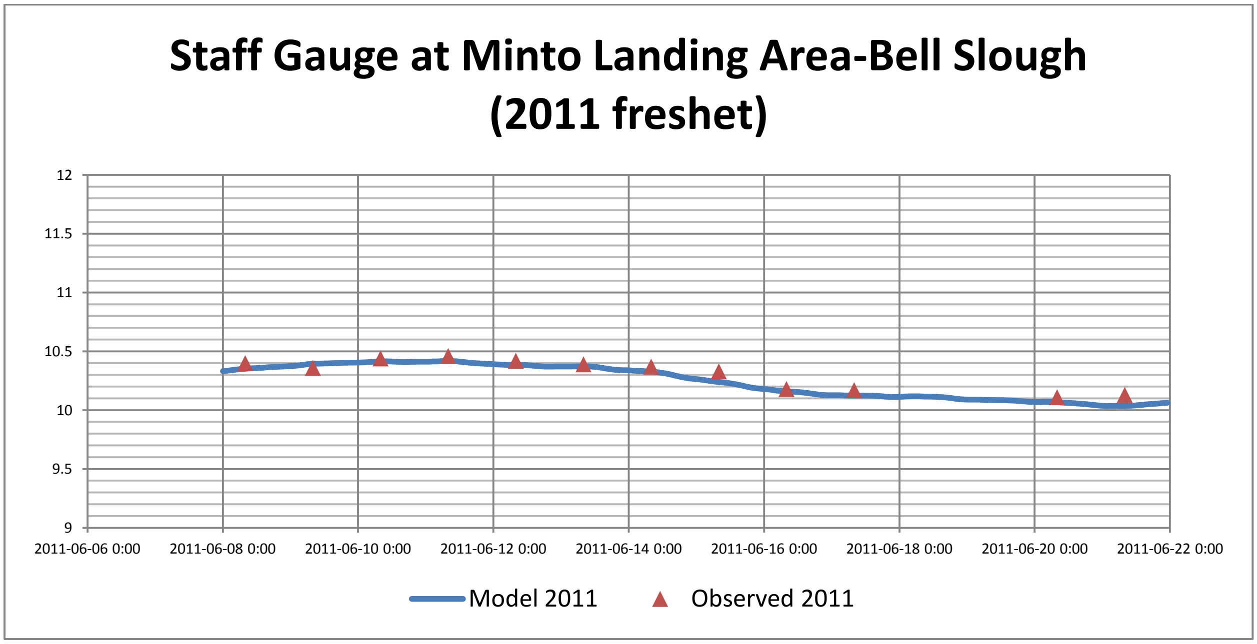


Staff Gauge at Quaamitch Slough (2011 freshet)
9
8.5
8
7.5
7
6.5
6
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2012
Observed 2012



Staff Gauge at Quaamitch Slough (2011 freshet)
9
8.5
8
7.5
7
6.5
6
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2012
Observed 2012

Figure 60


Staff Gauge at Minto Landing Area-Bell Slough
(2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

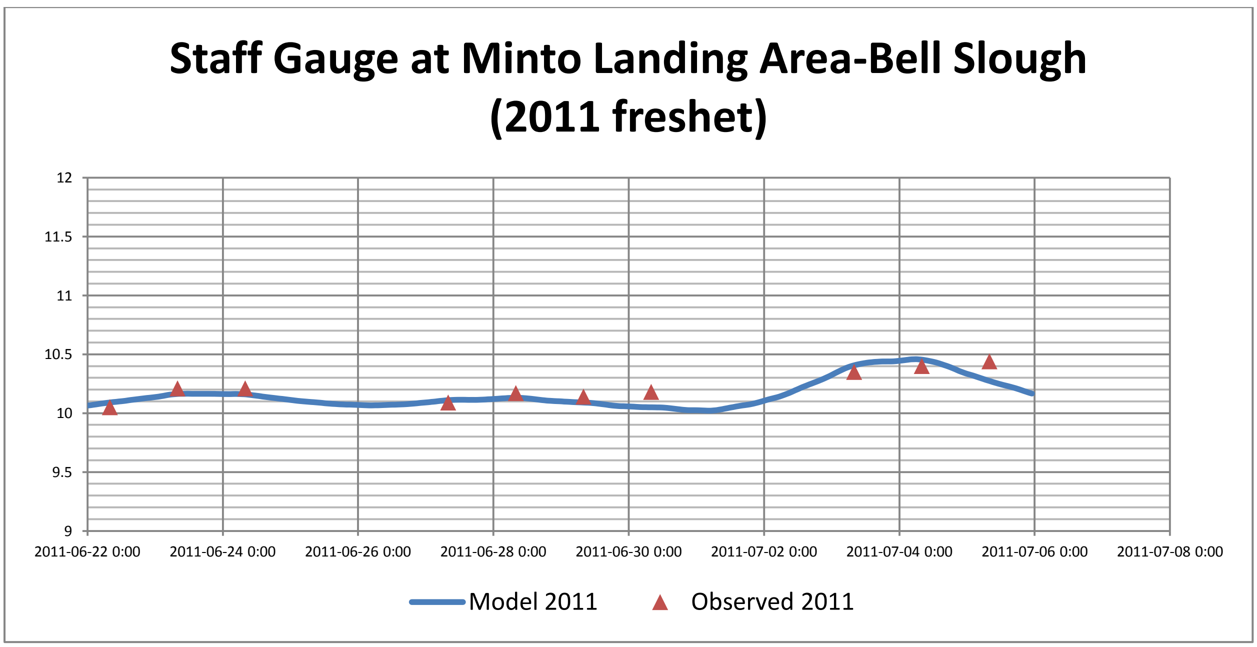
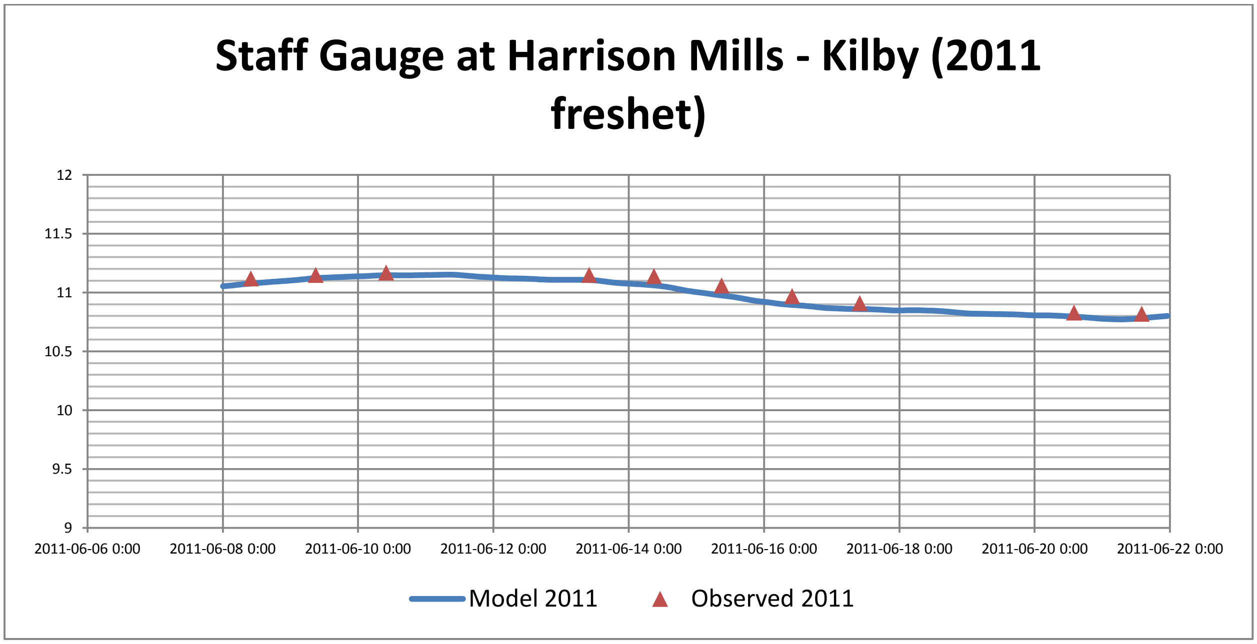
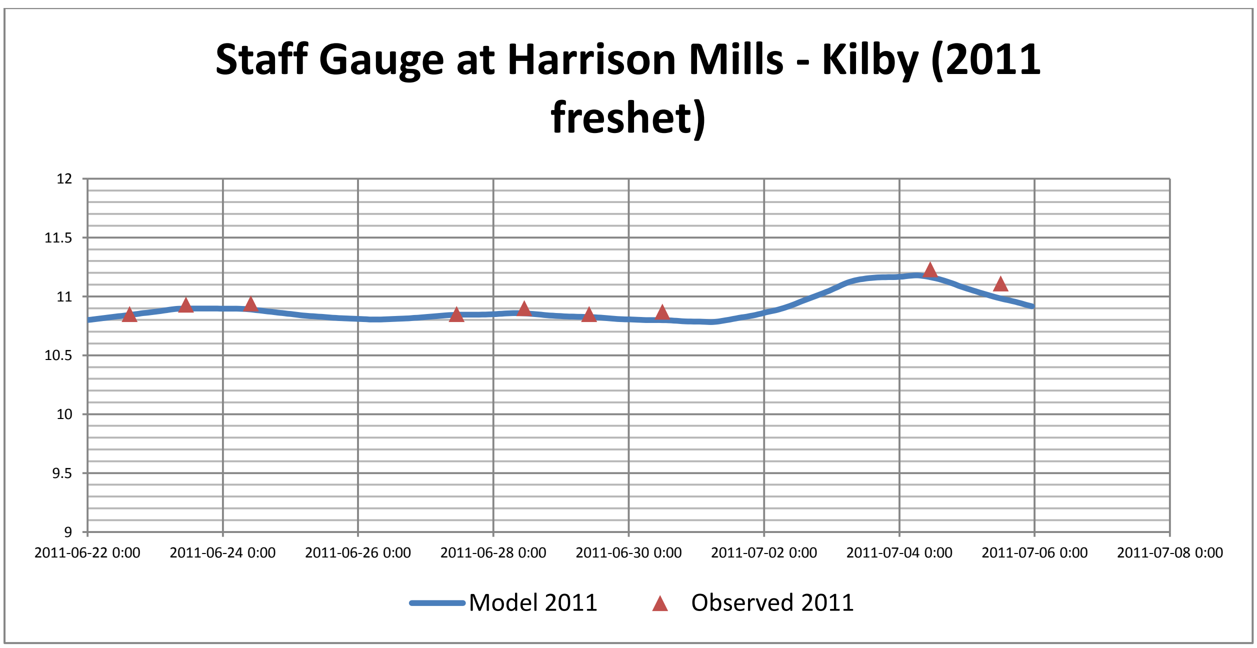

Staff Gauge at Minto Landing Area-Bell Slough
(2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 61

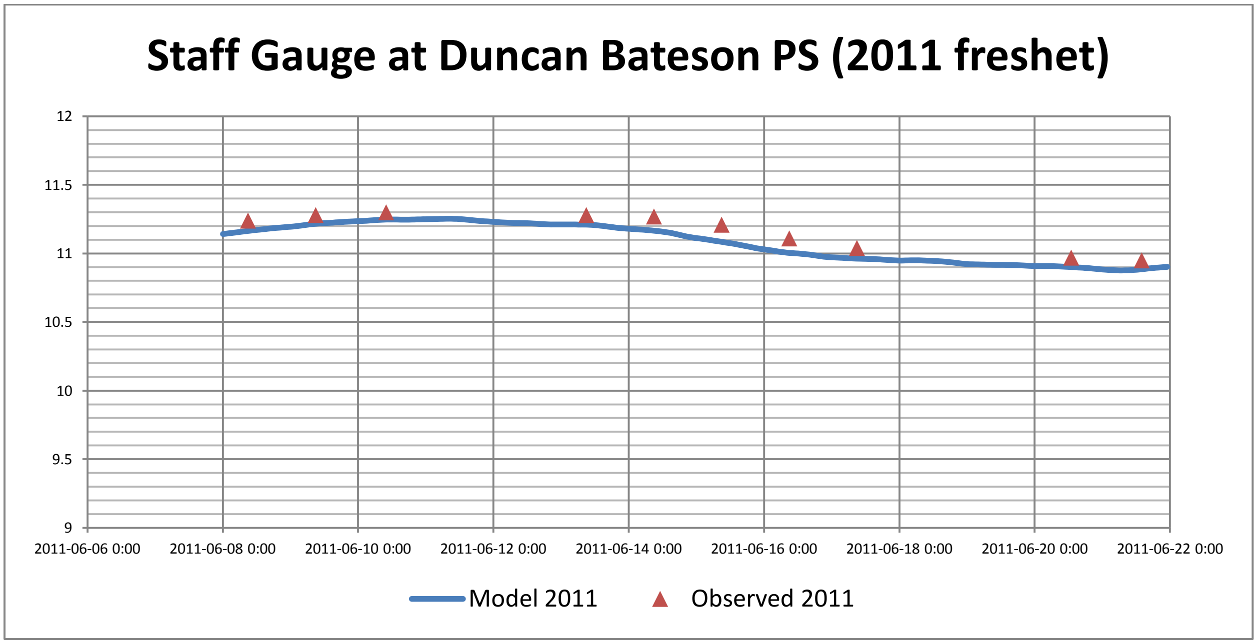


Staff Gauge at Harrison Mills - Kilby (2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

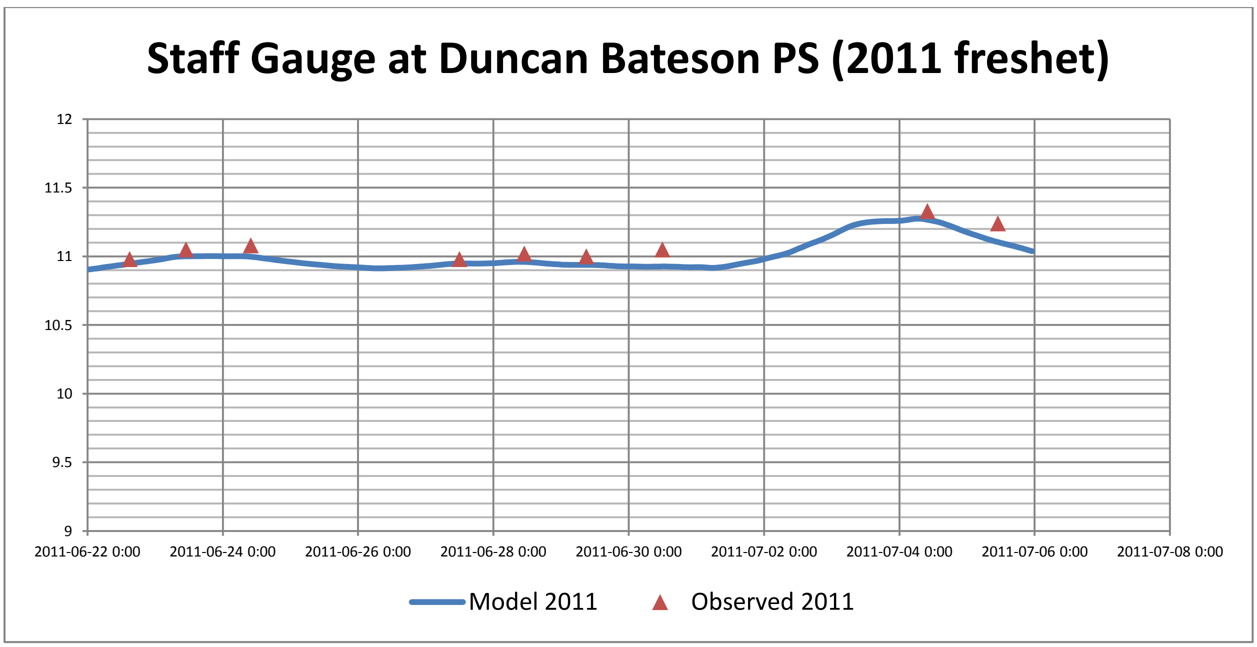


Staff Gauge at Harrison Mills - Kilby (2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 62

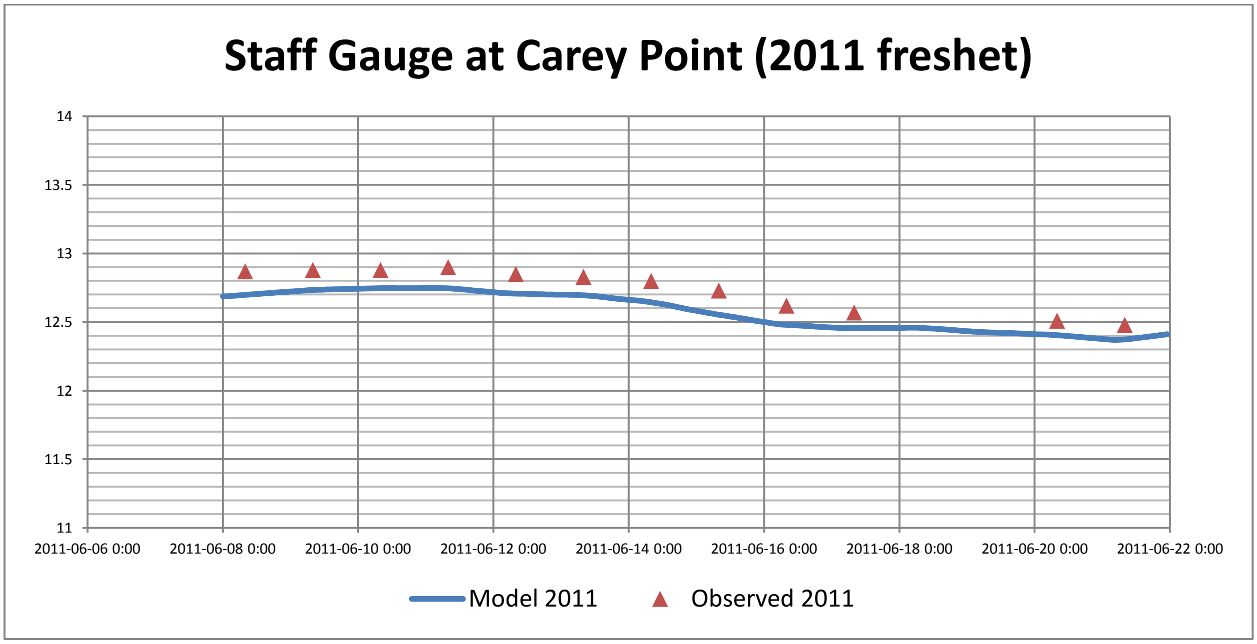


Staff Gauge at Duncan Bateson PS (2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011



Staff Gauge at Duncan Bateson PS (2011 freshet)
12
11.5
11
10.5
10
9.5
9
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 63


Staff Gauge at Carey Point (2011 freshet)
14
13.5
13
12.5
12
11.5
11
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

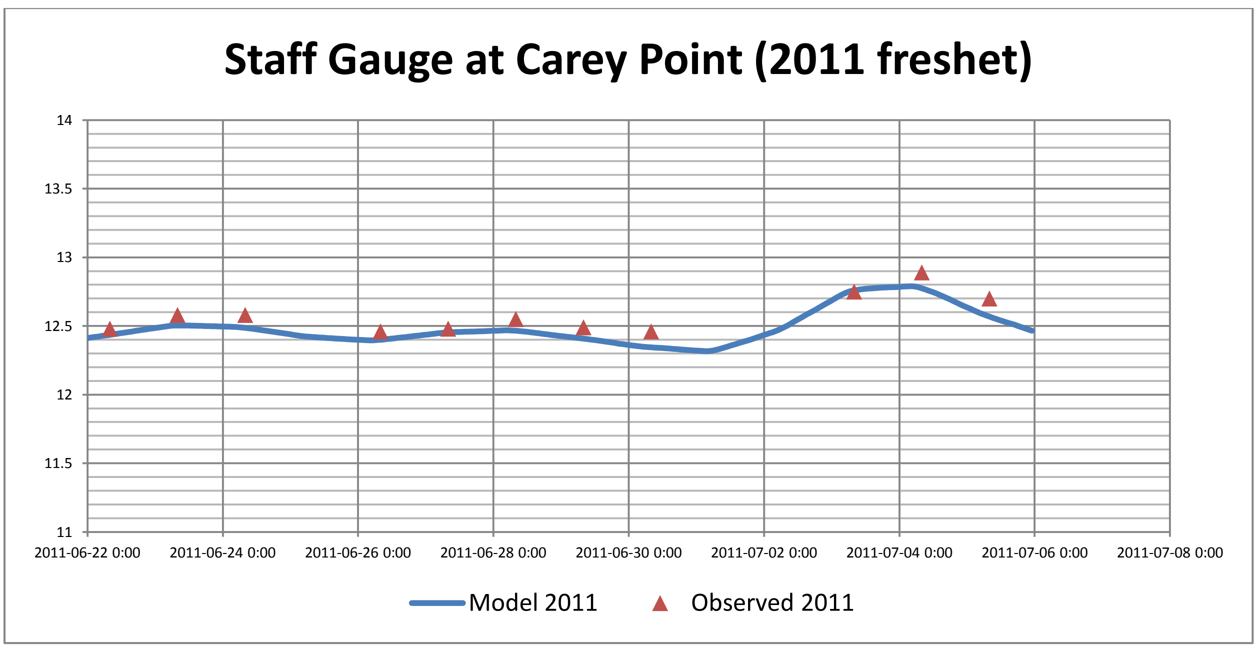
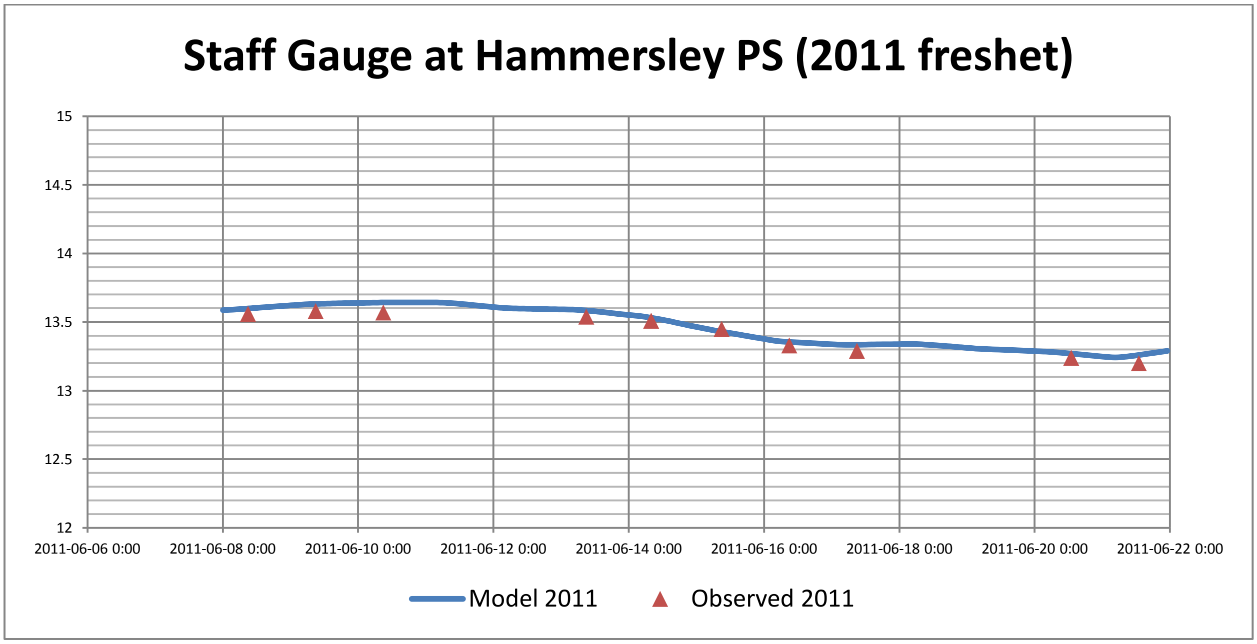
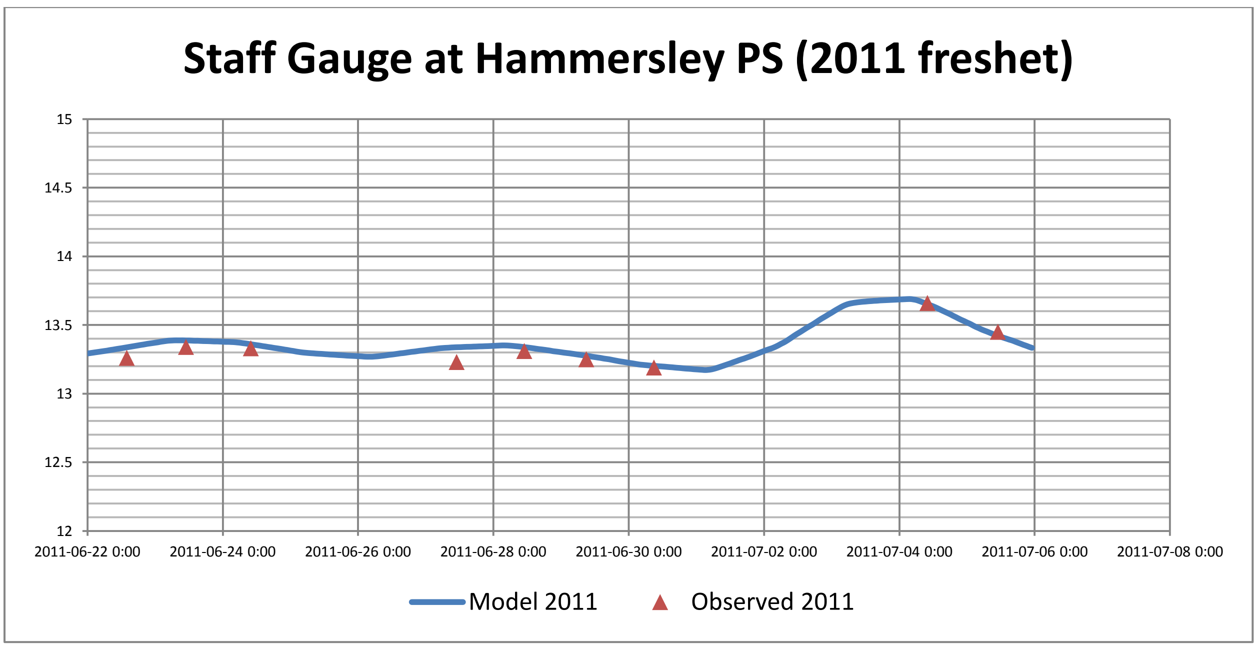

Staff Gauge at Carey Point (2011 freshet)
14
13.5
13
12.5
12
11.5
11
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 64

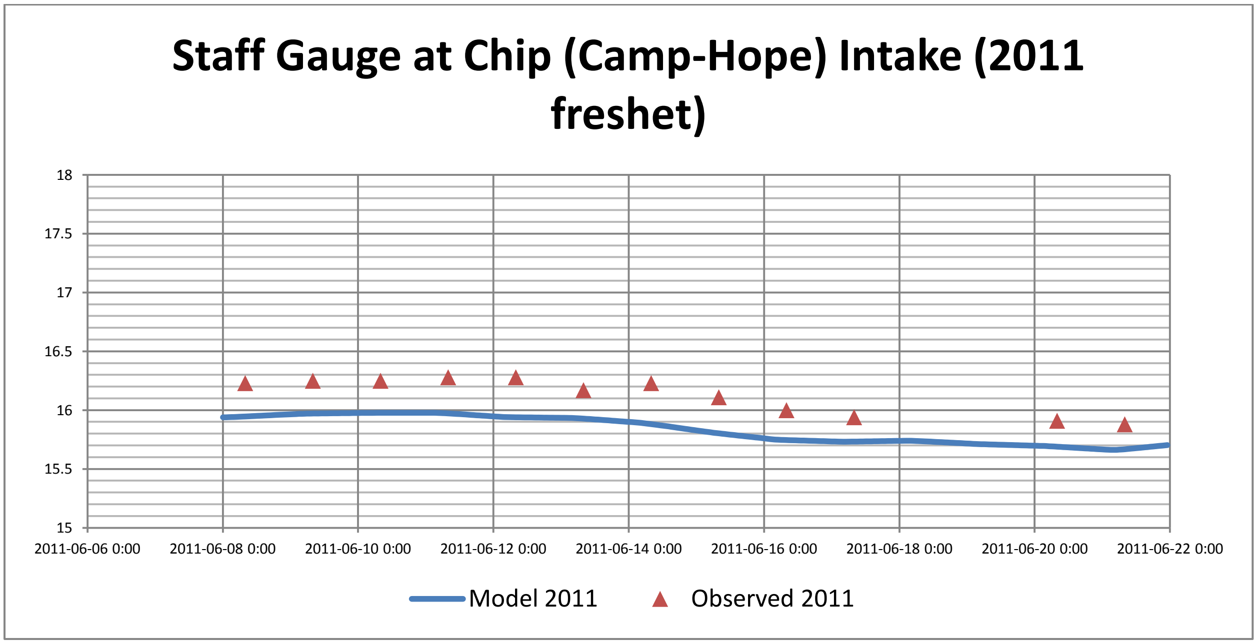


Staff Gauge at Hammersley PS (2011 freshet)
15
14.5
14
13.5
13
12.5
12
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

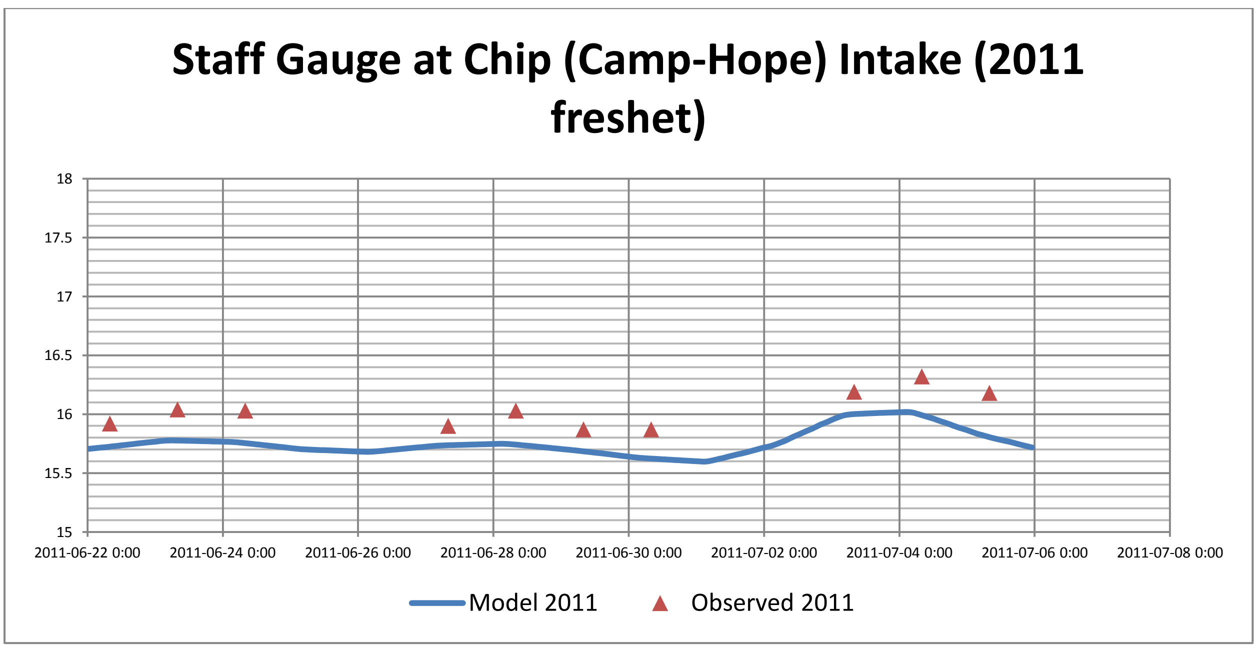


Staff Gauge at Hammersley PS (2011 freshet)
15
14.5
14
13.5
13
12.5
12
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 65

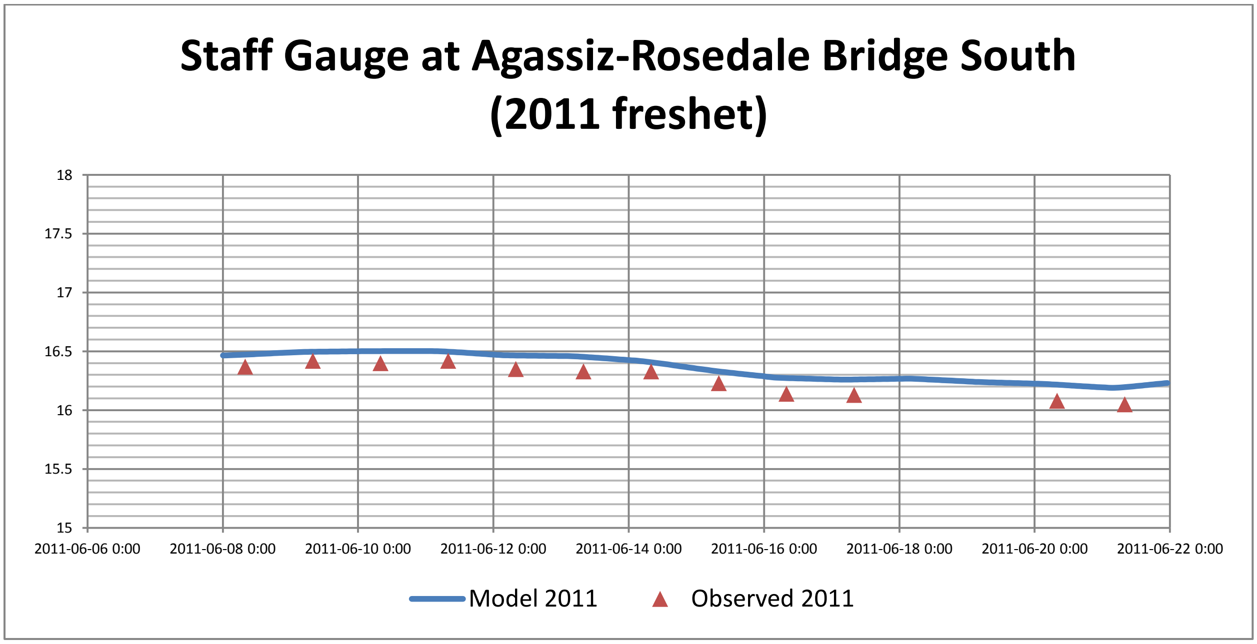


Staff Gauge at Chip (Camp-Hope) Intake (2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

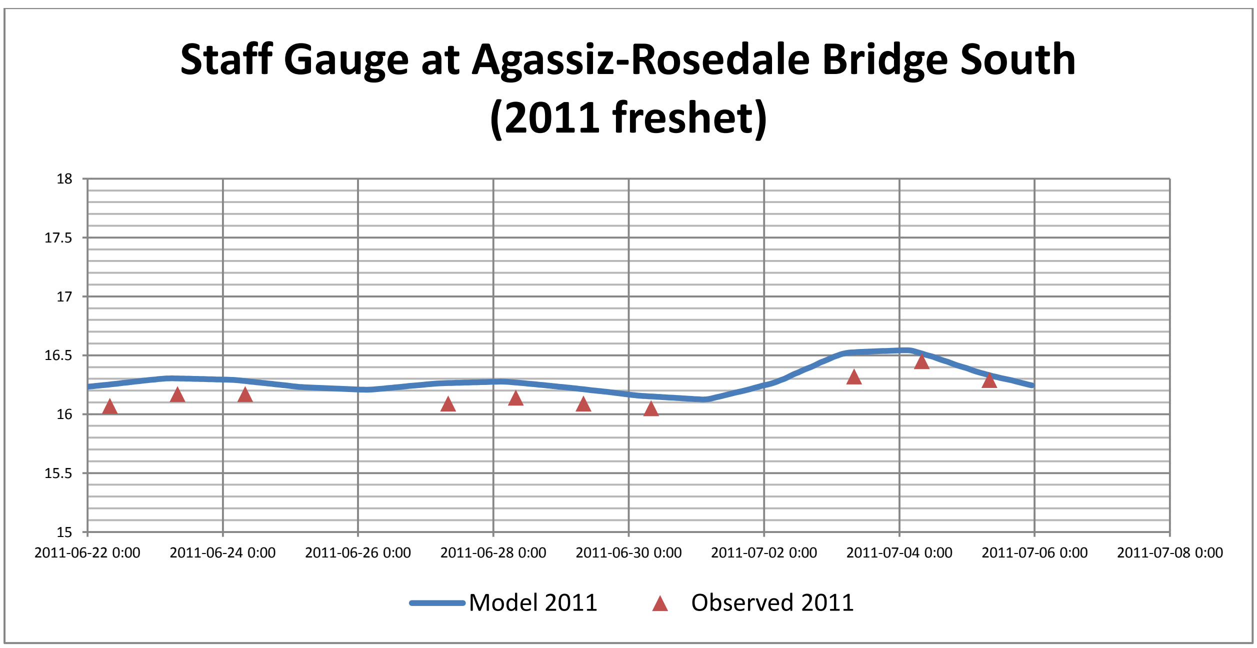


Staff Gauge at Chip (Camp-Hope) Intake (2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 66

