Applicability of CFD Modelling in Determining Accurate Weir Discharge–Water Level Relationships

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ABSTRACT

Being able to accurately determine weir discharges is of key importance in urban water management. The most common method is performing a level measurement and calculating the discharge using the standard weir equation. Since this equation is only valid in certain conditions, this can lead to large deviations from the actual discharge. In this paper, lab measurements and CFD calculations are applied to determine a new method for the derivation of accurate Q(h) relationships. Detailed scale model experiments have been performed for the internal weir of a SST. The scale model is precisely reproduced in a CFD model, with which corresponding calculations have been performed. It is shown that the water levels from the scale model can be reproduced by the CFD model without parameter tuning. Q(h) relationships have been derived from both the scale model experiments and the CFD calculations. They have been mutually compared with the relationship from the standard equation as well. It is shown that the derived relationships are very similar indicating the applicability of CFD for this purpose. All derived relationships form a much better description of the actual weir discharge than the standard equation.

KEYWORDS

Computational fluid dynamics, CSO; Q(h)-relationship, measurements, scale model, weir

INTRODUCTION

Information on the actual discharge of combined sewer overflow (CSO) structures is one of the key parameters in urban water management, e.g. in assessing the performance of CSOs, their impact on receiving waters, rehabilitation measures and any type of RTC (e.g. (Vanrolleghem, et al., (2005) and Dirckx, et al., (2011)). Accurately measuring discharges at CSO structures is expensive and difficult (El Bahlouli et al., 2013). Therefore, the discharge Q [m^3/s] is typically calculated using the following standard weir equation:

$$Q = 1.7mBH^n, \qquad (1)$$

with H [m] the water level above the weir crest at some distance upstream of the weir, B [m] the width of the weir crest and m and n constants. Default values for m and n are 0.8 [-] and

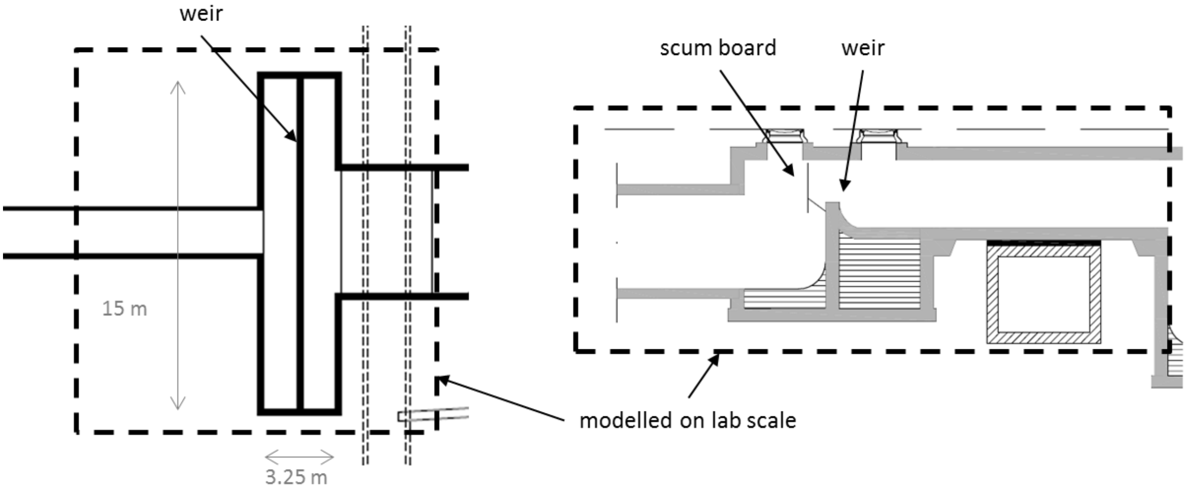

Figure 1 The internal weir and weir chamber. Top view (left) and cross section (right).

1.5 [-] respectively. This equation, however, is applicable only when standard conditions are met. Improper application of the standard equation can lead to substantial errors. The main sources of these errors are determined by the shape of the weir crest and the geometry of the weir chamber. The former can be dealt with by applying a more ideal crest shape to improve the discharge accuracy at low water levels above the weir crest (Brombach and Weis (2005)). For high water levels, the geometry of the CSO structure can become dominant.

