AN EVALUATION OF THE GRAVEL TRANSPORT

CAPABILITIES OF MIKE 11

CASE STUDY – THE FRASER RIVER GRAVEL REACH

By

JEFFREY BRUCE CROFTON

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Department of Civil Engineering
The University of British Columbia
Vancouver, BC Canada

Abstract

The morphological capabilities of the one-dimensional software package MIKE 11 were evaluated using the Fraser River Gravel Reach as a case study. A previously developed 'fixed bed' hydrodynamic model (UMA, 2001) was used as the basis of the MIKE 11 morphological model to evaluate if it could be easily altered to provide this functionality.

The evaluation found that MIKE 11 is not nearly far enough along in its development to perform sediment transport calculation to any high degree of accuracy when applied to a looped network of the complexity of the Fraser River. Many parts of the software were either found to be faulty or unable to handle the complexity of branched flow. A secondary objective of the investigation attempted to apply the morphological routines of MIKE 11 on a modified river network that included only the Fraser main stem. Initial results look promising, and this is proposed for further study.

An in-depth discussion of the attempts at model development and problems encountered is presented as well as recommendations for future advancements that would greatly improve the user interface and model computational characteristics.

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The author would like to thank the Danish Hydraulics Institute for supplying the MIKE 11 modeling software and providing technical support for the duration of this thesis. Deep gratitude is also expressed to Michael Church and Darren Ham of the University of British Columbia's Department of Geography for their input and expertise on the subject matter. Thanks also to Ron Henry of the Ministry of Water, Land and Air Protection for use of some of their collected data and digitized boundaries. Thanks to Yaroslav Shumuk for his direction and David Zabil for the countless questions he answered throughout the modeling process. Lastly, great thanks to my supervisor, Dr. Robert Millar for his guidance and understanding.

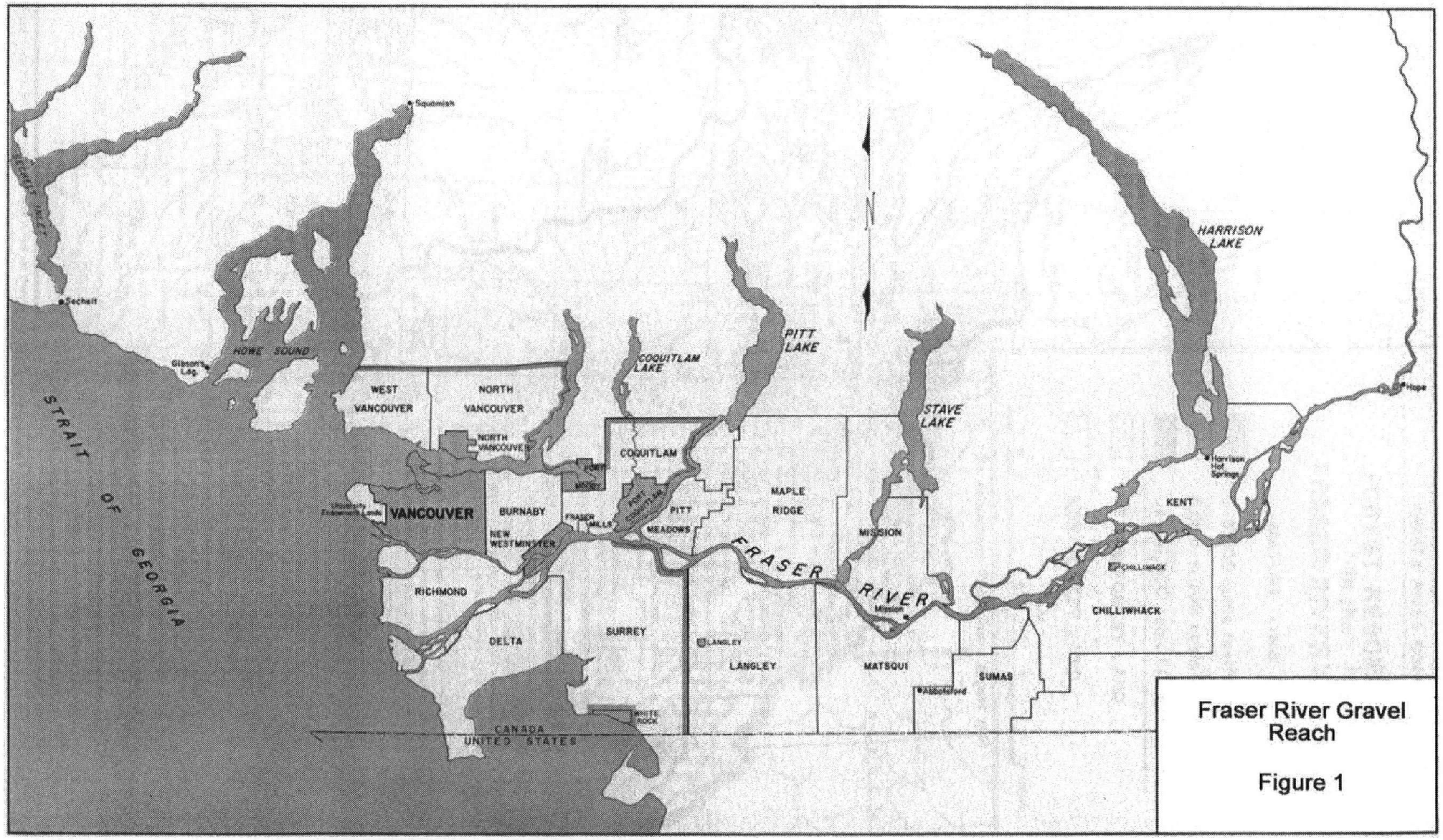
Jeff Crofton, 2003

1.0 INTRODUCTION

The Fraser River downstream of Hope, British Columbia has a catchment area of 217,000 km^2 (Environment Canada, 1990). The 65km of the Fraser River from Hope to Sumas Mountain represent the gravel reach (Church, 1999) whose location is depicted in Figure 1. The gravel bed in this region possesses valuable fish habitat (Church, Remple & Rice, 2000) and the river is bounded by valuable agricultural lands and large settlements such as Chilliwack, Abbotsford and Mission. The protection of these valuable lands and resources in an on-going concern due to the river's continual lateral movement and morphology.

The Fraser River morphology downstream of Laidlaw forms a confined alluvial fan in which the river was historically free to move laterally across the fan. Alluvial fans are created when high gradient rivers accumulate and transport sediment through erosion and tributary sediment input in the upper reach to a downstream lower gradient region. When a decrease in the river gradient is realized, the river can no longer support the transportation of its accumulated sediment and deposition occurs (Church, 1999).

This is the case in the Fraser River, which has a steep mountain gradient upstream of Laidlaw that flattens sharply as the river exits the mountain canyons. The resulting alluvial fan will continue to aggrade as long as the sediment supply is greater than that which can be transported across the fan (Church, 1999).



Fraser River Gravel Reach

Figure 1

Alluvial fans are characteristically unstable and rivers tend to move laterally across the fan as deposition creates an obstruction of the flow path and the bed level increases beyond the adjacent fan elevation (Church, 1999). Past development along the gravel reach in the form of settlements, dykes and railways have confined the Fraser River to a smaller portion of the historical alluvial fan, and as a result, all of the deposition that was once distributed across the entire fan is now constrained.

The difference in gravel entering the reach with that leaving is defined as the gravel budget. The annual gravel influx past Agassiz-Rosedale Bridge has been estimated at 285 000 m^3. This entire gravel load passing the Agassiz-Rosedale Bridge is deposited along the gravel reach upstream Sumas Mountain (Church et al, 2001). Therefore, this positive influx defines the gravel budget. Although several studies to predict this rate have been conducted by Ham, 2000; Church et al, 2001; and McLean, 1999; it is estimated that errors in estimation could range as high as +/- 40% (McLean et al, 1999).

As stated by Church in his 1999 Progress Report on sedimentation and flood hazard in the gravel reach of Fraser River, "confinement of the river raises flood water levels beyond those they would otherwise reach, and increases the rate of rise of the riverbed because sediment deposition occurs only within the restricted channel zone".

It follows that an increase in the flood profile caused by a rise in the bed level reduces the effectiveness of dykes protecting valuable lands and human life along the river. To evaluate this increasing risk, periodic updates to the water surface profile for the design flood event are required. The last update to the flood profile was complete by UMA Engineering Ltd. (UMA) in 2001.

UMA's flood study developed a MIKE 11 hydrodynamic model of the entire gravel reach and incorporated a complex network of side channels, floodplain reaches, tributaries and the Fraser River main stem as a realistic representation of storage and flood routing. The model achieved good calibration against the 1999 freshet, and was verified against the 1997 peak discharge. The model was subsequently used to predict the flood surface profile for two extreme events of record, namely the 1894 and 1948 flood events using 1999 bathymetry and the design flood discharge of 17,000 m^3/s (UMA, 2001).

The hydrodynamic model created by UMA was based on bathymetry from Water Survey of Canada soundings and Terra aerial laser surveys both performed in 1999. This 'fixed bed' model incorporated a stationary bed and did not allow bedload transport and therefore no update of the bathymetry during the simulation. For additional information on the development of this model the reader is referred to that study's final report to the City of Chilliwack (UMA, 2001).

The influence of increased bed levels as a result of sedimentation within the reach presents a significant potential flood hazard to human settlements within the Lower Mainland of British Columbia (Church, 1999). This is evident in the results of UMA's flood surface profile update, in which it was found that at a flow of 15,000 m^3/s, which is approximately equal to the 1948 flood discharge and substantially less than the design flood discharge of 17,000 m^3/s, three sections of dyke were significantly overtopped by depths of water ranging from 0.1 to 0.3 metres (UMA, 2000). For the design discharge it was found that sections of the Kent D dyke would deficient by almost 0.85m (UMA, 2001).

The costs for raising dykes that were identified as being below the Ministry of Water, Land and Air Protection standard of the flood crest elevation plus an additional 0.6m freeboard was also investigated during the UMA modeling study. The range of costs was initially estimated between $20.5 and $34.7 million depending on the approach taken (UMA. 2000). This was later refined to $17.5 million (UMA, 2001).

The development of a morphological model may provide consultants and managers with a tool whereby a river gravel management approach can be developed to reduce these costs and predict future influences of present gravel extraction, dyking and development activities along the reach.

1.1 Study Objectives

The objectives of this study were to:

- Evaluate the morphological capabilities of MIKE 11 by expanding the existing 'fixed bed' hydrodynamic model developed by UMA Engineering Ltd.,
- Compare the distributed gravel budget within the Fraser River Gravel Reach with that obtained by Church et al (2001), and
- Simulate the affect of future gravel deposition on the design flood profile.

1.2 Scope of the Study

To meet the study objectives outlined above, the following tasks were anticipated during this investigation:

- Modification of the existing UMA (2001) developed hydrodynamic model to a coupled hydrodynamic - morphological model based on 1983 bathymetry instead of 1999.
- Simulation of morphological impacts by running the model using flows for the period from 1983 to 1999.
- Comparison of model predicted bathymetry and cross-sectional characteristics for 1999 against bathymetry data collected by Water Survey of Canada.
- Simulation of future sedimentation affects on the flood design profile by running a simulation forward from 1999 for a period of 16 years to update the bed to model predicted cross-sections for the year 2015. This bed will then be used to predict the water surface profile for a discharge of 17,000 m^3/s.

A successful outcome would have produced a useful tool for consultants or managers to evaluate options for gravel extraction, new bank protection and dyking work. However, several problems were encountered that did not allow successful completion of the study. These are outlined below.

1.3 Problems Encountered

The anticipated objectives set forth in this study were not successfully completed. The current MIKE 11 morphological module is not able to handle the complexity of the Fraser River Gravel Reach morphology. As well, several software bugs and shortcomings were discovered that did not allow for the successful simulation of gravel transport or an evaluation of future affects on the flood design profile. Therefore, this thesis contains a description of attempts at model development, recommendations for future software improvement and possible avenues of on-going research.

1.4 Thesis Outline

This thesis is presented in the following manner. For a more in-depth description please refer to the Table of Contents.

Chapter 1 – Introduction (this section)
Chapter 2 – Previous Investigations
Chapter 3 – Model Development
Chapter 4 – Model Testing and Simulations
Chapter 5 – Conclusion
Chapter 6 – Recommendations
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Appendices

2.0 PREVIOUS INVESTIGATIONS

As mentioned in the introduction, numerous investigations have been conducted in the past attempting to quantify the sediment budget and update the hydrodynamics of the lower Fraser River (McLean and Church, 1986; McLean and Tassone, 1987; McLean et al, 1999; Ham, 2000; Church et al, 2001; UMA, 2001). This section will briefly review some of these earlier works, and is presented to the reader as background only. For detailed information on these studies, the reader is referred to the works cited.

2.1 Water Survey of Canada

Although there are no recent physical measurements of sediment influx to the gravel reach, the Water Survey of Canada (WSC) performed bedload transport measurements just downstream of the Agassiz-Rosedale Bridge for a period of 20 years from 1967 to 1986. These measurements become the basis for much of the research conducted by McLean and Church (1986) and re-examined by McLean et al (1987).

McLean et al (1999) subsequently developed a rating curve for sediment influx vs. discharge based on the former WSC measurements, but the curve exhibited much scatter. Despite the substantial scatter, the curve was used to estimate long term transport based on the following equation:

$$\log_{10}G = -17.7 + 5.41 \log_{10}Q \qquad \text{Eq. 1}$$

Where: G represents the gravel transport and Q is the discharge at Hope. Although the closest estimation possible given the data set, the equation indicated that the annual load was only specified to within +/- 40% (Church, 2001).

In an attempt to improve on this estimation, Church (2001) attempted to develop a relationship that would correlate more closely to standard indices. The result was an empirical equation based on the annual maximum daily discharge at the Hope gauge:

$$\log_{10}G_a = -18.668 + 6.037 \log_{10}Q_{max} \qquad \text{Eq. 2}$$

This proved to provide a much closer estimation of the gravel influx to the reach as shown by its regression value of R^2=0.873 compared to McLean's 0.53. A review of these computations can be found in Church, 2001.

2.2 Cross-section Comparisons

Darren Ham, who is currently completing his Doctoral Studies in the University of British Columbia's Department of Geography, has conducting several studies using comparative surveys of the Fraser River channel cross-section to verify the mass transport of the river system (Church et al, 2000, 2001).

Using sounding data from significant surveys conducted in 1952, 1984 and 1999, Ham created a digital elevation model of the river bed and compared cross-sectional areas to develop a net change in volume for the reach. The reach upstream of the Agassiz-Rosedale Bridge was not surveyed in 1984, therefore comparisons spanning from 1952 to 1999 were used for this part of the reach.

Based on studies completed to date, the gravel budget has been estimated in the range of 285,000 m^3/yr (Church et al, 2001). This represents a significant volume of gravel influx to the reach with a significant influence on the bed level approaching 3 cm/yr in some locations (Church, 1999).

2.3 UMA Engineering Hydrodynamic Update

As mentioned earlier, the UMA Engineering study forms the basis for this investigation. In 2000, UMA undertook a comprehensive hydraulic study of the Fraser River in an attempt to update the water surface profile for the design flood. For the Fraser, this has generally been established as a discharge of approximately 17,000 m^3/s.

This study was based on the 1-dimensional software package MIKE 11 as recommended by Millar and Barua (1999) and included a complex network consisting of the main stem, floodplains and side channels. This study predicted a significant rise in the water surface in many critical areas and estimated the potential economic impact of protecting developed areas.

2.4 Water Management Consultants Harrision Bar Study

In 2001, Water Management Consultants (WMC) conducted a morphological study on the portion of the gravel reach in proximity to the confluence with the Harrison River (WMC, 2001). This study investigated the effects of creating a large scale relief channel across Harrison Bar to reduce the water surface profile during a significant event.

Although the scope of this study was limited to the area of the Harrision River confluence, the UMA hydrodynamic model was used to provide all of the boundary conditions for the study.

2.5 Morphological Classification Study

In November 2000, a morphological classification study was also performed (Church, Remple and Rice, 2000). A portion of the findings from this paper reported that a trial scalping of Harrison Bar conserved and even increased available habitat depending on the methods used to remove gravel.

This is significant since gravel extraction is likely to form a significant part of any future Fraser River gravel management plan, with possible extraction volumes of up to 285 000 m^3/yr (Church et al, 2001). If these volumes are to be extracted, sustainability of habitat will be a large consideration.

2.6 Relevance of Past Investigations

In summary, past investigations reveal that gravel influx to the Fraser River Gravel Reach is an area of on-going study and accurate measurement or prediction of the sediment budget would provide a tool for analysis of future gravel management plans and affects on the flood surface profile.

Examination of the sediment collection studies performed by the WSC led to the development of the incipient motion criteria whereby initiation of bed gravel transport commences at approximately 5000 m^3/s (McLean et al, 1999). This finding was used during the development of the morphological model to greatly reduce the computational effort of the simulation.

The selection of MIKE 11 as the software package for the UMA hydrodynamic model was based on recommendations after a review of available modeling packages by Millar and Barua (1999). In addition to MIKE 11's hydrodynamic capabilities it offered the possibility of future morphological study using its sediment transport module. Although this was not a part of the UMA study, it was a secondary objective and therefore MIKE 11 was seen as the most applicable solution.

It is this recommendation to investigate the morphological capabilities of MIKE 11 that forms the objectives for this thesis. The next chapter presents a descriptive summary of the MIKE 11 morphological model development.

3.0 MODEL DEVELOPMENT

The development and analysis of MIKE 11's morphological capabilities forms the major component of this investigation. Using the 2001 UMA Engineering MIKE 11 hydrodynamic model as a basis, an attempt was made to transform this into a morphological model to verify software claims. This section describes the model development and transformation.

3.1 Hydrodynamic Model Background

A MIKE 11 hydraulic model of the Fraser River gravel reach was originally developed by UMA Engineering Ltd. in collaboration with the Ministry of the Environment and the City of Chilliwack. The model, developed in 2000 and updated in 2001, incorporates air-borne laser and sounding surveys to form the cross-sectional inputs to MIKE 11. These will be discussed further in the section on cross-sectional data.

The previous hydraulic model was calibrated against the 1999 freshet and verified against the peak discharge of 1997. The model was then used to predict the flood surface profile for the events of record in 1894 and 1948. However, to accomplish the prediction for 1894, it was necessary to exclude any geographical entities that were not present during this historic event. This included such things as the Matsqui dyke and the Canadian National Railway, which presents a distinct decrease in the cross-sectional area of the floodplain. This is included in the morphological model.

The hydraulic model was created with cross-sections approximately every 200 metres over the entire 65 kilometre length of the gravel reach, and incorporates a combination of floodplain, mainstem, and gravel bar branches in an attempt to gain accuracy in the final product and to address the differentiation in the Manning's roughness factors for these locations.

In order to transform the base hydrodynamic model into a functioning morphological model, specific elements were added or expanded upon. The most crucial of these is the complete revision of all the cross-sections for the main Fraser stem. The 1999 bathymetry was replaced with bathymetry from 1983. This was done to effect simulation with the morphological model using flows from the period 1983 – 1999 to evaluate if it correctly predicts the known 1999 cross-sectional characteristics.

Direct prediction of the 1999 cross-sections will not be possible, since a 1-dimensional model lacks the sophistication to calculate transverse velocity gradients which produce lateral shifts in the bathymetry. Rather, MIKE 11 calculates an average velocity across the entire cross-section and uses this to predict the change in bed elevation and the bulk sediment transport that has occurred. If compliance and prediction of the 1999 cross-sectional characteristics is found, the model can then be run forward to predict future morphological changes and affects on the water surface profile.

3.2 Planimetry

The user interface of MIKE 11 contains various dialogue boxes that encompass the areas of model development including horizontal layout of the river network, cross-sectional development, and hydraulic parameters. The network editor is the interface in which the user develops the horizontal layout of the system in real-world coordinates. Figure 2 portrays the MIKE 11 network interface. The complex network was developed through the aid of all the items listed below and represents the final configuration of the model including channel connections, locations of cross-sections and boundary conditions. The initial horizontal layout was completed as part of UMA's study, but was modified as noted below.

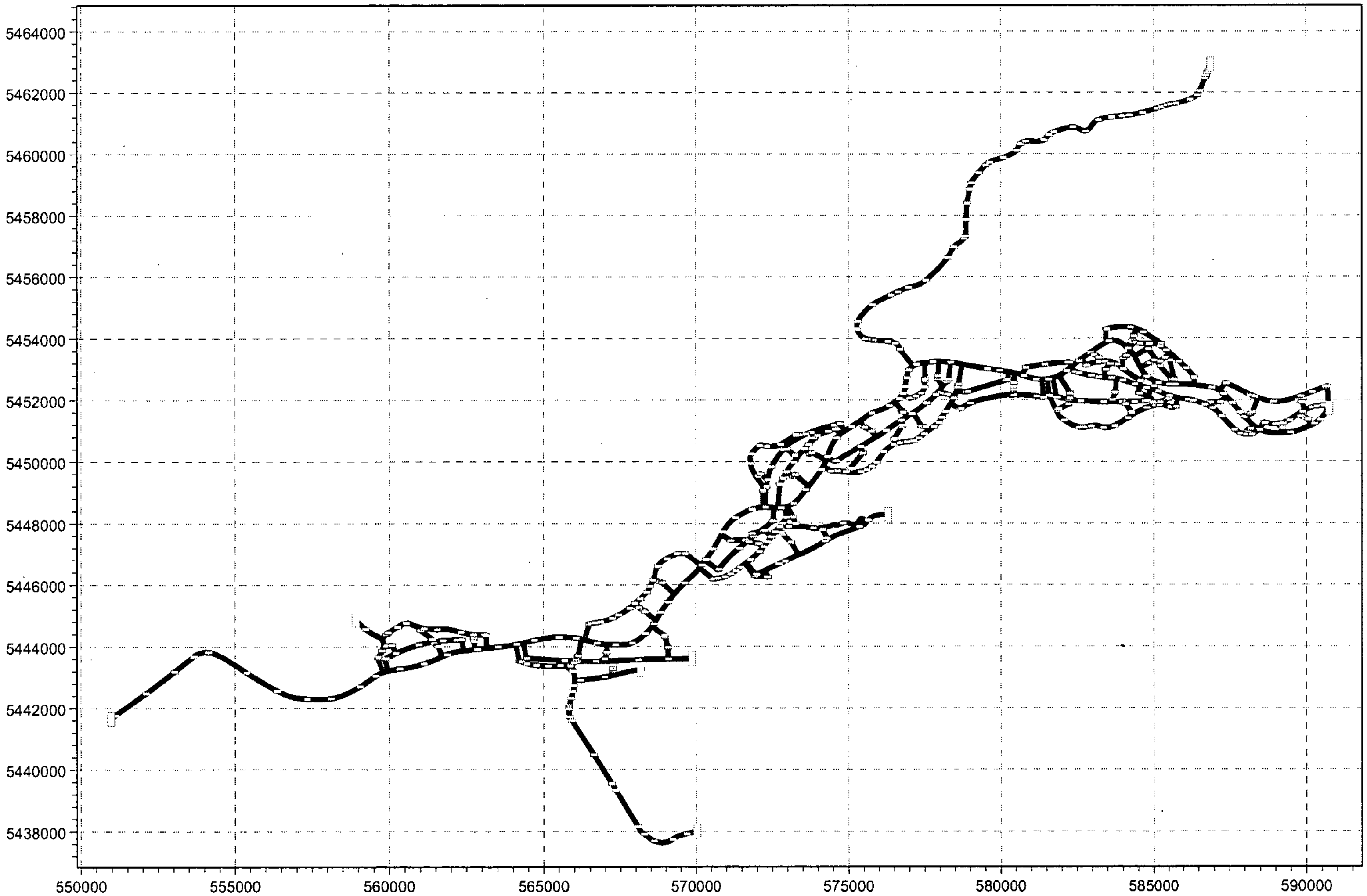
3.2.1 Photo Mosaic

To understand the morphology of the Fraser River and provide input on model parameters, it is critical to visually inspect the river environment and understand the vegetation and frictional elements that influence the hydrodynamics and hence the morphology.

Although it is impossible to go back in time and visually inspect the river and its environment in 1983, it is possible to gain much knowledge and understanding from aerial photo images. Air borne photographic images of the lower mainland have been collected since 1936 (Land Data BC).

The Department of Geography at the University of British Columbia holds a database of mapping and photo images in their Geographic Information Centre. The Centre estimates having over 300,000 aerial photo images of British Columbia for various years. At the outset of this project, a total of 104 aerial photos were obtained from

Figure 2 – MIKE 11 Fraser River Network Layout



the Centre that provided complete coverage of the study area. These were subsequently scanned using a high definition 600 DPI device to provide high quality electronic images.

The aerial photos required manipulation to remove the geographical and scaling errors introduced through the imaging process. Since the images were not tied to a defined coordinate grid, and are not calibrated for the curvature of the earth and flight angles, the photos are skewed and out of scale. Through a process known as "rubber sheeting" the photos were altered on a one-by-one basis to provide an acceptable fit to base mapping in the UTM NAD83 coordinate system.

Rubber sheeting consists of the following steps:

- The photo is imported into a graphics program; in this case, Autocad.
- Along with the photo image, a known cadastral fabric is imported into Autocad to provide the reference frame for the coordinate system. Digitized shorelines as well as geo-referenced 1995 photo imagery was used for this purpose (Triathlon Mapping Corporation, 1995).
- Using a series of known landmarks within the image, the photo is stretched as if it were a rubber sheet until it fits the landmarks of the known cadastral.
- Once complete, the next image is imported and the steps are repeated.

Although this is not a perfect technique, it does provide a finished product that is relatively accurate when related to the geographical scale of the entire river system.

Figure 3 shows the final product with the cadastral fabric of the Fraser River as an overlay. Both the cadastral overlay and the photos represent 1983 information.

The importance of this step cannot be over-emphasized. The photo mosaic, as it is termed, is used throughout the model development to provide indication of where the cross-sections should cease and the floodplain start. It is also essential to verify the amount and type of vegetation on exposed bars and floodplain areas.

Included in the photo mosaic are the boundary lines developed to indicate the outline of the bars, extent of the floodplains and side channels. In most cases, these delineate the change from cross-sections of the main channel to floodplain branches and side channel reaches.

3.2.2 Digital Terrain Model

As mentioned earlier, significant river bed surveys have been conducted in 1952, 1984 and 1999 by Water Survey of Canada (WSC). As the methodology states, the purpose of this investigation is to evaluate the morphological capabilities of MIKE 11 through the creation of a morphological computational model to see if it would predict gravel transport within the gravel reach.

In order to provide meaningful comparison, the results need to be gathered at similar locations between the simulation commencement year and the termination year. Since the 1999 river reach has already been hydrodynamically modeled (UMA, 2001), the location for the 1983 cross-sections were chosen to match their successors.

The sounding data gathered by WSC in 1984 consisted of approximately 85000 data points covering the reach from the Mission Bridge at station 85+400 upstream to the Agassiz-Rosedale Bridge at station 132+300. The majority of the sounding data did not line-up with the Public Works and Terra surveys completed in 1999. While this would have been the ideal situation, the sounding data were manipulated to provide estimations of the cross-sections at the same location.

This was undertaken using Autocad Land Development Desktop which allows the user to import raw survey data into a database. After importing the raw data into Autocad, the points were grouped into manageable packages and a digital triangulation was performed to create a three-dimensional representation of the river bed. In effect, the software triangulates between adjacent vertices and creates three dimensional faces that can be used to estimate elevations at points between the actual survey locations.

Surfaces of this nature are often referred to as digital terrain models (DTM) or digital elevation models (DEM). For the purposes of the Fraser River cross-sections a total of 7 surfaces were created with slight overlaps between adjacent surfaces. Using polylines, a two or three dimensional vector, new cross-sections were created from the surfaces developed from the 1983 soundings. The polylines were chosen at specific locations to coincide exactly with the 1999 survey and then post-processed to account for discontinuities and breaklines.

The process of creating the cross-sectional data from the polylines was an intensive undertaking. Since there is no easy way to extract the data in a format that MIKE 11 can use directly, manual manipulation was required. For each cross-section extracted, the process included the following steps:

- A polyline was drawn starting at the left hand side of the channel as if looking downstream and extended across the channel along the alignment of the 1999 cross-section to the right bank limit. This ensured that the stationing of the cross-section would be from left to right as required by MIKE 11.
- Polylines were only drawn from left boundary to right boundary as it pertains to the main channel (for Fraser River sections). This ensured that the cross-sectional widths were not overlapping with side channel sections or floodplain sections.

- A profile was then extracted from the polylines by reading a differential vertical distance from the polyline to the surface. Since the polylines are drawn with a 'Z' coordinate of 0.00, the distance is equivalent to the datum. The result is a text file including 6 columns of data with the horizontal distance from the start of the polyline and the corresponding vertical coordinate. The other columns are useless data and need to be stripped out of the file.
- To strip the un-needed data from the file, the .txt files are imported into a spreadsheet program. The import function of most spreadsheet software allows the user to choose certain columns for importing while excluding others.
- Two columns of data are imported which include the "L" and "Z" dimensions.
- Once the data is imported it is still not ready for direct input into MIKE 11. The format requires that 4 lines be inserted at the top of the file and the bottom of the data set is "closed" by a series of asterixes to tell MIKE 11 where the cross-section data ends. The four lines inserted at the top of the file tell MIKE 11 what reach to place the cross-section in, what topographical year it is for, the chainage of the cross-section and that it is of the "profile" form. An example of the data file is shown below.
- Once the data set is manipulated, the file is re-saved in .txt format and is ready for importing into MIKE 11.

The following sample depicts the raw data format for the cross sections in order to enable importing into MIKE 11. As stated above, the first four lines explain the geography of the cross-section. Starting with the fifth line the data becomes two columns, the first being the planimetric distance (L) and the second being the geodetic datum (Z) which formulate the cross-sections geometry. The data set ends with three asterixes to signify the end of the cross-sectional data for chainage 85+619.

Sample Cross-sectional Data File in MIKE 11 Format

```
1983
fraser_r
85619
profile
15.906466    -1.69798
26.532575    -4.538564
28.999132    -6.017897
39.902794    -7.923162
43.856751    -7.944734
49.398145    -7.727423
56.05341     -6.579986
76.520709    -5.990285
127.464854   -8.215092
141.852159   -8.198388
147.595606   -8.202194
159.380128   -8.396536
160.575964   -8.409623
172.888952   -7.96971
185.805923   -7.727751
187.211599   -7.979252
194.296068   -8.268599
205.821617   -8.00956
214.762286   -8.009392
243.096197   -7.798969
264.28467    -7.778326
276.244031   -7.920011
278.711288   -7.925877
293.824953   -7.752293
306.274402   -7.996972
306.673213   -8.003364
312.905388   -7.710939
327.668168   -7.809267
335.391582   -7.710472
340.001334   -7.645087
351.30202    -7.604335
352.445016   -7.604375
365.231541   -7.569619
368.800698   -7.595914
383.968011   -7.63782
411.720906   -7.593985
417.757755   -7.695921
444.566539   -8.050884
***
```

Each of the cross-sections that make up the entire model was developed through this process. Since MIKE 11 can only import one file at a time, this can be a rather lengthy process. Fortunately there is a way to combine the cross-sections prior to importing them. Using a text editor or simply DOS, the user can make one file from all the separate .txt files simply by performing a wildcard copy. The syntax looks like the following:

```
C:\>copy *.txt combined.txt
```

As long as all the individual .txt files are in the format described above, they will be combined one after the other into one large file named "combined.txt". The syntax above assumes that all the individual txt files are located in the root directory. The copy command syntax should be modified so that it is run from the location where the txt files are actually saved. Importing this new file into MIKE 11 will import all the bulk cross-sections at one time. It is important, however, to ensure that the original file format is fool proof, or the import process will fail.

The resulting cross-section locations are depicted in Figure 4. As in the original UMA hydrodynamic model development, river alignment geometry was used to modify the cross-sections based on their angle of flow incidence. This results in a more realistic normalized flow area.

3.2.3 Terra Surveys

Areas outside of the wetted perimeter were surveyed by Terra Surveys in 1999. This was accomplished through the use of air-borne laser equipment (Lidar). The land area outside the main river bed was not adjusted for use in the 1983 morphological model since the change in the floodplain areas was not expected to be significant. Also, these side channels are not expected to contribute to the overall sediment load (bedload), and will act in a hydrodynamic way only.

To stress this point, all of the side channels were set to passive mode during the simulation. This aspect and other modeling parameters will be discussed in more detail in later sections.

3.3 *Boundary Conditions*

To accurately model the river, MIKE 11 requires input at each of the free ends of the network as boundary conditions. These boundary conditions provide flow and water surface elevation data for the computational model to use during each time step. The Inland Waters Directorate, Water Resources Branch of Environment Canada collects streamflow data at various locations along the Fraser River. The extent of historical data available at gauges used in this study is summarized in Table 1. This database is available through the Canadian Hydrological Data CD-Rom entitled "HYDAT" (HYDAT, 2000).

The following section explains the choice of boundary conditions for the model and the efforts to collect and format the data.

3.3.1 Boundary Parameters

It is essential that a boundary condition is set at each free end in the network, otherwise this 'loose' end provides a computational unknown in the closed system. This boundary parameter will communicate to the program how the system is behaving outside the network and provides inputs for analysis. The following table lists the boundary conditions established for the morphological model.

Table 1 – Boundary Condition Parameters

Location	Gauge Number	Parameter
Fraser River @ Hope	08MF005	Flow
Fraser River @ Mission	08MF024	Level
Harrison River @ Harrison Hotsprings	08MG013	Flow
Chilliwack River @ Vedder Crossing	08MH001	Flow
DND_N	User	Flow
DND_S	User	Flow
Nicomen Slough	User	Flow
Hope Slough	User	Flow
Chilliwack River @ Vedder Crossing	User	Sediment Supply
Harrison River @ Harrision Hotsprings	User	Sediment Supply
DND_N	User	Sediment Supply
DND_S	User	Sediment Supply
Nicomen Slough	User	Sediment Supply
Hope Slough	User	Sediment Supply
Fraser River @ Agassiz	User	Sediment Supply

Although not shown in the above table, for each of the user input sediment supply boundary parameters, MIKE 11 requires a separate boundary condition for each fraction of sediment being modeled. For example, this simulation uses graded sediment containing 5 fractions. Therefore, at each of the sediment supply boundary sites listed above there are actually 5 separate boundary conditions.

For calibration of the hydrodynamic model, the downstream water level at the Mission Bridge is held to recorded values while an input hydrograph is applied at all other upstream free ends and the model is verified against a variety of staff gauges along the entire reach. While this was done for the original UMA hydrodynamic model, re-calibration was necessary to account for the modification of cross-sections from 1999 to

1983 bathymetry. The location and type of MIKE 11 boundary conditions applied during this study are shown in Figure 5.

3.4 *Time Series File*

MIKE 11 uses a time series file to provide interaction between the model and boundary conditions. The time series file provides flow, level and sediment inputs to the various boundary variables, in this case on a daily basis. Gaps in the time series file need to be dealt with so that the model has input information for each time step. The following section explains how these data gaps were corrected.

3.4.1 Missing Data

A review of available data for the boundary conditions revealed several periods when values were missing. In order to gain a full set of data to incorporate into the model, mathematical modifications were applied to the existing data to extrapolate for missing points.

3.4.2 Fraser River Discharge at Hope

Review of the HYDAT data for flows recorded at Hope revealed that there were two years of missing data for the period in question. The missing years were 1994 and 1995. The missing data for this period was obtained directly from the Water Survey of Canada, who had collected the data, but had failed to make it available on the CD database for unknown reasons.

3.4.3 Harrison River Flows

Similarly, there were numerous values missing for flows recorded on the Harrison River near Harrison Hotsprings. The missing values were replaced with the daily averaged values for the remaining years of data.

3.4.4 Fraser River Water Surface Levels at Mission

There was a significant amount of data missing from this gauge with no readings from January 1993 through February 1997. Statistically, the most valid correlation would be to create a rating curve from the flow and level data at the Mission gauge. Unfortunately, with the flow being intrinsically linked to the level recording, it too was missing for this period.

Consequently, the remaining years of data were correlated against the sum of the Fraser River discharge at Hope, the Harrison River discharge at Harrison Hotsprings and the Chilliwack River discharge at Vedder Crossing. Although there are likely to be minor errors for attenuation and loss, the data trendline provided a reasonably good fit and a high coefficient of correlation ($R^2 = 0.9651$) as shown in Figure 6. The equation of the trendline was then used to calculate the missing levels.

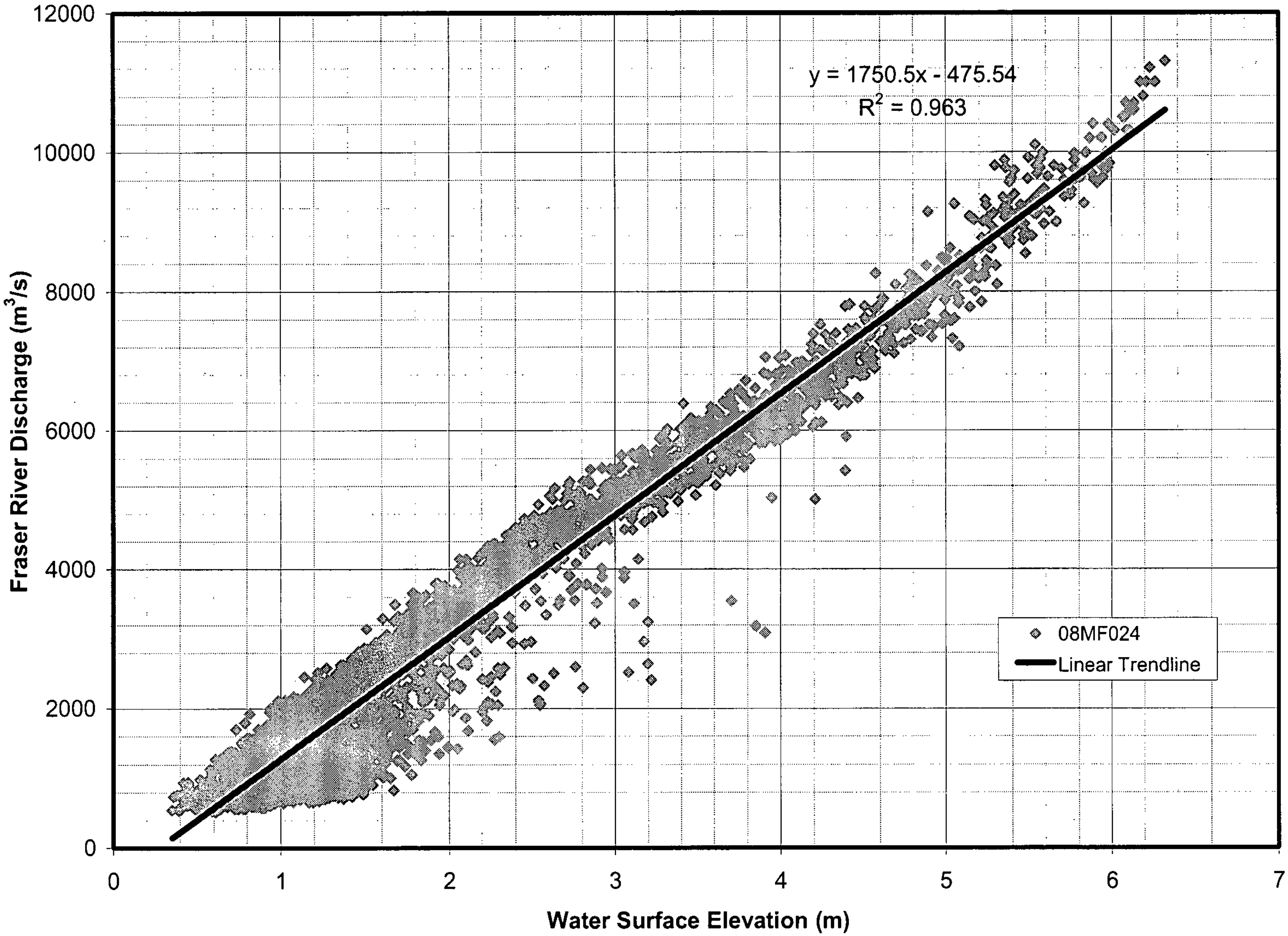


Figure 6 – Recorded Fraser River Level at Mission

Figure 7 represents the time series file for the hydrodynamic simulation only, as there is no time series file required for the morphological component of the investigation. This is a result of the morphological boundary conditions being set to sediment supply. A sediment supply boundary condition allows the model to calculate its own sediment transport potential, based on the hydrodynamics, and to apply it to the first time step. Consecutive time steps then use the previous value as their time series input.

A critical decision was made during the analysis of the gravel transport of this system to limit the time series file size. Initially, the time series contained daily data for the entire 16 year model period. In other words, this included 6209 entries for each of the boundary constraints. While this was easily handled during the preliminary hydrodynamic modeling, it became overwhelming to the simulation during the morphological investigation.

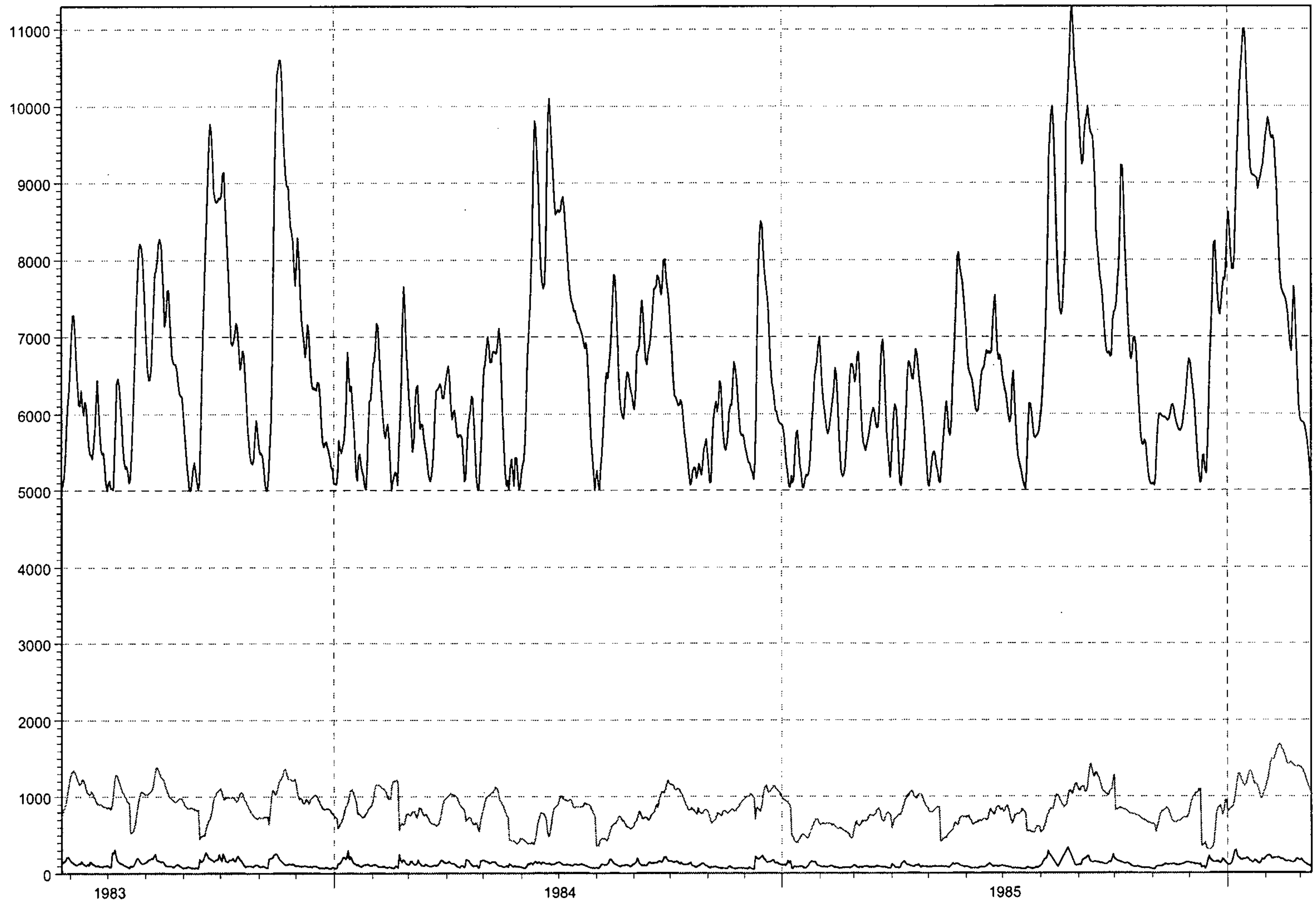


Figure 7 – MIKE 11 Time Series File

3.4.5 Reduction of the Time Series File based on Incipient Motion

Based on the incipient motion criteria established by the work of Church (2001) and McLean et al (1987), the time series file was modified to strip out all the days with discharge less than 5000 m^3/s. This discharge is associated with the initial movement of gravel in the Fraser River Gravel Reach; therefore discharges below this value are not relevant to this study. This greatly reduced the simulation time by dropping the number of computational nodes to 1021 from the original 6209.

