University of Southern Queensland

Faculty of Health, Engineering and Sciences

Numerical Modelling of Minor Waterway Barriers for Fish Passage in the Mary River Catchment

A dissertation submitted by

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Abstract

Waterway barriers have been constructed on waterways throughout Queensland and in many cases have obstructed the movement of native fish species.

This project uses Computational Fluid Dynamics (CFD) to numerically model fish passage designs recommended by the Queensland Department of Agriculture, Fisheries and Forestry (DAFF) minor waterway barrier works guidelines and aims to assess and refine the designs relevant to the free movement of native fish species of the Mary River catchment.

The construction of waterway barriers within Australian streams impacts on fish migration and is identified as a major cause of decline in native fish populations and localised extinction of some species. This project uses CFD modelling to expand on the laboratory, field and literary research used to develop the DAFF waterway barrier works guidelines.

Literary review was undertaken to determine the movement behaviour and swim performance of native fish species of the Mary River catchment. To assess the suitability of CFD as a design tool ANSYS CFX validation models were established based on data sourced from prior field and laboratory fish passage studies. Design models based on the requirements of the DAFF guidelines were then developed and assessed.

The results of the CFD modelling suggest that the DAFF minor waterway barrier requirements generally provide conditions adequate for fish passage however high flow velocity was identified as a barrier to fish passage in the 'Green' and 'Amber' DAFF fish passage design models. The design requirements of the DAFF self-assessable code WWBW01 were therefore considered inadequate in terms of the hydraulic conditions applicable to the swimming ability of native fish species of the Mary River catchment.

Further work is to be undertaken to further investigate alternatives to the design treatments included in the DAFF guidelines and to investigate refinement options.

The DAFF minor waterway barrier guidelines provide general requirements for facilitating fish passage through waterway barriers, however the requirements are not region or site specific therefore may not be suitable for all situations and conditions.

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ENG4111/2 ***Research Project***

Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

S. Petersen

Q99222958

Signature

Date

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Chapter 1

Introduction

1.1 Introduction

Free movement of fish along waterways is an essential requirement for many native freshwater species of fish in Queensland. Unimpeded movement of fish within waterways is vital to sustain healthy stocks because of the need for many species to move to habitats for the breeding or rearing of young or to access critical habitats for food and protection (DAFF 2011).

Waterway barriers such as concrete culvert structures have been constructed on waterways throughout Queensland and in many cases fish are unable to move upstream and downstream of these barriers.

The self-assessable development code, WWBW01: Minor waterway barrier works Part 3: Culverts (WWBW01) has been developed by the Queensland Government, Department of Agriculture, Fisheries and Forestry (DAFF) and is relevant to assessment against the Fisheries Act 1994 for operational works associated with waterway barriers within the minor waterways. This project focuses on the requirements of the code when constructing new or replacing existing waterway barrier culvert structures.

For this project Computational Fluid Dynamics (CFD) modelling is to be used to model the flow area of culvert design configurations recommended by the DAFF self-assessable code WWBW01. The performance of these DAFF design configurations are assessed in terms of hydraulic effectiveness, relevant to the movement of freshwater fish species native to the Mary River catchment.

It is anticipated that the results of this project will be of interest to divisions of local government, state authority, environmental interest groups, as well as professionals with background in fish passage concepts and fish passage design.

1.2 Motivations

In the months leading up to the undertaking of this project work I was involved as a civil design professional in the assessment of a number of timber bridge replacements within the Mary River catchment area between Maryborough and Hervey Bay, Queensland. The sites were located on streams identified as minor waterways under the Fisheries Act 1994 and were therefore subject to the requirements of the Queensland Department of Agriculture, Fisheries and Forestry.

This project was undertaken to further develop ones knowledge of the DAFF fish passage design requirements for minor waterways and to satisfy the questions;

- What are the legislative requirements for fish passage design in the Mary River catchment?
- Are these requirements suitable for the native fish species which exist in the Mary River catchment? and
- Can the passage design requirements be assessed numerically using computer software?

These questions established the motivation behind the implementation of the project work contained within this document.

1.3 Research Objectives

The primary goal of this project is to assess the DAFF self-assessable code WWBW01 in terms of the swimming ability of the native freshwater fish species of the Mary River

Catchment using CFD modelling software. In achieving this goal it is anticipated the following objectives will be satisfied;

- An assessment of the DAFF self-assessable code WWBW01 will determine whether the fish passage design guidelines recommended by DAFF facilitate the passage of fish within minor waterways of the Mary River catchment
- Computational fluid dynamics software will be validated for use as a fish passage design and assessment tool
- An understanding of the DAFF requirements for minor waterway barrier treatments will be obtained
- Knowledge of native freshwater fishes of the Mary River catchment will be greatly improved
- An understanding of fish swim ability and characteristics will be obtained
- Proficiency in the operation of CFD numerical modelling software will be established
- Communication networks with other environmental engineering professionals as well as representatives state and local government authorities and organisations will be established and maintained
- A well-researched project document will be produced which is of both interest to engineering professionals and may facilitate further research opportunities

Chapter 2

Fish Passage Guidelines

2.1 Chapter Overview

The purpose of this chapter is to provide a factual background of the historical and legislative requirements of fish passage in Queensland. The primary focus of this chapter is the fish passage requirements of the Queensland Department of Agriculture, Fisheries and Forestry (DAFF) self-assessable code, WWBW01: Minor waterway barrier works - Part 3: culvert crossings.

2.2 Queensland Department of Agriculture, Fisheries and Forestry

2.2.1 Introduction

The role of the Queensland Department of Agriculture, Fisheries and Forestry (DAFF) is to develop and implement polices and programs that ensure competitive, profitable and sustainable fisheries, agriculture and forestry industries (Queensland Department of Agriculture & Forestry (DAFF) 2013*c*). Fisheries Queensland, a subset of DAFF, provides a key role of DAFF by developing a policy framework to protect and conserve fisheries resources. This includes commercial, recreational and native fish stocks.

Waterway barrier works are regulated under the Fisheries Act 1994 and the Sustainable Planning Act 2009 when barriers to fish movement, including partial barriers, are installed across waterways (Queensland Department of Agriculture & Forestry (DAFF) 2013*a*). Waterway barrier works include construction, raising, replacement and some maintenance works on structures such as culvert crossings, bed level and low level crossings, weirs and dams, both permanent and temporary.

A waterway is defined as river, creek, stream, watercourse or inlet of the sea (Queensland Government 2012) and is deemed to include those marked on the DAFF data layer 'Queensland Waterways for Waterway Barrier Works' (see Section 2.2.3). For the purpose of WWBW01 a waterway barrier is defined as a waterway crossing that incorporates a culvert and is located on a waterway of interest to DAFF (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*).

In Queensland the majority of culvert crossings are generally constructed of reinforced concrete and are either rectangular (box) or circular (pipe) in cross sectional shape (Department of Transport & Main Roads (DTMR) 2002). The sizing of a culvert to take water under a road will depend on the allowable afflux or vertical clearance between water surface and roadway, the velocity at the culvert outlet and the proposed flood immunity of the road (Department of Transport & Main Roads (DTMR) 2002).

Refer to Figure 2.1 for a typical reinforced concrete box culvert (RCBC).

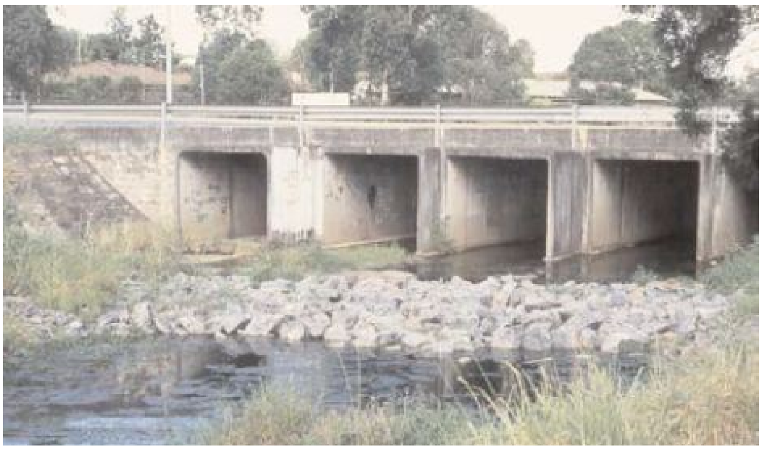

Figure 2.1: Culvert Crossing (Department of Transport & Main Roads (DTMR) 2002)

Waterway barrier works must adhere to the relevant self-assessable code or be carried out with a development approval issued under the Fisheries Act (Queensland Department of Agriculture & Forestry (DAFF) 2013*a*). This report is an assessment of the requirements of the self-assessable code, WWBW01: Minor waterway barrier works -

Part 3: culvert crossings.

2.2.2 WWBW01: Minor waterway barrier works - Part 3: culvert crossings

The self-assessable code, WWBW01: Minor waterway barrier works - Part 3: culvert crossings (WWBW01) was produced by DAFF for individuals and organisations to provide technical guidance when undertaking minor waterway barrier works that meet legislative and policy requirements under the Fisheries Act (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*). In complying with the standards and requirements of the code, works are able to proceed without the individual or organisation requiring development approval from DAFF; therefore reducing delays and avoiding additional fees associated with the development approval process.

2.2.3 Waterway Classification

The presence and abundance of fish species within a particular waterway are determined by the available habitat, stream flow characteristics and the geographical location of the waterway (Queensland Department of Agriculture & Forestry (DAFF) 2013*c*). By assessing the physical characteristics of streams, i.e. the stream order, stream slope, flow regime, stream diversity, as well as the biological requirements of native fish species DAFF have developed a waterway classification system based on risk of impact from waterway barrier works on fish movement and fish communities.

Streams are colour coded according to risk and represent the risk of adverse impact on fish movement that may occur as a result of waterway barrier works (Queensland Department of Agriculture & Forestry (DAFF) 2013*c*). WWBW01 does not however apply to all waterway barrier works. The Sustainable Planning Act allows for self-assessment to apply only to low-impact, minor waterways classified as either green (low), amber (moderate) or red (high). Major freshwater systems (purple), tidal systems (grey) as well as freshwater wetlands are subject to other state and federal legislation (Queensland Department of Agriculture & Forestry (DAFF) 2013*c*). This project is an assessment of the requirements of the self-assessable code WWBW01 which considers green, amber and red waterways only. Purple and grey waterways are beyond the scope of this project.

Table 2.1 outlines the assessment requirements for waterway barrier works specifically for culverts.

Table 2.1: Assesment requirements for minor culvert works

Waterway zoning colour	Risk of impact	Development Type
Green	Low	Self-assessable
Amber	Moderate	Self-assessable
Red	High	Self-assessable
Purple	Major	Development Approval
Grey	Major	Development Approval

DAFF has developed the Geographic Information System (GIS) data layer 'Queensland Waterways for Waterway Barrier Works' and the 'SARA Mapping Online System' website xxxxx to enable individuals or organisations to self-assess waterway barrier works proposals. These resources detail the extent of waterways which are of importance to the Fisheries Act.

Figure 2.2 has been compiled using the Queensland Waterways for Waterway Barrier Works mapping data layers.

2.2.4 Requirements For Waterway Barrier Works Fish Passage Culverts

By complying with the WWBW01 code, individuals and organisations must adhere to a number of general requirements for waterway barrier (culvert) works to be classed as self-assessable. Requirements include;

- Erosion and sediment control measures are in place during construction
- Disturbance to stream beds and banks beyond the waterway barrier site is minimised
- Works are scheduled during periods of low waterway flows
- DAFF is notified pre and post-construction

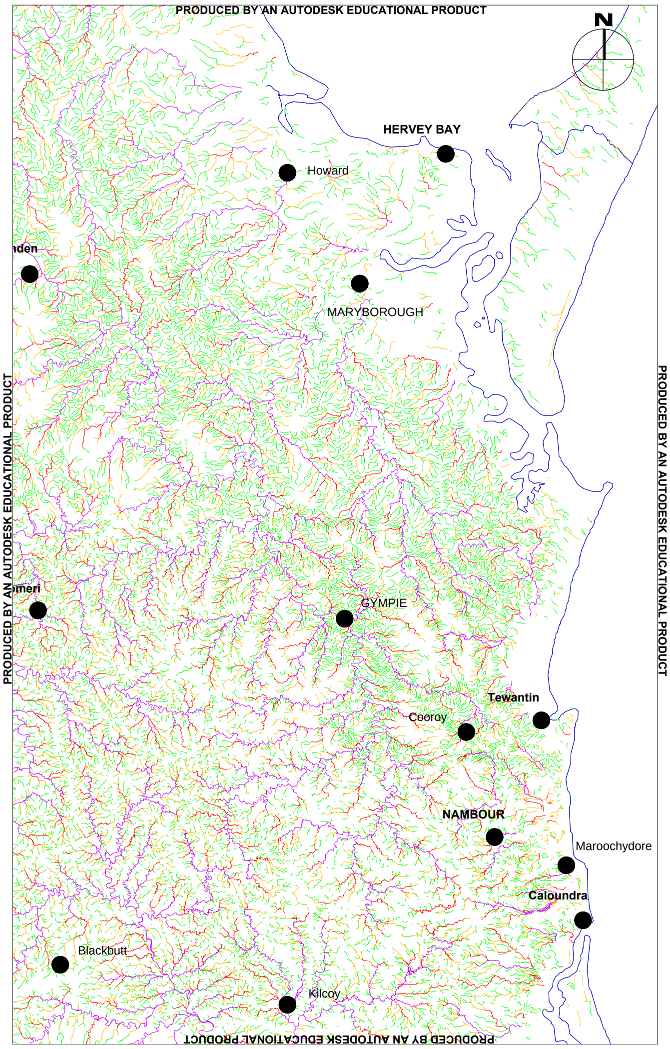

Figure 2.2: Queensland Waterways for Waterway Barrier Works (Queensland Department of Agriculture & Forestry (DAFF) 2013*c*)

WWB01 also requires specific requirements for culverts depending on the classification of the waterway;

High-impact 'Red' waterways (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

- The total width of the combined culvert structure must span a minimum of 75% of the main stream channel width
- Multiple culvert cells may be installed (placed side by side)
- Minimum width of each culvert cell to be equal to or greater than 1200 mm
- Culvert grade must be no steeper than existing stream gradient

- Outermost culvert cells must incorporate 'baffle' type roughening elements on bankside sidewalls for full height of the culvert cell. Baffles are to be placed at 600 mm intervals throughout the culvert barrel, and at 300 mm intervals within 1.20 m upstream and downstream of the culvert inlet. Refer to Figure 2.3, 2.4 and Chapter 4 for further details concerning baffle roughening elements.

- Baffles must be installed on the upstream wingwalls on both banks for the full height of the wingwall

- All culverts in the waterway barrier are to be set 300 mm minimum below stream bed level, where possible. If on bedrock, the natural stream bed surface must be maintained through the culvert

- Internal roof or obvert of the culvert must be a minimum of 600 mm above stream bed level

- Culvert aprons must be at the same level as adjoining culvert i.e. no drop in elevation

- Culvert aprons must be roughened to simulate the natural stream bed conditions

- Culvert aprons must be no steeper than the existing stream gradient

- Stream bed scour protection, downstream and upstream of aprons, installed no steeper than natural channel gradient

- Scour protection must include a low-flow channel

- Scour protection must consist of clean rocks of size no less than 100 mm in diameter

A typical red-zoned waterway barrier culvert arrangement is shown in Figure 2.3. The typical baffle detail is shown in Figure 2.4.

Moderate impact 'Amber' waterways (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

- Culvert width must have a minimum width of 2.4 m or span 100% of the main channel width

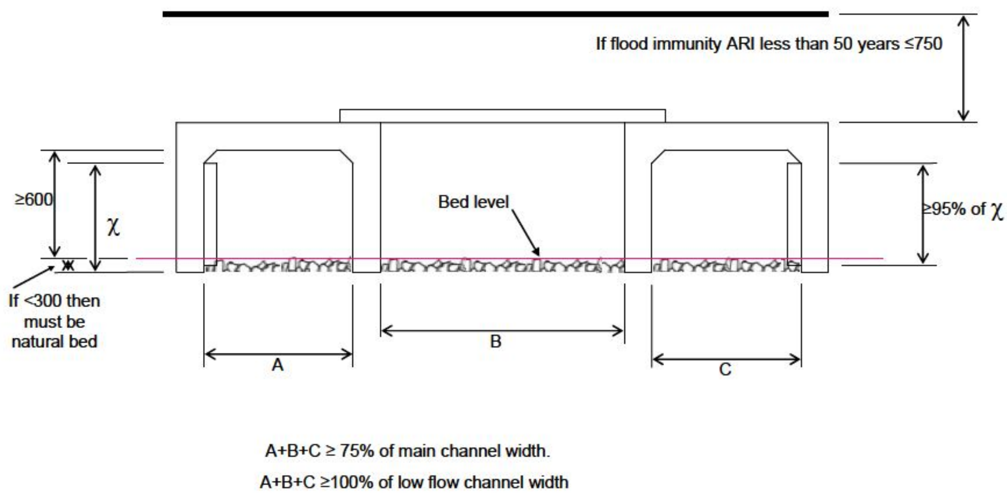

Figure 2.3: Red waterway barrier treatment (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

- All culverts in the waterway barrier are to be set 300 mm minimum below stream bed level, where possible. If on bedrock, the natural Stream bed surface must be maintained through the full length of the culvert
- Culvert and culvert apron must be installed no steeper than the existing stream gradient
- Stream bed scour protection in accordance with red-zoned waterways

A typical amber-zoned waterway barrier culvert arrangement is shown in Figure 2.5.

Low impact 'Green' waterways (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

- Culvert width must have a minimum width of 1.2 m or span 100% of the main channel width
- All culverts in the waterway barrier are to be set 300 mm minimum below stream bed level, where possible. If on bedrock, the natural stream bed surface must be maintained through the full length of the culvert
- Culvert and culvert apron must be installed no steeper than the existing stream gradient
- Stream bed scour protection in accordance with red-zoned waterways

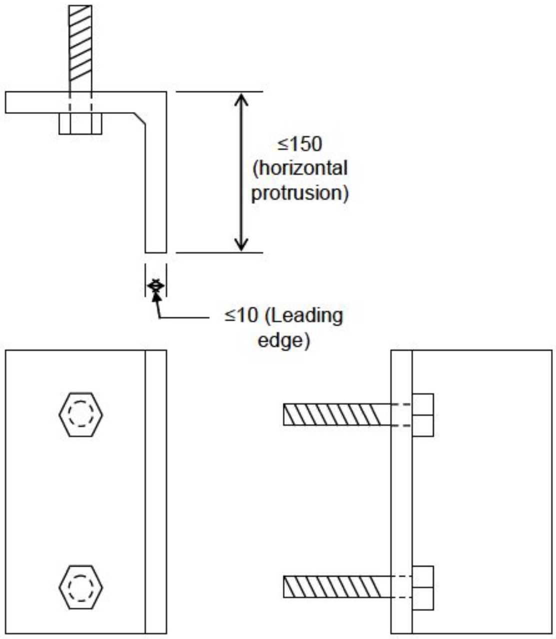

Figure 2.4: Typical baffle detail (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

Figure 2.5: Green and Amber waterway barrier treatment (Queensland Department of Agriculture & Forestry (DAFF) 2013*b*)

A typical green-zoned waterway barrier culvert arrangement is shown in Figure 2.5.

All waterway classifications require similar treatments and configurations, with the exception of red-zoned waterways which require baffle roughening elements. Baffle concepts are explained further in Chapter 4.

2.3 Chapter Summary

In summary, this chapter provides a background of the requirements necessary to comply with the DAFF self-assessible code WWBW01 for fish passage. The information discussed in this chapter are used to establish the DAFF fish passage numerical design models assessed in Chapter 8.

Chapter 3

Freshwater Fishes of the Mary River Catchment

3.1 Chapter Overview

The purpose of this chapter is to investigate the physical and biological diversity of the native freshwater fishes of the Mary River catchment and to develop measurable guidelines for freshwater fish swimming ability.

Topics to be addressed include;

- An assessment of the Mary River catchment and native freshwater fish species
- An assessment of fish movement behaviour and swim performance

3.2 Freshwater Fishes Of The Mary River Catchment

3.2.1 Introduction

The following section of the report provides general information regarding habitat, migration requirements and likely freshwater fish species native to the Mary River catchment.

3.2.2 The Mary River Catchment

The Mary River is situated in south-east Queensland approximately 150 km north of Brisbane, stretching approximately 250 km between the Bellthorpe - Maleny region to the south, and River Heads to the north. The Mary River catchment is approximately 9600 sq km in area and contains several major tribuatories including Obi Obi, Yabba, Little Yabba, Six Mile, Amamoor, Kandanga, Tinana, Deep, Munna and Wide Bay Creeks (Mary River Catchment Committee (MRCC) 2013). Refer to Figure 3.1 for locality plan.

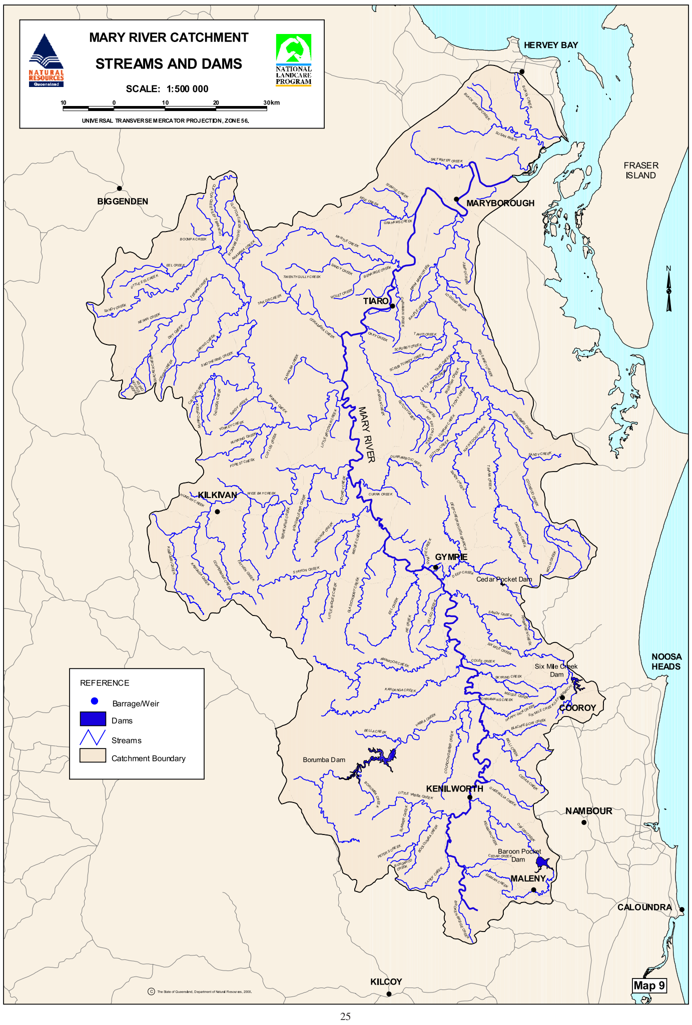

Figure 3.1: Mary River Catchment Locality (Department of Natural Resources (DNR) 2013)

With just over 400,000 ha of remnant vegetation, open forest is the dominant cover class, with closed forest and sparse woodland occupying 10 to 15% of remnant vegatation area. The remaining 55% of the catchment area is extensively cleared for farming, forestry or industrial and manufacturing purposes. Along the 2947 km of waterways in the Mary River Catchment, remnant freshwater riparian [1] communities of national conservation significance contain habitat for a number of rare and endangered freshwater fish, frogs, turtles and a number of riparian vegetation species (Mary River Catchment Committee (MRCC) 2013).

The lower reaches of the catchment are tidal, limited by the Mary River Barrage and Tinana Creek Barrage situated on both Mary River and Tinana Creek south of the Maryborough township. Non-tidal, freshwater systems exist upstream of these tidal barriers.

3.2.3 Fish Migration

Migration between habitats is a natural process for most fish and is an important facet as to why fish passage is required. Freshwater fish species can be separated into a number life cycle groups depending on their movement between and within freshwater and marine habitats for spawning or growth (Kapitzke 2010). These life cycle groups include species whose life cycle occurs within freshwater only (potamodromous) and those which migrate between freshwater and saltwater (diadromous). The diadromous life cycle group is split into catadromous and anadromous groups; species whom migrate from freshwater to saltwater (and vise versa) for spawning purposes. The final life cycle group, amidromous life cycle, include species which migrate between freshwater and saltwater (and vise versa) for non-spawning purposes (Allen, Midgley & Allen 2002).

3.2.4 Freshwater Fishes

The Mary River catchment is estimated to comprise approximately 64 species of freshwater fish, including 5 introduced and 3 threatened species (Stockwell, Hutchison, Wedlock & Ford 2004). Species known to occur in the Mary River catchment are categorised in terms of genus and life cycle in Table 1.1. The data in Appendix B was extracted from studies by Berghuis et all (2005), SKM (2007), discussions with Fisheries Queensland fish biologists, as well as the 2005 report drafted by Stockwell et al on behalf of the Burnett Mary Regional Group (BMRG) which itself was sourced from a number

[1] Riparian land is any land that adjoins or directly influences a body of water (Price & Lovett 2002)

of previous studies and publications. Size and descriptive characteristics were sourced from Allen et al (2002) and McDowall (1980).

The fish community for a particular catchment or waterway under consideration in a road corridor assessment of fish passage requirements, or for fish passage design at a waterway structure, will be a subset of the sub-regional fish community data for that area (Kapitzke 2010). It can therefore be assumed that not all species known to occur in the Mary River catchment will be present at a particular location.

Field surveys undertaken on behalf of BMRG found the deeper reaches of the Mary River system comprised Duboulay's rainbowfish, bony bream, bully mullet, Australian smelt, carp gudgeons and lungfish. The shallow sections of the Mary system were found to be dominated by small bodied species, including pacific blue-eye, Marjories hardyhead, Australian smelt, Duboulay's rainbowfish and carp gudgeons. The bulk of the biomass caught during the BMRG field surveys were comprised of long finned eels and eel- tailed catfish and the numerically dominant species were found to be carp gudgeons and Duboulay's rainbowfish.

In the abscence of detailed, site specific fauna survey data it is reasonable to assume that species common to a particular habitat are more than likely to exist if the waterway structure exists within that particular habitat. It is on this basis, and the field surveys completed by BMRG, that it is deemed acceptable to assume that small bodied fish species such as Duboulay's rainbowfish, Australian smelt and carp gudgeons, common to shallower waters, are likely to be present in most, if not all, green, amber and red waterways.

Figure 3.2: Duboulay's rainbowfish (Australian Museum 2013)

Duboulay's rainbowfish, Australian smelt and carp gudgeons all belong to the potamodromous life-cycle group i.e. life cycle occurs within freshwater only. These smaller fish species migrate within freshwater systems to facilitate spawning requirements, for feeding and to repopulate areas folllowing flood or drought (Kapitzke 2010).

Figure 3.3: Australian smelt (Australian Museum 2013)

Figure 3.4: Carp gudgeon (Australian Museum 2013)

The DAFF fish passage designs will be assessed based on the movement behaviour and swimming abilitiy of these smaller fish species.

3.3 Fish Movement Behaviour And Swim Performance

3.3.1 Introduction

To determine suitable engineering solutions for fish passage at a particular site it is essential to understand the movement behaviour and swimming performance of target fish species likely to be passing through the fish passage structure. The following section briefly investigates this area and provides comment on the variables to be used in the design component of this assessment.

3.3.2 Fish Swimming Ability

Delaere et al (2011) state that essentially there are two classes of fish swimming ability amongst Australian native freshwater fish species; small to medium sized fish with limited swimming ability, and large sized fish with much stronger swimming ability. It is generally accepted that fish passage design should accomodate both classes, however successful fish passage design should be governed by the 'lowest common denominator', i.e. the swimming ability of the small to medium sized fish species. It should be noted that introduced species are not considered target species and are therefore ignored.

The physiological components critical to fish movement can be catagorised into three key criteria; swim speed, tolerance to turbulence and tolerance to hydraulic drop (Kapitzke 2010, Bates 1999, Cotterell 1998).

3.3.3 Swim Speed

The ability for fish to overcome water flow velocity barriers at a culvert structure depends on the velocity of the water flowing through the culvert and the swim speed of the fish swimming against it (Kapitzke 2010). Swim speed is the velocity at which fish move through water and can be divided into three different 'modes' of travel (Kapitzke 2008, Cotterell 1998);

Burst speed: the highest speed possible which fish can travel and is generally sustained over short periods of time (5 to 20 seconds) before ending in fatigue;

Prolonged speed: the speed at which fish can travel for a much longer time period (20 seconds to 200 minutes) before suffering from fatigue; and

Sustained speed: the speed at which fish maintain without suffering from fatigue.

Numerous studies have been undertaken to identify swim speeds for freshwater fish, both in Australia and overseas. It is noted however that Australian freshwater fish species, similar to their New Zealand counterparts (Doehring, Young & McIntosh 2011), are significantly less energentic than species of the northern hemisphere (Hyde 2007, Kapitzke 2010). While medium sized Australian freshwater fish may be capable of burst speeds of 3 m/s over short distances (Mallen-Cooper 2001), prolonged swim speeds greater than 1 m/s cannot be sustained before fish become fatigued (Cotterell 1998).

Fish passage structures should be designed to accomodate the swimming cability of the target species likely to be using it (Kapitzke 2010). Kapitzke (2010) suggests that for a conservative approach, where no other swim speed is available, that 0.3 m/s or less, as recommended by Cotterell (1998) and Boubee (1999), be used for prolonged swim speed or where migration of all native species is required. Alternatively, prolonged swim speed may be based on a value of 3 fish body lengths per second down to a minimum swim speed of 0.15 m/s (Mallen-Cooper 2001).

Kapitzke (2008) suggests that, where no other data is available, a value of 2 x prolonged speed be used as a notional value for burst speed. The method by Kapitzke is used for the adoption of swim speeds in this project.

Minimal information is available on the fish movement behaviour specifically for the Mary River catchment. Generalised movement behavior such as migration cycles, fish descriptions, fish size and swimming characteristics has therefore been established primarly from the available literature. Nominal swim speeds included in Table 3.1 have been established from the report by Kapitzke (2008) and the theory of Cotterell (1998) and Mallen-Cooper (2001). The range of swim speeds for small native fish species of the Mary River catchment encompass 0.15 to 0.3 m/s for prolonged speed and 0.3 to 0.6 m/s for burst speed.

Table 3.1: Swim speed (Kapitzke 2008, Cotterell 1998, Mallen-Cooper 2001)

Fish movement capability	**Common length of fish**	**Prolonged swim speed**	**Burst speed**
Medium size fish species	adults 15 - 25cm	0.45m/s - 0.75m/s	0.9m/s - 1.5m/s
Small fish species	adults < 10cm	0.3m/s	0.6m/s
Medium size fish species	juveniles < 10cm	0.30m/s - 1.0m/s	1.4m/s
Small fish species	juveniles < 5cm	0.15m/s	0.3m/s

The combination of stream flow velocity, culvert length and/or distance between rest areas are therefore critical to successful fish passage. The relationship between stream flow velocity and swim speed can be used to roughly determine distance travelled by fish against the stream flow, and therefore the maximum spacing of rest areas within culvert structures. For calculation of distance travelled refer to Equation 3.1 (Kapitzke 2010).

$$X = (U - V)\, t_m \tag{3.1}$$

where X is the distance travelled (m), U is the maximum swim speed of fish, V is stream flow velocity and t_m is prolonged swim speed time (20 seconds).

Figure 3.5 shows the relationship between stream flow velocity and fish swim speed for a range of distances. From this chart it can be seen that for a fish to travel 2 m at a burst swim speed of 0.6 m/s, the opposing stream flow velocity must be less than 0.5 m/s.

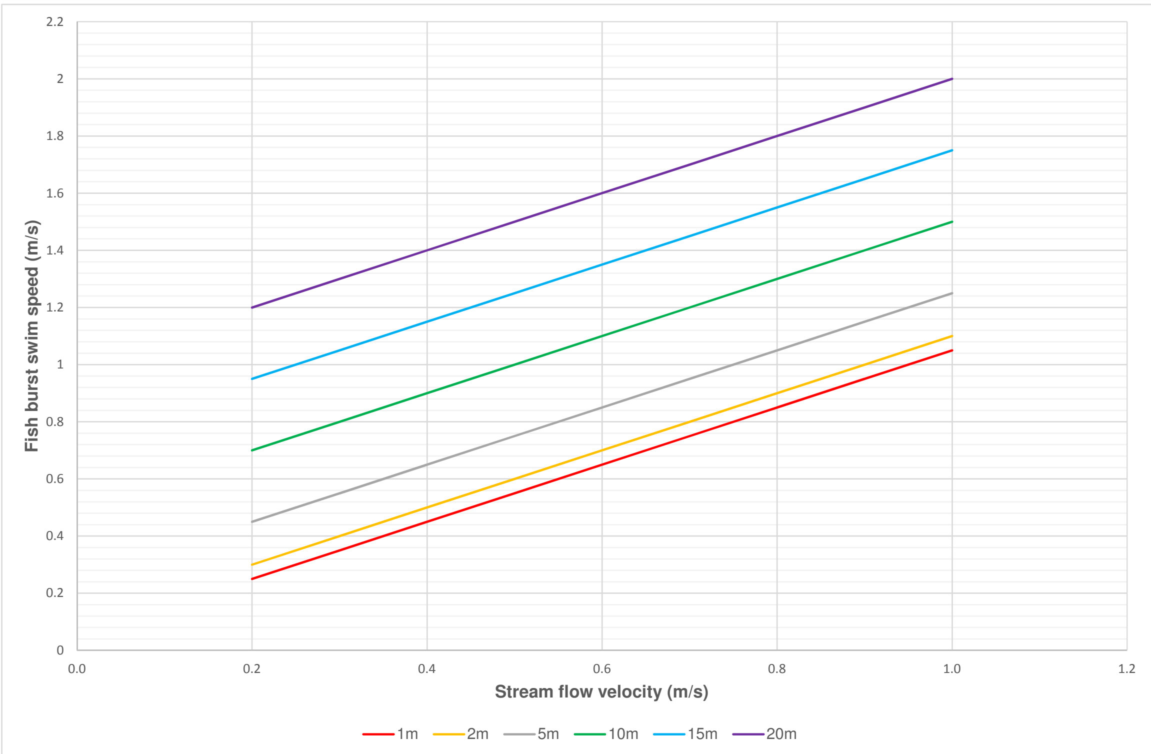

Figure 3.5: Swim speed, stream flow velocity and distance travelled

3.4 Chapter Summary

In summary, this chapter provides a background of the native fish species likely to exist in the Mary River catchment area as well as the swimming ability of these fish species. The background information discussed in this chapter is used in the assessment of the DAFF fish passage designs in Chapter 8 and 9.

Chapter 4

Fish Passage Concepts

4.1 Chapter Overview

Fish movement through waterways is critical for the survival of native fish (Department of Transport & Main Roads (DTMR) 2010). The movement of fish allows access to food and shelter, protection from predators and for migration for reproduction and spawning.

Traditionally waterway crossings have been designed and constructed based on hydraulic capacity, with little consideration for the needs of fish passage (Boubee, Jowett, Nichols & Williams 1999). The installation of culverts alters the hydraulic and physical conditions of the waterway at its location and as a result may create a 'waterway barrier' impeding movement of fish, both within the culvert and at the inlet and outlet.

4.2 History Of Fish Passage In Australia

The effects of culverts on fish movement is considered a significant factor contributing to the decline in fish populations world wide (Copeland, Johnson & Bunn 2004, Gibson, Haedrich & Wernerheim 2005). The construction of waterway barriers within Australia impacts on fish migration and has been identified as a major cause of decline in native fish populations (Doehring et al. 2011) and localised extinction of some diadromous species (O'Brien, Perera & Lewis 1999).

4.3 Barriers To Fish Passage

Fish passage (specifically when considering upstream migratory movement) may be restricted at a culvert crossing as a result of any of the following (Cotterell 1998, Kapitzke 2010, Bates 1999, Boubee et al. 1999, Hyde 2007);

High water flow velocity: water flow velocity created in the waterway is too high in relation to the swimming ability of fish

High water turbulence: turbulence caused by the culvert is too great, or too widespread to allow free-movement of fish through culvert

Hydraulic drop at outlet: a sudden drop in water level as a result of perched culvert outlet may prevent fish from entering the culvert

Culvert length: culvert length is too long in relation to the swimming ability of fish. If culvert length is too great, fish may become fatigued before reaching the other end and be swept downstream

Lack of resting place: lack of resting areas where excessive water flow velocity combined with culvert length impedes the passage of fish

Culvert width: confined culvert profile and openings increase water flow velocity

Culvert slope: steep culverts result in increased water flow velocity

Reduced flow depth: culverts generally convey high flows during times of flood or significant rainfall events. Flow depth in the culvert and at inlet and outlet during low flows can be insufficient for fish passage

Blockages due to poor maintenance: culverts can often be blocked by debris and as a result restrict water flow and increase flow velocity and turbulence

Cummulative culvert effects: cummulative culvet effects can be identified by a group of culverts in series, with each displaying characteristics inhibiting fish movement. The result is a combined barrier which stresses fish during passage.

Traditional culvert designs must be modified to overcome the above barriers.

4.3.1 Flow Depth

Kapitzke (2010) states that hydraulic conditions affecting fish passage through a waterway structure must consider a range of stream flows encompassing the design flow range for fish passage. Kapitzke has identified three flow depth ranges;

- Low flow condition - less than 0.5 m deep
- Medium flow condition - 0.5 to 1.5 m deep
- High flow condition - greater than 1.5m deep

Both Kapitzke (2010) and Cotterell (1998) suggest a low flow condition of between 0.2 and 0.5m will ensure successful fish passage through culverts. Flow depths greater than 0.5 m may result in stream flow velocities greater than those acceptable for upstream fish migration.

4.3.2 Turbulence

> *Turbulent flows are characterised by unpredictable behaviour whereby fluid particles move in very irregular paths and patterns causing an exchange of momentum from one portion of the fluid to another* (Lesieur 1994)

Bates (1999) suggests that in order to maintain a desired velocity, energy must be dissipated as turbulence. Turbulence within a culvert is defined by the energy dissipation per unit volume of water and can be assessed using the Navier-Stokes equations (refer to Chapter 6).

Turbulence may occur due to a sudden change in flow direction, physical obstructions and surface roughness and is evident in most practical cases of stormwater drainage including open channel and culvert design (Chanson 2004). In theory, culvert properties such as size and roughness could be altered so the velocity meets fish passage requirements however, as a result of sudden reduction in velocity, the intensity of the energy dissipation or turbulence increases which itself can become a barrier to fish passage.

Very little research has been undertaken to establish specifically why turbulence creates a barrier to fish passage. Cotterell (1998) suggests however that turbulence most likely becomes an issue as a consequence of the creation of air pockets through which fish cannot swim. The results of a report by Berghuis and Piltz (2005) concerning fish passage at the Mary River Barrage fishway is one study which supports this assumption. The study found that fish movement through the Mary River Barrage fishway was highest at high tide during periods of high tailwater and low turbulence, and lowest at low tide when turbulence increased.

Cotterell (1998) and Delaere et al (2011) recommend a turbulence of less than 30 W/m^3 be used to encourage migration of small to medium fish through fishways.

Though considered important in fish passage design, turbulence was not examined during the assessment of the DAFF fish passage design guidelines discusssed later in this project report.

4.3.3 Hydraulic Drop

Unlike northern hemisphere fish species such as salmon and trout, most Australian native fishes do not jump (Kapitzke 2010, Cotterell 1998). This becomes a problem should there be a sudden drop in water level at a culvert crossing. Sudden change in water level, particularly at the outlet of culverts, should therefore be avoided. Refer to Figure 4.1 for an example of a perched culvert outlet.

Figure 4.1: Perched culvert outlet as a result of erosion (Cotterell 1998)

4.4 Culvert Zones

Waterway or culvert crossings can be split and assessed as four hydraulic zones (Kapitzke 2010). Kapitzke states that flow conditions within each hydraulic zone of the culvert should be examined to determine if fish using the culvert are able to negotiate within and between each zone over a range of flow conditions. Fish passage may therefore be assessed in terms of fish swimming ability based on the configuration of each zone and the waterway flow conditions passing through it. The four hydraulic zones identified by Kapitzke (2010) are shown in Figure 4.2.

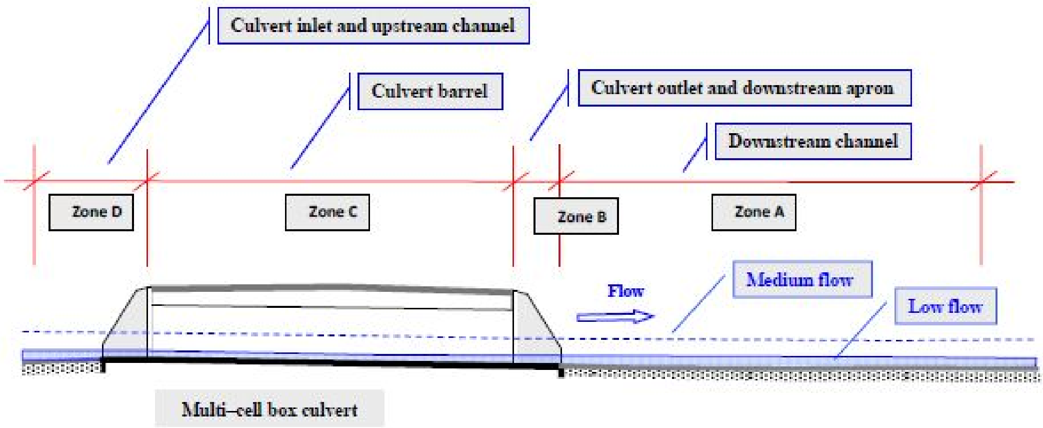

Figure 4.2: Culvert Zones (Kapitzke 2010)

The culvert zones are decribed as follows;

Zone A: Downstream channel: fish passage at the downstream channel concerns the stream channel immediately downstream of the culvert outlet. It is common in this zone to experience problems arising from high velocities away from the channel edge as well as physical obstructions within the stream channel.

Zone B: Culvert outlet: fish passage at the outlet concerns the culvert end treatment and the culvert apron. It is common in this zone to experience problems arising from high velocities away from the channel edge as well as hydraulic drop between culvert barrel and apron, or apron and downstream channel.

Zone C: Culvert barrel: the culvert barrel zone includes the walls and floor of the culvert. Problems may arise in this zone as a result of high velocities in the barrel and lack of waterway devices offering opportunities for shelter or rest.

Zone D: Culvert inlet: like the culvert outlet, fish passage at the inlet concerns the culvert end treatment and the culvert apron. High velocities can occur away from the channel edge in this hydraulic zone.

It is therefore evident that for fish passage to occur the design must consider the whole structure i.e. individual hydraulic zones as well as the interaction between each zone. Failure to identify hydraulic barriers within zones and at the interface between zones may lead to further fish passage issues if not correctly assessed.

This research will assess only the zones applicable to the requirements of the DAFF Waterway Barrier Works Code: WWBW01; Zone B - Culvert outlet, Zone C - Culvert barrel and Zone D - Culvert inlet.

4.5 Culvert Design Strategies For Fish Passage

There are various design strategies which can be implemented for improving fish passage through culverts. Strategies may range from maintaining the natural form and shape of the stream channel (i.e. bridge spanning bank to bank therefore not impacting on stream channel) to specifically designed structures which provide the desired hydraulic conditions for fish passage at a particular location. Kapitzke (2010), Boubee et al. (1999) and Bates (1999) describe different design strategies as follows;

Stream simulation: stream simulation design is a design process aimed at re-creating the natural stream and/or pool configuration within a culvert structure so that fish passage mimics that of a natural channel. The culvert will essentially preserve the ecosystem within the stream with regards to migration and fish habitat therefore allow for passage of most species of fish.

Plain 'no slope' culvert: the plain or 'no slope' culvert approach involves the design of wide and flat culvert structures which are installed below the existing stream bed. A culvert countersunk below the natural stream bed allows for natural movement of bed material (sediment, rocks etc) to form a stable bed inside the culvert. The flow velocities within plain 'no slope' culverts are generally considered higher than those in a natural stream channels (Bates 1999).

Hydraulic design: for the hydraulic design strategy waterway devices such as baffles, blocks and other devices are installed within the culvert to provide hydraulic conditions for the target species likely to be using the culvert structure. Hydraulic design can be applied to new, replacement and/or retrofit culvert installations and allow for passage of target species with or without the need for resting areas. This fish passage design process must consider culvert hydraulics which provide depths, hydraulic profile and velocities suitable for the movement behaviour of the target fish species therefore engineering design, hydrology and topographical survey information is required. Hydraulic design has an advantage of plain culvert design as it improves hydraulic conditions (velocity, turbulence etc.) for culverts smaller in size and steeper in slope. The waterway devices attached to culverts can however reduce the effective flow area of the culvert impacting on the hydraulic performance of the culvert and result in a loss in hydraulic conveyance

Hybrid design: the hybrid design strategy is a combination of the hydraulic design strategy and the stream simulation design strategy or the plain ‘no slope’ design strategy. Kaptizke (2010) suggests that while this design strategy partially represents a natural stream it is not as effective as the stream simulation design strategy because it is not a moveable bed system and does not represent the adjoining stream channel. The hydraulic conditions of hybrid designs are also difficult to model due to the non-uniform nature of rocks and stones on the culvert floor. It is on this basis that hybrid designs are relatively untested (Kapitzke 2010).

The DAFF fish passage design requirements are considered hybrid designs of both plain ‘no slope’ culvert and hydraulic design strategies. Generally under the WWBW code for red-zoned waterway barriers, the culvert structure is to be set a minimum of 300 mm below bed level (or roughened to simulate natural bed conditions of the adjacent stream), culvert aprons are to be roughened to simulate natural bed conditions and baffle waterway devices are to be attached to the outermost culvert cells on the bankside walls.

4.6 Waterway Devices For Fish Passage

Two approaches are generally considered to assist fish passage through culvert structures (Kapitzke 2010);

Roughness approach: the roughness-type approach utilises waterway devices such as baffles, blocks, ridges or specifically placed rocks to increase the hydraulic roughness of the culvert and therefore decrease the average cross sectional flow velocity. Roughness-type treatments can be positioned against the culvert walls and floor to accomodate and satisfy the swim speed of fish passing through the culvert. The aim of this approach is to achieve relatively uniform velocities to enable fish to pass through the structure without the need to rest.

Pool approach: the aim of the pool-type approach is to create zones of varying velocity conditions simulating slow moving 'pools'. These pools provide rest areas allowing fish to use burst speed patterns to advance through the culvert in stages.

The roughness-type approach or pool-type approach may be used at each hydraulic zone depending on the culvert design strategy implemented and waterway devices used.

As stated in Chapter 2 baffles are a requirement of the self-assessable code WWBW01 (2013). Baffles are waterway devices which are an example of both the roughness-type approach and pool-type approach to fish passage. Baffles are used to modify the uniform high-speed velocity within culverts to provide both areas of shelter for fish to rest and large scale roughness elements simulating the flow conditions of natural pools and streams (Katopodis & Williams 2012). Baffles are added to culverts as rougheness elements and operate best in series, placed relatively close together, where they will act as weirs at low flows and gradually transition to roughness elements as flows increase (Bates 1999). Baffle fishway designs for culverts include, but are not limited to, angle baffles, side baffles, weir baffles and corner baffles. Many of these treatments have been used in North America for more than 60 years, however generally they have not been used extensively for fish passage design in Australia (Kapitzke 2010).

The velocities and turbulence created by baffles at the 'boundary layer' must meet the swimming ability of the fish species likely to be using the fish passage structure (Feurich, Boubee & Olsen 2012). Basic principles of fluid mechanics, open channel flow and the relevance of the boundary layer to fish passage are explained in Chapter 6.

4.7 Chapter Summary

In summary, this chapter provides the final background components necessary to undertake an assessment of the DAFF self-assessible code WWBW01 for fish passage in the Mary River catchment. The background information discussed in this chapter as well as the theoretical background information contained in Chapter 6 is used as the foundation for the DAFF fish passage design assessment discussed in Chapters 8 and 9.

Chapter 5

Literature Review

5.1 Chapter Overview

The purpose of this chapter is to provide a summary of some of the recent work which has been undertaken involving the use of computational fluid dynamics software to model the hydraulic performance of fish passage designs.

5.2 Previous Work

Recent CFD studies have been undertaken to assess the hydraulic characteristics of fish passage.

Feurich et al (2012) carried out a study of circular (pipe) culverts using CFD to assess the affect of a range of baffle sizes on circular culvert flow velocities. Using both field, laboratory and numerical trials (CFD), the study confirmed that baffles can be used to reduce water velocities, however suggested the geometry of baffles must consider the swimming ability of fish likely to be using it. Feurich et al (2012) also found that the effect of baffles (of constant width) on surface roughness caused a decrease in hydraulic losses (as turbulence) as culvert diameter increased. Whilst the installation of baffles improve fish passage, baffles do increase hydraulic losses and water depth therefore reducing the culvert flow capacity (Feurich et al 2012).

The investigations by Feurich et al (2012) confirmed that the field and laborary data could be successfully verified by the CFD modelling used in their research. The CFD modelling could therefore be used to confirm that the installation of baffles facilitated the upstream migration of fish in circular culverts.

A paper by Delaere et al (2011) presented the relationship between river flow and fish ecology associated with the conceptual design of several fishway options for the Burrum River Weir No. 1, Queensland. The design involved the CFD modelling of three options for fish passage;

- Fishlock
- Vertical slot
- Natural bypass

The study established the fish species native to the Burrum River and the swimming ability of these fish based on recent literature (Berghuis 2000, Cotterell 1998, Mallen-Cooper 1996). Delaere et al (2011) stressed the importance of understanding the fish species, fish ecology and fish biology in developing the design criteria for fish passage design. The maintenance capabilities of the infrastructure owner was also deemed to be of high importance. It was concluded that a natural bypass type fishway was the preferred option based on fish biology, need to accomodate variable flow conditions and other considerations.

Refer to Figure 5.1 for overview of the Burrum River weir natural bypass fish passage structure.

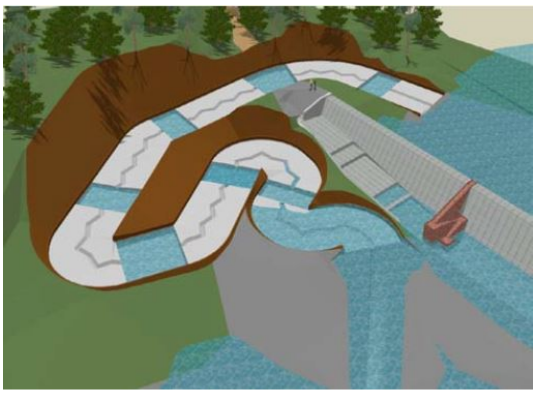

Figure 5.1: Proposed natural bypass fish passage layout (Delaere et al. 2011)

The 2006 report by Kapitzke was an assessment undertaken by James Cook University in collaboration with the Burnett Mary Region Group (BMRG) and DAFF for the upgrade of an existing waterway crossing near Bundaberg, Queensland. The Heales Road crossing situated on Splitters Creek, a tributary of the Burnett River, was identified by BMRG as a high priority site for the remediation of fish passage barriers in the Burnett River system (Kapitzke 2008). The crossing was chosen as part of the Burnett Mary Regional Biopassage Strategy as a demonstration site for the development of culvert fishway structure in order to mitigate barriers to upstream fish migration at waterway barriers/crossings in the Burnett River catchment.

Similarly to the works by Delaere et al (2011), the Heales Road crossing project involved an initial scoping stage to identify the native freshwater fish species, followed by literature review to determine the swimming ability of fish native to the site. The project established fishway concepts for the site based on streamflow and hydraulic characteristics of the Heales Road culvert, including identification of hydraulic zones and fish movement pathways. Laboratory and field testing of various fish passage devices was undertaken by James Cook University as part of the design process to determine the hydraulic characteristics of waterway devices to be implemented in the proposed design. Waterway devices included baffles and rock ramps.

The work by Kapitzke did not include numerical modelling or CFD as part of the Heales Road culvert fish passage design. In light of this, the author was contacted to obtain permission to use the laboratory and field data for validation of CFD models during the assessment phase of this project.

5.3 Chapter Summary

The previous work by Feurich, Delaere and Kapitzke highlighted the importance of establishing an understanding of the fish species and associated swimming ability when developing the design criteria for fish passage. The research by Feurich and Delaere provided an insight into the scale at which CFD can be applied to fish passage assessment i.e. a culvert compared to an extensive natural bypass. Both papers proved that CFD could be used as a tool to assess fish passage at waterway barriers.

The lab and field work by James Cook University will be used to expand on the work previously undertaken by Kapitzke and will prove valuable when validating the CFD model for this work associated with the fish passage requirements of the self-assessable code, WWBW01.

Chapter 6

Theoretical Model

6.1 Chapter Overview

In order to understand the way in which fluids act through fish passage devices one must have a general understanding of the basic principles of fluid mechanics and the hydraulics of culvert flow.

Fluid mechanics concerns the study of all aspects related to the behaviour of fluids (Chadwick & Morfett 1998) and hydraulics is related to the application of the fluid mechanics principles to water engineering structures, including civil and environmental engineering facilities such as pipes, culverts, dams, weirs and open channels (Chanson 2004).

6.2 Theory of Fluid Flow

The theoretical model of steady fluid flow comprises a general relationship between continuity, energy and momentum. The continuity equations are developed from the physical principle of mass conservation (Streeter & Wylie 1975), whereby mass within a system remains constant with time (Anderson Jr, Degroote, Degrez, Dick, Grundmann & Vierendeels 2009).

The continuity equation in cartesian coordinates can be written as follows (Chanson

2004);

$$\frac{\partial \rho}{\partial t} + \bigtriangledown \cdot (\rho \bar{v}) = 0 \tag{6.1}$$

where ρ is water density, t is time, $\bar{v}$ is the instantaneous velocity vector and $\bigtriangledown = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k$.

The Navier-Stokes equations are derived by applying Newton's second law and the continuity equation and a constitutive relationship describing the motion of viscous fluids (Versteeg & Malalasekera 2007). The Navier-Stokes equations, assuming a stationary frame of reference, can be written as follows;

x-momentum equation:

$$\frac{\partial \rho u}{\partial t} + \bigtriangledown \cdot (\rho u \bar{v}) = -\frac{\partial p}{\partial x} + \bigtriangledown \cdot (\mu \bigtriangledown u) + S_{MX} \tag{6.2}$$

y-momentum equation:

$$\frac{\partial \rho v}{\partial t} + \bigtriangledown \cdot (\rho v \bar{v}) = -\frac{\partial p}{\partial y} + \bigtriangledown \cdot (\mu \bigtriangledown v) + S_{MY} \tag{6.3}$$

z-momentum equation:

$$\frac{\partial \rho w}{\partial t} + \bigtriangledown \cdot (\rho w \bar{v}) = -\frac{\partial p}{\partial z} + \bigtriangledown \cdot (\mu \bigtriangledown w) + S_{MZ} \tag{6.4}$$

where ρ is water density, t is time, u is the instantaneous x-component of velocity, v is the instantaneous y-component of velocity, w is the instantaneous z-component of velocity, p is instantaneous pressure, S_{MX} is the gravity force in the x-direction, S_{MY} is the gravity force in the y-direction, S_{MZ} is the gravity force in the z-direction, μ is the dynamic viscosity of water and $\bigtriangledown = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k$.

These equations describe the instantaneous motion of fluids however they do not make any allowance for the effects of turbulence on the motion of fluids. Versteeg and Malalesekara (1995) state that turbulence adds additional stresses on fluids, termed Reynolds' stresses. Reynolds had proposed that fluid flow at a particular point in the fluid is always unsteady and that the velocity at that location in time is equal to the sum of the mean and fluctuating velocity components (Versteeg & Malalasekera 2007);

$$\bar{v} = \bar{V} + \bar{v'} \tag{6.5}$$

$$u = U + u' \tag{6.6}$$

$$v = V + v' \tag{6.7}$$

$$w = W + w' \tag{6.8}$$

$$p = P + p' \tag{6.9}$$

where $\bar{V}$ is the average velocity vector, $\bar{v}'$ is the average velocity fluctuation, U is the average velocity in the x-direction, V is the average velocity in the y-direction, W is the average velocity in the z-direction and P is the average pressure.

