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Science and Technology

A river routing model for Orkla river

Cao Tri Nguyen

Hydropower Development
Submission date: June 2017
Supervisor: Oddbjørn Bruland, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

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I, Nguyen Cao Tri hereby declare that this master's thesis titled "A routing model for Orkla river" and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

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2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

3. Where I have consulted the published work of others, this is always clearly attributed.

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5. I have acknowledged all main sources of help.

6. This thesis is based on work done by myself with the guidance of my supervisor Professor Oddbjørn Bruland and co-supervisor Frode Vassenden.

Signature: Nguyen Cao Tri

Date and Time: 8th of June, 2017, Trondheim, Norway

ACKNOWLEDGEMENTS

First of all I would like to convey my deepest appreciate towards my supervisor, Professor Oddbjørn Bruland, whose always support me from the beginning of the project til the successful completion of my work. I was impressed by his expertise and knowledge of hydraulic science and most of all, his guidance. Professor Oddbjørn continuously encourage me to provide better results and suggest the ideals for the topic. The communications did help me to go deeper into the topic and open up new ideals.

I also would like to thank you Mr. Frode Vassenden from Trønderenergi. As a mathematician and a hydrologist, Mr. Frode gaves me a clear insight about the modeling and provided me all of the data needed for my analisys. Without his support I would hardly finish my thesis successfully.

Futhermore I would like to express my sincere gratitude for Professor Knut Alfredsen and the research at the department, Abebe Girmay Adera for great help at the early stage of the project.

Nguyen Cao Tri

ABSTRACT

In a large and complex hydropower system with multiple intake and outlet locations, the time lag in stream flow has a significant impact on downstream hydropower production. The impact becomes more important for power producer in an Energy Market. This is even more important in a Cascade Hydropower system where how to maximize utilize the water released from the upstream power plant is always an important question.

At Orkla river, the Time Delay has been estimated since 2009 with a fix Time Delay of about 4 hours for Grana production flow and 12 hours for Brattset production flow. However, Time Delay and Time Constant has a mutual interaction and are vary in different flow conditions. Therefore, how to identify precisely Time Delay is an important task to look into in this thesis.

The project aims to:

a. Understand the flow pattern in Orkla river in different operations flow from Brattset and Grana power plan, both on dry and wet weather condition.

b. Determine Time Delay in Orkla river in above conditions

c. Have an overview of developed river routing model, and build a model that can reproduce the flow in Orkla river

d. Produce a reference to estimate the Time Delay in other hydropower systems.

Upon investigation, a brief summary of river routing models has been provided. Based on that, a model has been built to meet specific conditions at Orkla river. The model is verified to use with several historical data sets. Due to itæs simpleness, the model is fast and easy to embedded into current hydropower control system. Furthermore, a reference to estimate Time Delay was made for further research and application.

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I. INTRODUCTION

1.1. Hydropower in Norway

More than 99 percent of electricity in Norway comes from hydropower. Representing the fifth largest hydropower system in the world and regarded by many as the most efficient and modern, the Norwegian hydropower system generates an average of 11500GWh of electricity a year and has a total installed capacity of 29.932MW (Ziegler, Summer 1993). Additionally, Norway has the world's largest per capita hydropower production, and is the sixth largest hydropower producer in the world and the largest hydropower producer in Europe (Enoksen, 23/3/2007).

1.2. Power market:

“Norway could find itself in a very advantageous position as an energy supplier” (Olsen, 2011). The Nord Pool Markets (NPMs) provides an effective coordination of supply and demand for its member countries and helps to sustain a necessary level of investments. As a leading power market in Europe, NPMs is expected to secure power supply for its members, . The figure below indicates current member countries of Nord Pool Markets (Nord Pool Spot, n.d.)

The concept of NPMs follows simple economic principle: the power price is determined by the balance between supply and demand. Free competition power producers enter the market and bid their price for the next day (day-ahead market). When all members have submitted their orders, equilibrium between the aggregated supply and demand curve is established for all bidding areas, then the area prices are calculated and published. Today there are five bidding areas in Norway. Eastern Denmark and Western Denmark are treated as two different bidding areas. Finland, Estonia, Lithuania and Latvia constitute one bidding area each; Sweden was divided into four bidding areas on 1 November 2011. Thanks to different bidding areas, thus different area prices due to bottlenecks in the transmission system, the power will always go from the lower price area to the higher one. This principle is beneficial for society: "the commodity ought to move towards the high price where the demand for power is the highest" (Nord Pool Spot, n.d.)

As an emerging European market, it is expected that more and more different power sources will enter the grid: hydro, thermal, nuclear, wind and solar. Therefore, improving transmission capacity, balancing the grid and how to efficiently integrate different power sources are main challenges in the future.

1.3. Scope of the thesis

As a matter of course, power market and grid balancing development require more detailed information about hydropower system. It is needed to determine precisely time delay and magnitude of flow to optimum water use settlement and preventing of spillage. This is especially important in a cascade hydropower system with start-stop operation.

The main objective of this study is to simulate flow condition of a cascade hydropower system at Orkla river. The study site contains two river power plants Brattset and Svorkmo separated by a 40 km river stretch. Midway between the two river plants the production water from the Grana power plant enters the river. The topic includes but not limited to:

- Understanding the Orkla hydropower system and its flow patterns in different operation strategies and weather conditions.
- Have an overview of developed river routing model, and build a routing model that can reproduce the flow in Orkla river.
- Results from the simulation could be used to minimize water loss during operation control of the power system based on real-time operation.
- Provide a reference to predict time delay in the another river systems.

II. OVERVIEW OF RIVER FLOW MODELLING

There has been developed many models for numerical flow simulation in the river. Those models are based on the Saint Venant Equations (SVE) (Saint-Venant, 1871) such as HEC-RAS, MIKE 11, SOBEK and so on that gives good simulation results. However, those models require huge input data and use large computation capacity. For practical purpose, numerous efforts were used to simplified the full SVE equation to reduce computation time and input data. The famous method bases on lag-and-route method was Muskingum model (Meyer, 1941). The method assumes a linear relationship between discharge and reservoir storage and take into consideration of lag time and routing reservoir. An upgrade of this routing method was made by Bentura and Michel (Bentura PLF, 1997) which uses two components as quadratic routing reservoir and lag time. The model was used and calibrated for uniform flow in a wide channel. However, both models did not relate to physical attributes of the channel.

A better approach was developed by (Rauschenbach, 2001). This model using two parameters time constant and time delay to estimating outflow characteristics of the river. However, the model use fixed time delay and time constant, and so couldn't provide good result. To overcome this drawback, a river routing technique using similar approach was developed by (Litrico X, 2010). This nonlinear model use vary time constant and time delay in response to different inflow values. Several physical parameters are also used to calibrate the model such as length of the river stretch, slope, Manning coefficient and the river width. The outcome of the model was validated for a large river and give good performance. However, "this model is only valid for slow variations of the state. It is also an underlying hypothesis for the diffusive wave model. If the discharge varies very quickly, the celerity and the diffusion depending on the discharge would certainly give results different from physical observations" (Litrico X, 2010). In other words, this routing model could not provide as good result as a complex hydraulic model due to the assumption of simplified geometry characteristics.

A further extension of Litrico's model, adaptive time delay model, was made by (Nguyen LD, 2015) and a procedure of this model has been developed to identify time delay and time constant using Hec-Ras software (Nguyen LD K. D., 2016). This model can be said as a simplified version of Hec-Ras and showed good results at Thu Bon river, Vietnam. However, both Litrico and Nguyen's models assume no lateral inflow is present in the system, which is not good enough for Power Market operation because more details of information are required. This study developed a possible method to apply Adaptive Time Delay model in daily operation at cascade hydropower system at Orkla river. Additionally, a reference to quickly predict Time Delay in another river systems has been developed using the model.

III. MATERIALS AND METHODOLOGY

3.1. STUDY SITE

General: The river Orkla is the longest river in Sør-Trøndelag county, Norway. The river follows the Orkdalen valley, discharging into the Orkdalsfjord, an arm of Trondheim Fjord, at the village of Orkanger. The river runs through the municipalities of Oppdal, Tynset, Rennebu, Meldal, and Orkdal. Most of the municipalities are in Sør-Trøndelag county, while Tynset municipality is in Hedmark county. The Orkla is well-known for salmon fishing, about an 88 Km long stretch of the river through Orkdal, Meldal, and Rennebu is used for salmon fishing throughout the season from June through August.

Total length of 179 Km, Orkla river drains a catchment of 3050 Km^2 with an average annual runoff of 71 m^3/s, whereas the annual average winter runoff is given by (K.T.Alfredsen, 2009) with 50 m^3/s.

Figure 1: Open of Orkla river to the fjord, photo by Trondheim Havn/Åge Hojem

Due to its importance for hydropower and salmon resources, many of the studies has been carried out along Orkla river. Orkla river is described as a predominantly run water with a large hydraulic diversity due to a variety of pools and riffles (Morten Stickler, 2007). First, it runs through a narrow valley in the upper region before the valley becomes wide and flat in the lower part (Borsányi, 2005). The figure below illustrates the study site and gives an overview of installed power plants (regulated and unregulated), reservoirs and intakes. The flow direction is from Brattset outlet to Svorkmo intake. Between them is an inflow generated by Grana power plant. Additionally, the reach of the modeling work is yellow highlighted.

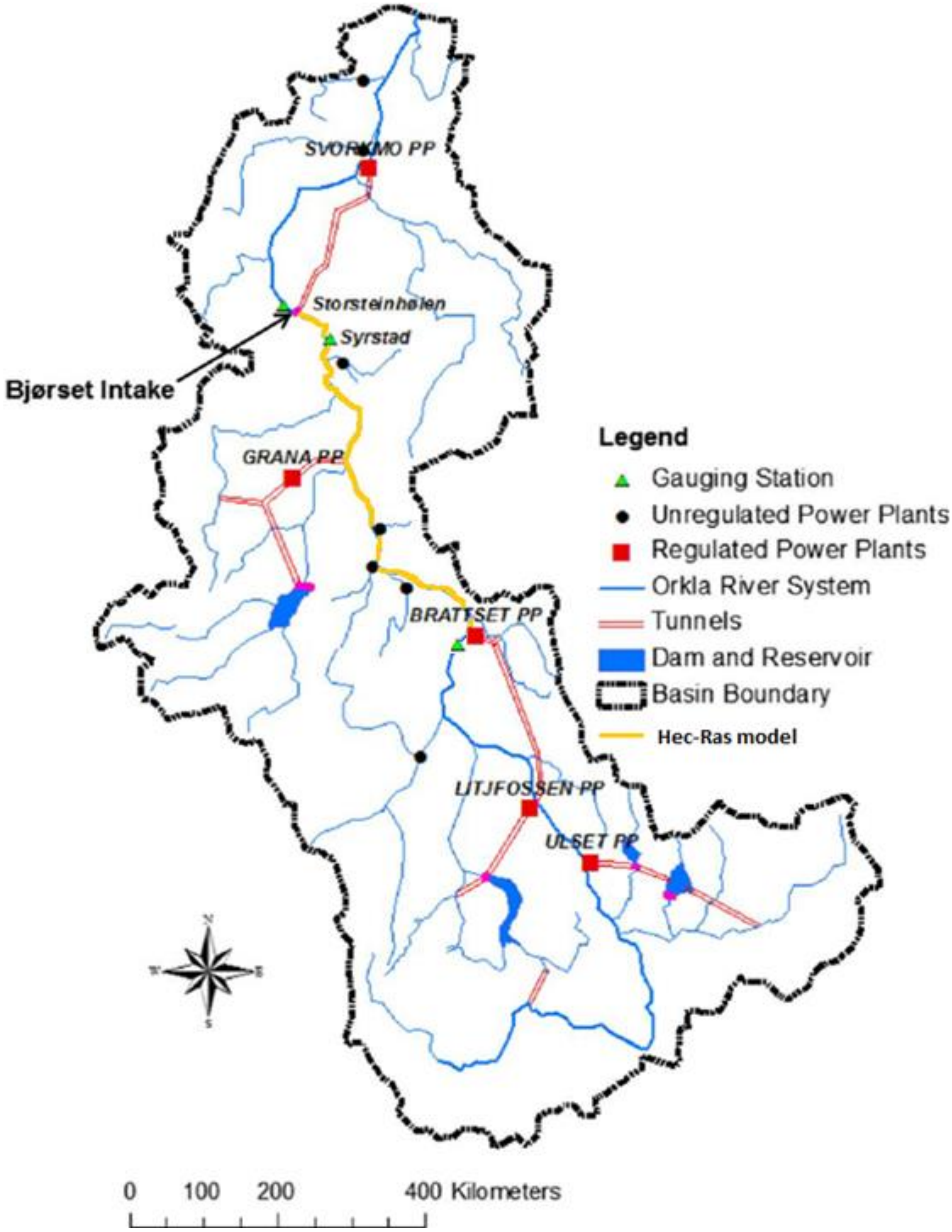


Figure 2: Overview of Orkla Study Site

Hydropower development in the area: The regulation of the river and the expansion of the watercourse took place in the period between 1978 and 1985 (KVO, n.d.). Nowadays, 5 Power plants control the river regime, Svorkmo, Grana, Brattset, Litfjossen and Ulset. There are four regulated reservoirs which two of them artificially formed, several transfer tunnels and mountain intakes with outlets in the river regulate the scheme efficiently (Nils Arne Hvidsten, 2004), (Gebre, 2009). The total installed capacity is 320 MW and the annual average production is 1250GWh - about 1% of Norway's power consumption (KVO, n.d.)..

The study focus on the region defined by a cascade hydropower system, from the outlet of Brattset power plant to Bjørset intake of Svorkmo power plant. The water regime in the study area is mainly characterized by the production of Brattset and Grana power plant. Brattset power plant mainly utilizes flow from Litjfossen Hydropower Plant and Grana utilizes water from Granasjøen: The lake was formed by the construction of a dam across the river Grana by Nerskogen. It is a regulation reservoir for Grana power plant. Lowest and highest water level is 610m and 650m. The lake has a maximum extent of 6.61km² and a capacity of 144 Mm^3 (NVE, 2004). Downstream of the study site is Svorkmo power plan, which utilizes water released from Brattset, Grana, and a small catchment at Svorka river intake. The details information for those power plants is described as the information below:

Power Plant	**Brattset**	**Grana**	**Svorkmo**
Developed	1982	1982	1983
Installed capacity	2 x 40 MW	75 MW	34 + 20.5 MW
Catchment [Km^2]	433.1	291.6	1309
Annual runoff [Mm^3]	252	261	913
Water head [m]	273	462	99
Energy equivalent [KWh/m^3]	0.062	1.095	0.22
Expected power generation	400 GWh/year	280 GWh/year	270

Table 1: Summary of Hydropower Plans in the area (KVO, n.d.)

3.2. INTRODUCTION TO HEC-RAS MODEL

Hec-Ras (Hydraulic Engineering Center's – River Analysis System) is a well-known software used in hydraulic simulation, developed by US Army Corps of Engineer. The latest version of this software until the time writing this thesis is 5.0.3 and it is also the model being used throughout the study. Hec-Ras can perform both 1D and 2D computations, steady and unsteady state for river reaches. It also can do water quality computation and sediment transport simulation (Brunner, 2010). This study use 1D simulation, so 2D simulation, sediment and quarter quality analysis will not be discussed. The interested reader is referred to User's manual from (Brunner, 2010)

3.2.1. Steady Flow Simulation using Hec-Ras

The component steady flow analysis allows the user to perform a steady condition of flow. It calculates water surface profiles for gradually varied flow, both on subcritical, supercritical and mixed flow regime. HEC-RAS calculates the water elevations from downstream cross section to upstream cross section by solving the one-dimensional Energy Equation below (Brunner, 2010):

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + h_e + \frac{\alpha_1 V_1^2}{2g} \tag{3.1}$$

Where:

Z_1, Z_2	Elevation of main channel inverts	m
Y_1, Y_2	depth of water at considering cross sections	m
V_1, V_2	Average velocities	ms^{-1}
α_1, α_2	Velocity weighting coefficients	-
g	Gravitational acceleration	ms^{-2}
h_e	Energy head loss	m

Energy head loss is calculated through contraction and expansion losses in the considering cross sections and by friction losses from Manning's equation. The head loss can be determined by using the equation below:

$$h_e = L\overline{S_f} + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \tag{3.2}$$

Where:

L	Discharge weighted reach length	m

$\overline{S_f}$	Representative friction slope between two sections	-
C	Expansion of contraction loss coefficient	-

As equation above, the factor C influences the head loss due to contraction and expansion once the velocity head differs between two cross sections. Hec-Ras user can modify C coefficient following Hec-Ras Reference Manual. Typically, C is set to 0.1 for contraction coefficient and 0.3 for expansion coefficient. Those number is kept unchanged in the whole study and can be found under Gradual Transition part in the user manual.

L and S_f can be solved by using equations below:

$$L = \frac{\bar{Q}_{lob}L_{lob} + \bar{Q}_{ch}L_{ch} + \bar{Q}_{rob}L_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad (3.3)$$

Where:

L_{lob}	Reach length in left overbank	m
L_{ch}	Reach length in main channel	m
L_{rob}	Reach length in right overbank	m

Flow can be calculated using equations 3.4 and 3.5 as below:

$$Q = KS_f^{\frac{1}{2}} \quad (3.4)$$

$$K = \frac{1.486}{n}AR^{\frac{2}{3}} \quad (3.5)$$

Where:

K	Conveyance for subdivision	-
n	Manning's roughness coefficient for subdivision	$sm^{-1/3}$
A	Flow area for sub division	m^2
R	Hydraulic radius for subdivision	m

In case of geometry complexity cause rapidly varying flow situations instead of gradually varied flow situation, Hec-Ras uses momentum equation for computing the profiles in such conditions. This happens when the flow turns from subcritical condition to critical condition or vice versa. Hec-Ras decides a flow condition as critical whenever Froude number is greater than 0.94 to avoid computations errors in real life application (Brunner, 2010). Equation 3.6 is used for computation once known the critical depth.

$$P_2 - P_1 + W_x - F_f = Q\rho\Delta V_x \tag{3.6}$$

Where:

P_1, P_2	Hydrologic pressure force at cross section1 and 2	-
Wx	Water weight force in the x direction	-
Ff	External friction losses from 1 and 2	-
Q	Discharge	m^3s^{-1}
ρ	Density of water	kgm^{-3}
ΔV_x	Change on velocity from cross section 1 to 2 in x direction	ms^{-1}

For calibration, the user has to specify Manning values n. Here, a high Manning number corresponds to high stages, which means much more available storage, more attenuation and smoothing of the downstream hydrograph. Hec-Ras allows users input various Manning number along the river and entire cross section to achieve desired flow condition.

This study inherits a calibrated Hec-Ras model for studying site from (Beckers, Jan 2014). However, this model needs to be re-calibrate by the student to meets the topic’s requirements. The aim of calibration process is to adjust the model’s parameters, such as roughness and hydraulic structure coefficients, so that the model reproduces observed flow data to an acceptable accuracy. Procedure for calibration is as follow (Brunner, 2010):

1) Run a range of discharges in the Steady Flow mode, and calibrate n values to establish rating curves at known gauges and high water marks.
2) Select specific events to run in Unsteady Flow mode. Ensure the event goes from low flow to high flow, and back to low flow conditions.
3) Adjust storage and lateral weirs to get good reproduction of flow hydrographs. The user should concentrate on timing, peak, volume and hydrograph shape.
4) Adjust Manning’s n values to reproduce stage hydrographs.
5) Fine tune calibration for stages low to high by using Discharge Roughness Factors where and when appropriate.
6) Further refine calibration for long term modeling with Seasonal Roughness Factors where and when appropriate.