3.5 Grain Size Distribution

Grain size is an important variable in estimating the amount of sediment transport that occurs in a given reach for a given flow rate. In the case of the Fraser River, D.G. McLean collected samples in 1983 (reported in McLean, 1990) and the UBC Department of Geography collected sample in 2000 (Church et al, 2001).

The significant change in stream bed gradient of the Fraser River downstream of Hope decreases the carrying capacity of the branch and provides a mechanism whereby sediment is released from suspension back into the system. Although this statement generally applies to the washload sediment, it applies to the bedload as well during high flows. The reduction in gradient is directly linked to the velocity and critical shear stress. As we move further downstream from the point of gradient change, a distinct spatial distribution of grain sizes is noted.

This is a general phenomenon seen in rivers with high sediment transport and can partially account for the transverse and longitudinal sorting of sediments (Deigaard, 1980).

3.5.1 Transverse and Longitudinal sorting

Samples and measurements of grain sizes at various locations along the gravel reach have been collected for 1983 (McLean, 1990) and 2000 (Church et al, 2001). The following summary gives an indication of the gravel sizes encountered. It should be noted however, that the grain sizes are relatively small compared to those visually noted during site visits. This was verified through further discussion with Dr. Church, who agreed that grain sizes noted in the collection exercise do appear smaller than visual inspection would suggest.

This is likely the results of samples being taken from the bar and overbank areas where higher stage flows would result in shallow flow depth and less fluid shear stress. It is anticipated that grain sizes in the thalweg would be considerably larger due to the increased shear stresses present there.

Figures 8 and 9 visually depict the spatial distribution of the grain sizes sampled within the Fraser River Gravel Reach for the years of 1983 (reported in McLean, 1990) and 2000 (Church et al, 2001) respectively. The data for both of these figures was provided to the writer directly from Dr. Church. Both the figures reveal a spatial reduction of grain size from upstream to downstream areas within the reach. It should also be noted that there is considerable scatter in the plots. This is likely due to a number of factors including sampling error and transverse sorting of gravel across the sample zone. A linear trendline has been added to these figures as a visual representation of this spatial sorting but is not statistically relevant.

As for temporal variance, the figures suggest that the timing of the sample program does not play a large role. This was also confirmed by Church et al (2001) in comparison of the same results where no significant variation was found between the two sample years. In Figure 10, the values for the two sample years have been superimposed to emphasize that there is no significant shift in the sample data between the sample years.

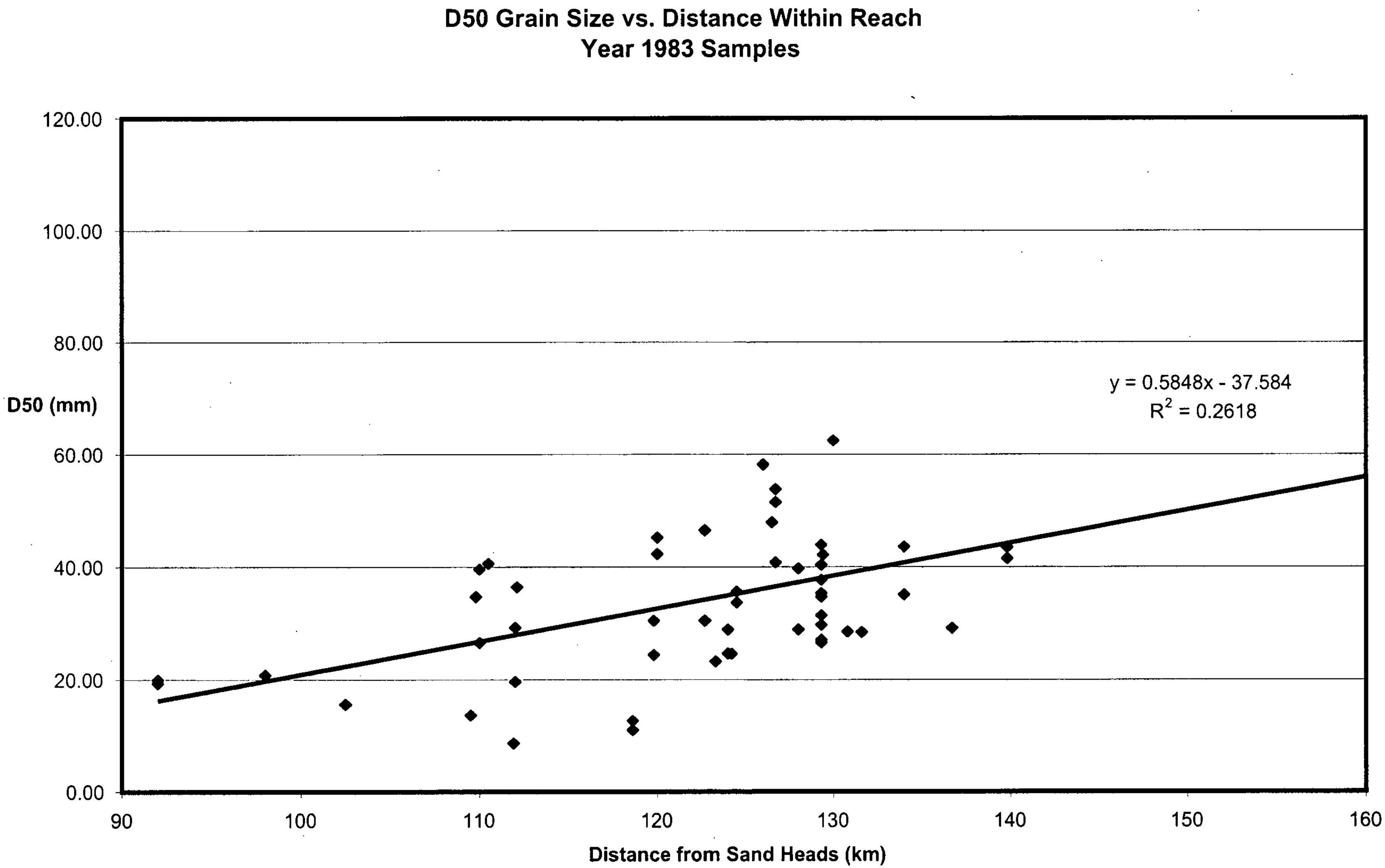


Figure 8 – D50 Grain Size vs. Distance Within Reach (reported in McLean, 1990)

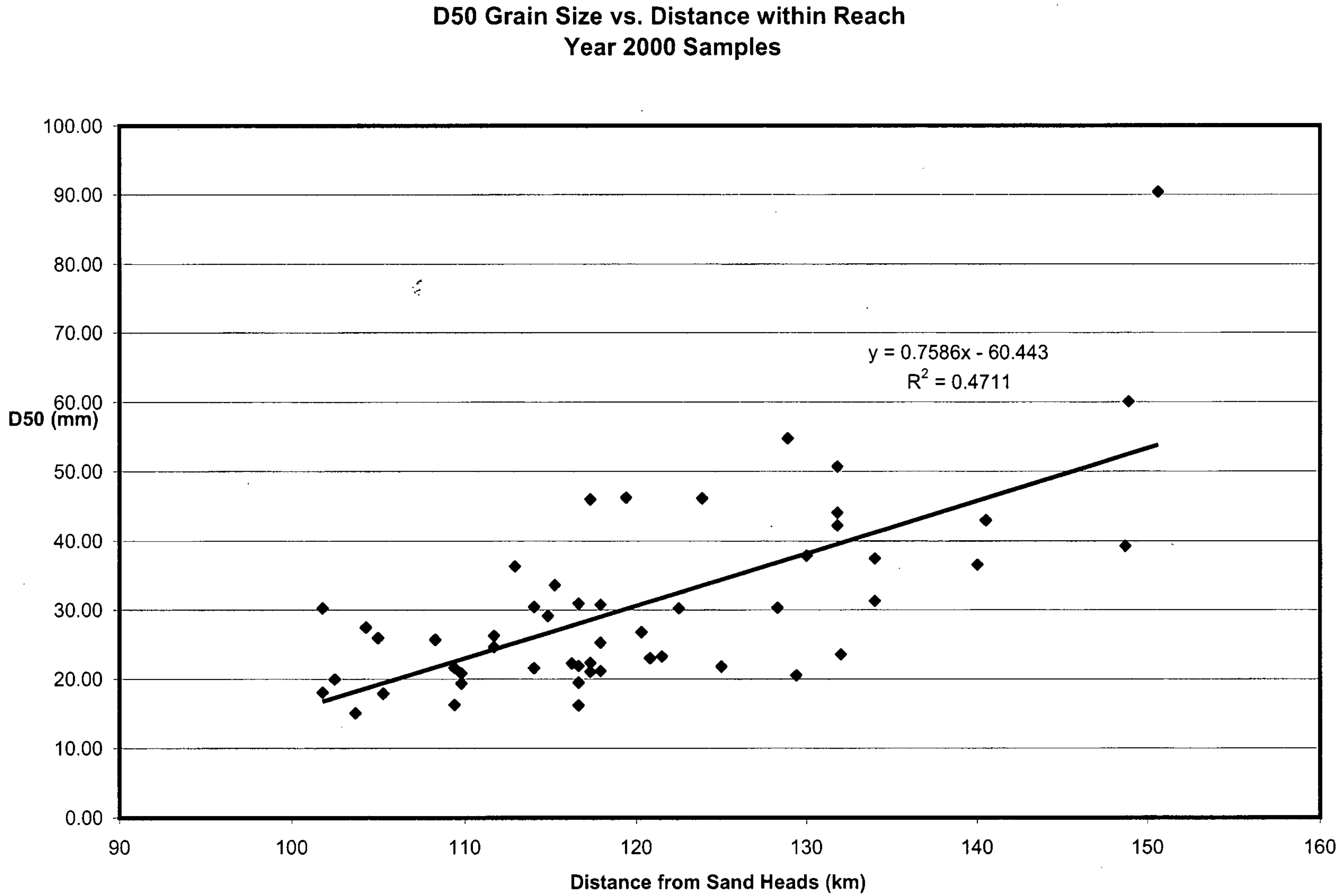


Figure 9 – D50 Grain Size vs. Distance Within Reach (Church et al, 2001)

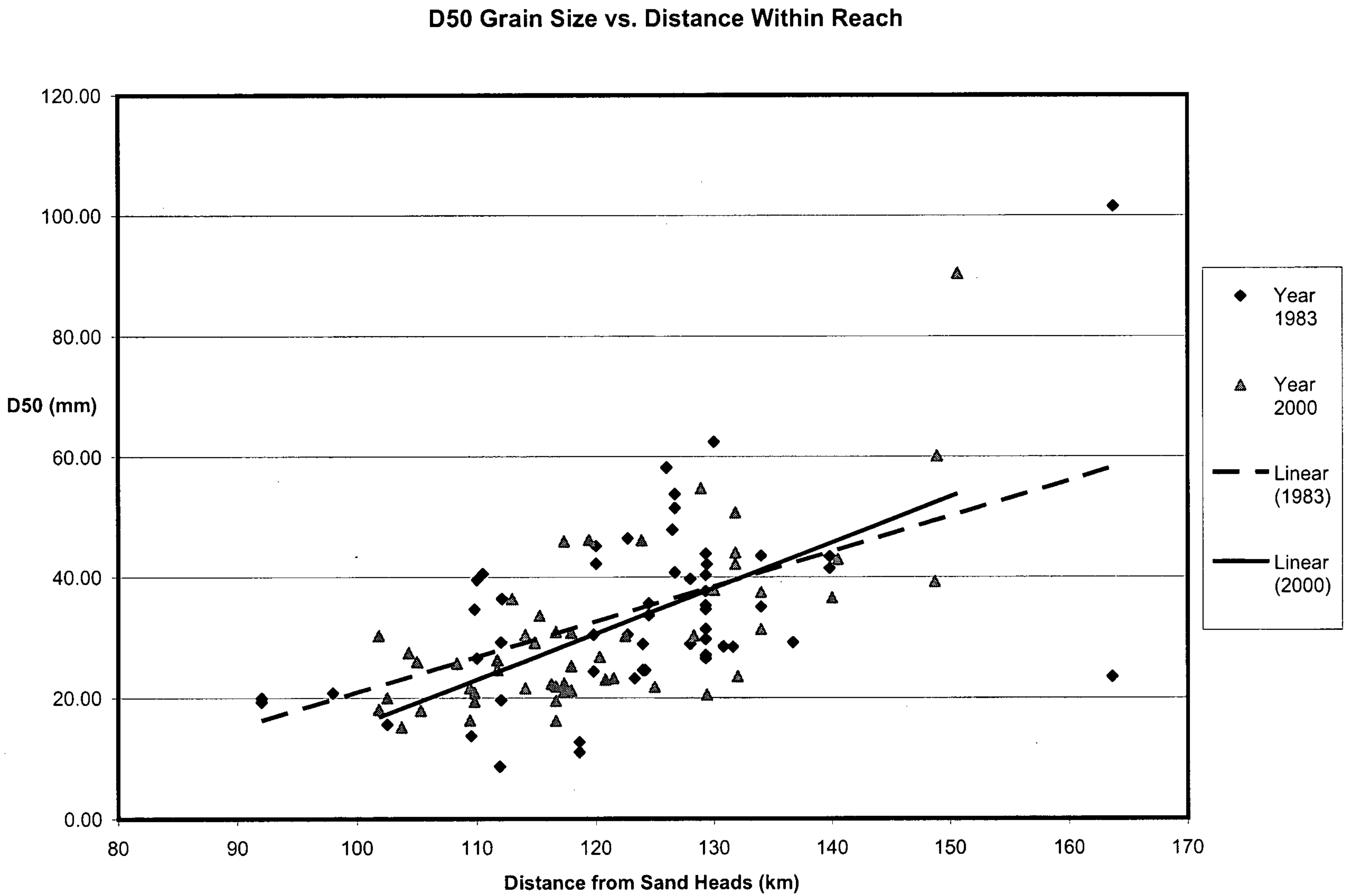


Figure 10 – D50 Grain Size vs. Distance Within Reach (1983 & 2000)

3.5.2 Sediment Fractions used in model

To provide a realistic cross-section of the sediment sizes found throughout the gravel reach a range of 5 sediment sizes was used in a graded sediment simulation format. These are summarized in the following table. This gradation is based on specific sieve samples analyzed under previous studies (McLean, 1990; Church et al, 2001) and forms a representation of the typical sediment in proximity to Harrison Bar.

Table 2 – MIKE 11 Graded Sediment Distributions

Fraction Diameter (mm)	Active Layer (%)	Passive Layer (%)
8	8	8
16	40	40
22	35	35
45	15	15
100	2	2
Total	**100**	**100**

The above sediment gradation represents the initial condition used in the first time step of the simulation. As the simulation proceeds, MIKE 11 modifies the passive and active layer compositions based on the amount of sediment transport occurring (DHI, 2003). The extent of armouring is also calculated at each time step as the simulation proceeds.

Based on the gradation at each time step, and depending on the transport model chosen, MIKE 11 resolves the sediment transport for each fraction independently. The user has the choice of whether to save the total sediment transport volume or save the transport for each fraction individually. Independently calculated fractional sediment transport rates are subsequently modified by the Egiazaroff equation (Egiazaroff, 1965) under certain transport models to account for particle interaction (DHI, 2003).

Armouring is also a condition seen in the Fraser River and can be accounted for in the MIKE 11 model through the use of an active and passive layer. In order to use this functionality, the modeler needs to supply data as to the original passive layer thickness and the minimum depth of the active layer. This is important since erosion of the passive layer will cause the model to crash once it is depleted. For this investigation armouring was activated and the minimum depth of the active layer was set to 1 metre, while the initial depth of the passive layer was set to 5 metres.

3.6 Sediment Transport Models

MIKE 11 offers a wide variety of sediment transport models to choose from which are summarized below. As the objective of this study was to simulate the transportation of graded gravel sediment on the Fraser River bed, only bedload and total load models were considered. The Ackers-White model was applied as it applies to graded sediments and is a well accepted model (Yang, 1996).

Table 3 – Sediment Transport Models Included in MIKE 11

Type of Model	Name
Suspended Load Models	Lane and Kalinski
Bedload Models	Meyer-Peter Müller Van Rijn Smart and Jaeggi Sato, Kikkawa and Ashida Engelund and Hansen
Total Load Models	Ackers-White Engelund and Fredsoe Ashida and Michiue

3.6.1 MIKE 11 Sediment Transport

Sediment transport in MIKE 11 is performed under several assumptions. Firstly, the software's main goal is to resolve the St. Venant equations with respect to hydrodynamics. The inherent nature of a one-dimensional model is that it solves hydrodynamic equations in only the longitudinal direction. MIKE 11 solves the momentum equation in order to resolve the depth and velocity at any given point in the river system and uses this average velocity to calculate the bed shear stress for application to the sediment transport routine.

Upon review of the above models provided by MIKE 11, it is anticipated that the Ackers-White model will provide the most accurate results. This is also supported by comparative studies performed by White et al (1975) and Yang (1976) that evaluated various sediment transport functions for their accuracy. Both of these independent studies concluded that their own equations were the least inaccurate. However, compilation of the two studies revealed that Yang's equations (1973) would most consistently predict bed-material load with Ackers and White (1973) relatively close in accuracy (Yang, 1996).

As shown in Figure 11, the parameters required are the relative sediment density as well as choosing the representation of the grain sizes as either the 35 or 65 % finer diameters. Although not specifically related to the Ackers-White simulation, the kinematic viscosity is also required and in this case has a value of 1 x 10^{-6}.

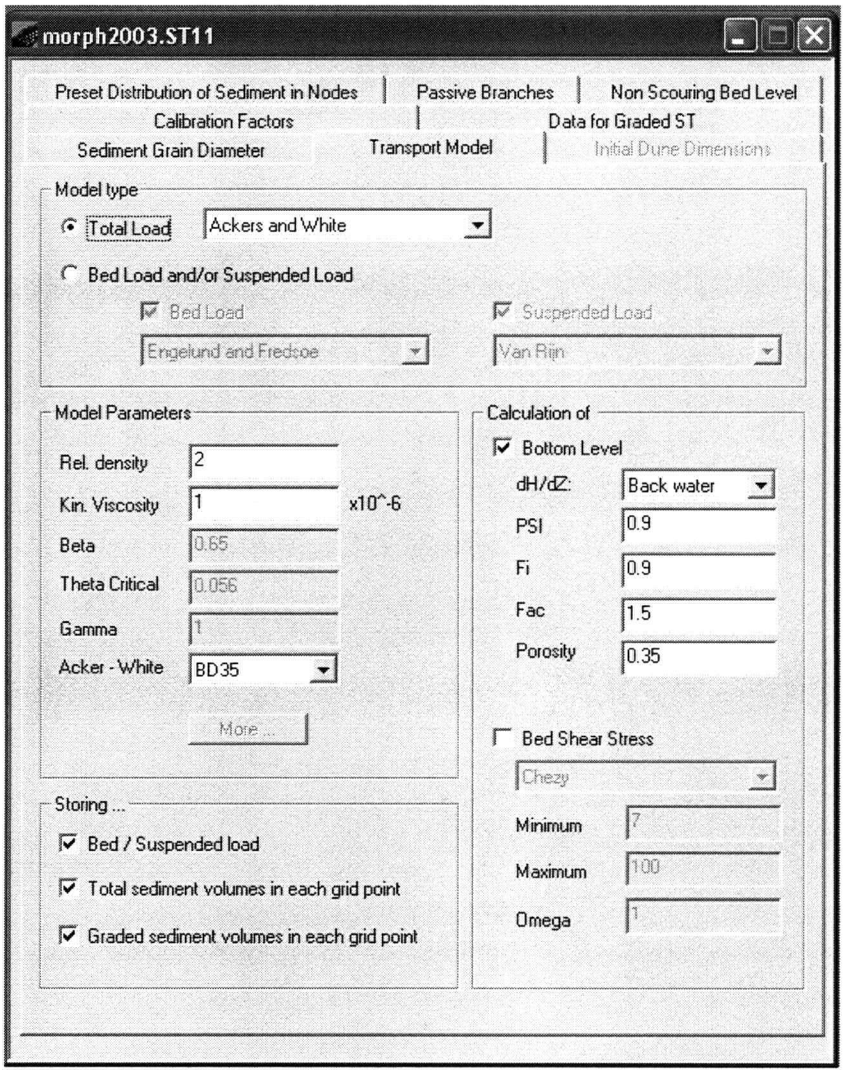


Figure 11 – MIKE 11 Transport Model User Interface

3.7 Hydrodynamic vs. Morphological

The conversion of the 'fixed bed' hydrodynamic model to a morphological model presented several modeling challenges that were not described anywhere within the MIKE 11 documentation and were only discovered through trial and error. The following items were only discovered when it was found that the morphological model would not run without crashing. Subsequent discussions with DHI resulted in confirmation that these items cause model instability. In both cases, these elements provided excellent results and accuracy for the hydrodynamic model.

3.7.1 Link Channels

The Fraser River is a wandering river and in order to ensure that proper routing and storage are addressed properly, link channels were inserted during the development of the 1-D hydrodynamic model (UMA, 2000). A link channel is a connection between two adjacent branches which allows for transverse flow between the two based on the momentum energy. The model assesses the water surface elevation in the two adjacent channels and, to satisfy the conservation of energy, transfers flow between the two.

The link channels worked sufficiently well in the hydrodynamic simulation, but failed miserably during morphological calculations since the model cannot resolve velocity components within them. To complete the morphological simulation, all of the existing link channels needed to be replaced with natural channels.

The link channels in the hydrodynamic model were constructed from rectangular sections except in approximately 10% of the instances when they were constructed from survey information (UMA, 2000). When these link channels were replaced, the cross-sectional area and form were retained in the natural cross-sections.

The transition, however, from link channels to regular channels was not easily accomplished. Link channels in MIKE 11 are developed in a very different way than regular channels and their cross-sections do not exist in the cross-section editor. Rather than the standard distance/datum representation, link channels are represented using a width/depth table (DHI, 2003). Where standard cross-sections are constructed from left to right by going out a distance (L) to a datum (Z), the link channels start in the middle bottom. As the depth of water in the cross-section increases, it is represented by the width across the top.

To modify these links, the data was extracted and modified on a one-by-one basis. The link channels have the same cross-sectional shape for their entire length and are therefore only depicted once along with an associated length. Upon conversion to regular channels, each link channel had to be formulated into the typical cross-sectional structure described earlier and imported to MIKE 11. The 54 link channels in the original model were replaced through the creation of 54 new regular channels consisting of 3 or 4 cross-sections in each.

3.7.2 Side Channels

The side channels in the hydrodynamic model represent the flood plains as well as several branches of the wandering network. These channels are typically dry at low stage flows, but provide conveyance and storage during higher return period events. These branches also have higher manning's roughness values as a result of thicker vegetation. All of the river branches within the model, with the exception of the main Fraser River stem, could be considered side channels from a morphological point of view.

In the original hydrodynamic simulation, these side channels joined the main channels or other side channels through a branch connection from the channel end to a point on the stem of another branch at a given chainage. In the hydrodynamic simulation (UMA, 2001) the connection of these channels at the exact same elevation was not required. For example, a hydraulic connection was made between branch A and branch B, but the elevations in the connecting cross-sections were different. As is seen in nature, side channels may enter a collector stream from a higher elevation acting similar to a weir, with cascading flow.

When it came time to convert the model to a morphological simulation, all of these inaccuracies in elevation needed to be addressed. MIKE 11's morphological routine requires that all branch connections occur at the same elevation (lowest point in the cross-section) or the simulation will become unstable. In order to correct this problem, additional cross-sections were added to each of the side channels at the point of connection.

To accomplish this task, a copy of the last cross-section in the branch was created at some distance (x) from the end. A datum shift was then applied to the end cross-section at a given value so that it matched the elevation of the channel with which it is connected. The distance that the copied cross-section is inserted from the end varied based on the datum shift that was required. If the datum shift was large the cross-section was inserted further away from the end to provide a mild grade to the end of the channel. In most cases the distance was chosen based on a combination of this factor and the distance to the next cross-section in the branch. To satisfy the requirements of the morphological model, 154 new cross-sections were inserted in this manner.

3.8 Modeling Method

The MIKE 11 sediment transport module provides several methods of simulation which are described below.

3.8.1 Explicit Sediment Transport Mode

The explicit mode of sediment transport calculation provides the user with the simplest form of analysis. While running in explicit mode, the sediment transport calculations are performed based on the results of a previously performed hydrodynamic simulation results file. The calculations can also be performed during a parallel hydrodynamic simulation. The important aspect of the explicit mode is that there is no feedback from the morphological module to the hydrodynamic module. In other words, if deposition or erosion is taking place, the cross-sections for the hydrodynamic model are not being updated concurrently and the calculation of velocity or water surface profile is unaffected by the resulting morphology.

3.8.2 Morphological Mode

Contrary to the explicit mode, calculations in the morphological mode are made in parallel to the hydrodynamic simulation and the results are fed back to the simulation at every time-step. This is the most realistic method and should provide results that represent what is actually taking place in nature. However, there are shortcomings to this method as well, as will be seen in the section on model testing.

3.8.3 Unsteady Simulation

The user must choose which type of hydrodynamic simulation to perform. If an unsteady simulation is chosen, the hydrodynamic calculations are based on time variable hydrodynamic flow conditions.

3.8.4 Quasi-steady Simulation

Alternatively, the user can choose to perform a quasi-steady simulation. In this instance the model is resolved at each hydrodynamic node until a steady state solution is found. Once a steady state is accomplished, the model uses these results as input to the next time step.

There are benefits and short comings to the quasi-steady simulation. The main benefit is that the Courant stability criterion does not need to be satisfied. The Courant criterion states that the time step needs to be limited so that the hydrodynamic wave will not pass more than one computational node during time step. The celerity or wave speed of the kinematic wave, the time step and computational spacing are related by cT/L <=1. Where "c" is the wave speed, "T" is the time step and "L" is the distance between computational nodes. To satisfy the Courant criterion the time step during this simulation needed to be less than 3 minutes.

Under a quasi-steady simulation the time step does not enter into the hydrodynamic calculation, therefore it can be increased, resulting in a shorter simulation time. The accompanying sacrifice, however, is that the results do not realistically depict what is actually taking place in nature. The Fraser River is not a steady state river; it is highly 3-dimensional in some areas, and cannot be realistically modeled with a steady state model. In any case, during this investigation, a quasi-steady model was attempted, and would not run to completion. Software and modeling problems such as this are discussed further in later sections.

It should also be noted that the unsteady and quasi-steady modes are not both part of the base software package. The base package includes one mode and the other must be purchased separately as an add-on module.

4.0 MODEL TESTING AND SIMULATIONS

In section 3, the development of the model was finalized and was prepared for testing and calibration. Modeling of a river network can only provide a meaningful result if the simulation is accurately predicting what happens in nature. To provide this level of re-assurance, the model needs to be calibrated. This is usually done by setting variables in the model setup until the predicted results reasonably resemble actual field measurements through a series of trial and error model runs.

Due to the nature of this model, the calibration process needs to be completed in two distinct steps. Initially, the hydrodynamic model needs to be calibrated to observed water surface profiles so that is can effectively pass accurate information to the morphological sub-routines. If this is not done, instabilities in the hydrodynamic model are magnified in the morphological simulation. Once the hydrodynamic model is sufficiently calibrated, the sediment transport model can be calibrated as well, resulting in an overall calibrated model.

In the hydrodynamic simulation, calibration means that the model accurately predicts the water surface profile at a given number of staff gauges along the river network. For the morphological simulation the meaning is two-fold. Firstly, the hydrodynamic portion must predict as stated above, and secondly, the morphological module should accurately predict the amount of sediment transport that has occurred in relation to previous studies or measurements.

4.1 Hydrodynamic Calibration

As stated earlier, this model was based on the previous calibrated model developed by UMA Engineering Ltd (UMA, 2001). However, since all of the main stem cross-sections were replaced, it was essential to re-calibrate the model before proceeding to the morphological simulation. The table below shows the list of all staff gauges along the reach that were available for verification of the model.

Table 4 – Coordinates of Fraser River Basin Staff Gauges

Gauge#	Gauge name	UTM Easting	UTM Northing
12	Dewdney PS	555685.7	5443633.0
15	Robson PS	560135.1	5444734.5
25	McGillivray Slough PS	565861.2	5442082.0
41	Quaamitch Slough	567816.3	5445966.5
37	Collinson PS	567241.1	5439572.5
24	Chilliwack Creek PS (Wolfe Rd.)	573311.4	5446009.5
16	Bell Dam (Out side)	572521.2	5450997.0
40	Minto landing area	577268.9	5450570.5
17	Harrison Mills (Kilby)	575655.5	5454115.1
39	Carey Point	581582.9	5452143.5
19	Duncan Bateson	577798.0	5455595.1
20	Hammersley PS	583272.8	5454428.5
38	Cottonwood Slough	588405.5	5452581.5
22	Agassiz Rosedale Bridge	589043.2	5450824.0
21	Maria Slough	592099.4	5455726.5
44	Herrling	596094.0	5455726.0
42	Seabird Island	594418.2	5458600.5
43	Johnson Slough	598830.9	5464775.0
45	Wahleach (Jones) Creek	599755.7	5463771.0
Chwk # 2	Chip Intake	587553.1	5450794.5
Chwk # 4	Carry Pt.@ dyke@ Greyell Slough	582058.0	5451084.3
Chwk # 7	BellSlough 2 Ballam Rd.	577071.7	5450545.4
Chwk # 10	Wing Dyke Boat Launch	574496.7	5449489.8
Chwk # 12	Hope Slough @ Young St.	576282.2	5448269.9
Kent # 2	Cuthbert	592163.8	5454833.5
Kent # 3	Tranmer	591490.5	5453106.4
Kent # 5	Agassiz Rosedale Bridge	589144.2	5451274.3
Kent # 8	Scowlitz	577243.7	5453483.7

The locations of the gauges are shown in Figure 12. Since the staff gauge readings are not automated, data is only available on certain days. The verification data used in this instance were staff gauge readings from the summer of 1997. This date represents a period of maximum flow during this simulation period. The discharge recorded at Hope peaked at a value of 11300 m^3/s on June 5, 1997.

The resulting calibration graph is shown in Figure 13, with the following table depicting the readings at each location against the difference in water level between the actual readings and the model predictions.

Table 5 – Recorded Staff Gauge Readings vs. Model Predictions

Gauge Number	Gauge Name	Recorded Level (m)	Model Prediction (m)	Difference (m)
12	Dewdney PS	6.86	6.85	-0.01
15	Robson PS	7.37	7.28	-0.09
25	McGillivray Slough PS	7.81	7.73	-0.08
37	Collinson PS	7.82	7.73	-0.09
24	Chilliwack Creek PS	8.85	8.77	-0.08
16	Bell Dam	9.42	9.41	-0.01
17	Harrison Mills	11.88	11.73	-0.15
39	Carey Point	13.48	13.23	-0.25
19	Duncan Bateson	11.95	11.83	-0.12
20	Hammersley PS	14.22	14.12	-0.10
38	Cottonwood Slough	16.26	16.35	+0.09
22	Agassiz-Rosedale Br.	17.10	17.17	+0.07

The calibration of the hydrodynamic portion of the model was quite successful and provided a reasonable match to observed water surface elevations including the increase in water surface level at the Harrison River confluence. This can be seen as an abrupt change in the water surface profile approximately 117,000 metres upstream of the sand heads. Proceeding with the sediment transport calibration presented a significant modeling challenge as will become clear in the following section.

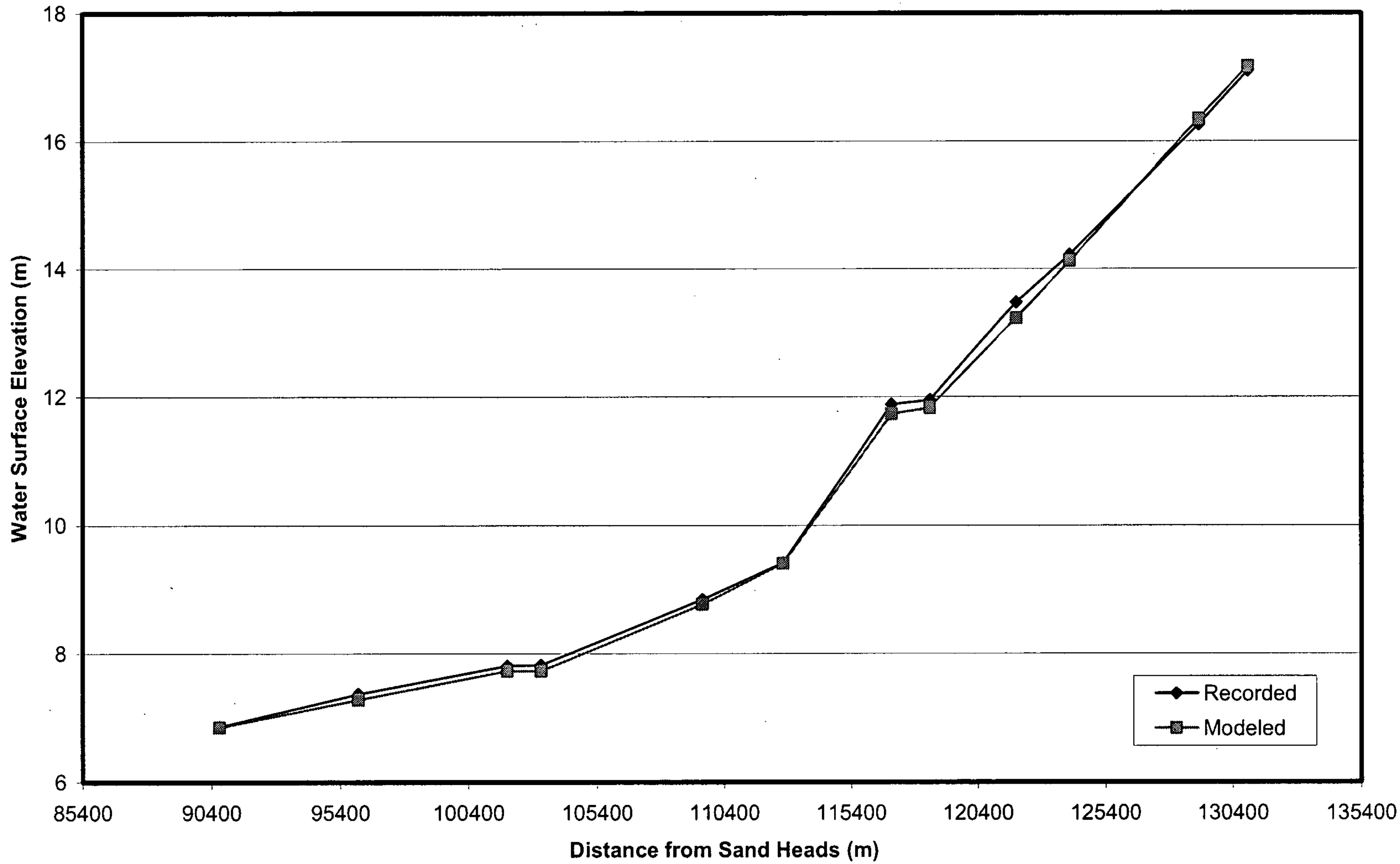


Figure 13 – Hydrodynamic Calibration Graph

4.2 Sediment Transport Simulations

With the hydrodynamic model sufficiently calibrated, the calibration of the morphological model was attempted. Calibration of the morphological model was substantially more difficult and provided numerous failures that eventually resulted in abandonment of the morphological simulation. The reasons for the simulation failures will become more apparent shortly, but in essence can be attributed to several factors, including:

- Software limitations,
- Computational limitations, and;
- Results viewer limitations.

Although the simulation of morphological changes taking place in the gravel reach was eventually abandoned, it is important to define the steps that were attempted to achieve the final goal as the aim of this thesis was to evaluate MIKE 11's functionality in this regard. The following sections summarize the events surrounding the morphological simulations challenges.

4.3 Modeling Complications

The analysis of sediment transport using a 1-dimensional model presents challenges due to limitations in the calculation of velocity and shear stresses being averaged across the entire cross-section. By averaging the velocity, areas of high velocity are potentially reduced below the incipient motion threshold.

Regardless of these limitations, the objective of this thesis was to evaluate the ability of MIKE 11 to predict the sediment budget by adapting the existing hydrodynamic model (UMA, 2001) and reduce the overall effort of developing a morphological model from scratch. Beyond boundaries associated with MIKE 11's 1-dimensionality, the following critical limitations were also encountered and eventually lead to the abandonment of the investigation.

4.3.1 Software Limitations

When the idea for this thesis was originally conceived, MIKE 11 was in its 2000b release. The scope of the study was generally agreed upon and the software was obtained under agreements with DHI. A quick review of the user's manual revealed that the morphological components were in their infancy at this time.

For example, as stated earlier, bed shear stresses play a dominant role in the calculation of sediment transport. Referring to section 10.3.1 of the MIKE 11 user manual for Version 2000b, the user is notified that the updating of bed shear stress in not implemented in the kernel of MIKE 11 2000 and that the selection of this check box will have no effect on the simulation results. In addition, storing of total sediment volumes and graded sediments at each grid point were also features not implemented in the computational kernel.

With the understanding that this might limit the study effectiveness, the development of the model proceeded with the knowledge that the software developer anticipated these items would be included in future versions. Discussions with Water Management Consultants revealed that they too found the 2000 kernel failed during their study of Harrison Bar and they were provided a recompiled version of the kernel in order to address crashes.

Attempts to implement the morphological simulation were attempted again under the 2001 release of MIKE 11. Although the apparent limitation listed above had been corrected in this version, there were other problems that continued to cause stagnation of the sediment transport simulation.

Initial attempts to run the model resulted in errors referencing a bad limit to Chezy roughness coefficients. The entire simulation was based on Manning's 'n' values and there is no way to physically set the Chezy coefficients except in the aforementioned bed shear stress routine that had been previously excluded from the kernel.

It was discovered through a trial and error process that this error appeared and crashed the simulation whether the bed shear stress option was checked or not. This problem was eventually resolved through a patch to the MIKE 11 executable file.

The next error to develop was an immediate crash of the simulation upon initialization of the sediment transport parameters file. As MIKE 11 begins a simulation, it reads model parameters into their routines from the various files indicated on the simulation input tab. A number of weeks were spent trying to locate the error, but in the end DHI recommended upgrading to the next version of software in which this was likely to be addressed. By this time, a considerable effort had been expended in attempts to formulate a working 2000 and 2001 simulation.

The next version to be evaluated was release 2003. The results here were not much better, as the model would now initialize but would instantly crash with the error message “abnormal termination of simulation”. Conversations with technical support leaded to the conclusion that this error message represents a “catch all” for the software kernel and that the error could be caused by an unlimited number of items. Once again, months were spent trying to troubleshoot the simulation and find the error, but with no success.

In the spring of 2003 a service pack was released which mysteriously resolved this error indicating that it was yet again another software bug and the simulation files had been properly configured all along. The spring of 2003 was the first time that the model actually ran past the initialization dialogue box. After 2 years of updates and patches, it appeared success was at hand.

4.3.2 Computational Limitations

Running in morphological mode with the sediment transport routines providing feedback to the hydrodynamic modules presented its own series of limitations. At this stage of the software evaluation, the time series file being used had not been reduced based on the incipient motion criteria.

The initial attempts to simulate the 16 year period resulted in modeling runs approaching weeks in duration. This was unacceptable since calibration would require the simulation of dozens of trial runs. Satisfaction of the Courant stability criteria along with processing 6209 time steps of daily data both played a significant role in the simulation duration.

Exploration of ways to decrease the simulation duration commenced and resulted in the reduction of the time series file to include only those days where flows exceeded the incipient motion discharge of approximately 5000 m^3/s. This greatly reduced the computational nodes and resulted in a reduction of simulation time to approximately 120 hours. Although still not ideal, this was a workable timeframe.

Under this scenario, simulations proceeded but continued to result in abnormal terminations. Although DHI had been involved in the model development from the commencement of the hydrodynamic model nearly three years prior, it wasn't until this time that their technical support personnel indicated that the morphological routines will not work with a network that includes link channel. The re-development of all the link channels was then undertaken as described in section 3.7.1.

At the same time as the link channels were noted as causing problems to the morphological simulation, the execution of the service patch on the MIKE 11 2003 executable resulted in numerous new warning messages from the kernel. Although the warning messages did not cause the simulation to crash, they did cause erroneous results to be generated. The warning messages were all centered around the connection elevation of channels. According to the messages, unless these channels were modified so that the elevations of two channels at the connection point matched exactly, instabilities could be caused in the model. As described in section 3.7.2, all of the side channel connection points were modified to correct these warning messages.

4.3.3 Results Viewer Limitations (MIKE VIEW)

When all the past warning and error messages appeared to finally be corrected, the model proceeded through its first full simulation in the summer of 2003. This is, however, when problems associated with the results viewer were first discovered. Viewing of results is accomplished through a separate piece of software that provides viewer functionality for all MIKE based products and is aptly named MIKE View.

During previous use of the viewer, with results from the hydrodynamic simulation, it performed excellently. However, when the results for the first sediment transport calibration run were viewed, a serious problem was noted. The initial dialogue box after opening a results file asks the user to select the time step period to load and the data types to include. The user is then presented with the network layout and must select the portion of the reach to view.

Since MIKE View can only display one data type at a time, it then asks a second time which one of the included data types from the initial selection set the user would now like to view. Herein was the problem: no data types were available in the second dialogue box. In other words no results could be viewed.

Upon bringing this to the attention of DHI, they attempted to find a solution for the problem, but stated that they had not heard of this problem in the past. However, MIKE 11 also includes a DOS program that can be used to extract data from the results files into a text format. Although rudimentary, this allowed another avenue to try and retrieve the data for calibration purposes. Unfortunately a considerable effort was also required to get this program working properly. Not so much from a proficiency point of view, but more logistically, since the documentation on how to construct the data files in order to extract the results is very limited in the MIKE 11 documentation.

Upon initial extraction of the data, several things could be noted that did not look promising. Although the simulation had been set-up to store results on a daily basis, it appears that the results were actually being stored hourly. Although this provides more data coverage, it also accounts for each of the results files being in excess of 700 Mb. The second, more disturbing thing that was noted, was that all the results, for all time steps, at all cross-sections, were zero.

Attempts to refine the simulation were made, with no better results. After approximately two weeks passing and many communications back and forth to the DHI technical support staff, the developer of MIKE View in Prague revealed that he had found a serious programming error and was in the process of correcting the issue. A new executable file was forwarded within several days which fixed some of the problems, but still resulted in only some of the data sets being available. It did, however, allow visualization of some of the data in the graphical viewer.

4.3.4 Abandonment of the Networked Simulation

After 2 years of model development, numerous software versions, and the errors described above, one final attempt was made to refine the model and get it working sufficiently to provide some rudimentary results. The gradations of sediment were looked at, as well as an attempt to run other transport models, namely a Meyer Peter Müller simulation.

These refinements resulted in yet more crashes of the simulation with an error stating that the passive layer in channel *LinkGreyell4* was less than or equal to zero and that the initial depth should be increased in the sediment transport parameters file. This presented a rather interested dilemma, since as described in section 3.2.3, all of the channels, with the exception of the Fraser River main stem, had been defined as passive channels and therefore no sediment transport should be occurring and there would be no possibility of the sediment layers becoming depleted.