Several attempts have been made to determine the Q(h)-relations for weirs where the geometry of the CSO chamber is the dominant factor. For example Fach et al., (2009) and Isel et al., (2013) have applied computational fluid dynamics (CFD) calculations. These models, however, were calibrated using incomplete data or literature values. Bos and Kruger-Van der Griendt (2007) performed lab measurements on 1:1 scaled models, but had to build and measure these models for each new CSO structure. The research presented here combines lab measurements and CFD calculations to determine a new method for the derivation of accurate Q(h)-relationships for every CSO structure.

MATERIALS AND METHOD

This research is centred around the internal weir of a stormwater settling tank (SST) in the city of Eindhoven, the Netherlands. A top view and cross section of this weir is displayed in Figure 1. Please note that the in- and outlet of the weir chamber are not centred in the chamber and that the weir is equipped with a scum board to keep floating debris from entering the SST. The width and height of the weir crest are 14.93 m and 13.90 m AD.

Lab model

The internal weir of the SST has been built in the lab (scaled 1:8), including the inlet, weir chamber and outlet, as shown in the left side of Figure 2. Water levels have been measured for known applied flows at six locations along the width of the weir simultaneously. Sets of measurements have been taken with the sensors located before and after the weir. Measurements have been performed for 5-10 min using wave height sensors (Deltares, 2014) and were recorded with a frequency of 1 kHz. The sensors have been calibrated for this setup. The sensor locations have been indicated in the top view of the weir chamber in the right side of Figure 2. The flows applied range from 0.004-0.030 m^3/s, which were estimated based on the expected flow over the modelled weir at a certain water level above the weir crest.

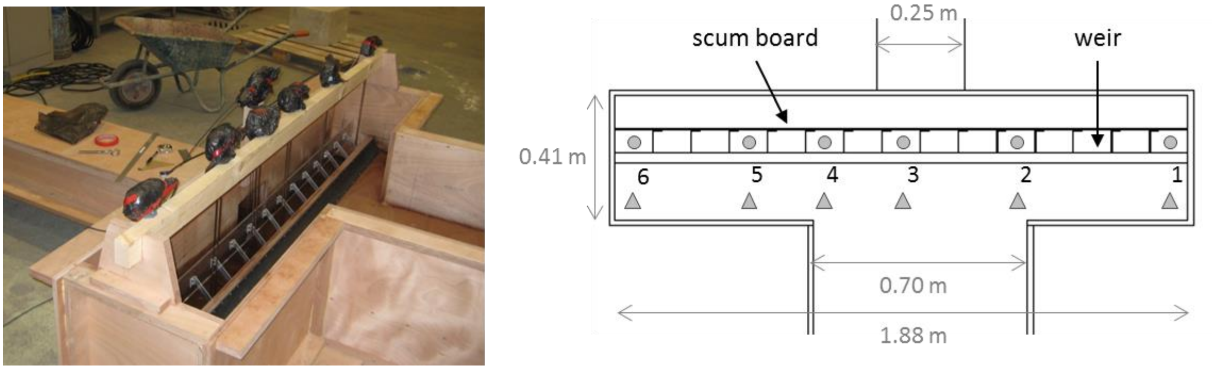

Figure 2 Picture of the lab scale model (left) and schematic top view of the weir chamber with sensor locations before (indicated with circles) and after (triangles) the weir (right).

The experiments have been used to investigate the hydraulic behaviour of the internal weir and weir chamber. Average water levels with 95% uncertainty intervals have been calculated for all flows and each sensor location. All experiments have been performed with free outflow conditions, as the most common condition for overflowing CSO structures. In this specific case it corresponds to the filling of the SST.

CFD model

The aim of the CFD modelling activity has been to demonstrate that CFD can be effectively used to determine an accurate Q(h)-relationship on a weir of arbitrary shape, using a general-purpose CFD code, on standard hardware, within a time frame compatible with an industrial project. The commercial code ANSYS-CFX (release 14.5) has been used to set up a 3D CFD model, exactly matching the lab scale model. The selection of the simulation tool has been performed only based on its availability at the moment the project was carried out.