3.2.2. Unsteady Flow simulation using Hec-Ras

Unsteady flow simulation is performed after the model has been calibrated using Steady State simulation. Hec-Ras uses Saint Venant equation for 1D simulation purpose as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \qquad (3.7)$$

Where:

A	Area of cross sectional flow	m^2
Q	Discharge	m^3s^{-1}
q_t	Lateral inflow per unit length	m^2s^{-1}

$$\frac{\partial QV}{\partial x} + \frac{\partial Q}{\partial t} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \qquad (3.8)$$

Where:

V	Velocity	ms^{-1}
$\frac{\partial z}{\partial x}$	Water surface slope	-
S_f	Friction slope	-

The physical laws which govern the flow of water in a stream are: the principle of conservation of mass continuity and the principle of conservation of momentum. These laws are expressed mathematically in the form of partial differential equations. The equation 3.7 is a simplification for conservation of mass into one-dimensional form: It is states that the net rate of flow into the volume be equal to the rate of change of storage inside the considering volume. Similarly, the same simplification is applied in equation 3.8 for conservation of momentum: The net rate of momentum entering the volume plus the sum of all external forces acting on the volume is equal to the rate of accumulation of momentum. (Brunner, 2010)

3.3. METHODOLOGY USES IN THE STUDY

3.3.1. Methodology

Conceptually, the study uses the Adaptive Time Delay (ADT) model developed by (Nguyen et al, 2015) and (Litrico et al, 2010) to simulate the flow of Orkla river. However, the model was developed with the assumption that no lateral flow is included - which is not the case in this study. Therefore, some modification and new approaching method was developed in this thesis to match specific requirements.

The figure below displays step-by-step to build ADT model:

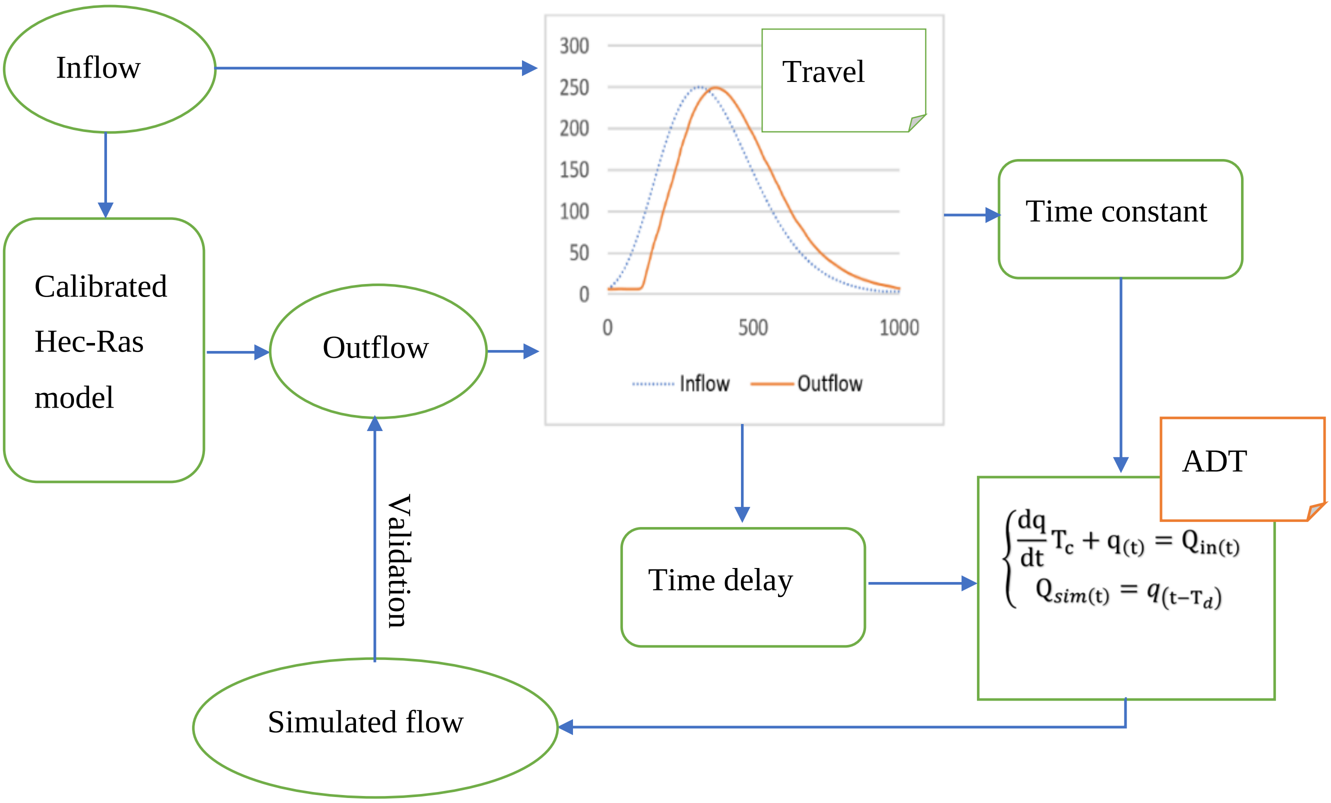


Figure 3: Methodology used in the study

- Step 1: Re-calibrate Hec-Ras model of Orkla river. The reason why Hec-Ras model acquired from (Beckers, Jan 2014) is needed to recalibrate will be discussed in the next section.
- Step 2: A period of time was chosen to simulate by Hec-Ras. The chosen period should contain both base flow and several flood events to ensure the stability of ADT model. In this step, the Travel time, timing and magnitude of downstream flow are derived by Hec-Ras.
- Step 3: Derive set of time constant and time delay for ADT model in according to magnitude of river flow and travel time found on step 2, using non-linear optimization programming. The results will be a range of T_c and T_d accordance to the inflow Q.
- Validate the parameters. The simulated flow from ADT model must fit to simulated results from Hec-Ras in another period of time. The student also verifies ADT model with observed data to check its performance.

3.3.2. Model Definition

The structure of the Adaptive Time Delay (ADT) model is described as equation below:

$$\begin{cases} \frac{\mathrm{dq}}{\mathrm{dt}}\mathrm{T_c} + \mathrm{q_{(t)}} = \mathrm{Q_{in(t)}} \\ \mathrm{Q}_{sim(\mathrm{t})} = q_{(\mathrm{t}-\mathrm{T}_d)} \end{cases} \tag{3.9}$$

Where:

t	Time step	hours
T_c	Time Constant	hours
T_d	Time Delay	hours
$Q_{in(t)}$	Upstream inflow	m^3/s
$q_{(t)}$	State of the system	m^3/s
$Q_{sim(t)}$	Simulated outflow	m^3/s

The parameters of ADT model Time Constant and Time Delay are derived from travel time which is generated by Hec-Ras software. “In terms of ADT model, the time constant is responsible for attenuation of peak whilst a pure time delay is the duration of the flow signal to appear downstream of a reach” (Nguyen LD K. D., 2016). The travel time generated in Hec-Ras is assumed as a combination of time constant and time delay of ADT model, which is described in the equations below:

$$T_c = \propto T_{HEC} \tag{3.10a}$$

$$T_d = \beta T_{HEC} \tag{3.10b}$$

$$Conditions: \begin{cases} \alpha > 0 \\ \beta > 0 \\ \alpha + \beta \leq 1 \end{cases} \tag{3.10c}$$

The parameters α and β are estimated using constrained non-linear programming technique. In order to find α and β, accordance with travel time, the optimization is performed using objective function below:

$$min \sum_{i=1}^{n} (Q_{HecRas}^{i} - Q_{ATD}^{i})^2 \tag{3.11}$$

$$OR: Max: 1 - \frac{\sum_{i=1}^{n} (Q_{HecRas}^{i} - Q_{ATD}^{i})^2}{\sum_{i=1}^{n} (Q_{HecRas}^{i} - Q_{Average})^2} \tag{3.12}$$

Details of analytical work will be discussed in the next sections.

3.3.3. Re-Calibrate Hec-Ras model

As said in the section 3.2.1, the thesis use calibrated model from (Beckers, Jan 2014). The model is verified to use in his thesis to simulate the formation of ice in Orkla river due to the operation of Brattset and Grana hydropower plan. It has a good Nash-Sutcliffe Efficiency at 0.824 as displayed in the figure below:

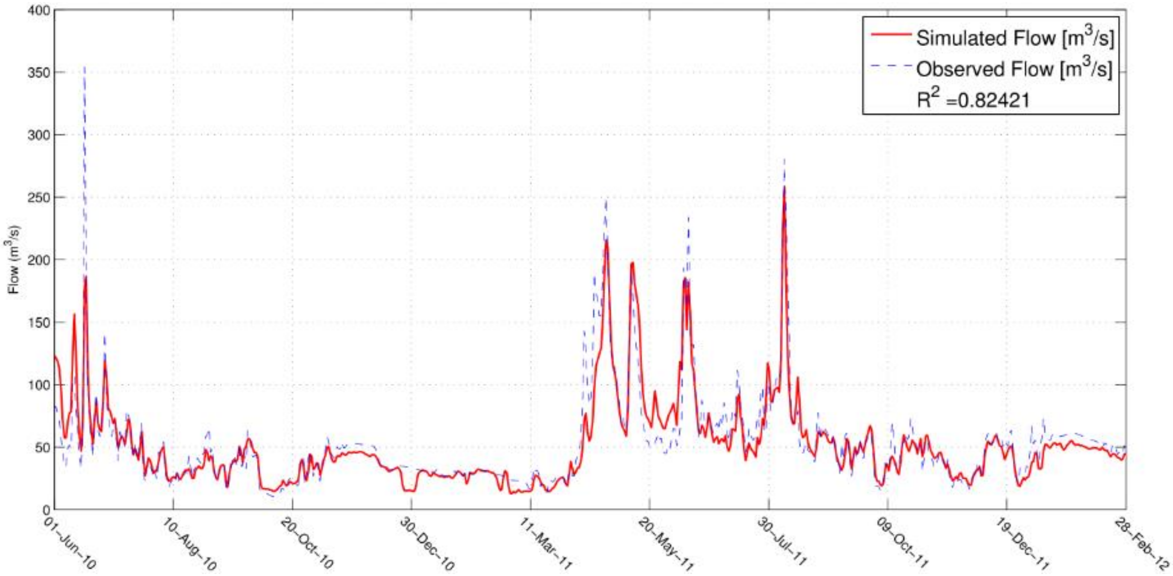


Figure 4: Calibrated Hec-Ras model by (Beckers, Jan 2014)

However, the model is not suitable to use to derive Time Delay and Time Constant for the ADT model. If we zoom into the hydrograph as below, we would notice that the simulated flow is “smoothed out” compares with observed flow. Instead of swiftly decrease and increase of flow hydrograph due to the multi-start-stop operation at Grana and Brattset, the flow simulated by Hec-Ras is stretched out, and results in a much gradual hydrograph.

Period from 8/3/2015 to 15/3/2015 was chosen to check the performance of Hec-Ras model. The reason to choose this period are:

- Stable production flow from Brattset power plan,
- No precipitation event, and
- Multi-start-stop operation at Grana power plan.

The chosen period therefore illustrates clearly the performance of Hec-Ras model towards observed flow at Syrstad station. This phenomenon is displayed in the figure below:

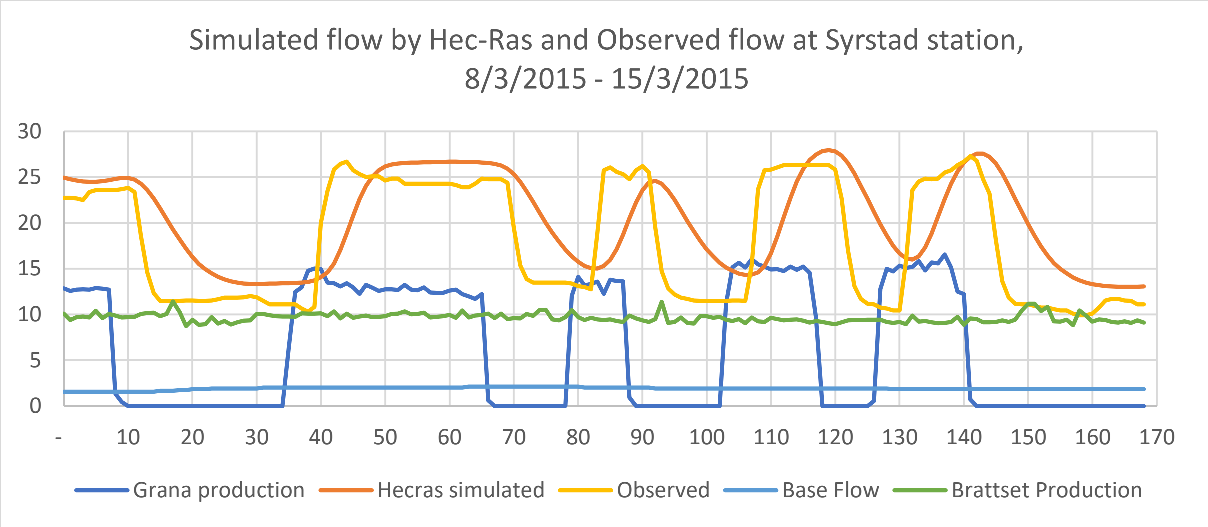


Figure 5: Performance of Hec-Ras model by (Beckers, Jan 2014)

The reader can easily notice the wave movement of simulated flow in figure 5 above. For the first "stop" operation at Grana power plan, the observed flow shows a drop 4 hours later and reach bottom value in the next 4 hours, while Simulated flow by Hec-Ras shows a drop 5 hours later and reach the bottom in the next 10 hours. Therefore, the available model is not sufficient to use to derive Time Delay and Time Constant for ADT model.

One possible reason for the "smooth out" effect of Hec-Ras model developed by (Beckers, Jan 2014) is the unrealistic Manning's coefficient. It is typically in the range of 0.03 to 0.06 plus or minus for large river as a suggestion in (Brunner, 2010), definitely not in the range 0.1 to 0.3 in the model. The details Manning's coefficient table is displayed at Appendix A

The objective of re-calibration process is to:

- Reproduce the right timing of simulated flow compares with observed flow.
- Try to catch the peak in the summer and provide better flow magnitude in the winter, because the time constant and time delay mutually interact, are vary, and significantly depend on flow condition in the river.

a) Method for calibration:

To recalibrate the model, the student use equation developed by (Jarrett, 1985) as following:

$$N = 0.39 \times S^{0.38} \times R^{-0.16} \tag{3.13}$$

Where:

S	Geometry Slope	-
R	Hydraulic radius	m

The hydraulic radius is measured at 25 m^3/s to calculate Manning's coefficient. River sections between calculated Manning's coefficient are assumed to have the same value as calculated one. Then the table of the coefficient is multiplied with several multiple factors following the calibration procedure mentioned above.

No.	**River Station**	**Hydraulic Radius**	**Slope**	**Manning's coefficient**
1	110	0.884075763	0.002639	0.04166518
2	101	0.6333301	0.002639	0.043949178
3	90	0.927755959	0.002639	0.041344922
4	81	0.644248952	0.002639	0.043829143
5	71	1.116576149	0.002639	0.040137419
6	61	0.458921491	0.002639	0.046273615
7	52*	0.417088608	0.002937	0.04893635
8	42	0.439390214	0.002937	0.048530196
9	32	1.345249294	0.002937	0.040575106
10	22	0.769051095	0.002937	0.044372641
11	12	0.665321186	0.002937	0.045413303
12	1	0.610623044	0.002937	0.046040963

Table 2: List of measured Hydraulic Radius and their Manning's coefficient

b) Lateral Flow calculation

In the original model, a constant lateral inflow was calculated by scaling specific runoff of Eggafoss gauging station with catchment area at Grana, Syrstad, Brattset and Bjørset.

Catchment name	Constant lateral inflow [m^3s^{-1}]
Brattset	9.03
Grana outlet	4.67
Syrstad	5.24
Bjørset	4.41

Table 3: Lateral flow used before re-calibration (Beckers, Jan 2014)

The new method uses dynamic lateral inflow by scaling observed flow at unregulated gauging station just upstream Brattset outlet and observed flow at Eggafoss station. By doing this, the student assumes that:

- The precipitation event is evenly distributed in the whole catchment,
- The specific runoff is unchanged in the considering river section, and
- The response to the event is unchanged from upstream Brattset to downstream Bjørset dam.

However, only lateral inflow results scaled from upstream Brattset station is good enough for further process, so the result using Eggafoss station will not be mentioned further.
The calculation of scaled lateral inflow can be calculated using the equation below:

$$\frac{Q}{qA} = \frac{Q_U}{A_U q_u} \tag{3.14}$$

Where:

Q	Discharge	m^3s^{-1}
Q_U	Observed discharge of upstream Brattset outlet station	m^3s^{-1}
A	Catchment area	km^2
A_U	Catchment area of upstream Brattset outlet station	km^2
q	Specific runoff	$ls^{-1}km^{-2}$
q_u	Specific runoff of upstream Brattset outlet station	$ls^{-1}km^{-2}$

Because the specific runoff is unchanged in the same region, equation (3.14) is equal to:

$$\frac{Q}{A} = \frac{Q_U}{A_U} \tag{3.15}$$

Catchment areas are displayed in the table below:

Catchment name	Total catchment area [km^2]	Contributing lateral flow area [km^2]
Brattset	1514.55	460.33
Grana outlet	2008	238.07
Syrstad	2275.5	224.6

Bjørset	2318	267.1

Table 4: Catchment areas used in the study (Beckers, Jan 2014)

c) Hec-Ras model setup

After acquired Manningæs coefficient and lateral flow has been calculated, the model setup is as following data input and boundary conditions table:

Terms	Cross section	Remark	Data uses as	Type
Upper boundary condition	110	Brattset outlet	Production flow at Brattset	Flow hydrograph
Lateral flow	55	Just upstream Grana outlet	Scaled lateral flow	Flow hydrograph
Lateral flow	54	Grana outlet	Production flow at Grana	Flow hydrograph
Lateral flow	22	Just upstream Syrstad station	Input data	Flow hydrograph
Control point	21	Syrstad station	Observed value	-
Lower boundary condition	1	Bjørset	Regulated water level	Stage hydrograph, constant value at 129.14m

Table 5: Data input and Boundary conditions for new Hec-Ras model

An observed data set from Jun, 2010 to Dec, 2016 at Syrstad station was considered to determine initial condition for Hec-Ras. The data resolution is every hour and is downloaded from http://www.senorge.no. Station ID is 121.22.0.1001 and coordinator is at X=233480 & Y=7000137. The production data at Grana and Brattset power plan was given by Mr. Frode Vassenden, TrønderEnergi company.

Base flow Q95 was used in the whole simulation work as base flow. The procedure is as following:

- Sort the flow data from highest to lowest value and remove any duplicate if existing.

- Rank the data from 1 (highest flow value) to n (lowest flow value).
- Percent of exceedance of a flow value is determined as following:

$$P = 100 \times \frac{m}{n+1} \tag{3.16}$$

Where:

P The probability that a given flow will be equaled or exceeded (% of time)

m The ranked position on the listing (dimensionless)

n The number of events for period of record (dimensionless)

Two period of time was chosen for simulation in order to check the stability of the new model, one is Jun 2010 – Feb 2012 and another is Jan – Dec 2016. The reason for choosing the period Jun 2010 – Feb 2012 is to compare the performance of the new model with the old one. The other period of time is chosen just to make sure the new model works well.

d) Derive Travel Time from Hec-Ras

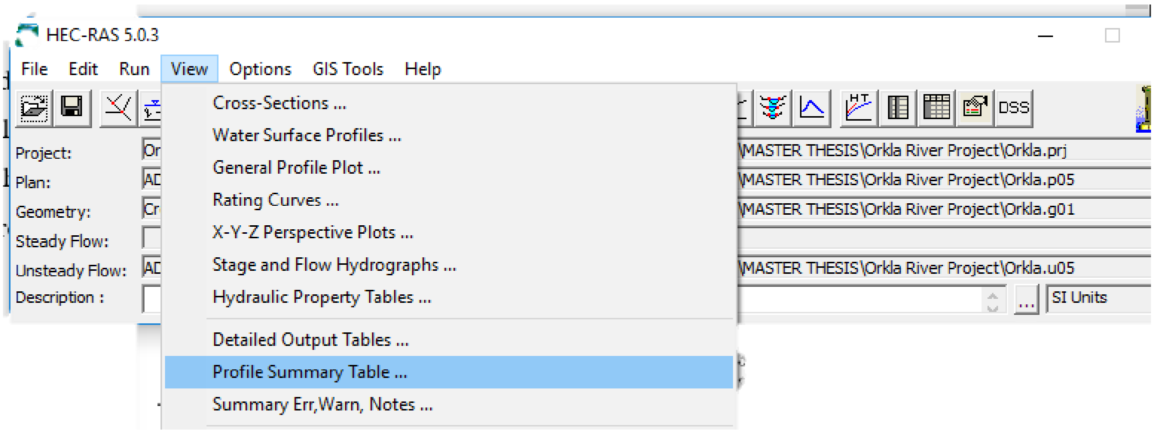
After the new model has been validated, the student run simulation in the period 1/3/2011 – 30/09/2011 to derive travel time. The reason is that this period contains base flow and several flood events in which one of these has the highest flood peak in the whole data series. The observed data in the winter period is excluded due to ice problems at Syrstad station, making the data insufficient to use.