This initiated, yet again, another flurry of discussion with DHI and the hopes of a timely resolution. As seen in the following figures, the error message is shown alongside a confirmation that the channel was indeed defined as a passive channel as noted at line 78. While waiting for a response, the side channels were investigated in MIKE View and it was confirmed that sediment transport was occurring regardless of the passive definition. The transport in the side channels had never been checked before this point, since it was thought to be superfluous.

The final response received from Denmark was to say that there was a serious bug in version 2003 of MIKE 11 that resulted in the passive definition of branches being ignored. It is unknown if this bug was limited to version 2003 or existed in all prior versions. Whatever the case, it appears that this functionality of MIKE 11 had not been explored by many modelers in the past if the bug was only being discovered now. This is significant, since it is unknown if other studies completed with MIKE 11 have produced erroneous results, or if passive channels were not used in those studies. In the case where they were implemented, modelers should verify whether the passive channels have been applied correctly.

It was at this point that a decision was made to completely abandon the attempts to simulate sediment transport in the multi-branched Fraser River model. Given that the passive definitions of branches cannot be included, the results from a working model would over-estimate the transport and distribution of sediment in the reach and would not represent that seen in nature.

A final attempt was made to verify the software against the sediment transport of the main channel alone. To accomplish this, a morphological simulation with all other branches deleted was conducted

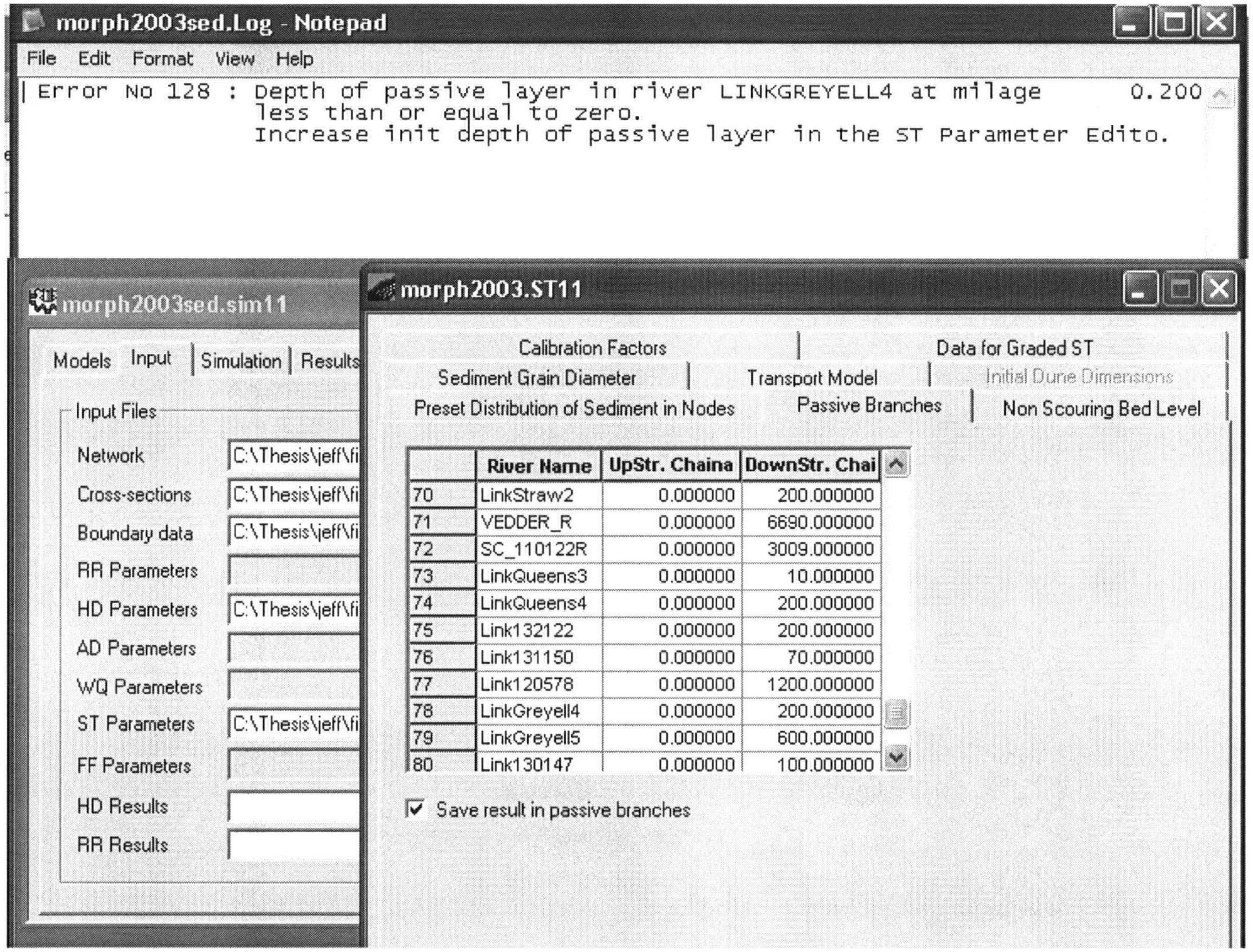


Figure 14 – Passive Branch Error Message

4.3.5 Attempts to Model the Fraser Main Stem Only

Although modeling the main stem alone would not provide meaningful results that could be analyzed against past studies, it may at least provide an indication of erosion and aggradation cells along the main channel. As there would be no time or data to go back and calibrate a new hydrodynamic model based on the main stem only, the network layout was simply modified to delete all side channels and the model was re-run.

Running the simulations in this format has not presented any critical error messages, and the initial results do confirm that transport is occurring in the uppermost portions of the reach and diminish as the flow approaches the Mission Bridge. The following figures depict the sediment transport occurring at a snapshot time during the simulation period and the resulting bed level compared to the initial time step.

Although this investigation did not explore the sediment transport provided by the main stem alone, it could provide an interesting topic of study for further research. A great deal of model modifications will be required to ensure that the storage and routing of the natural river system is effectively modeled by the single channel system. As well, since the original networked model separated the main stem from its floodplain sections, these should be re-incorporated into the main channel cross-sections. This should provide better results beyond bank full stage.

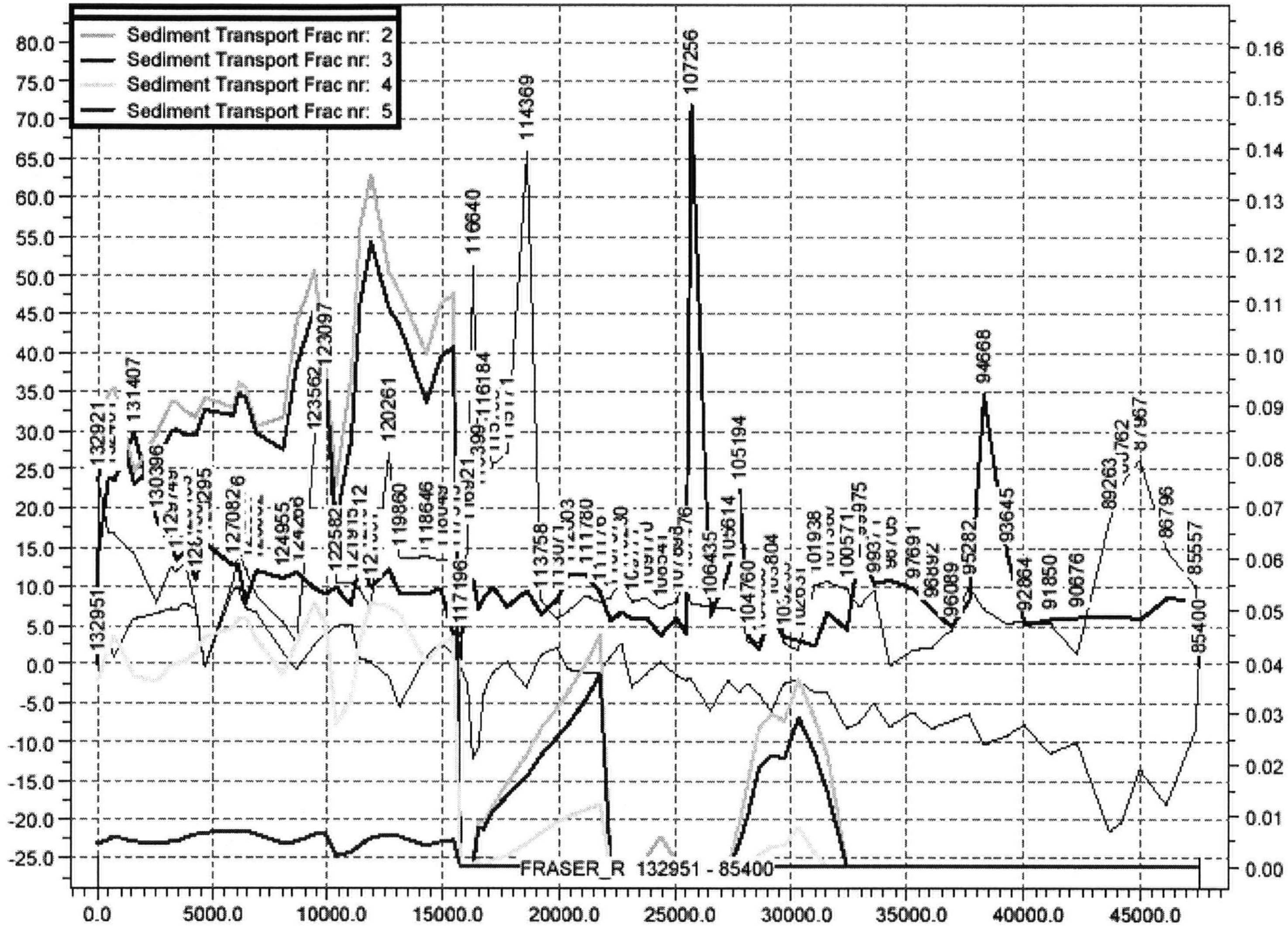


Figure 15 – Main Channel Only Fractional Sediment Transport Test

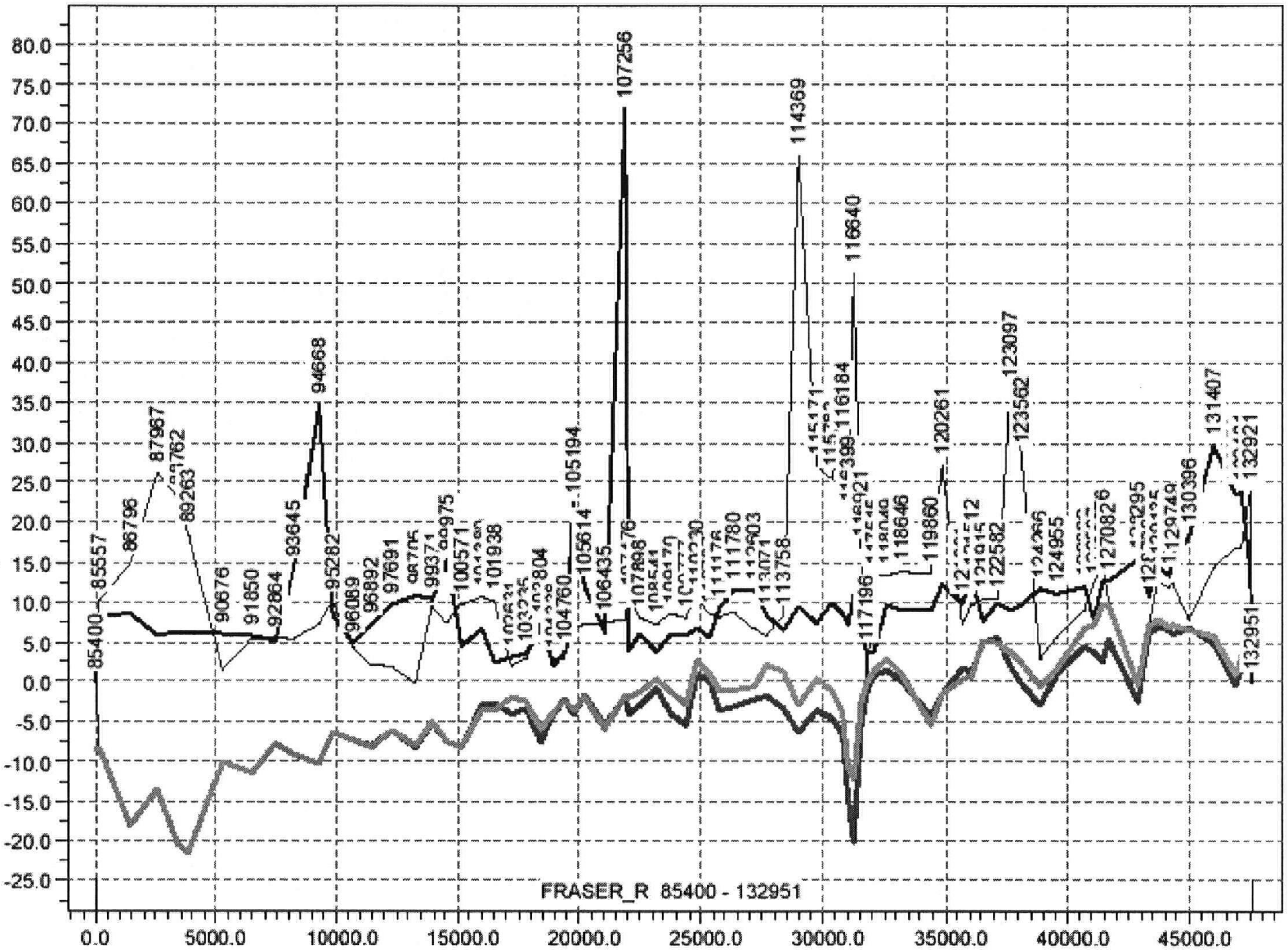


Figure 16 – Main Channel Only Bed Level Comparison

5.0 CONCLUSION

The goal of this thesis was to evaluate the morphological and sediment transport capabilities of the 1-dimensional software package MIKE 11. An existing hydrodynamic model developed by UMA Engineering formed the basis of a morphological case-study of the Fraser River Gravel Reach.

The purposes for providing this investigation are both financial and logistical. The purchase of MIKE 11 is a large capital investment, especially if many of the add-on modules are purchased. Since the software developer claims that the product can also perform sedimentation routines, the purchaser believes they are getting a certain list of services for their expenditure. Therefore, the ability of MIKE 11 to perform these tasks as claimed should ensure the user does not have to make another capital purchase to provide this functionality.

The second purpose is logistical. A well calibrated, accurate hydrodynamic model already exists and is providing service to the user who developed it. As morphology is an increasingly important topic on the Fraser River, the ability to provide good quantitative analysis of the sediment transport is essential to providing and developing long term management plans. Being able to easily expand the existing model provides the owner with a cost effective means of producing beneficial sediment information without having to construct another model completely from scratch.

Although MIKE 11 performs excellently at its primary function of providing hydrodynamic information regarding water surface profiling, it failed as a viable sediment transport analysis tool in this case study.

The reasons for qualifying that statement are two-fold. Firstly, the original hydrodynamic model constructed by UMA was not developed under the scenario that it may become a sediment transport model in the future. Therefore, many elements, such as link channels, would no doubt have been tackled differently in the original model knowing the implications on a morphological simulation in the future.

Secondly, it is felt that the complexity of the Fraser River looped network was computationally overwhelming for the 1-dimensionality of MIKE 11. It is likely, as simulations done very late in the analysis seem to indicate, that MIKE 11's morphological routines are better suited a single branch incised channel.

During the evaluation process, it was concluded by the researcher that the morphological capabilities and routines of MIKE 11 had not been fully developed and tested. This is evident in the number and critical instances of bugs discovered. The reasons for this are unknown, but it can be hypothesized that sediment transport software development efforts were focused on the MIKE 21C 2-dimensional products since it was felt that these packages would be used in most instances of morphological study.

From discussions with many of the sediment transport experts at DHI, many of the bugs uncovered during this study had never been experienced before and this is likely an indication that most users do not explore the sediment transport functionality of MIKE 11.

Perhaps the recommendations that follow and the discovery of software bugs will lead to further development of the product and result in a modeling package that gains acclaim in the industry as a leading sediment transport simulator.

6.0 RECOMMENDATIONS

The following recommendations are provided with the aim to aid software development and improve the user interface of MIKE 11 and MIKE View.

6.1 Representation of Channel Roughness

The investigation revealed the inability to vary the channel roughness laterally across the river sections in a user friendly fashion was a significant shortcoming. This ability does exist in other one-dimensional models and allows the modeler an easy way to account for bank vegetation and other changes in roughness transversely within the cross-section using well defined and known roughness factors.

MIKE 11 treats this somewhat differently in that a global roughness coefficient is set for the subject reach or portions of the reach. If the modeler would like to increase the roughness coefficient at various points within the cross-section, this is accomplished using a multiplication factor at each cross-sectional datum point. The result is a less user-friendly interface when looking at the cross-sectional information. Instead of seeing exactly what the roughness coefficient is at any given point, the modeler must remember what the global setting is, then multiply this by the factor in the cross-section to know what value is being applied.

Although it would take additional effort and re-programming, it would be more user friendly to represent this visually to the modeler, and list the roughness coefficients being applied. Another good visual effect would be to represent these changes in roughness in the cross-sectional plot window, i.e. the modeler could then see a change of roughness visually over bar areas or in the over-bank regions.

6.2 Update of Bed Options

From a morphological point of view, the model lacks many user interfaces that should be easy to add. Most notable of these is the bed level update settings. MIKE 11 offers the modeler 5 methods of how to update the bed level as sediment transport occurs. These options are listed below.

Table 6 - Bed Level Update Methods

Option	Methodology
1	Deposition in horizontal layers from the bottom, erosion proportional with depth below bank level.
2	Deposition and erosion uniformly distributed below the water surface. No deposition or erosion above the water surface.
3	Deposition and erosion proportional with depth below the water surface. No deposition or erosion above the water surface.
4	Deposition and erosion uniformly distributed over the whole cross-section (regardless of where the water surface may be)
5	Deposition and erosion proportional with depth below bank level.

The default setting used by the software 'out of the box' is option 4. Since this doesn't make much sense from a modeling point of view, it is surprising that this would be the default setting.

In order to change the bed update option to something that is more realistic, the modeler must create a text file that will be read during the simulation initialization sequence. The text file, as described by MIKE 11 documentation, is very simple and only includes two lines. The first line is not read by the software and can contain comments or notes for the modelers benefit. The second line is to contain the option number for bed updating. The file then has to be saved as "bedlevel.txt" and placed in the simulation folder.

The problem is that the software seems to contain a bug whereby when a change to the update method is attempted, the model will crash with the "abnormal termination of simulation" error. Discussions with DHI did not result in a workable solution, despite them sending a customized file in an attempt to troubleshoot the error.

There are two possible solutions for this problem that would make the interface better for the modeler. The suggestions are this:

- Place the bed update option variable in the MIKE.ini file alongside many of the other modeling variables that currently are stored there. Similar to other variables, an easy solution is to set the variable in a format such as ***variable = value***.
- Better yet, it would be desirable to set this variable in the ST Parameters menu box along with the other sediment transport variables such as model type, porosity, etc. This could be easily accomplished through the use of a radio button style interface or a drop down list selection interface.

Both of these solutions will not address the inherent programming fault with setting the variable and allowing the simulation to proceed, but once those issues are resolved, it ensures that the modeler has thought about the model update method and is conscious that it exists and is set appropriately for the simulation.

6.3 Documentation

The documentation included with the software package is inadequate, and could use some serious updates and expansion. For example, there are instances when the modeler is required to create text files in order to interface with the model. It would be a great addition if the format and general requirements of these files were explained in greater detail and an example was included.

Another example revolves around the use of the DOS results extraction program called "res11read". The modeler must create a text file to extract the data from the results file. Although the file is described in general terms, it is not stated in which text format the file is to be saved (comma, space or tab delimited). Unfortunately only one of these works, but until this is discovered, the extraction process fails.

MIKE 11 provides feedback to the modeler in the form of warning and error messages as the simulation proceeds. The simulation will continue as long as only warning messages are encountered, but if any error messages occur, the simulation is terminated. Providing feedback to the modeler is a great way for the user to troubleshoot the simulation. Unfortunately, the feedback provided inadequate commentary with no description of how to correct the problem encountered. It would be very beneficial, if a common way to address the messages were included along with typical reasons why these error messages usually appear.

Unfortunately, the problem of troubleshooting is compounded by the global error message "**abnormal termination of simulation**". This is akin to the "blue screen of death" that many a Windows user has experienced over the years and is sure to send chills down the spine of the modeler. As described by DHI, this error message is a catch all for pretty much anything that could be wrong with the simulation and is impossible to troubleshoot since the user has no idea where to even begin to look. This error message was by far the one that appeared the most during the case study and can usually be attributable to instabilities in the model, but could also be something as simple as the bed level update error noted above.

In any case, the abnormal termination error is one that requires much more description in the user documentation to instruct the modeler to look into instabilities, to check the Courant Criteria, or numerous other possible areas.

6.4 Software Bugs

In general, all of the bugs encountered during this investigation require immediate attention and correction. These include:

- Resolution of errors associated with the definition of passive branches,
- Resolution of bed update options,

- Errors associated with viewing sediment transport added output files.

6.5 MIKE View

Malfunctions and shortcomings were also found in the results viewer MIKE View. The most serious problem being that results from morphological added output files could not be viewed at all. Although in the initial menu interfaces that data was shown as being there, when the data was chosen for viewing they would not be available. This made it impossible to view any sediment transport for the graded fractions. The total transport could be viewed since this is not part of the added output data set. However, the fractional transport is considered added output and could not be analyzed (this is dependant on the transport model chosen). An initial patch was forwarded, but some of the output data is still not available to the user.

More frustrating from a user point of view is the way in which reaches are chosen for viewing. The user is presented with a window showing the entire layout of the river system being modeled as in Figure 2. To view the profile for a desired reach, the user picks the reach using the mouse and left button. If you are analyzing a single branch system this works well since you only need to click once. If, however, you are analyzing a multi-branch river system, as in the case study, where there are side channels and other reaches attached to the main stem at various locations, you must follow the reach and click as many times as there are connection points. Not following the reach with the mouse cursor while clicking results in the selection diverting to side channels. For the

Fraser River, this meant clicking on the main stem a minimum of 69 times each and every time you needed to view results.

A much easier way to address this issue in a user-friendly approach would be to present the modeler with a menu interface listing each of the reaches in the network and the upstream and downstream chainage. The modeler could then choose the desired reach and even the chainage section.

Another suggestion that would benefit the user would be the ability to choose the viewing session by date rather than time step. For instance, currently the Fraser River simulation has approximately 12000 time steps (this is dependent on the storing frequency). If the user wants to view the section for calibration purposes and needs to look at a particular date, he needs to make a guess of the time step range that might include it. A better solution would be to choose the actual date you wanted to view. This should not be overly taxing from a programming perspective, since all of the required information is already included. The model knows the start and end dates and times and it also knows the time step (1 min, 1 hour...etc) therefore it should be quite easy to provide this flexibility in the user interface.

Lastly, it would be beneficial to have the ability to view the results file directly from MIKE 11. This should only entail a link from MIKE 11 to the MIKE View executable. Otherwise, the modeler must change programs and interfaces to view the results of a simulation.

6.6 Future Studies and Research

This study has shown that the use of MIKE 11 as a sediment transport simulator is not conducive to studying the complexity of the looped Fraser River network. However, future studies could attempt to create a single channel representation of the Fraser River main stem. The groundwork for a study of this nature has already been established through this case study which indicates that a representative model may eventually be obtained.

A secondary consideration could be given to analysis of the looped network velocity fields. As part of the hydrodynamic results, the velocities at each cross-section were able to be extracted. Physical manipulation of these values and manual computation of sediment transport based on first principal theories could provide some indication of the realistic transport in the multi-branched system.

Consideration should be given to applying correction factors to the velocities if this is investigated. Since the 1-dimensionality of MIKE 11 provides only average velocities across the entire cross-sectional area, the shear stress on the bed is reduced in areas where it may actually be higher. Through an evaluation of the cross-sectional area distribution, some corrections could be applied to retain the average velocity overall - increasing it in some areas while reducing it in others. All of the cross-sectional plots have been included in the appendices for visualization of how this might be applied. The cross section plots represent both the 1983 and 1999 cross sections so lateral shifts that have occurred can easily be seen.

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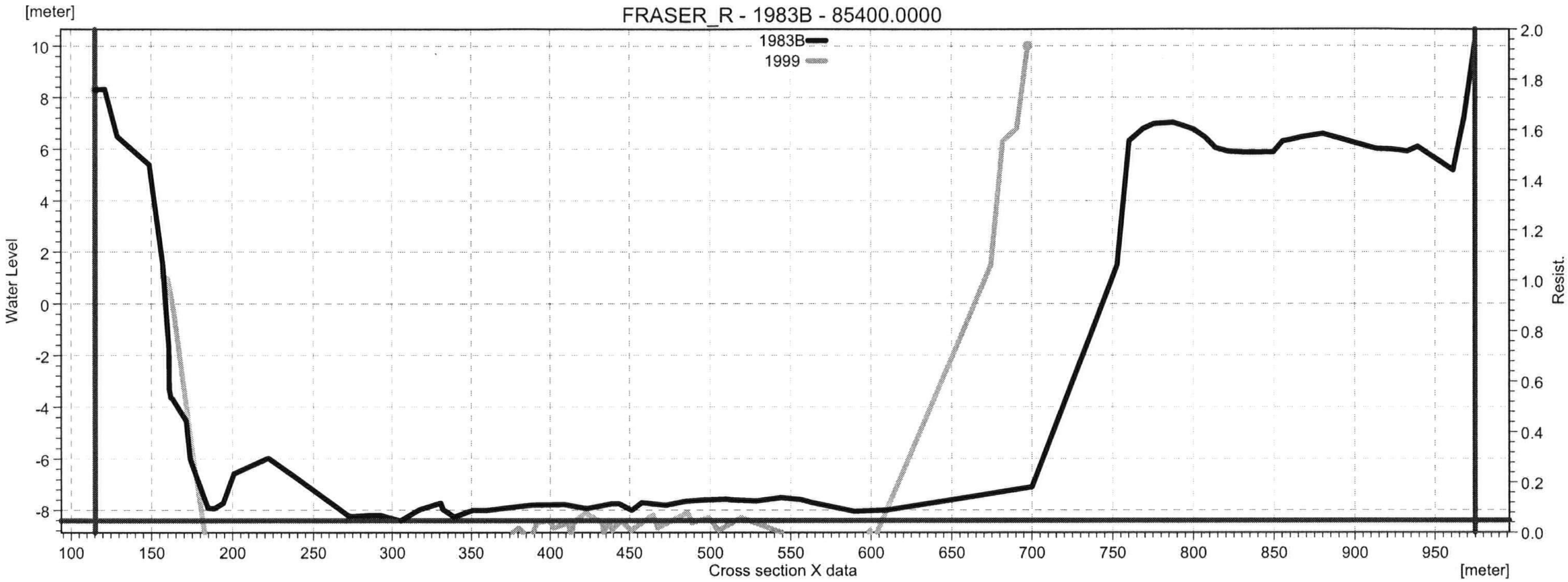
APPENDIX 1 – FRASER RIVER CROSS-SECTIONS



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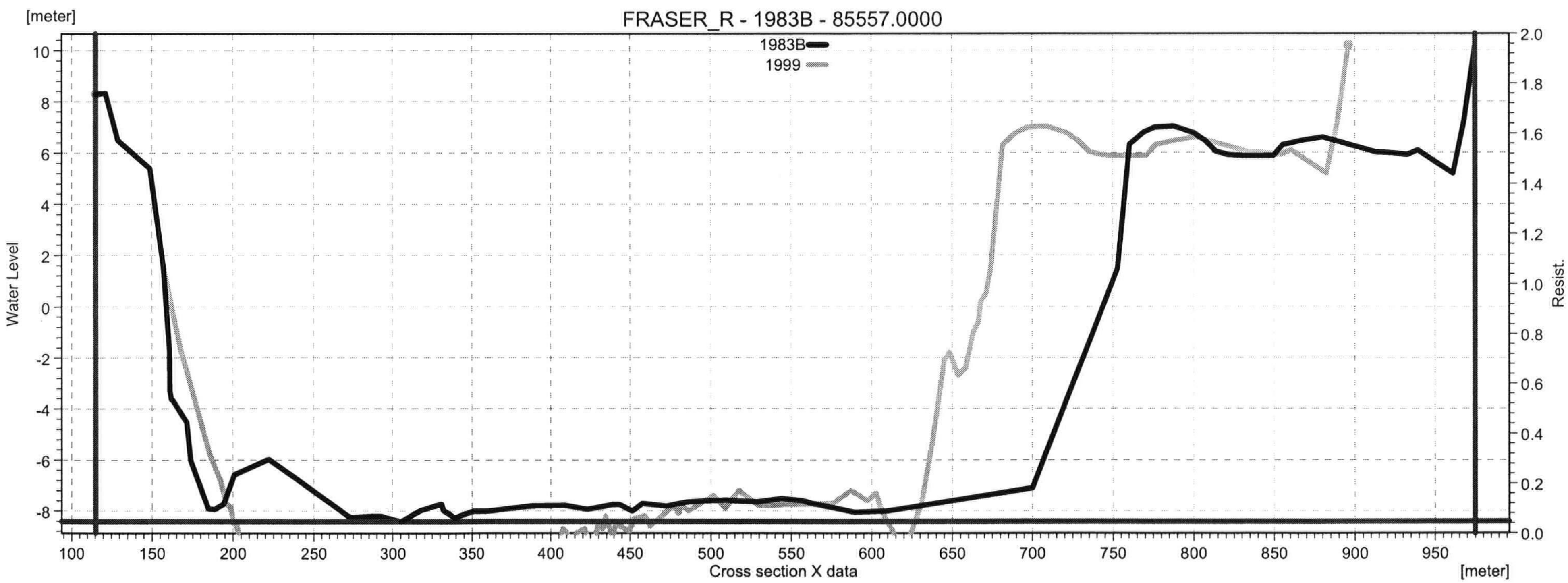

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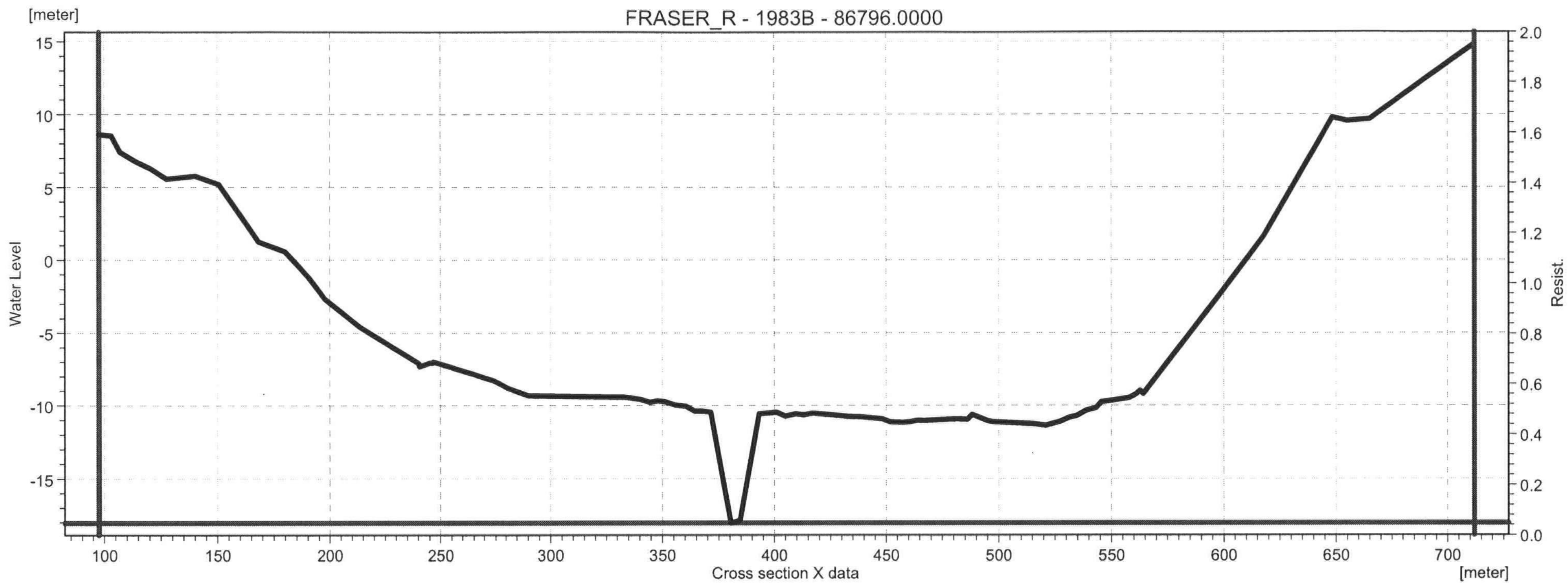

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1.4
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1.0
0.8
0.6
0.4
0.2
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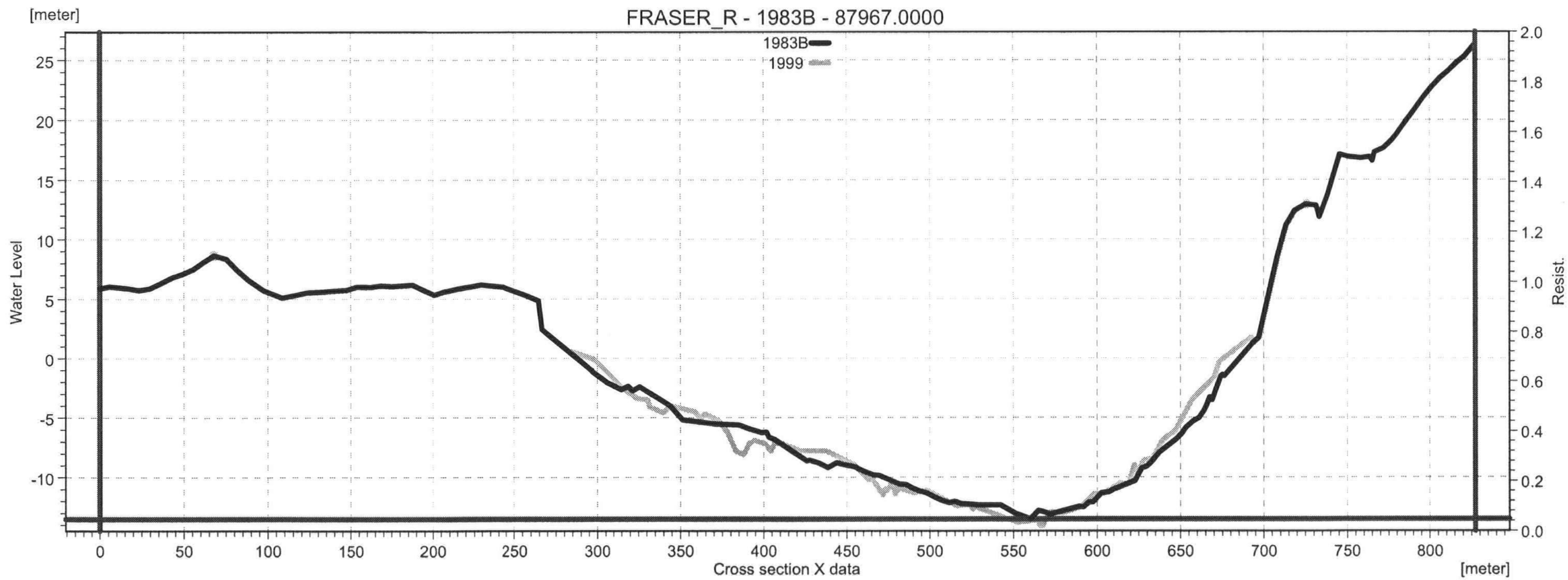

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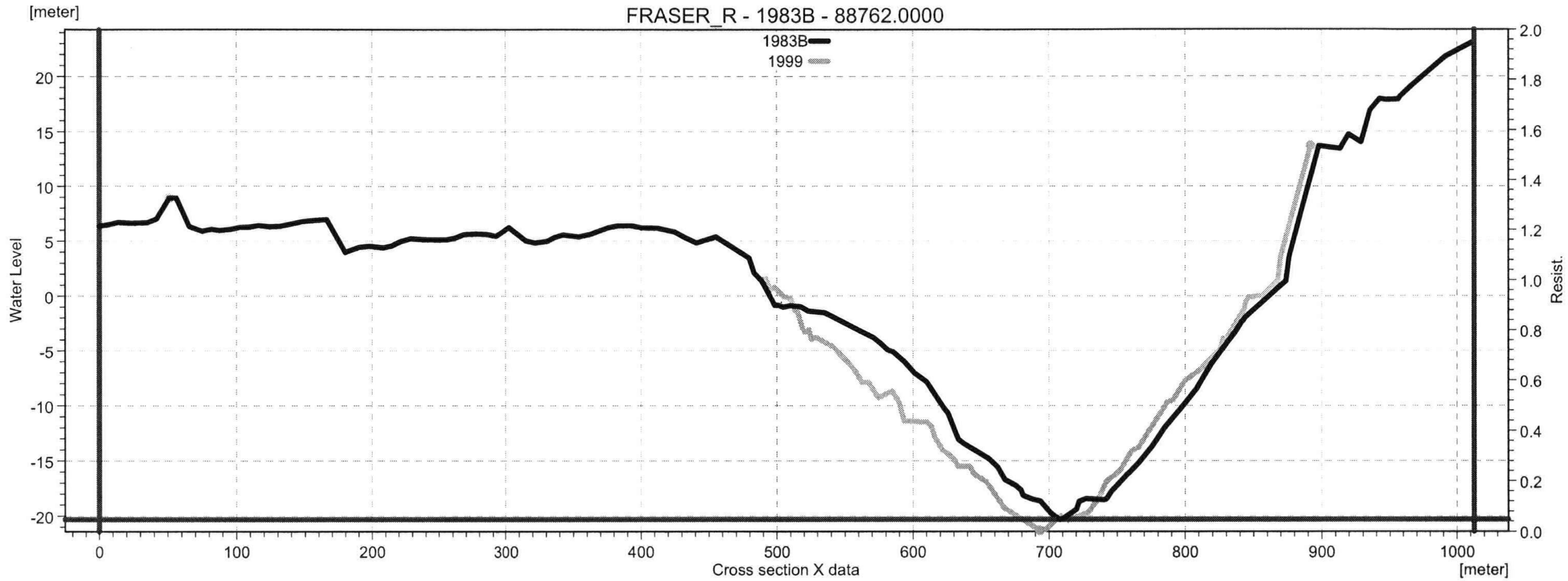

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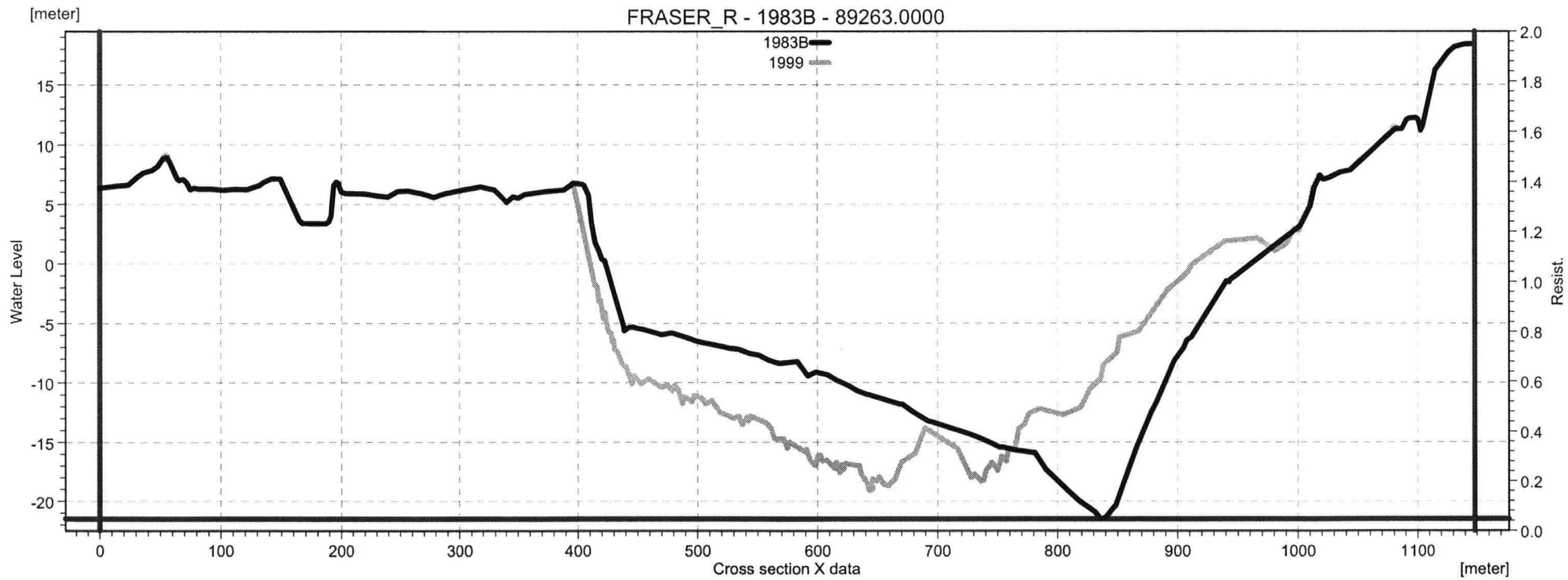