By replacing the instantaneous flow variables with the sum of the mean and fluctuating velocity components, the Navier-Stokes equations become the Reynolds Averaged Navier Stokes (RANS) equations and can be re-written (Versteeg & Malalasekera 2007);

x-momentum equation:

$$\frac{\partial (\rho U)}{\partial t} + \bigtriangledown \cdot (\rho U \bar{V}) = -\frac{\partial P}{\partial x} + \bigtriangledown \cdot (\mu \bigtriangledown U) + \left[-\frac{\partial \left(\rho \bar{u'^2} \right)}{\partial x} - \frac{\partial (\rho \bar{u'} \bar{v'})}{\partial y} - \frac{\partial (\rho \bar{u'} \bar{w'})}{\partial z} \right] + S_{MX} \tag{6.10}$$

y-momentum equation:

$$\frac{\partial(\rho V)}{\partial t}+\bigtriangledown\cdot(\rho V\bar{V}) = -\frac{\partial P}{\partial y}+\bigtriangledown\cdot(\mu\bigtriangledown V)+\left[-\frac{\partial\left(\rho\bar{u'}\bar{v'}\right)}{\partial x}-\frac{\partial\left(\rho\bar{v'^2}\right)}{\partial y}-\frac{\partial\left(\rho\bar{v'}\bar{w'}\right)}{\partial z}\right]+S_{MY} \tag{6.11}$$

z-momentum equation:

$$\frac{\partial(\rho W)}{\partial t}+\bigtriangledown\cdot(\rho W\bar{V}) = -\frac{\partial P}{\partial z}+\bigtriangledown\cdot(\mu\bigtriangledown W)+\left[-\frac{\partial\left(\rho\bar{u'}\bar{w'}\right)}{\partial x}-\frac{\partial\left(\rho\bar{v'}\bar{w'}\right)}{\partial y}-\frac{\partial\left(\rho\bar{w'^2}\right)}{\partial z}\right]+S_{MZ} \tag{6.12}$$

In order to predict turbulent flows using the RANS equations it is necessary to develop turbulence models to predict the Reynolds stresses and the scalar transport terms and close the system of mean flow equations 4.1, 4.10, 4.11 and 4.12 (Versteeg & Malalasekera 2007).

The κ-ε standard model by Launder and Spaulding (1974) combines the Boussinesq theory of Reynolds stress approximation with equations for turbulent kinetic energy and rate of dissipation of turbulent kinetic energy to approximate the effects of turbulence and to assist in solving turbulent flow.

The κ-ε model equations can be written as follows;

Turbulent kinetic energy (κ) equation:

$$\frac{\partial(\rho\kappa)}{\partial t}+\bigtriangledown\cdot(\rho\kappa\bar{V}) = \bigtriangledown\cdot\left(\frac{\mu_t}{\sigma_t}\bigtriangledown\kappa\right)+2\mu_1 E_{ij}\cdot E_{ij}-\rho\varepsilon \tag{6.13}$$

Dissipation of turbulent kinetic energy (ε) equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\bigtriangledown\cdot(\rho\varepsilon\bar{V}) = \bigtriangledown\cdot\left(\frac{\mu_t}{\sigma_\varepsilon}\bigtriangledown\varepsilon\right)+C_{1\varepsilon}\frac{\varepsilon}{\kappa}2\mu_t E_{ij}\cdot E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} \tag{6.14}$$

where σ_t, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and C_μ are constants, i and j are indices used to represent Einstein notation, and E is the strain tensor.

The RANS and κ-ε standard model equations require complex calculation techniques for even the simplest of problems (Versteeg & Malalasekera 2007). Computational fluid dynamics numerical modelling software can be used to solve these equations in the abscence of simpler analytical methods. Computational fluid dynamics numerical modelling is discussed further in Chapters 7 and 8.

6.2.1 The Boundary Layer

Prandtl developed the concept of the boundary layer in 1904. Prandtl hypothesised,

> *For fluids having relatively small viscosity, the effect of internal friction in a fluid is appreciable only in a narrow region surrounding the fluid boundaries* (Prandtl 1904)

Prandtl found that the flow region next to a solid boundary (stream bed, culvert wall, pipe wall etc.) is affected by the presence of the boundary and its frictional characteristics and that the flow outside of the narrow region near the solid boundary may be considered ideal or potential flow (Streeter & Wylie 1975).

Boundary layer flow is characterized by a range of velocities across the boundary layer region from zero at the solid boundary to the free-stream velocity at the outer edge of the boundary layer (Chanson 2004). This range of velocities is a result of shear forces acting on the fluid at the solid boundary that reduce the flow velocity relative to the boundary (Streeter & Wylie 1975).

The boundary layer begins as a 'laminar boundary layer' adjacent to the solid boundary in which the fluid particles move in smooth layers. As the laminar boundary layer increases, so too does the turbulence of the fluid to a point where the laminar boundary layer transforms into a 'turbulent boundary layer'. The calculation of the boundary-layer growth and its properties require complex and advanced mathematical calculations (Streeter & Wylie 1975), however can be readily analysed using computer software and computational fluid dynamics which is discussed further in the following section.

It can therefore be assumed that the boundary layer, of reduced velocity and increased turbulence, is present in varying degree against the walls and floor of fish passage culvert structures.

The boundary layer is relevant to fish movement as it provides a zone of reduced velocity in which fish can travel. Research observations have found that fish are likely to use this zone to rest, or swim upstream through culverts (Behlke, Kane, McLean & Travis 1989, Powers & Osborn 1986). It has therefore become common practice to implement waterway devices, such as baffles (see Chapter 4), which increase roughness and decrease boundary layer velocity (Hotchkiss & Frei 2007).

Figure 6.1 is taken from a study by Delaere et al (2011) which concerned computational fluid dynamics of options for fish passage devices in the Burrum River, Queensland. The objects shaded grey in Figure 6.1 represent concrete blocks placed within the bed of a man-made, natural bypass channel. The coloured shading between the concrete blocks represents the flow velocity within the channel. It can be seen that flow velocities range from 0 - 0.2 m/s nearest the concrete blocks up to 1.5 - 1.7 m/s towards the outer edge of the boundary layer. It is the 0 - 0.2 m/s flow velocity zone in which smaller fish species are mostly likely to travel.

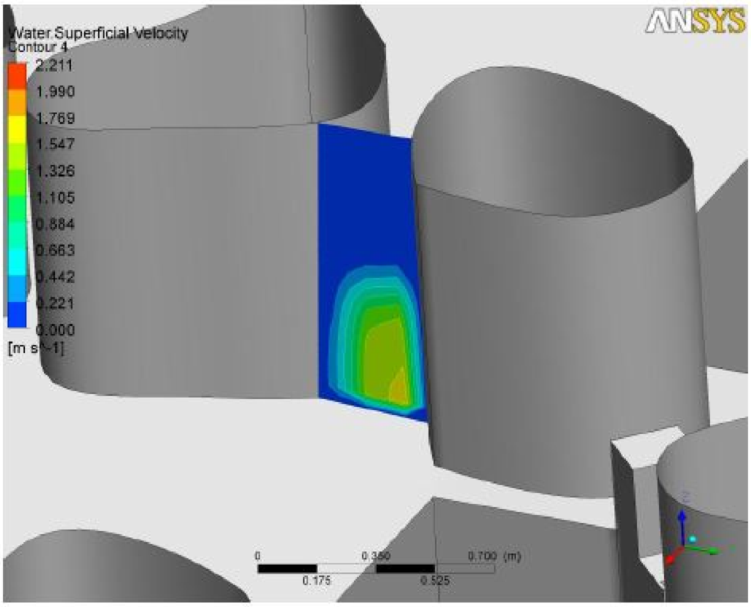

Figure 6.1: Boundary Layer effect on velocity (Delaere et al. 2011)

6.3 Open Channel Flow

6.3.1 Introduction

An open channel is a waterway, canal or conduit in which a liquid flows with a free surface, whereby the liquid is water and the air above the flow is usually at rest and at standard atmospheric pressure (Chanson 2004). Rectangular 'box' culverts, as required by WWBW01, when flowing partially full are a typical example of open channels.

The main component of open channel analysis is the depth of flow and the location of the 'free' surface. The location of the free surface is generally not known beforehand, as it rises and falls in response to characteristics such as flow volume, open channel geometry and open channel roughness (Chanson 2004).

Natural streams with varying geometry, roughness and slope convey 'steady non-uniform' flow i.e. the discharge is constant with time, but the cross-sectional area varies with distance (Featherstone & Nalluri 1995). Flow through open channels with constant cross-section, friction and flow is generally classed as 'steady uniform' flow i.e. there is no change in flow volume and depth with time (Fenton 2005). The uniform profile of both open channels and rectangular box culverts which are used in this project are considered to convey steady uniform flow.

6.3.2 Manning's Equation

The WWBW01 fish passage designs are considered as open channels as the free surface of the water is open to the atmosphere. The Manning's equation is most commonly used throughout Australia for the analysis of uniform flow conditions within open channels (Department of Energy & Water Supply (DEWS) 2013). The Manning's equation was used to determine flow depths and approach velocities in the CFD modelling phase of this project.

$$V = \left(\frac{1}{n}\right) R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{6.15}$$

where V is average flow velocity (m/s), n is Manning's roughness value, S is the channel slope (m/m) and R is the hydraulic radius (m);

$$R = \frac{A}{P} \tag{6.16}$$

where A is the effective channel flow area (m^2) and P is the wetted perimeter of flow (m).

The choice of a suitable Manning's roughness value is subjective requiring a degree of engineering judgement (Department of Energy & Water Supply (DEWS) 2013). For this project the Manning's values were chosen based on the prescribed values by Chow (1959) and Book 7 of Australian Rainfall and Runoff (1998).

6.3.3 Froude Number

The Froude number is a dimensionless value used in hydraulic engineering to express the relative importance of inertia and gravity forces in open channel hydraulics (Fenton 2005). Froude number F is proportional to the square root of the ratio of the inertial forces over the weight of the fluid (Chanson 2004);

$$F = \sqrt{\frac{Q^2 B}{g A^3}} \propto \sqrt{\frac{inertial force}{weight}} \tag{6.17}$$

where Q is the flow (m^3/s), B is the width of flow and A is the cross sectional area of flow.

Flows which are slow and deep have low Froude numbers whilst fast and shallow flows have high Froude numbers. Froude flow conditions are defined in Table 6.1.

Table 6.1: Froude Flow Conditions

Froude Number	**Flow Regime**	**Description**
Less than 1	Subcritical	Slow velocity, deep flow
Equal to 1	Critical	Transitional flow
Greater than 1	Supercritical	Fast velocity, shallow flow

In open channel flow, subcritical, low energy state flow is considered stable and occurs when the flow depth is larger than the critical flow depth. Supercritical, high energy state flow occurs when the flow depth is less than the critical flow depth. Critical flow occurs when the flow conditions such as specific energy are at a minimum. Small changes in specific energy at critical flow may cause large changes in flow depth and generally unstable flow conditions (Chanson 2004).

The CFD models developed in this project are generally established to achieve subcritical flow conditions.

6.4 Chapter Summary

This chapter provided a background of the basic principles of fluid mechanics and open channel hydraulics. The relationship between fluid theory and the computational fluid dynamics is discussed further in Chapter 7.

Chapter 7

Research Methodology

7.1 Chapter Overview

The purpose of this chapter is to provide a brief background on the Computational Fluid Dynamics modelling process as well as the methodology undertaken to establish the CFD models developed for this project.

7.2 Computational Fluid Dynamics (CFD)

7.2.1 Introduction

Versteeg and Malalesekara (1995) defines Computational fluid dynamics (CFD) as,

> *The analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation*

CFD consists of numerical algorithms designed to solve the governing fluid flow and has a wide range of applications in areas such as hydraulics and hydrology, aerodynamics, heating and ventilation, biomedical and chemical processes.

As discussed in Chapter 6, the fundamental physical aspects of fluid flow are governed by continuity, momentum and energy, all of which are expressed by mathematical equations. CFD essentially converts the partial differentiation component of these equations to numbers and advances these numbers through time and space to obtain a numerical flow field solution for the area of interest (Anderson Jr et al. 2009).

CFD was chosen as the assessment tool for this project as it enables the user to undertake virtual, numerical experiments (simulations) and solve a particular problem using a laptop or desktop computer at any time of day. The amount of potentially costly traditional experimentation can therefore be significantly reduced if CFD is used.

7.2.2 ANSYS CFX Software

ANSYS-CFX sofware is used for the computational fluid dynamics modelling of fish passage structures in this project. ANSYS CFX is computational fluid dynamics software suited for fluid dynamics modelling applications (ANSYS Incorporated 2010) and has been made available for use by the University of Southern Queensland.

ANSYS CFX was chosen due to the ability of the software to successfully simulate open channel or multi-phase, free surface flows (ANSYS Incorporated 2010). The software was also chosen as it was made freely available by the University of Southern Queensland with support provided by both the University and employment colleagues.

7.2.3 The Homogeneous Model

Homogeneous flow models occur where a common flow field is shared by multiple fluids i.e. multiphase flow. Free surface flow is the most common application of homogeneous multiphase flow (ANSYS Incorporated 2012). The homogeneous model assumes that for a given process the quantities for that process (excluding volume fraction) are the same for all phases (ANSYS Incorporated 2012). The theory of volume conservation ensures that the volume fractions of water and air sum to unity.

Open-channel and fish passage culvert flows are an example of homogeneous multiphase flow whereby there are essentially two fluids; water and air (Ferreira, Dimakopoulos & Ferreira 2011). ANSYS CFX uses multiphase modelling technology to capture the interaction between multiple fluids in order to model the free surface interface between these fluids (ANSYS Incorporated 2010).

The homogenous model option available in ANSYS CFX is used to simulate the three-dimensional (3D) RANS equations, the Reynolds averaged mass conservation for each phase α, a pressure constraint denoting that each phase share the same pressure field $\bar{p}$ and a mass constraint forcing phases to fill up every fluid cell (ANSYS Incorporated 2012).

The equations may be written as follows;

$$\frac{r_\alpha \rho_\alpha}{\partial t} + \bigtriangledown \cdot (r_\alpha \rho_\alpha \bar{u}) = 0 \tag{7.1}$$

$$\bar{p_\alpha} = \bar{p} \tag{7.2}$$

$$\sum_{\alpha=1}^{N_p} r_\alpha = 1 \tag{7.3}$$

where $\bar{p_\alpha}$ is the pressure associated with phase α, ρ_α is the density of the phase α, r_α is the volume fraction of phase α and N_p is the total number of phases.

7.2.4 ANSYS CFX-Solver

ANSYS CFX Solver (CFX-Solver) forms part of the ANSYS software suite. CFX-Solver is a fully implicit, node centred, finite-volume based code, where the integral formulation of the conservation laws are discretized over each control volume and solved in a coupled manner by an algebraic multigrid acceleration technique (Ferreira et al. 2011).

The coupled solver solves the hydrodynamic parameters of u, v, w and p as a single system of equations and uses a fully implicit discretization of the equations at any given time step (ANSYS Incorporated 2012). For transient flow analysis (i.e. time dependent) the coupled solver accelerates the simulation, reducing the number number of iterations used to calculate the solution for each time step.

CFX-Solver is an iterative solver whereby the exact solution of the equations are approached during the course of several iterations. When solving fields in the CFX-Solver, the outer (or time step) iteration is controlled by the time step for transient analyses, respectively. Multiple inner iterations are performed per time step in transient analyses.

7.2.5 Transient Flow Analysis

Two types of flow analysis can be considered when using ANSYS CFX;

Steady state flow: Occurs where the fluid properties at any location in the system do not change with time.

Transient flow: Occurs where the fluid properties change with time. Transient flow generally persist as velocity and pressure oscillates for some time after the original event that caused it.

Multiphase flow can be considered transient (ANSYS Incorporated 2012). It is possible to complete steady state analysis of multiphase flow, however unsteady fluctuations within the flow profile must be ignored. Transient flow analysis is therefore applied to all CFX simulations for this project work. Transient flow then defines the numerical algorithm which CFX will use for the transient term in the simulation.

The default Second Order Backward Euler implicit time-stepping algorithm/scheme is adopted for all simulations. Though not as stable as First Order Backward Eular, this scheme is generally recommended for transient runs due to it's accuracy. The Euler's scheme is an algorithm which advances a solution through space and is generally appropriate for open channel simulations where quantities may only be known approximately (Fenton 2005).

7.2.6 Courant Number

For transient flow analysis the maximum and root mean square (RMS) Courant numbers are displayed on screen and written to the output file at every timestep. The Courant number is of fundamental importance to transient flows. Courant is defined as;

$$C = \frac{u\Delta t}{\Delta x} \tag{7.4}$$

where C is the Courant number, u is the velocity of the fluid, Δt is the time step and Δx is the mesh size. Small time step and mesh size therefore results in small Courant number.

The Courant number calculated in ANSYS CFX is a multidimensional generalization of this expression where the velocity and length scale are based on the mass flow into the control volume and the dimension of the control volume (ANSYS Incorporated 2012). For transient analysis CFX uses the Courant number to calculate the 'blend' between the previous timestep and any chosen extrapolation options.

A Courant number less than 1 will typically improve convergence (ANSYS Incorporated 2012).

7.2.7 Convergence

> *Convergence describes the limiting behaviour, particularly of an infinite sequence or series toward some limit. To assert convergene is to claim the existing of a limit, which may be itself unknown. For any fixed standard of accuracy, you can always be sure to be within it, provided you have gone far enough* (International Association for the Engineering Modelling & Simulation Community (NAFEMS) 2013)

Fluid mechanics is involved with non-linear processes, dealing with inherently unstable phenomena such as turbulence. CFD software is intended to simulate these physical processes, and therefore is subject to the same issues as the processes it is trying to represent (University of Birmingham (UB) 2013).

CFD problems in general are non-linear, and the solution techniques use an iterative process to successively improve a solution, until convergence is reached (International Association for the Engineering Modelling & Simulation Community (NAFEMS) 2013). Convergence needs to be associated with some level of accuracy. Though the exact solution of the problem may be unknown, ideally the end result must be sufficiently close to the solution for a particular required level of accuracy.

Convergence is often measured by the level of residuals, the amount by which discretised equations are not satisfied, and not by the error in the solution. The user should therefore be aware of this, in deciding what convergence criterion should be used to assess a solution (International Association for the Engineering Modelling & Simulation Community (NAFEMS) 2013)

The most important measure of convergence is the residual (University of Birmingham (UB) 2013). The residual is a measure of the local imbalance of each equation being solved, and so ideally the residual should decrease as the solution proceeds approaching the final solution (ANSYS Incorporated 2012). CFX Solver terminates the run when the equation residuals calculated are below the Residual Target value. The Root Mean Square (RMS) type of residual is used in CFX with the the default RMS target being 0.0001.

Courant number can be used to monitor the convergence of transient flows. As stated previously, a courant number of less than 1 will typically result in improved convergence.

For transient simulations, CFX Solver solves the governing equations at regular time intervals (time steps). To achieve convergence at each time step, a number of loop iterations have to be performed before reaching convergence. Once convergence has been achieved at one time step, or the maximum number of coefficient loops reached, the solver proceeds to the next time step. This process repeats until convergence requirements are satisfied.

The maximum coefficient loops sets the maximum number of iterations that can be performed at each time step. If the specified convergence criterion is not met by the end of the last iteration (coefficient loop), the solver will move to the next time step. Whilst a large number of time steps gives better accuracy and requires a smaller number of iterations per time step to achieve convergence, it does however prolong the simulation considerably. So the choice of the time step size and the number of iterations per timestep is generally a trade-off between accuracy and simulation time.

This project adopts a time step of 0.01 seconds and a total duration of 20 seconds for all simulations. Convergence settings are set at default values;

- Minimum coefficient loops = 1

- Maximum coefficient loops = 100
- Residual target value = 0.0001 (RMS)

These values ensure that a relatively low Courant number is achieved at each time step and convergence achieved within the overall duration of the simulation.

7.3 Establishing ANSYS CFX Simulations

7.3.1 Introduction

This section provides a brief explanation of the processes involved in setting up the ANSYS CFX models.

ANSYS CFX models were developed for two scenarios;

- Validation; and
- Design

These scenarios are discussed in detail in Chapter 8, however the CFX setup criteria for each is relatively the same.

7.3.2 Domain and Mesh Generation

The mesh is a 3D representation of the fluid body or domain inside the structure, model or conduit with which the fluid interacts. For this project the validation and design models are 3D representations of fish passage culverts; as both scaled laboratory models and full scale field models. The mesh for the models used in this project are of hexagonal form rather than tetrahedral. Hexagonal mesh generally improves accuracy and may result in faster simulation times depending on the complexity of the model (ANSYS Incorporated 2012).

As discussed previously, the Courant number is directly related to the mesh size. A fine mesh will result in improved convergence and more accurate results, however the size of the mesh model, in terms of individual mesh elements (nodes), is increased. The final mesh size is often a trade-off between mesh size (therefore number of nodes) and anticipated accuracy of simulation results.

As discussed, the mesh is a 3D representation of the fluid domain. The following parameters were assigned to the fluid domain using CFX Solver;

- Fluid domain includes both Air and water
- Buoancy reference density = $1.185kg/m^3$
- Fluid temperature = $25degC$

All other parameters were set to default values.

7.3.3 Boundary Conditions

Boundary conditions were defined to the sides, bottom, top, floor, and ends of the fluid domain. Boundaries can be defined within CFX as either walls, inlets, outlets, or openings.

Inlet: An inlet boundary is located at the upstream end of each fluid domain. The inlet condition is defined by a known water velocity in all cases. Turbulence is set at a conservative value of 5% (ANSYS Incorporated 2012) and volume fractions are defined by the numerical expressions described in Section 7.3.5.

Outlet: An outlet boundary is located at the downstream end of each fluid domain. The outlet conditions are generally unknown and are therefore defined by the downstream pressure distribution (refer to Section 7.3.5)

Surfaces: Surfaces such as walls and floors of the fluid domain are defined as rough walls with a given sand grain roughness value k_s. The k_s value is dependent on the surface i.e. concrete wall, gravel stream bed etc. (refer to Section 7.3.5)

Top: The top, surface, roof or ceiling of the fluid domain is defined as an 'opening'. An opening boundary condition allows the fluid to cross the boundary surface in either direction (ANSYS Incorporated 2012). By defining conditions such as pressure and turbulence gradients, the opening boundary condition essentially defines the behaviour of the free surface flow.

Any parameters not specifically mentioned were set as default values.

7.3.4 Initial Conditions

Initial conditions must be specified to describe the fluid domain conditions at the beginning of the simulation (time = 0 seconds). The initial conditions are generally consistent with the inlet boundary conditions i.e. velocity, pressure and volume fraction settings.

7.3.5 Expressions

In order to simulate the free surface flows within each model a number of expressions are required to be input into ANSYS CFX. For all simulations the following conditions were defined with expressions;

- An inlet boundary where the volume fraction above the free surface is '1' for air and '0' for water
- An inlet boundary where the volume fraction below the free surface is '0' for air and '1' for water
- A pressure specified outlet boundary, where the pressure above the free surface is constant
- A pressure specified outlet boundary, where the pressure below the free surface is a hydrostatic distribution
- An inlet pressure field for the domain with a similar pressure distribution to that of the outlet boundary

The following expressions were used to represent the above conditions;

$$Va_u = step((z - H_u)/1) \tag{7.5}$$

$$Vf_u = 1 - Vau \tag{7.6}$$

$$p_u = \rho_W \cdot g \cdot Vf_u \cdot (H_u - z) \tag{7.7}$$

$$Va_d = step((z - H_d)/1) \tag{7.8}$$

$$Vf_d = 1 - Vad \tag{7.9}$$

$$p_d = \rho_W \cdot g \cdot Vf_d \cdot (H_d - z) \tag{7.10}$$

where Va_u is the upstream volume fraction of the air, Vf_u is the upstream volume fraction of the fluid (water), p_u is the upstream pressure distribution, Va_d is the downstream volume fraction of the air, Vf_d is the downstream volume fraction of the fluid (water), p_d is the downstream pressure distribution, H_u is the upstream free surface height, H_d is the downstream free surface height, ρ_f is the density of the fluid (water = 998 kg/m^3), z is a height within the fluid/air domain and *step* is an argument profile which checks if the depth z is within the air or fluid both upstream or downstream and returns a value of 1 for 'yes' and 0 for 'no'.

Any parameters not specifically mentioned were set at default values.

7.4 Modelling Natural Stream Beds Using CFD

7.4.1 Introduction

Maintaining a stream's natural characteristics along the culvert floor, as prescribed by WWBW01, poses a problem when developing CFD models (Nicholas 2005). Carney (2006) suggests that although CFD has been used to successfully model complex stream systems in the past, adequately simulating the characteristics of irregular gravel and cobble stream beds is difficult due to the inadequacy of traditional roughness representations used to characterise these roughness elements.

Stream beds may include roughness elements (gravel, sand, rocks etc.) which scale a range of grain size, grain shape and roughness characteristics (Rameshwaran, Naden & Lawless 2011). It is difficult to obtain high-resolution topography data for entire river reaches, therefore representing the boundary rougheness and topography of natural channels, presents problems for CFD modelling (Rameshwaran et al. 2011).

7.4.2 Approaches to Stream Bed Roughness

Several approaches have been developed which attempt to resolve the effects of 'large scale' boundary roughness elements on stream flow.

Resolution and Porosity approach: The resolution and porosity approach was developed by Olsen and Stokseth (1995) to model the roughness elements in river beds. This approach uses high-resolution digital topography to develop models at millimetre resolution. It is currently impractical to apply this approach to natural stream bed CFD models due to the high processing requirements not achievable by most of today's computers (Rameshwaran et al. 2011).

Stochastic approach: Nicholas (2001) developed a stochastic approach whereby the roughness of a stream bed is divided into sub-grid and supra-grid roughness elements. These elements were then further divided into large-scale roughness elements i.e. pools, riffles, channels, bars etc. which were mapped and included as part of the model mesh. Nicholas (2001) concluded that stochastic modelling approaches may not be appropriate for modelling of stream bed roughness due to the sensitivity of the near-bed flow fields obtained when mapping the spatial dimensions of the model mesh.

Drag force approach: The drag-force approach, combined with spatial averaging of the flow in the roughness layer, has been widely used for developing models of atmospheric flows (Wilson & Shaw 1977). Nicholas (2005) developed a drag force approach whereby boundary profiles are established based on roughness parameters derived from simple stochastic models. The drag force approach has been successfully adopted for use in open channel hydraulics to represent both the boundary roughness and vegetative roughness ((Rameshwaran et al. 2011). The advantage of this approach is that unlike the resolution and porosity approach, the drag force approach does not require high-resolution topography, but is instead represented by statisitically sampled, spatially-averaged parameters to characterise the roughness elements of natural stream beds (Rameshwaran et al. 2011).

For this project a simple drag force approach was used whereby specific sand grain roughness values were applied based on particular surface treatments (concrete, gravel etc.) within the CFX models.

7.4.3 Surface Roughness and Flow Depth

Surface roughness effects the flows of interest and can typically lead to an increase in turbulence produced near the walls (ANSYS Incorporated 2012). Roughness can be described by an equivalent sand grain roughness. The sand grain roughness value k_s defines the smoothness of a particular surface in terms of equivalent sand grain size.

The k_s for large scale roughness surfaces (i.e. natural stream bed and culvert floor) was calculated using the following process;

1. Manning's roughness value, n was calculated based on assumed stream bed rock/gravel diameter using the equation (United States Geological Survey Water (USGSW) 2013);
$$n = \frac{(0.8204)\, R^{\frac{1}{6}}}{1.16 + 2\log\left(\frac{R}{D_{84}}\right)} \tag{7.11}$$
2. The calculated n value was compared for suitability using the values recommended by both the Queensland Urban Drainage Manual (2013) and Chow (1959)
3. The values were then converted to equivalent k_s values using the equation (Hey 1979)
$$k_s = 3.5D_{84} \tag{7.12}$$

where n is the Mannings roughness value, R is the hydraulic radius of flow and D_{84} is the particle/rock/gravel diameter (m) that equals or exceeds the diameter of 84 percent of the particles. D_{84} was based on an assumed 50 mm diameter coarse gravel (United States Geological Survey Water (USGSW) 2013) stream bed.

The k_s for small scale roughness surfaces (i.e. concrete culvert walls and wingwalls) was calculated using the following process;

1. The n value for concrete was adopted based on the values recommended by both the Queensland Urban Drainage Manual (2013) and Chow (1959)

2. The values were then converted to equivalent k_s values using the equation (Rameshwaran et al. 2011)

$$k_s = \left(n\left(8.25\sqrt{g}\right)\right)^6 \tag{7.13}$$

Representing low flow depth with high boundary roughness presents a problem for CFX modelling (Rameshwaran et al. 2011). It was found for all simulations the calculated large scale roughness k_s values caused CFX simulations to end suddenly due to turbulence computational issues adjacent to the rough surface.

The porous body method described by Carney et al (2006) can be used to overcome this problem. In order to compute the fluid behaviour adjacent to rough surfaces, porous zones can be created in CFX that correspond to the difference in grain heights assuming all grain heights have a common base level i.e. culvert floor. Refer to figure 7.1 for theoretical arrangement of porous body plains for all grain sizes (Carney et al. 2006). The dotted lines represent the height of porous zones and the shaded elipses represent different grain sizes.

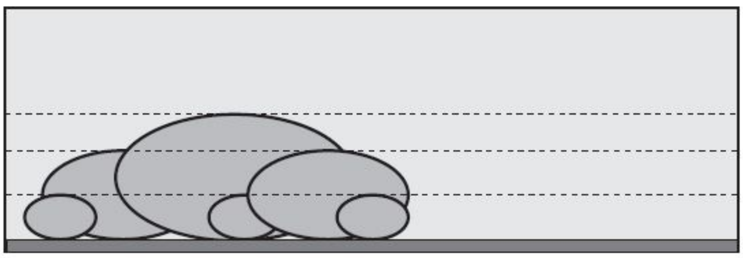

Figure 7.1: Theoretical arrangement of porous body plains for all grain sizes (Carney et al. 2006)

Working down from the heighest porous zone or grain height, the influence of each additional porous zone is added to the inertial loss until the common base level is reached where the total of all porous zones represents all grain heights in the distribution (Carney et al. 2006).

As the models being assessed in this project are quite simple, with typically low velocities, it was decided a k_s value would be chosen that does not cause the CFX turbulence issues encountered when using the initial large scale roughness values. After a number of iterations it was found that a maximum k_s value of 0.03 could be used. Backwards calculation found the k_s of 0.03 equates to an n value of 0.022 which represents a fine gravel or coarse sand (Chow 1959, Department of Energy & Water Supply (DEWS) 2013).

It is anticipated that the model roughness can be revisited in future using the porous body method.

7.5 Chapter Summary

In summary this chapter provided the methodology required to establish the ANSYS CFX models for validation and assessment. It is anticipated that the information, expressions, variables and values defined in this chapter can be used when developing multi-phase, free surface fluid simulations for future fish passage modelling and assessment.

Chapter 8

Numerical Model

8.1 Chapter Overview

The purpose of this chapter is to discuss the numerical models which were established to assess the DAFF fish passage design recommendations. As stated in Chapter 7 ANSYS CFX was the computational fluid dynamics software used for this task.

This chapter will first discuss the process which was undertaken to validate the use of ANSYS CFX software as a fish passage assessment tool for 'in culvert' fish passage treatments such as baffles. The assessment of the DAFF fish passage design recommendations will then be discussed.

8.2 Validation of ANSYS CFX

8.2.1 Introduction

Validation was deemed important in establishing the numerical model for this report as very little literature is available which either supports or denies the use of CFD software as a fish passage assessment tool. Though it is accepted that validation processes occur in the development of CFD software such as ANSYS CFX, it was decided that some form of validation should form part of this project to support the assessment of DAFF design recommendations.

As discussed in Chapter 5, experimental data sourced from James Cook University, Townsville was used for the validation process. Two sets of experimental data were obtained;

- Discovery Drive prototype hydraulic monitoring
- Laboratory model hydraulic monitoring

The experimental data for the above sites comprised flow velocity measurements taken at specific locations within structures containing the Corner 'EL' baffle design. The corner 'EL' baffle was developed by Mr Ross Kapitzke of James Cook University as an alternative to the standard baffle type discussed in Chapter 2.

8.2.2 Discovery Drive Prototype Hydraulic Monitoring

Introduction

The Discovery Drive hydraulic monitoring experimental data was measured at an existing culvert crossing located near the James Cook University Douglas campus in Townsville. The culvert comprised a 3 cell, 3.60m x 3.0m concrete drainage structure located on University Creek, a tributory of the Ross River. The Discovery Drive culvert is 22.0 m in length and has a longitudinal slope of 0.5%. Refer to Figure 8.1 for image of the Discovery Drive culvert.

Figure 8.1: Discovery Drive Culvert (Kapitzke 2007)

University Creek is considered the largest and least altered tributary entering the lower reaches of the Ross River in the city of Townsville, Queensland (Kapitzke 2007). The waterway represents a significant corridor for terrestrial and aquatic fauna and was assigned as a high conservation priority area by the Centre for Tropical Water and Aquatic Ecosystem Research, James Cook University (1998).

The Discovery Drive culvert caused a fish passage barrier as a result of the following (Kapitzke 2010);

- Water surface drop at the culvert outlet (Zone B)
- Shallow flow depths during low flows (Zones B, C and D)
- High velocities and lack of resting places (Zones B, C and D
- Turbulence at the culvert outlet (Zone B)

Corner 'EL' Baffles

Corner 'EL' baffles were developed by Mr Ross Kapitzke as a means to overcome the velocity and lack of shelter barrier issues within Zone C - Culvert barrel.

Some of the key objectives of the prototype corner 'EL' baffles were as follows;

- Provide for fish passage through the culvert during critical periods over a range of flow profiles and rainfall events
- Ensure flow capacity of the waterway and culvert was not worsened as a result of the fish passage devices
- Maintain natural flow and sediment processes in University Creek; and
- Comply with local and regional sustainability goals.

The corner 'EL' baffle prototype fish passage device was intended to address the fish passage barriers within the Discovery Drive culvert itself. The baffle design was developed by Ross Kapitzke based on similar designs by Bates (1999) and Engel (1974). The prototype was designed as a hybrid roughness and pool type fish passage device intended to provide conditions suitable for a range of flow depths and fish species.

The prototype corner 'EL' baffle is shown in Figure 8.2. The horizontal leg of the baffle is 0.7 m in length and the vertical leg extends 0.9 m vertically up the culvert wall.

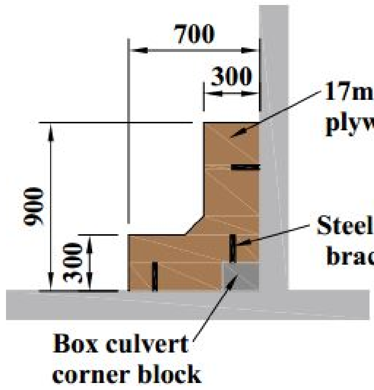

Figure 8.2: Corner 'EL' Baffle Detail (Kapitzke 2007)

The Discovery Drive Prototype

The baffles were located along the outside wall of the Discovery Drive culvert as a method of enhancing the boundary layer effect along the outer wall and to therefore provide improved flow conditions for fish passage. The baffles were placed at 2.0 m intervals through the culvert barrel and at 1.0 m intervals at the inlet and outlet of the culvert. A plan view of the Discovery Drive culvert with corner 'EL' baffles is shown in Figure 8.3 and an image of the culvert barrel is shown in Figure 8.4.

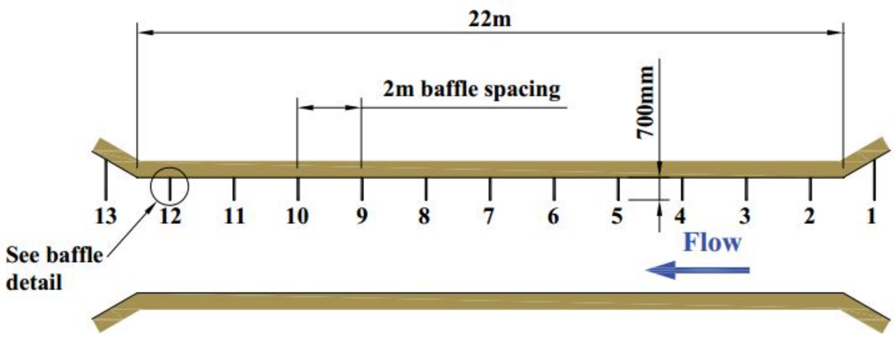

Figure 8.3: Corner 'EL' Baffle - Plan View (Kapitzke 2007)

Hydraulic monitoring of the Discovery Drive prototype fishway was undertaken under several flow conditions, however flow observations were restricted to shallow flow when the culvert could be safely accessed by University staff and students. Velocity and flow depth measurements were recorded at several locations within the culvert barrel as well as at the inlet and outlet. Velocity measurements were taken by James Cook

Figure 8.4: Corner 'EL' Baffle - Culvert Barrel (Kapitzke 2007)

University students and staff using a Swoffer Instruments Model 3000 data logging flow meter with 50 mm diameter propeller and adjustable length and extension. Velocity measurements were typically taken by standing in the flowpath and positioning the flow meter towards the direction of flow at the following locations;

- Outer edge of the open channel adjacent to the end of baffles
- Within the open channel opposite baffles
- Outer edge of the open channel between baffles
- Culvert side (inner wall) edge of the open channel between baffles

The locations of where velocity measurements were recorded are shown in Figure 8.5.

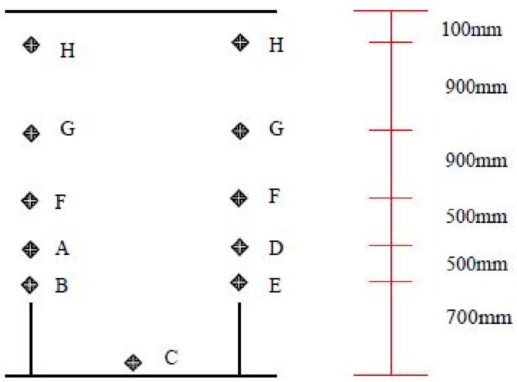

Figure 8.5: Data Collection Points for the Prototype Corner Baffles (Ferrando 2006)

The Discovery Drive Prototype ANSYS CFX Simulation

The Discovery Drive prototype ANSYS CFX simulation was established based on the experimental data for a flow case recorded in April 2006. This event was chosen due to the completeness and consistency of available data. The flow conditions for this event were as follows;

- Upstream (headwater) depth - 300 mm
- Downstream (tailwater) depth - 400 mm
- Inlet velocity - 0.69 m/s
- Outlet velocity - 0.40 m/s

All flow velocity measurements were recorded at half flow depth i.e. 150 mm.

The above criteria defined the inlet and outlet boundary conditions from which the Discovery Drive prototype ANSYS CFX model was established. All solid boundaries were defined as 'rough surfaces'. An equivalent sand roughness coefficient of 0.002 m was adopted which is consistent with the brushed concrete finish of concrete pipes and box culverts (Chow 1959). The model was then simulated using the convergence and solver conditions specified in Chapter 7.

Comparison of Experimental and Numerical Results

Velocity plots of the ANSYS CFX simulation results overlaying the experimental data are provided in the CFX report in Appendix C.

Flow velocity plots were produced in CFX laterally, i.e. across the culvert cell, between baffles 2 and 3, 5 and 6 and 11 and 12 as well as longitudinally, i.e. in the direction of flow, along the Discovery Drive culvert through ponts A, B, C, F, G, and H.

The flow velocity plots were assessed for visual correlation. Generally good correlation was evident in all lateral plots and some of the longitudinal plots. The largest discrepancies in experimental and numerical velocity data occured at points A and H, i.e.

locations of high flow adjacent to solid boundaries. It is assumed that this occured due to some or all of the following;

- Numerical modelling equivalent sand roughness values did not specifially match experimental values
- Inconsistency in location of velocity measurements at each data collection point
- Inconsistency in handling of the velocity flow meter
- Velocity measurements affected by users standing in flow path
- Debris and silt build-up in the culvert barrel

It is anticipated that with more precise recording techniques the correlation between numerical and experimental data may improve.

8.2.3 Laboratory Model Hydraulic Monitoring

Introduction

The James Cook University laboratory model hydraulic monitoring experimental data was measured in the hydraulics lab at the James Cook University Douglas campus in Townsville. The laboratory model comprised a 1:10 scale version of the Discovery Drive culvert fitted with 1:5 scale corner 'EL' baffles. The model was 2.2 m in length with a longitudinal slope of 0.05%.

The laboratory model was developed by final year engineering students as a means to model the effects of different fish passage devices and treatments.

The Hydraulics Laboratory Model

Similar to the Discovery Drive culvert, the corner 'EL' baffles were located along the outside wall of the laboratory model as a method of enhancing the boundary layer effect along this edge of the culvert. The baffles were placed at 0.4 m intervals through the culvert barrel and commenced 0.1 m from the upstream and downstream ends. A plan view of the Discovery Drive culvert with corner 'EL' baffles is shown in figure 8.6 and an image of the culvert model is shown in figure 8.7.

The corner 'EL' baffles used in the laboratory model were a 1:5 scaled version of the prototype baffles used in Discovery Drive. The horizontal leg of the baffle was 0.15 m in length and the vertical leg extended 0.18 m vertically up the culvert wall. Both the laboratory culvert and corner 'EL' baffles were constructed from 3 mm thick transluscent perspex.

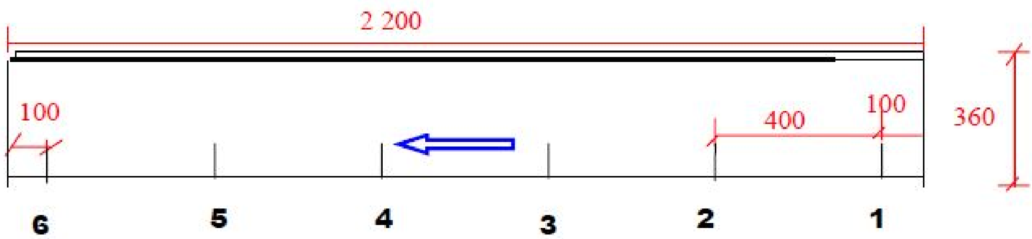

Figure 8.6: Corner 'EL' Baffle - Plan View (Ferrando 2006)

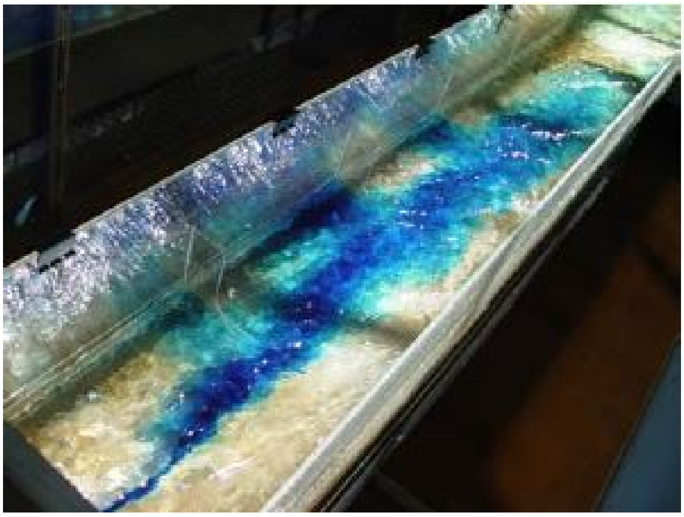

Figure 8.7: Hydraulics Laboratory Model (Ferrando 2006)

Hydraulic monitoring of the laboratory fishway were undertaken under several flow depths. Refer to Figure 8.8 for flow depth details. Q1, Q2, Q3 and Q4 represent the flow depths which were modelled.

Layers 1, 2, 3 and 4 represent the location of flow measurements. Velocity and flow depth measurements were recorded at several locations within the culvert barrel as well as at the inlet and outlet and were recorded using a Swoffer Instruments Model 3000 data logging flow meter with 50 mm diameter propeller and adjustable length and extension. Velocity measurements were taken by positioning the flow meter at the

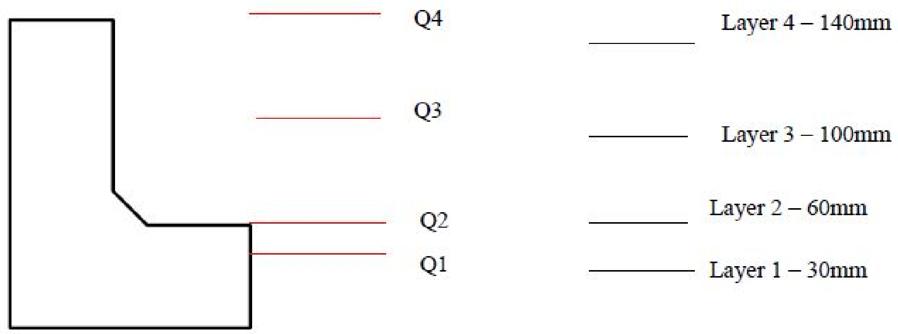

Figure 8.8: Laboratory model flow depths (Ferrando 2006)

following locations using a fixed bracket;

- Outer edge of the open channel adjacent to the end of baffles
- Within the open channel opposite baffles
- Outer edge of the open channel between baffles
- Culvert side (inner wall) edge of the open channel between baffles
- Immediately upstream and downstream of baffles

The locations of where velocity measurements were recorded are shown in figure 8.9.

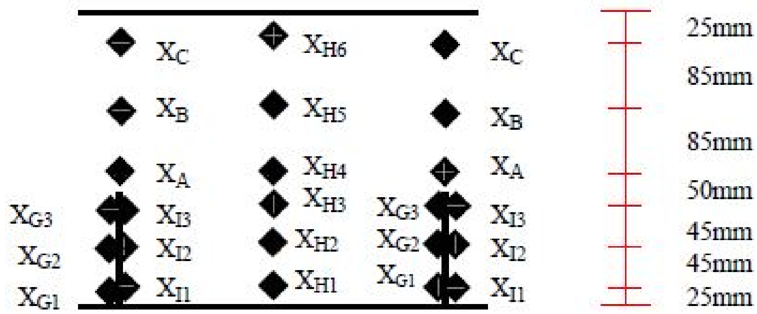

Figure 8.9: Data Collection Points for the Model Corner Baffles (Ferrando 2006)

The Laboratory Model ANSYS CFX simulation

The laboratory model ANSYS CFX simulation was established based on the experimental data by Ferrandol (2006). The flow conditions for this study were as follows;

- Upstream (headwater) depth - 180 mm

- Downstream (tailwater) depth - 180 mm
- Inlet velocity - 0.61 m/s

The above criteria defined the inlet and outlet boundary conditions from which the hydraulics laboratory ANSYS CFX simulation was established. The model was simulated using the convergence and solver conditions specified in Chapter 7. All solid boundaries, i.e. walls, floor and baffles, were defined as 'smooth surfaces'.

For ease of interpretation a representative section was chosen for investigation. Baffle set 3-4 was selected for this purpose as it was least affected by the inlet and outlet therefore provided a good indication on how the culvert behaved hydraulically.

Velocity contour plots are shown in Figures 8.10 to 8.13 to demonstrate the boundary layer effect as a result of baffle fish passage devices. It is evident that flow velocities are lower adjacent to baffles when compared to velocities in the main channel flow path and that velocities increase with respect to distance from the baffles. It is also evident that the 'thickness' of the boundary layer, i.e. zone of reduced velocity, is greatest adjacent to the leg of the corner 'EL' baffle (see Figure 8.10 and 8.11). Figure 8.14 is a flow velocity contour profile taken midway along the laboratory culvert model. The boundary layer is clearly evident on the right hand side of the profile adjacent to the corner 'EL' baffles.

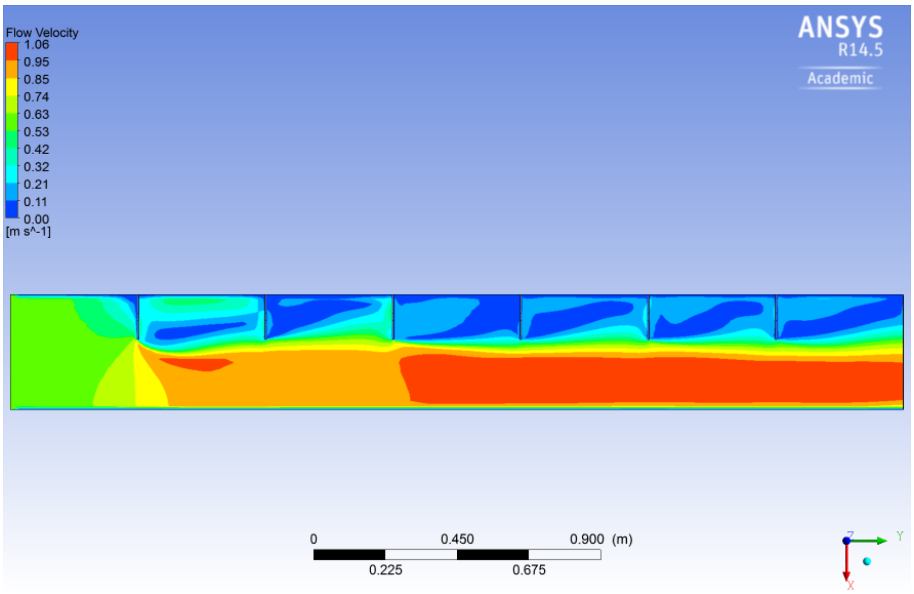

Figure 8.10: Flow velocity contour plot - laboratory model, 30 mm flow depth

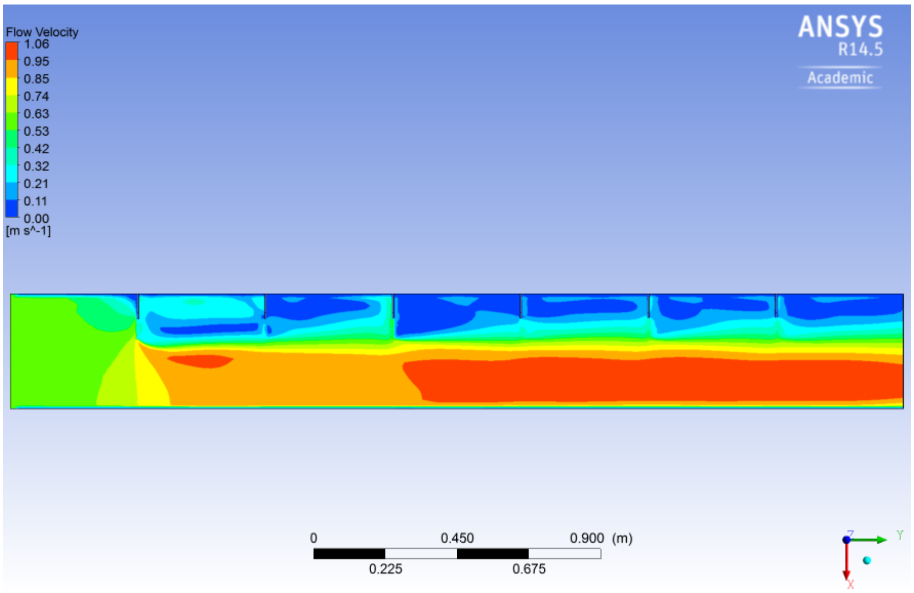

Figure 8.11: Flow velocity contour plan - laboratory model, 60 mm flow depth

Comparison of Experimental and Numerical Results

Velocity plots of the ANSYS CFX simulation results overlaying the experimental data are provided in the CFX report in Appendix D.

Flow velocity plots were produced in CFX vertically at all collection points shown in Figure 8.9 and assessed for visual correlation.

Generally very good correlation was evident in all velocity plots. The experimental data was much improved when compared to that recorded in the Discovery Drive prototype. This is assumed to be due to greater control over the measurement technique and a reduction in outside influences which may have affected the model itself.

8.2.4 Discussion of Validation Results

The validation component of this project work was deemed a successful exercise. Though experimental and numerical results were fair to satisfactory at an uncontrolled site (see Discovery Drive), the correlation was generally very good to excellent in a controlled environment (see JCU laboratory data). On this basis the correlation between experimental and numerical results was deemed acceptable therefore validating the use of ANSYS CFX as a fish passage assessment tool for 'in culvert' treatments.

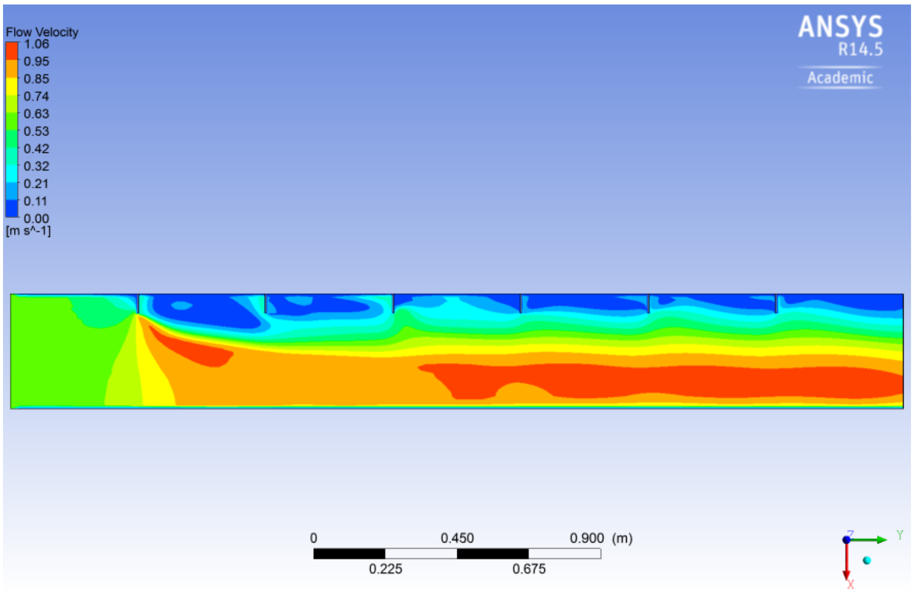

Figure 8.12: Flow velocity contour plan - laboratory model, 100 mm flow depth

It is noted that a statistical examination of the experimental and numerical data correlation was not undertaken as this was considered beyond the scope of this project and therefore potentially a follow-up investigation.

8.3 Numerical Assessment of DAFF Design Recommendations

8.3.1 Introduction

This section represents the results from the CFD modelling of the DAFF fish passage design guidelines using ANSYS CFX. The appendices contain the ANSYS CFX reports and velocity profiles for all models. Evaluation of the data is presented in Chapter 9.