Instead of using Hydrograph Width Analysis as procedure developed by (Nguyen LD K. D., 2016), in this section, the student developed new procedure to derive travel time and so the time delay and time constant. It is because the Hydrograph Width Analysis is developed to analyze flood events and have some drawbacks, such as the designed peak flow appears to be inconsistent with properties of a catchment, and the design event method derives a flood hydrograph from a single combination of inputs (rainfall depth, rainfall duration, rainfall profile and catchment wetness index). This combination does not always result in a hydrograph peak of the required return period (Kieran O'Connor, 2014). Additionally, the study objective is to derive time delay and time constant with different start-stop Hydropower operation and different river flow conditions, so the method developed by (Nguyen LD K. D., 2016) is not suitable to use in this case.

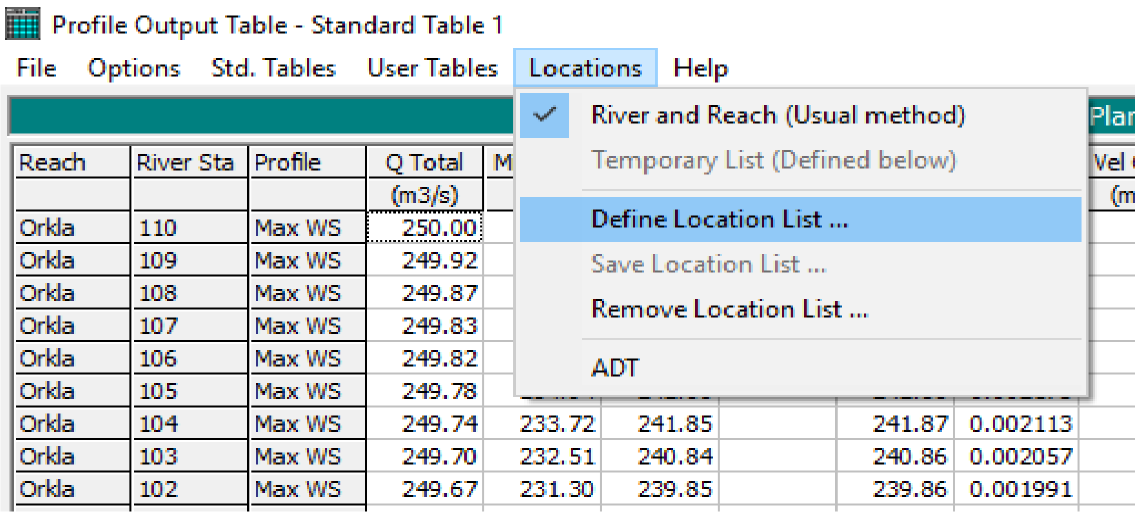
Method to acquire Travel Time using Hec-Ras:

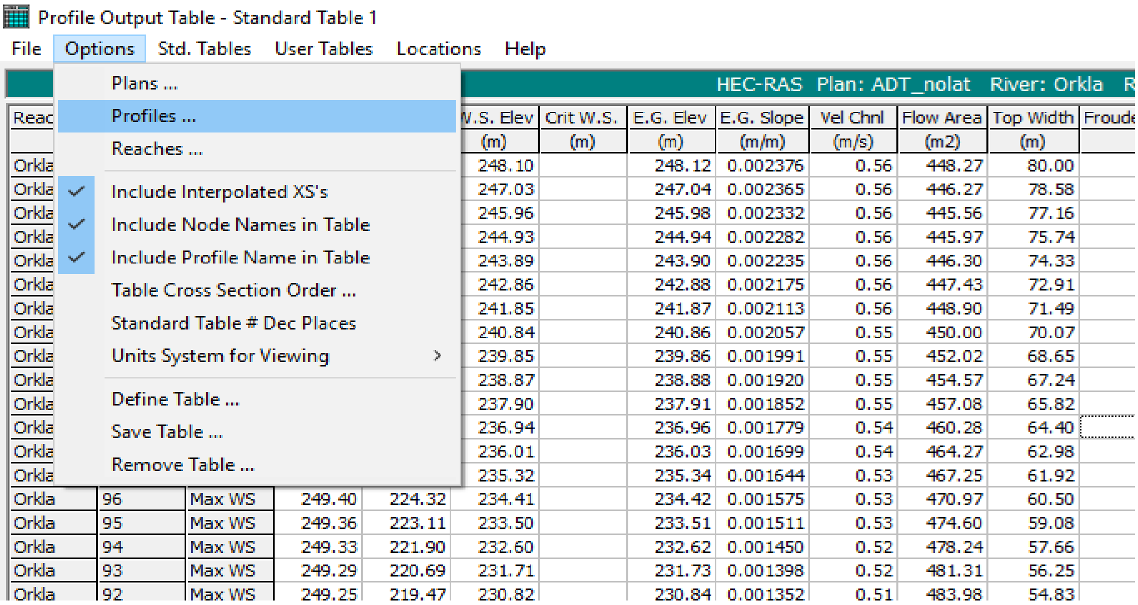
After running simulation by Hec-Ras, user can get details Travel Time table as following:

- In the main program interface, choose View → Profile Summary Table



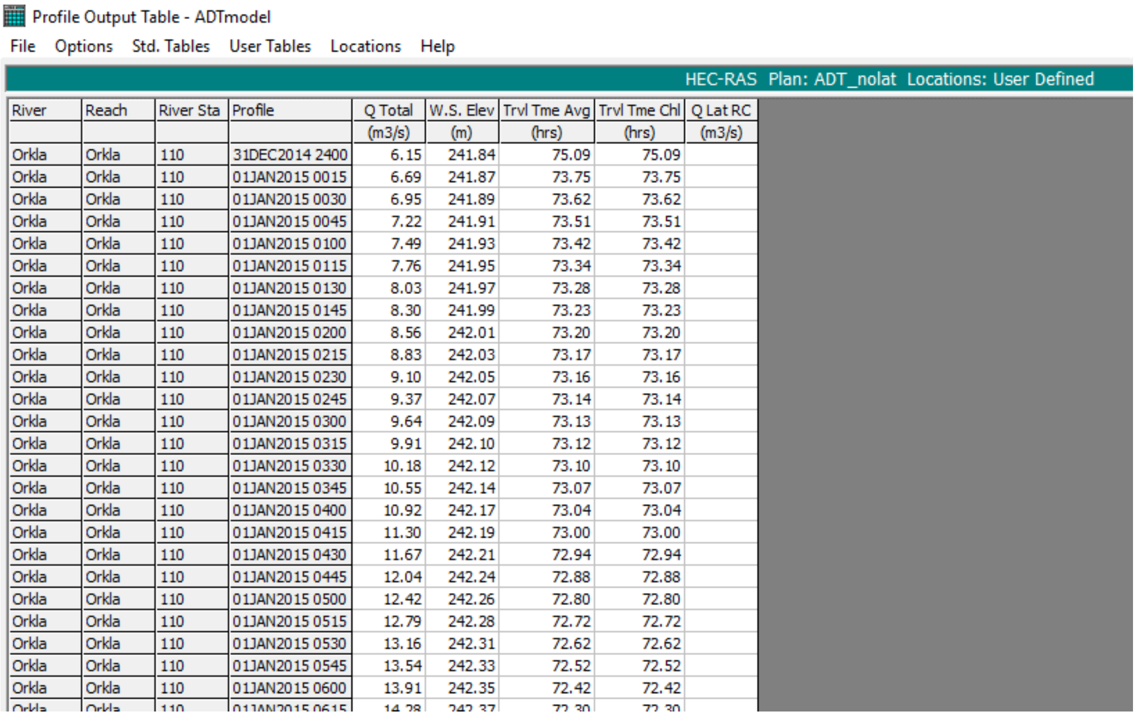
- In the Profile Output Table interface, user can choose Cross Sections, Water Profiles (Profiles) and Define Table by Select Variables to display the result. To define location, choose Locations → Define Location List. To define profiles, choose Options → Profiles. To define Table, choose Options → Define Table and then Select Variables tab insert or delete variables to be displayed.





Reac					W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude
					(m)	(m)	(m)	(m/m)	(m/s)	(m2)	(m)	
Orkla					248.10		248.12	0.002376	0.56	448.27	80.00	
Orkla					247.03		247.04	0.002365	0.56	446.27	78.58	
Orkla					245.96		245.98	0.002332	0.56	445.56	77.16	
Orkla					244.93		244.94	0.002282	0.56	445.97	75.74	
Orkla					243.89		243.90	0.002235	0.56	446.30	74.33	
Orkla					242.86		242.88	0.002175	0.56	447.43	72.91	
Orkla					241.85		241.87	0.002113	0.56	448.90	71.49	
Orkla					240.84		240.86	0.002057	0.55	450.00	70.07	
Orkla					239.85		239.86	0.001991	0.55	452.02	68.65	
Orkla					238.87		238.88	0.001920	0.55	454.57	67.24	
Orkla					237.90		237.91	0.001852	0.55	457.08	65.82	
Orkla					236.94		236.96	0.001779	0.54	460.28	64.40	
Orkla					236.01		236.03	0.001699	0.54	464.27	62.98	
Orkla					235.32		235.34	0.001644	0.53	467.25	61.92	
Orkla	96	Max WS	249.40	224.32	234.41		234.42	0.001575	0.53	470.97	60.50	
Orkla	95	Max WS	249.36	223.11	233.50		233.51	0.001511	0.53	474.60	59.08	
Orkla	94	Max WS	249.33	221.90	232.60		232.62	0.001450	0.52	478.24	57.66	
Orkla	93	Max WS	249.29	220.69	231.71		231.73	0.001398	0.52	481.31	56.25	
Orkla	92	Max WS	249.25	219.47	230.82		230.84	0.001352	0.51	483.98	54.83	

- The final results could look like this:



River	Reach	River Sta	Profile	Q Total	W.S. Elev	Trvl Tme Avg	Trvl Tme Chl	Q Lat RC
				(m3/s)	(m)	(hrs)	(hrs)	(m3/s)
Orkla	Orkla	110	31DEC2014 2400	6.15	241.84	75.09	75.09	
Orkla	Orkla	110	01JAN2015 0015	6.69	241.87	73.75	73.75	
Orkla	Orkla	110	01JAN2015 0030	6.95	241.89	73.62	73.62	
Orkla	Orkla	110	01JAN2015 0045	7.22	241.91	73.51	73.51	
Orkla	Orkla	110	01JAN2015 0100	7.49	241.93	73.42	73.42	
Orkla	Orkla	110	01JAN2015 0115	7.76	241.95	73.34	73.34	
Orkla	Orkla	110	01JAN2015 0130	8.03	241.97	73.28	73.28	
Orkla	Orkla	110	01JAN2015 0145	8.30	241.99	73.23	73.23	
Orkla	Orkla	110	01JAN2015 0200	8.56	242.01	73.20	73.20	
Orkla	Orkla	110	01JAN2015 0215	8.83	242.03	73.17	73.17	
Orkla	Orkla	110	01JAN2015 0230	9.10	242.05	73.16	73.16	
Orkla	Orkla	110	01JAN2015 0245	9.37	242.07	73.14	73.14	
Orkla	Orkla	110	01JAN2015 0300	9.64	242.09	73.13	73.13	
Orkla	Orkla	110	01JAN2015 0315	9.91	242.10	73.12	73.12	
Orkla	Orkla	110	01JAN2015 0330	10.18	242.12	73.10	73.10	
Orkla	Orkla	110	01JAN2015 0345	10.55	242.14	73.07	73.07	
Orkla	Orkla	110	01JAN2015 0400	10.92	242.17	73.04	73.04	
Orkla	Orkla	110	01JAN2015 0415	11.30	242.19	73.00	73.00	
Orkla	Orkla	110	01JAN2015 0430	11.67	242.21	72.94	72.94	
Orkla	Orkla	110	01JAN2015 0445	12.04	242.24	72.88	72.88	
Orkla	Orkla	110	01JAN2015 0500	12.42	242.26	72.80	72.80	
Orkla	Orkla	110	01JAN2015 0515	12.79	242.28	72.72	72.72	
Orkla	Orkla	110	01JAN2015 0530	13.16	242.31	72.62	72.62	
Orkla	Orkla	110	01JAN2015 0545	13.54	242.33	72.52	72.52	
Orkla	Orkla	110	01JAN2015 0600	13.91	242.35	72.42	72.42	
Orkla	Orkla	110	01JAN2015 0615	14.28	242.37	72.30	72.30	

Hec-Ras generates two Travel times: Travel Time Average (Trvl Tme Avg) is "cumulative travel time based on the average velocity of the *entire cross section*, per reach.", and Travel Time Channel (Trvl Tme Chl) is "cumulative travel time based on the average velocity of the *main channel*, per reach" (Brunner, 2010). As the definition given, the student decided to use Travel Time Average to derive Time Constant and Time Delay.

3.3.4. Estimation of the Time Constant and Time Delay for ADT model

As mentioned in the 3.3.1 section, Adaptive Time Delay model does not consider lateral flow, which is not suitable to use in this study. Additionally, the scenarios below are considered to develop the model correctly.

- Scenario 1&2: Only Brattset power plan release the water, with& without precipitation event.
- Scenario 3&4: Only Grana power plan release the water, with or without precipitation event.
- Scenario 5&6: Both Brattset and Grana release the water, with or without precipitation event.

It is easy to point out that time delay and time constant are pretty much variables in these scenarios. For example, the flow condition changes significantly in the middle of the river when the water released from Grana power plan enter the river, or a suddenly stop operation at Grana power plan. This will result in an unstable Time Delay if we build the model for the whole river reach. Because of this, a possible solution that works well with different river flow conditions and different scenarios is that, the student divided the river wherever there is a contribution to flow hydrograph (for example: lateral flow enters the river or Production flow released from Grana power plan). Orkla river is divided into 5 parts as following:

Area	Cross Sections (CS)	Note	Input data
Part 1	110-55	From outlet of Brattset power plan to upstream outlet of Grana power plan	Production flow at Brattset PP
Part 2	55-54	To the outlet of Grana power plan	Lateral inflow at CS 55 + simulated outflow at CS 55
Part 3	54-22	To upstream of Syrstad station	Production flow at Grana + simulated outflow at CS 54
Part 4	22-21	To Syrstad station	Simulated outflow + Lateral flow at CS 22
Part 5	21-2	To Bjørset reservoir	Simulated flow at CS 21
Total inflow to Bjørset reservoir			Simulated outflow at CS 2 + Lateral inflow at CS 2

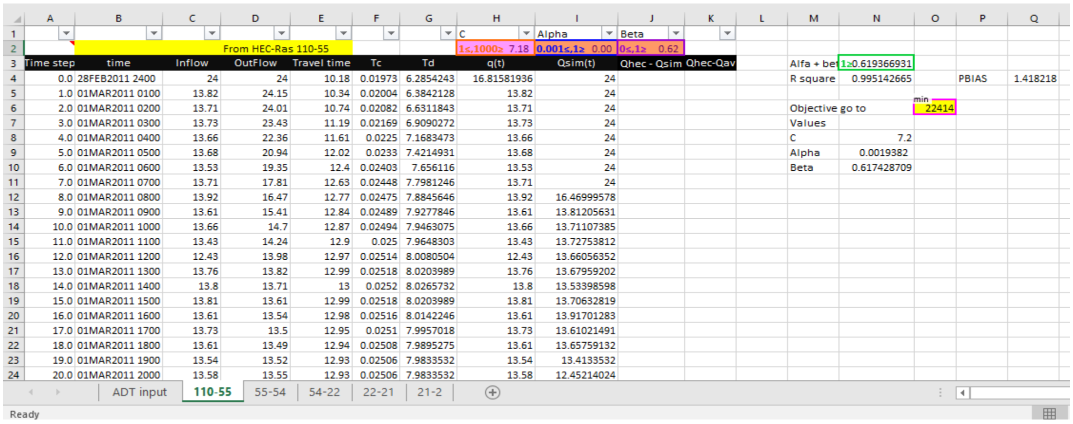
Table 6: Adaptive Time Delay model setup locations

Syrstad station was not required in the work. It means that the river can be divided into 4 parts only. However, this is the only observed data available to validate the performance of the model, thus it was taken into consideration. River section 55-54 and 22-21 are added in order to add lateral inflow into the model and are treated as inflow for cross sections downstream the river. Conceptually, the inflow of considering cross section is equal to simulated outflow generated from previous section + lateral inflow. In other words, the final model is a combination of 5 smaller models and each model uses their own Time Constant - Inflow and Time Delay - Inflow curves.

Hec-Ras generates cumulative travel time from downstream cross section to upstream cross section, so the travel time shown at cross section 110 is the total travel time from upstream to downstream. It means that the total time water travel from cross section 110→55 is the travel time at cross section 110 minus the travel time at cross section 55. This concept is applied similarly to other parts of the river.