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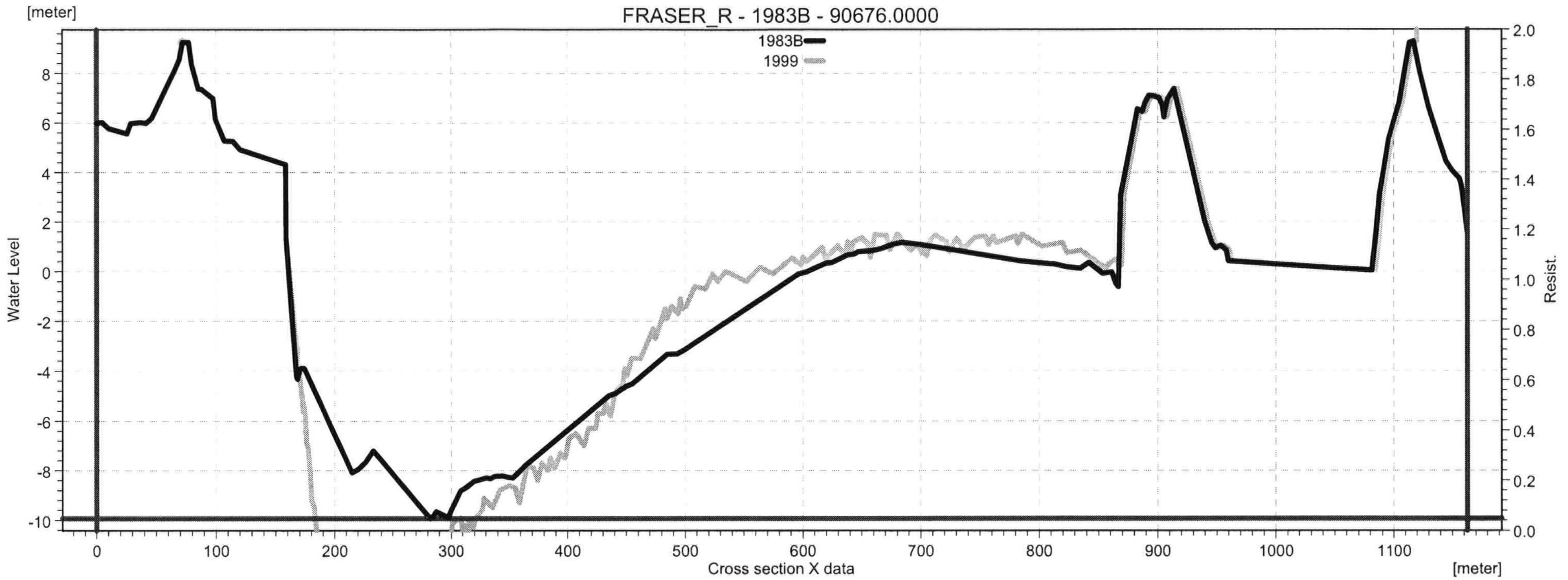
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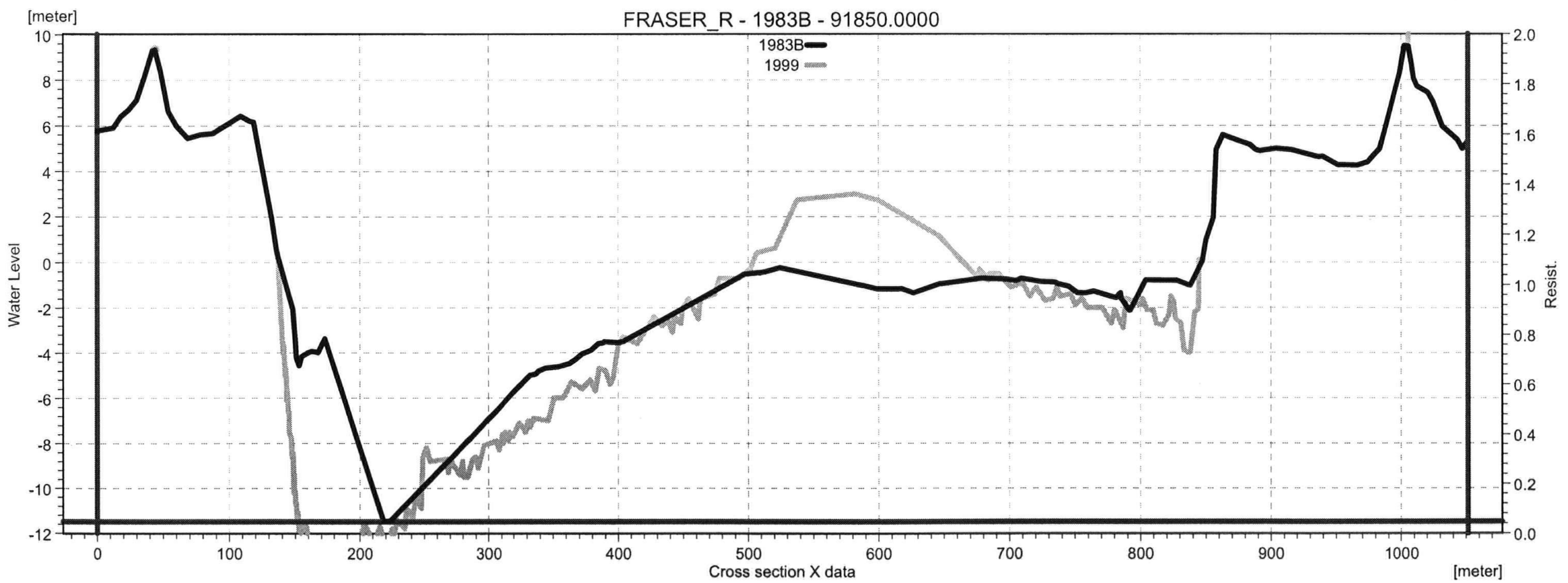
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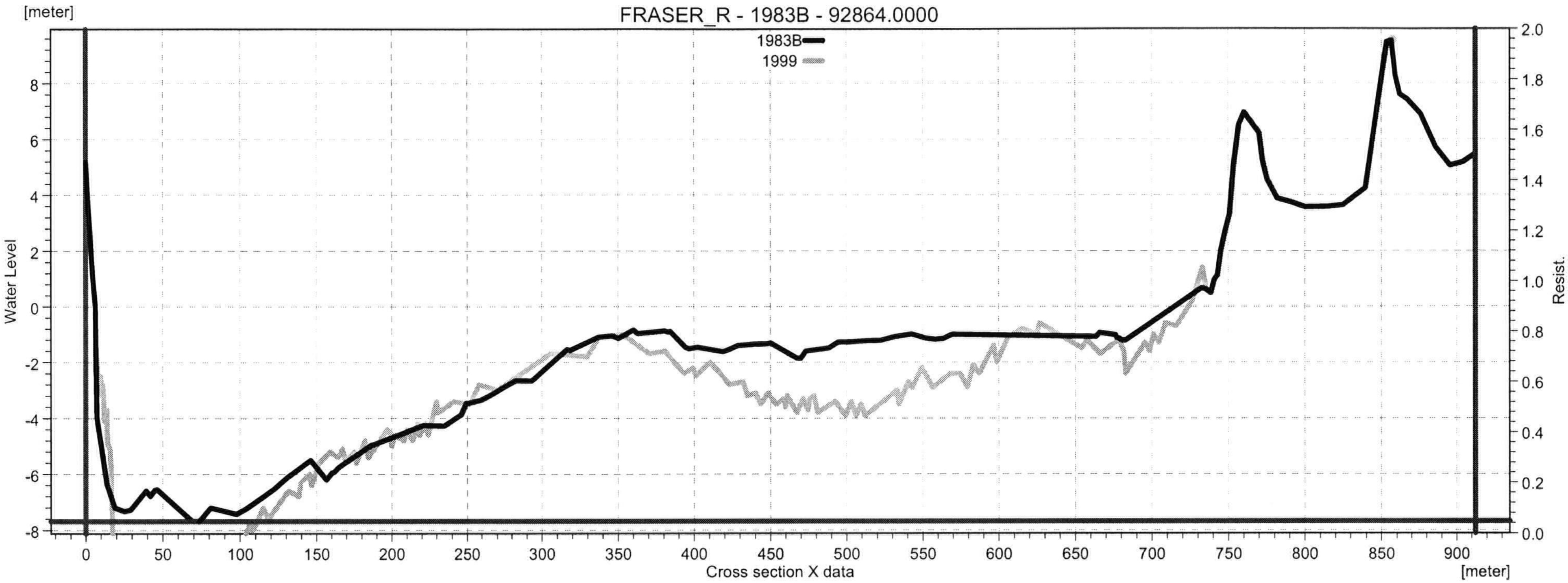

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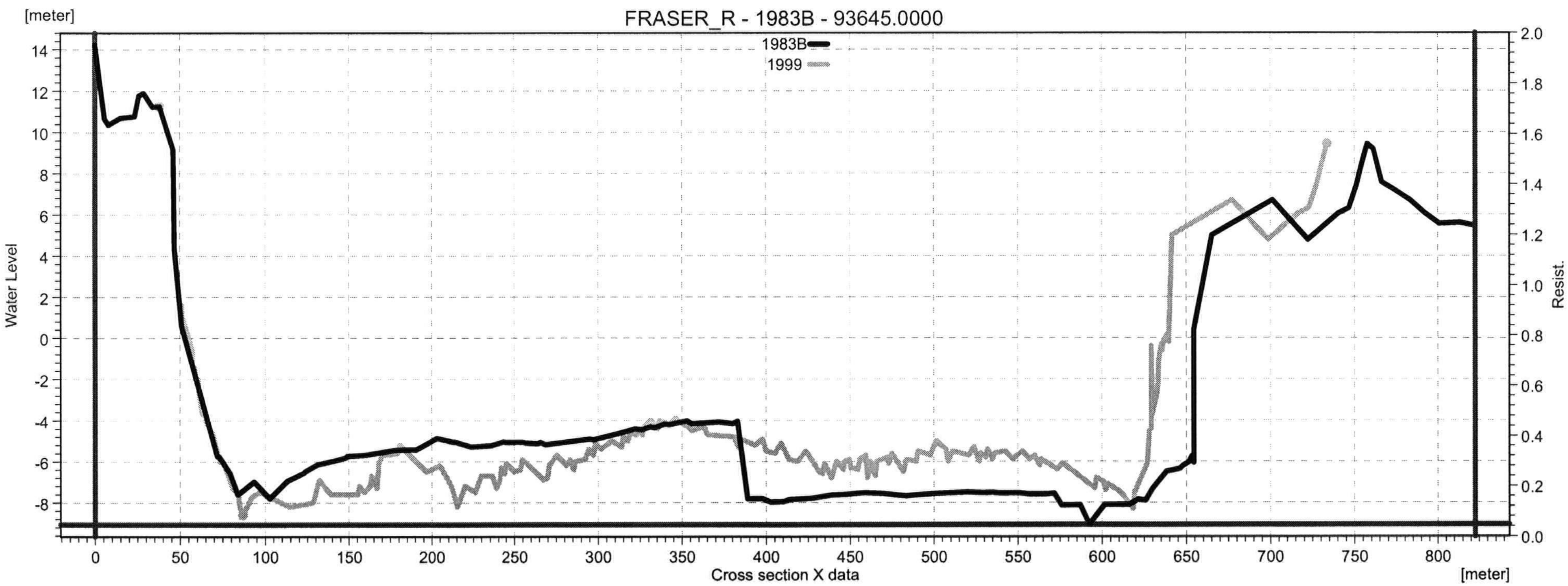

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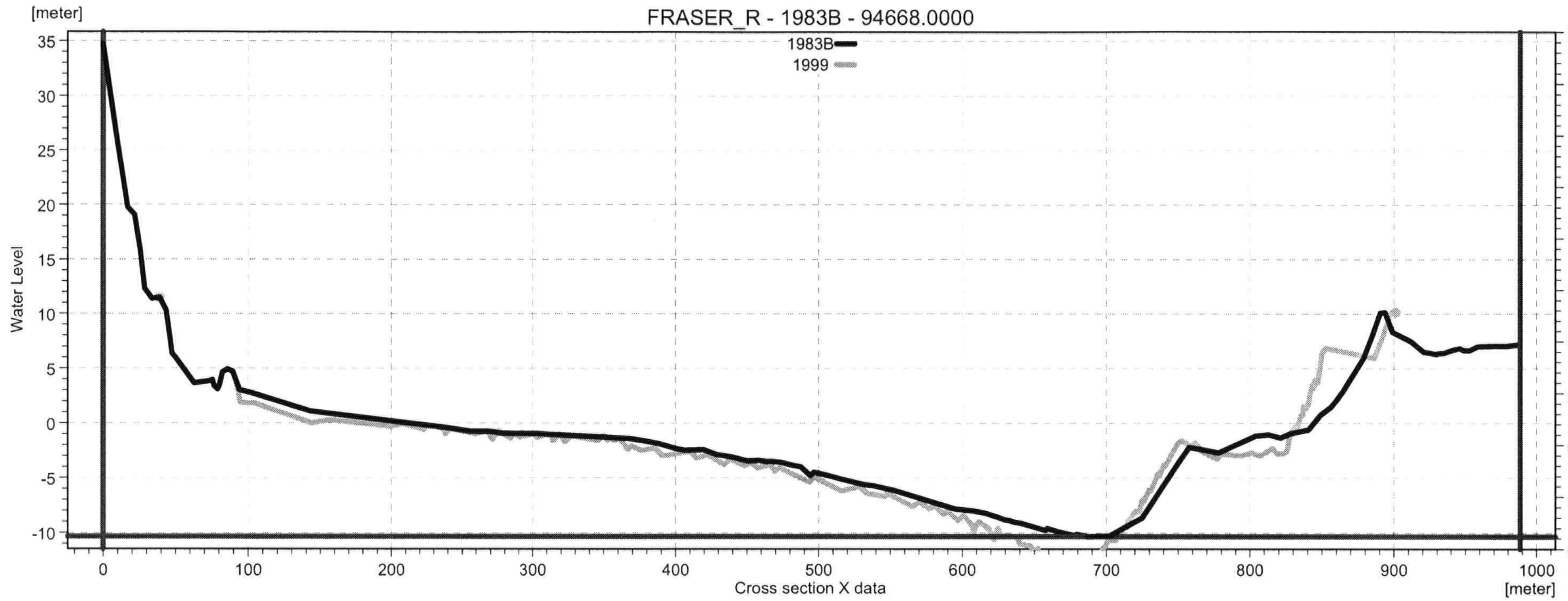
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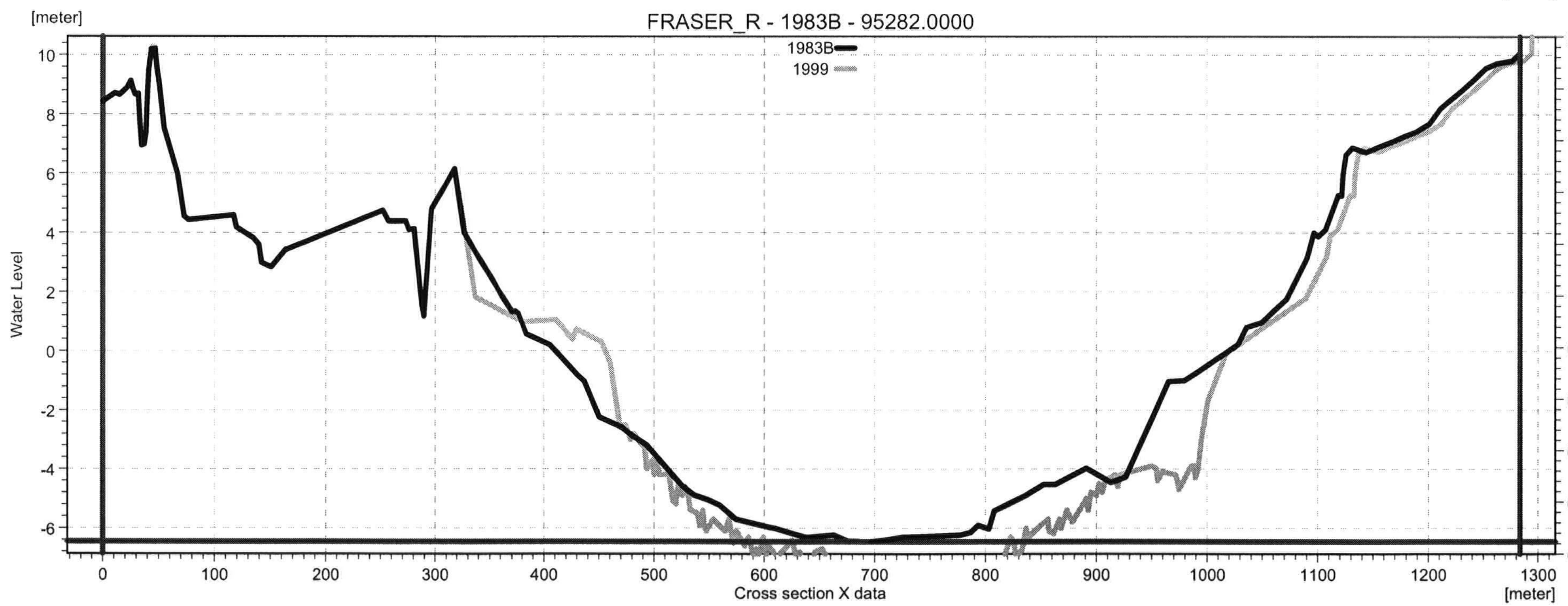
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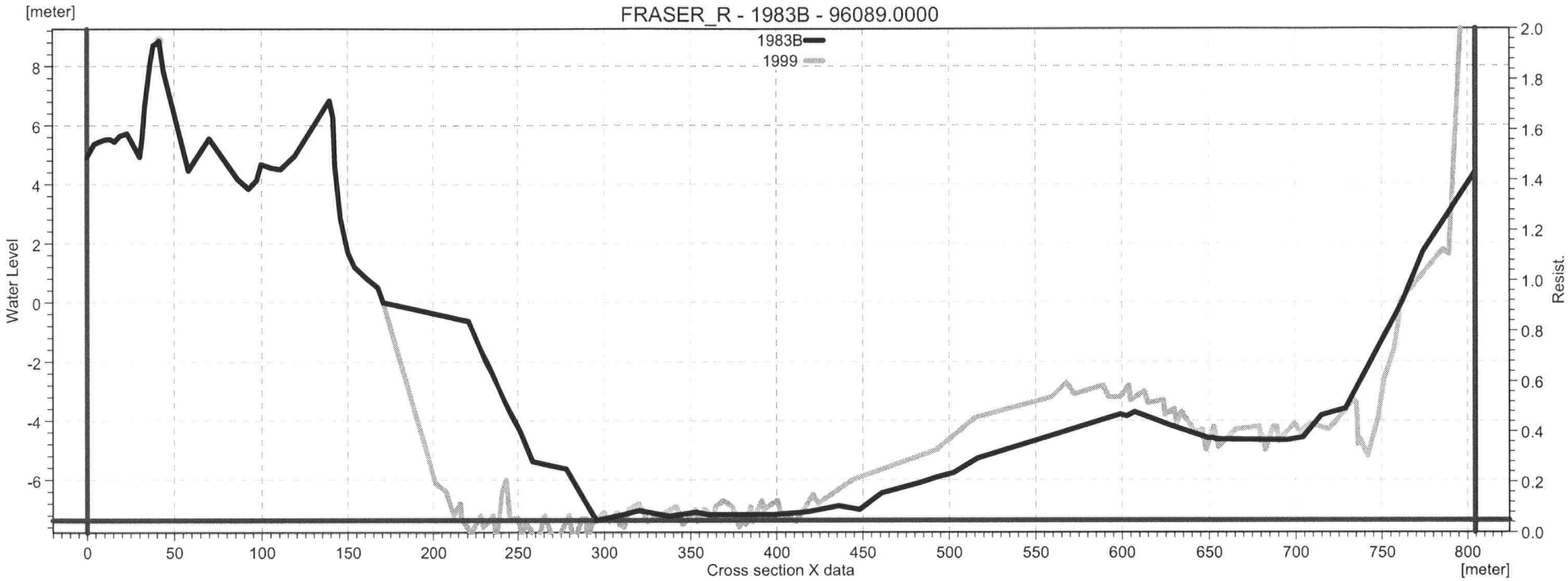
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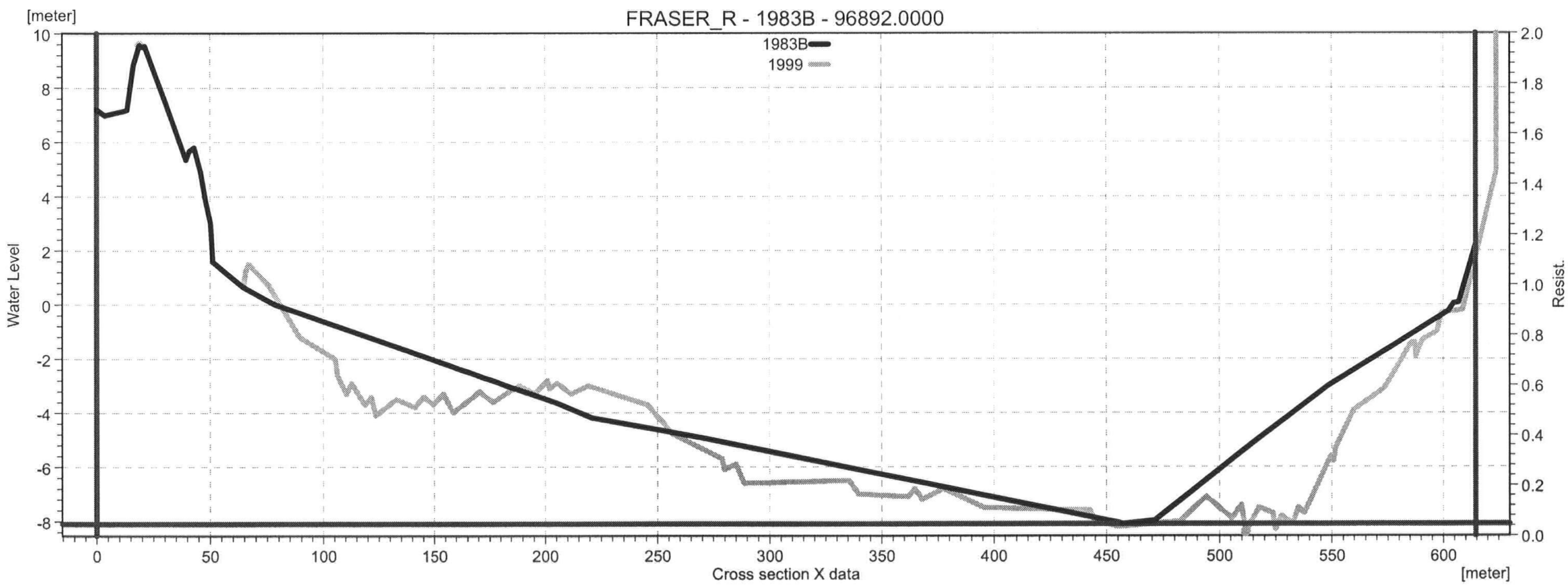
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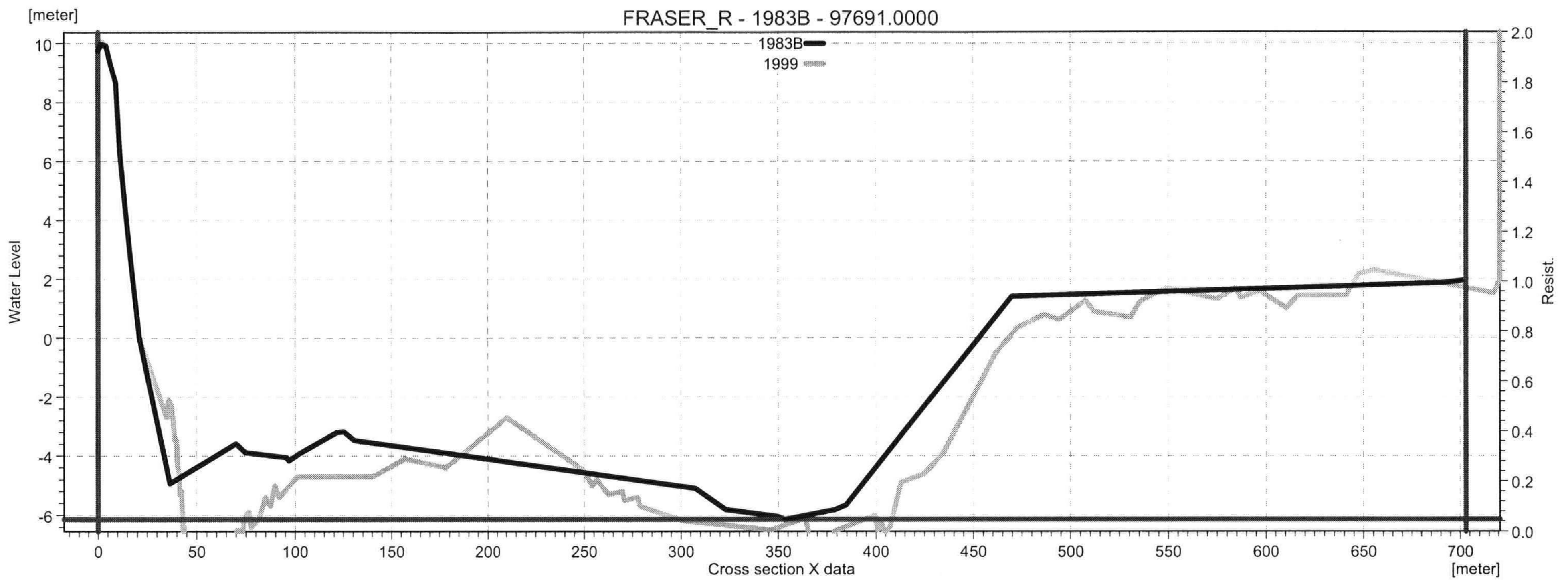
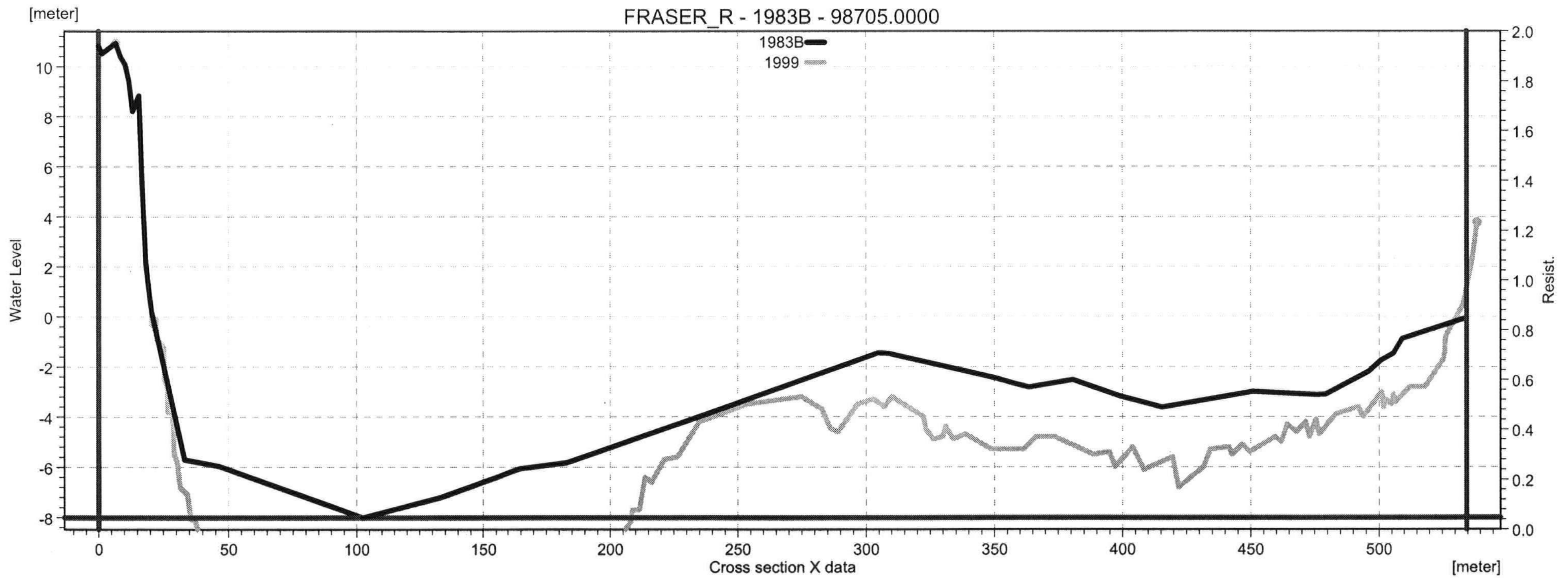
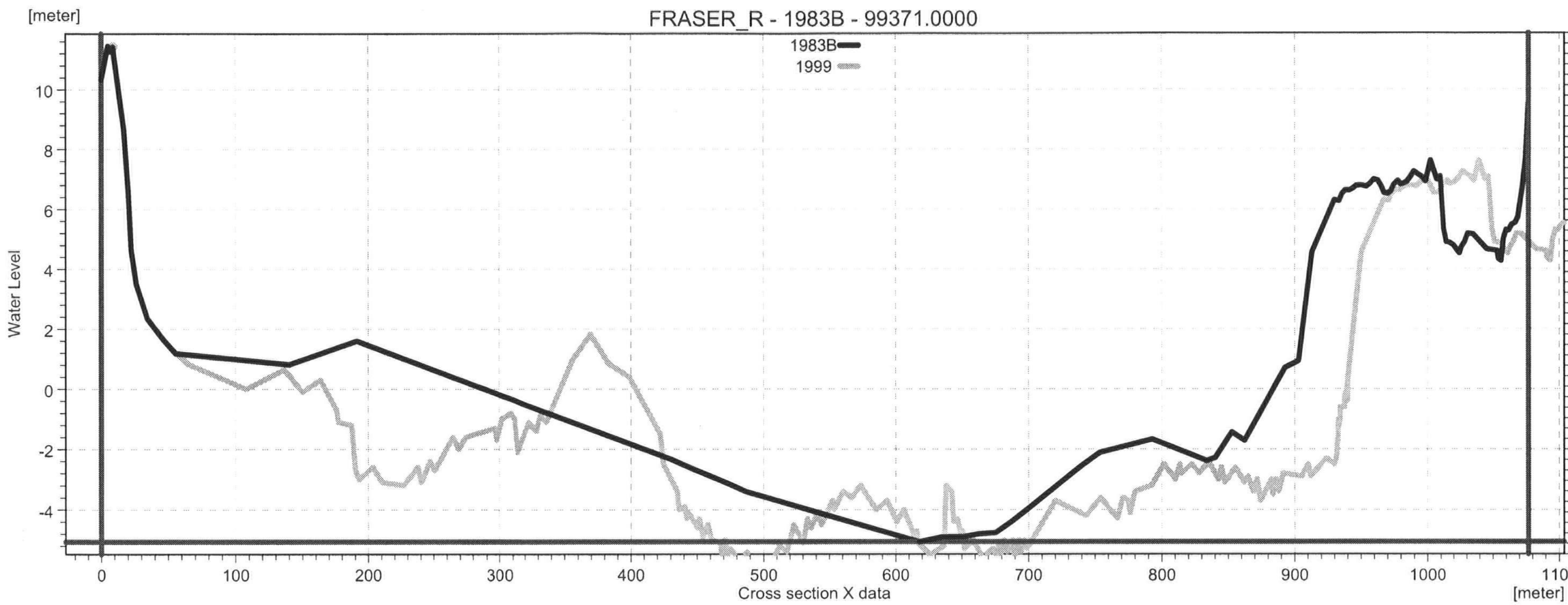
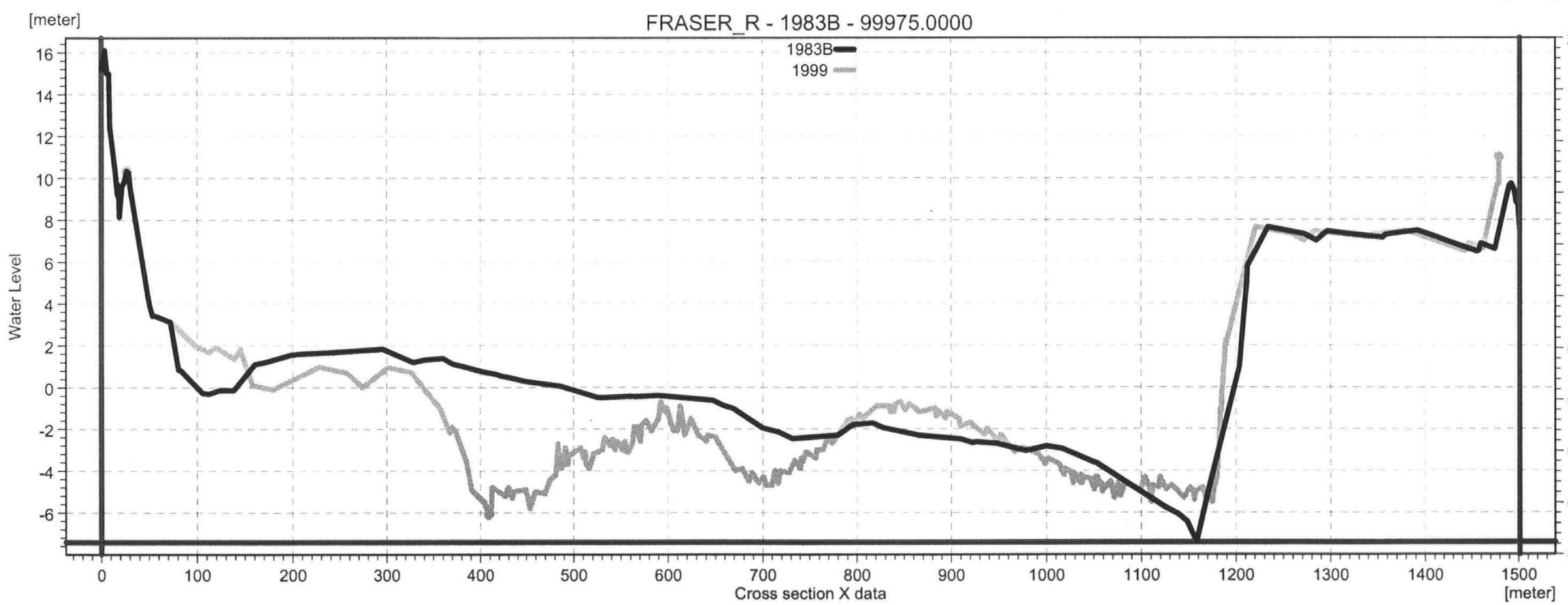
Cross section X data
[meter]

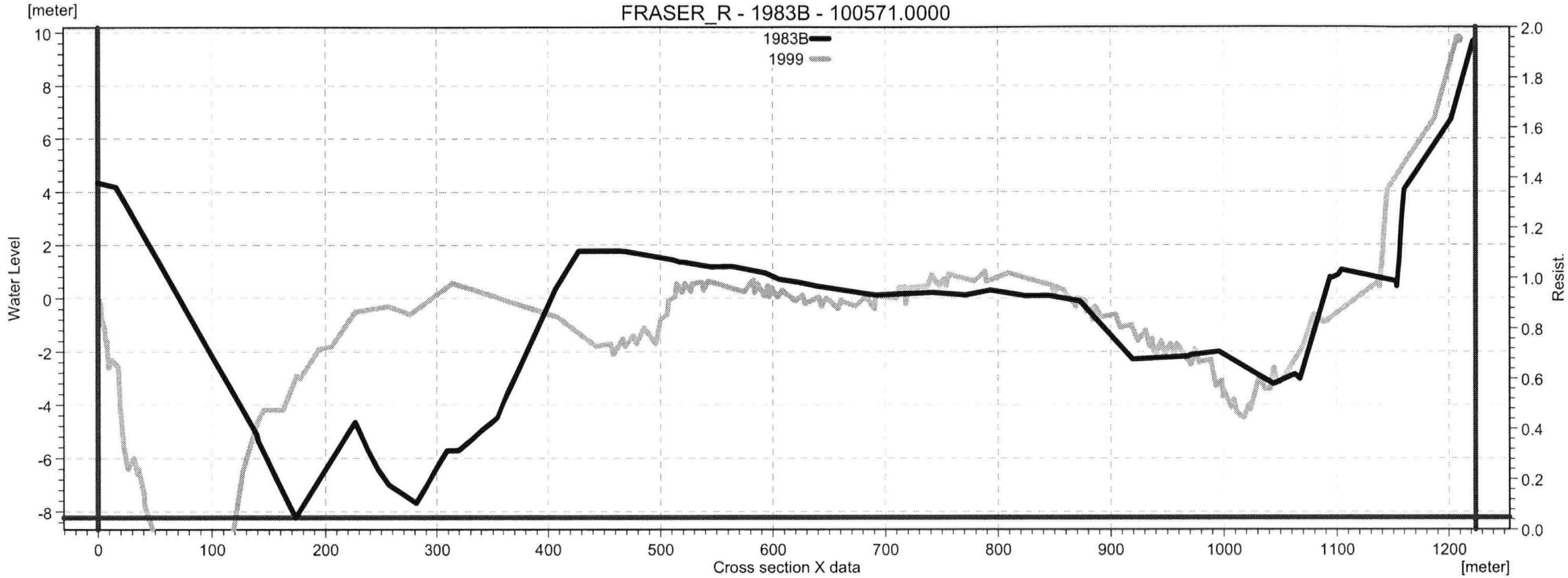

FRASER_R - 1983B - 97691.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]


