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VERIFICATION OF THEORETICAL CULVERT FORMULAE

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VERIFICATION OF THEORETICAL CULVERT FORMULAE

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A project report submitted in partial fulfillment of the requirement for the degree of

BACHELOR OF ENGINEERING (CIVIL ENGINEERING)

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PROJECT REPORT SUMMARY

VERIFICATION OF CULVERT FORMULAE

AS VERBYTSKA

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Department: Civil Engineering

University: University of Pretoria

Degree: Bachelor of Engineering (Civil engineering)

Summary:

This research project aims to look into the hydraulics of culvert structures. A culvert is a structure which controls stream flow through and underneath a roadway and embankments. The verification of the effectiveness of theoretical equations and its coefficients is vital for adequate prediction of the effect on areas surrounding a culvert structure. There are numerous theoretical culvert equations that reflect culvert hydraulics. This research report will focus on the verification of three theoretical culvert equations used in the industry, as well as a study of application of two hydraulic programs. The culvert system can function under two hydraulic controls. This study is focused on the culvert system under inlet control and covers analysis of rectangular and square portal frame culverts. The study will involve building a physical model and obtaining/gathering data for theoretical, physical, and software model comparison of culvert hydraulics. The results of the study produce a number of discharge rating curves/performance curves for the culvert system; to aid in verification process. The study will give the ability to comment on the level of performance of the theoretical equations and of the software application in comparison to the physical relationship of head water level and flow rate of culvert structures. The study also focuses on the effect of the slope of the culver system on the discharge rating curves.

DECLARATION

I, the undersigned herby declare that:

I understand what plagiarism is and I am aware of the University's policy in this regard;

The work contained in this report is my own original work;

I did not refer to work of current or previous students, lecture notes, handbooks or any other study material without proper referencing;

Where other people's work has been used this has been properly acknowledged and referenced;

I have not allowed anyone to copy any part of my report;

I have not previously in its entirety or in part submitted this report at any university for a degree.

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AS Verbytska

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20 July 2010

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f) My family for their encouragement and support during the study.

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Symbol	Description
$\sum h_{l1-2}$	Secondary losses between upstream and downstream (m)
A	Full cross-sectional area of the culvert, (m^2).
B	Width (inside) (m)
c	Constants that vary with shape and entrance conditions
C	Chezy constant.
C_b	Side contraction coefficient
C_c	Soffit contraction coefficient
C_d	Discharge coefficient
D	Height (inside) (m)
H_1	Upstream energy level (m).
H_2	Downstream energy level, (m).
H_c	Specific head at critical depth (dc + $V_c^2/2g$), (m).
h_{f1-2}	Friction losses between inlet and outlet (m).
H_M	Head of model, (m).
H_P	Head of prototype, (m).
HW_1	Headwater energy depth above the invert of the culvert inlet, (m).
K	Constants that vary with shape and entrance conditions
K	Orifice equation constant ($\sqrt{2g}AC$).
K	Secondary loss coefficient.
K_{in}	Inlet secondary loss coefficients
K_{out}	Outlet secondary loss coefficients.
K_u	Constants that vary with shape and entrance conditions
L	Length of the culvert (m).
M	Constants that vary with shape and entrance conditions
$_M$	Model (physical model).
n	Manning's roughness coefficient ($s/m^{1/3}$)
n_l	The horizontal scales.
n_x	The x value at the prototype/ The corresponding x value at the model.
n_y	The vertical scales.
$_P$	Prototype (real life size).
Q	Discharge through the culvert, (m^3/s).
$Q_{3.0}$	Discharge at which $HW_1/D = 3$

Symbol	Description
Q_M	Flow of the model, (m^3/s).
Q_P	Flow of the prototype, (m^3/s).
R	Hydraulic radius (m).
S	Culvert slope, (m/m).
So	Slope of the culvert (m/m).
v	Velocity (m/s).
Y	Constants that vary with shape and entrance conditions.
y	Water elevation/head, H (m).
Z	Bed elevation at position, (m).

CHAPTER 1

Introduction

1 Introduction

1.1 Background

The reason for this project is to verify the effectiveness of the theoretical culvert equations and hydraulic software. There are number of theoretical culvert equation that have been developed to date. A number of manuals are available for culvert design and analysis with different theoretical relationships between water flow and water surface elevation for culvert systems.

A number of studies were carried out in the past, but mainly focused on determining a single theoretical equation with defined constants for different shapes and sizes. Other studies were carried out to obtain new sets of equations that best describe the hydraulics of culvert.

This research report will focus on the verification of three different theoretical equations used in the industry, as well as a study of application of two hydraulic programs. The implication of this study could be a certain equation/software package maybe more effective than another for use in hydraulic design and analysis.

1.2 Objectives of study

- The main objective of this study is to verify the theoretical culvert equations in predicting head water level versus flow rate under inlet control conditions.
- The second objective of this study is to study the application of hydraulic software used in the industry.
- Another objective of this study is to obtain physical performance curves for different portal culverts sizes.
- The last aim of this study is to see if the slope of the culvert system has an effect on the discharge and water surface elevation under inlet control in culvert systems.

1.3 Scope of the report

The culvert system can function under two hydraulic controls, namely inlet and outlet control. This study will focus on the culvert system under inlet control. This research report will analyse rectangular and square portal frame culverts. The study will only cover steady uniform set up conditions. The study will not include: modification to the culvert structure; erosion around culvert structures; variation in approach angle; and effect of the debris in culvert systems. The research project limited to the verification parameters listed below.

Theoretical culvert equations under inlet control from:

- SANRAL Drainage manual
- American Hydraulic Design Manual
- Project Report Nr0-2109-S

Hydraulic software:

- HEC-RAS, River Analysis System
- HY-8, Hydraulic Design of Highway Culverts

The slope of the culvert system:

- Slope of 1%
- Slope of 2%
- Slope of 3%

1.4 Methodology

The required steps to reach a conclusion about the current application of theoretical equations and hydraulic software:

- Construct a physical hydraulic model of culverts.
- Run the model and obtain flow rate and relevant water surface elevation at the inlet of the culvert.
- Obtain physical model, theoretical model and software model performance curve.
- Compare the results and comment on the application of the theoretical and software models.

1.5 Organisation of the report

The report consists of the following chapters and appendices:

- Chapter 1 – Introduction of the study.
- Chapter 2 – Literature review about culvert structures.
- Chapter 3 - Experimental set up for the theoretical, physical and software models.
- Chapter 4 – Results of the analysis of all the models mentioned in previous chapter.
- Chapter 5 - Conclusion and Recommendations of the analysis.
- The Reference list.
- Appendix A – Additional photographs and images of physical model.
- Appendix B - Performance curves obtained from the study.
- Appendix C - Research project CD.
- Appendix D – Evaluation form.

CHAPTER 2

Literature Review

2 Literature Review

2.1 Introduction

A culvert is a structure which controls stream flow through and underneath a roadway and embankments. The verification of the effectiveness of theoretical equations and its coefficients is vital for adequate prediction of the effect on areas surrounding a culvert structure. Erosion is an ecological concern of the adjacent area. The design parameters should be taken special consideration on the most efficient way of conveying flow through the structure. Minimum effect on surrounding areas should be considered in terms of erosion. Design parameters that influence capacity are: size, shape, and entrance conditions play a vital role in capacity of the structure, (Ozdemir, & Hsu, 2007; Philip & Creamer, 2007).

2.2 Culvert types

The commonly found culverts in South Africa are circular, pipe arch, portal, rectangular and box, (**Figure 2.2.1 and 2.2.2**). Circular culverts made from concrete, corrugated and plastic pipes; pipe arch constructed from steel sheeting; portal, rectangular and box culverts are made of concrete due to the ease in construction of precast concrete. Wide range of sizes for concrete culverts can be viewed in **Table 2.2.1**. The dimensions for rectangular culverts (four sides) are the same as for portal culvert (three sides), (Philip & Creamer, 2007).

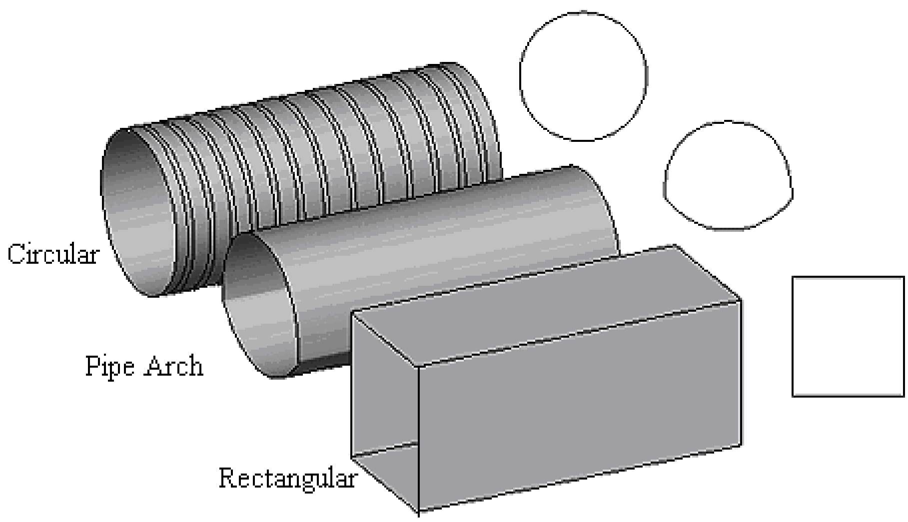


Figure 2.2.1: Types of culverts, (Copstead, Johansen, & Moll 1997).

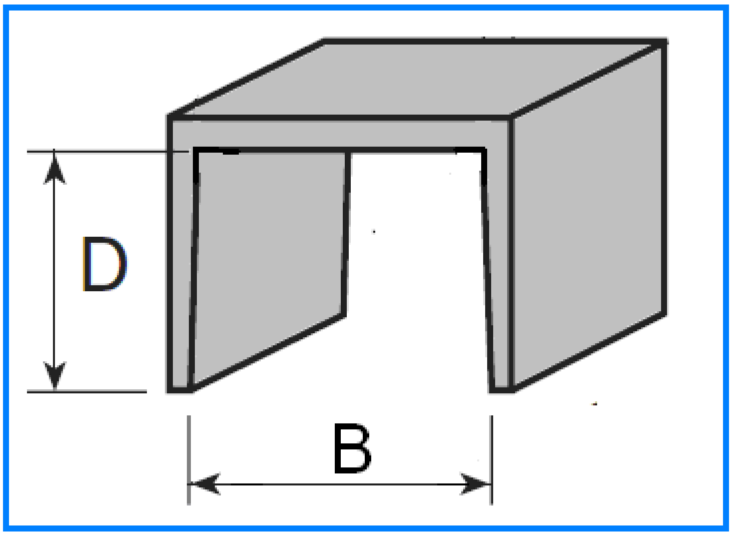


Figure 2.2.2: Portal culvert, (ROCLA, 2000)

Table 2.2.1: Standard culvert sizes

Portal Culverts		**Portal Culverts**		**Box culverts**	**Circular Culverts**
D (mm)	**B (mm)**	**D (mm)**	**B (mm)**	**D = B (mm)**	**Diameter (mm)**
450	300	1500	1000	450	300
	375		1200	600	375
	450		1500	750	450
600	300	1800	600	900	525
	450		900	1200	600
	600		1200	1800	675
750	300	2000	1000	2400	750
	450		1500	3000	825
	600		1800	3600	900
	750		2000	4200	1050
900	450	2500	1500	4800	1200
	600		2000		1350
	750		2500		1500
	900	3000	1000		1800
1200	450		1500		
	600	3000	2000		
	1200		2500		
1500	600		3000		
	750	3600	2400		
	900		3000		

2.3 General characteristics of culverts

There are many different shapes and sizes of culverts (circular, box, and rectangular, etc.). The variety of entrance conditions includes different wing wall configuration, fillets, and upstream slope. Wing walls increase the flow performance through structure as well as reduce severity of scour at inlets, (Humes, 2004). It is an acceptable phenomenon that the culvert entrance width is smaller than the channel water way. The conditions therefore create backwater effect, also known as damming upstream, (Conn DOT, 2002; Philip, & Creamer, 2007).


Figure 2.3.1: Photograph of portal and rectangular culverts, (Entranceways, 2010; Midstate Precast, 2010).

Environmental contribution for culvert installation makes use of a 3 side culvert (Portal culverts), where the top and the vertical sides are the same material and the bottom is an alluvial material (natural channel bed). The manning roughness value of the structure depends on culvert material and the river bad. Characteristics of concrete culverts provide strength and stability under a load that the roadway carries as well as hydraulic strength to withstand water pressure, (CMA 2003, Philip, & Creamer, 2007).

2.4 Hydraulics

"Floodplain and environmental regulations are changing the types of culverts design engineers are specifying today. However, culvert hydraulic design procedures are still applicable when used with modifications to reflect the current culvert crossing characteristics" from Philip, & Creamer, (2007).

Hydraulic culvert design requires the transport of a certain flow rate through a roadway or embankment, without producing undesirably high backwater level. The selection of culvert system is designed so that the flow passes safely without overtopping and damaging the road. Culvert hydraulics consists of two types control systems the upstream (inlet) control and the downstream (outlet) control, (Philip, & Creamer, 2007).

2.4.1 Inlet control

The system will be considered upstream control when the inlet conditions govern the flow and the downstream water level does not affect upstream. The factors that have influence on inlet characteristics are: upstream water level (HW); inlet geometry; wing walls configuration; slope (So); culvert shape, and size. With upstream control the culvert is able to transport more discharge than the culvert inlet can allow, refer to **Figure 2.4.1**. The inlet analysis has to incorporate both continuity and equilibrium equations, (Philip, & Creamer, 2007; Sterling Jones, Kornel Kerenyi, & Stein, 2006).

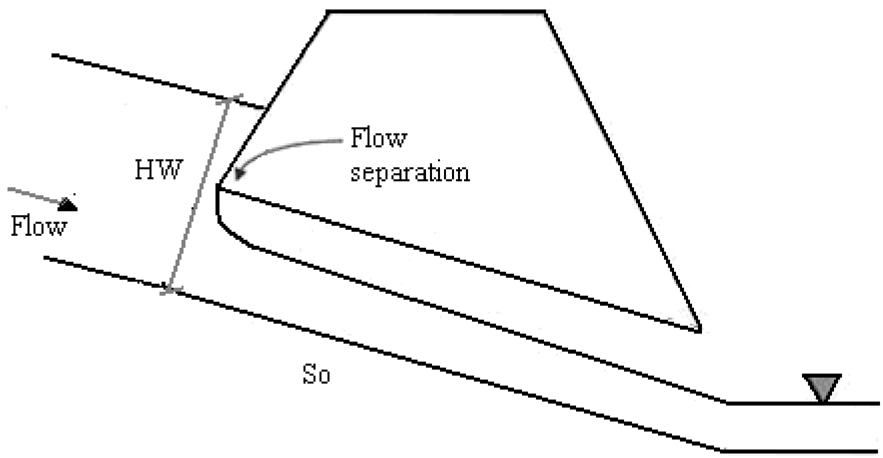


Figure 2.4.1: Typical submerged inlet control system, (Philip, & Creamer, 2007).

The flow under inlet conditions can be analysed in two different ways depending on HW and the HW/D ratio (where D is the inside height of the culvert). The flow through the culvert can be submerged or unsubmerged in **Figure 2.4.1** and **2.4.2**. If the water level at the culvert entrance is lower than the full height of the culvert, then a weir flow behaviour can be observed.

In the case of submerged entrance the discharge operates as orifice flow. Therefore different theoretical analysis is performed at the inlet control depending on HW, (Philip, & Creamer, 2007).

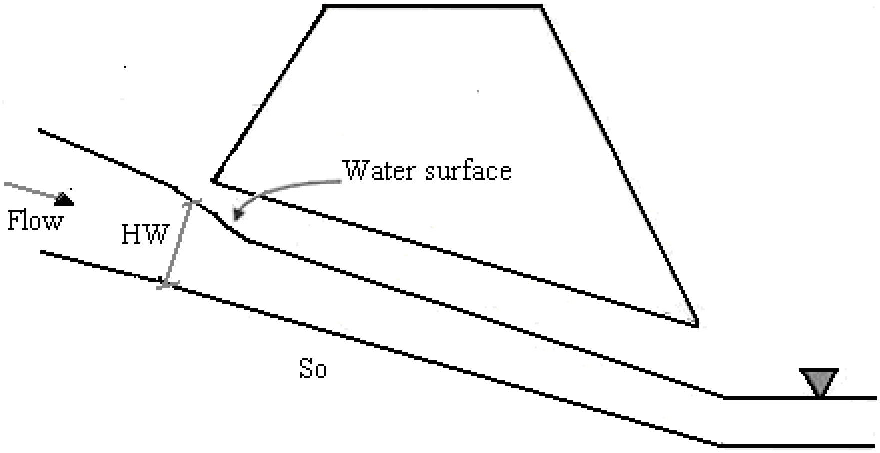


Figure 2.4.2: Unsubmerged inlet, (Ozdemir, & Hsu, 2007).

The capacity for various cases can be determined using theoretical relationship between discharge and water level, referred to as the discharge rating curve (performance curve). The graphical representation is obtained using the applicable control system. An example of performance curve can be seen in **Figure 2.4.3,** (Ozdemir, & Hsu, 2007; Philip, & Creamer, 2007).

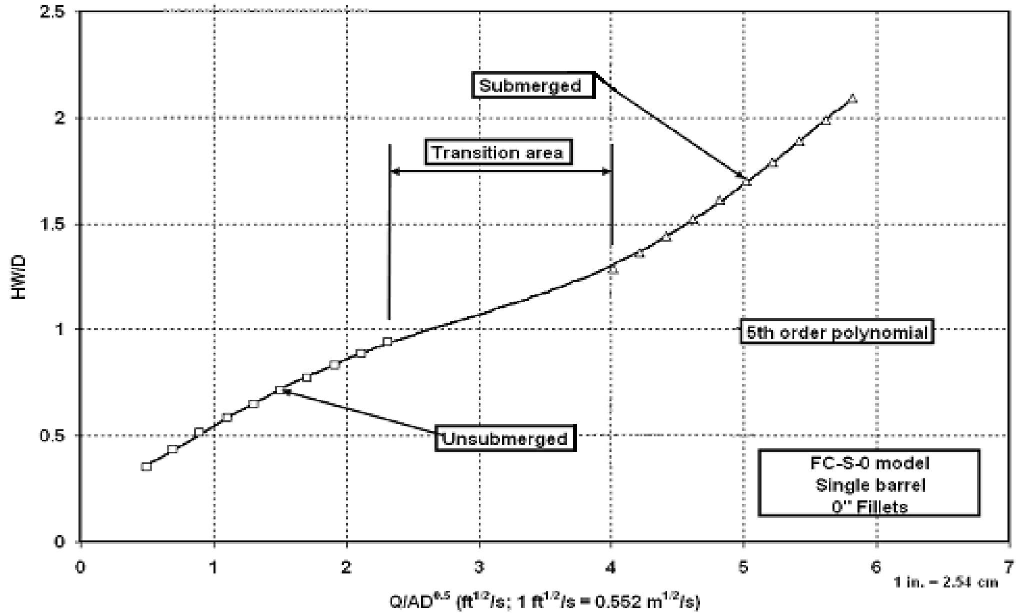


Figure 2.4.3: Transition area, unsubmerged and submerged inlet flow conditions, (Sterling Jones, Kornel Kerenyi, & Stein, 2006).

2.4.2 Outlet control

The system is classified to be outlet control when the downstream flow has an influence on the upstream water level and the culvert flowing full. The discharge through an outlet control system can flow full or partially, for the purpose of hydraulic analysis it is assumed that the culvert is flowing full over its entire length. The factors influencing the downstream control are: length, roughness, secondary losses, friction losses, slope, and tail water level of the culvert, (**Figure 2.4.4**).

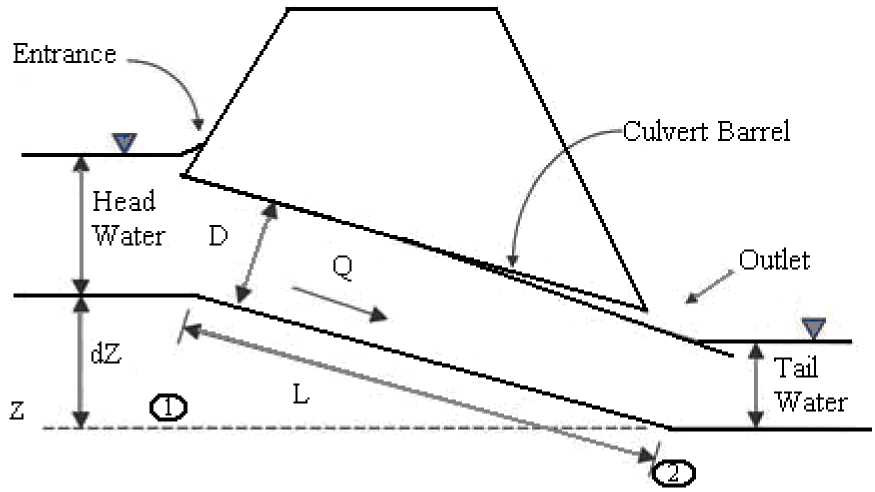


Figure 2.4.4: Outlet control system, (Philip, & Creamer, 2007).

The control analysed using mathematical models of energy balancing between upstream and downstream, (**Equation 1**). The friction losses between upstream and downstream of the culvert can be determined using Manning's or Chezy equations, and outlet control equations in section 2.6.2. The secondary loss coefficient (K) can be obtained from **Table 2.4.1.**

$$Z_1 + y_1 + \frac{v_1^2}{2g} = Z_2 + y_2 + \frac{v_2^2}{2g} + \sum K \frac{v^2}{2g} + h_{f1-2} \qquad \ldots(1)$$

Where:

y = water elevation at position 1 or 2 (m).

Z = bed elevation at position 1 or 2 (m).

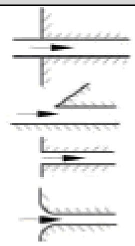
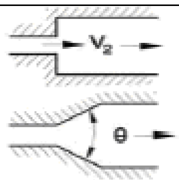
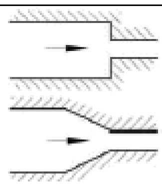
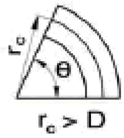
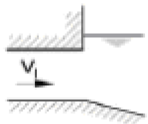
v = velocity upstream or downstream (m/s).

K = secondary loss coefficient.

And

h_{f1-2} = friction loss between position 1 and 2 (m).

Table 2.4.1: Typical secondary loss coefficients (K), (Kruger, E. (Editor), 2007).

Description		**Sketch**	**K-value**
Inlets $h_1 = \frac{K\bar{v}^2}{2g}$ ($\bar{v}$ = average velocity in conduit)	Protruding Oblique Blunt Well-rounded		0.9 0.7 0.5 0.2
Diverging sections $h_1 = \frac{K(\bar{v}_1 - \bar{v}_2)^2}{2g}$	Sudden Cone45°<θ<180° θ = 30° θ = 15°		1.0 1.0 0.7 0.2
Converging sections $h_1 = \frac{K\bar{v}^2}{2g}$	Sudden Cone		0.5 0.25
Bends $h_1 = \frac{K\bar{v}_2^2}{2g}$	θ = 90° θ = 45°		0.4 0.3
Outlets $h_1 = \frac{K\bar{v}_1^2}{2g}\left(1 - \frac{A_1}{A_2}\right)^2$	Sudden		1.0

2.5 Influences on culvert capacity

2.5.1 Erosion at inlet of culvert structures

Erosion is defined as particle movement from upstream to downstream of the channel/river. The main cause of this event is the forces of moving water. Other factors that influence intensity of erosion are: slope; contraction of flow area; bed, fill and embankment materials. Major scour occurs when the elevation of the water level and the velocity increases due to high floods.

In a culvert system the contraction of flow path at the entrance also induces high velocities against the embankments and sloped fill upstream of the channel. This may result in scour damage all around the structure. Small slope can lead to sediment build up in the corners and inside the conduit. Blockage decreases capacity of the system and could lead to increase in water level and further scouring of embankments and surface layers.

The system has to be protected against scouring by means of wing walls, cut off walls, or rip-rap side protection. The variation of wing walls dimensions and angle of installation changes erosion potential. Previous studies were conducted on inlet wing wall and their positive impact on reduction of scour. Erosion of culvert structures adopted from Conn DOT, (2002) and Sterling Jones, Kornel Kerenyi, and Stein, (2007).

2.5.2 Wing walls

Wing walls guide water particles towards the culvert opening and as the result maximum designed flow can be obtained through the system. Less sediment movement may occur due to less drastic contraction of flow into a culver. The structural components decrease sedimentation at the corners of culvert opening. The use of wing walls decreases secondary loss coefficient in outlet controlled culverts. From previous studies it was concluded that 45 degree wing walls are sufficient at minimizing scour at inlets unlike 8 degree wing walls. View the difference in **Figure 2.5.1.** The use of wing walls increases the structural stability of system under flood conditions, (Conn DOT, 2002; Humes, 2004).

a) b)

Figure 2.5.1: Photographs: a) 45 degree configuration; b) 8 degree configuration; (Sterling Jones, Kornel Kerenyi, & Stein, 2007).

2.5.3 Debris

Figure 2.5.2: Debris, (Fish Habitat Nexus, 2004 and FHWA, 2009).

Large debris (tree branches etc) can considerably decrease the capacity of the structure, as it reduces area of flow through the culvert. Provision must be made for maintenance and removal of large objects that may clog the system therefore the culvert size should be big enough for a person. For smaller debris grids should be installed at the inlet of the culvert. The secondary losses due to grid system need to be taken into account when designing a culvert as it may reduce capacity, (Kruger, E. (Editor),2007).

2.5.4 Approach angle

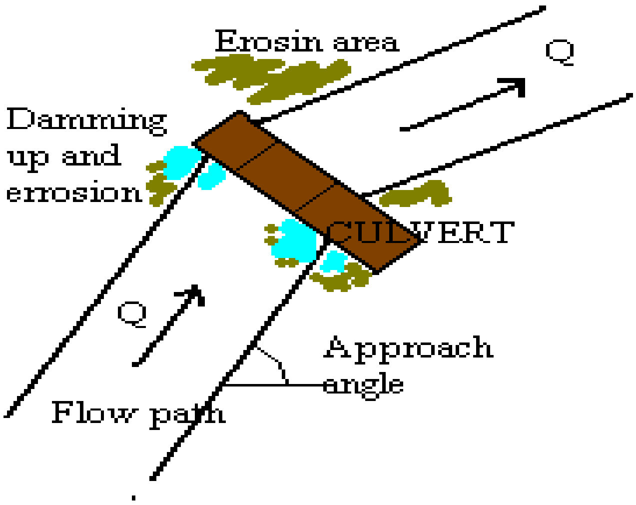


Figure 2.5.3: Consequences of altering the approach angle.

The angle of flow on the approaching side of the structure should not be altered drastically as it will decrease the capacity of the culvert and induce additional damming up and a possible risk of overtopping in flood conditions. On the downstream side the flow angle should be not be altered as it may increase erosion.

If the approaching flow is supercritical alteration of flow direction can cause substantial damming up and sediment transport. Supercritical can not change its direction drastically unless converted to subcritical flow, which could result in significant increase inflow depth, (Kruger, 2007).

2.6 Formulas to determine culvert capacity

2.6.1 Inlet control

Table 2.6.1: Inlet control equations

Inlet control equations for a Rectangular/Box culvert		
	Unsubmerged Conditions	Submerged Conditions
SANRAL Drainage manual	For: *$0 < H_1/D \leq 1.2$* $Q = \frac{2}{3} C_B B H_1 \sqrt{\frac{2}{3} g H_1}$ Where: C_B = 1.0 for rounded inlets (r>0.1B) C_B = 0.9 for square inlets	For: *$H_1/D > 1.2$* $Q = C_h BD \sqrt{2g(H_1 - C_h D)}$ Where: C_h = 0.8 for rounded inlets C_h = 0.6 for square inlets
American Hydraulic Design Manual	For: *$0.5 \leq HW_1/D \leq 3.0$* $HW_1 = [a + bF + cF^2 + dF^3 + eF^4 + F^5]D - 0.5DS_o$ Where: $F = 1.8113 \frac{Q}{BD^{1.5}}$. And a = 0.144138; b = 0.461363; c = -0.09215; d = 0.020003; e = -0.00136; f = 0.000036	For: *$HW_1/D > 3$* $HW_1 = \left[\frac{Q}{k}\right]^2 + \frac{D}{2}$ Where: $k = 0.6325 \frac{Q_{3.0}}{D^{0.5}}$

Project report 0-2109-S, USA	For: $HW_1/D \leq 3/2C_c$ $$\frac{HW_1}{D} = \frac{3}{2}\left(\frac{1}{C_b}\right)^{2/3}\left(\frac{Q}{BD\sqrt{gD}}\right)^{2/3}$$ Where: $C_b = 1$	For: $HW_1/D > 3/2C_c$ $$\frac{HW_1}{D} = \frac{1}{2C_d{}^2}\left(\frac{Q}{BD\sqrt{gD}}\right)^2 + C_c$$ Where: $C_c = 0.667$ $C_d = 0.667$
HY-8	For: $Q/AD^{0.5} \leq 1.93$ $$\frac{HW_1}{D} = \frac{H_c}{D} + K\left[\frac{K_u Q}{AD^{0.5}}\right]^M - 0.5S$$ And $$\frac{HW_1}{D} = K\left[\frac{K_u Q}{AD^{0.5}}\right]^M$$ Where: Ku = 1.811; K = 0.061; M = 0.75;	For: $Q/AD^{0.5} \geq 2.21$ $$\frac{HW_1}{D} = c\left[\frac{K_u Q}{AD^{0.5}}\right]^2 + Y - 0.5S$$ Where: c = 0.0423; Y = 0.82
HEC-RAS	For: $Q/AD^{0.5} \leq 1.93$ $$\frac{HW_1}{D} = \frac{H_c}{D} + K\left[\frac{Q}{AD^{0.5}}\right]^M - 0.5S$$ and $$\frac{HW_1}{D} = K\left[\frac{Q}{AD^{0.5}}\right]^M$$	For: $Q/AD^{0.5} \geq 2.21$ $$\frac{HW_1}{D} = c\left[\frac{Q}{AD^{0.5}}\right]^2 + Y - 0.5S$$
Where: A = full cross-sectional area of the culvert, (m^2). B = width (inside) (m) C_d = discharge coefficient		

C_c = soffit contraction coefficient C_b = side contraction coefficient D = height (inside) (m) H_c = specific head at critical depth (dc + V_c^2/2g), (m). HW_1 = headwater energy depth above the invert of the culvert inlet, (m). K, K_u, M, c and Y = constants that vary with shape and entrance conditions. k = orifice equation constant (√2gAC). $Q_{3.0}$ = discharge at which HW_1/D = 3 Q = discharge through the culvert, (m^3/s). S = culvert slope, (m/m).

2.6.2 Outlet control

$$H_1 = H_2 + h_{f1-2} + \sum h_{l1-2} - S_0 L \,, \qquad \ldots(2)$$

Where:

H_1 and H_2 = upstream and downstream energy level (m).

h_{f1-2} = friction losses between inlet and outlet (m).

$\sum h_{l1-2}$ = secondary losses between upstream and downstream (m)

So = slope of the culvert (m/m).

and

L = length of the culvert (m).

$$\sum h_{l1-2} = K_{in} \frac{v_1^2}{2g} + K_{out} \frac{v_2^2}{2g} \qquad \ldots(3)$$

Where:

K_{in} and K_{out} = inlet and outlet secondary loss coefficients, (**Table 2.4.1**).

and

v = velocity (m/s).

Manning's:

$$h_{f1-2} = \frac{v^2 n^2 L}{R^{4/3}} \qquad \ldots(4)$$

Where:

n = manning roughness coefficient (s/m1/3)

and

R = hydraulic radius (m).

Chezy:

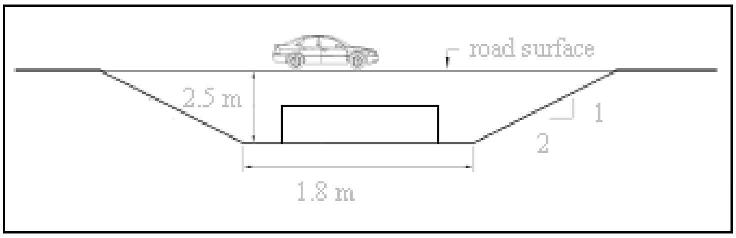
$$h_{f1-2} = \frac{v^2 L}{C^2 R} \qquad \text{...(5)}$$

Where:

C = Chezy constant.

2.6.3 Example

The culvert system below is inlet controlled. The culvert dimensions are 1500x900 mm. Determine a) culvert capacity just before the road surface is overtopped; b) discharge ratting curve.



Given:

$C_h = 0.6$

B = 1.5m

D = 0.9m

$H_{1max} = 2.5$m

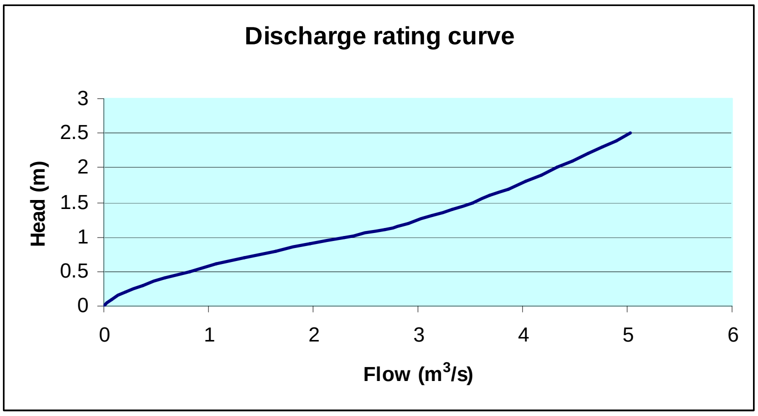
a)

The $H_1/D = 2.5/0.9 = 2.78 > 1.2$ Therefore the following equation (SANRAL) is used:

$$Q = C_h BD\sqrt{2g(H_1 - C_h D}$$

$$Q = 0.6 \cdot 1.5 \cdot 0.9 \cdot \sqrt{2 \cdot 9.81 \cdot (2.5 - 0.6 \cdot 0.9)} = 5.02 m^3 / s$$

b)



2.7 Model studies

Modeling of hydraulic systems aids the formulation and verification of theoretical relationships. Culvert physical modeling of upstream control system has various factors that will influence construction of the model, taken out from study on the “Effects of Inlet Geometry on Hydraulic Performance of Box Culverts”, (Sterling Jones, Kornel Kerenyi, & Stein, 2006).

For the physical model to be adequate for inlet control the model is build so that the water level at the inlet is not influenced by the water level downstream or the conditions in the culvert. To eliminate submerged conditions downstream, the slope at the exit must be sufficiently steep to transport the water away from culvert outlet. Another solution to tailwater effect can be abrupt cut off point of the channel and let the water flow out into different box/channel, (Sterling Jones, Kornel Kerenyi, & Stein, 2006).

The length of the culvert does not influence inlet control, therefore it is not designed. There is no need of full width opening, as the long span culverts are outlet control, (Sterling Jones, Kornel Kerenyi, & Stein, 2006). The channel on the upstream side usually has grids and nets to aid the reduction of wave formation and stabilize the water level upstream of the structure. Point gauges are set up a distance away from entrance to measure water level at the inlet, (Verbytska, 2009; DWAF, 2001).

Figure 2.7.1: Photos of grids and point gauges.

The scale of the model depends on Reynolds or Froude uniformity. Application of Reynolds uniformity looks at aspects/conditions of turbulent flow in and around the culvert structure (Ozdemir, & Hsu, 2007).

Froude's law of similarity contains the gravitational and kinetic forces, which are the main factors influencing the fluid flow, (DWAF, 2001).

The factors that will have an influence on the inlet control are: discharge intensity and geometry of the culvert opening. The culvert opening dimensions scaled so that accuracy of measurements will not be compromised. Good flared wing walls configuration for the inlet is a standard of 30° and 45°, for box culverts, (Sterling Jones, Kornel Kerenyi, & Stein, 2007).

Many model studies were carried out in the past years with different approaches on modeling the culvert system. Various projects are described below.

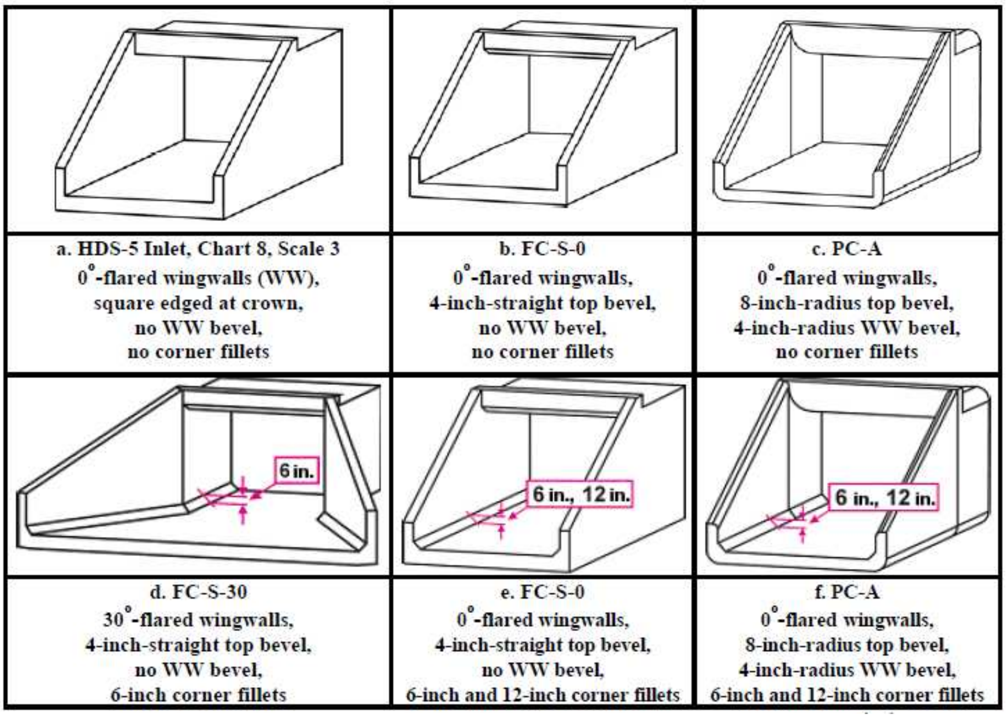
- 3-Dimensional analysis was performed by the University of Florida focusing on characterizing the energy and momentum continuity, as well as the pressure and velocity distribution as a function of discharge in a culvert system. The objective of the study was to verify the correctness of discharge coefficients that are used in a 1-Dimensional analysis. The study was carried out by means of Computational Fluid Dynamics (CFD) using Reynolds-average approach. Turbulent kinetic energy, turbulent dissipation rate, and average flow kinetic energy were deduced from the CFD modeling. The head water losses and the position of the majority energy dissipation in the system were then acquired, (Department of Civil and Coastal Engineering, 2007).

- 3-Dimensional analysis of discharge around culvert structures was carried out by Ozdemir and Hsu (2007). The use of CFD modeling was utilized and improvements were made on the discharge rating curves by means of lumped method. Large-eddy simulation of turbulent flow was done to evaluate the efficiency of Reynolds-average method for complex flows, (Ozdemir, & Hsu, 2007).

- A study was carried out by Sterling Jones, Kornel Kerenyi, & Stein about the effects of inlet geometry on hydraulic performance of box culverts. The study involved the use of regression equation (equ.6) for inlet control of box culvert systems. The focus was put on the computation of coefficients (a, b, c, d, e, and f) in the regression equations.

The verification and data gathered for a fifth-order polynomial equation was obtained from physical model study. The coefficients were tested for various sizes, and entrance conditions (**Figure 2.7.2**); the results of their experimental work can be found in **Table 2.7.1.**

$$\frac{HW_1}{D} = a + b\left[\frac{K_u Q}{AD^{0.5}}\right] + c\left[\frac{K_u Q}{AD^{0.5}}\right]^2 + d\left[\frac{K_u Q}{AD^{0.5}}\right]^3 + e\left[\frac{K_u Q}{AD^{0.5}}\right]^4 + f\left[\frac{K_u Q}{AD^{0.5}}\right]^5 \quad (6)$$



1 inch = 25.4 mm

Figure 2.7.2: Culverts configurations, (adopted from Sterling Jones, Kornel Kerenyi, & Stein, 2006).

Table 2.7.1: Coefficients of regression model, (Sterling Jones, Kornel Kerenyi, & Stein, 2006).

Inlet	Model	Slope (%)	Fillet (inches)	Span: Rise	a	b	c	d	e	f
1.1	FC-S-0	3	0	1:1	0.21	0.22	0.21	-0.12	0.02	-0.002
1.2	FC-S-0	3	6	1:1	0.22	0.25	0.19	-0.11	0.02	-0.002
1.3	FC-S-0	3	12	1:1	0.25	0.22	0.21	-0.12	0.02	-0.002

Inlet	Model	Slope (%)	Fillet (inches)	Span: Rise	a	b	c	d	e	f
1.4	PC-A	3	0	1:1	0.19	0.31	0.11	-0.08	0.016	-0.001
1.5	PC-A	3	6	1:1	0.2	0.31	0.11	-0.08	0.016	-0.001
1.6	PC-A	3	12	1:1	0.21	0.31	0.1	-0.07	0.014	-0.001
1.7	PC-A	3	6	2:1	0.19	0.48	-0.07	-0.003	0.003	-0.0003
1.8	PC-A	3	12	2:1	0.19	0.5	0.09	0.006	0.002	-0.0002
1.9	PC-A hybrid	3	0	1:1	0.24	0.31	0.16	-0.11	0.02	-0.002
1.10	FC-S-0 hybrid	3	0	1:1	0.32	0.033	0.43	0.22	0.045	-0.003

The results of the model study were plotted for further comparison. The inlet control discharge rating curves for various inlet modifications can be seen in **Figure 2.7.3.** From the discharge ratting curves it can be seen that the culvert entrance conditions only affect the performance when inlet is submerged.

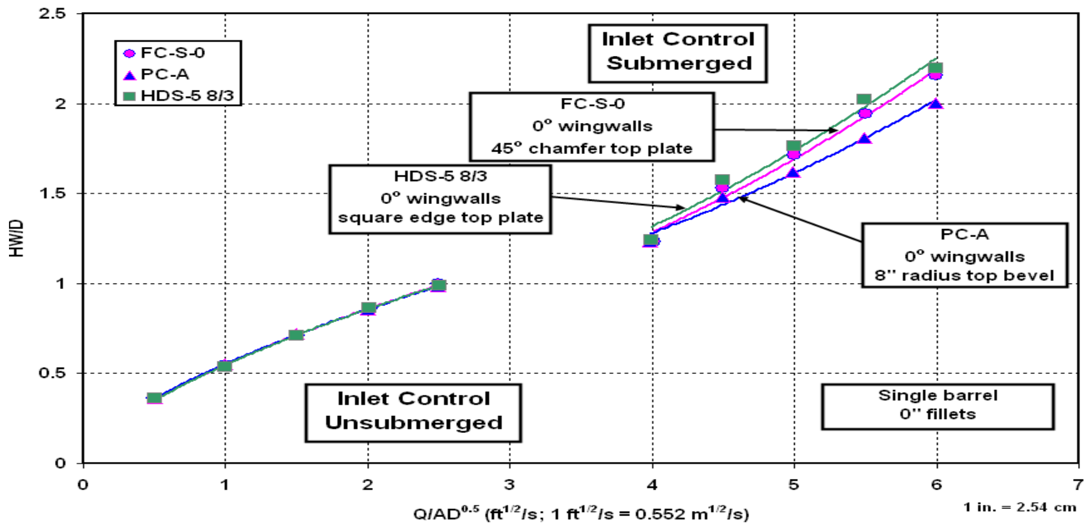


Figure 2.7.3: Culvert discharge rating curve, (Sterling Jones, Kornel Kerenyi, & Stein, 2006).

2.8 HEC-RAS software

HEC-RAS is an open channel/river modelling software. In addition it can model obstructions in the flow path like culverts, bridges etc. Information needed for HEC-RAS modelling is: inlet geometry, geometry of upstream and downstream, geometry of culvert, and the material characteristics of the culvert and the channel/river. Typical long section and culvert cross section can be seen in **Figure 2.8.1** and **Figure 2.8.2** respectively, (Pappenbergera, F. Bevena, K. Horrithb, M. & Blazkovac, S. 2005).

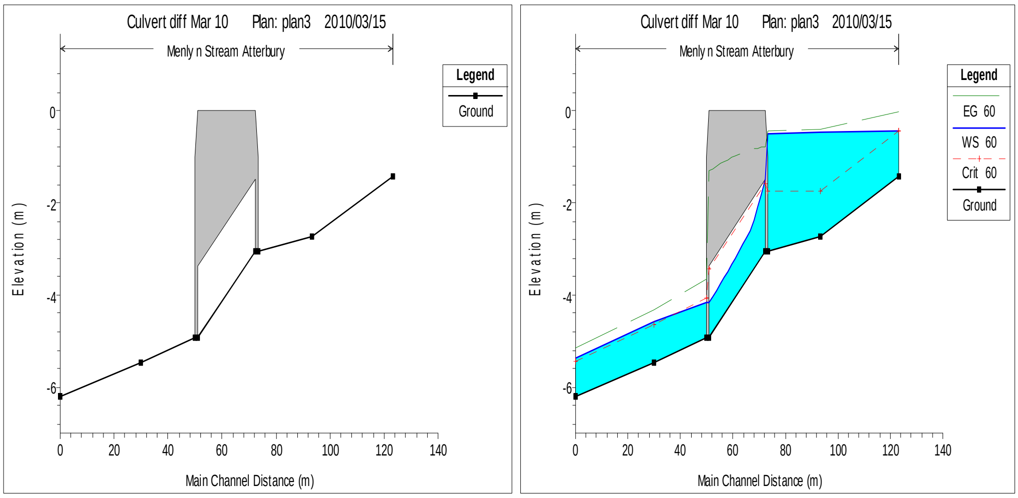


Figure 2.8.1: Long section of a culvert system under inlet control adopted from HEC-RAS.

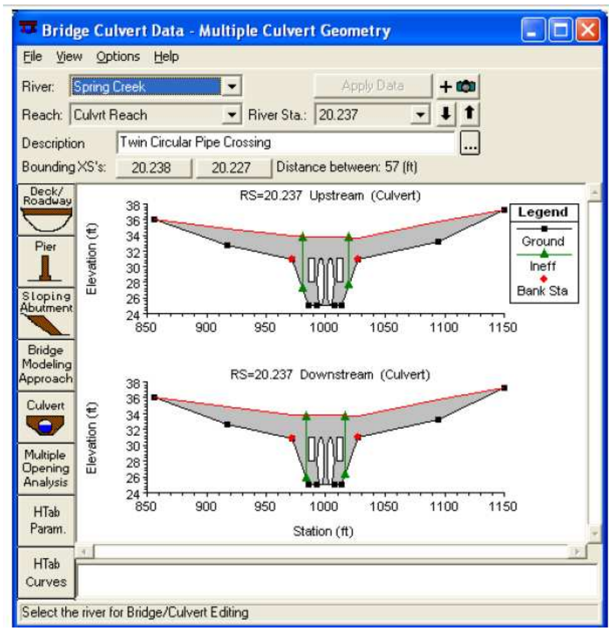


Figure 2.8.2: Culvert cross section, (Brunner, G. W. 2008).

Since a culvert is an obstruction in the natural flow path, the model calculates various energy losses throughout the system. The main loss sectors can be seen in **Figure 2.8.3** and they are:

- Immediately upstream of the culvert - where the flow path converging (contraction) towards the opening of the structure.
- Flow at entrance, through, and exit of the culvert – losses occur due to roughness, length, entrance and exit conditions.
- Immediately downstream of the culvert – where the flow diverges (expansion) out from the structure, (Brunner, G. W. 2008).