8.3.2 Assumptions and Limitations

A number of common assumptions were adopted when establishing the DAFF ANSYS CFX models. They were;

- The CFD models were used to assess flow velocities only

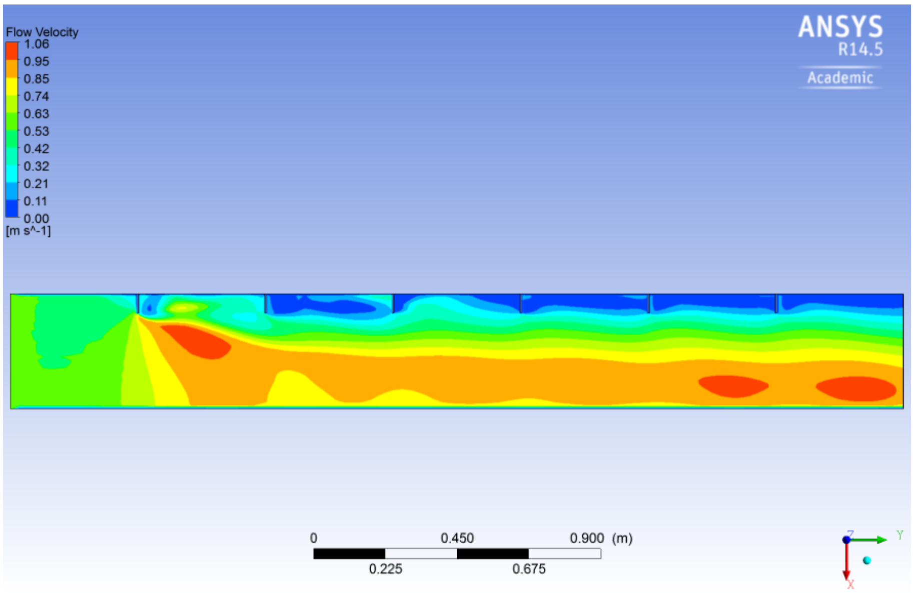

Figure 8.13: Flow velocity contour plan - laboratory model, 140 mm flow depth

- Uniform flow conditions were sought in all models to allow measurements to be made without the effects caused by hydraulic jumps and increased velocities which would otherwise become determining factors in the functionality of the DAFF designs
- A longitudinal grade of 0.5% was adopted for all models. This is applied to the upstream stream bed, the culvert barrel and the downstream stream bed
- Culvert concrete walls and wingwalls roughness value of 0.002 adopted based on small scale roughness calculations. See Chapter 7
- Stream bed and culvert floors roughness value of 0.030 adopted based on large scale roughness and the Mannings equation. See Chapter 7. This roughness value is equivalent to coarse sand (Chow 1959)
- Inlet flow velocities based on Mannings equation. See Chapter 7
- 0.90 m internal height assumed for all culvert structures
- Culvert length of 12.0 m adopted for all DAFF designs. This length allows for a typical 9.0 m wide roadway with 1 in 4 batter slopes
- Standard precast end units (headwalls) assumed for all culvert structures

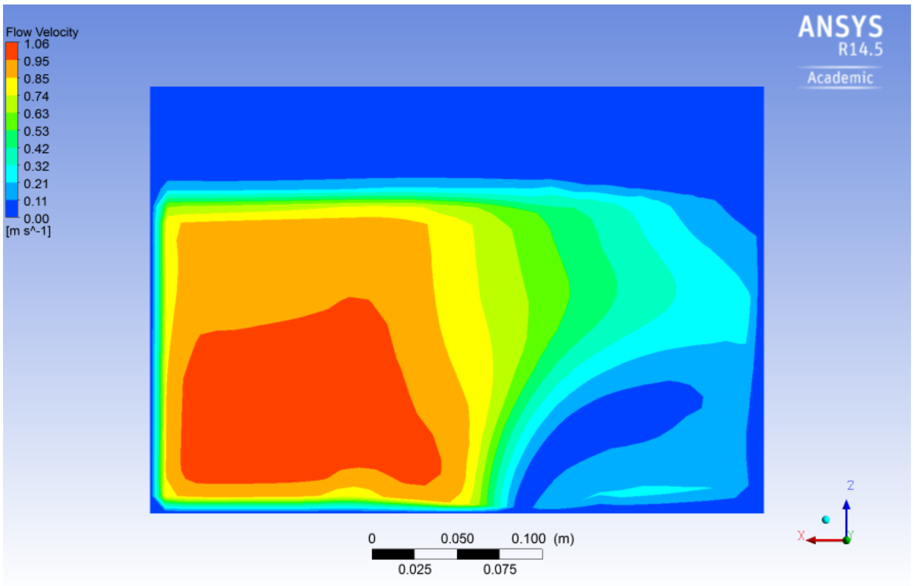

Figure 8.14: Flow velocity contour profile - laboratory model, 140 mm flow depth

8.3.3 DAFF ANSYS CFX Models

Introduction

ANSYS CFX simulations were established for the DAFF fish passage design recommendations based on the methodology outlined in Chapter 7. Each DAFF fish passage design model was simulated and assessed for two separate flow depths, 200 mm and 500 mm, representing the range in which native fish are most likely to migrate (see Chapter 4).

DAFF 'Green' Fish Passage Design Model

As discussed in Chapter 2 the DAFF Green fish passage design model comprises a single 1.20 m wide concrete culvert with an open or roughened base. A detail of this fish passage design is shown in Figure 8.15. A 3-dimensional, ANSYS CFX representation of the fish passage design model is shown in Figure 8.16.

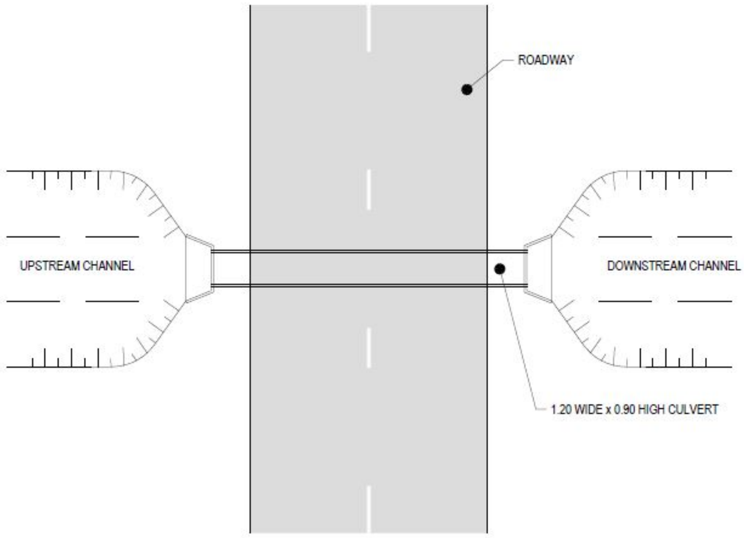

Figure 8.15: DAFF 'Green' Design Layout

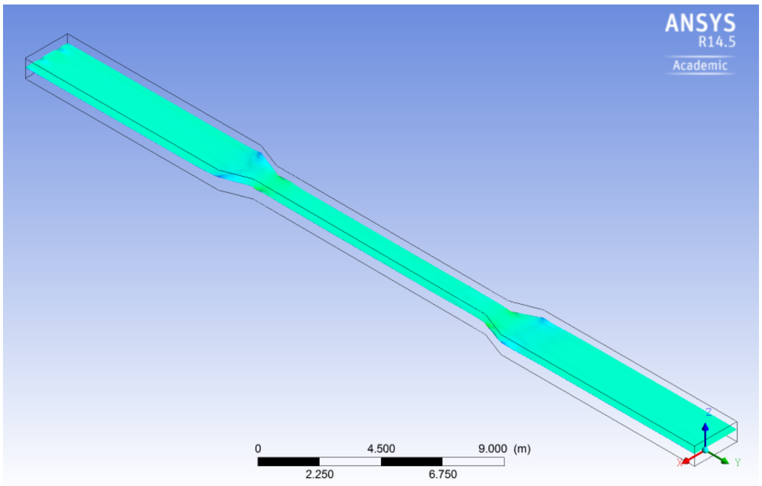

Figure 8.16: DAFF 'Green' ANSYS CFX Model

DAFF 'Amber' Fish Passage Design Model

As discussed in Chapter 2 the DAFF Amber fish passage design model comprises a single 2.40 m wide concrete culvert with an open or roughened base. A detail of this fish passage design is shown in Figure 8.17. A 3-dimensional, ANSYS CFX representation of the fish passage design model is shown in Figure 8.18.

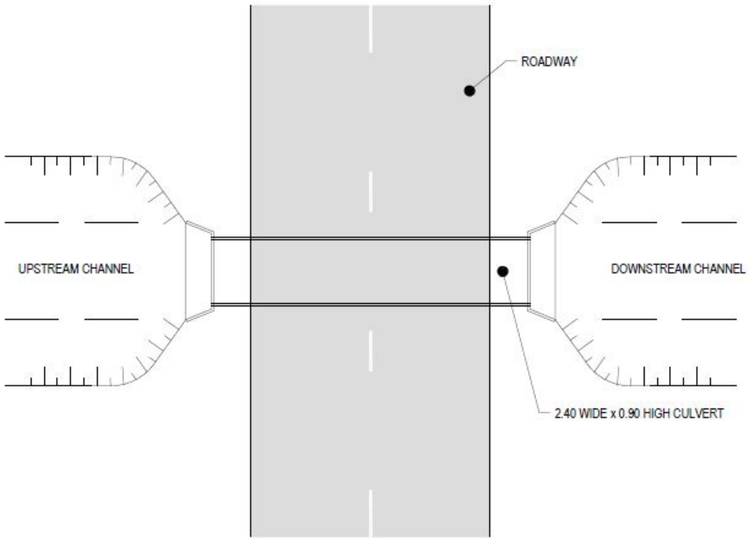

Figure 8.17: DAFF 'Amber' Design Layout

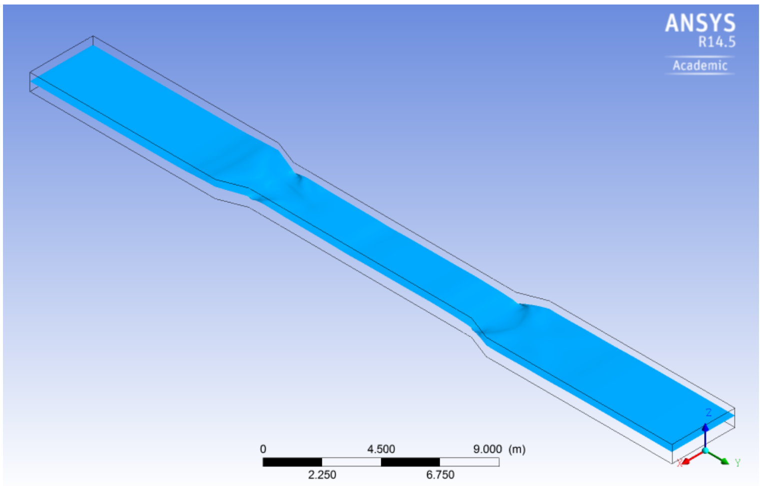

Figure 8.18: DAFF 'Amber' ANSYS CFX Model

DAFF 'Red' Fish Passage Design Model

As discussed in Chapter 2 the DAFF Red fish passage design configuration is to comprise a multi-cell culvert structure spanning a minimum of 75% of the main stream channel width. The design models in this project consist of three, 2.40 m wide concrete culvert cells with an open or roughened base. 150 mm wide steel baffles are attached to the outer walls of the culvert structure at regular spacings. A detail of this fish passage design is shown in Figure 8.19. A 3-dimensional, ANSYS CFX representation of the fish passage design model is shown in Figure 8.20. A plane of symmetry is positioned along the centre of the middle culvert cell. Refer to Chapter 2 for specific baffle details.

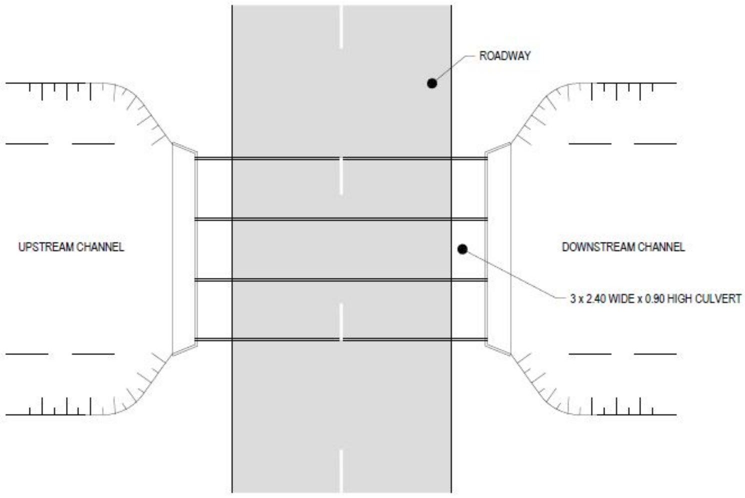

Figure 8.19: DAFF 'Red' Design Layout

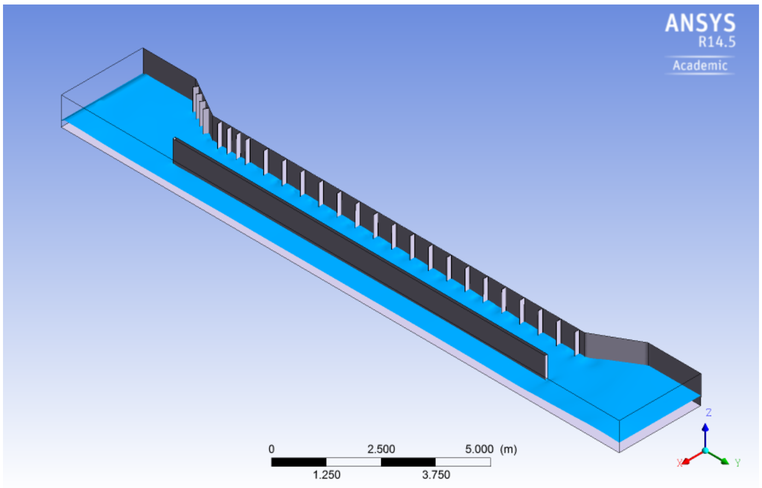

Figure 8.20: DAFF 'Red' ANSYS CFX Model

8.3.4 Results

Velocity profiles provide a numerical and visual description of the change in flow through the culverts. Velocity profile plots were taken at the collections points shown in Figure 8.21. The velocity profiles extend from the upstream channel, through the culvert barrel, and into the downstream channel therefore representing a complete velocity profile as flows enter, go through and leave the culvert structure.

Velocity profile plots are included in Appendix E, F and G and discussed further in Chapter 9.

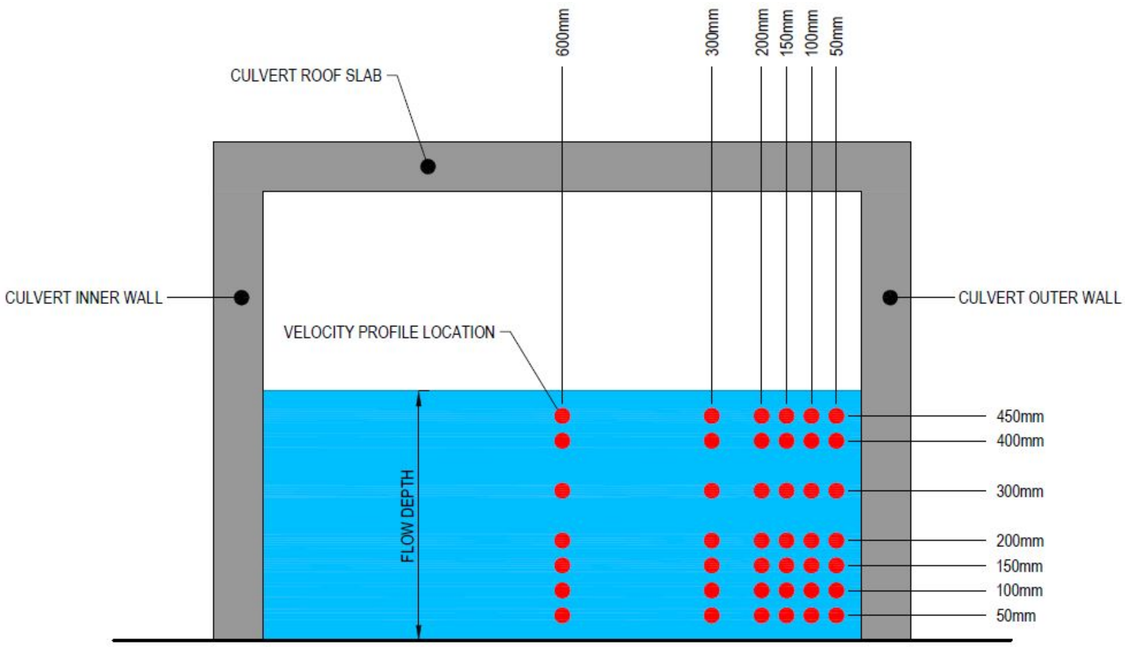

Figure 8.21: Velocity Colleciton Points

8.4 Chapter Summary

In summary, this chapter first provided the validation required to support the use of ANSYS CFX as a fish passage assessment tool and to therefore carry out an assessment of DAFF fish passage design recommendations. It is anticipated that the validation component of this chapter may form a platform for future statistical analysis of experimental and numerical fish passage assessment methods.

Following the validation of ANSYS CFX, this chapter then discussed the process used to establish the ANSYS CFX simulations for the DAFF fish passage designs. The velocity profile plot results produced by the DAFF fish passage design ANSYS CFX simulations are discussed in detail in Chapter 9.

Chapter 9

Discussion of Results

9.1 Chapter Overview

The purpose of this chapter is to discuss the velocity profile plots produced from the DAFF fish passage design ANSYS CFX simulations from Chapter 8. The discussion will assess these results against the swimming ability of native fishes of the Mary River catchment, as well as include an assessment of the DAFF fish passage designs with regards to other fish passage barriers such as hydraulic drop, resting places, culvert length, culvert width, flow depth and culvert slope. The final section of this chapter proposes recommendations aimed at optimising the current DAFF fish passage designs.

9.2 Discussion of Results

9.2.1 Introduction

This section evaluates the results presented in Chapter 8 and discusses the conclusions found. The data is assessed in terms of the fish passage requirements discused in Chapter 4 and the assumed swimming ability of fish species of the Mary River catchment discussed in Chapter 3. The assessment is undertaken to gain an understanding of how effective the DAFF fish passage designs are in comparison to what was observed in the ANSYS CFX numerical modelling.

General comments are first presented with regards to fish passage concepts common to all DAFF fish passage design configurations. Each DAFF fish passage design is assessed based on flow velocity and recommendations for improvement are provided where possible.

Flow turbulence was not assessed as part of this research project.

9.2.2 General Comments

All DAFF designs were assessed based on 12.0 m standard length, 0.5% slope and culvert widths in accordance with the DAFF recommended culvert configurations.

Culvert Width

The culvert width requirement for all culverts was considered adequate, however each caused increased flow velocities at the culvert inlet as a result of the sudden flow width contraction. This is discussed further in Section 9.2.3.

Culvert Slope

Constant bed slope of 0.5% is maintained from upstream channel to downstream channel in accordance with WWBW01 guidelines. A slope of 0.5% is considered consistent with similar structures encountered within the field and is within the acceptable limits for stormwater drainage culvert design (Department of Energy & Water Supply (DEWS) 2013). It is noted that 0.5% bed slope does not create flow velocities which may impede fish passage along the outer edges of the upstream and downstream stream channels.

Culvert Length

Culvert length is an area of concern which is discused in more detail in the following sections. In both the Green and Amber design scenarios the flow velocities combined with culvert length produce conditions which may restrict fish movement throughout the culvert structure. As stated in Chapter 4 a lack of resting places within culverts can create a fish passage barrier where velocities are in excess of the fish swimming ability.

Hydraulic Drop

Hydraulic drop does not create fish passage issues for any of the DAFF designs. As discussesd in Chapter 4 all DAFF design configurations must incorporate a continuous stream bed profile from upstream channel, through culvert barrel, and into downstream channel. Culverts are placed on the existing stream bed therefore no sudden changes in culvert or bed level are introduced as a result of the DAFF design configurations.

9.2.3 Flow Velocity

The velocity results of the ANSYS CFX simulations for DAFF fish passage designs are included in Appendix E, F and G.

Assessment Criteria

As discussed in chapter 4 the maximum (burst) swim speed of small fish is 0.3 m/s for juveniles and 0.6 m/s for adults. These maximum velocities are used to assess the adequacy of the DAFF fish passage designs. Equation 9.1 (Kapitzke 2010) can be used to calculate the maximum distance small fish can travel for both burst and prolonged swim speed under increasing flow velocities. Refer to Figure 9.1 and 9.2 for charts of maximum swim distance due to flow velocity. It is noted that flow velocities must be less than maximum swim speed should the fish theoretically progress upstream against the direction of flow.

$$X = (U - V)\, t_m \tag{9.1}$$

where X is the distance travelled (m), U is the maximum swim speed of fish, V is stream flow velocity and t_m is burst or prolonged swim speed time (5 or 20 seconds).

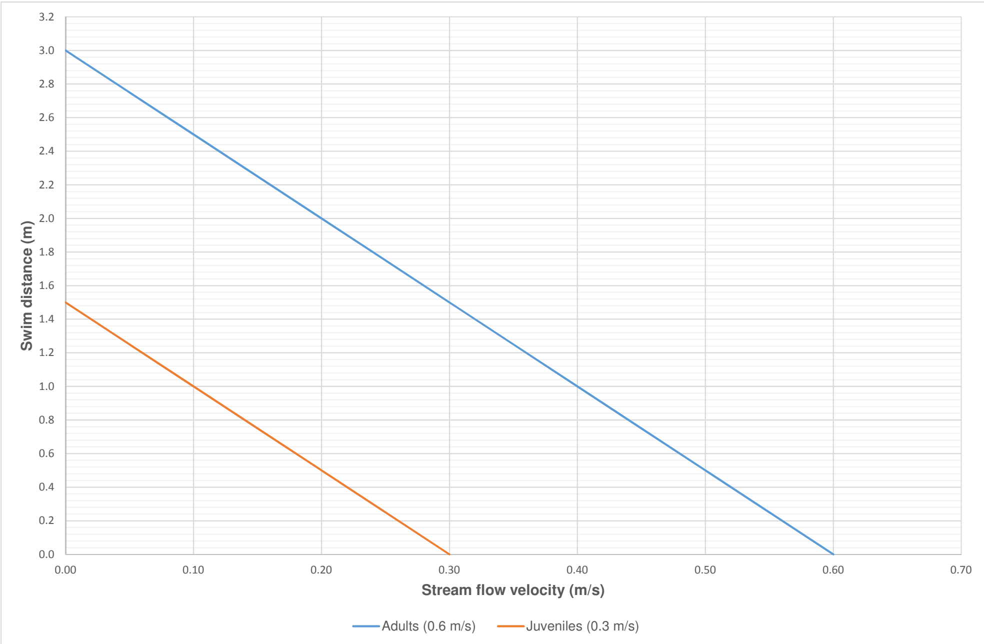

Figure 9.1: Stream flow velocity and distance travelled - Burst swim speed

DAFF 'Green' and 'Amber' Fish Passage Designs

The DAFF 'Green' and 'Amber' fish passage designs presented similar velocity results therefore are assessed concurrently.

As stated in the previous section, the reduction in flow width at the culvert inlet causes an increase in flow velocities as a result of the sudden flow width contraction. It is noted that for both the 200 mm and 500 mm flow depth simulations, the flow velocities are in the order of twice that within the upstream channel, well above what is deemed acceptable for movement of small fish species. Refer to Figure 9.3 and Figure 9.4 for ANSYS CFX contour planes of flow velocities for 500 mm and 200 mm flow depths. The contour planes are taken at mid-flow depth and represent the average flow velocity within the simulation.

A contour plan and cross section of flow velocity at the inlet of the culvert further emphasises the barrier to fish passage created at this location.

It is noted that a boundary layer of low flow velocity is evident along the base of the

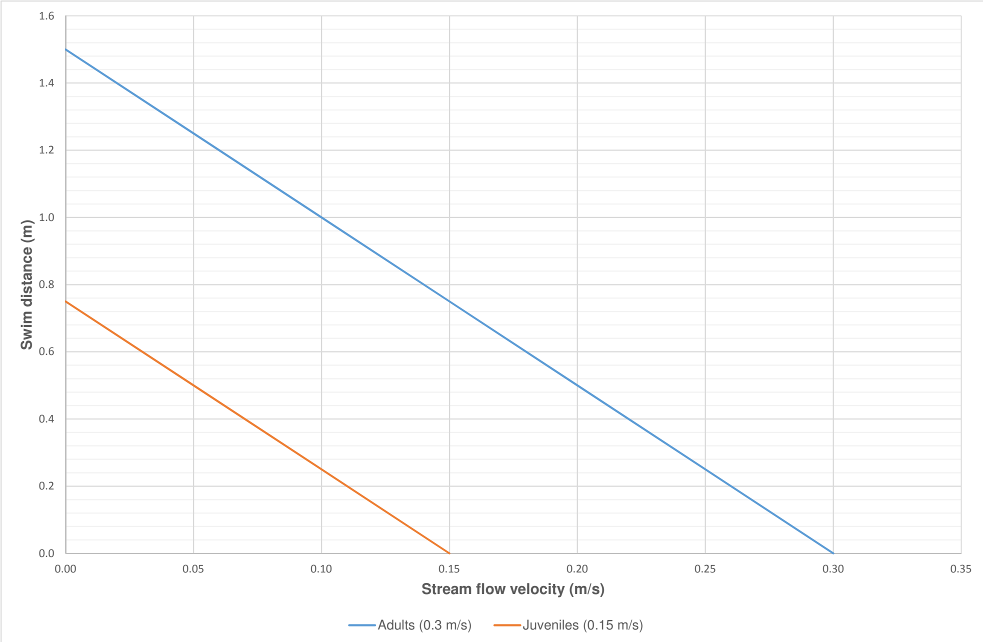

Figure 9.2: Stream flow velocity and distance travelled - Prolonged swim speed

culvert (see Figure 9.6). The velocities in this region could be considered satisfactory, however the thickness of the boundary layer (less than 50 mm) combined with a lack of resting places within the culvert barrel create unsuitable conditions for fish passage.

As stated previously, for fish to theoretically progress upstream, against the direction of flow, the water flow velocities must be less than the maximum swim speed of the fish. It is clearly evident from Figure 9.1 and 9.2 that the length of Green and Amber culverts are too great for fish to pass through without becoming fatigued. It is assumed that the provision of resting places may create improved conditions.

DAFF 'Red' Fish Passage Design

The DAFF 'Red' fish passage design presents a very different and much improved scenario for fish passage. This improvement is primarily due to the addition of baffles within the culvert barrel and at the inlet headwall.

The baffles create a large-scale roughening along the outer wall, and as a result a thicker boundary layer is developed and flow velocities reduced. Refer to Figure 9.7,

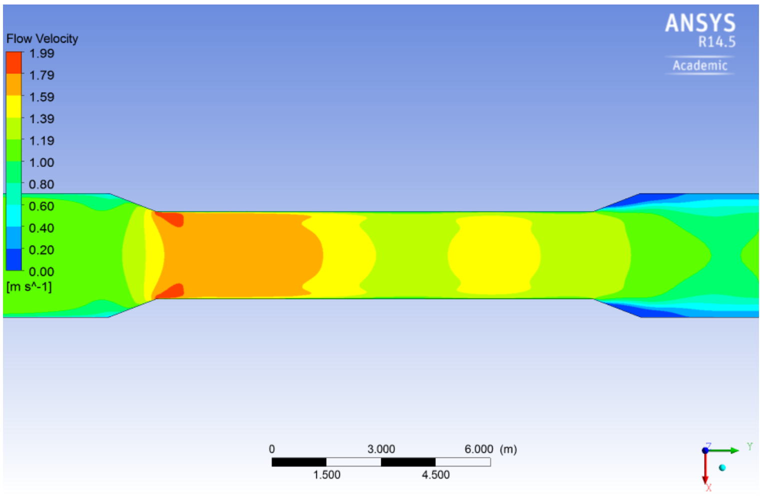

Figure 9.3: Average Flow Velocity - DAFF 'Amber' Design, 500 mm flow depth

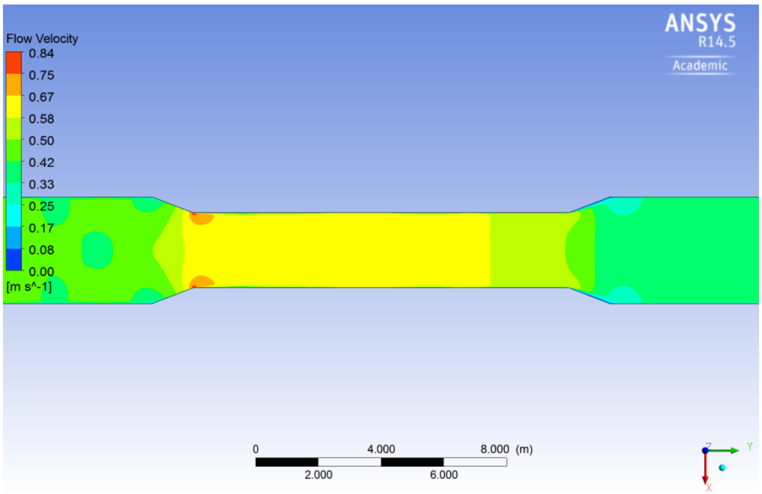

Figure 9.4: Average Flow Velocity - DAFF 'Amber' Design, 200 mm flow depth

9.8, 9.9 and 9.10 for contour plots of the DAFF Red ANSYS CFX design model. The 500 mm flow depth model is presented as higher flow velocities were produced in this scenario. The boundary layer of reduced flow velocity is evident along the outer edge of the culvert adjacent to the baffles. This zone extends from the upstream channel, through the culvert barrel and into the downstream channel. Sections are taken at the inlet, mid-culvert and at the outlet to highlight the boundary layer and reduced flow velocities as a result of the barrels.

The flow velocities along the outer edge of the culvert are between zero and 0.25 m/s therefore falling within flow velocities which can be negotiated by small fish species. It should also be noted that at 600 mm spacing (see Chapter 2), the baffles provide resting places at intervals which satisfy the swimming ability and rest requirements of

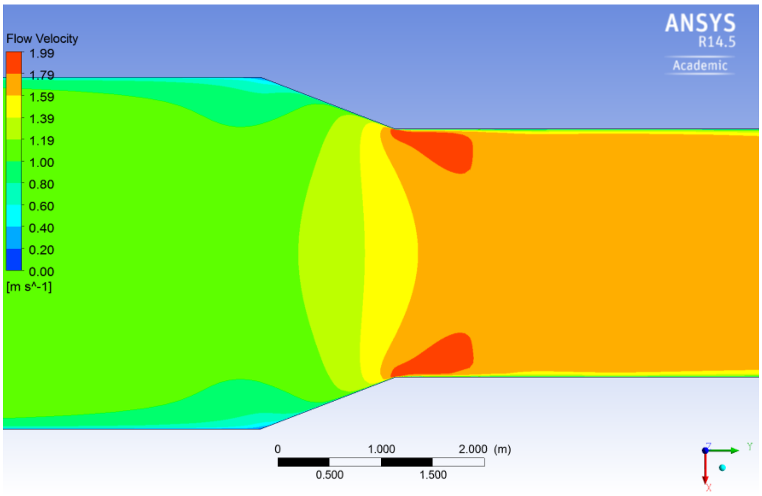

Figure 9.5: Flow Velocity - DAFF ‘Red’ Design culvert inlet, 500 mm flow depth

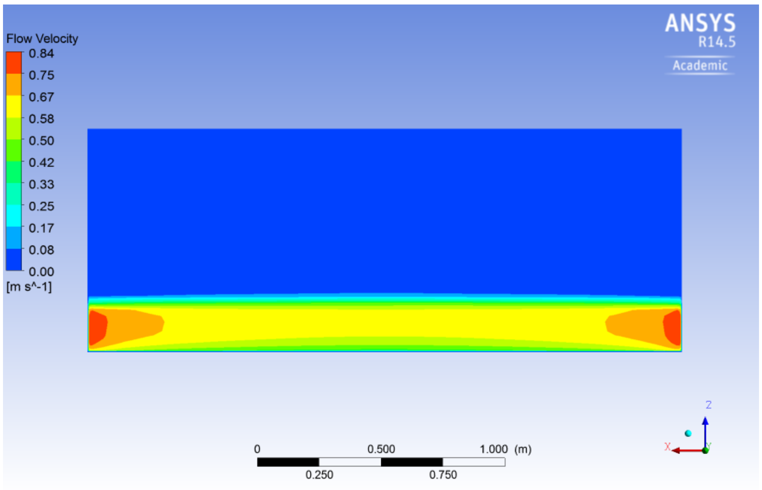

Figure 9.6: Flow Velocity - DAFF ‘Red’ Design culvert inlet, 200 mm flow depth

both adult and juvenile fish (see Figure 9.1).

An area of some concern however is the ‘pinch point’ at the culvert inlet. The velocity profile plots in Appendix G show a sudden increase in flow velocity at this location. See Figure 9.11 for an example of this flow increase. The ANSYS CFX model illustrates that at 100 mm offset from the outer wall, the flows upstream of the inlet are within acceptable velocities, the flow then suddenly increases to values much higher than acceptable, then reduces to below acceptable values. Figure 9.12 demonstrates why this is occuring.

The sudden increase in flow velocity at the culvert inlet is due to the narrowing of the boundary layer as a result of the placement and spacing of baffles upstream and downstream of this location. The boundary layer is still quite evident, and assumed

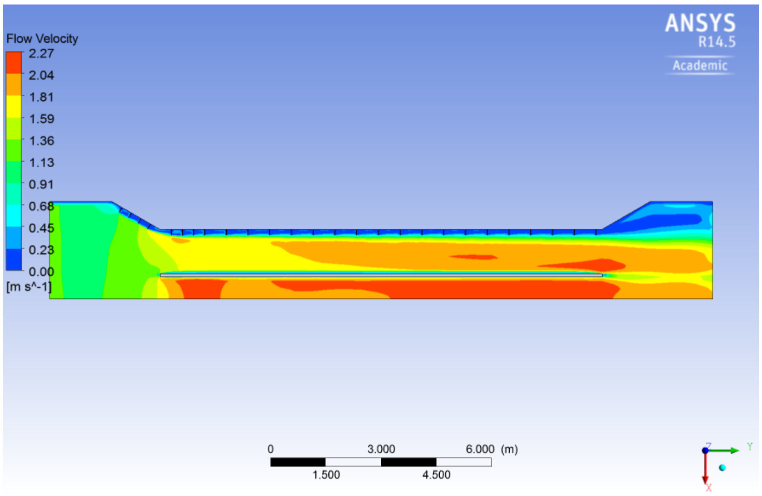

Figure 9.7: Average Flow Velocity - DAFF 'Red' Design, 500 mm flow depth

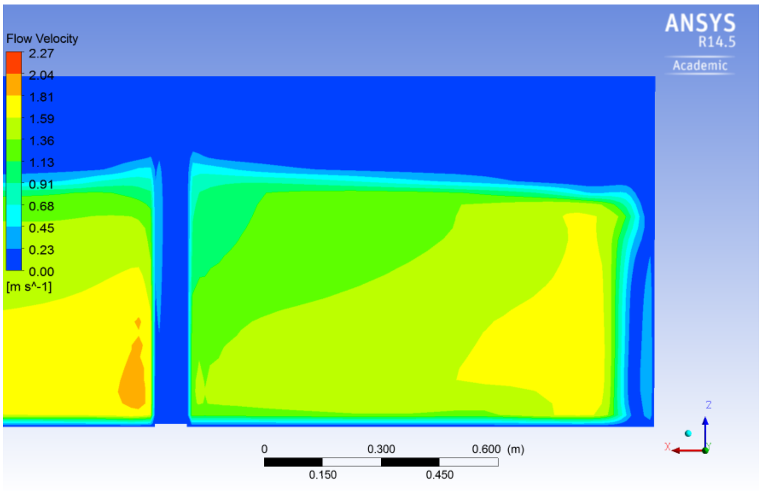

Figure 9.8: Flow Velocity - DAFF 'Red' Design culvert inlet, 500 mm flow depth

wide enough for small fish to use, however is approximately 50 mm less in width at the culvert inlet. Reconfiguration of the baffle placement and/or spacing at this location may produce a more consistent boundary layer width.

9.3 Recommendations

The ANSYS CFX simulations demonstrate that the DAFF designs require further development in order to completely satisfy the fish passage requirements for native fish species of the Mary River catchment. Several recommendations were established which may facilitate improved results for fish passage. It is noted that the below recommendations are yet to be tested.

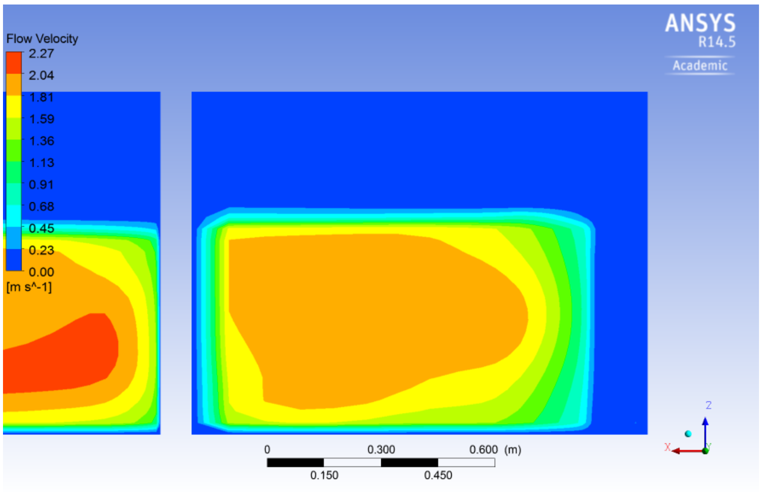

Figure 9.9: Flow Velocity - DAFF 'Red' Design mid-culvert, 500 mm flow depth

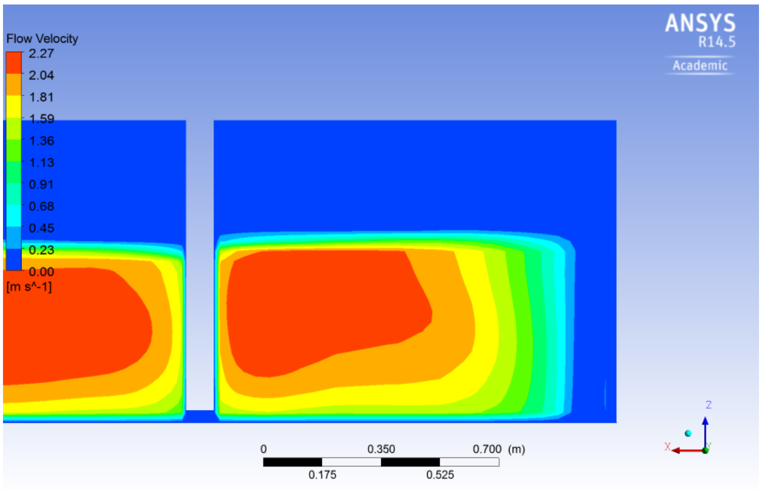

Figure 9.10: Flow Velocity - DAFF 'Red' Design culvert outlet, 500 mm flow depth

Several recommendations for further investigation into the improvement of DAFF fish passage designs have been established and are summarised below.

Trial baffles in all culverts

It is anticipated that the inclusion of baffles within the Green and Amber designs will result in flow velocities similar to those witnessed in the Red design models. It is therefore assumed that baffles will improve the conditions for fish passage in the Green and Amber design models.

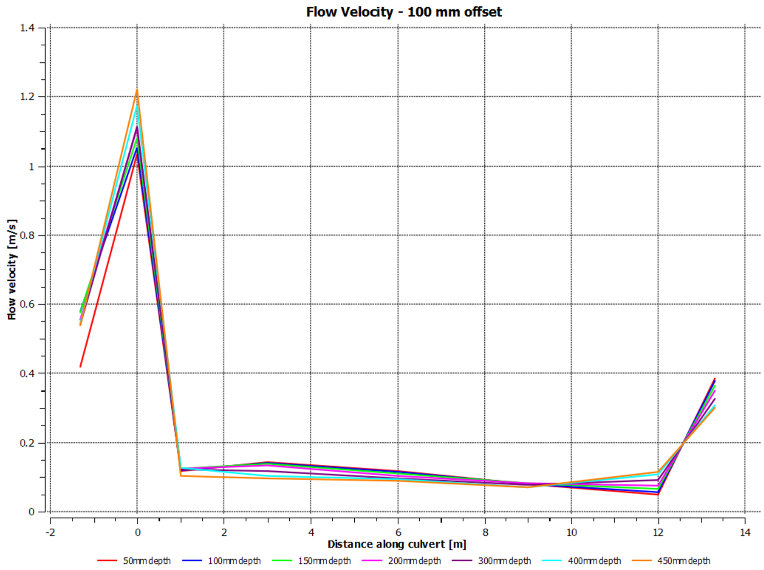

Figure 9.11: Flow Velocity Profiles - DAFF 'Red' Design, 100 mm offset from outer wall

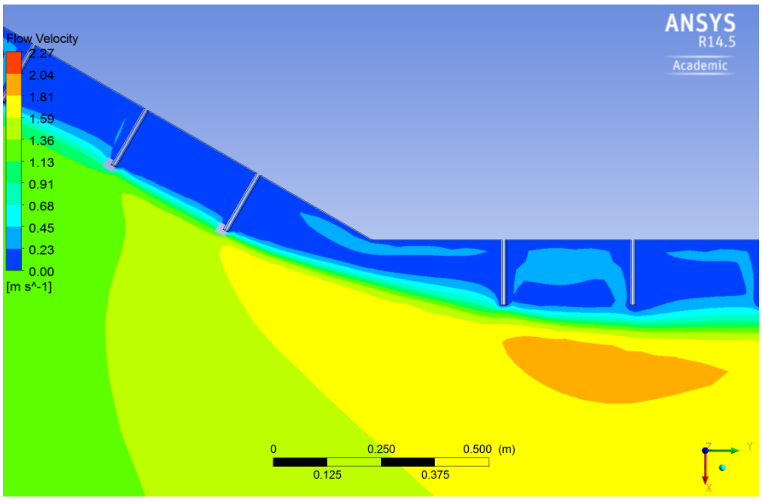

Figure 9.12: Average Flow Velocity - DAFF 'Red' Design culvert inlet, 500 mm flow depth

Trial different stream bed roughness values

The limitations of ANSYS CFX software meant that a conservative value for stream bed roughness was applied to all DAFF design CFD models. By implementing the porous body method (see Chapter 6) it is anticipated that larger stream bed roughening elements can be tested. Larger stream bed roughening elements i.e. rocks may produce both reduced flow velocities and resting places along the culvert floor of Green and Amber designs.

Trial different baffle spacing and baffle placement at the culvert inlet

The spacing and positioning of baffles may be refined to further improve the fish passage conditions in the Red design. It is anticipated that a more consistent boundary layer thickness may be achieved as a result of this refinement.

9.4 Chapter Summary

In summary this chapter provided a discussion of the results from the DAFF fish passage design ANSYS CFX models. All designs generally produced results which are acceptable in terms of culvert length, width, slope and hydtraulic drops. It was found however that the Green and Amber models did not produce flow velocities which were consistent with the requirements for fish species of the Mary River catchment. The DAFF Red design model produced satisfactory flow velocities results and, with some refinement, may be considered acceptable in its current form.

Chapter 10

Conclusions

10.1 Achievement of Project Objectives

Waterway barriers have been constructed on waterways throughout Queensland and in many cases have created physical barriers to fish migration resulting in the decline of native fish stocks. Through literary research, software validation and finally assessment of the Department of Agriculture, Fisheries and Forestry self-assessable code, WWBW01: Minor waterway barriers Part 3: Culverts, this project was able to assess the DAFF design recommendations in terms of the swimming ability of the native freshwater fish species likely to occur in minor waterways within the Mary River catchment.

In undertaking this project work the following objectives have been addressed;

Assessment of the DAFF self-assessable code WWBW01 fish passage designs using computational fluid dynamics software

ANSYS CFX was used to assess the DAFF self-assessable code WWBW01 Green, Amber and Red fish passage designs in terms of fish passage concepts and the swimming ability of native fish species of the Mary River catchment.

The DAFF minor water waterway barrier works guidelines provide general requirements for facilitating fish passage through waterway barriers, however the requirements are not region or site specific therefore are not suitable to all situations and conditions.

The assessment found that the Green and Amber fish passage designs do not produce hydraulic conditions which are conducive to the movement of small native fish species likely to exist in the Green and Amber stream classifications. The Red fish passage design does however produce hydraulic conditions which facilitate the movement of small native fish species.

Several design recommendations were established as part of the assessment as a means to improve the fish passage conditions for use in the Mary River catchment. These recommendations are deemed suitable for future investigation.

Validation of computational fluid dynamics software as a fish passage design tool

Experimental data obtained from James Cook University was used to validate ANSYS CFX computational fluid dynamics software as a fish passage assessment tool. Good to excellent correlation was found to exist between the experimental and numerical data therefore validating the use of ANSYS CFX.

Obtain understanding of DAFF requirements

A thorough review was undertaken of the DAFF self-assessable code WWBW01: Minor waterway barrier works - Part 3: culvert crossings to determine the legislative requirements for minor waterway barrier works in Queensland.

Obtain general knowledge of native freshwater fishes of the Mary River catchment

Fauna surveys of the Mary River catchment were used to develop a list of freshwater fish species endemic to the region.

Obtain undertstanding of fish swim ability

Previous work by fish passage professionals suchs as Kapitzke, Cotterell and Mallen-Cooper were used to develop measurable swim requirements of native freshwater fishes of the Mary River catchment. The work focused on smaller fish species most likely to exist in minor freshwater streams.

Obtain general understanding of fluid mechanics and the boundary layer theory

A general review of fluid mechanics, hydraulic design, open channel and boundary layer theory was undertaken to obtain an understanding of the theoretical component of fluid modelling.

Establish networks with other environmental professionals

Representatives of DAFF and James Cook University were approached at various stages throughout this project to obtain a better understanding of fish passage concepts, the Mary River catchment area and the requirements of the WWBW01 self-assessable code. It is anticipated that these contacts will help form the basis of future work within the field.

10.2 Further Work

The assessment of the fish passage design recommendations of WWBW01 are far from complete. The assessment carried out as part of Chapter 8 and 9 highlighted several areas of further testing which are to be undertaken before suitable recommendations can be presented to the Department of Agriculture, Fisheries and Forestry. Areas of further work include;

- Complete further CFD modelling of the DAFF fish passage designs and assess flow velocities produced due to the following investigations
    - Larger roughening elements on the stream and culvert floor

  - Inclusion of baffles within the Green and Amber fish passage design models
  - Refined baffle spacing and positioning

- Assessment of hydraulic efficiency due to baffle installation
- Assessment of the construction cost implications of installing baffles in all DAFF fish passage designs
- Present findings to the Department of Agriculture, Fisheries and Forestry
- Further collaboration with Mr Ross Kapitzke of James Cook University

10.3 Closing Statement

The assessment of the DAFF self-assessable code WWBW01 was a topic of great interest. This project work was not only a benefit towards my engineering tertiary studies but my interest in fish passage engineering as a future employment pathway. It is anticipated that the knowledge and understanding obtained from this project work may be used in future to assist both colleagues and clients make improved design decisions when developing engineering solutions to fish passage issues.

References

Allen, G. R., Midgley, S. H. & Allen, M. (2002), *Field Guide to the Freshwater Fishes of Australia*, Western Australian Museum, Perth.

Anderson Jr, J. D., Degroote, J., Degrez, G., Dick, E., Grundmann, R. & Vierendeels, J. (2009), *Computational Fluid Dynamics - An Introduction*, 3rd edn, Springer, Berlin.

ANSYS Incorporated (2010), 'Ansys cfx', `http://www.ansys.com/staticassets/ANSYS/staticassets/resourcelibrary/brochure/`.

ANSYS Incorporated (2012), *CFX-Solver Theory Guide*.

Australian Museum (2013), 'Fishes', http://australianmuseum.net.au/Fishes/.

Bakker, A. (2008), 'Extensive multiphase flow capabilities', *ANSYS Advantage* **2**(4).

Bates, K. (1999), *Fish Passage Design at Road Culverts*, Washington Department of Fish and Wildlife, Washington.

Behlke, C. E., Kane, D. L., McLean, R. F. & Travis, M. D. (1989), 'Field observations of arctic grayling passage through highway culverts', *Transportation Research Record* **1224**, 63–66.

Berghuis, A. (2000), 'The establishment of fish passage over man-made barriers to facilitate the restoration of the historical range of freshwater fish species in southern queensland.', *Hydro 2000: Interactive Hydrology; Proceedings* pp. 842–847.

Blank, M. D. (2008), Advanced studies of fish passage through culverts.

Boubee, J., Jowett, I., Nichols, S. & Williams, E. (1999), *Fish Passage at Culverts - A review, with possible solutions for New Zealand indigenous species*, New Zealand Department of Conservation, Wellington.

Carney, S. K., Bledsoe, B. P. & Gessler, D. (2006), 'Representing the bed roughness of coarse-grained streams in computational fluid dynamics', *Earth Surface Processes and Landforms* **31**, 736–749.

Chadwick, A. & Morfett, J. (1998), *Hydraulics in Civil and Environmental Engineering*, 3rd edn, E and FN Spon, London.

Chanson, H. (2004), *The Hydraulics of Open Channel Flow: An Introduction*, 2nd edn, Elsevier Butterworth-Heinemann, Oxford.

Chow, T. E. (1959), *Open Channel Hydraulics*, McGraw Hill, New York.

Copeland, T., Johnson, J. & Bunn, P. (2004), *Natural Production Monitoring and Evaluation; Idaho Department of Fish and Game, 2003-2004 Annual Report*, Idaho Department of Fish and Game, Boise.

Cotterell, E. (1998), *Fish Passage in Streams*, Queensland Department of Primary Industries, Brisbane.

Delaere, L., Stuart, I., Ewing, T. & Marsh, D. (2011), Burrum weir fishway - fish biology and river flows: Two faces.

Department of Energy & Water Supply (DEWS) (2013), *Queensland Urban Drainage Manual*, 3rd edn, Brisbane.

Department of Natural Resources (DNR), Q. (2013), 'Mary River Catchment Locality', `http://www.mrccc.org.au/downloads/maps/`.

Department of Transport & Main Roads (DTMR) (2002), *Road Drainage Manual*.

Department of Transport & Main Roads (DTMR) (2010), *Fauna Sensitive Road Design Manual*, Brisbane.

Doehring, K., Young, R. G. & McIntosh, A. R. (2011), 'Factors affecting juvenile galaxiid fish passage at culverts', *Marine and Freshwater Research* **62**, 38–45.

Engineers Australia (EA) (2010), 'Our code of ethics', `http://www.engineersaustralia.org.au/sites/default/files/shado/About%20Us/Overview/Governance/`.

Featherstone, R. E. & Nalluri, C. (1995), *Civil Engineering Hydraulics*, 3rd edn, Blackwell Science Ltd, Oxford.

Fenton, J. (2005), *Open channel hydraulics*, University of Melbourne, Melbourne.

Ferrando, T. (2006), Performance characteristics of offset baffle and corner baffle fishways for box culverts.

Ferreira, E. A. C., Dimakopoulos, A. S. & Ferreira, R. M. L. (2011), 'Cfd modeling of rought-bed open-channel flows', *Congress on Numberical Methods in Engineering* .

Feurich, R., Boubee, J. & Olsen, N. R. B. (2012), 'Improvement of fish passage in culverts using cfd', *Ecological Engineering* **47**, 1–8.

Gibson, J. R., Haedrich, R. L. & Wernerheim, C. M. (2005), 'Loss of fish habitat as a consequence of inappropriately constructed stream crossings', *Fisheries* **30**(1), 10–17.

Hey, R. D. (1979), 'Flow resistance in gravel-bed rivers', *Journal of the Hydraulics Division* **105**, 365–379.

Hirt, C. W. & Nichols, B. D. (1981), 'Volume of fluid (vof) method for the dynamics of free boundaries', *Journal of Computational Physics* **39**, 201–225.

Hotchkiss, R. H. & Frei, C. (2007), *Design for fish passage at roadway-stream crossings: Synthesis report*, Federal Highway Administration, Virginia.

Hyde, V. B. (2007), 'Civil engineering for passage of fish and fauna', *Australian Journal of Water Resources* **11**(2), 193–206.

Institute of Engineers (IE) (1997), *Towards sustainable engineering practice: engineering frameworks for sustainability*, Canberra.

International Association for the Engineering Modelling, A. & Simulation Community (NAFEMS) (2013), 'What is convergence?', http://www.nafems.org/resources/cfdconvergence/Page0/.

Kapitzke, R. (2007), *University Creek Prototype Culvert Fishways*, James Cook University, Townsville.

Kapitzke, R. (2008), *Burnett Mary Regional Biopass Strategy - Splitters Creek*, James Cook University, Townsville.

Kapitzke, R. (2010), *Culvert Fishway Planning and Design Guidelines*, James Cook University, Townsville. `http://www.jcu.edu.au/fishpassagedesign/public/groups/.../jcuprd1_053872.pdf`.

Katopodis, C. & Williams, J. G. (2012), 'The development of fish passage research in a historical context', *Ecological Engineering* **48**, 8–18.

Launder, B. E. & Spalding, D. B. (1974), 'The numerical computation of turbulent flow', *Computer Methods in Applied Mechanics and Engineering* **3**, 269–289.

Lesieur, M. (1994), *La Turbulence (The Turbulence)*, Collection Grenoble Sciences, France.

Mallen-Cooper, M. (1996), Fishways and freshwater fish migration in south-eastern australia.

Mallen-Cooper, M. (2001), 'Fish passage in off-channel habitats of the lower river murray'.

Mary River Catchment Committee (MRCC) (2013), 'A History of the Mary River Catchment', `http://www.mrccc.org.au/downloads/publications/`.

McDowall, R. (1980), *Freshwater Fishes of South-Eastern Australia*, Reed Books, Chatswood.

Nicholas, A. P. (2001), 'Computational flud dynamics modelling of boundary roughness in gravel bed rivers: an investigation of the effects of random variability in bed elevation', *Earth Surface Processes and Landforms* **26**, 345–362.

Nicholas, A. P. (2005), 'Roughness parameterization in cfd modelling of gravel bed rivers', *Computational Fluid Dynamics: Applications in Environmental Hydraulics* pp. 329–355.

O'Brien, T., Perera, S. & Lewis, B. (1999), Providing for fish passage at small instream structures, Technical report, Department of Natural Resources and Environment, Victoria.

Olsen, N. R. B. & Stokseth, S. (1995), 'Three-dimensional numerical modelling of water flow in a river with large bed roughness', *Journal of Hydraulic Research* **33**, 571–581.

Powers, P. & Osborn, J. (1986), *Analysis of barriers to upstream fish migration*, U.S. Department of Energy, Portland.

Prandtl, L. (1904), 'On the motion of fluids of very small viscosity', *International Congress of Mathematicians* **3**, 481–491.

Price, P. & Lovett, S. (2002), 'Managing riparian land - fact sheet 1', `http://lwa.gov.au/files/products/river-landscapes/`, Canberra.

Queensland Department of Agriculture, F. & Forestry (DAFF) (2013*a*), 'About Us – Agriculture, Fisheries and Forestry – Queensland Goverment', `http://www.daff.qld.gov.au/31.htm`. [Online; accessed April-2013].

Queensland Department of Agriculture, F. & Forestry (DAFF) (2013*b*), *Code for self-assessable development – Minor waterway barrier works – Part 3: culvert crossings*.

Queensland Department of Agriculture, F. & Forestry (DAFF) (2013*c*), *Guide for the determination of waterways using the spatial data layer Queensland waterways for waterway barrier works*.

Queensland Government (2012), 'Fisheries act 1994', `http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/F/FisherA94.pdf`.

Rameshwaran, P., Naden, P. S. & Lawless, M. (2011), 'Flow modelling in gravel-bed rivers: rethinking the bottom boundary condition', *Earth Surface Processes and Landforms* **36**, 1350–1366.

Sinclair Knight Merz (SKM) (2006), *Traveston Crossing Dam - Environmental Impact Statement*, Sinclair Knight Merz, Brisbane.

Stockwell, B., Hutchison, M., Wedlock, B. & Ford, E. (2004), Freshwater aquatic biodiversity in the burnett mary region, Technical report, Department of Primary Industries and Fisheries.

Streeter, V. L. & Wylie, E. B. (1975), *Fluid Mechanics*, 6th edn, McGraw-Hill, London.

United States Geological Survey Water (USGSW) (2013), 'Guide for selecting manning's roughness coefficients for natural channels and flood plains', http://library.usgs.gov.

University of Birmingham (UB) (2013), 'Cfx pre', https://intranet.birmingham.ac.uk/.

Versteeg, H. K. & Malalasekera, W. (2007), *The Hydraulics of Open Channel Flow: An Introduction*, 2nd edn, Pearson Education Limited, Essex.

Wilson, N. R. & Shaw, R. H. (1977), 'A higher order closure model for canopy flow', *Journal of Applied Meteorology* **16**, 1197–1205.

Appendix A

Project Specification

ENG 4111/2 Research Project

Project Specification

For:	**Simon Petersen**
Topic:	In-culvert roughening treatments for fish passage in the Fraser Coast region
Supervisors:	Dr. Ruth Mossad
Sponsorship:	Faculty of Engineering & Surveying
Project Aim:	To investigate in-culvert roughening treatments as recommended by the self-assessable development code, 'WWBW01: Minor waterway barrier works Part 3: Culverts' and evaluate for fish species of the Fraser Coast region

Program: Issue B, 26^{th} March 2013

1. Research background information regarding aquatic fauna endemic to the Fraser Coast region, aquatic fauna passage, fluid boundary layer dynamics, basic stormwater drainage design and computational fluid dynamics modelling software options.
2. Critically examine the Queensland Government Department of Agriculture, Fisheries and Forestry code for self-assessable development for waterway barrier works 'WWBW01: Minor waterway barrier works Part 3: Culverts', extract recommended in-culvert roughening treatments and establish typical base scenario.
3. Establish computer model of base scenario and undertake computational fluid dynamic modelling of in-culvert roughening treatments using adopted computer modelling software.
4. Evaluate in-culvert roughening treatments based on criteria such as fish passage compliance, hydraulic effectiveness, maintainability and cost.
5. Submit an academic dissertation on the research.

As time and resources permit:

1. Design an improved in-culvert roughening treatment by refining a selected option.
2. Present results of research to Fraser Coast Regional Council.