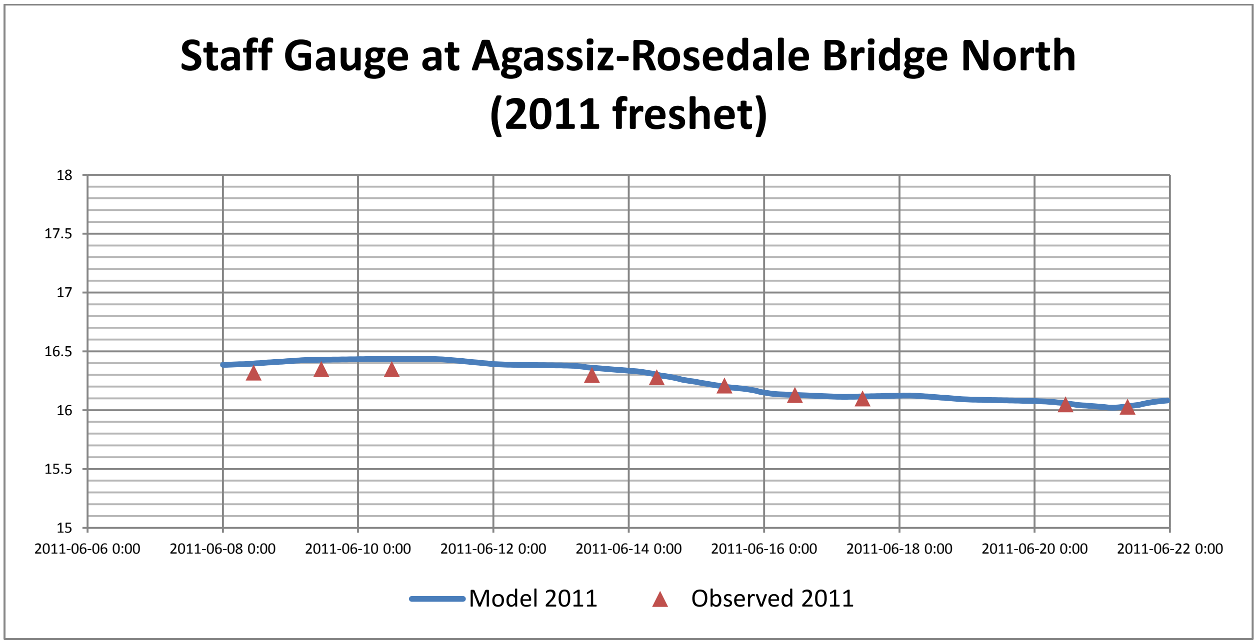


Staff Gauge at Agassiz-Rosedale Bridge South
(2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011



Staff Gauge at Agassiz-Rosedale Bridge South
(2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 67


Staff Gauge at Agassiz-Rosedale Bridge North (2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

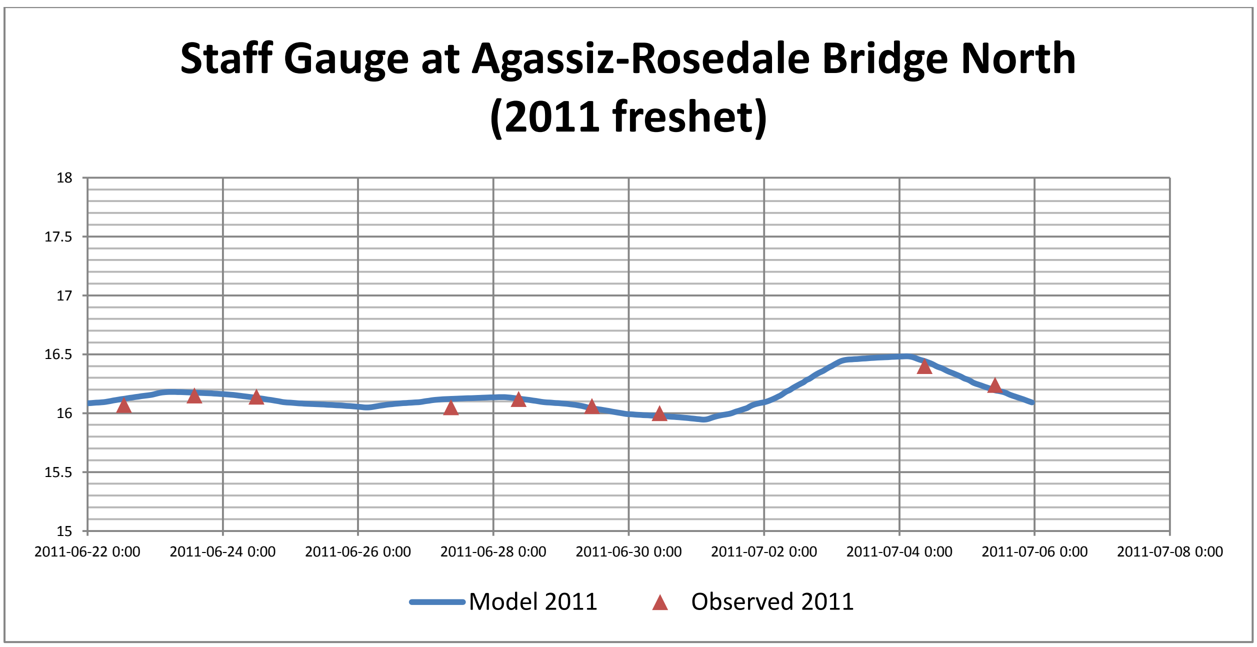
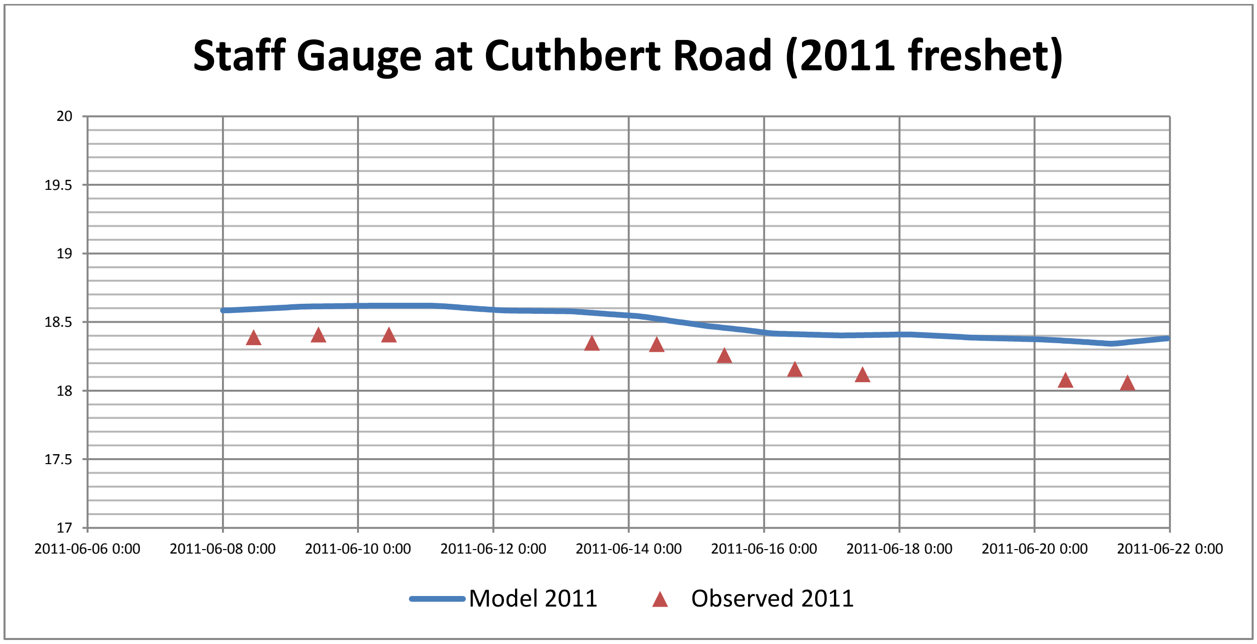
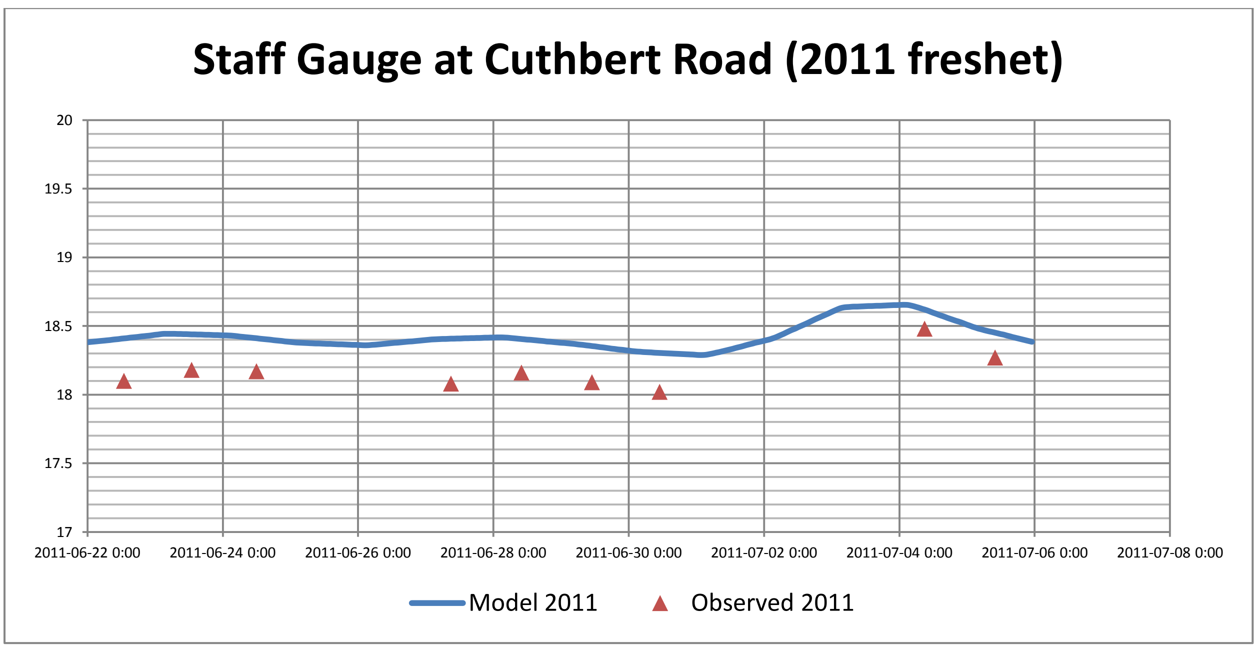

Staff Gauge at Agassiz-Rosedale Bridge North (2011 freshet)
18
17.5
17
16.5
16
15.5
15
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 68

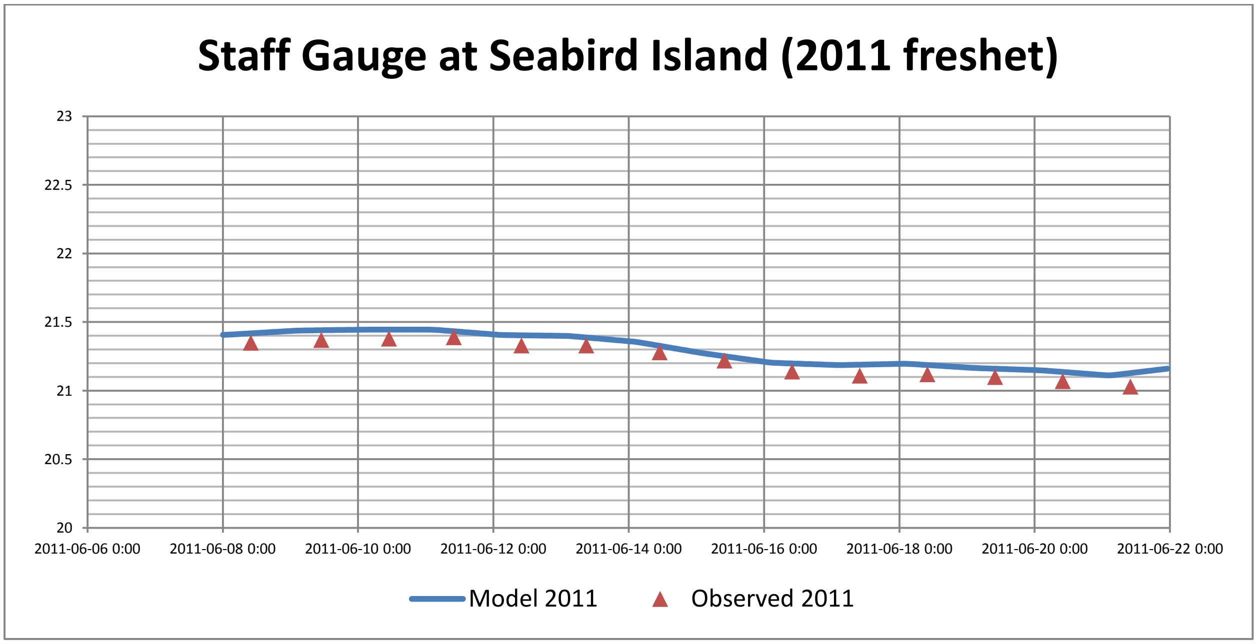


Staff Gauge at Cuthbert Road (2011 freshet)
20
19.5
19
18.5
18
17.5
17
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

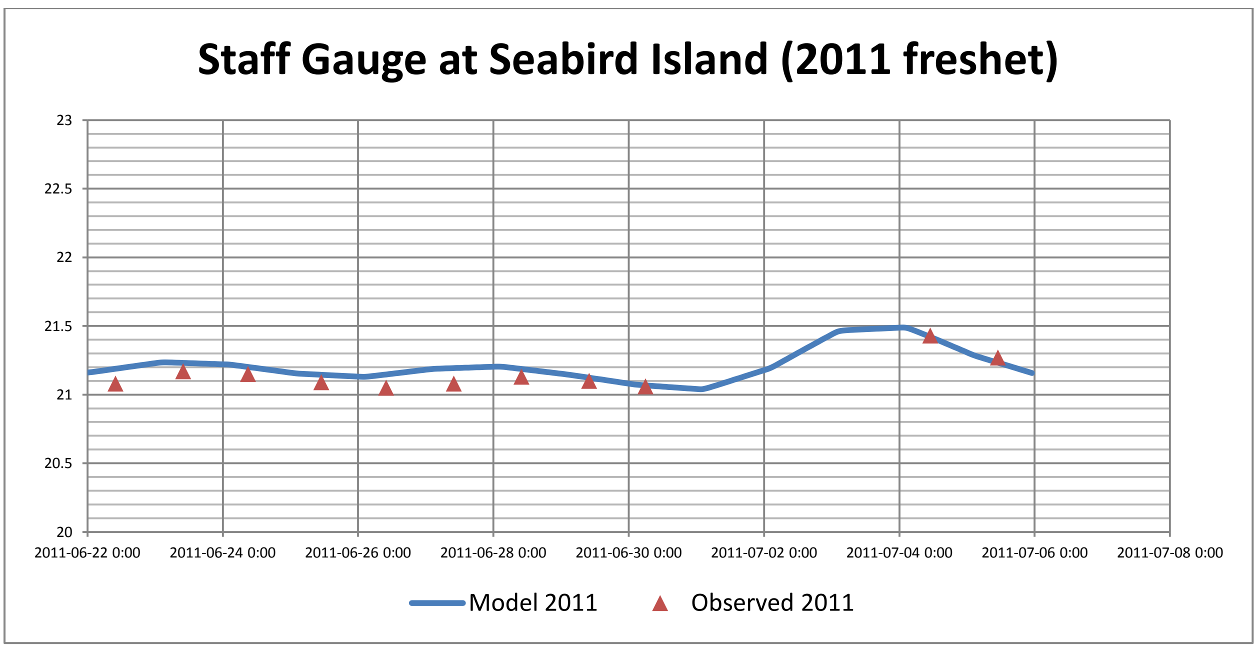


Staff Gauge at Cuthbert Road (2011 freshet)
20
19.5
19
18.5
18
17.5
17
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 69

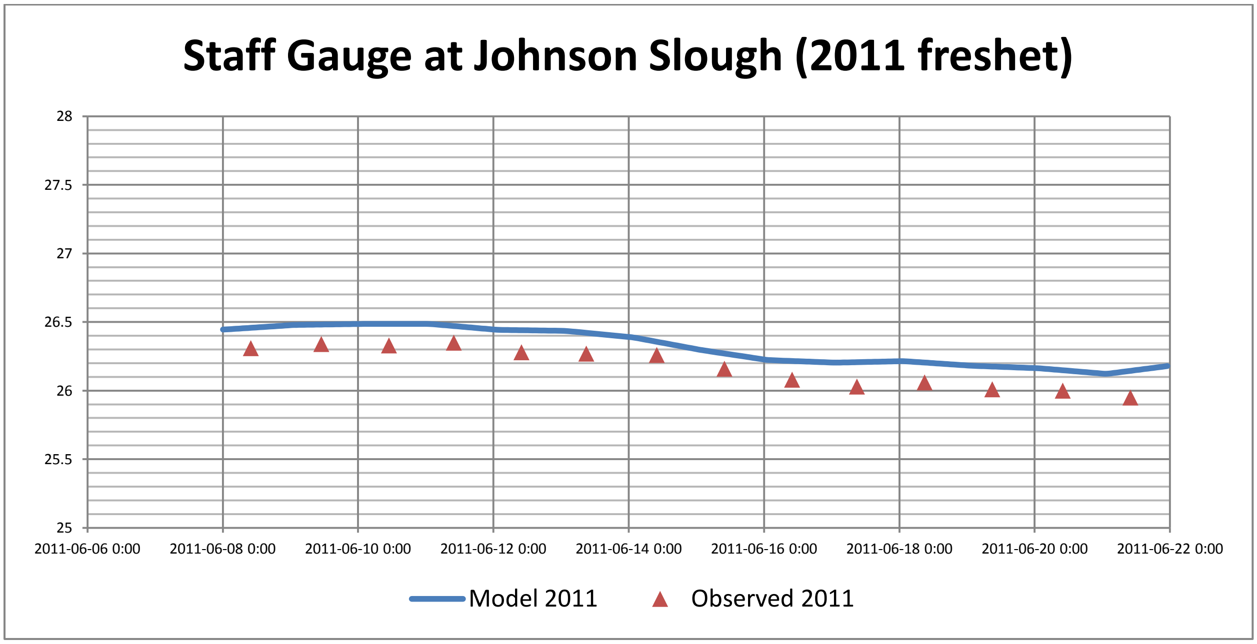


Staff Gauge at Seabird Island (2011 freshet)
23
22.5
22
21.5
21
20.5
20
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

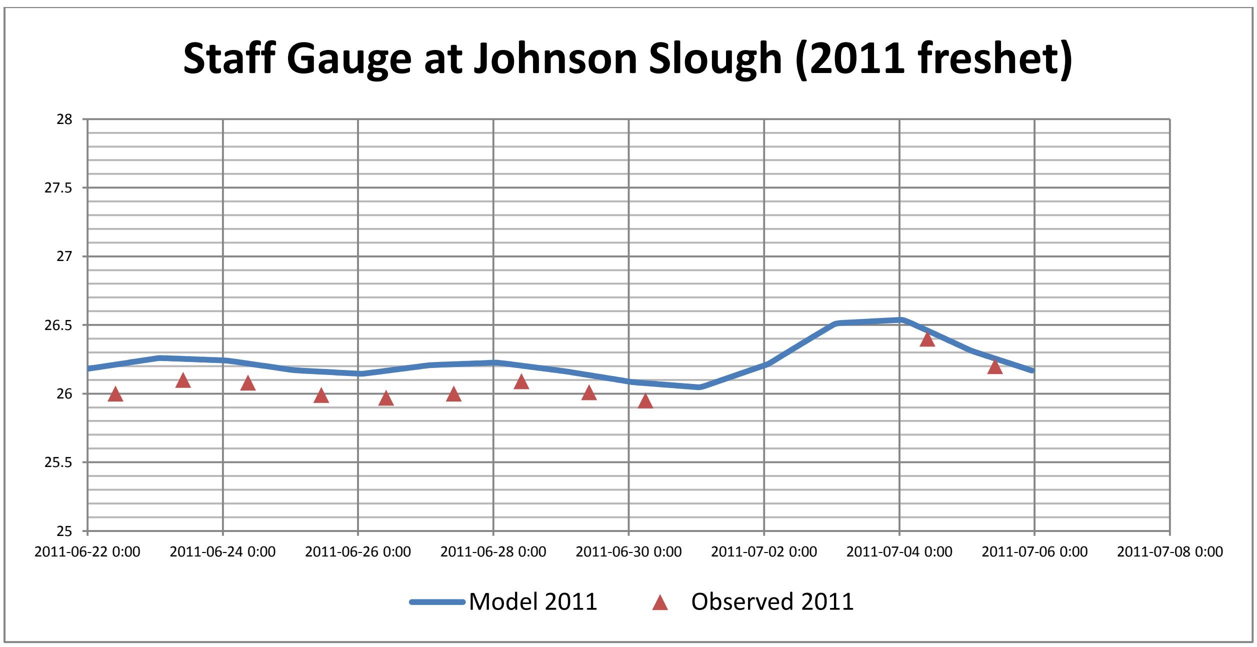


Staff Gauge at Seabird Island (2011 freshet)
23
22.5
22
21.5
21
20.5
20
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 70

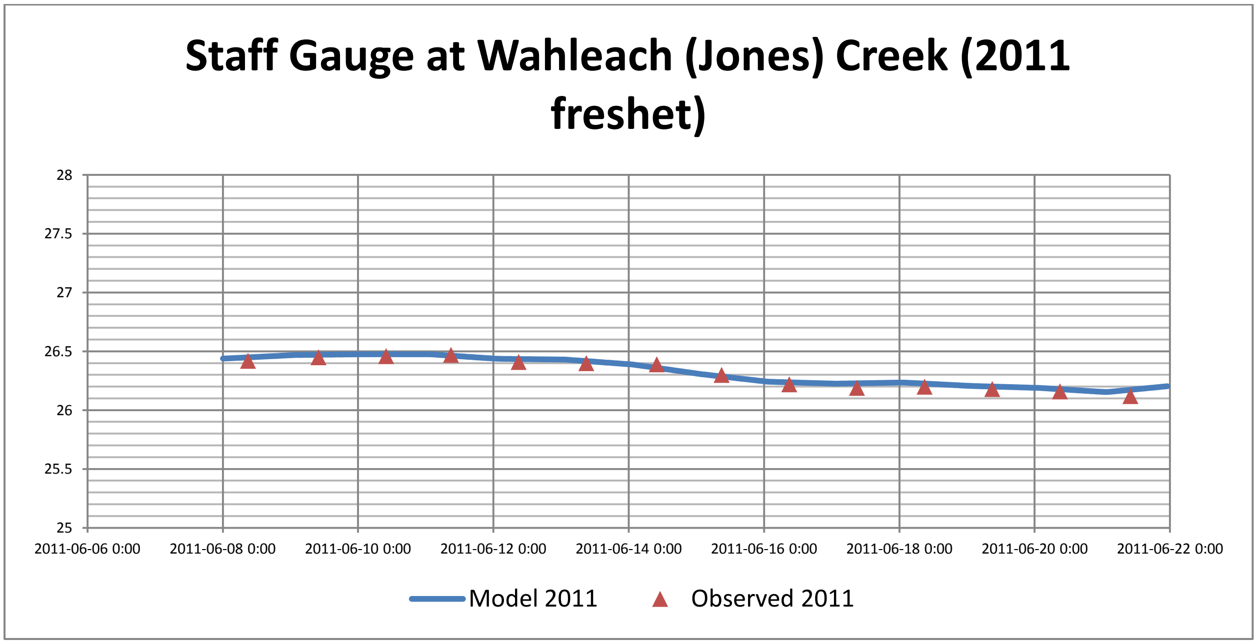


Staff Gauge at Johnson Slough (2011 freshet)
28
27.5
27
26.5
26
25.5
25
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

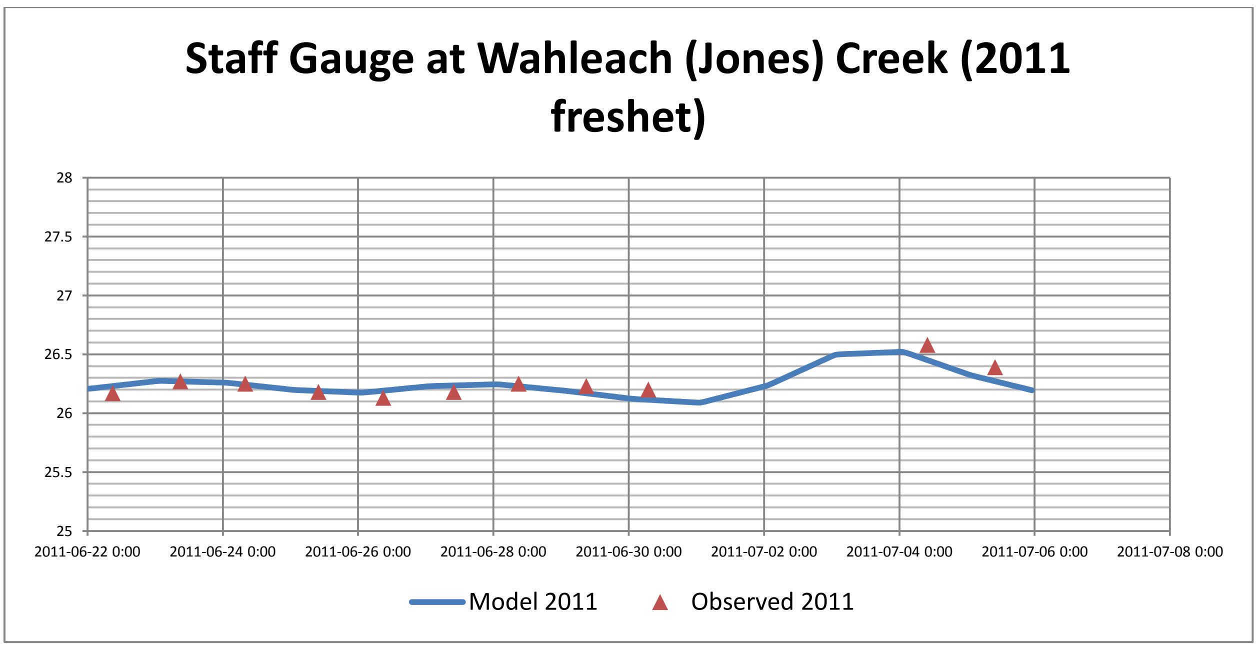


Staff Gauge at Johnson Slough (2011 freshet)
28
27.5
27
26.5
26
25.5
25
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 71

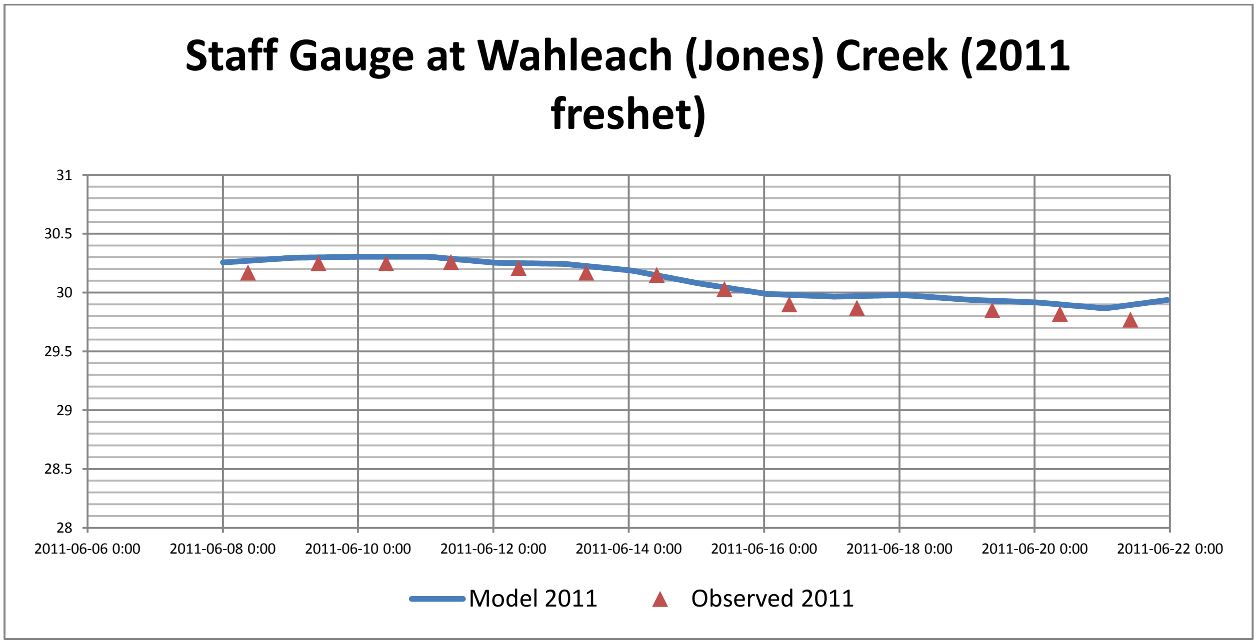


Staff Gauge at Wahleach (Jones) Creek (2011 freshet)
28
27.5
27
26.5
26
25.5
25
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011



Staff Gauge at Wahleach (Jones) Creek (2011 freshet)
28
27.5
27
26.5
26
25.5
25
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 72


Staff Gauge at Wahleach (Jones) Creek (2011 freshet)
31
30.5
30
29.5
29
28.5
28
2011-06-06 0:00
2011-06-08 0:00
2011-06-10 0:00
2011-06-12 0:00
2011-06-14 0:00
2011-06-16 0:00
2011-06-18 0:00
2011-06-20 0:00
2011-06-22 0:00
Model 2011
Observed 2011

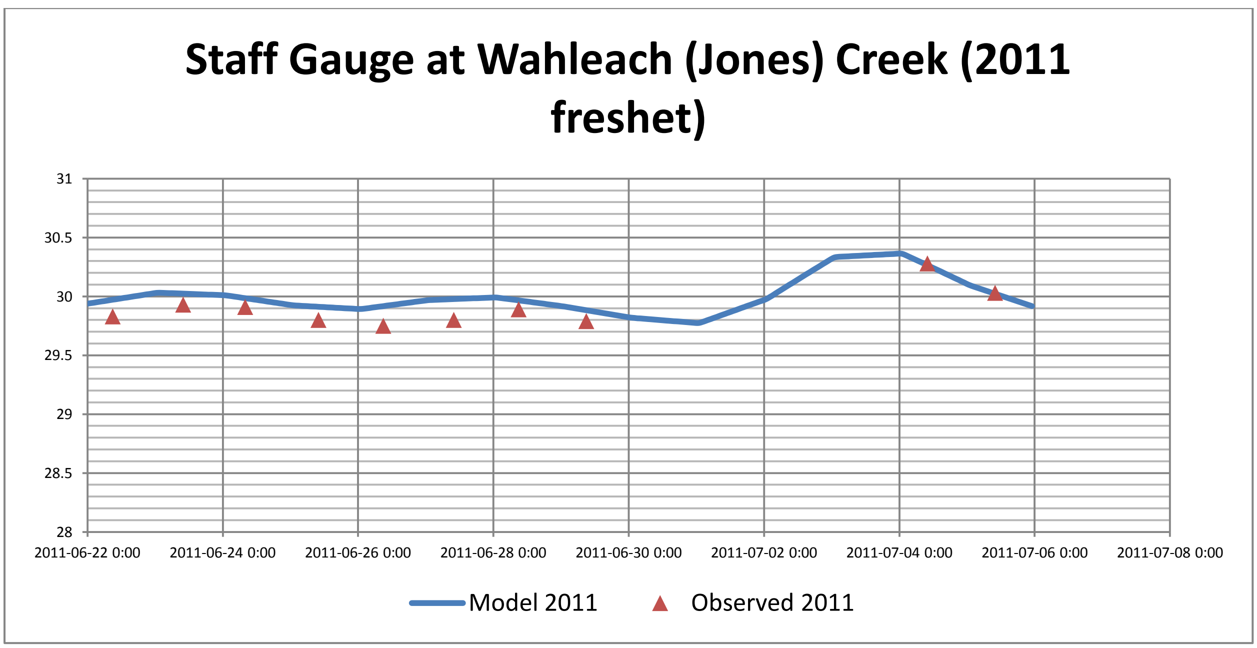

Staff Gauge at Wahleach (Jones) Creek (2011 freshet)
31
30.5
30
29.5
29
28.5
28
2011-06-22 0:00
2011-06-24 0:00
2011-06-26 0:00
2011-06-28 0:00
2011-06-30 0:00
2011-07-02 0:00
2011-07-04 0:00
2011-07-06 0:00
2011-07-08 0:00
Model 2011
Observed 2011