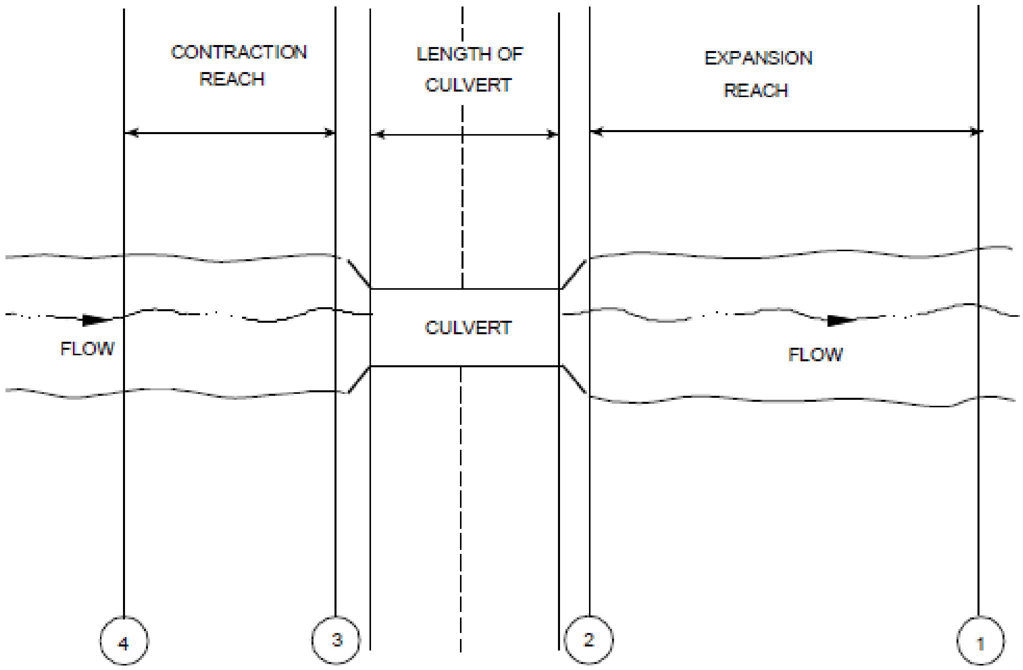


Figure 2.8.3: Sections of energy loss, (Brunner, 2008).

Important factors and characteristics:

- When modelling low gradients channels/rivers HEC-RAS has a 1.2% validation error, as for high gradients the accuracy suffers from a 20.8 % error. High gradients cause drastic energy changes in the model, the default settings will recommend that more cross-sections be used, (May, Lopez, & Brown, 2000).

- In spacing of cross section of a channel are to far apart it results in computation of the algorithm becoming unstable and HEC-RAS has difficulties balancing the energy equation. Therefore the number of cross sections needs to be increased. Several additional sections can be added closer to the inlet and outlet of culvert, (Heasted Meathods, Dyhouse, Hatchett, & Benn, 2003).

- Extra cross section should be placed at the beginning and end of contraction or expansions. Coefficients for contraction and expansions for single conduit are 0.6 and 0.8 respectively according in Floodplain Modeling using HEC-RAS, (Heasted Meathods, Dyhouse, Hatchett, & Benn, 2003).

- The HEC-RAS software is calibrated with use of the Manning's roughness coefficient (n-value). In the case of different material used around the perimeter of the culvert, the friction losses are determined separately (for each side) and added. An example of different materials would be an alluvial base and three concrete culvert sides, (May, Lopez, & Brown, 2000; Philip, & Creamer, 2007).

- The software takes the velocity head into consideration in the determination of the hydraulic energy line. This is unlike various theoretical methods where the head water elevation or energy grade line at the culvert inlet is the same of the water level at the inlet therefore, taking velocity head at the entrance as negligible, (Heasted Methods, Dyhouse, Hatchett, & Benn, 2003).

- In the simulation process the software finds that the headwater energy depth above the invert of the culvert inlet is higher for inlet control than the one for the outlet control, the software will carry out additional calculations to verify that the culvert is not flowing full at any point inside the culvert. If it is found that a hydraulic jump forms inside the conduit and a culvert flowing full the program will instantly declare a system as outlet controlled at that point of simulation. This effect can be seen on the performance cure below (**Figure 2.8.4**). The accuracy of the inlet control computations is 10%, (Brunner, 2008).

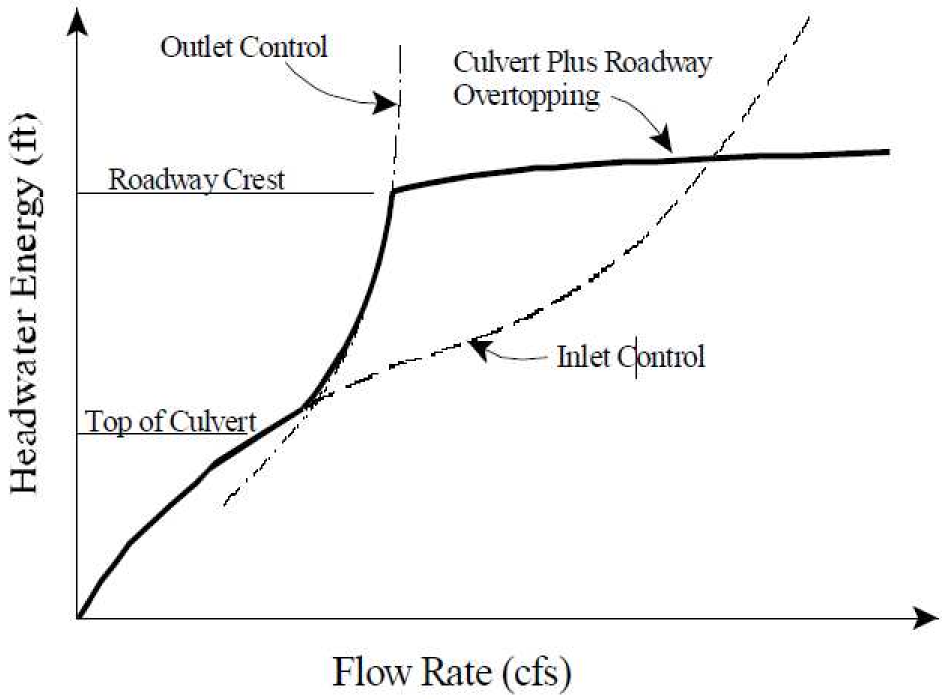


Figure 2.8.4: Performance curve, (Brunner, 2008).

2.9 HY-8 software

HY-8 software can be used for hydraulic design of highway culverts. The program produces results and put emphasis on its performance curves, (**Figure 2.9.1**). The program produces study of: multiple culvert barrels at a single and multiple intersections; roadway overtopping; and report in form of graphs tables and all important input variables of the analysis, (Norman, Houghtalen, & Johnston, 2001).

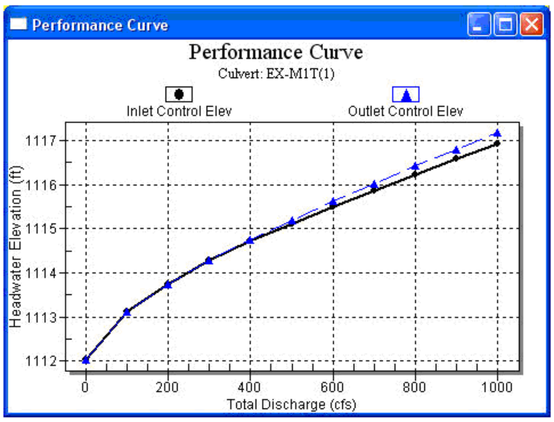


Figure 2.9.1: Discharge rating curve, (Norman, Houghtalen, & Johnston, 2001).

In the situation of the water level at the inlet exceeding the road level, overtopping will take place, (**Figure 2.9.2**). When the software runs the overtopping scenario the system will determine the discharge for every culvert opening and the weir flow over the roadway that will produce the same water elevation at the inlet, (Norman, Houghtalen, & Johnston, 2001).

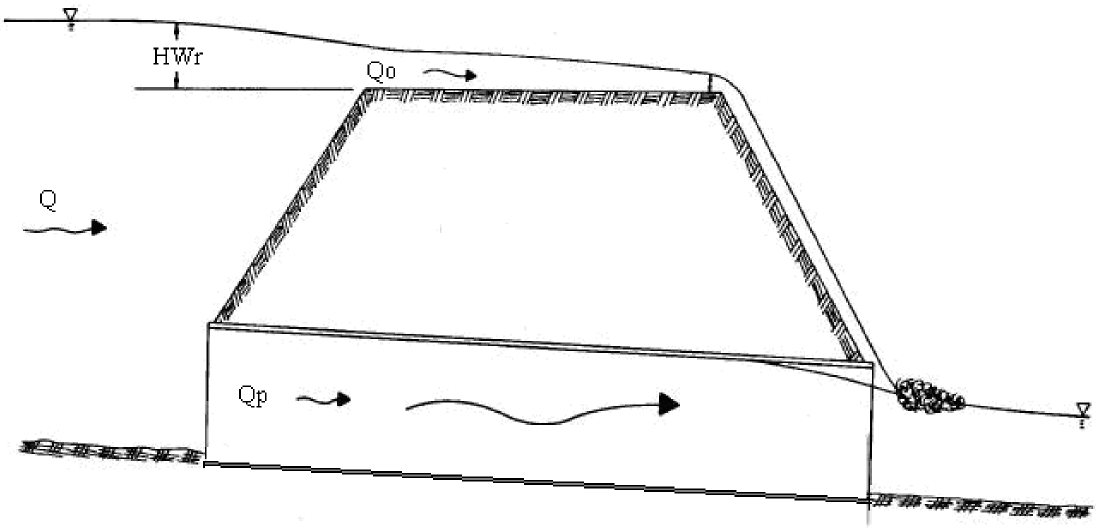


Figure 2.9.2: Overtopping of the culvert structure, (Norman, Houghtalen, & Johnston, 2001).

The program requires a hydrological study that engages the estimation of design discharge based on watershed and climatological characteristics. The results of such analysis may have statistical uncertainties, unlike the results of hydraulic analysis of the culvert. The hydrological analysis is advisable to perform first, (Norman, Houghtalen, & Johnston, 2001).

<u>New and improved features of the software:</u>

- One of the new features of the software is that the user may bury a conduit to embedment depth. Thus may help with the planning for fish passage function.

- The procedure by burying (depression of the inlet) the inlet may aid in gaining an increase of head for steep culverts under inlet control. Depression is a vertical drop of inlet control below the base of the channel bed, (**Figure 2.9.3**).

- Fall slope is a slope between channel bed and face invert of the culvert. The range of fall slope is set to be between 2:1 and 3:1.

- Crest width is a length of the weir crest at the top of the fall slope. The crest width is an iteration procedure, as the designer needs to select a length large enough so that the crest does not affect the headwater calculations. In the situation when the crest width is not big enough the software will generate a higher head than the conduit throat. The user than needs to iterate the length until it has no effect on the inlet control, (Norman, Houghtalen, & Johnston, 2001).

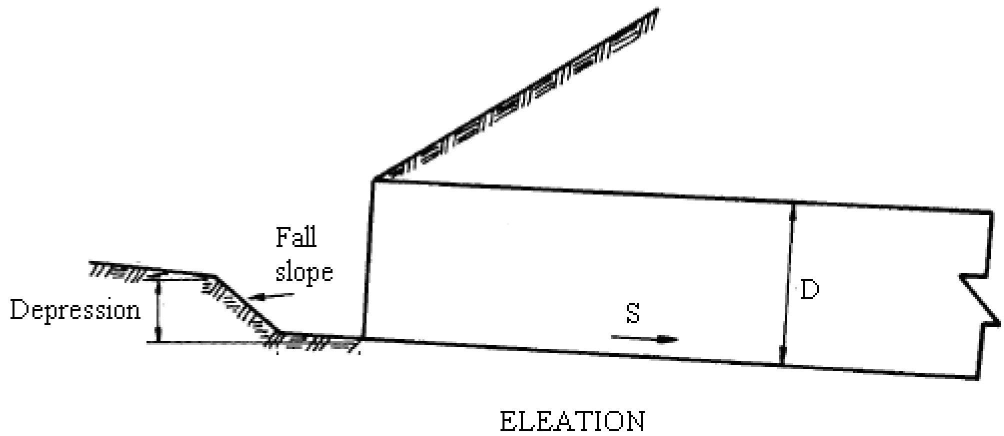


Figure 2.9.3: Depression and fall slope in a culvert structure, (Norman, Houghtalen, & Johnston, 2001).

<u>The three basic culvert inlet types provided by HY-8 are:</u>

- Conventional no additional modifications.

- Side Tapered inlet is with modification to increase performance of the culvert structure by providing efficient upstream control. The inlet has an enlarged elliptical section with conversion to a circular shape culvert.

- Slope Tapered is an inlet with modification to increase performance of the culvert by means of providing fall and better control section at the throat, (Norman, Houghtalen, & Johnston, 2001).

Important fact and characteristics

- In creating discharge rating curves the software analyses both the inlet and outlet control curves, as governing control can be difficult to predict at certain head. Also control may change from inlet to outlet over a range of discharge.

- If culvert under inlet control and does not operate at its capacity, it is advised to flatten the slope of the conduit or increase roughness of the culvert so that the velocity at the outlet is decreased. Thus will result in reduction of erosion at the outlet.

- The software requires at least three cross section of the: inlet, outlet and natural channel to establish the river/channel slopes.

- The Manning's value needs to be determined in order to evaluate projected discharge conditions of the system.

- Conditions that will increase tailwater level during floods needs to be investigated. Such conditions are: downstream impoundments, obstructions, junctions and channel constrictions.

- The software is able to analyse an intersection defined by one to six culverts, and every culvert may have multiple barrels.

- The software enables user to display road maps or an aerial photographs using the Microsoft Virtual Map locator tool.

- The program will analyse the culvert system based on the input minimum and maximum flow rate values. The software will produce discharge ratting curve on ten equal intervals between the input flow rate values.

- If the user wants a 0 % slope of the culvert the software will input 0.000001 m/m slope for calculation purposes, (Norman, Houghtalen, & Johnston, 2001).

CHAPTER 3

Experimental set up

3 Experimental Set Up

3.1 Introduction

The experimental set up for this research is about verification of inlet control equations for a culvert structure. The system will consider upstream control, when the inlet conditions govern the flow and the downstream water level does not affect upstream. The modelling of culvert hydraulics will reflect the procedures to keep the inlet control governing throughout the experimental process.

The experimental set up is based on different modeling approaches of culvert structures. The experimental approaches are as follows: basic theoretical equations, physical modeling and software modeling. The different models shall be compared to gain the feel for accuracy of theoretical application with the physical behaviour. The use of theoretical equations in the modeling software will be reviewed. The culvert parameters of interest are dependent on the shape, entrance conditions and slope of physical model for a consistent comparison and verification.

3.2 Theoretical model

Theoretical modeling approach will put focus on the formula used to determine or analyze culvert capacity. The equations that are used in the analysis are in section **2.6.1**. The theoretical analysis will lead to graphical representation of theoretical discharge rating curve for various sizes and shapes of culverts under inlet control. With the help of graphical comparison between the models and statistical analysis the accuracy of the models can be determined.

3.2.1 Required information and characteristics of model

The characteristics of the theoretical model are dependant on the physical model. The consistency is an important factor in verification of the correlation between physical and theoretical behaviour of the culvert hydraulics.

Assumptions:

- The slope of the culvert, upstream and downstream does not influence the theoretical equation.
- The culvert flows under inlet control at all times, although it could change from unsubmerged to submerged conditions.
- Discharge coefficients, (C_b and C_h) are for square corners are taken as 0.6 and 0.9 for different head to depth ratios of the culvert.

Limitations:

- One –Dimensional hydraulic analysis.
- Uncertainty about the point when the culvert system becomes submerged.
- Different upper and lower limits of ratio between headwater energy depth above the invert of the culvert inlet and inside depth of culvert, (H_1/D) for use of theoretical equations.

Variables:

- Flow that the culvert can transport (m^3/s).
- The headwater energy depth above the invert of the culvert inlet / Head, (H_1 in m).
- Ratio between headwater energy depth above the invert of the culvert inlet and inside depth of culvert, (H_1/D).
- Size of the culvert.
- Shape of the structure.

The shape of the culvert to be modeled is a portal culvert (**Figure 2.2.1**). A portal culvert is similar to a rectangular and a box conduit, but has three sides to it; the base portion of the system is an alluvial material (natural material).

The sizes of the set up were chosen carefully so that the scales of the physical model were not exceeding 1:40, (**Table 3.2.1**). This is done to ensure accuracy when comparing the models.

Table 3.2.1: The sizes of culverts of interest

Culvert sizes	
B / D = 1	**B / D = 1.5**
B x D (mm x mm)	**B x D (mm x mm)**
450x450	450x300
600x600	900x600
750x750	1800x1200
900x900	3600x2400
1200x1200	
1800x1800	
2400x2400	

3.2.2 Hydraulic relationship and procedures

The flow under inlet conditions can be analysed in two different ways depending on H_1 and the H_1/D ratio. The flow through the culvert is unsubmerged when the water level at the culvert entrance is lower than the full height of the culvert and weir flow behaviour can be observed. In the case of submerged entrance the discharge operates as orifice flow, (**Figure 3.2.2**). Therefore there are two sets of equations that are guided by the H_1/D ratio reflecting the submergence and unsubmergence of the system.

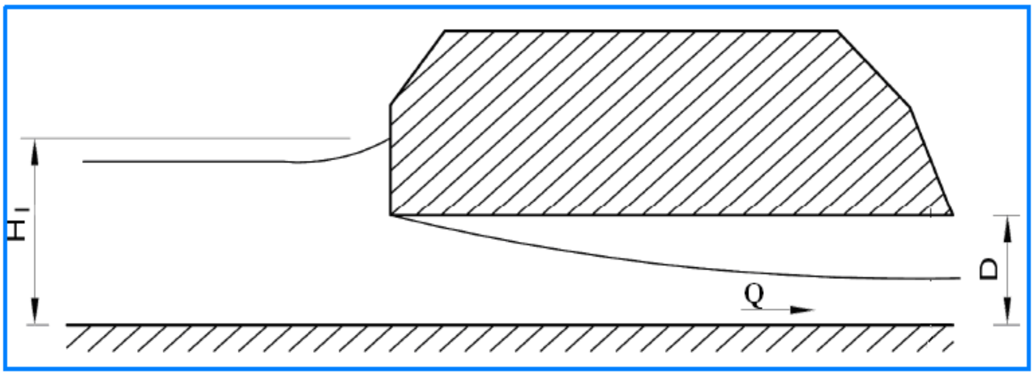


Figure 3.2.2: Inlet control

There are many different theoretical equations that are available for culvert analysis. The alternatives of theoretical formulas for inlet control can be found in the **Table 2.6.1,** section **2.6.1**.

The procedures of theoretical set up as follows:

- The various flow rates will be entered (0-65m^3/s).
- The relative head then will be calculated, (m).
- A graph will be compiled using H_1 vs. Q relationship for all formulas.

3.2.3 Expected results and interpretation

The capacity for various cases can be deduced using theoretical relationship between discharge and water level, referred to as the discharge rating curve (performance curve). The graphical representation is obtained using the inlet control equations. The performance curve will represent the submergence and unsubmerged state of the culvert system.

The expected shape of the curve is a fifth order polynomial curve as it best describes the head-flow values. This also was proven to be the correct shape (order of polynomial regression equation) of the performance curve from a study of the effects of inlet geometry on hydraulic performance of box culverts done by Sterling Jones, Kornel Kerenyi, & Stein, (2006).

3.3 Physical model

The physical modeling of a culvert provides a scaled down real life simulation, which shows the behaviour of flow through the system under inlet control. The culvert modeling of inlet control has various factors that will influence construction of the model. The culvert opening dimensions scaled so that sufficient accuracy is obtained when measuring.

The approach of this set up is to observe and collect data from constructed model. The variables that will have influence on the observed data are: discharge intensity and geometry of the culvert opening. The raw data is to be studied further by means of scaling it up to a standard culvert sizes and evaluation of the water elevation at culvert entrance and flow relationship is to be performed.

3.3.1 Model building

The physical model was build at the Experimental farm on the premises of LC de Villiers. The physical model was constructed to ensure inlet control. The model consists of a culvert box, channel and an outlet box, (**Figure 3.3.1**).

Figure 3.3.1: Physical model

<u>Channel</u>

The constructed channel is a 400 mm wide, 250 mm high and 2300 mm long. The material for the base of the channel was wood and the sides were made of 5mm thick Perspex. The channel rested on a steel frame with hinges to vary the slope of the system. The flow was delivered/pumped through a 50 mm class 6 PVC pipe.

The discharge into the mould produced large waves in the channel, and therefore grid, netting and a Perspex lifting gate with teeth was installed on the upstream side of the channel to reduce wave formation and stabilize the water level and upstream at the entrance of the culvert structure. The set up of the system can be seen in **Figure 3.3.2**.

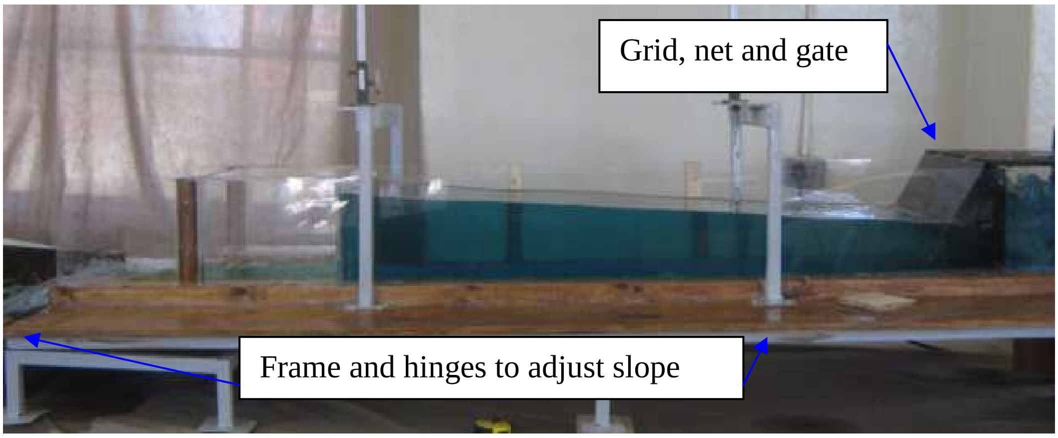


Figure 3.3.2: The channel of the model

Outlet box

The outlet box was constructed so that the outlet control is prevented and there is no submergence occurring on the downstream side of the culvert. The outlet box made out of wood and has a trapezoidal shape. The water from culvert downstream side falls into the outlet box and two 75 mm class 12 PVC pipes in parallel transfers water back to the pump sump. The set up can be viewed in **Figure 3.3.3**.

Figure 3.3.3: Trapezoidal outlet box

Culvert

Two culverts were constructed out of 5 mm Perspex. The design size of the culvert opening was dependent on the flow of water being delivered by the pump and the damming up that will occur at the culvert.

Since the maximum flow of the pump was 0.01 m^3/s the size of the opening had to be less than 100 x 100 mm (cross sectional area is 0.01 m^2). To ensure enough damming occurred (for further analysis) the culvert sizes were determined to be 80 x 80 and 90 x 60 mm (width x height).

The length of the culvert does not influence inlet control, therefore it is not designed but for aesthetical reasons it was decided to be 300 mm in length. The culvert box is a 400 mm wide, 250 mm high and 300 mm long with the opening as mentioned above. The set up can be seen in **Figure 3.3.4**.

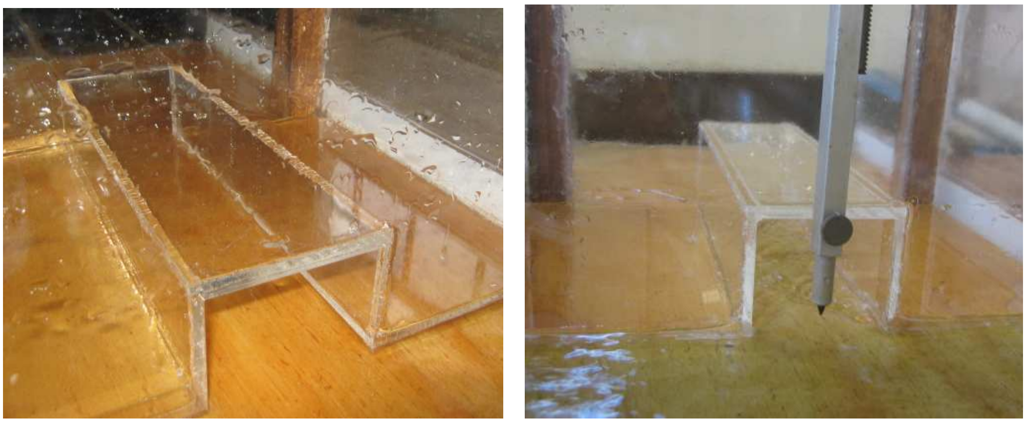


Figure 3.3.4: 90 x 60 and 80 x 80 mm culverts

3.3.2 Required information and characteristics of model

Limitations:

- Slight inaccuracy in measured data can be expected, (human error).
- Slight error of the instruments readings, (instruments accurate to a certain degree).
- Concern to the uniformity/stability of flow delivered by the pump.
- Effectiveness and leveling of the model

Variables:

- Flow (m^3/s).
- Head (H_1 in mm).
- Slope, (m/m).

The information needed for the analysis of this model are the overall model dimensions, and data series obtained from the physical model. Various devices are installed to control and measure the variables of this set up.

<u>Measuring and control devices.</u>

- Pump- V(WQ) Model Submergible sewage pump was used max delivery 10 l/s, (**Figure 3.3.5a**).
- Ultrasonic flow meter. The flow meter was installed upstream of the bypass system, (**Figure 3.3.5b**). The flow meter measures the flow by means of sending and receiving transducers (transmit signals) in the pipe measuring the difference between two transit times the instrument is able to calculate a flow rate in the pipe, (www.sensorland.com).

a)

b)

Figure 3.3.5: a) pump and b) sensors of the flow meter

- Valves and the by-pass system is the control device for the flow in the system (**Figure 3.3.7**). The by-pass system is build to aid in the flow variation in the system. So that the pump does not deliver max inflow all the time. The by-pass system works as follows: Valve 2 controls the water flow from the pump sump up to the upstream end of the model; Valve 1 discharges the pumped water flow back to the sump. With closing and opening of the valves it is then possible to vary the flow delivered to the channel.

- Point gauges- two point gauges were set up, (**Figure 3.3.6**). One at the culvert inlet (measures the H_1) and the second one upstream of the culvert (measures depth a distance away from the culvert). The measurement of water surface elevation under steady flow conditions. This is accomplished by means of adjusting a rounded point to touch water surface, and taking the readings of depth from a scale/venire at the top of the instrument, **Figure 3.3.6**. The depth measured of the water is relative to the position of the instrument in the model, therefore the first reading is taken to the channel base. The point gauge used has a scale up to 600 mm.

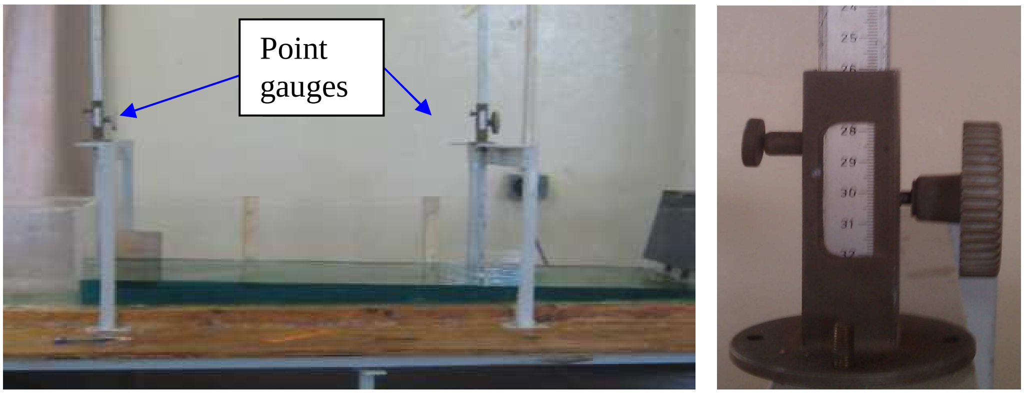


Figure 3.3.6: Two point gauge set up

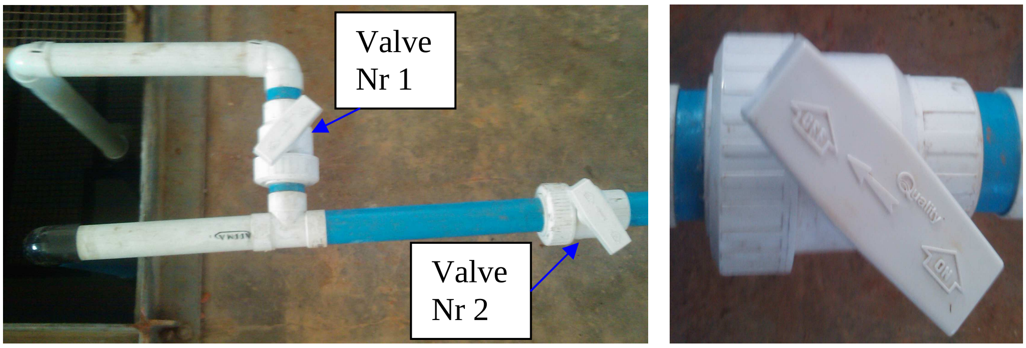


Figure 3.3.7: By-pass system; closing/opening the valve.

3.3.3 Hydraulic relationship and procedures

The factors that will have an influence on the inlet control are: discharge intensity and geometry of the culvert opening. The culvert opening dimensions scaled so that accuracy of measurements will not be compromised. The maximum scale of the model is taken as 1:40 as anything bigger may compromise the accuracy of the readings obtained from the model.

The scaling of the model is done by means of Froude uniformity. Froude's law of similarity contains the gravitational and kinetic forces, which are the main factors influencing the fluid flow. The following relationships were obtained from Froude's uniformity:

$Fr_P = Fr_{M,}$

Which is:

$$\frac{v_p}{\sqrt{g \cdot y_p}} = \frac{v_m}{\sqrt{g \cdot y_m}}$$

Where:

$_P$ = prototype (real life size).

$_M$ = model (physical model).

v = velocity (m/s).

And

y = water elevation/head, H (m).

Therefore:

$$\sqrt{\frac{H_P}{H_M}} = \sqrt{n_y}$$

Then

$$H_P = n_y H_M \ ,$$

Where:

H_P = head of prototype, (m).

H_M = head of model, (m).

And

n_x = the x value at the prototype/ the corresponding x value at the model.

And

The n_y and n_l are the vertical and horizontal scales.

And to determine the flow rate:

$$\frac{Q_P}{Q_M} = n_l n_y^{3/2}$$

But $n_l = n_y$ (undistorted model),

$$Q_P = n_y^{5/2} Q_m$$

Where:

Q_P = flow of the prototype, (m^3/s).

And

Q_M = flow of the model, (m^3/s).

For the accuracy of the results of scaling the model is undistorted. The horizontal and vertical scales are equal for all sizes and shapes of interest. The sizes, shapes and scales are shown in the **Table 3.3.1**.

Table 3.3.1: Portal culvert sizes and the scales of the set up

Culvert sizes and horizontal and vertical scales					
Square portal frame			**Rectangular portal frame**		
B x D (mm)	n_y	n_l	**B x D (mm)**	n_y	n_l
450x450	5.625	5.625	450x300	5.0	5.0
600x600	7.50	7.50	900x600	10.0	10.0
750x750	9.375	9.375	1800x1200	20.0	20.0
900x900	11.25	11.25	3600x2400	40	40.0
1200x1200	15.0	15.0			
1800x1800	22.5	22.5			
2400x2400	30.0	30.0			

Procedures

- The various flow rates are acquired by opening/closing of the valves. (0-0.08m^3/s).
- The relative head is then measured by means of point gauges, (m).
- The data gathering is then repeated for the 80 x 80 and 90 x 60 mm culverts at different slopes, (1%, 2% and 3%).
- The raw data measured from the physical model is to be scaled up to a standard culvert sizes.
- The scaled up Q (flow) and H (head) are then plotted on a graph.
- Through the data a trend line is fitted.
- The physical model discharge ratting curve than can be compared to the theoretical curve to draw up a conclusion on the verification of the culvert equations.

3.3.5 Expected results and interpretation

The data gathered from the model should create a curve close to one in the theoretical set up. The data series shall not have major outliers as the measurement techniques were carefully carried out. It is expected that the data series will follow a curve pattern similarly to the theoretical set up.

Therefore the data series will be trend lined to a regression polynomial of fifth degree, as this will provide a clear view of possible differences and concrete similarity in the natural and theoretical relationship of discharge and headwater energy depth above the invert of the culvert inlet/head.

For the purpose of the analysis the regression curve will be checked by calculation of *Coefficient of Determination*, (R^2). The coefficient is used to evaluate the efficiency of a polynomial and any other regression curve. In other words the R^2 is a square of the correlation between H_1 and Q. The R^2 is a percentage in accuracy of the curve; therefore the closer it is to one the better performance curve is represented, (Montgomery, & Runger, 2007).

It is also expected that the different slope set ups will have no effect on the physical discharge rating curve; in other word they should very closely the same.

3.4 HEC-RAS model

The hydraulic modelling was undertaken using the HEC-RAS, Version 4.1, developed by the US Army Corps of Engineers. The model was set up to operate in the SI unit system.

The information needed for HEC-RAS culvert modelling is: inlet geometry, geometry of upstream and downstream, geometry of culvert, the material characteristics of the culvert and the channel/river, and boundary conditions for flow analysis.

When all the necessary data is inputted in the program the program can analyse the system. After the analysis has been performed the software provides results/output of its computations in a tabular and graphical format.

3.4.1 Characteristics of the model

Assumptions:

- Energy losses immediately upstream of the culvert – K = 0.5, for a headwall parallel to the embankment.
- Energy losses immediately downstream of the culvert – K = 1.

Limitations

- The accuracy of the inlet computations is 10%, section **2.8.1**.
- When modelling low gradients channels/rivers HEC-RAS has a 1.2% validation error, as for high gradients the accuracy suffers from a 20.8 % error, section **2.8.1**.
- In spacing of cross section of a channel are to far apart it results in computation of the algorithm becoming unstable and HEC-RAS has difficulties balancing the energy equation, section **2.8.1**.

Variables:

- Flow profiles (m^3/s).
- Head (H_1 in m).

3.4.2 Hydraulic relationship

There are two equations for an unsubmerged inlet condition, from a theoretical perspective the first equation is more applicable, and the application of the second equation is much easier. HEC-RAS uses both equations in computation of the results. The equations can be found in **Table 2.6.1**, section **2.6.1**.

3.4.3 Software set up

The require information to set up a HEC-RAS model that varies with the culvert dimensions can be seen in **Table 3.4.1**. There are number of tab to be filled out before the program runs analysis, they are: geometric data schematic layout, cross sections, culvert characteristics and flow data for boundary conditions.

Table 3.4.1: Data required in setting up the HEC-RAS model

Required information for analysis / Culvert sizes	Width of the channel (m)	Length of the channel (m)	Length of the culvert (m)	Height of the right/left banks (m)	Max. flow (m^3/s)	5 cross-sections on interval of (m)
450x450	2.25	13.0	1.7	1.4	0.7	2.6
600x600	3.0	17.3	2.3	1.9	1.5	3.5
750x750	3.75	21.6	2.8	2.3	2.0	4.3
900x900	4.5	25.9	3.4	2.8	3.0	5.2
1200x1200	6.0	34.5	4.5	3.8	7.0	6.9
1800x1800	9.0	51.8	6.8	5.7	18.0	10.4
2400x2400	12.0	69.0	9.0	7.5	35.0	13.8
450x300	1.0	11.5	1.5	1.25	0.5	2.3
900x600	2.0	23.0	3.0	2.5	2.0	4.6
1800x1200	4.0	46.0	6.0	5	12.0	9.2
3600x2400	8.0	92.0	12.0	10	62.0	18.4

Fixed data for the set up:

- The shape of the channel is rectangular; the dimensions are available in **Table 3.4.1**.
- The standard contraction coefficient and expansion coefficient are 0.1and 0.3 respectively.
- Manning friction coefficient ("n" values), main channel n = 0.018, ($s/m^{1/3}$) left/right banks n = 0.018, ($s/m^{1/3}$).
- Extra cross section will be placed at the beginning and end of contraction or expansions.
- Coefficients for contraction and expansions are 0.6 and 0.8 respectively.
- The slope is 1%, as a higher slope may decrease the accuracy of the results, section **2.8.1**.
- Roughness of the culvert ("n" value) is 0.012, ($s/m^{1/3}$).

3.4.4 Expected results and interpretation

Software analysis

- The software takes the velocity head into consideration in the determination of the hydraulic energy line.
- In the culvert simulation process the control should be specified to the inlet control as it is the control of the study.
- If the software finds that the headwater energy depth above the invert of the culvert inlet is higher for inlet control than the one for the outlet control, the software will carry out additional calculations to verify that the culvert is not flowing full at any point inside the culvert.

Results

The results that the software produces are: rating curves, velocity distribution output graphs, cross section and profile of the system, water surface profile, general profiles, X-Y-Z perspective plots, detailed tabular output at single location and summary tabular output at many cross sections. The main results of interest are the rating curve.

The rating curves are obtained at the specific cross section in the schematic layout. The upstream cross section of the culvert is the section where the software will produce a curve for the culvert structure. The graph will represent water surface elevation and flow rate relationship. The obtained discharge rating curves then can be compared to the theoretical model results.

Graphical representation will provide a good feel if the program running successfully. The errors in the input data of the software can be easily spotted with visual results. The program also creates an errors document that will give guidance on possible needed in changes in the set up.

3.5 HY-8 model

3.5.1 Characteristics of the model:

<u>Limitations</u>

- The culvert data editor has limited amount of culvert entrance conditions and types of fill above the culvert.
- The values of head water elevation and flow in the results table slightly differ to the values of the performance curve, which were produced by the program.
- The software rounds up all the inputted values to the 3 decimal place.

<u>Variables:</u>

- Max. Flow (m^3/s).
- Head (H_1 in m).
- Channel characteristics, (m).

3.5.2 Hydraulic relationship

There are two equations for an unsubmerged and one for the submerged conditions under inlet control. The software uses all the equations to obtain the best discharge rating curve for the culvert system. The equations can be found in **Table 2.6.1**, section **2.6.1**.

3.5.3 Software set up

The program does not require large amount of the data input for a single culvert analysis. The software has one editing tab for a culvert system. There are many options on the tailwater data and site data inputs, on main editing tab. The option of rectangular channel was chosen as it is the same as the physical model set up. Culvert invert data was chosen for the site data section, as the fill above the culvert is rectangular. The set up requires input of the max flow so that it could create its own flow profile. The inputted value in the crossing data/culvert data tab can be seen in the **Table 3.5.1**.

Table 3.5.1: Data required in setting up the HY-8 model

Required information for analysis / Culvert sizes	Width of the channel (m)	Crest length (m)	Crest elevation (m)	Max. flow (m^3/s)	Design flow (m^3/s)
450x450	2.25	2.25	1.4	0.7	0.7
600x600	3.0	3.0	1.9	1.5	1.5
750x750	3.75	3.75	2.3	2.0	2.0
900x900	4.5	4.5	2.8	3.0	3.0
1200x1200	6.0	6.0	3.8	7.0	7.0
1800x1800	9.0	9.0	5.7	18.0	18.0
2400x2400	12.0	12.0	7.5	35.0	35.0
450x300	1.0	1.0	1.25	0.5	0.5
900x600	2.0	2.0	2.5	2.0	2.0
1800x1200	4.0	4.0	5	12.0	12.0
3600x2400	8.0	8.0	10	62.0	62.0

Fixed data for the set up:

- The shape of the channel is rectangular; the dimensions are available in **Table 3.5.1**.
- Manning friction coefficient (“n” values), main channel n = 0.018, ($s/m^{1/3}$) left/right banks n = 0.018, ($s/m^{1/3}$).
- The slope was chosen to be 1%.
- Length of the culvert was set to be 10m as it does not effect the inlet control computations.
- Top width was set to the length of the culvert, due to the fact that the fill above the culvert needed to be rectangular shape as in the physical model.

3.5.4 Expected results and interpretation

Software analysis

The software performs culvert analysis under inlet and outlet control simultaneously. The program determines all the variables of the culvert system and the channel. The system also produces a table with flow types that approaching the culvert entrance. The system warns on possible hydraulic jumps occurring inside and upstream of the culvert.

Results

The software produces:

- Crossing summary table and its performance curve.
- Culvert summary table and its performance curve.
- Water surface profiles.
- Improved inlet tables.
- Customized by user tables.

3.6 Procedures to obtain results

All the necessary data for all the set up is to be logged in the Excel spreadsheets, (on the supporting CD in **Appendix C**) for the analysis of the set up mentioned in **Chapter 3.** The output data from the programs is extracted to the spreadsheets for further analysis. The acquired data sets for the models is then compared, and presented in a chart form in **Chapter 4.**

CHAPTER 4

Results

4 Results

4.1 Theoretical model

The theoretical model was analyzed and the performance/discharge rating curves were acquired for 3 different sets of equations from section **2.6.1, Table 2.6.1**. The curves show similar shapes, (**Figure 4.1.1**). The inlet control under unsubmerged conditions shows the same trend but as the system becomes submerged the curves shift apart as the difference in upper and lower limit of H_1/D ratio differ for different sets of equations. The same analysis was done for all culvert sizes in **Table 3.1.1**, section **3.1.1**, the performance curves can be found in **Appendix B** and in Excel spreadsheets on the supporting CD, attached in **Appendix C**.

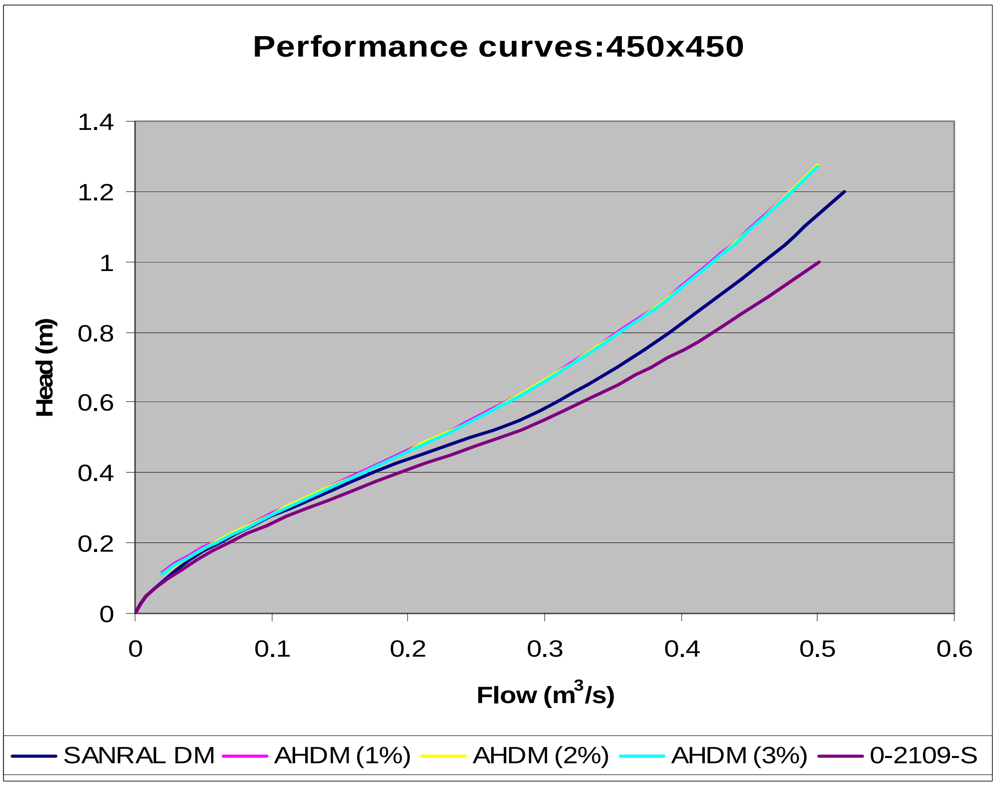


Figure 4.1.1: Discharge rating curves for a 450 mm x 450 mm culvert

Where:

SANRAL DM = SANRAL Drainage manual chapter 7.

AHDM = American Hydraulic Design Manual, (Slope in degrees), chapter 8 section 3

0-2109-S = Report project Nr 0-2109-S

The performance curves for rectangular (**Figure 4.1.2**) and box culverts show the same pattern, same unsubmerged conditions results and a bit shifted upwards/downwards curves result for submerged conditions. The values and spreadsheets that were used to produce the performance curves can be found on the supporting CD.

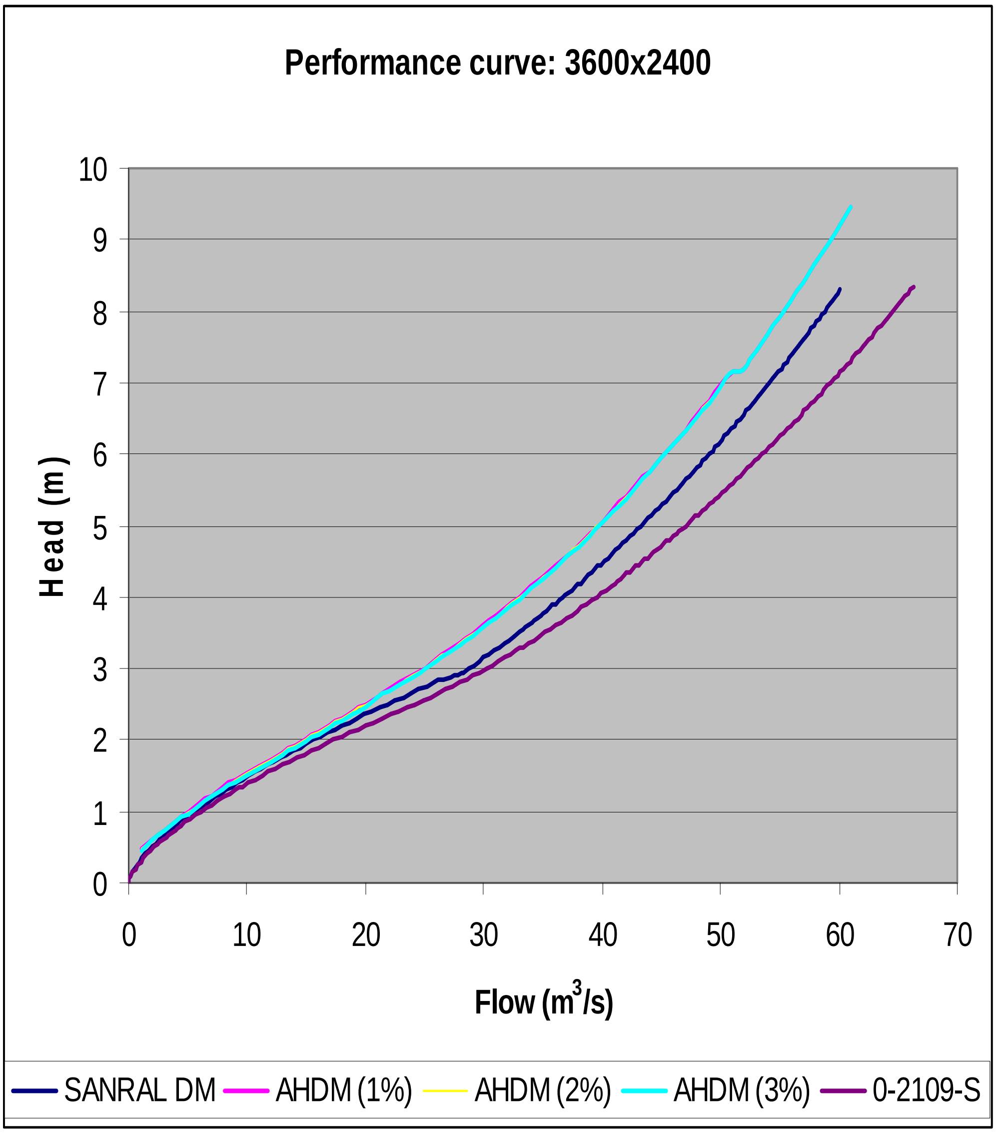


Figure 4.1.2: Performance curve for rectangular shape culvert, 3600 mm x 2400 mm

4.2 Physical model

The data required for physical model analysis was obtained and scaled up to a various standard culvert sizes. The raw data, analyzed data and all the spreadsheets are available on a supporting research project CD.

The graph in **Figure 4.2.1** shows that the set ups of different slopes are closely similar. Therefore it can be said that the slope of the culvert does not affect the discharge rating curve of the physical model. The performance curves of all the sizes and shapes that were mentioned in **Table 3.1.1** in section **3.1.1** are available in the **Appendix B** and supporting CD.