After acquires the travel time, the next step is to determine optimum value of α and β, and so Time Constant and Time Delay through optimization. As mentioned above, nonlinear programming technique is applied to obtain a set of required values. In this study, the student use Microsoft Excel and Open Solver to solve the problems. Open solver is an open source optimization add-in for Excel, written in VBA programming language and is developed and maintained by (Mason, 2011). The optimization procedure is out of scope of this study and will not be mentioned further. Interested reader can find more information at https://opensolver.org/

Another add-in could be used is Solver engine, which is developed by a private company Frontline Systems Inc. This add-in is good in solving big data and complex problems. Frontline System's website is http://www.solver.com/. The details optimization model is displayed as figure below:



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1								C	Alpha	Beta							
2		From HEC-Ras 110-55						1≤,1000≥ 7.18	0.001≤,1≥ 0.00	0≤,1≥ 0.62							
3	Time step	time	Inflow	OutFlow	Travel time	Tc	Td	q(t)	Qsim(t)	Qhec - Qsim	Qhec-Qav		Alfa + bet	1≥0.619366931			
4	0.0	28FEB2011 2400	24	24	10.18	0.01973	6.2854243	16.81581936	24				R square	0.995142665		PBIAS	1.418218
5	1.0	01MAR2011 0100	13.82	24.15	10.34	0.02004	6.3842128	13.82	24								
6	2.0	01MAR2011 0200	13.71	24.01	10.74	0.02082	6.6311843	13.71	24				Objective go to		min 22414		
7	3.0	01MAR2011 0300	13.73	23.43	11.19	0.02169	6.9090272	13.73	24				Values				
8	4.0	01MAR2011 0400	13.66	22.36	11.61	0.0225	7.1683473	13.66	24				C	7.2			
9	5.0	01MAR2011 0500	13.68	20.94	12.02	0.0233	7.4214931	13.68	24				Alpha	0.0019382			
10	6.0	01MAR2011 0600	13.53	19.35	12.4	0.02403	7.656116	13.53	24				Beta	0.617428709			
11	7.0	01MAR2011 0700	13.71	17.81	12.63	0.02448	7.7981246	13.71	24								
12	8.0	01MAR2011 0800	13.92	16.47	12.77	0.02475	7.8845646	13.92	16.46999578								
13	9.0	01MAR2011 0900	13.61	15.41	12.84	0.02489	7.9277846	13.61	13.81205631								
14	10.0	01MAR2011 1000	13.66	14.7	12.87	0.02494	7.9463075	13.66	13.71107385								
15	11.0	01MAR2011 1100	13.43	14.24	12.9	0.025	7.9648303	13.43	13.72753812								
16	12.0	01MAR2011 1200	12.43	13.98	12.97	0.02514	8.0080504	12.43	13.66056352								
17	13.0	01MAR2011 1300	13.76	13.82	12.99	0.02518	8.0203989	13.76	13.67959202								
18	14.0	01MAR2011 1400	13.8	13.71	13	0.0252	8.0265732	13.8	13.53398598								
19	15.0	01MAR2011 1500	13.81	13.61	12.99	0.02518	8.0203989	13.81	13.70632819								
20	16.0	01MAR2011 1600	13.61	13.54	12.98	0.02516	8.0142246	13.61	13.91701283								
21	17.0	01MAR2011 1700	13.73	13.5	12.95	0.0251	7.9957018	13.73	13.61021491								
22	18.0	01MAR2011 1800	13.61	13.49	12.94	0.02508	7.9895275	13.61	13.65759132								
23	19.0	01MAR2011 1900	13.54	13.52	12.93	0.02506	7.9833532	13.54	13.4133532								
24	20.0	01MAR2011 2000	13.58	13.55	12.93	0.02506	7.9833532	13.58	12.45214024								

ADT input | 110-55 | 55-54 | 54-22 | 22-21 | 21-2

Ready

Figure 6: Example of Optimization model used in the study

Where:

- Solver engine used in the model is NOMAD (Non-smooth Optimization by Mesh Adaptive Direct search), (J.E, 2006)
- Option to choose in the model: “Make unconstrained variable cells non-negative”, Precision = 0.0001
- $T_c = \propto T_{HEC}$ and $T_d = \beta T_{HEC}$
- Variables: t, inflow $Q_{in(t)}$, C, α and β. While C, α and β are changed during optimization process to find global optimum value.
- Constrains conditions: C >0; α > 0; β > 0 and α + β ≤ 1
- Objectives function: $min \sum_{t=0}^{n}(Q_{Outflow}^{t} - Q_{sim}^{t})^2$; t is Time step
- $Q_{sim(t)}$ is defined by solving equation (3.9) as follow:

$$q_{(t)} = Q_{in(t)} - \mathrm{C} \times e^{-\frac{t-T_d}{T_c}} \tag{3.17a}$$

And:

$$Q_{sim(t)} = q_{(t-T_d)} \tag{3.17b}$$

Developed excel function:

$q_{(t)}$ = C4 - $H$2 * EXP(-A4/F4)

And:

$Q_{sim(t)} = q_{(t-T_d)}$ = IF(IF(A4<G4,$C$4,INDEX($H$4:$H$5140,ROUNDDOWN(A4-G4,0)+1,1)*(1-(A4-G4)+ROUNDDOWN(A4-G4,0))+INDEX($H$4:$H$5140, ROUNDDOWN(A4-G4,0)+2,1)*((A4-G4)-ROUNDDOWN(A4-G4,0)))<0,0, IF(A4<G4,$C$4,INDEX($H$4:$H$5140,ROUNDDOWN(A4-G4,0)+1,1)*(1-(A4-G4)+ ROUNDDOWN(A4-G4,0))+INDEX($H$4:$H$5140,ROUNDDOWN(A4-G4,0)+2,1) * ((A4-G4)-ROUNDDOWN(A4-G4,0))))

Where:

- Initial state of the model is defined at time step 0
- $Q_{sim(t)}$ is interpolated if the value of ($t-T_d$) is not an integer number.
- It is noted that the above function just works in this specific format. Interested readers can use a combination of Index and Match function to find required value of $Q_{sim(t)}$

and apply to another format. However, the combination of these 2 functions will consume huge computation time, because, as context of the function, Excel will keep searching for the whole data set for matching Q value whenever the variables C, α and β are changed during the optimization process.

After the optimization, values of C, α and β are derived and so the Time Constant and Time Delay. The table of Q and Time constant (Q-T_c) and Time delay (Q-T_d) is derive by taking median value after the optimization.

3.3.5. The Correspondence of Time Delay and Geometry conditions

The purpose of this section is to check the correspondence of Time Delay as a result of Slope, River Length, Flow condition and River Cross Section. It is to provide a reference for further research. With a known table of the inflow and time delay, the student hope that the Time Delay can be predicted for another case, in another river. However, this reference need more Time Delay data to verify its usage.

The method is quite simple, using Manning's equation as following:

$$Q = VA = \frac{1}{n} * R^{\frac{2}{3}} * S^{0.5} \tag{3.18a}$$

And:

$$L = V * T \tag{3.18b}$$

The Time Delay is calculated as:

$$T_2 = \frac{L_2 * S_1^{0.5} * T_1 * R_1^{\frac{2}{3}} * n_2 * A_2}{L_1 * S_2^{0.5} * R_2^{\frac{2}{3}} * n_1 * A_1} \tag{3.19}$$

Where:

T	Time Delay	hours
L	Length of the considering river section	m
R	Hydraulic radius	m
n	Manning's coefficient	$s*m^{-1/3}$
A	Average area of the considering river cross section	m^2

Equation 3.19 is used to calculate the Time delay at river section 54-22 (from Grana outlet to just upstream Syrstad station), using the Time Delay in river section 110-55 (from Brattset

outlet to just upstream Grana outlet). The results will be compares with the Time Delay of the same river section which derived from the ADT model.

Due to the considering river section is in the same river, the student assumed: $A_1 = A_2, R_1 = R_2\ and\ n_1 = n_2$. The equation 3.19 is equal to:

$$T_2 = \frac{L_2 * S_1^{0.5} * T_1}{L_1 * S_2^{0.5}} \tag{3.20}$$

River length for Brattset – Grana is 24064.49 m and Grana – Syrstad is 15151.67 m.

IV. RESULTS & DISCUSSION

4.1. HEC-RAS RECALIBRATION RESULTS

Full Manning's coefficient table before and after calibration are displayed in Appendix A of this study. After that, the student simulated the river flow in the period 1/6/2010 – 28/2/2012 to compare with the old model. Additional simulation in the period 1/1/2015 – 30/12/2016 is perform to make sure the stability of the new model.

Simulated flow from Hec-Ras period 1/6/2010 – 28/2/2012; R^2 = 0.8679

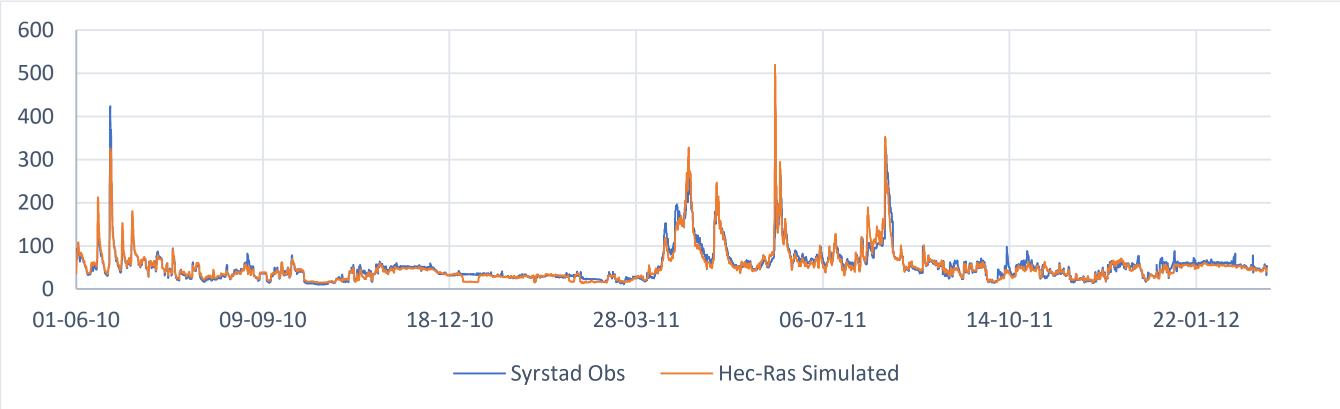


Figure 7: Simulated flow from Hec-Ras period 1/6/2010 – 28/2/2012

Simulated flow from Hec-Ras period 1/1/2015 – 31/12/2016; R^2 = 0.9028

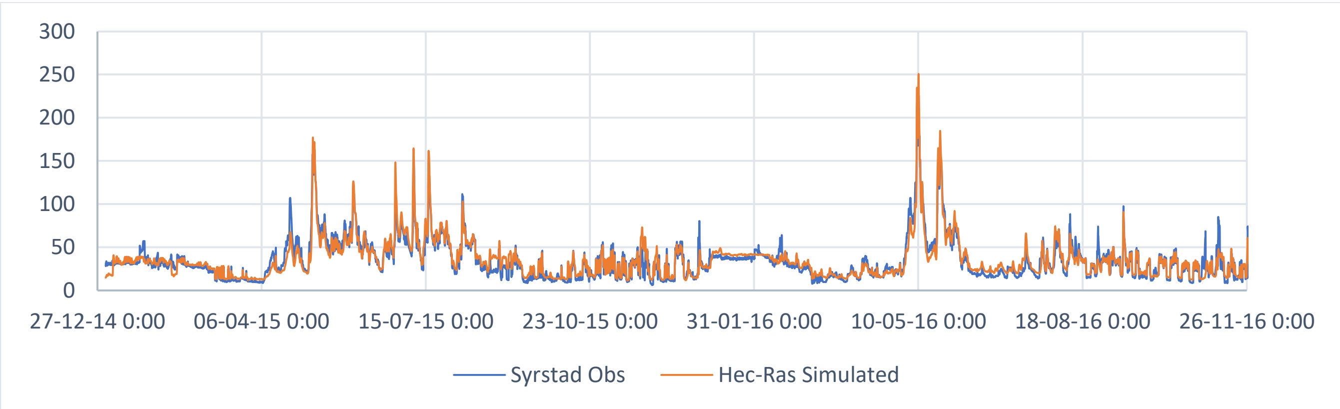
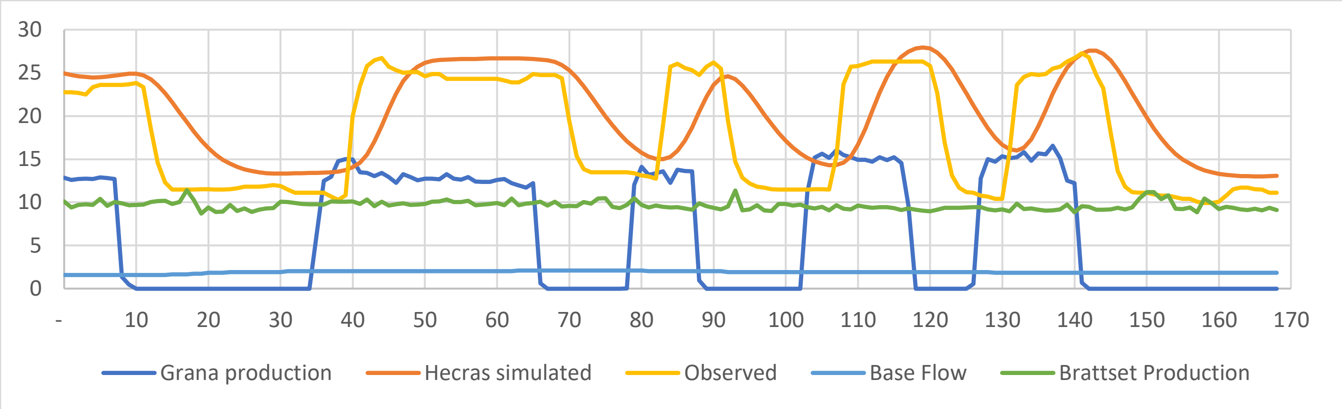


Figure 8:Simulated flow from Hec-Ras period 1/1/2015 – 30/12/2016

It is easy to notice that the new method provides stable results and better catch peak flow compares with the old one. This is also proved by showing that the new model gives better value of Nash-Sutcliffe Efficiency (Nash, 1970). The first period has R^2 = 0.87 and the second period has R^2 = 0.9. Noted that the data for winter period 2016 was kept unchanged, while pre-processing of the observed data was necessary in (Beckers, Jan 2014), as there are some winter events influenced by ice. For this purpose, peak flows in November 2010/ December 2010, December 2010/ January 2011, February 2011and January 2012/ February 2012 were removed and replaced by even lines with linear interpolated points. So, we observe some differences between simulated and observed flow due to ice problems at Syrstad gauging station at winter 2016. However, the patent of the simulated flow is consistent with observed flow.

Another note is that the start-stop operation of Grana power plan is observed quite well in the figure 9 below. In figure 9, period 8/3/2015 – 15/3/2015 is considered to simulate the multi-start-stop operation at Grana power plan. The vertical line stands for 1-hour time-step.

Repeat Figure 5: Performance of Hec-Ras model before calibration.



After calibration:

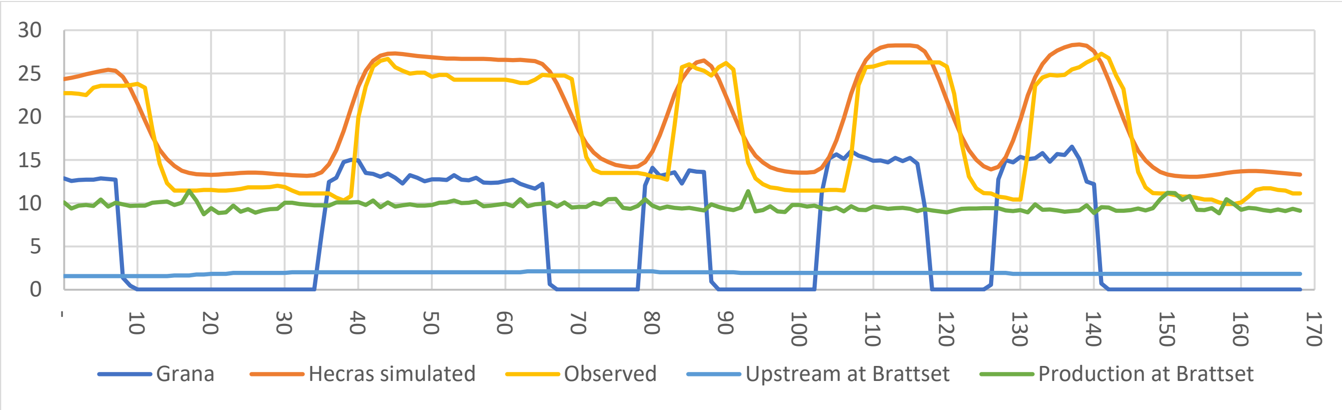


Figure 9: Performance of Hec-Ras model after calibration, 8-15 Mar2015

The comparison shows that the new model simulate perfect timing in comparison with observed flow. We could say that the new model is sufificient to use to derive parameters for Adaptive Time Delay model.

4.2. PARAMETERS FOR ADT MODEL

4.2.1. Derived α and β results:

a) Results for Travel time generated by Hec-Ras

Hec-Ras is use to simulate the flow from 1/3/2011 to 30/9/2011, R^2= 0.89. An initial flow at 14.7 m^3/s is used as base flow for the model. As mentioned above, the period was chosen to derive parameters for ADT model because it contains both the low flow and the highest peak event in the whole data set. The results for Travel Time in different river sections are displayed as figures below.

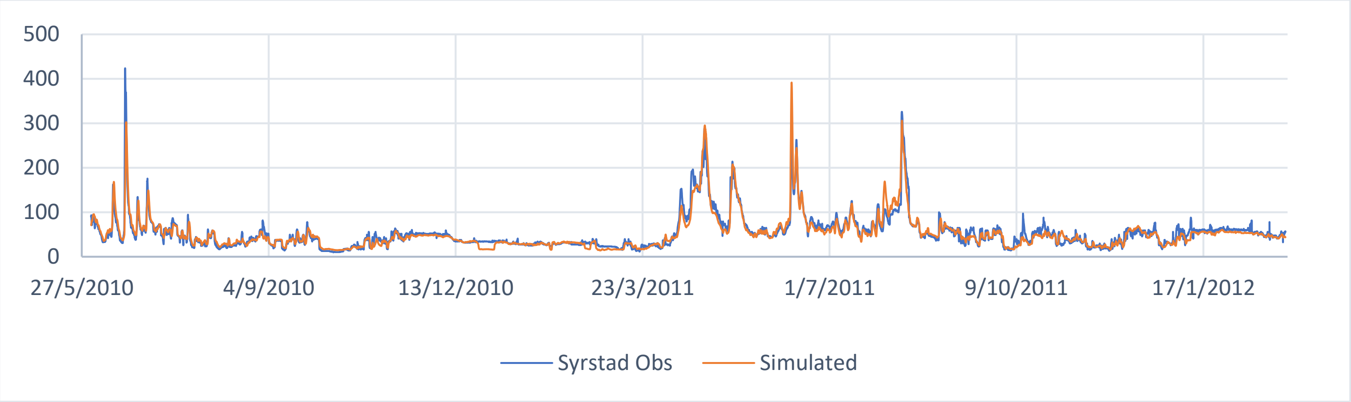


Figure 10: Simulated flow by Hec-Ras to derive ADT's parameters

After simulation, Travel time is generated from Hec-Ras and is displayed as following:

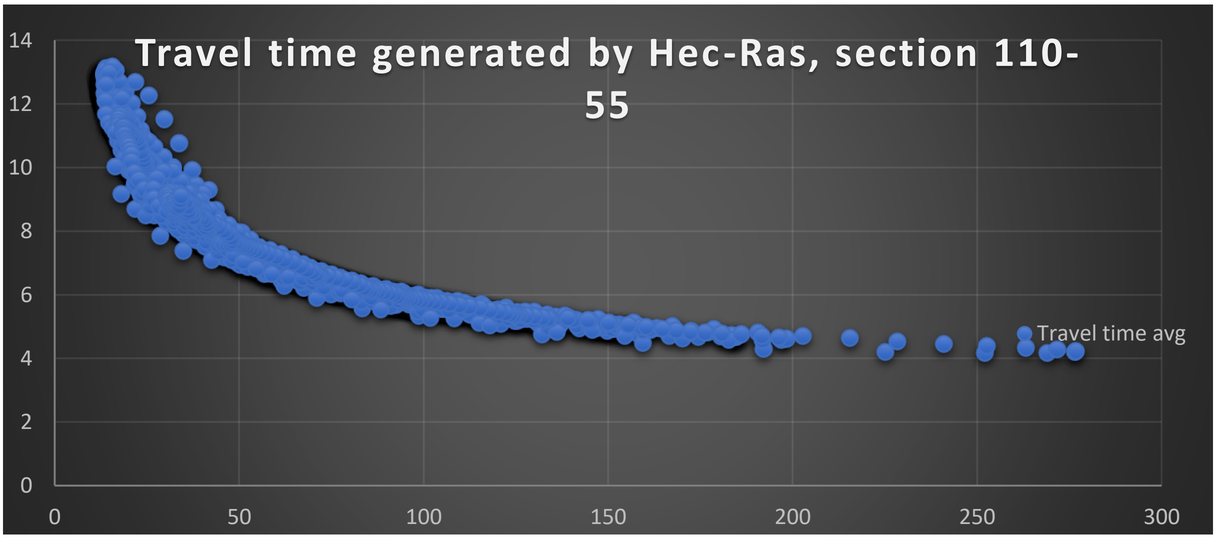


Figure 11: Travel time generated by Hec-Ras, section 110-55

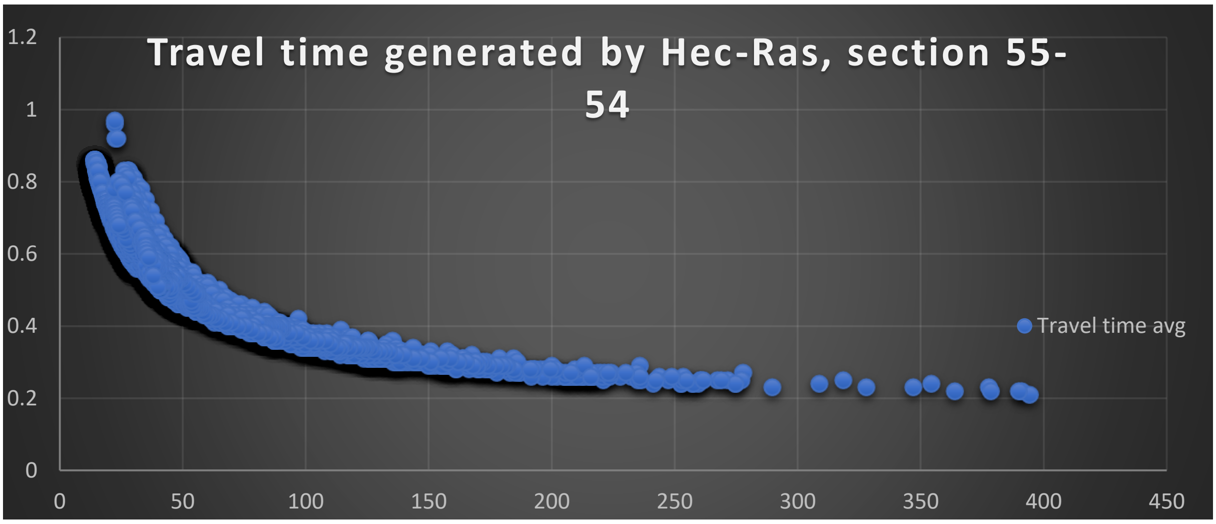


Figure 12: Travel time generated by Hec-Ras, section 55-54

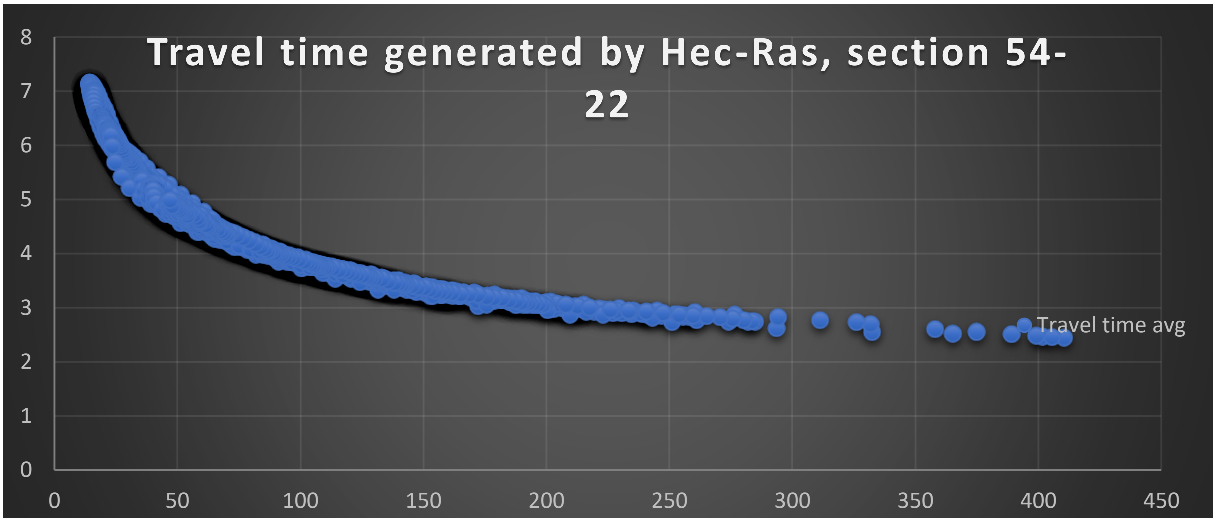


Figure 13: Travel time generated by Hec-Ras, section 54-22

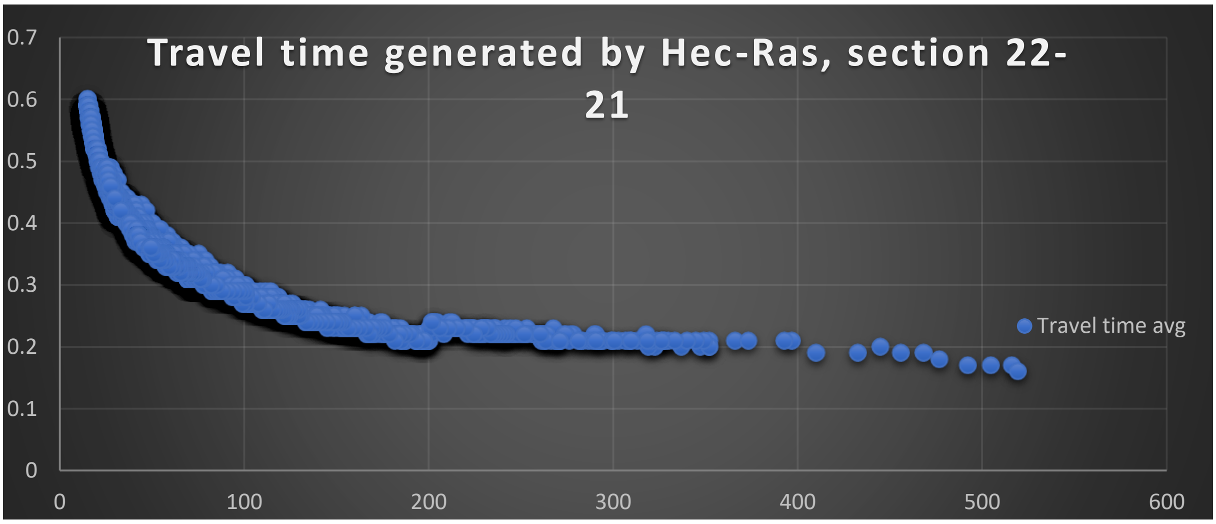


Figure 14: Travel time generated by Hec-Ras, section 22-21

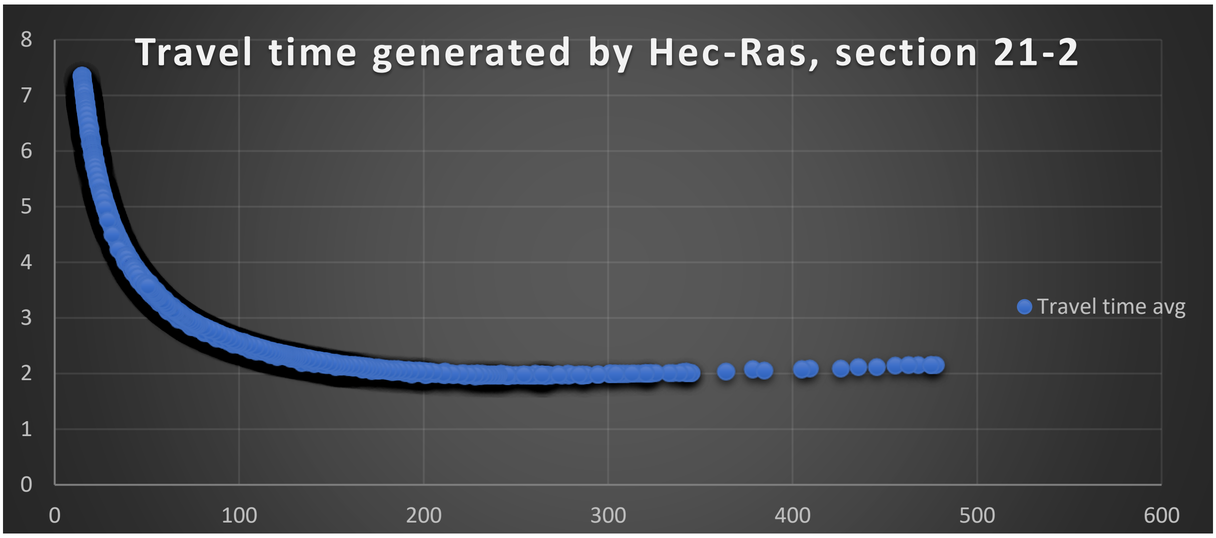


Figure 15: Travel time generated by Hec-Ras, section 21-2

Time delay and Time constant generated from Hecras after Optimization are as following table results:

River section	C	α	β
110-55	7.1841806	0.0019382	0.6174287
55-54	1	0.0067810	0.4173390
54-22	2.6150359	0.0066324	0.6694964
22-21	1	0.1548719	0.7067663
21-2	1	0.0010677	0.8937970

Table 7: Optimization results

4.2.2. Time Constant and Time Delay after optimization

Time Constant and Time Delay for each river section are calculated from the above C, α, and β tables. The results for Time Constant and Time Delay are displayed in details in Appendix B and illustrated as figures below:

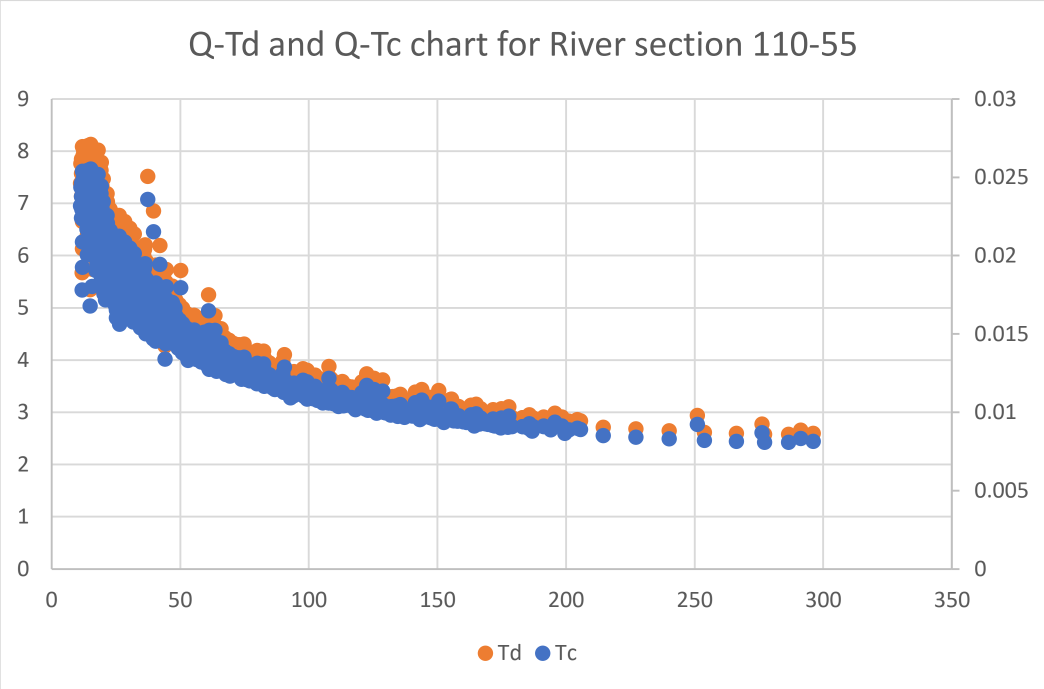


Figure 16: Time constant and Time Delay for river section 110-55

Note that the secondary Axis on the right side of the chart is used to display Tc value. Similarly, we have results for the other river sections as following:

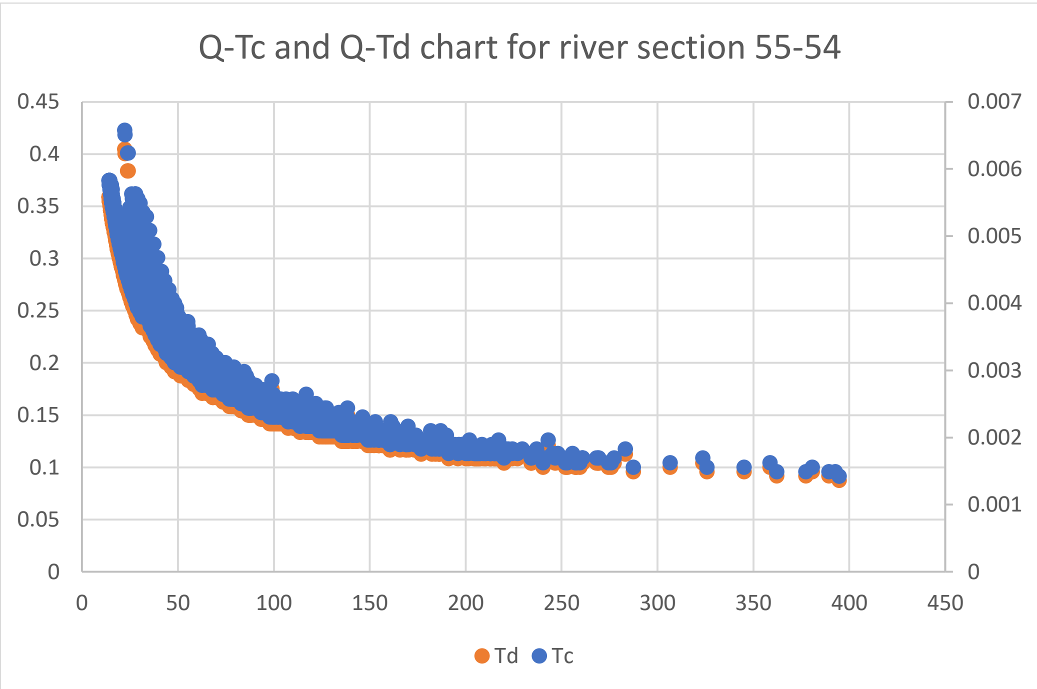


Figure 17: Time constant and Time Delay for river section 55-54

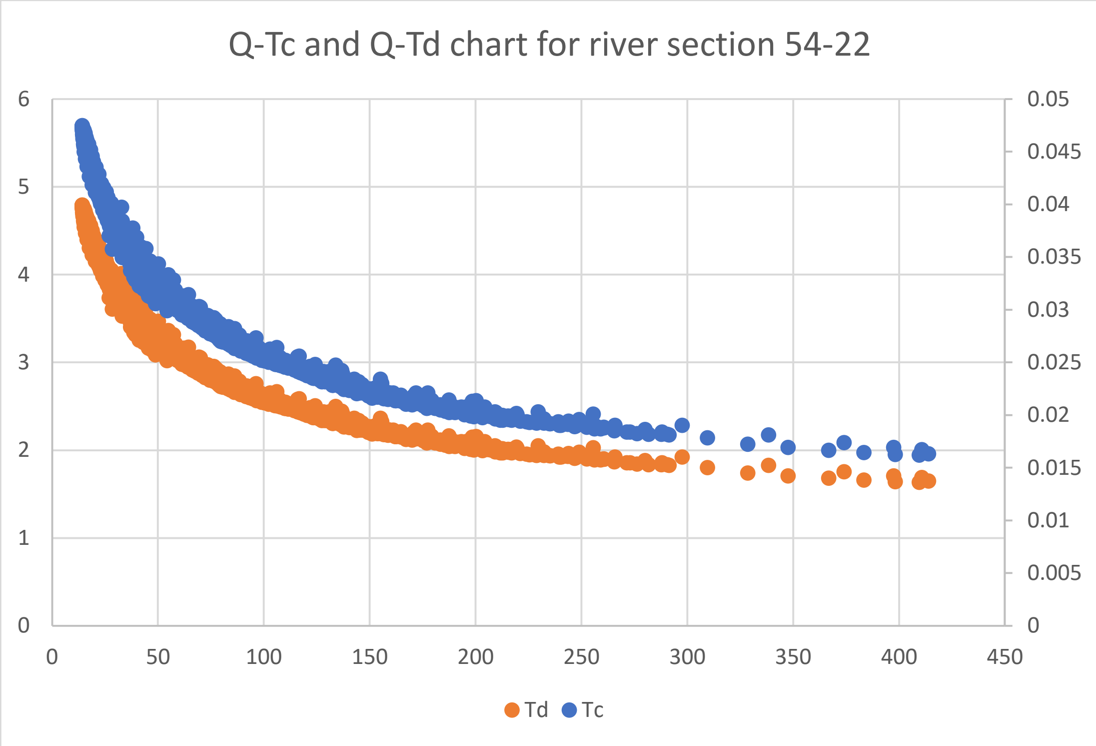


Figure 18: Time constant and Time Delay for river section 54-22

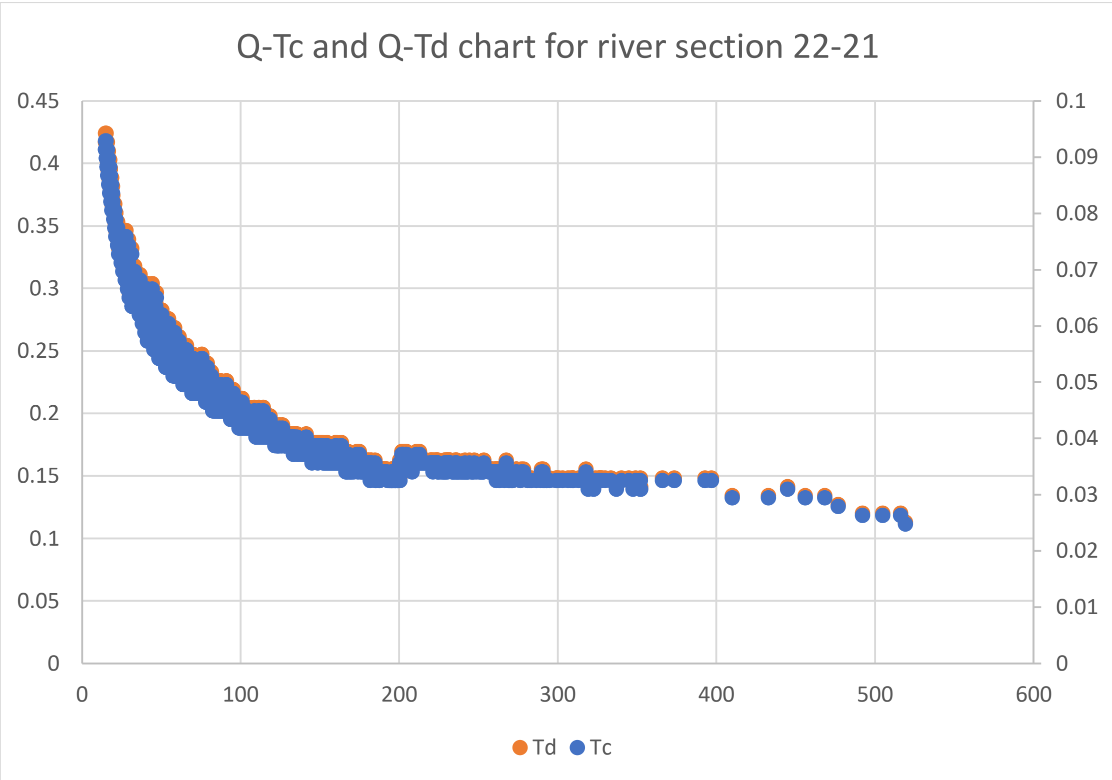


Figure 19: Time constant and Time Delay for river section 22-21

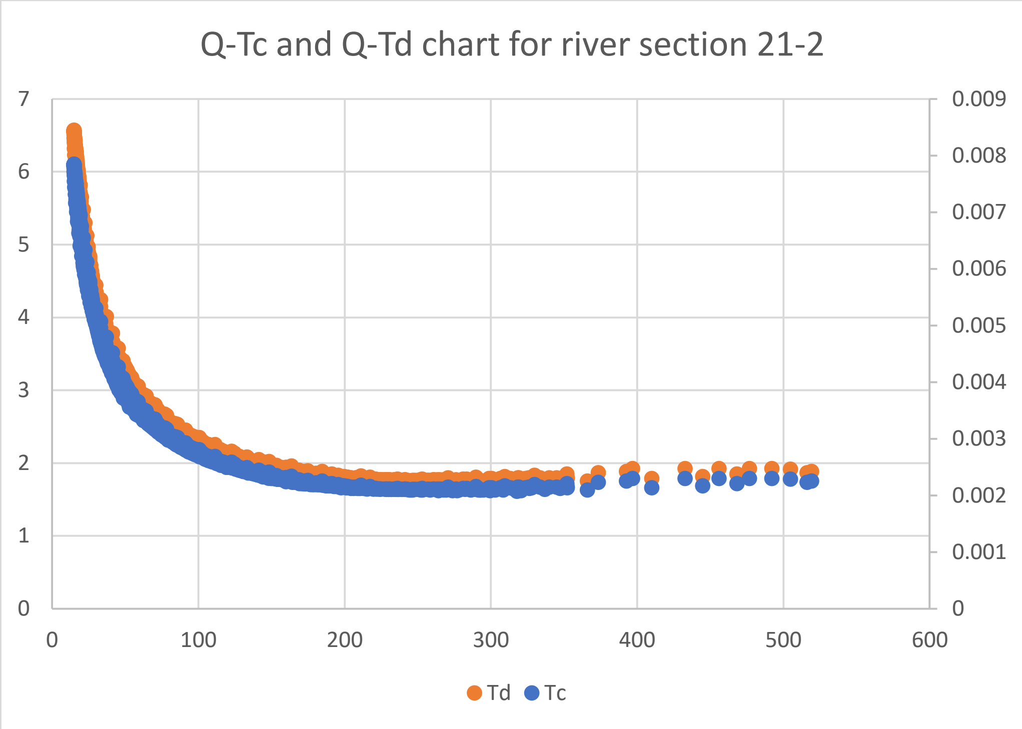


Figure 20: Time constant and Time Delay for river section 21-2

Finally, the chart Q_{in}-T_c and Q_{in}-T_d are built by taking median value of the data above. The results are displayed as following:

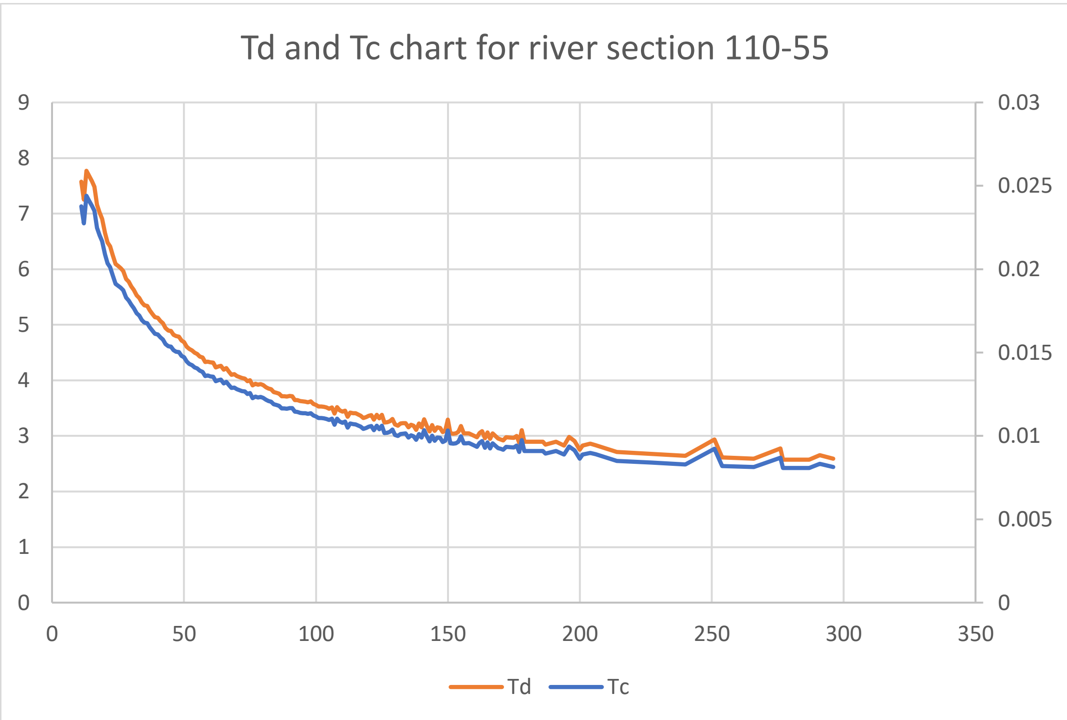


Figure 21: T_d and T_c chart for river section 110-55

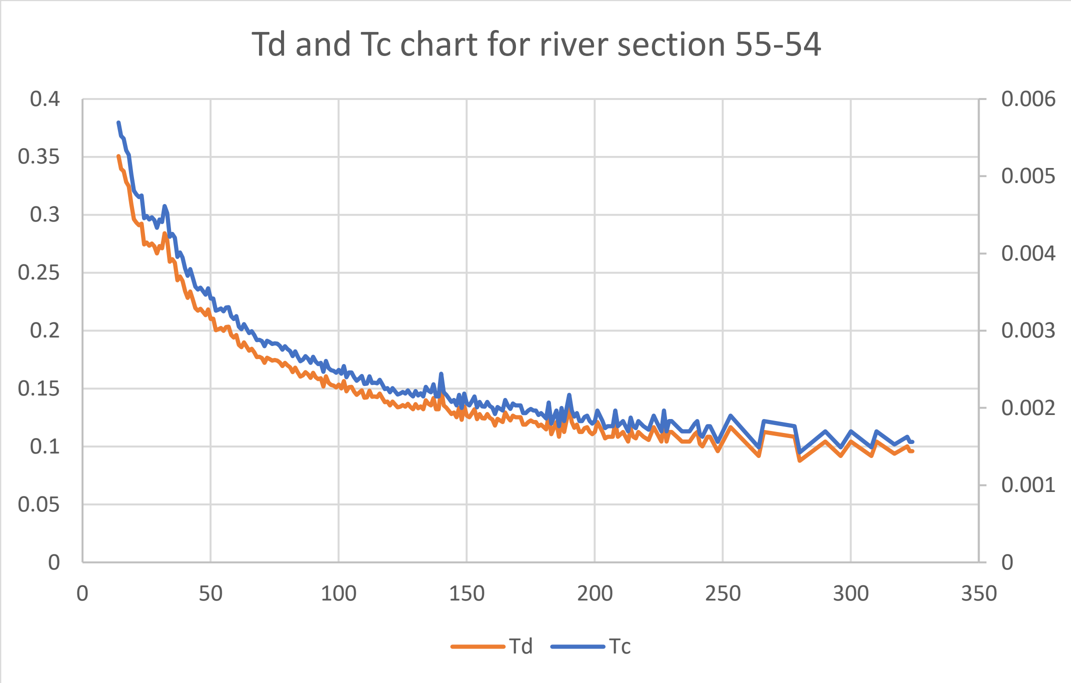


Figure 22: T_d and T_c chart for river section 55-54

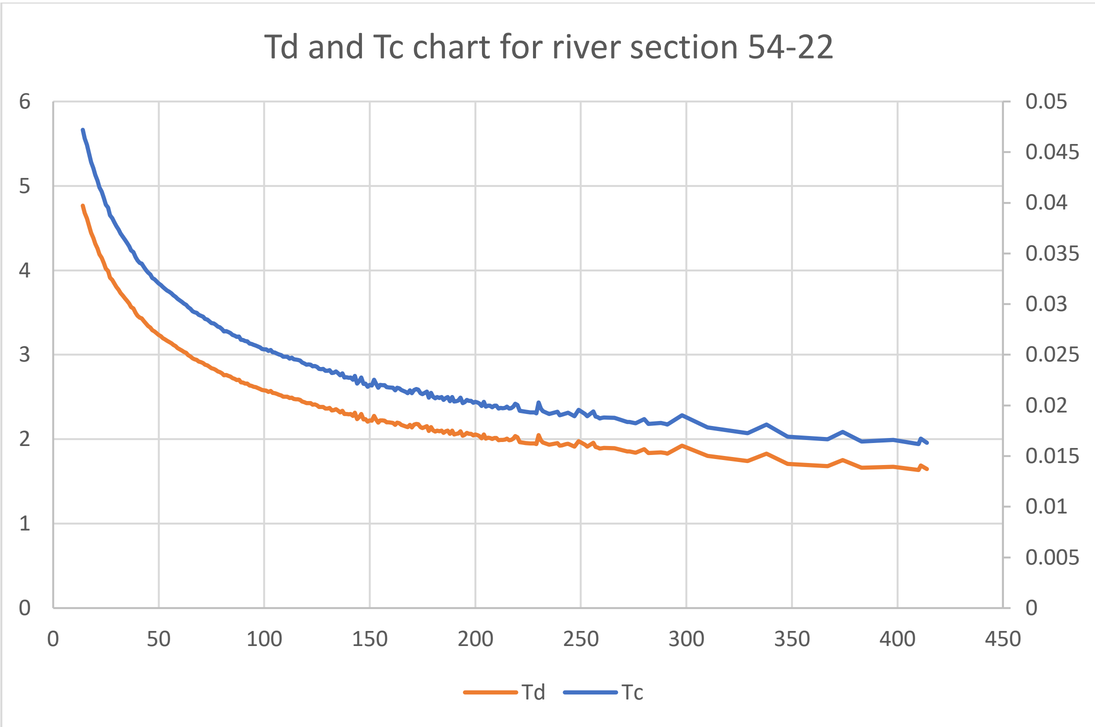


Figure 23: T_d and T_c chart for river section 54-22

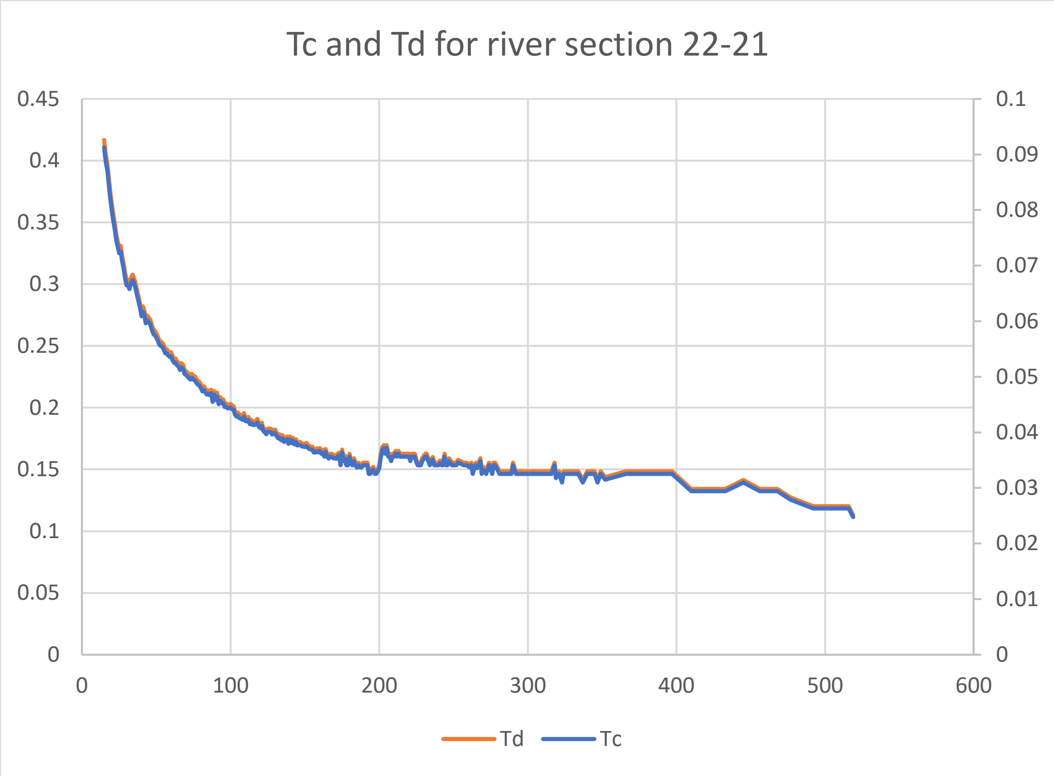


Figure 24: T_d and T_c chart for river section 22-21

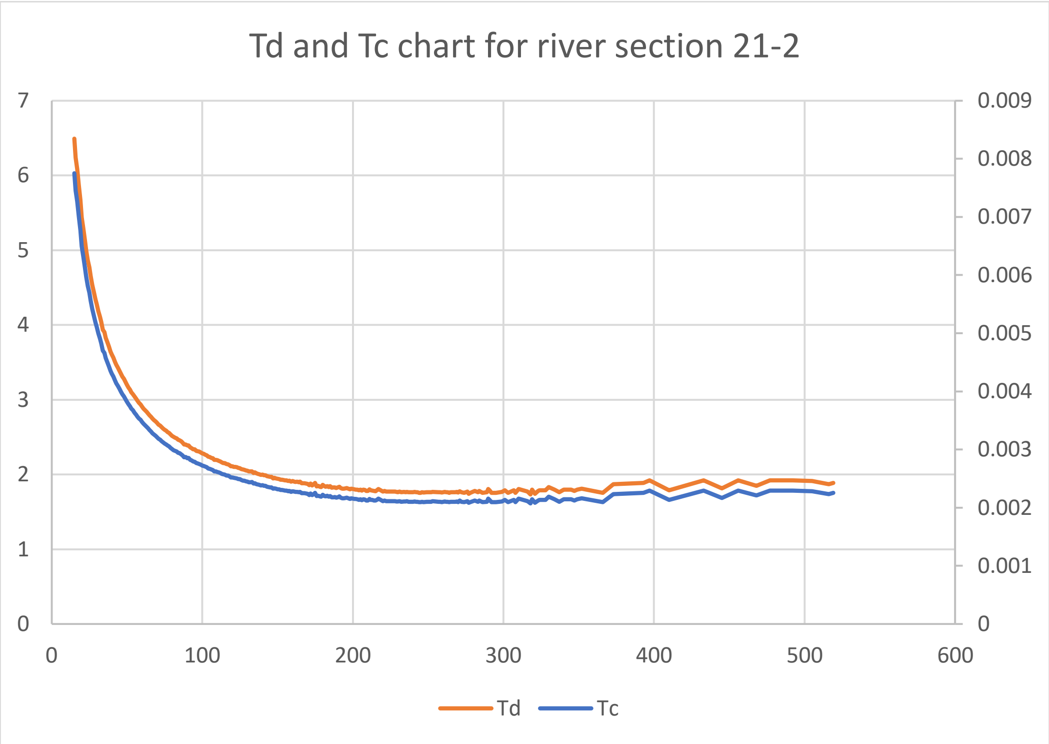


Figure 25: T_d and T_c chart for river section 21-2

4.3. ADT MODEL SIMULATION RESULT

4.3.1. Compare ADT model and Hec-Ras model

After all of the parameters have been derived, the ADT model is built and validate with Hec-Ras and observed flow at Syrstad for different flow period as below:

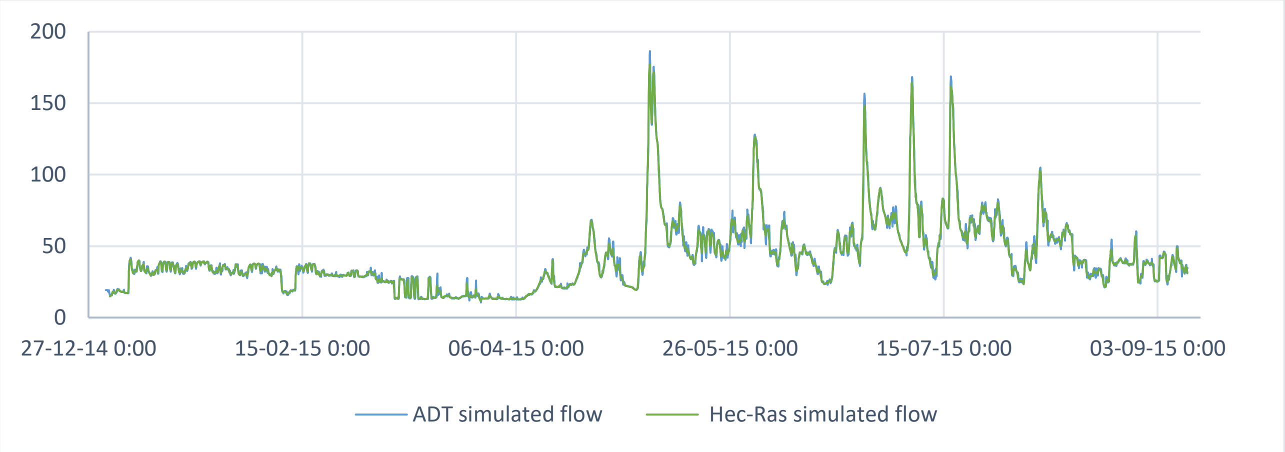


Figure 26: Simulated flow by Hec-Ras model and ADT model in 2015, R^2 = 0.975

We would see that the two model have very good corelation and so the outflows simulated by them are almost alike. After that the simulated flow by ADT model is compared with observed flow for the same period:

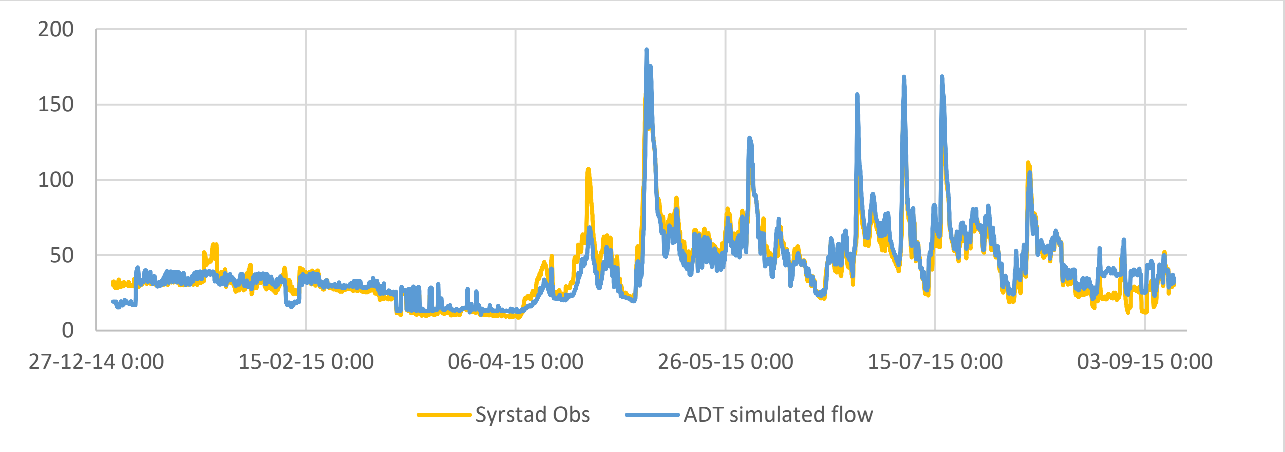


Figure 27: Simulated flow by ADT model compares with Observed flow in 2015, R^2 = 0.883

We would see that ADT model successed to simulate the outflow at Syrstad station quite well. To further check the performance of ADT model, two period of time was chosen to illustrate as following:

<u>Case 1</u>: Multi-start-stop operation at Brattset power plan, medium-high flow condition, time period consider is May 2015.

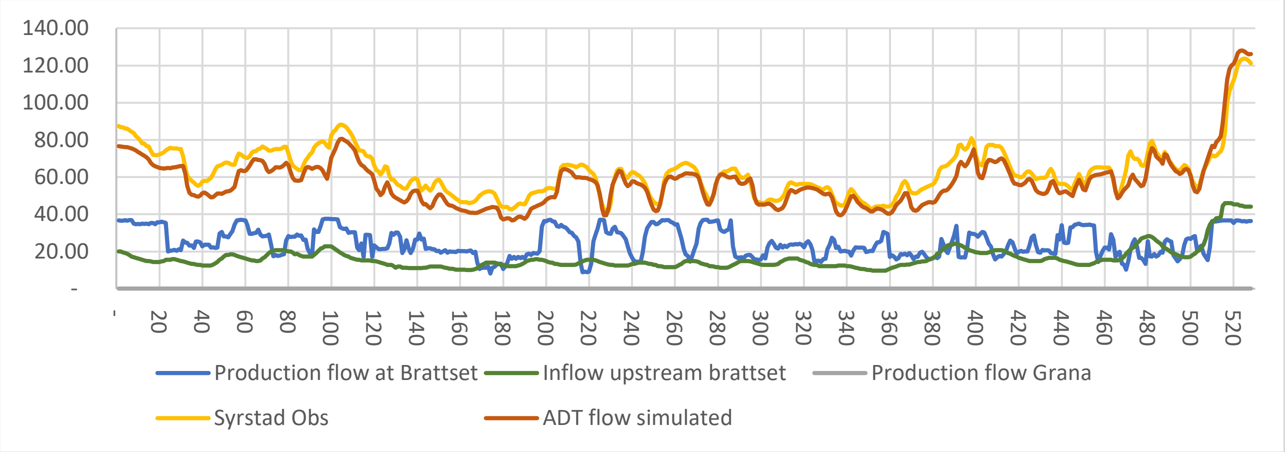


Figure 28: Performance of ADT model, case 1

<u>**Case 2:**</u> Multi-start-stop operation at Grana power plan, low flow condition, period 8-15/3/2015.