Figure 73

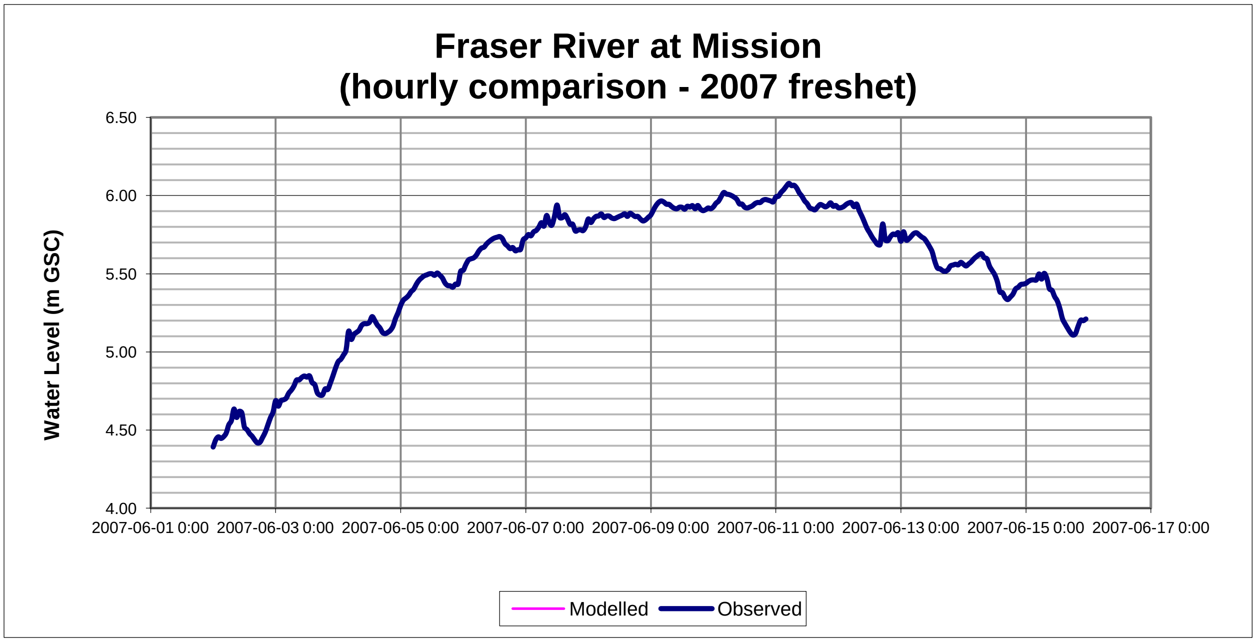


Figure 74

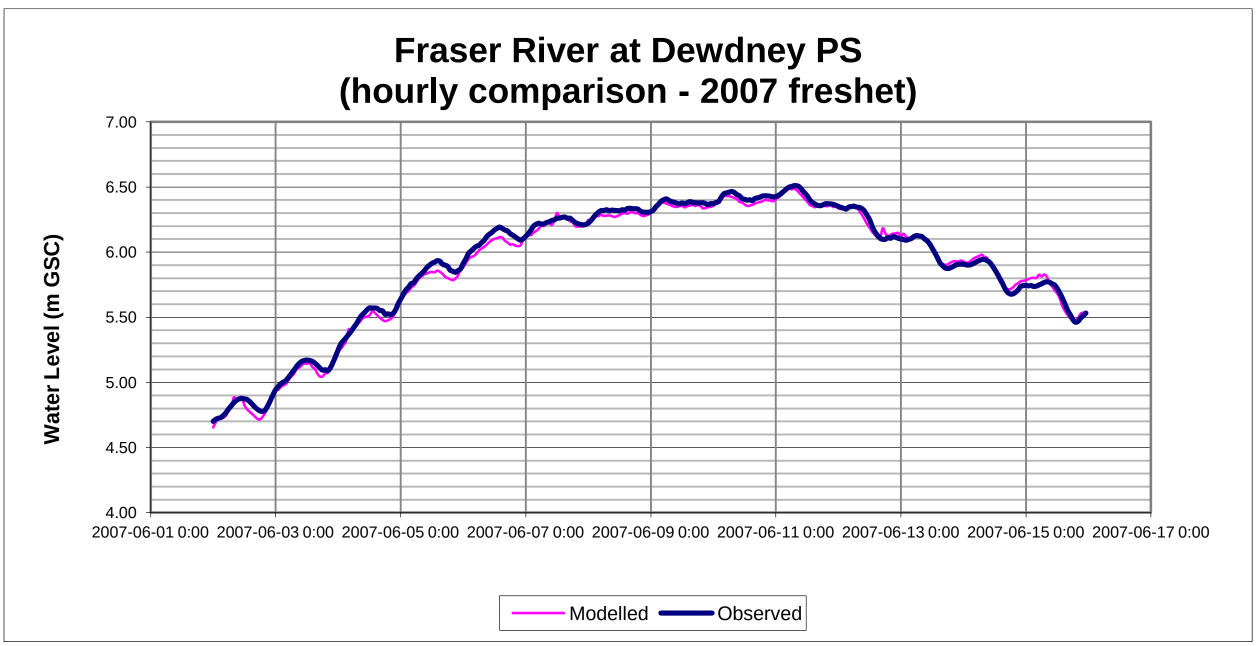


Figure 75

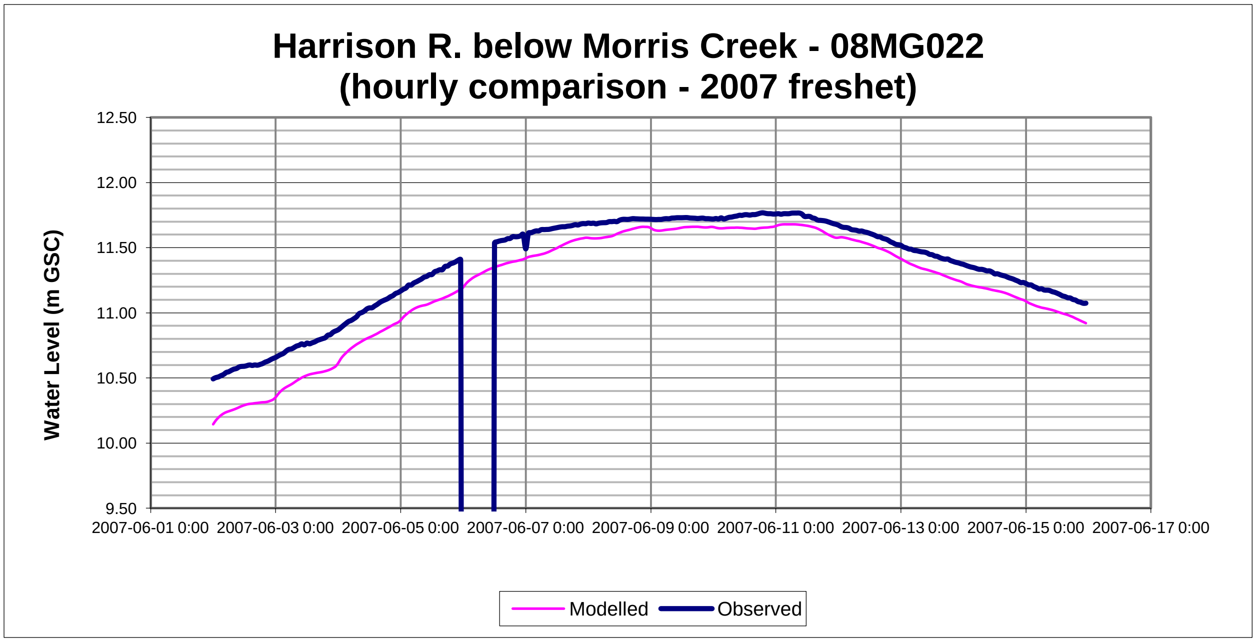


Figure 76

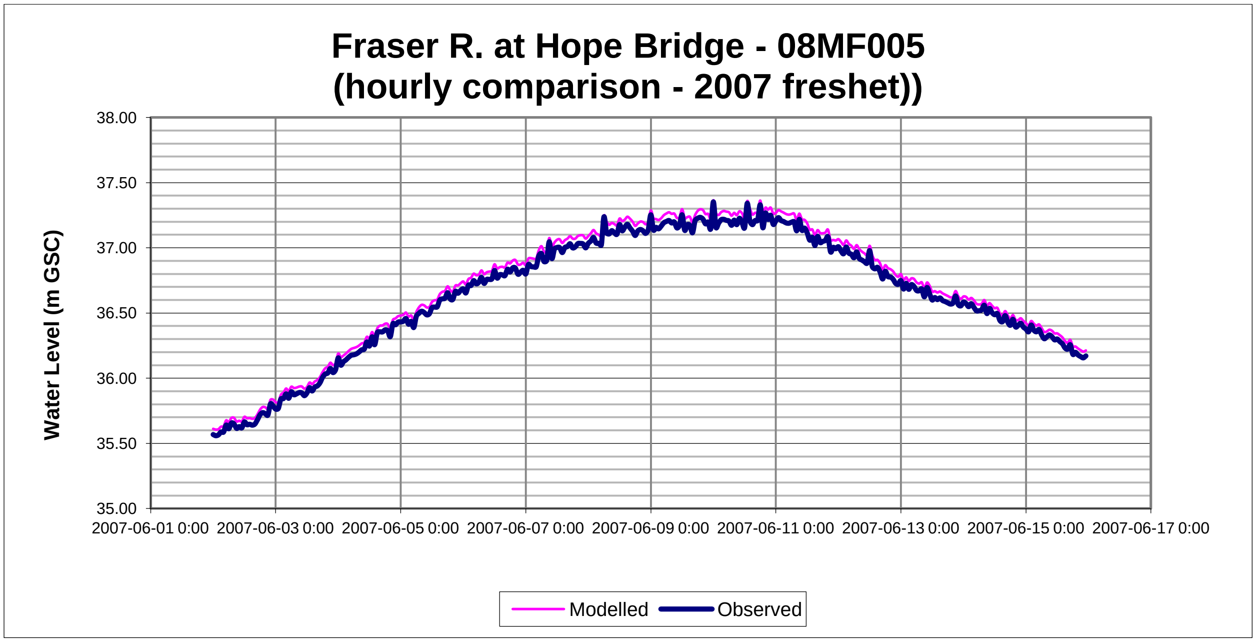


Figure 77

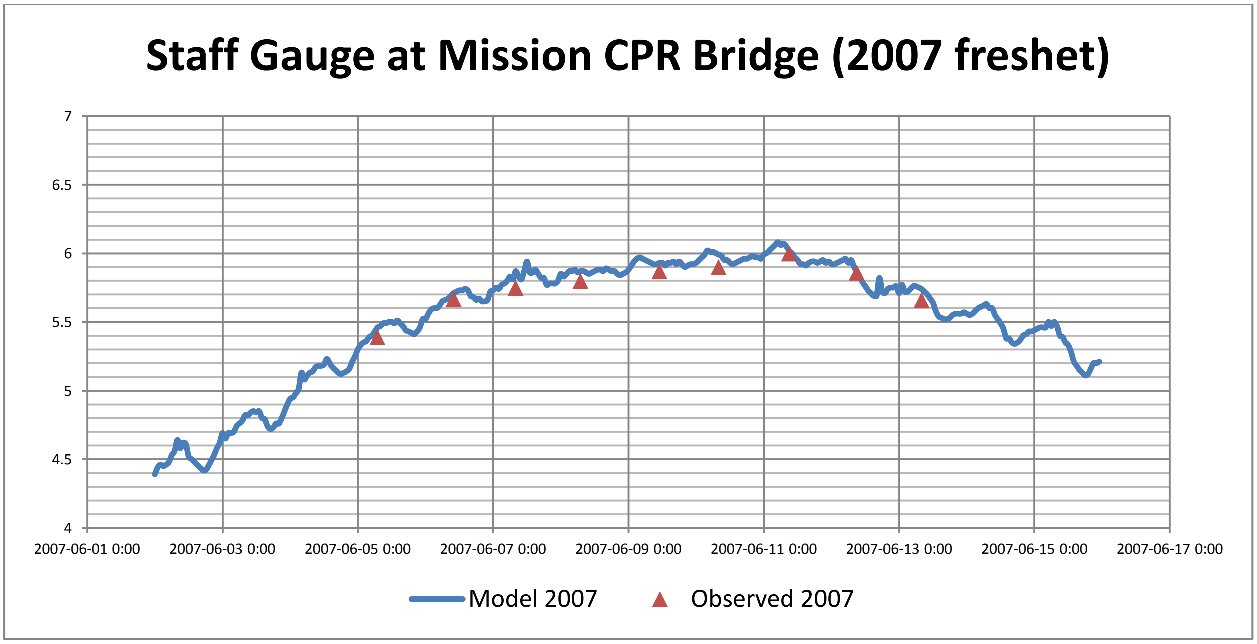


Figure 78

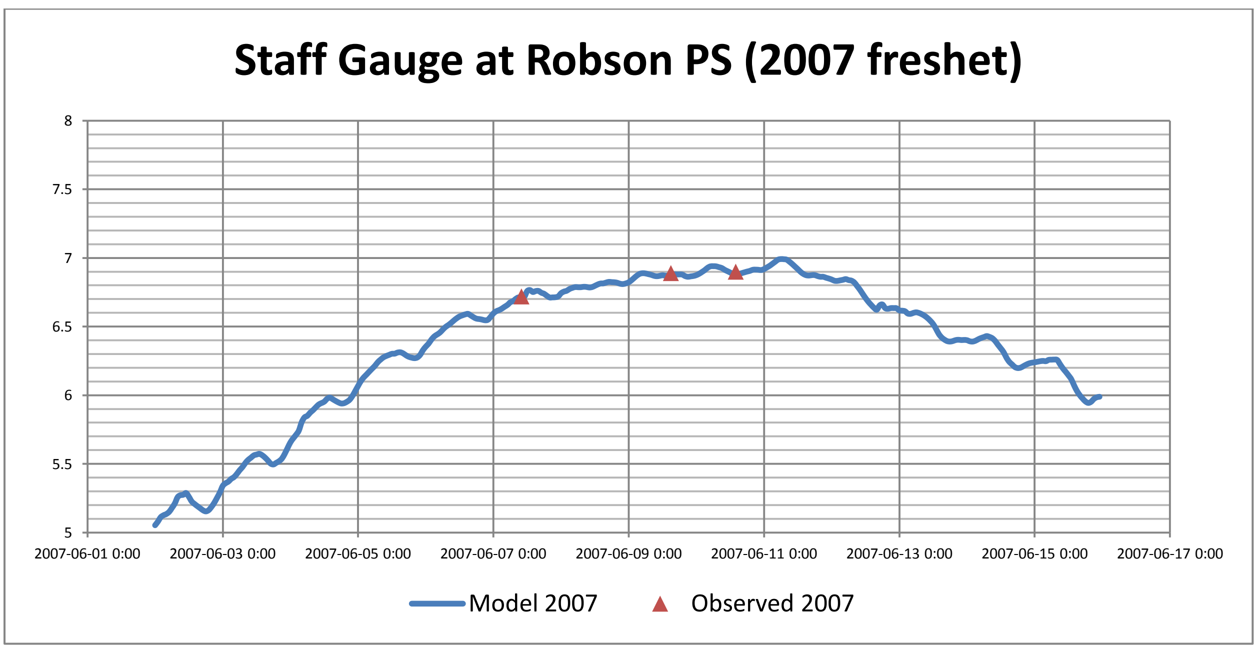


Figure 79

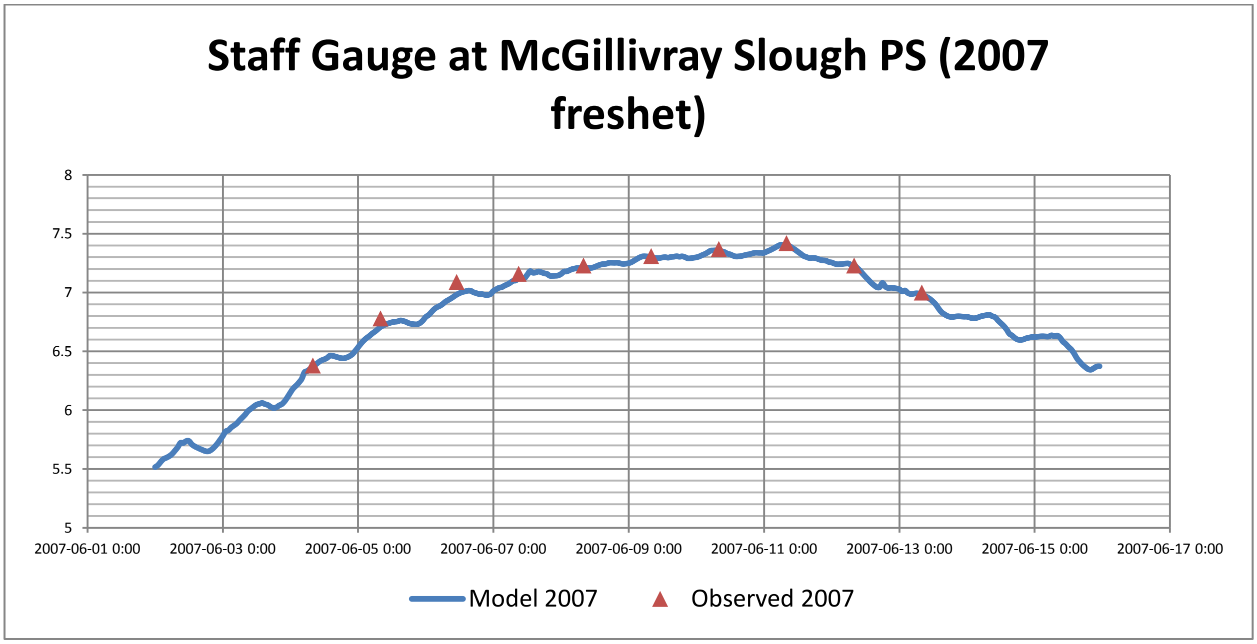


Figure 80

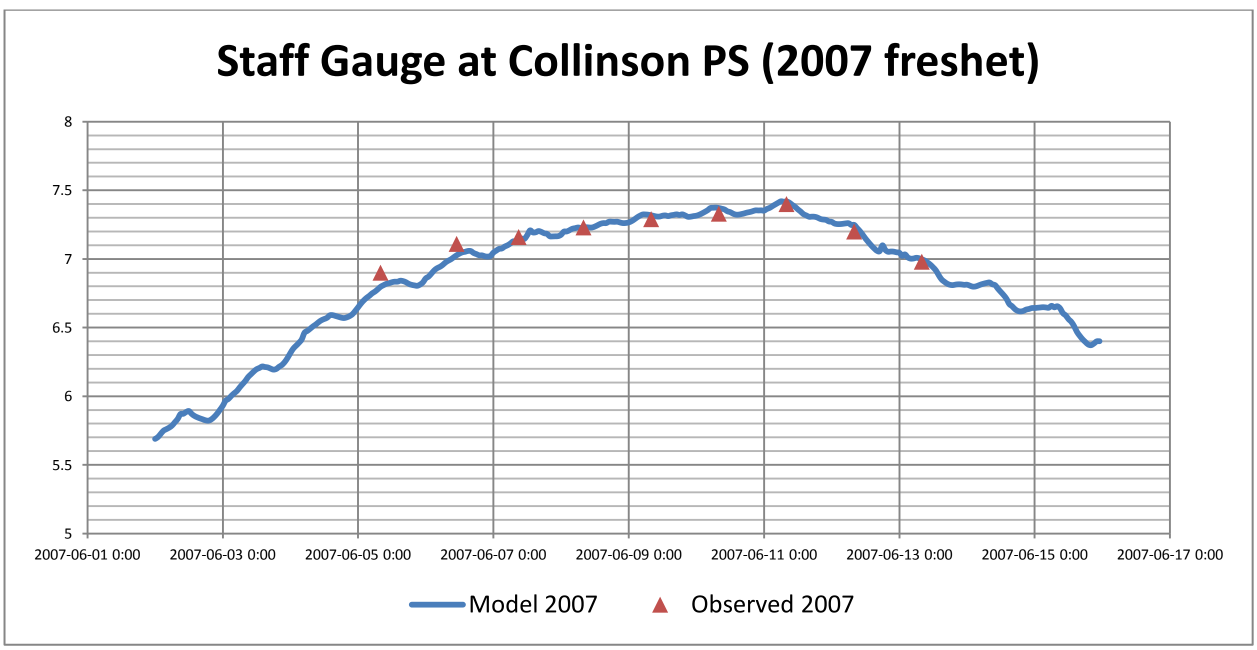


Figure 81

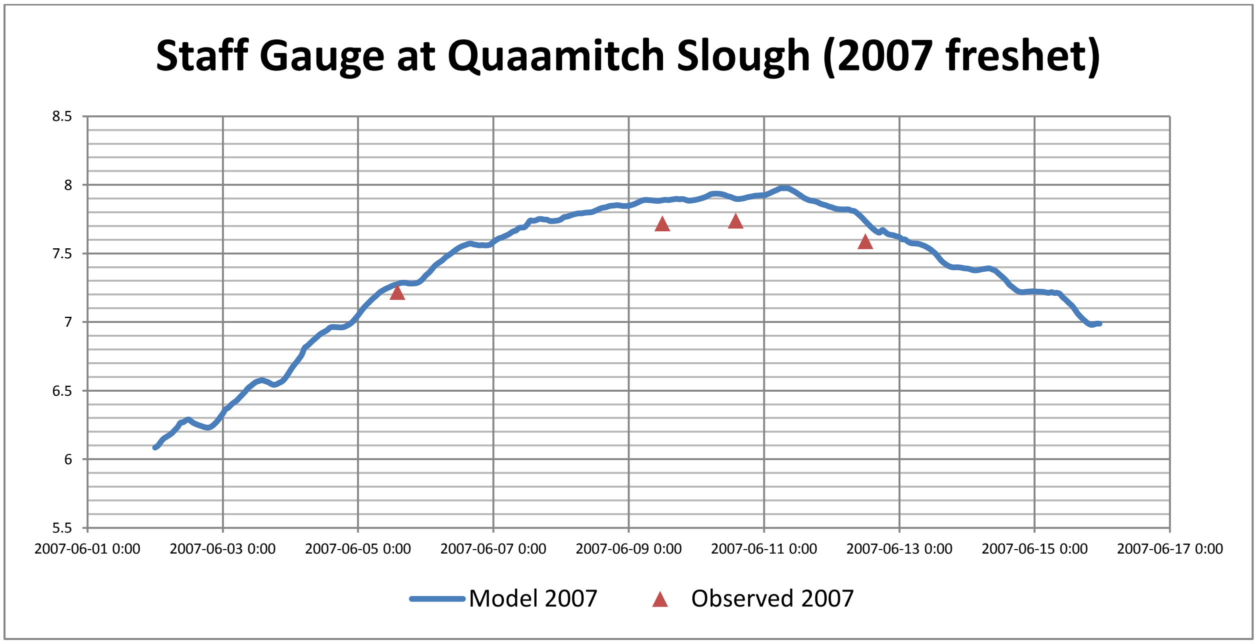


Figure 82

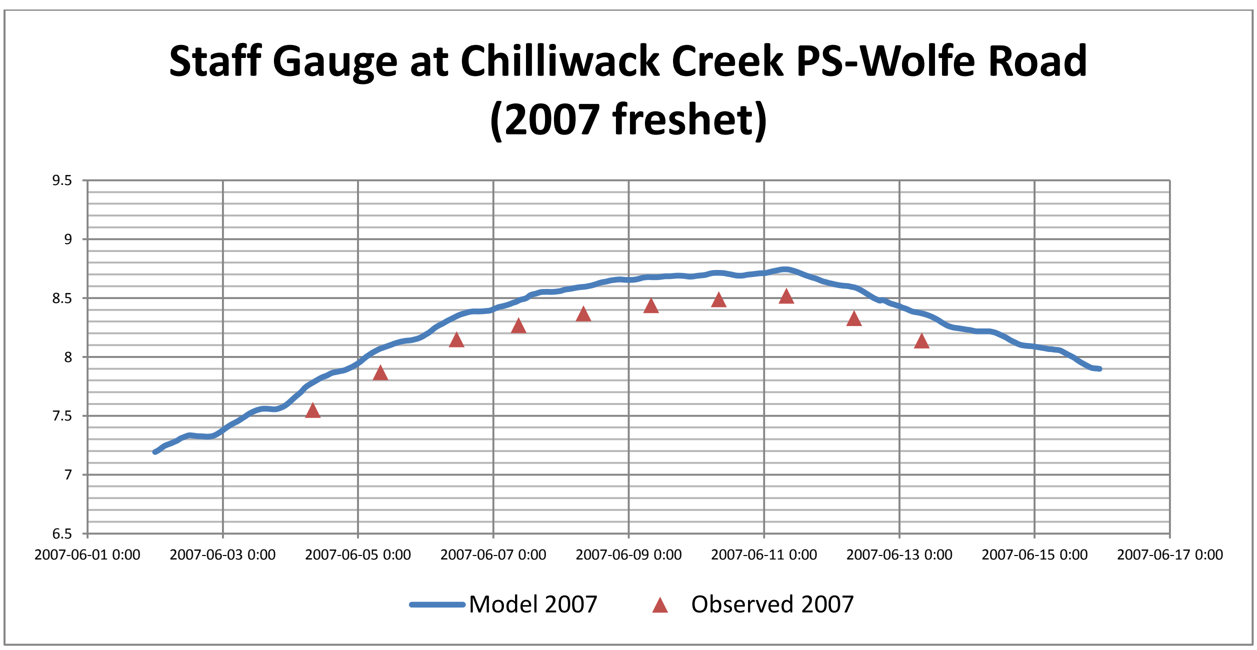


Figure 83

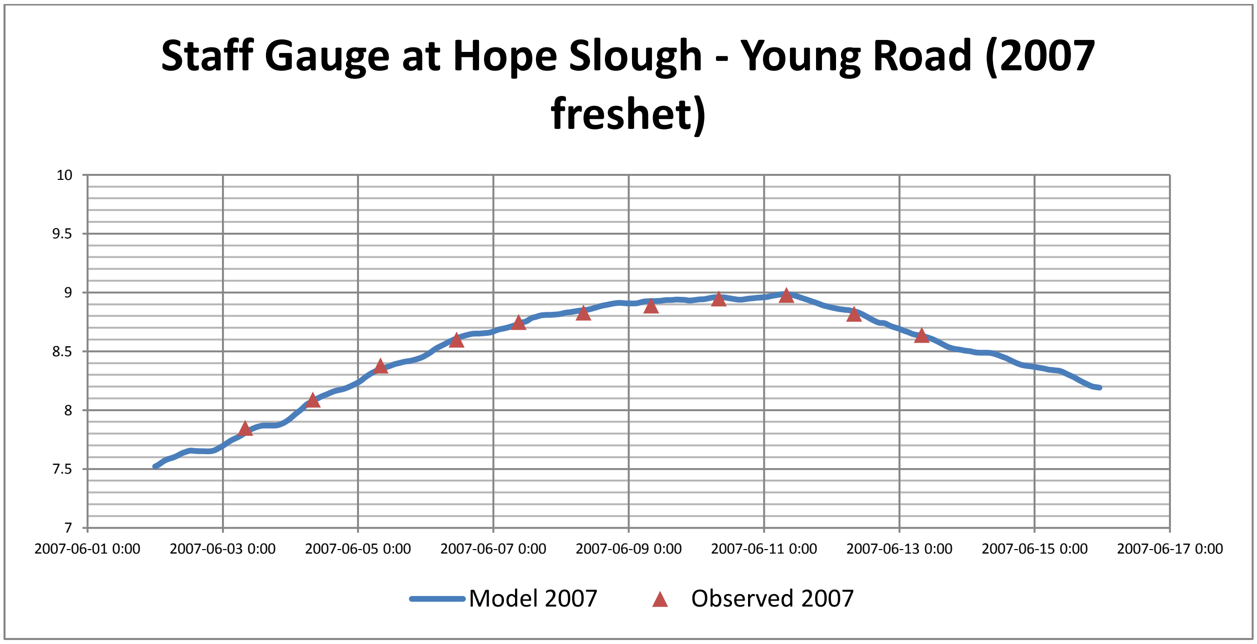


Figure 84

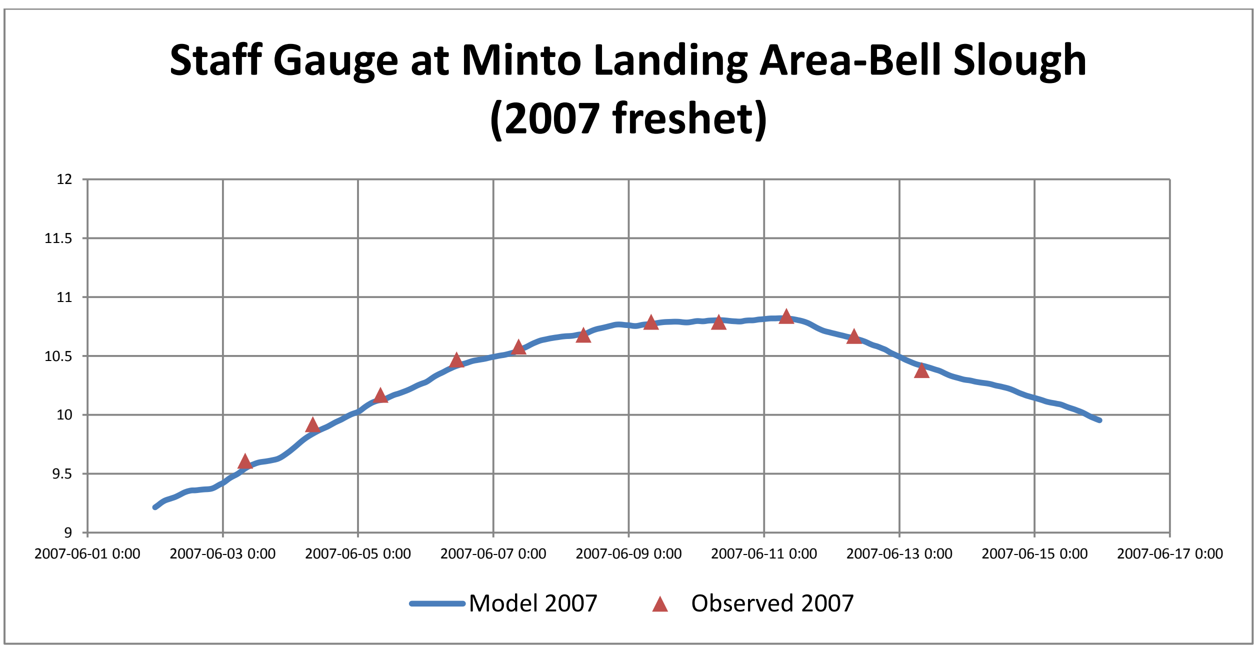


Figure 85

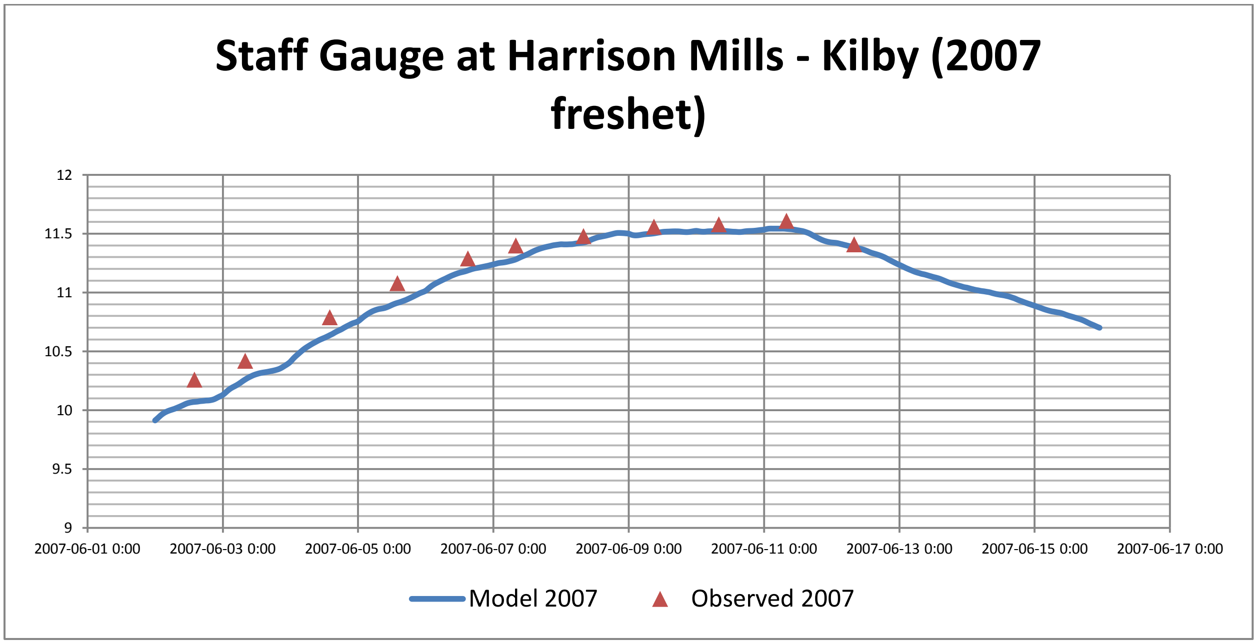


Figure 86

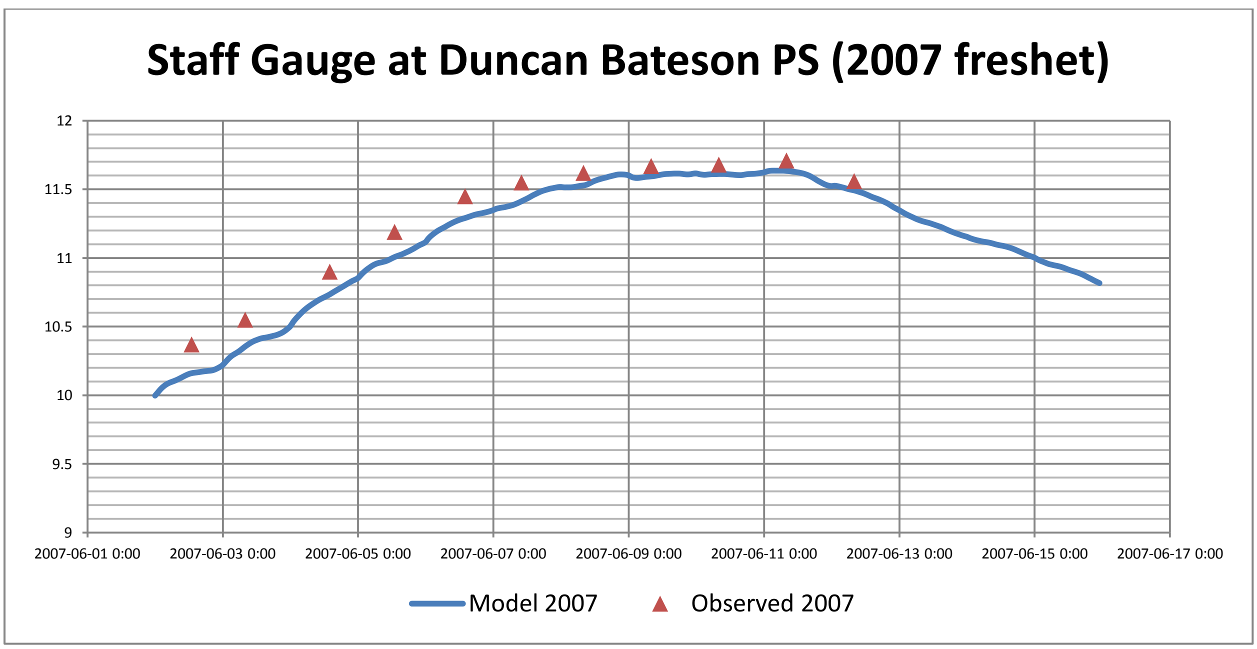


Figure 87

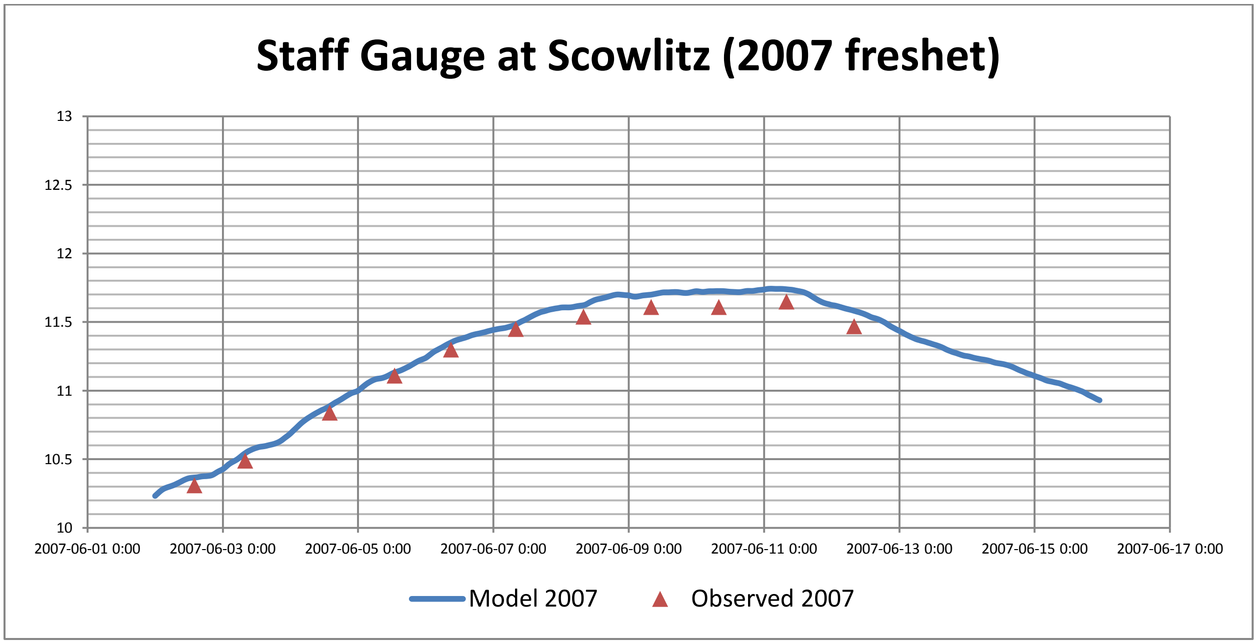