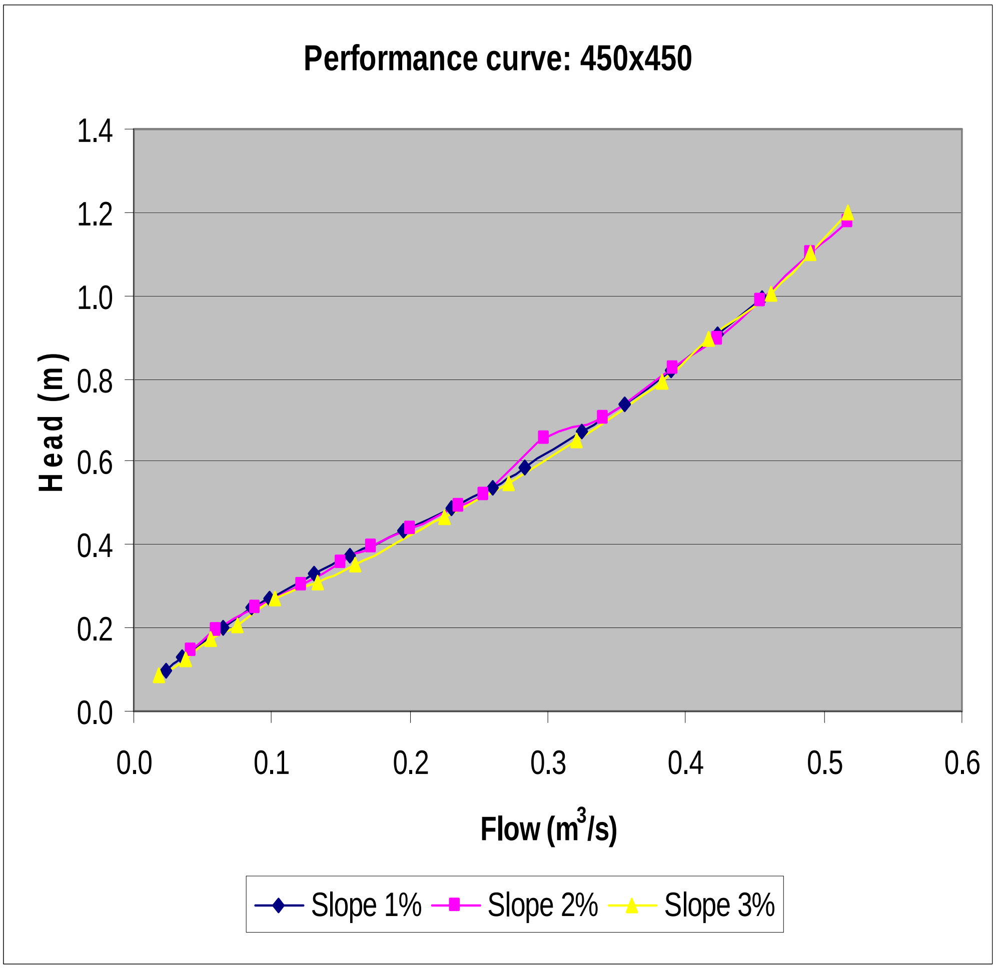


Figure 4.2.1: Performance curve for 450 mm x 450 mm culvert with different culvert system slopes.

The physical model data was fitted with a trend line, (fifth polynomial equation) as it best describes the submerged and unsubmerged conditions of the culvert system. The polynomial equation can be seen in **Figure 4.2.2** and **Appendix B**. The Coefficient of Determination, (R^2) was determined to be very close to 1 therefore the fitted fifth order polynomial describes the data range well.

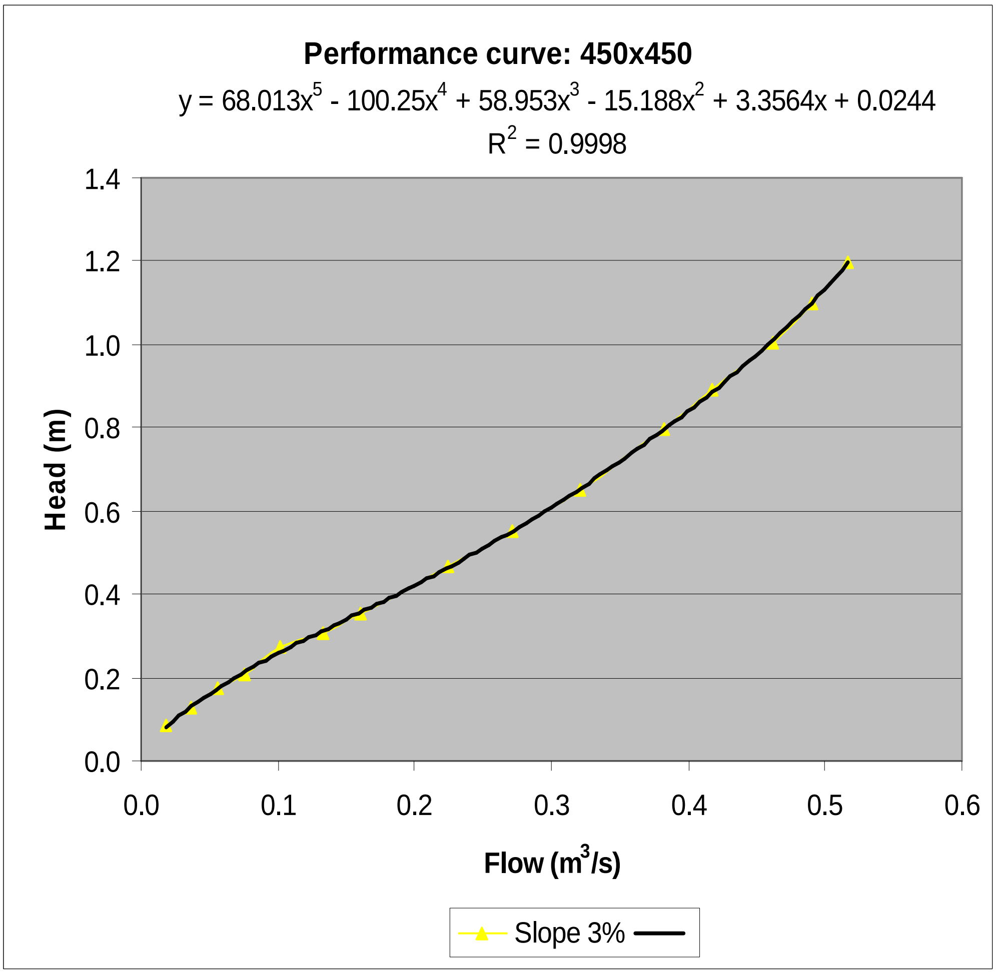


Figure 4.2.2: Performance curve and equation for 450 mm x 450 mm culvert

The data obtain from the physical model produced a curve close to one in the theoretical set up. The data series follows the performance curve pattern of the theoretical model for the equations from SANRAL drainage Manual Chapter 7, (**Figure 4.2.3**).

The curve from AHDM equations shifts upward and shows a lower performance of culvert structure under submerged inlet conditions, as the culvert system experiences higher head water elevation at same flow rates as the physical model. The rating curve from Project Report 0-2109-S equations shows a higher performance of the culvert under submerged inlet conditions, (**Figure 4.2.3**).

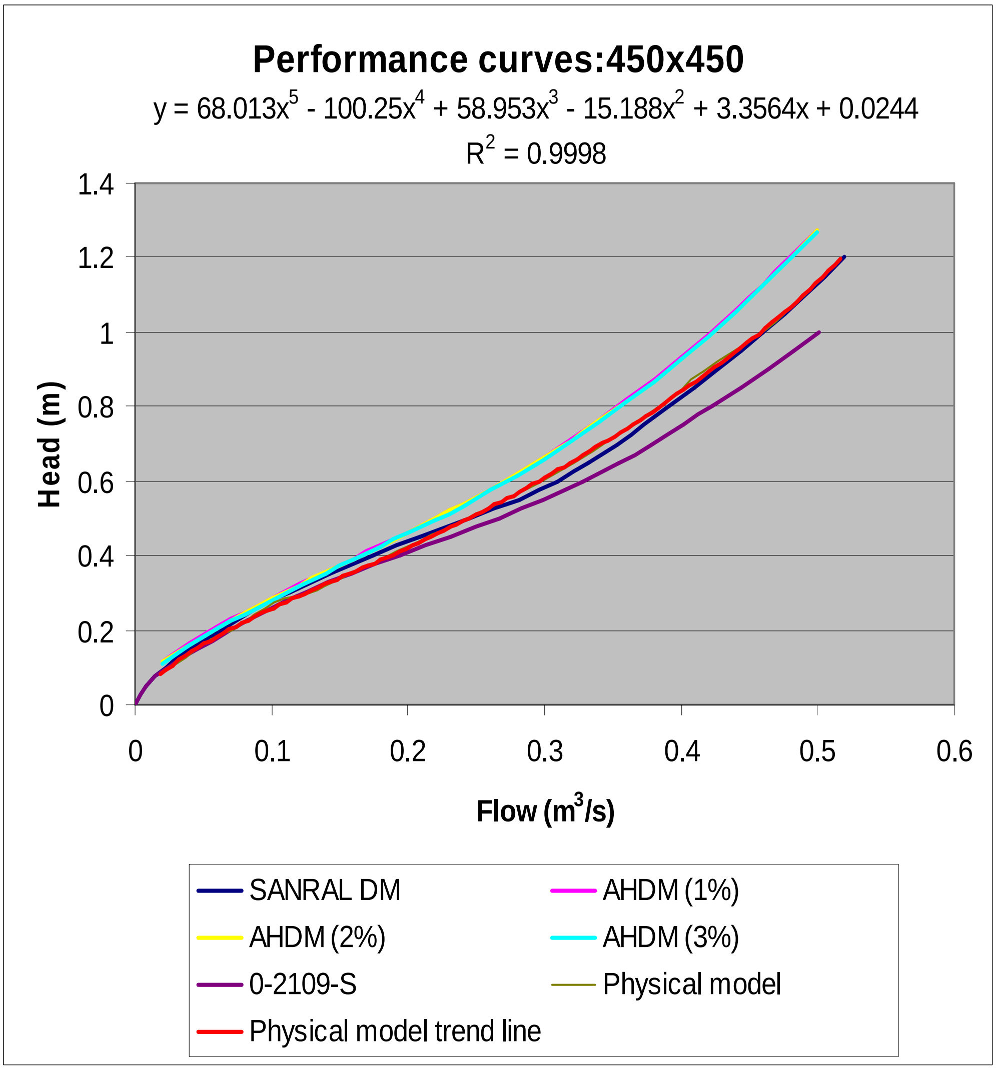


Figure 4.2.3: Physical and theoretical performance curves

The similarity of pattern between the theoretical and physical discharge rating curve is best shown in **Figure 4.2.4**. The theoretical equations that describes the physical model is from SANRAL Drainage Manual mentioned in section **2.6.1 Table 2.6.1**

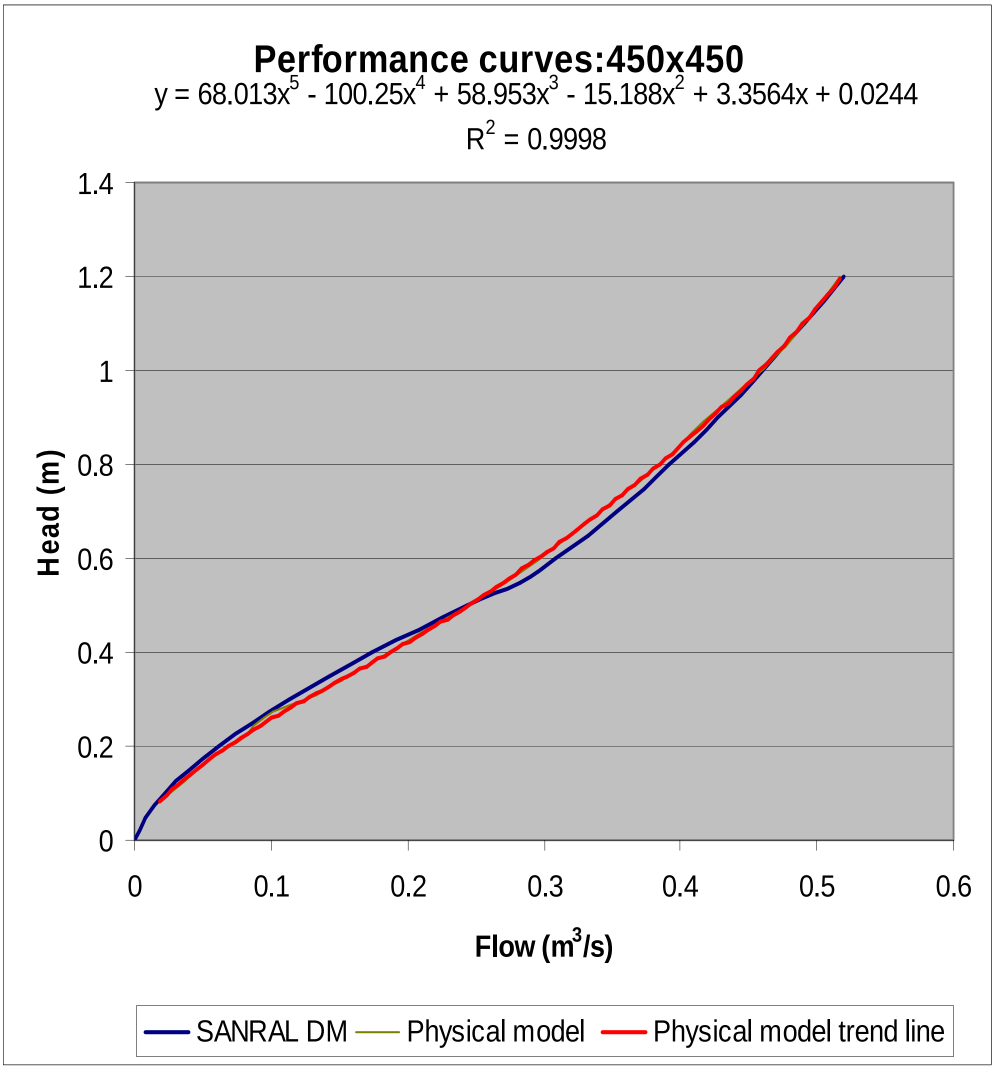


Figure 4.2.4: Physical and theoretical performance curves for 450 mm x 450 mm culvert

4.3 HEC-RAS model:

The data required for HEC-RAS analysis was obtained from the physical model set up and the channel characteristics were scaled up using scales from section **3.2.3**. The analyzed data and tabular format results are available in the HEC-RAS Excel spreadsheets and the software set up files on a supporting research project CD.

The graph in **Figure 4.3.1** shows the performance curve that was obtained from the software. The performance curves of all the culvert sizes and shapes that were mentioned in **Table 3.3.1** in section **3.3.3** are available in the **Appendix B** and supporting CD.

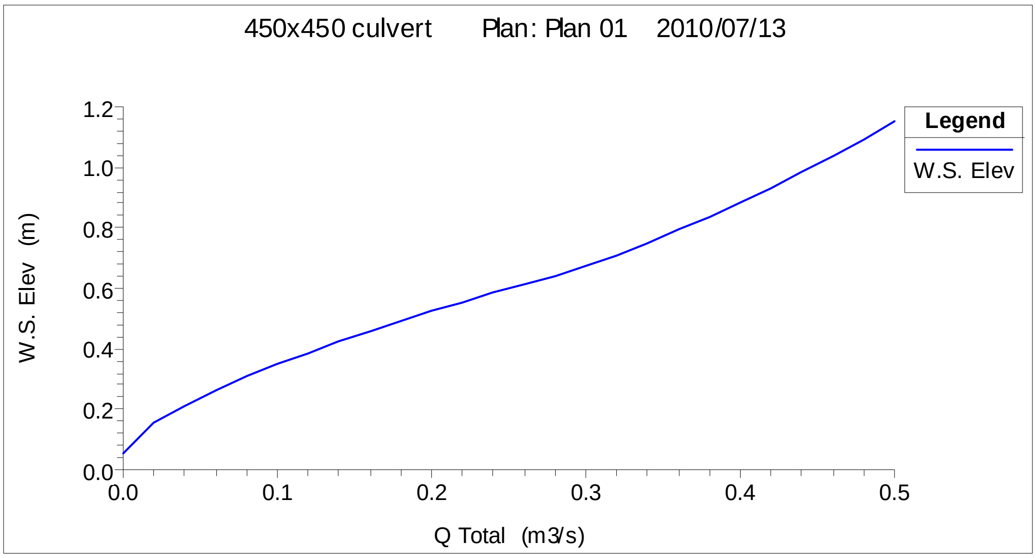


Figure 4.3.1: Discharge rating curve for 450 x 450 culvert

The physical and HEC-RAS discharge rating curve have similar pattern and follow each other under unsubmerged conditions. Under the submerge conditions HEC-RAS shows a slightly lower performance of the culvert, as the head water elevation is higher for the same flow rates of the theoretical model, (**Figure 4.3.2**).

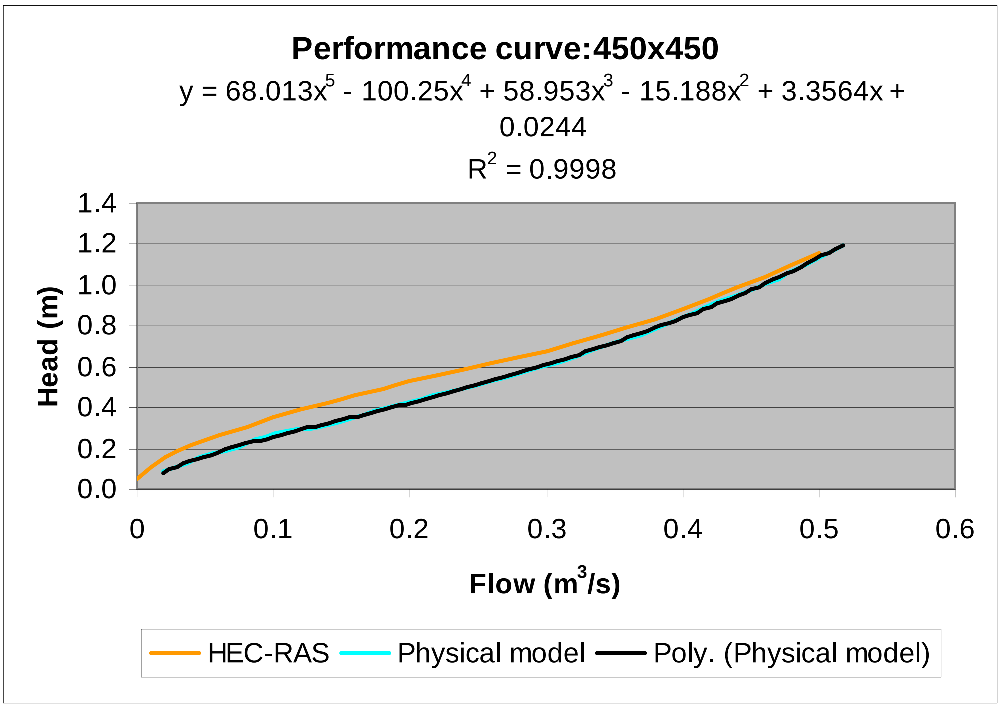


Figure 4.3.2: HEC-RAS and physical model performance curves

4.4 HY-8 model

The data required for HY-8 analysis was the same data used in the HEC-RAS model. The analyzed data and tabular format results are available in the HY-8 Excel spreadsheets and software set up files on a supporting research project CD.

The graph in **Figure 4.4.1** shows the performance curve that was obtained from the software. The performance curves of all the culvert sizes and shapes that were mentioned in **Table 3.4.1** in section **3.4.3** are available in the **Appendix B** and supporting CD.

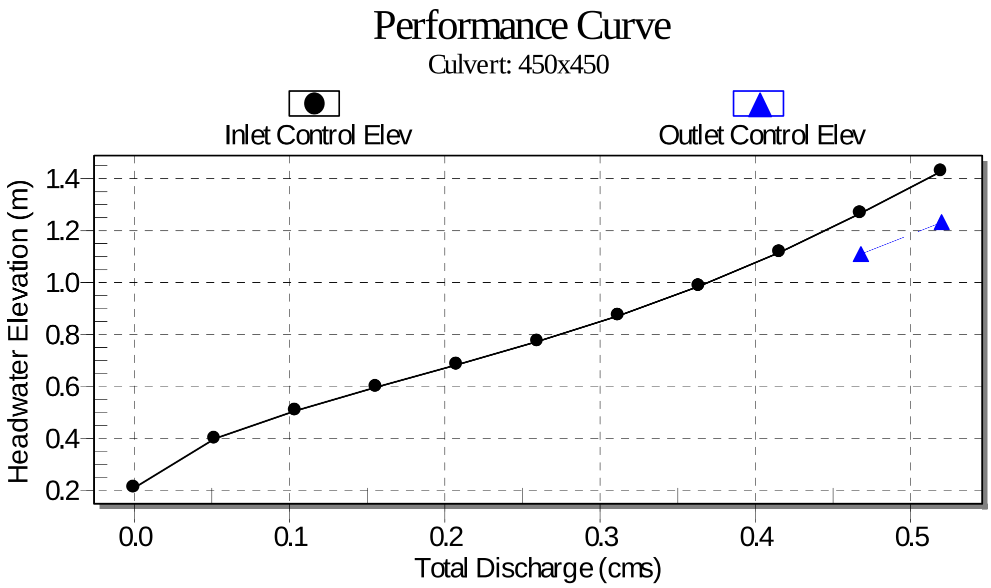


Figure 4.4.1: HY-8 performance curve of 450 x 450 culvert

The physical and HY-8 discharge rating curve have similar pattern and follow each other under unsubmerged and submerged conditions. The curves are not directly on top of each other but apart by fairly constant factor. The HY-8 curve is a factor of 0.93 apart from the physical model, (**Figure 4.4.2**).

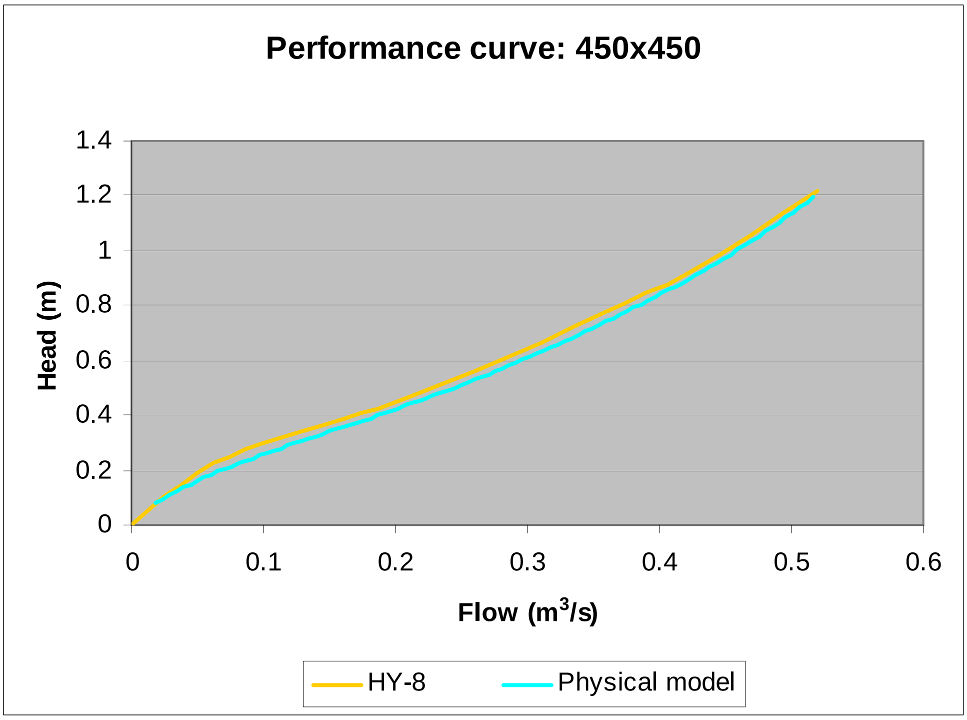


Figure 4.4.2: HY-8 and physical model performance curves

The **Figure 4.4.3** shows the comparison between HY-8, HEC-RAS and physical discharge rating curve. It is then seen that the HY-8 software produces a curve closer to that of the physical model performance curve than the HEC-RAS program.

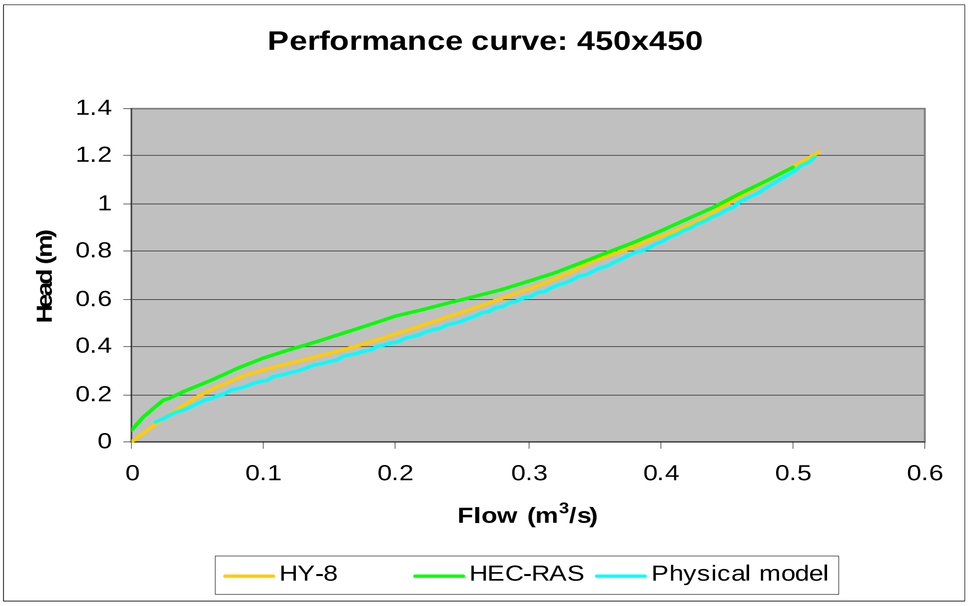


Figure 4.4.3: Comparison of performance curves under different model

CHAPTER 5

Conclusion and recommendations

5 Conclusion and recommendations

5.1 Conclusion

5.1.1 Summary of the results

The results of the study produced a number of discharge rating curves/performance curves for the culvert system under inlet control, for submerged and unsubmerged entrance condition. The study verified the similarity of the theoretical culvert equations and physical performance of the culvert. The study gave the ability to comment on the level of performance of the theoretical equations and of the software application in comparison to the physical relationship of head water level and flow rate, (performance curves) of culvert structures. The study also focused on the effect of the slope of the culver system on the discharge rating curves.

5.1.2 Conclusion on the verification of theoretical culvert equations

The three equations that were analysed for the verification of the relationship between head water elevation proved themselves to have a similar shape as the one of the physical model performance curve, (**Figure 4.2.3,** section **4.2**). The study showed that the equation from the SANRAL Drainage Manual Chapter 7, (**Table 2.6.1**, section **2.6.1**) describes the physical behaviour of a culvert system under inlet control the best. This can be seen from the compared discharge rating curve in **Figure 4.2.4**, section **4.2**.

The study of theoretical culvert equation from the American Hydraulic Design Manual Chapter 8 Section 3 and the Project Report 0-2109-S, (**Table 2.6.1**, section **2.6.1)** shows a similar shape rating curve as the physical model curve and follows the trend under unsubmerged conditions. When the hydraulic inlet control becomes submerged, the curves shift apart from physical rating curve. The curve from AHDM equations shows a lower performance of culvert structure under submerged inlet conditions. The rating curve from Project Report 0-2109-S equations shows a higher performance of the culvert under submerged inlet conditions, (**Figure 4.2.3**, section **4.2**).

5.1.3 Conclusion on the application of hydraulic software

The study shows that the HY-8 program produces a more accurate performance curve as the curve trends the same way as the physical model curve, with an average 93% similarity, (**Figure 4.4.2,** section **4.2**). The discharge rating curves for all the sizes and shapes in the **Table 3.2.1**, section **3.2.1** can be found in **Appendix B** and on the supporting CD in **Appendix C.**

The HEC-RAS analysis resulted in a similar shape and trends of the discharge rating curve as the physical model curve under submerged inlet conditions. In the unsubmerged inlet condition the curve software produces a slightly lower performance of the culvert system. The discharge rating curves for all the sizes and shapes in the **Table 3.2.1**, section **3.2.1** can be found in **Appendix B,** and in the software set up files on the supporting CD.

5.1.4 Conclusion on the performance curves

The discharge performance curves has been acquired for all the shapes and sizes of culverts in the **Table 3.2.1**, section **3.2.1.** The trend of the physical performance curve produced fifth order polynomial equation that can be used in initial hydraulic analysis and design of culvert structures, the equation can be seen on the performance curve charts. The performance curves for the entire models set up can be found in the **Appendix B** and on in the Excel spreadsheets on the supporting CD in **Appendix C**.

5.1.5 Conclusion on the effect of slope on the culvert system

The slope of the culvert system has minimal to none effect on the culvert system under physical model study this can be seen in **Figure 4.2.1** in section **4.2**. The slope of the theoretical model also does not affect the discharge ratting curve, as the equations from the Project Report 0-2109-S and the SANRAL Drainage Manual in section **2.6.1** does not include slope of the system in its computation. The equation from AHDM in section **2.6.1** has slope as variable in its formula, but as seen from **Figure 4.1.1** section **4.1**, the variation in slope (1%, 2% and 3%) does not influence the performance curve. Therefore it may be said that the slope of the culvert system has minimal to no effect on the discharge ratting curve.

5.1.6 Conclusion on accuracy of the study

Possible factors that may affect the accuracy of the study:

- Human error.
- Measuring techniques.
- Reliability of measuring equipment.
- Accuracy of the software, section **2.8**.

5.2 Recommendations

5.2.1 Recommendation on the use of the theoretical culvert equations

The three equations that were studied can be used. The choice of set of equations, (**Table 2.6.2**, section **2.6.1**) depends on the level of performance of culvert desired, but it is advisable to consider various alternatives to obtain the best design/analysis of the culvert system. The theoretical formulas that were verified are only for the inlet controlled culvert systems.

5.2.2 Recommendation on the use of the software application

The use of software allows the designer to model different scenarios of culvert systems, section **2.8-2.9**. The software set up files are available on the supporting CD and were created based on the characteristics and dimensions of the physical model. Therefore the set up files of the programs should not be used as a design set up for other culvert structures. It is advisable to study the software manuals and examples before creating a new project.

5.2.3 Recommendation on the use of the performance curves

The performance curves and their equations can be used in choosing of initial culvert size for the hydraulic analysis and design calculations. It is unwise to use the performance curves for analysis of existing culvert as the characteristics, hydraulics and influences on culvert capacity may vary, see section **2.3-2.5**. The performance curves of this study only apply to the shape and sizes mentioned in **Table 3.2.1**, section **3.2.1.**

5.2.4 Recommendation on the effect of slope on the culvert system

This study shows that the slope of the culvert has minimal to no effect on the relationship of head water elevation and flow rate under inlet control, nevertheless the slope should be taken into the consideration as some culvert systems can have more complex upstream and downstream conditions, section **2.9**.

CHAPTER 6

Reference list

6 Reference list

6.1 Reference list to documents

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6.2 Reference list to photographs

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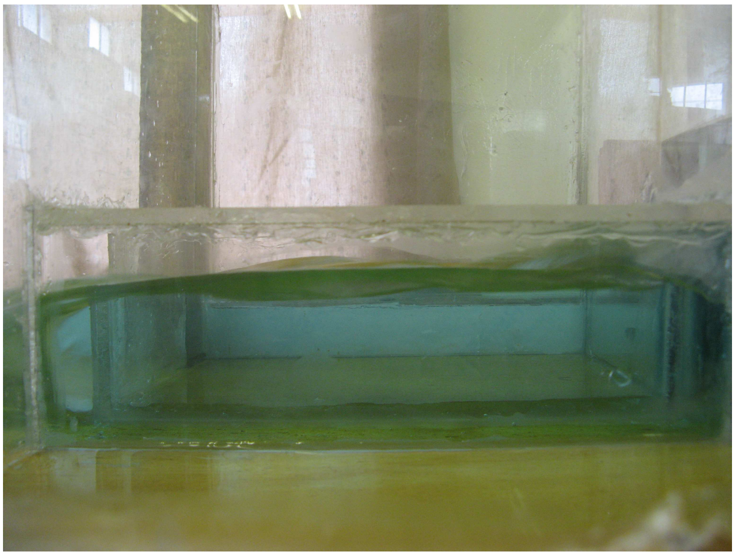
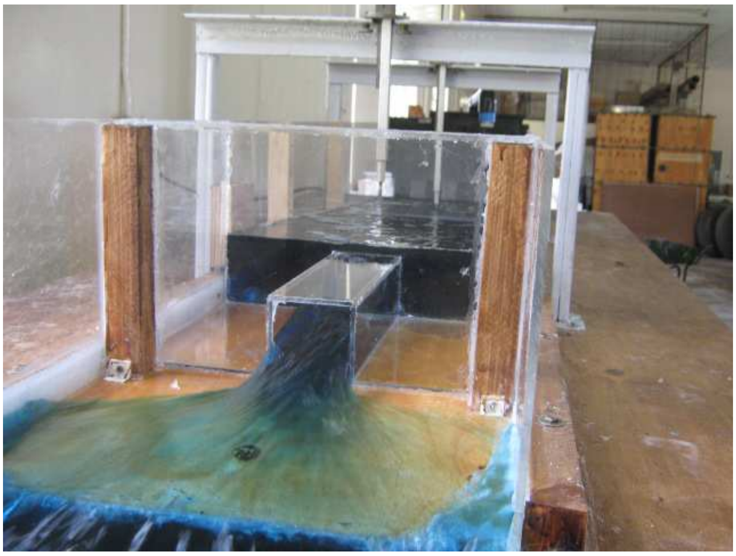
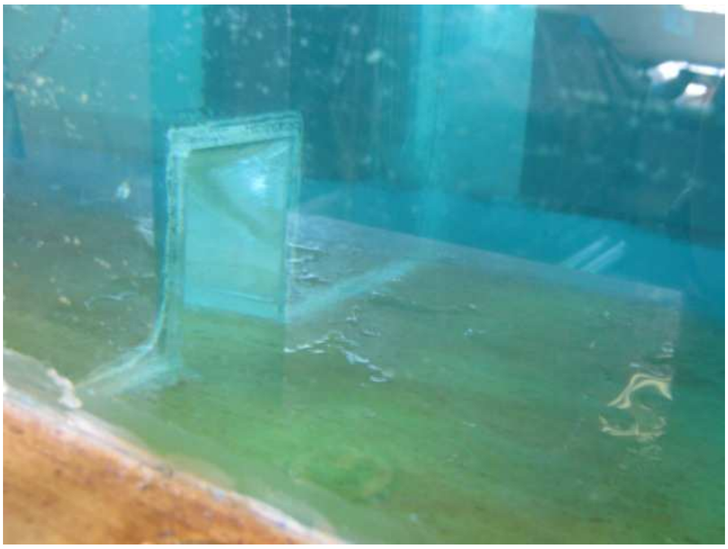
Appendix A:

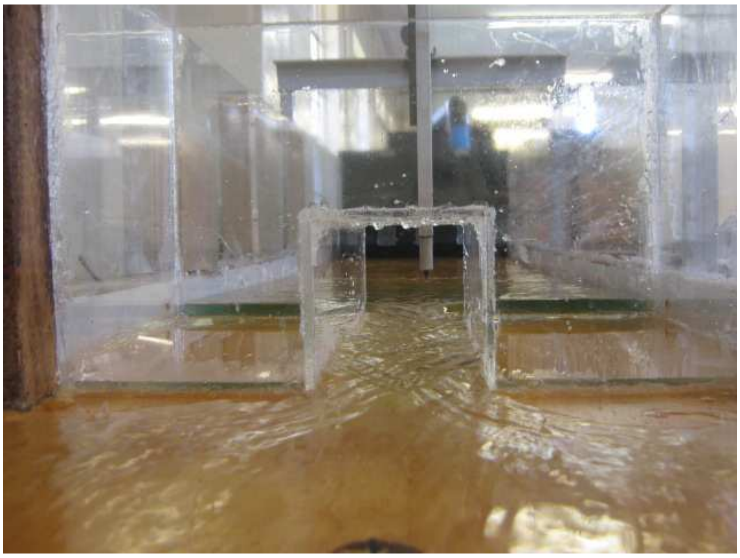
Photographs and images

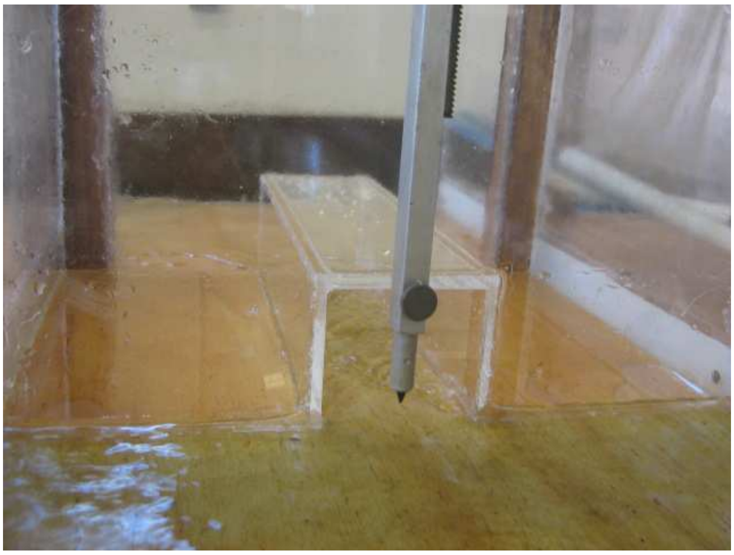
The physical model

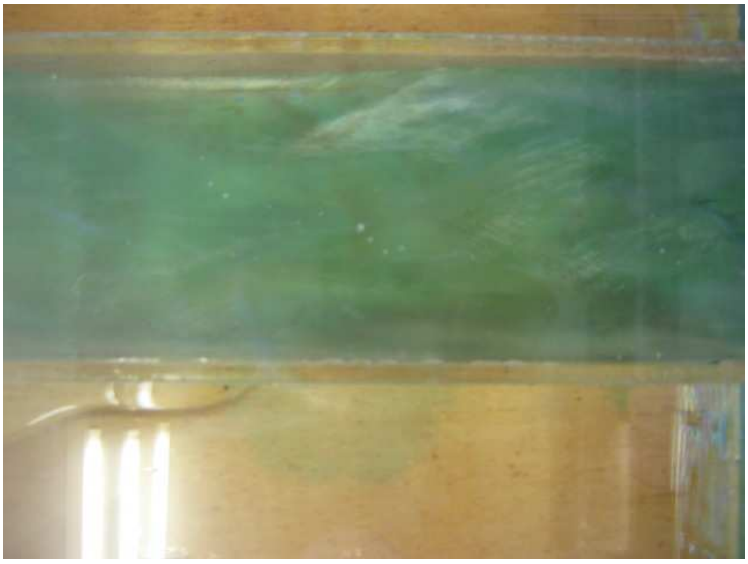
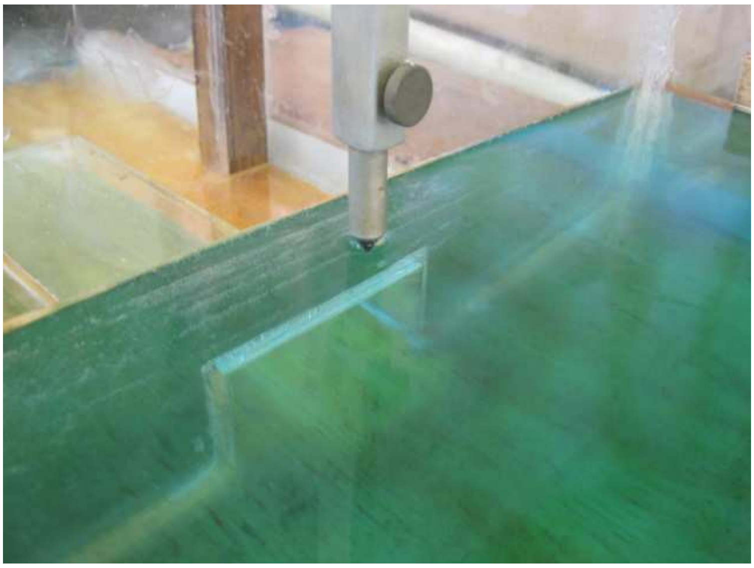
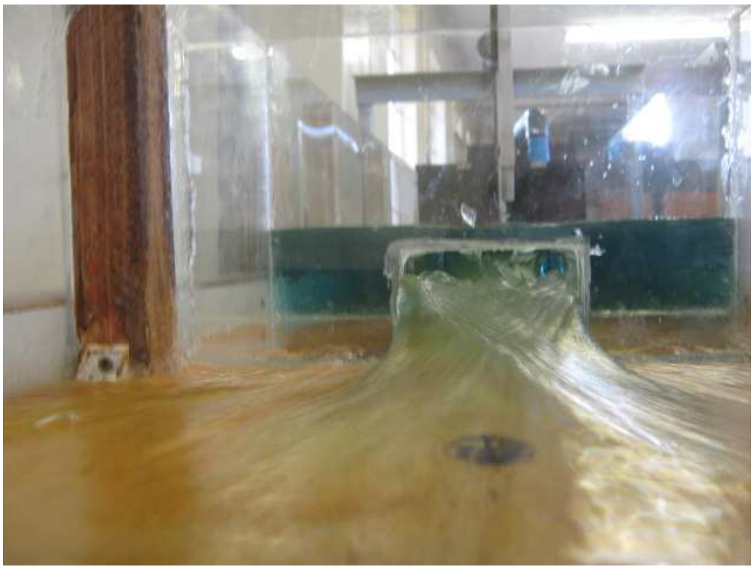


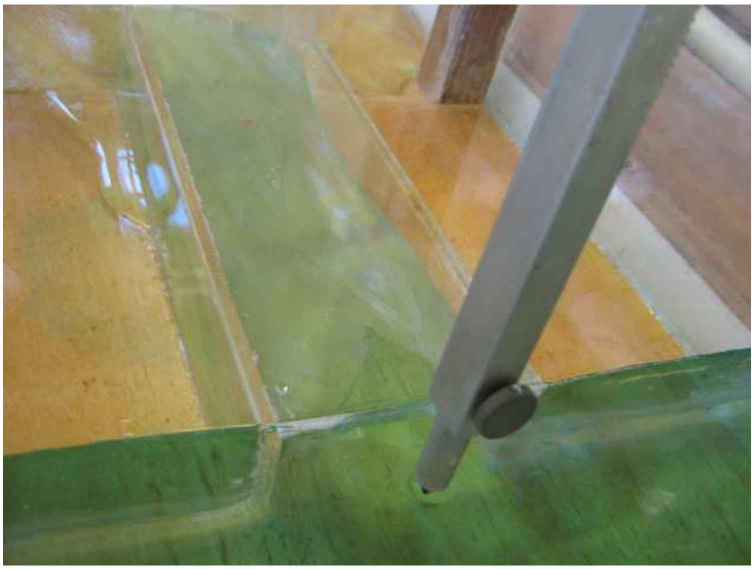
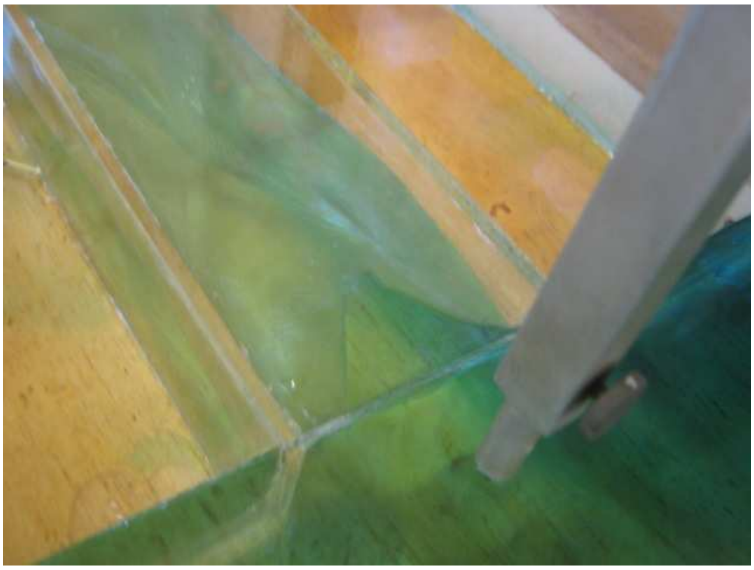