Agreed:

Student Name:
Date:

Supervisor Name:
Date:

Examiner/Co-Examiner:
Date:

Appendix B

Fishes of the Mary River Catchment

Common name	Family, species	Life cycle	Comments
Basses and cods	*Percichthydidae*		
Mary River cod	*Maccullochella peelii mariensis*	Potamodromous	Threatened; recreational
Golden perch	*Macquaria ambigua*	Potamodromous	Recreational; translocated; fish stocking
Australian bass	*Macquaria novemaculeata*	Catadromous	Recreational
Blue-eyes	*Pseudomugilidae*		
Pacific blue-eye	*Psuedomugil signifer*	Potamodromous	
Cardinalfishes	*Apogonidae*		
Mouth almighty	*Glossamia aprion*	Potamodromous	
Cyprinids	*Cyprinidae*		
Carp	*Cyprinus carpio*	Amphidromous	Exotic/introduced
Diamondfishes	*Monodactylidae*		
Diamond fish	*Monodactylus argenteus*	Amphidromous	Estuary only post barrage construction
Eels	*Anguillidae*		
Short-finned eel	*Anguilla australis*	Catadromous	
Long-finned eel	*Anguilla reinhardtii*	Catadromous	
Eel-tailed catfish	*Plotosidae*		
Hyrtl's tandan	*Neosilurus hyrtlii*	Potamodromous	
Rendahls catfish	*Porochilus rendahli*	Potamodromous	
Eel-tailed catfish	*Tandanus tandanus*	Potamodromous	Recreational
Flagtails	*Kuhliidae*		
Jungle perch	*Kuhlia rupestris*	Catadromous	Recreational; estuary only post barrage construction
Flathead	*Platycephalidae*		

Common name	Family, species	Life cycle	Comments
Dusky flathead	*Platycephalus fuscus*	Amphidromous	Recreational; commercial; estuary only post barrage construction
Fork-tailed catfish	*Ariidae*		
Fork-tailed catfish	*Arius graeffei*	Potamodromous	
Garfishes	*Hemiramphidae*		
Snub-nosed garfish	*Arrhamphus sclerolepis*	Amphidromous	Commercial; recreational
Glassfishes	*Ambassidae*		
Aggassiz's glassfish	*Ambassis agassizi*	Potamodromous	
Estuary perchlet	*Ambassis marianus*	Amphidromous	
Gobies	*Gobiidae*		
Goby	*Afurcagobius (Favinogobius) sp*	Catadromous	Estuary only post barrage construction
Speckled goby	*Redigobius bikolanus*	Catadromous	
Grunters	*Terapontidae*		
Silver perch	*Bidyanus bidyanus*	Potamodromous	Recreational
Sooty grunter	*Hephaestus fuliginosus*	Potamodromous	Recreational
Spangled perch	*Leipotherapon unicolor*	Potamodromous	Recreational
Barcoo grunter	*Scortum barcoo*	Potamodromous	Recreational
Gudgeons	*Eleotrididae*		
Striped gudgeon	*Gobiomorphus australis*	Potamodromous	
Empire gudgeon	*Hypseleotris compressa*	Potamodromous	
Fire-tail gudgeon	*Hypseleotris galii*	Potamodromous	
Western carp gudgeon	*Hypseletris klunzingeri*	Potamodromous	

Common name	Family, species	Life cycle	Comments
Midgley's carp gudgeon	*Hypseletris sp 1*	Potamodromous	
Purple spotted gudgeon	*Mogurnda adspersa*	Potamodromous	
Flathead gudgeon	*Philypnodon grandiceps*	Potamodromous	
Dwarf flathead gudgeon	*Philypnodon sp*	Potamodromous	
Hardyheads	*Atherinidae*		
Marjorie's hardyhead	*Craterocephalus marjoriae*	Potamodromous	
Fly-speckled hardyhead	*Craterocephalus stercusmuscarum*	Potamodromous	
Herring	*Clupeidae*		
Bony bream	*Nematalosa erebi*	Potamodromous	
Southern herring	*Herlotsichthys castelnaui*	Catadromous	Estuary only post barrage construction
Livebearers	*Poeciliidae*		
Mosquitofish	*Gambusia holbrooki*	Potamodromous	Exotic/introduced
Platy	*Xiphorus maculatus*	Potamodromous	Exotic/introduced
Swordtail	*Xiphorus helleri*	Potamodromous	Exotic/introduced
Guppy	*Poecilia reticulata*	Potamodromous	Exotic/introduced
Longtoms	*Belonidae*		
Freshwater longtom	*Strongylura kreftii*	Potamodromous	Recreational
Lungfish	*Ceratodidae*		
Australian lungfish	*Neoceratodus forsteri*	Potamodromous	Threatened
Milkfishes	*Chanidae*		
Milkfish	*Chanos chanos*	Amphidromous	
Mullets	*Mugilidae*		
Freshwater mullet	*Myxus petardi*	Catadromous	Recreational

Common name	Family, species	Life cycle	Comments
Bully mullet	*Mugil cephalus*	Amphidromous	Recreational; commercial
Flat-tailed mullet	*Liza dussmieri*	Amphidromous	Commercial; estuary only post barrage construction
Green-back mullet	*Liza subviridis*	Amphidromous	Commercial; estuary only post barrage construction
Pygmy perches	*Nannopercidae*		
Oxleyan pygmy perch	*Nannoperca oxleyana*	Potamodromous	Threatened
Rainbowfishes	*Melanotaeniidae*		
Duboulay's rainbowfish	*Melanotaenia duboulayi*	Potamodromous	
Ornate rainbowfish	*Rhadinocentrus ornatus*	Potamodromous	
Scats	*Scatophagidae*		
Spotted scat	*Scatophagus argus*	Amphidromous	
Striped scat	*Selenotoca multifasciata*	Amphidromous	Estuary only post barrage construction
Scorpionfishes	*Scorpaenidae*		
Bullrout	*Notesthes robusta*	Catadromous	
Sea bass	*Centropomidae*		
Barramundi	*Lates calcarifer*	Catadromous	Recreational; commercial
Silver biddies	*Gerreidae*		
Threadfin silver biddy	*Gerres filamentosus*	Amphidromous	Estuary only post barrage construction
Snappers	*Lutjanidae*		
Mangrove jack	*Lutjanus argetimaculatus*	Amphidromous	Recreational; estuary only post barrage construction

Common name	Family, species	Life cycle	Comments
Southern smelts	*Retropinnidae*		
Australian smelt	*Retropinna semoni*	Potamodromous	
Breams	*Sparidae*		
Yellowfin bream	*Acathopagrus australis*	Amphidromous	Recreational; commercial
Swamp-eels	*Synbranchidae*		
Swamp eel	*Ophisternon spp*	Potamodromous	
Tarpon	*Megalopidae*		
Oxeye herring	*Megalops cyprinoides*	Catadromous	
Tenpounders	*Elopidae*		
Giant herring	*Elops hawaiensis*	Amphidromous	Estuary only post barrage construction
Toadfishes	*Tetraodontidae*		
Banded toadfish	*Marilyna pleurosticta*	Amphidromous	Estuary only post barrage construction
Trevallies	*Carangidae*		
Big-eye trevally	*Caranx sexfasciatus*	Amphidromous	Recreational
Whaler sharks	*Carcharhinidae*		
Bull shark	*Carcharhinus leucas*	Catadromous	Estuary only post barrage construction

Appendix C

CFX Report - Corner 'EL' Baffle Model, James Cook University Hydraulics Laboratory

Title

James Cook University, Hydraulics Lab CFD

Author

Simon Petersen

Date

2013/10/03 11:25:30

Contents

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1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Validation\Multiphase\lab_mp_files\dp0\CFX\CFX\CFX_012.res
File Date	03 October 2013
File Time	08:57:40 AM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements
Default Domain Modified	348725	330414

3. Physics Report

Table 3. Domain Physics for CFX

Domain - Default Domain Modified	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.18 [m], 0.18 [m], 0.25 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 4. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain Modified	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	6.0000e-01 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - walls_baffles	
	Type	WALL
	Location	BAFFLE1, BAFFLE2, BAFFLE3, BAFFLE4, BAFFLE5, BAFFLE6
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Smooth Wall
	Boundary - walls_culvert	
	Type	WALL
	Location	wall
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Smooth Wall

4. Solution Report

Table 5. Boundary Flows for CFX

Location	Type	Mass	Momentum		
			X	Y	Z
inlet (Air)	Boundary	1.7111e-02			
inlet (Bulk)	Boundary		-6.1073e-06	1.0314e+02	-3.1148e-01
inlet (Water)	Boundary	3.9442e+01			
outlet (Air)	Boundary	-1.7234e-02			
outlet (Bulk)	Boundary		9.6362e-01	-9.3730e+01	-8.5154e-02
outlet (Water)	Boundary	-3.9098e+01			
roof (Air)	Boundary	2.5943e-04			
roof (Bulk)	Boundary		-8.7064e-03	-2.0699e-01	-4.4471e-01
roof (Water)	Boundary	-4.5935e-01			
walls_baffles (Air)	Boundary	0.0000e+00			
walls_baffles (Bulk)	Boundary		3.1419e+00	-1.4052e+01	1.8909e+00
walls_baffles (Water)	Boundary	0.0000e+00			
walls_culvert (Air)	Boundary	0.0000e+00			
walls_culvert (Bulk)	Boundary		-3.9252e+00	4.0285e+00	1.8811e+03
walls_culvert (Water)	Boundary	0.0000e+00			

5. User Data

Chart 1.

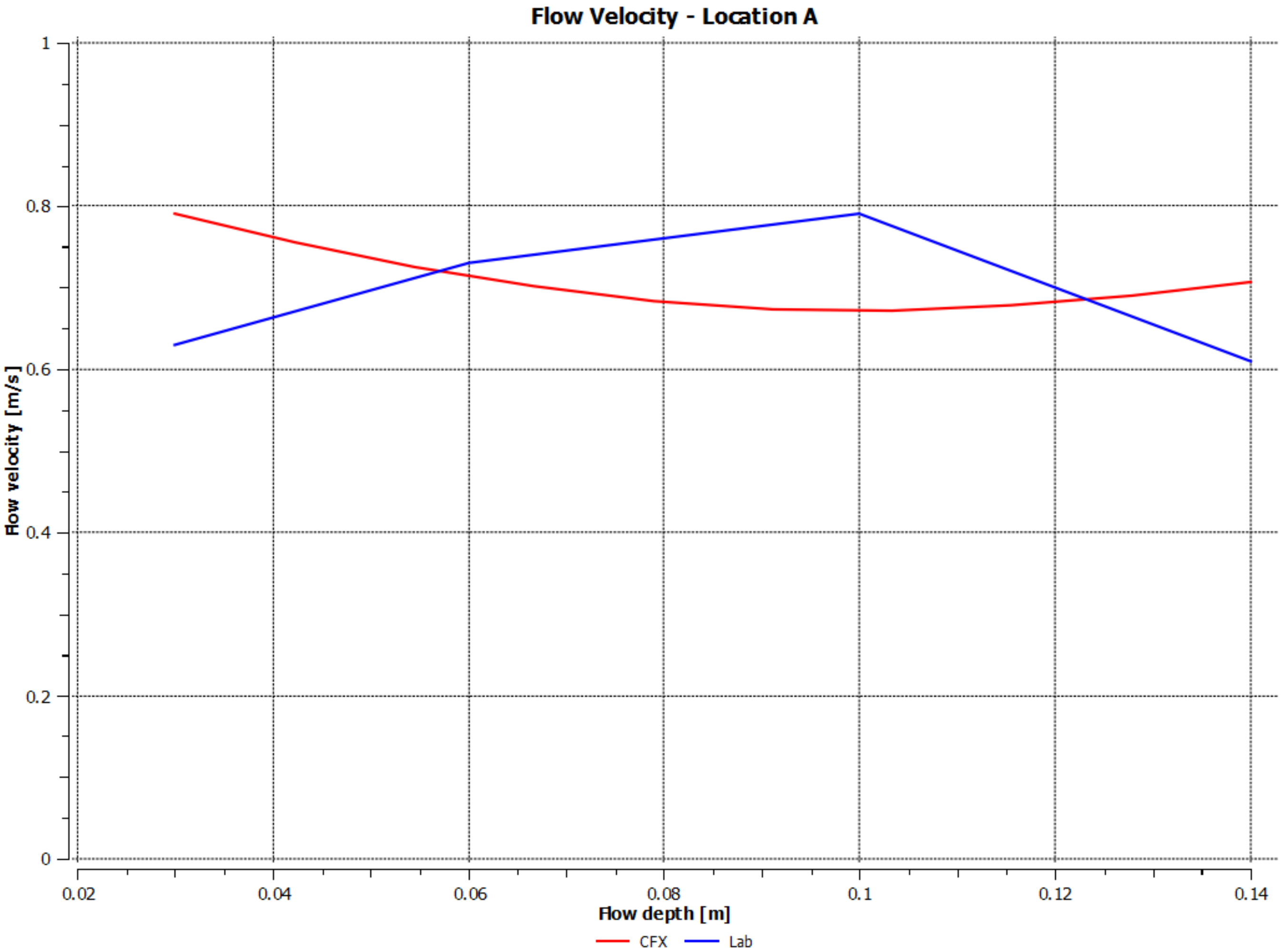


Chart 2.

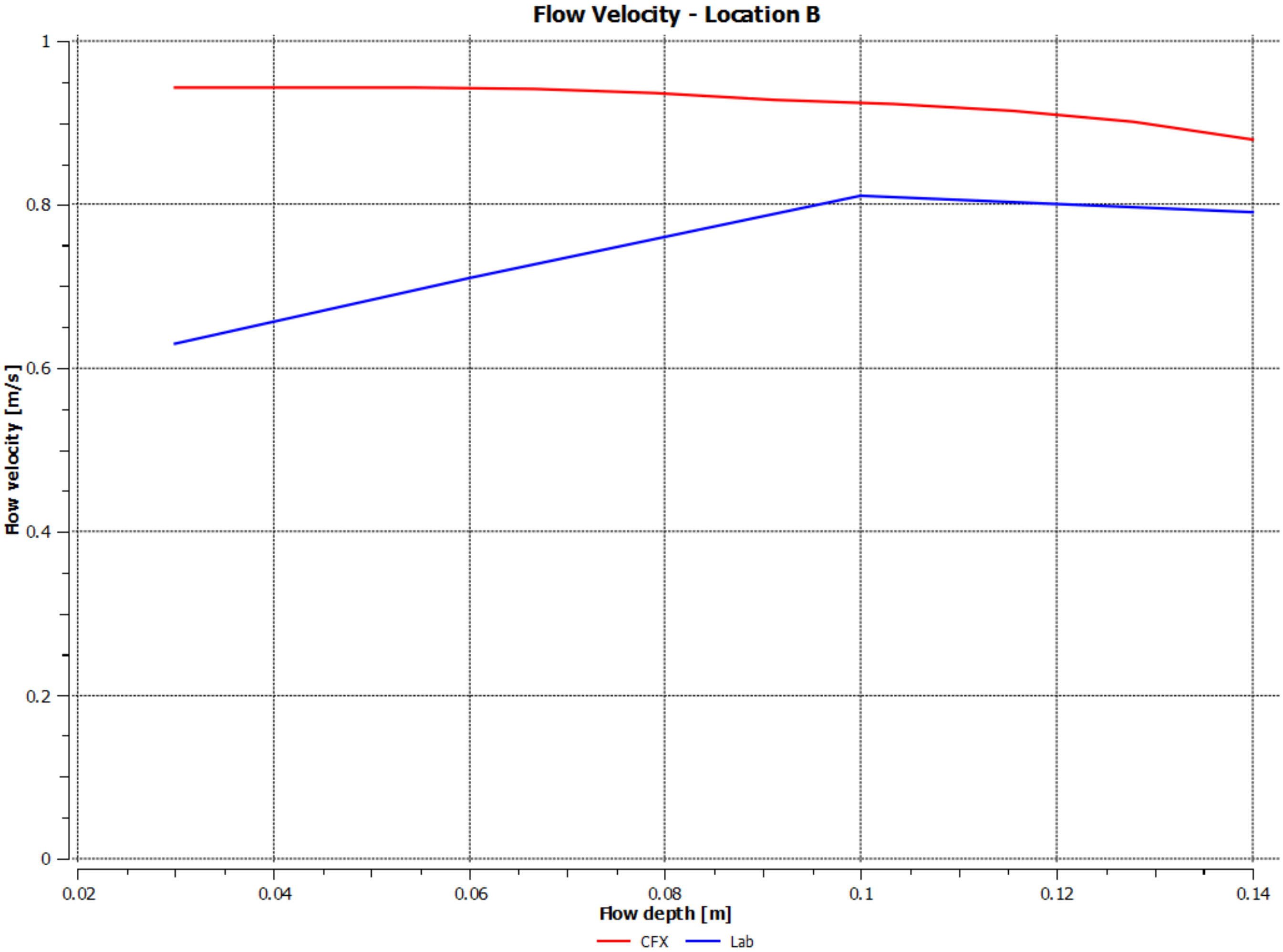

Flow Velocity - Location B
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 3.

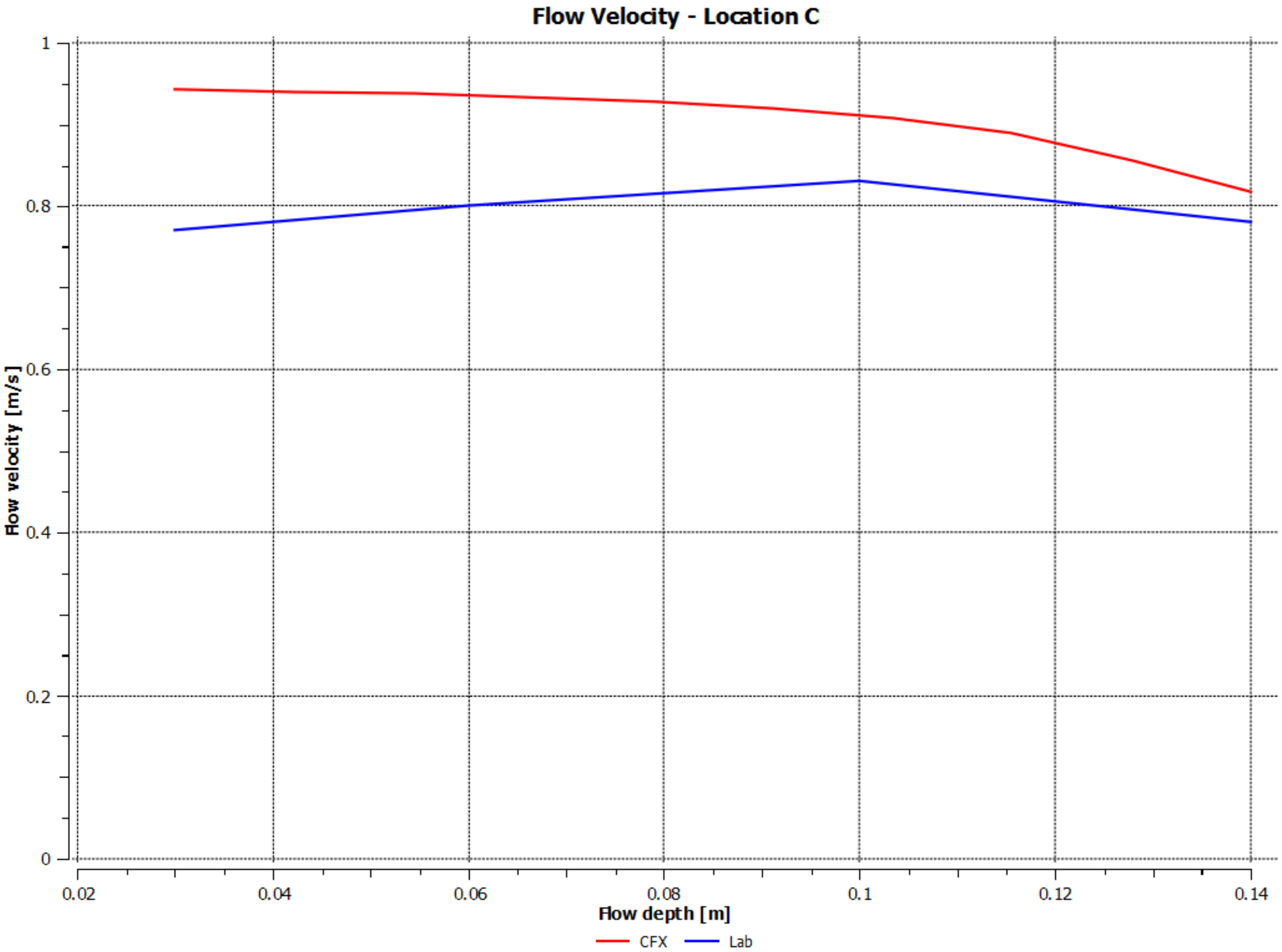

Flow Velocity - Location C
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 4.

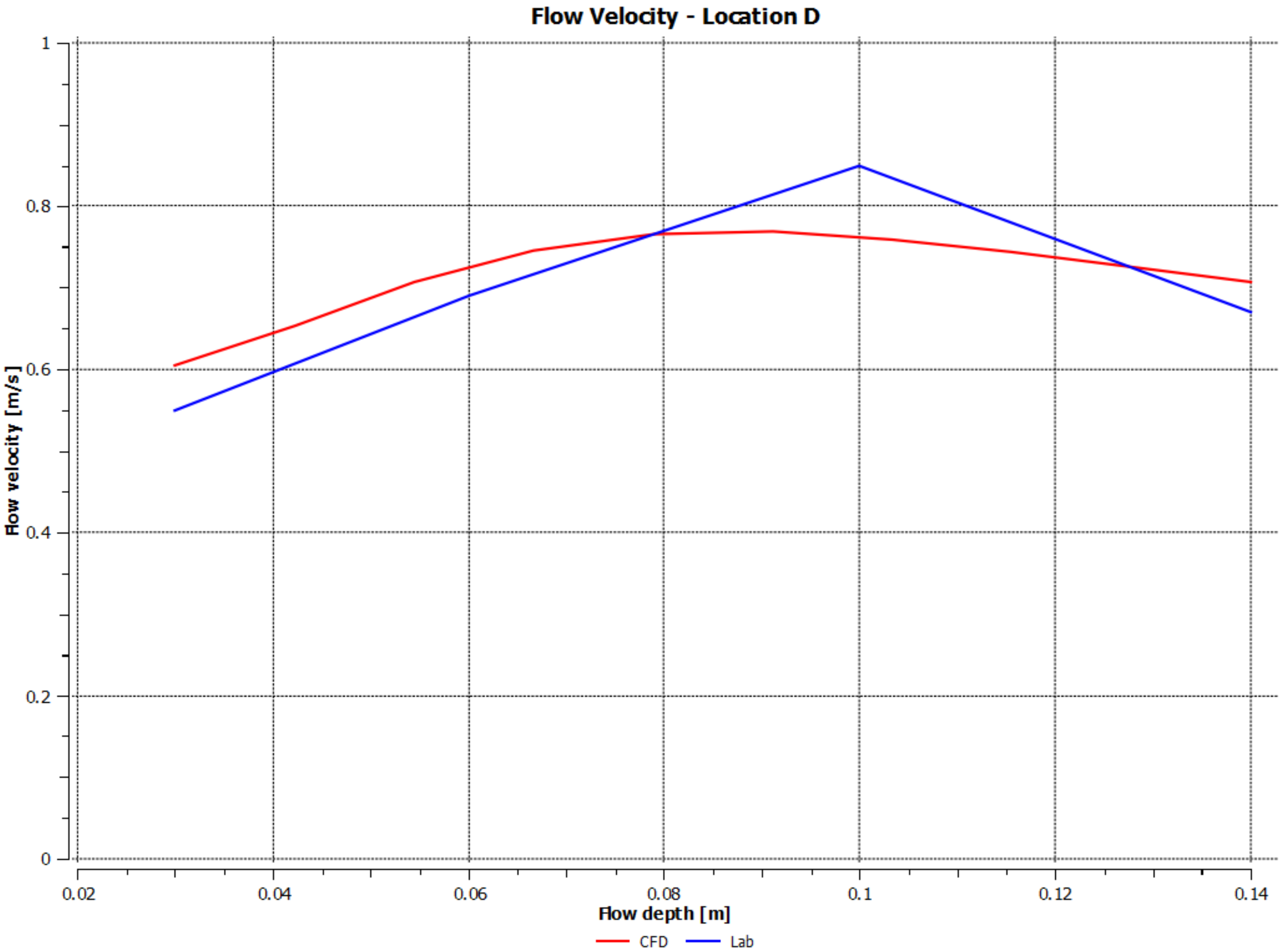
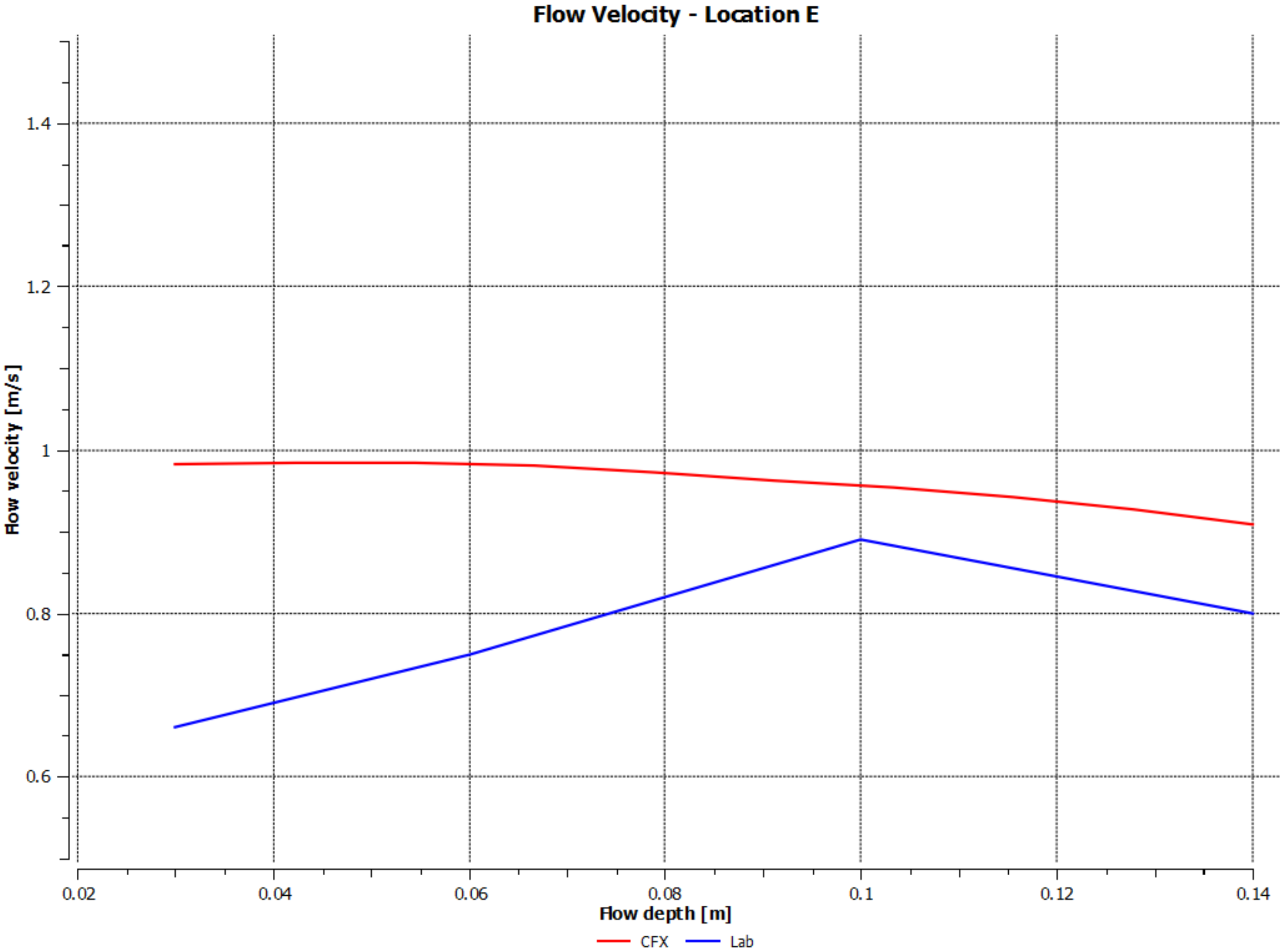

Flow Velocity - Location D
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFD
Lab

Chart 5.



Flow Velocity - Location E
Flow velocity [m/s]
1.4
1.2
1
0.8
0.6
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 6.

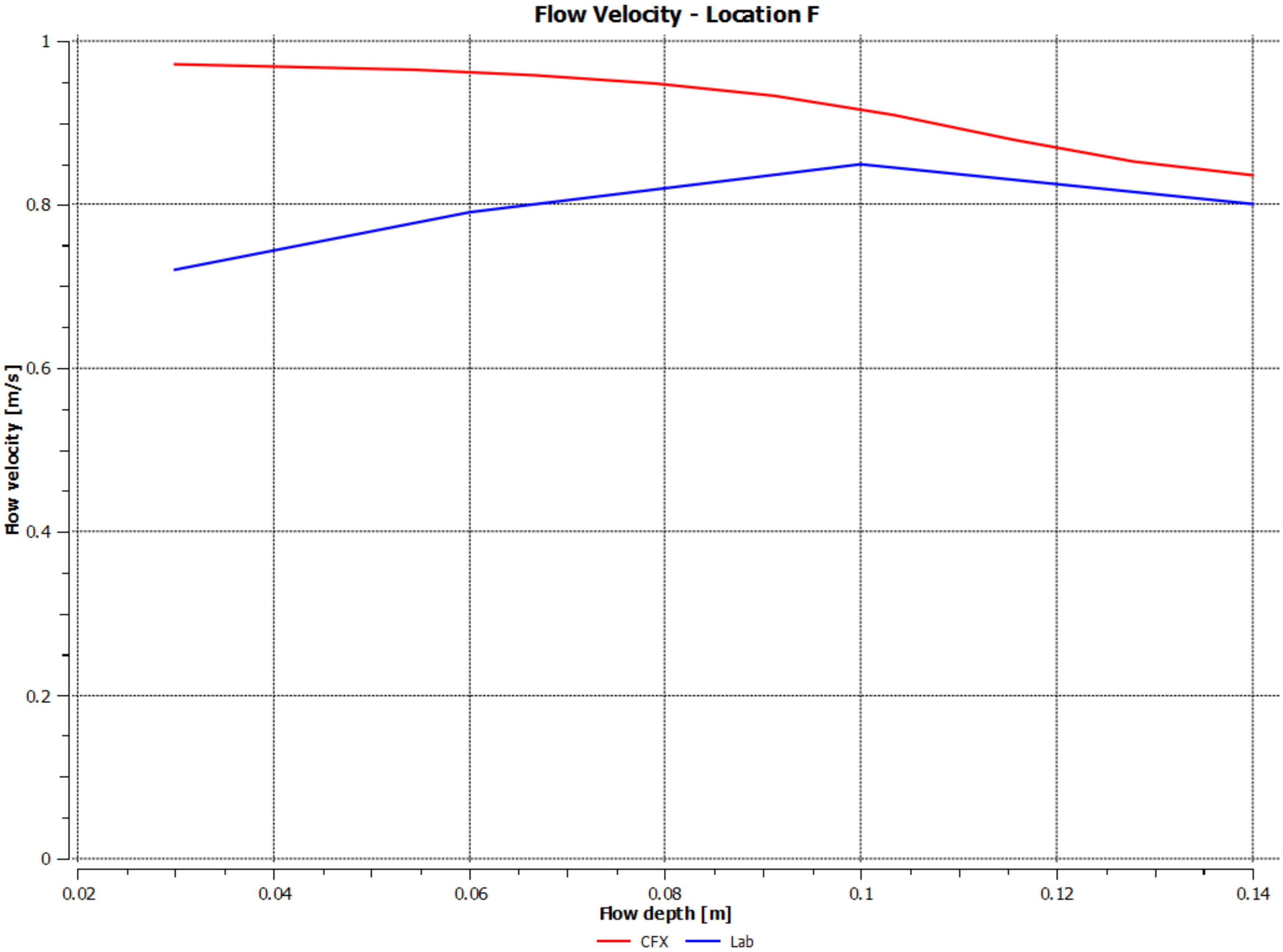

Flow Velocity - Location F
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 7.

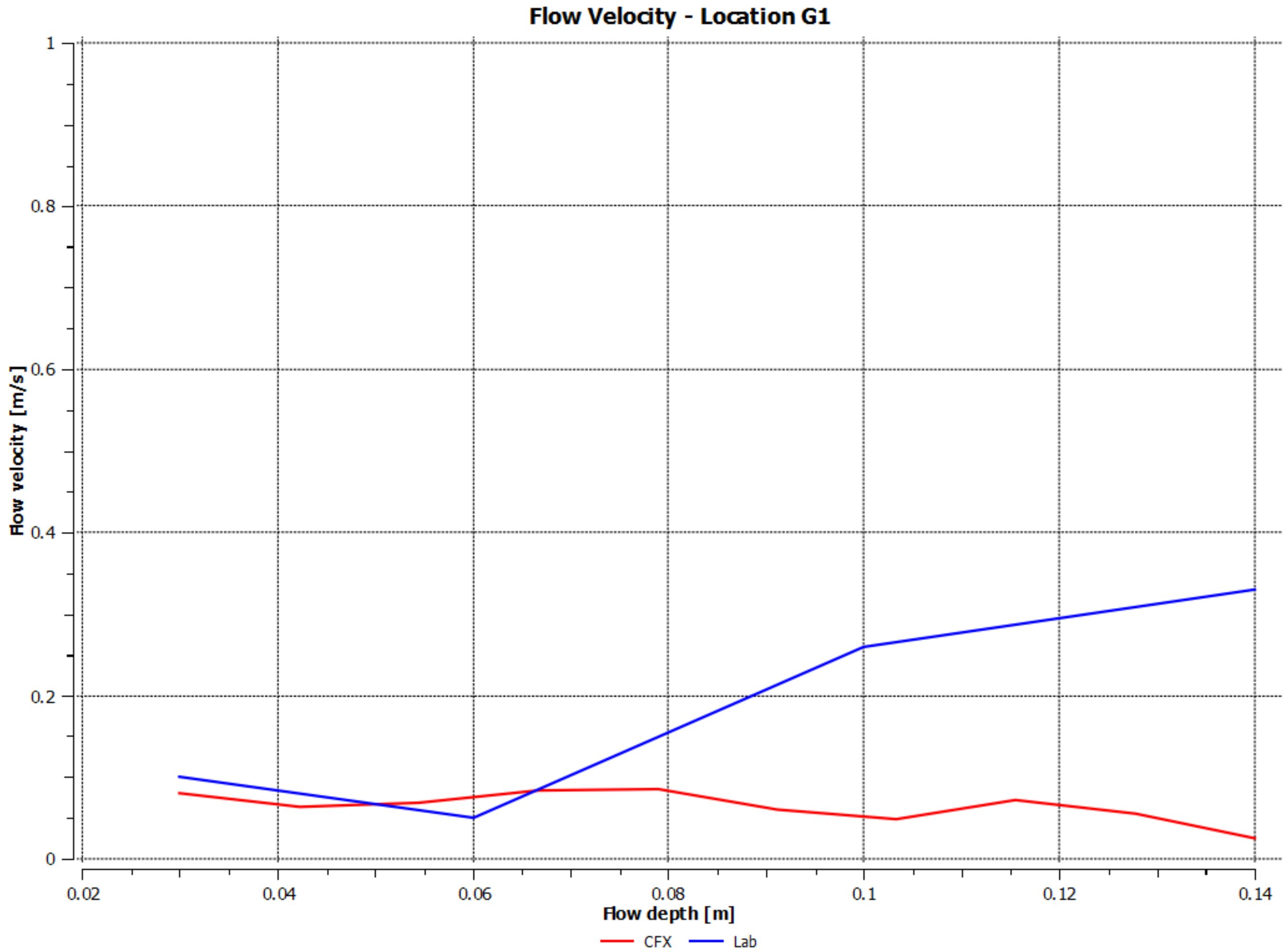
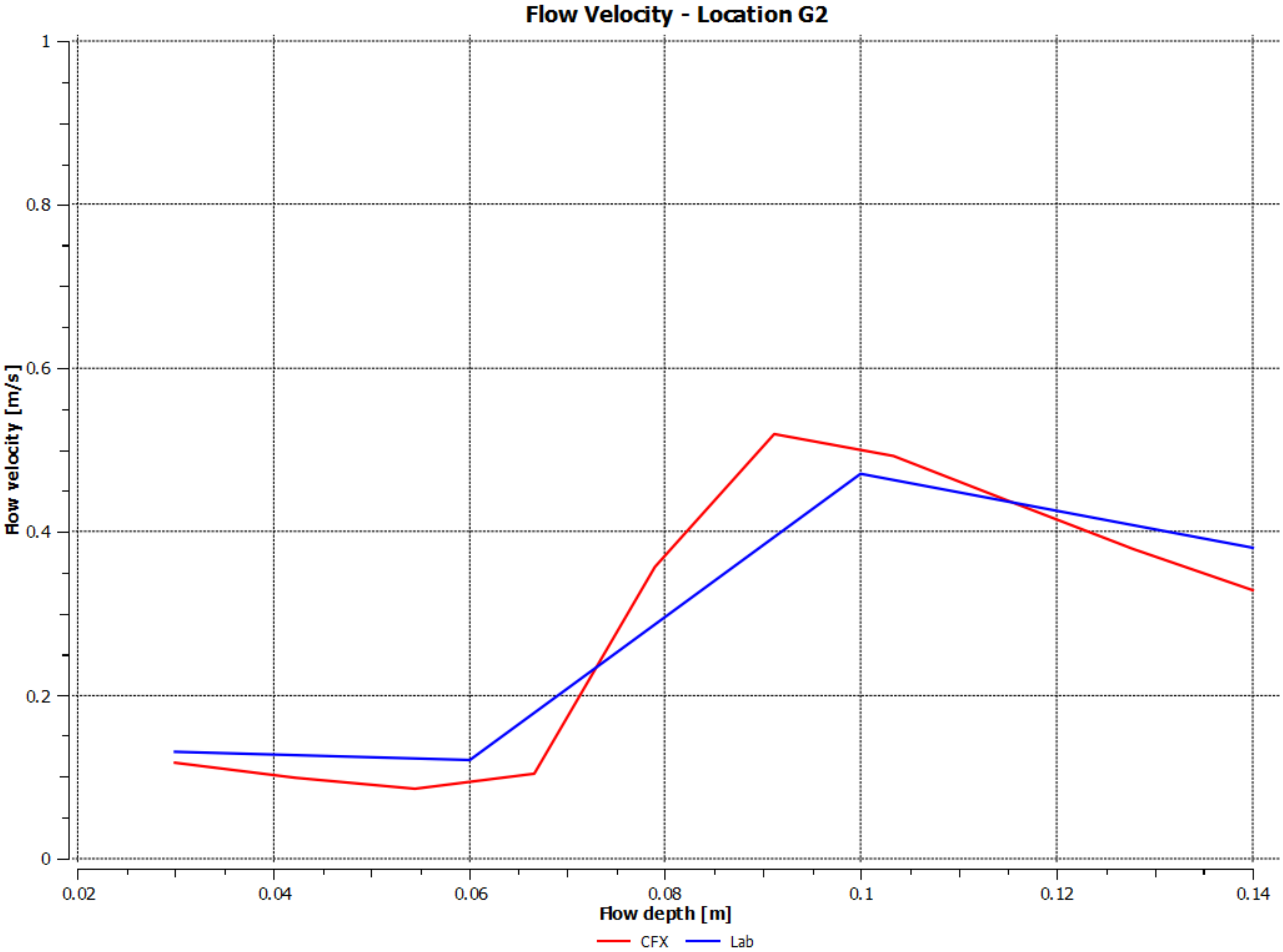

Flow Velocity - Location G1
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 8.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Flow velocity [m/s]
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0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 9.

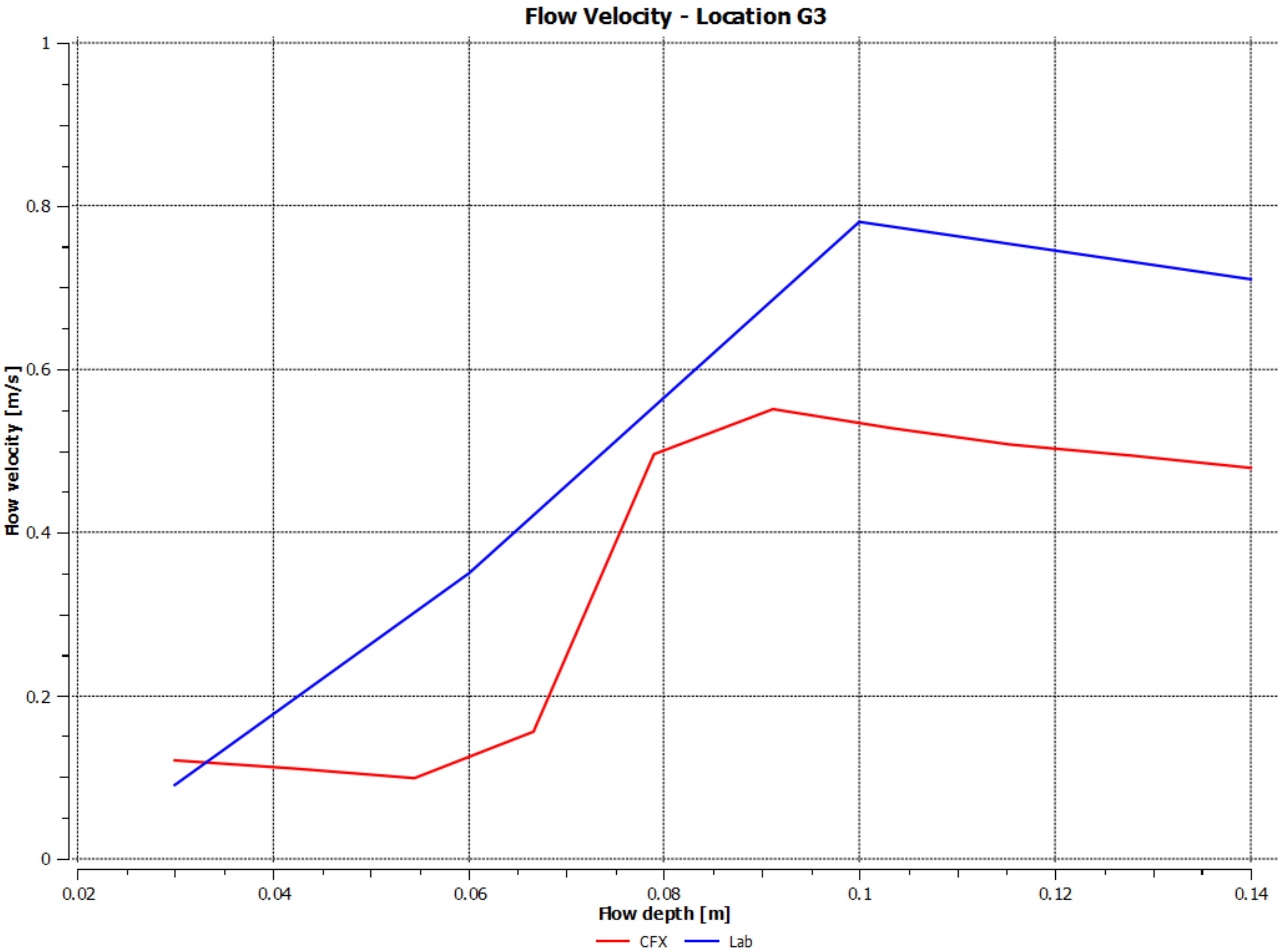

Flow Velocity - Location G3
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 10.

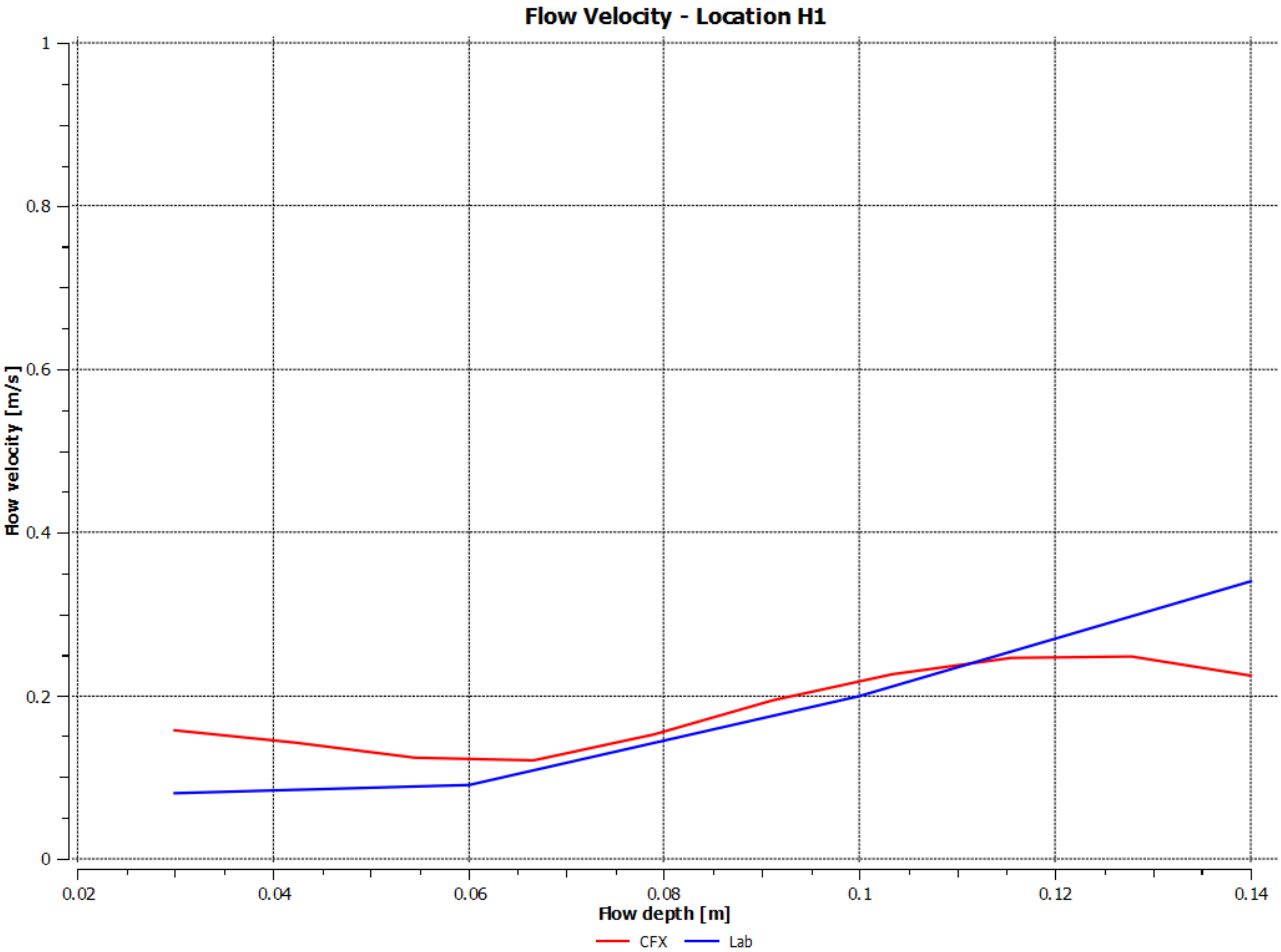

Flow Velocity - Location H1
Flow velocity [m/s]
0
0.2
0.4
0.6
0.8
1
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 11.

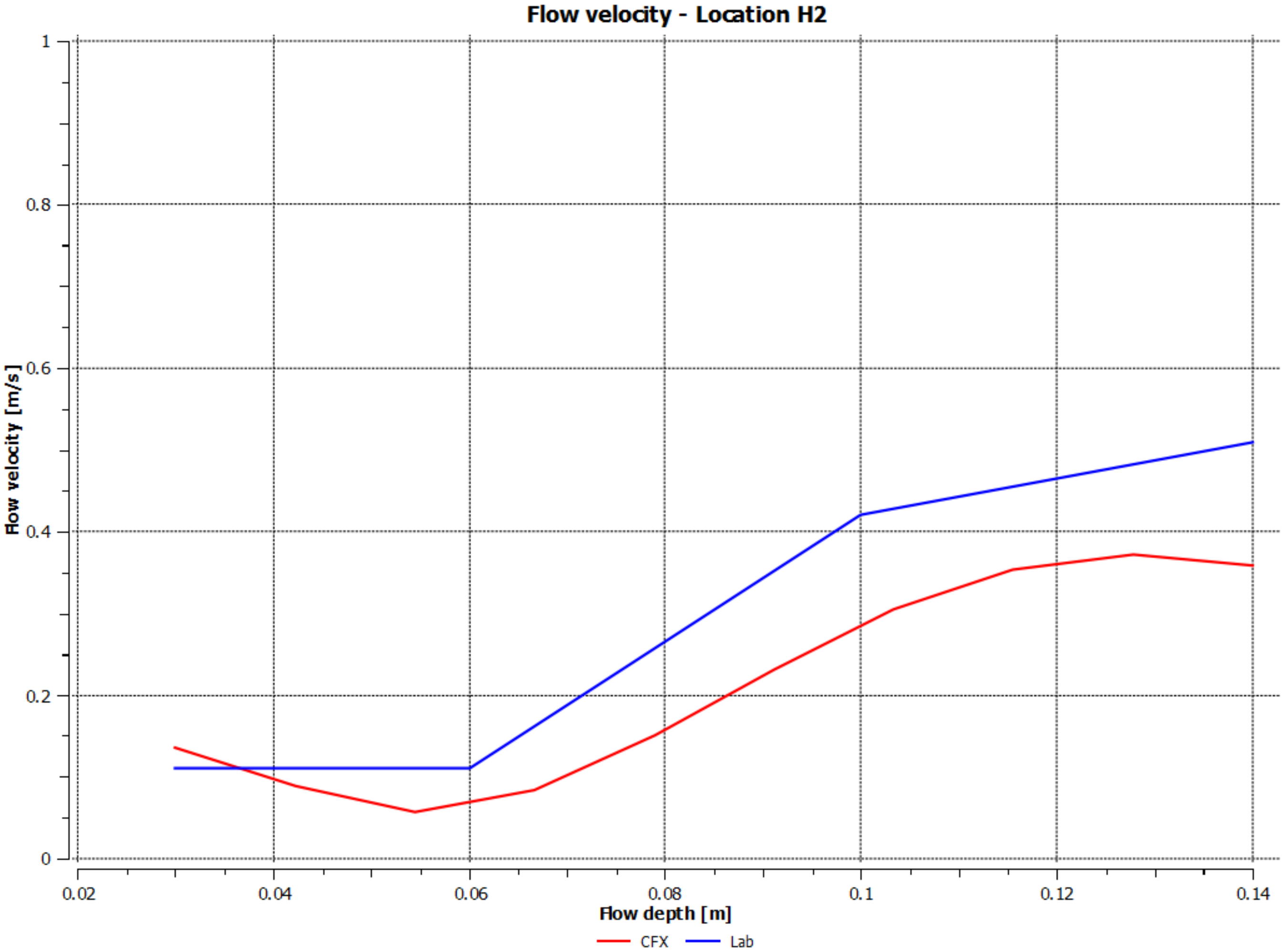

Flow velocity - Location H2
Flow velocity [m/s]
0
0.2
0.4
0.6
0.8
1
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 12.

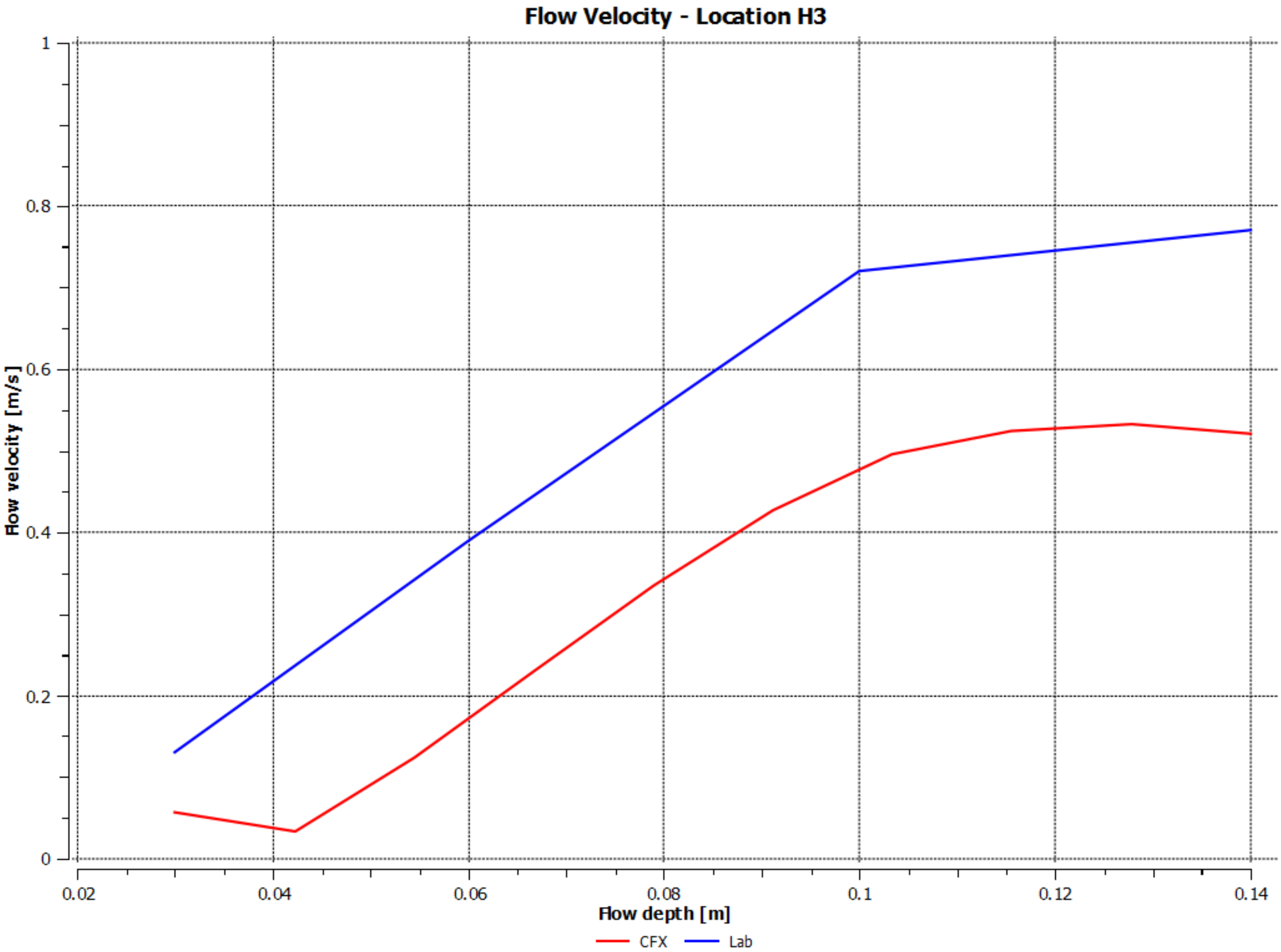

Flow Velocity - Location H3
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 13.