Figure 88

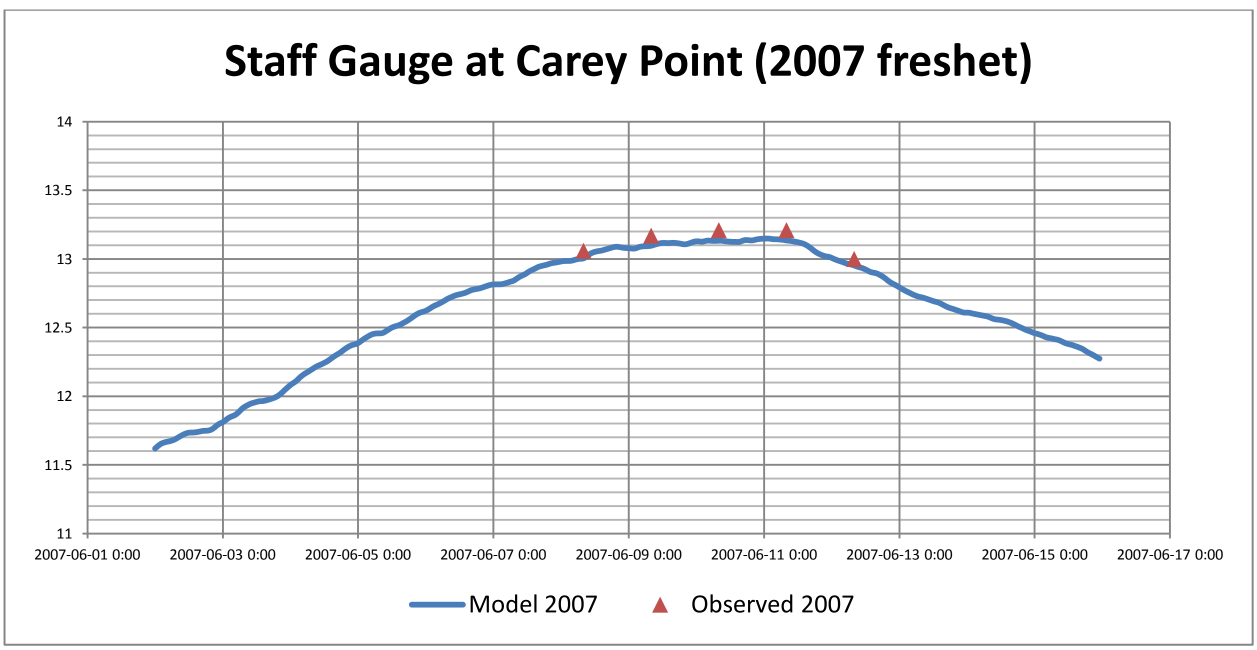


Figure 89

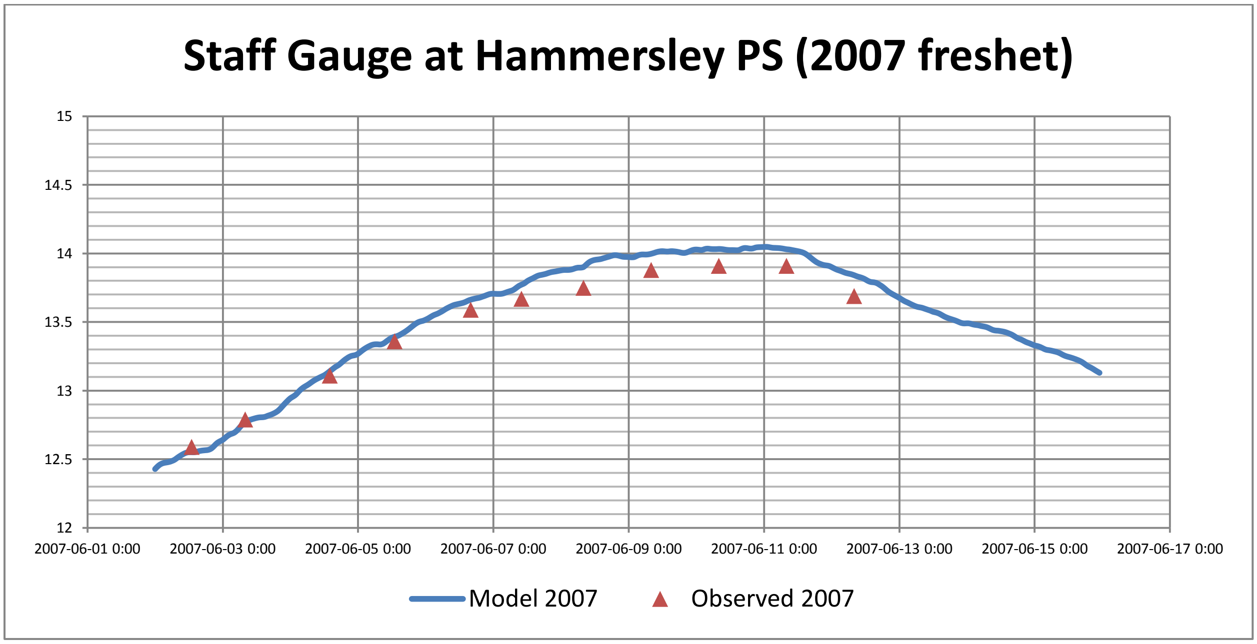


Figure 90

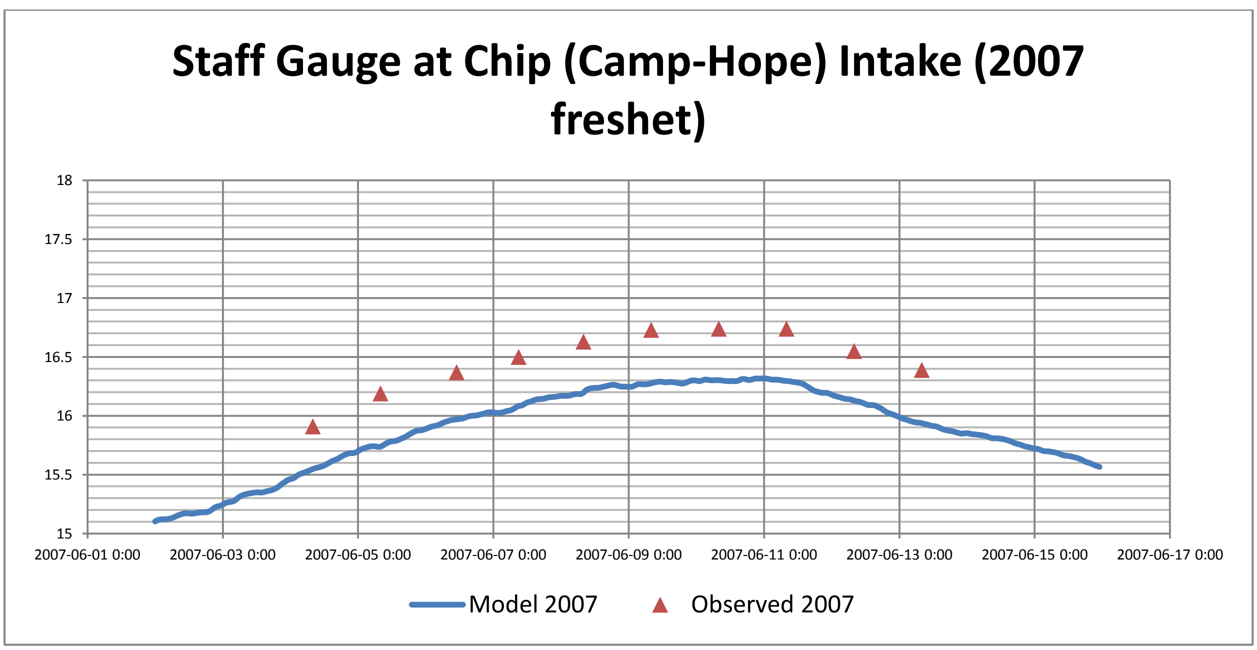


Figure 91

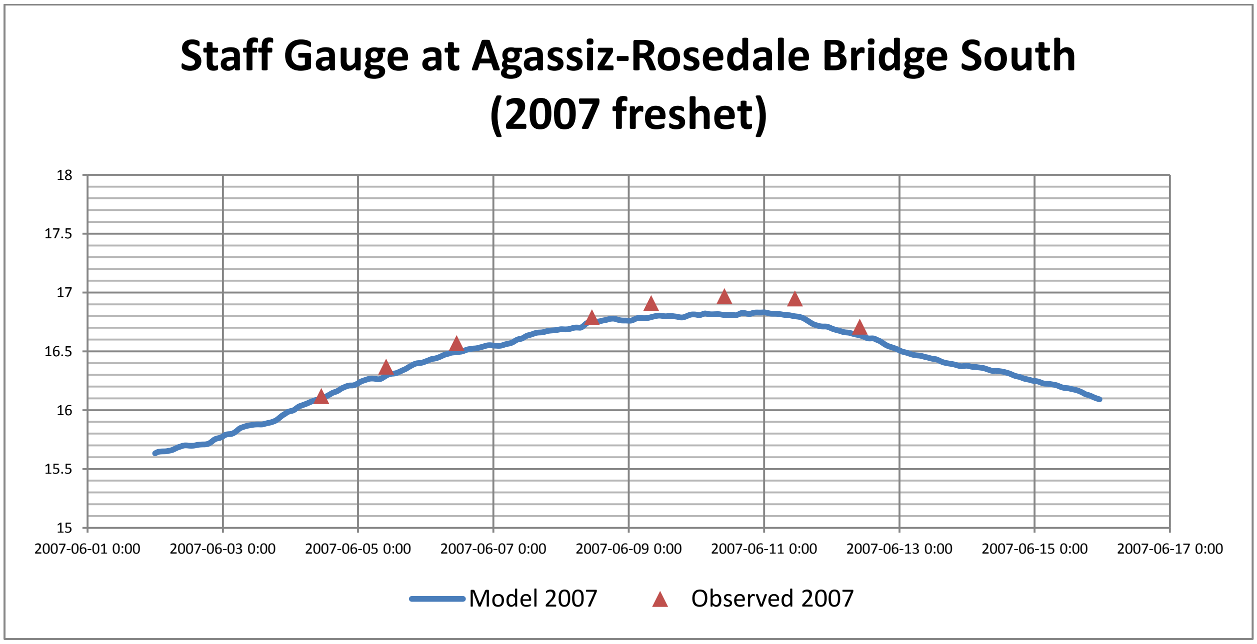


Figure 92

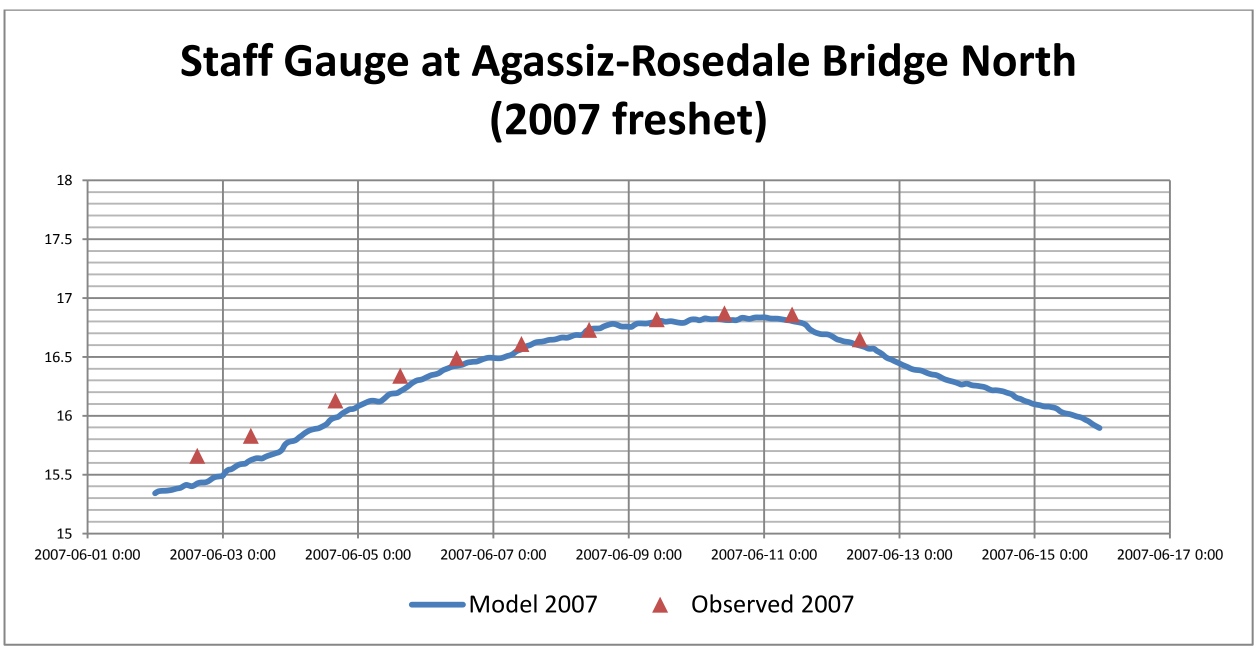


Figure 93

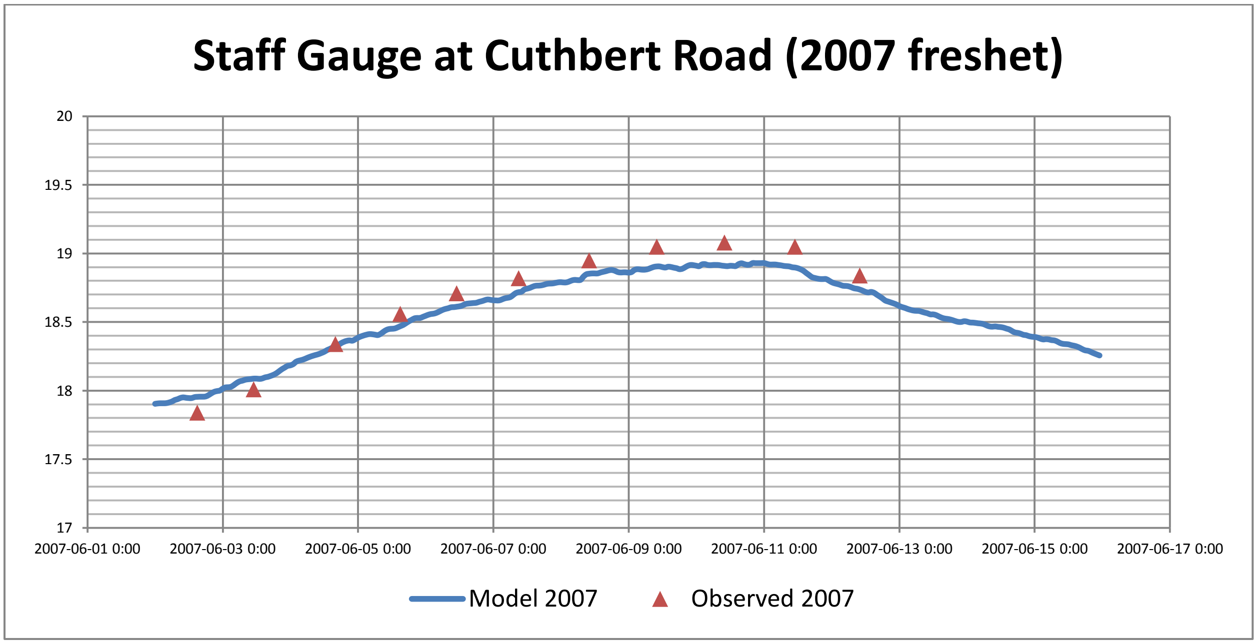


Figure 94

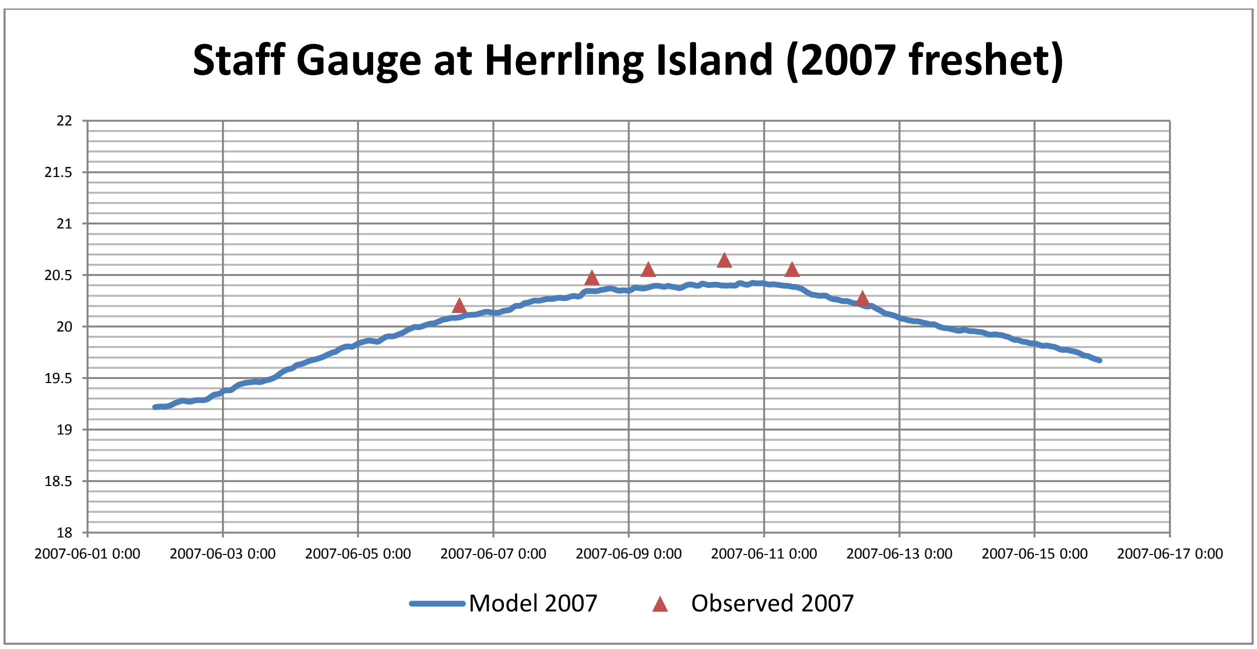


Figure 95

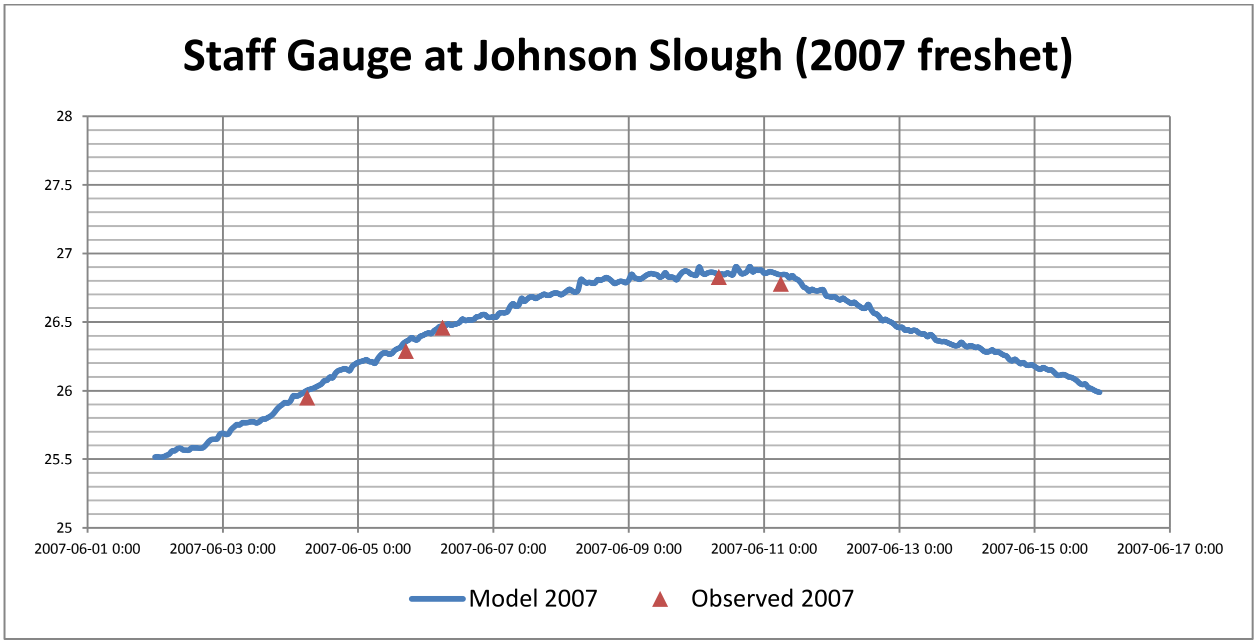
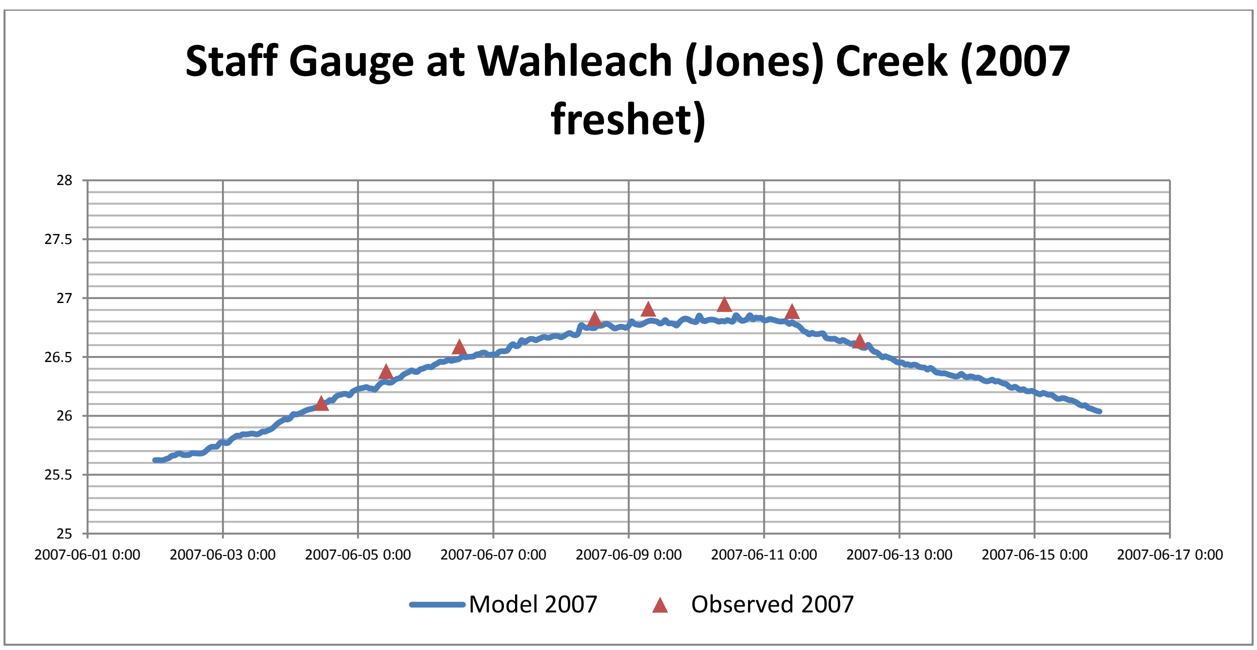
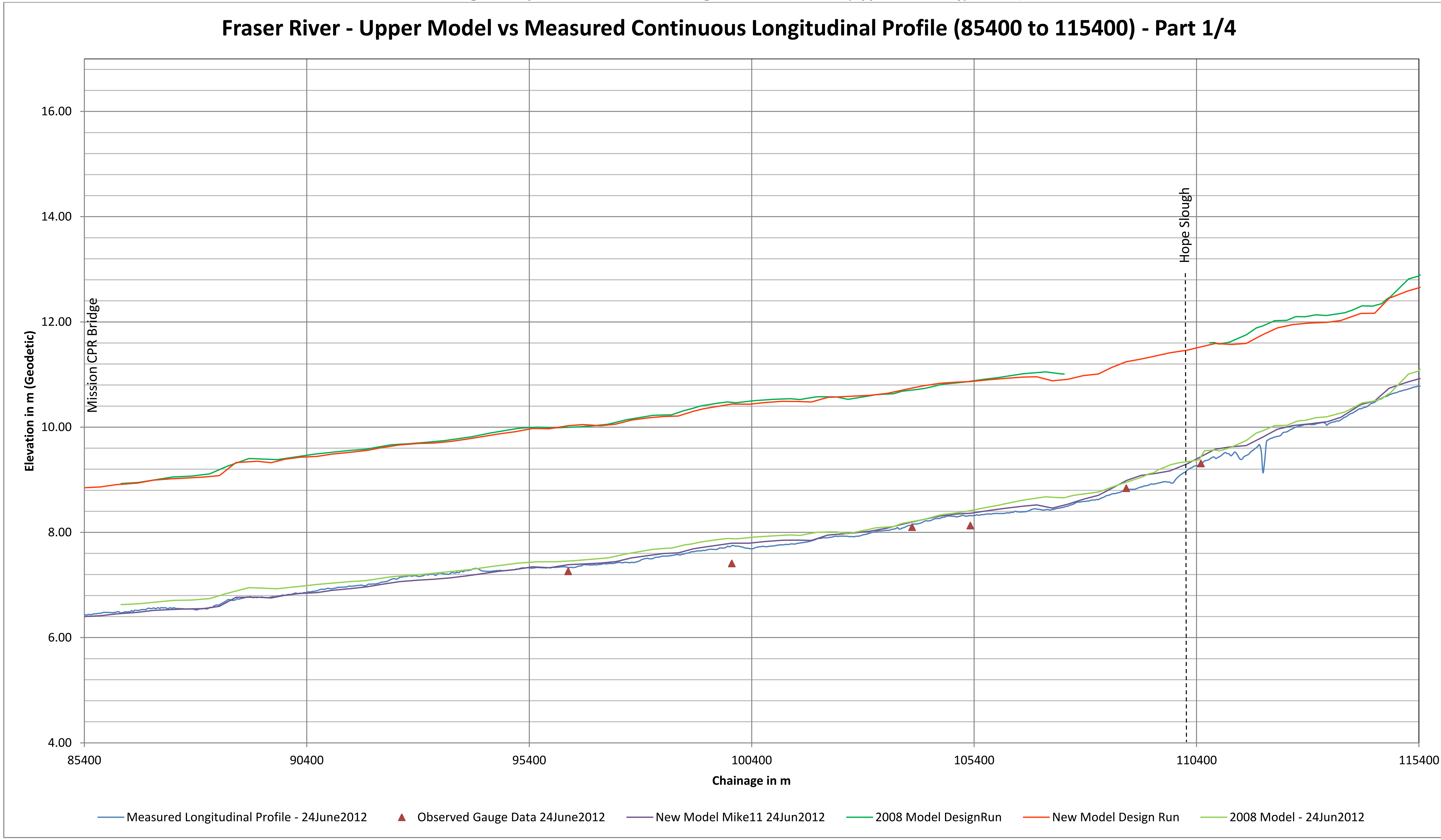


Figure 96

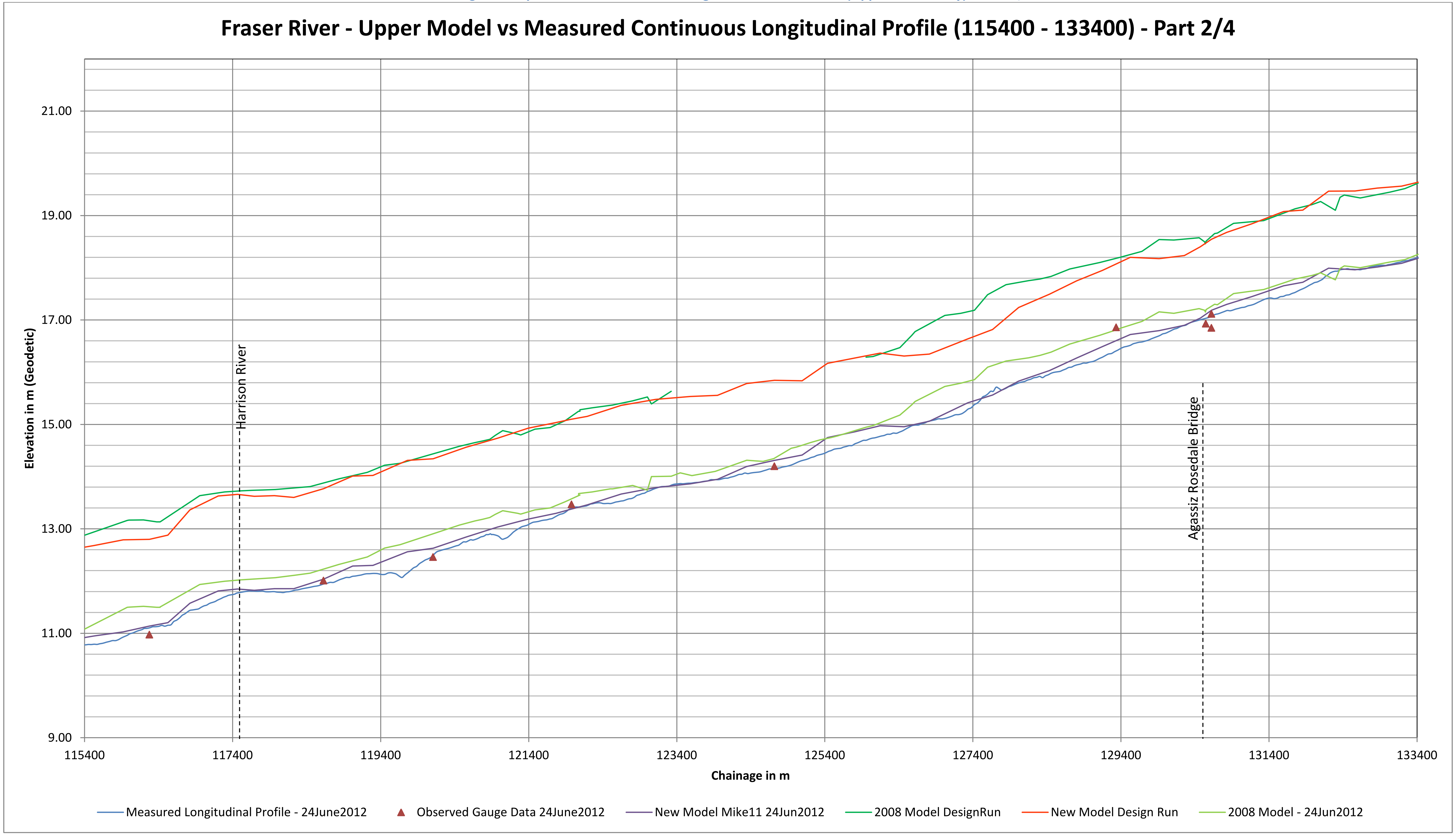


DRAWINGS

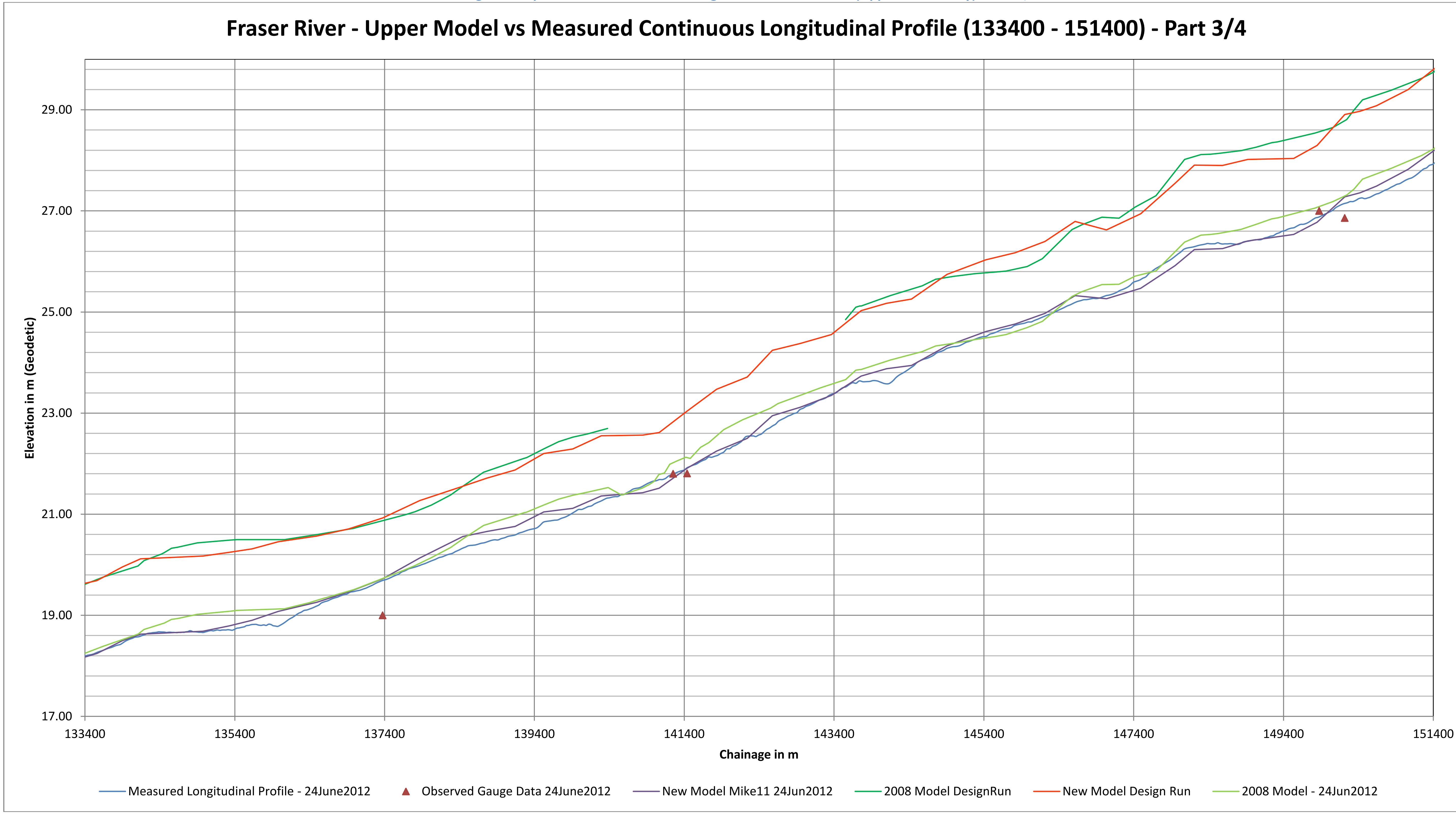
Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only) – Part 1/4



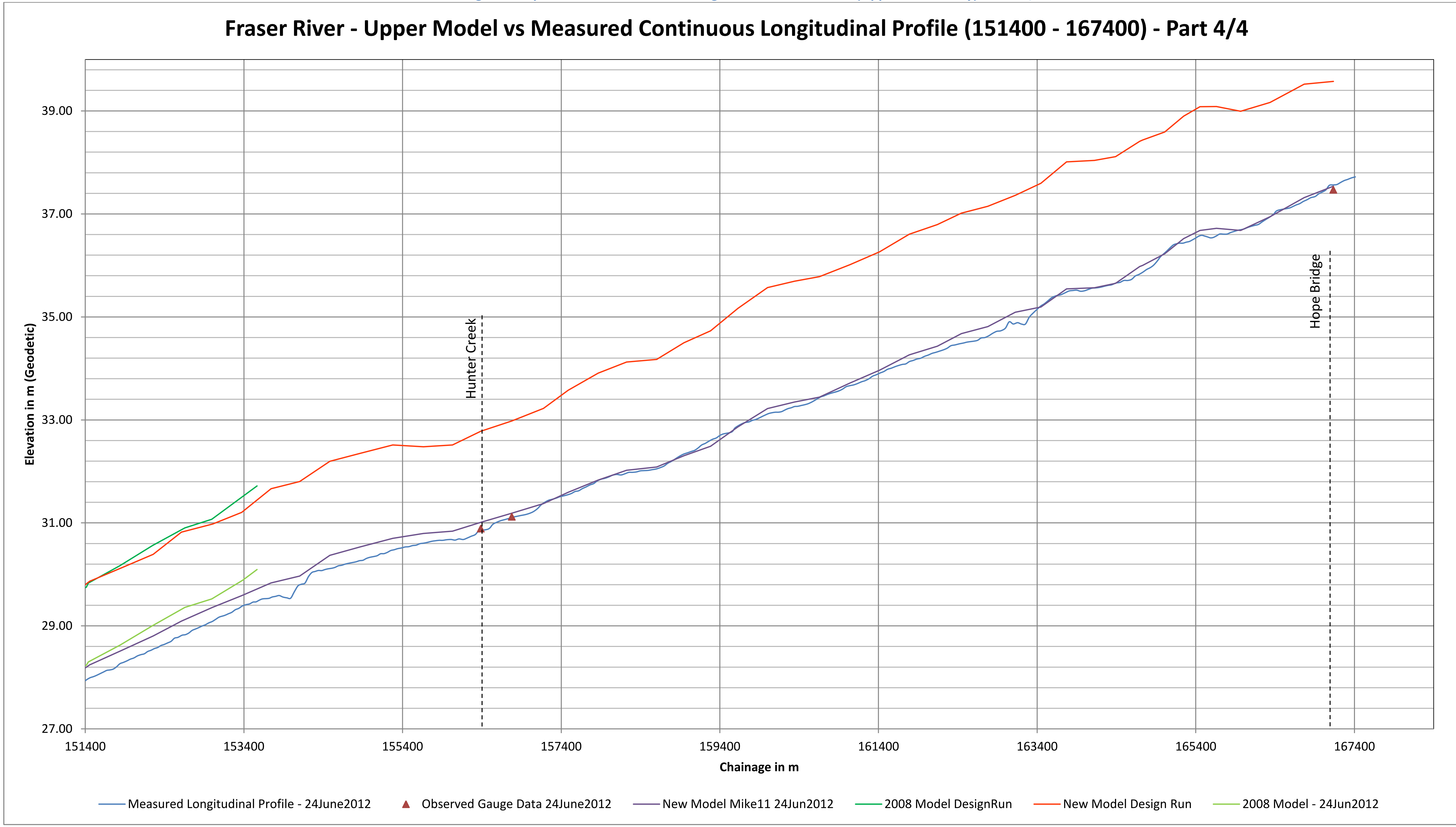
Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only) – Part 2/4