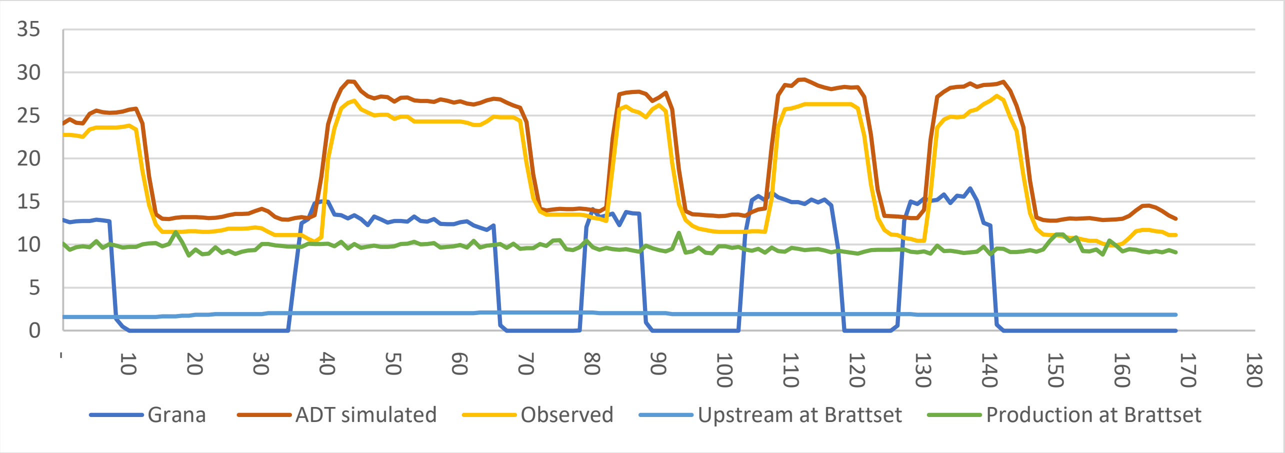


Figure 29: Performance of ADT model, case 2

4.3.2. Correlation between Time Delay and geometry conditions

The calculated Time Delay for river section 55-54 is calculated from Time Delay of river section 110-55 and is displays as figure below:

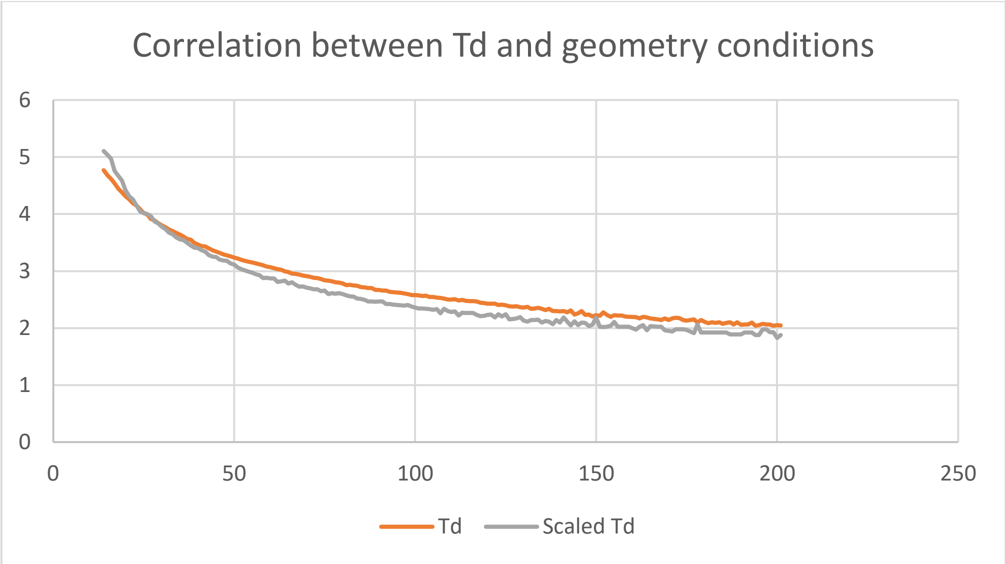


Figure 30: Correlation between Td and Geometry conditions

The average deviation between Scaled Time Delay and Derived Time Delay is about 10 min. So probably we could use this method to quick guest the Time Delay in a different river area.

4.4. DISCUSSION

The study presents a new approach to expand the usage of the river routing model developed by (Litrico X, 2010) and (Nguyen LD K. D., 2015). The curve of Time Constant T_c and Time Delay T_d versus Q are developed. With the parameters derived from the provided data, the model is valid for flow routing application in this river reach corresponding to the designed range of flow rate. It is very fast, simple and accurate, so it is easy to apply in existing hydropower system in daily planning and Operation control.

The model also has some drawbacks, such as it needs a good Hec-Ras model to derive its parameters, which sometimes this is a problem. Another drawback is caused by the mathematic definition of the model: the simulated hydrograph outflow will follow the patterns of the inflow upstream. It means that the model will not provide sufficient outflow at the end of the simulation if the considering river reach has a different outflow patterns from the inflow hydrograph (For example: in a river that have a high fluctuation flow hydrograph at upstream, but have a smooth flow hydrograph at downstream.). One possible solution to this drawback is to divide the river where the transition of the flow hydrograph appears.

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APPENDIX A: MANNING'S COEFFICIENT TABLE BEFORE & AFTER RE-CALIBRATION

		Before Re-calibration				**Calibrated**			
River	Frctn	n #1	n #2	n #3	n #4	n #1	n #2	n #3	n #4
110	n	0.27	0.03			0.0583	0.0750		
109	n	0.27	0.03			0.0583	0.0750		
108	n	0.27	0.03			0.0583	0.0750		
107	n	0.27	0.03			0.0583	0.0750		
106	n	0.27	0.03			0.0583	0.0750		
105	n	0.27	0.03			0.0583	0.0750		
104	n	0.27	0.03			0.0583	0.0750		
103	n	0.27	0.03			0.0583	0.0750		
102	n	0.27	0.03			0.0583	0.0750		
101	n	0.27	0.03			0.0615	0.0791		
100	n	0.27	0.03			0.0615	0.0791		
99	n	0.27	0.03			0.0615	0.0791		
98	n	0.27	0.03			0.0615	0.0791		

97	n	0.27	0.03			0.0615	0.0791		
96	n	0.27	0.03			0.0615	0.0791		
95	n	0.27	0.03			0.0615	0.0791		
94	n	0.27	0.03			0.0615	0.0791		
93	n	0.27	0.03			0.0615	0.0791		
92	n	0.27	0.03			0.0615	0.0791		
91	n	0.27	0.03			0.0615	0.0791		
90	n	0.27	0.03			0.0579	0.0744		
89	n	0.27	0.03			0.0579	0.0744		
88	n	0.27	0.03			0.0579	0.0744		
87	n	0.27	0.03			0.0579	0.0744		
86	n	0.27	0.03			0.0579	0.0744		
85	n	0.27	0.03			0.0579	0.0744		
84	n	0.27	0.03			0.0579	0.0744		
83	n	0.27	0.03			0.0579	0.0744		
82	n	0.27	0.03			0.0579	0.0744		

81	n	0.3	0.03			0.0614	0.0789		
80	n	0.3	0.03			0.0614	0.0789		
79	n	0.26	0.03			0.0614	0.0789		
78	n	0.22	0.03			0.0614	0.0789		
77	n	0.19	0.03			0.0614	0.0789		
76	n	0.18	0.03			0.0614	0.0789		
75	n	0.17	0.03			0.0614	0.0789		
74	n	0.15	0.03			0.0614	0.0789		
73	n	0.14	0.03			0.0614	0.0789		
72	n	0.1	0.03			0.0614	0.0789		
71	n	0.1	0.03			0.0562	0.0722		
70	n	0.1	0.03			0.0562	0.0722		
69	n	0.1	0.03			0.0562	0.0722		
68	n	0.1	0.03			0.0562	0.0722		
67	n	0.1	0.03			0.0562	0.0722		
66	n	0.1	0.03			0.0562	0.0722		

65	n	0.1	0.03			0.0562	0.0722		
64	n	0.13	0.03			0.0562	0.0722		
63	n	0.13	0.03			0.0562	0.0722		
62	n	0.13	0.03			0.0562	0.0722		
61	n	0.13	0.03			0.0648	0.0833		
60	n	0.13	0.03			0.0648	0.0833		
59	n	0.13	0.03			0.0648	0.0833		
58	n	0.13	0.03			0.0648	0.0833		
57	n	0.13	0.03			0.0675	0.0867		
56	n	0.13	0.03			0.0675	0.0867		
55	n	0.13	0.03			0.0675	0.0867		
54	n	0.13	0.03			0.0482	0.0482		
53.9	n	0.13	0.03			0.0482	0.0482		
53.8	n	0.13	0.03			0.0482	0.0482		
52*	n	0.12	0.03			0.0489	0.0489		
51*	n	0.12	0.03			0.0489	0.0489		

50*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
49*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
48*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
47*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
46*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
45*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
44*	n	0.04	0.12	0.12	0.04	0.0400	0.0500	0.0489	0.0400
43*	n	0.05	0.12	0.12	0.04	0.0480	0.0500	0.0489	0.0400
42	n	0.04	0.12	0.04		0.0400	0.0485	0.0400	
41	n	0.04	0.12	0.04		0.0400	0.0485	0.0400	
40	n	0.04	0.12	0.04		0.0400	0.0485	0.0400	
39	n	0.04	0.14	0.04		0.0400	0.0485	0.0400	
38	n	0.04	0.16	0.04		0.0400	0.0485	0.0400	
37	n	0.04	0.16	0.04		0.0400	0.0485	0.0400	
36	n	0.04	0.14	0.04		0.0400	0.0485	0.0400	
35	n	0.04	0.14	0.04		0.0400	0.0485	0.0400	

34	n	0.04	0.13	0.04		0.0400	0.0485	0.0400	
33	n	0.04	0.13	0.04		0.0400	0.0485	0.0400	
32	n	0.04	0.12	0.04		0.0400	0.0406	0.0400	
31	n	0.04	0.1	0.04		0.0400	0.0406	0.0400	
30	n	0.04	0.1	0.04		0.0400	0.0406	0.0400	
29	n	0.04	0.1	0.04		0.0400	0.0406	0.0400	
28	n	0.04	0.16	0.16	0.04	0.0400	0.1560	0.0406	0.0400
27	n	0.04	0.23	0.04		0.0400	0.0406	0.0400	
26	n	0.04	0.23	0.04		0.0400	0.0406	0.0400	
25	n	0.04	0.23	0.04		0.0400	0.0406	0.0400	
24	n	0.04	0.3	0.04		0.0400	0.0406	0.0400	
23	n	0.04	0.27	0.04		0.0400	0.0406	0.0400	
22	n	0.04	0.21	0.04		0.0400	0.0444	0.0400	
21	n	0.04	0.15	0.04		0.0400	0.0444	0.0400	
20	n	0.04	0.13	0.04		0.0400	0.1260	0.0400	
19	n	0.04	0.11	0.04		0.0400	0.1060	0.0400	

18	n	0.04	0.1	0.04		0.0400	0.0960	0.0400	
17	n	0.04	0.07	0.03		0.0400	0.0720	0.0300	
16	n	0.07	0.03			0.0720	0.0300		
15	n	0.07	0.03			0.0720	0.0300		
14	n	0.07	0.03			0.0720	0.0300		
13	n	0.07	0.03			0.0720	0.0300		
12	n	0.04	0.07	0.04		0.0400	0.0740	0.0400	
11	n	0.04	0.08	0.04		0.0400	0.0760	0.0400	
10	n	0.04	0.08	0.04		0.0400	0.0780	0.0400	
9	n	0.04	0.09	0.04		0.0400	0.0900	0.0400	
8	n	0.08	0.03			0.0800	0.0300		
7	n	0.04	0.1	0.04		0.0400	0.1000	0.0400	
6	n	0.04	0.16	0.04		0.0400	0.1600	0.0400	
5	n	0.04	0.16	0.04		0.0400	0.1600	0.0400	
4	n	0.04	0.11	0.04		0.0400	0.1100	0.0400	
3	n	0.04	0.08	0.04		0.0400	0.0800	0.0400	

2	n	0.04	0.08	0.04		0.0400	0.0800	0.0400	
1	n	0.04	0.08	0.04		0.0400	0.0800	0.0400	

APPENDIX B: TIME CONSTANT AND TIME DELAY RESULTS

River section 110-55			55-54		54-22		22-21		21-2	
Inflow	Tc	Td	Tc	Td	Tc	Td	Tc	Td	Tc	Td
11	0.024	7.573	-	-	-	-	-	-	-	-
12	0.023	7.250	-	-	-	-	-	-	-	-
13	0.024	7.773	-	-	-	-	-	-	-	-
14	0.024	7.683	0.006	0.351	0.047	4.766	-	-	-	-
15	0.024	7.585	0.006	0.340	0.046	4.678	0.091	0.417	0.008	6.490
16	0.023	7.484	0.005	0.338	0.046	4.614	0.089	0.405	0.007	6.238
17	0.022	7.161	0.005	0.328	0.045	4.536	0.087	0.398	0.007	6.082
18	0.022	7.023	0.005	0.325	0.044	4.445	0.085	0.387	0.007	5.866
19	0.022	6.905	0.005	0.309	0.043	4.384	0.082	0.375	0.007	5.669
20	0.021	6.654	0.005	0.296	0.043	4.314	0.080	0.365	0.006	5.437
21	0.020	6.482	0.005	0.293	0.042	4.259	0.078	0.357	0.006	5.291
22	0.020	6.411	0.005	0.291	0.042	4.190	0.077	0.350	0.006	5.134
23	0.020	6.255	0.005	0.292	0.041	4.149	0.075	0.340	0.006	4.998
24	0.019	6.092	0.004	0.274	0.040	4.084	0.073	0.335	0.006	4.865
25	0.019	6.057	0.004	0.276	0.040	4.018	0.072	0.330	0.006	4.767
26	0.019	6.020	0.004	0.273	0.040	3.992	0.073	0.331	0.006	4.654
27	0.019	5.968	0.004	0.275	0.039	3.915	0.071	0.323	0.005	4.532
28	0.018	5.826	0.004	0.273	0.038	3.886	0.069	0.317	0.005	4.439
29	0.018	5.775	0.004	0.267	0.038	3.842	0.068	0.310	0.005	4.340
30	0.018	5.692	0.004	0.273	0.038	3.804	0.066	0.303	0.005	4.276
31	0.018	5.625	0.004	0.271	0.037	3.769	0.066	0.303	0.005	4.183
32	0.017	5.531	0.005	0.284	0.037	3.731	0.066	0.300	0.005	4.110
33	0.017	5.485	0.005	0.278	0.037	3.700	0.067	0.305	0.005	4.039
34	0.017	5.403	0.004	0.259	0.036	3.669	0.067	0.308	0.005	3.933
35	0.017	5.351	0.004	0.262	0.036	3.639	0.067	0.305	0.005	3.902
36	0.017	5.337	0.004	0.259	0.036	3.605	0.066	0.301	0.005	3.828
37	0.017	5.260	0.004	0.243	0.035	3.563	0.065	0.295	0.005	3.769

38	0.016	5.197	0.004	0.247	0.035	3.548	0.064	0.290	0.004	3.710
39	0.016	5.137	0.004	0.243	0.035	3.495	0.062	0.285	0.004	3.644
40	0.016	5.127	0.004	0.234	0.034	3.464	0.061	0.278	0.004	3.603
41	0.016	5.067	0.004	0.228	0.034	3.439	0.062	0.282	0.004	3.561
42	0.016	5.029	0.004	0.234	0.034	3.431	0.061	0.278	0.004	3.506
43	0.016	4.939	0.004	0.227	0.034	3.398	0.060	0.272	0.004	3.466
44	0.015	4.896	0.004	0.220	0.033	3.366	0.060	0.275	0.004	3.429
45	0.015	4.891	0.004	0.217	0.033	3.342	0.060	0.273	0.004	3.387
46	0.015	4.823	0.004	0.219	0.033	3.323	0.059	0.271	0.004	3.341
47	0.015	4.797	0.004	0.216	0.033	3.290	0.058	0.267	0.004	3.308
48	0.015	4.788	0.003	0.213	0.032	3.277	0.058	0.263	0.004	3.277
49	0.015	4.717	0.004	0.218	0.032	3.256	0.057	0.262	0.004	3.235
50	0.015	4.688	0.003	0.210	0.032	3.236	0.057	0.261	0.004	3.202
51	0.014	4.609	0.003	0.210	0.032	3.218	0.056	0.258	0.004	3.165
52	0.014	4.564	0.003	0.200	0.032	3.199	0.056	0.255	0.004	3.132
53	0.014	4.536	0.003	0.201	0.032	3.182	0.056	0.254	0.004	3.100
54	0.014	4.497	0.003	0.202	0.031	3.166	0.055	0.253	0.004	3.075
55	0.014	4.476	0.003	0.200	0.031	3.152	0.055	0.251	0.004	3.042
56	0.014	4.431	0.003	0.203	0.031	3.136	0.054	0.247	0.004	3.014
57	0.014	4.409	0.003	0.203	0.031	3.117	0.054	0.247	0.004	2.986
58	0.014	4.332	0.003	0.196	0.031	3.101	0.054	0.246	0.004	2.957
59	0.014	4.339	0.003	0.194	0.031	3.080	0.054	0.244	0.004	2.937
60	0.014	4.322	0.003	0.196	0.030	3.066	0.054	0.245	0.003	2.910
61	0.014	4.320	0.003	0.188	0.030	3.049	0.053	0.242	0.003	2.882
62	0.013	4.232	0.003	0.186	0.030	3.033	0.053	0.240	0.003	2.860
63	0.013	4.249	0.003	0.190	0.030	3.021	0.053	0.240	0.003	2.839
64	0.013	4.261	0.003	0.186	0.030	2.997	0.052	0.237	0.003	2.817
65	0.013	4.190	0.003	0.183	0.030	2.982	0.052	0.237	0.003	2.789
66	0.013	4.218	0.003	0.184	0.029	2.958	0.051	0.234	0.003	2.769
67	0.013	4.155	0.003	0.181	0.029	2.948	0.052	0.236	0.003	2.747
68	0.013	4.100	0.003	0.177	0.029	2.940	0.051	0.235	0.003	2.728
69	0.013	4.110	0.003	0.177	0.029	2.922	0.051	0.231	0.003	2.708

70	0.013	4.080	0.003	0.176	0.029	2.914	0.050	0.230	0.003	2.691
71	0.013	4.059	0.003	0.172	0.029	2.902	0.050	0.228	0.003	2.665
72	0.013	4.040	0.003	0.177	0.029	2.882	0.050	0.227	0.003	2.651
73	0.013	4.034	0.003	0.176	0.028	2.875	0.050	0.226	0.003	2.631
74	0.013	3.986	0.003	0.174	0.028	2.859	0.050	0.227	0.003	2.616
75	0.013	4.003	0.003	0.175	0.028	2.840	0.050	0.226	0.003	2.599
76	0.012	3.908	0.003	0.174	0.028	2.834	0.049	0.225	0.003	2.586
77	0.012	3.939	0.003	0.173	0.028	2.822	0.049	0.223	0.003	2.568
78	0.012	3.920	0.003	0.170	0.028	2.805	0.049	0.222	0.003	2.555
79	0.012	3.932	0.003	0.172	0.028	2.797	0.048	0.221	0.003	2.531
80	0.012	3.913	0.003	0.170	0.028	2.780	0.048	0.219	0.003	2.517
81	0.012	3.877	0.003	0.168	0.027	2.756	0.047	0.216	0.003	2.501
82	0.012	3.854	0.003	0.164	0.027	2.761	0.048	0.217	0.003	2.491
83	0.012	3.839	0.003	0.168	0.027	2.750	0.047	0.215	0.003	2.481
84	0.012	3.791	0.003	0.164	0.027	2.742	0.047	0.213	0.003	2.465
85	0.012	3.779	0.003	0.160	0.027	2.722	0.047	0.214	0.003	2.457
86	0.012	3.758	0.003	0.162	0.027	2.716	0.047	0.213	0.003	2.442
87	0.012	3.713	0.003	0.164	0.027	2.701	0.047	0.215	0.003	2.428
88	0.012	3.713	0.003	0.162	0.027	2.705	0.045	0.208	0.003	2.400
89	0.012	3.707	0.003	0.159	0.026	2.673	0.047	0.213	0.003	2.402
90	0.012	3.719	0.003	0.164	0.026	2.672	0.046	0.209	0.003	2.386
91	0.012	3.715	0.003	0.160	0.026	2.659	0.046	0.212	0.003	2.388
92	0.011	3.647	0.003	0.158	0.026	2.657	0.045	0.206	0.003	2.362
93	0.011	3.647	0.003	0.159	0.026	2.636	0.046	0.208	0.003	2.351
94	0.011	3.627	0.002	0.152	0.026	2.632	0.045	0.206	0.003	2.337
95	0.011	3.620	0.003	0.161	0.026	2.622	0.045	0.207	0.003	2.335
96	0.011	3.617	0.003	0.155	0.026	2.617	0.045	0.203	0.003	2.316
97	0.011	3.606	0.002	0.153	0.026	2.606	0.045	0.203	0.003	2.310
98	0.011	3.619	0.002	0.153	0.026	2.596	0.044	0.202	0.003	2.305
99	0.011	3.576	0.002	0.151	0.026	2.582	0.044	0.202	0.003	2.294
100	0.011	3.558	0.002	0.154	0.026	2.579	0.044	0.203	0.003	2.280
101	0.011	3.528	0.002	0.150	0.026	2.576	0.044	0.201	0.003	2.276