An Euler-Euler two-phase simulation, including air and water, has been set up. Turbulence has been modelled by means of the popular Shear Stress Transport method, using wall functions to model the flow behaviour close to the walls. The reader is referred to the CFX modelling guide for further details over the mathematical modelling. The water level is defined as the locus of points where the volume fraction is 50%. Simulations are performed on a predominantly hexahedral grid, as shown in figure 3. A grid sensitivity study has been performed, aimed at obtaining a sufficiently sharp definition of the interface: a grid spacing of 3 mm has been found to provide an acceptable accuracy of the results.

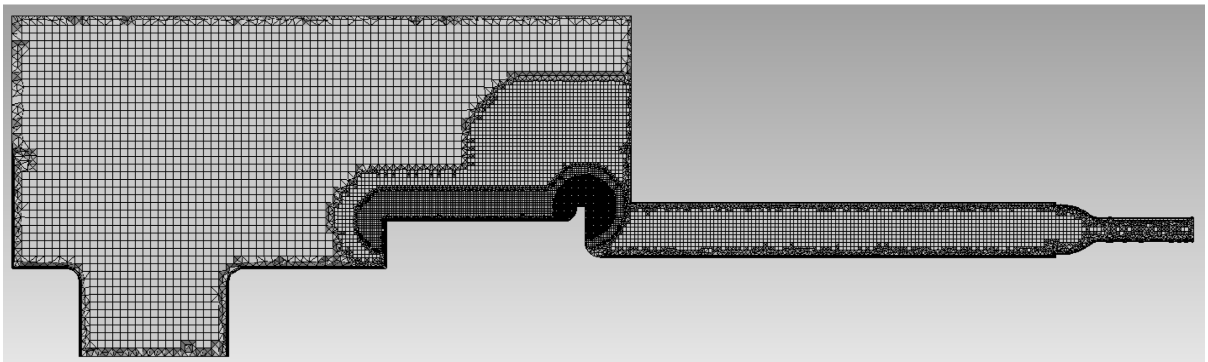

Figure 3 Grid refinement

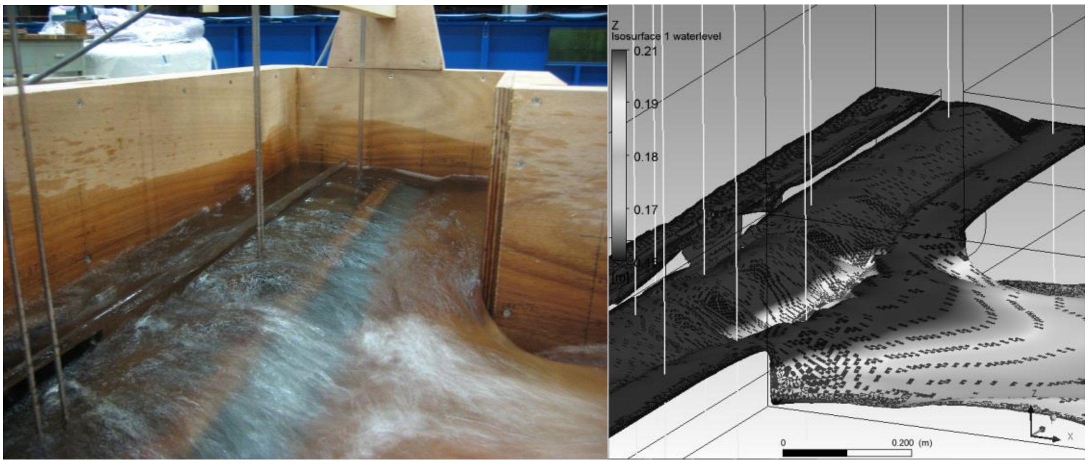

Figure 4 Left: picture of water surface in lab model at a flow of 0.026 m3/s. Right: corresponding CFD figure

With this model, transient calculations for flows of 0.008, 0.012, 0.020 and 0.026 m^3/s have been performed. Water levels at the same locations as the measurements in the lab model are determined for each flow at a 100 Hz frequency. The water levels have been checked using the lab experiment results, as described later on and displayed in Figure 4, thereby validating the schematisation of the CFD model and the simulation parameters. The order of magnitude of the throughput time can be measured in tens of hours, when simulations are performed on an eight-core system: a more accurate estimate would be very much case-dependant, and is omitted here.

