CENTAUR: Cost Effective Neural Technique for Alleviation of Urban flood Risk

Deliverable 3.2 – Report on the performance of the pilot CENTAUR and recommendations

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Acronyms

AC	AC Aguas De Coimbra EM
EMS	Environmental Monitoring Solutions
FCD	Flow Control Device
FL	Fuzzy Logic
GA	Genetic Algorithm
LMCS	Local Monitoring and Control System
LMS	Depth Monitoring Site
SWMM	Storm Water Management Model
UoC	Universidade de Coimbra
USFD	University of Sheffield

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Executive Summary

This report is a deliverable from the Cost Effective Neural Technique for Alleviation of Urban Flood Risk (CENTAUR) project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 641931. It corresponds to Deliverable 3.2 - Report on the performance of the pilot CENTAUR and recommendations.

CENTAUR is a flood risk reduction system that aims to reduce local flood risk using a dynamic Flow Control Device (FCD) to utilise the unused storage in sewer networks and piped drainage systems during rainfall events. It can be installed within manholes with minimal new infrastructure, and the FCD is regulated using a data-driven control system. The control system is informed by a local water depth sensing system that is an integral part of a CENTAUR system. The first phase of the project involved the development and integration of the hardware systems (flow control device, local communication and sensing system) and the development and integration of the software (communication and control algorithms) needed for this local real-time control flood risk reduction system. In the second phase of the project, a complete pilot CENTAUR system has been manufactured based on the hardware and software developed in the first phase and has been installed in Av Júlio Henriques in Coimbra, Portugal to conduct a field testing program.

This report presents results from the pilot installation of the CENTAUR system in Coimbra, PT, and assesses the performance of the system and the impact on water depths and flow rates. A brief description of the location of the pilot and the installation of the CENTAUR system is also provided. The pilot system in Coimbra operated (defined as operation of the FCD) during 41 rainfall events over the testing period. The report presents a detailed analysis of a subset of seven rainfall events during in which the CENTAUR FCD was activated; these were selected from the 41 measured events to cover a range of rainfall event characteristics (i.e. different rainfall depths and durations). The analysis presents measured results from the CENTAUR system and compares these to results from a calibrated hydrodynamic model. This model is then used to compare the system state with and without a CENTAUR system for the seven analysed rainfall events. The pilot testing has shown that the CENTAUR system operates as expected and reduces water depths at the downstream location. Detailed analysis indicates that, in the range of rainfall events that the CENTAUR system has been designed for, the peak flow rate and depth at the manhole downstream of the FCD can be reduced by up to 37% and 19% respectively compared to the system with no active control. The design range of the CENTAUR system is linked to the range of flow rates that can be controlled by the FCD. Finally, a summary of key lessons learned is included to improve future CENTAUR systems.

This report describes the activities of Task 3.2 and had the participation of the following project partners: University of Coimbra (UoC), AC Águas de Coimbra, EM (AC), Environmental Monitoring Solutions (EMS), Steinhardt GmbH Wassertechnik (Steinhardt) and University of Sheffield (USFD). This report signifies the completion of Task 3.2.

CONTENTS

1 Introduction

The project CENTAUR (Cost Effective Neural Technique for Alleviation of Urban Flood Risk) is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 641931. CENTAUR is a flood risk reduction system that aims to reduce local flood risk using a dynamically controlled Flow Control Device (FCD) to utilise the unused storage in sewer networks and piped drainage systems during rainfall events. It can be installed within manholes with minimal new infrastructure and the FCD is regulated using a data-driven control system. The control system is informed by a local water depth sensing system, installed at the downstream target location and upstream of the FCD. The first phase of the project involved the development and integration of the hardware systems (flow control device, local communication and sensing system) and the development and integration of the software (communication and control algorithms) needed for a local real-time control flood risk reduction system.

The technology development activities in the project are organised into three technical work packages; WP1 Device Integration and Manufacture, WP2 System Control and Software Development and WP3 Demonstration and Implementation.

The elements of the CENTAUR system are (1) the local monitoring and control system (LMCS, developed in Task 1.1); (2) the flow control device (FCD, developed in Task 1.2); (3) the Fuzzy Logic control algorithm (developed in Tasks 2.1 and 2.3). These elements were integrated in Task 1.3 and then tested in Task 1.4. The Coimbra drainage system has been modelled in detail (Task 2.2), and this model has been used to the aid the selection of the pilot site and also to carry out 'virtual' testing of the CENTAUR system using computer models before the installation of the pilot CENTAUR system (Task 2.3). Task 3.1 involved the installation of the pilot CENTAUR system into the pilot site in Coimbra, PT. Task 3.2 involved assessing the performance of the pilot system using data collected during rainfall events and supporting modelling studies.