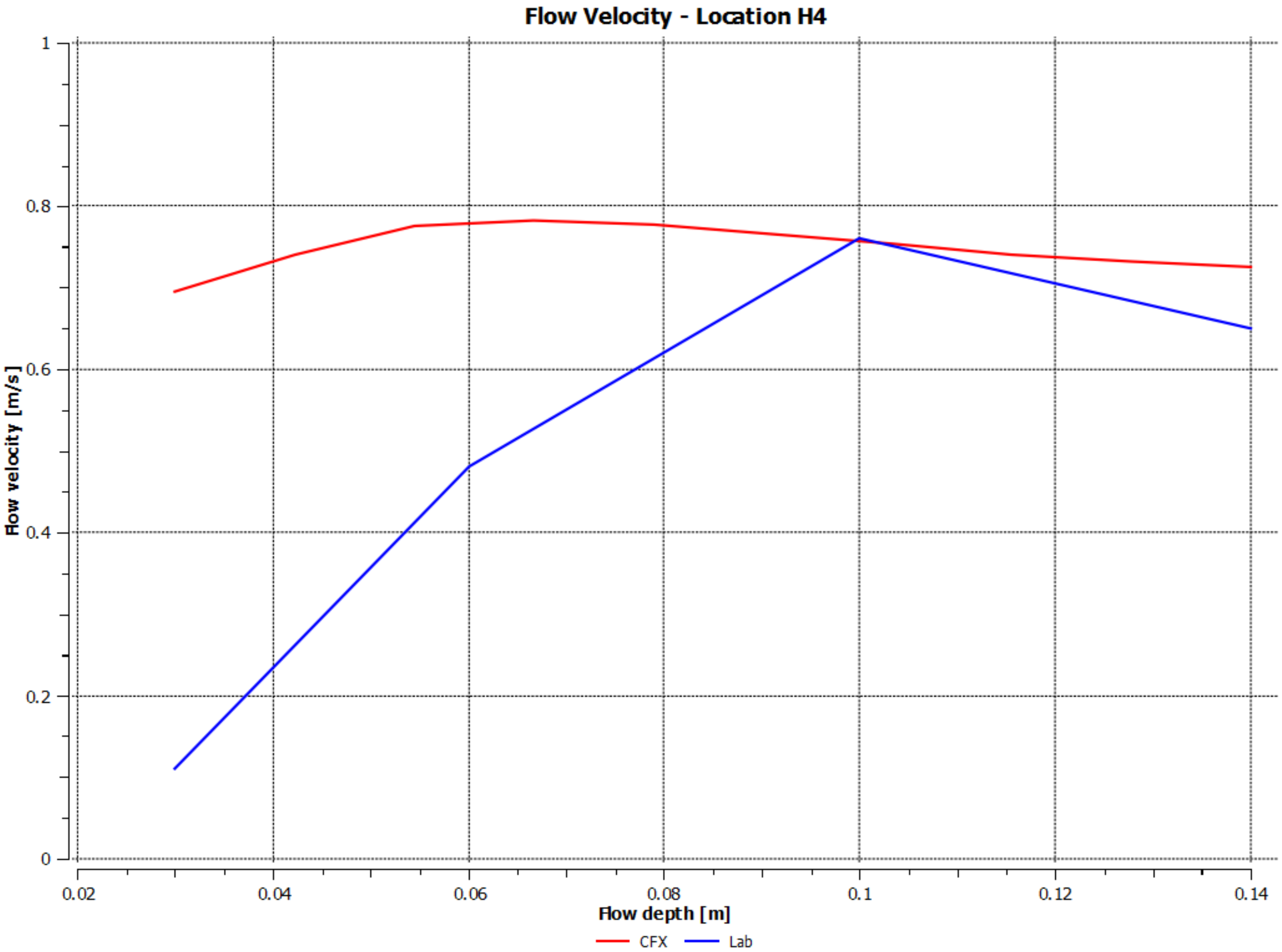

Flow Velocity - Location H4
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 14.

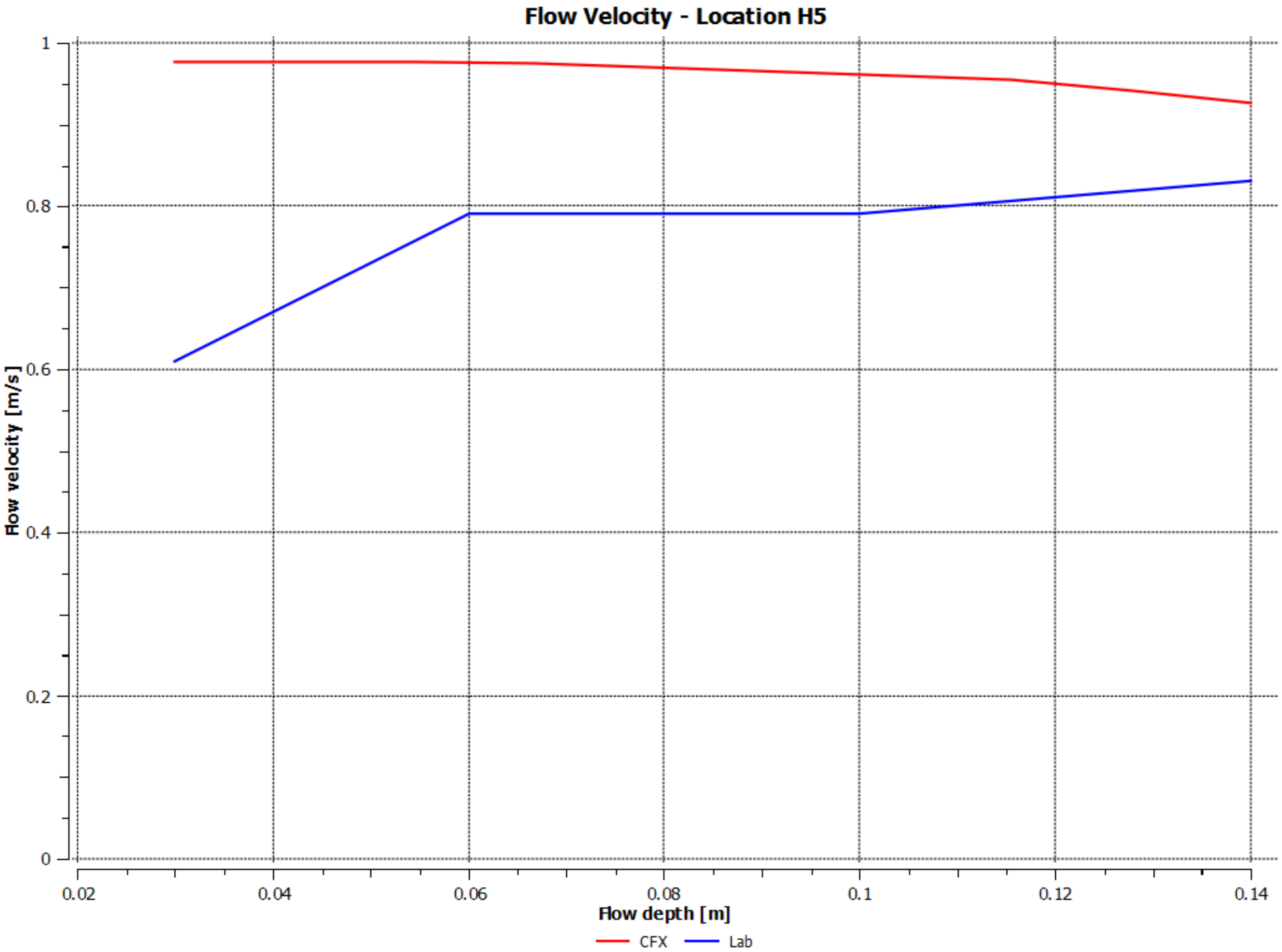

Flow Velocity - Location H5
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 15.

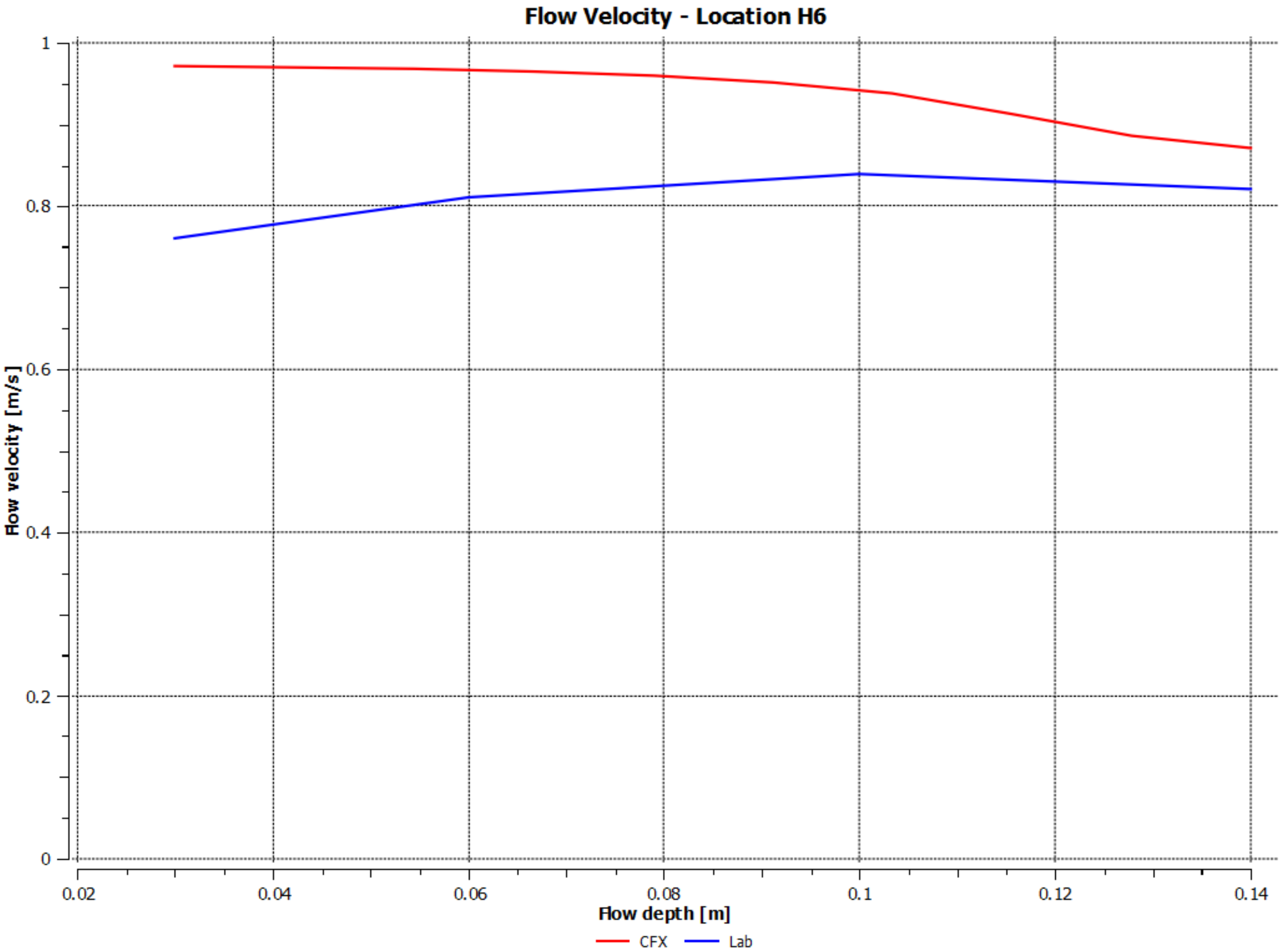

Flow Velocity - Location H6
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 16.

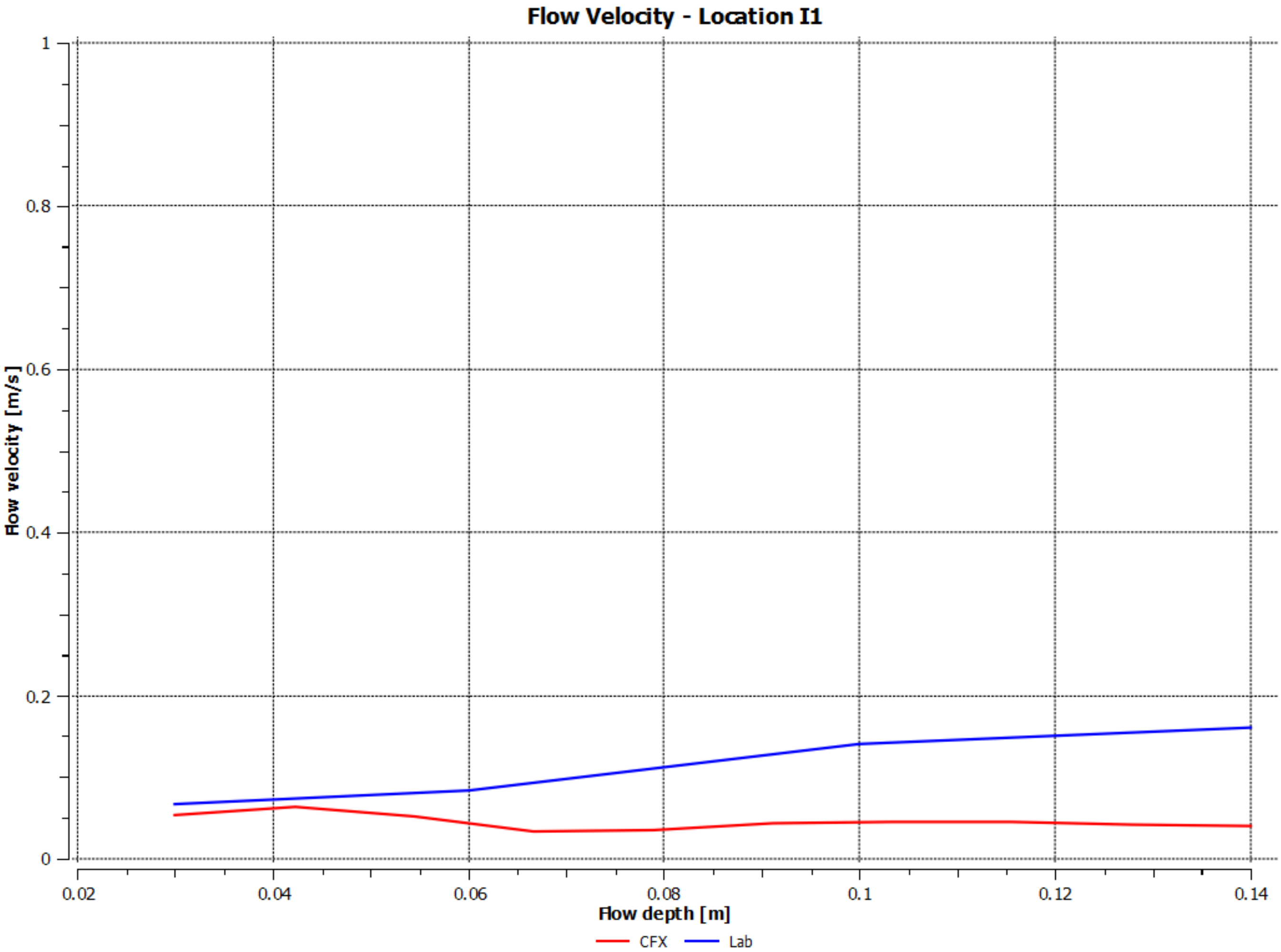

Flow Velocity - Location I1
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 17.

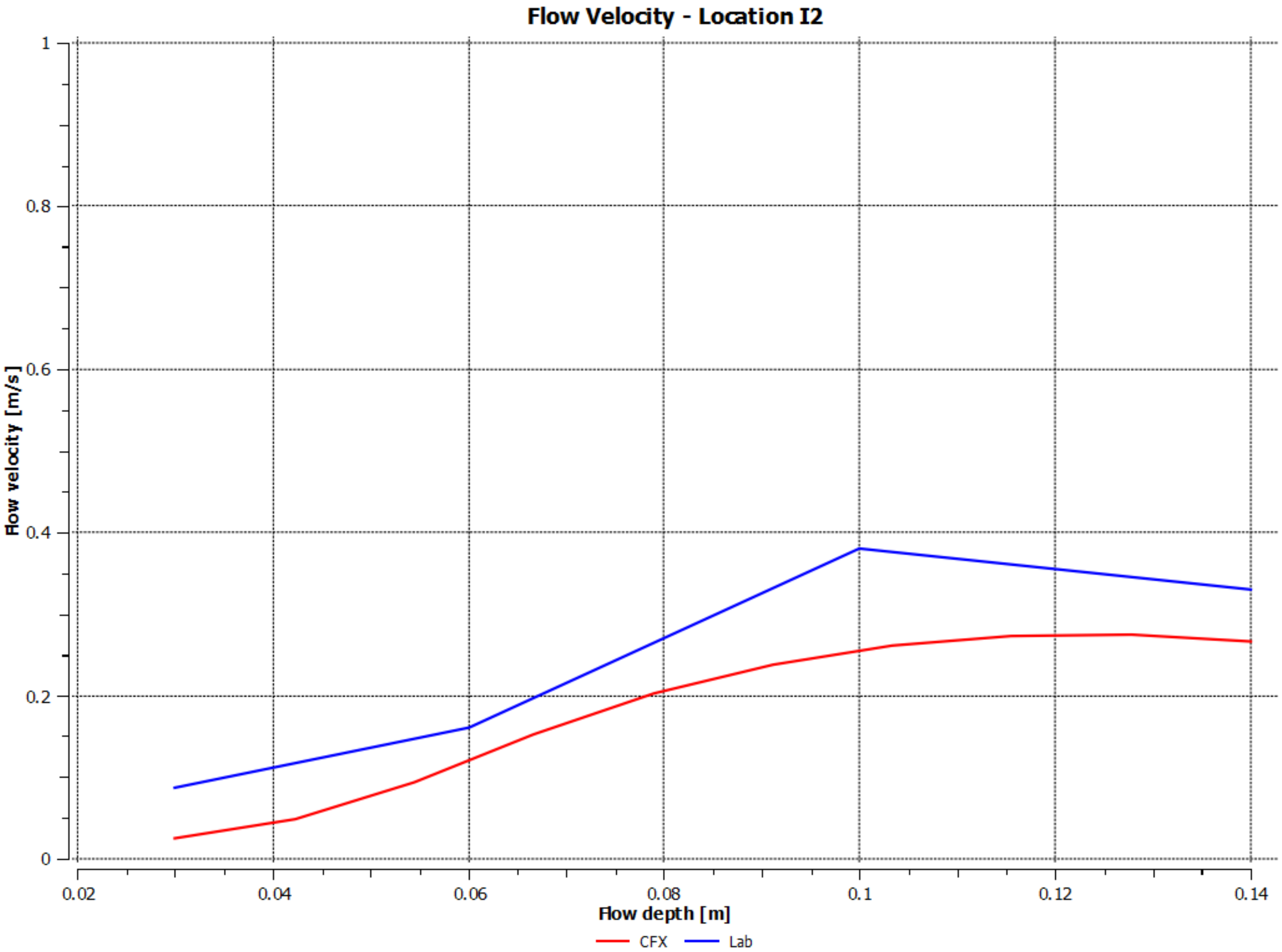
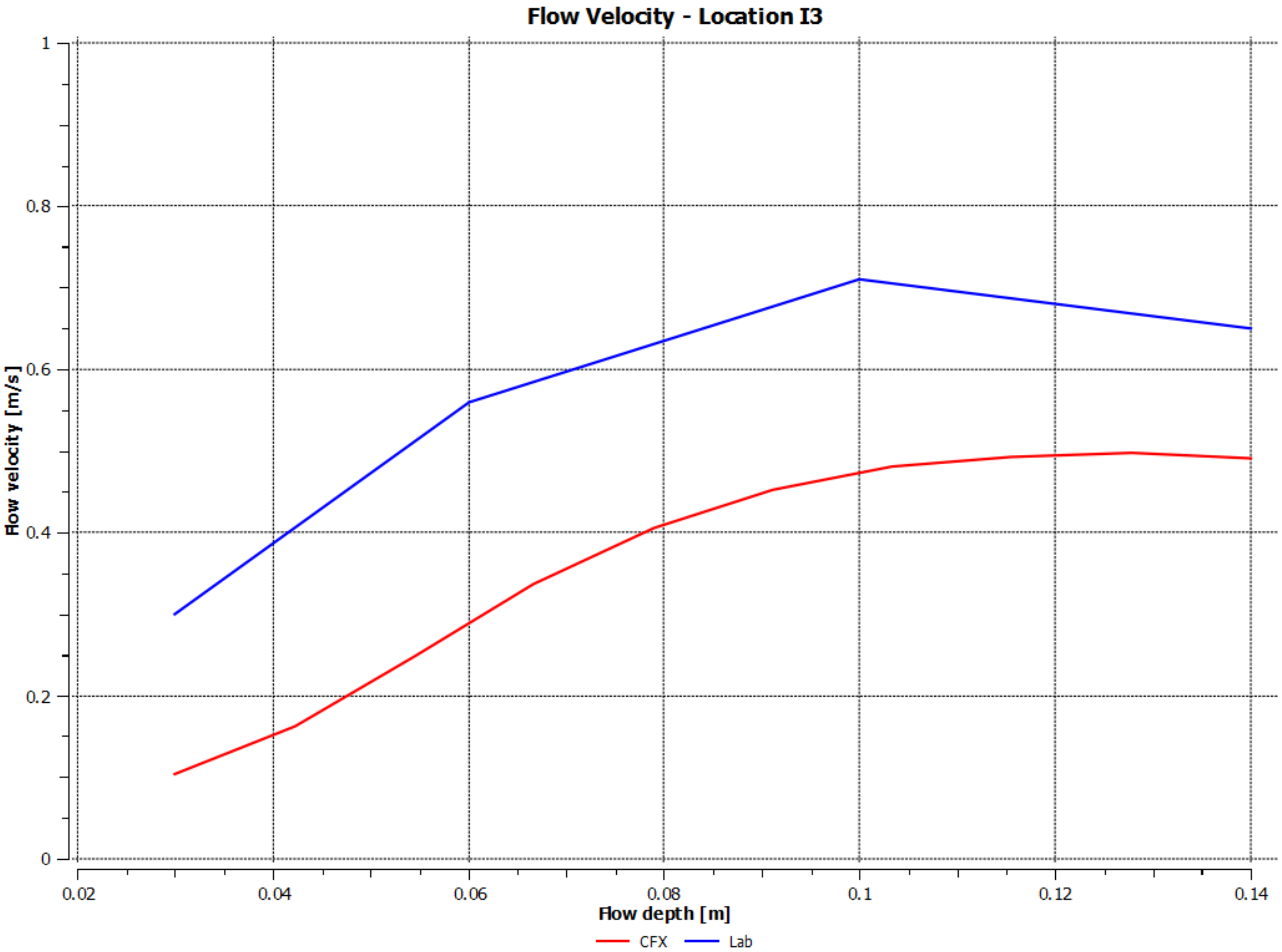

Flow Velocity - Location I2
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Chart 18.


Flow Velocity - Location I3
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Flow depth [m]
CFX
Lab

Appendix D

CFX Report - Corner 'EL' Baffle Prototype, James Cook University Discovery Drive

Title

CFX Report - Corner 'EL' Baffle Prototype, James Cook University Discovery Drive

Author

Simon Petersen

Date

2013/10/03 11:52:44

Contents

1. File Report

Table 1. File Information for discovery

Case	discovery
File Path	C:\Modelling\Validation\Multiphase\discovery_r2_files\dp0\CFX\CFX\CFX_005.res
File Date	02 October 2013
File Time	03:32:12 PM
File Type	CFX5
File Version	14.0

2. Mesh Report

Table 2. Mesh Information for discovery

Domain	Nodes	Elements
Default Domain	3440513	3299003

3. Physics Report

Table 3. Domain Physics for discovery

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 4. Boundary Physics for discovery

Domain	Boundaries	
Default Domain	Boundary - inlet	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	6.9000e-01 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water

	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - sym	
	Type	SYMMETRY
	Location	SYM
	Settings	
	Boundary - walls_culvert	
	Type	WALL
	Location	wall
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

4. olution Report

Table . Boundary Flows for discovery

ocation	Type	Mass	Momentum		
inlet (Air)	Boundary	1.5551e+01			
inlet (Bulk)	Boundary		1.6640e-06	4.4767e+03	-2.2344e+01
inlet (Water)	Boundary	1.5587e+03			
outlet (Air)	Boundary	-1.3560e+01			
outlet (Bulk)	Boundary		5.2565e+00	-1.1090e+04	2.4437e+01
outlet (Water)	Boundary	-9.3787e+02			
roof (Air)	Boundary	-2.7288e+00			
roof (Bulk)	Boundary		-4.7130e-01	-2.0142e+00	-1.6220e+00
roof (Water)	Boundary	-2.2988e-12			
sym (Air)	Boundary	0.0000e+00			
sym (Bulk)	Boundary		-2.9637e+04	0.0000e+00	0.0000e+00
sym (Water)	Boundary	0.0000e+00			
walls_culvert (Air)	Boundary	0.0000e+00			
walls_culvert (Bulk)	Boundary		2.8757e+04	3.4259e+03	8.6527e+05
walls_culvert (Water)	Boundary	0.0000e+00			

. ser Data

Chart 1. Discovery Drive, Baffle 2

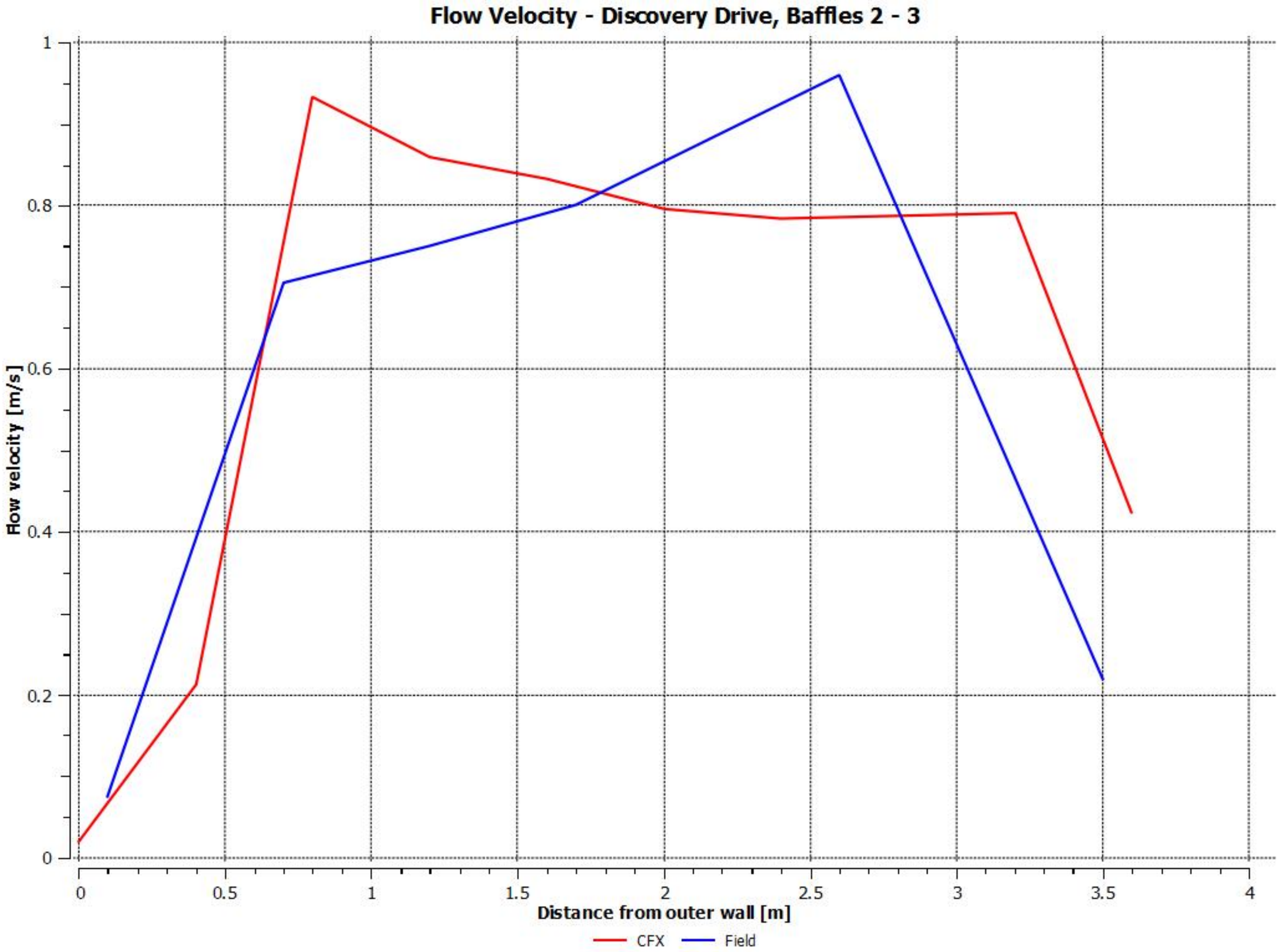


Chart 2. Discovery Drive, Baffle 2

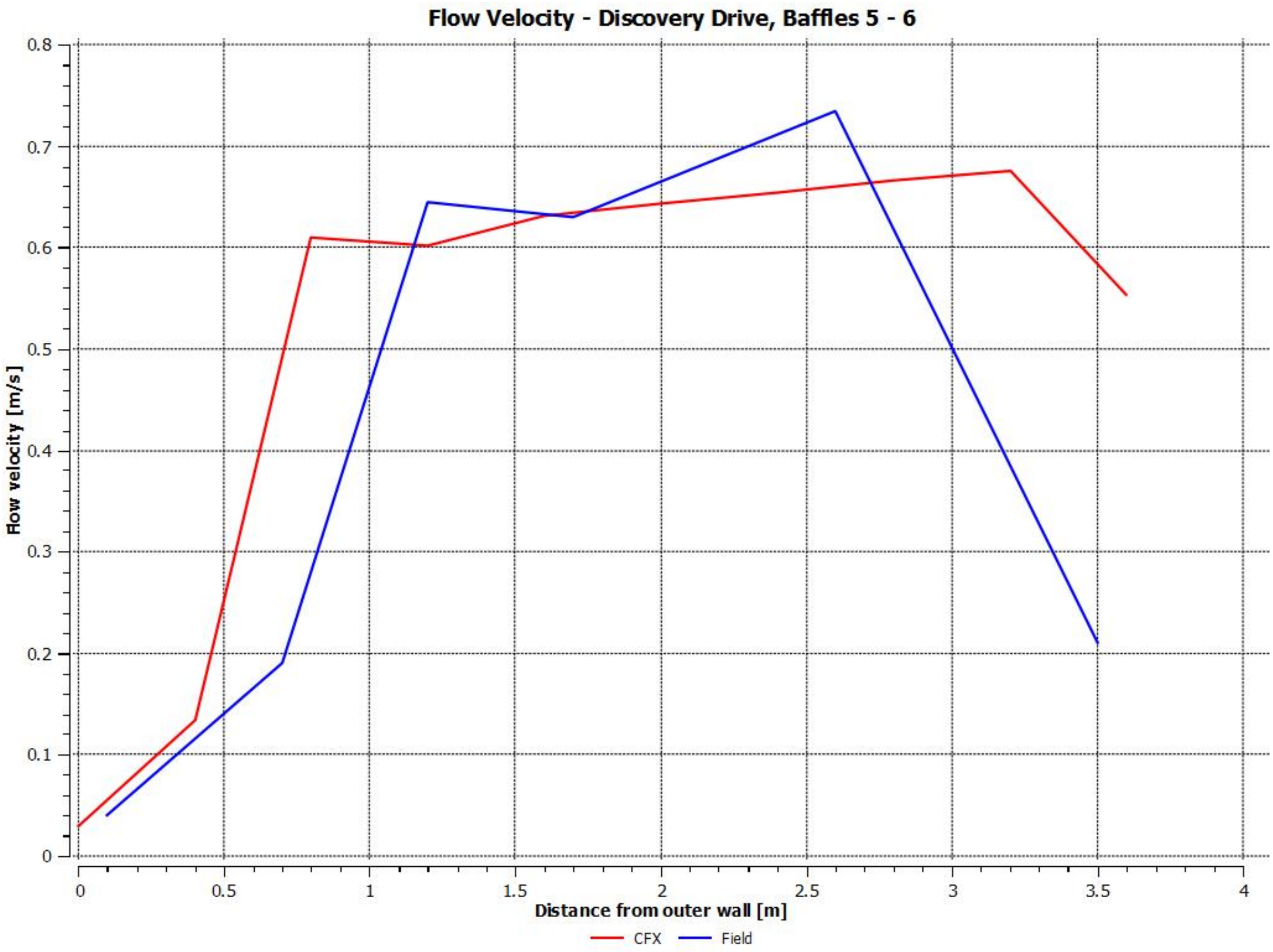


Chart 3. Discovery Drive, Baffle 2

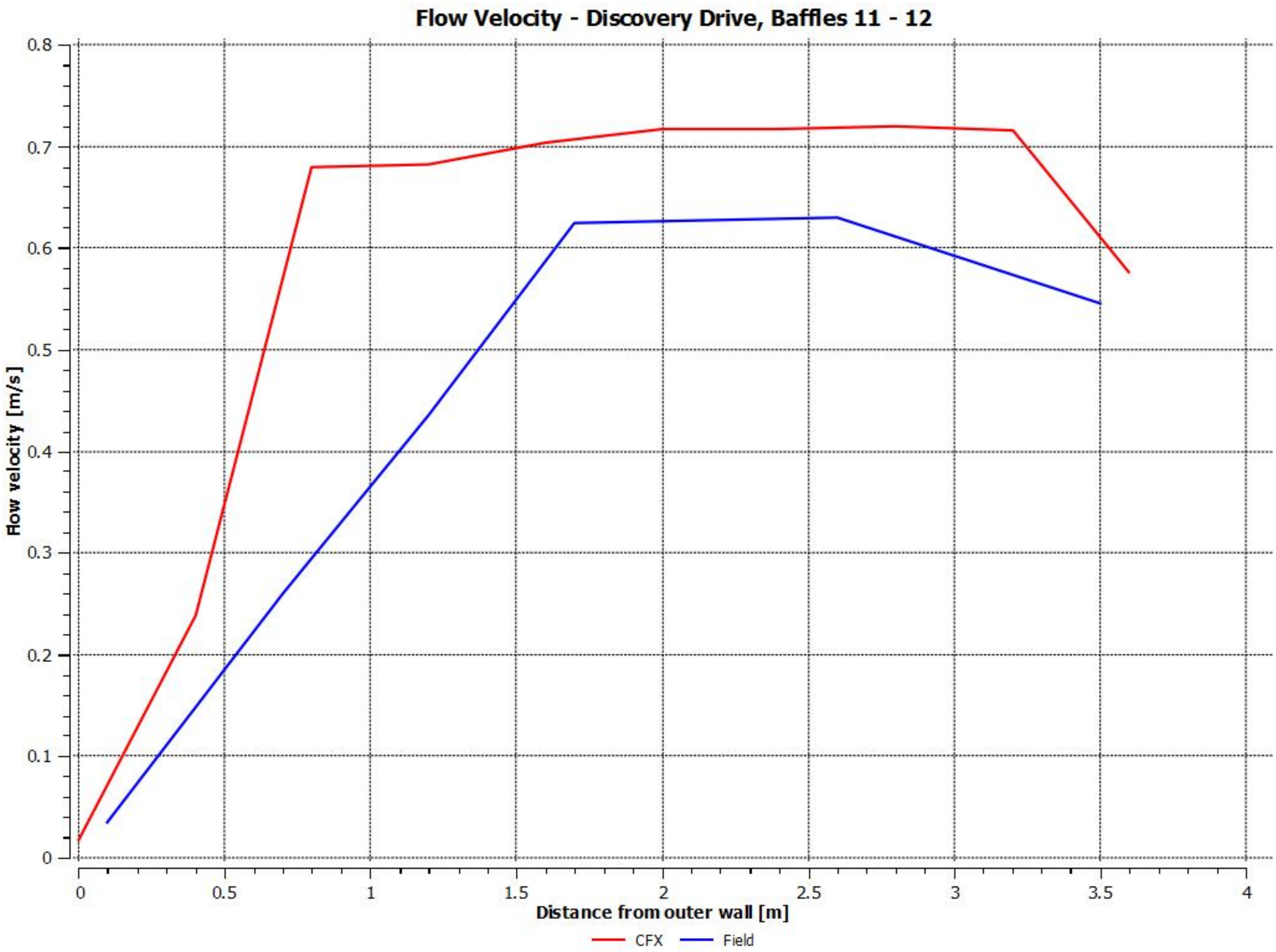


Chart 4. Discovery Drive, Baffle 2

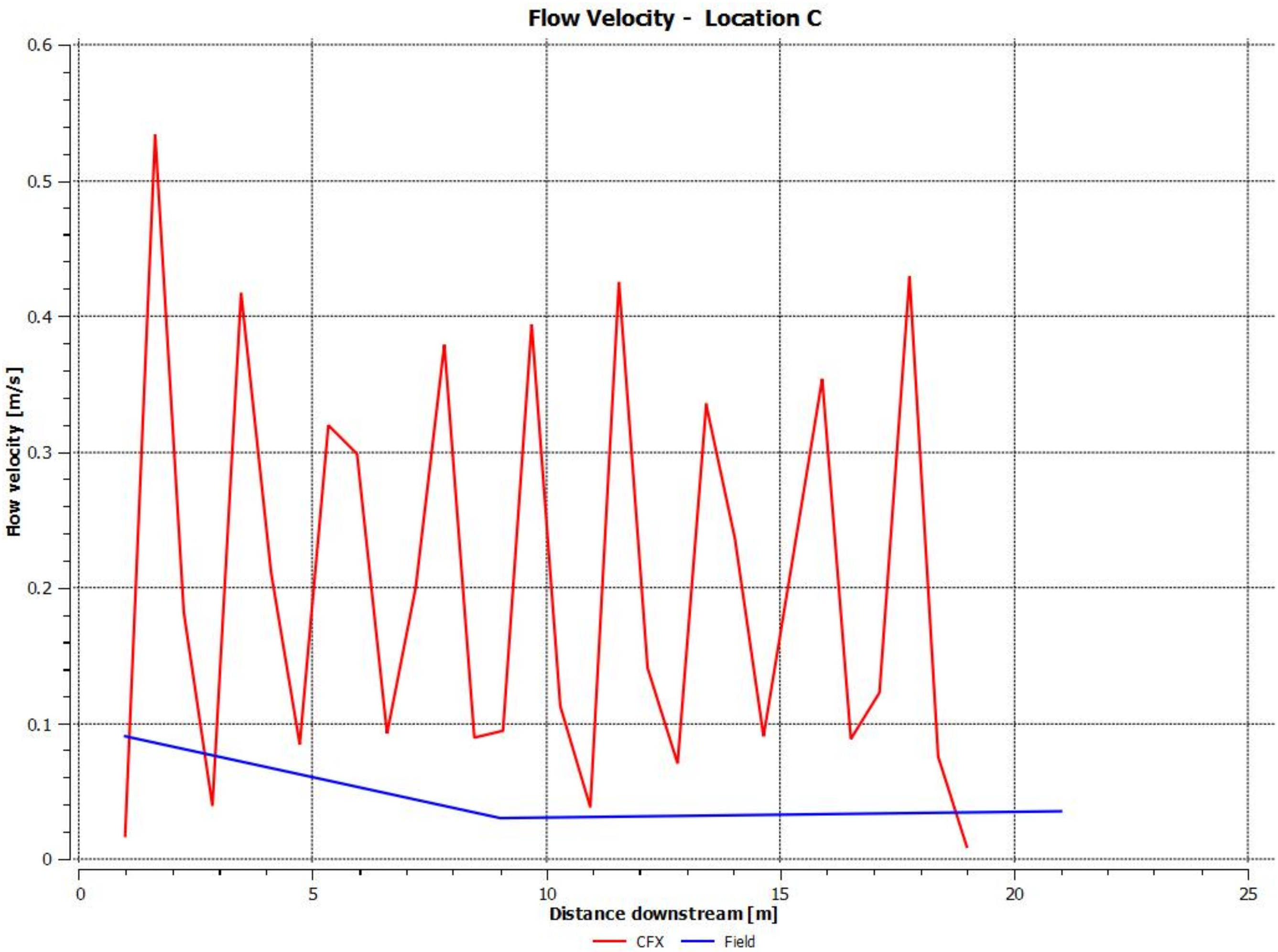


Chart . Discovery Drive, Baffle 2

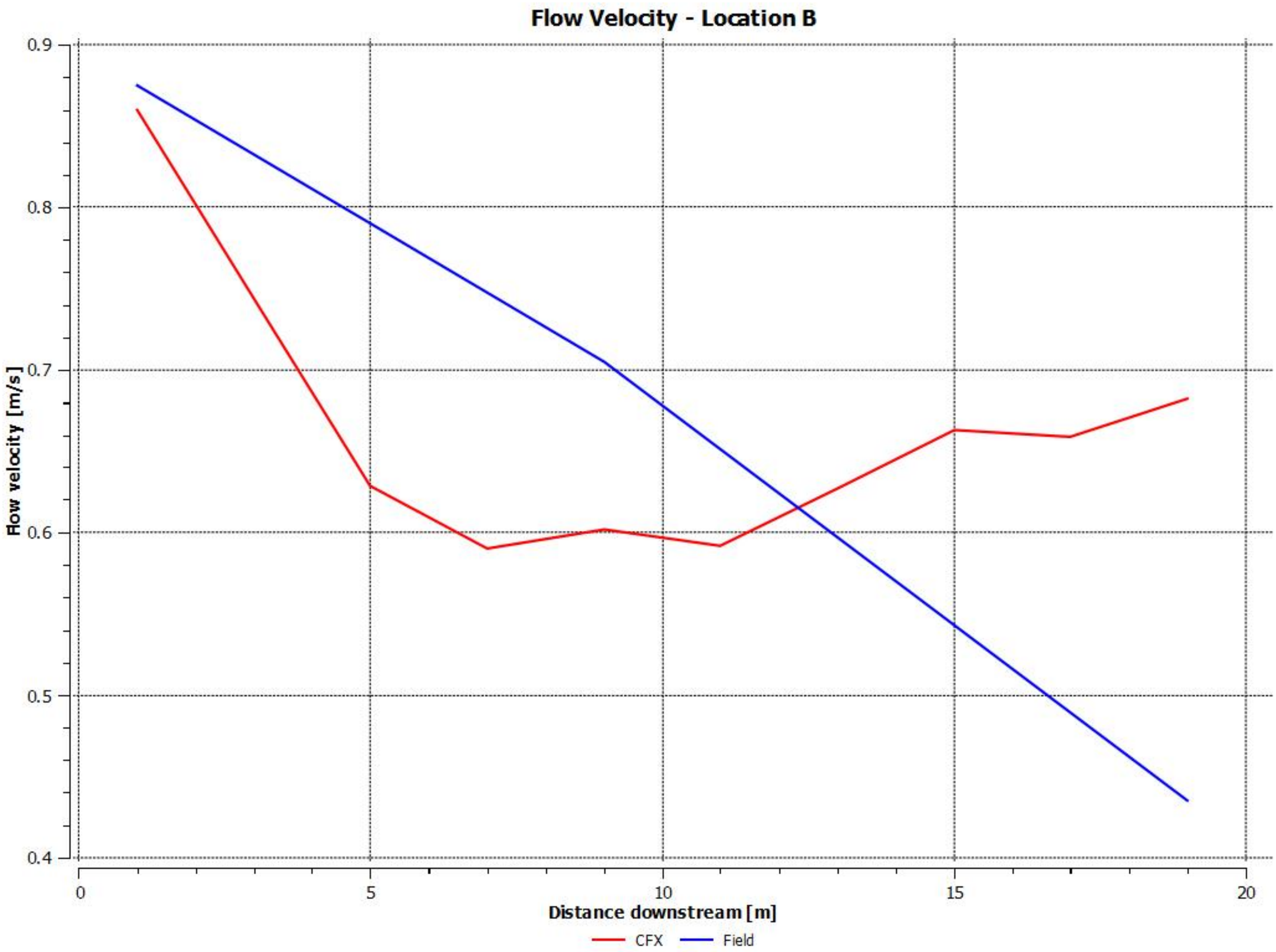


Chart . Discovery Drive, Baffle 2

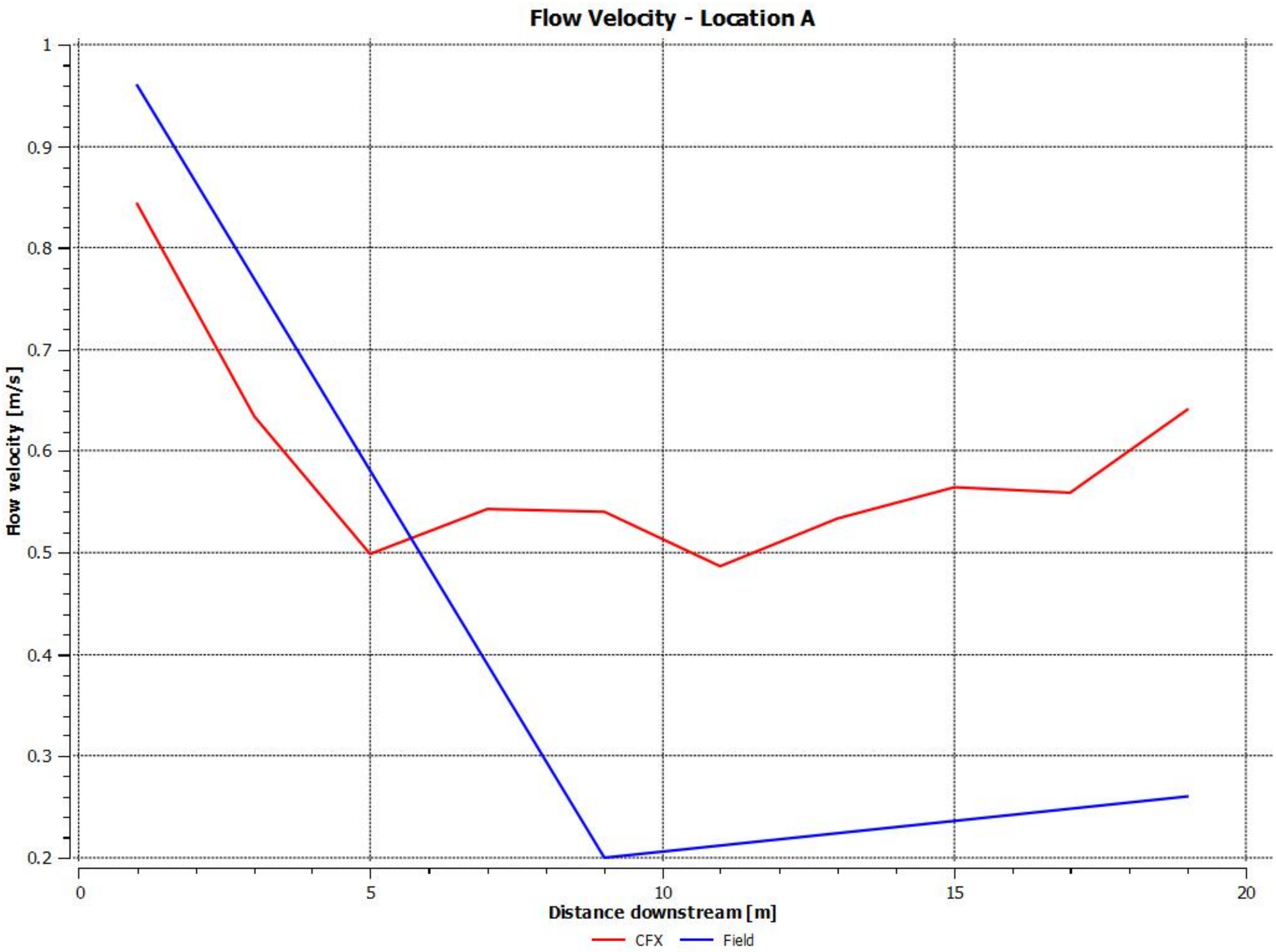


Chart . Discovery Drive, Baffle 2

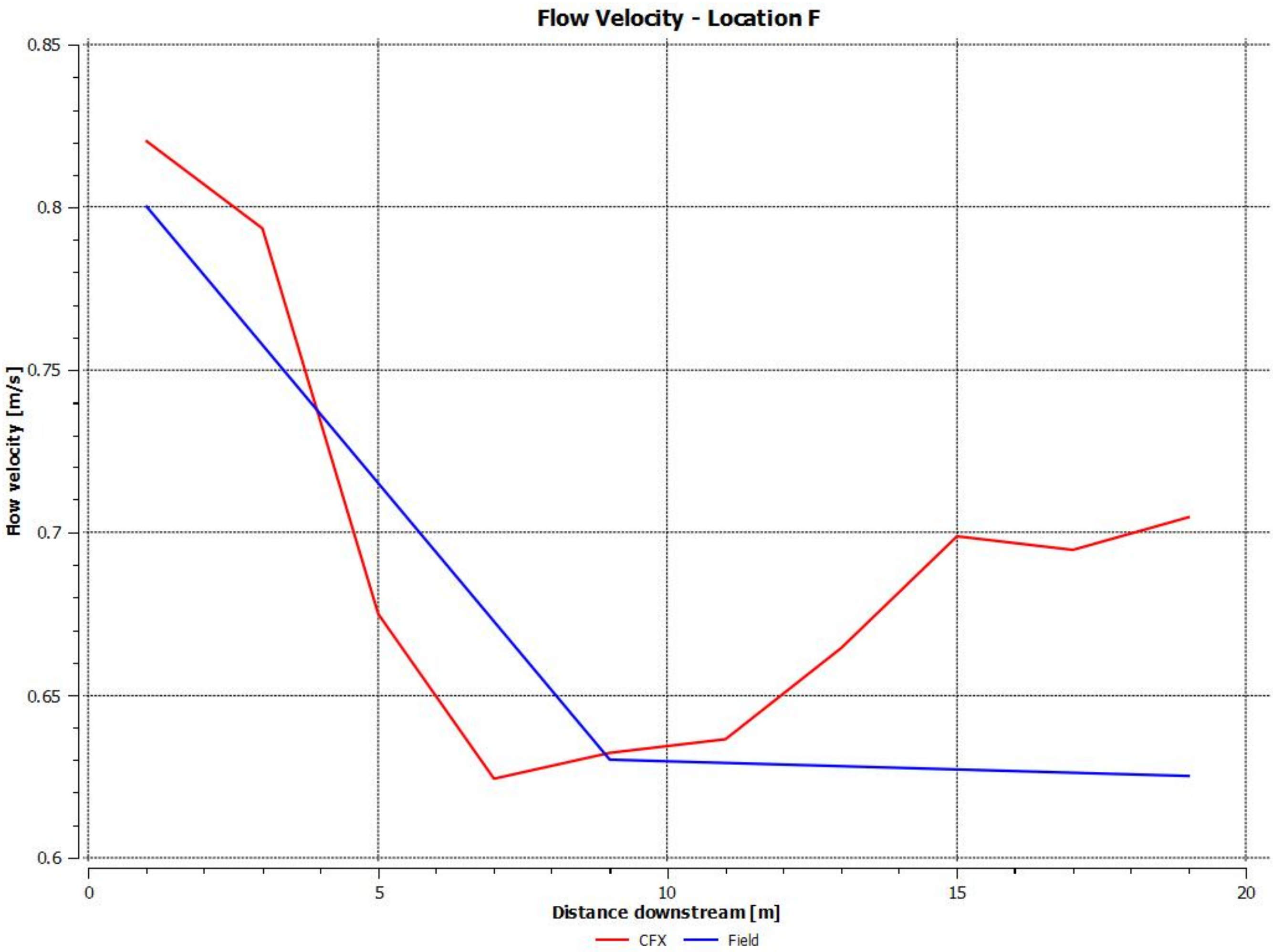


Chart . Discovery Drive, Baffle 2

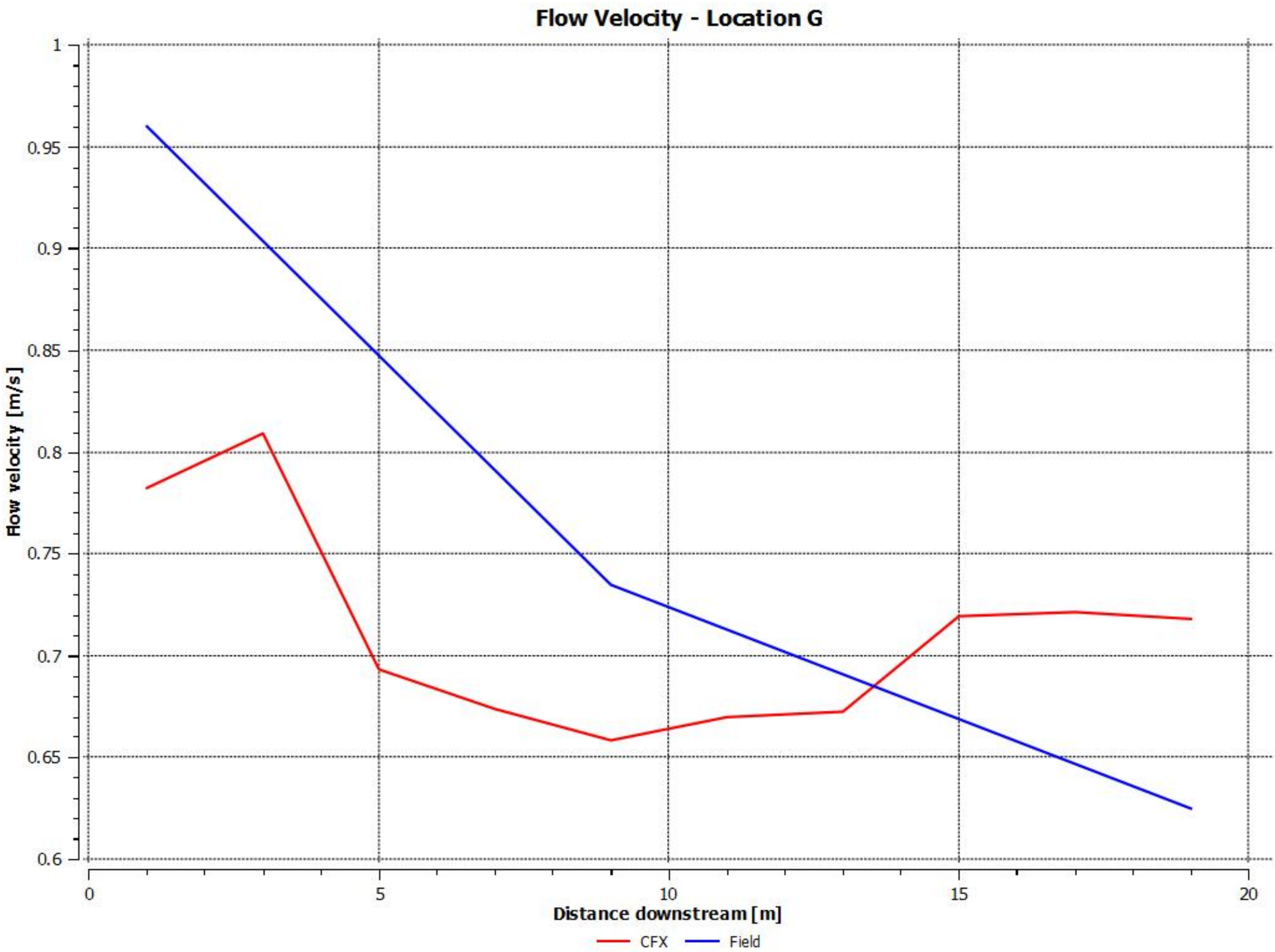
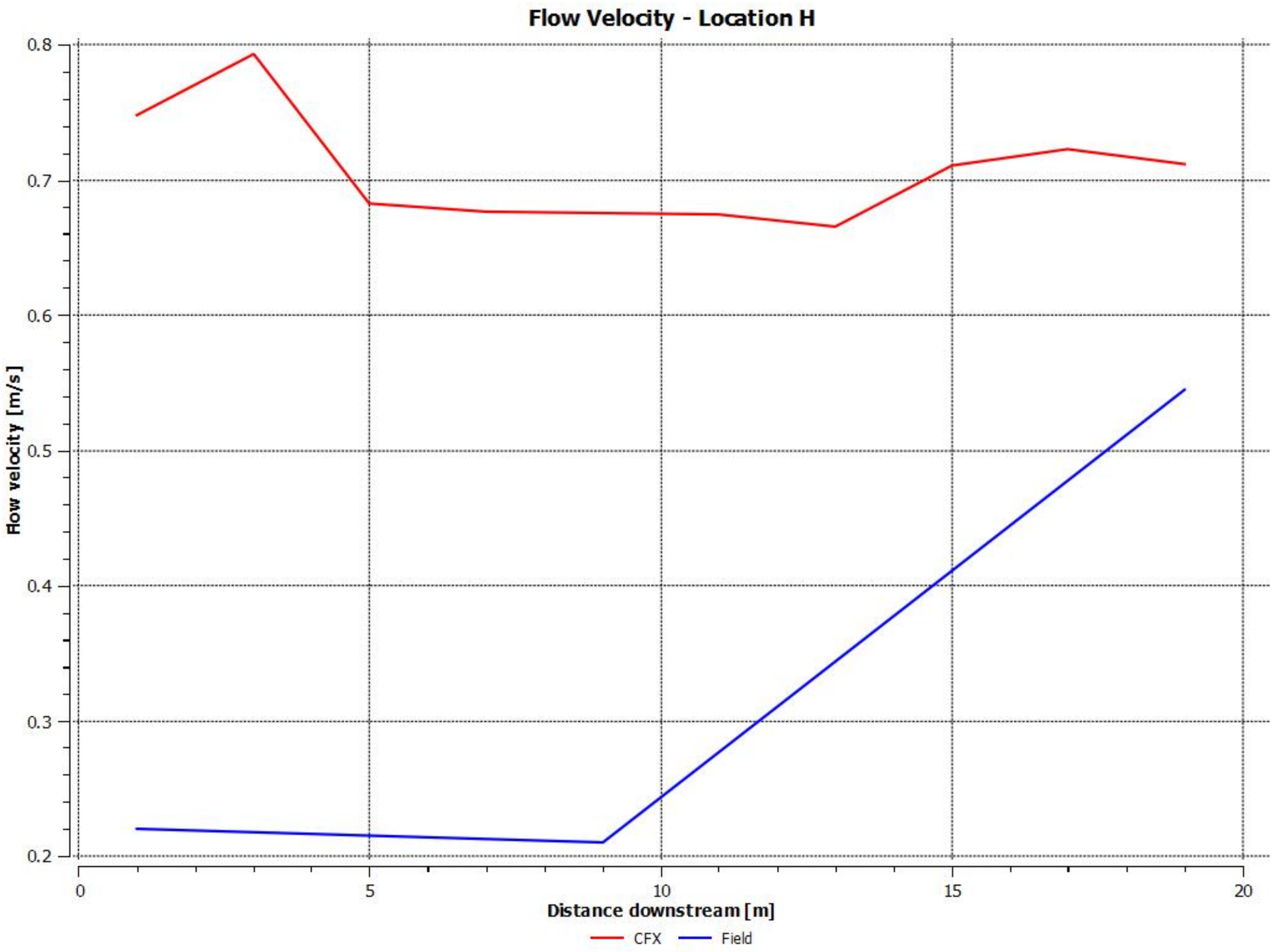


Chart . Discovery Drive, Baffle 2


Flow Velocity - Location H
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
5
10
15
20
Distance downstream [m]
CFX
Field

Appendix E

CFX Report - DAFF 'Green' Fish Passage Design - 200mm and 500mm flow depths

Title

DAFF 'Green' Fish Passage Design, 200mm flow depth

Author

Simon Petersen

Date

2013/10/10 13:37:22

Contents

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\green_200_mp_files\dp0\CFX\CFX\CFX_015.res
File Date	03 October 2013
File Time	03:12:18 PM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	461371	429792	0	0	0	429792	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	32.4561 [degree]	151.268 [degree]	100.153	28.1077	1	10

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	4.5000e-01 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - floor	
	Type	WALL
	Location	FLOOR1, FLOOR2, FLOOR3, FLOOR4, FLOOR5
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	3.0000e-02 [m]
	Boundary - walls_culvert	
	Type	WALL
	Location	WALL1, WALL2, WALL3, WALL4, WALL5, WALL6, WALL7, WALL8, WALL9, WALL10
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1. Velocity Profiles

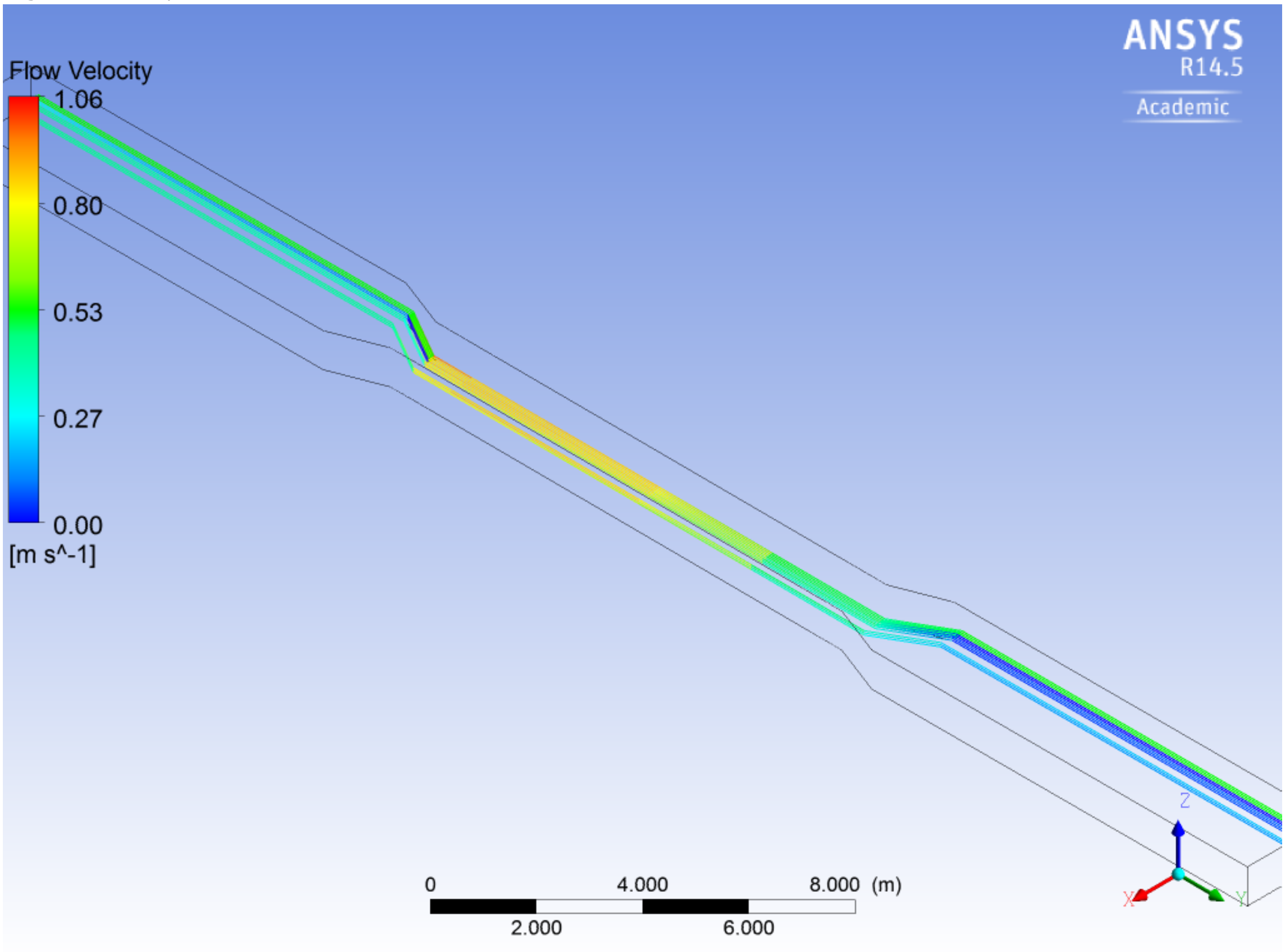


Chart 1.