Q(h)-relationships

For both the lab model measurements and the CFD model calculations, for all sensor locations before the weir, Q(h)-relationships have been derived. This was done by performing a nonlinear regression analysis, based on the Levenberg-Marquardt algorithm, on the water level-flow pairs to determine the values for the constants m and n in equation 1.

Several comparisons can be made between the derived Q(h)-relationships and the standard relationship (equation 1 with default coefficients):

- derived relationships between measuring locations.
- derived relationships from lab scale experiments, the CFD model calculations and the standard relationship.

From these comparisons conclusions on the accuracy and applicability of the derived relationships and the standard equation will be drawn.

RESULTS

Hydraulic behaviour

The lab scale model experiments gave much insight in the hydraulic behaviour of the weir and weir chamber. Ideally the overflow behaviour of the weir is identical along the width of the weir. For low flows this is observed. For high flows the behaviour varies a lot along the width of the weir. To illustrate this some pictures of the water level at low and high flows are shown in Figure 5.

Figure 5. Pictures of the water level in the scale model at flows of 0.008 (low, left) and 0.028 m^3/s (high, right).

The design of the weir chamber is crucial in this respect. The width of the chamber is ten times the distance from the inlet of the chamber to the weir or from the weir to the outlet, as shown in the right side of Figure 2. At low flows the water has enough time to spread evenly before the weir and can get to the outlet after the weir, leading to almost identical overflow behaviour along the width of the weir, see left of Figure 5. At increasing flows the water becomes more turbulent and is pushed up against the weir, leading to an unstable convex water level along the width of the chamber. After the weir the water is pushed up by the chamber walls, leading to an unstable concave water level. These two effects result in very different overflow behaviour along the width of the weir with subcritical submerged overflow at the sides of the weir and supercritical free outflow centred between the inlet and outlet, as shown in the right side of Figure 5.

The role of the scum board is twofold. As it is located in between the chamber inlet and the weir, it acts as a barrier that helps the water spread more evenly along the width of the weir. At high flows, however, it seems to increase the turbulence as the water is forced under the scum board before it can go over the weir. The sharp corners of the in- and outlet of the weir chamber and the asymmetrical design all add to the complex hydraulic behaviour of this structure.

Comparison of water levels

The water levels calculated with the CFD model have been compared with the water levels measured in the lab experiments. A typical result has been given in Figure 6, where the water levels with their 95% confidence bands have been given for sensor location 2. It is stressed that no parameter tuning of the CFD model took place.

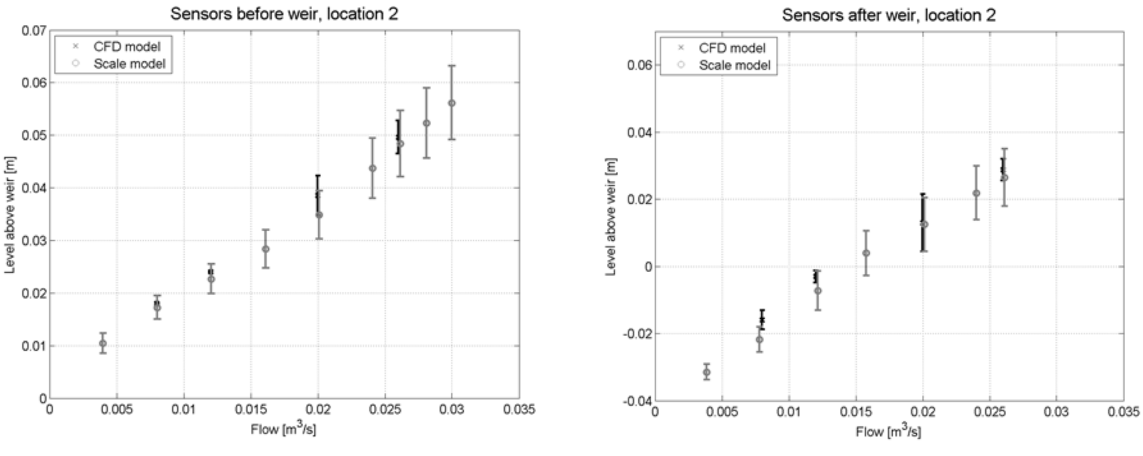

Figure 6. Comparison of measured and modelled water levels at sensor location 2.