FRASER_R - 1983B - 98705.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

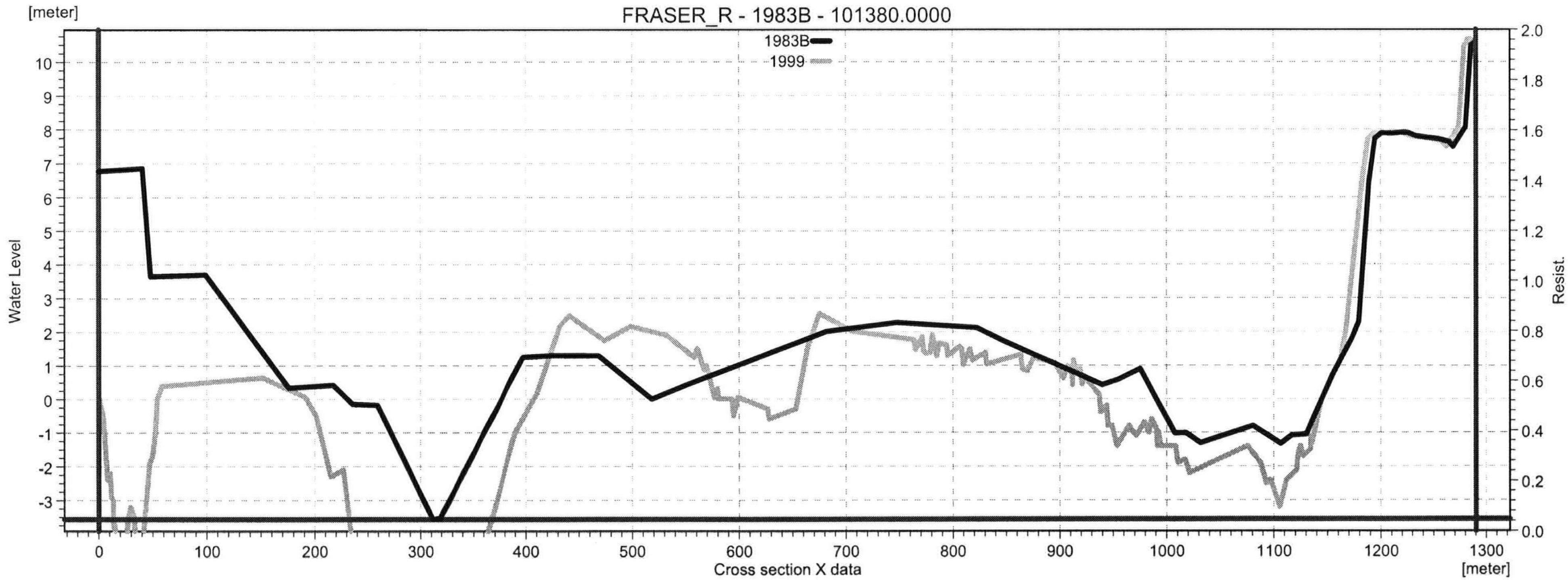

FRASER_R - 1983B - 99371.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

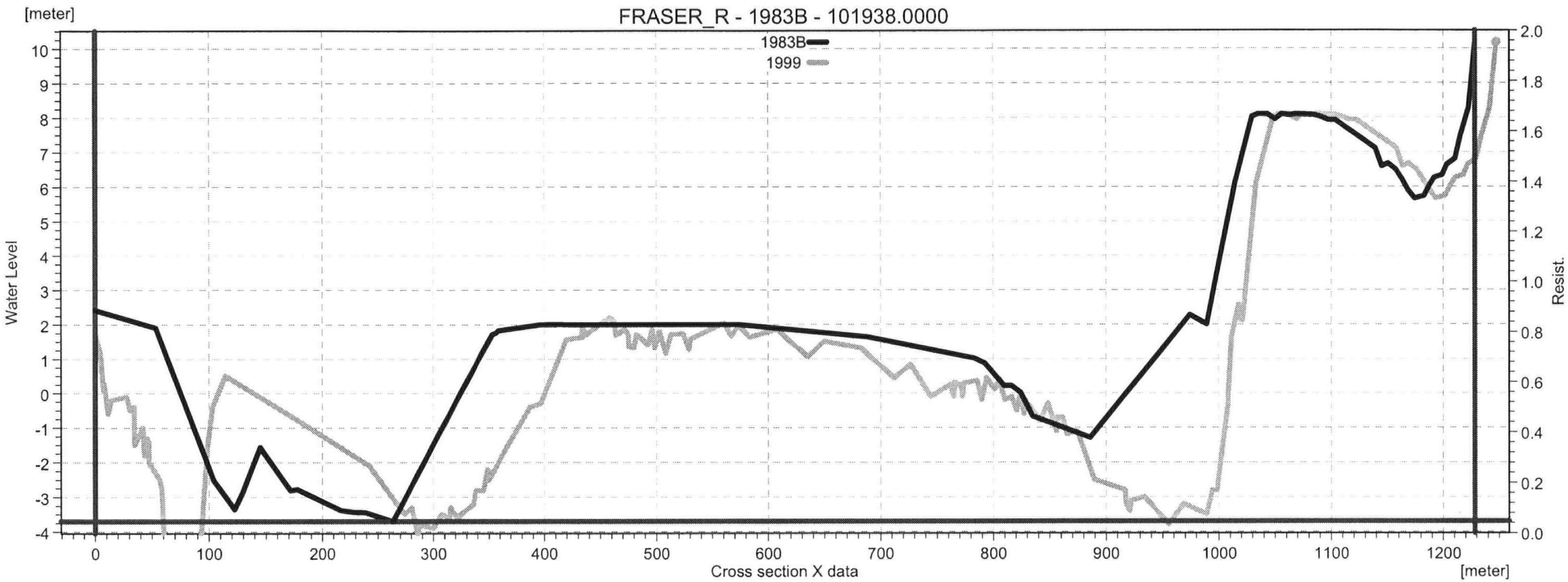

FRASER_R - 1983B - 99975.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

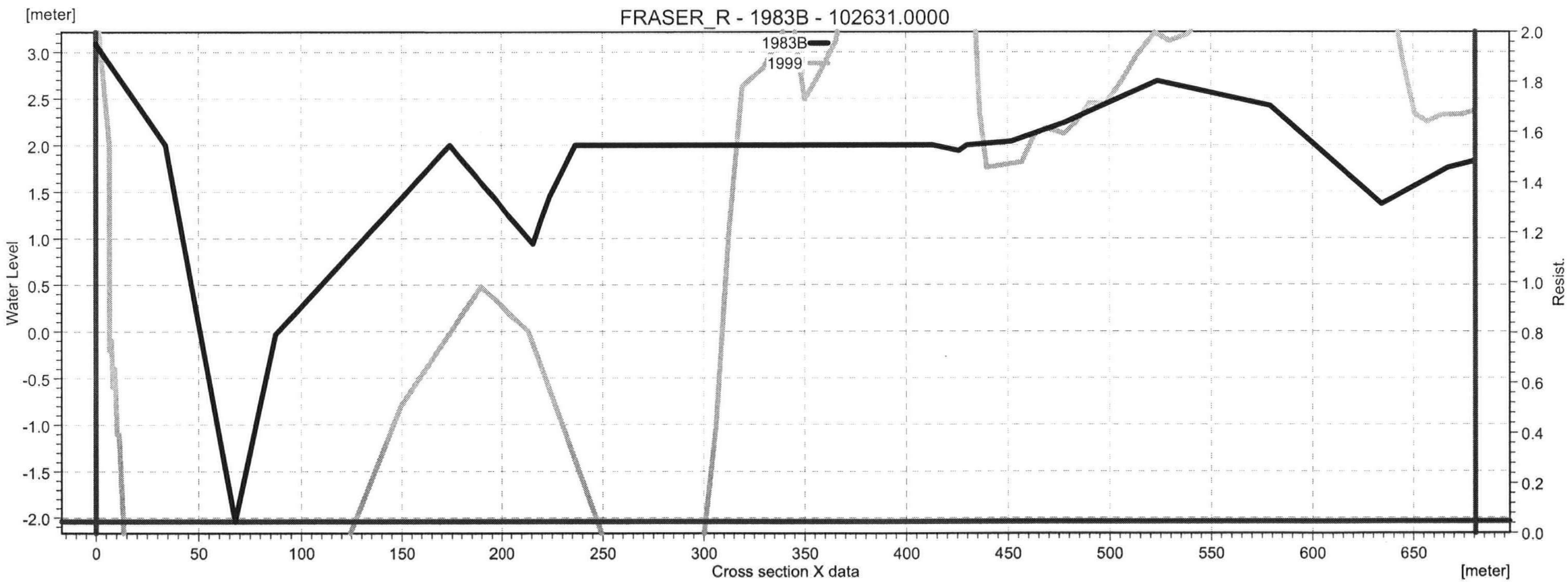
FRASER_R - 1983B - 100571.0000

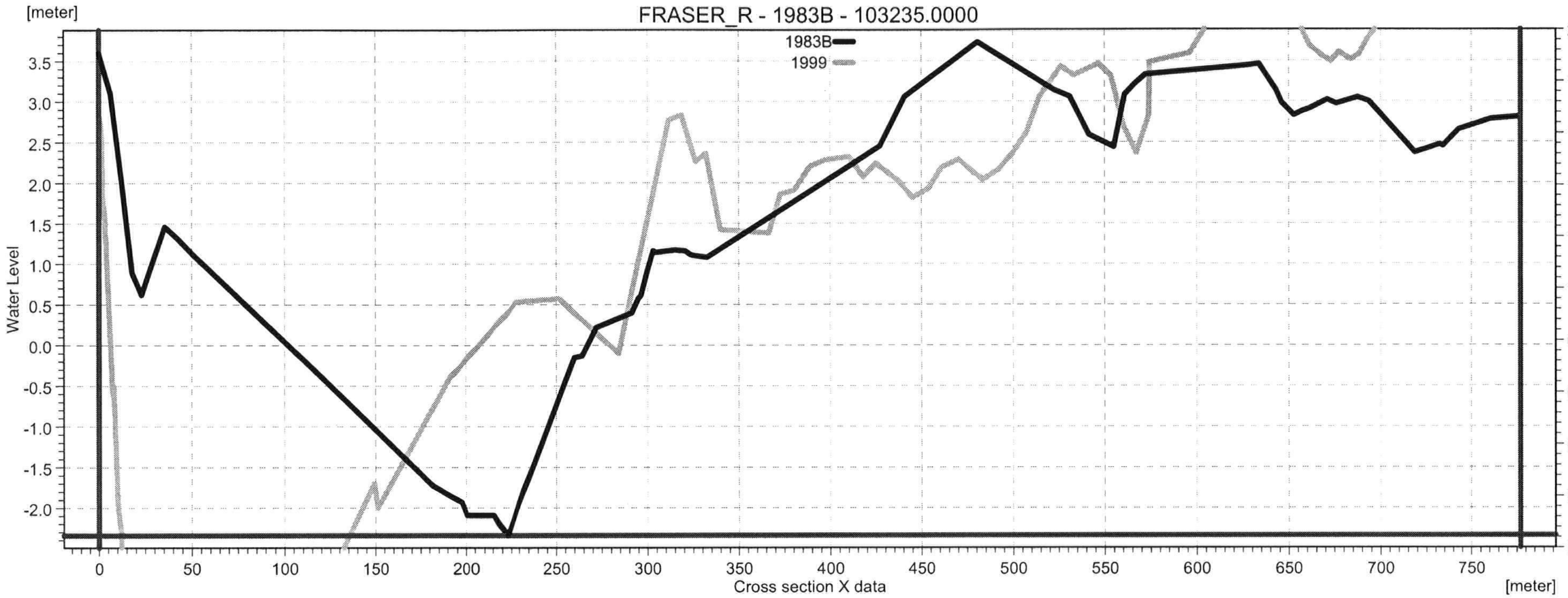


FRASER_R - 1983B - 101380.0000

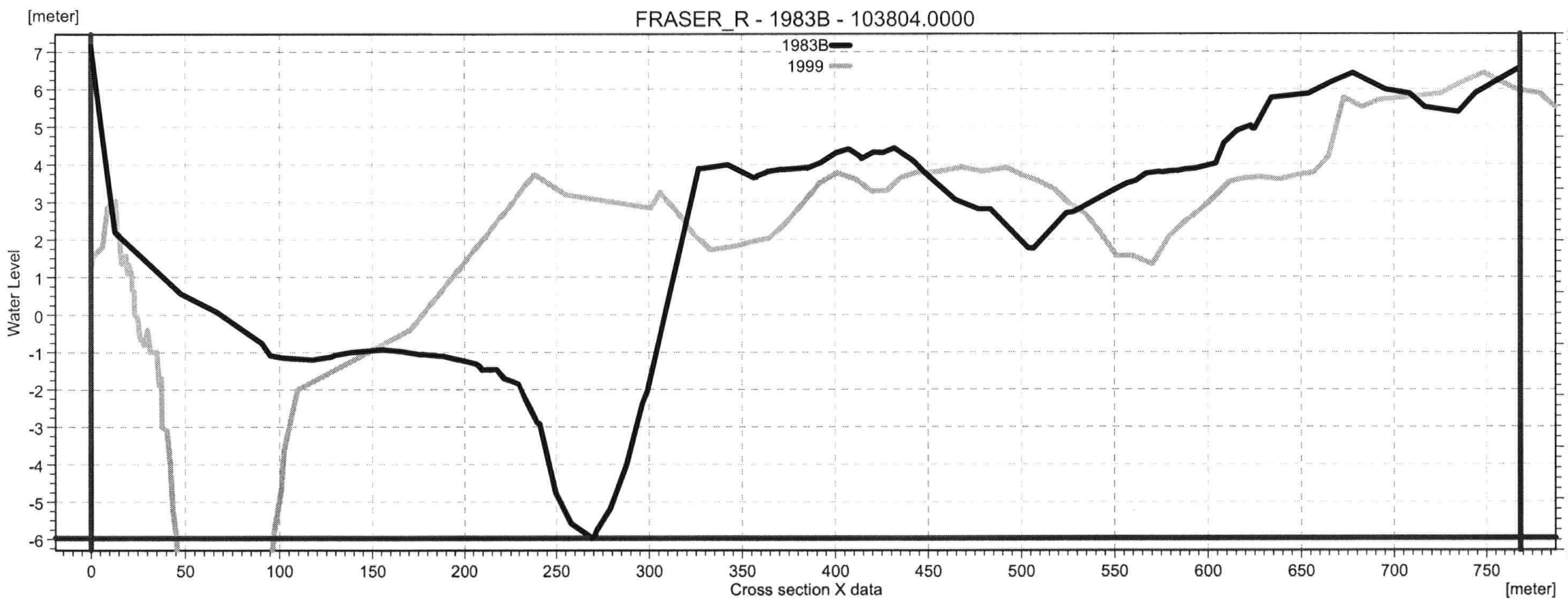



FRASER_R - 1983B - 101938.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

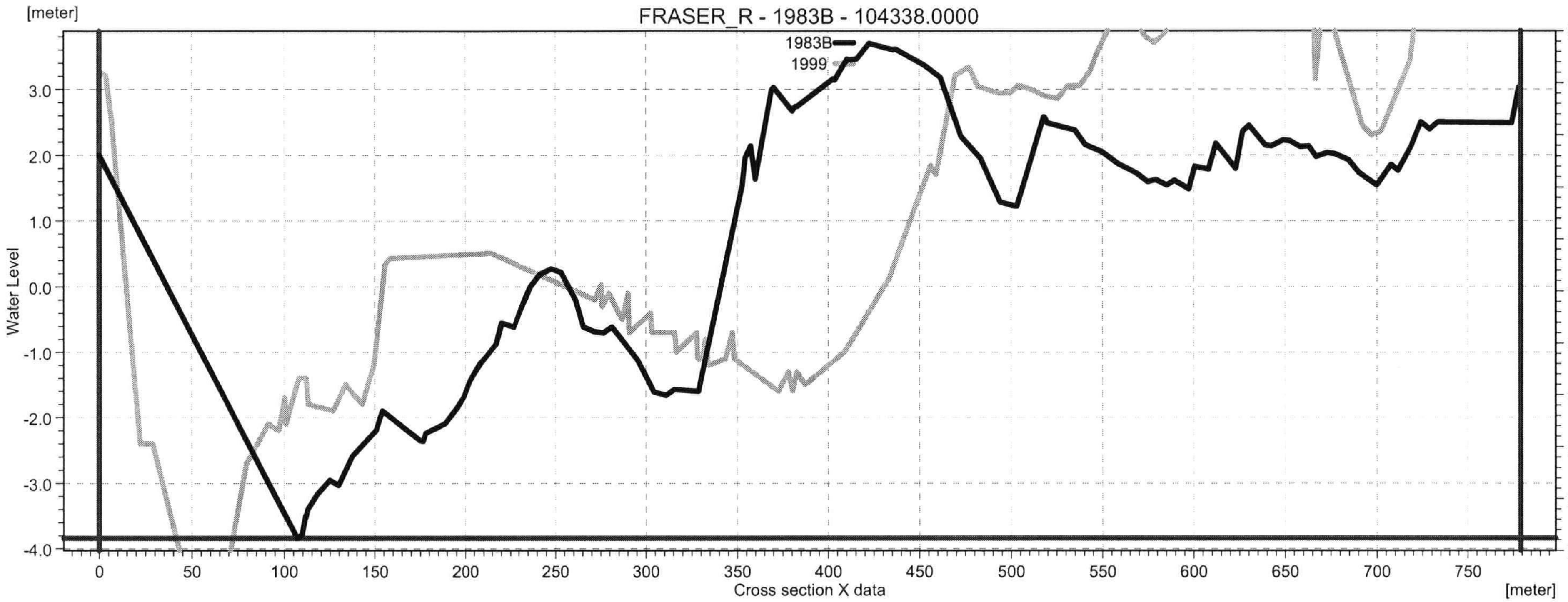

FRASER_R - 1983B - 102631.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

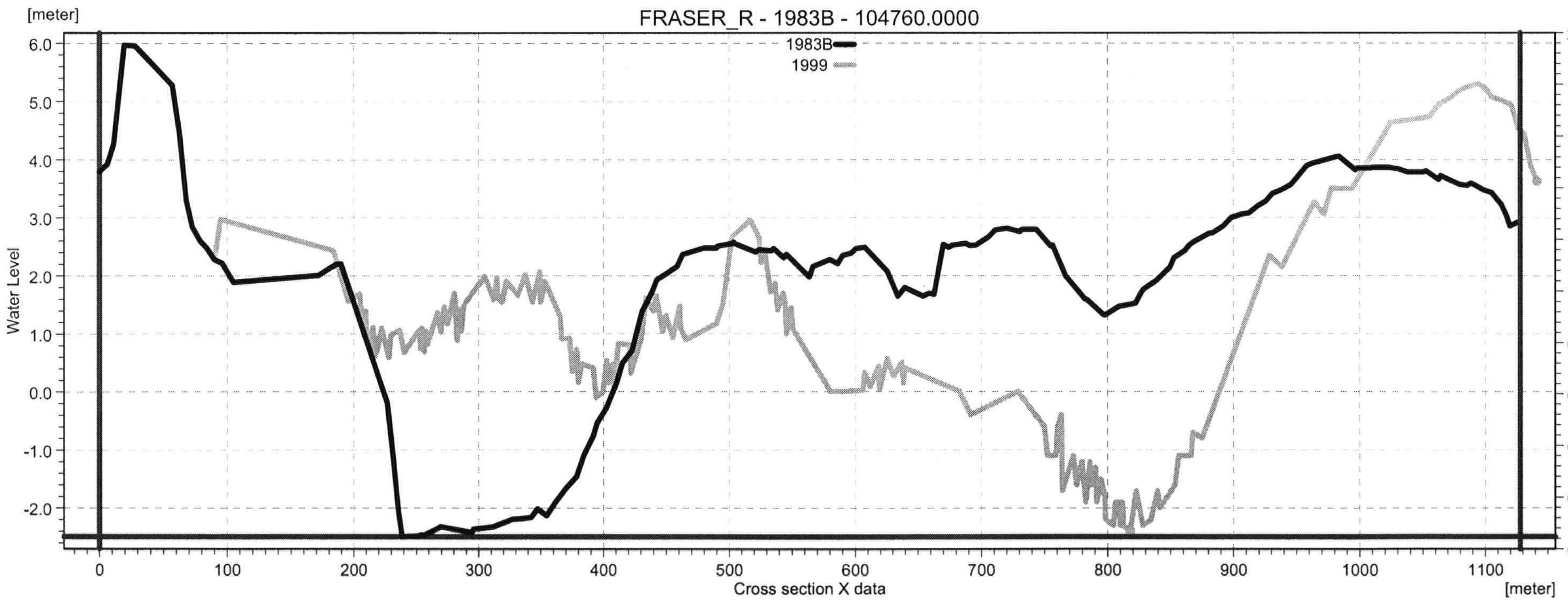


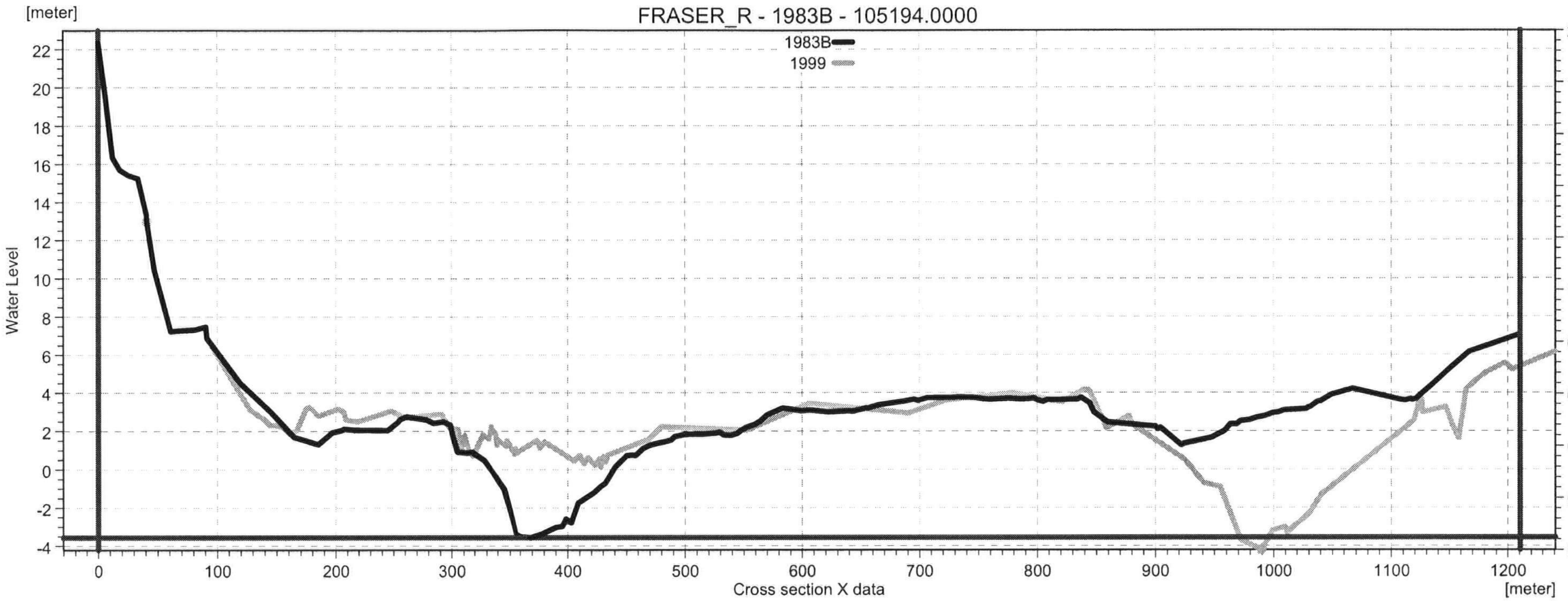
[meter]
FRASER_R - 1983B - 103235.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

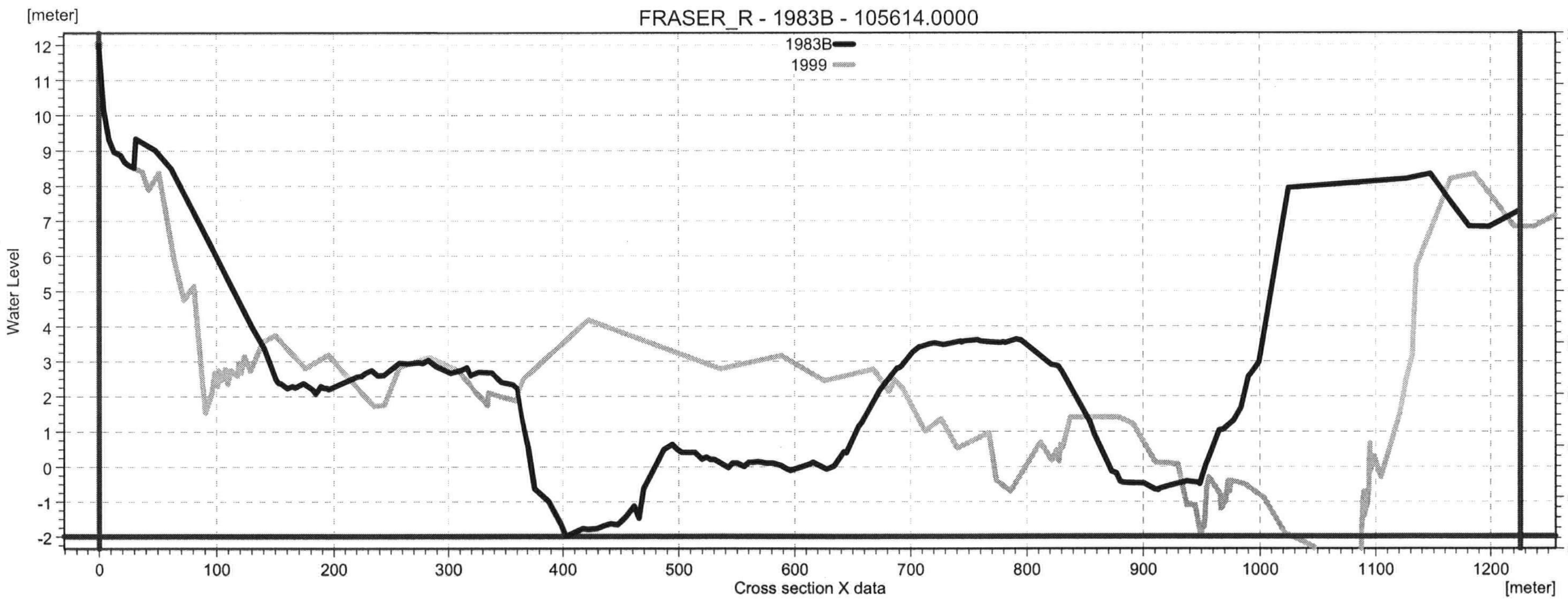


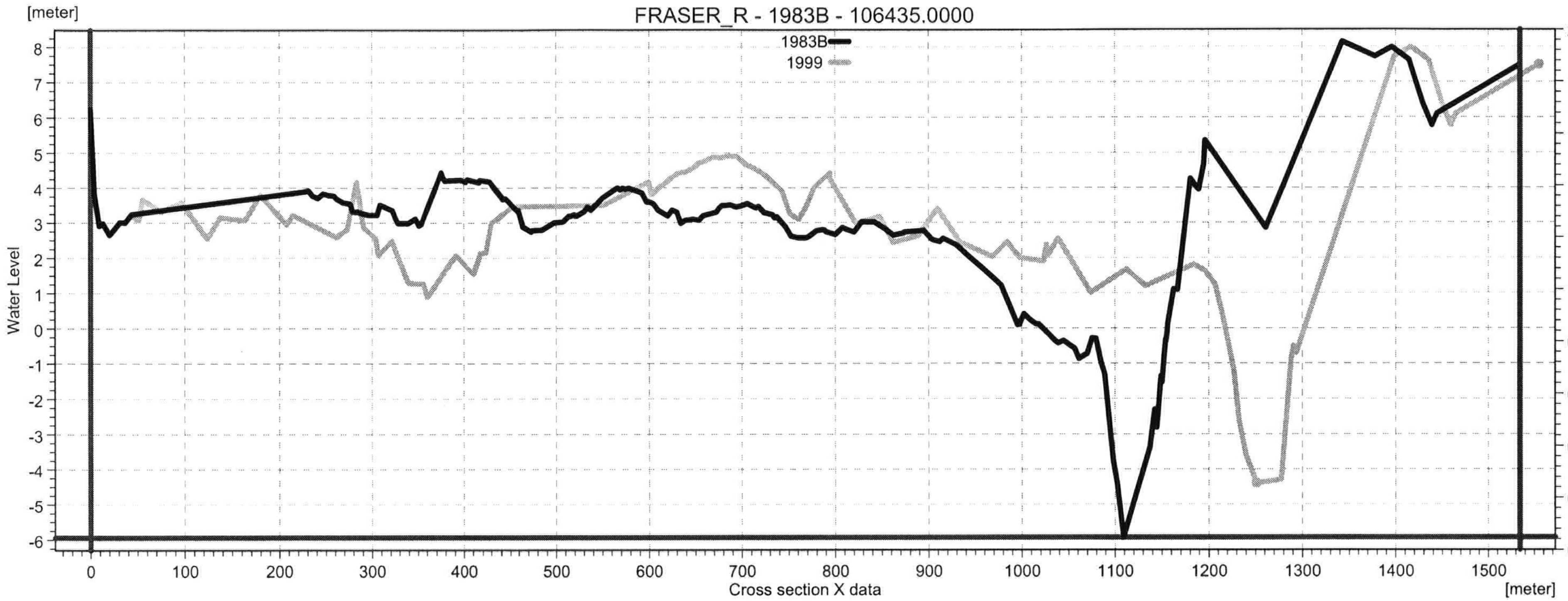
[meter]
FRASER_R - 1983B - 103804.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

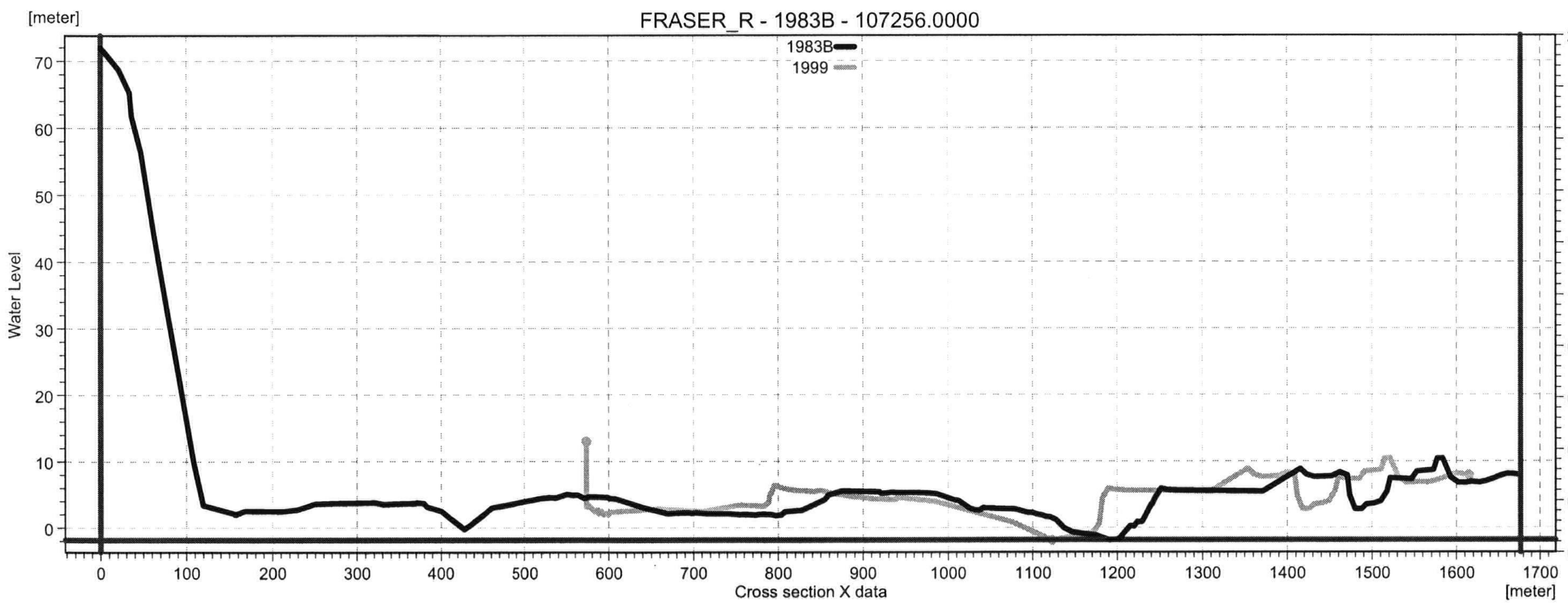

FRASER_R - 1983B - 104338.0000
1983B
1999
Water Level
[meter]
Resist.
Cross section X data
[meter]

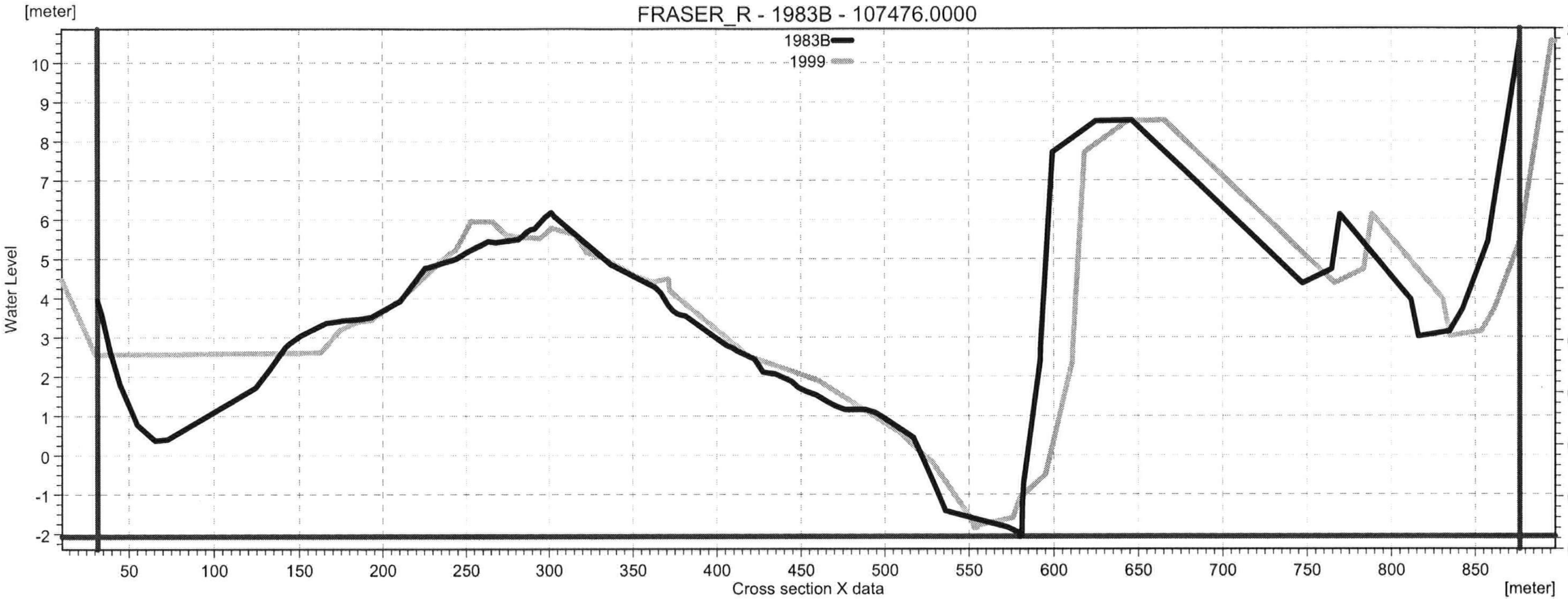

FRASER_R - 1983B - 104760.0000
1983B
1999
Water Level
[meter]
Resist.
Cross section X data
[meter]

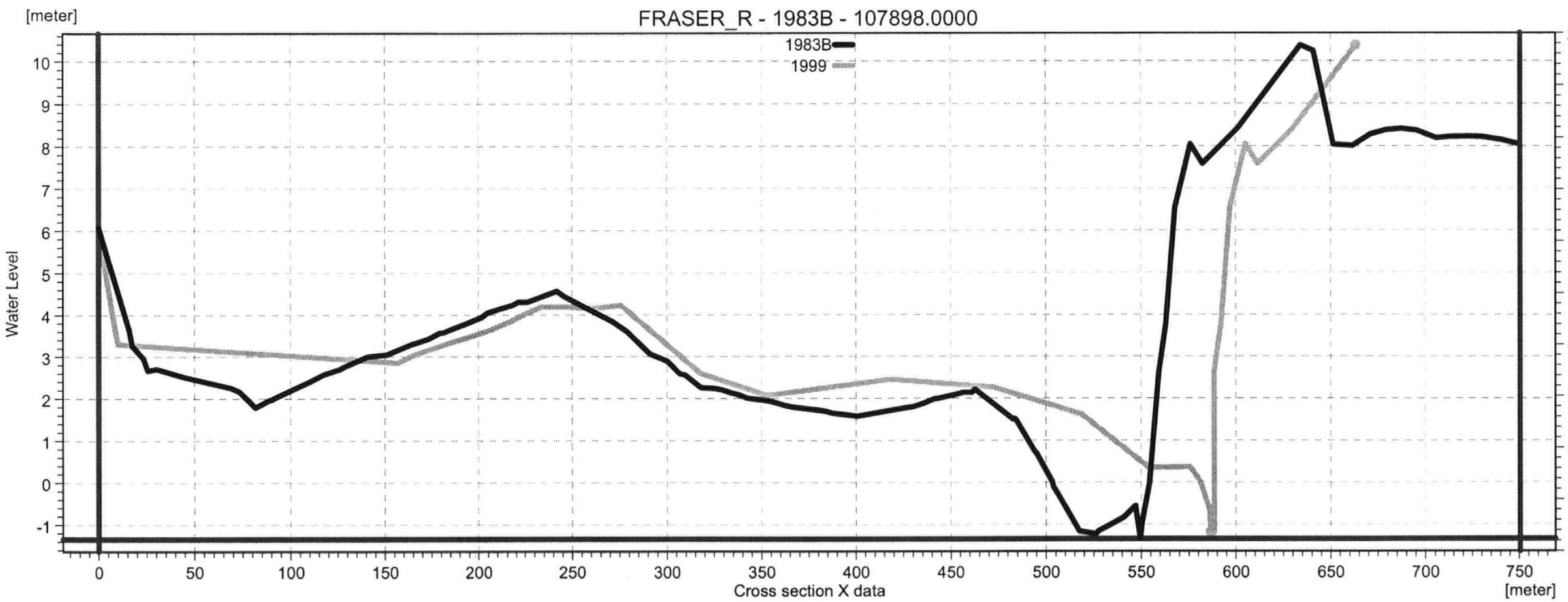

[meter]
FRASER_R - 1983B - 105194.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

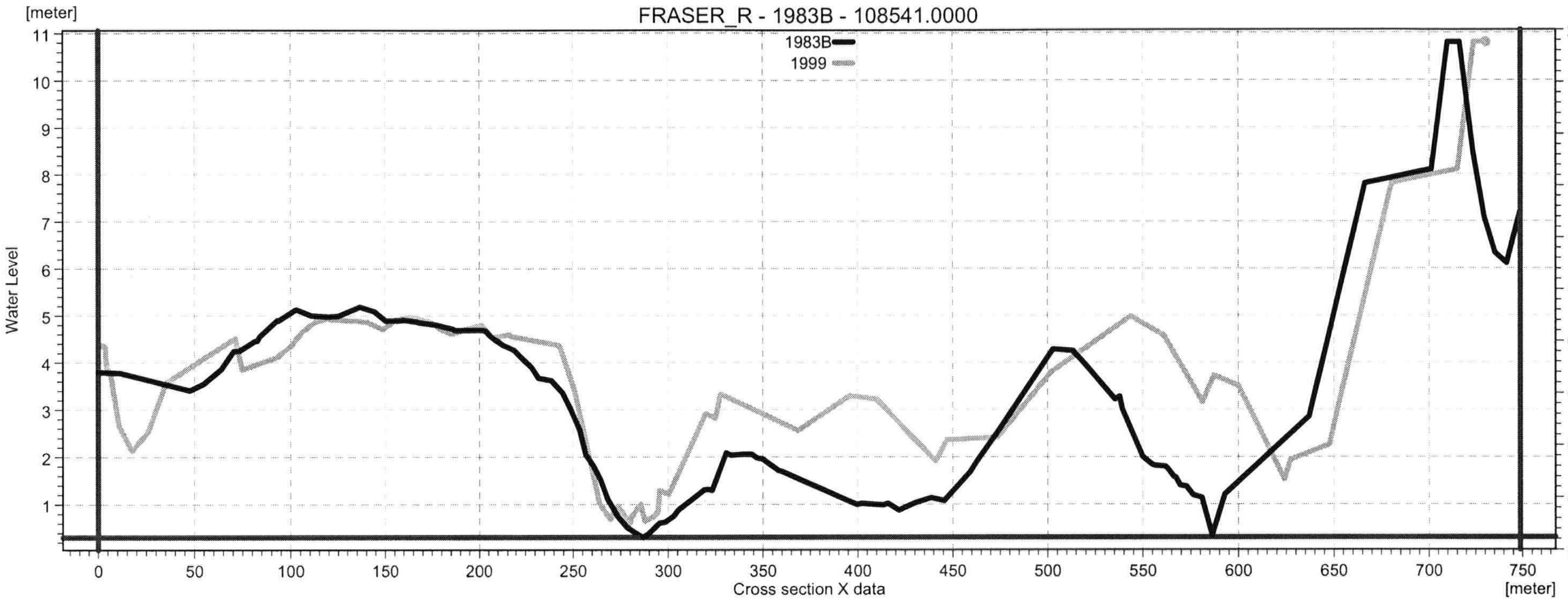

[meter]
FRASER_R - 1983B - 105614.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

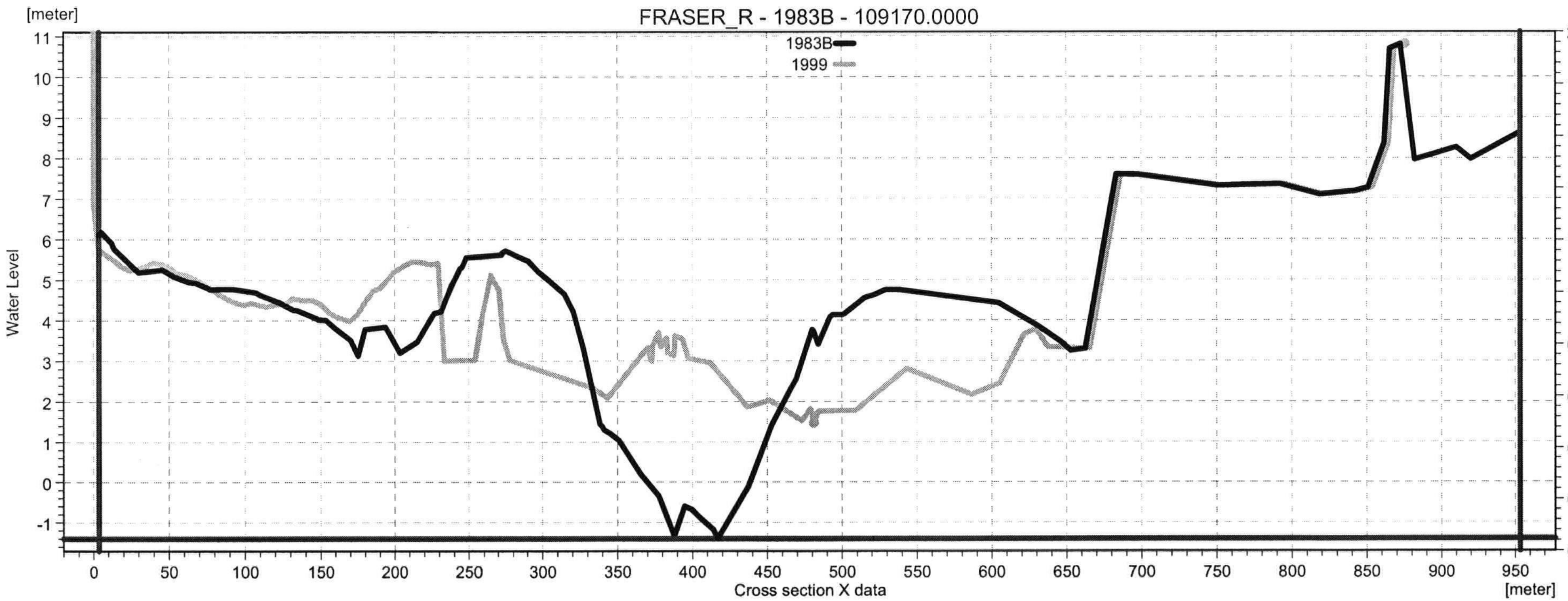

FRASER_R - 1983B - 106435.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

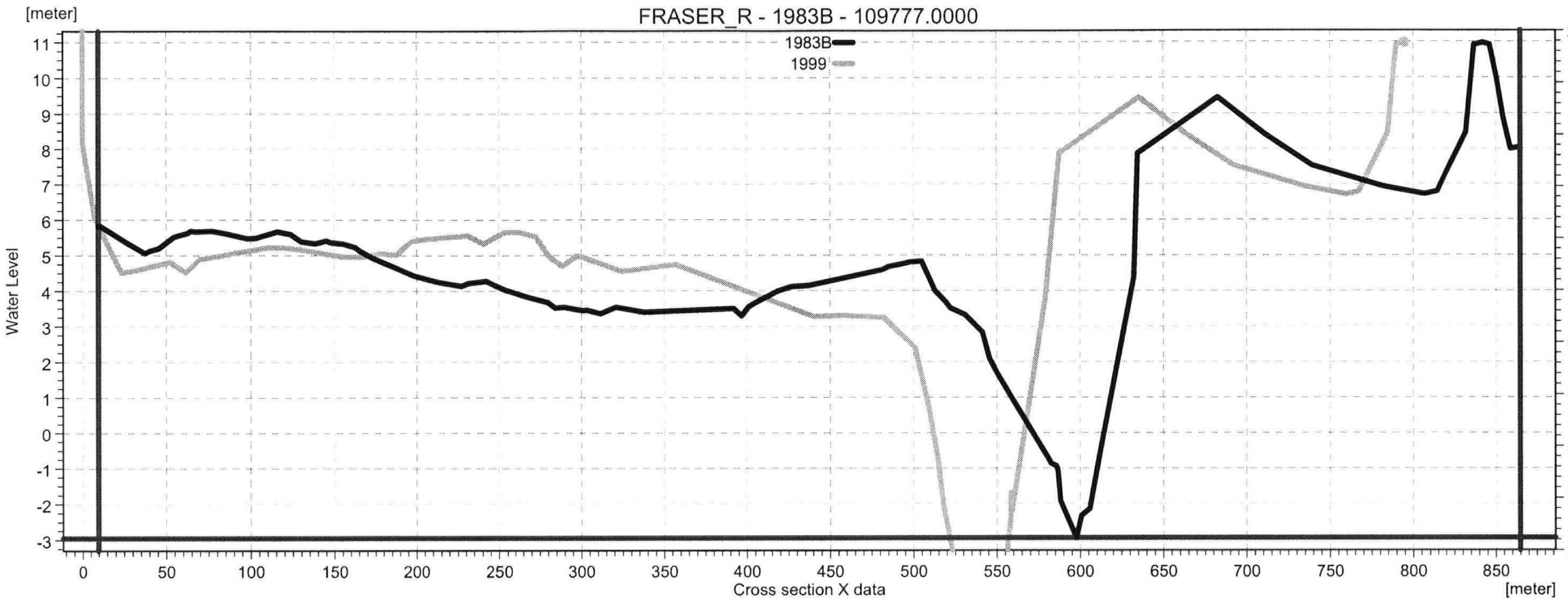

FRASER_R - 1983B - 107256.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

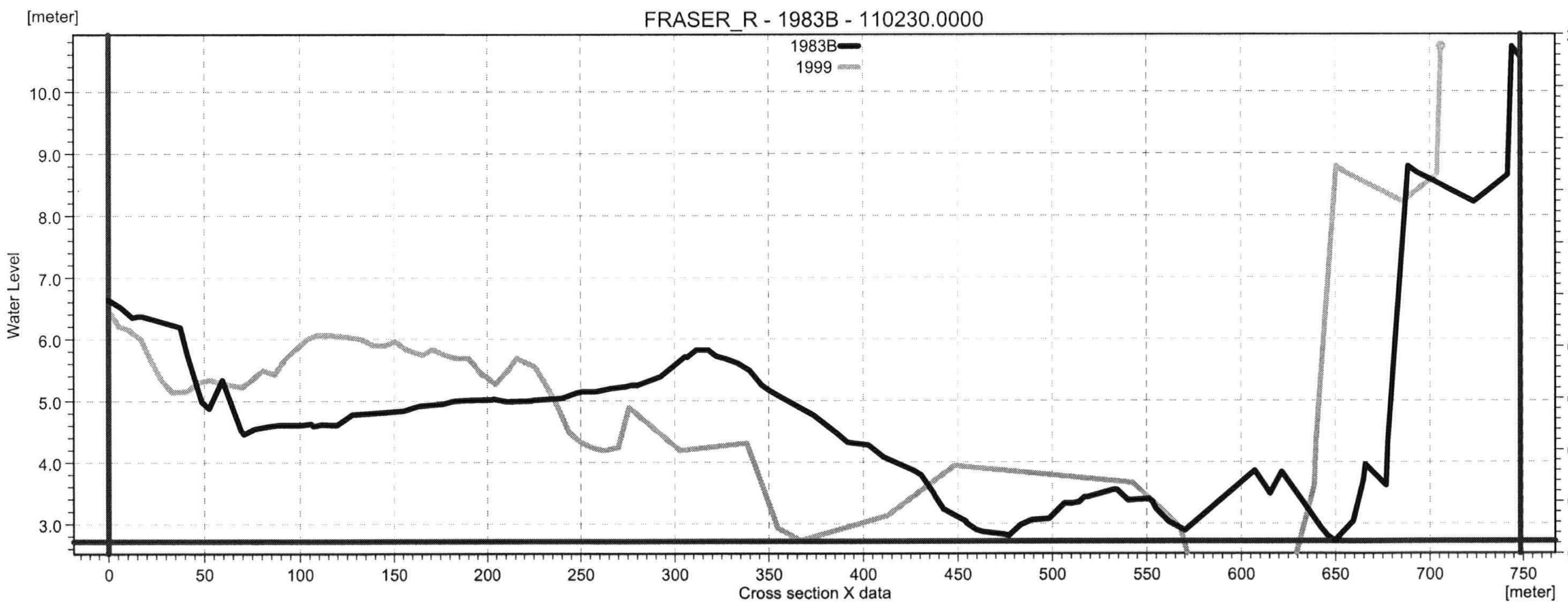

[meter]
FRASER_R - 1983B - 107476.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

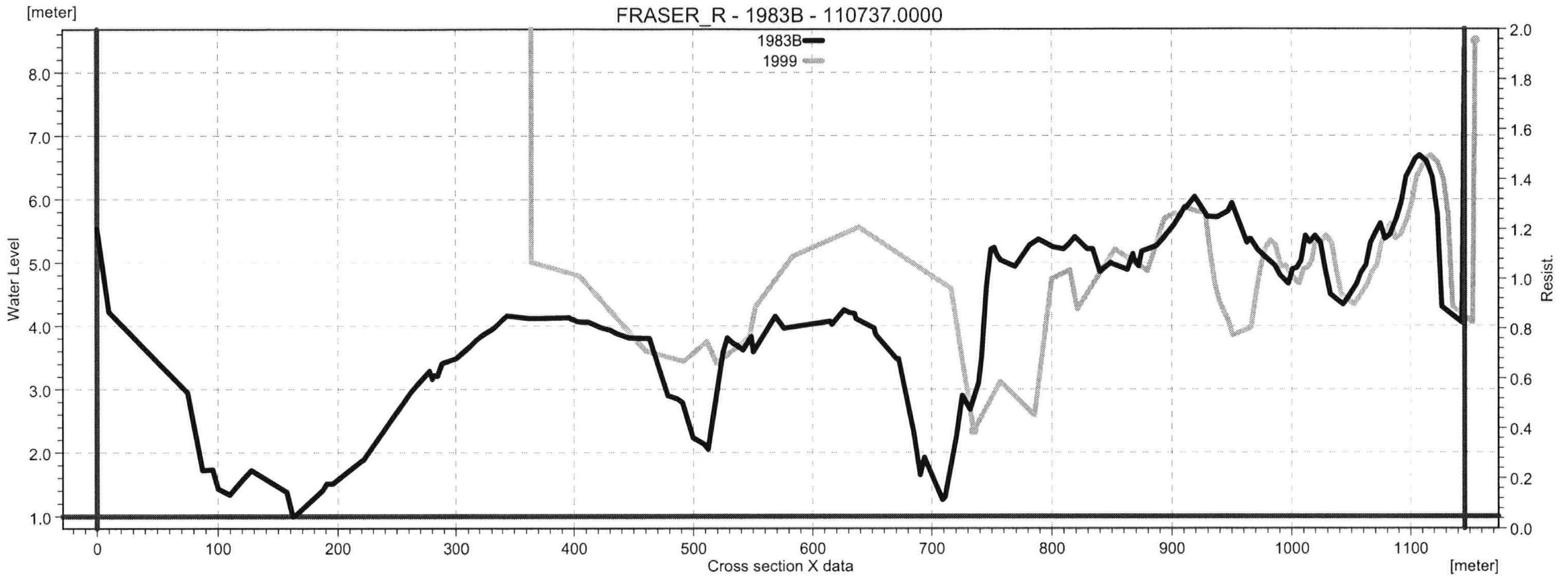

[meter]
FRASER_R - 1983B - 107898.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]