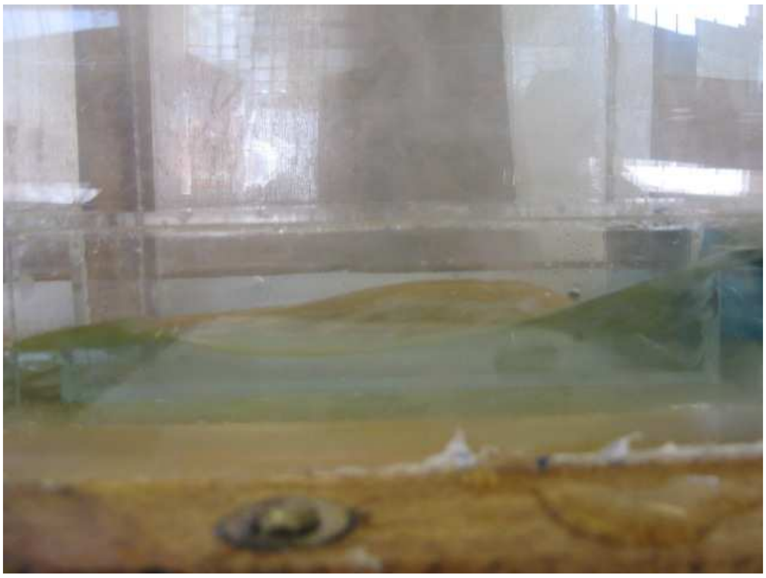


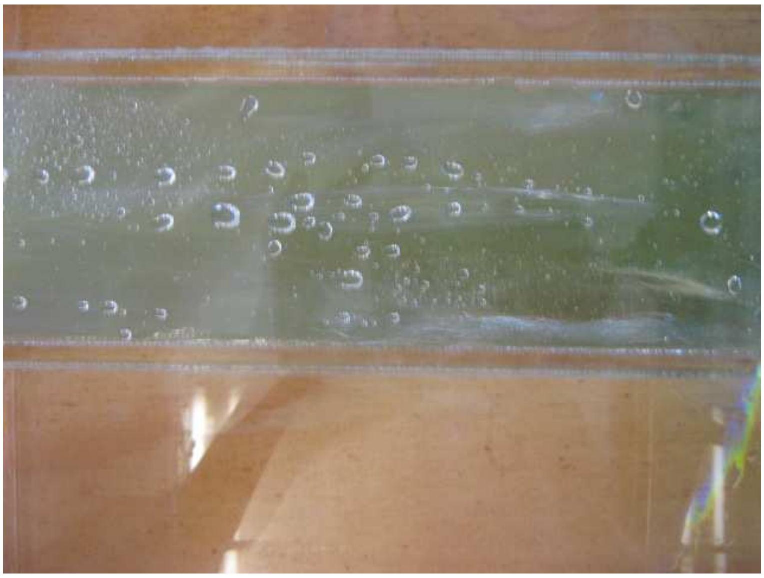


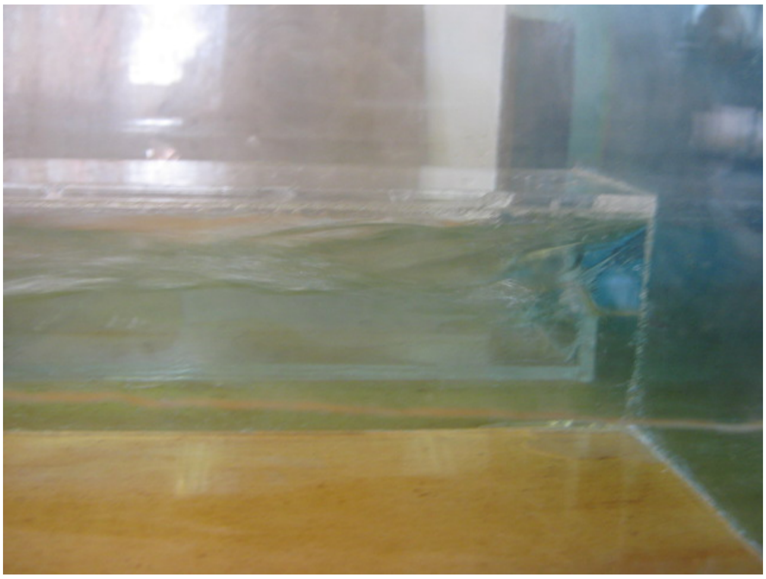


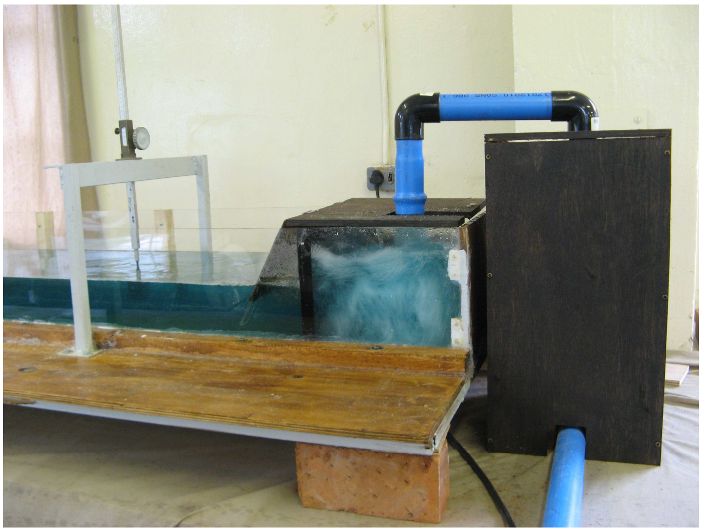
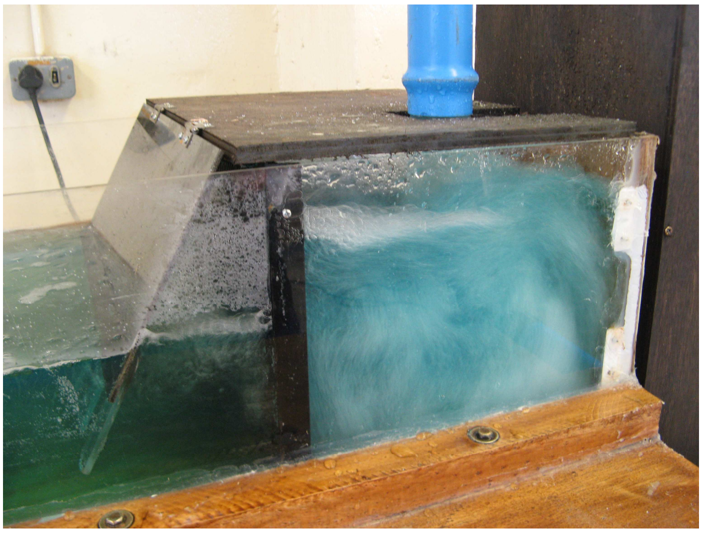
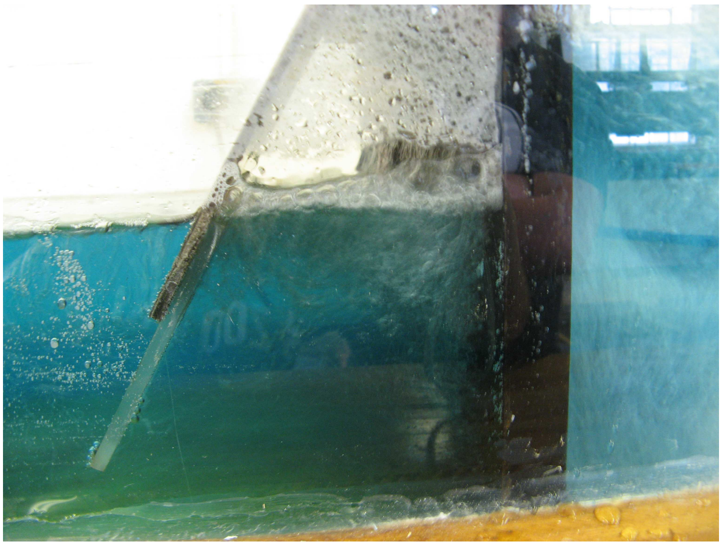




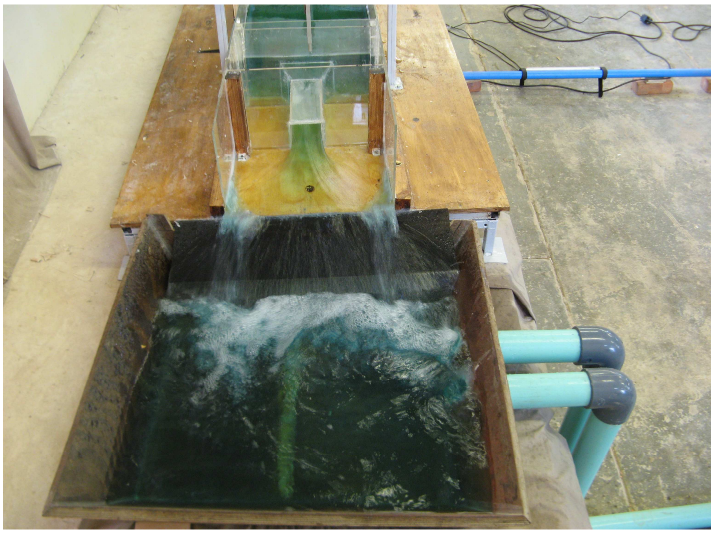



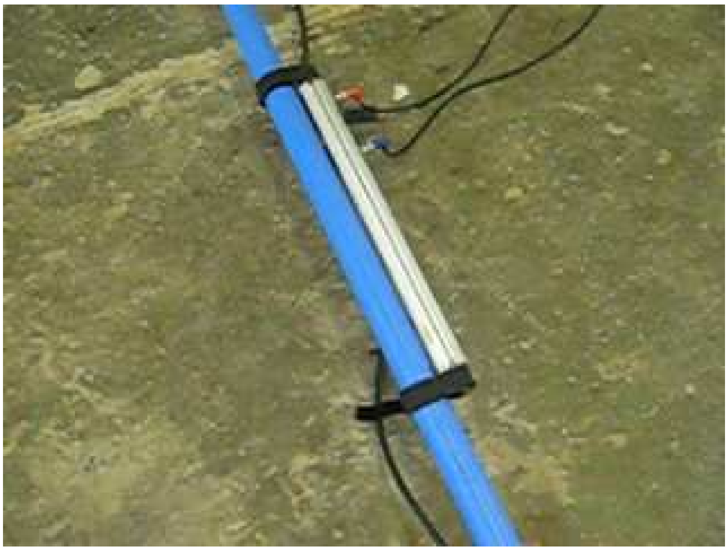



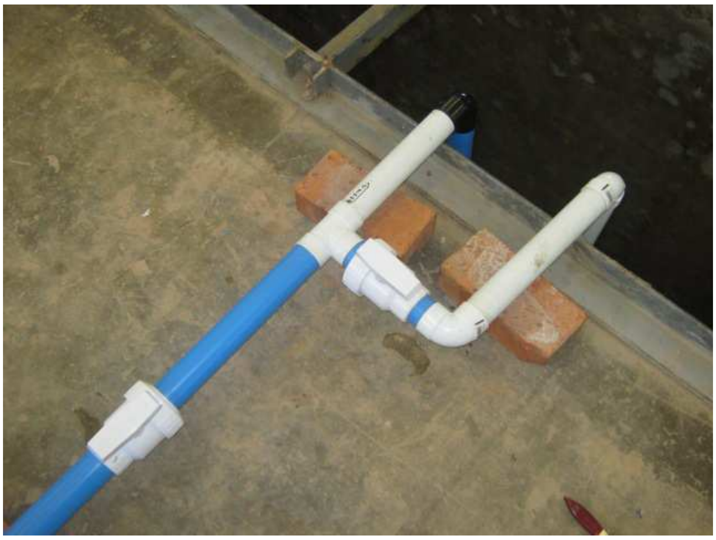


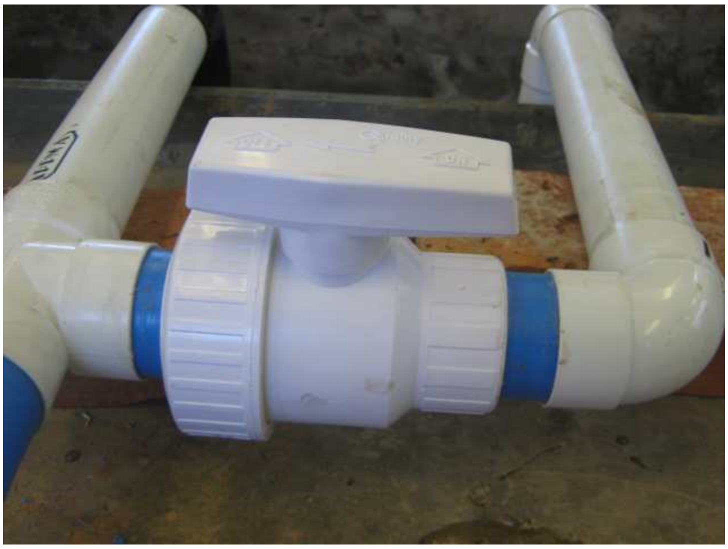








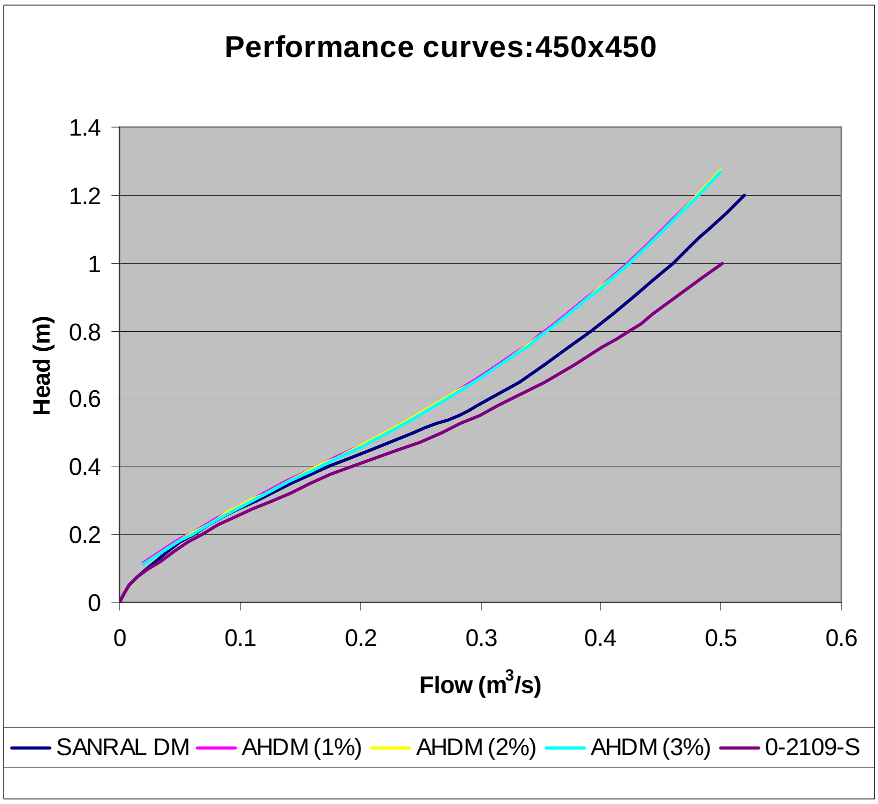


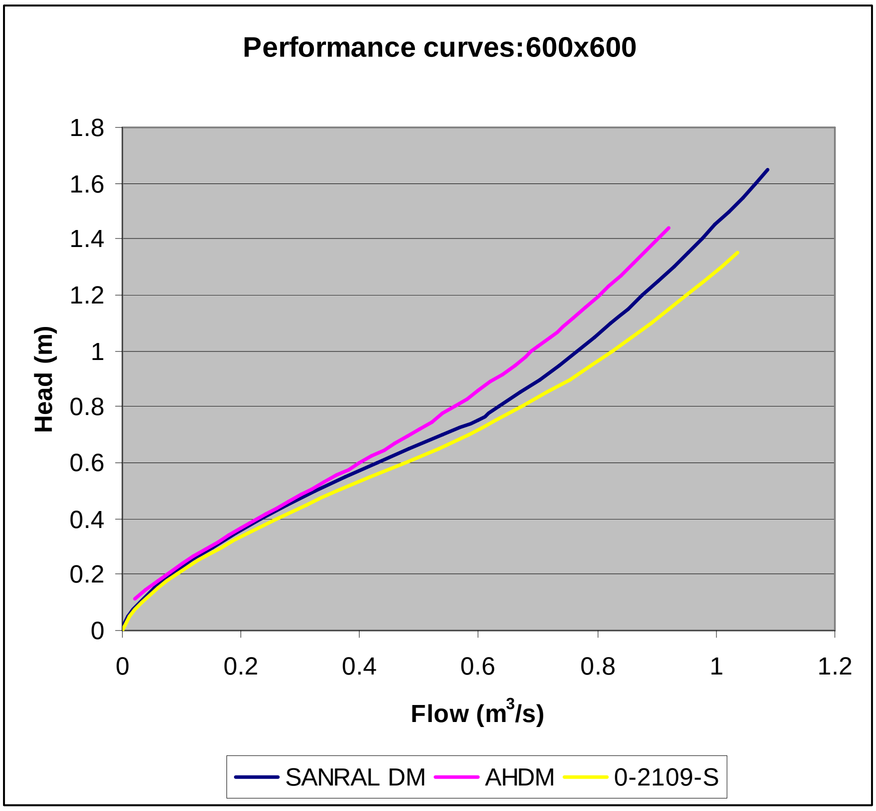

31
32
33
34
37
38
39
40

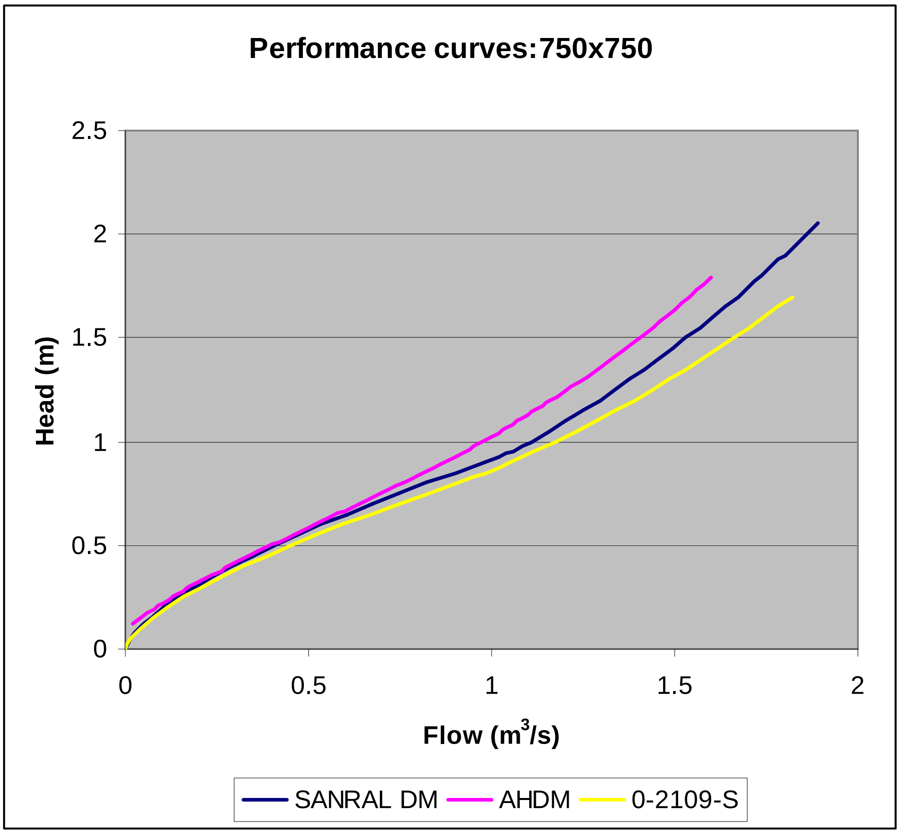
Appendix B:

Performance curves

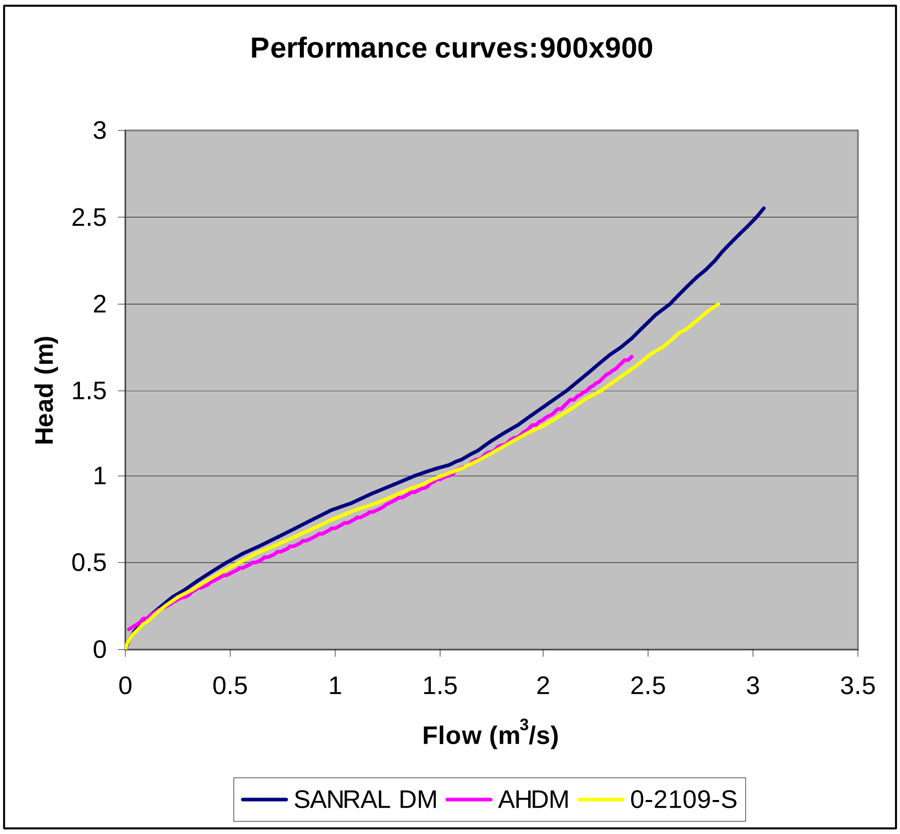
Theoretical Model



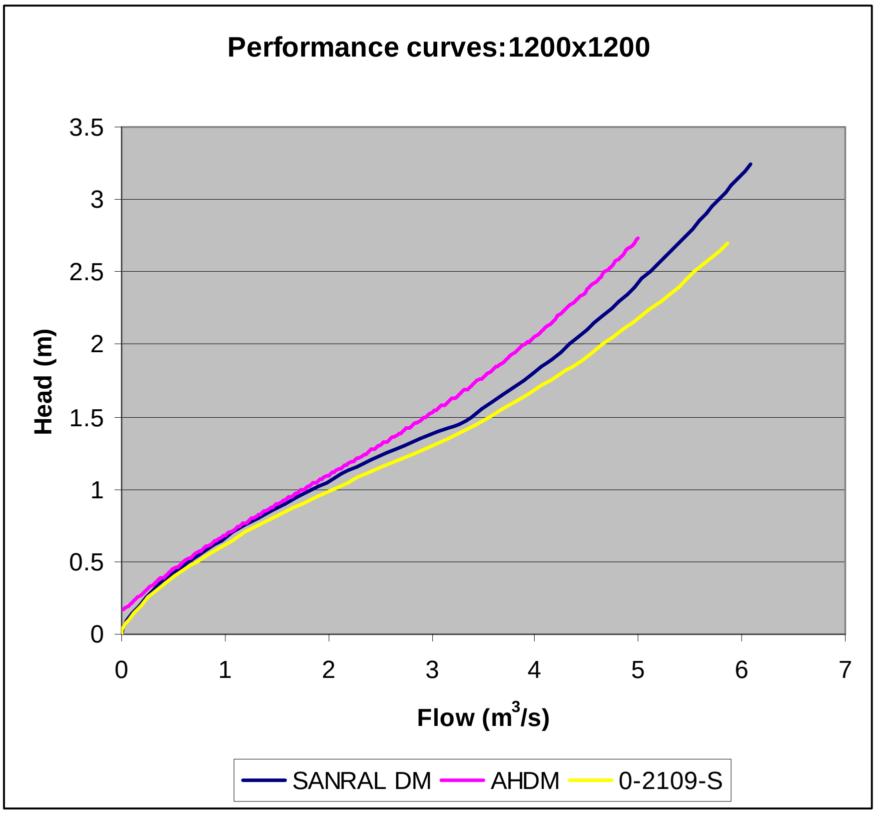


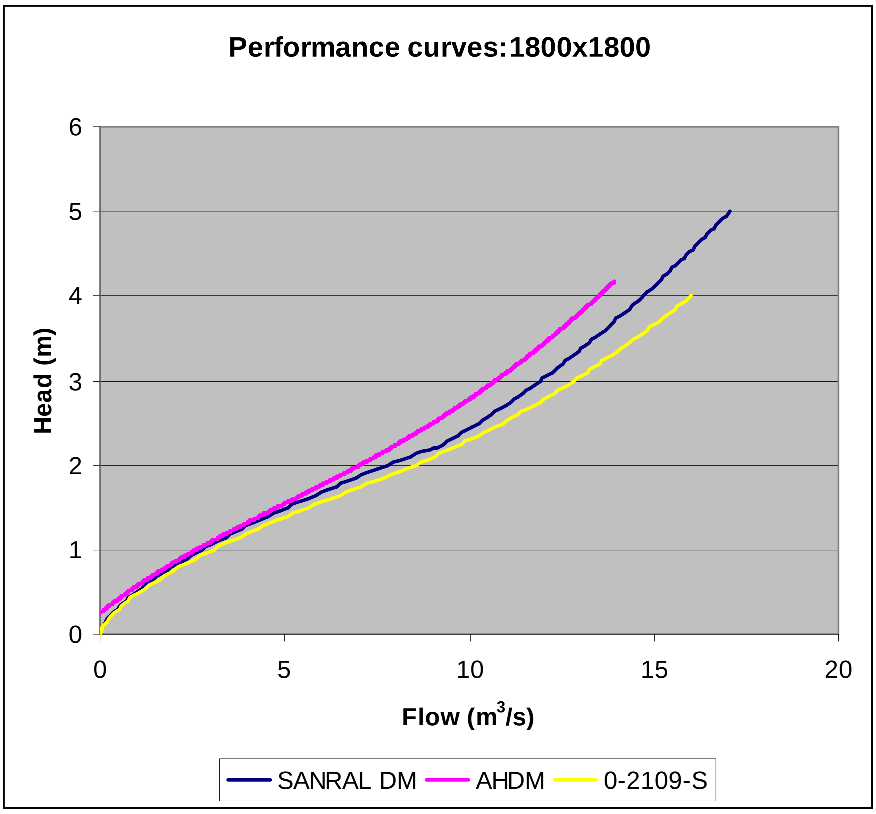


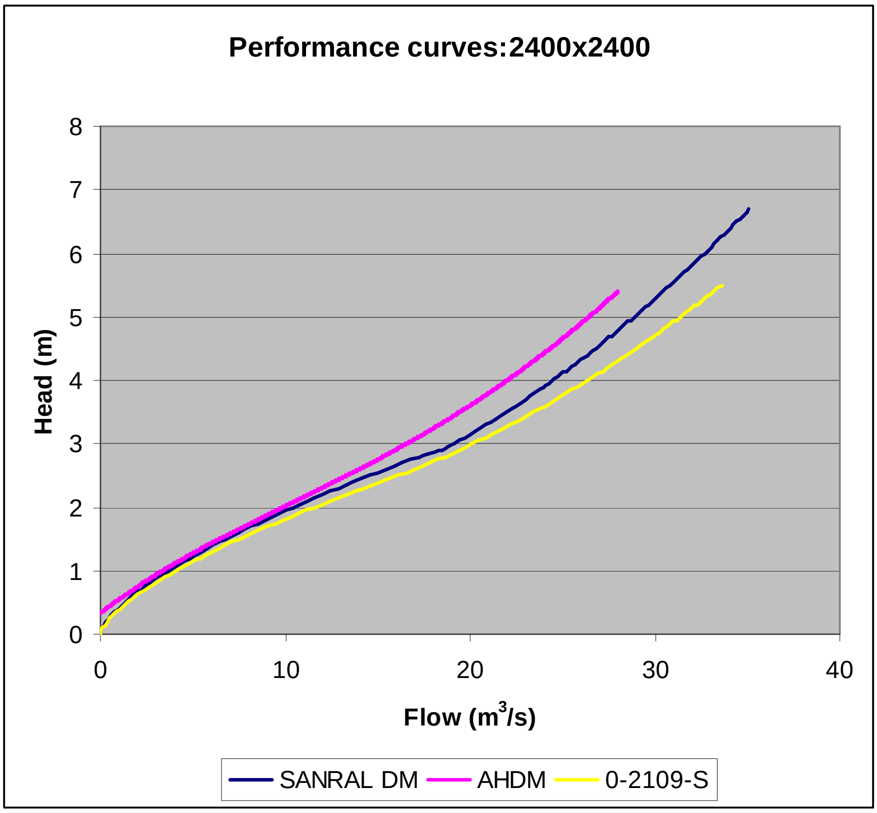
Performance curves:750x750
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

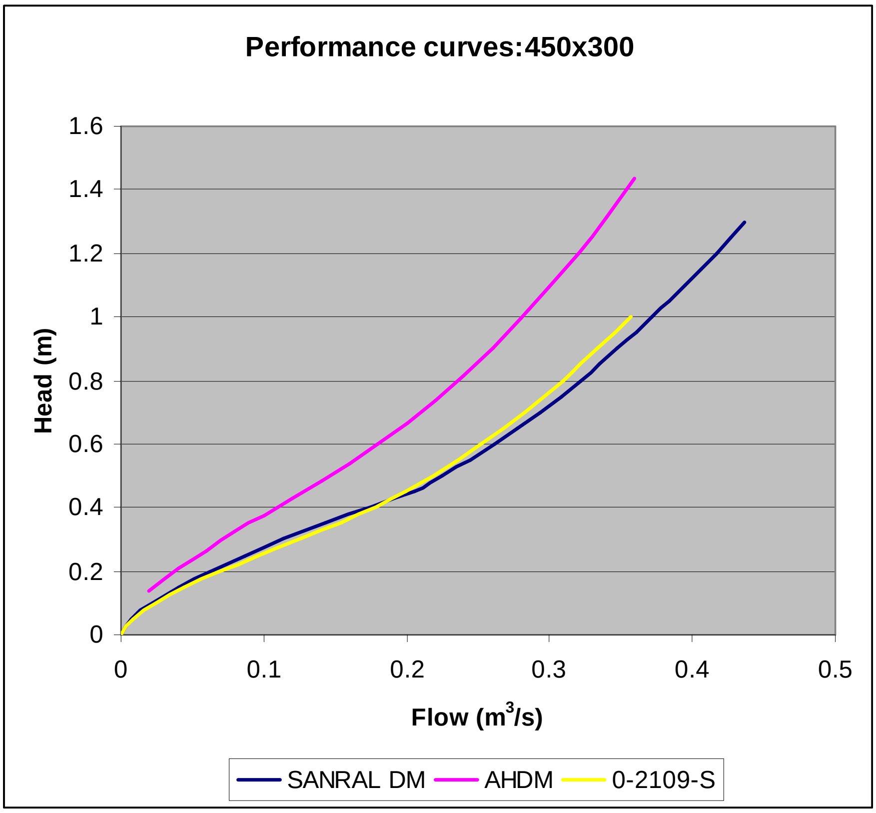


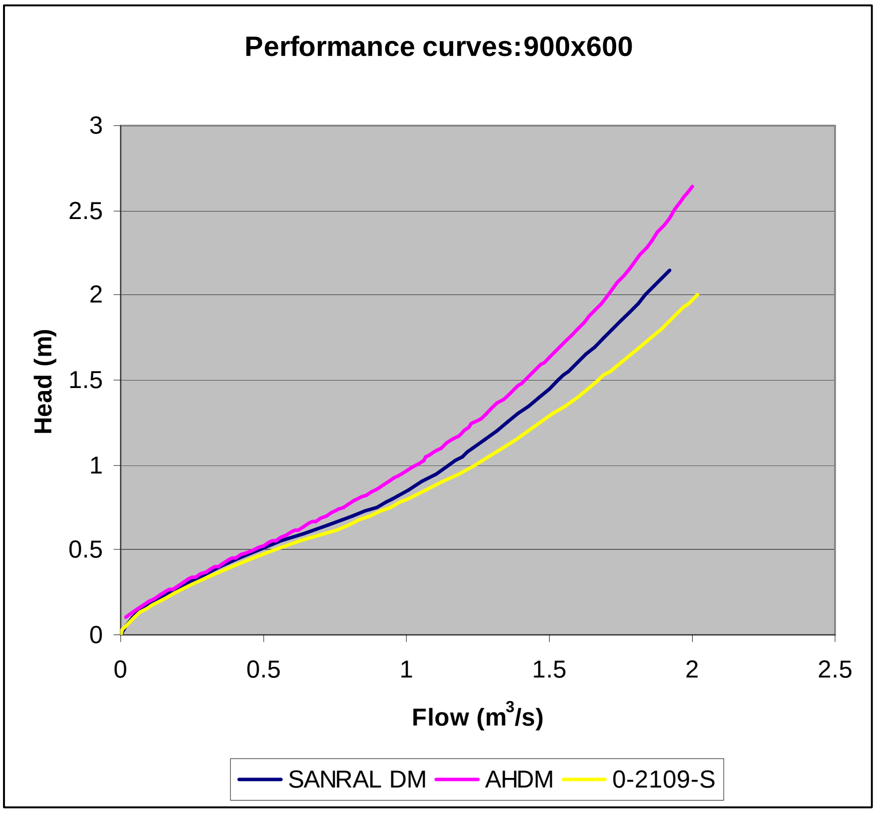
Performance curves:900x900
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

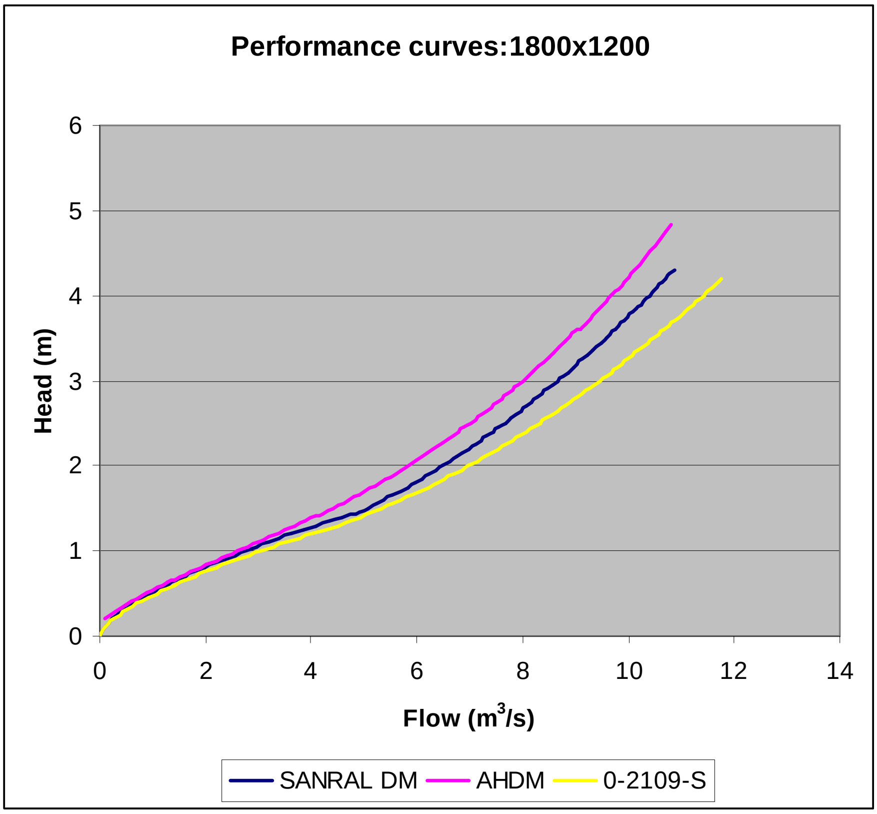

Performance curves:1200x1200
Head (m)
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

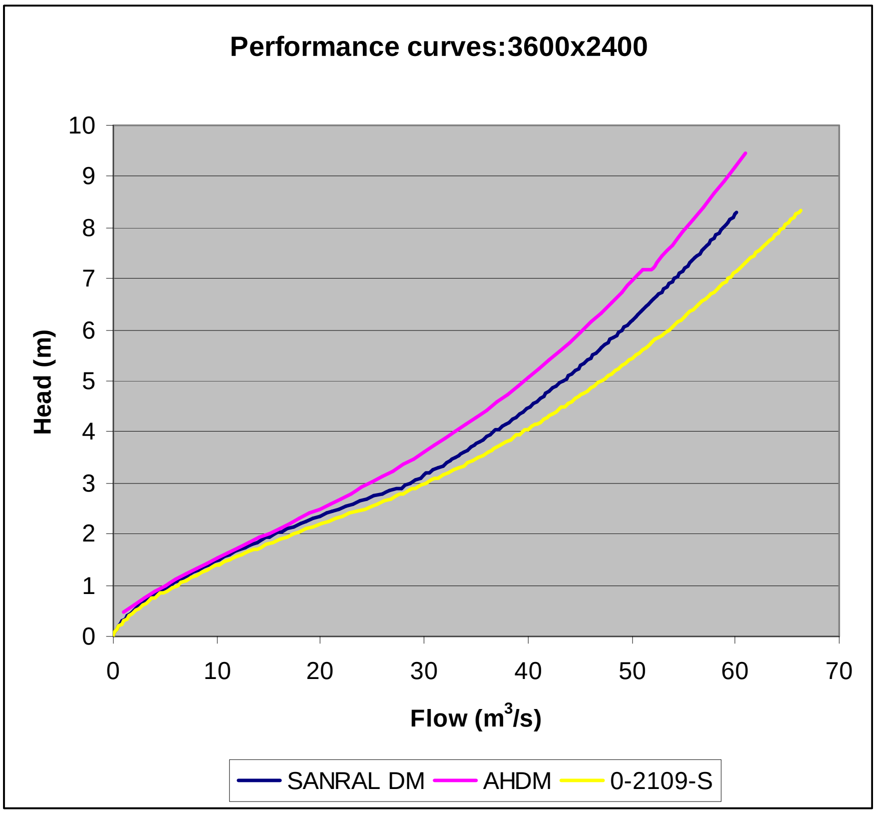

Performance curves:1800x1800
Head (m)
6
5
4
3
2
1
0
0
5
10
15
20
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S


Performance curves:2400x2400
Head (m)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S


Performance curves:450x300
Head (m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

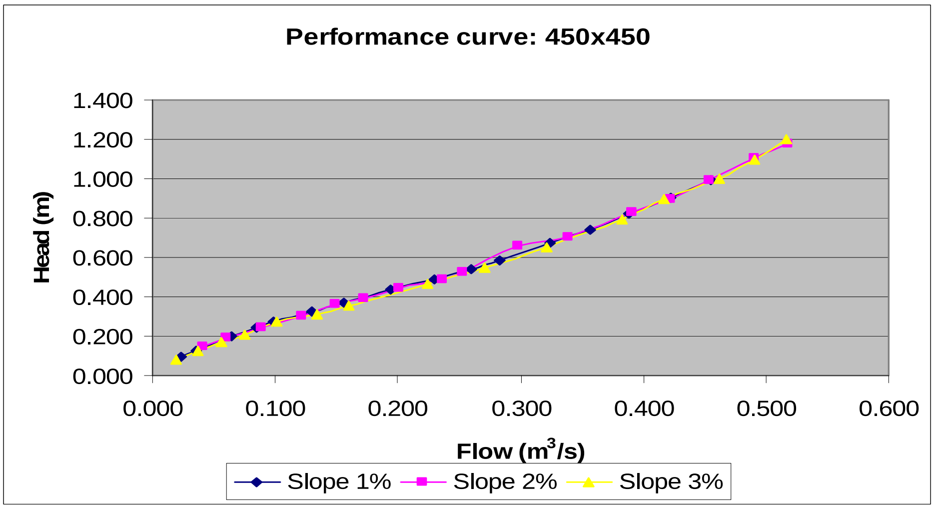

Performance curves:900x600
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

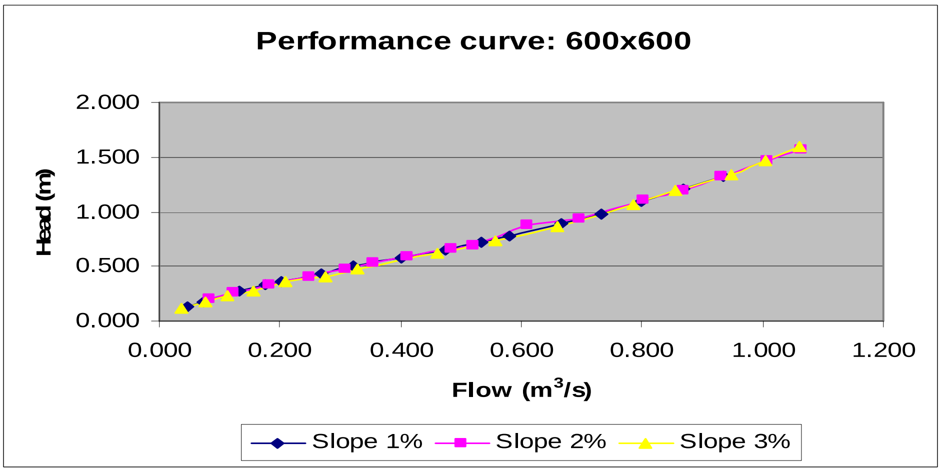

Performance curves:1800x1200
Head (m)
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

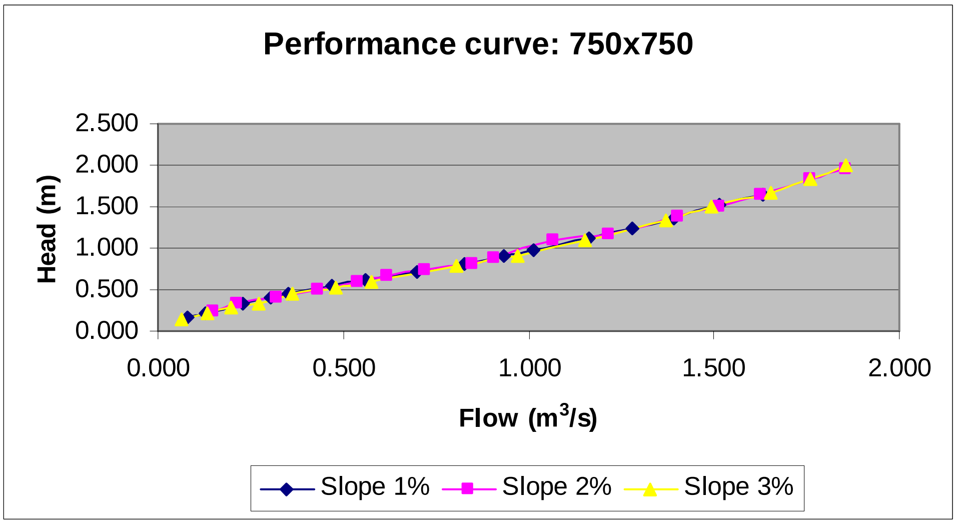


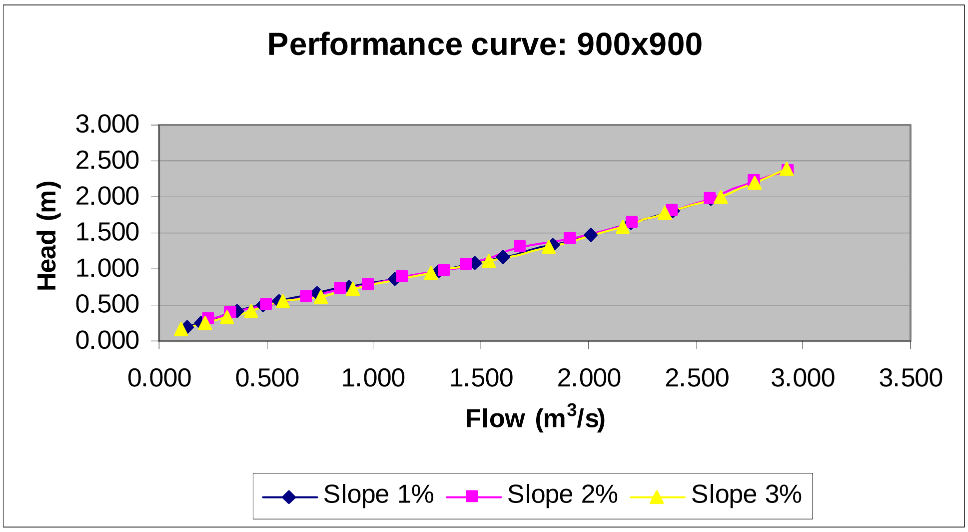
Performance curves:3600x2400
Head (m)
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S

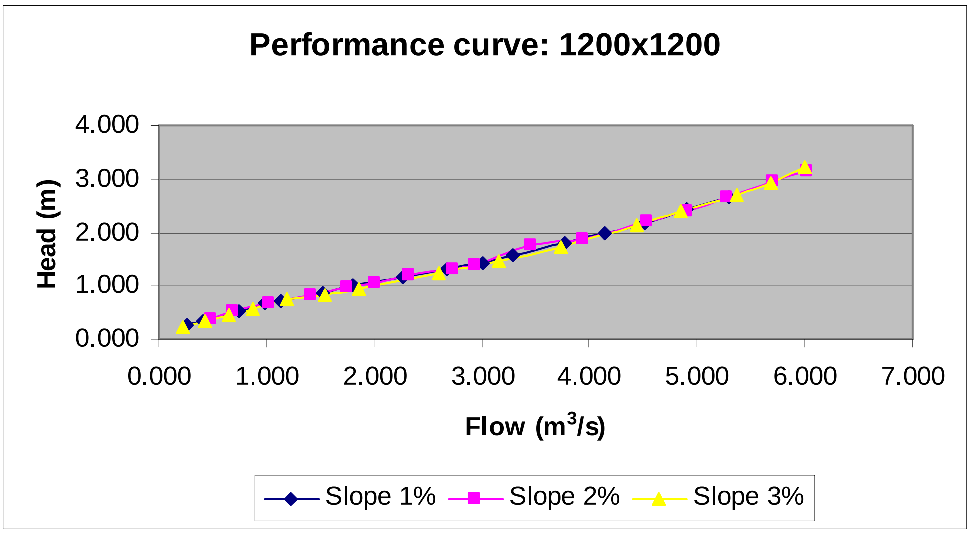
Physical model curves

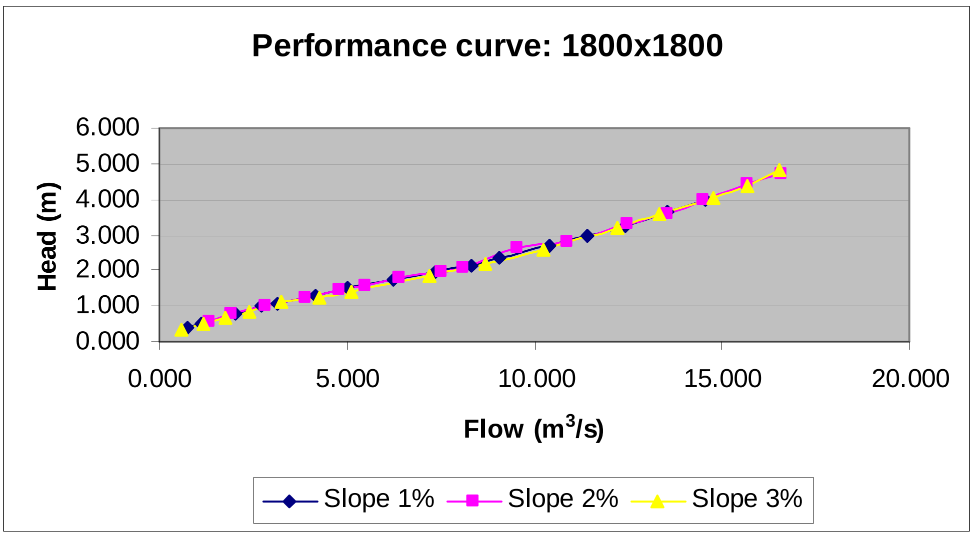


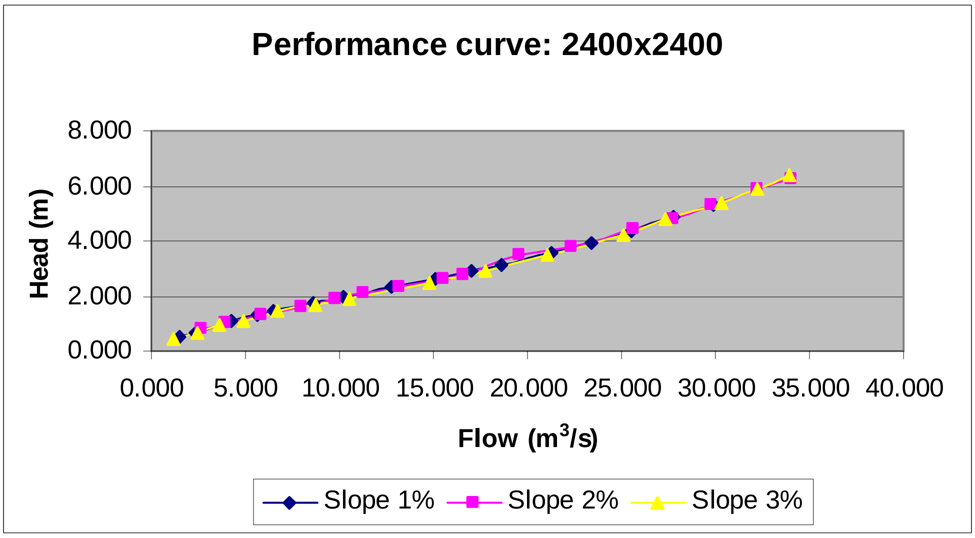





Performance curve: 900x900
Head (m)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

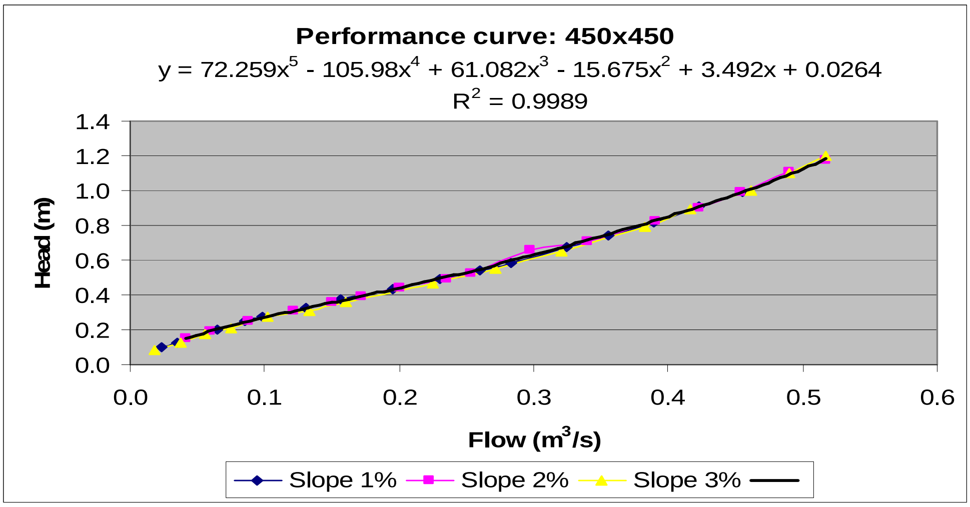

Performance curve: 1200x1200
Head (m)
4.000
3.000
2.000
1.000
0.000
0.000
1.000
2.000
3.000
4.000
5.000
6.000
7.000
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