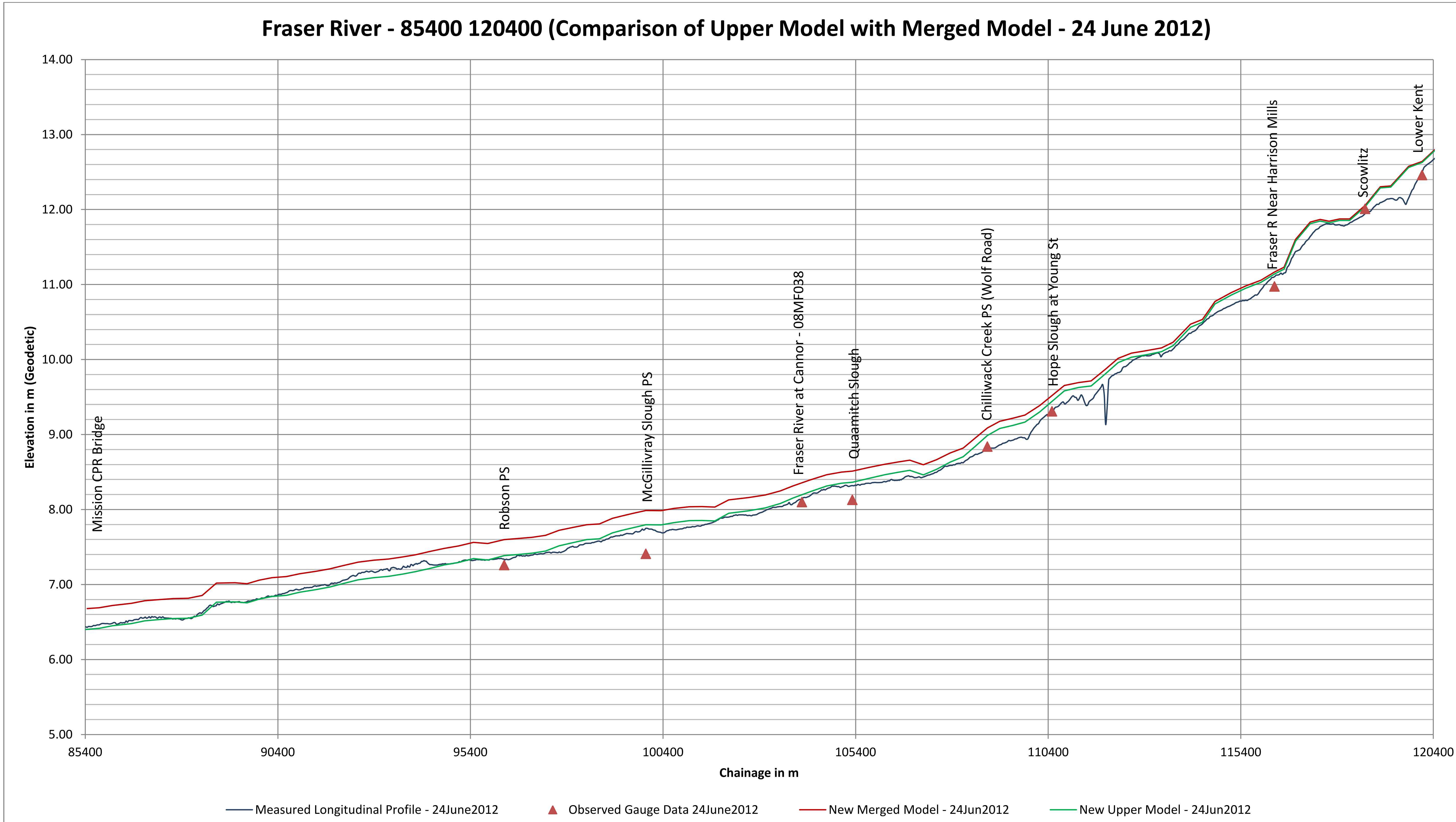
Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only) – Part3/4



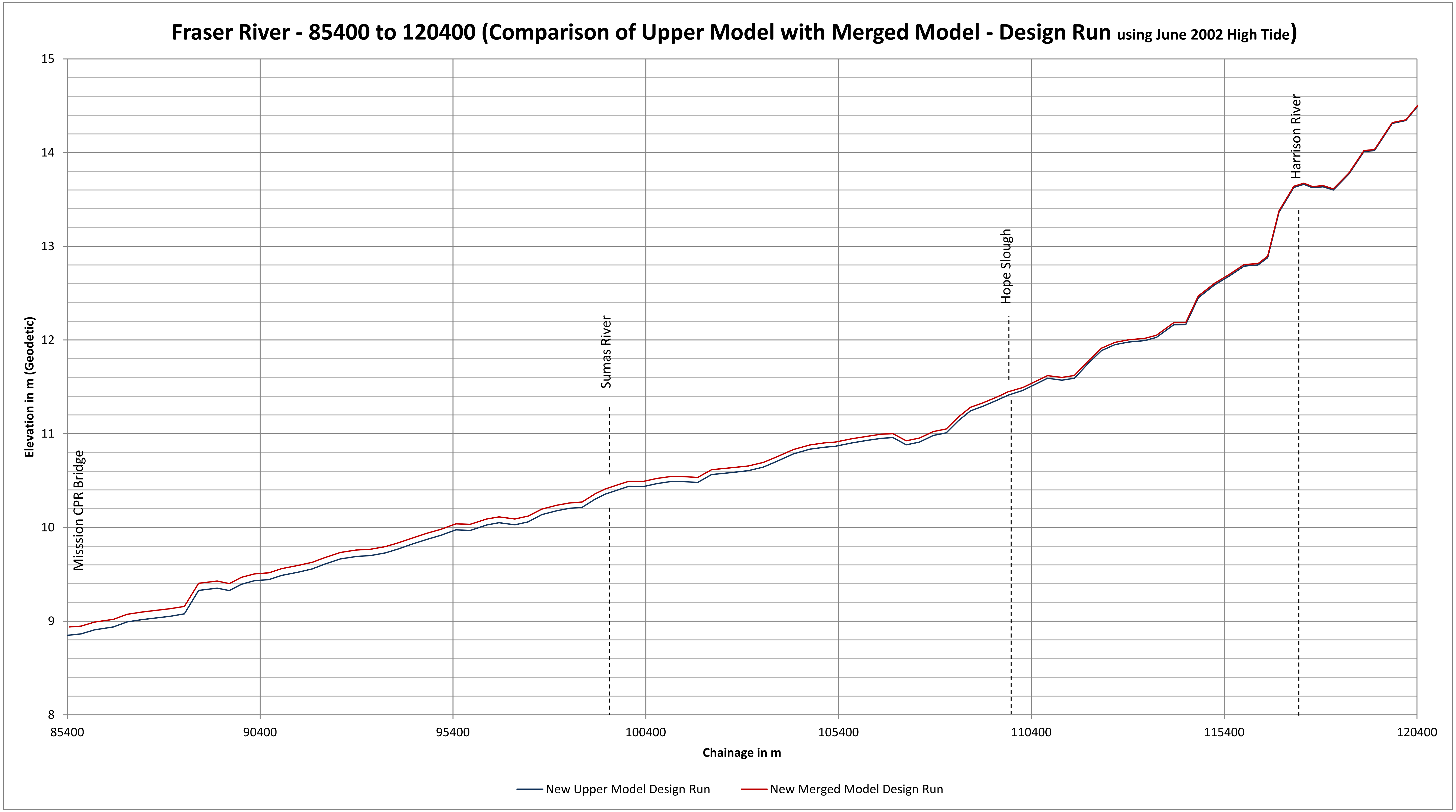
Drawing 1 - Comparison with Continuous Longitudinal Water Profile (Upper Model only) – Part 4/4



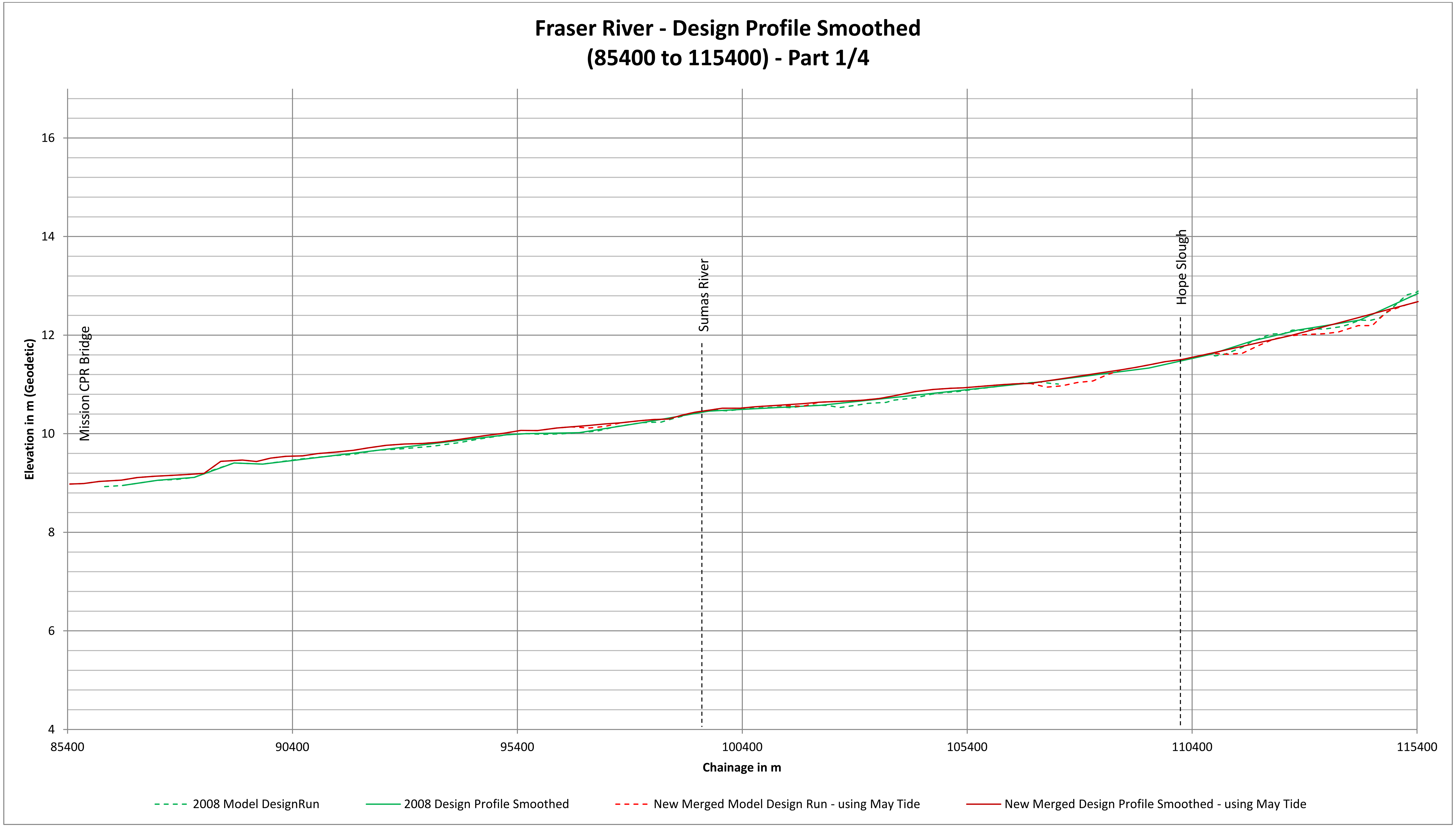
Drawing 2 - Comparison of Upper Model with Merged Model - 2012 data



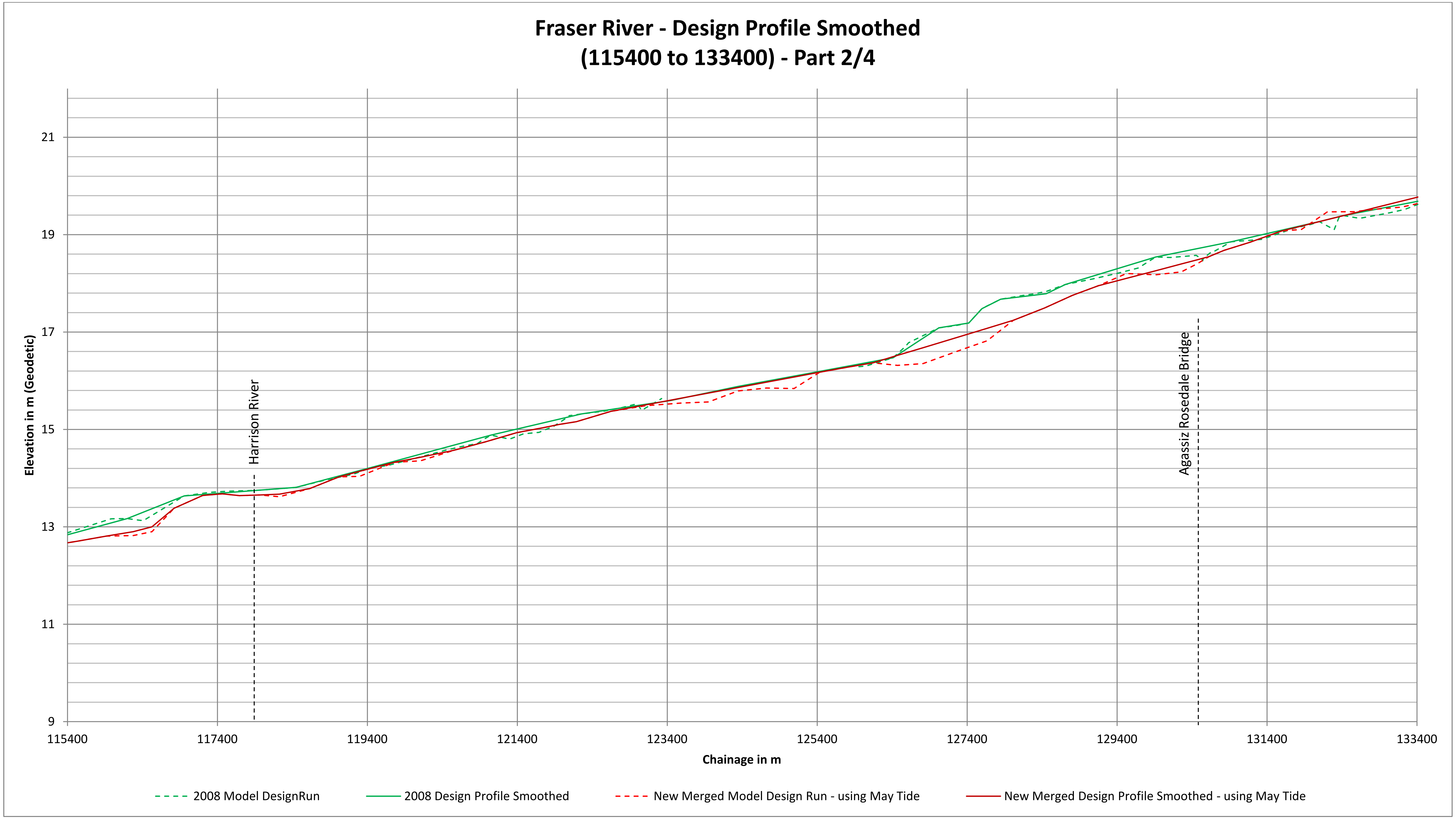
Drawing 3 - Comparison of Upper Model with Merged Model - Design Run



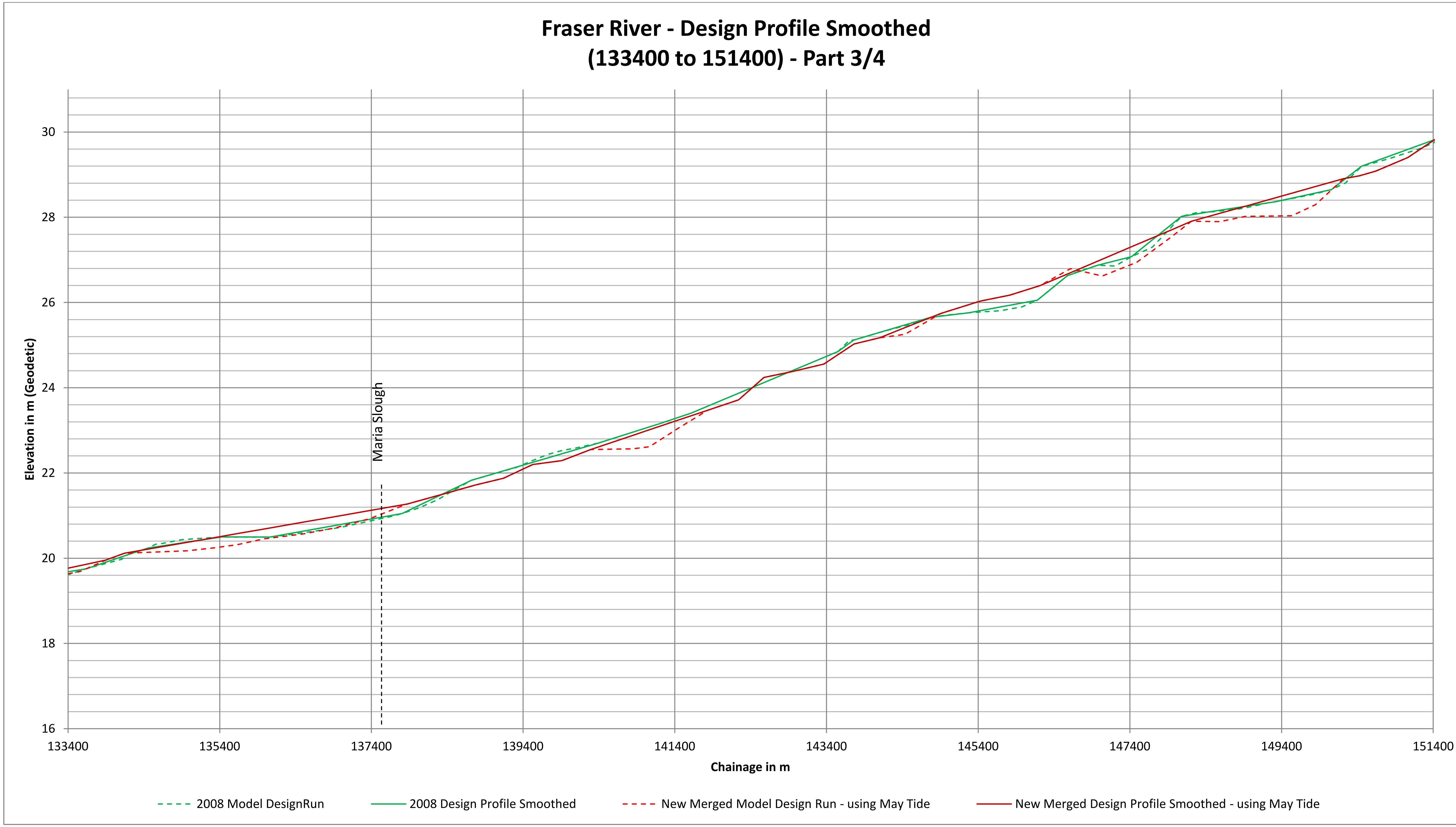
Drawing 4 - Design Profile Smoothed (Part 1/4)



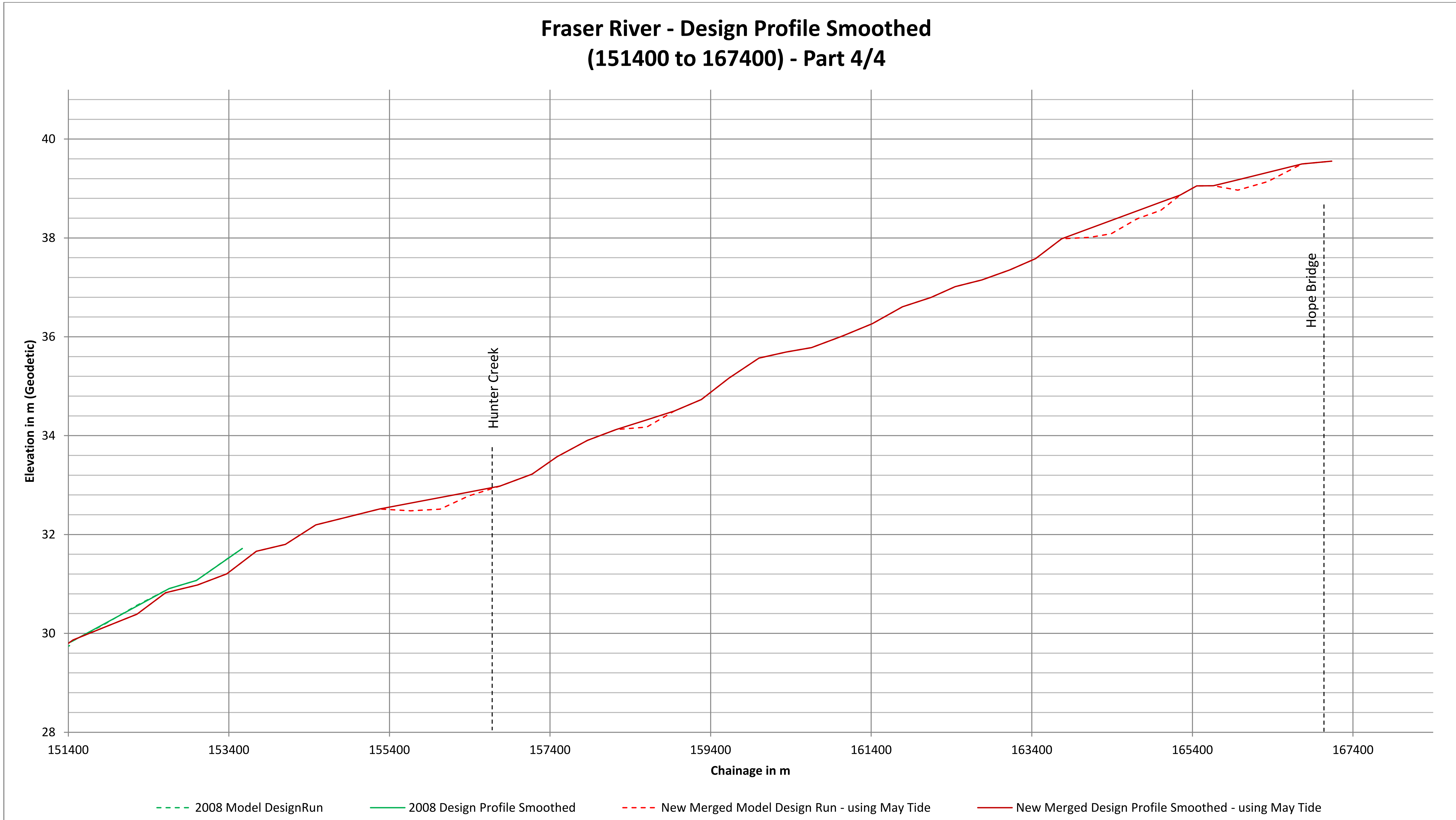
Drawing 4 – Design Profile Smoothed (Pat 2/4)



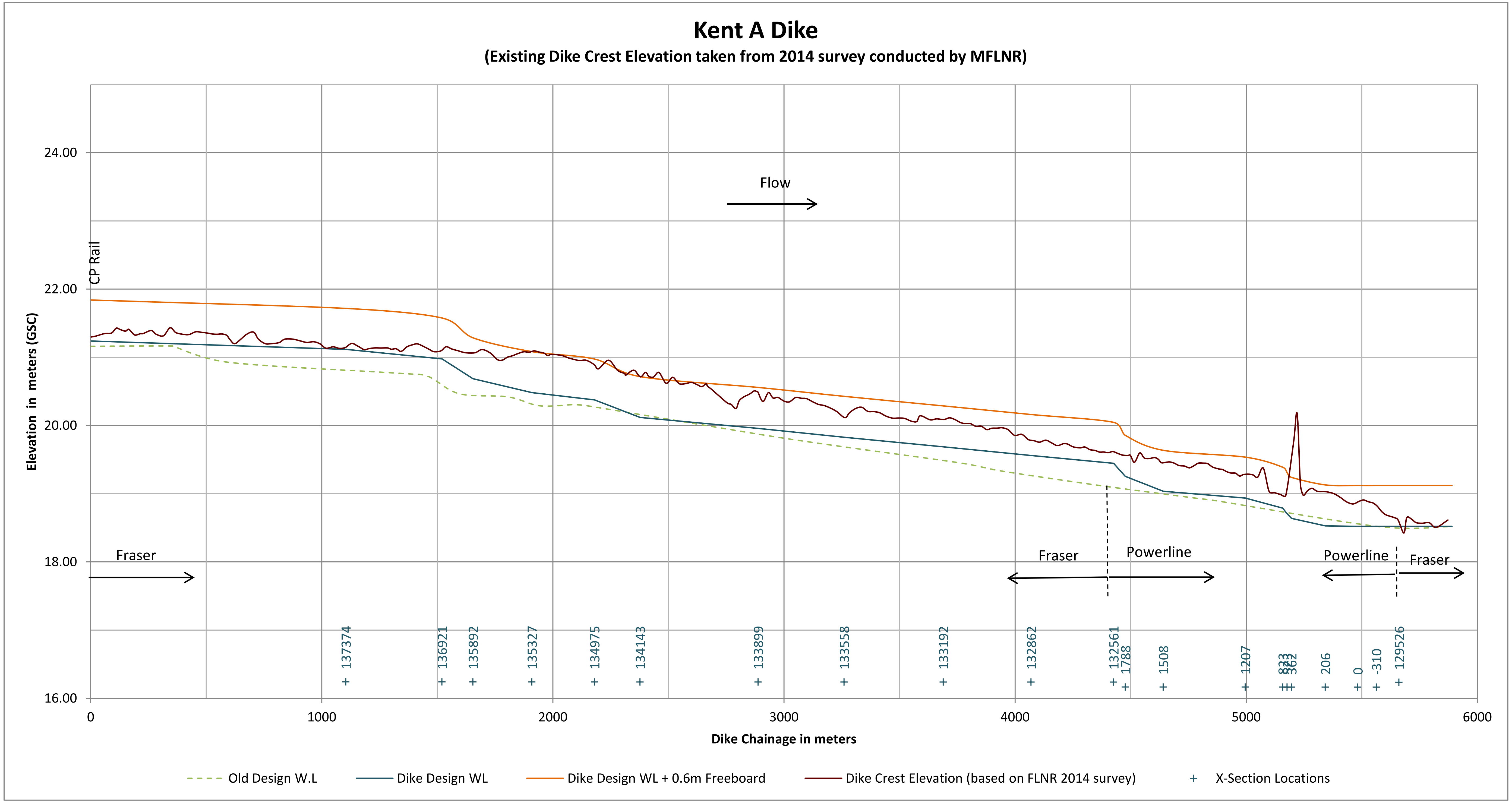
Drawing 4 – Design Profile Smoothed (Pat 3/4)



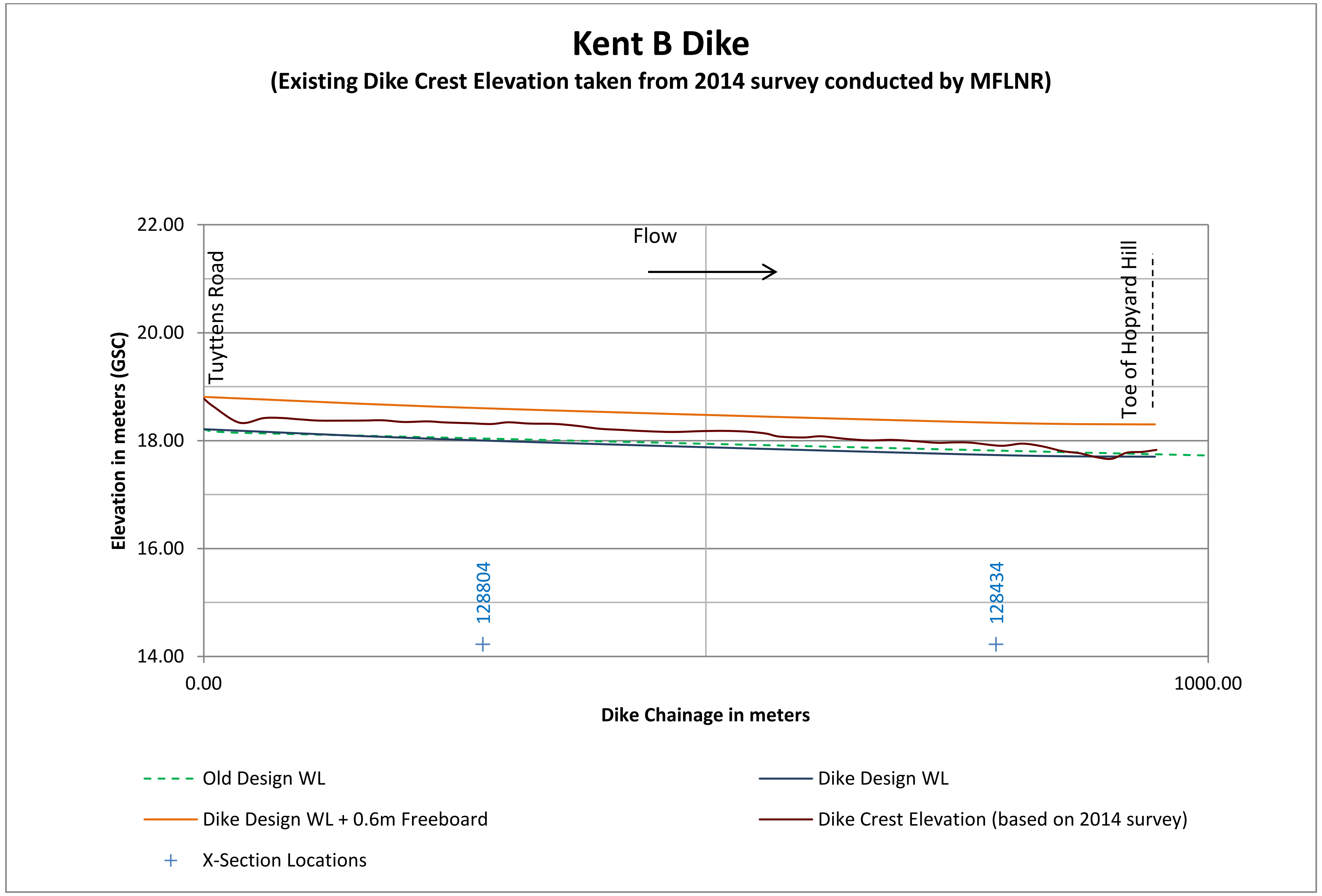
Drawing 4 – Design Profile Smoothed (Pat 4/4)



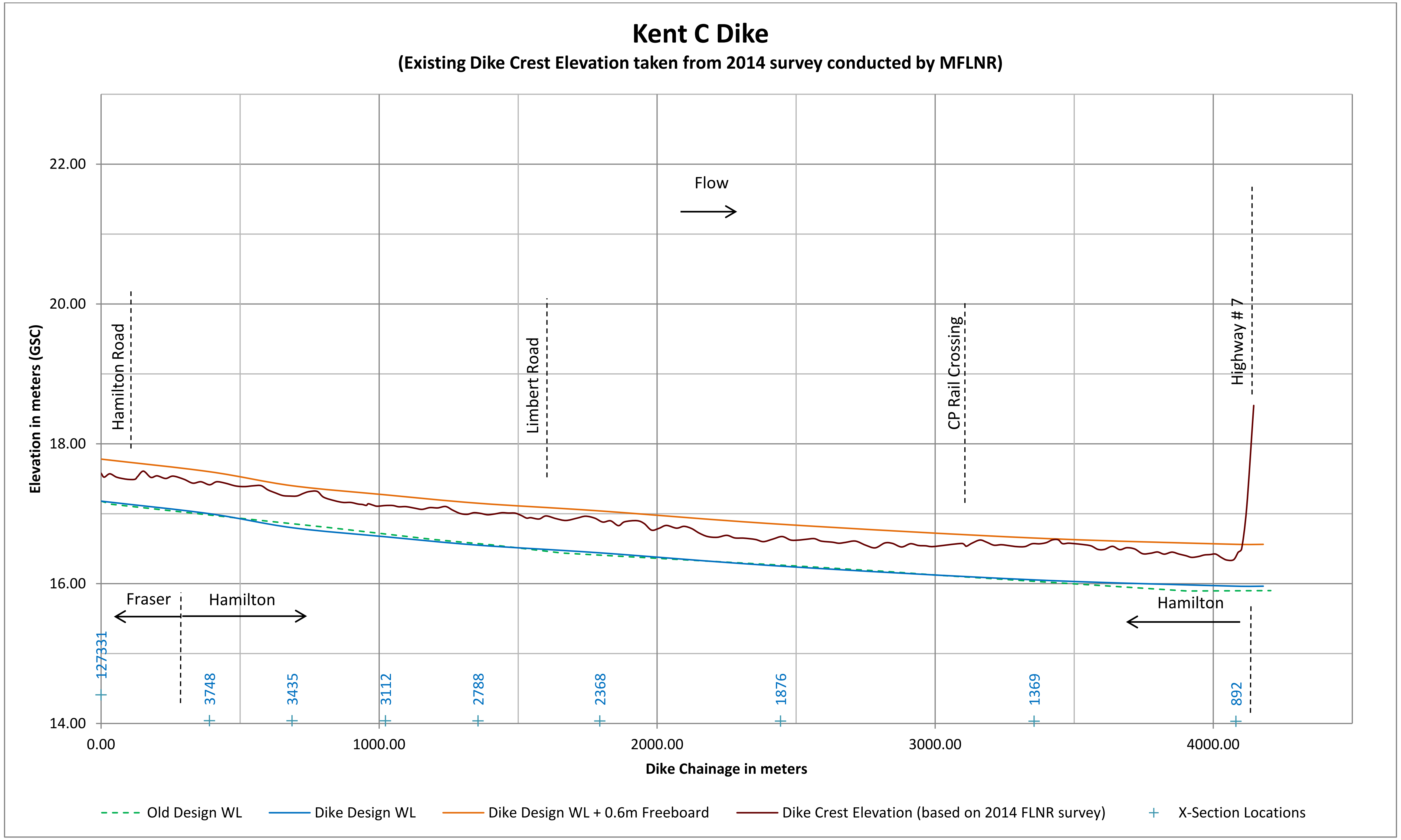
Drawing 5 - Dike Crest Profile Comparisons



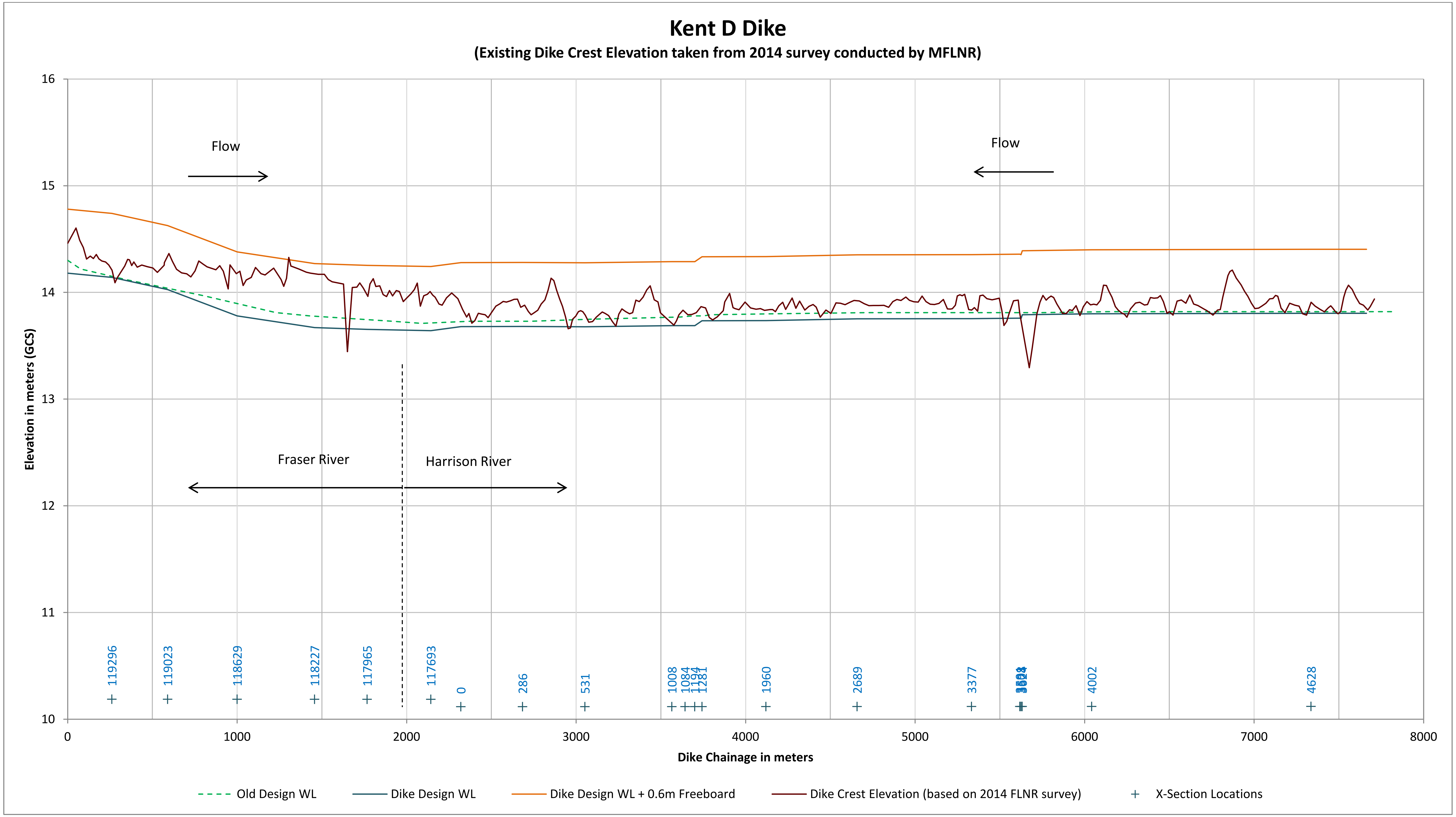
Drawing 6 - Dike Crest Profile Comparisons (cont.)