FRASER_R - 1983B - 108541.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

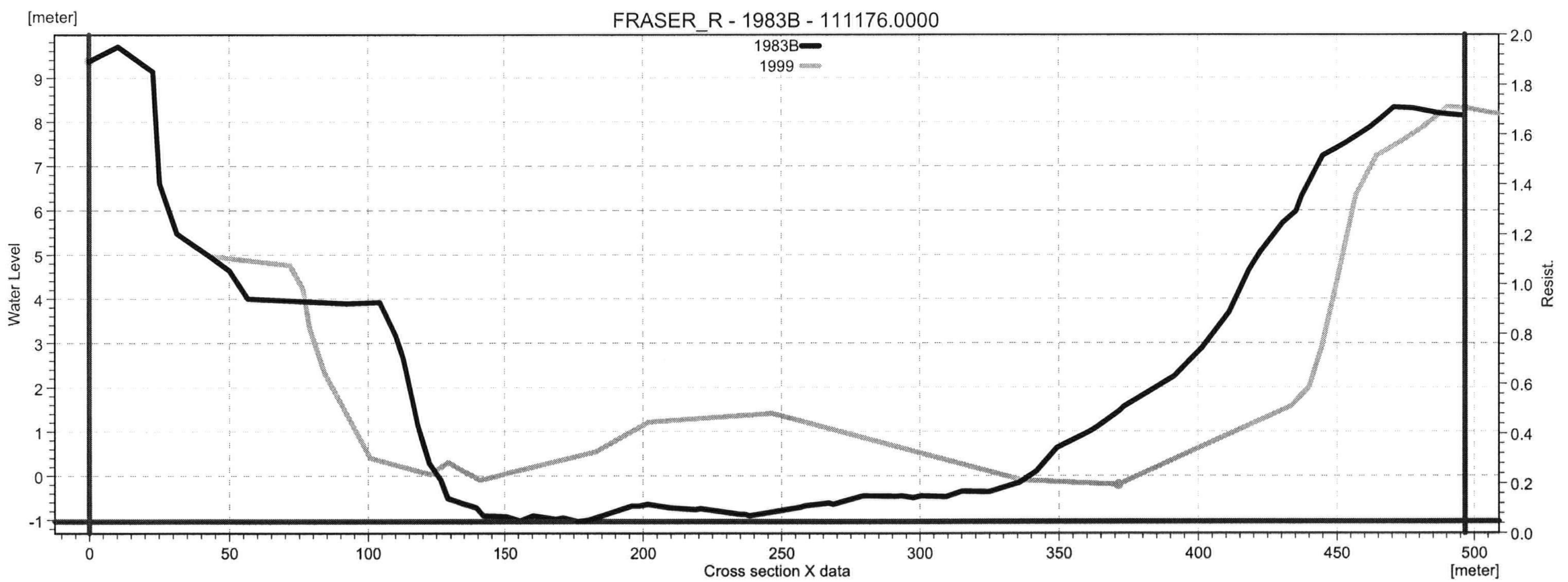

FRASER_R - 1983B - 109170.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]


[meter]
FRASER_R - 1983B - 109777.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

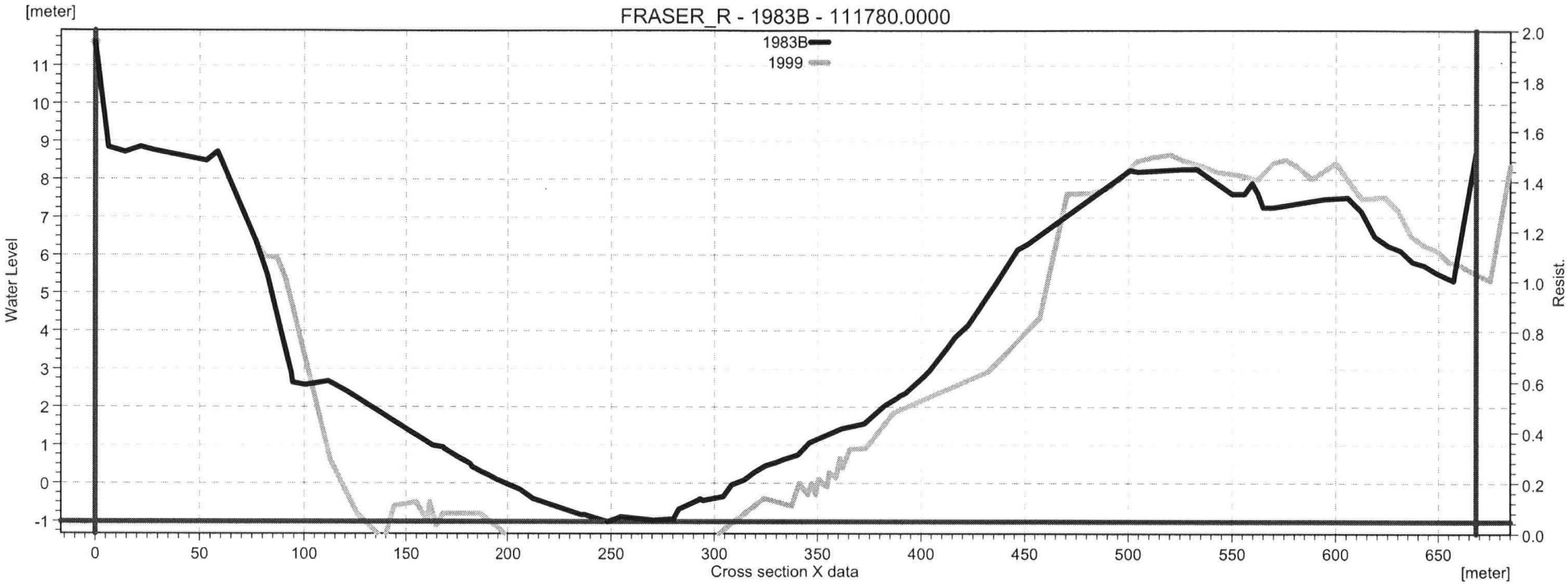

[meter]
FRASER_R - 1983B - 110230.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

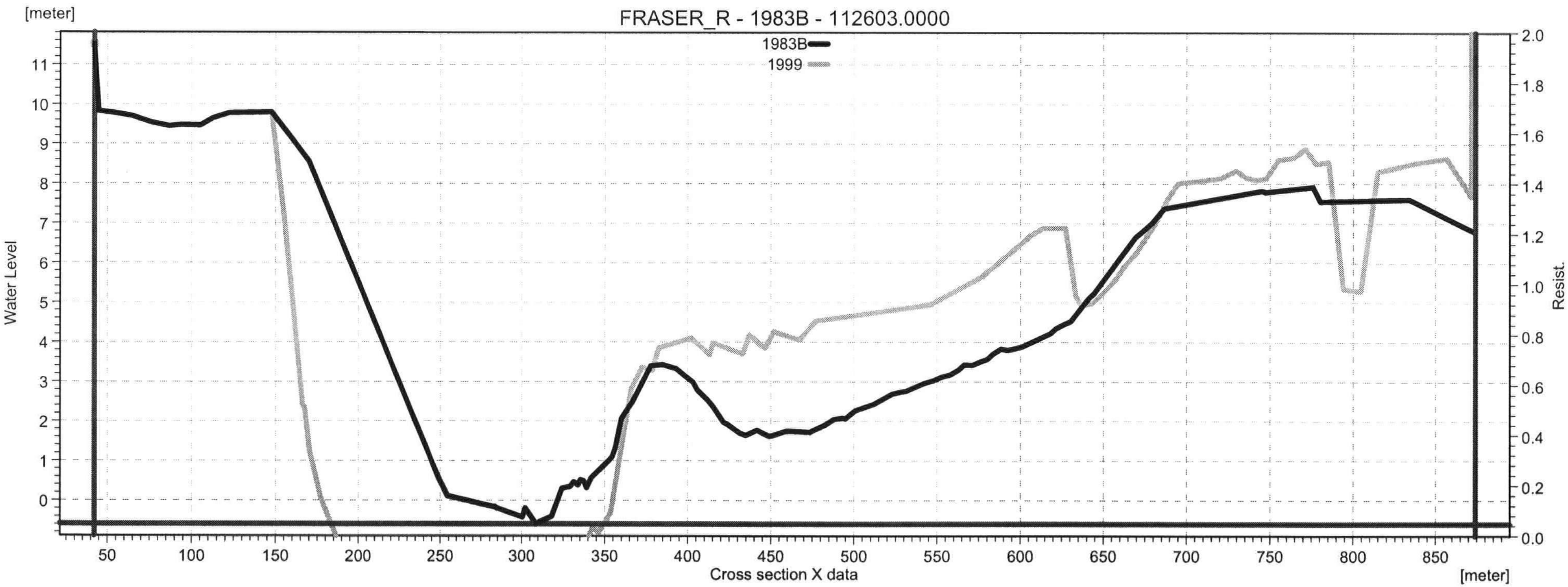


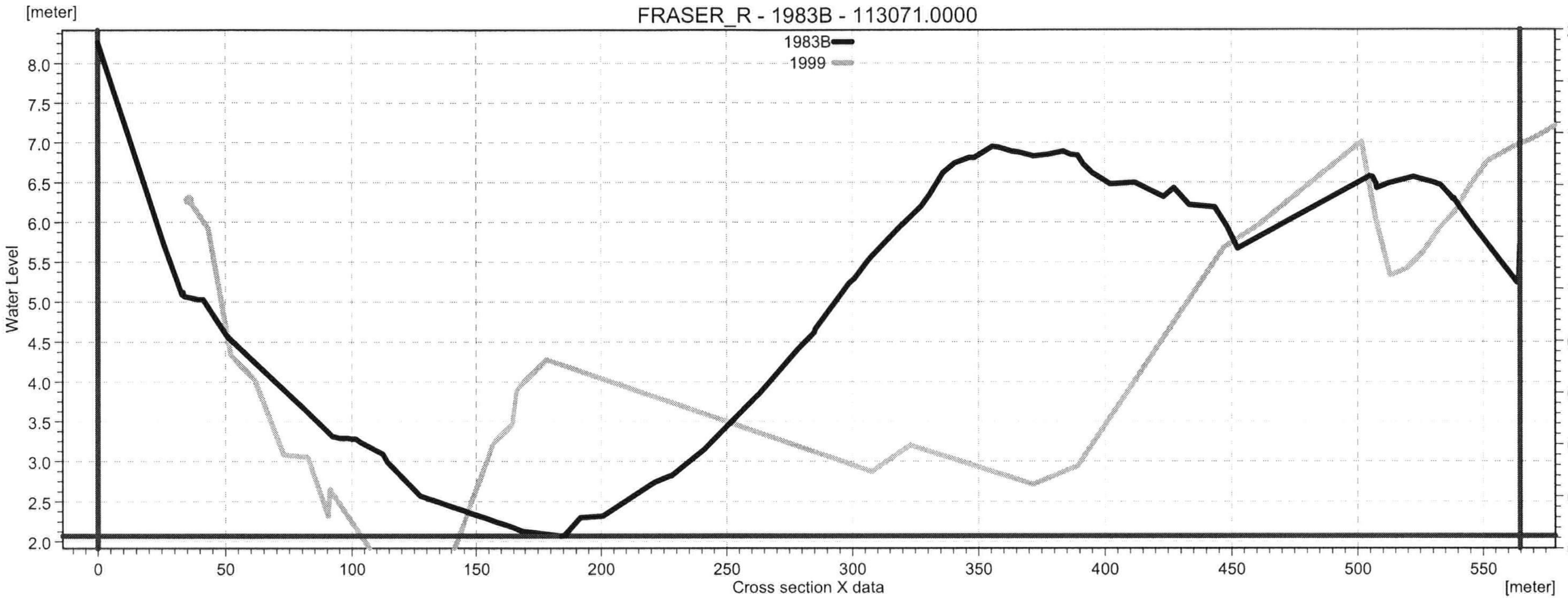
FRASER_R - 1983B - 110737.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



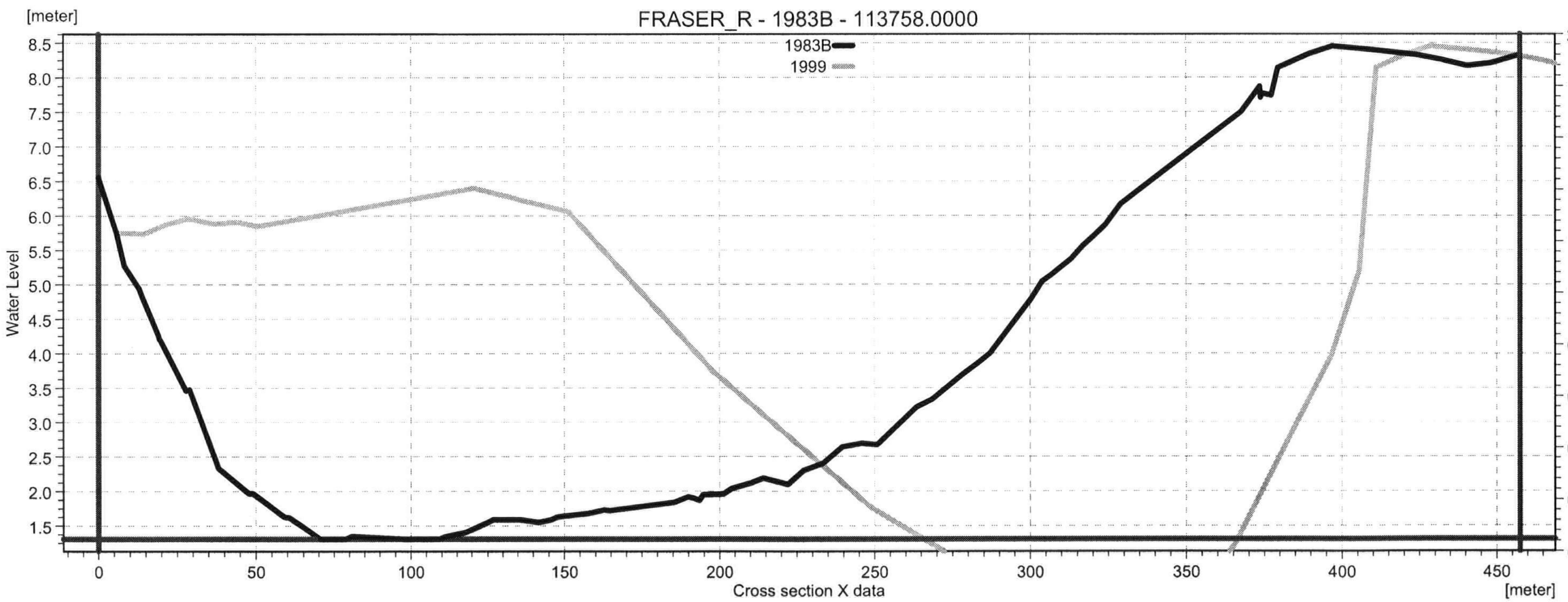
FRASER_R - 1983B - 111176.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]


[meter]
FRASER_R - 1983B - 111780.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

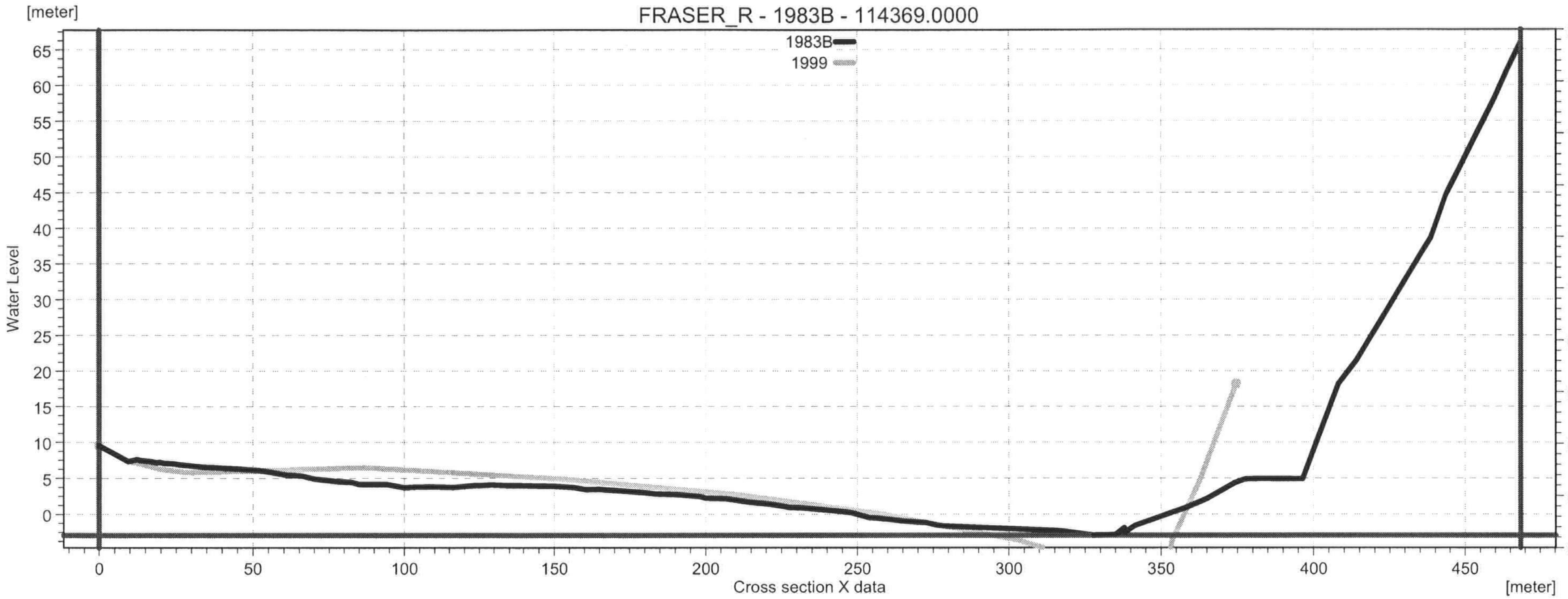

[meter]
FRASER_R - 1983B - 112603.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]



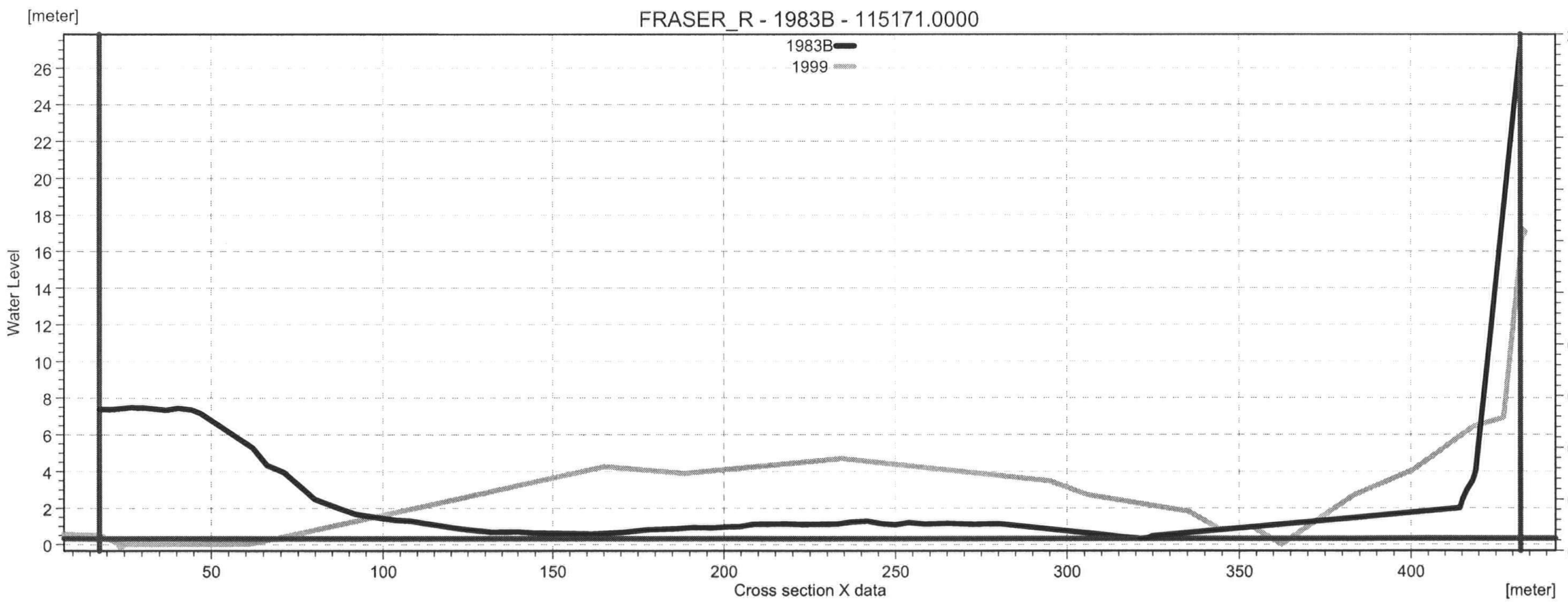
FRASER_R - 1983B - 113071.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



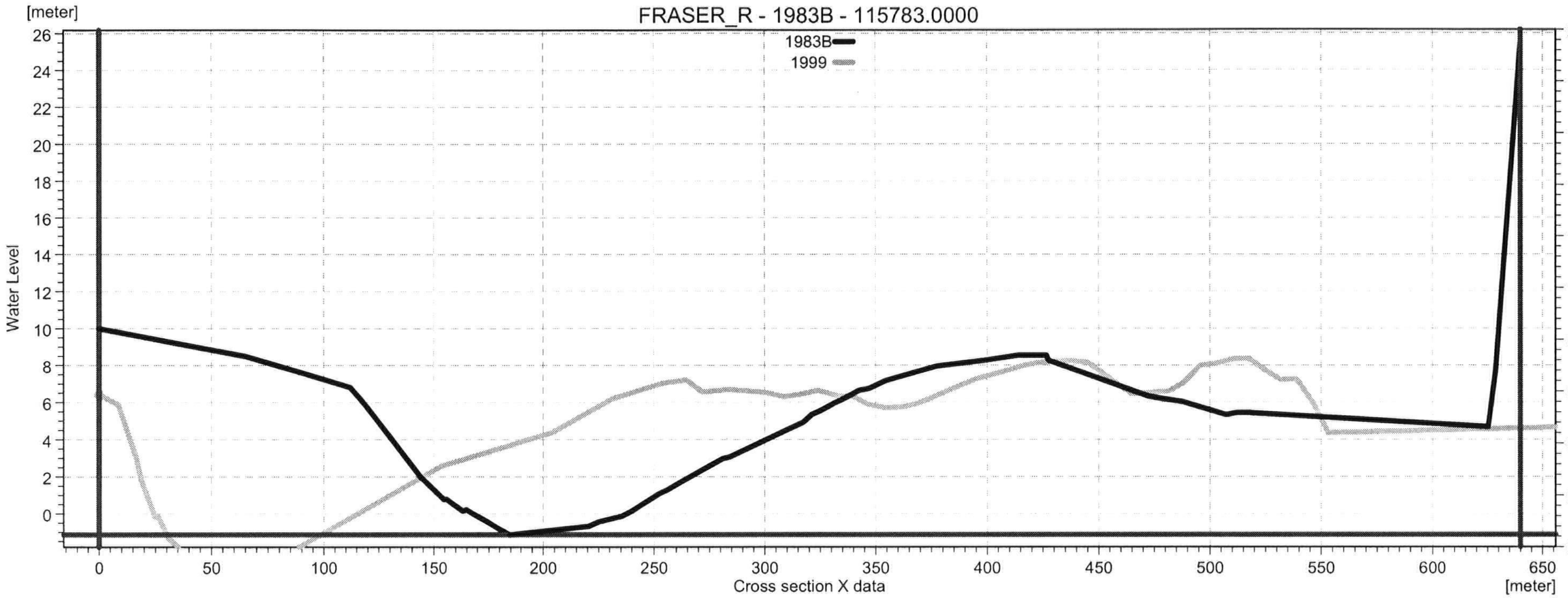
FRASER_R - 1983B - 113758.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

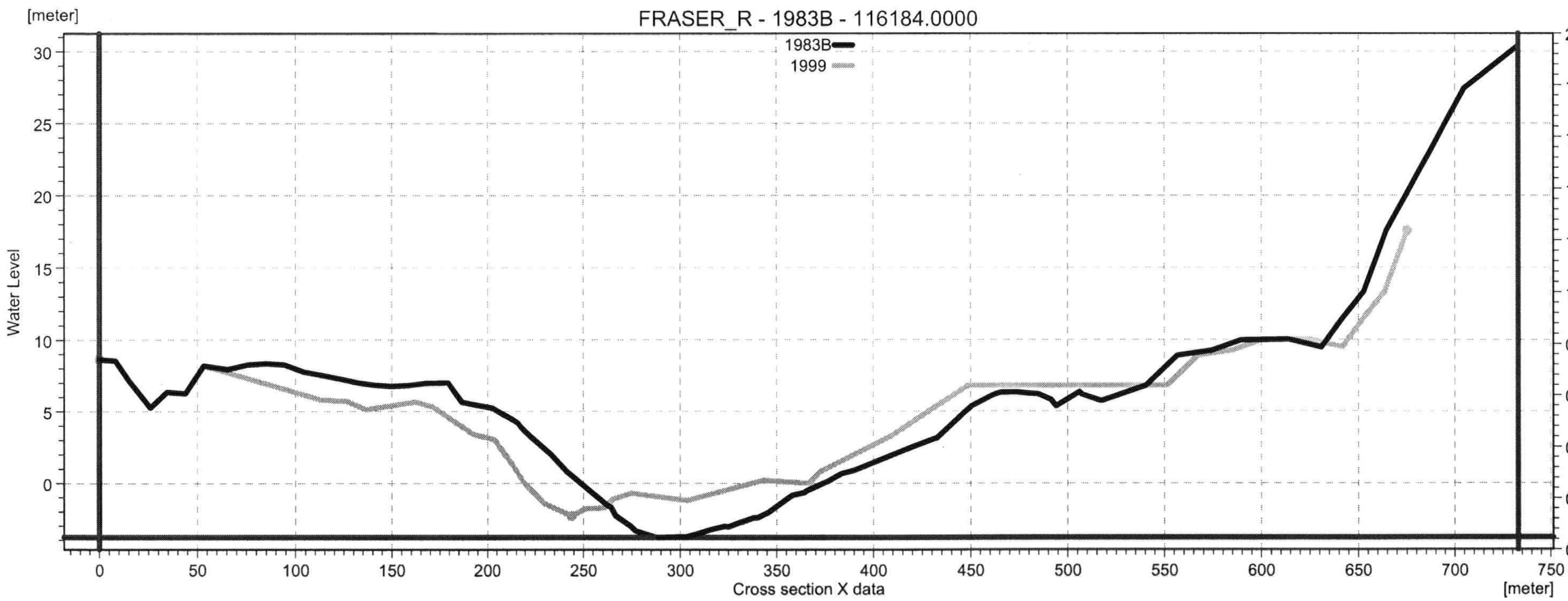


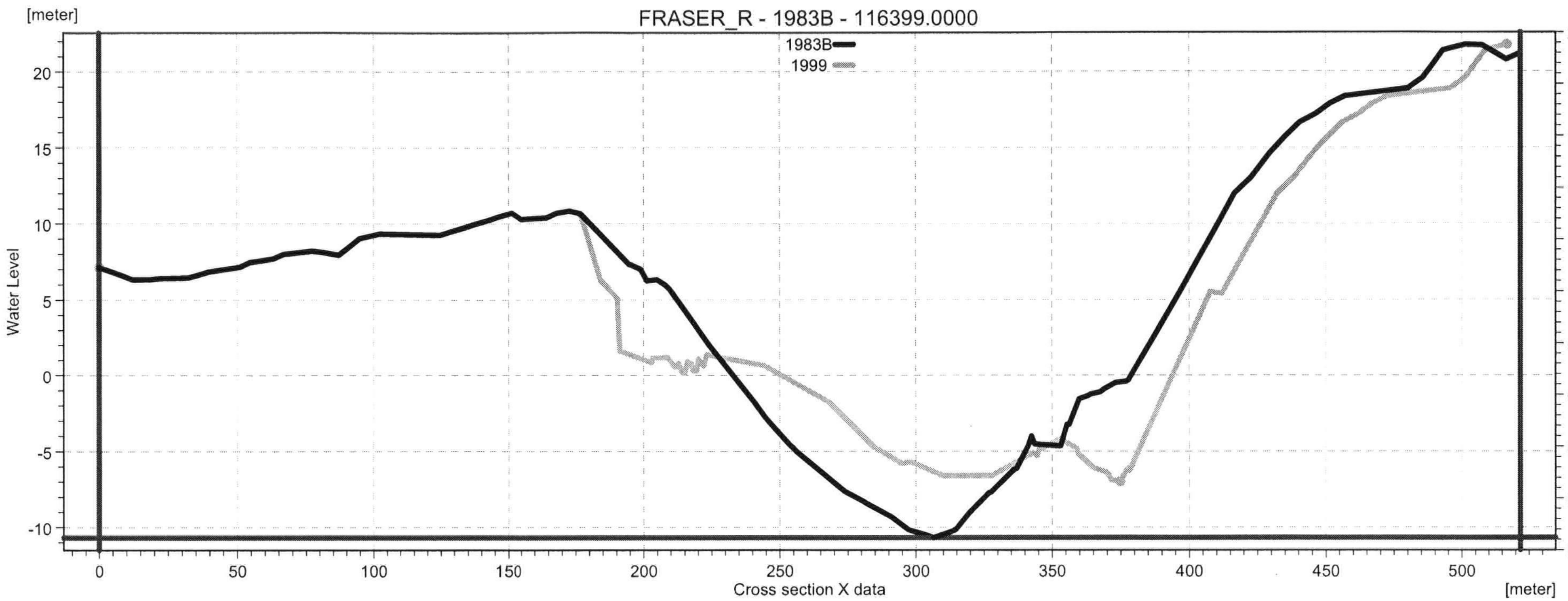
FRASER_R - 1983B - 114369.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

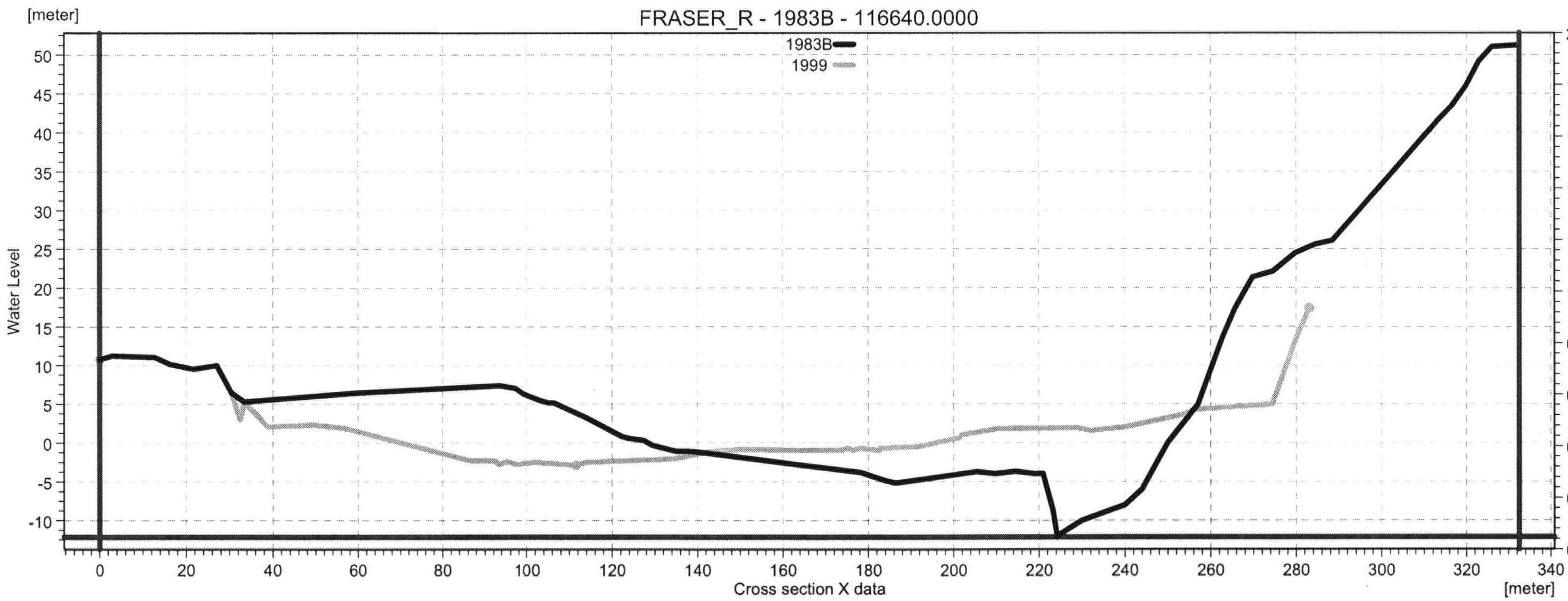


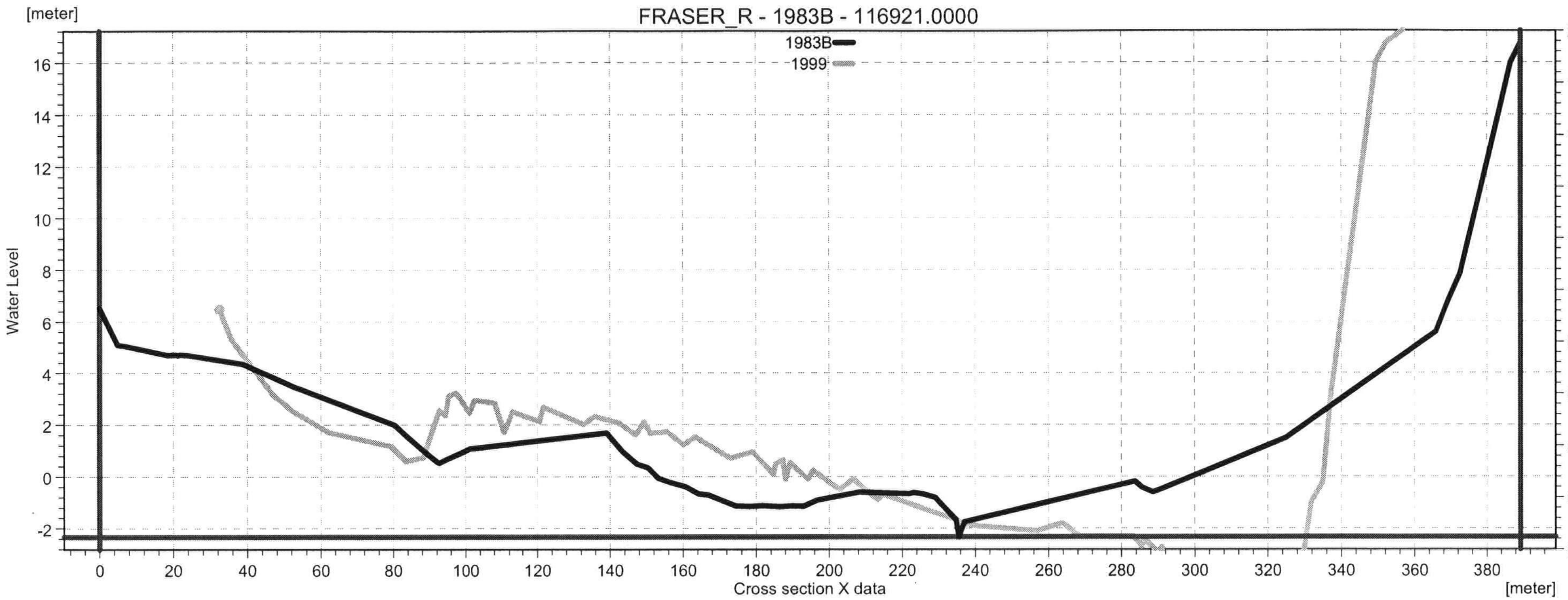
FRASER_R - 1983B - 115171.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

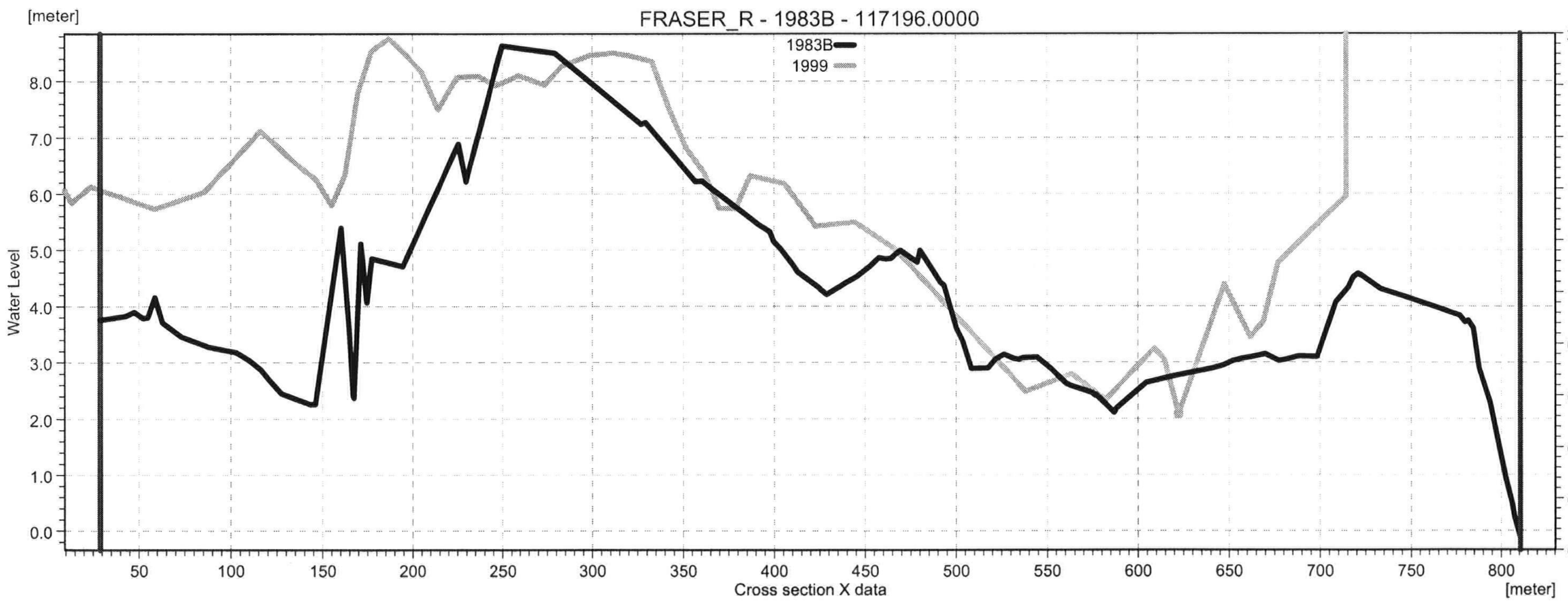

[meter]
FRASER_R - 1983B - 115783.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

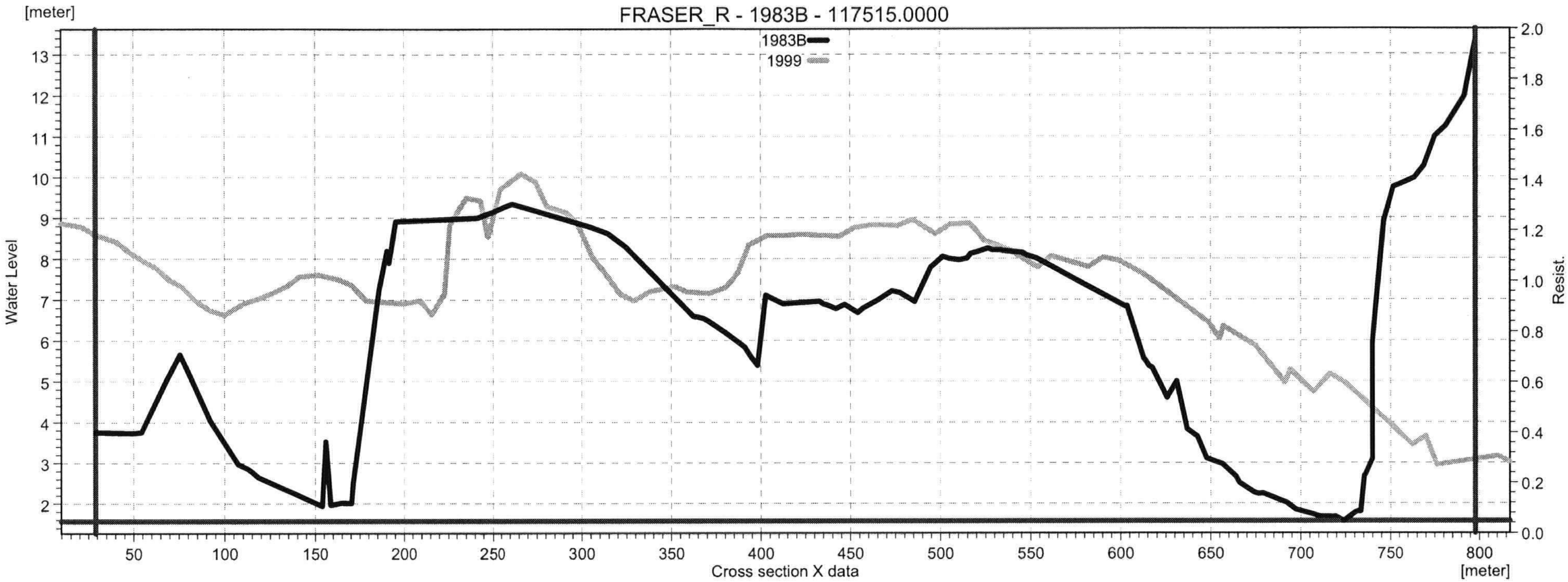

[meter]
FRASER_R - 1983B - 116184.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

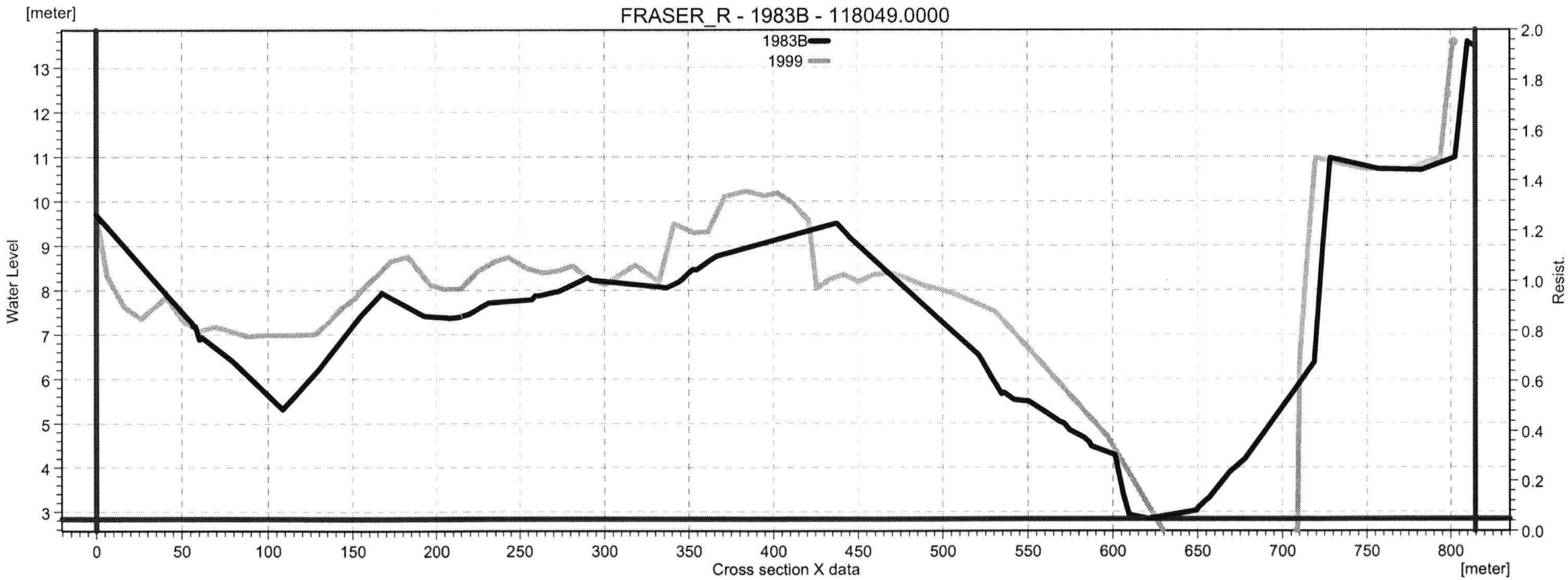

[meter]
FRASER_R - 1983B - 116399.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