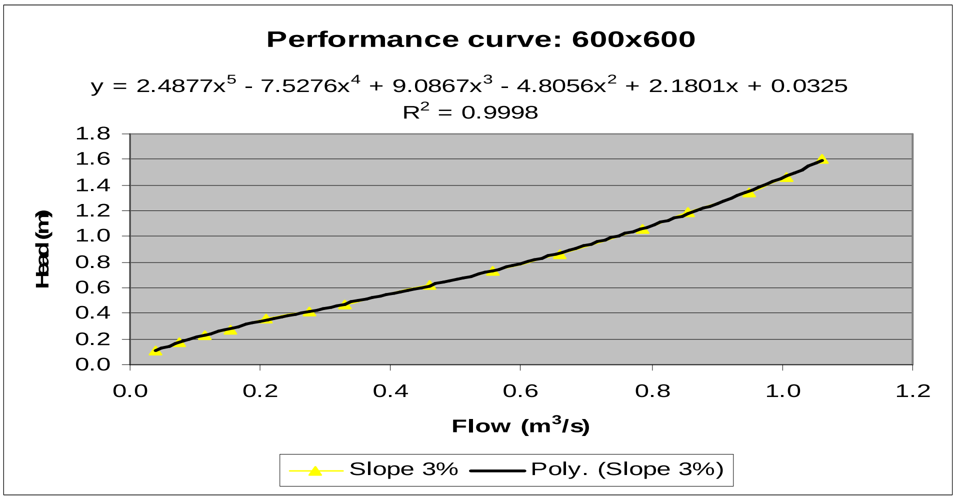

Performance curve: 1800x1800
Head (m)
6.000
5.000
4.000
3.000
2.000
1.000
0.000
0.000
5.000
10.000
15.000
20.000
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

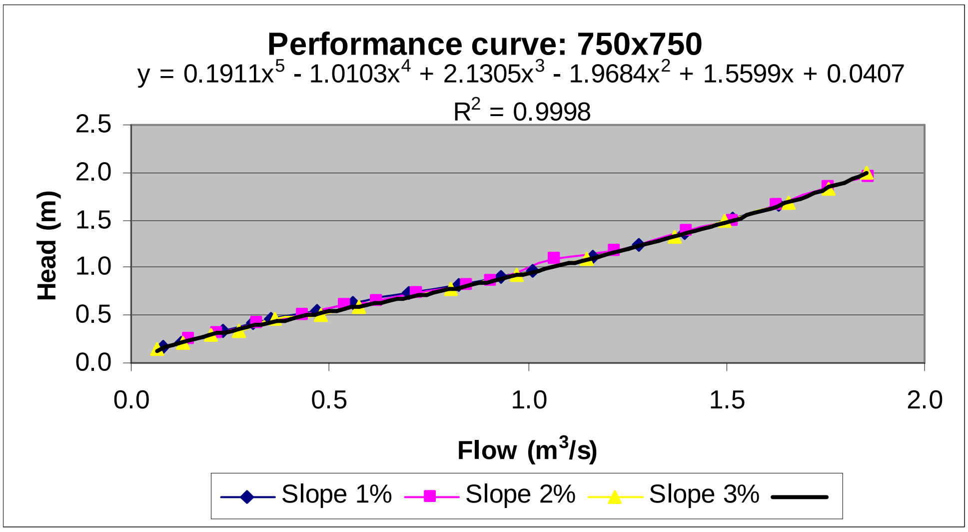


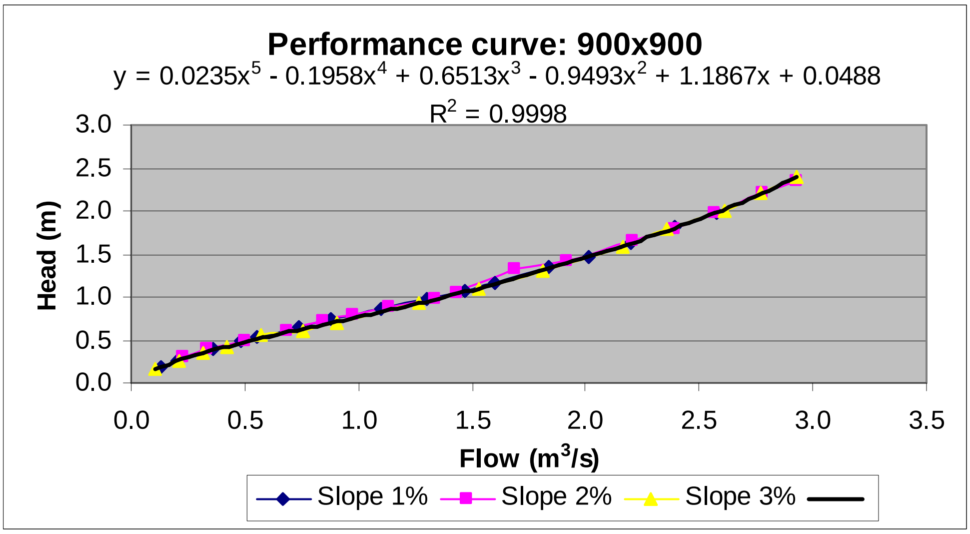
Performance curve: 2400x2400
Head (m)
8.000
6.000
4.000
2.000
0.000
0.000
5.000
10.000
15.000
20.000
25.000
30.000
35.000
40.000
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

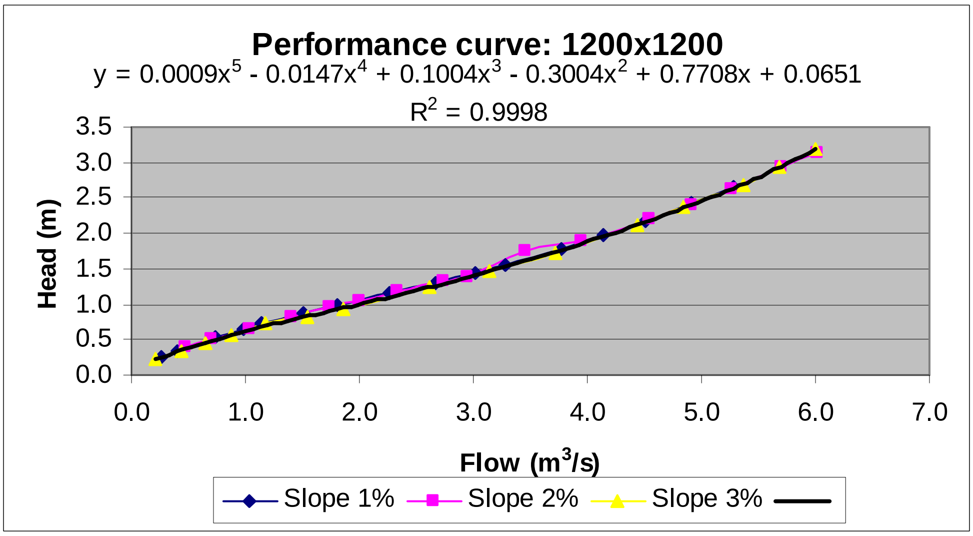
Physical Model Trend line and equation

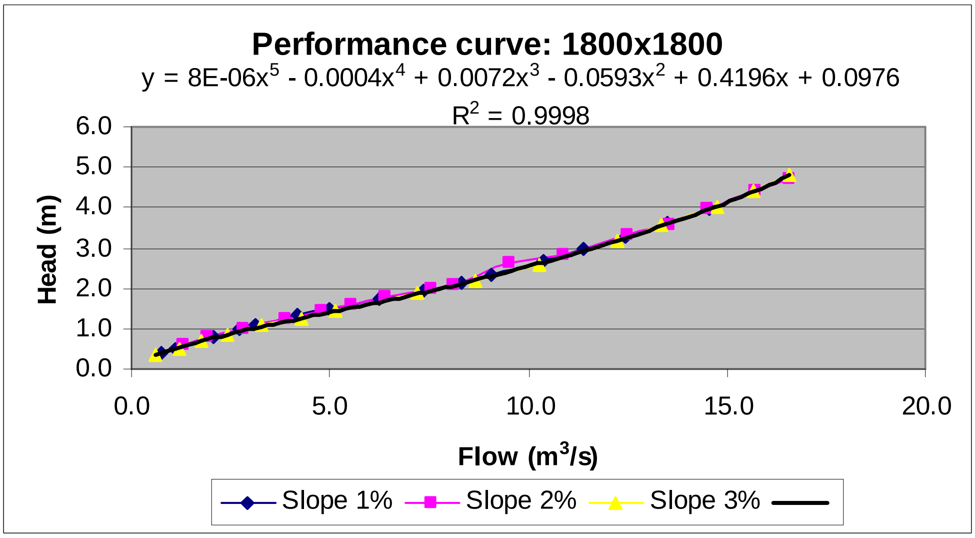


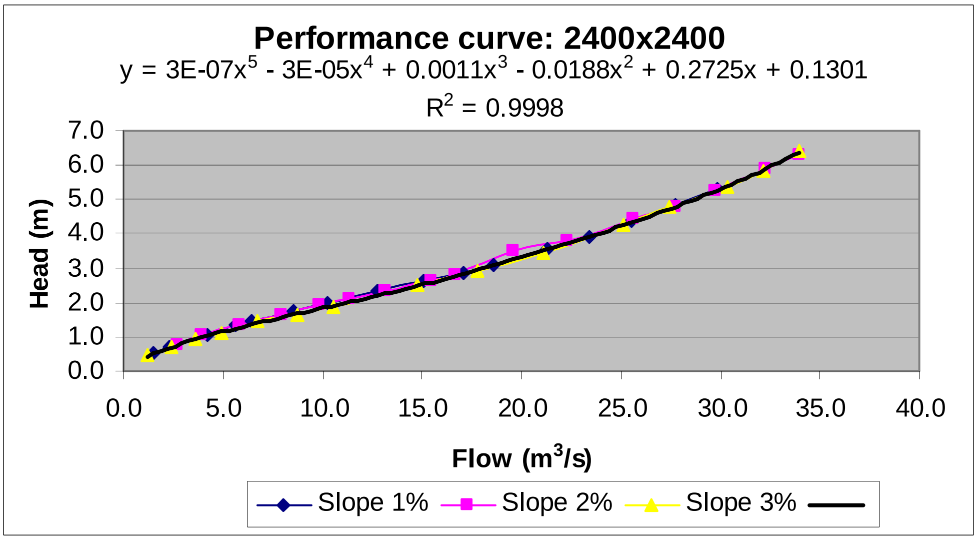





Performance curve: 900x900
y = 0.0235x5 - 0.1958x4 + 0.6513x3 - 0.9493x2 + 1.1867x + 0.0488
R2 = 0.9998
Head (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

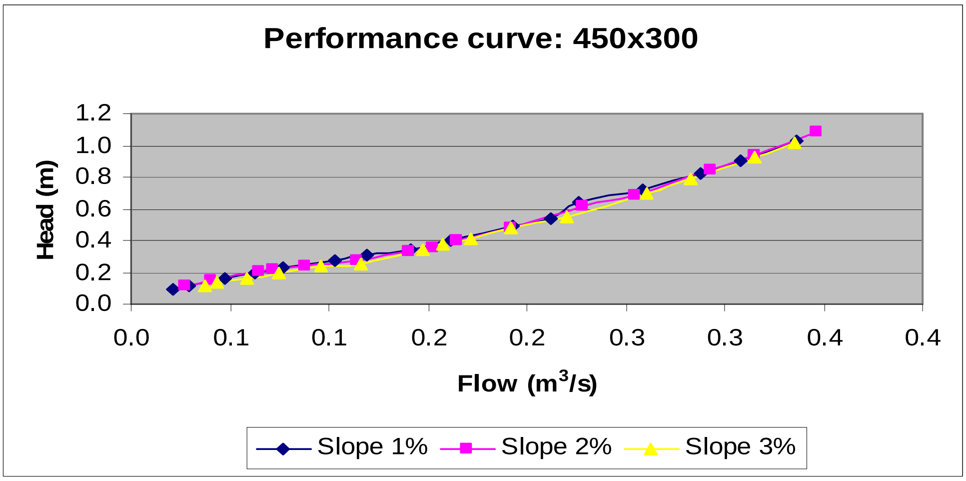

Performance curve: 1200x1200
y = 0.0009x5 - 0.0147x4 + 0.1004x3 - 0.3004x2 + 0.7708x + 0.0651
R2 = 0.9998
Head (m)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

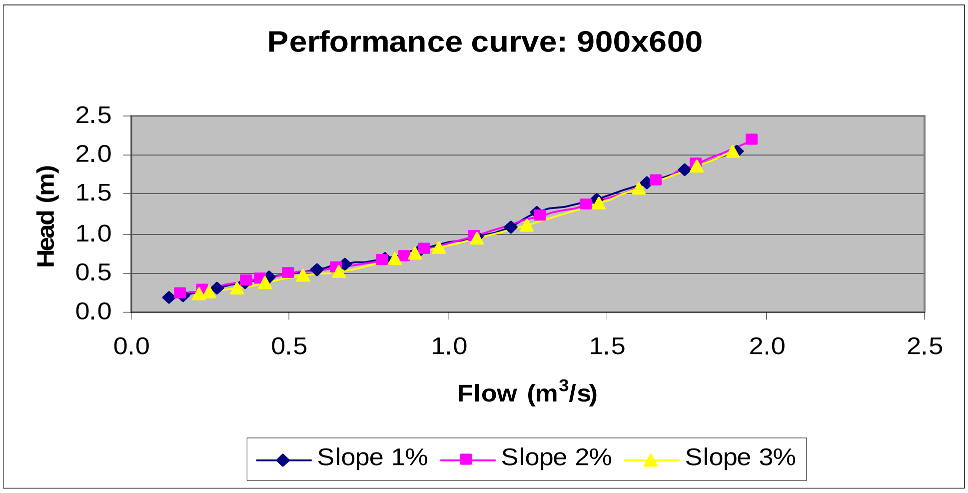

Performance curve: 1800x1800
y = 8E-06x5 - 0.0004x4 + 0.0072x3 - 0.0593x2 + 0.4196x + 0.0976
R2 = 0.9998
Head (m)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
5.0
10.0
15.0
20.0
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

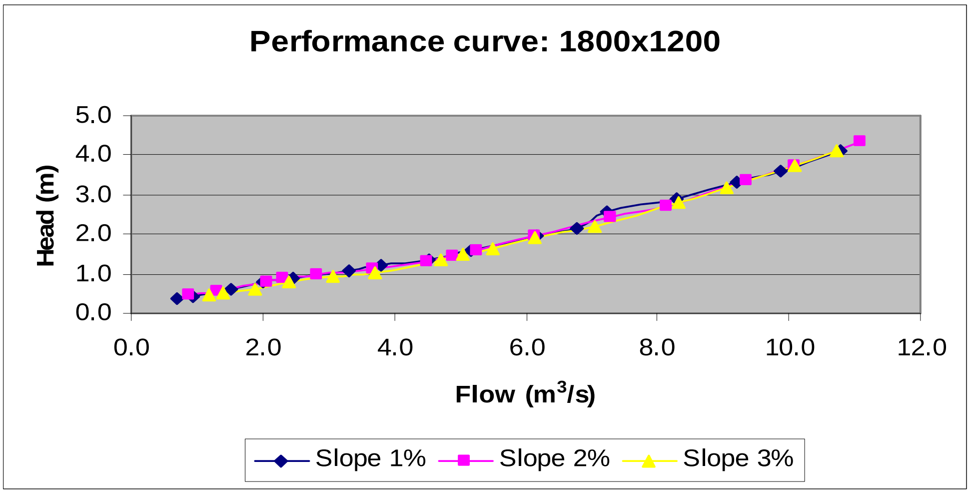


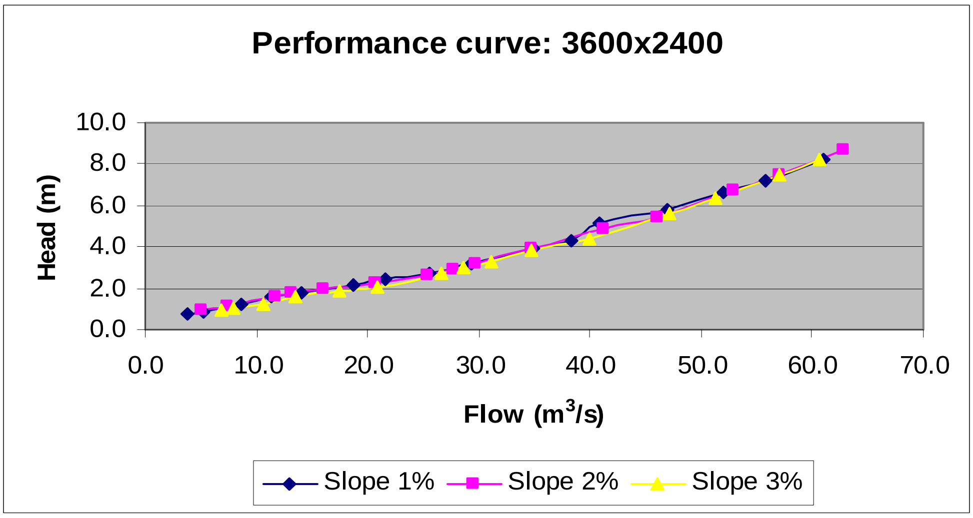
Performance curve: 2400x2400
y = 3E-07x5 - 3E-05x4 + 0.0011x3 - 0.0188x2 + 0.2725x + 0.1301
R2 = 0.9998
Head (m)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

Physical models curves

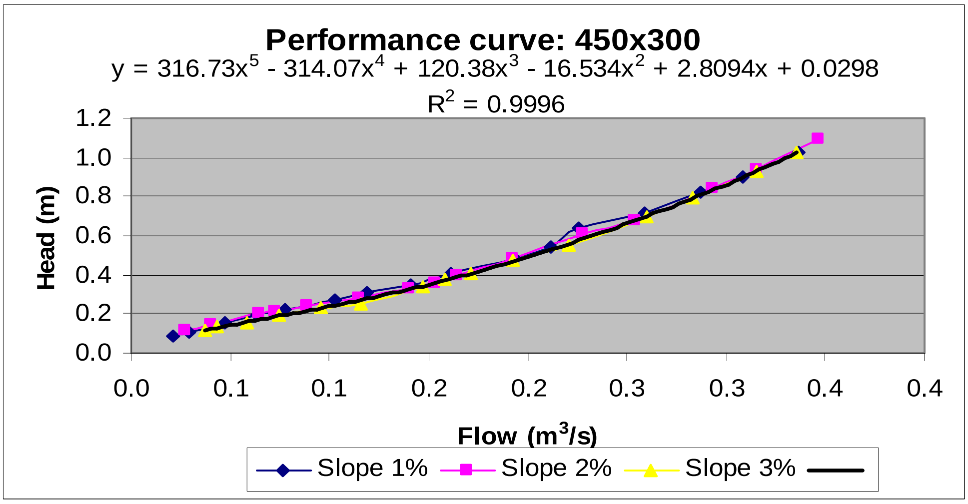


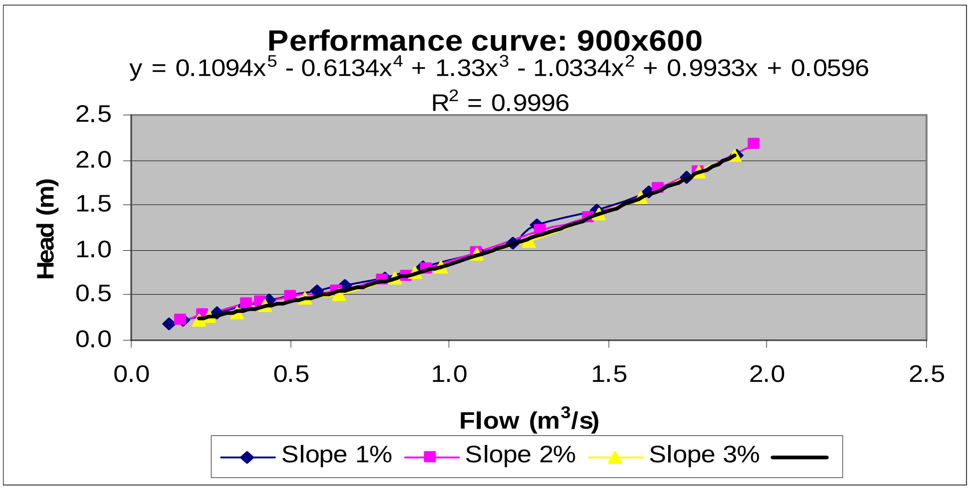


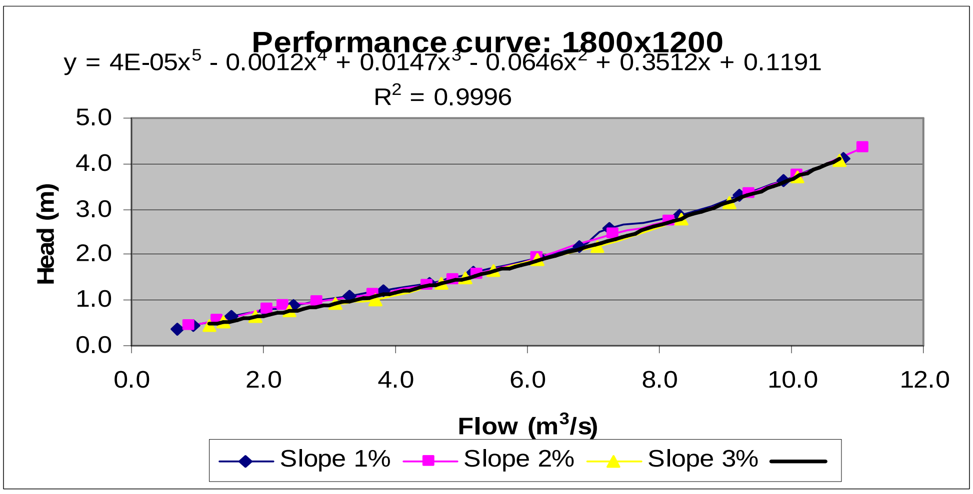


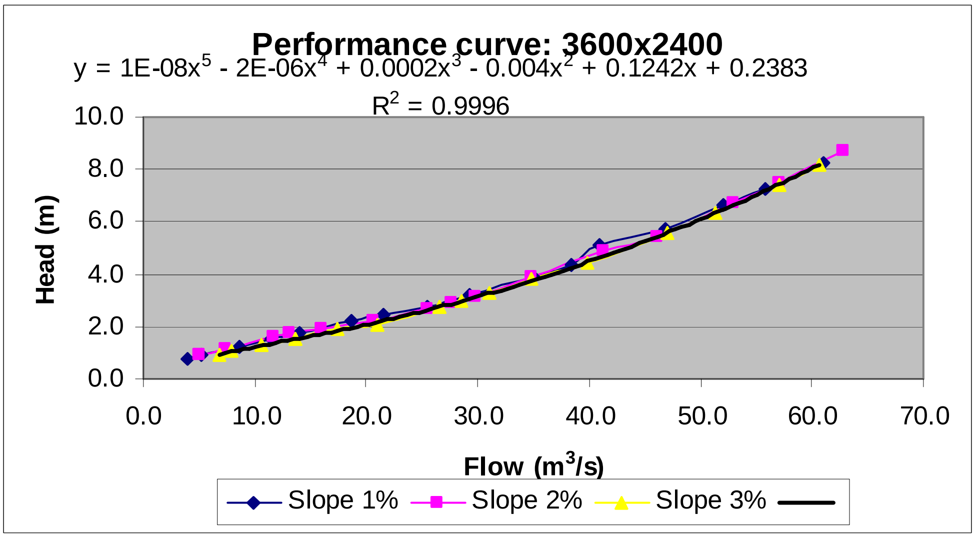

Performance curve: 3600x2400
Head (m)
10.0
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

Physical model trend line curves

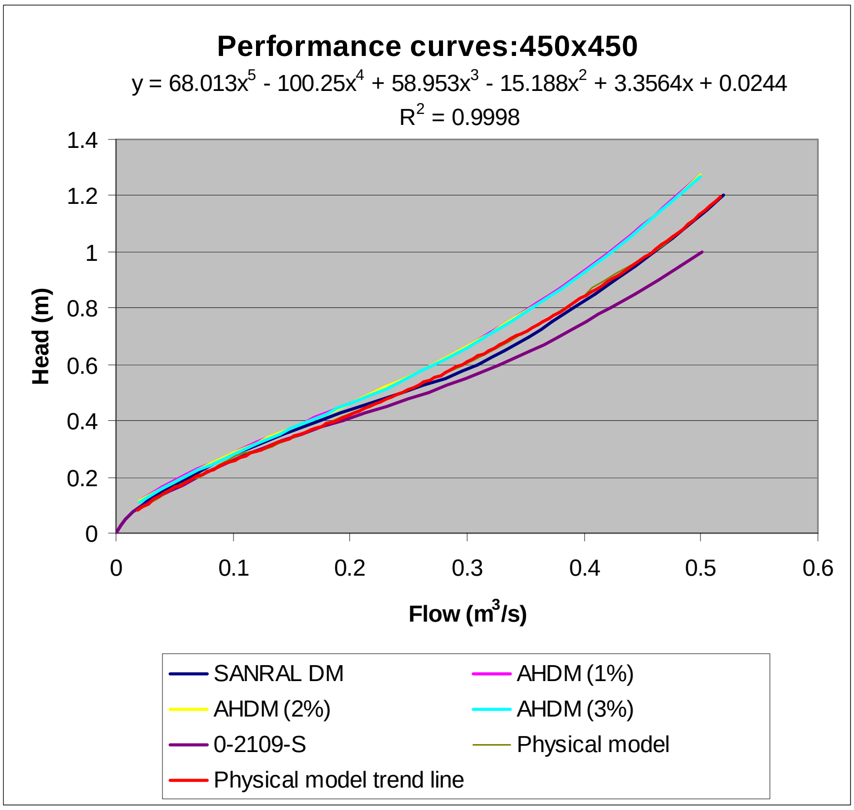


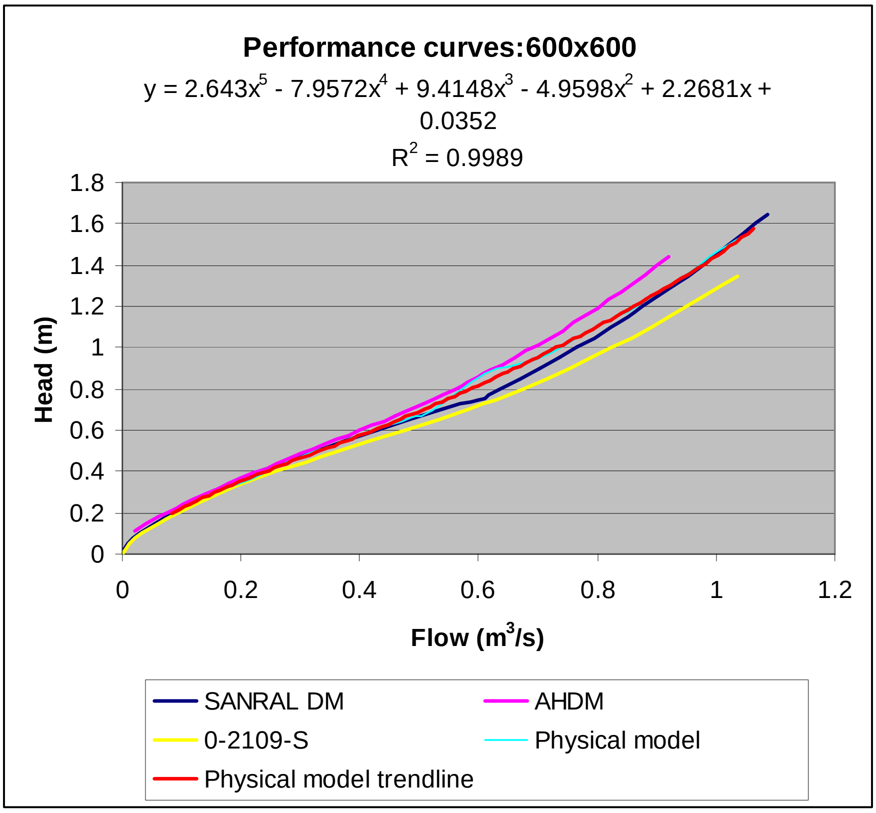


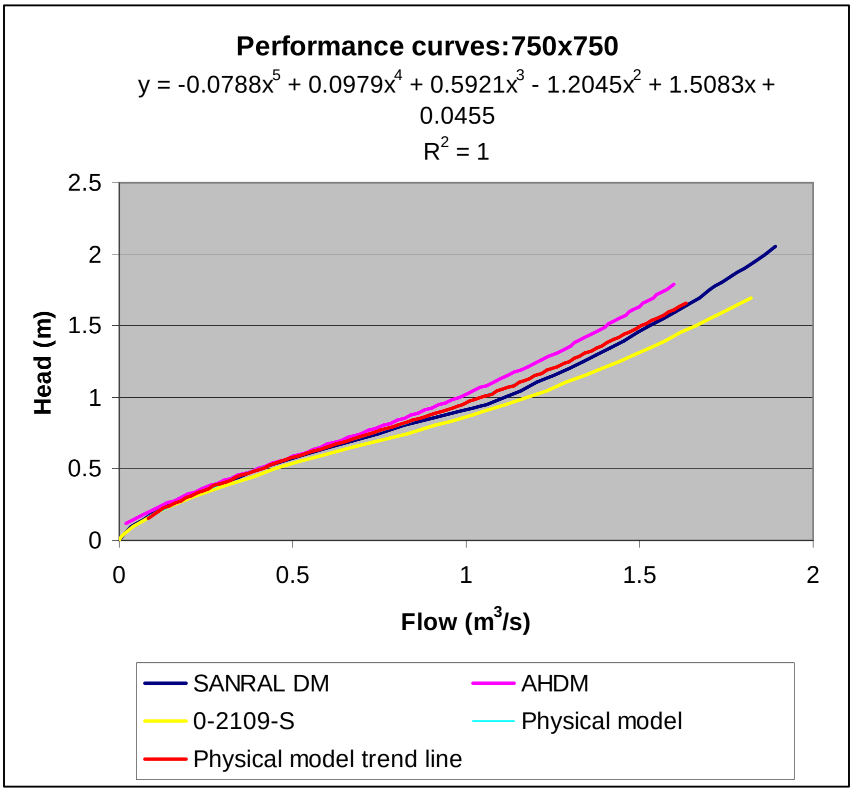


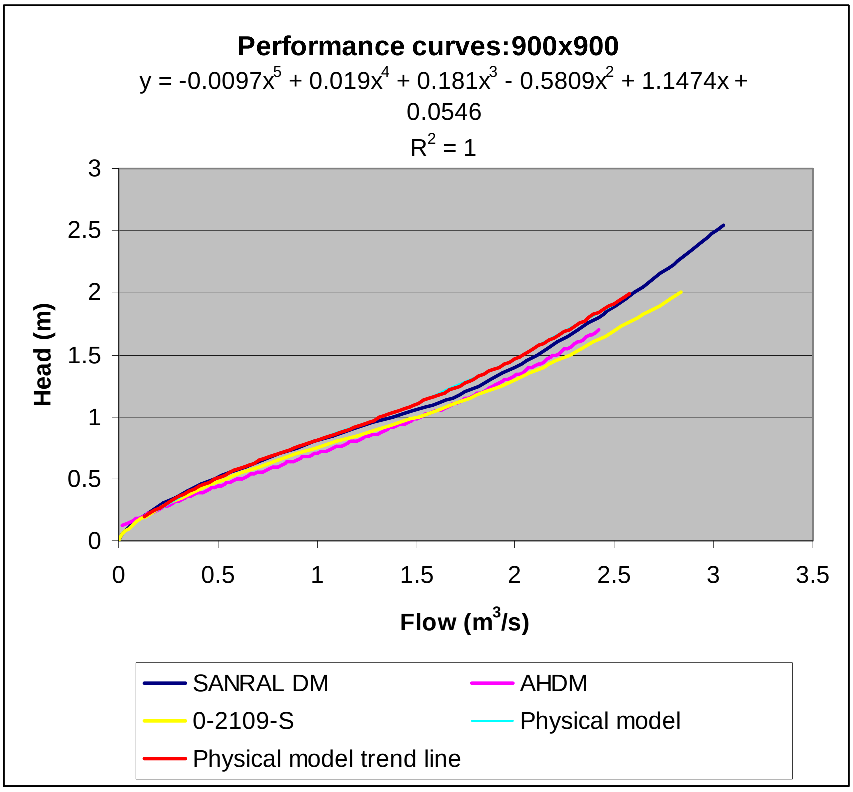

Performance curve: 3600x2400
y = 1E-08x5 - 2E-06x4 + 0.0002x3 - 0.004x2 + 0.1242x + 0.2383
R2 = 0.9996
Head (m)
10.0
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Flow (m3/s)
Slope 1%
Slope 2%
Slope 3%

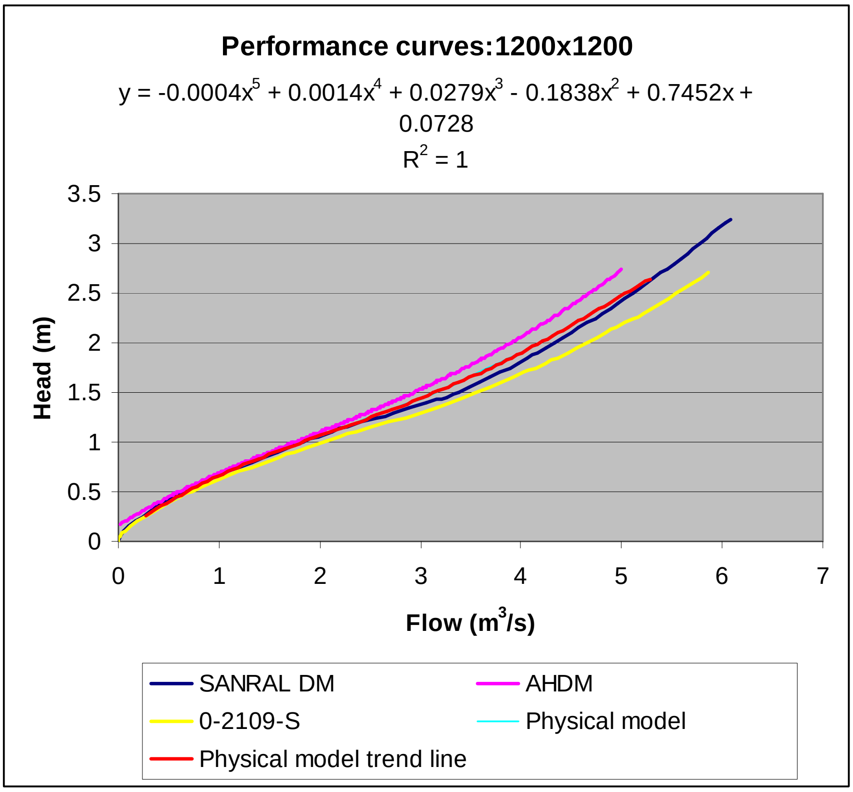
Theoretical and physical model curves



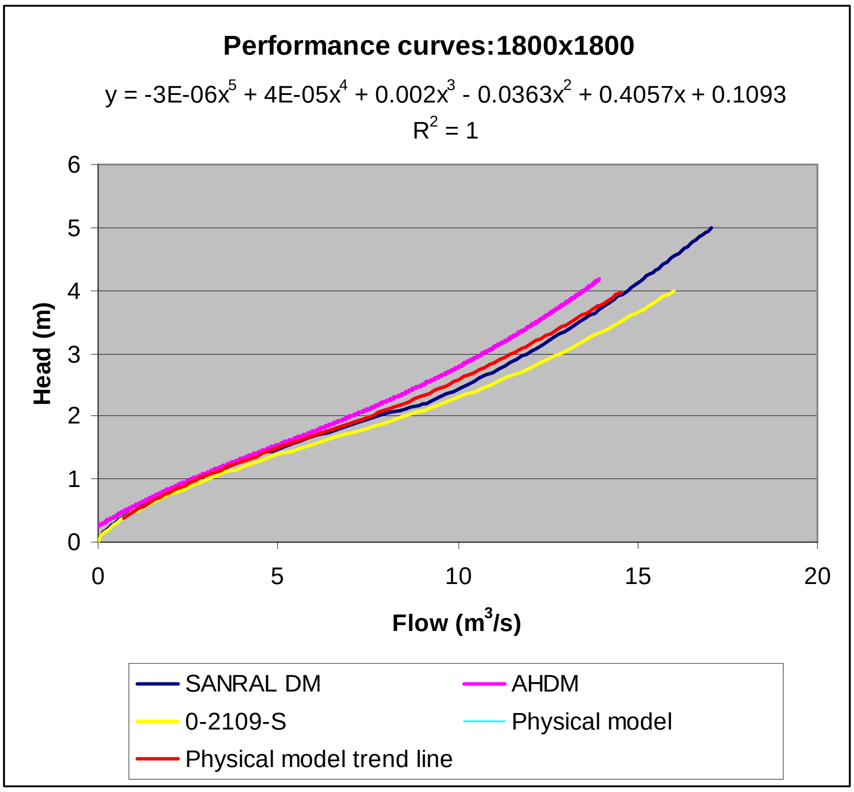



Performance curves:750x750
y = -0.0788x5 + 0.0979x4 + 0.5921x3 - 1.2045x2 + 1.5083x + 0.0455
R2 = 1
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line

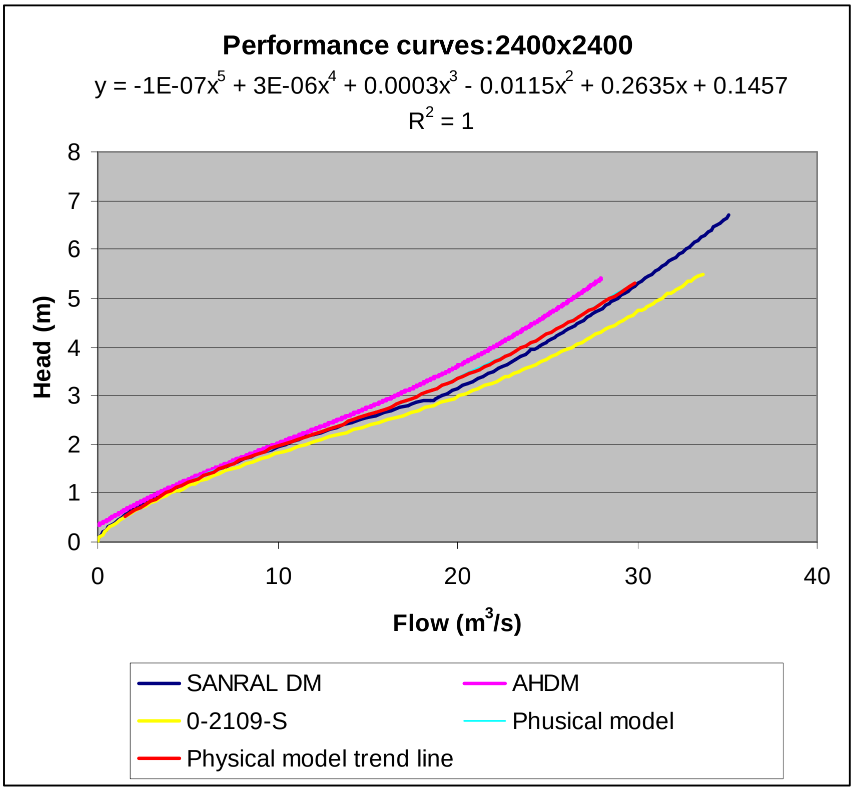

Performance curves:900x900
y = -0.0097x5 + 0.019x4 + 0.181x3 - 0.5809x2 + 1.1474x + 0.0546
R2 = 1
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line

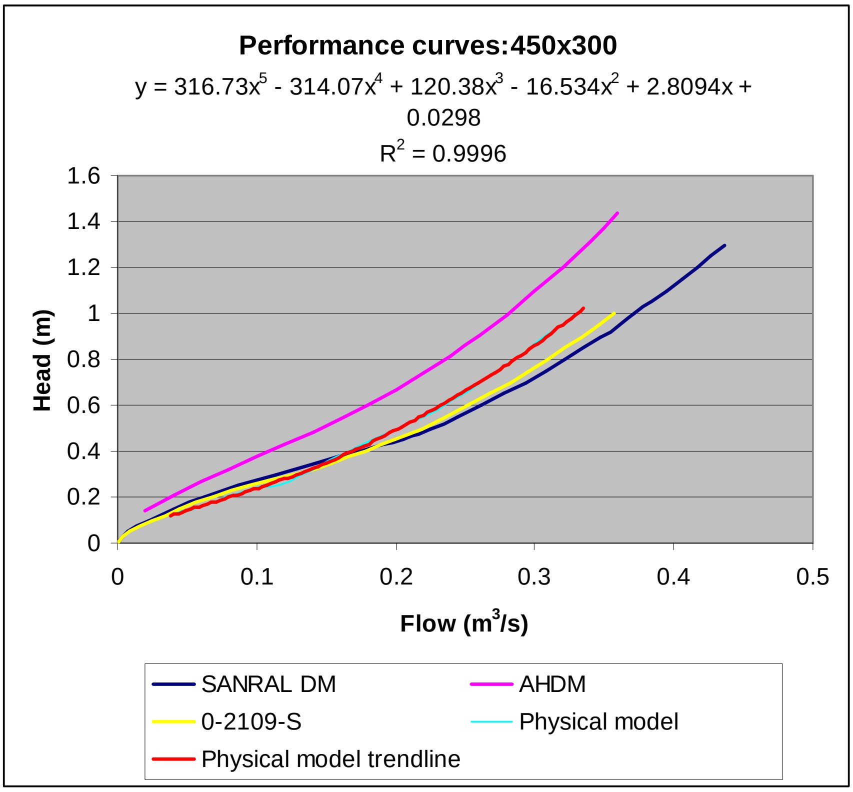


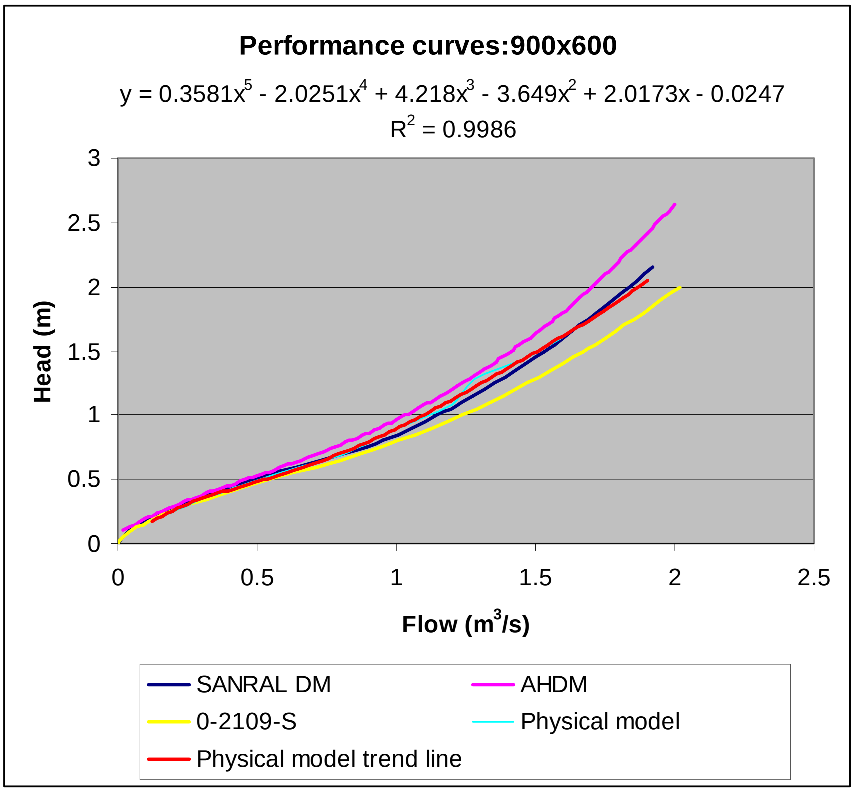
Performance curves:1200x1200
y = -0.0004x5 + 0.0014x4 + 0.0279x3 - 0.1838x2 + 0.7452x + 0.0728
R2 = 1
Head (m)
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line



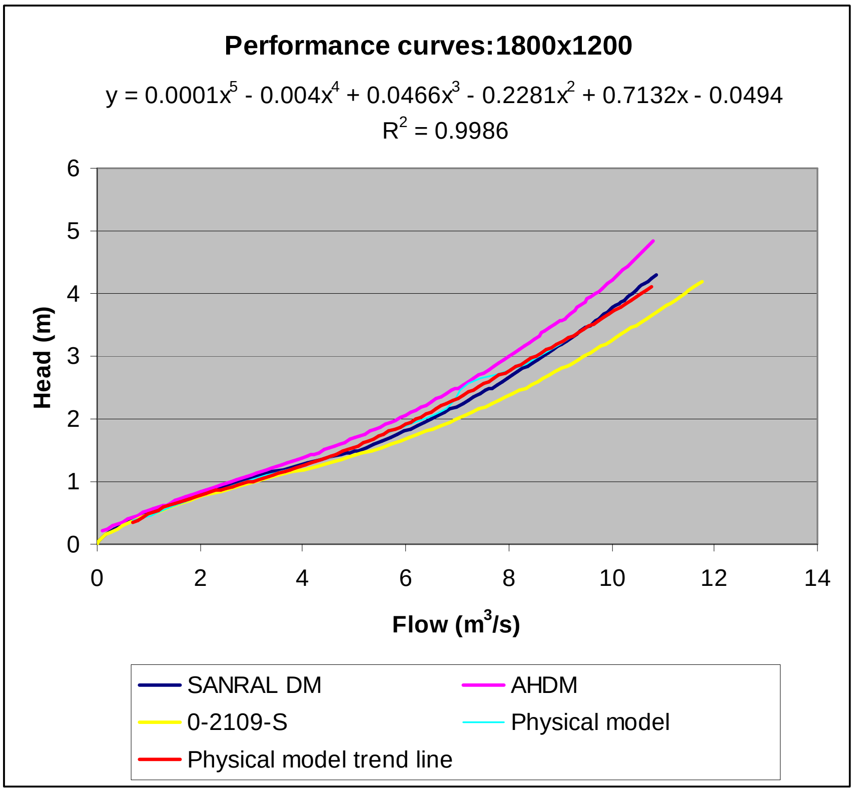
Performance curves:1800x1800
y = -3E-06x5 + 4E-05x4 + 0.002x3 - 0.0363x2 + 0.4057x + 0.1093
R2 = 1
Head (m)
6
5
4
3
2
1
0
0
5
10
15
20
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line


Performance curves:2400x2400
y = -1E-07x5 + 3E-06x4 + 0.0003x3 - 0.0115x2 + 0.2635x + 0.1457
R2 = 1
Head (m)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Phusical model
Physical model trend line

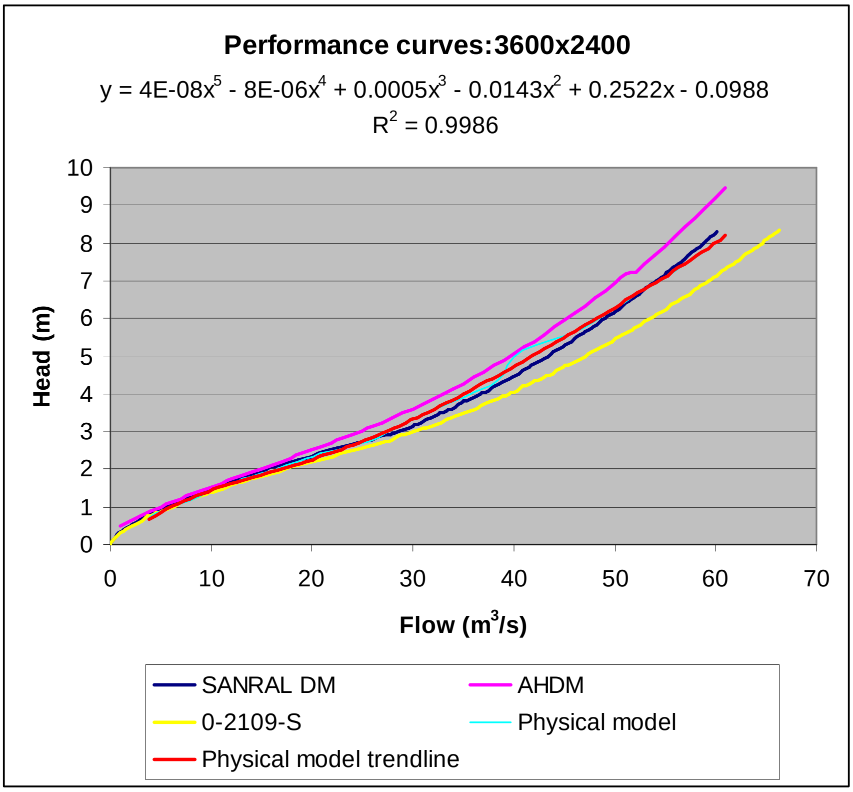

Performance curves:450x300
y = 316.73x5 - 314.07x4 + 120.38x3 - 16.534x2 + 2.8094x + 0.0298
R2 = 0.9996
Head (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
0.1
0.2
0.3
0.4
0.5
Flow (m3/s)
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trendline