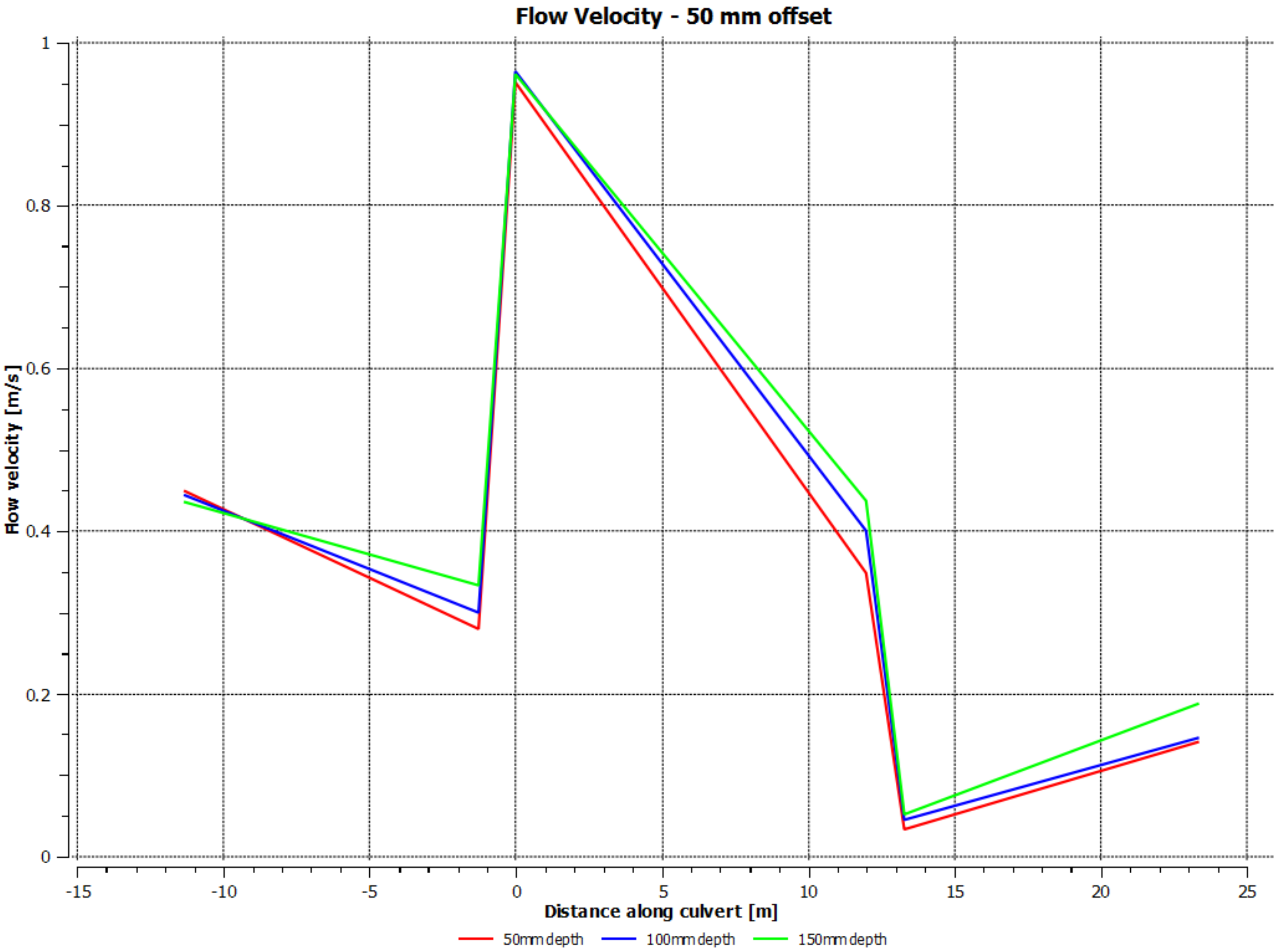

Flow Velocity - 50 mm offset
Flow velocity [m/s]
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 2.

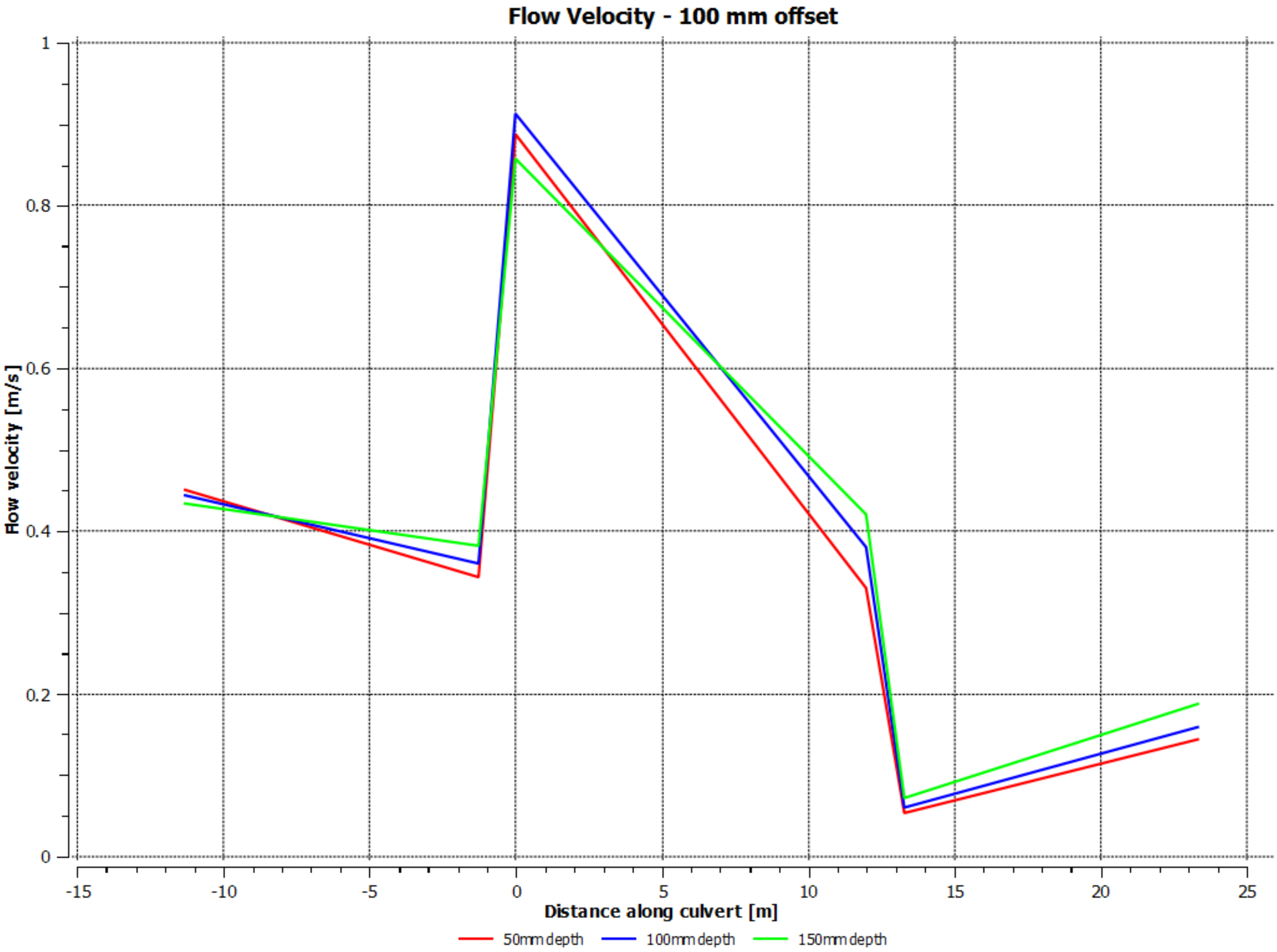

Flow Velocity - 100 mm offset
Flow velocity [m/s]
0
0.2
0.4
0.6
0.8
1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 3.

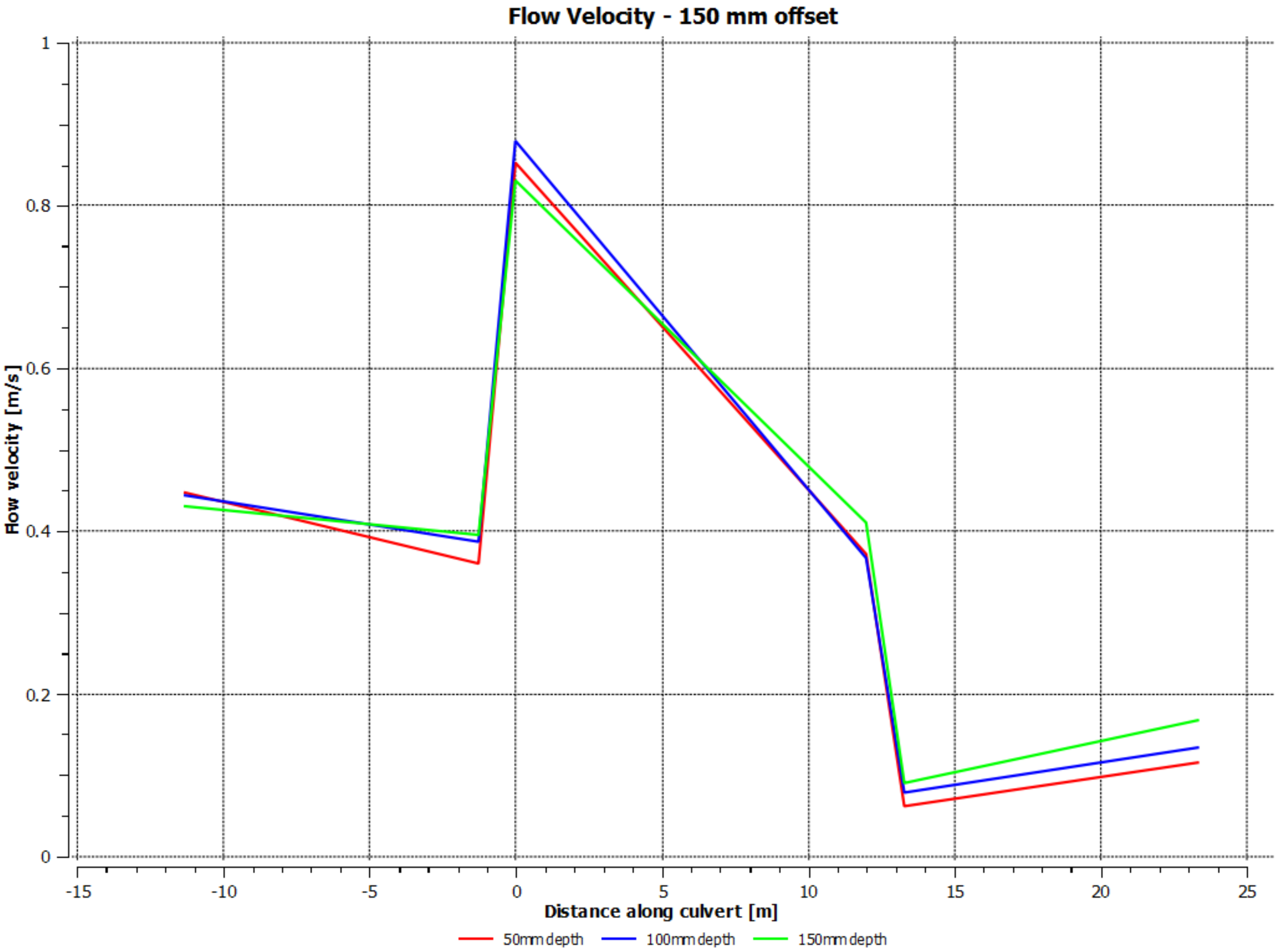

Flow Velocity - 150 mm offset
Flow velocity [m/s]
0
0.2
0.4
0.6
0.8
1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 4.

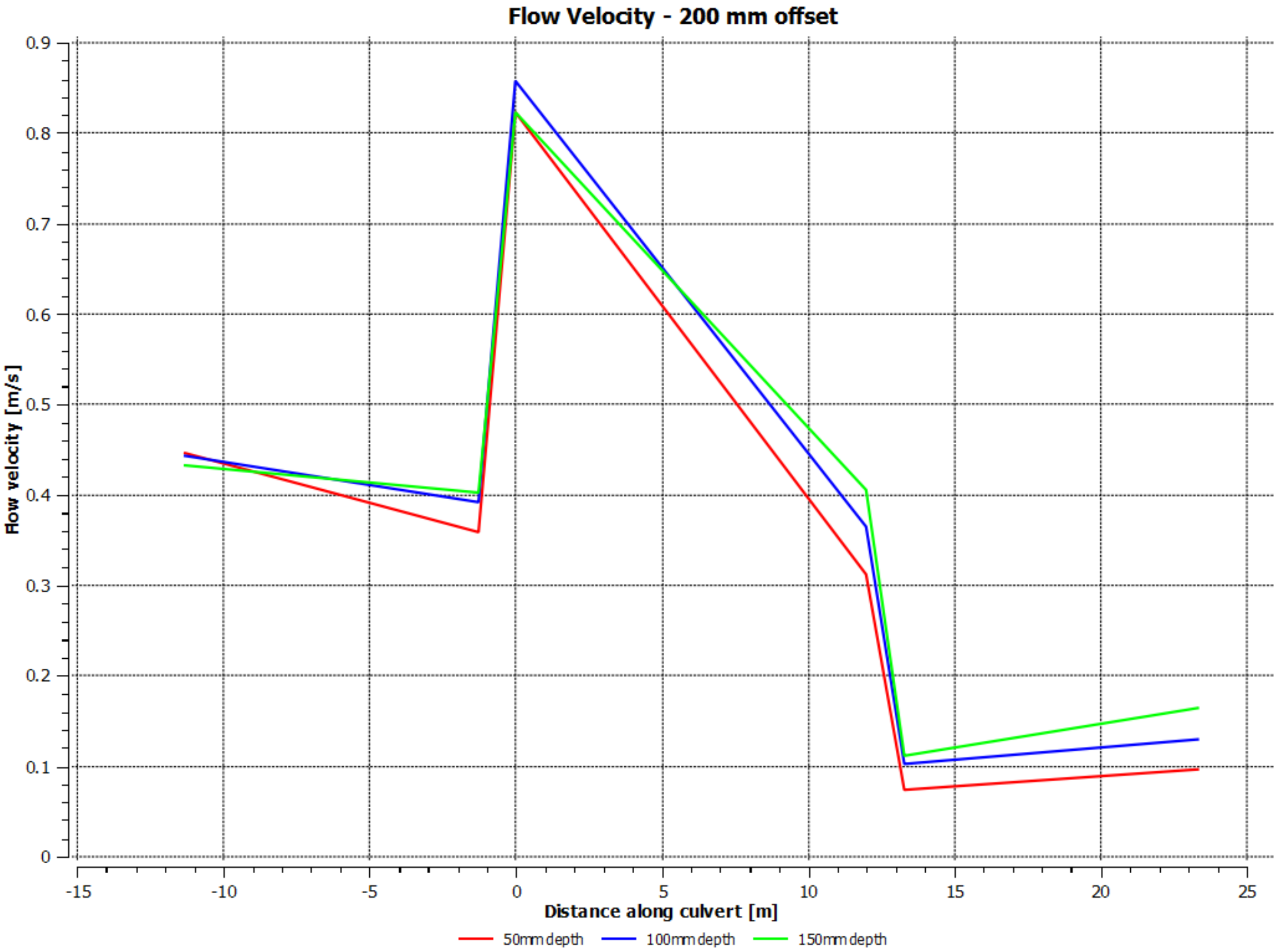

Flow Velocity - 200 mm offset
Flow velocity [m/s]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 5.

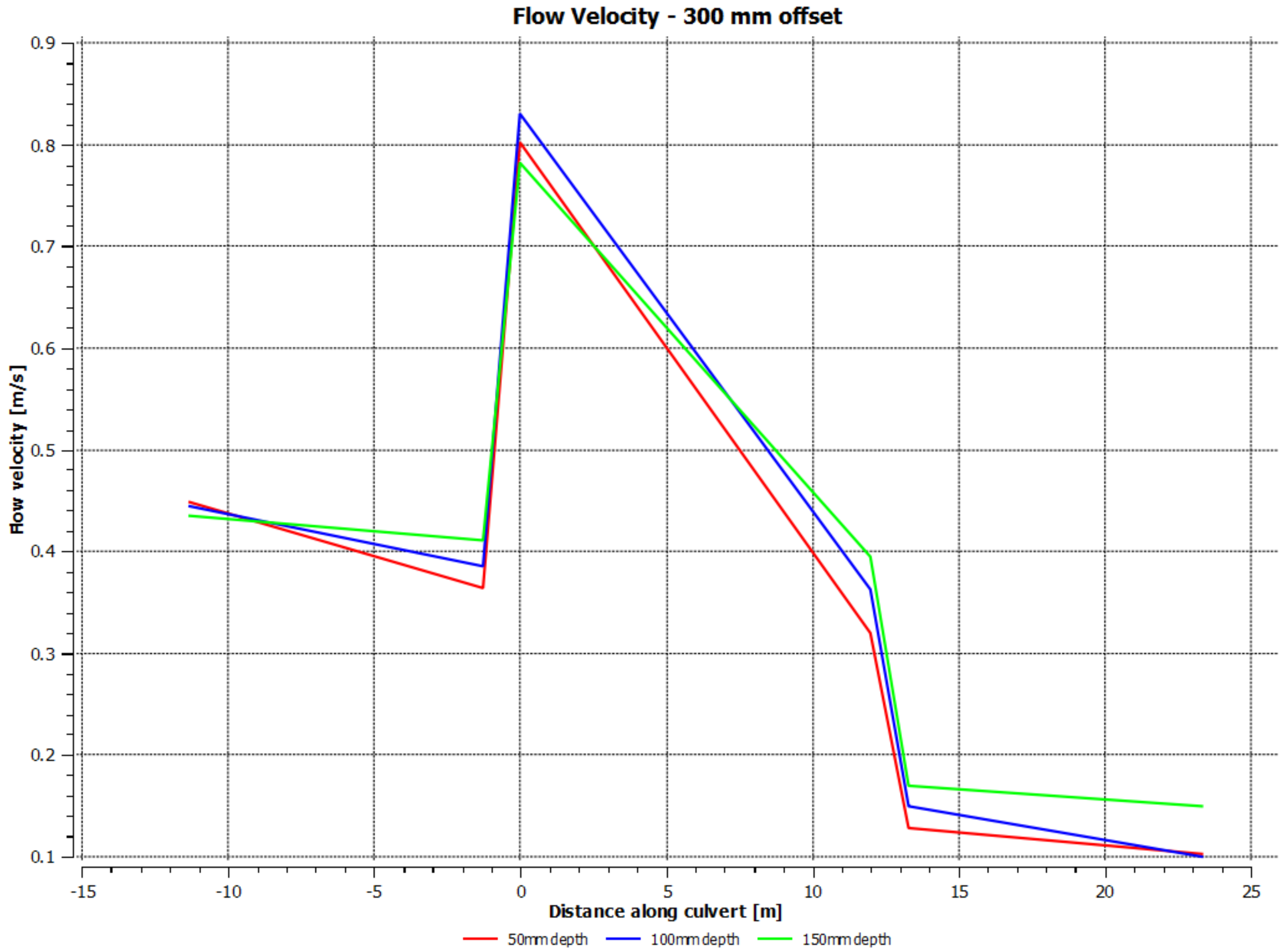
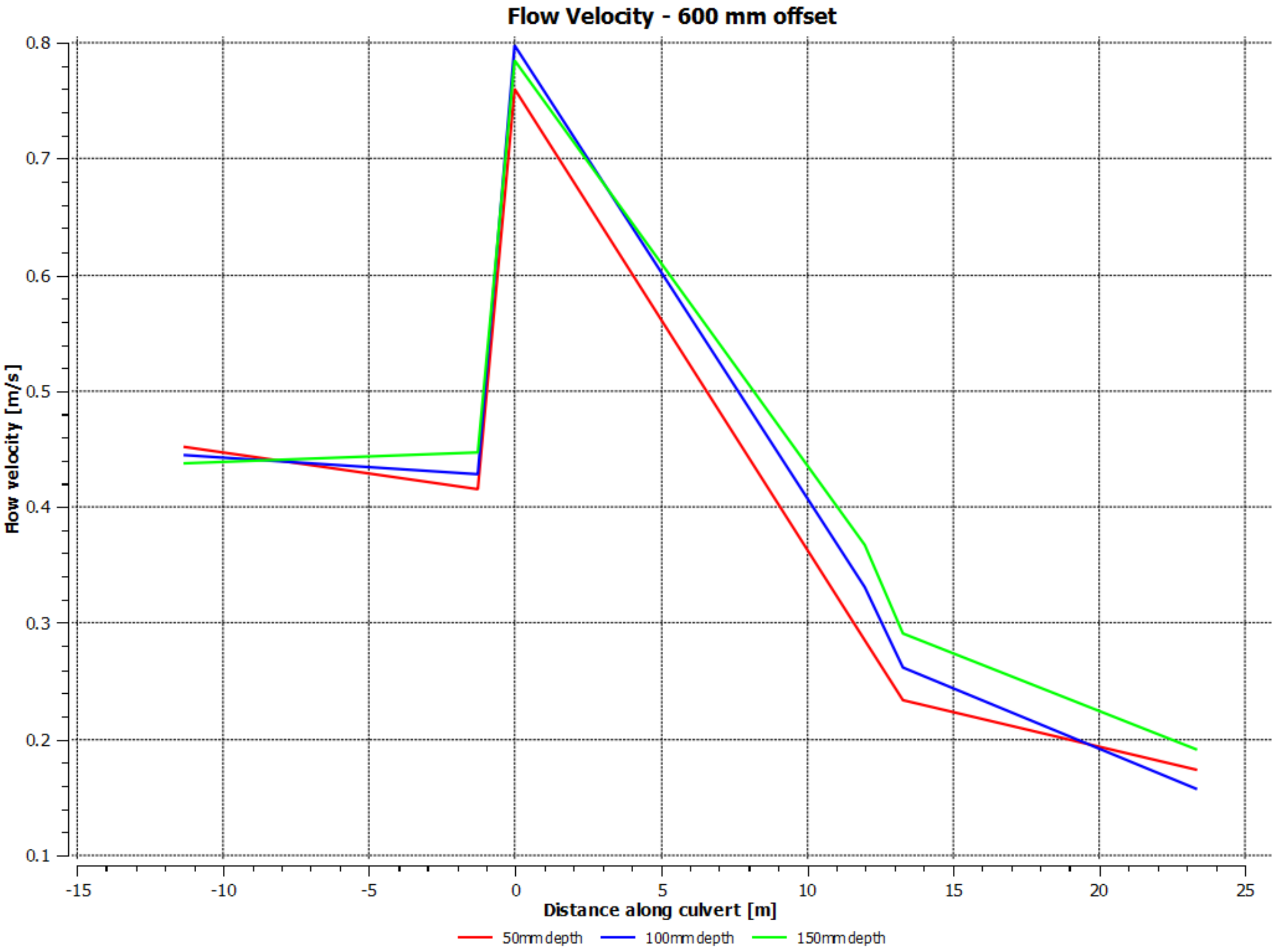

Flow Velocity - 300 mm offset
Flow velocity [m/s]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Title

DAFF 'Green' Fish Passage Design, 500mm flow depth

Author

Simon Petersen

Date

2013/10/10 14:35:18

Contents

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\green_500_mp_files\dp0\CFX\CFX\CFX_014.res
File Date	03 October 2013
File Time	03:52:38 PM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	461371	429792	0	0	0	429792	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	32.4561 [degree]	151.268 [degree]	100.153	28.1077	1	10

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	1.0000e+00 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - floor	
	Type	WALL
	Location	FLOOR1, FLOOR2, FLOOR3, FLOOR4, FLOOR5
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	3.0000e-02 [m]
	Boundary - walls_culvert	
	Type	WALL
	Location	WALL1, WALL2, WALL3, WALL4, WALL5, WALL6, WALL7, WALL8, WALL9, WALL10
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1. Velocity profiles

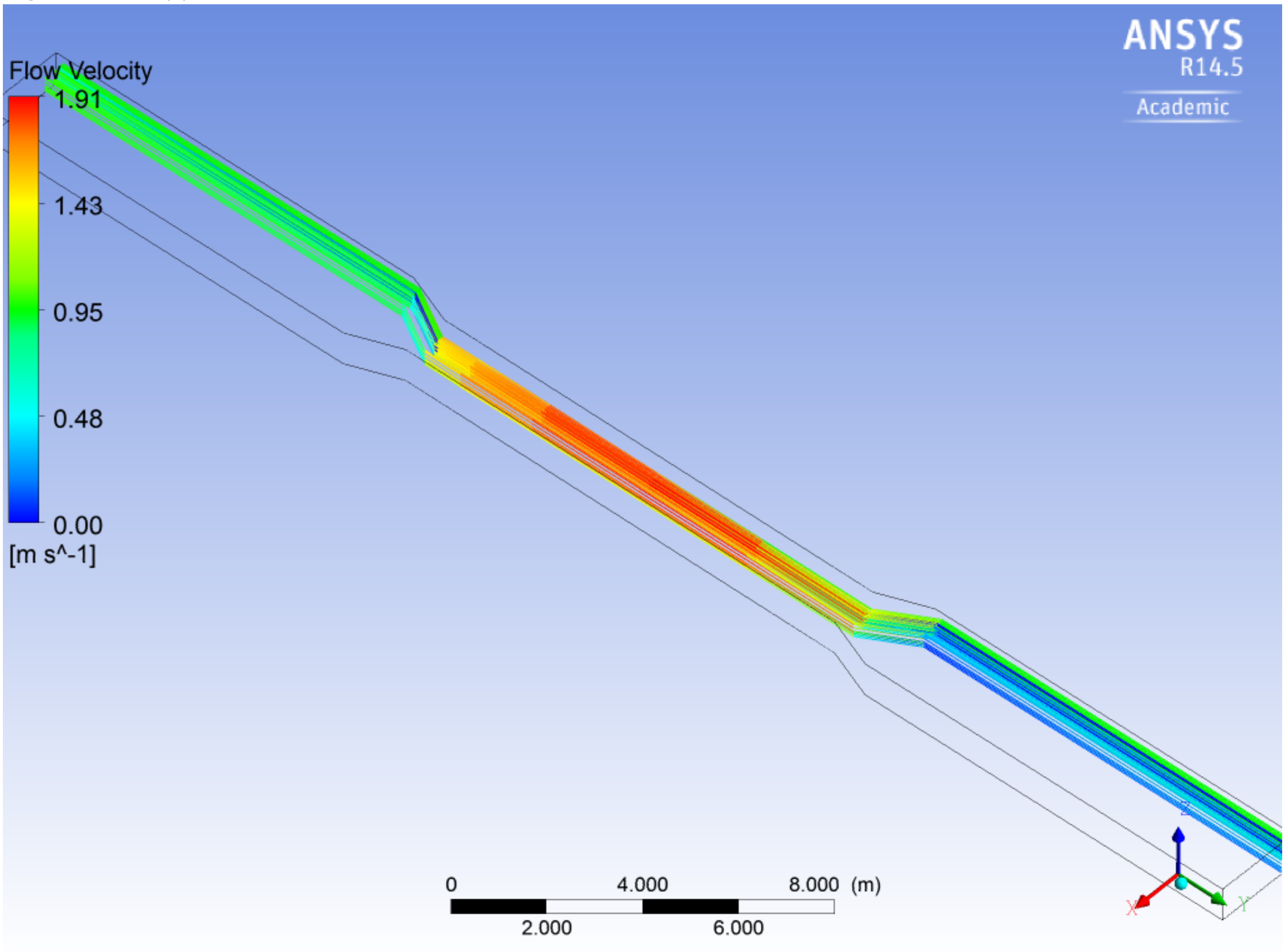


Chart 1.

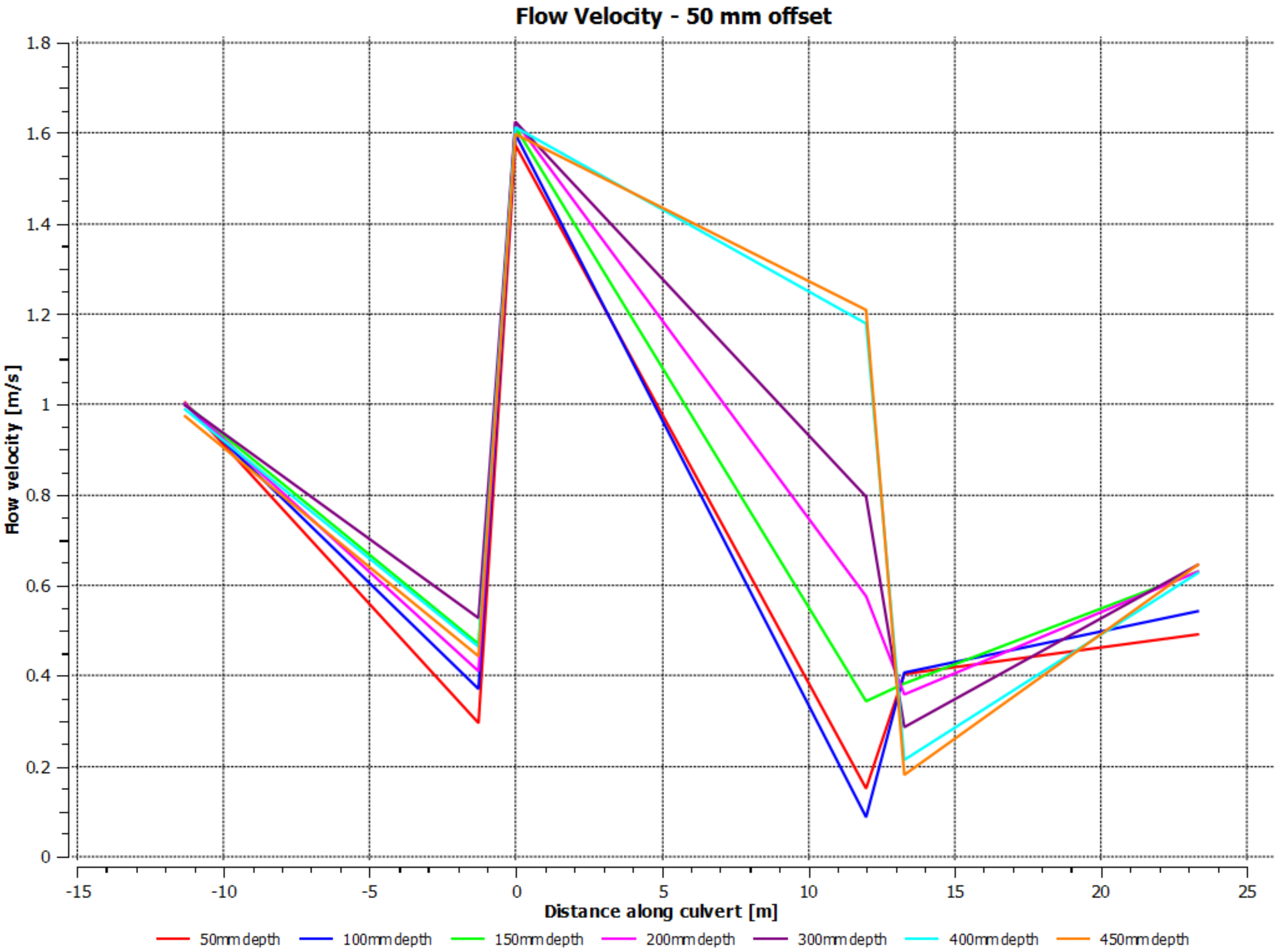

Flow Velocity - 50 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 2.

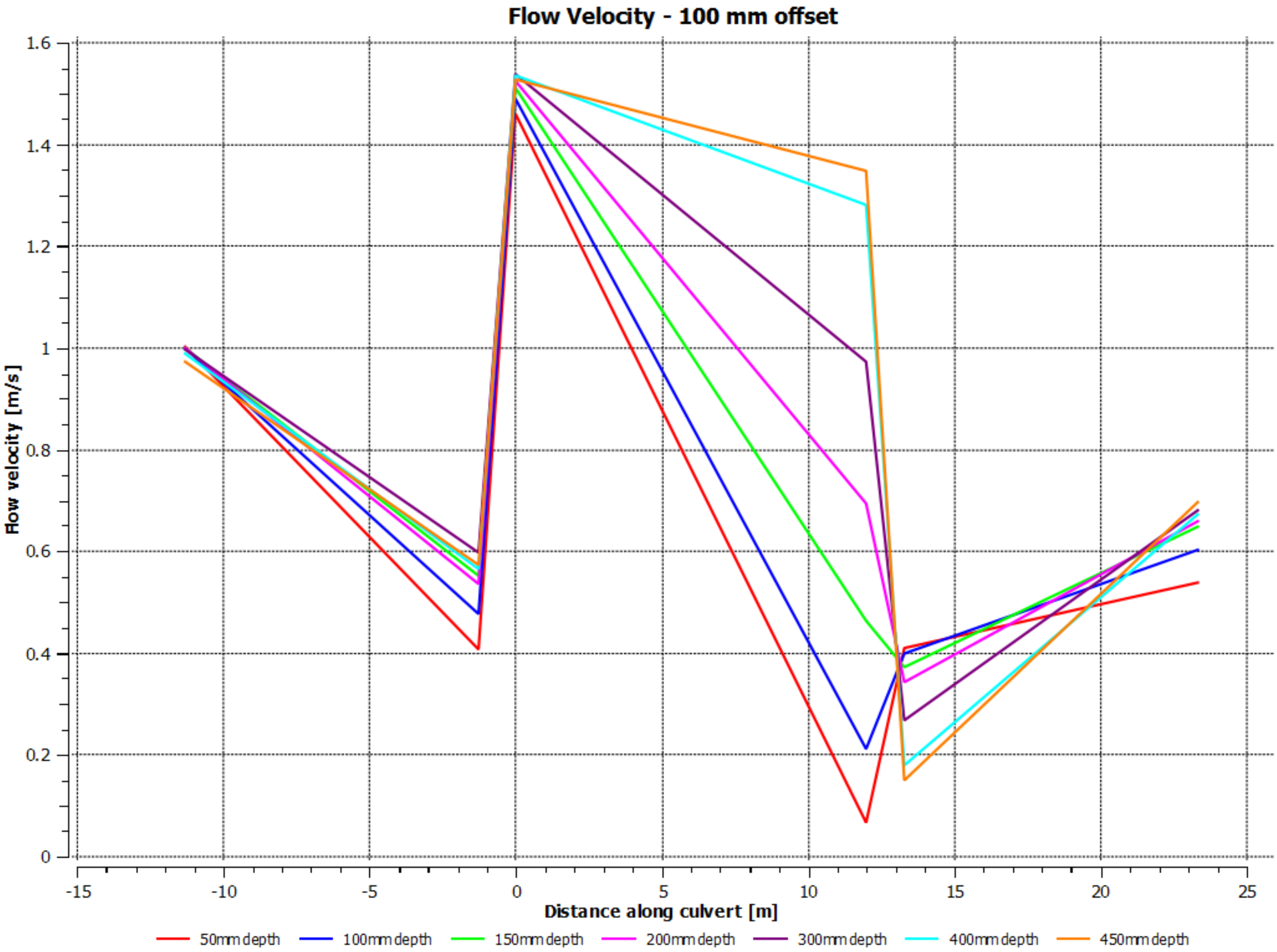

Flow Velocity - 100 mm offset
Flow velocity [m/s]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 3.

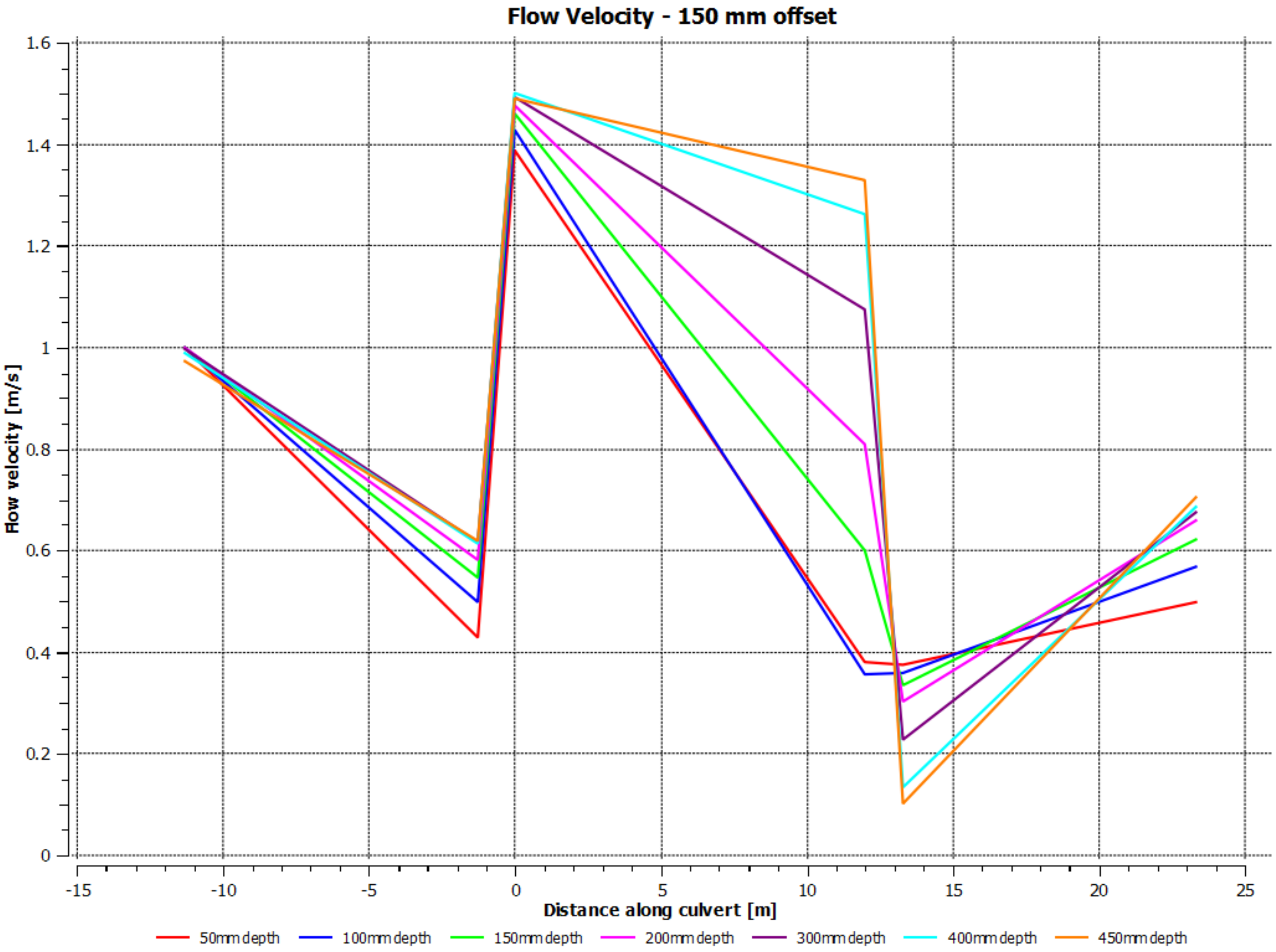

Flow Velocity - 150 mm offset
Flow velocity [m/s]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 4.

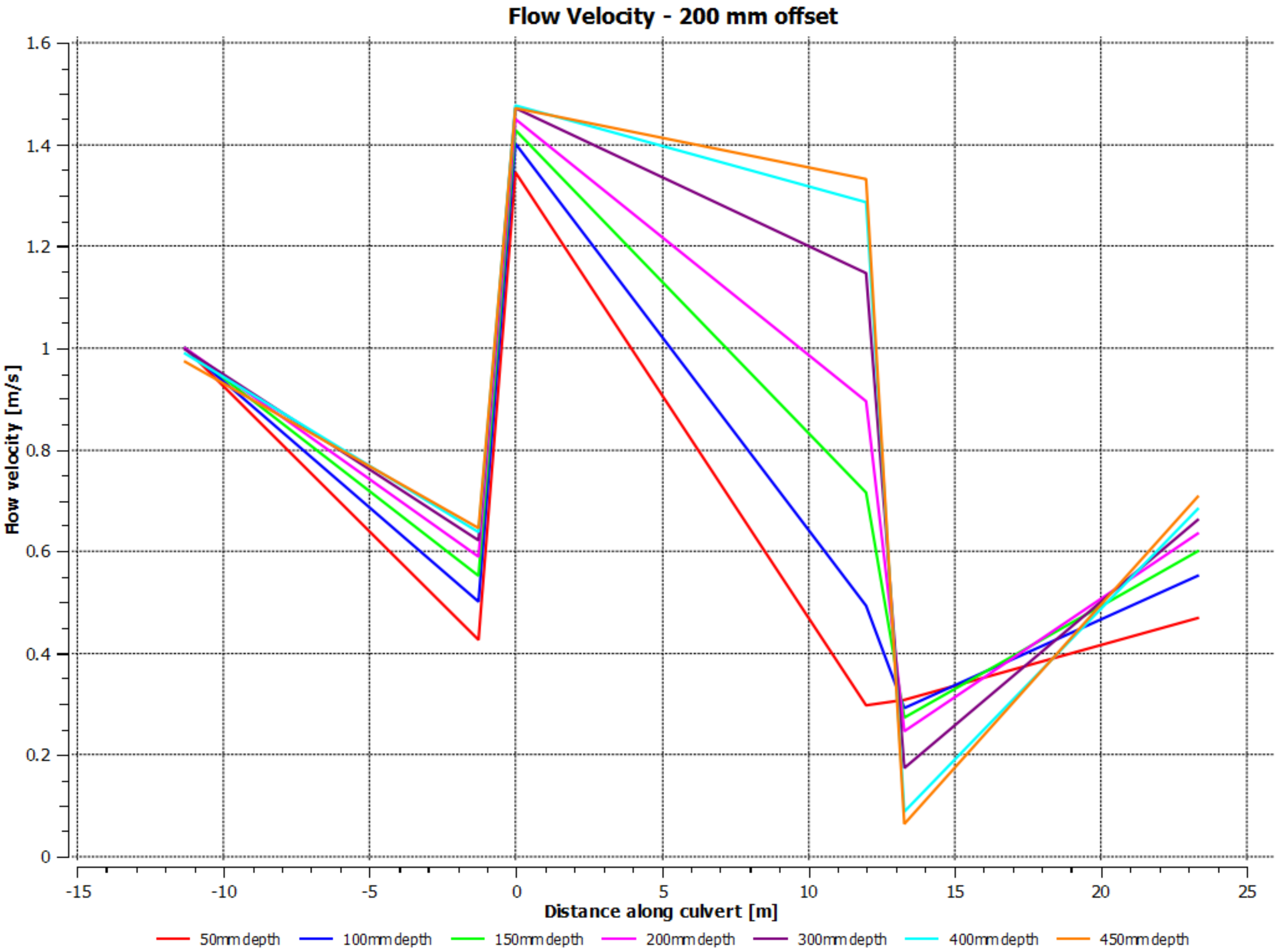

Flow Velocity - 200 mm offset
Flow velocity [m/s]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 5.

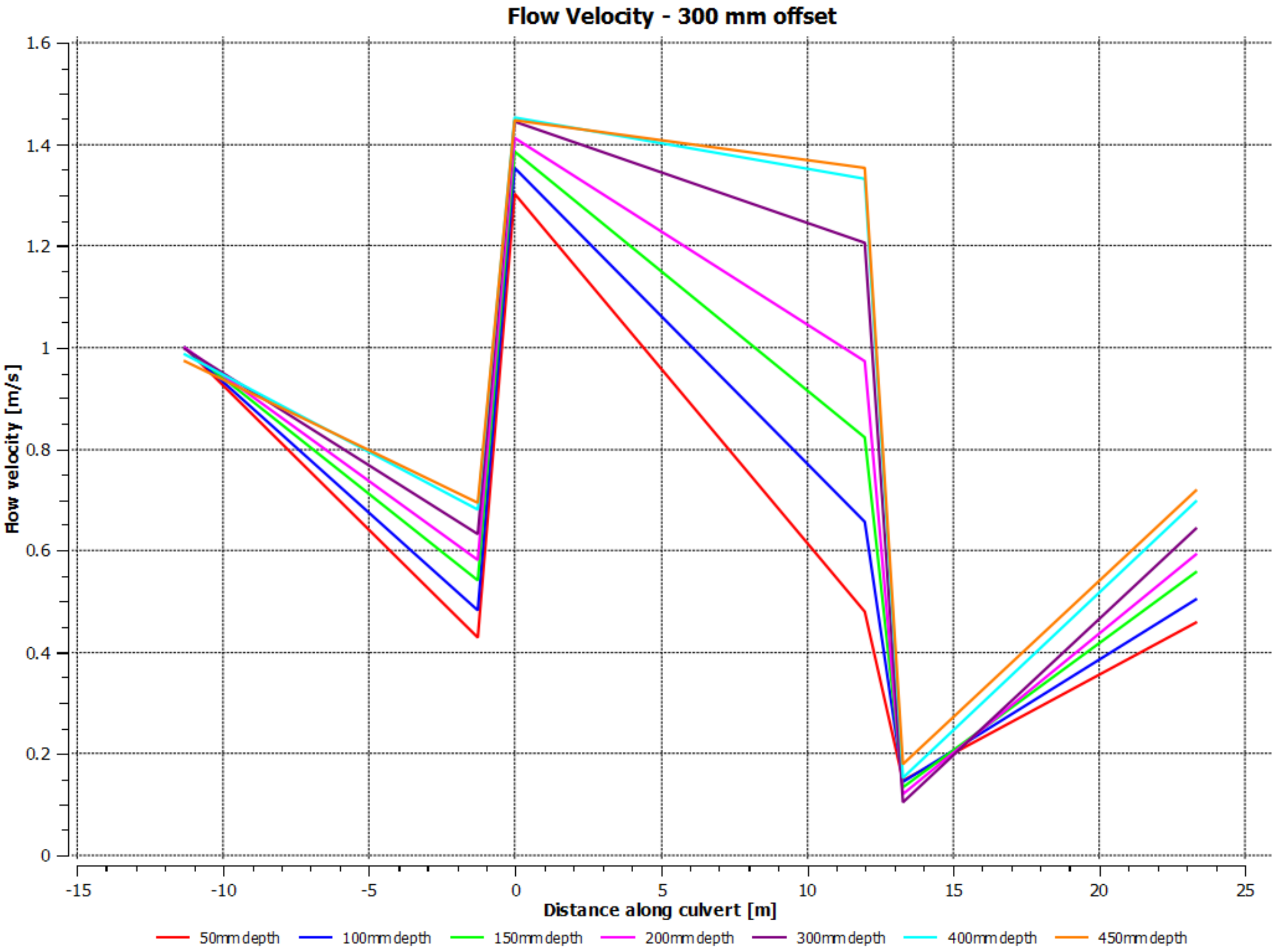
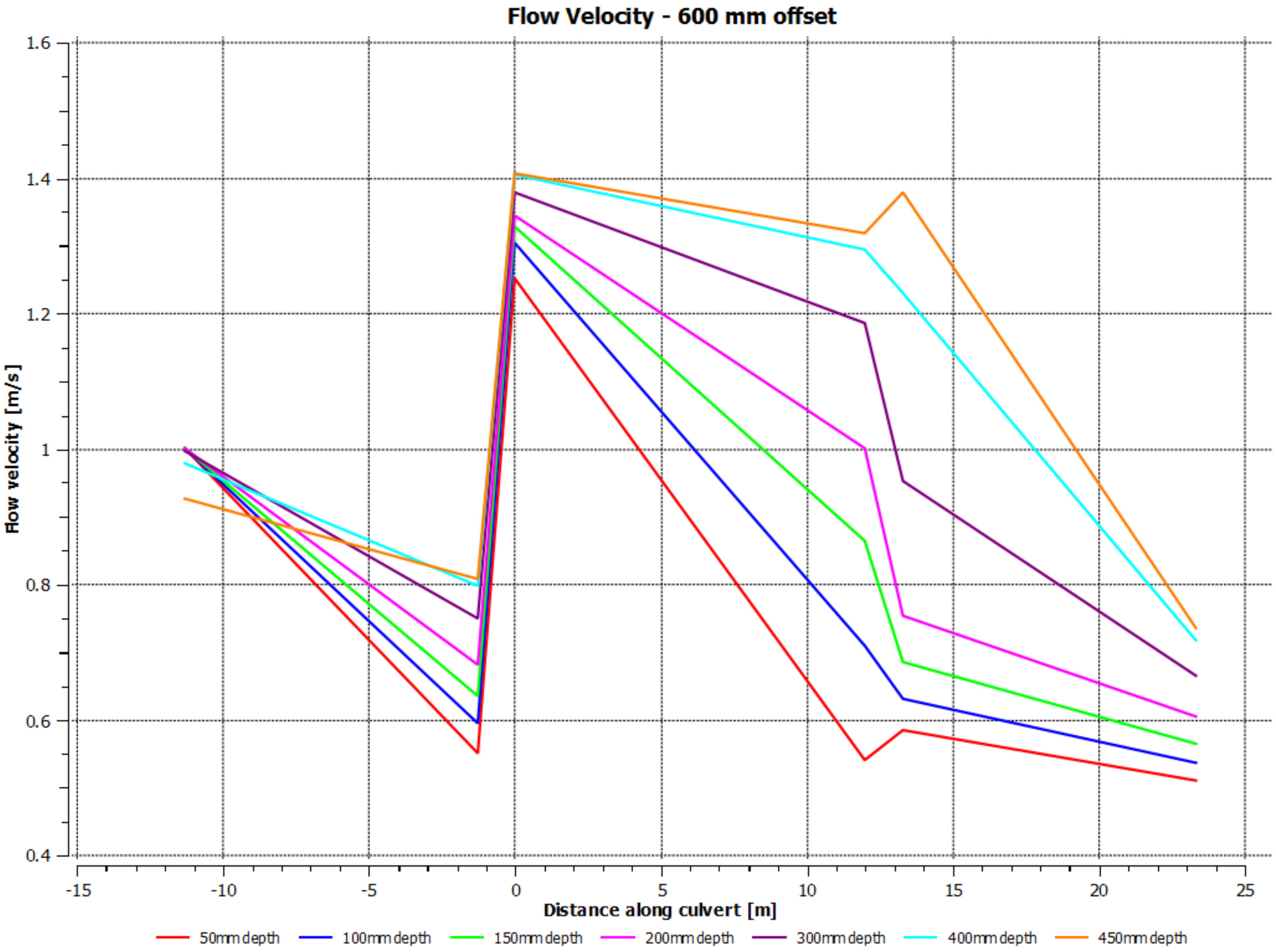

Flow Velocity - 300 mm offset
Flow velocity [m/s]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
1.6
1.4
1.2
1
0.8
0.6
0.4
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Appendix F

CFX Report - DAFF 'Amber' Fish Passage Design - 200mm and 500mm flow depths

Title

DAFF 'Amber' Fish Passage Design, 200mm flow depth

Author

Simon Petersen

Date

2013/10/10 14:05:37

Contents

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\amber_200_mp_files\dp0\CFX\CFX\CFX_015.res
File Date	06 October 2013
File Time	10:35:00 AM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	507129	480480	0	0	0	480480	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	60.0295 [degree]	119.971 [degree]	100.153	9.30341	1	8

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	5.0000e-01 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - floor	
	Type	WALL
	Location	FLOOR1, FLOOR2, FLOOR3, FLOOR4, FLOOR5
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	3.0000e-02 [m]
	Boundary - walls_culvert	
	Type	WALL
	Location	WALL1, WALL2, WALL3, WALL4, WALL5, WALL6, WALL7, WALL8, WALL9, WALL10
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1. Velocity Profiles

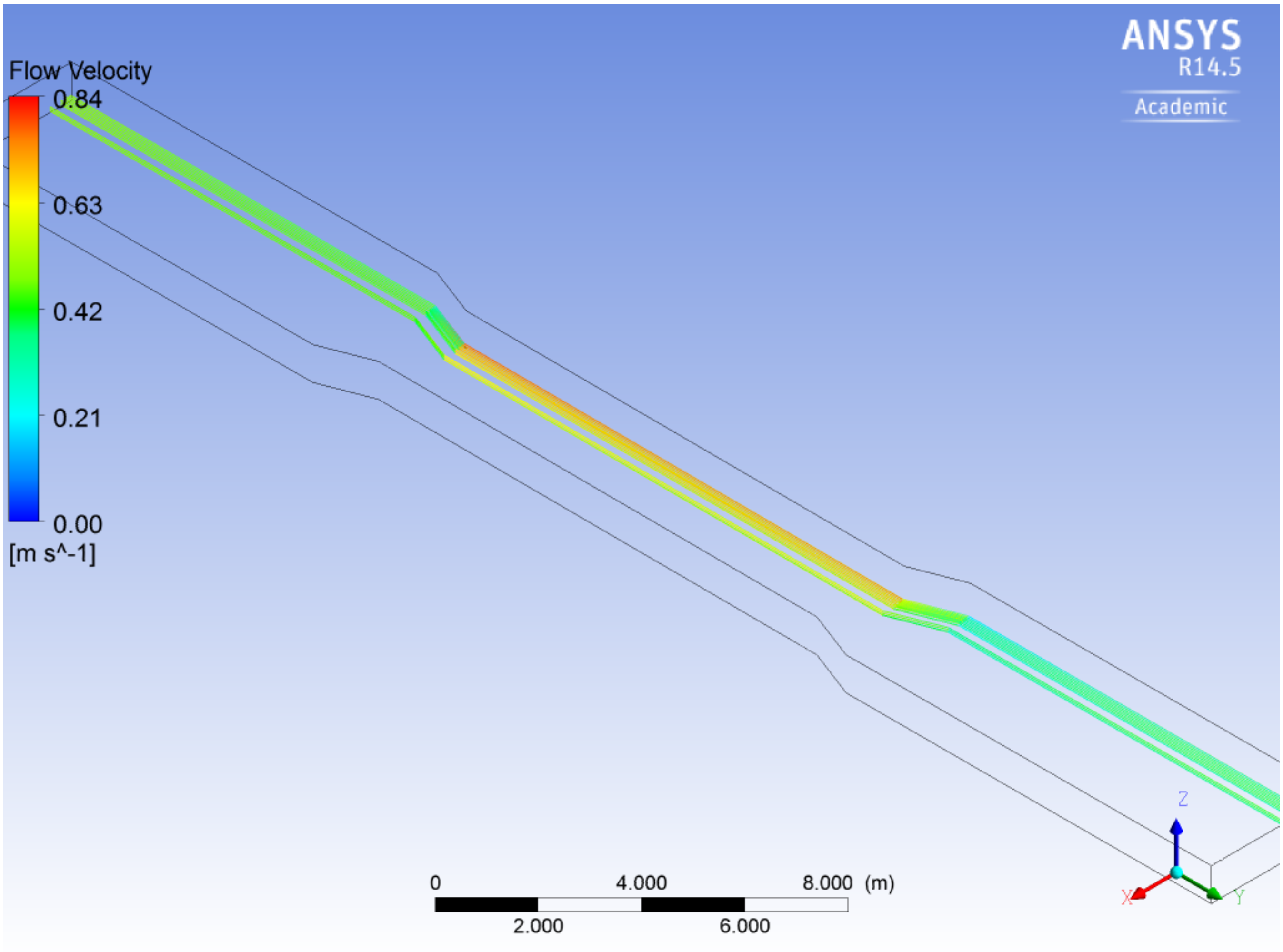


Chart 1.