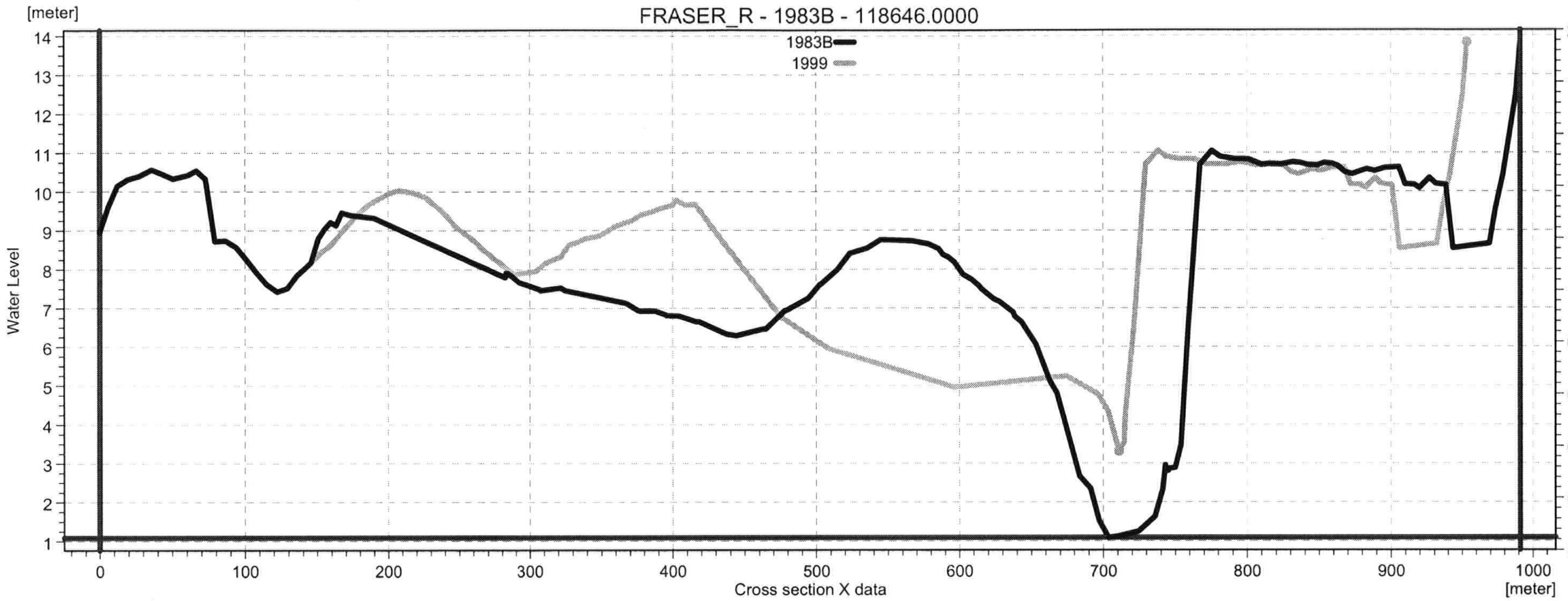

[meter]
FRASER_R - 1983B - 116640.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]


FRASER_R - 1983B - 116921.0000
[meter]
Water Level
Resist.
1983B
1999
Cross section X data
[meter]
-2
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

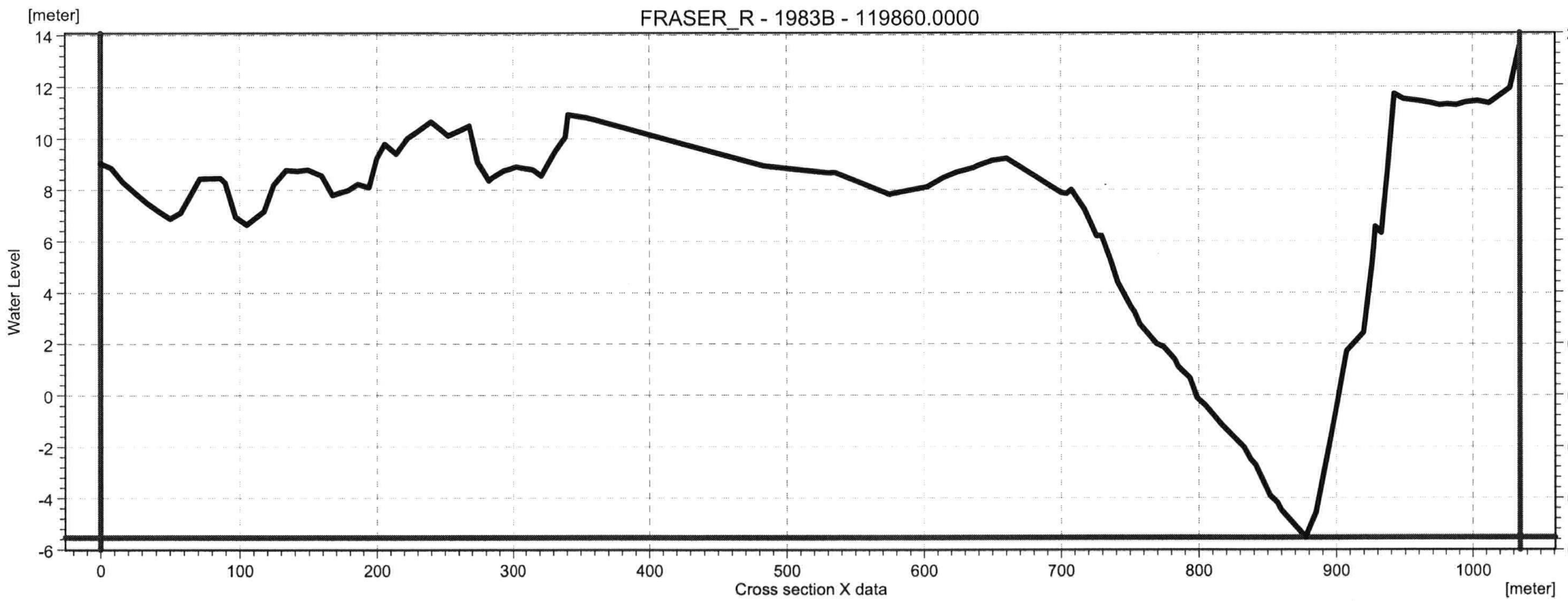

FRASER_R - 1983B - 117196.0000
[meter]
Water Level
Resist.
1983B
1999
Cross section X data
[meter]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0


[meter]
FRASER_R - 1983B - 117515.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

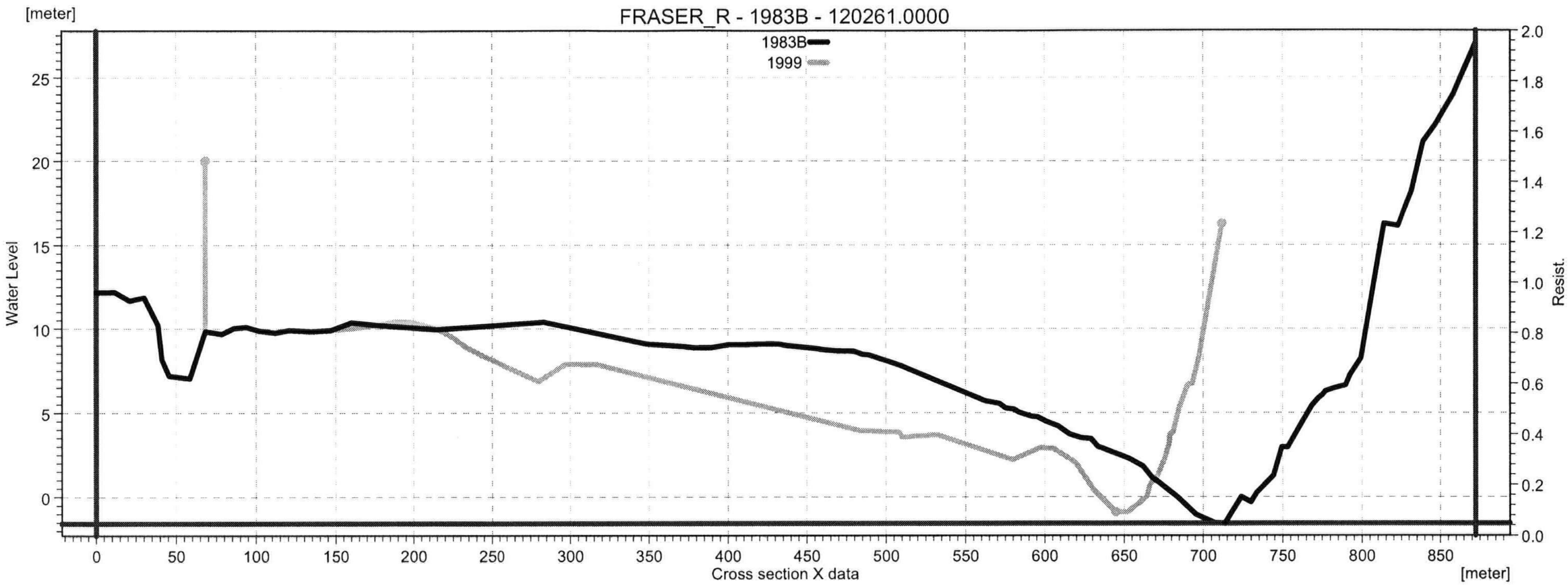

[meter]
FRASER_R - 1983B - 118049.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

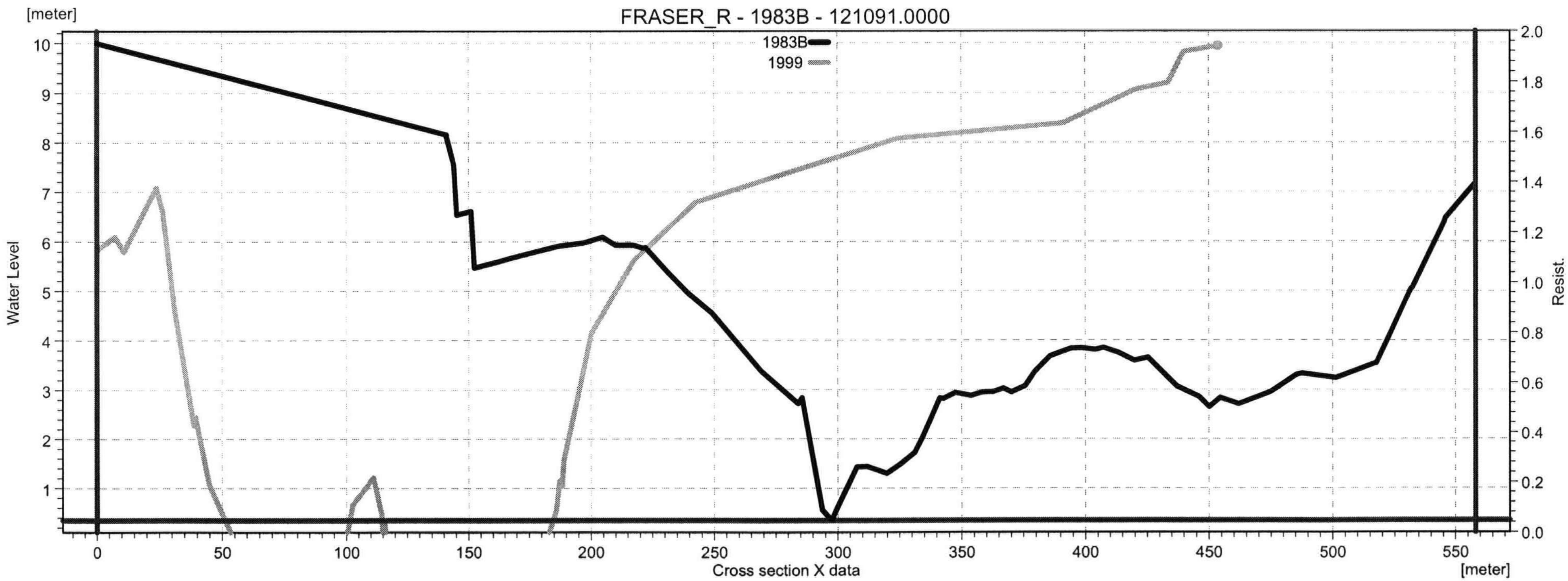


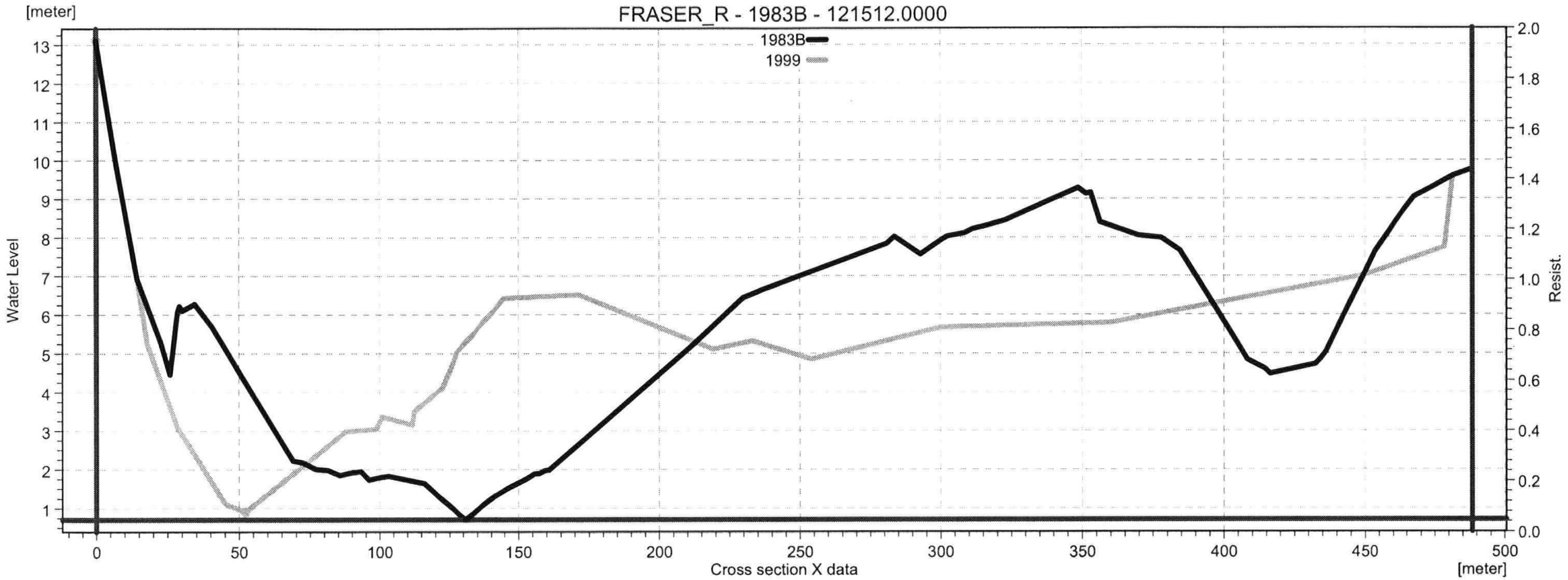
[meter]
FRASER_R - 1983B - 118646.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]



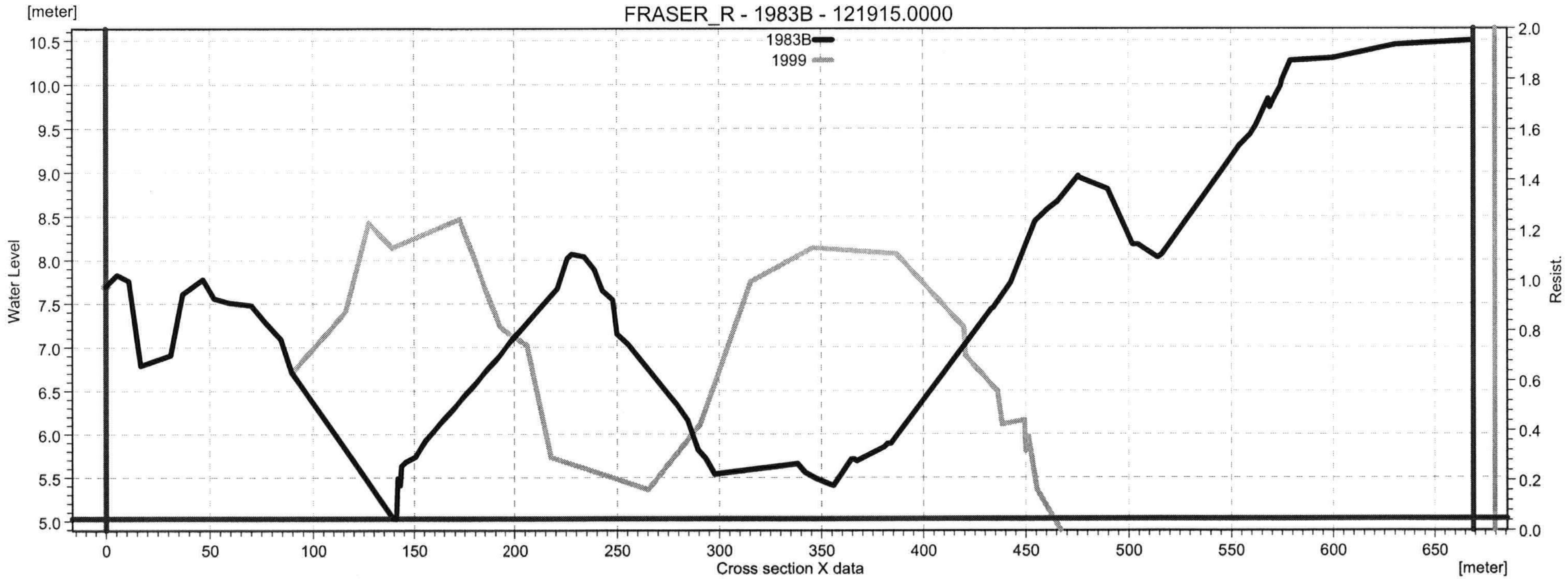
[meter]
FRASER_R - 1983B - 119860.0000
Water Level
Resist.
Cross section X data
[meter]


FRASER_R - 1983B - 120261.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

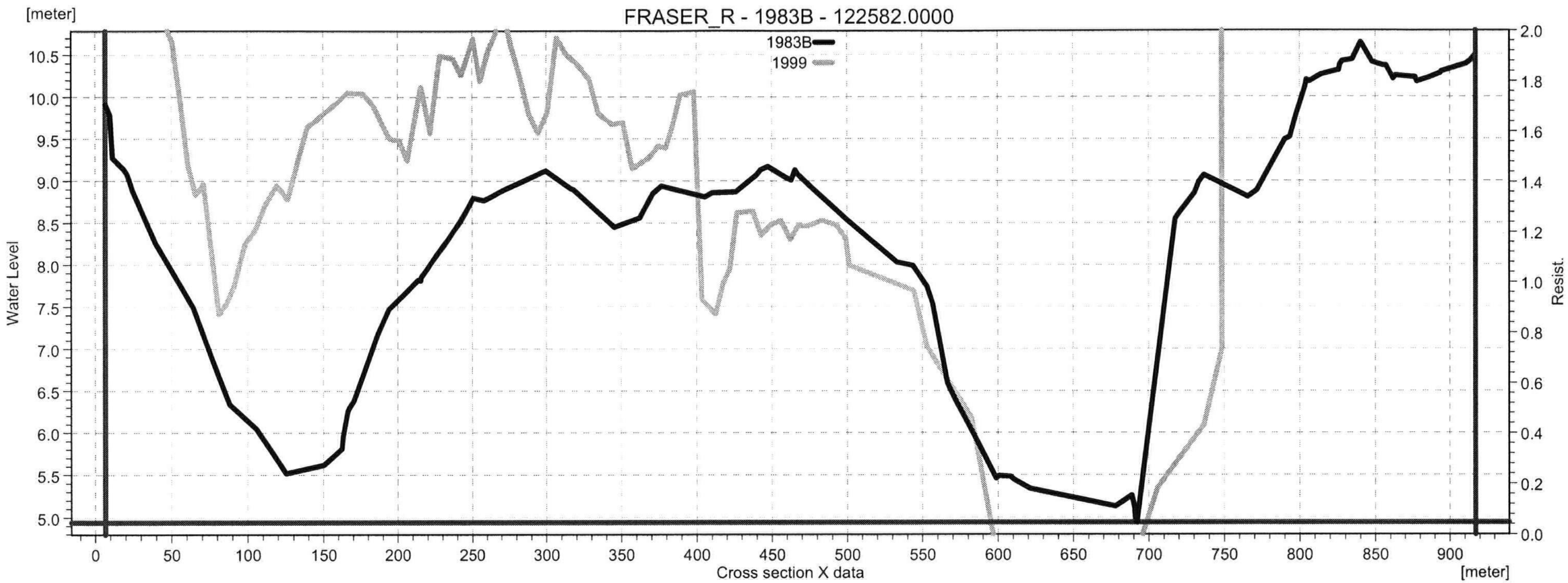

FRASER_R - 1983B - 121091.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



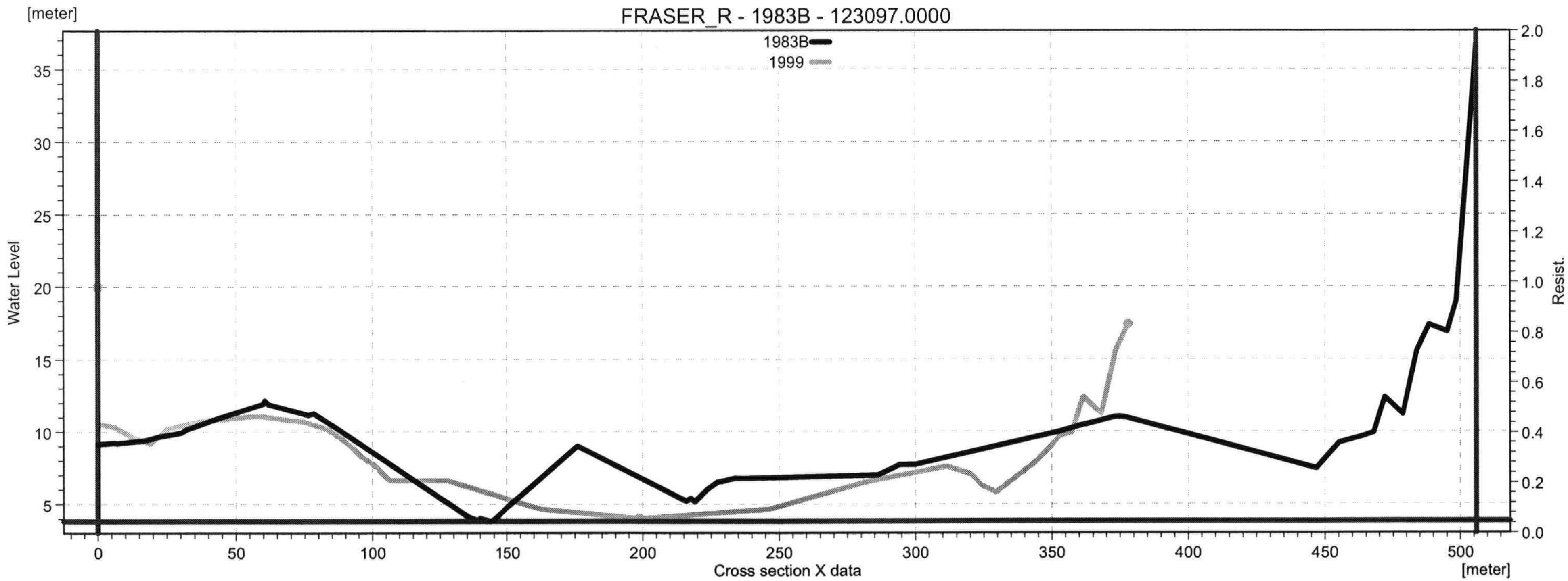
[meter]
FRASER_R - 1983B - 121512.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]



[meter]
FRASER_R - 1983B - 121915.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

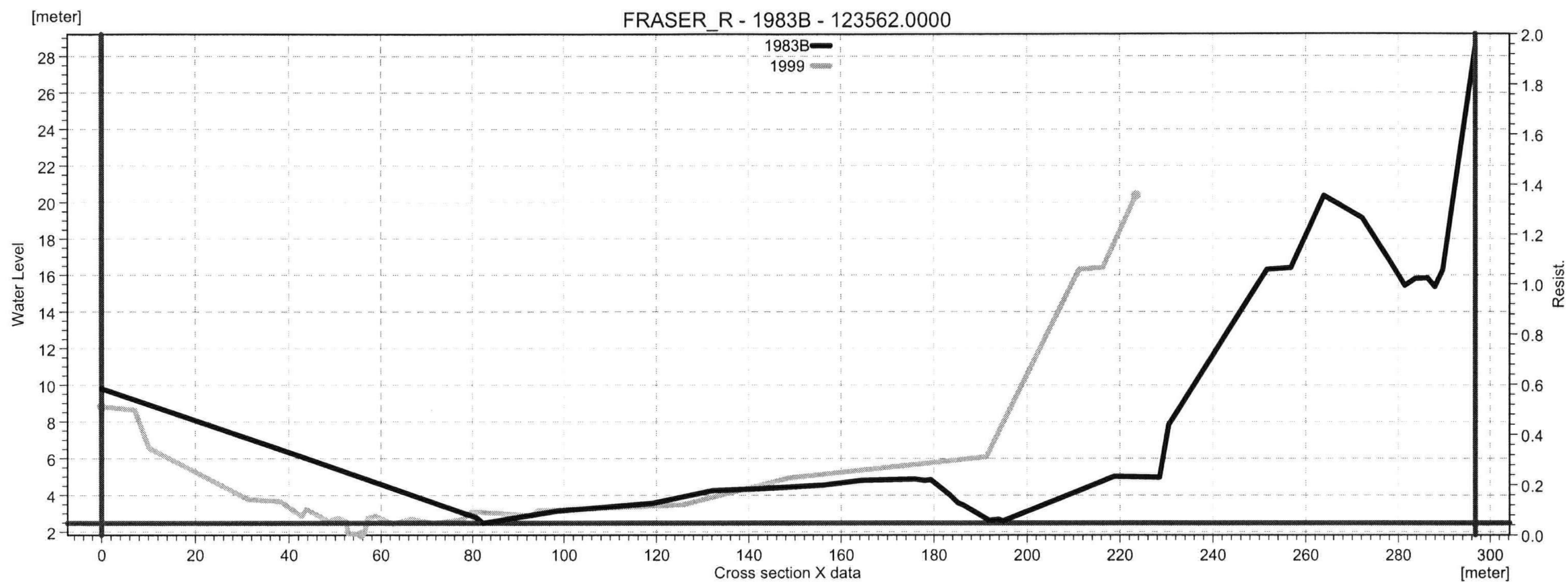


[meter]
FRASER_R - 1983B - 122582.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

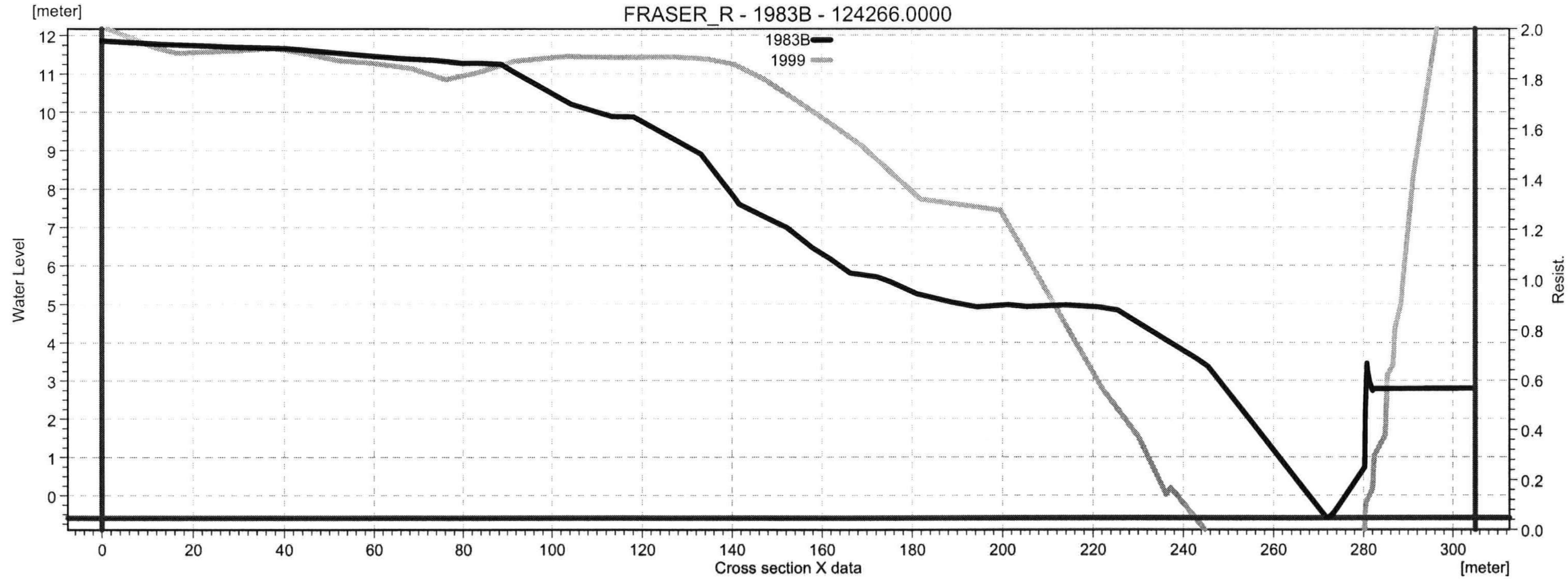


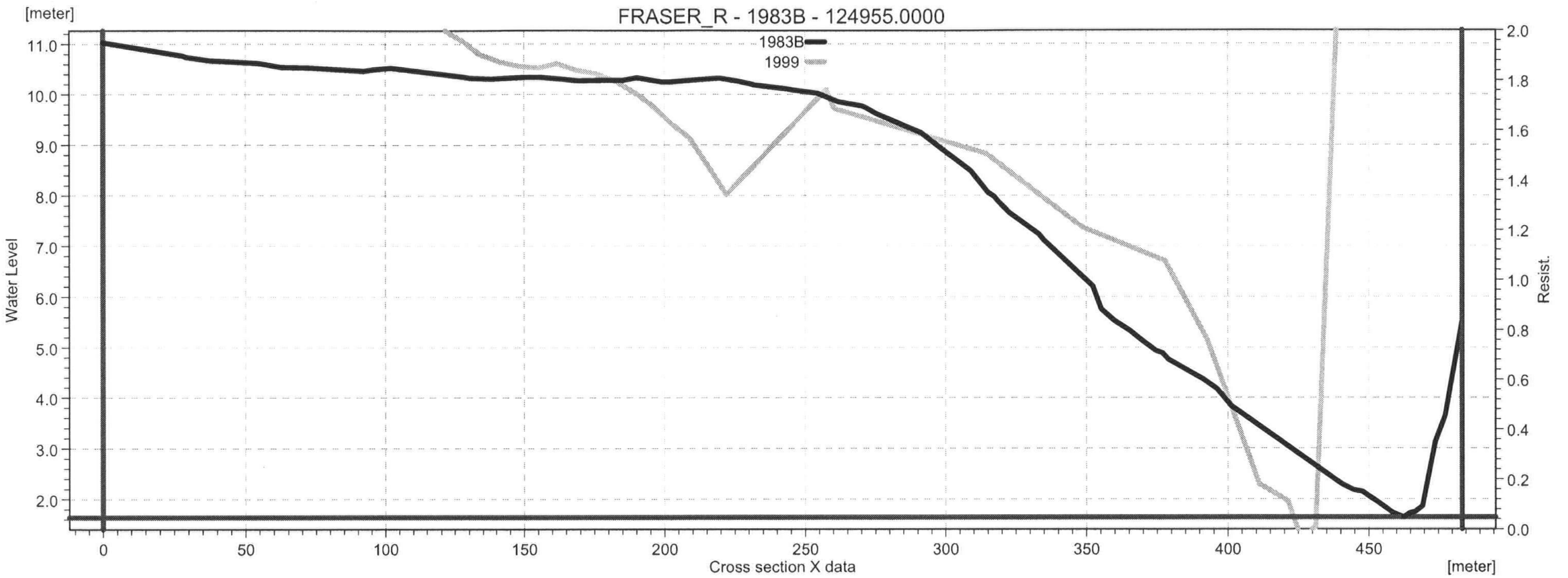
[meter]
FRASER_R - 1983B - 123097.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

FRASER_R - 1983B - 123562.0000

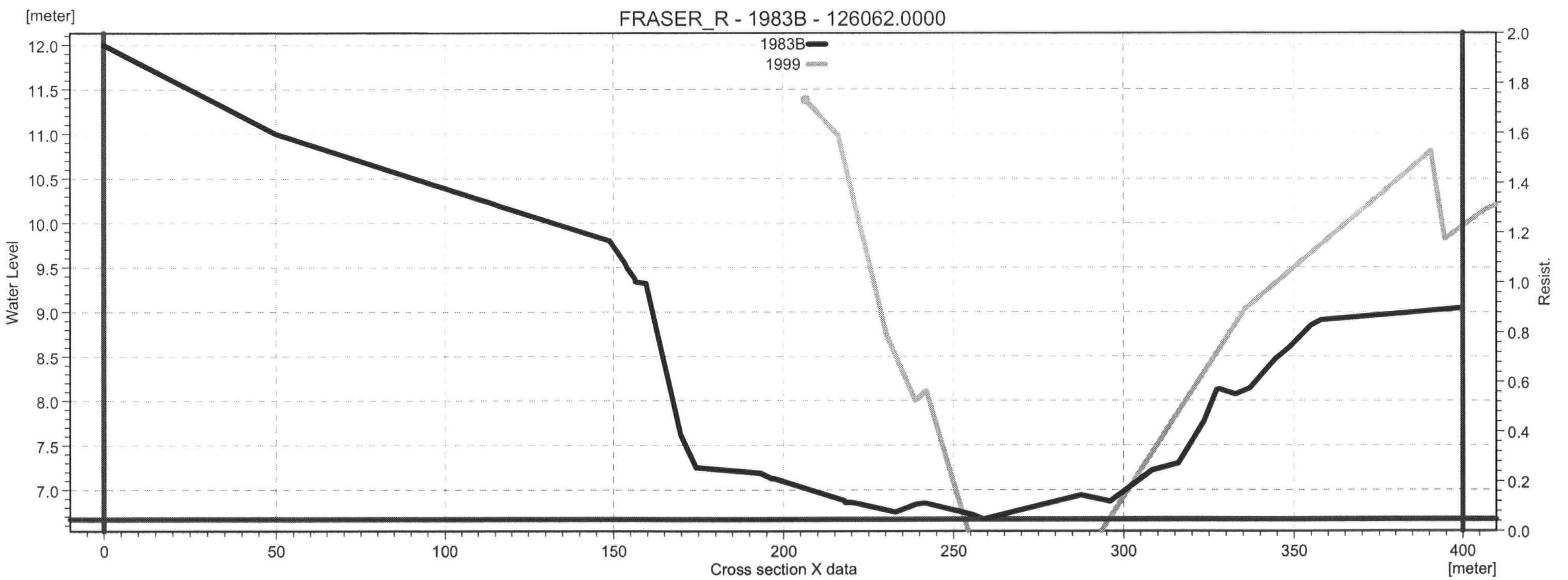


FRASER_R - 1983B - 124266.0000

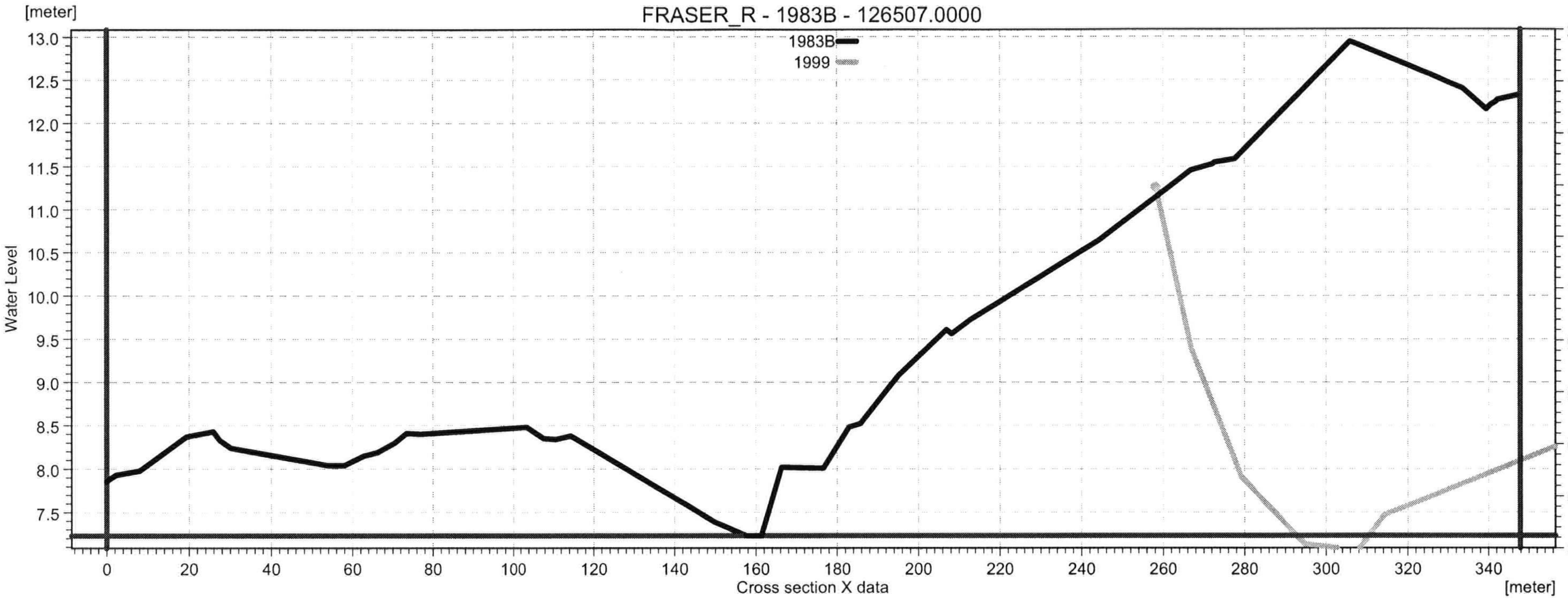




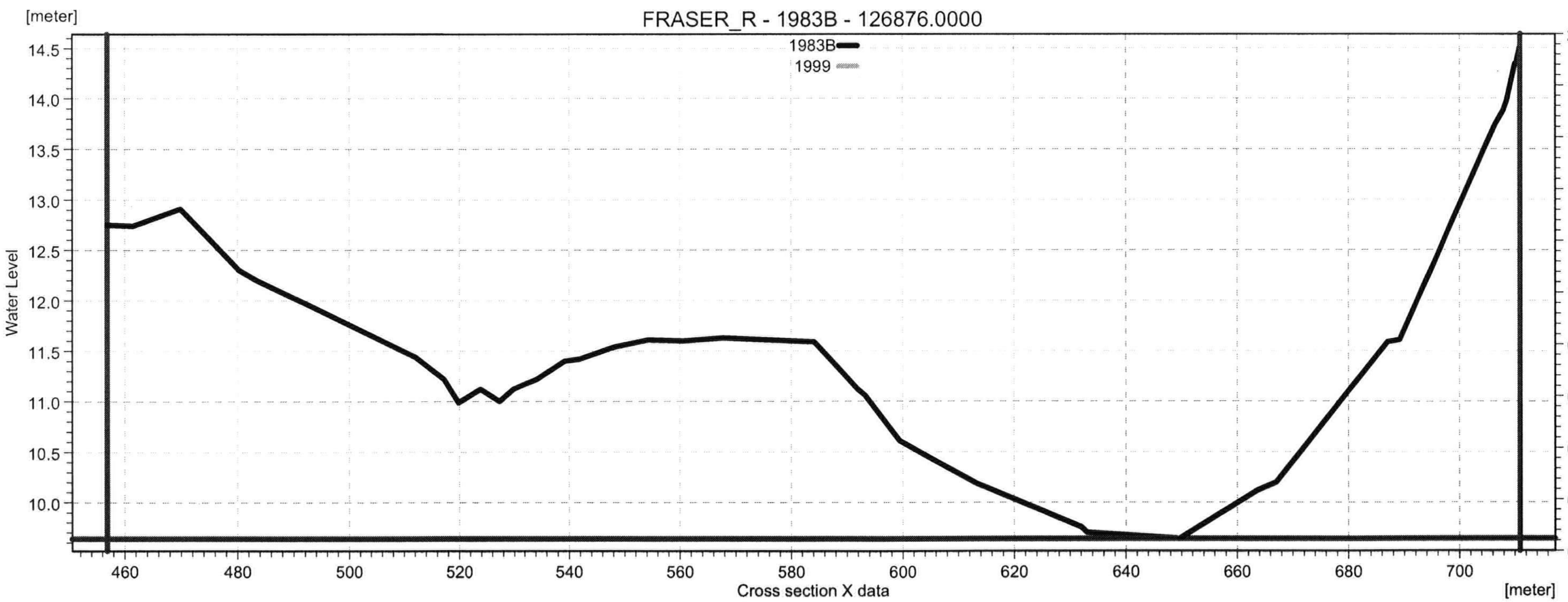
FRASER_R - 1983B - 124955.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



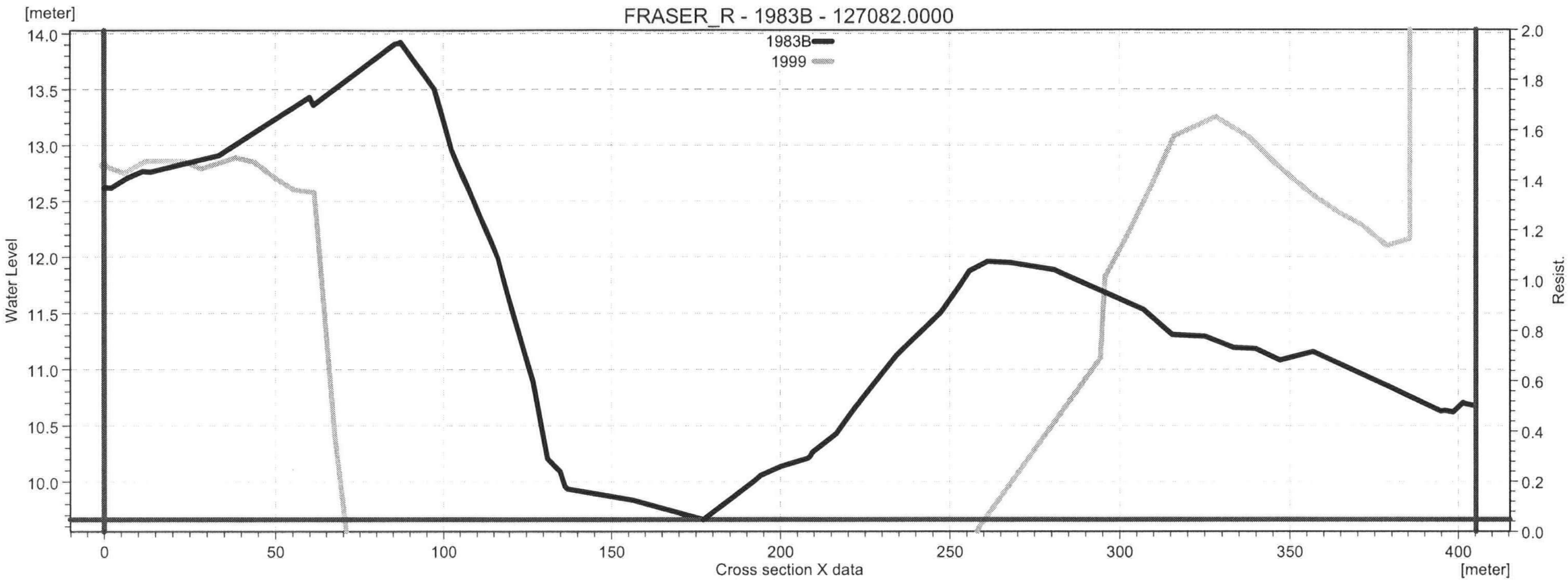
FRASER_R - 1983B - 126062.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