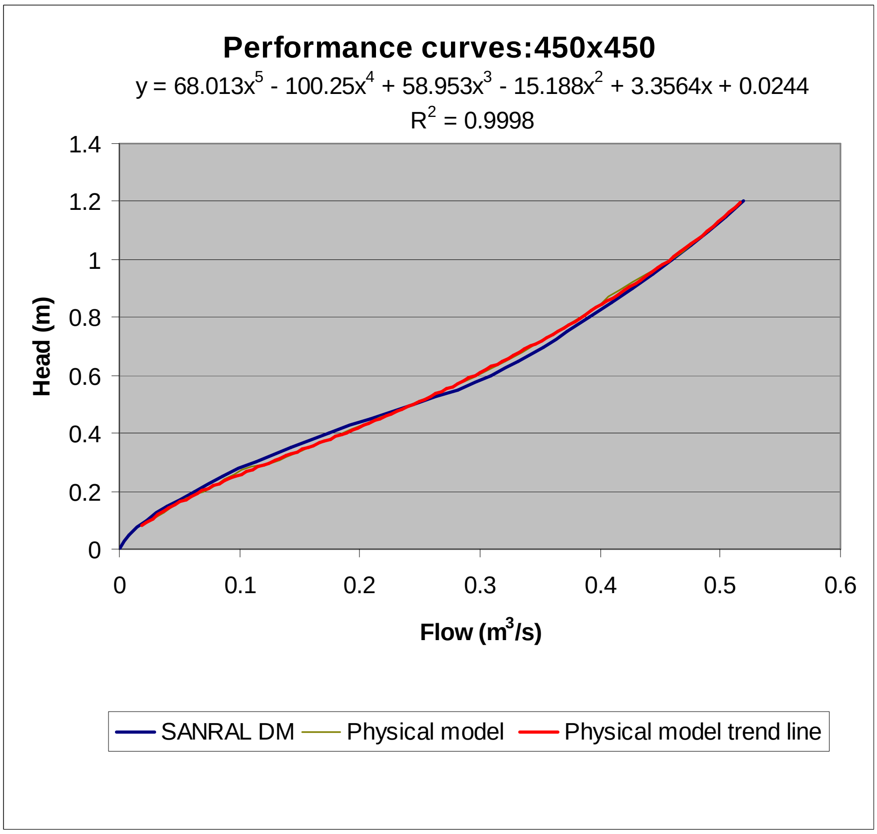
Performance curves:900x600
y = 0.3581x5 - 2.0251x4 + 4.218x3 - 3.649x2 + 2.0173x - 0.0247
R2 = 0.9986
Head (m)
Flow (m3/s)
0
0.5
1
1.5
2
2.5
3
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line

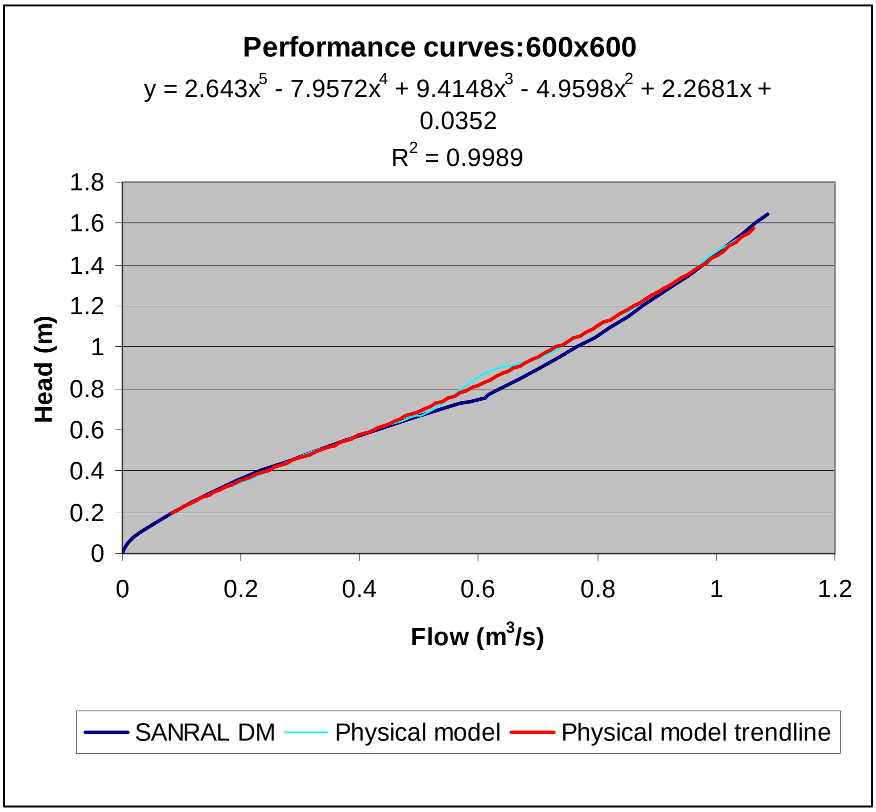


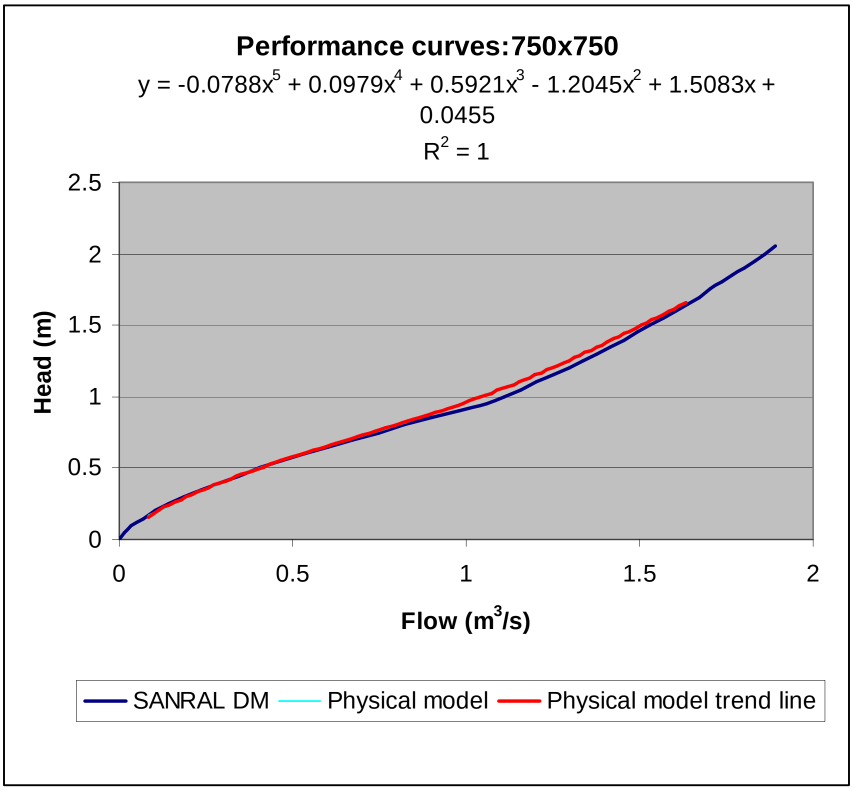
Performance curves:1800x1200
y = 0.0001x5 - 0.004x4 + 0.0466x3 - 0.2281x2 + 0.7132x - 0.0494
R2 = 0.9986
Head (m)
Flow (m3/s)
0
1
2
3
4
5
6
8
10
12
14
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trend line

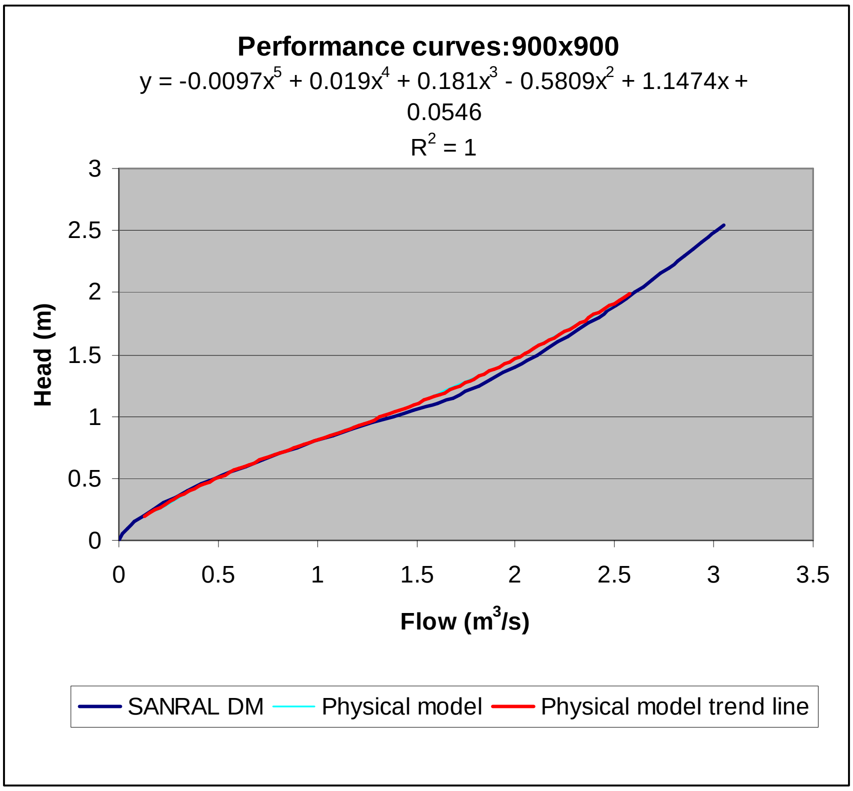

Performance curves:3600x2400
y = 4E-08x5 - 8E-06x4 + 0.0005x3 - 0.0143x2 + 0.2522x - 0.0988
R2 = 0.9986
Head (m)
Flow (m3/s)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
SANRAL DM
AHDM
0-2109-S
Physical model
Physical model trendline

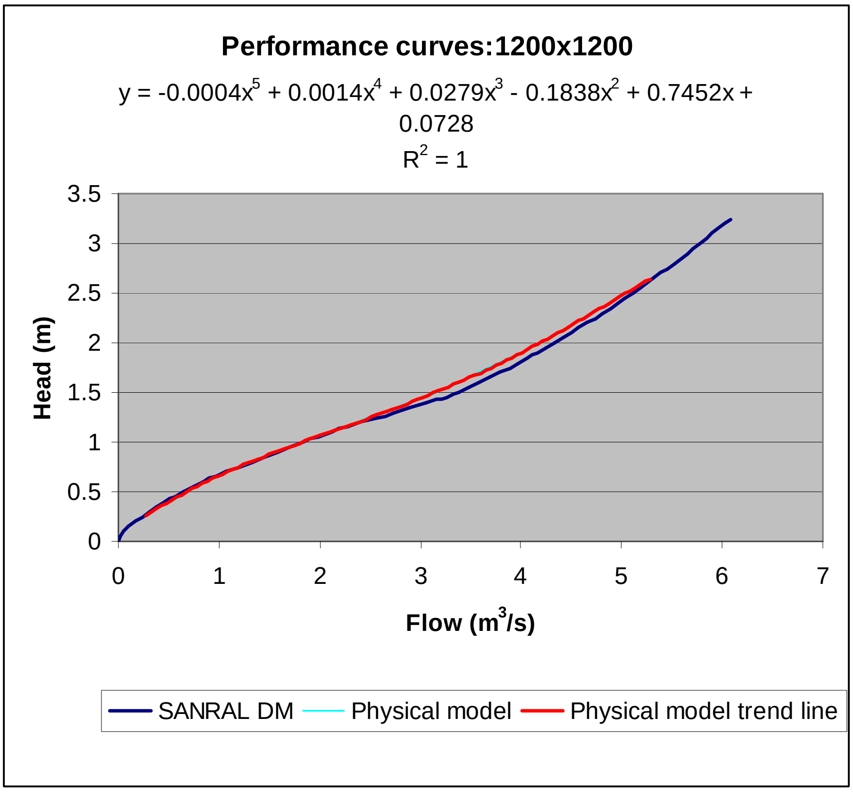
Best performance curve that describes the physical model

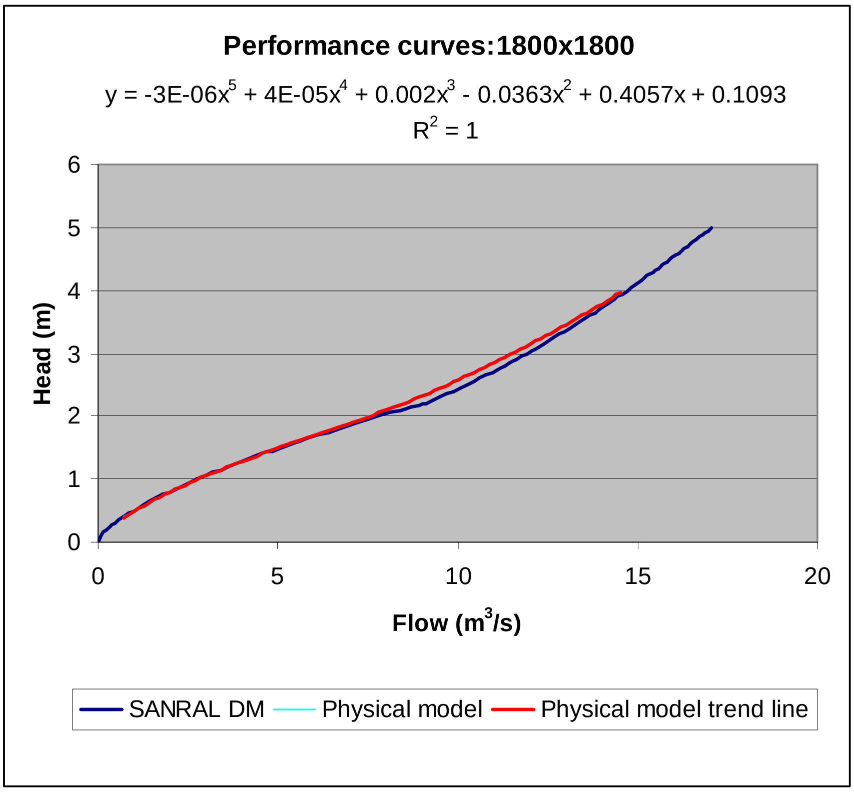


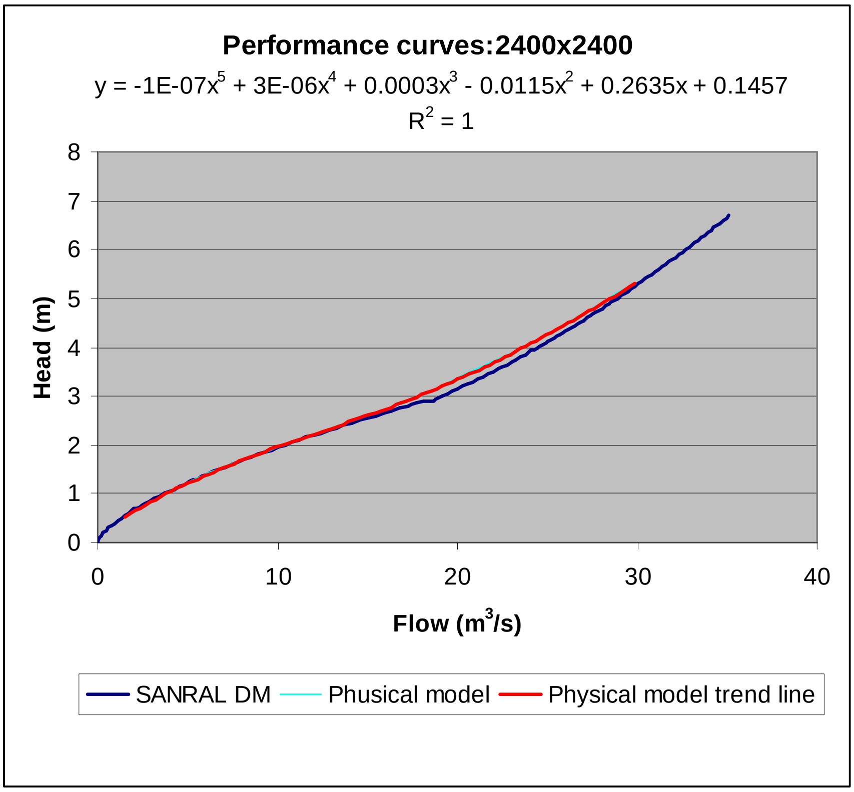


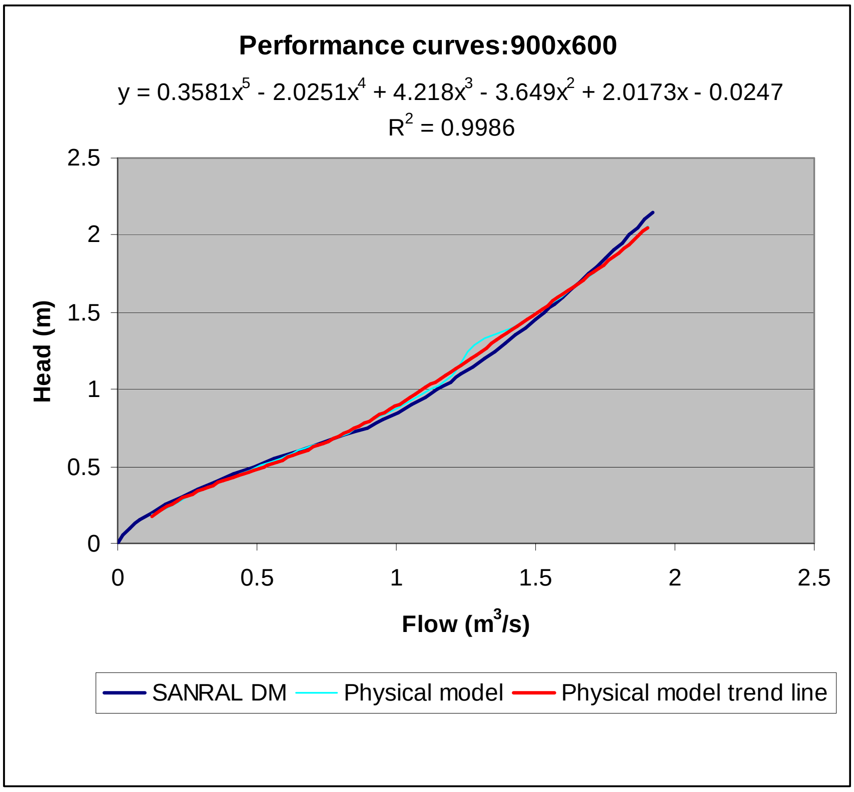

Performance curves:750x750
y = -0.0788x5 + 0.0979x4 + 0.5921x3 - 1.2045x2 + 1.5083x + 0.0455
R2 = 1
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line

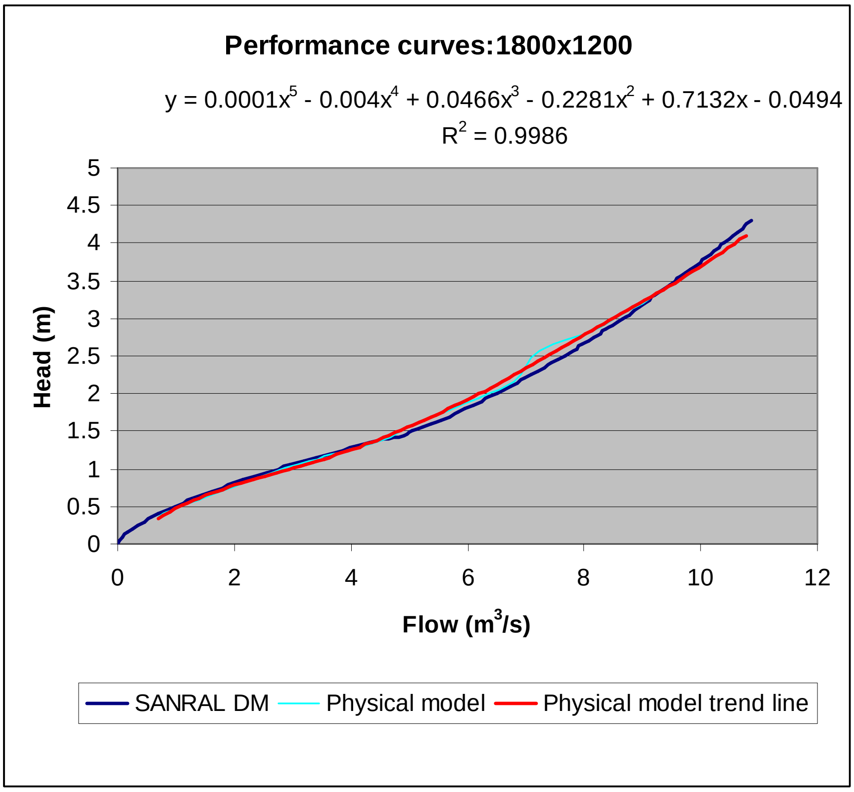

Performance curves:900x900
y = -0.0097x5 + 0.019x4 + 0.181x3 - 0.5809x2 + 1.1474x + 0.0546
R2 = 1
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line

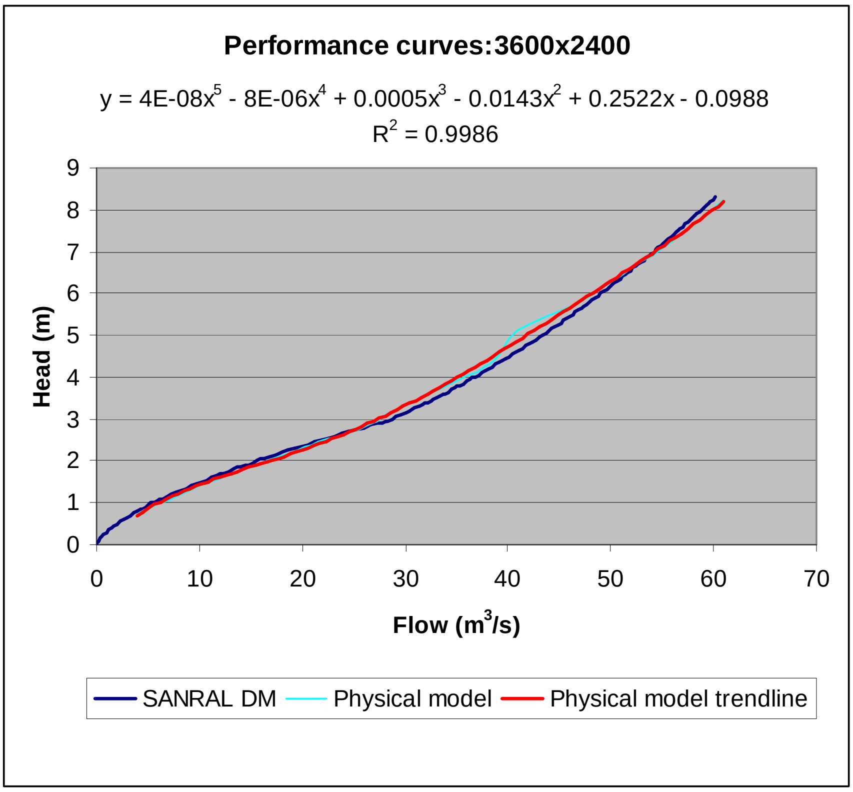

Performance curves:1200x1200
y = -0.0004x5 + 0.0014x4 + 0.0279x3 - 0.1838x2 + 0.7452x + 0.0728
R2 = 1
Head (m)
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line

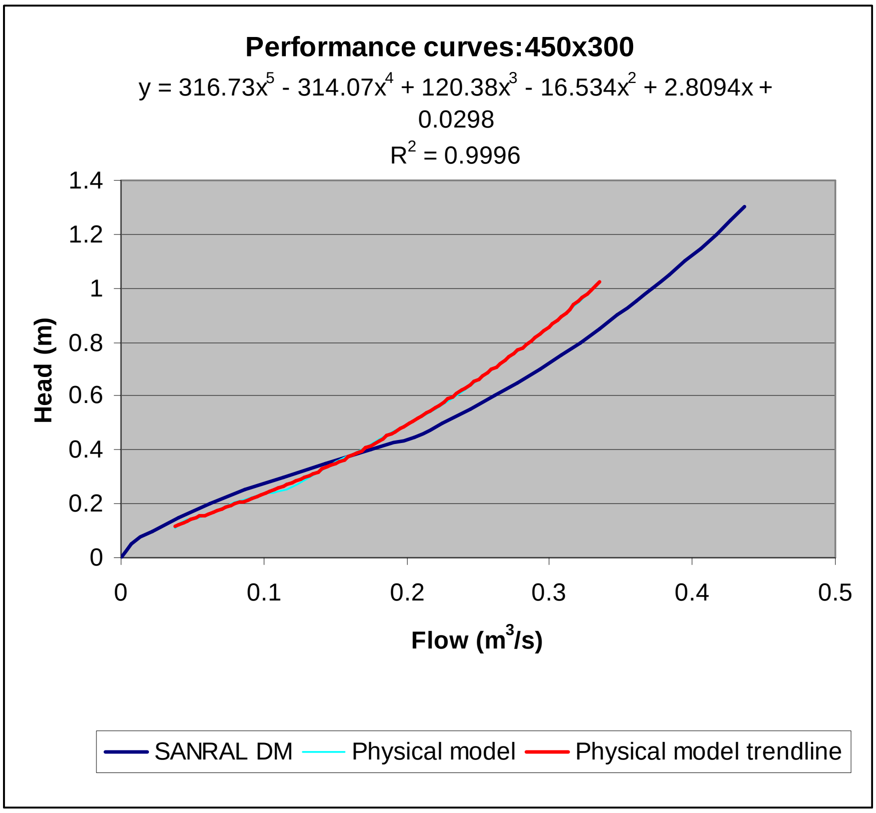

Performance curves:1800x1800
y = -3E-06x5 + 4E-05x4 + 0.002x3 - 0.0363x2 + 0.4057x + 0.1093
R2 = 1
Head (m)
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line


Performance curves:2400x2400
y = -1E-07x5 + 3E-06x4 + 0.0003x3 - 0.0115x2 + 0.2635x + 0.1457
R2 = 1
Head (m)
Flow (m3/s)
SANRAL DM
Phusical model
Physical model trend line

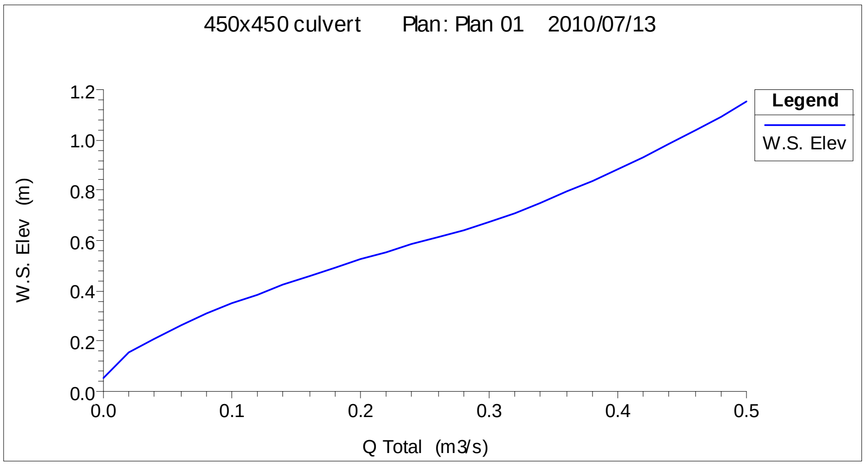

Performance curves:900x600
y = 0.3581x5 - 2.0251x4 + 4.218x3 - 3.649x2 + 2.0173x - 0.0247
R2 = 0.9986
Head (m)
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line

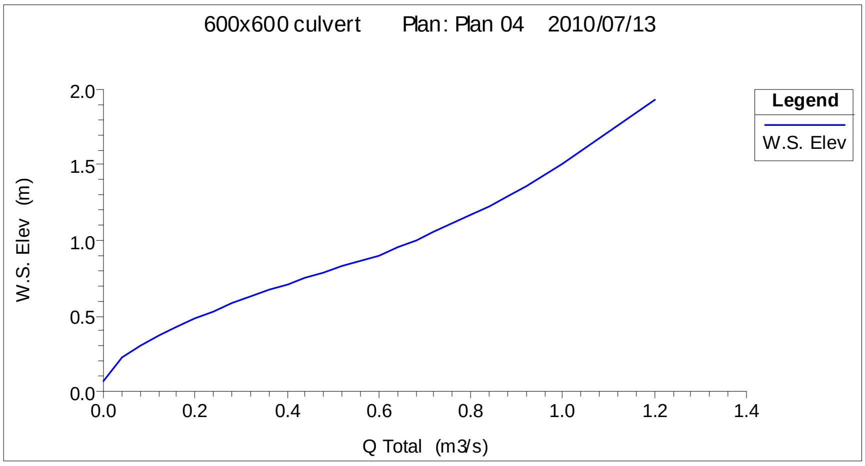

Performance curves:1800x1200
y = 0.0001x5 - 0.004x4 + 0.0466x3 - 0.2281x2 + 0.7132x - 0.0494
R2 = 0.9986
Head (m)
Flow (m3/s)
SANRAL DM
Physical model
Physical model trend line

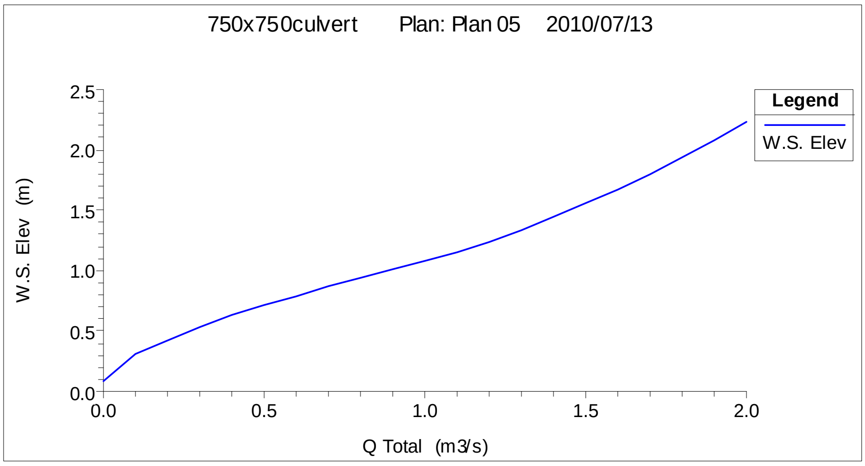

Performance curves:3600x2400
y = 4E-08x5 - 8E-06x4 + 0.0005x3 - 0.0143x2 + 0.2522x - 0.0988
R2 = 0.9986
Head (m)
Flow (m3/s)
SANRAL DM
Physical model
Physical model trendline

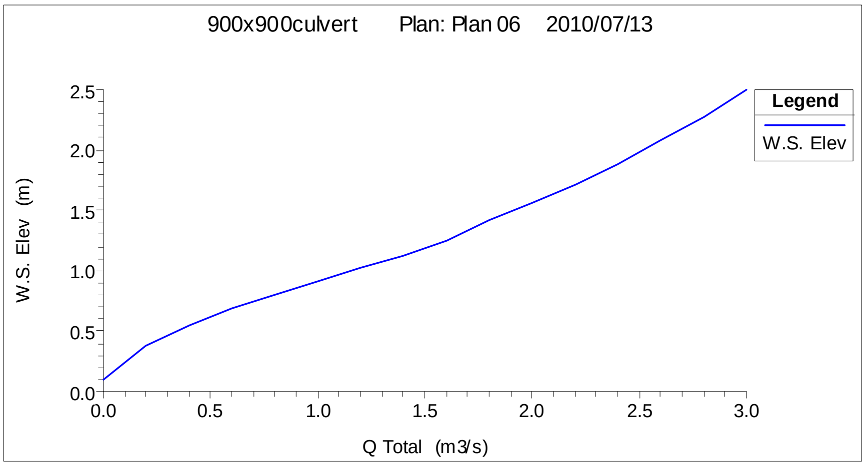

Performance curves:450x300
y = 316.73x5 - 314.07x4 + 120.38x3 - 16.534x2 + 2.8094x + 0.0298
R2 = 0.9996
Head (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
Flow (m3/s)
SANRAL DM
Physical model
Physical model trendline

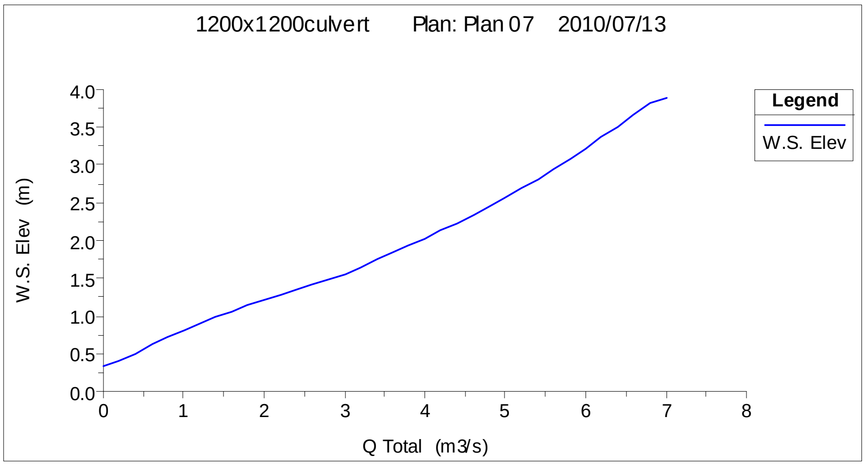
HEC-RAS performance curves:

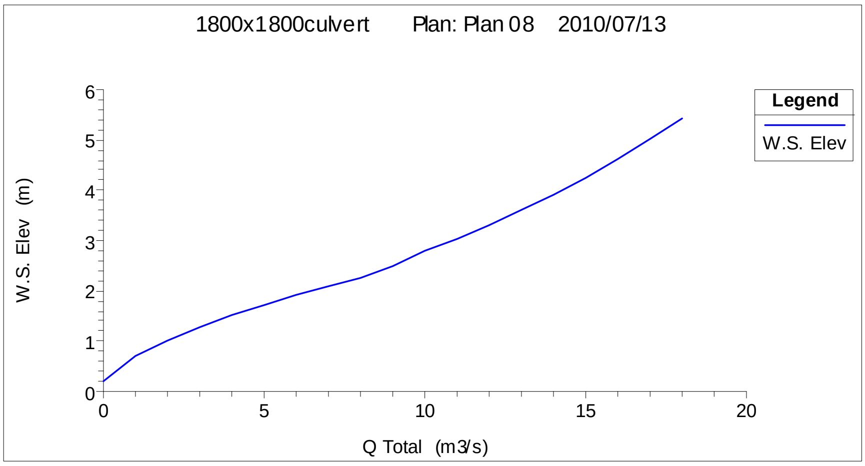


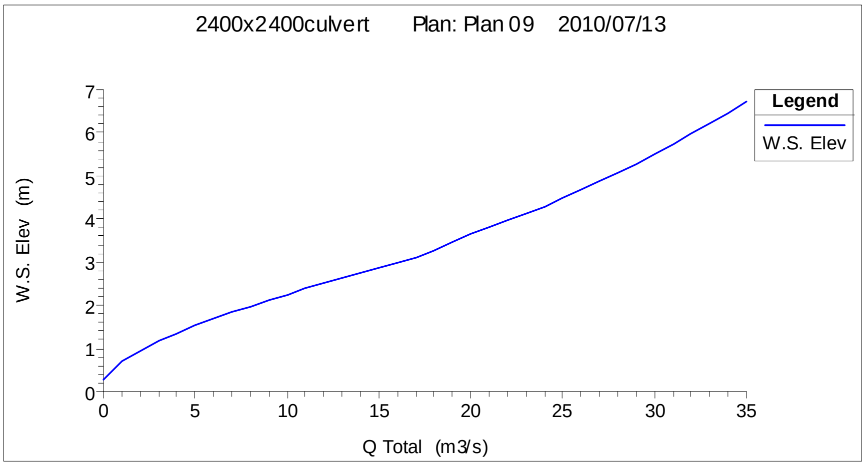


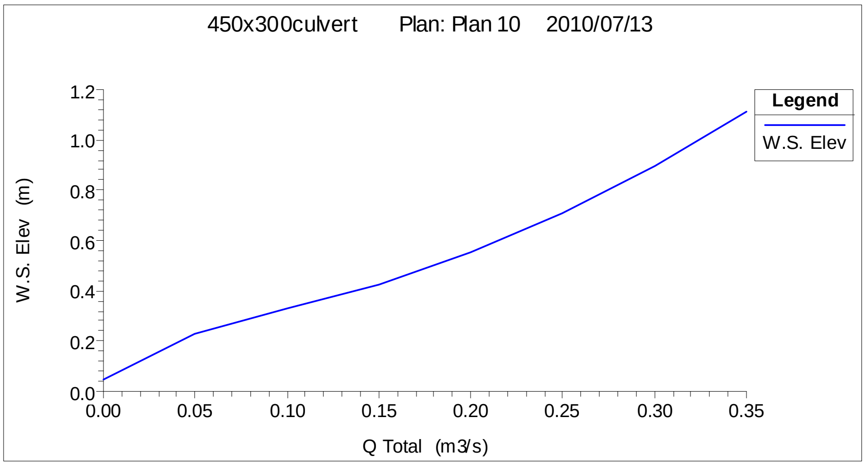


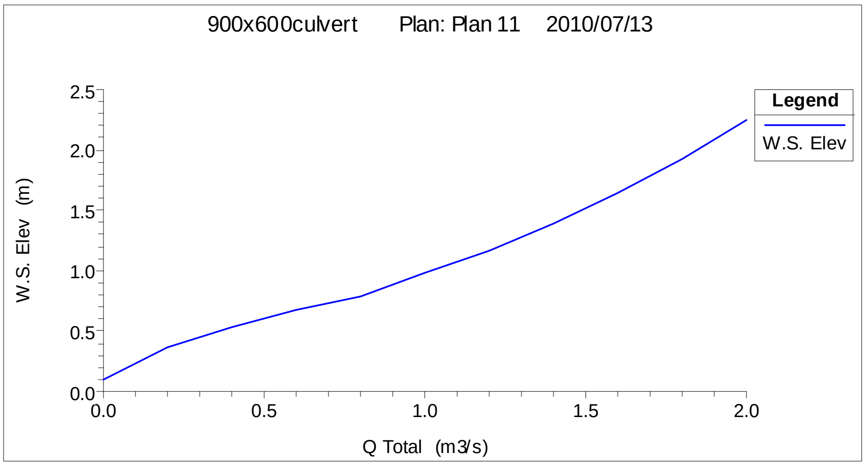

900x900culvert Plan: Plan 06 2010/07/13
W.S. Elev (m)
Q Total (m3/s)
Legend
W.S. Elev
0.0
0.5
1.0
1.5
2.0
2.5
3.0

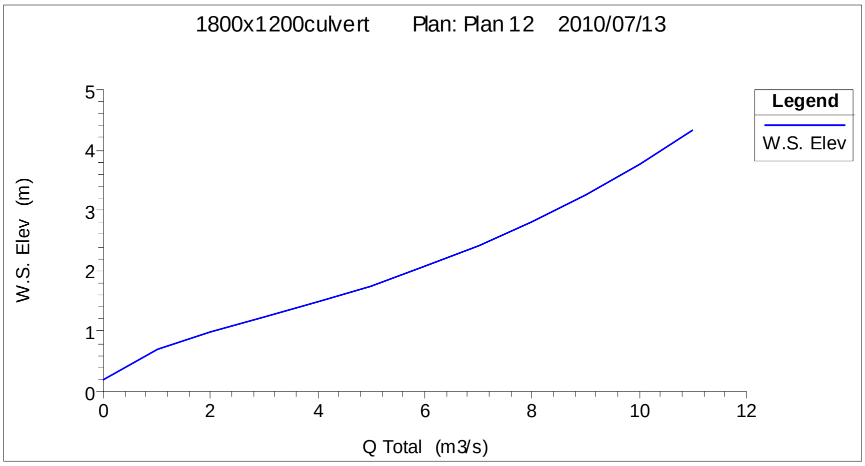

1200x1200culvert Plan: Plan 07 2010/07/13
W.S. Elev (m)
Q Total (m3/s)
Legend
W.S. Elev
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
1
2
3
4
5
6
7
8

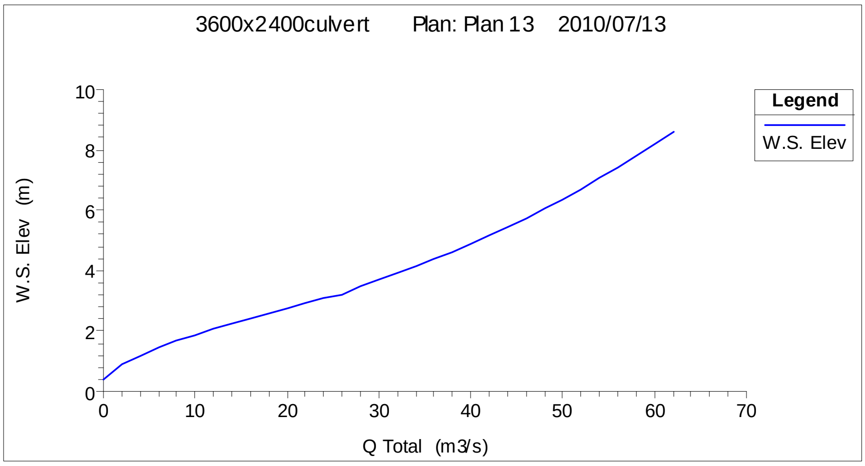

1800x1800culvert Plan: Plan 08 2010/07/13
W.S. Elev (m)
Q Total (m3/s)
Legend
W.S. Elev
0
1
2
3
4
5
6
10
15
20


2400x2400culvert Plan: Plan 09 2010/07/13
Legend
W.S. Elev
W.S. Elev (m)
Q Total (m3/s)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35

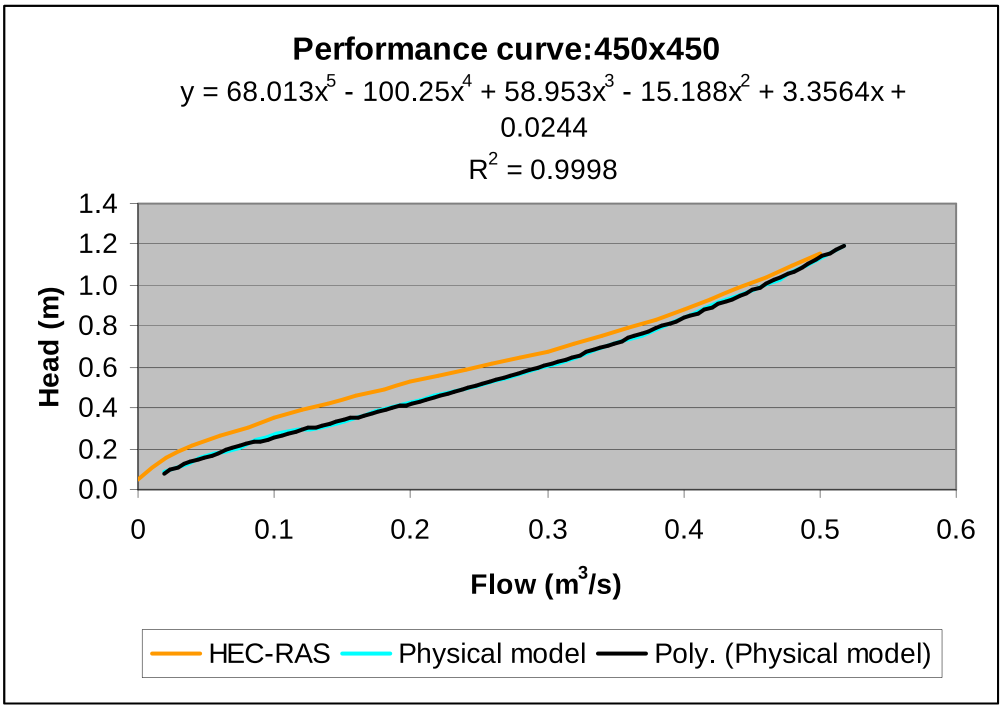

450x300culvert Plan: Plan 10 2010/07/13
Legend
W.S. Elev
W.S. Elev (m)
Q Total (m3/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

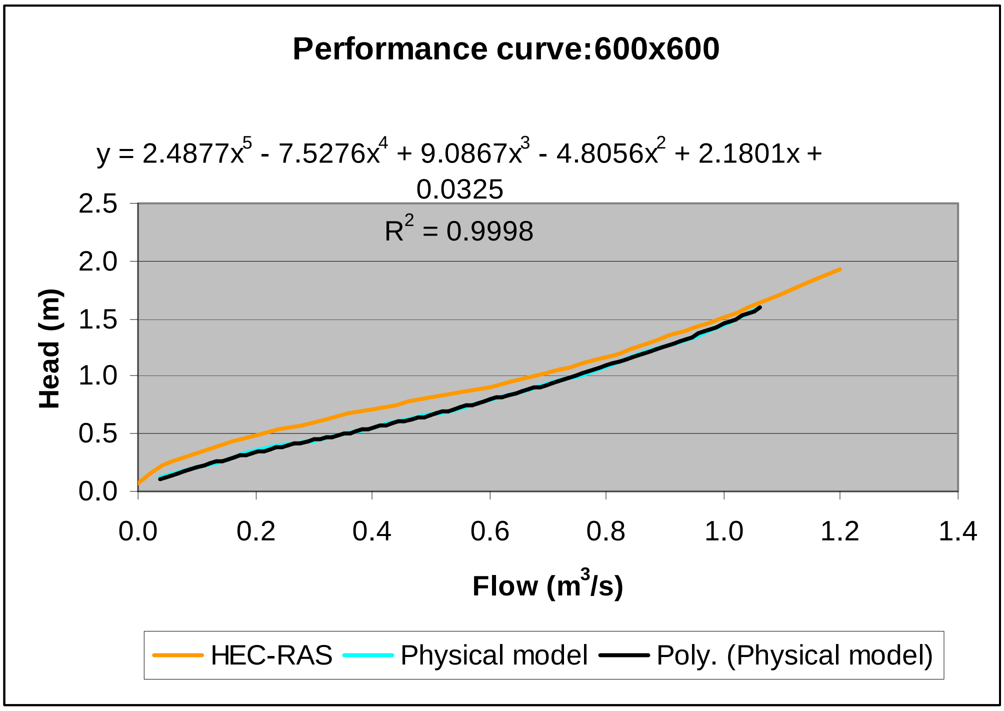

900x600culvert Plan: Plan 11 2010/07/13
Legend
W.S. Elev
W.S. Elev (m)
Q Total (m3/s)
0.0
0.5
1.0
1.5
2.0
2.5
0.0
0.5
1.0
1.5
2.0