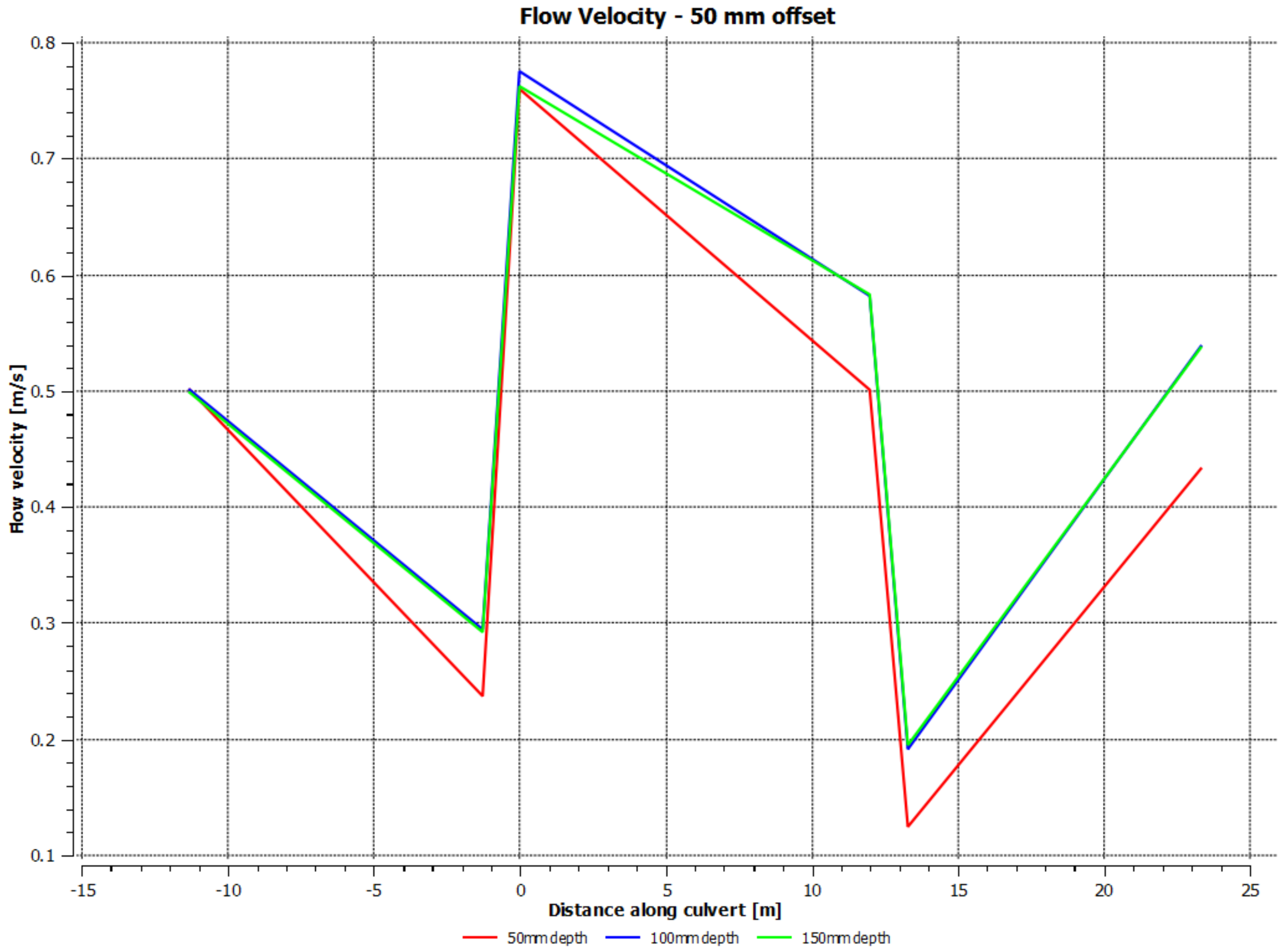

Flow Velocity - 50 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 2.

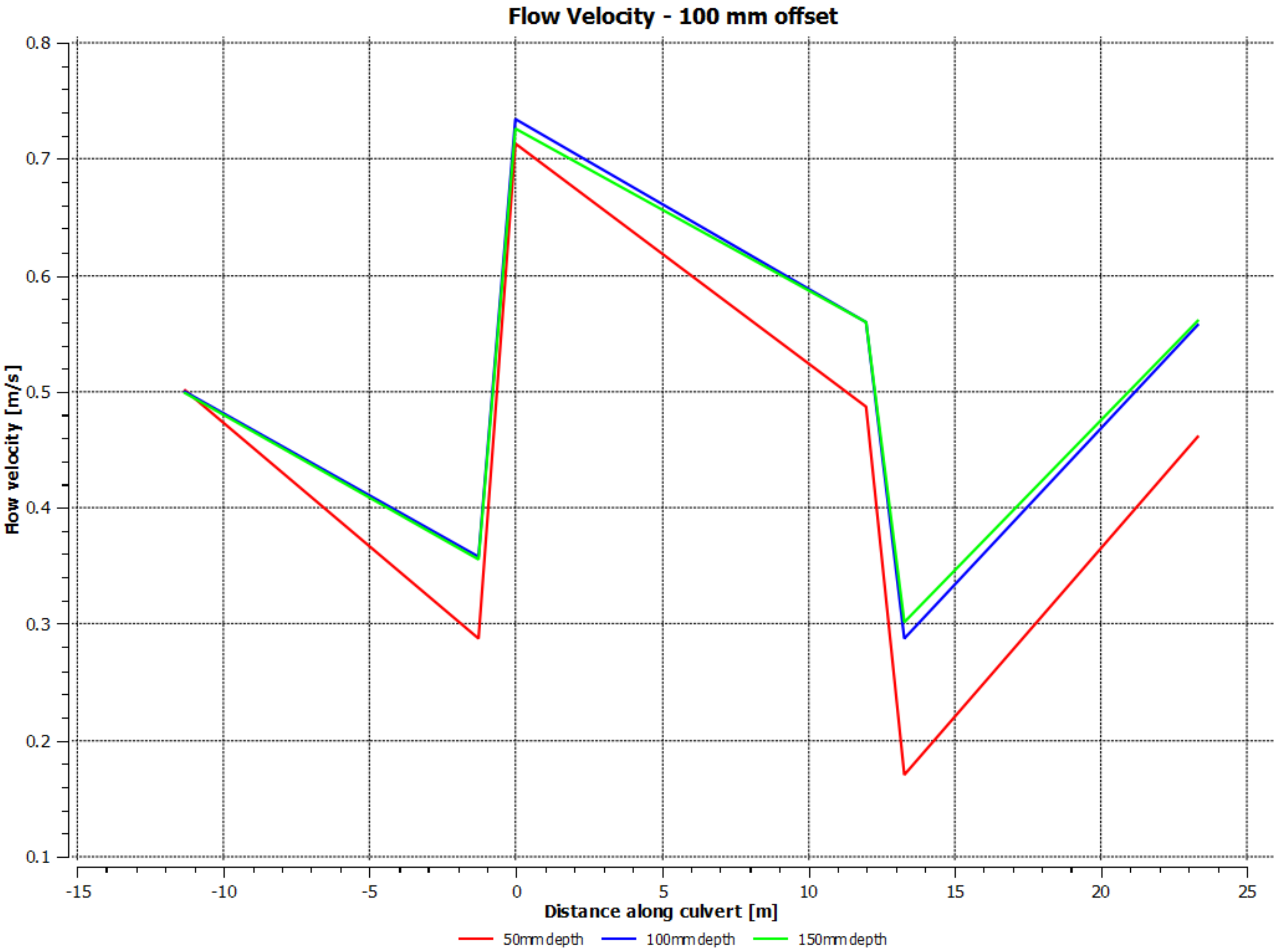

Flow Velocity - 100 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 3.

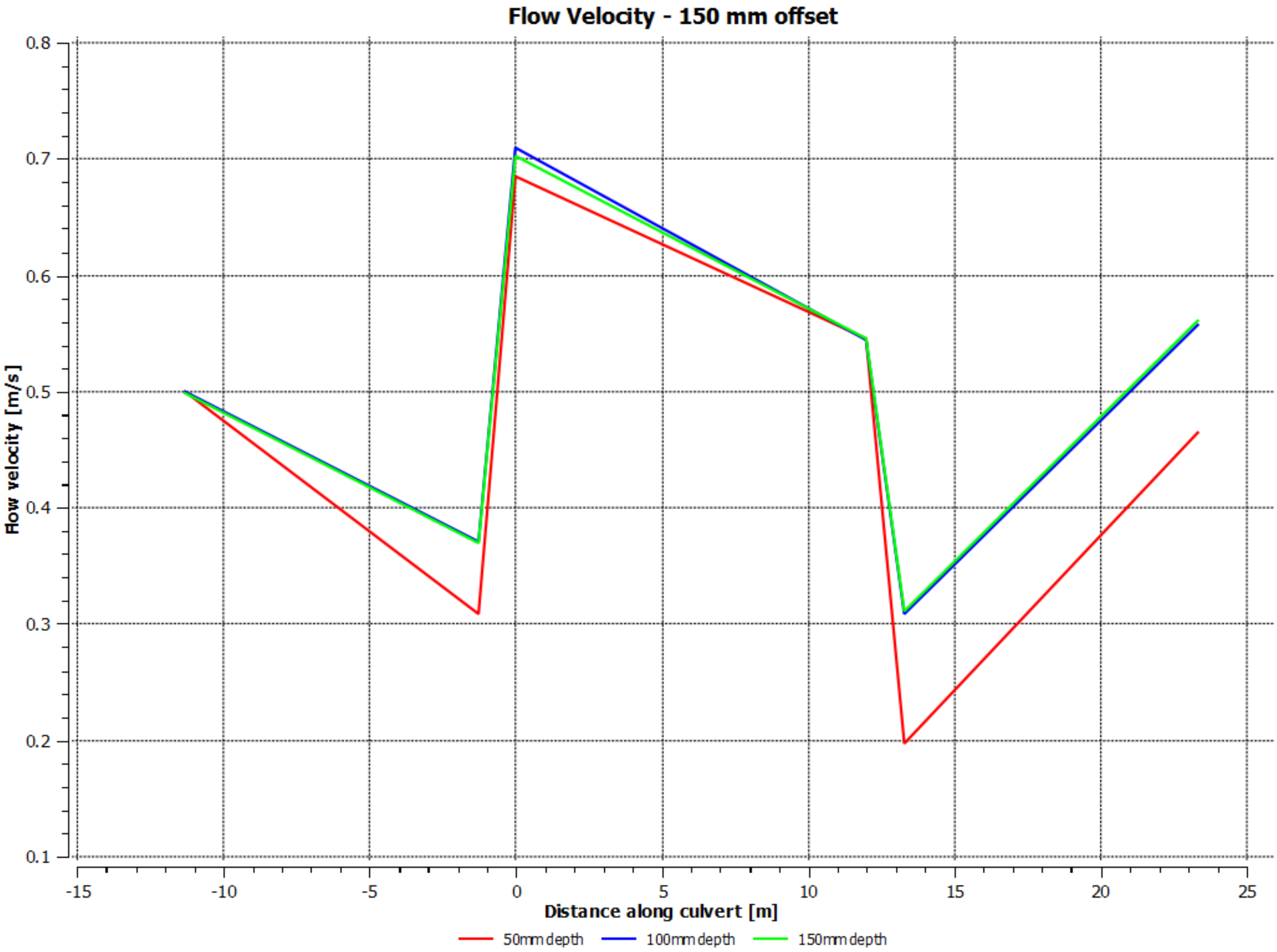

Flow Velocity - 150 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 4.

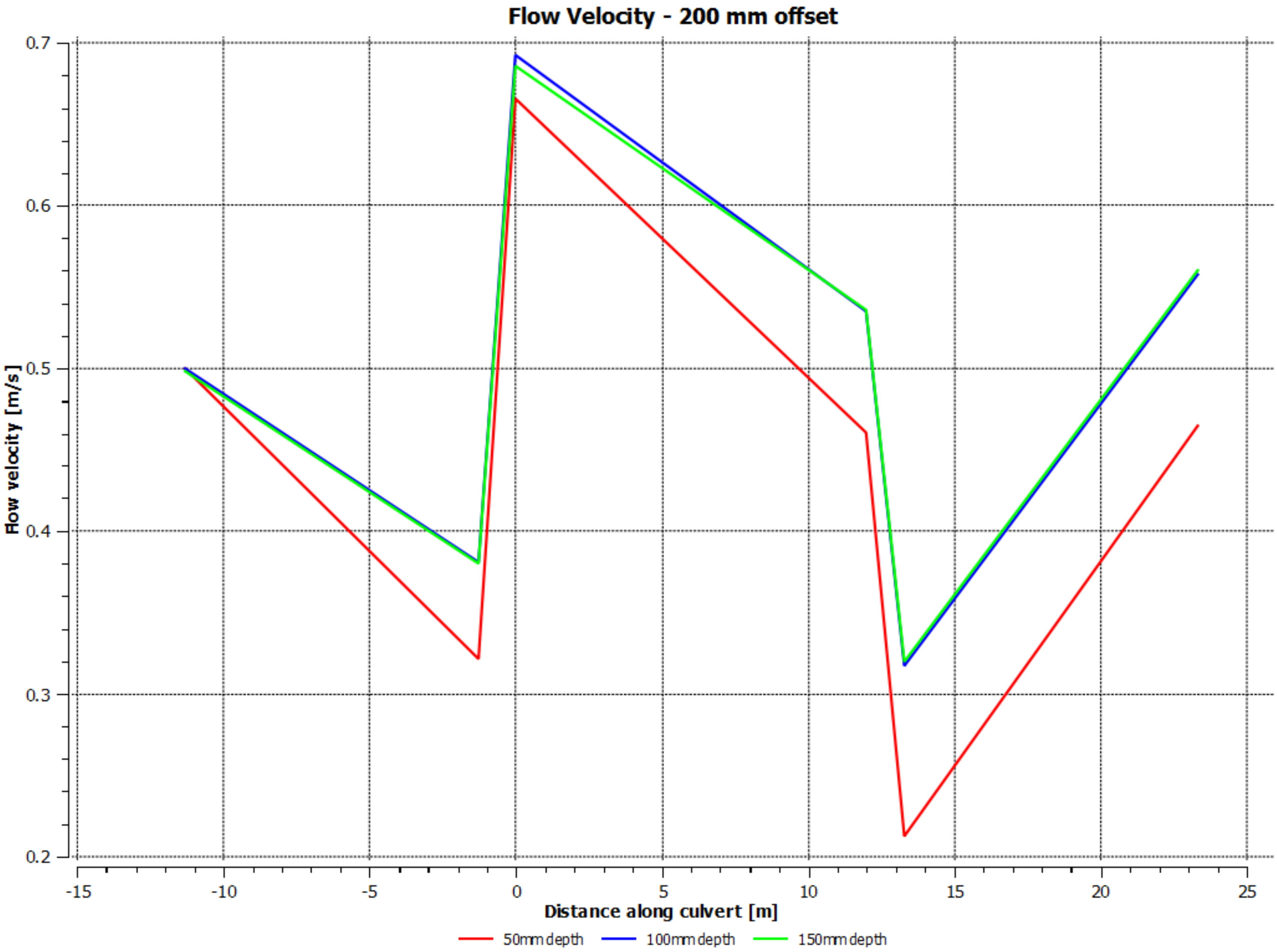

Flow Velocity - 200 mm offset
Flow velocity [m/s]
0.7
0.6
0.5
0.4
0.3
0.2
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 5.

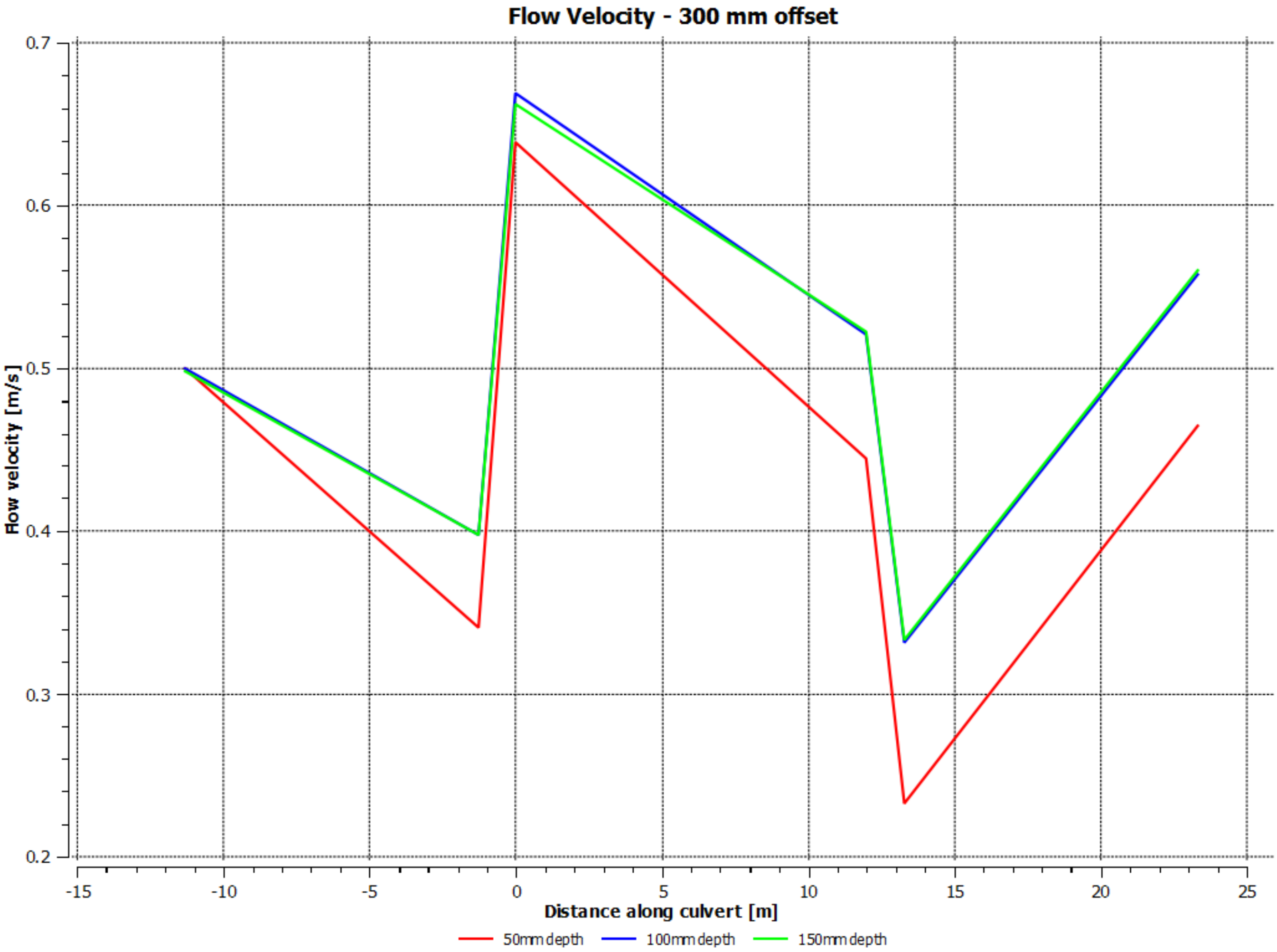
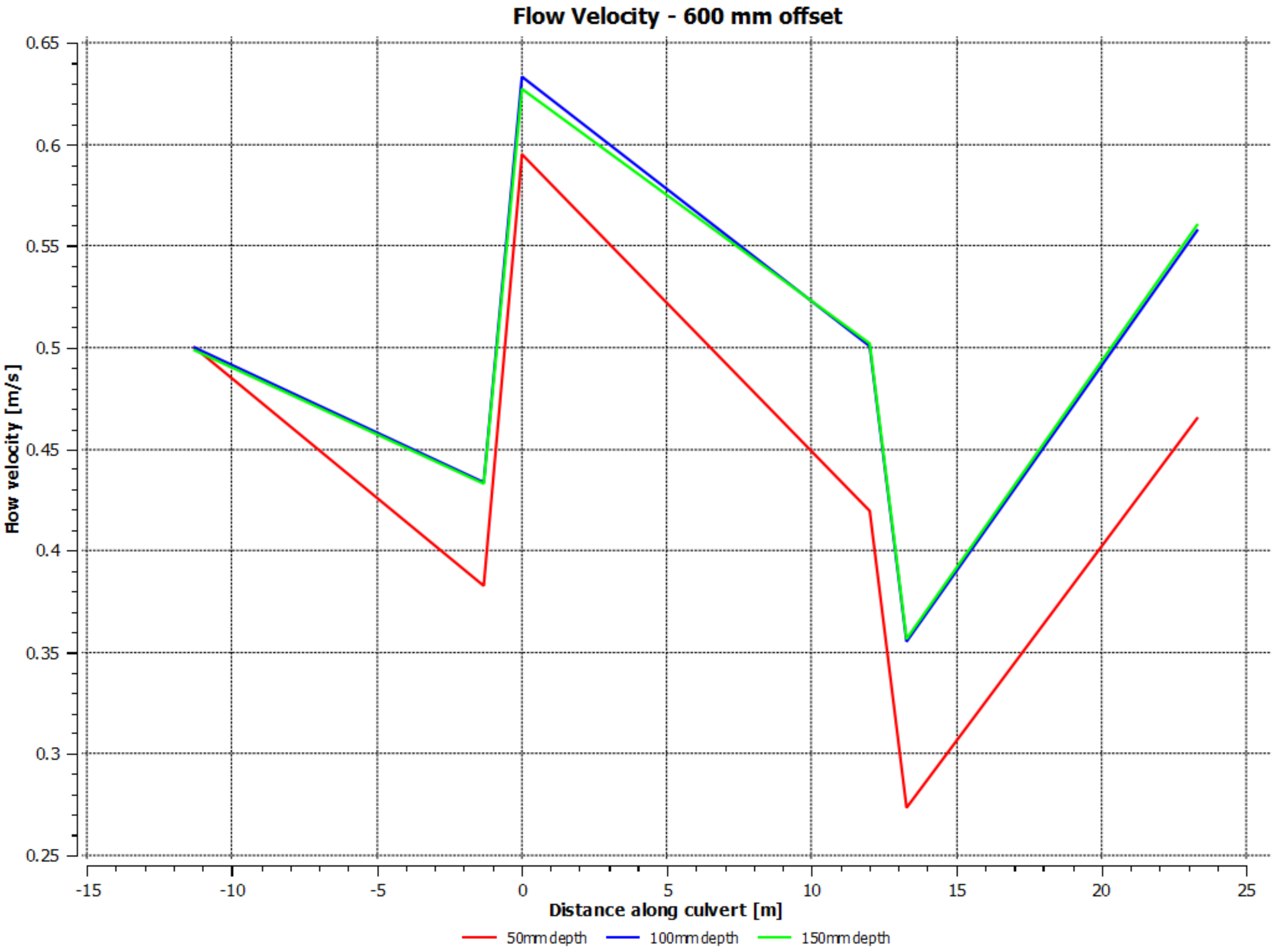

Flow Velocity - 300 mm offset
Flow velocity [m/s]
0.7
0.6
0.5
0.4
0.3
0.2
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Title

DAFF 'Amber' Fish Passage Design, 500mm flow depth

Author

Simon Petersen

Date

2013/10/10 14:48:11

Contents

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1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\amber_500_mp_files\dp0\CFX\CFX\CFX_015.res
File Date	03 October 2013
File Time	04:49:27 PM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	507129	480480	0	0	0	480480	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	60.0295 [degree]	119.971 [degree]	100.153	9.30341	1	8

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	1.1000e+00 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

Flow Regime	Subsonic
Mass And Momentum	Static Pressure
Relative Pressure	DownPres
Boundary - floor	
Type	WALL
Location	FLOOR1, FLOOR2, FLOOR3, FLOOR4, FLOOR5
Settings	
Mass And Momentum	No Slip Wall
Wall Roughness	Rough Wall
Sand Grain Roughness Height	3.0000e-02 [m]
Boundary - walls_culvert	
Type	WALL
Location	WALL1, WALL2, WALL3, WALL4, WALL5, WALL6, WALL7, WALL8, WALL9, WALL10
Settings	
Mass And Momentum	No Slip Wall
Wall Roughness	Rough Wall
Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1. Velocity profiles

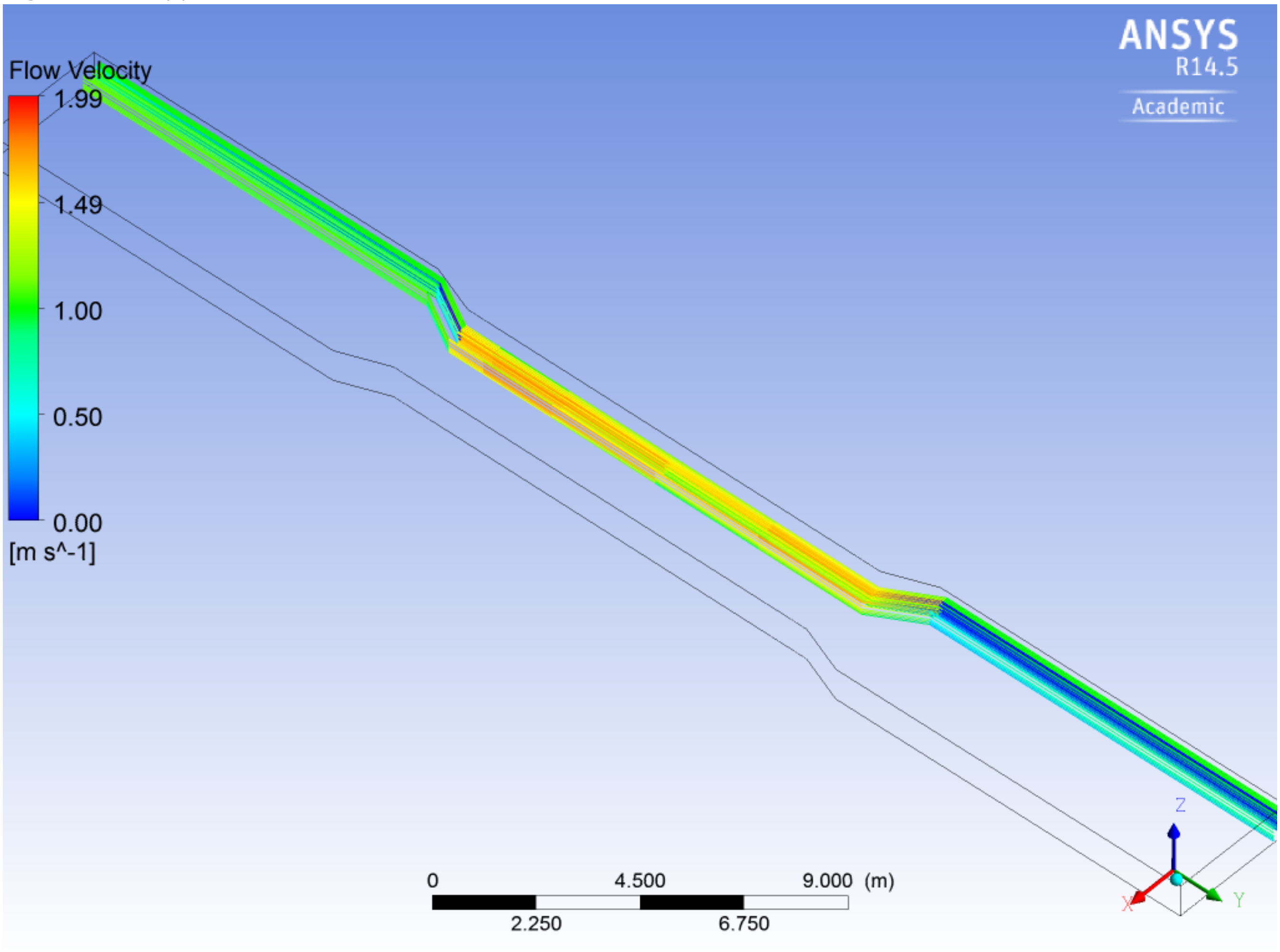


Chart 1.

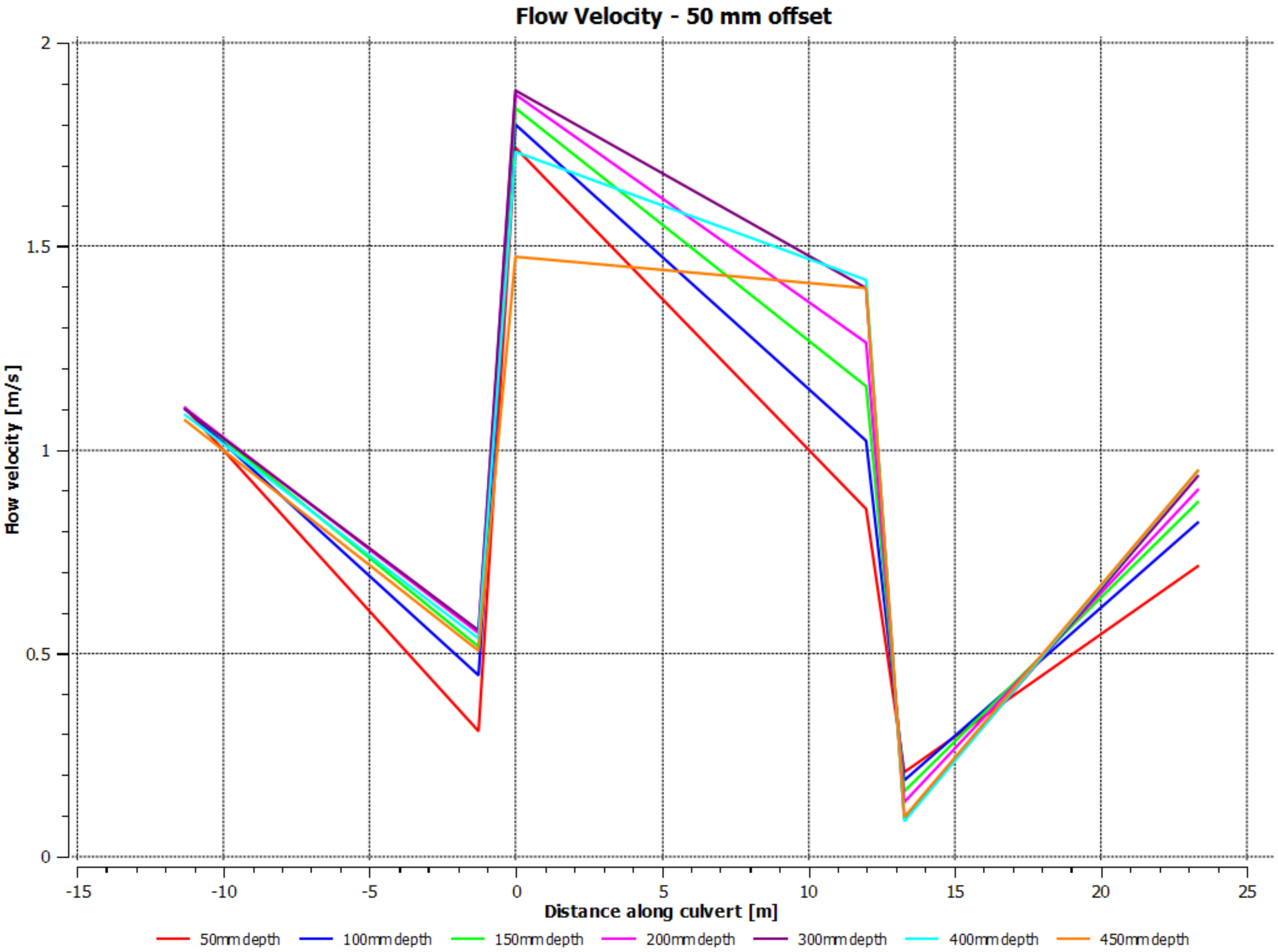

Flow Velocity - 50 mm offset
Flow velocity [m/s]
2
1.5
1
0.5
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 2.

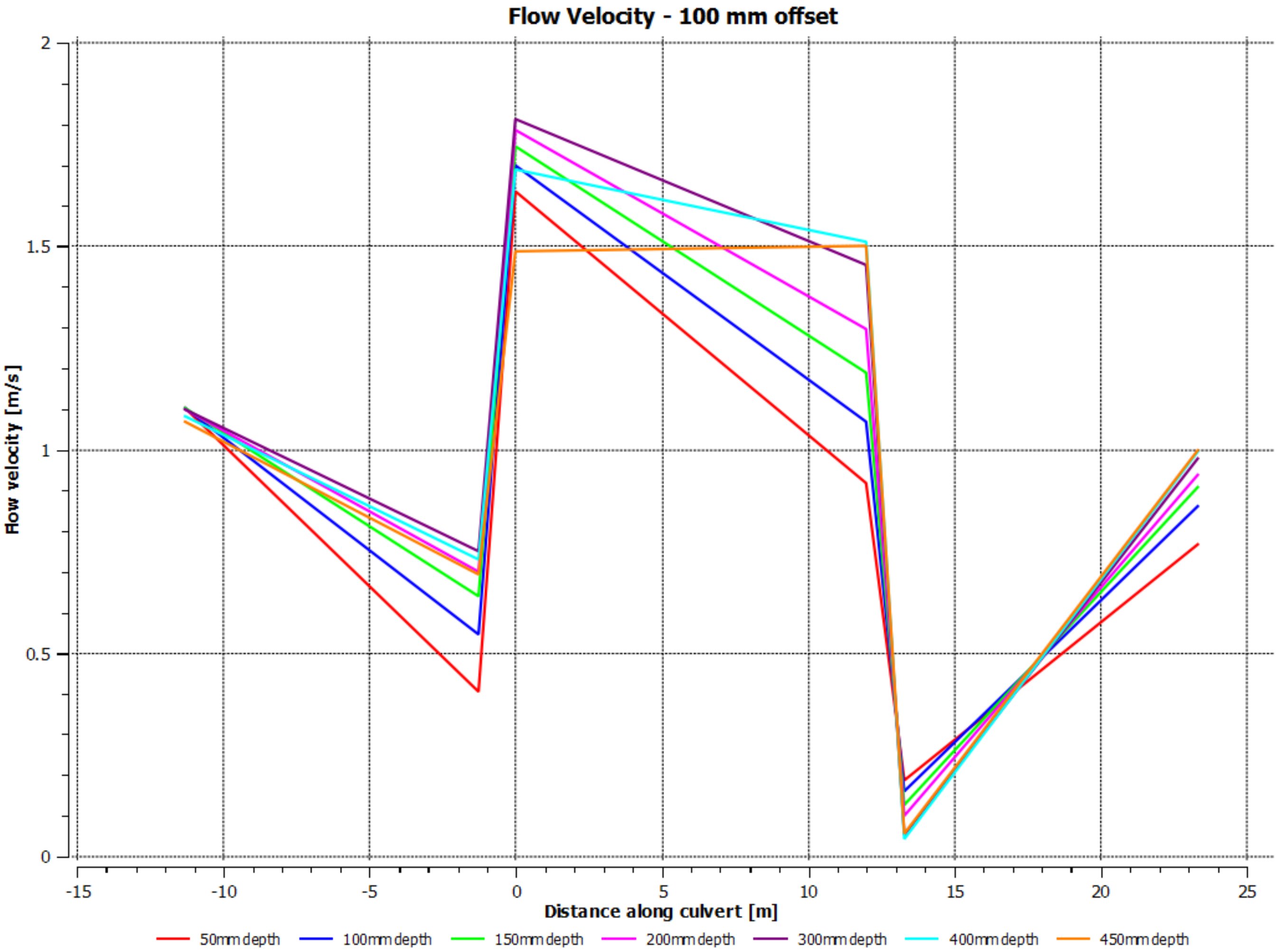

Flow Velocity - 100 mm offset
Flow velocity [m/s]
2
1.5
1
0.5
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 3.

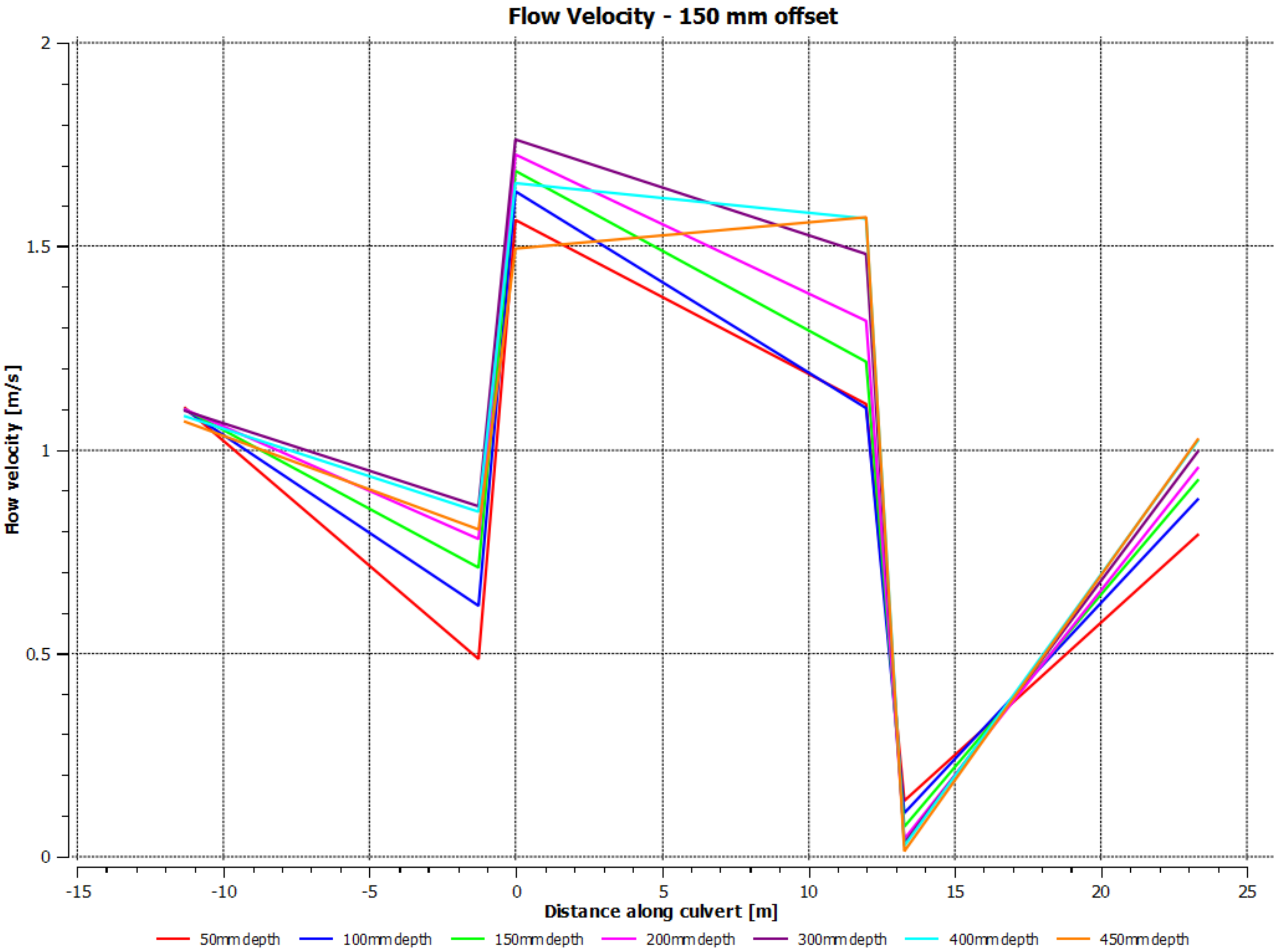

Flow Velocity - 150 mm offset
Flow velocity [m/s]
2
1.5
1
0.5
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 4.

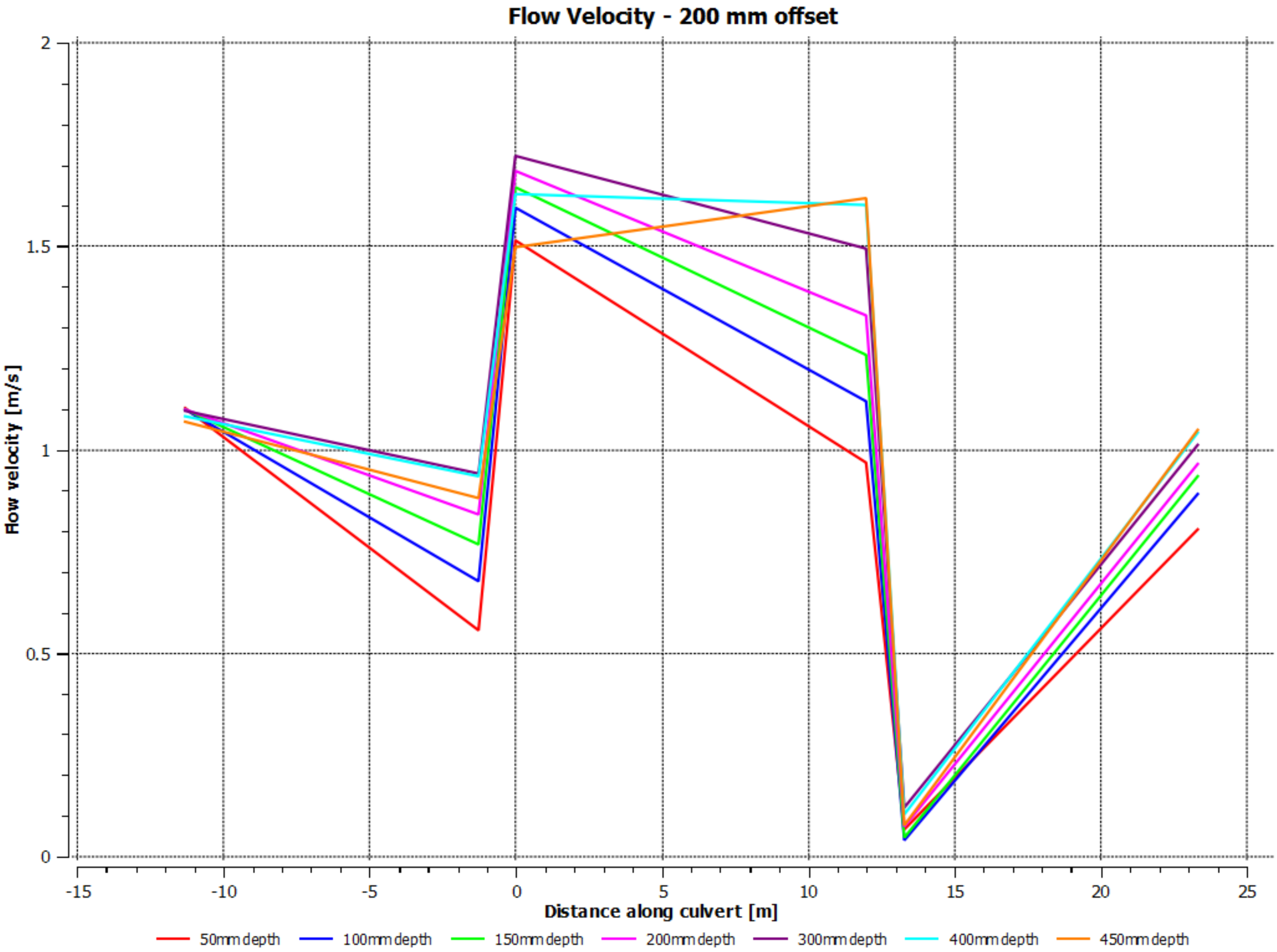

Flow Velocity - 200 mm offset
Flow velocity [m/s]
2
1.5
1
0.5
0
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 5.

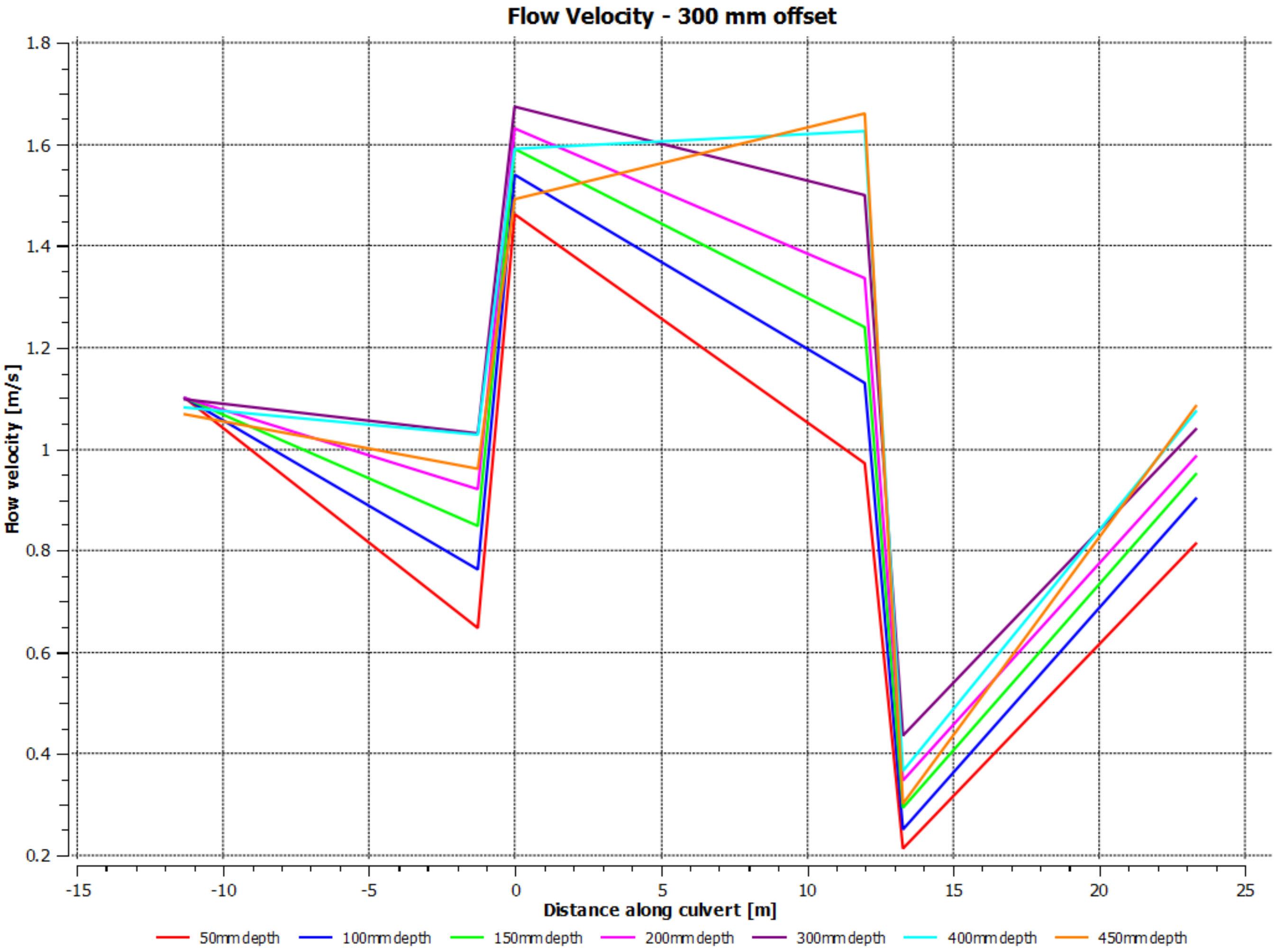
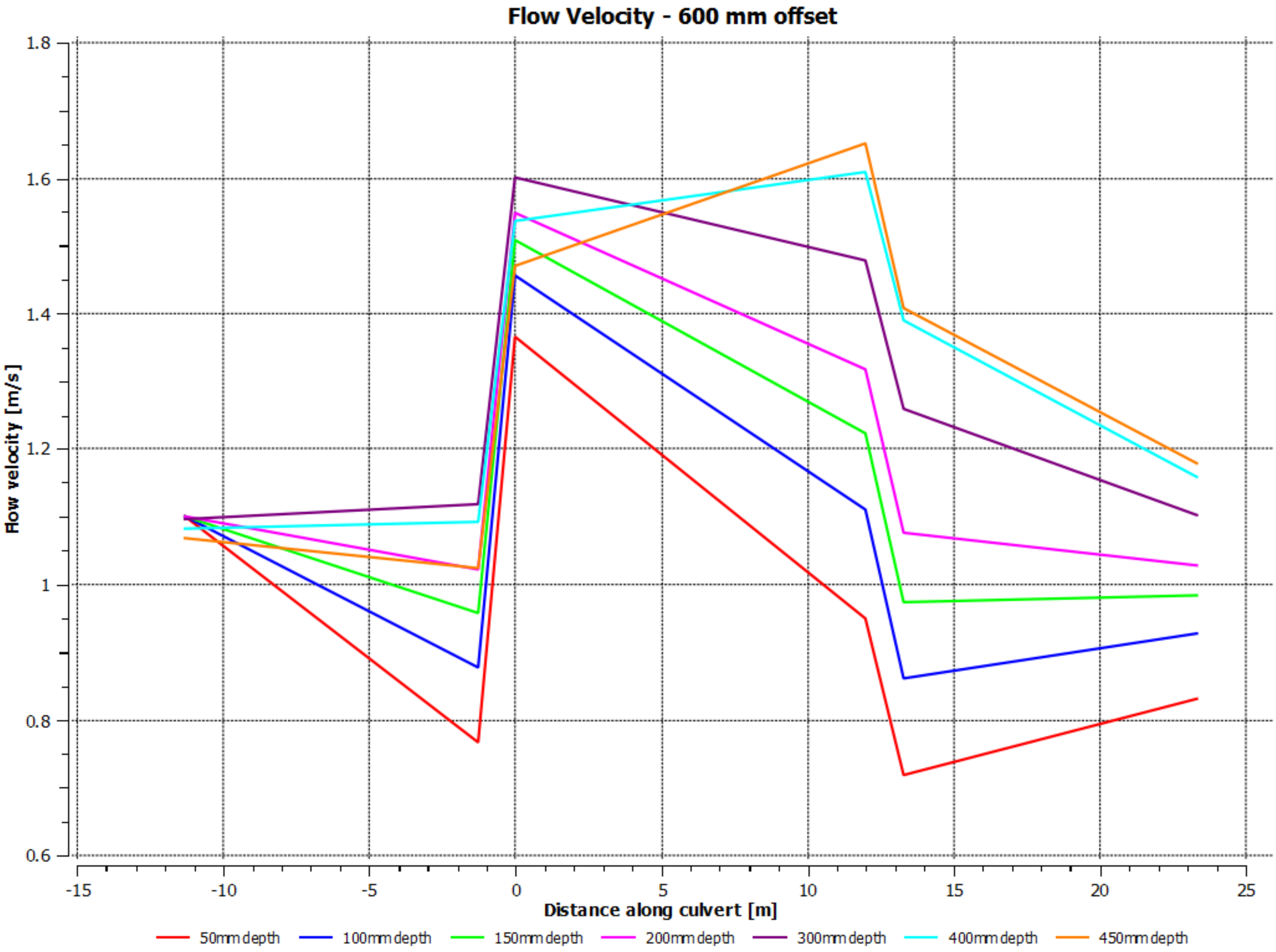

Flow Velocity - 300 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
-15
-10
-5
0
5
10
15
20
25
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Appendix G

CFX Report - DAFF 'Red' Fish Passage Design - 200mm and 500mm flow depths

Title

DAFF 'Red' Fish Passage Design, 200mm flow depth

Author

Simon Petersen

Date

2013/10/06 13:46:19

Contents

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\red_200_mp_files\dp0\CFX\CFX\CFX_017.res
File Date	01 October 2013
File Time	07:07:58 AM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	502169	467460	0	0	0	467460	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	46.8646 [degree]	135.262 [degree]	44.0302	27.0288	1	10

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	5.0000e-01 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - symetry	
	Type	SYMMETRY
	Location	SYM
	Settings	
	Boundary - walls_culvert	
	Type	WALL
	Location	wall
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1.