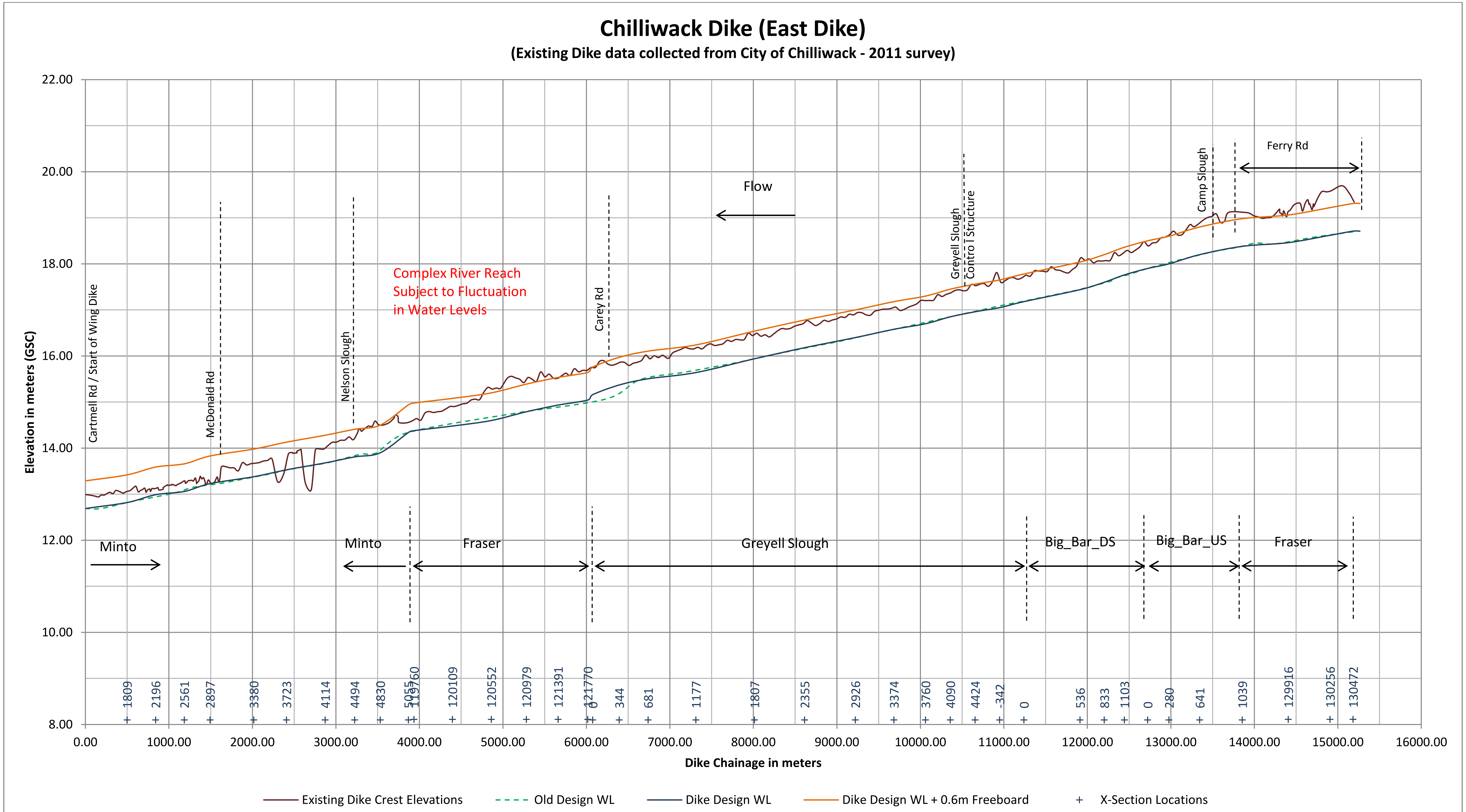
Drawing 7 - Dike Crest Profile Comparisons (cont.)



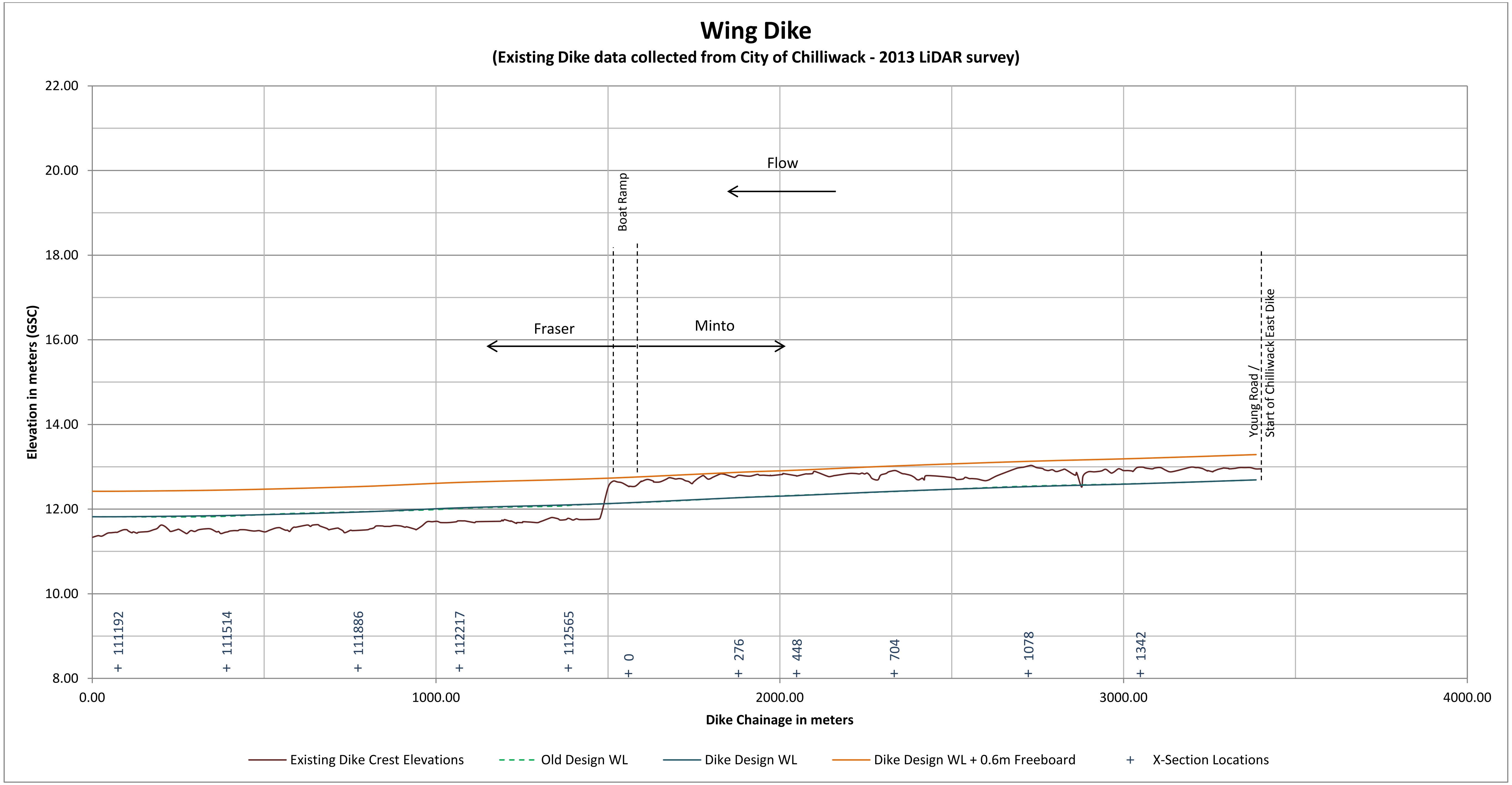
Drawing 8 - Dike Crest Profile Comparisons (cont.)



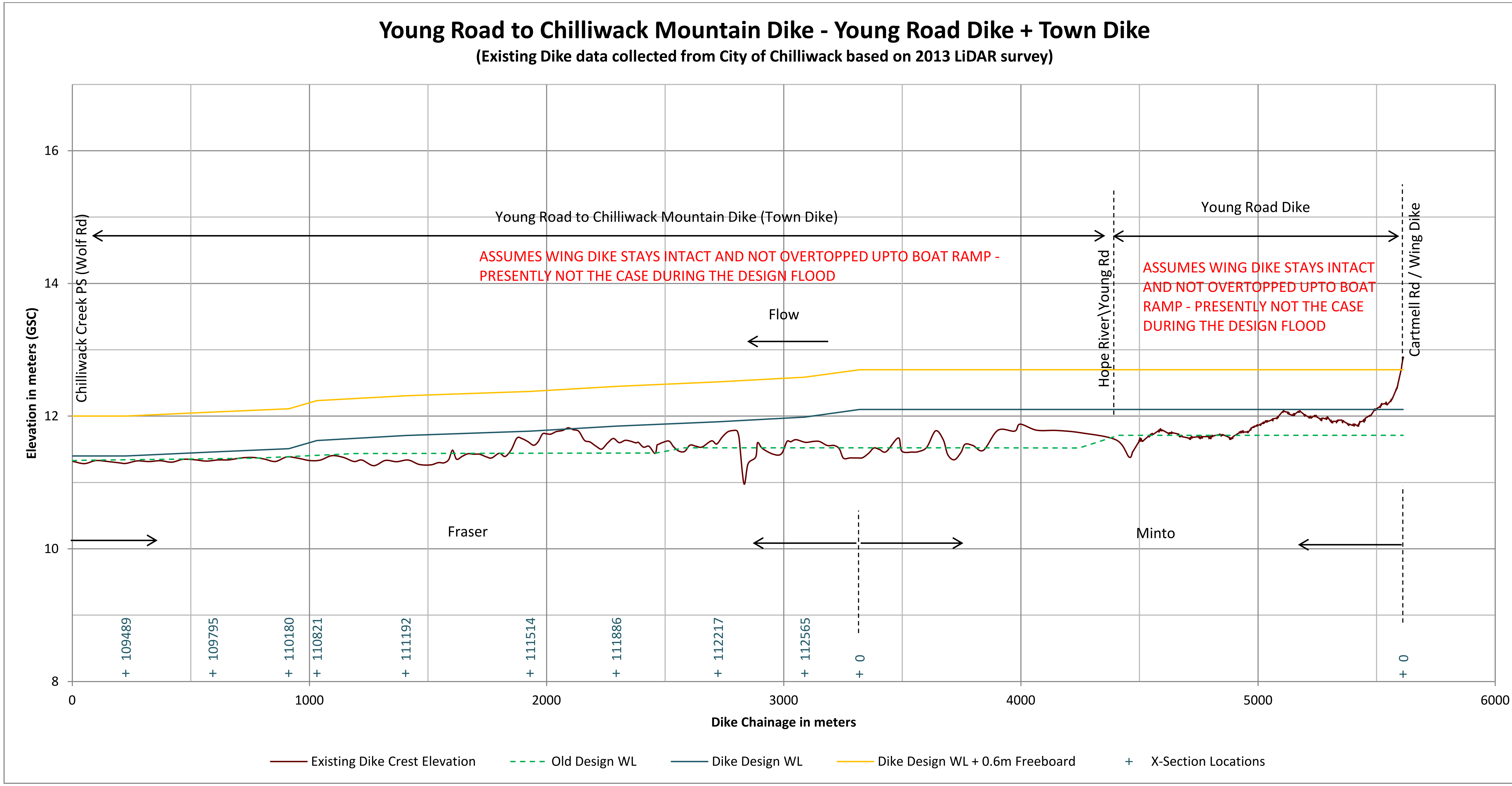
Drawing 9 - Dike Crest Profile Comparisons (cont.)



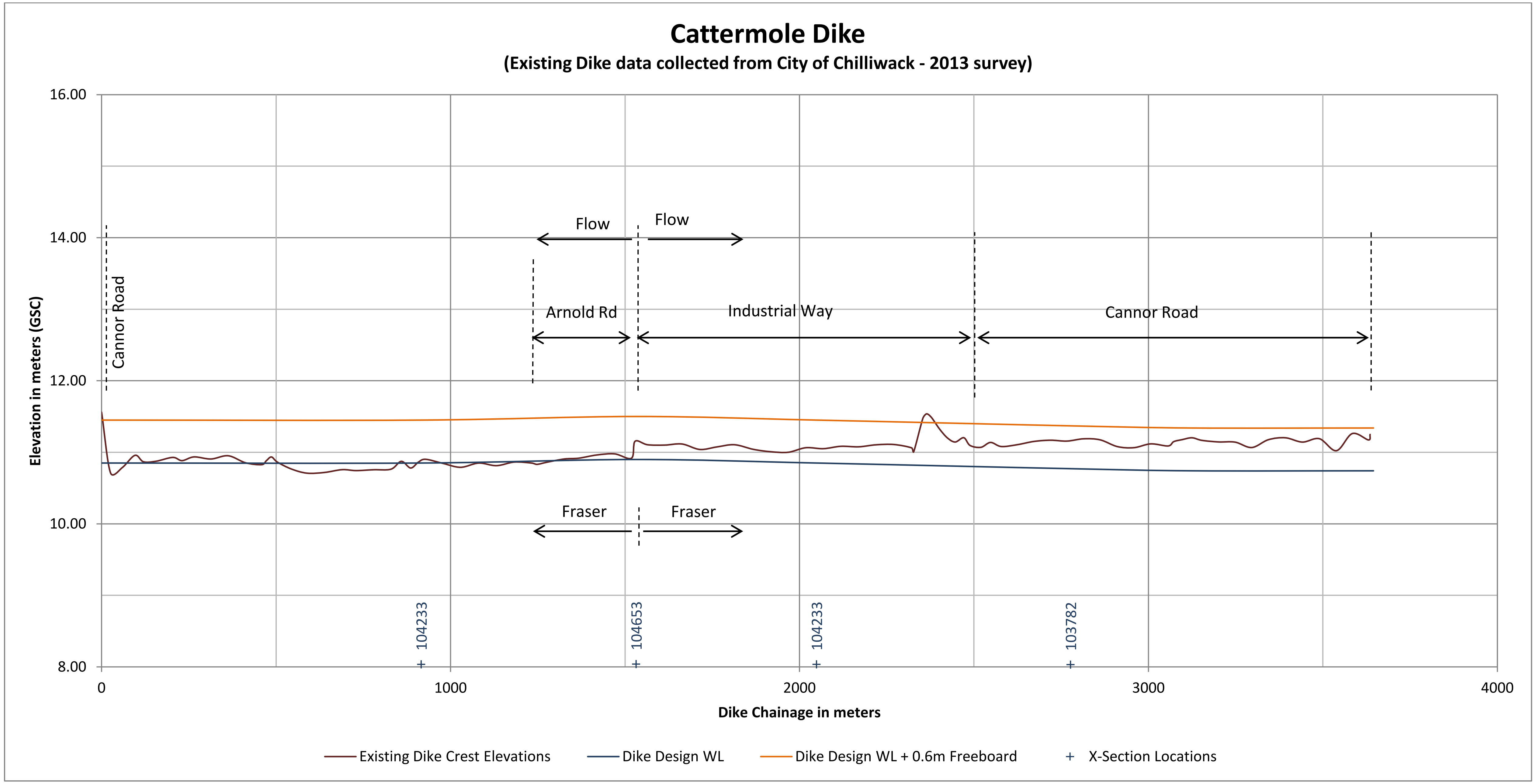
Drawing 10 - Dike Crest Profile Comparisons (cont.)



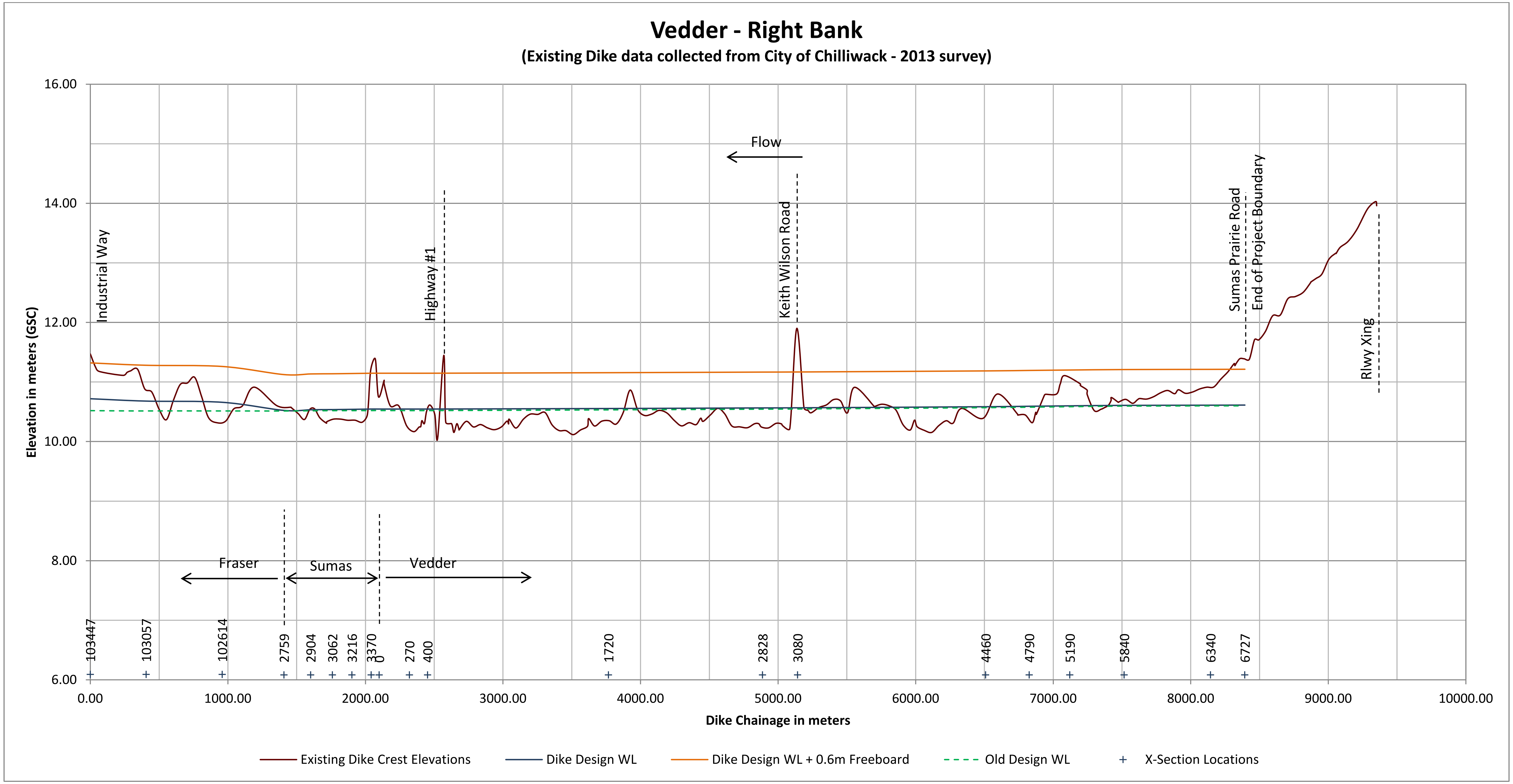
Drawing 11 - Dike Crest Profile Comparisons (cont.)



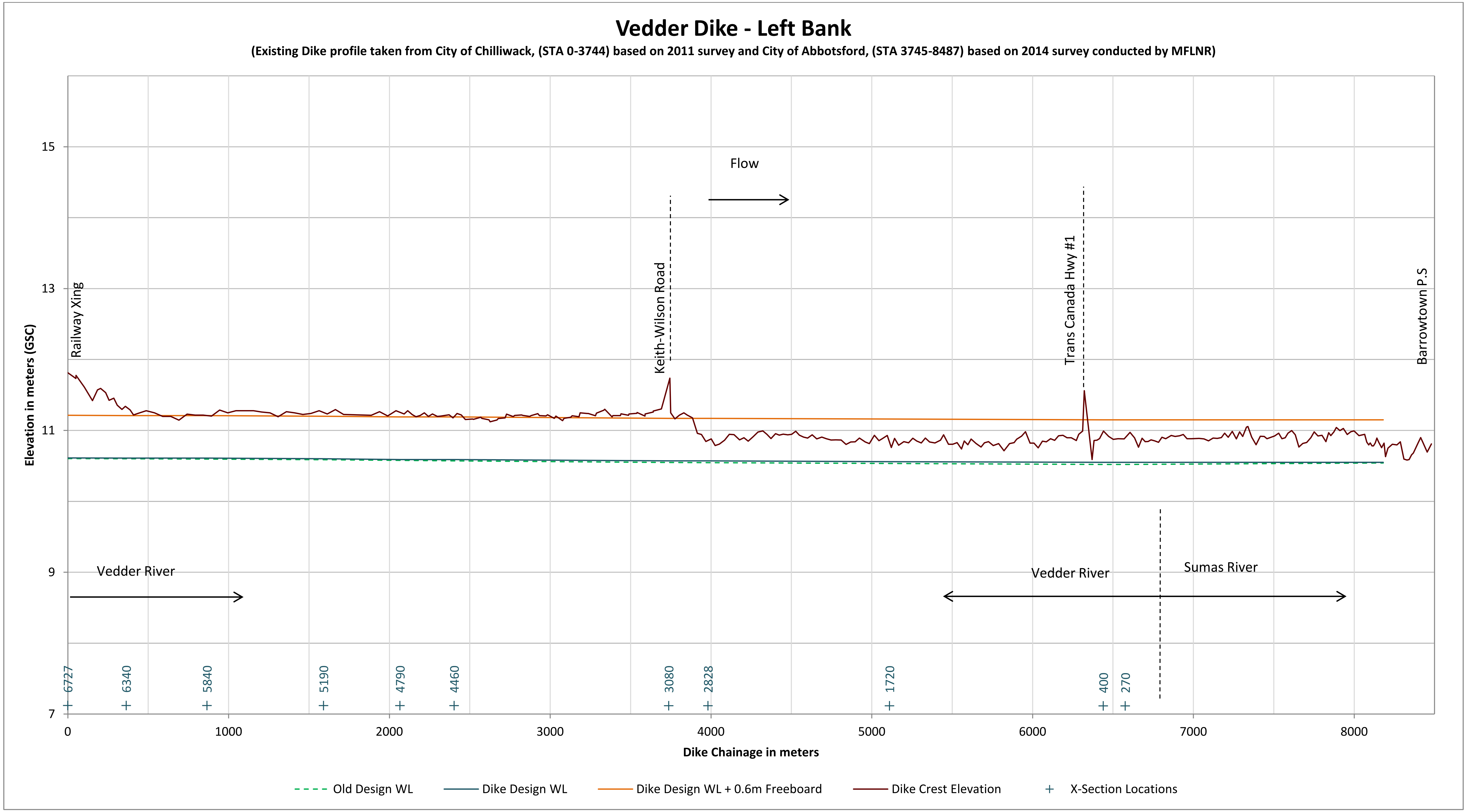
Drawing 12 - Dike Crest Profile Comparisons (cont.)



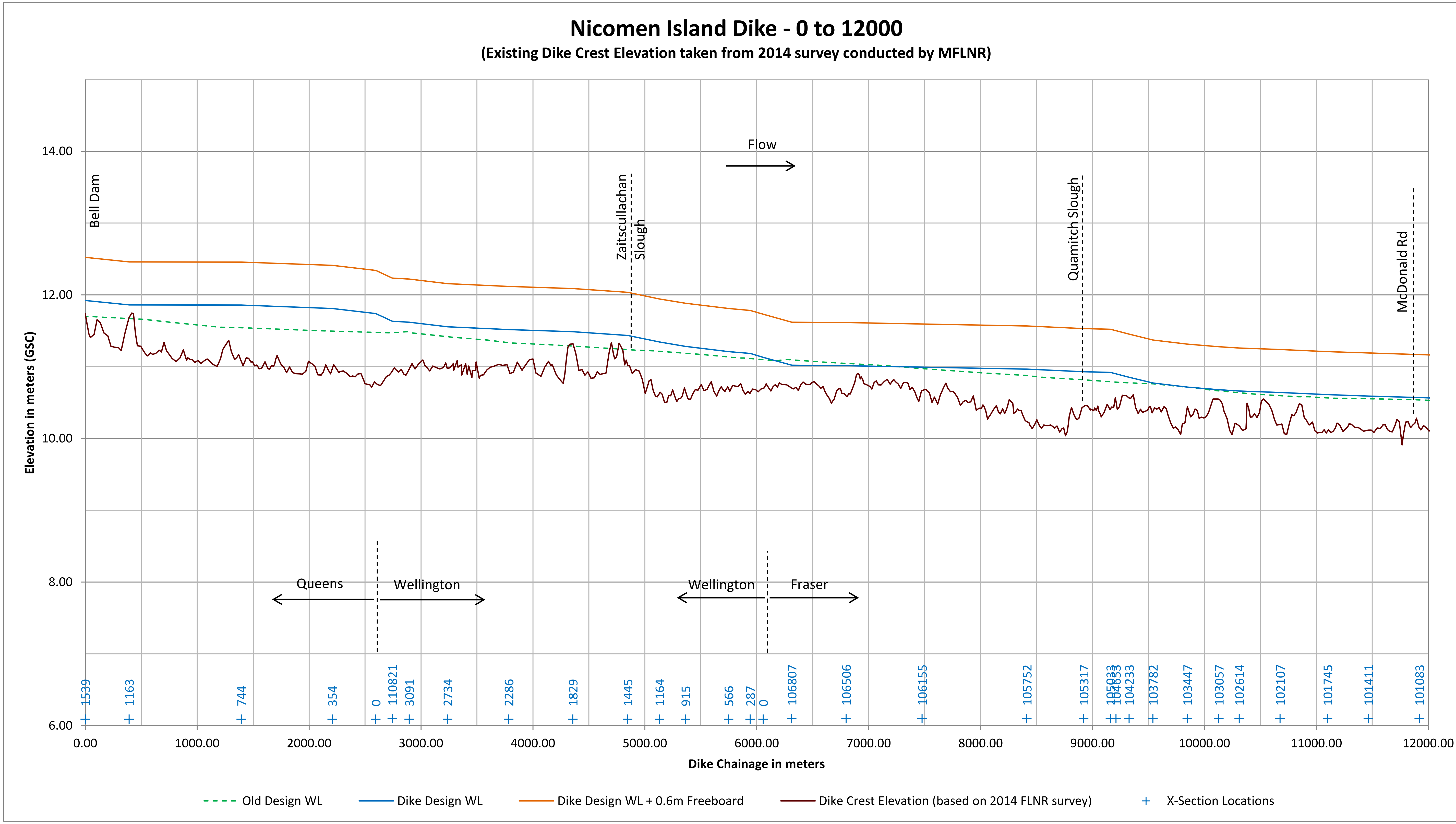
Drawing 13 - Dike Crest Profile Comparisons (cont.)



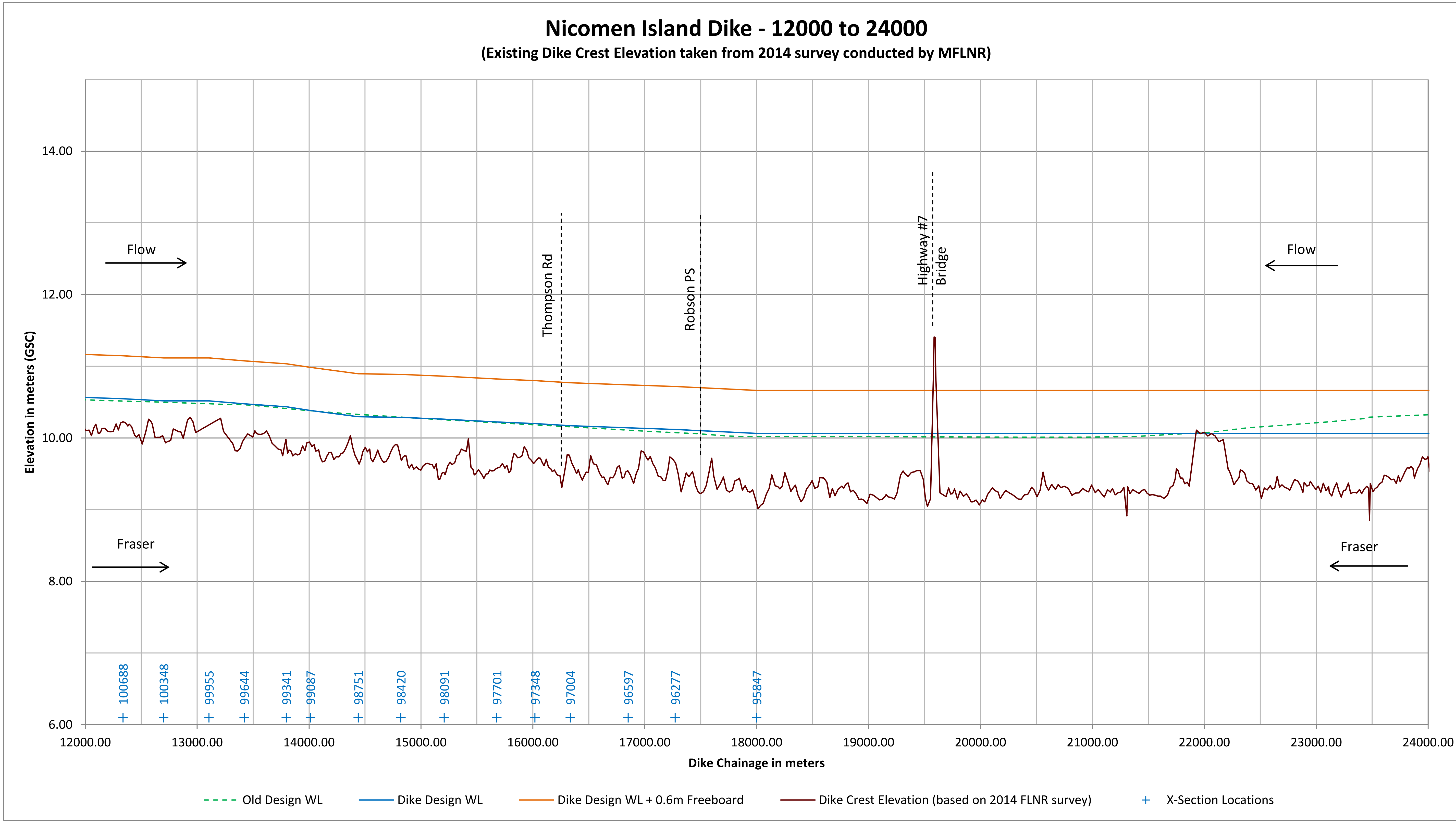
Drawing 14 - Dike Crest Profile Comparisons (cont.)



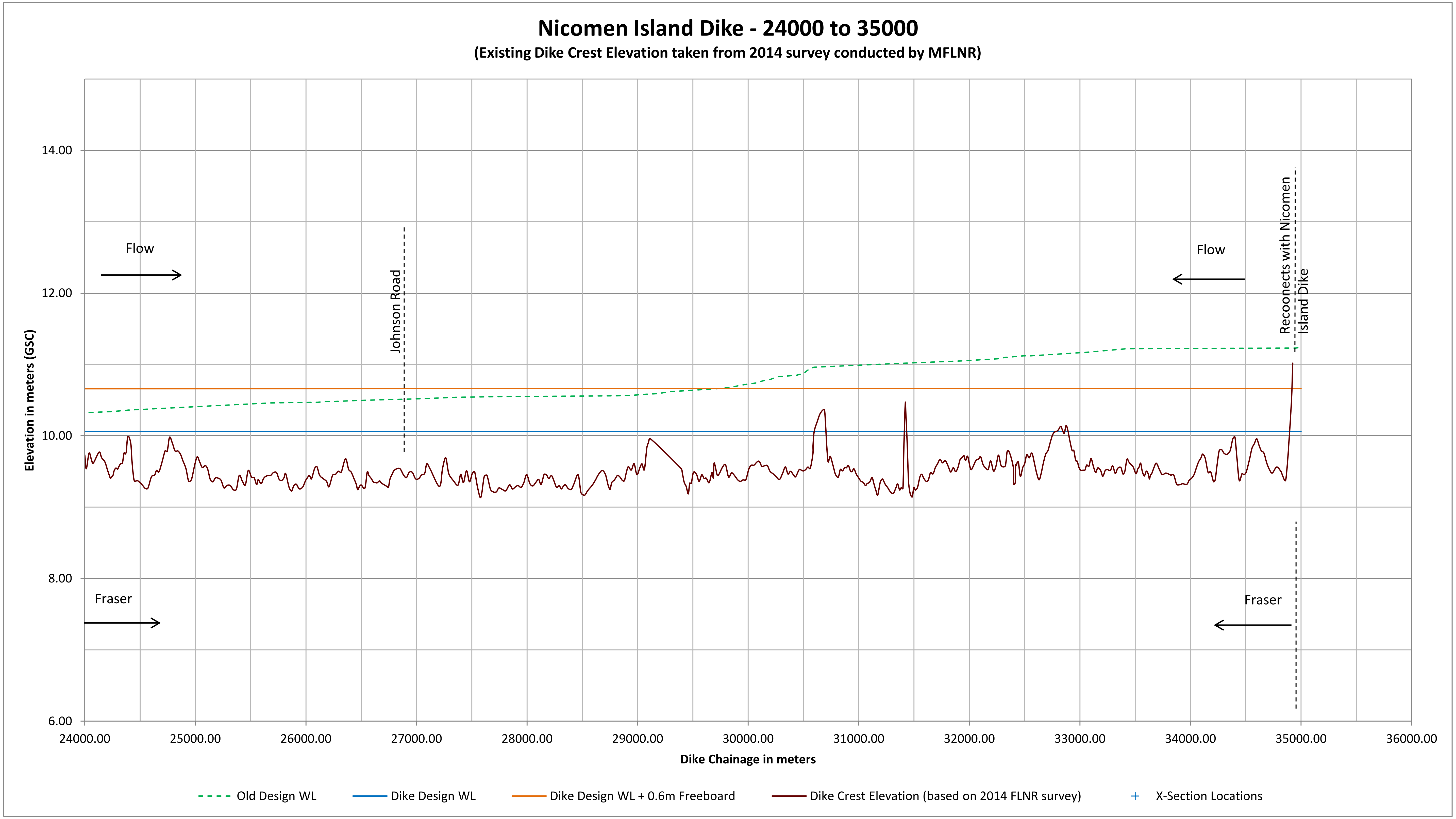
Drawing 15 - Dike Crest Profile Comparisons (cont.)