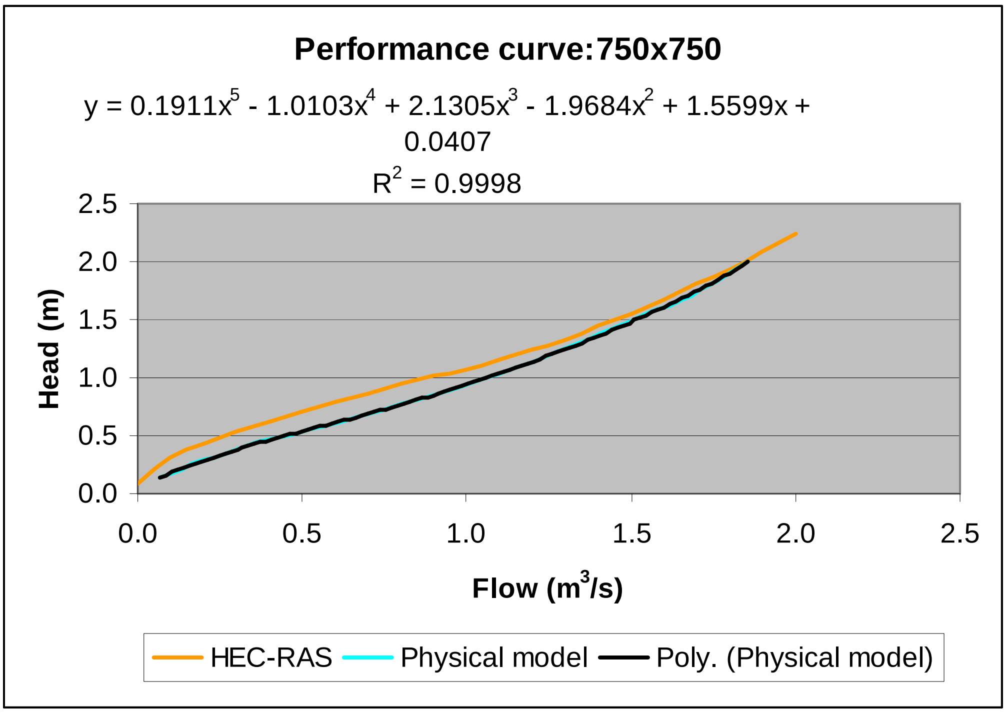

1800x1200culvert Plan: Plan 12 2010/07/13
Legend
W.S. Elev
W.S. Elev (m)
Q Total (m3/s)
0
1
2
3
4
5
0
2
4
6
8
10
12


3600x2400culvert Plan: Plan 13 2010/07/13
Legend
W.S. Elev
W.S. Elev (m)
Q Total (m3/s)
0
2
4
6
8
10
0
10
20
30
40
50
60
70

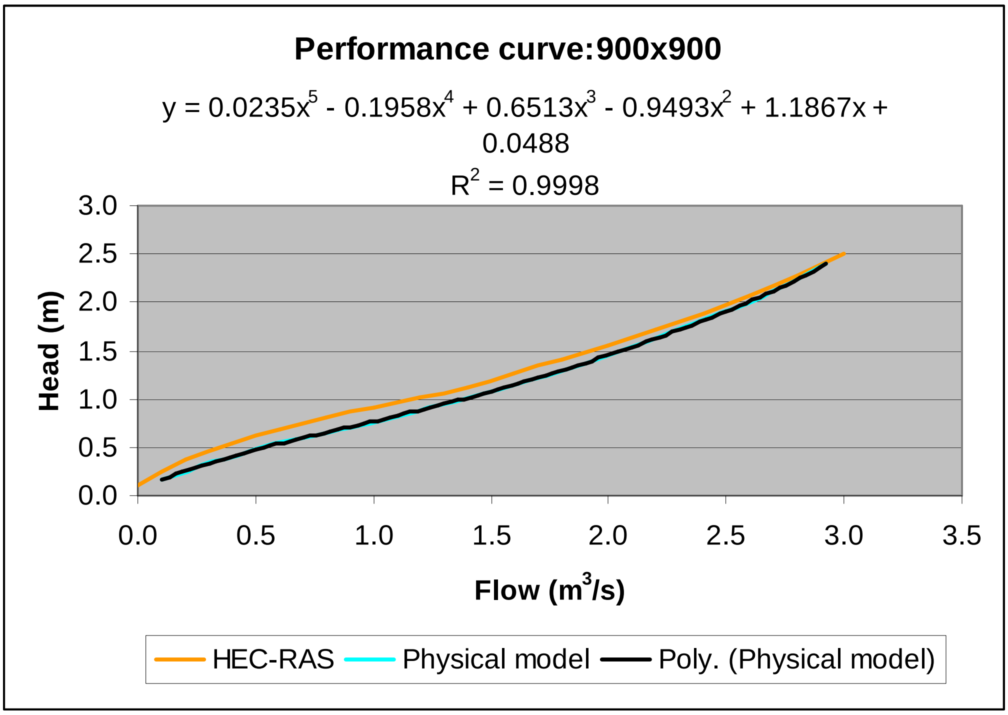
HEC-RAS Comparison to the physical model



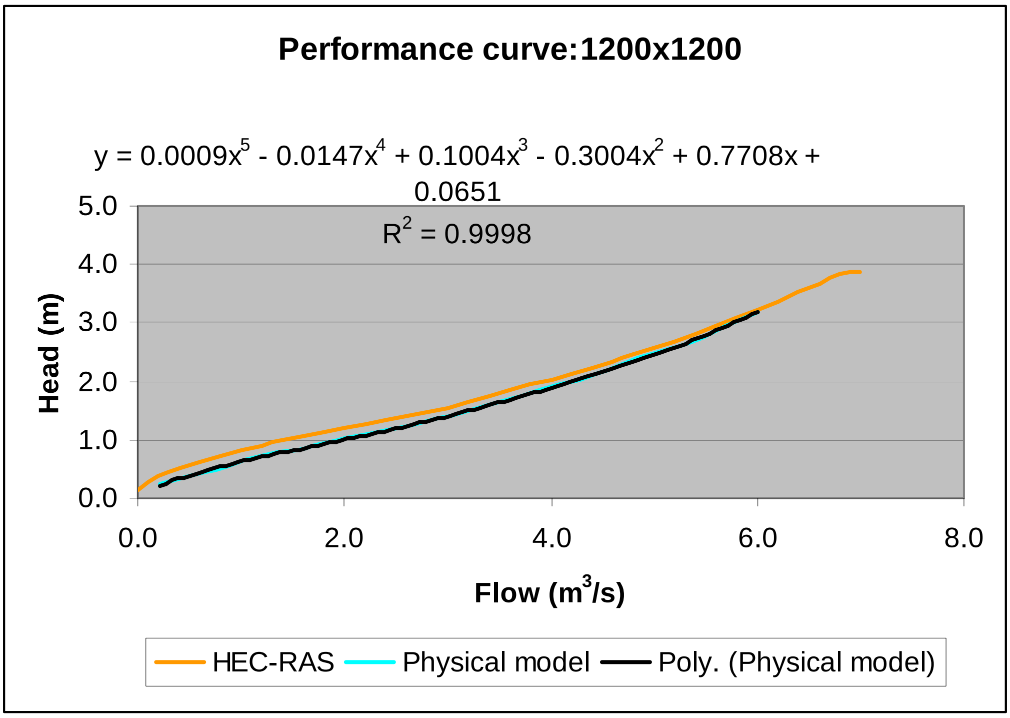


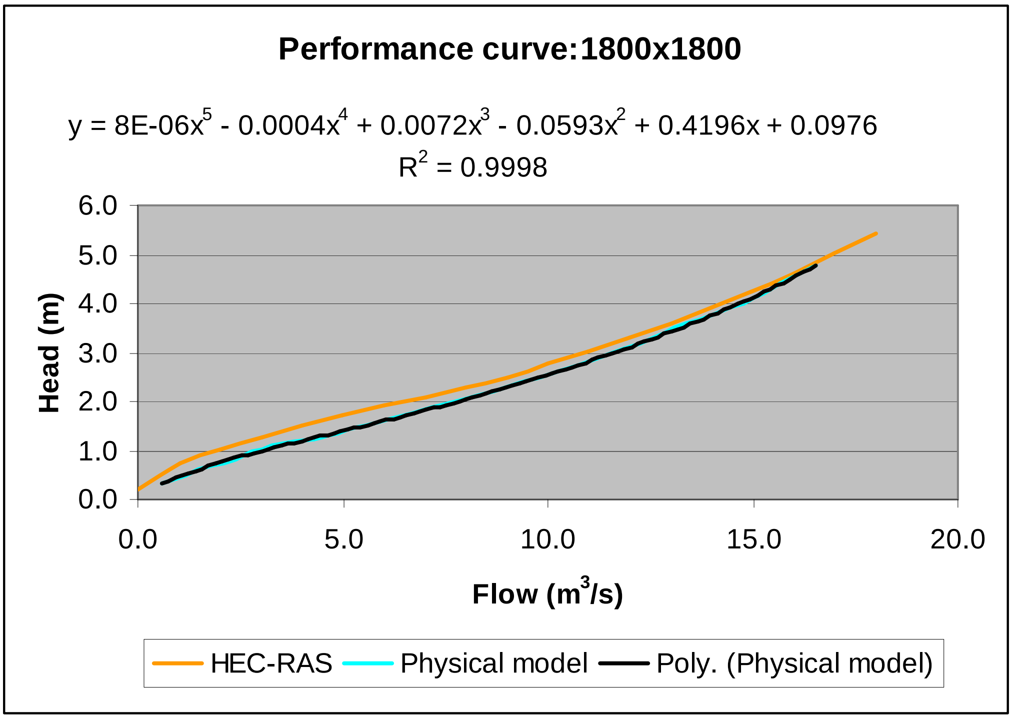


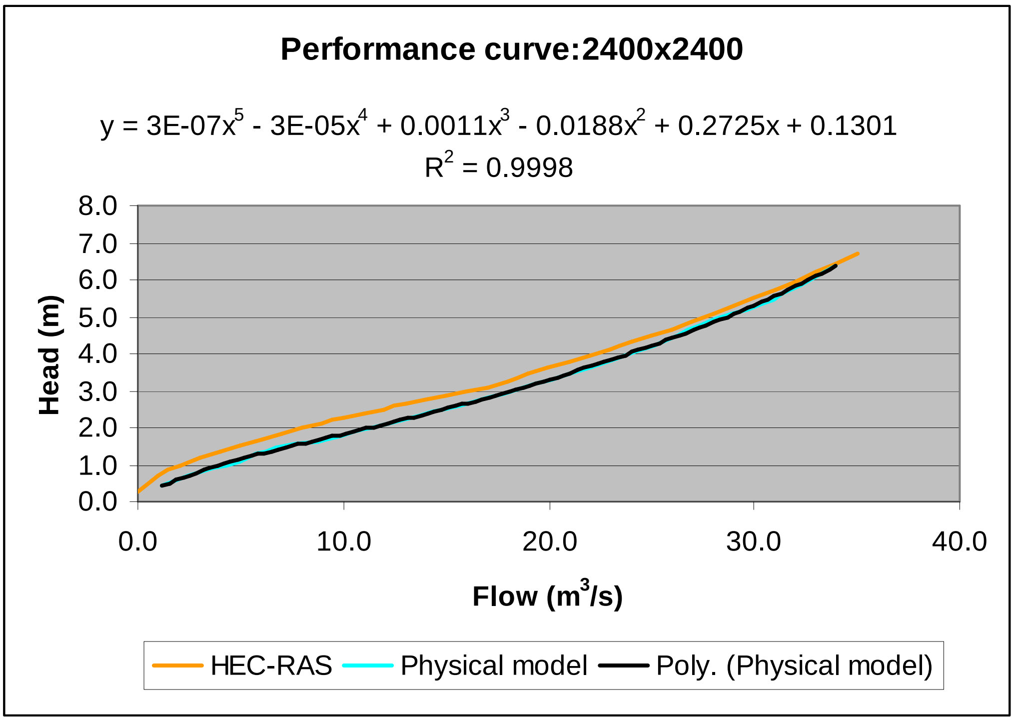
Performance curve:750x750
y = 0.1911x5 - 1.0103x4 + 2.1305x3 - 1.9684x2 + 1.5599x + 0.0407
R2 = 0.9998
Head (m)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)



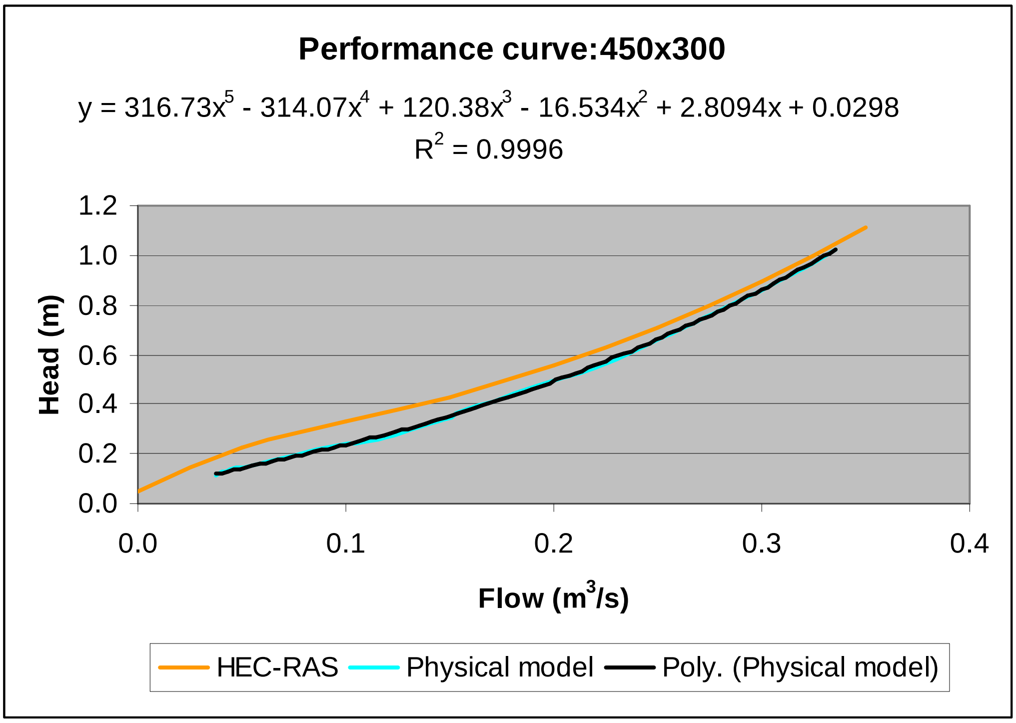
Performance curve:900x900
y = 0.0235x5 - 0.1958x4 + 0.6513x3 - 0.9493x2 + 1.1867x + 0.0488
R2 = 0.9998
Head (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)


Performance curve:1200x1200
y = 0.0009x5 - 0.0147x4 + 0.1004x3 - 0.3004x2 + 0.7708x + 0.0651
R2 = 0.9998
Head (m)
5.0
4.0
3.0
2.0
1.0
0.0
0.0
2.0
4.0
6.0
8.0
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

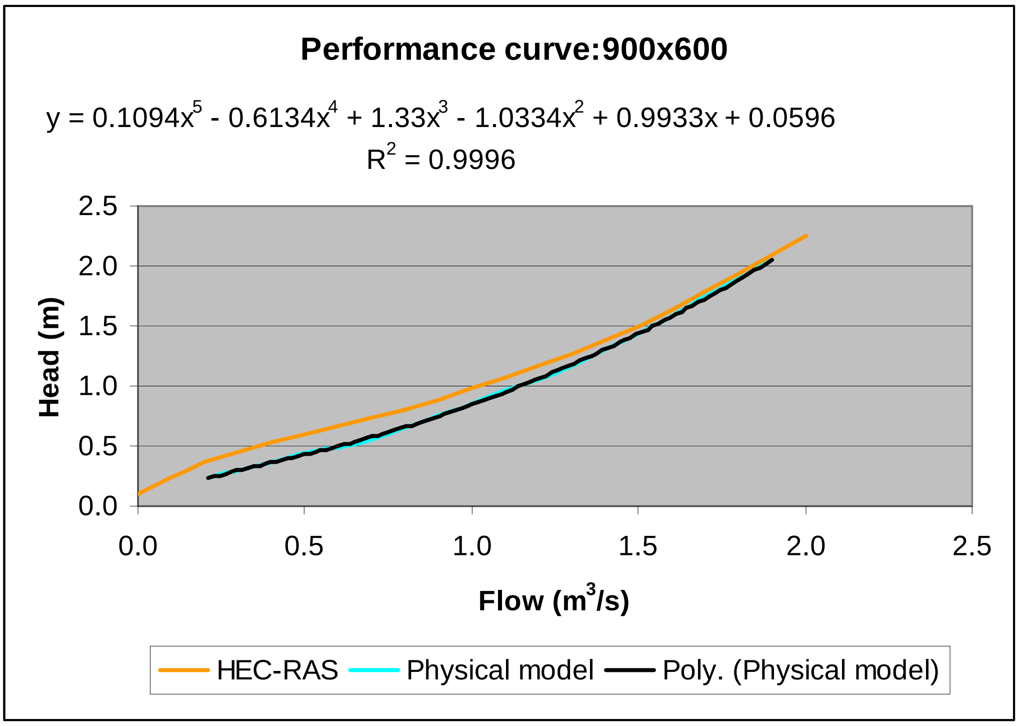

Performance curve:1800x1800
y = 8E-06x5 - 0.0004x4 + 0.0072x3 - 0.0593x2 + 0.4196x + 0.0976
R2 = 0.9998
Head (m)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
5.0
10.0
15.0
20.0
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

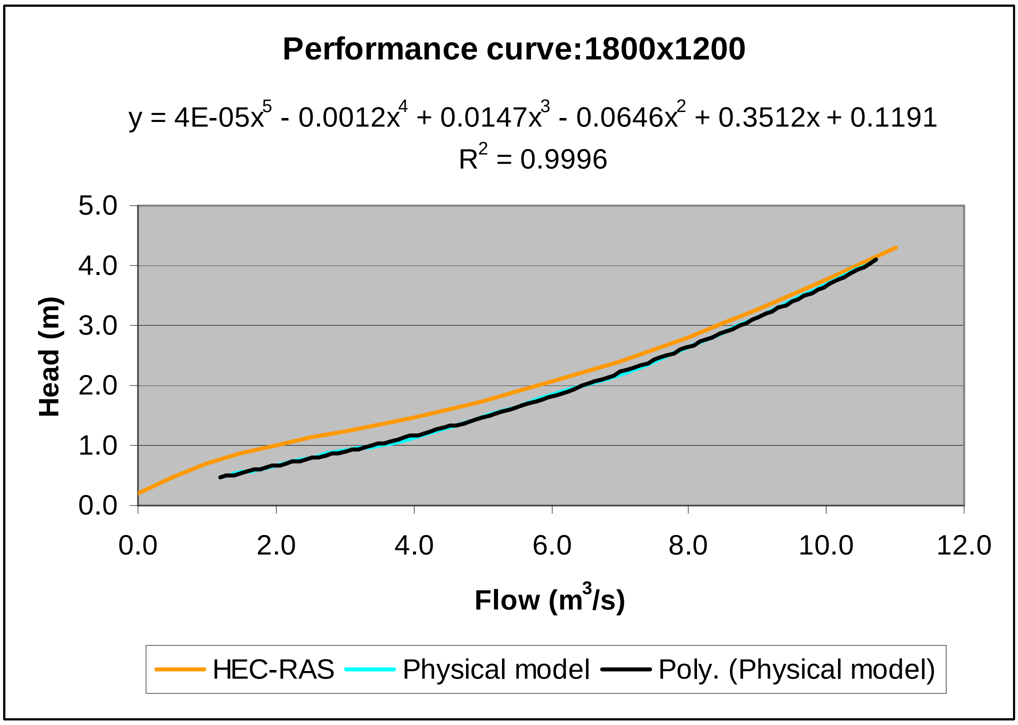


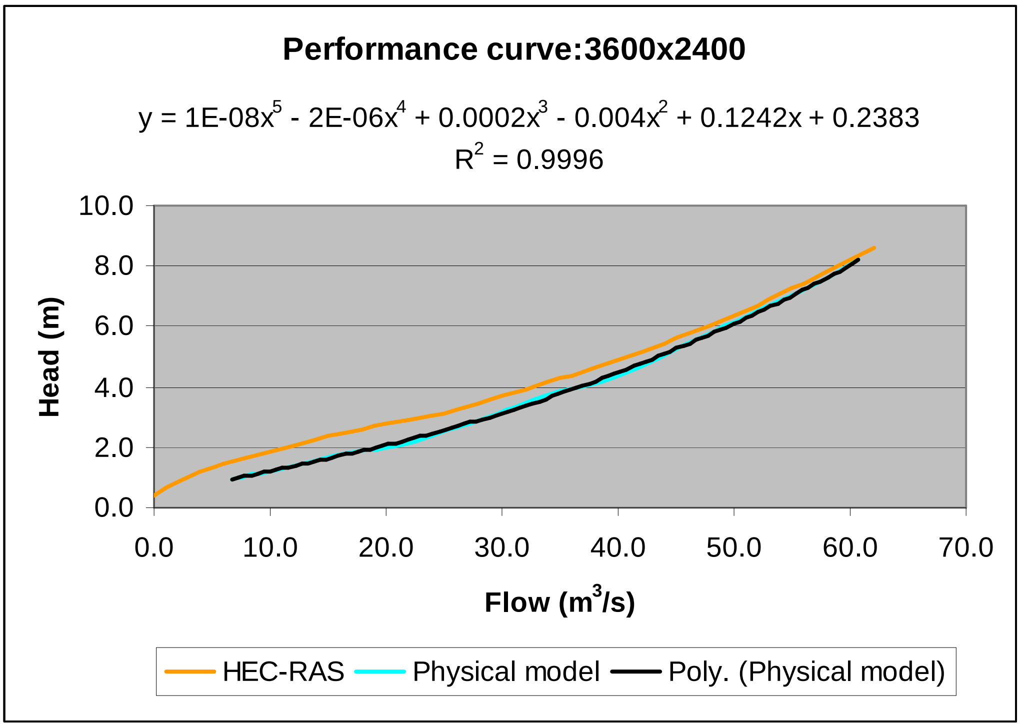
Performance curve:2400x2400
y = 3E-07x5 - 3E-05x4 + 0.0011x3 - 0.0188x2 + 0.2725x + 0.1301
R2 = 0.9998
Head (m)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
10.0
20.0
30.0
40.0
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)



Performance curve:450x300
y = 316.73x5 - 314.07x4 + 120.38x3 - 16.534x2 + 2.8094x + 0.0298
R2 = 0.9996
Head (m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

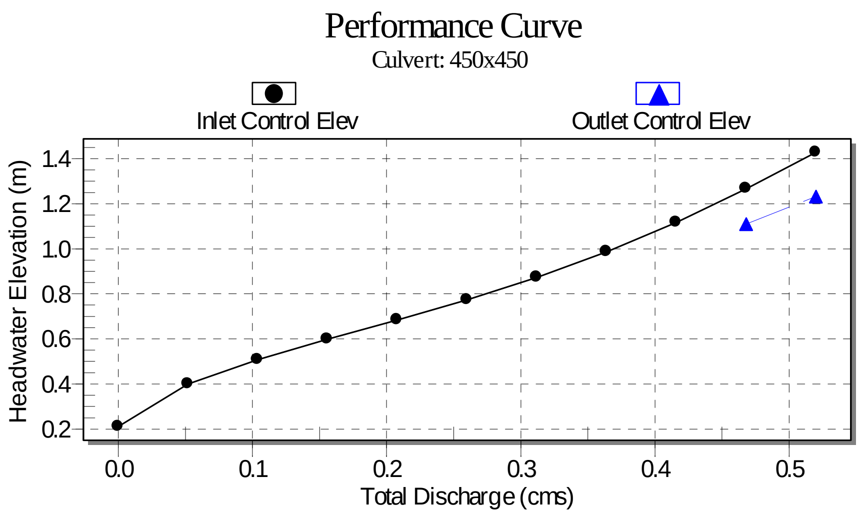

Performance curve:900x600
y = 0.1094x5 - 0.6134x4 + 1.33x3 - 1.0334x2 + 0.9933x + 0.0596
R2 = 0.9996
Head (m)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

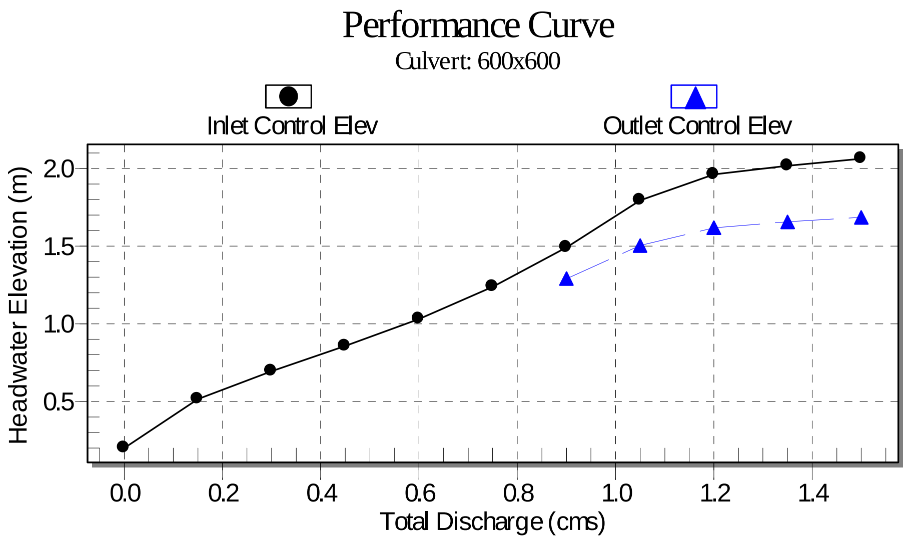

Performance curve:1800x1200
y = 4E-05x5 - 0.0012x4 + 0.0147x3 - 0.0646x2 + 0.3512x + 0.1191
R2 = 0.9996
Head (m)
5.0
4.0
3.0
2.0
1.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

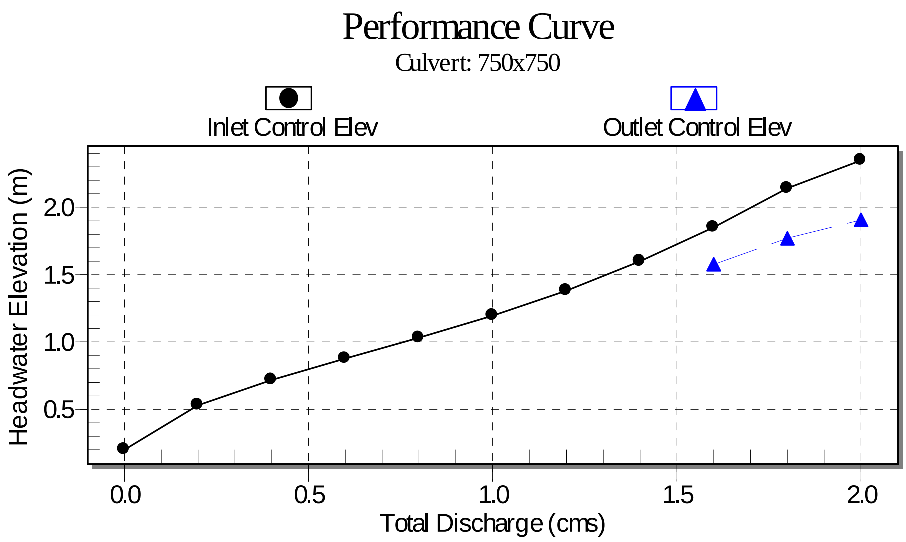


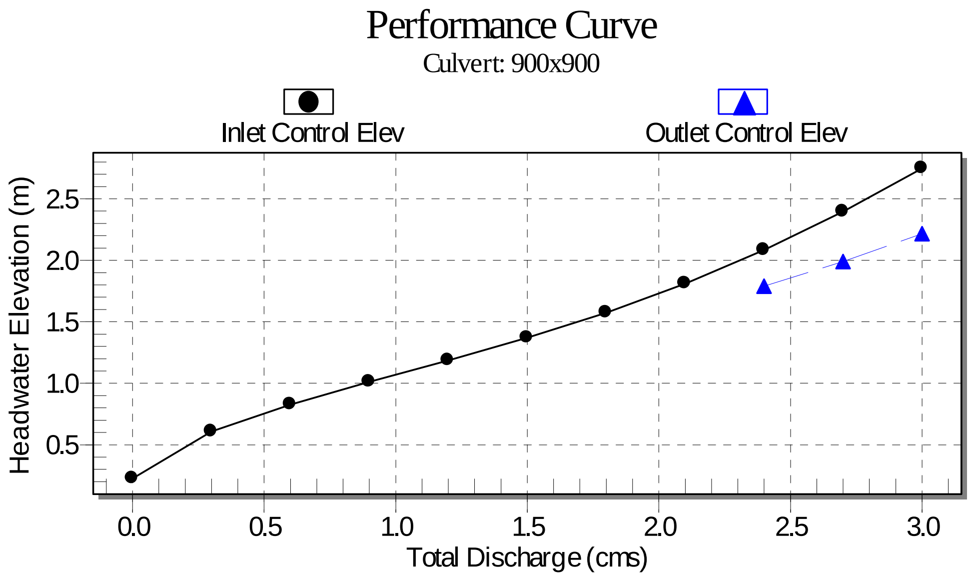
Performance curve:3600x2400
y = 1E-08x5 - 2E-06x4 + 0.0002x3 - 0.004x2 + 0.1242x + 0.2383
R2 = 0.9996
Head (m)
10.0
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Flow (m3/s)
HEC-RAS
Physical model
Poly. (Physical model)

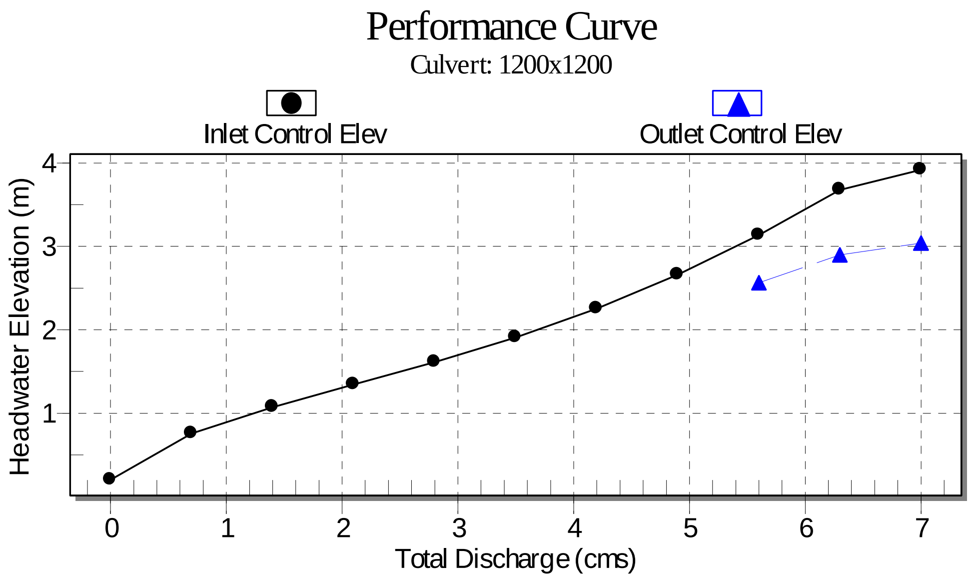
HY-8 performance curves

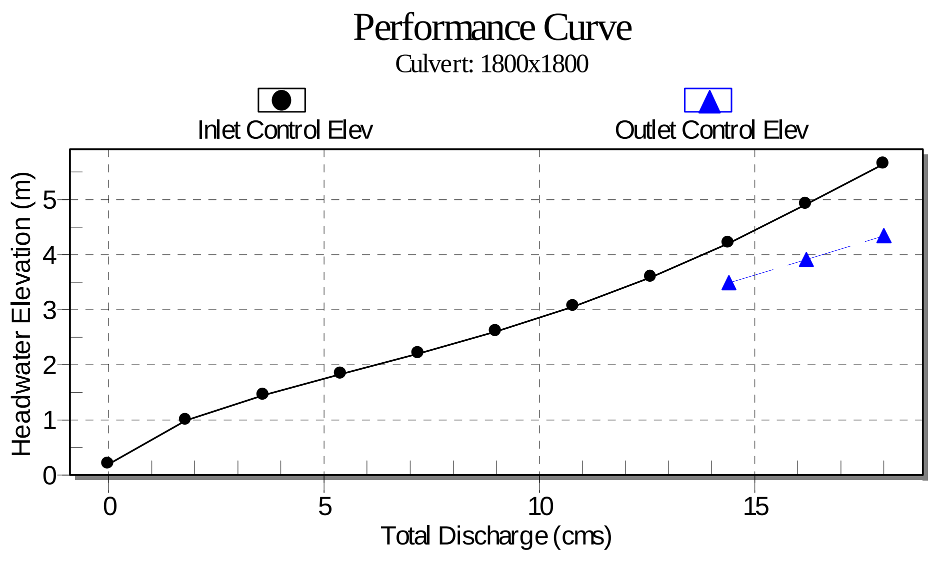


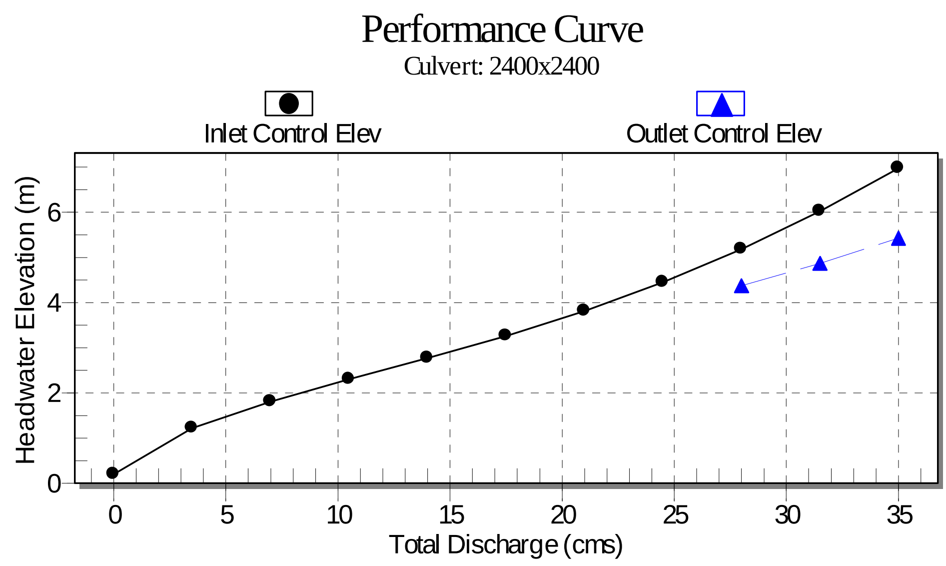




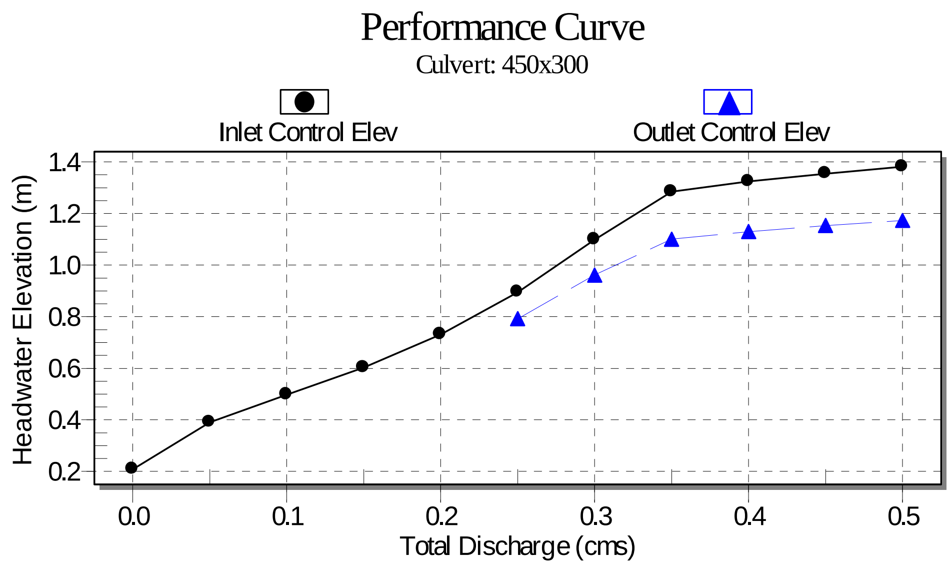

Performance Curve
Culvert: 900x900
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
0.5
1.0
1.5
2.0
2.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Total Discharge (cms)


Performance Curve
Culvert: 1200x1200
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
1
2
3
4
0
1
2
3
4
5
6
7
Total Discharge (cms)

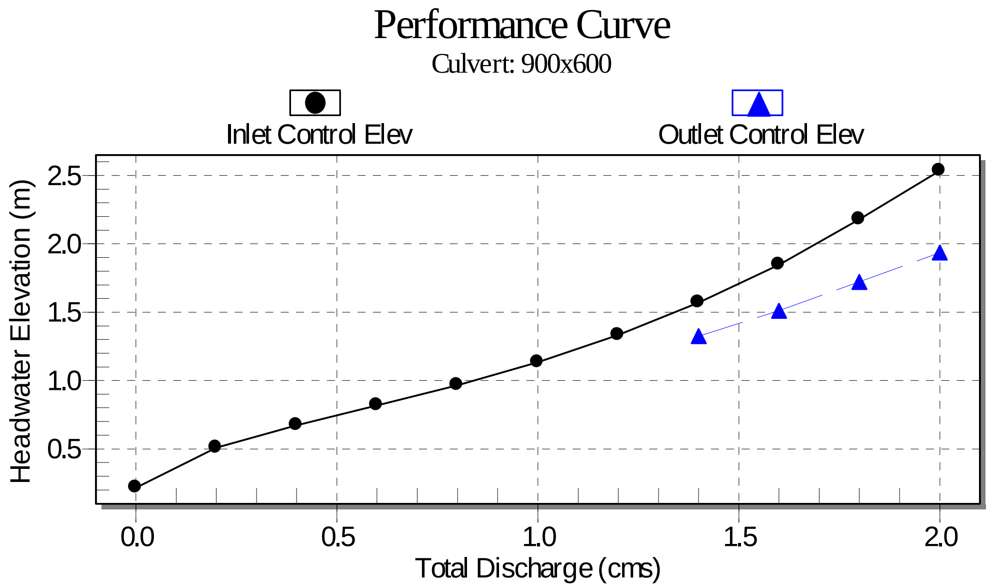

Performance Curve
Culvert: 1800x1800
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
0
1
2
3
4
5
0
5
10
15
Total Discharge (cms)



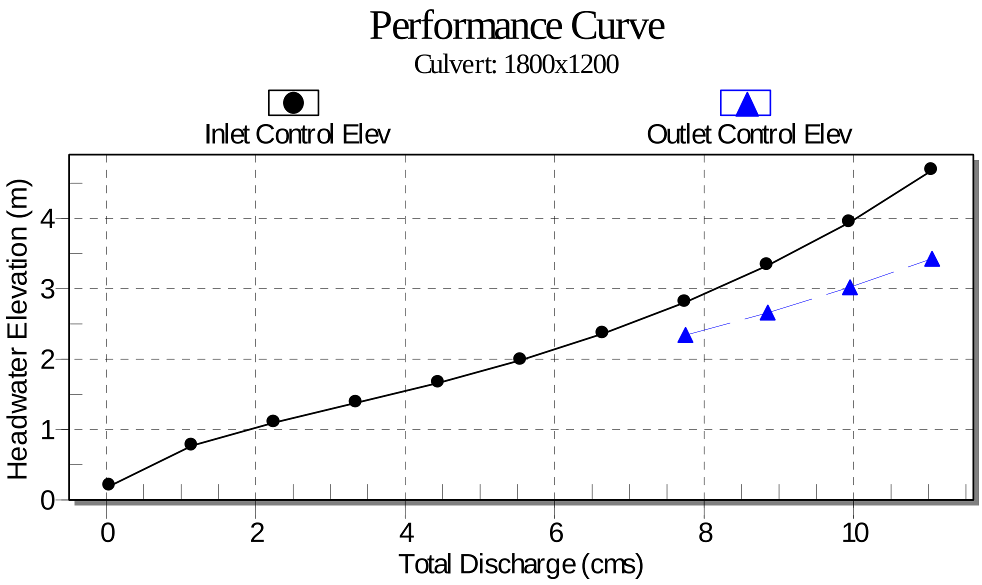
Performance Curve
Culvert: 2400x2400
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
0
2
4
6
0
5
10
15
20
25
30
35
Total Discharge (cms)

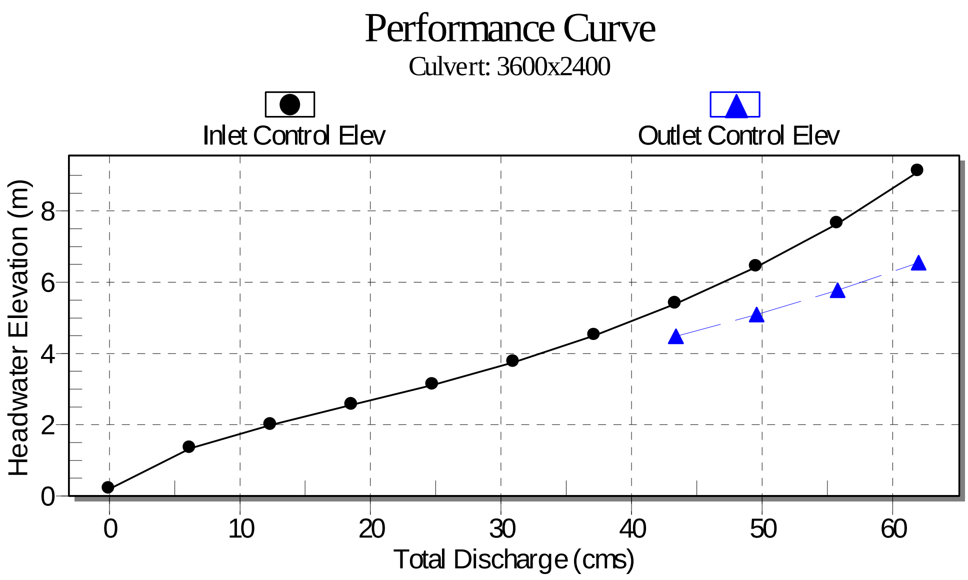


Performance Curve
Culvert: 450x300
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
Total Discharge (cms)

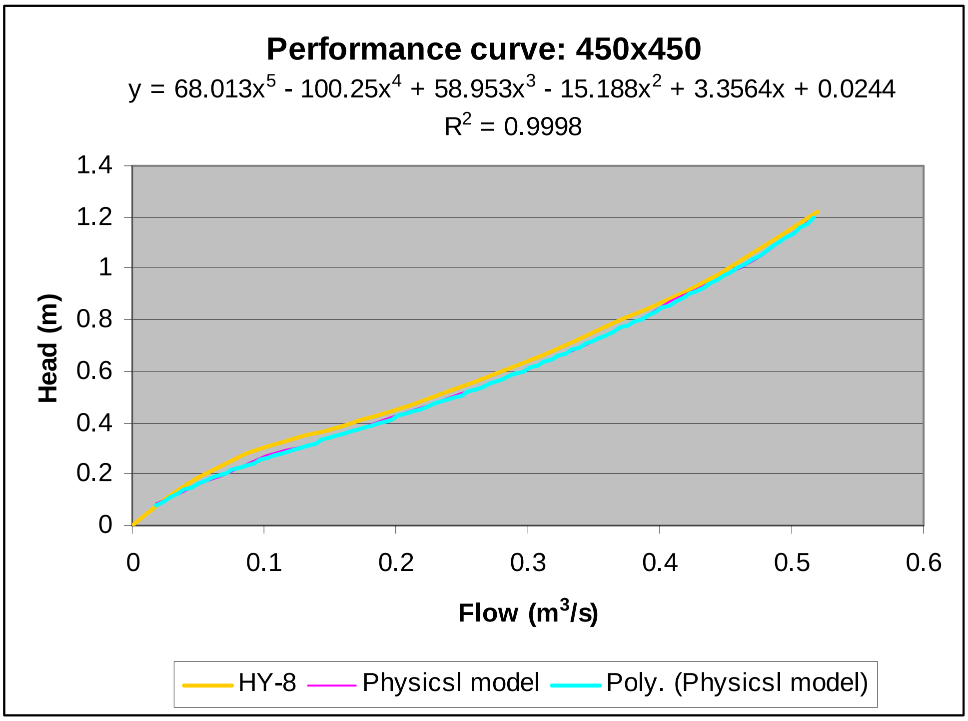


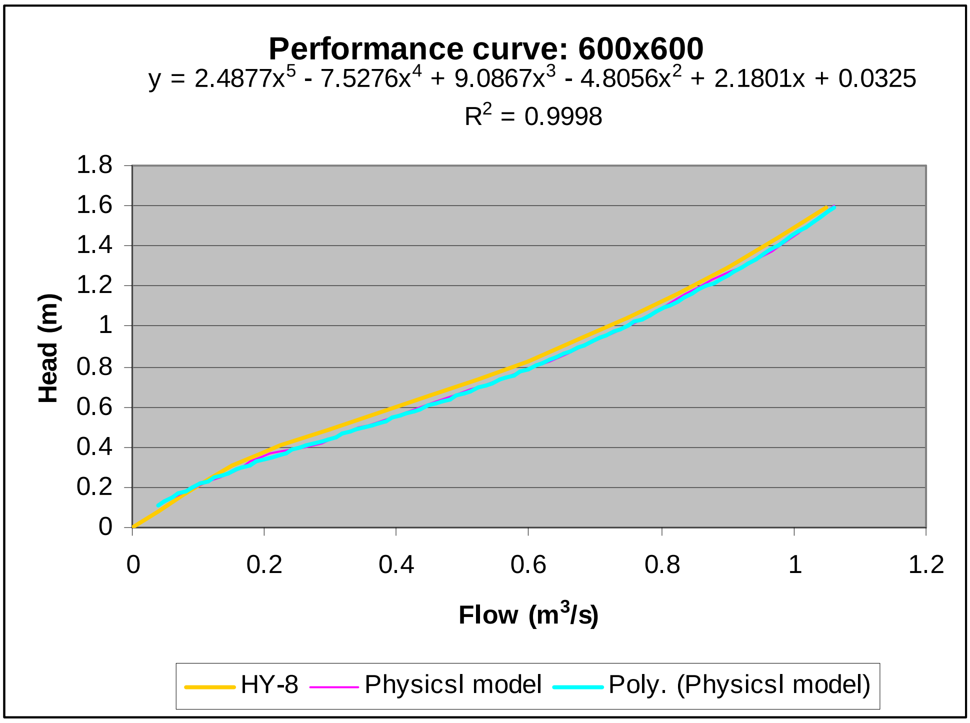
Performance Curve
Culvert: 900x600
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
Total Discharge (cms)

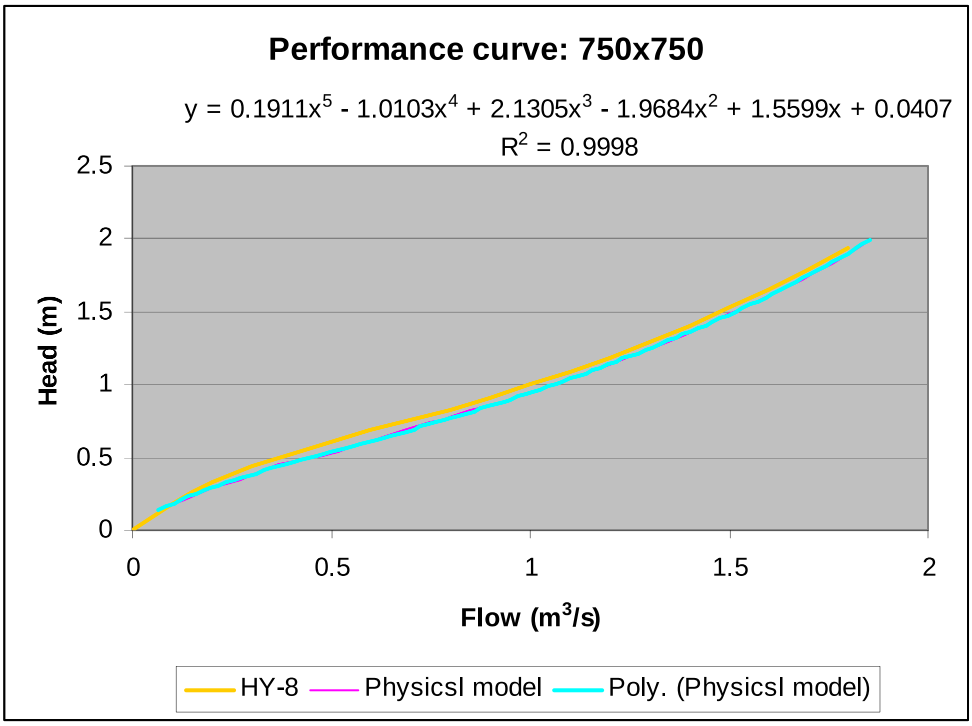

Performance Curve
Culvert: 1800x1200
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
0
1
2
3
4
0
2
4
6
8
10
Total Discharge (cms)