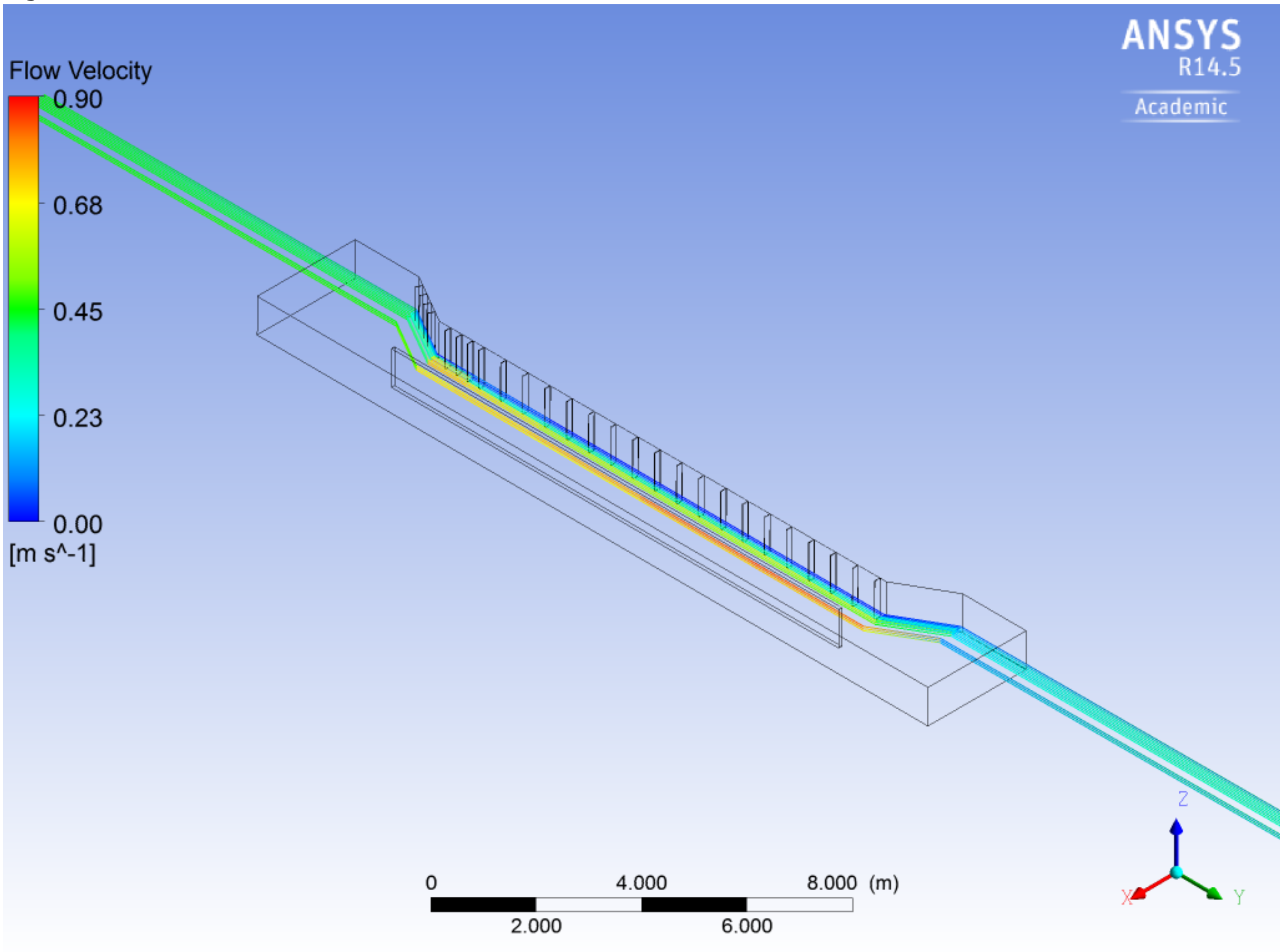


Chart 1.

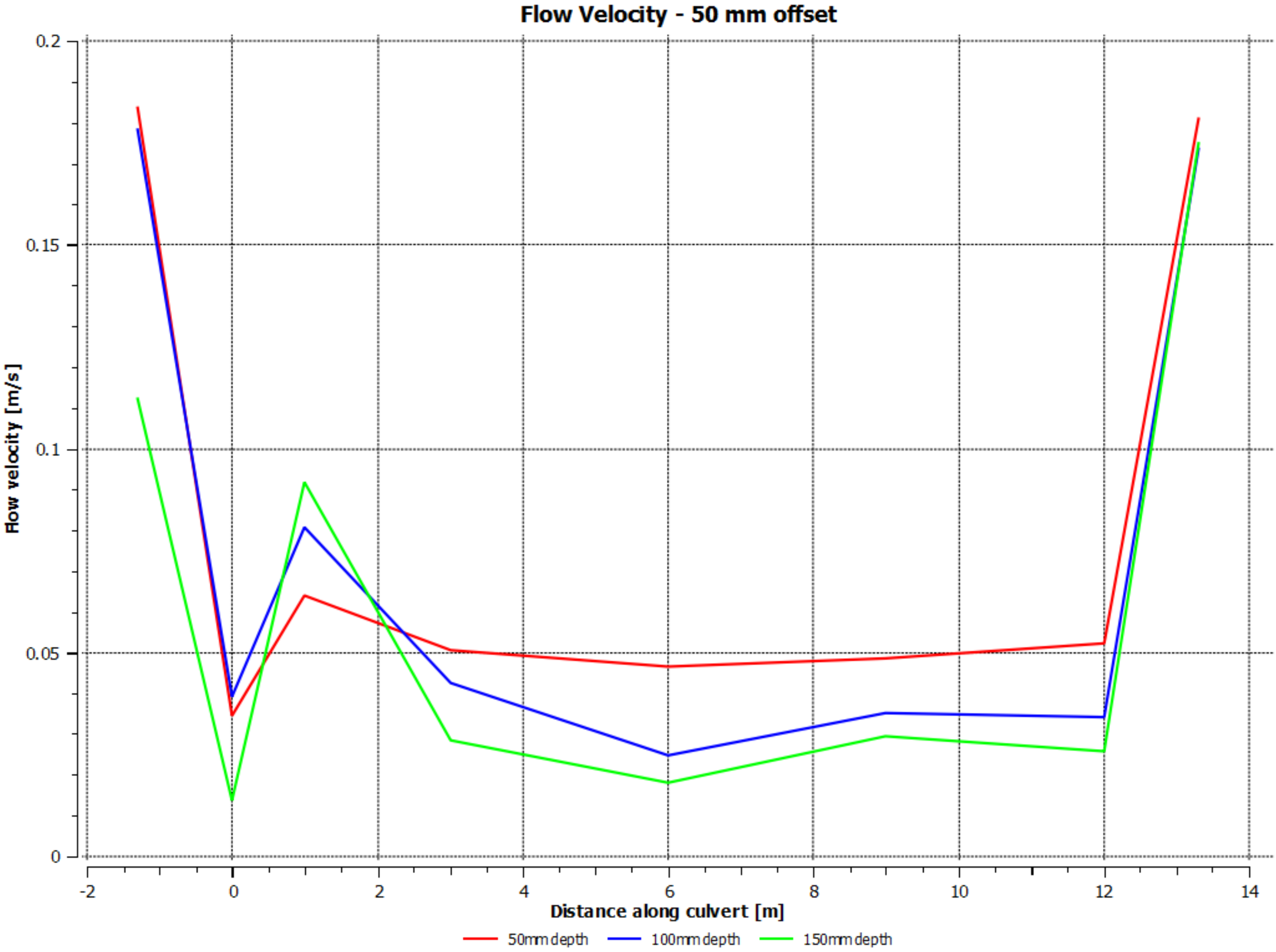

Flow Velocity - 50 mm offset
Flow velocity [m/s]
0.2
0.15
0.1
0.05
0
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 2.

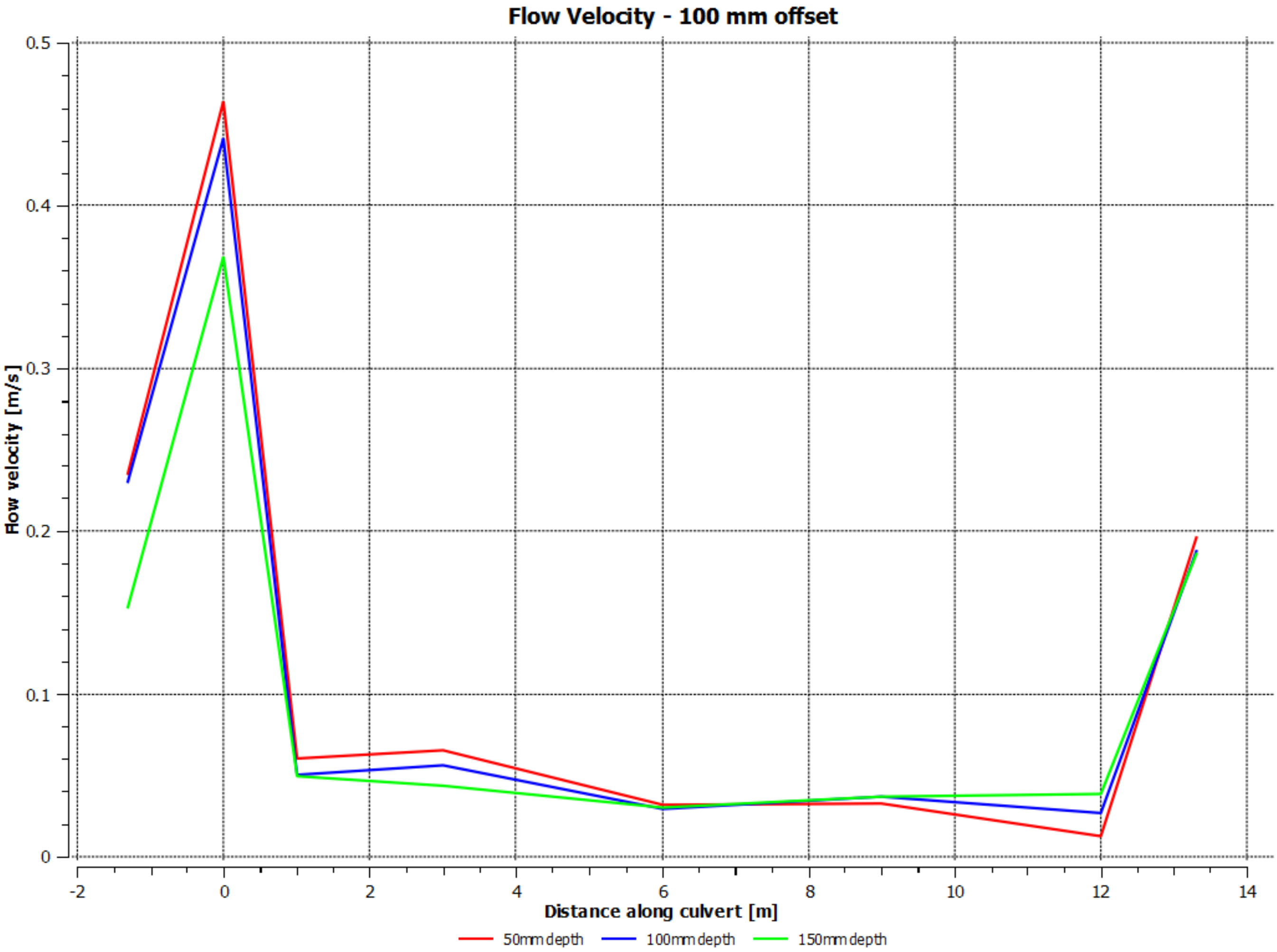

Flow Velocity - 100 mm offset
Flow velocity [m/s]
0.5
0.4
0.3
0.2
0.1
0
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 3.

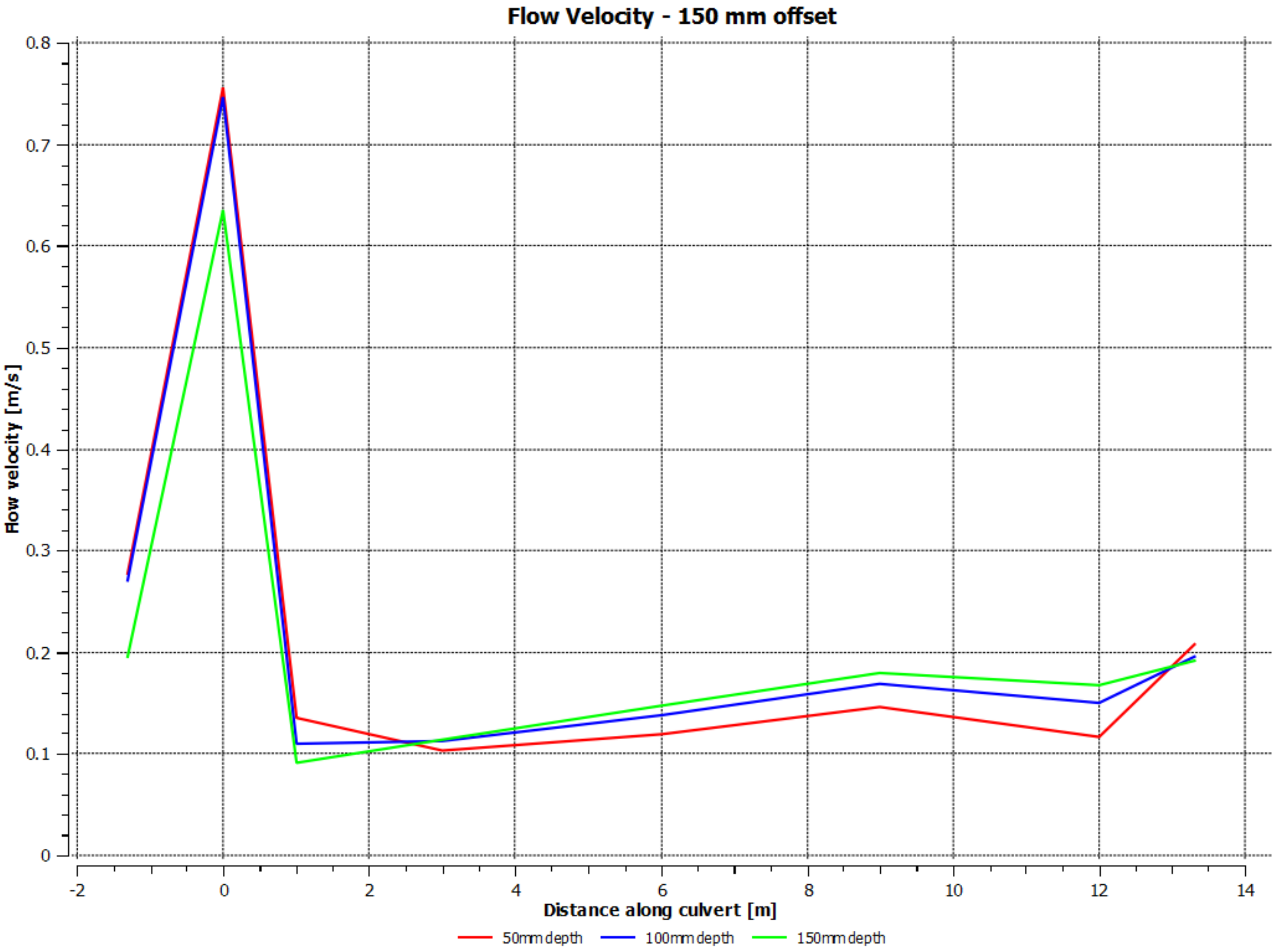

Flow Velocity - 150 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 4.

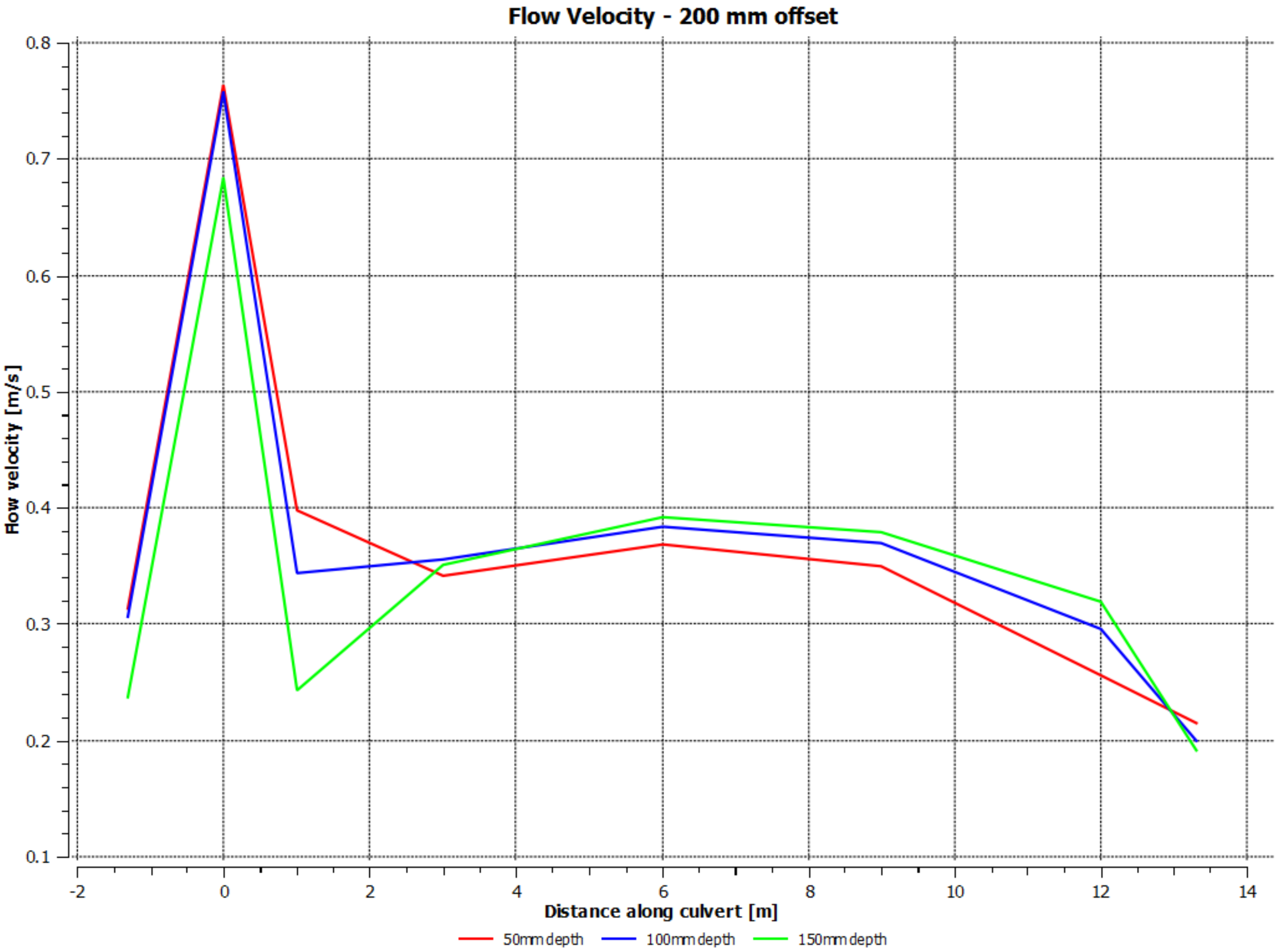

Flow Velocity - 200 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 5.

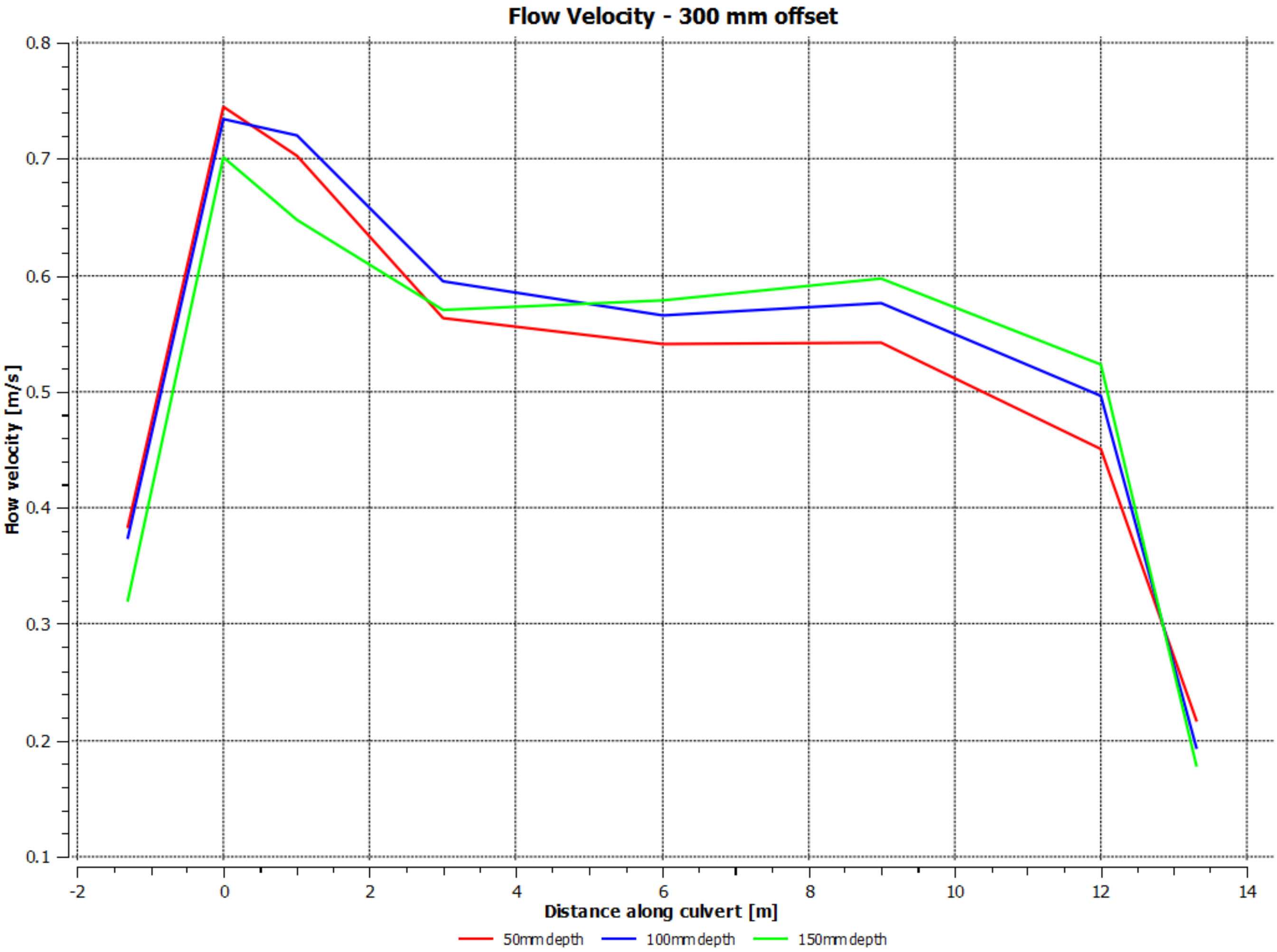
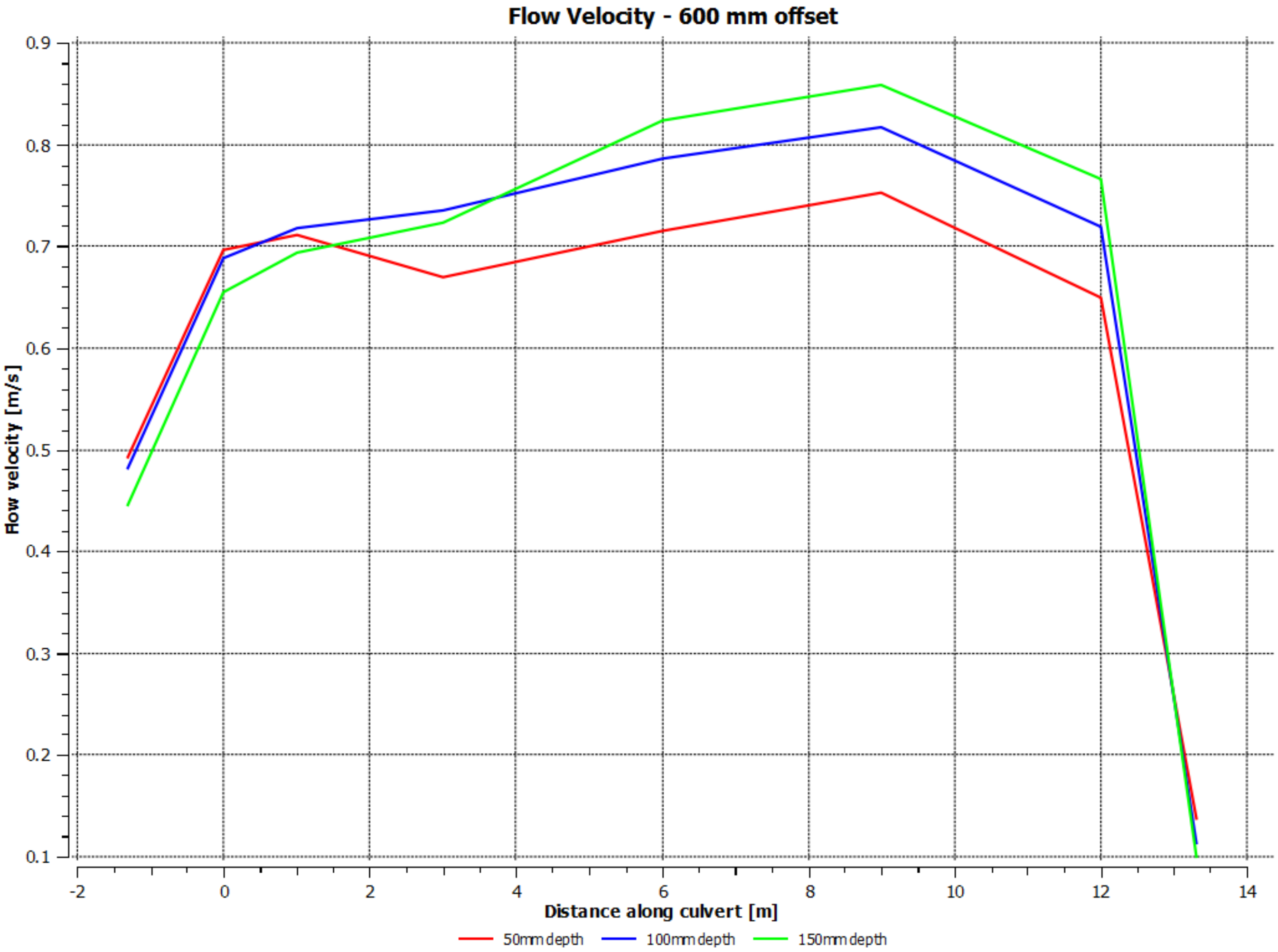

Flow Velocity - 300 mm offset
Flow velocity [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth

Title

DAFF 'Red' Fish Passage Design, 500mm flow depth

Author

Simon Petersen

Date

2013/10/06 14:11:36

Contents

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Modelling\Design\Multiphase\red_500_mp_r2_files\dp0\CFX\CFX\CFX_019.res
File Date	27 September 2013
File Time	06:38:52 AM
File Type	CFX5
File Version	14.5

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra	Polyhedra
Default Domain	502169	467460	0	0	0	467460	0

Table 3. Mesh Statistics for CFX

Domain	Minimum Face Angle	Maximum Face Angle	Maximum Edge Length Ratio	Maximum Element Volume Ratio	Connectivity Range	
Default Domain	46.8646 [degree]	135.262 [degree]	44.0302	27.0288	1	10

3. Physics Report

Table 4. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	fluid
Materials	
Air at 25 C	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Buoyant
Buoyancy Reference Density	DenRef
Gravity X Component	0.0000e+00 [m s^-2]
Gravity Y Component	0.0000e+00 [m s^-2]
Gravity Z Component	-g
Cartesian Coordinates	0.5 [m], 0.5 [m], 0.85 [m]
Buoyancy Reference Location	Cartesian Coordinates
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Homogeneous Model	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable

Table 5. Boundary Physics for CFX

Domain	**Boundaries**	
Default Domain	**Boundary - inlet**	
	Type	INLET
	Location	INLET
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Normal Speed
	Normal Speed	1.2000e+00 [m s^-1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	UpVFAir
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	UpVFWater
	Boundary - roof	
	Type	OPENING
	Location	ROOF
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Entrainment
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Zero Gradient
	Fluid	Air
	Volume Fraction	Value
	Volume Fraction	1.0000e+00
	Fluid	Water
	Volume Fraction	Value
	Volume Fraction	0.0000e+00
	Boundary - outlet	
	Type	OUTLET
	Location	OUTLET
	Settings	

	Flow Regime	Subsonic
	Mass And Momentum	Static Pressure
	Relative Pressure	DownPres
	Boundary - symetry	
	Type	SYMMETRY
	Location	SYM
	Settings	
	Boundary - walls_culvert	
	Type	WALL
	Location	wall
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Rough Wall
	Sand Grain Roughness Height	2.0000e-03 [m]

Figure 1. Velocity profiles

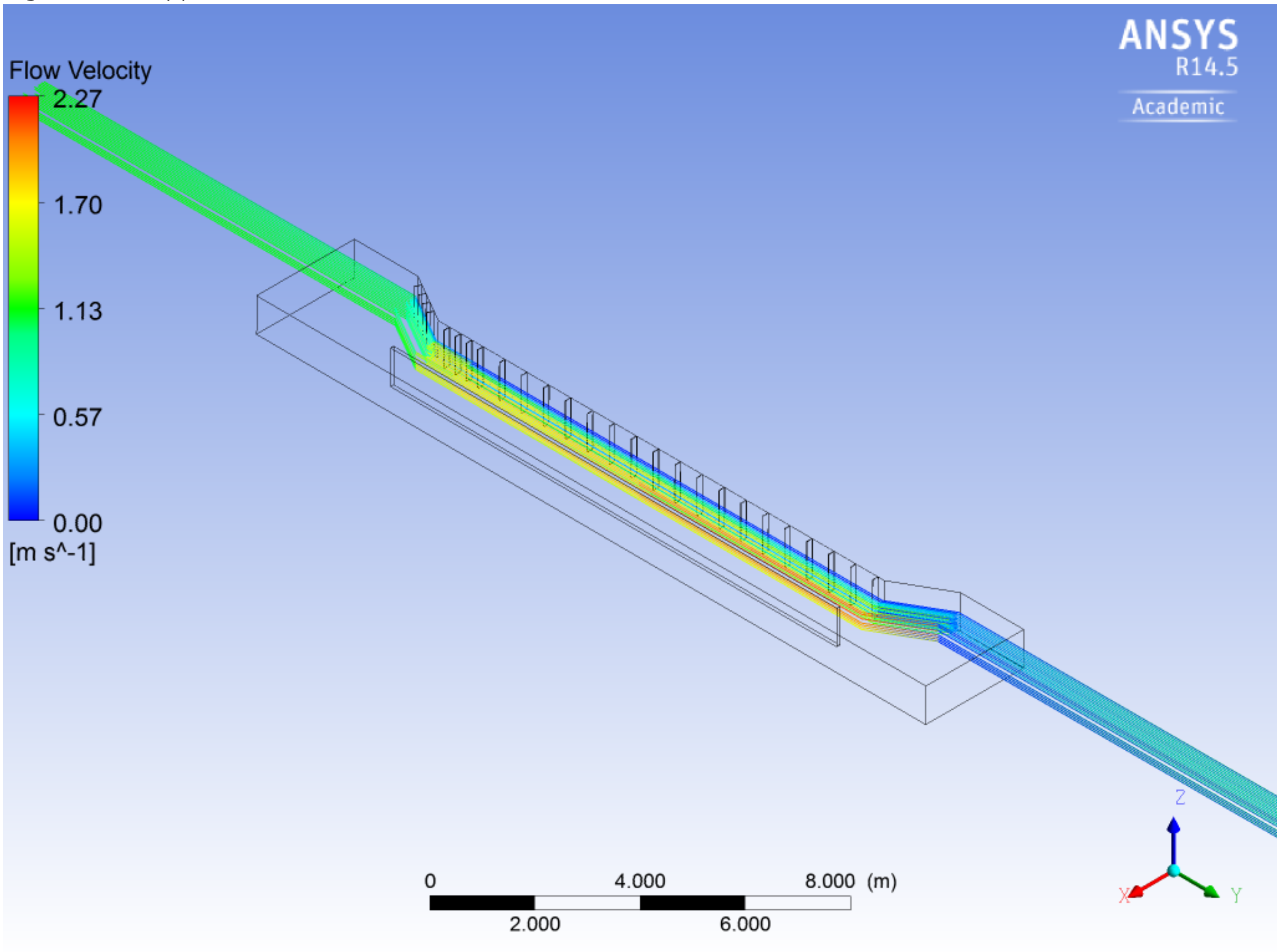


Chart 1.

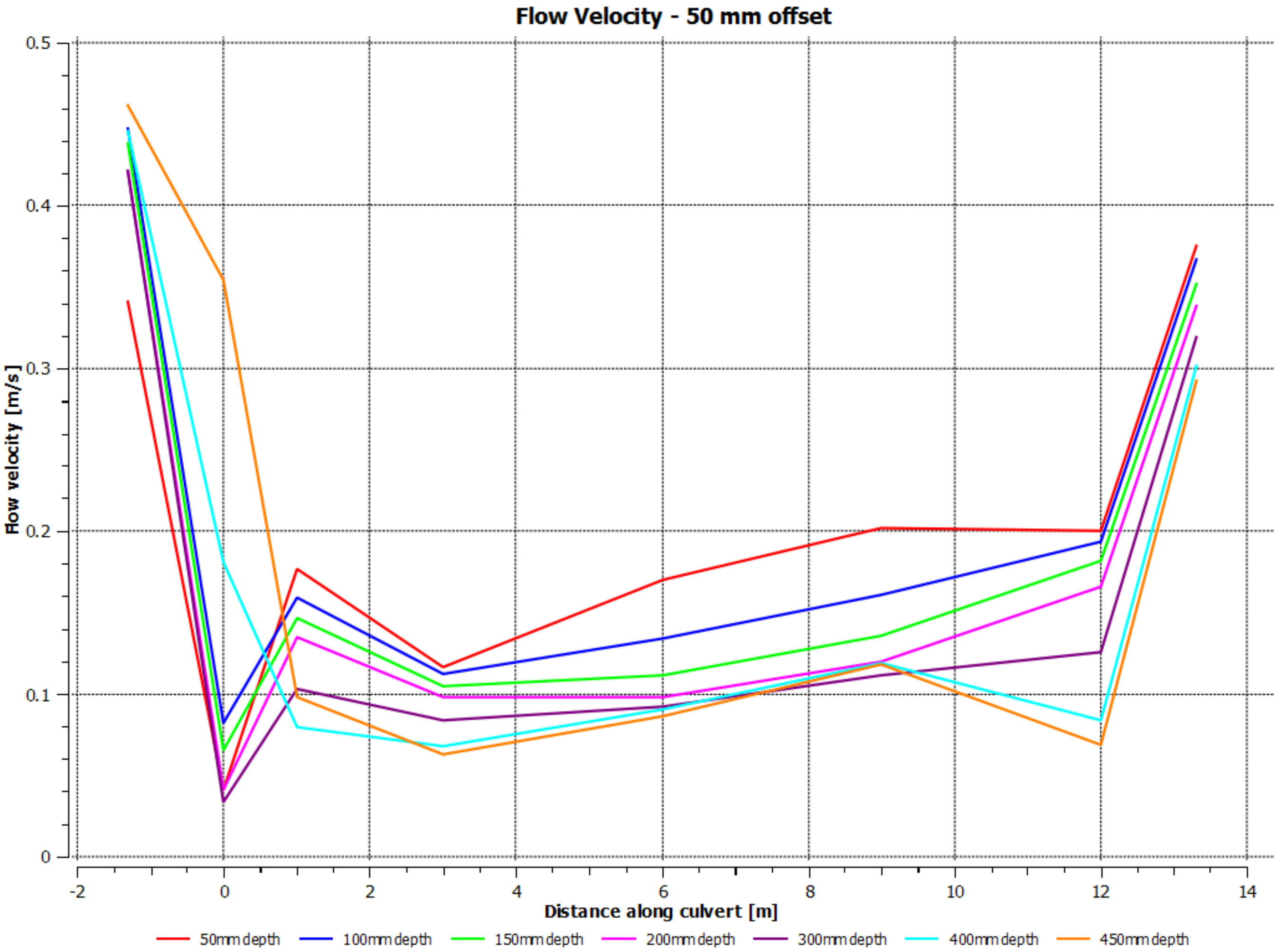

Flow Velocity - 50 mm offset
Flow velocity [m/s]
0.5
0.4
0.3
0.2
0.1
0
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 2.

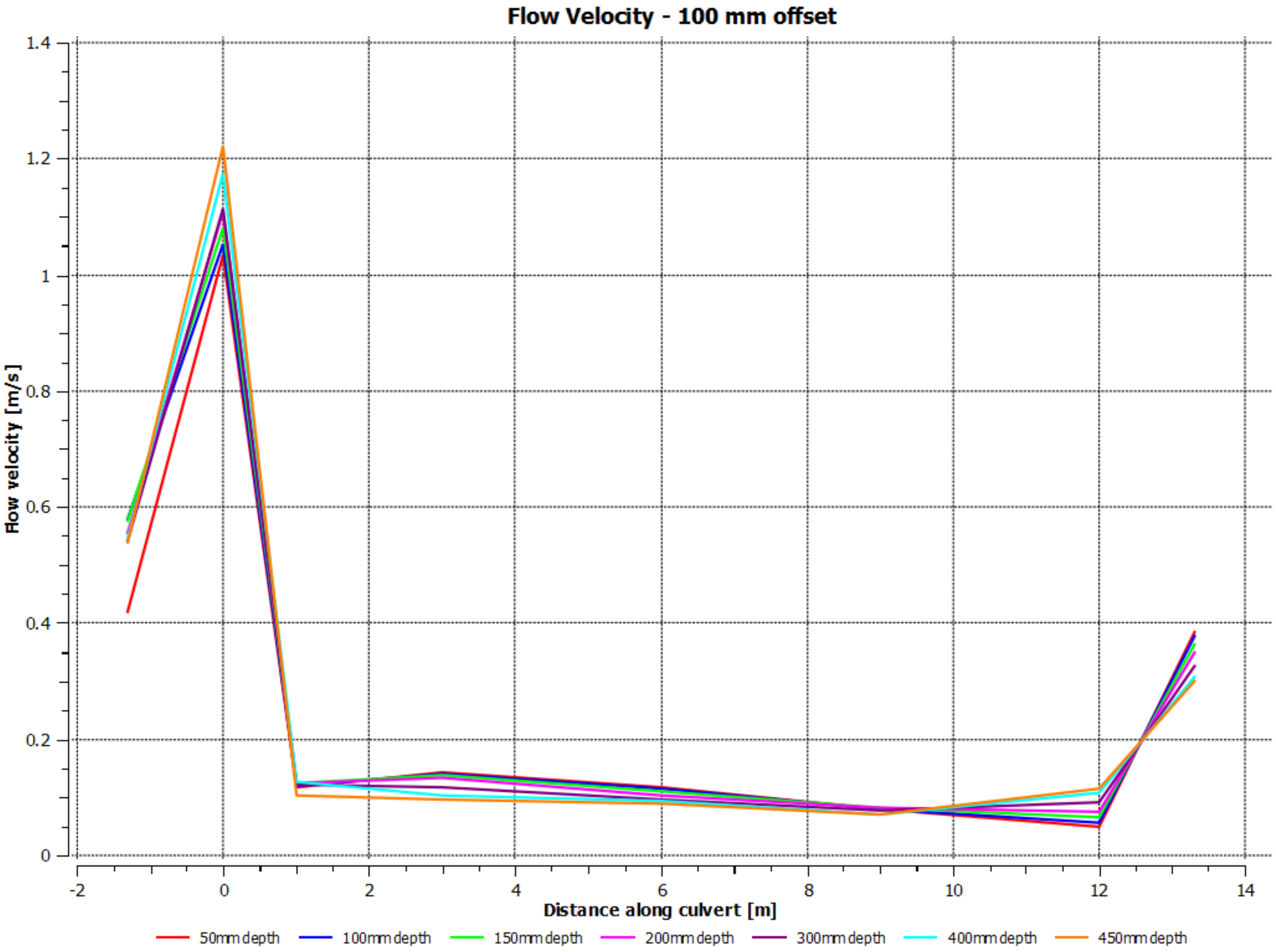

Flow Velocity - 100 mm offset
Flow velocity [m/s]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 3.

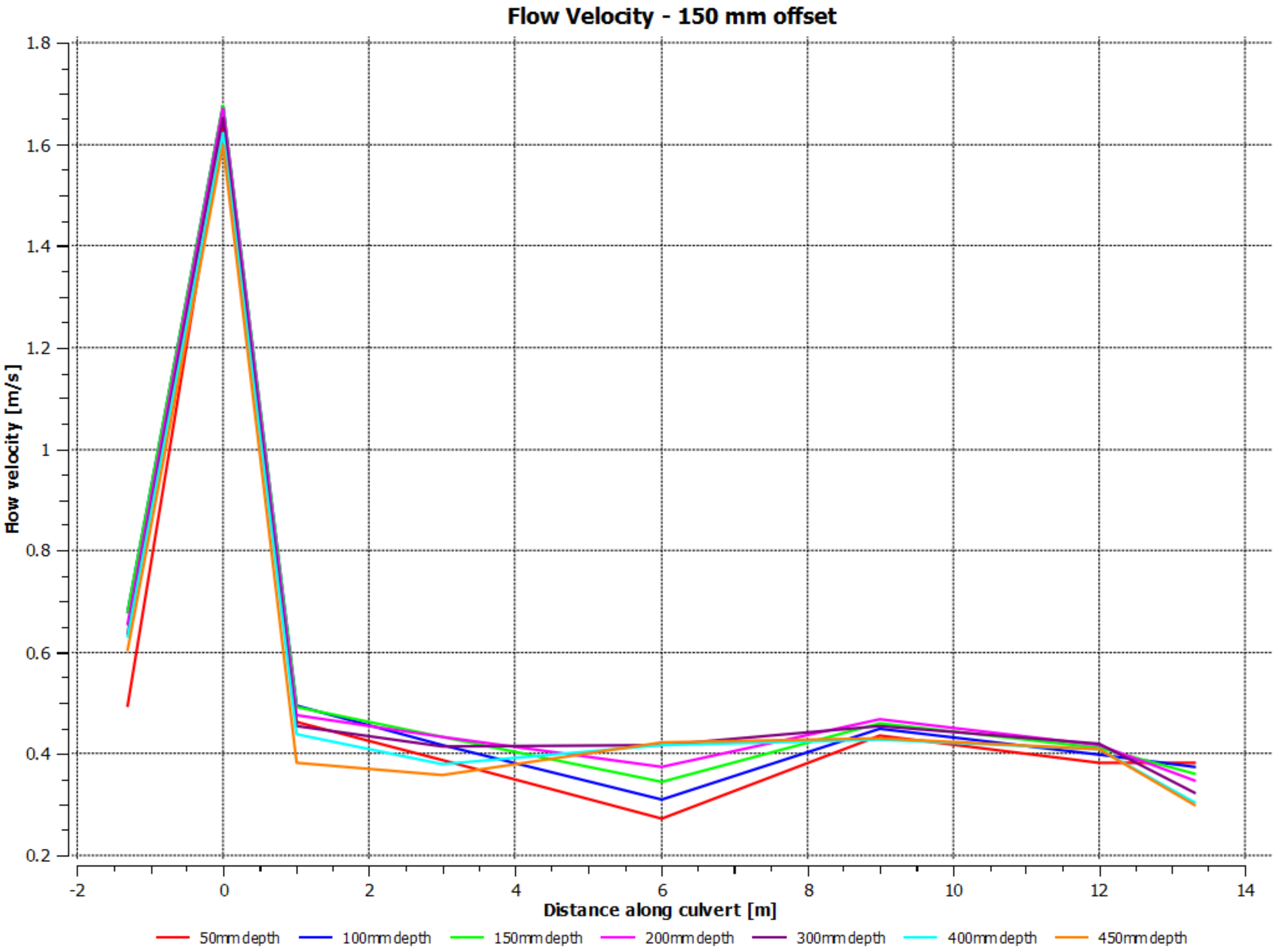

Flow Velocity - 150 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 4.

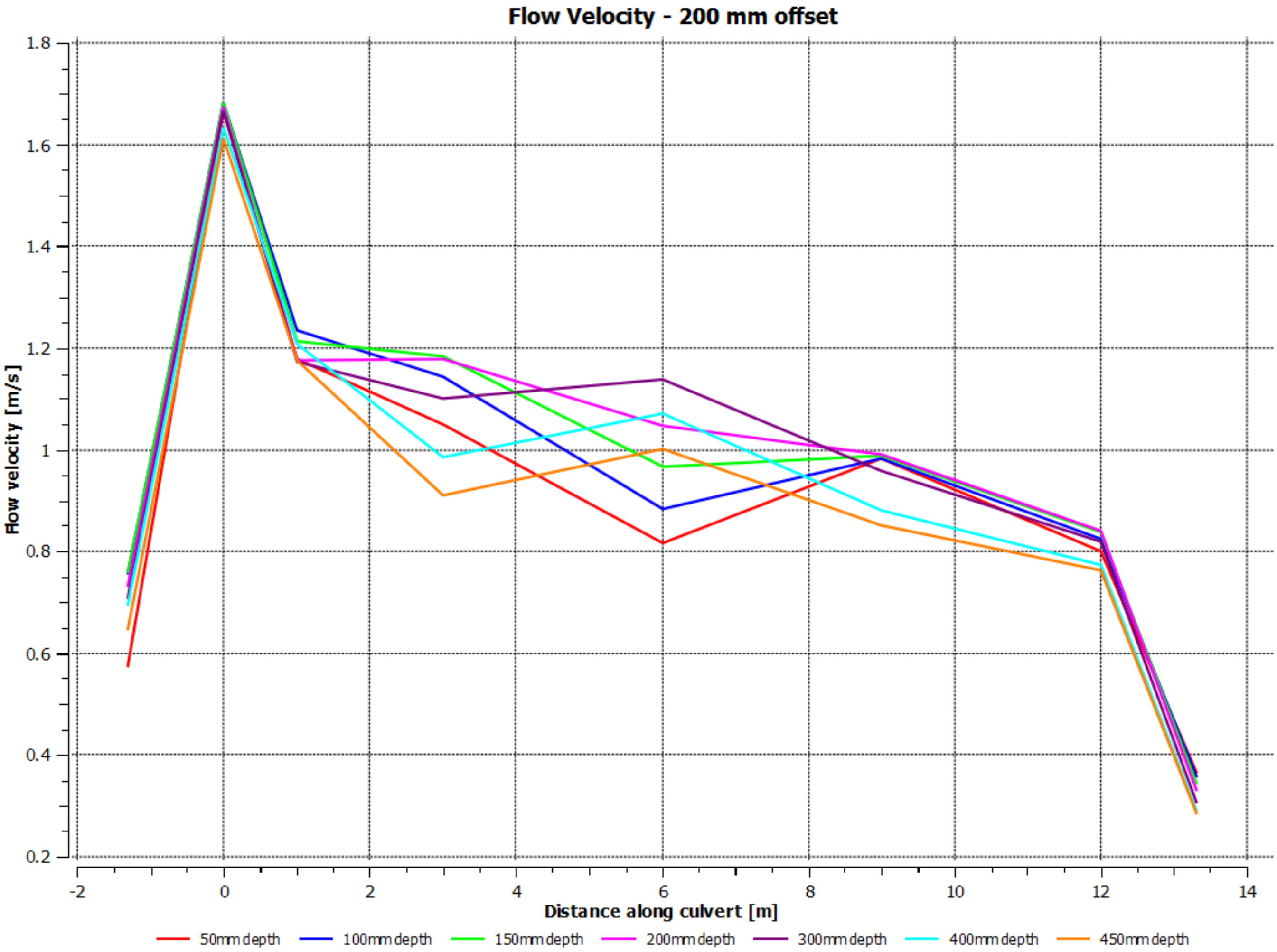

Flow Velocity - 200 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 5.

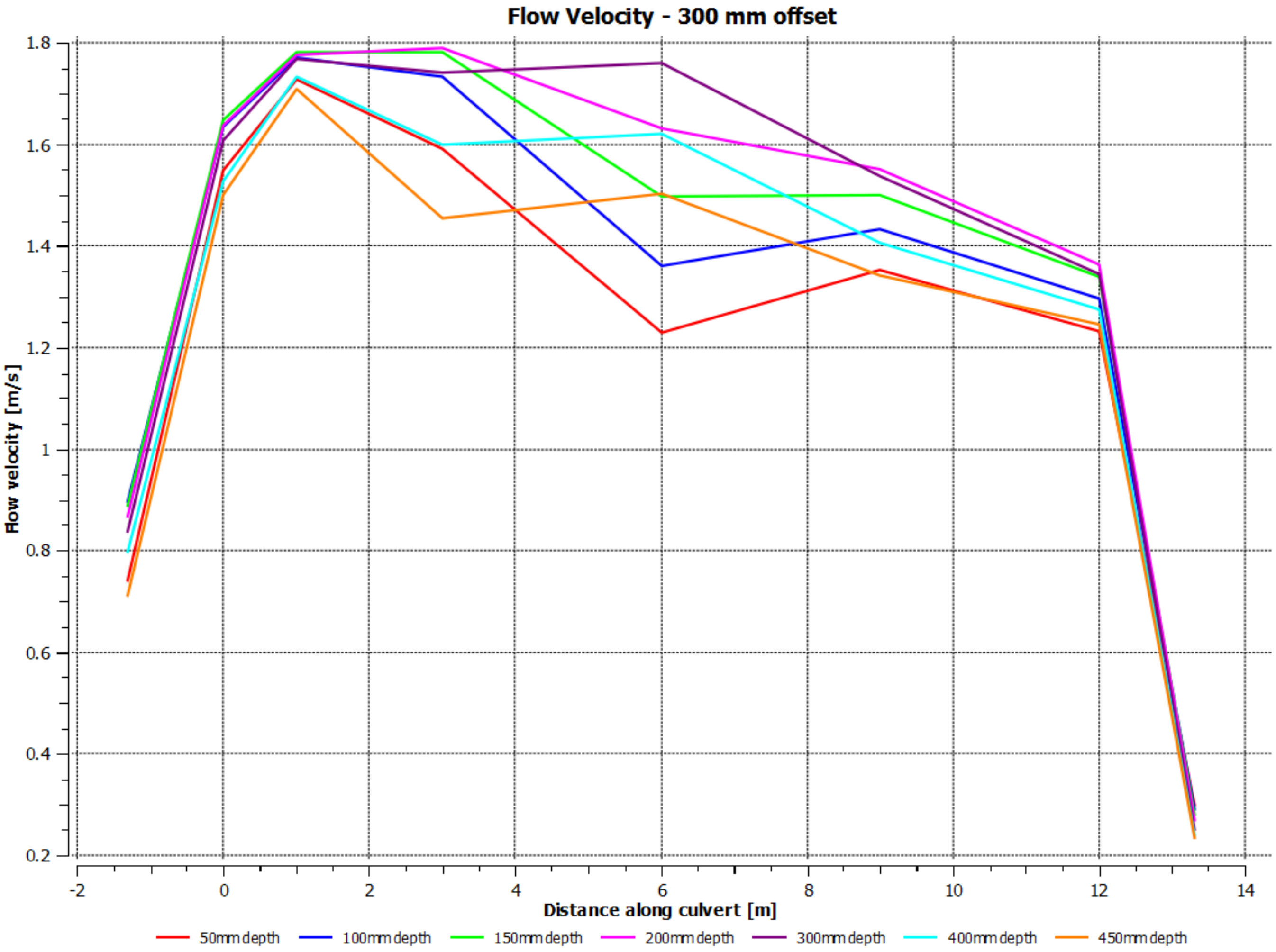
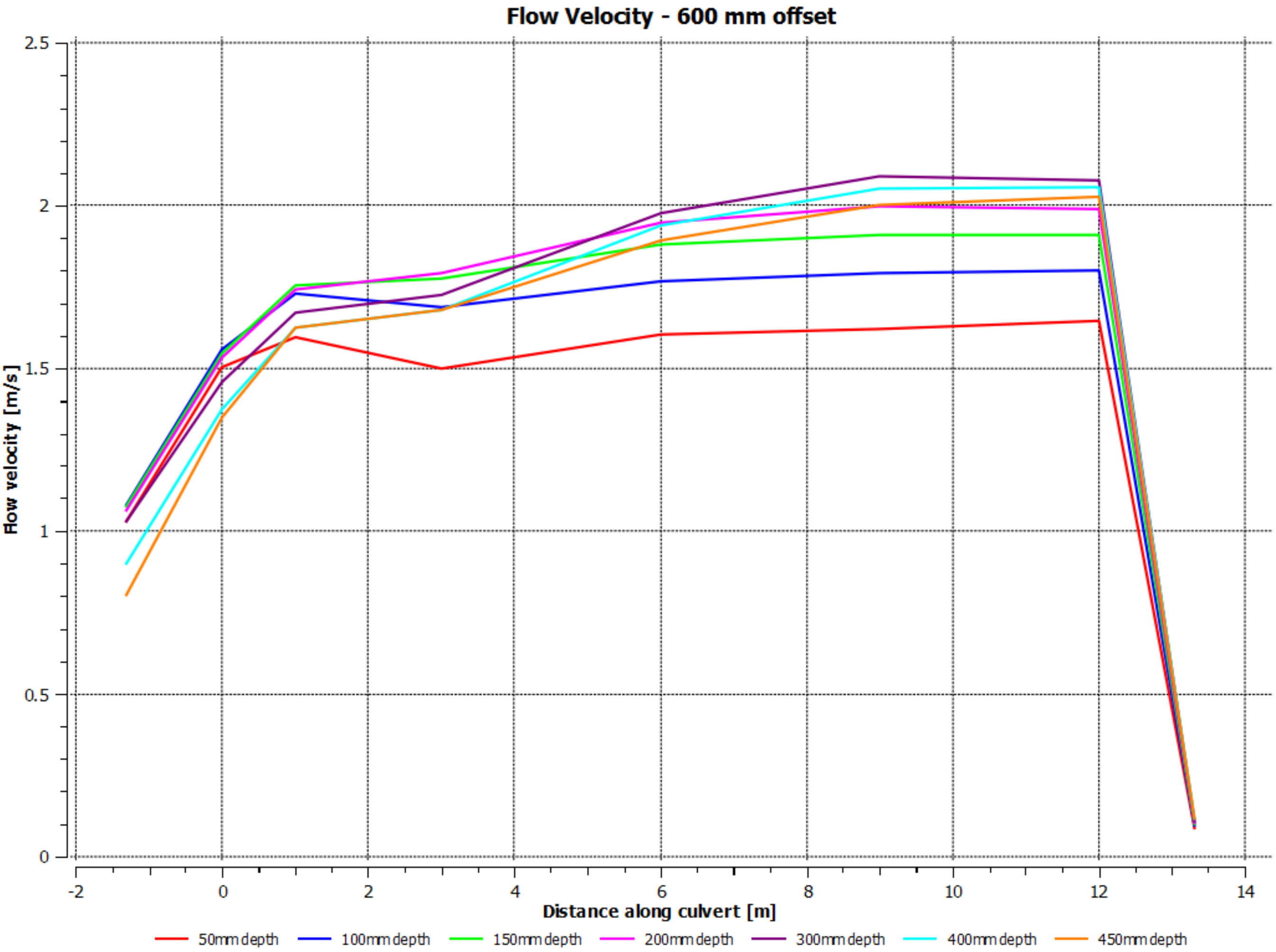

Flow Velocity - 300 mm offset
Flow velocity [m/s]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
-2
0
2
4
6
8
10
12
14
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth

Chart 6.


Flow Velocity - 600 mm offset
Flow velocity [m/s]
Distance along culvert [m]
50mm depth
100mm depth
150mm depth
200mm depth
300mm depth
400mm depth
450mm depth