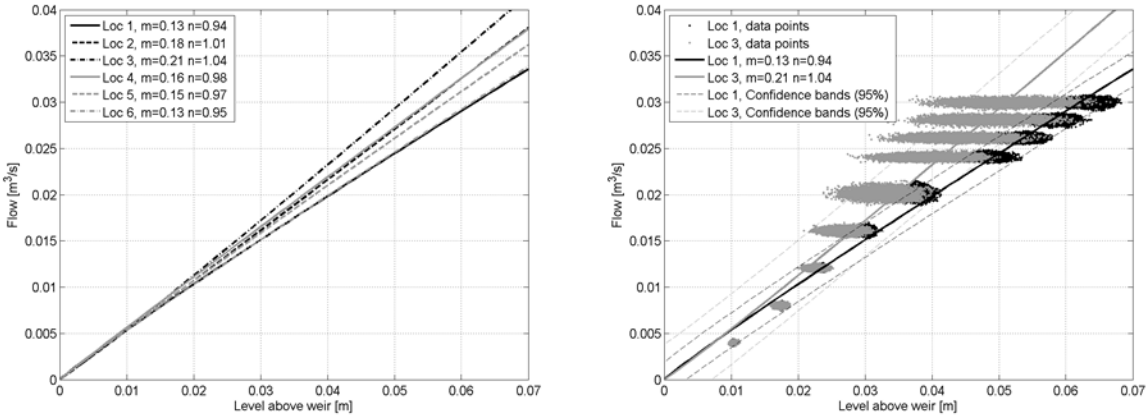

Figure 7. Q(h)-relationships determined with the scale model measurements for all locations (left), and locations 1 and 3 with data points and confidence bands (right).

The modelled water levels for the sensors located before the weir all fall within the uncertainty bands from the measured water levels, expect for the 2 lowest flows for location 3. This is the central location between the in- and outlet and displays the most turbulent behaviour. The modelled water levels for the sensors located after the weir fall within the uncertainty bands of the measured water levels for the larger discharges. Only for the lowest flow of 0.008 m^3/s the deviation is larger than the uncertainty in 4 out of 6 locations. From this comparison it is concluded that the CFD model calculations predict the measured water levels well.

Comparison of Q(h)-relationships between sensor locations

A comparison between the derived Q(h)-relations for the different sensor locations has been made. The results found were very similar for the scale model and the CFD model. Only results based on the scale model are discussed.

In Figure 7 Q(h)-relationships for all locations are displayed on the left side. On the right side the relations for the two locations that differ most (i.e. 1 and 3) are displayed once more, together with the corresponding data points and 95% confidence bands. Please note that location 1 is at the side of the weir, while location 3 is centred between the in- and outlet of the weir chamber. As previously described, the flow is much more stable at location 1 than at location 3 leading to smaller confidence bands.

The derived Q(h)-relationships differ little between locations for low water levels over the weir: at 1 cm water above the weir only 2% between locations 1 and 3. This is to be expected from the stable overflow situation at low flows. For increasing flows the difference steadily increases to a maximum of 20% between locations 1 and 3 at 5 cm water level above the weir, following the more unstable hydraulic behaviour. Please note that similar sensor locations (1-6, in the corners and 2-4 near the middle) lead to very similar relationships.

Comparison of Q(h)-relationships between models

The Q(h)-relationships derived from scale model measurements and the CFD calculations have been compared for each sensor location. In Figure 6 representative examples of these comparisons are plotted for locations 1 and 3. For all locations the derived relationships from the scale model are similar to those from the CFD model. The relationships are close to one another and all fall within each other’s confidence bands, as is shown in Figure 8 location 1. For location 3 the deviation is largest due to the unstable hydraulic conditions, but there is