1.1 Partners involved in deliverable

UoC – Coordination of the task, monitoring and organisation of field data collection campaign, data analysis, and hydrodynamic modelling.

AC – Provision of catchment and sewer system data and field campaign support.

EMS – Design, manufacture and installation of LMCS and field campaign support.

Steinhardt – Design, manufacture and installation of the FCD.

USFD – Algorithm development, technical support and coordination with other project tasks.

1.2 Deliverable objectives

The report will describe the reduction in flood risk achieved based on observations during the monitoring of the pilot Centaur system and complimentary modelling results from UoC. Staff from UoC and AC will report on the maintenance requirements of the system. USFD and UoC will report on the performance of the CENTAUR system. Recommendations for future work based on these experiences will be made. This deliverable will be based on the activities carried out in Task 3.2.

2 The pilot site

The site for the testing of the pilot CENTAUR system is in Coimbra, PT, it was selected earlier in the project. Full details of the site selection process are described in Deliverable 2.5, while the installation of the pilot CENTAUR system is described in Deliverable 3.1, both of which are available on the CENTAUR website (https://www.sheffield.ac.uk/centaur/outputs). In this section, the selected site is briefly presented.

The site selection procedure investigated possible locations in the Coimbra drainage network for the installation of the CENTAUR system. The sites were analysed for the available upstream volume which could be used for storage at the peak of design rainfall events. For the pilot system it was also important to minimise the number of property connections to the storage length to minimise the risk of damaging connected properties through the surcharging of the storage length. Based on this procedure a site on Av. Júlio Henriques was selected, the site has a length of large diameter combined sewer pipe that provides a suitable upstream storage volume and has a small number of connected properties.

The pilot testing phase needed a realistic target which could be achieved multiple times during the planned testing period of less than one year. Downstream flooding occurs on average less than once per year (i.e. with a return period of greater than 1 year). The objective for the pilot CENTAUR was therefore defined as being to reduce the downstream in-sewer flows, based on a depth criterion. Figure 1 shows the location of the CENTAUR pilot system, LMS1 (Depth Monitoring Site 1) is the target location in Praça Republica and the FCD is located on Av. Júlio Henriques further upstream in the network at the same location as LMS2. A blue box shows the pipes which form the storage volume in the left side of Figure 1. In addition to the main CENTAUR system monitoring, an additional depth monitor at the manhole immediately downstream of the FCD location is labelled DS.

Praça da Republica was selected as the downstream control point because it has good conditions for monitoring water depth (a shallow gradient and reasonable depth range), flood locations often exhibit similar characteristics to this site. Between this location and the FCD there is a long, relatively steep road with a bifurcation (where the sewer splits into two parallel pipes). The steepness and bifurcation make obtaining good quality monitoring data between Praça da Republica and Av. Júlio Henriques infeasible. Furthermore, Praça da Republica is also a practical place to access the sewer system where necessary.