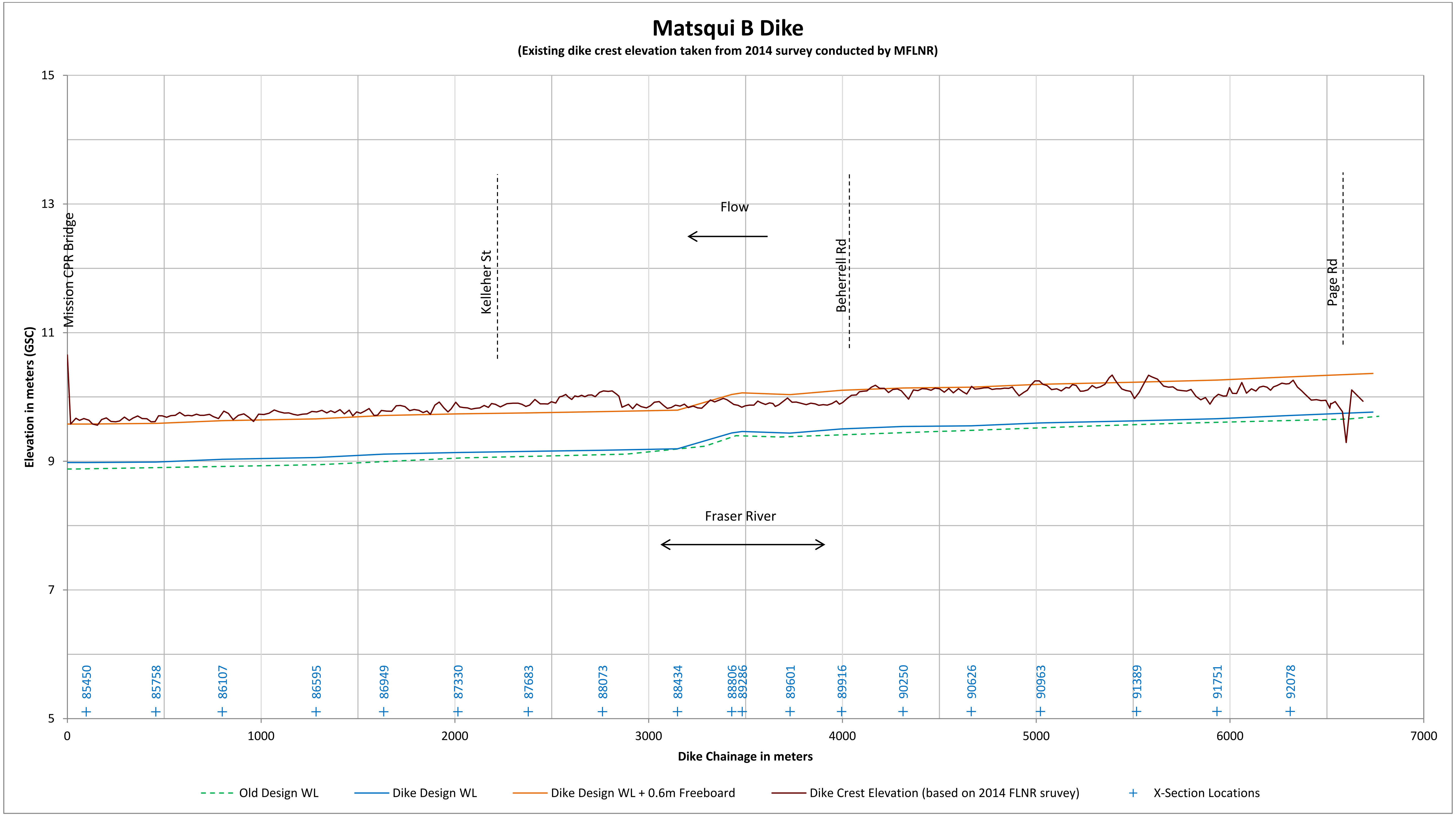
Drawing 16 - Dike Crest Profile Comparisons (cont.)



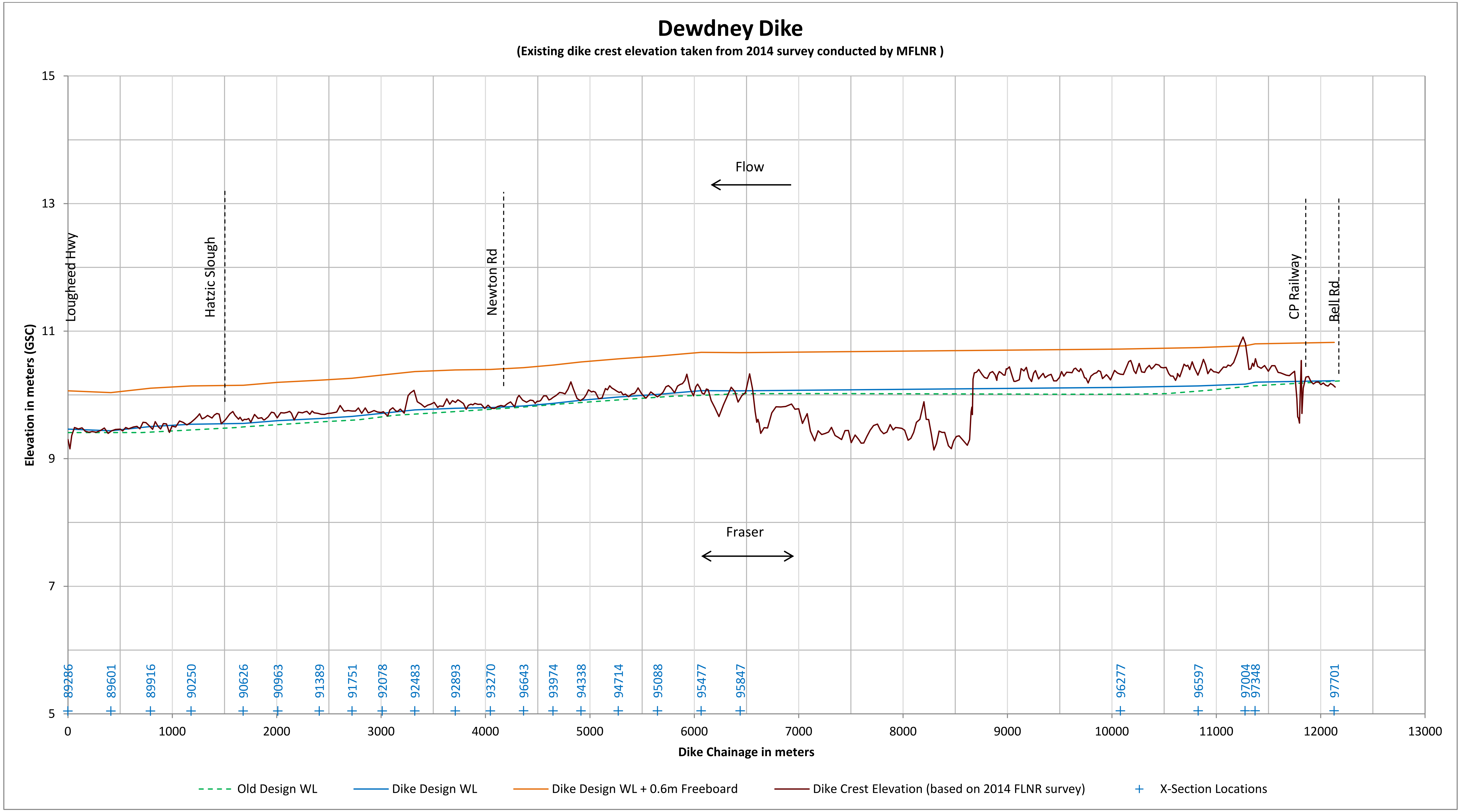
Drawing 17 - Dike Crest Profile Comparisons (cont.)



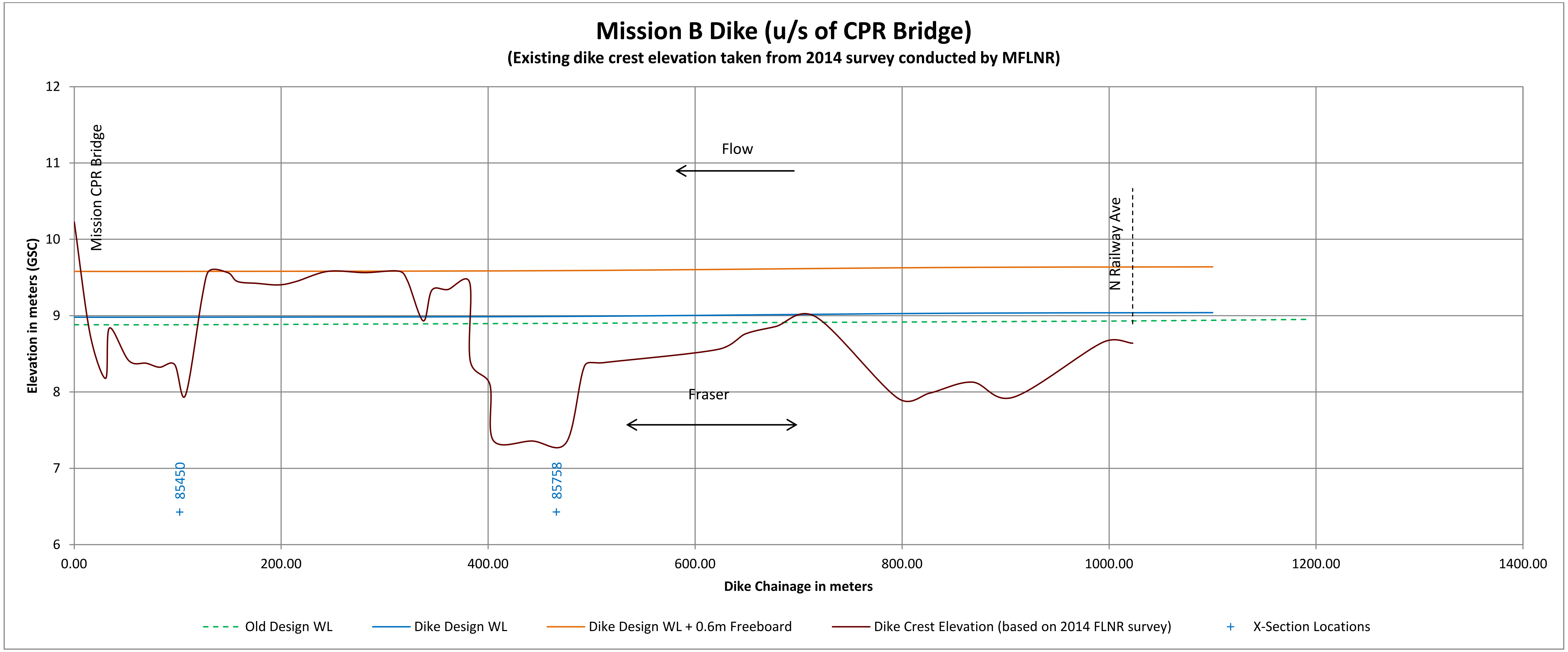
Drawing 18 - Dike Crest Profile Comparisons (cont.)



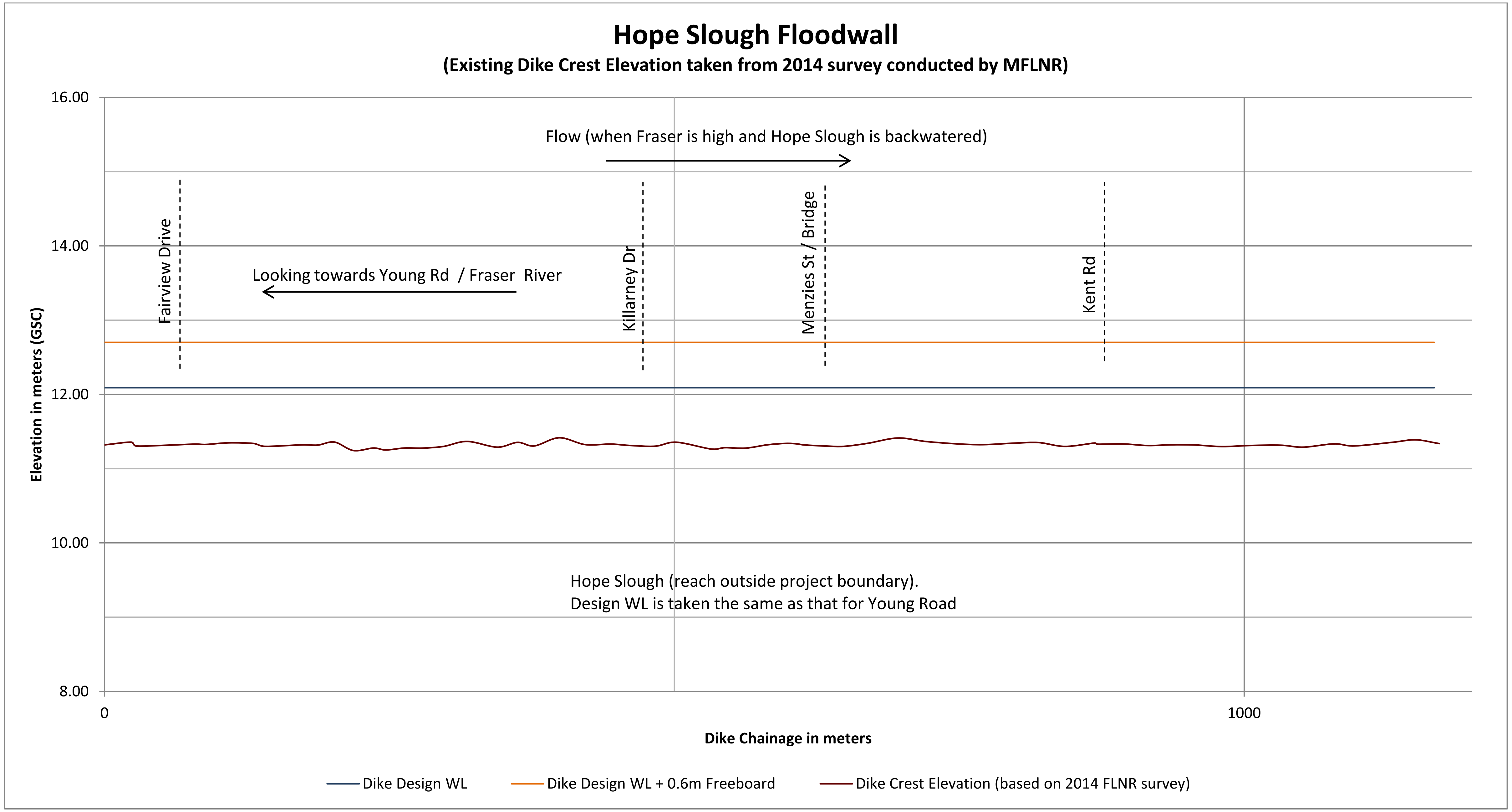
Drawing 19 - Dike Crest Profile Comparisons (cont.)



Drawing 20 - Dike Crest Profile Comparisons (cont.)



Drawing 21 - Dike Crest Profile Comparisons (cont.)



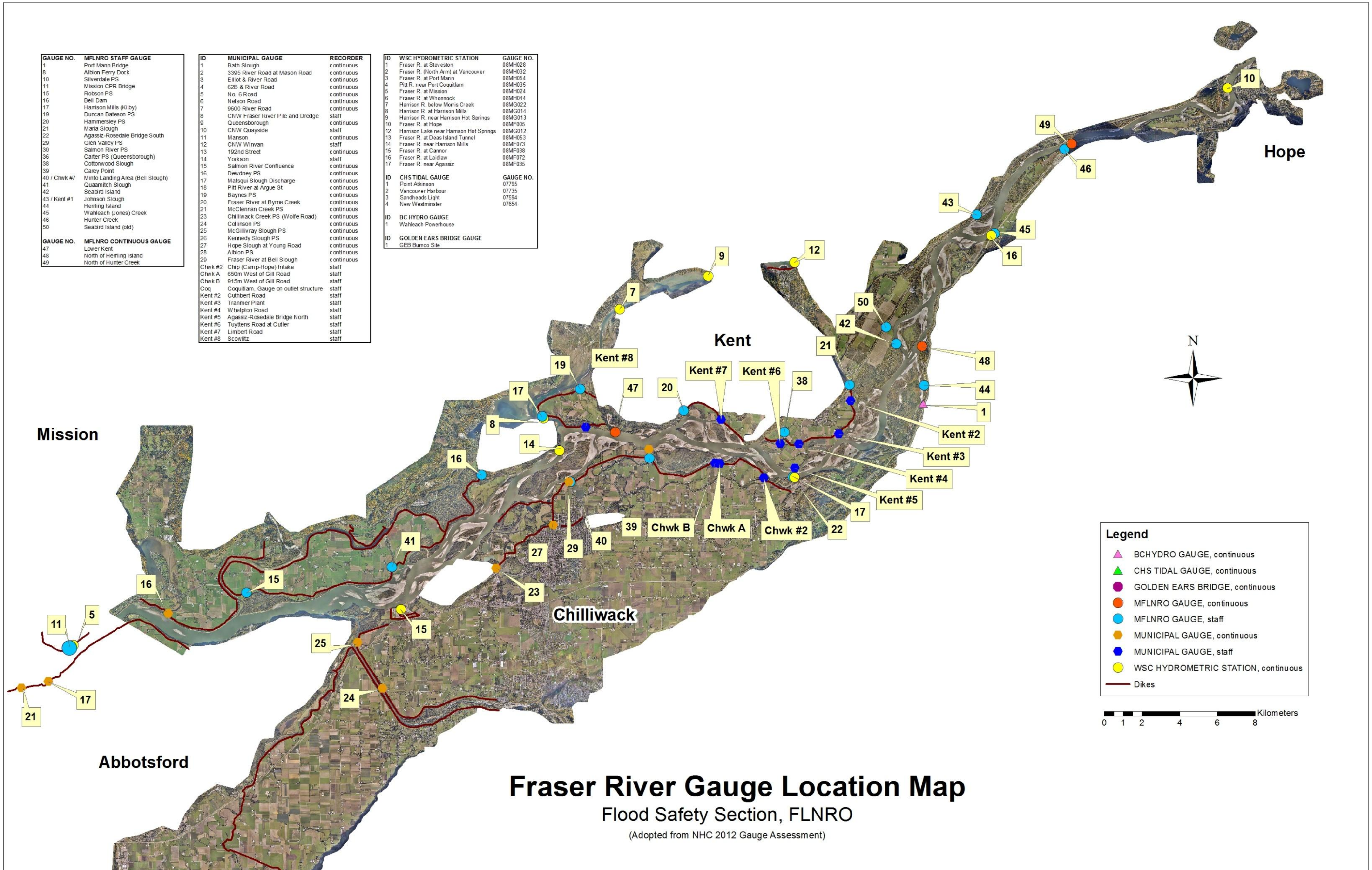
MAPS

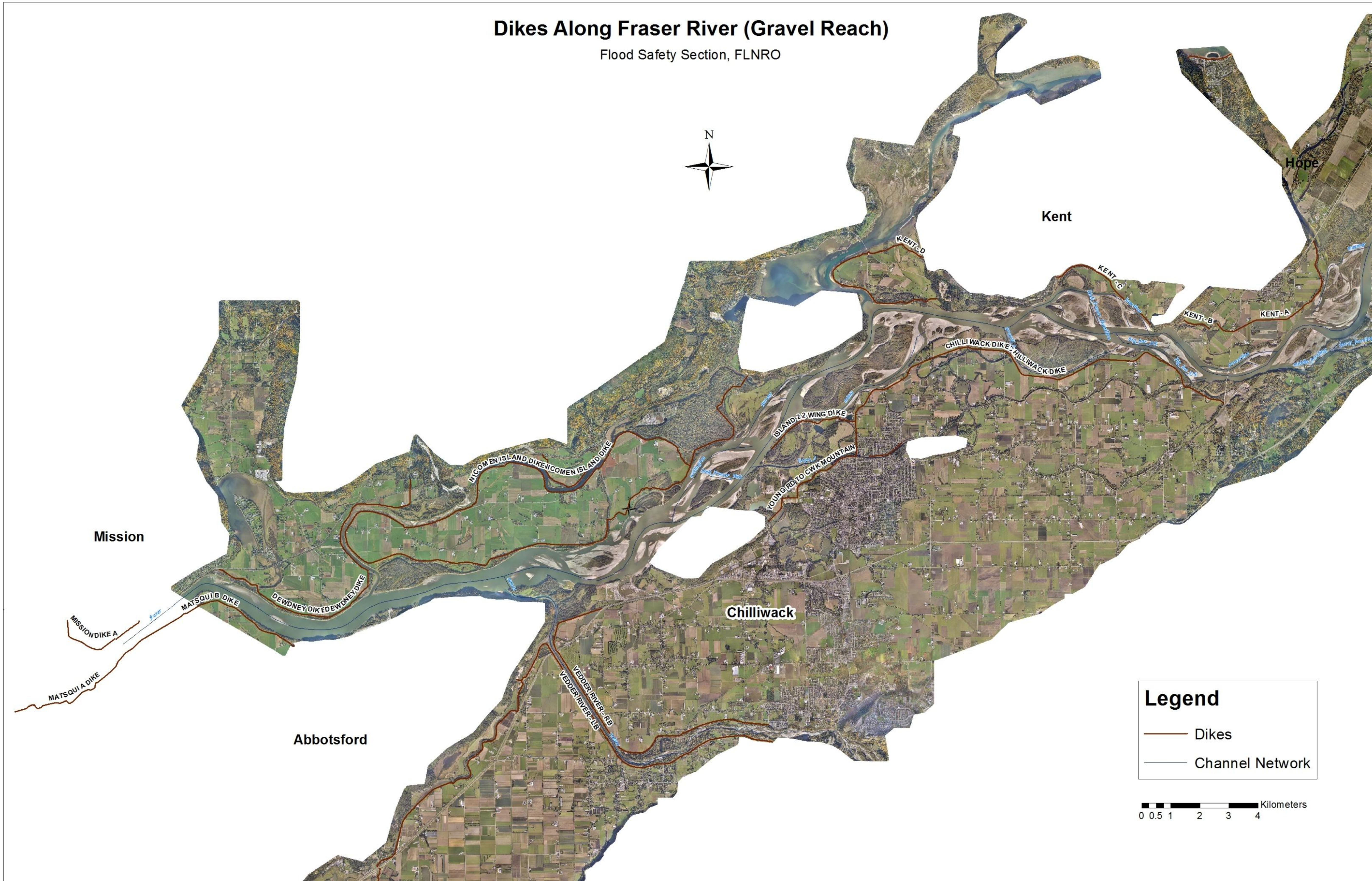
Map 1 - Gauge Location Map

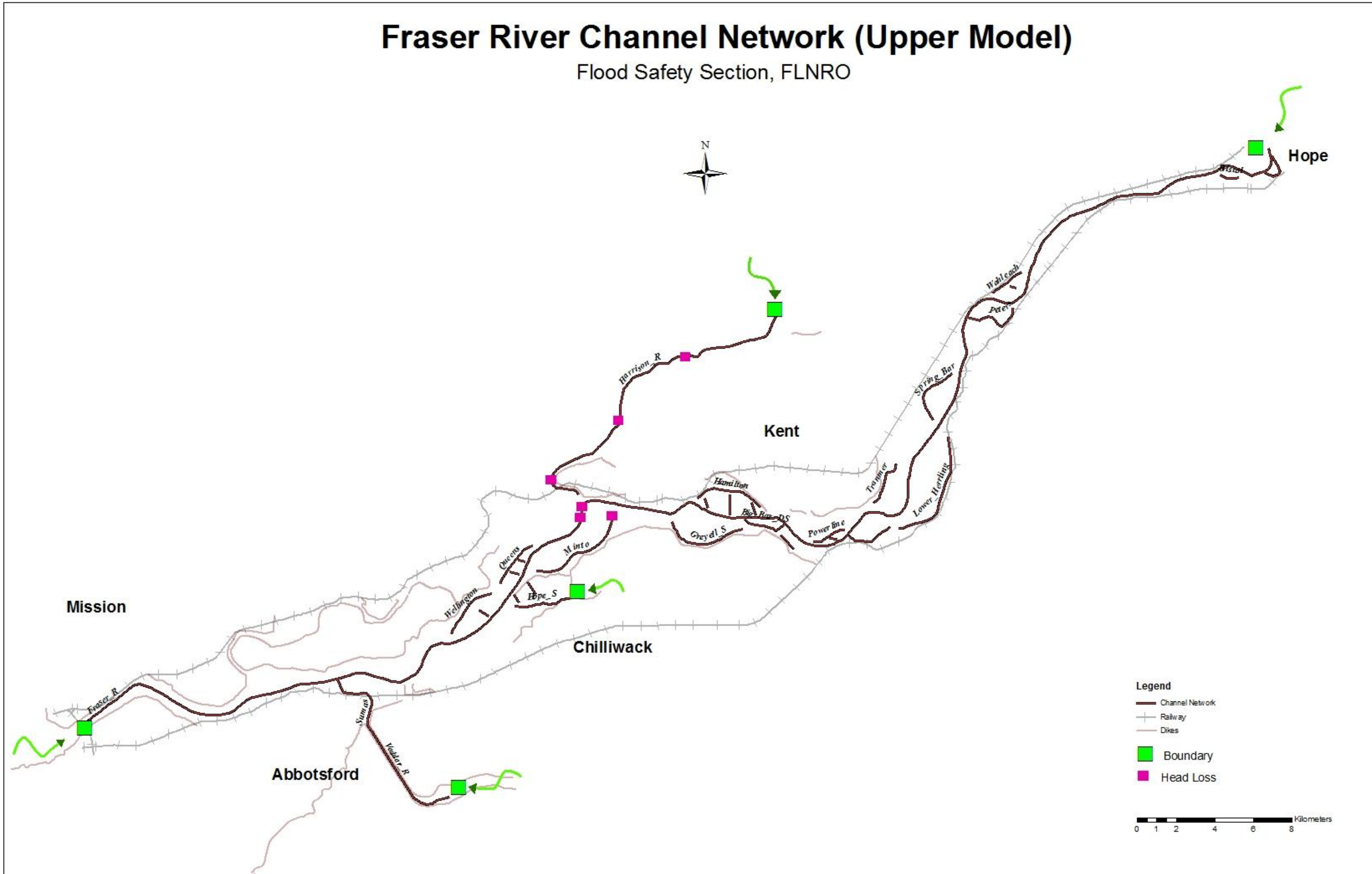
GAUGE NO.	MFLNRO STAFF GAUGE
1	Port Mann Bridge
8	Albion Ferry Dock
10	Silverdale PS
11	Mission CPR Bridge
15	Robson PS
16	Bell Dam
17	Harrison Mills (Kilby)
19	Duncan Bateson PS
20	Hammersley PS
21	Maria Slough
22	Agassiz-Rosedale Bridge South
29	Glen Valley PS
30	Salmon River PS
36	Carter PS (Queensborough)
38	Cottonwood Slough
39	Carey Point
40 / Chwk #7	Minto Landing Area (Bell Slough)
41	Quaamitch Slough
42	Seabird Island
43 / Kent #1	Johnson Slough
44	Herrling Island
45	Wahleach (Jones) Creek
46	Hunter Creek
50	Seabird Island (old)
GAUGE NO.	**MFLNRO CONTINUOUS GAUGE**
47	Lower Kent
48	North of Herrling Island
49	North of Hunter Creek

ID	MUNICIPAL GAUGE	RECORDER
1	Bath Slough	continuous
2	3395 River Road at Mason Road	continuous
3	Elliot & River Road	continuous
4	62B & River Road	continuous
5	No. 6 Road	continuous
6	Nelson Road	continuous
7	9600 River Road	continuous
8	CNW Fraser River Pile and Dredge	staff
9	Queensborough	continuous
10	CNW Quayside	staff
11	Manson	continuous
12	CNW Winvan	staff
13	192nd Street	continuous
14	Yorkson	staff
15	Salmon River Confluence	continuous
16	Dewdney PS	continuous
17	Matsqui Slough Discharge	continuous
18	Pitt River at Argue St	continuous
19	Baynes PS	continuous
20	Fraser River at Byrne Creek	continuous
21	McClennan Creek PS	continuous
23	Chilliwack Creek PS (Wolfe Road)	continuous
24	Collinson PS	continuous
25	McGillivray Slough PS	continuous
26	Kennedy Slough PS	continuous
27	Hope Slough at Young Road	continuous
28	Albion PS	continuous
29	Fraser River at Bell Slough	continuous
Chwk #2	Chip (Camp-Hope) Intake	staff
Chwk A	650m West of Gill Road	staff
Chwk B	915m West of Gill Road	staff
Coq	Coquitlam, Gauge on outlet structure	staff
Kent #2	Cuthbert Road	staff
Kent #3	Tranmer Plant	staff
Kent #4	Whelpton Road	staff
Kent #5	Agassiz-Rosedale Bridge North	staff
Kent #6	Tuyttens Road at Cutler	staff
Kent #7	Limbert Road	staff
Kent #8	Scowlitz	staff

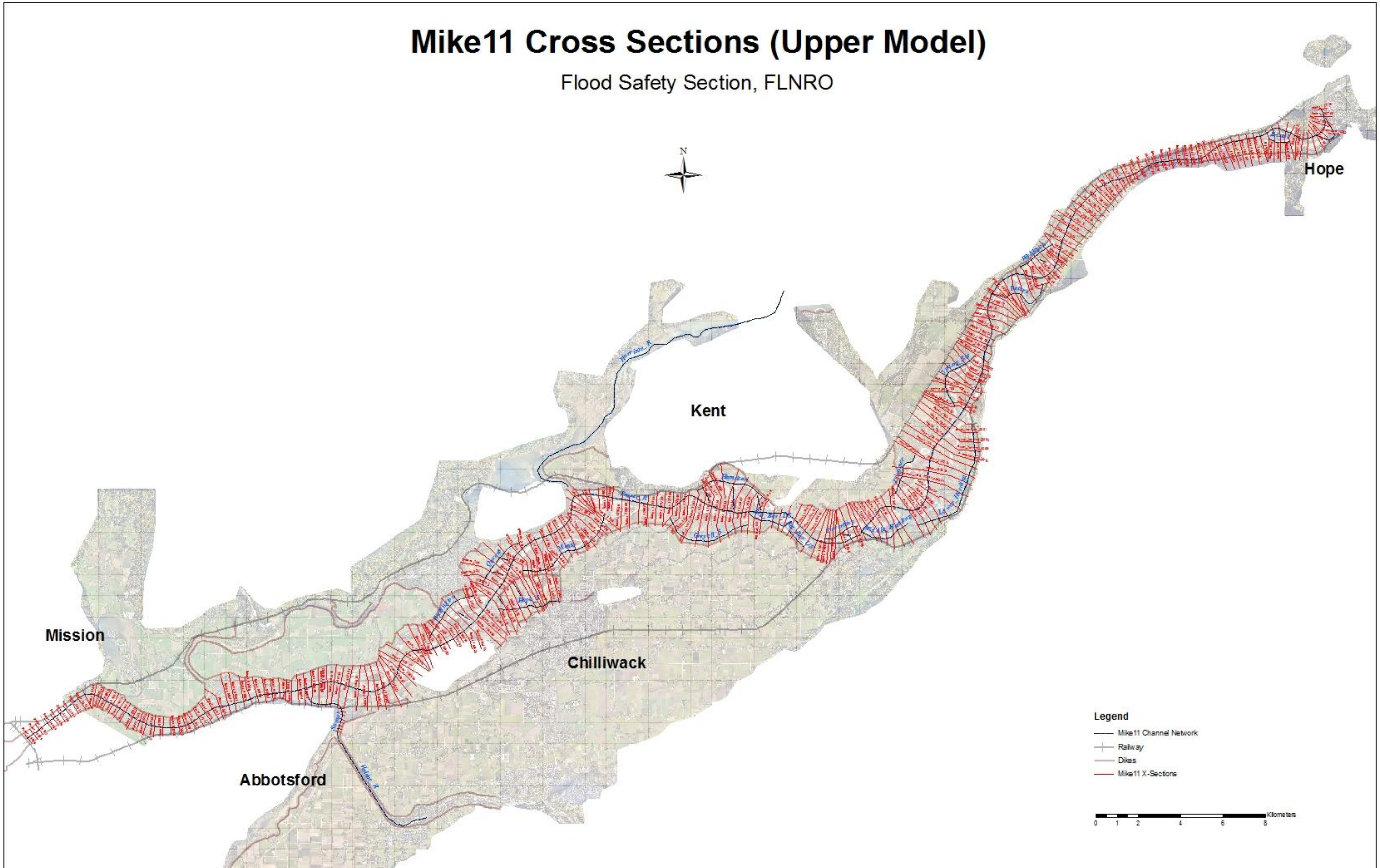
ID	WSC HYDROMETRIC STATION	GAUGE NO.
1	Fraser R. at Steveston	08MH028
2	Fraser R. (North Arm) at Vancouver	08MH032
3	Fraser R. at Port Mann	08MH054
4	Pitt R. near Port Coquitlam	08MH035
5	Fraser R. at Mission	08MH024
6	Fraser R. at Whonnock	08MH044
7	Harrison R. below Morris Creek	08MG022
8	Harrison R. at Harrison Mills	08MG014
9	Harrison R. near Harrison Hot Springs	08MG013
10	Fraser R. at Hope	08MF005
12	Harrison Lake near Harrison Hot Springs	08MG012
13	Fraser R. at Deas Island Tunnel	08MH053
14	Fraser R. near Harrison Mills	08MF073
15	Fraser R. at Cannor	08MF038
16	Fraser R. at Laidlaw	08MF072
17	Fraser R. near Agassiz	08MF035
ID	**CHS TIDAL GAUGE**	**GAUGE NO.**
1	Point Atkinson	07795
2	Vancouver Harbour	07735
3	Sandheads Light	07594
4	New Westminster	07654
ID	**BC HYDRO GAUGE**	
1	Wahleach Powerhouse	
ID	**GOLDEN EARS BRIDGE GAUGE**	
1	GEB Burnco Site	