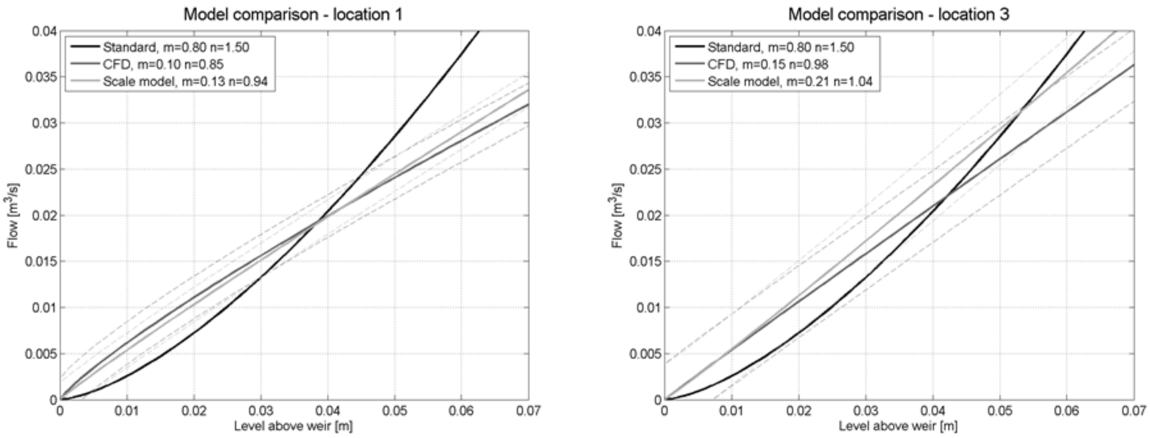

Figure 8. Comparison of Q(h)-relationships for the scale model, CFD calculations (both with 95% uncertainty bands) and standard equation for location 1 (left) and location 3 (right).

still overlap in the results. In general deviations are small at low water levels and increase for higher water levels.

The standard equation shows completely different behaviour compared to the scale model and CFD model results, as can also be found from Figure 8. For all sensor locations the standard equation underestimates the flow for low water levels above the weir, and overestimates the flow for high water levels. For most locations, represented by location 1, the deviation is larger than the 95% confidence bands. Only for location 3 the standard equation falls within the confidence bands for all but the highest water levels.

DISCUSSION

In the standard equation, equation 1, H is the water level above the weir crest measured at some distance upstream from the weir, so that the velocity head is approximately 0. In standard conditions H is about 3/2 times the actual level above the weir crest, where the velocity head is nonzero. In the lab experiments the measuring locations are in between the scum board and the weir, much closer to the weir than a sensor would normally be located. This level is used directly as H in fitting the Q(h)-relationships. The experiments showed that the energy head at these locations is still relatively small, so the errors involved are acceptable.

In the derivation of the Q(h)-relationships only the measuring locations before the weir were used and the differences between the flow conditions along the width of the weir were neglected. All these aspects are incorporated in one Q(h)-relationship per sensor location. This is due to practical considerations. For a Q(h)-relationship to have any practical significance, it should be applicable with as little investment possible. As performing accurate level measurements is already a challenge, simultaneously performing multiple measurements along the width of the weir and on both sides of the weir seems unfeasible.

CONCLUSIONS AND FUTURE RESEARCH

From the comparison of the water levels from the scale model and the CFD calculations it is found that an uncalibrated CFD model, built by an experienced user, is capable of reproducing the hydraulic behaviour of complex structures. The similarity between the Q(h)-relationships derived from the scale model and the CFD model shows that it is possible to determine accurate Q(h)-relationships based on a calculations with a validated CFD model.

The comparison of the derived relationships with the standard equation show that the standard equation is not applicable for the scaled weir and weir chamber. The hydraulic behaviour is found to be unstable, resulting in very different Q(h)-relationships. The standard equation underestimates flow at low water levels above the weir crest, and overestimates flow at high water levels. Furthermore, also due to the unstable hydraulic conditions the derived relationships vary between sensor locations. At low water levels the deviation is around 1%, increasing to a maximum of 20% for high water levels.

Future research will focus on including measurements that have been performed in the original SST: before the internal and external weir and at different locations in the tank. From these measurements the Q(h)-relationships can be derived for the full scale weir. Comparing this to the up-scaled modelling results and the standard equation will lead to a very complete picture of the functioning of the weir and the discharged flows. Together with a thorough uncertainty analysis, this will found a strong basis on which to draw conclusions on the applicability of the standard equation in this weir and the capability of CFD to compute Q(h)-relationships for other CSO structures.

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