102	0.011	3.530	0.003	0.157	0.025	2.562	0.044	0.201	0.003	2.265
103	0.011	3.522	0.002	0.148	0.025	2.571	0.043	0.197	0.003	2.256
104	0.011	3.511	0.002	0.151	0.025	2.549	0.043	0.196	0.003	2.237
105	0.011	3.492	0.002	0.151	0.025	2.545	0.043	0.196	0.003	2.232
106	0.011	3.515	0.002	0.147	0.025	2.538	0.043	0.194	0.003	2.222
107	0.011	3.402	0.002	0.145	0.025	2.527	0.042	0.194	0.003	2.217
108	0.011	3.517	0.002	0.147	0.025	2.519	0.042	0.193	0.003	2.196
109	0.011	3.461	0.002	0.149	0.025	2.504	0.043	0.196	0.003	2.197
110	0.011	3.439	0.002	0.142	0.025	2.504	0.042	0.192	0.003	2.189
111	0.011	3.458	0.002	0.142	0.025	2.505	0.042	0.191	0.003	2.184
112	0.010	3.344	0.002	0.148	0.025	2.487	0.042	0.192	0.003	2.176
113	0.011	3.422	0.002	0.143	0.025	2.494	0.041	0.189	0.003	2.161
114	0.011	3.411	0.002	0.143	0.025	2.478	0.042	0.190	0.003	2.153
115	0.011	3.408	0.002	0.143	0.025	2.474	0.041	0.189	0.003	2.152
116	-	-	0.002	0.146	0.025	2.473	0.041	0.189	0.003	2.138
117	0.011	3.364	0.002	0.142	0.024	2.465	0.041	0.189	0.003	2.135
118	0.010	3.323	0.002	0.138	0.024	2.448	0.042	0.191	0.003	2.126
119	0.010	3.339	0.002	0.139	0.024	2.439	0.041	0.187	0.003	2.109
120	0.011	3.360	0.002	0.136	0.024	2.426	0.041	0.186	0.003	2.109
121	0.011	3.372	0.002	0.139	0.024	2.428	0.041	0.188	0.003	2.103
122	0.010	3.296	0.002	0.136	0.024	2.426	0.040	0.184	0.003	2.100
123	0.011	3.381	0.002	0.134	0.024	2.407	0.040	0.183	0.003	2.096
124	0.010	3.316	0.002	0.134	0.024	2.413	0.040	0.181	0.002	2.087
125	0.011	3.381	0.002	0.136	0.024	2.403	0.040	0.183	0.002	2.086
126	0.010	3.240	0.002	0.135	0.024	2.382	0.040	0.183	0.002	2.073
127	0.010	3.248	0.002	0.137	0.024	2.381	0.040	0.183	0.002	2.065
128	0.010	3.266	0.002	0.134	0.024	2.383	0.040	0.181	0.002	2.064
129	0.010	3.305	0.002	0.132	0.023	2.364	0.040	0.182	0.002	2.056
130	0.010	3.204	0.002	0.137	0.023	2.363	0.040	0.182	0.002	2.048
131	0.010	3.186	0.002	0.133	0.023	2.370	0.039	0.180	0.002	2.040
132	0.010	3.223	0.002	0.135	0.023	2.341	0.039	0.178	0.002	2.040
133	0.010	3.229	0.002	0.132	0.023	2.345	0.039	0.178	0.002	2.042

134	0.010	3.232	0.002	0.140	0.023	2.357	0.039	0.176	0.002	2.020
135	0.010	3.157	0.002	0.137	0.023	2.338	0.039	0.178	0.002	2.027
136	0.010	3.200	0.002	0.136	0.023	2.319	0.038	0.175	0.002	2.014
137	0.010	3.182	0.002	0.142	0.023	2.337	0.038	0.175	0.002	2.007
138	0.010	3.112	0.002	0.132	0.023	2.297	0.039	0.177	0.002	2.004
139	0.010	3.223	0.002	0.132	0.023	2.299	0.038	0.173	0.002	1.995
140	0.010	3.157	0.002	0.150	0.023	2.294	0.039	0.177	0.002	1.996
141	0.010	3.297	0.002	0.136	0.023	2.298	0.038	0.174	0.002	1.990
142	0.010	3.183	0.002	0.134	0.023	2.275	0.038	0.176	0.002	1.988
143	0.010	3.079	-	-	0.023	2.313	0.038	0.173	0.002	1.975
144	0.010	3.194	0.002	0.128	0.022	2.238	0.038	0.174	0.002	1.972
145	0.010	3.093	0.002	0.129	0.022	2.263	0.038	0.172	0.002	1.968
146	0.010	3.157	0.002	0.125	0.023	2.298	0.038	0.172	0.002	1.966
147	0.010	3.146	0.002	0.134	0.022	2.233	0.038	0.172	0.002	1.948
148	0.010	3.069	0.002	0.123	0.022	2.236	0.037	0.171	0.002	1.954
149	0.010	3.095	0.002	0.135	0.022	2.206	0.037	0.171	0.002	1.946
150	0.010	3.291	0.002	0.127	0.022	2.224	0.037	0.170	0.002	1.941
151	0.010	3.044	0.002	0.125	0.022	2.218	0.038	0.171	0.002	1.937
152	0.010	3.041	0.002	0.129	0.023	2.276	0.037	0.170	0.002	1.928
153	0.010	3.046	0.002	0.132	0.022	2.235	0.037	0.169	0.002	1.929
154	0.010	3.075	0.002	0.124	0.022	2.196	0.037	0.168	0.002	1.923
155	0.010	3.178	0.002	0.128	0.022	2.224	0.037	0.168	0.002	1.919
156	0.010	3.046	0.002	0.124	0.022	2.221	0.036	0.166	0.002	1.920
157	0.010	3.044	0.002	0.124	0.022	2.220	0.036	0.166	0.002	1.913
158	0.010	3.049	0.002	0.128	0.022	2.201	0.037	0.167	0.002	1.917
159	-	-	0.002	0.125	0.022	2.200	0.036	0.166	0.002	1.902
160	0.009	3.001	0.002	0.123	-	-	0.037	0.167	0.002	1.911
161	0.009	2.976	0.002	0.118	0.022	2.194	0.036	0.165	0.002	1.906
162	0.010	3.050	0.002	0.124	0.021	2.170	0.036	0.166	0.002	1.901
163	0.010	3.087	-	-	0.022	2.196	0.036	0.163	0.002	1.902
164	0.009	2.957	0.002	0.121	0.022	2.189	0.036	0.166	0.002	1.895
165	0.010	3.062	0.002	0.129	0.022	2.171	0.036	0.163	0.002	1.904

166	0.009	2.945	0.002	0.125	-	-	0.035	0.161	0.002	1.884
167	0.010	3.047	0.002	0.122	0.021	2.152	0.036	0.163	0.002	1.881
168	-	-	0.002	0.127	0.021	2.142	0.036	0.163	0.002	1.884
169	0.009	2.951	0.002	0.125	0.021	2.169	0.035	0.161	0.002	1.877
170	0.009	2.939	0.002	0.125	0.021	2.141	0.035	0.162	0.002	1.872
171	0.009	2.920	0.002	0.125	0.022	2.173	0.035	0.161	0.002	1.855
172	0.009	2.979	0.002	0.119	0.022	2.183	0.036	0.163	0.002	1.877
173	-	-	0.002	0.119	0.022	2.176	0.036	0.164	0.002	1.854
174	-	-	0.002	0.121	0.021	2.142	0.034	0.155	0.002	1.868
175	0.009	2.967	0.002	0.122	0.021	2.132	0.036	0.166	0.002	1.886
176	0.009	3.001	0.002	0.121	-	-	0.035	0.159	0.002	1.841
177	0.009	2.877	0.002	0.121	0.021	2.156	0.035	0.161	0.002	1.847
178	0.010	3.106	0.002	0.118	0.021	2.098	0.034	0.155	0.002	1.837
179	0.009	2.899	0.002	0.119	0.021	2.145	0.034	0.155	0.002	1.832
180	-	-	-	-	0.021	2.107	0.036	0.163	0.002	1.859
181	-	-	0.002	0.115	0.021	2.089	0.034	0.157	0.002	1.843
182	-	-	0.002	0.127	0.021	2.102	0.034	0.155	0.002	1.836
183	0.009	2.896	0.002	0.111	0.021	2.094	0.035	0.159	0.002	1.846
184	-	-	-	-	0.021	2.102	0.034	0.155	0.002	1.832
185	-	-	0.002	0.121	0.021	2.075	0.034	0.154	0.002	1.843
186	0.009	2.896	0.002	0.109	0.021	2.092	0.034	0.155	0.002	1.823
187	0.009	2.846	0.002	0.123	0.021	2.102	0.034	0.154	0.002	1.825
188	-	-	0.002	0.113	0.020	2.062	0.034	0.154	0.002	1.828
189	-	-	-	-	0.021	2.102	0.034	0.155	0.002	1.819
190	-	-	0.002	0.134	0.020	2.058	0.034	0.155	0.002	1.825
191	0.009	2.899	0.002	0.121	0.020	2.062	0.034	0.155	0.002	1.837
192	-	-	0.002	0.116	0.020	2.067	0.034	0.155	0.002	1.819
193	-	-	0.002	0.119	0.021	2.096	0.033	0.148	0.002	1.810
194	0.009	2.828	0.002	0.113	0.020	2.042	0.033	0.148	0.002	1.811
195	-	-	0.002	0.113	0.020	2.050	0.033	0.151	0.002	1.814
196	0.009	2.982	0.002	0.116	0.021	2.075	0.033	0.152	0.002	1.817
197	-	-	0.002	0.117	0.020	2.065	0.033	0.148	0.002	1.808

198	0.009	2.908	0.002	0.113	0.020	2.064	0.033	0.148	0.002	1.800
199	-	-	0.002	0.111	0.020	2.044	0.033	0.150	0.002	1.808
200	0.009	2.754	0.002	0.113	0.020	2.054	0.034	0.153	0.002	1.804
201	0.009	2.828	0.002	0.121	0.020	2.049	0.035	0.161	0.002	1.801
202	-	-	-	-	0.020	2.038	0.037	0.168	0.002	1.799
203	-	-	0.002	0.113	0.020	2.012	0.037	0.170	0.002	1.797
204	0.009	2.859	0.002	0.107	0.020	2.055	0.036	0.165	0.002	1.788
205	-	-	0.002	0.109	0.020	2.008	0.037	0.170	0.002	1.797
206	0.009	2.834	-	-	0.020	2.017	0.036	0.163	0.002	1.783
207	-	-	0.002	0.109	0.020	2.015	0.036	0.163	0.002	1.797
208	-	-	0.002	0.121	0.020	2.002	0.035	0.159	0.002	1.792
209	-	-	0.002	0.109	0.020	2.015	0.036	0.163	0.002	1.779
210	-	-	-	-	0.020	2.015	0.036	0.163	0.002	1.779
211	-	-	0.002	0.113	0.020	1.988	0.036	0.165	0.002	1.800
212	-	-	0.002	0.109	0.020	1.993	0.036	0.163	0.002	1.788
213	-	-	0.002	0.104	0.020	1.992	0.036	0.165	0.002	1.785
214	0.009	2.711	0.002	0.115	0.020	1.995	0.036	0.163	0.002	1.779
215	-	-	0.002	0.109	0.020	2.008	0.036	0.163	0.002	1.776
216	-	-	0.002	0.107	0.020	1.988	0.036	0.163	0.002	1.788
217	-	-	0.002	0.113	0.020	1.991	0.036	0.163	0.002	1.805
218	-	-	-	-	0.020	2.008	-	-	0.002	1.770
219	-	-	0.002	0.109	0.020	2.035	-	-	0.002	1.779
220	-	-	-	-	0.020	2.022	0.036	0.163	0.002	1.770
221	-	-	0.002	0.106	0.019	1.965	0.035	0.159	0.002	1.770
222	-	-	-	-	-	-	0.036	0.163	0.002	1.770
223	-	-	0.002	0.117	-	-	0.036	0.163	0.002	1.770
224	-	-	0.002	0.113	0.019	1.955	0.036	0.163	0.002	1.770
225	-	-	-	-	-	-	0.035	0.158	0.002	1.770
226	-	-	0.002	0.104	0.019	1.948	0.034	0.155	0.002	1.765
227	0.008	2.680	0.002	0.121	-	-	-	-	0.002	1.763
228	-	-	0.002	0.104	0.019	1.948	0.034	0.155	0.002	1.770
229	-	-	0.002	0.113	0.019	1.942	0.035	0.159	0.002	1.761

230	-	-	0.002	0.113	0.020	2.049	0.035	0.161	0.002	1.765
231	-	-	-	-	0.020	1.988	0.036	0.163	0.002	1.764
232	-	-	-	-	0.019	1.962	0.036	0.163	0.002	1.767
233	-	-	0.002	0.106	-	-	-	-	0.002	1.761
234	-	-	0.002	0.104	-	-	0.034	0.155	0.002	1.761
235	-	-	-	-	0.019	1.935	0.035	0.158	0.002	1.761
236	-	-	0.002	0.104	-	-	0.035	0.160	0.002	1.765
237	-	-	0.002	0.104	-	-	0.034	0.155	0.002	1.761
238	-	-	-	-	-	-	-	-	0.002	1.761
239	-	-	0.002	0.111	0.019	1.955	0.034	0.155	0.002	1.752
240	0.008	2.643	0.002	0.113	0.019	1.921	0.034	0.155	0.002	1.752
241	-	-	0.002	0.102	0.019	1.928	0.034	0.157	0.002	1.761
242	-	-	0.002	0.100	-	-	0.034	0.155	0.002	1.756
243	-	-	0.002	0.104	0.019	1.942	0.034	0.155	0.002	1.761
244	-	-	0.002	0.109	0.019	1.945	0.036	0.163	0.002	1.761
245	-	-	0.002	0.109	-	-	0.034	0.155	0.002	1.761
246	-	-	0.002	0.104	-	-	0.034	0.155	0.002	1.767
247	-	-	-	-	0.019	1.911	0.035	0.159	0.002	1.761
248	-	-	0.002	0.096	-	-	-	-	0.002	1.761
249	-	-	-	-	0.020	1.975	0.034	0.155	0.002	1.756
250	-	-	-	-	-	-	-	-	0.002	1.765
251	0.009	2.939	-	-	-	-	0.034	0.155	0.002	1.761
252	-	-	-	-	0.019	1.935	0.034	0.155	0.002	1.761
253	-	-	0.002	0.117	0.019	1.910	0.035	0.158	0.002	1.755
254	0.008	2.612	-	-	-	-	-	-	0.002	1.761
255	-	-	-	-	-	-	-	-	0.002	1.761
256	-	-	-	-	0.019	1.958	-	-	0.002	1.761
257	-	-	-	-	0.019	1.908	0.034	0.155	0.002	1.761
258	-	-	-	-	0.019	1.901	0.034	0.155	0.002	1.765
259	-	-	-	-	0.019	1.888	0.034	0.155	0.002	1.756
260	-	-	-	-	0.019	1.895	-	-	0.002	1.776
261	-	-	-	-	0.019	1.898	0.034	0.154	0.002	1.761

262	-	-	-	-	-	-	0.034	0.155	0.002	1.752
263	-	-	-	-	-	-	0.033	0.148	0.002	1.770
264	-	-	0.001	0.092	-	-	0.034	0.153	0.002	1.743
265	-	-	-	-	-	-	0.034	0.155	0.002	1.752
266	0.008	2.593	0.002	0.113	0.019	1.895	0.034	0.153	0.002	1.779
267	-	-	-	-	-	-	0.034	0.155	0.002	1.761
268	-	-	-	-	-	-	0.035	0.159	0.002	1.779
269	-	-	-	-	-	-	0.033	0.148	0.002	1.752
270	-	-	-	-	-	-	0.033	0.152	0.002	1.761
271	-	-	-	-	-	-	0.033	0.151	0.002	1.805
272	-	-	-	-	0.018	1.855	0.033	0.148	0.002	1.783
273	-	-	-	-	0.018	1.855	-	-	0.002	1.752
274	-	-	-	-	-	-	0.034	0.155	0.002	1.752
275	-	-	-	-	-	-	-	-	0.002	1.752
276	0.009	2.772	-	-	0.018	1.841	0.033	0.148	0.002	1.765
277	0.008	2.575	-	-	-	-	0.034	0.155	0.002	1.788
278	-	-	0.002	0.109	-	-	0.034	0.155	0.002	1.752
279	-	-	-	-	-	-	-	-	0.002	1.788
280	-	-	0.001	0.088	0.019	1.881	-	-	0.002	1.752
281	-	-	-	-	-	-	0.033	0.148	0.002	1.805
282	-	-	-	-	0.018	1.834	-	-	0.002	1.788
283	-	-	-	-	-	-	0.033	0.148	0.002	1.770
284	-	-	-	-	-	-	0.033	0.148	0.002	1.734
285	-	-	-	-	-	-	-	-	0.002	1.797
286	-	-	-	-	-	-	0.033	0.148	0.002	1.743
287	0.008	2.575	-	-	-	-	-	-	0.002	1.779
288	-	-	-	-	0.018	1.844	-	-	0.002	1.788
289	-	-	-	-	-	-	0.033	0.148	0.002	1.788
290	-	-	0.002	0.104	0.018	1.834	0.034	0.155	0.002	1.788
291	0.008	2.655	-	-	0.018	1.828	0.033	0.152	0.002	1.788
292	-	-	-	-	-	-	0.033	0.148	0.002	1.832
293	-	-	-	-	-	-	0.033	0.148	0.002	1.797

294	-	-	-	-	-	-	-	-	0.002	1.761
295	-	-	-	-	-	-	0.033	0.148	0.002	1.797
296	0.008	2.593	0.001	0.092	-	-	-	-	0.002	1.797
297	-	-	-	-	-	-	-	-	0.002	1.779
298	-	-	-	-	0.019	1.921	-	-	0.002	1.797
299	-	-	-	-	-	-	0.033	0.148	0.002	1.811
300	-	-	0.002	0.104	-	-	-	-	0.002	1.752
301	-	-	-	-	-	-	0.033	0.148	0.002	1.868
302	-	-	-	-	-	-	-	-	0.002	1.886
303	-	-	-	-	-	-	0.033	0.148	0.002	1.922
304	-	-	-	-	-	-	-	-	0.002	1.788
305	-	-	-	-	-	-	-	-	0.002	1.922
306	-	-	-	-	-	-	-	-	0.002	1.814
307	-	-	-	-	-	-	0.033	0.148	0.002	1.922
308	-	-	0.001	0.092	-	-	0.033	0.148	0.002	1.850
309	-	-	-	-	-	-	-	-	0.002	1.922
310	-	-	0.002	0.104	0.018	1.801	0.033	0.148	0.002	1.922
311	-	-	-	-	-	-	-	-	0.002	1.913
312	-	-	-	-	-	-	-	-	0.002	1.868
313	-	-	-	-	-	-	0.033	0.148	0.002	1.886

NOTES