Performance Curve
Culvert: 3600x2400
Inlet Control Elev
Outlet Control Elev
Headwater Elevation (m)
0
2
4
6
8
0
10
20
30
40
50
60
Total Discharge (cms)

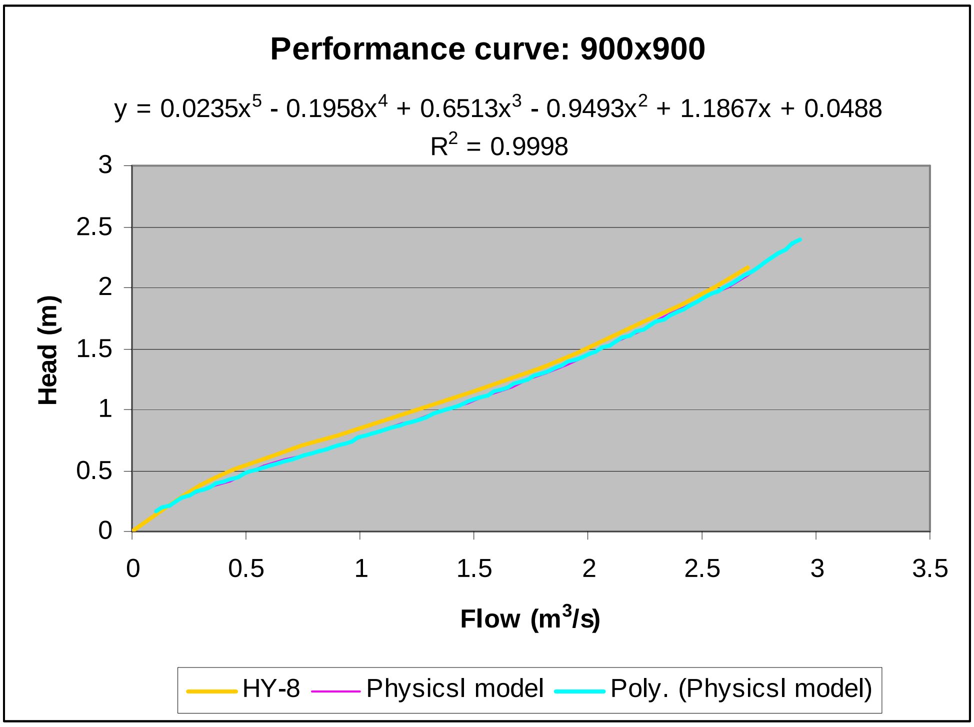
HY-8 and physical model performance curves comparison



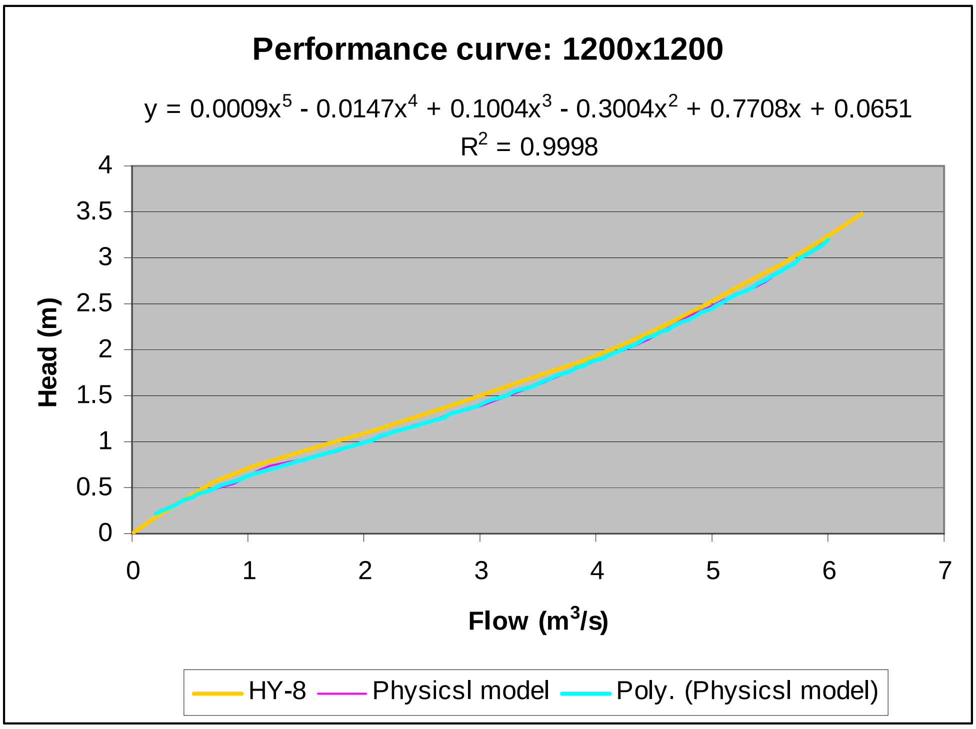


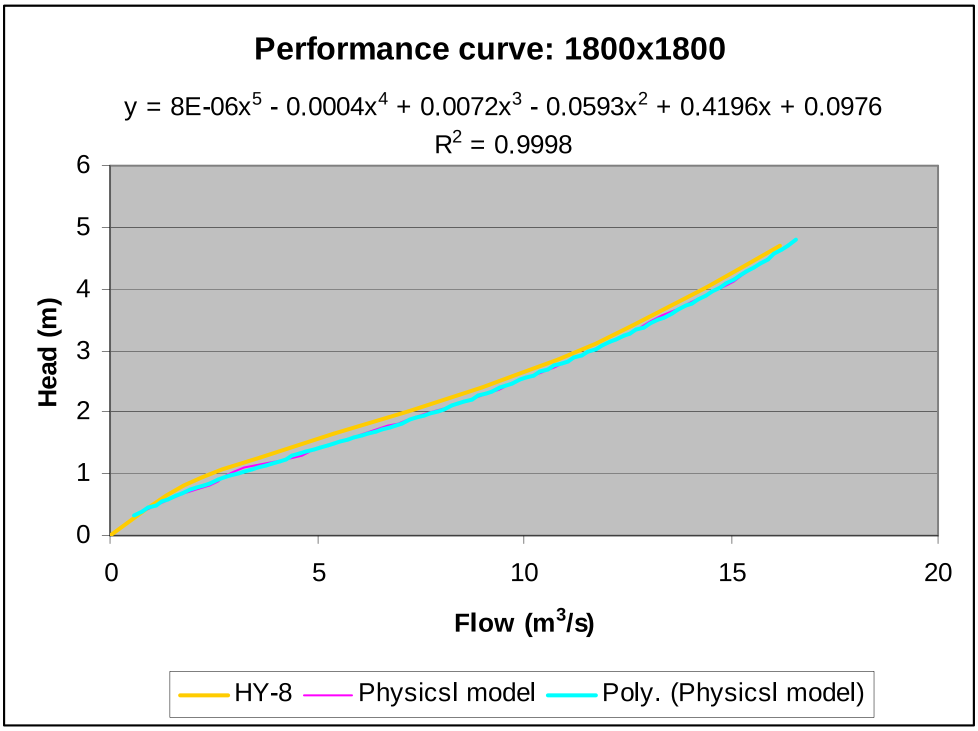


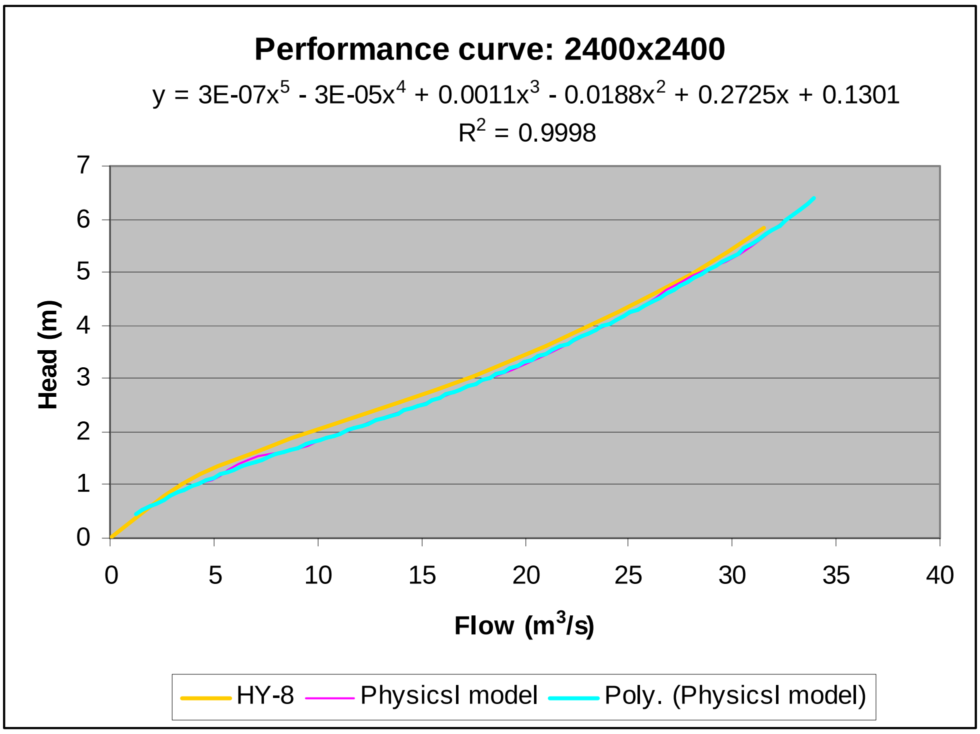
Performance curve: 750x750
y = 0.1911x5 - 1.0103x4 + 2.1305x3 - 1.9684x2 + 1.5599x + 0.0407
R2 = 0.9998
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)

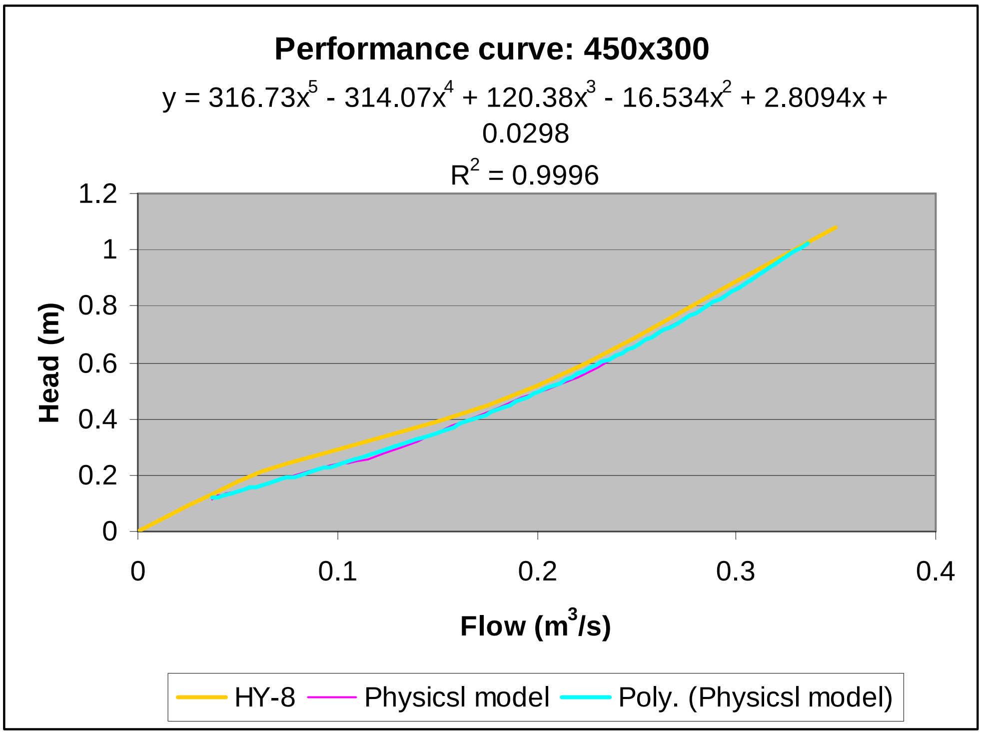


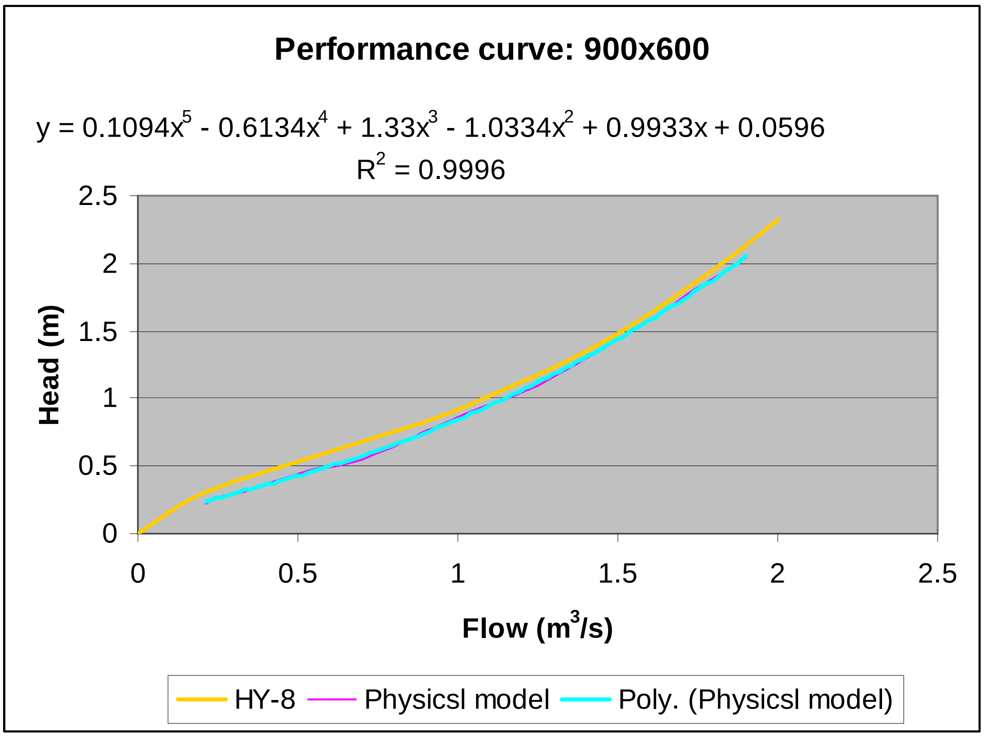
Performance curve: 900x900
y = 0.0235x5 - 0.1958x4 + 0.6513x3 - 0.9493x2 + 1.1867x + 0.0488
R2 = 0.9998
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)


Performance curve: 1200x1200
y = 0.0009x5 - 0.0147x4 + 0.1004x3 - 0.3004x2 + 0.7708x + 0.0651
R2 = 0.9998
Head (m)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)

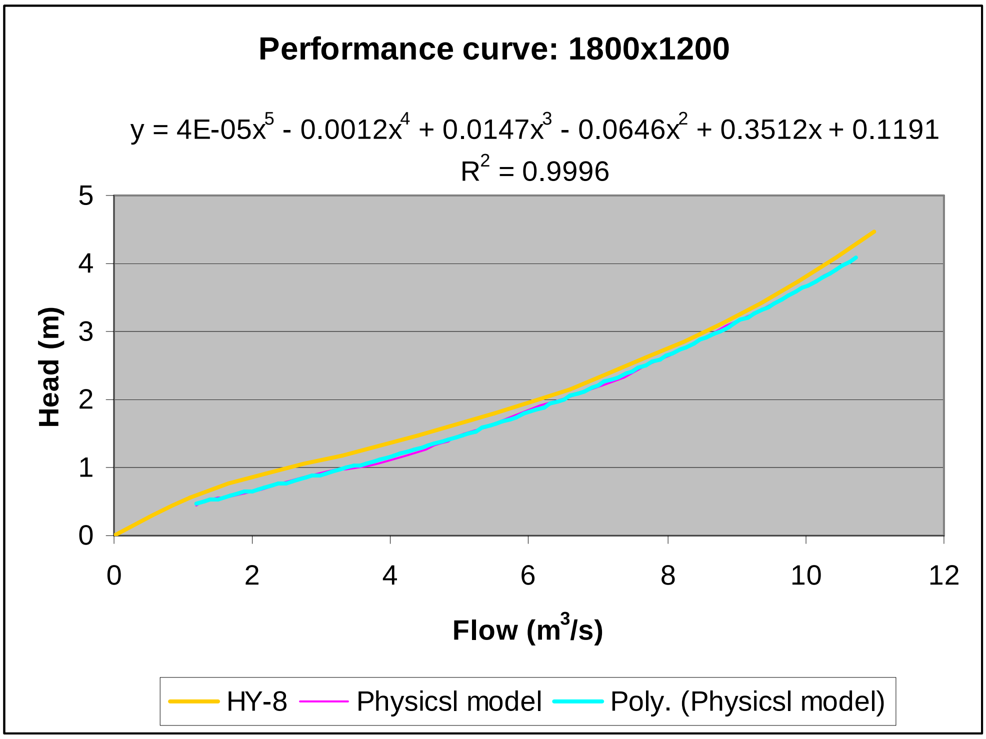

Performance curve: 1800x1800
y = 8E-06x5 - 0.0004x4 + 0.0072x3 - 0.0593x2 + 0.4196x + 0.0976
R2 = 0.9998
Head (m)
6
5
4
3
2
1
0
0
5
10
15
20
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)


Performance curve: 2400x2400
y = 3E-07x5 - 3E-05x4 + 0.0011x3 - 0.0188x2 + 0.2725x + 0.1301
R2 = 0.9998
Head (m)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)

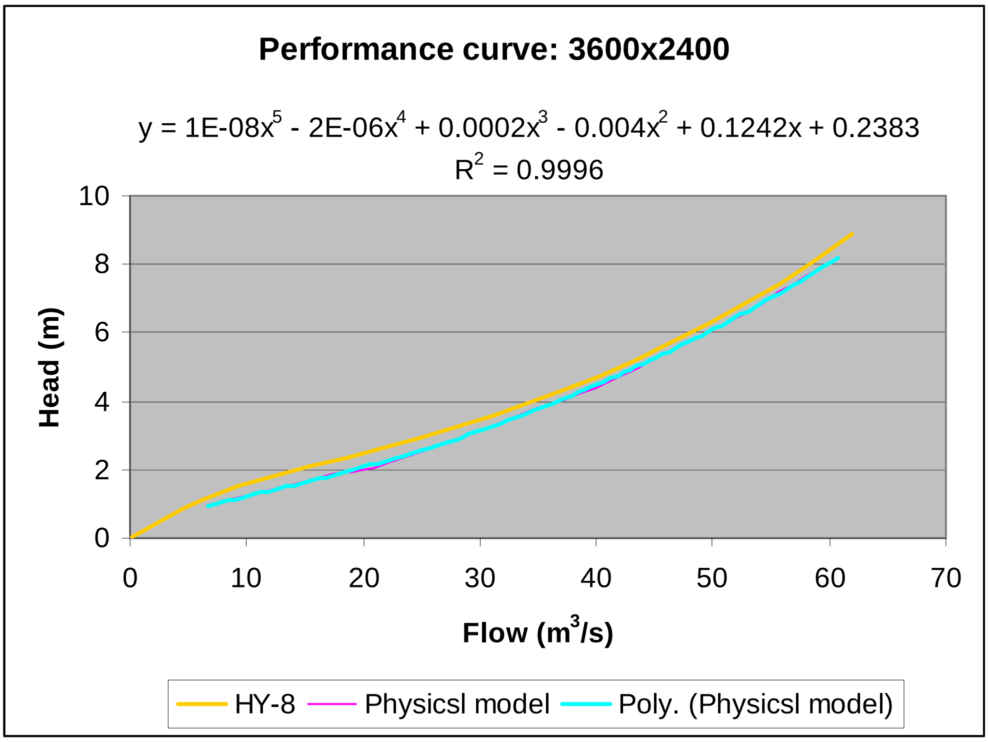

Performance curve: 450x300
y = 316.73x5 - 314.07x4 + 120.38x3 - 16.534x2 + 2.8094x + 0.0298
R2 = 0.9996
Head (m)
0
0.2
0.4
0.6
0.8
1
1.2
0
0.1
0.2
0.3
0.4
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)



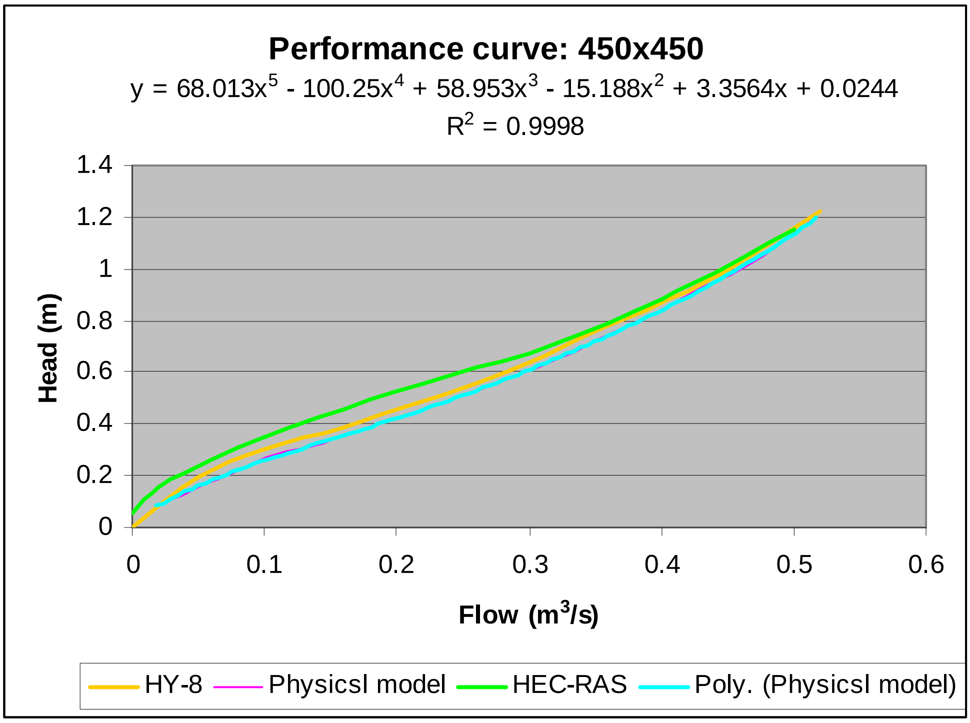
Performance curve: 900x600
y = 0.1094x5 - 0.6134x4 + 1.33x3 - 1.0334x2 + 0.9933x + 0.0596
R2 = 0.9996
Head (m)
Flow (m3/s)
0
0.5
1
1.5
2
2.5
HY-8
Physicsl model
Poly. (Physicsl model)

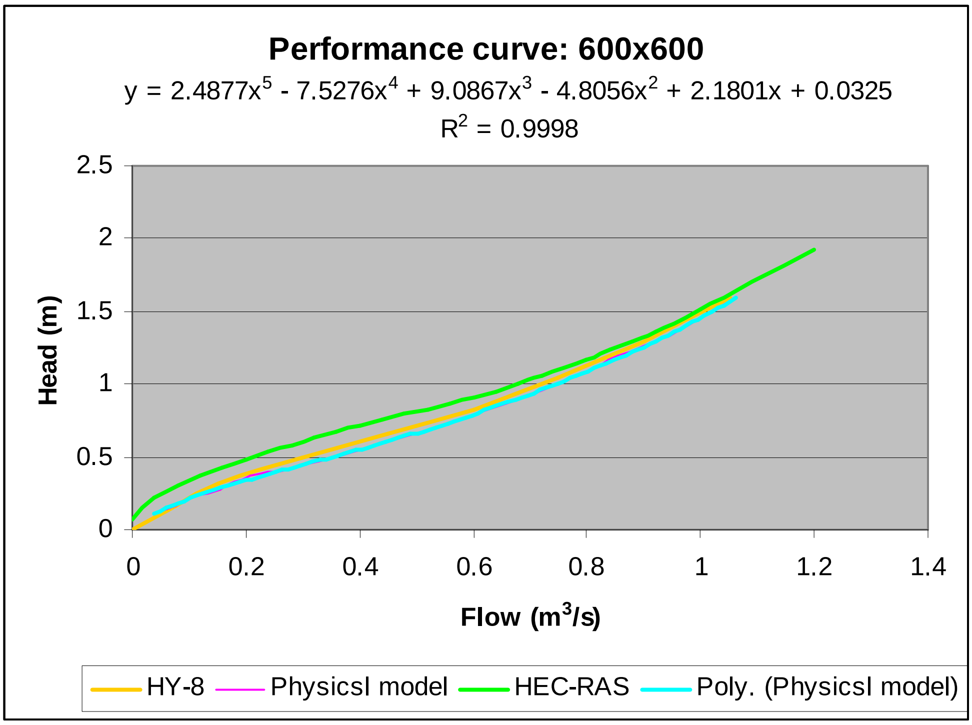


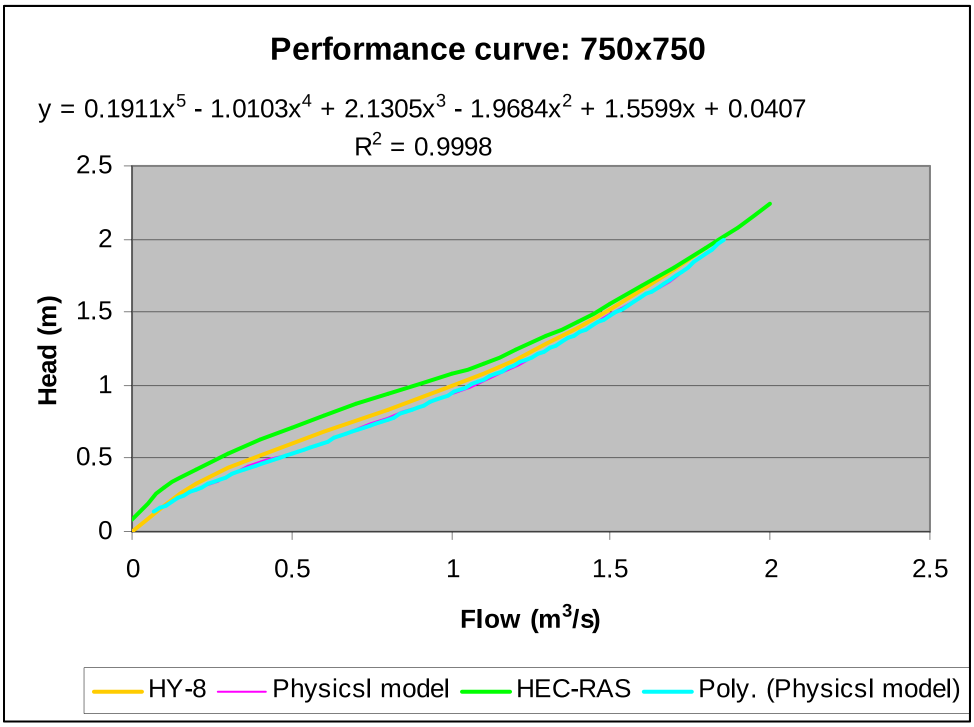
Performance curve: 1800x1200
y = 4E-05x5 - 0.0012x4 + 0.0147x3 - 0.0646x2 + 0.3512x + 0.1191
R2 = 0.9996
Head (m)
Flow (m3/s)
0
1
2
3
4
5
0
2
4
6
8
10
12
HY-8
Physicsl model
Poly. (Physicsl model)


Performance curve: 3600x2400
y = 1E-08x5 - 2E-06x4 + 0.0002x3 - 0.004x2 + 0.1242x + 0.2383
R2 = 0.9996
10
8
6
4
2
0
Head (m)
0
10
20
30
40
50
60
70
Flow (m3/s)
HY-8
Physicsl model
Poly. (Physicsl model)

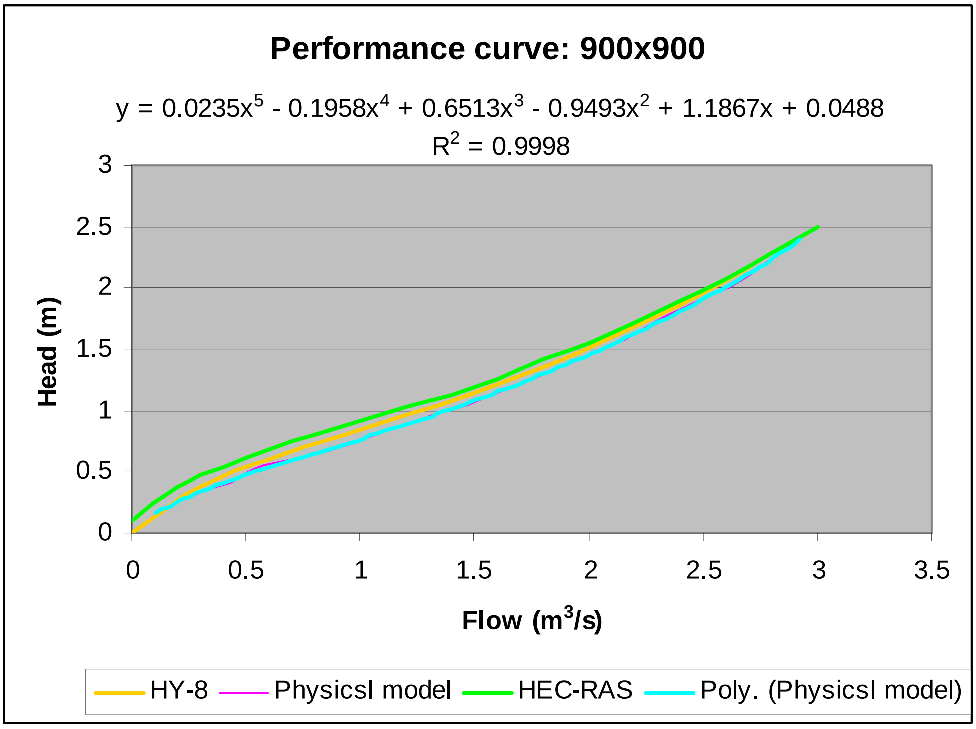
HY-8, HEC-RAS and physical model comparison



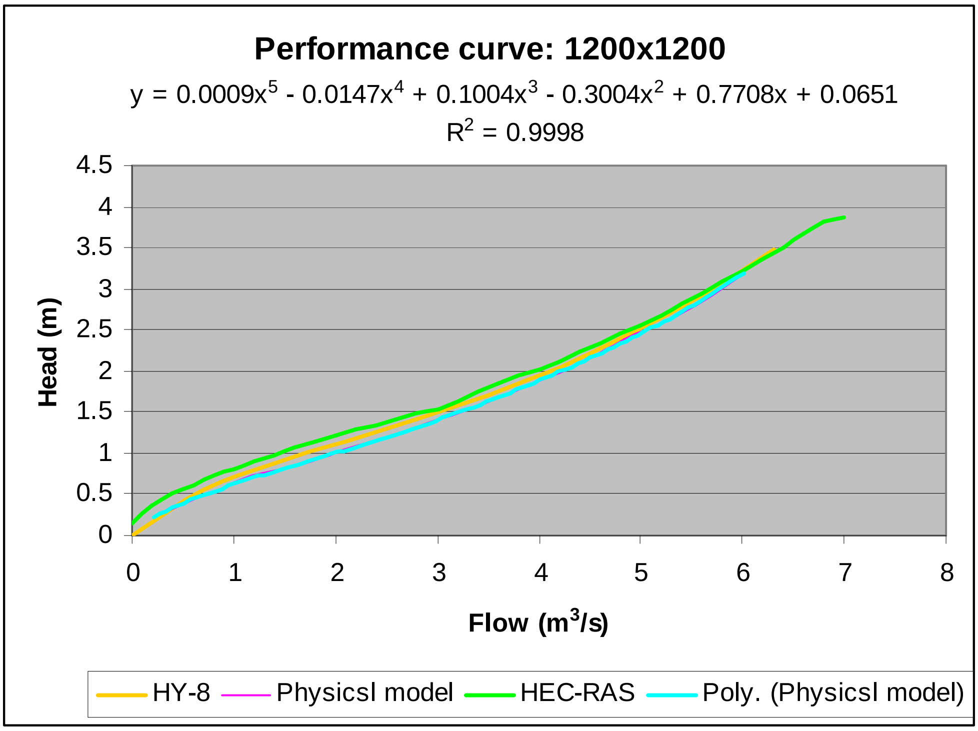


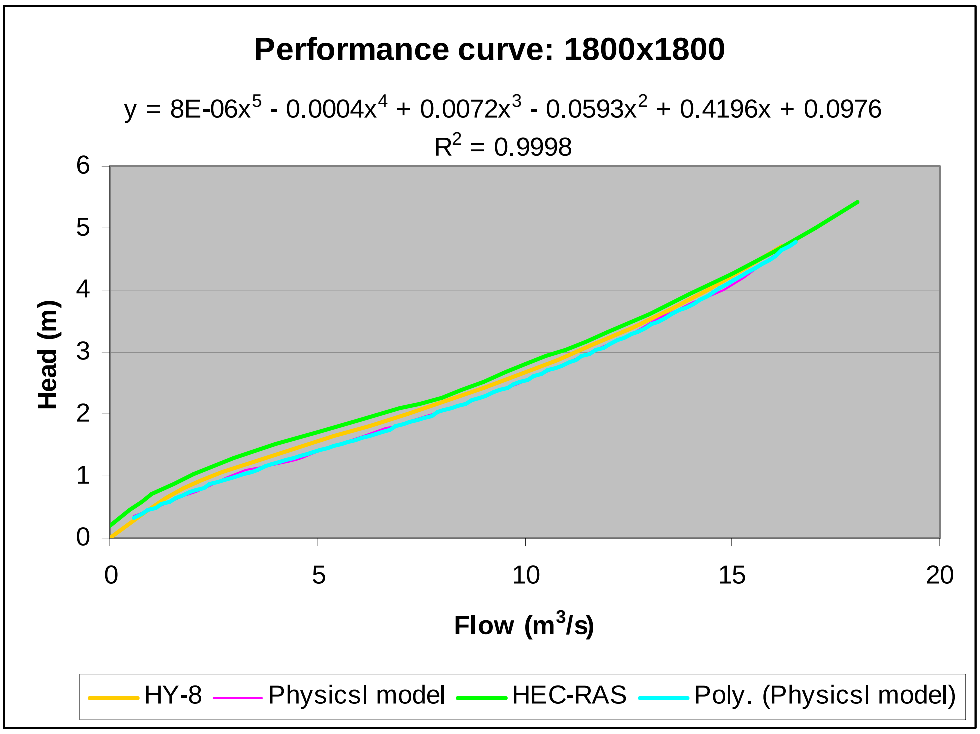


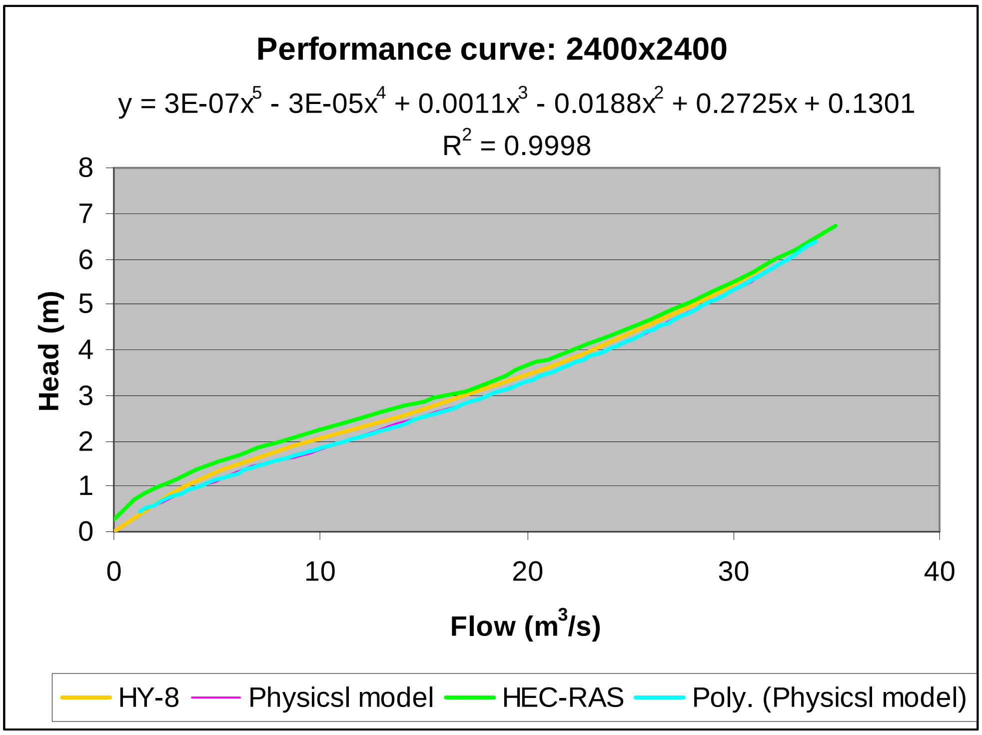
Performance curve: 750x750
y = 0.1911x5 - 1.0103x4 + 2.1305x3 - 1.9684x2 + 1.5599x + 0.0407
R2 = 0.9998
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)

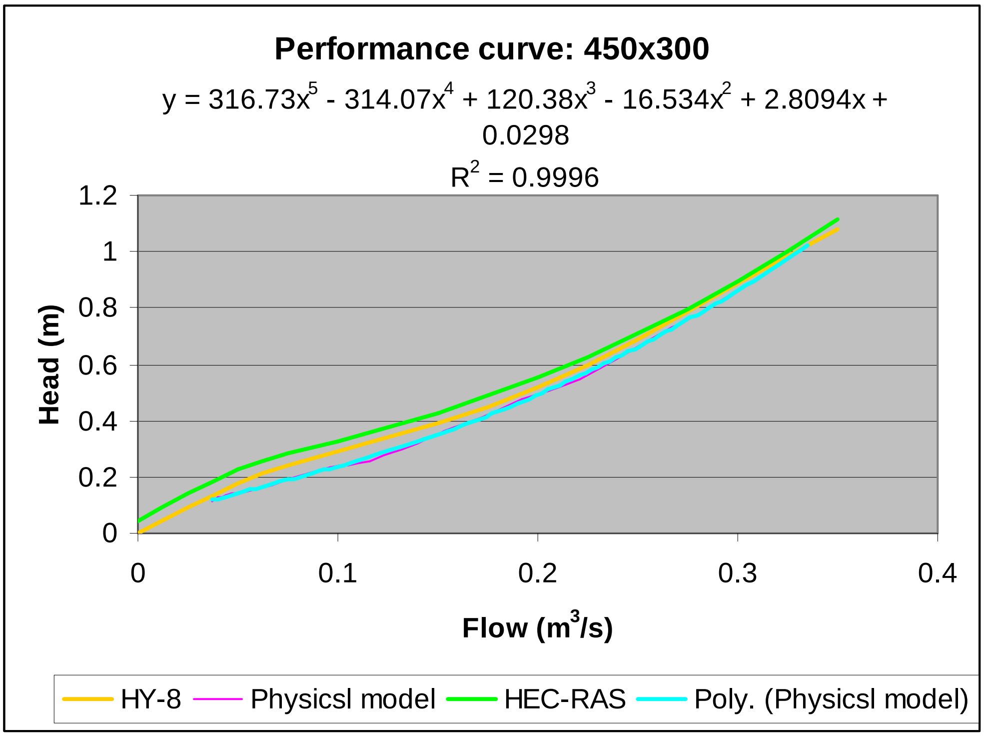


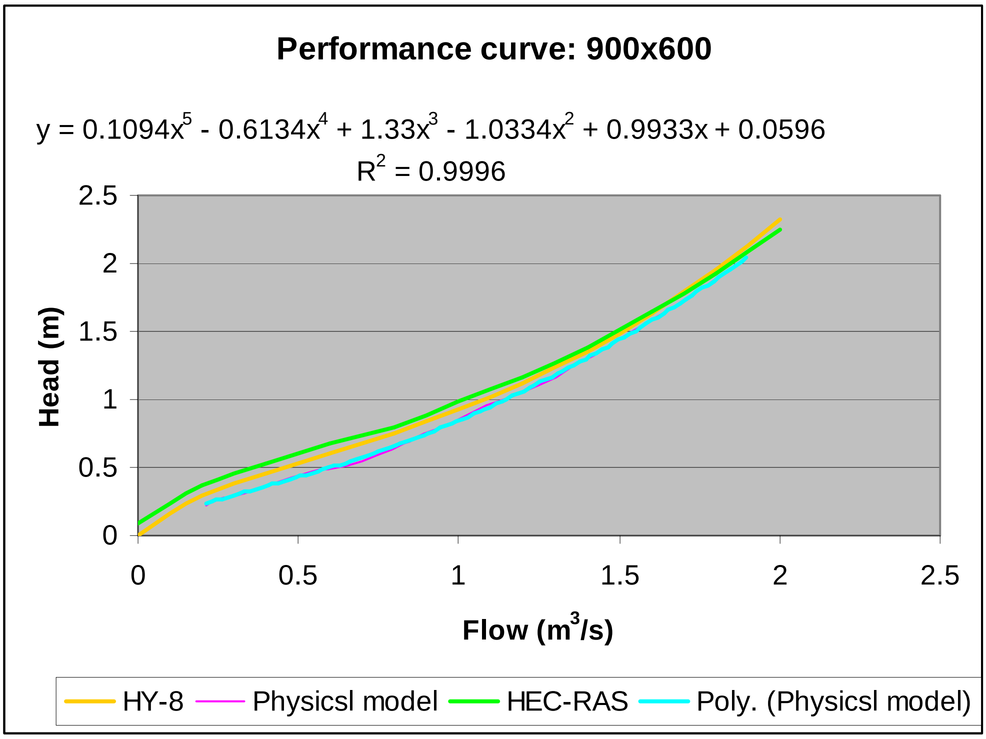
Performance curve: 900x900
y = 0.0235x5 - 0.1958x4 + 0.6513x3 - 0.9493x2 + 1.1867x + 0.0488
R2 = 0.9998
Head (m)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)

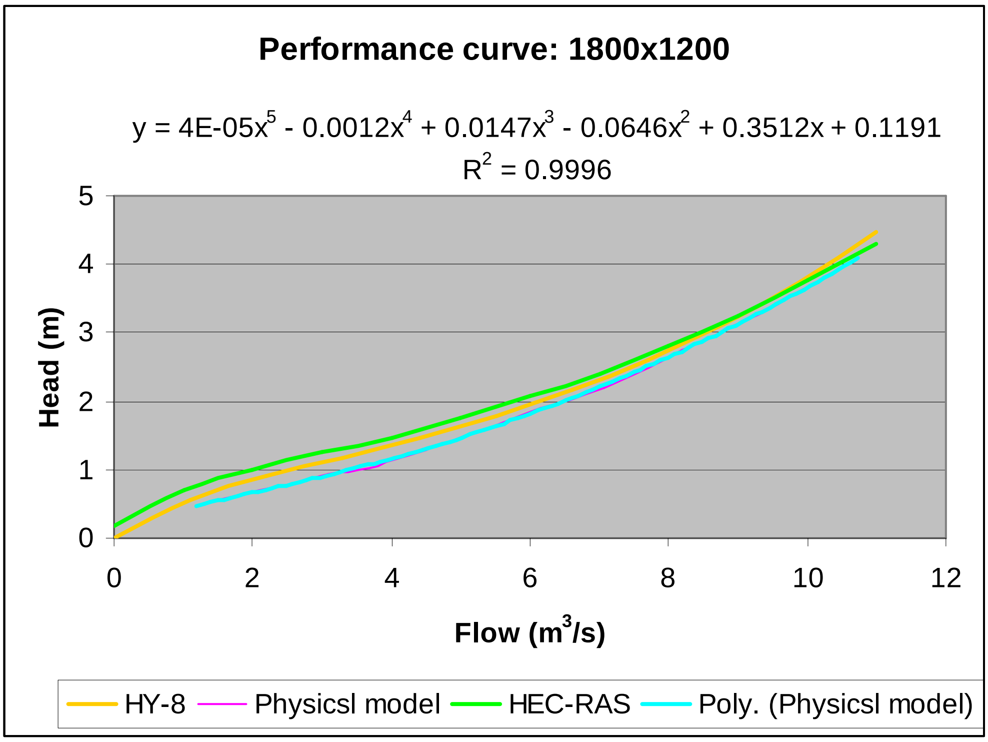

Performance curve: 1200x1200
y = 0.0009x^5 - 0.0147x^4 + 0.1004x^3 - 0.3004x^2 + 0.7708x + 0.0651
R^2 = 0.9998
Head (m)
Flow (m^3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)

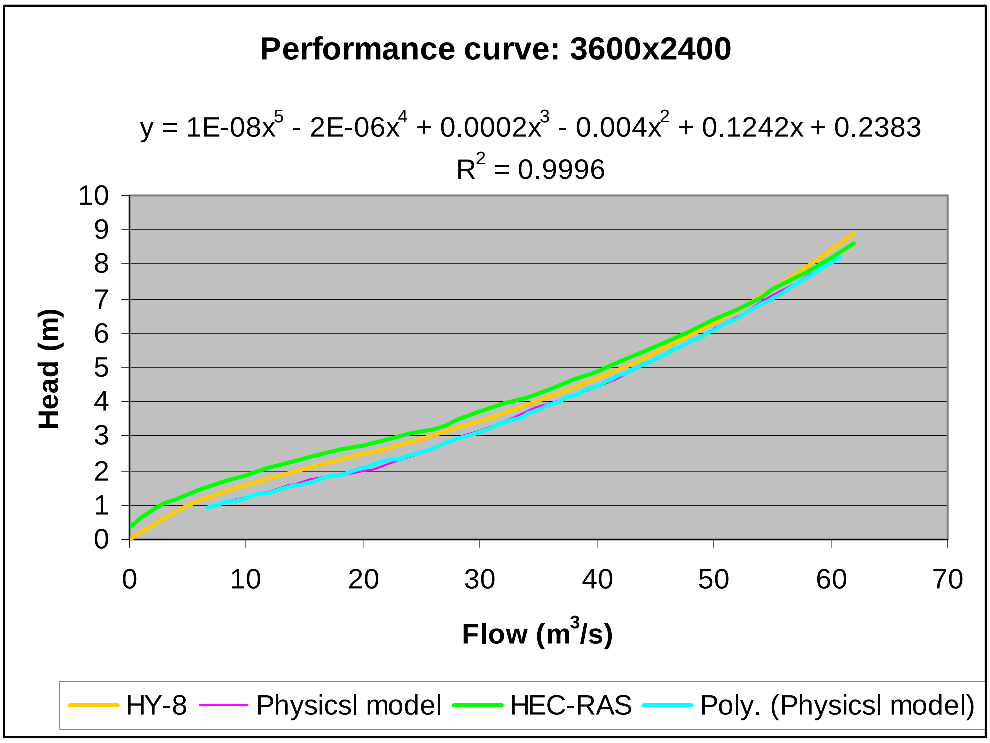

Performance curve: 1800x1800
y = 8E-06x^5 - 0.0004x^4 + 0.0072x^3 - 0.0593x^2 + 0.4196x + 0.0976
R^2 = 0.9998
Head (m)
Flow (m^3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)


Performance curve: 2400x2400
y = 3E-07x5 - 3E-05x4 + 0.0011x3 - 0.0188x2 + 0.2725x + 0.1301
R2 = 0.9998
Head (m)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)


Performance curve: 450x300
y = 316.73x5 - 314.07x4 + 120.38x3 - 16.534x2 + 2.8094x + 0.0298
R2 = 0.9996
Head (m)
0
0.2
0.4
0.6
0.8
1
1.2
0
0.1
0.2
0.3
0.4
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)


Performance curve: 900x600
y = 0.1094x5 - 0.6134x4 + 1.33x3 - 1.0334x2 + 0.9933x + 0.0596
R2 = 0.9996
Head (m)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)


Performance curve: 1800x1200
y = 4E-05x5 - 0.0012x4 + 0.0147x3 - 0.0646x2 + 0.3512x + 0.1191
R2 = 0.9996
Head (m)
5
4
3
2
1
0
0
2
4
6
8
10
12
Flow (m3/s)
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)



Performance curve: 3600x2400
y = 1E-08x5 - 2E-06x4 + 0.0002x3 - 0.004x2 + 0.1242x + 0.2383
R2 = 0.9996
Head (m)
Flow (m3/s)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
HY-8
Physicsl model
HEC-RAS
Poly. (Physicsl model)

Appendix C:

Research project CD

Appendix D:

Evaluation form