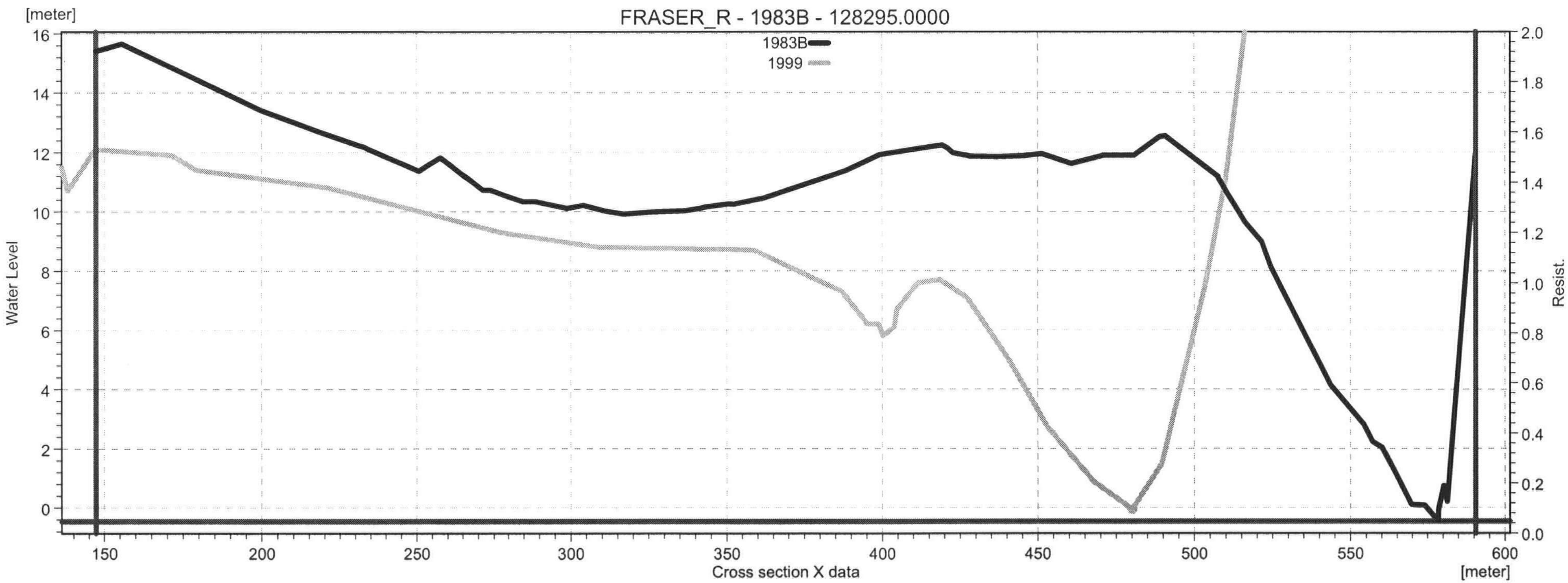
FRASER_R - 1983B - 126507.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



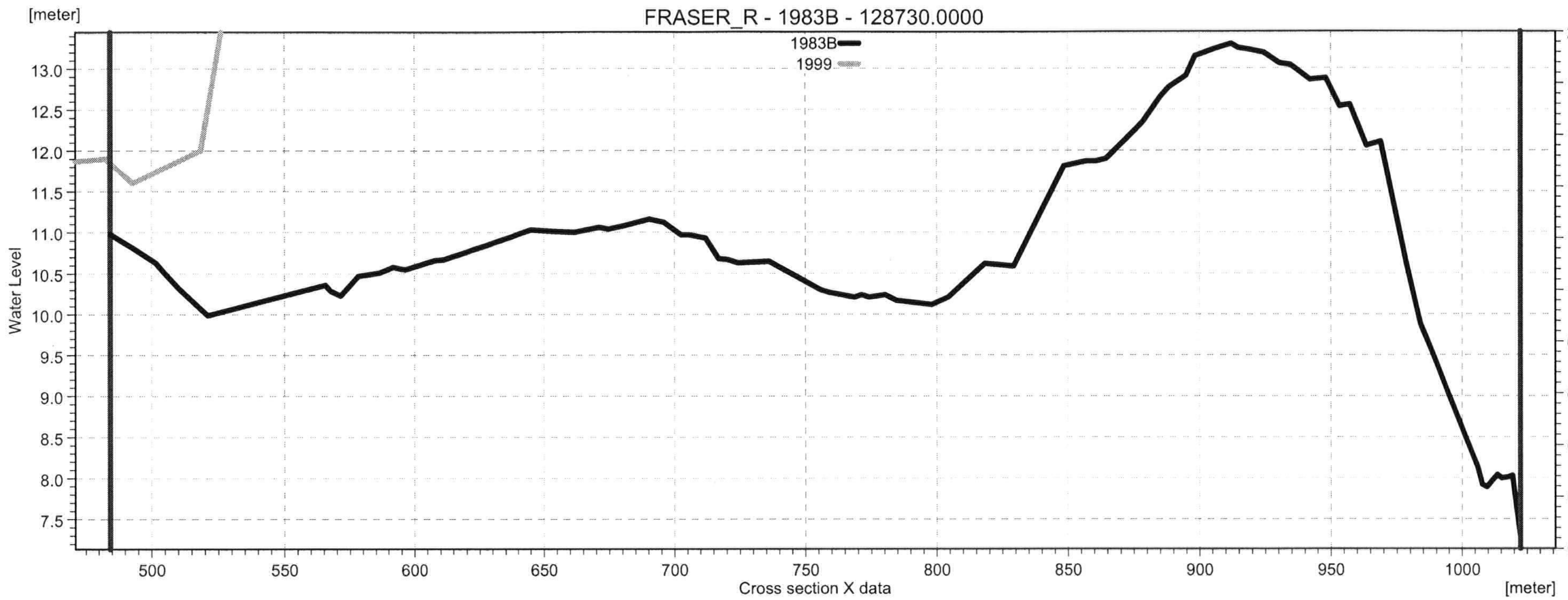
FRASER_R - 1983B - 126876.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

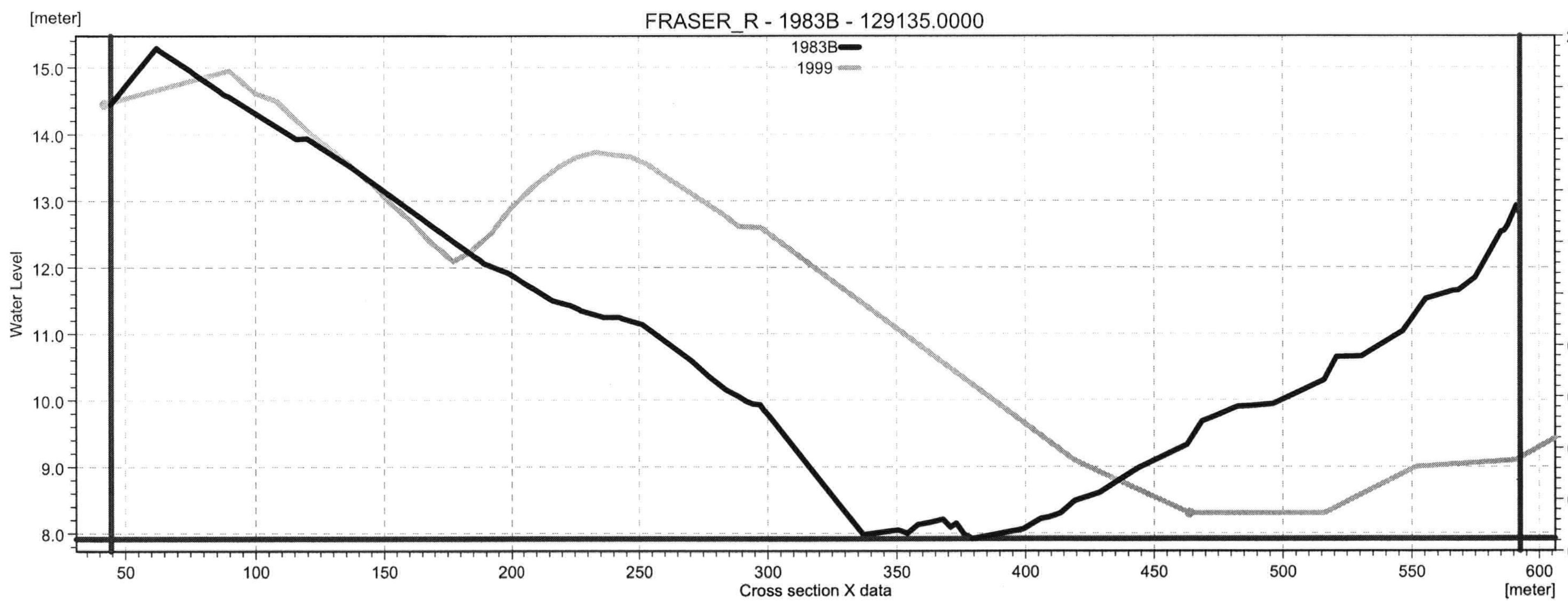


FRASER_R - 1983B - 127082.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

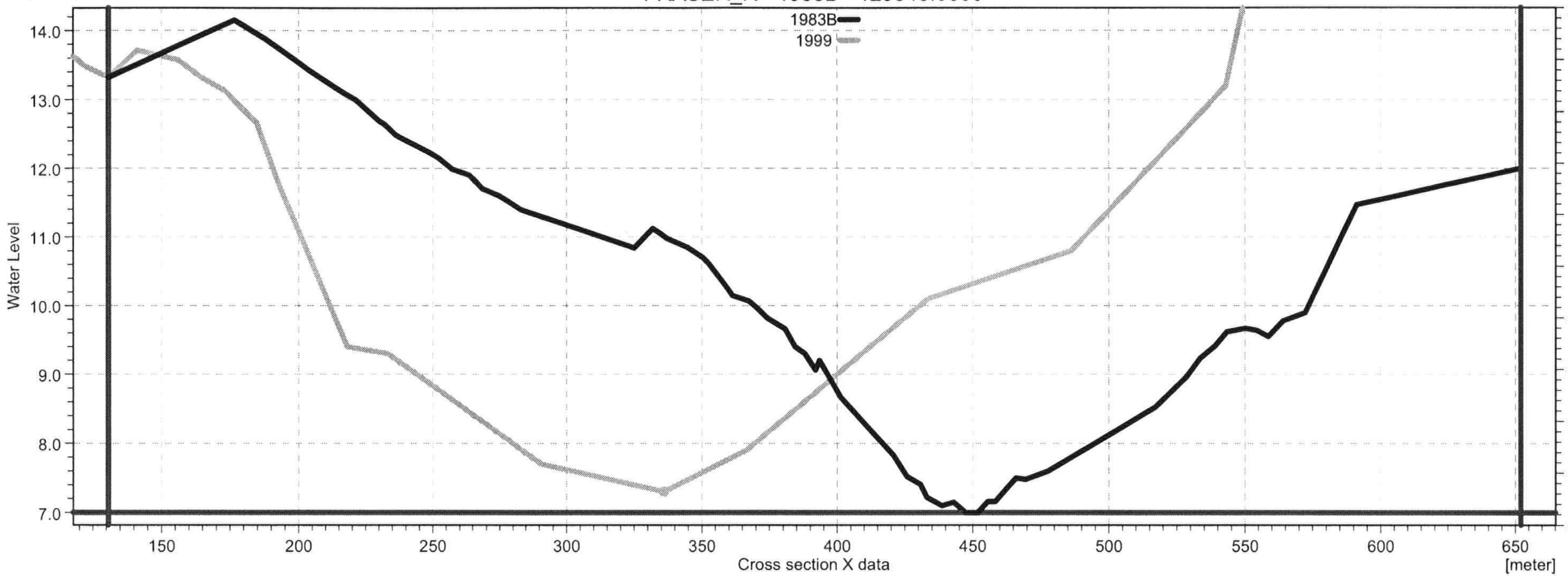


FRASER_R - 1983B - 128295.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]

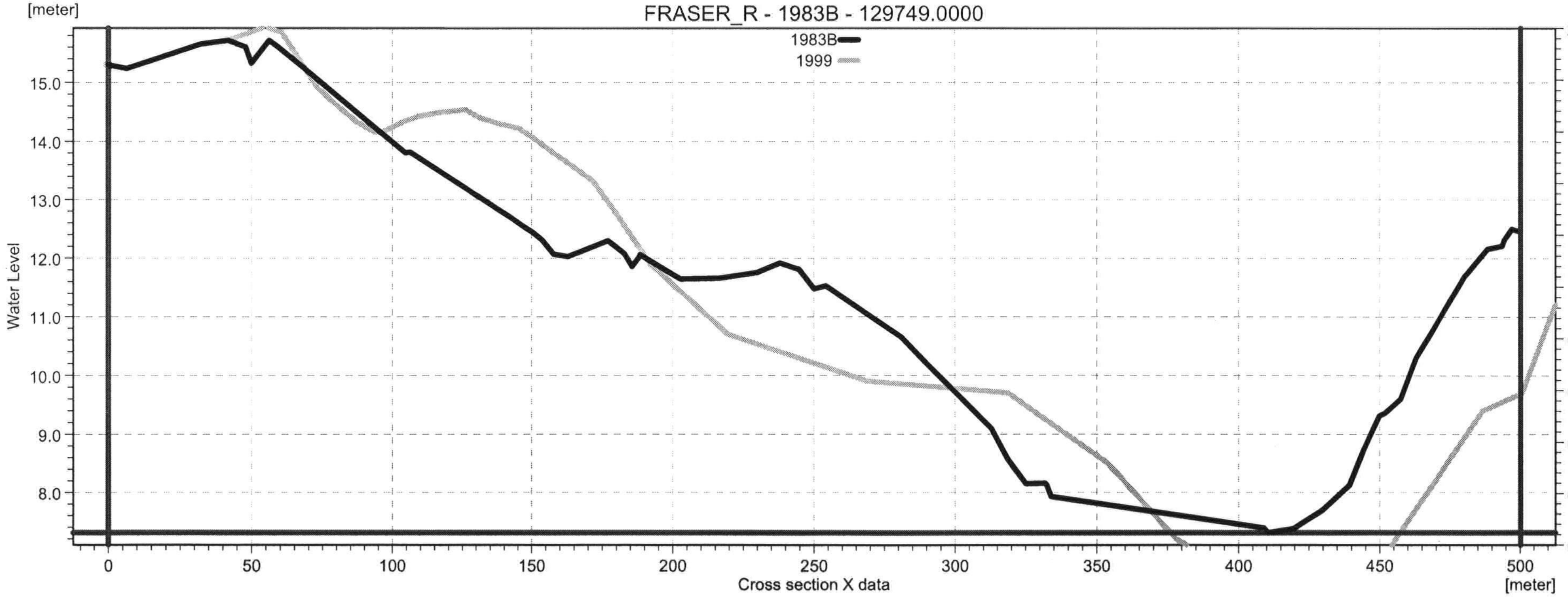

[meter]
FRASER_R - 1983B - 128730.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

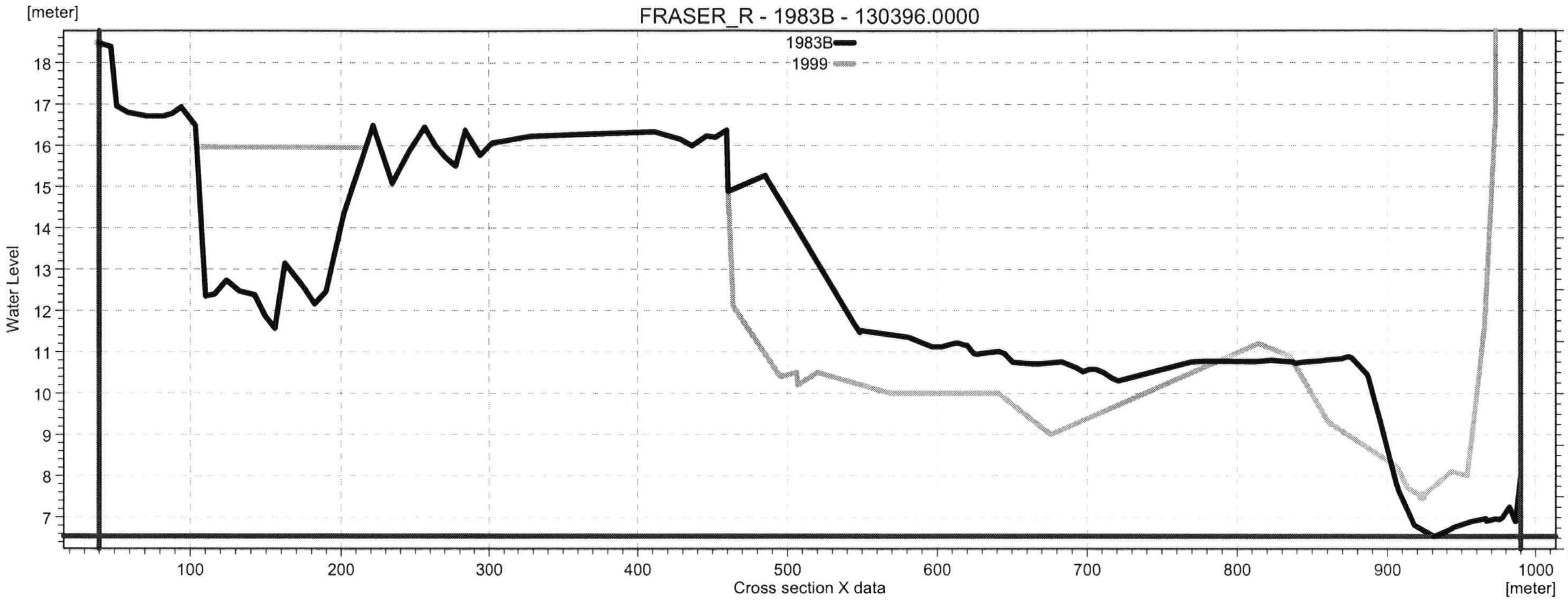

[meter]
FRASER_R - 1983B - 129135.0000
1983B
1999
Water Level
Resist.
Cross section X data
[meter]

FRASER_R - 1983B - 129543.0000

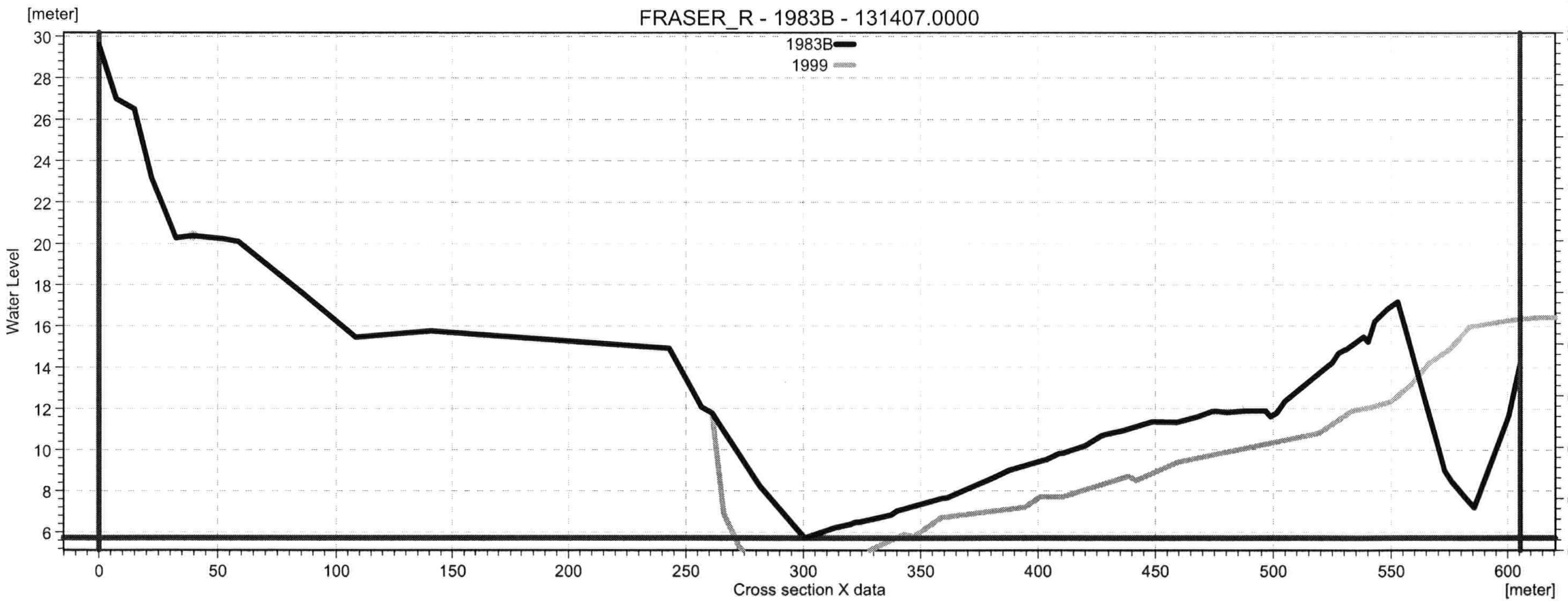


FRASER_R - 1983B - 129749.0000

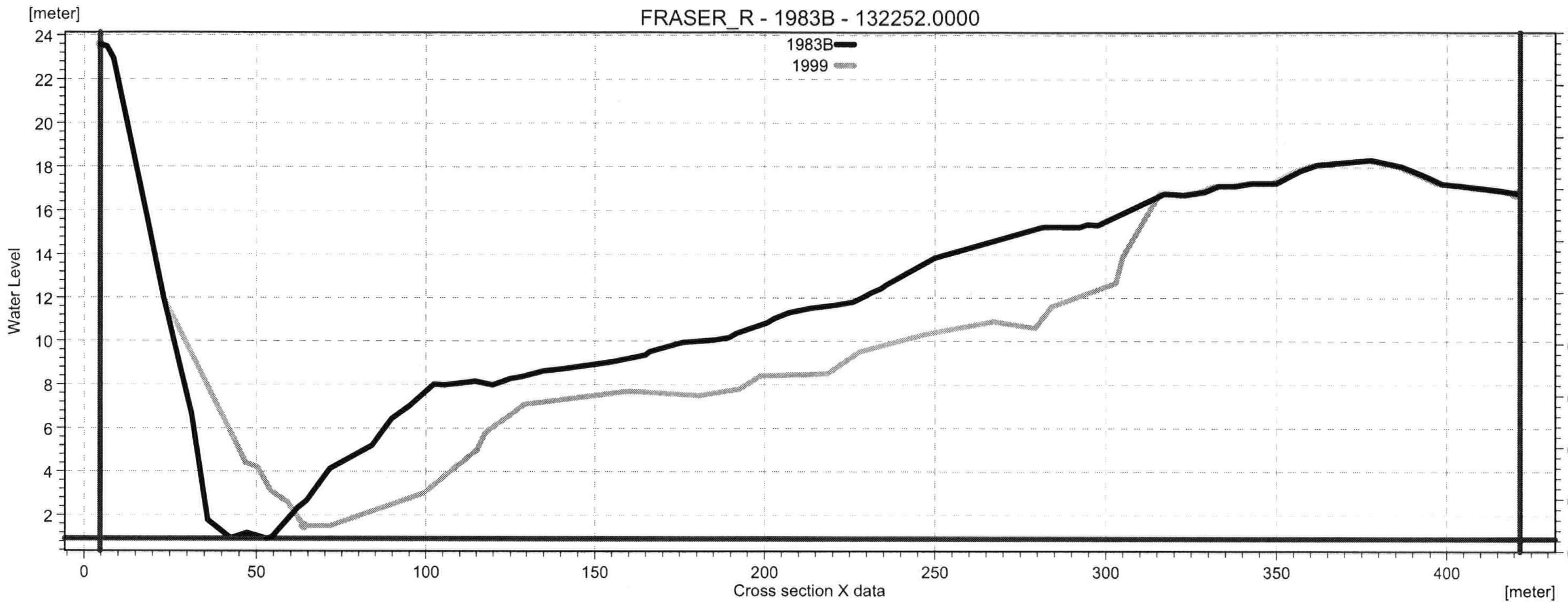




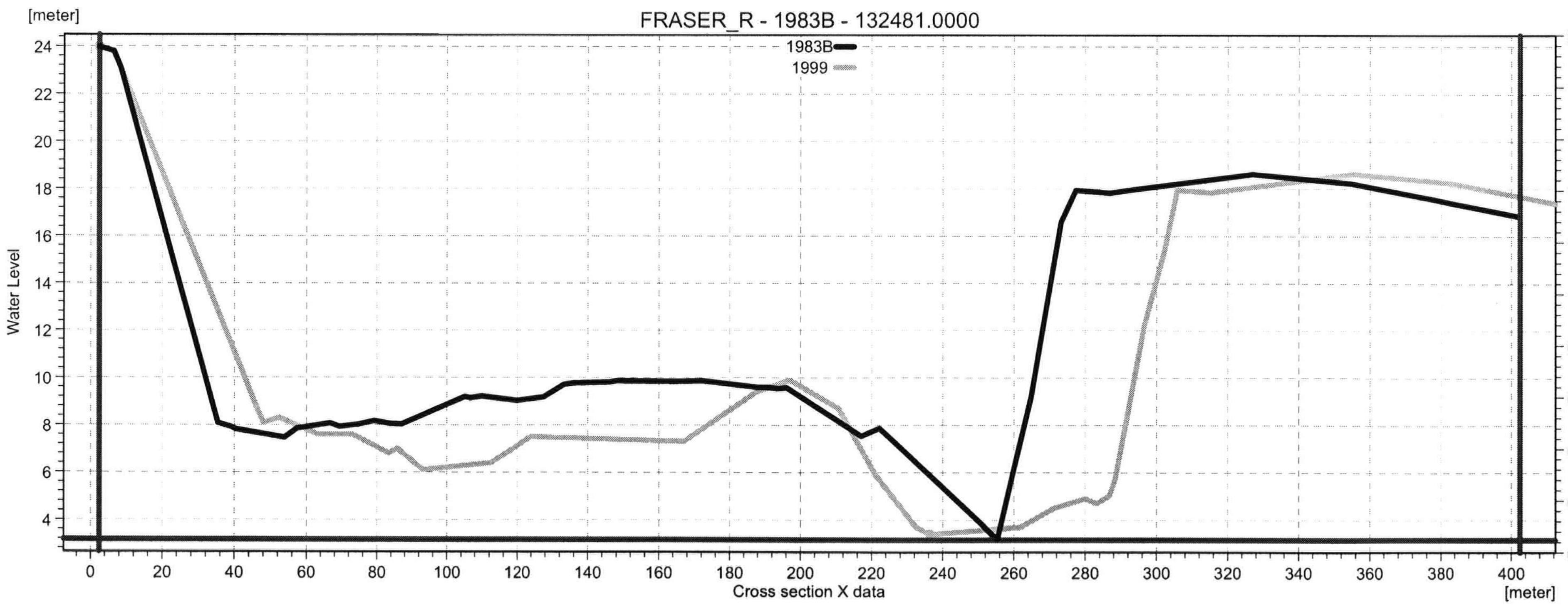
FRASER_R - 1983B - 130396.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]



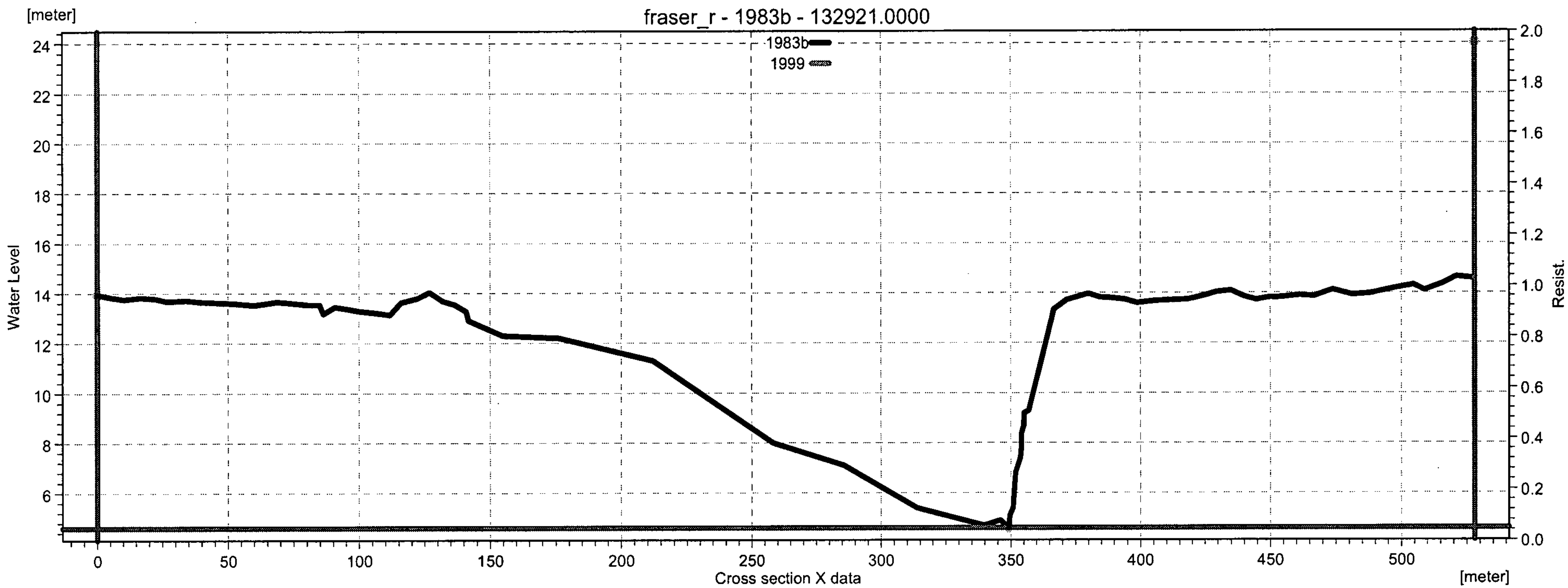
FRASER_R - 1983B - 131407.0000
[meter]
1983B
1999
Water Level
Resist.
Cross section X data
[meter]



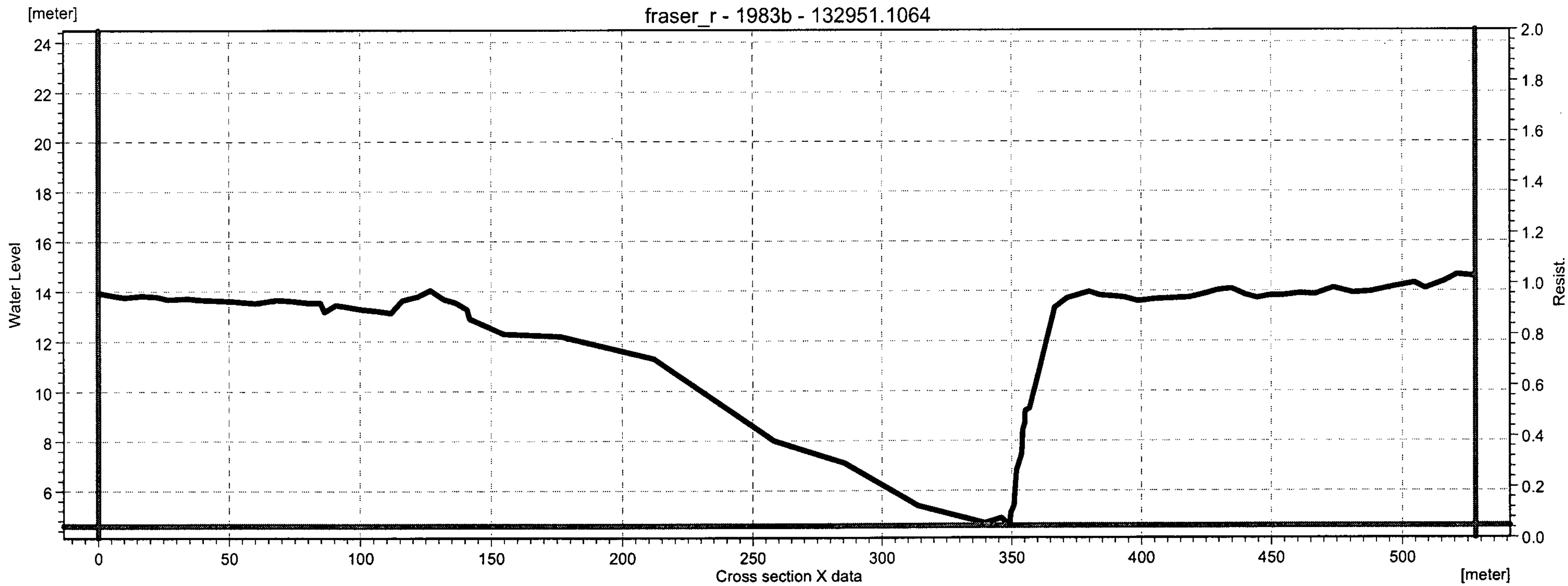
FRASER_R - 1983B - 132252.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



FRASER_R - 1983B - 132481.0000
1983B
1999
[meter]
Water Level
Resist.
Cross section X data
[meter]



fraser_r - 1983b - 132921.0000
[meter]
Water Level
1983b
1999
Resist.
Cross section X data
[meter]



fraser_r - 1983b - 132951.1064
[meter]
Water Level
Resist.
Cross section X data
[meter]

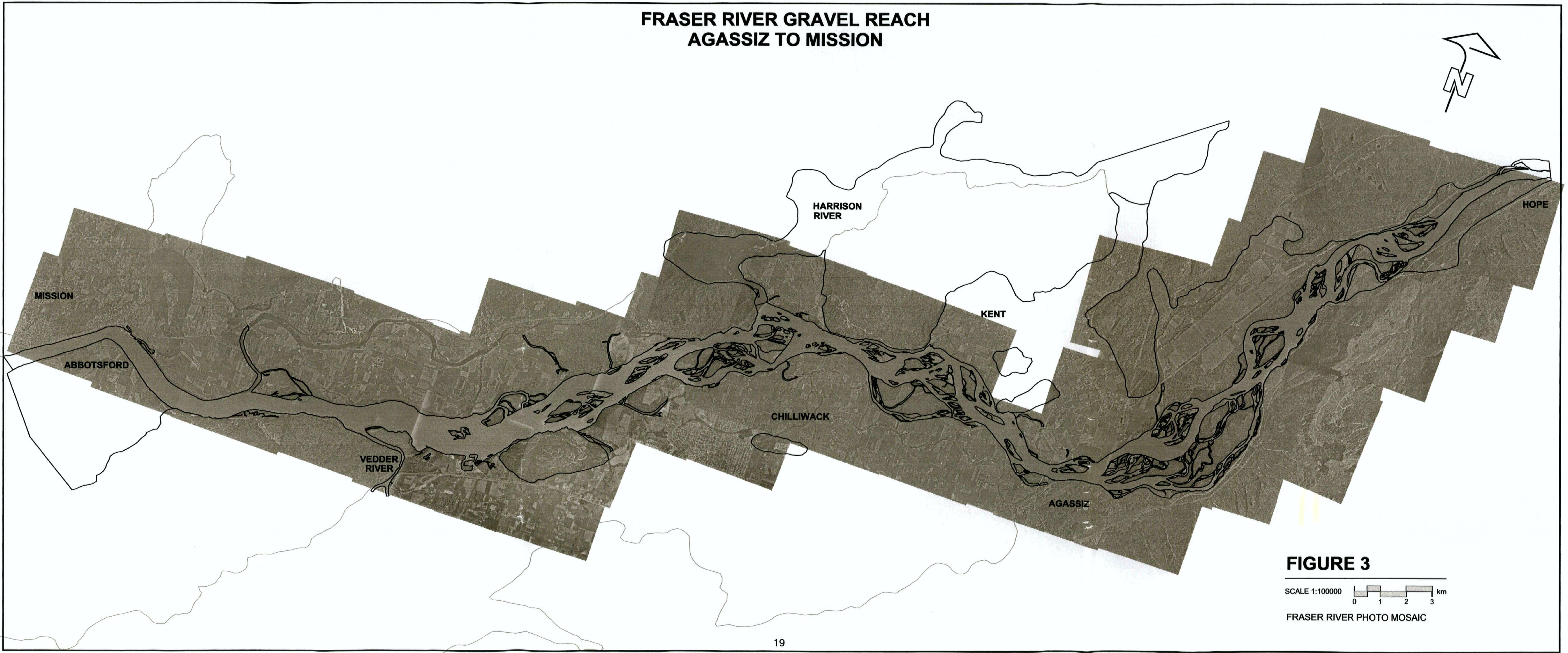


FIGURE 3

FRASER RIVER PHOTO MOSAIC

FRASER RIVER GRAVEL REACH
AGASSIZ TO MISSION

FIGURE 4

SCALE 1:100000 0 1 2 3 km

MIKE 11 MODEL 1983 CROSS-SECTION LOCATIONS

FRASER RIVER GRAVEL REACH
AGASSIZ TO MISSION

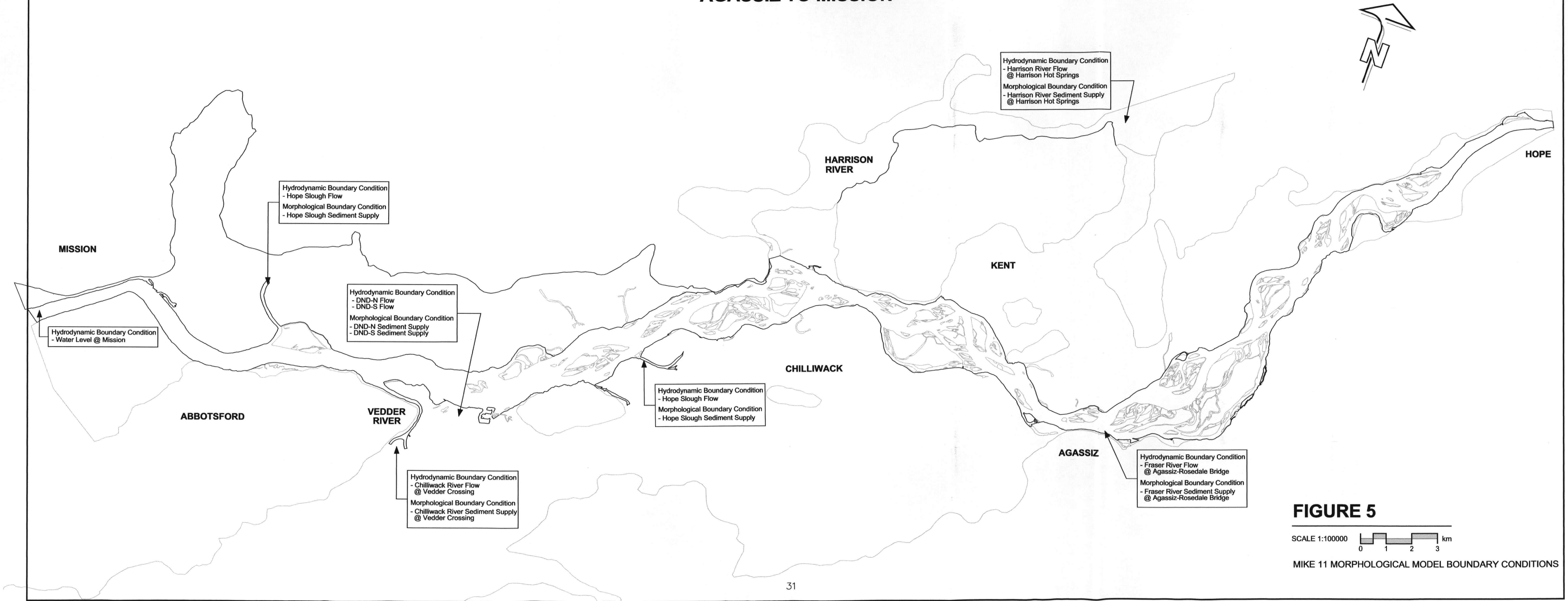


FIGURE 5

MIKE 11 MORPHOLOGICAL MODEL BOUNDARY CONDITIONS

FRASER RIVER GRAVEL REACH
AGASSIZ TO MISSION

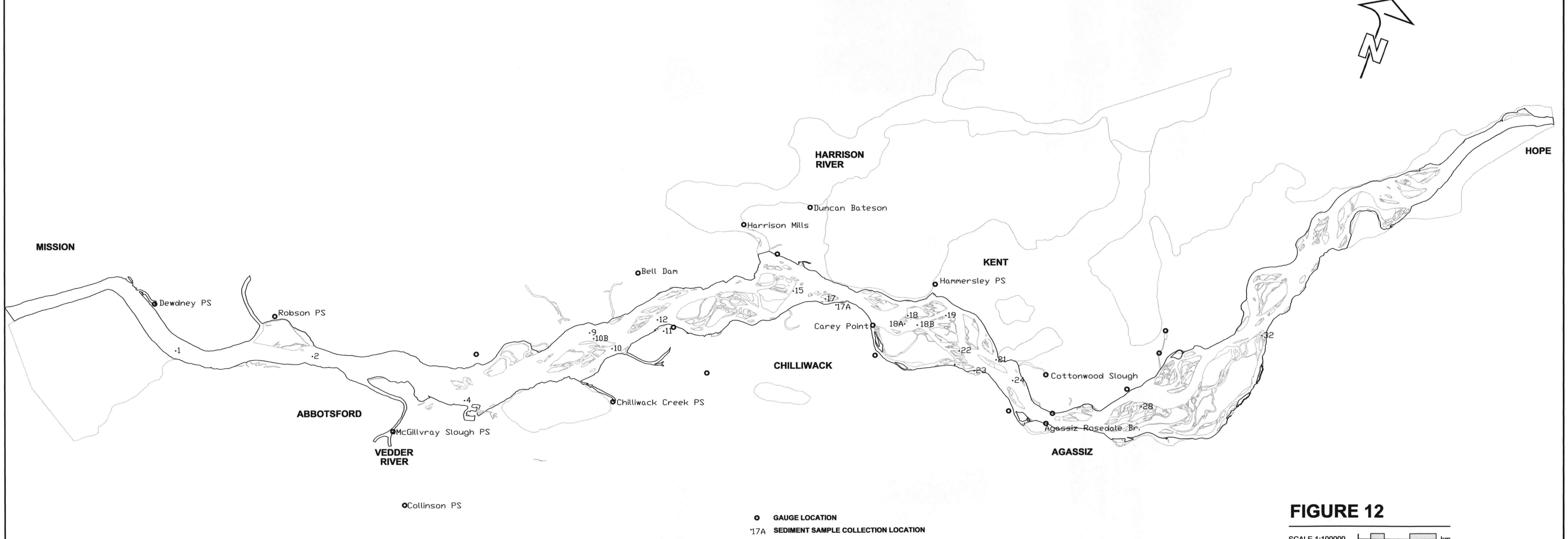


FIGURE 12

SCALE 1:100000 0 1 2 3 km

FRASER RIVER STAFF GAUGE LOCATIONS