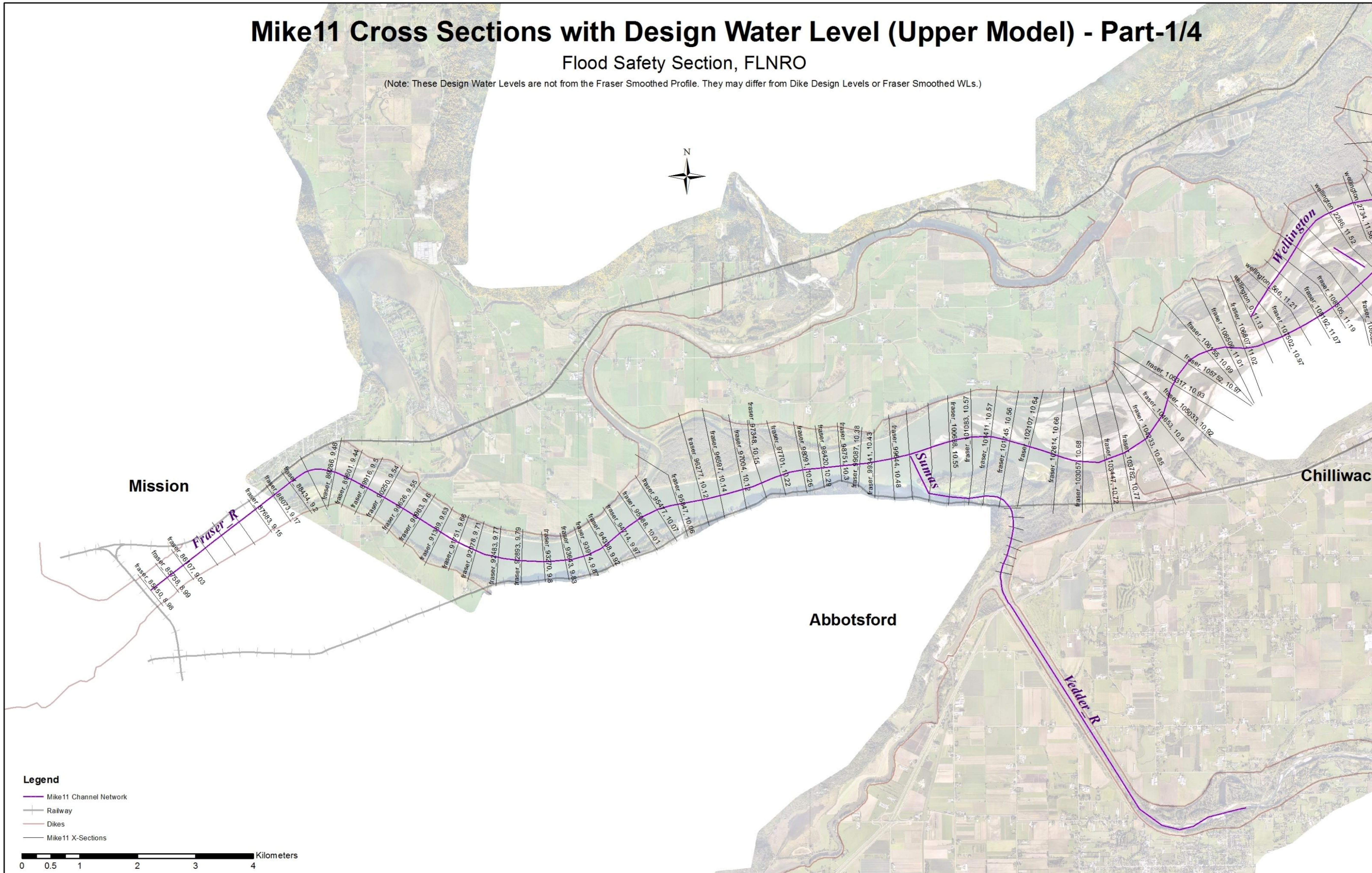


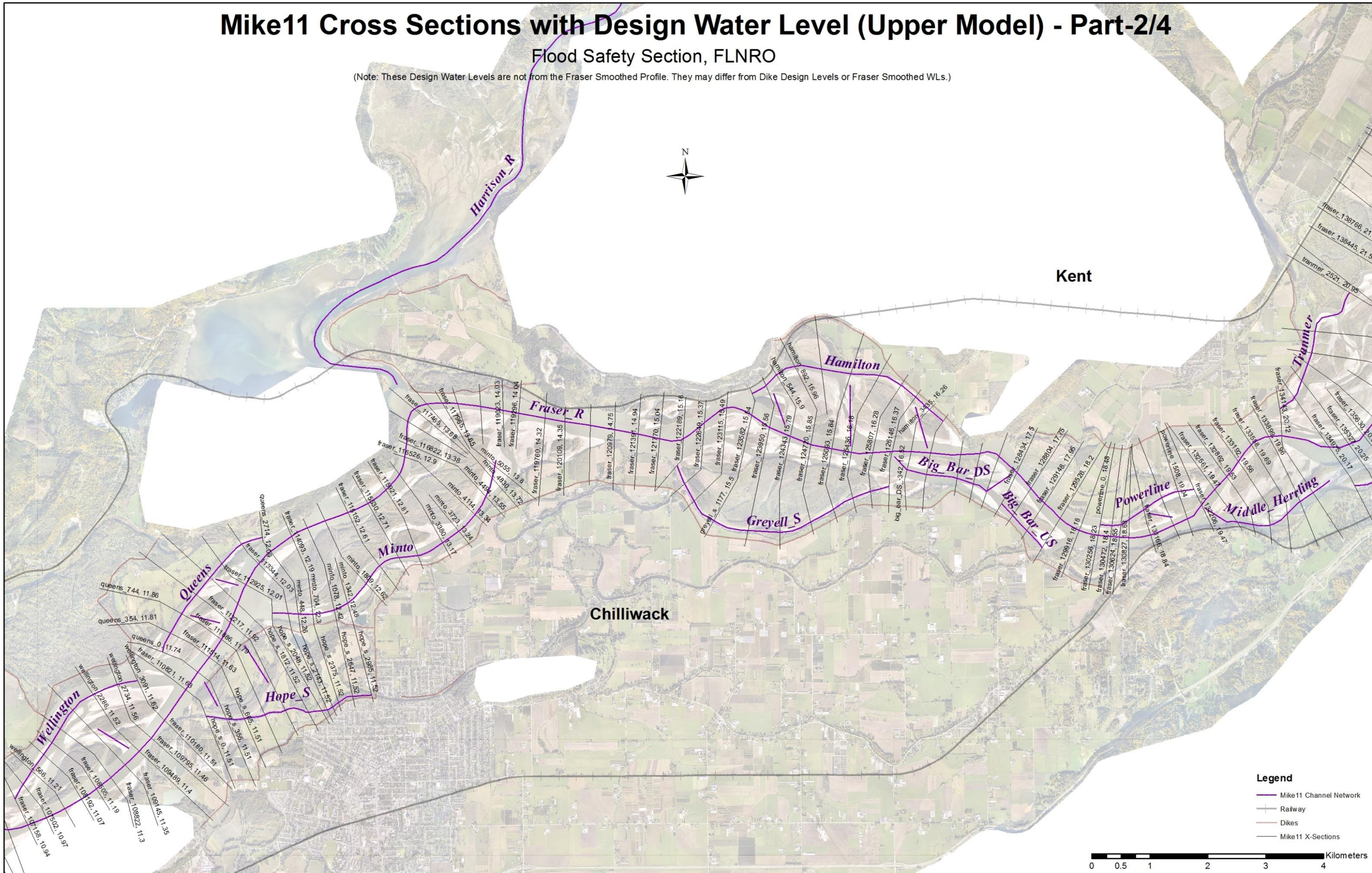

Dikes Along Fraser River (Gravel Reach)
Flood Safety Section, FLNRO
N
Hope
Kent
KENT - D
KENT - C
KENT - B
KENT - A
CHILLIWACK DIKE
ISLAND 22 WING DIKE
YOUNG RD TO CWK MOUNTAIN
NICOMEN ISLAND DIKE
Mission
DEWDNEY DIKE
MATSQUI B DIKE
MISSION DIKE A
MATSQUI A DIKE
Chilliwack
VEDDER RIVER - RB
VEDDER RIVER - LB
Abbotsford
Legend
Dikes
Channel Network
Kilometers
0 0.5 1 2 3 4

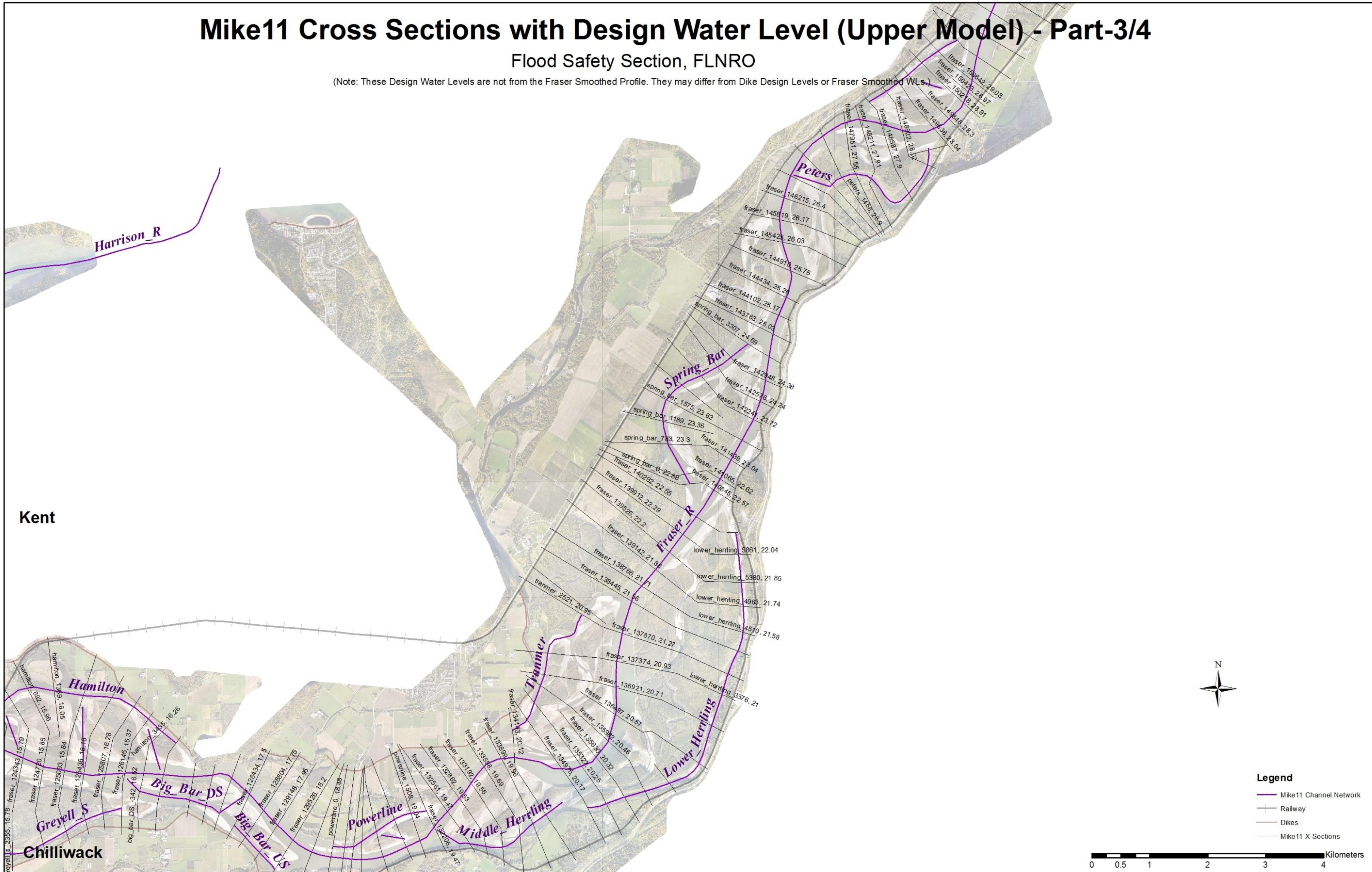

Fraser River Channel Network (Upper Model)
Flood Safety Section, FLNRO
N
Hope
Kent
Mission
Chilliwack
Abbotsford
Harrison_R
Fraser_R
Sumas
Vedder_R
Wellington
Queens
Minto
Hope_S
Hamilton
Greyell_S
Big_Bar_DS
Power line
Tranmer
Lower_Herrling
Spring_Bar
Peters
Wahleach
Legend
Channel Network
Railway
Dikes
Boundary
Head Loss
0 1 2 4 6 8
Kilometers

Map 4 - MIKE 11 Cross Sections (Upper Model)

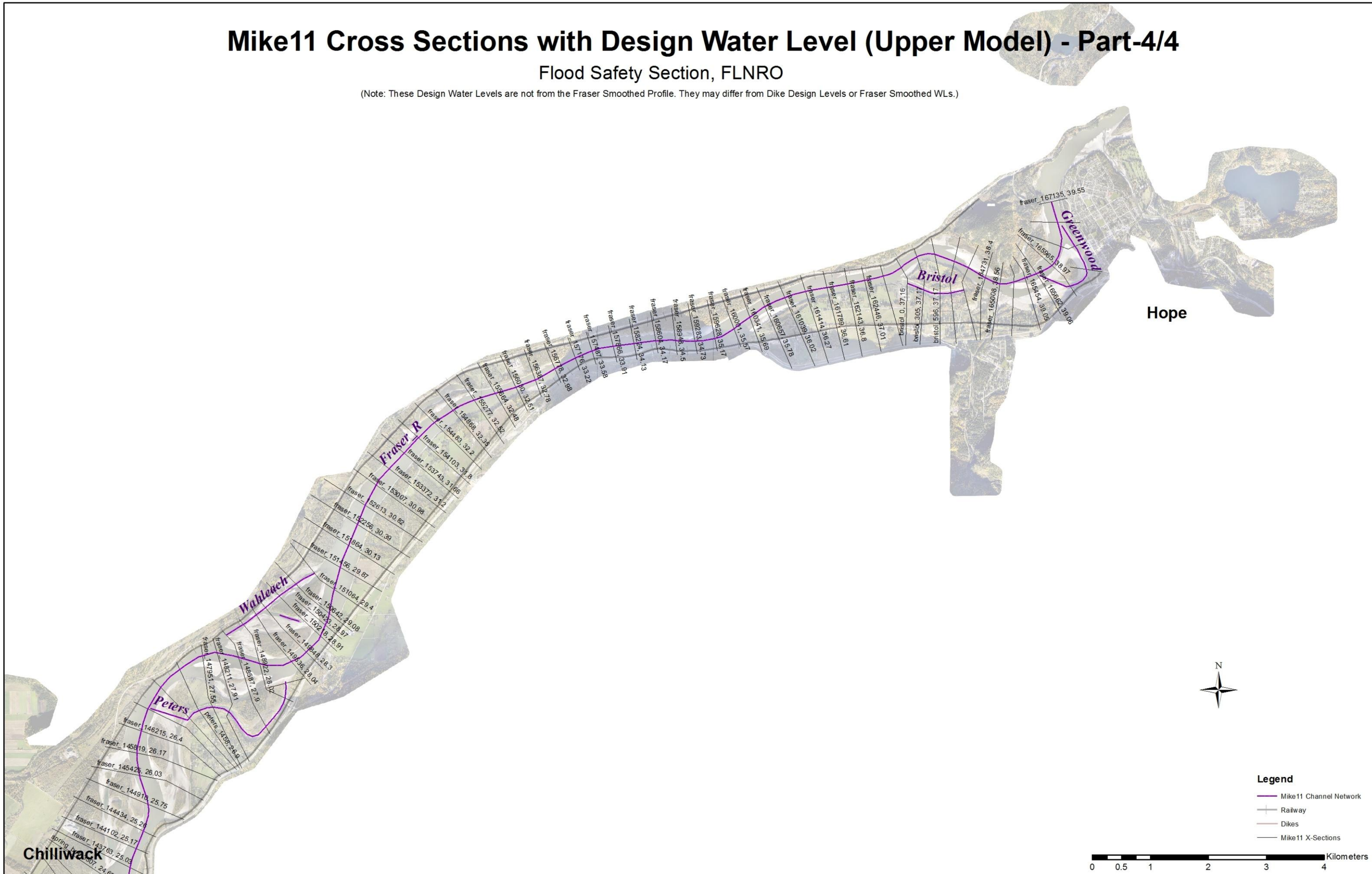



Mike11 Cross Sections with Design Water Level (Upper Model) - Part-1/4
Flood Safety Section, FLNRO
(Note: These Design Water Levels are not from the Fraser Smoothed Profile. They may differ from Dike Design Levels or Fraser Smoothed WLs.)
N
Mission
Abbotsford
Chilliwack
Fraser_R
Sumas
Vedder_R
Wellington
Legend
Mike11 Channel Network
Railway
Dikes
Mike11 X-Sections
Kilometers
0
0.5
1
2
3
4


Mike11 Cross Sections with Design Water Level (Upper Model) - Part-2/4
Flood Safety Section, FLNRO
(Note: These Design Water Levels are not from the Fraser Smoothed Profile. They may differ from Dike Design Levels or Fraser Smoothed WLs.)
N
Kent
Chilliwack
Harrison_R
Fraser_R
Hamilton
Big_Bar_DS
Big_Bar_US
Greyell_S
Powerline
Middle_Herrling
Tranmer
Minto
Queens
Hope_S
Wellington
Legend
Mike11 Channel Network
Railway
Dikes
Mike11 X-Sections
0
0.5
1
2
3
4
Kilometers


Mike11 Cross Sections with Design Water Level (Upper Model) - Part-3/4
Flood Safety Section, FLNRO
(Note: These Design Water Levels are not from the Fraser Smoothed Profile. They may differ from Dike Design Levels or Fraser Smoothed WLs.)
Harrison_R
Peters
Spring_Bar
Fraser_R
Tranmer
Lower_Herrling
Middle_Herrling
Powerline
Big_Bar_DS
Big_Bar_US
Hamilton
Greyell_S
Kent
Chilliwack
fraser_146215, 26.4
fraser_145819, 26.17
fraser_145425, 26.03
fraser_144434, 25.28
fraser_144102, 25.17
spring_bar_1575, 23.62
spring_bar_1189, 23.36
spring_bar_783, 23.3
lower_herrling_5861, 22.04
lower_herrling_5380, 21.85
lower_herrling_4963, 21.74
lower_herrling_4510, 21.58
fraser_137870, 21.27
fraser_137374, 20.93
fraser_136921, 20.71
lower_herrling_3376, 21
tranmer_2521, 20.95
N
Legend
Mike11 Channel Network
Railway
Dikes
Mike11 X-Sections
0
0.5
1
2
3
4
Kilometers

Map 8 - MIKE 11 Cross Sections with Water Levels (Upper Model) - Part-4/4



APPENDICES

Appendix 1

Transposition calculation from Tenas Narrows to Harrison Lake inlet

A summary of the tests conducted by WSC are as follows. The gauge was operated from May 7 to Oct 29, 2012 with final approved flows from May 15 to Aug 24. The data at the start and end of the operation period was thrown away due to dry sensors. A total of 8 discharge measurements were made using ADCP tethered boat. Four of these measurements were discarded due to difficulties collecting data because of large eddies downstream of the bridge. At high flows, the eddies were washed away thus making the ADCP tethered boat successful. However, the remaining three measurements were done upstream of the bridge using an open boat with mounted ADCP which proved to be a better method. Using the four successful measurements, a stage discharge relationship was developed. Number of measurements was not enough to determine if hysteresis was occurring. WSC approved the data for use and decided to continue with the temporary location of the gauge in 2013 suggesting a total of 6 visits from May to August. WSC recommended taking the flow measurements using an ADCP tethered boat deployed from a small manned boat upstream of the bridge.

Since this gauge is located 52 km upstream of the Harrison lake inlet, in order to transpose this data to the inlet, NHC suggested using the following calculations (based on Watt et al. (1989) Hydrology of Floods in Canada: A Guide to Planning and Design. National Research Council of Canada) .

The drainage-area ratio method commonly is used to estimate stream flow for sites where no stream flow data are available using data from one or more nearby stream flow gauging stations.

$Qu = Qg\ (Au/Ag)^m$

where,
Qu = flow at ungauged location in river basin
Qg = flow at gauged location in river basin (1136 m^3/s)
Au = drainage area for ungauged location (1,310,580 ha)
Ag = drainage area for gauged location (1,151,420 ha)
m = exponent to adjust for systematic difference in the ratio of drainage-area to flow.

Applicable for two locations with catchments that:
- are in the same climatic regime
- have similar hydrogeological characteristics
- are similar in size (within 50%)
- are unregulated

Exponent values of 0.6 and 0.9 were used (Watt et al. pg 59-60) resulting in increases of 12% and 8%. A 10% increase was selected. The travel time of 5 hours was estimated based on a distance of 52 km and assuming an average flow velocity of 3 m/s.

It is important that WSC turns Tenas Narrows into a real-time reporting gauge and that the WARNS model be updated accordingly.

Appendix 2

NHC Endorsement Letter

30 Gostick Place | North Vancouver, BC V7M 3G3 | 604.980.6011 | www.nhcweb.com

nhc
northwest hydraulic consultants

Project No. 300120
June 6, 2013

B.C. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO)
Flood Safety Section
Suite 200, 10428-153rd Street
Surrey, BC, V3R 1E1

Attention: **Khalid Khan, P.Eng.**
Senior Flood Safety Engineer

Dear Mr. Khan:

Subject: **Fraser River Gravel Reach – Hydraulic Model Update**
Work Phases I to IV
Letter of Endorsement

1 INTRODUCTION

An accurate and up-to-date hydraulic model of the Fraser River forms an important tool to:

- Establish the design flood profile for dikes and other infrastructure.
- Allow real-time flood level forecasting during freshets for emergency response.

In 2000, City of Chilliwack in cooperation with Ministry of Environment (MOE) retained UMA Engineering Ltd (UMA) to prepare a one-dimensional hydrodynamic model of the 65 km long gravel bed reach from Laidlaw to Mission. The model, using MIKE11 software, included Harrison River below Harrison Lake and the lower Vedder River (UMA, 2001).

In 2006, the Fraser Basin Council with support from MOE retained Northwest Hydraulic Consultants (NHC) to develop a MIKE11 model for the 85 km Fraser River sand bed reach from Mission to the Strait of Georgia (NHC 2006). Following this work, under a project initiated by MOE, NHC merged the upper and lower models and revised the design profile, corresponding to the 1894 flood of record. Some improvements were also incorporated into the upper model (NHC 2008a). During the 2007 freshet, the model was ready for real-time flood level forecasting and provided valuable input for flood response along the river (NHC 2007). Since then, the model has been operated every freshet, except for year 2010 which had flows well below average. For the first few years the forecast model was run by NHC but subsequently, with NHC's guidance, MFLNRO has operated the model.

Due to on-going river changes, UMA (2001) recommended that the gravel bed channel and adjacent floodplain be resurveyed and the model updated every 10 years. In 2008, MOE arranged for the collection of new bathymetry and LiDAR data to replace the previous model geometry from 1999. Data was also collected for the 15 km reach between Laidlaw and Hope to extend the model upstream. With the long-term goal of MFLNRO developing expertise for updating and running the model, MFLNRO undertook to update and extend the gravel reach model in-house with guidance from NHC.

The purpose of this letter is to summarize NHC's review of the model update and assess the quality of work completed by MFLNRO. In addition, comments on the accuracy of the updated model are provided along with a comparison of the previous and revised design profiles. Recommendations on future usage and forecasting are also listed.

Key NHC staff involved in the project included Dave McLean (Review Principal); Tamsin Lyle (Model Engineer Phases I and II); Vanessa O'Connor (Model Engineer Phases III and IV); Sarah North (GIS Specialist) and Darren Ham (Geomorphologist). The project was managed by Monica Mannerström.

2 SUMMARY OF WORK COMPLETED

The work was carried out in four phases, with each phase completed annually from 2010 to 2013. Key tasks involved with each phase were as follows:

Phase I:

- Develop a DEM (Digital Elevation Model) using river soundings collected by Public Works and Government Services Canada (PWGSC) during the 2008 freshet and LiDAR collected in the fall of 2008 by Terra Remote Sensing.

Phase II:

- Develop a MIKE11 network and cross-section layout.
- Cut cross-sections from the DEM and import data into MIKE11.
- Generate boundary condition and parameter files.

Phase III:

- Test the model.
- Review and modify as necessary the network layout, cross-section geometry, initial roughness coefficients and other model parameters.
- Review initial calibration/validation data and results.
- Review initial assessment of design profile.

Phase IV:

- Incorporate model revisions from Phase III.
- Update the DEM in the reach near Agassiz with river soundings collected during the 2012 freshet.
- Recalibrate the model using data from the 2012 freshet and validate to 2007 and 2011 data.
- Merge the model with the sand bed reach model.
- Generate an up-to-date design profile.
- Add Harrison Lake and prepare the model for freshet real-time flood level forecasting (to be completed).

3 Review Process And Assessment of Work Completed

For each phase, NHC initially provided an overview of the work required, suggested ways to complete the necessary tasks, reviewed the work carried out by MFLNRO, provided revisions as necessary and confirmed final results. All MFLNRO work components were reviewed and approved before the next task was commenced.

Throughout the project, there was excellent communication and cooperation between MFLNRO and NHC. MFLNRO's work was of high quality, and the model development was completed to NHC's satisfaction.

Ideally, a model update should be completed shortly after the collection of new survey data. The present update, forming a training exercise and limited by MFLNRO budget and time constraints, took longer than initially envisioned.

4 Model Accuracy

The MIKE11 software, developed by the Danish Hydraulic Institute, is a one-dimensional hydrodynamic modelling tool used world-wide. The Fraser River model, based on this software, is considered an excellent tool for simulating water levels along the river over a range of flows, based on known upstream and tributary inflows and downstream water levels.

4.1 Calibration and Validation Results

The gravel reach model was calibrated to extensive flow and water level data collected during the relatively high 2012 freshet. ADCP flow measurements were collected at 34 transects on three separate occasions. A network of 17 continuous and 30 staff gauges was in operation and a continuous long profile of Fraser River water surface elevations was collected near the peak of the freshet. Unfortunately, some uncertainty is still associated with the inflows entering from the Harrison system and other minor tributaries which combined contribute in the order of 10% of the total flow at Mission.

In 2012, the Fraser River peak flow had a return period of about 40 years at Prince George but the return period is estimated at less than 20 years at Hope. Observed Water Survey Canada (WSC) flows are not yet finalized and preliminary values were used in the calibration. Results should be confirmed once final flows are available. The model was validated to 2007 and 2011 freshet flows.

Calibration and validation results are summarized in Table 1. Based on the differences between modelled and observed water levels at the peak flows, the model accuracy over a range of flows is estimated to be +0.1 m (on average) ranging up to a maximum of +0.43 m locally for 2007 at the Camp Hope Intake Project (CHIP), with the model generally predicting levels slightly higher than observed. It should be recognized that some gauges located in side branches are unrepresentative of water levels in the main channel.

The agreement between observed and simulated water levels is considered good and is similar to that of previous modelling. A number of attempts to improve the agreement were made by MFLNRO but were unsuccessful. Although, the model agreement can be improved within the calibration/validation flow range, any modifications that are unrepresentative of channel and floodplain physical conditions are not recommended and could produce erroneous results at different flows.

Table 1. Calibration and validation results

Flow at Hope (m^3/s)	Freshet Year	No. of Observations	Absolute Difference in Modelled and Observed Water Levels (m)			
			Average	Median	Min	Max
9,780	2011	11	0.09	0.06	0.01	0.22
11,125	2007	22	0.10	0.09	0.01	0.43
11,870	2012	27	0.10	0.08	0.02	0.25

4.2 Model Limitations

Like any one-dimensional hydraulic model, the Fraser model update has some inherent limitations:

- The gravel reach of the Fraser contains a number of bars, mid-channel islands and sharp bends giving rise to complex flow patterns. By definition, a one-dimensional model cannot account for two or three dimensional flows and represents velocities and water levels as sectional averages. In some areas, such as at Agassiz Bridge, near CHIP Intake and at Harrison Knob this limitation is fairly significant.
- A hydraulic model represents a snap-shot of a river at the time of surveys. The gravel reach is actively changing both in the long-term and during a particular flood. Over time, the channel will continue to change as avulsions take place, meanders grow and vertical bed level changes occur. To accurately represent the river, the model will require regular updating. During a large flood, the channel is likely to undergo significant changes that even a recently updated model may be unable to portray accurately. The model assumes a fixed bed, flow confined by dikes and a particular lateral configuration. In the event of avulsions, severe scour or a dike breach, water levels in the channel may be lower than modelled. Potential increased sinuosity would have the opposite effect.
- The model accuracy is influenced by the magnitude of the flows used for calibration and validation. Whereas the data collected in 2012, 2011 and 2007 were of excellent quality, the adopted design flood would be more than 40% higher. At flows well outside the calibration/validation range, the accuracy of the model is difficult to assess.
- The gravel reach model is sensitive to the starting level used at Mission. Any inaccuracies in the Mission boundary condition are transferred upstream for some distance.

5 Comparison of Updated and Previous Design Profiles

The Fraser River design flood (17,000 m^3/s at Hope) corresponds to the 1894 flood of record, estimated to have had a return period of about 500 years (NHC 2008b). The equivalent estimated flow at Mission, assuming flow confinement between dikes, would be 18,900 m^3/s, corresponding to a water level of 8.9 m GSC at Mission gauge (NHC 2006). To compare the MFLNRO updated design profile based on 2008 surveys with the previous profile derived based on 1999 surveys, these boundary conditions were adopted. Identical tributary inflows were assumed for both models.

A direct comparison is difficult due to the modifications made to the new model network and the changes that have taken place in the river. Due to shifts in the Fraser River main channel, the distance along the river thalweg has changed. These shifts were most pronounced at Hamilton Bar, Lower Herrling Island and Peters Island. The updated model chainage was adopted for the comparison.

In general, the simulated design water levels were within ± 0.2 m for the two profiles. Larger differences of 0.5 m up to 0.8 m were computed at the few locations where significant channel shifts occurred between 1999 and 2008 (Hamilton, Herrling, Peters). Typically, the updated profile was lower than the previous profile. It is unclear to what extent the model improvements rather than the river modifications influenced the results. General observations are:

- The two profiles are fairly similar, although they were derived using different survey data and were based on slightly different modelling approaches.

- Lateral channel changes can have significant impact on flood levels, falling outside the current freeboard allowance of 0.6 m. For determining Flood Construction Levels (FCL's), consideration should be given to basing the design profile on the higher of the two simulated design profiles except in reaches where the reason for the water level reduction is clearly understood and due to improved modelling/ calibration data. Over time, as the model is updated based on new channel geometries, it is suggested that the upper envelope curve of the different simulated design profiles be adopted for dike crest design.

- As was observed during previous work, the simulated design profile showed a series of minor computational irregularities. These are typically observed at branch junctions and, in spite of a number of attempts to fine-tune the model, could not be eliminated. Mathematically (or graphically) smoothing the design profile based on modelling experience/judgement is recommended.

6 FUTURE REAL-TIME FORECASTING

For future real-time flood level forecasting, MFLNRO joined the updated gravel reach model with the previously developed model downstream of Mission. The merged model was found to give somewhat higher water levels near Mission than the lower (sand bed) model. For future forecasting, it is important that the merged model be calibrated to the 2012 data by adjusting roughness coefficients downstream of Mission. Currently, the merged model is over-predicting water levels at Mission by 0.24 m (2012 freshet) and 0.21 m (2007 freshet). The likely reasons for the lower model giving different results than the merged model are:

- The lower model uses WSC flows at Mission for input, based on a rating curve that ignores tidal influences and incorrectly assumes that the peak discharge occurs at the same time as tidal peak water level. Also, the bed level at Mission is continuing to degrade as seen over the past 40 years or so, affecting the WSC rating.

- The lower model ignores the routing and attenuation of peak flows that occur in the river system, resulting in peak flows at Mission being lower than the summation of upstream flows.

The lower model was calibrated in 2007 to a Mission flow that was subsequently revised by WSC to a higher value. It is recommended that the accuracy of the WSC 2012 ADCP measurements be reviewed with WSC and that these be used for re-calibration, considering the WSC reported flows at Mission disregard tidal influences.

WSC should be encouraged to install permanent ADCP measurement equipment at Mission which would improve flow observations and hence the accuracy of freshet forecasting. Ideally, observed and simulated flows at Mission should be monitored throughout the freshet to adjust upstream tributary flows and resolve current minor discrepancies.

Previous work by NHC, which modelled the 1948 flood using 1950 bathymetry, implied that bed forms downstream of Mission (river km 47 to 85.4) may reduce in size for discharges in the 12,000 m^3/s to 15,000 m^3/s range, potentially allowing a reduction in n-values from 0.028 to 0.027. Consequently, four hydraulic parameter files were generated for this flow range. The 2012 freshet flow, which exceeded 12,000 m^3/s, is within the flow range where roughness was found to vary with flow. A re-calibration of the lower model needs to take this into account and roughness coefficients for flows less than 12,000 m^3/s should likely be increased beyond the values derived from the calibration to the 2012 peak data.

For flood level forecasting, it is important that Harrison Lake be incorporated in the model and that RFC be able to provide accurate flow predictions for Lillooet River at Harrison Lake inlet. A new WSC gauge was installed at Tenas Narrows and now reports in real-time. NHC is currently carrying out hydrologic analyses on Lillooet River for the Lower Stl'atl'imx Tribal Council and final results, when available, may be of interest to MFLNRO.

The model should be run annually, even during moderate freshets, to regularly verify the agreement between observed and simulated water levels. The gauge network should be maintained or preferably expanded, particularly along the main channel. Some of the present gauges, located in side channels and influenced by backwater, cannot accurately be represented in the model. In some locations, the model is known to have limited accuracy due to the presence of strong two-dimensional flow patterns. In these areas, such as CHIP Intake, the model under-predicts water levels and special alerts should be issued with any forecasted water levels.

The limitations outlined in Section 4.2 also apply to the forecasting model. In addition to these limitations, the model accuracy is also limited by the accuracy of the discharge forecasts issued by RFC.

7 CONCLUSIONS AND RECOMMENDATIONS

MFLNRO developed a high quality 1D model of the Fraser River gravel reach. The model was calibrated and validated using an extensive set of flow and water level measurements which showed the model to have an overall accuracy typically within ± 0.1 m for the specific flood events in 2007, 2011 and 2012. The accuracy of the model under the much higher design flood condition, or after morphologic changes may be substantially different. To better understand the impact of lateral channel changes on the design profile, further investigation following river avulsions, should be carried out.

Although a direct design profile comparison is difficult due to changes in channel morphology and some differences in modelling approach, the updated design profile shows relatively small variations (± 0.2 m) from the previous design profile over most of the study reach. More significant differences (± 0.5 to 0.8 m) were computed upstream of channel locations where significant morphologic changes took place between 1999 and 2008.

It is recommended that the updated model be used for future work. Basing FCL's on the higher of the two simulated design profiles is suggested. Mathematical or graphical smoothing of this "upper envelope" design profile is recommended to remove any minor computational irregularities. In view of the dynamic nature of the river and the magnitude of bed changes that occur, special consideration should be given to selecting an appropriate freeboard for establishing flood construction levels. In addition to the degree of morphologic change and modelling uncertainty, freeboard should also be assessed in terms of flood risks. The selection process would involve a series of sensitivity analyses, assessment of hypothetical channel shifts (as per personal communication with Dr. M. Church) and risk assessments.

It is recommended that a two-dimensional model be developed to improve model performance where 2D hydraulics play an important role and water levels between the right and left banks vary significantly. Software and computational performance have improved considerably over the last few years making it more feasible to model the gravel reach of the Fraser River using a two-dimensional model.

It is recommended that the reach downstream of Mission in the merged 1D model be recalibrated to WSC 2012 ADCP measurements and validated to revised 2007 flows. The re-calibration needs to take into account that roughness coefficients for flows less than 12,000 m^3/s may be higher than those derived based on the peak 2012 data. Roughness coefficients for the design flow (based on the 1950's historic model) would not be expected to change but need to be confirmed in view of the flow differences between the lower and merged models at Mission.

WSC should be encouraged to install permanent ADCP measurement equipment at Mission which would be invaluable during freshet forecasting to resolve discrepancies between actual flows at Mission and the summation of upstream flows. The WSC gauge for Lillooet River at Tenas Narrows now reports in real-time and should be used by RFC for flow forecasting.

During forecasting, attention should be given to the model's limitations in simulating complex hydraulic conditions at certain known locations.

The gravel reach model will need updating at least every 10 years, or more frequently following very large floods, to reflect changes in the river geometry. The sand bed model will similarly require updating, tentatively in 2014-2015, 10 years following the previous surveys. More recent bathymetric data may be readily available from PWGSC for the navigation reach downstream of Port Mann.

Over time, climate change will impact Fraser River peak flows and flood levels. Presently, these impacts are not well understood and should be investigated.

* * * * *

If you have any questions, please do not hesitate to contact us at 604.980.6011.

Sincerely,

northwest hydraulic consultants ltd.

original signed by

Vanessa O'Connor, P.Eng.
Hydraulic Modelling Engineer

original signed by

Monica Mannerström, P.Eng.
Associate

Reviewed by:

original signed by

David McLean, P.Eng.
Principal

CC: Mr. Neil Peters, P.Eng., MFLNRO, Head, Flood Safety Section

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DISCLAIMER