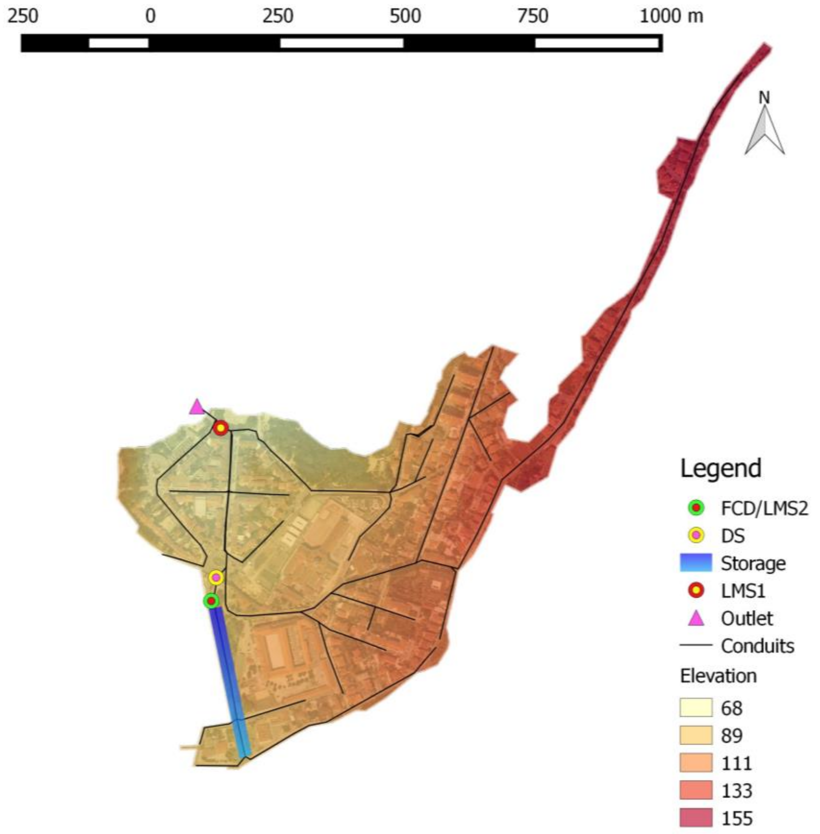

Figure 1 Pilot study catchment, FCD location and affected pipes.

The FCD installed on Av. Júlio Henriques was designed to provide control of flow rates in the range reasonably expected to be seen on multiple occasions during the testing period. During the earlier flow monitoring campaign carried out during 2016, peak flows of around 0.150 m^3/s were seen in this pipe, these are significantly lower than the flows expected for a 2 year return period event (the minimum return period in the Portuguese legislation (RGSPPDADAR, 1995). It was therefore decided to install a FCD to control flows in the range of those measured in 2016. The chosen FCD can provide good control of flows between 0.05 and 0.15 m^3/s, although when fully open and with a high storage depth the FCD orifice can pass significantly higher flows. The FCD was also designed to incorporate fail safes to ensure that in the event of a failure no flooding would occur upstream of the FCD location. These fail safes are an overtopping weir and high depth flap valves which can pass flows resulting from design rainfall up to the 100 year return period without causing any additional upstream flood risk. These valves and weir will also operate once the storage volume is full.

The CENTAUR system installation was described in Deliverable 3.1.

3 Operation and performance of the pilot CENTAUR system

The CENTAUR pilot system was made operational on 11th October 2017 and has been run continuously ever since that date. A total of 41 rainfall events occurred in the period from 11th October 2017 to 24th February 2018 where the rainfall was large enough to cause the FCD to operate and the upstream storage volume to be at least partially filled.

Within this section of the report, the collected field data will be presented alongside data from the hydro-dynamic SWMM (Storm Water Management Model, US EPA) model of the current Coimbra network with the Centaur system installed. This is to show the operation of the CENTAUR system in the field and to validate the performance of this version of the SWMM network model against collected field data. Also presented are simulation results from an earlier version of the Coimbra SWMM model where the CENTAUR system is not installed. Comparison between these model versions allows the benefit of the CENTAUR system to be assessed.

The earlier version of the SWMM model (without the Centaur system) had been verified in line with the UK modelling code of practice (WaPUG, 2002). It should be noted that the results from the latest version of the SWMM model with the Centaur system are not expected to be an exact match to the measured data, especially for the smaller rainfall events where there is greater uncertainty in the amount of predicted runoff which enters the drainage network. The Fuzzy Logic (FL) control algorithm is data driven and hence if there is a difference between the predicted and actual water depths at the control location, then the different data input to the FL will produce different outputs. The FL outputs control the FCD position, hence here will be differences in the FCD position and the effects of the FCD will be different between the observed and modelled situations.

In Task 2.1 a study to determine the form of the CENTAUR control algorithm examined the use of a self learning Artificial Neural Network and a Fuzzy Logic algorithm. For a number of practical and scientific reasons, it was determined that a Fuzzy Logic algorithm would be better suited to the problem of flood risk reduction[1]. During the development of the CENTAUR control algorithm, the use of a Genetic Algorithm (GA) to optimise the FL membership functions has also been investigated using hydro-dynamic network models. While this GA based optimisation has given good results on the rainfall events used as input to the optimisation (the training events), it has been found that the optimised membership functions tend not to improve performance on unseen ‘test’ rainfall events and can sometimes reduce performance. Given this uncertainty and lack of enhancement it has therefore been decided not to incorporate optimisation in the pilot system. The FL membership functions for the pilot site have been developed using expert knowledge and refined through the ‘virtual testing’ process using a hydro-dynamic network model and the laboratory testing on a physical model.

During the field studies described in this report the Fuzzy Logic algorithm was not changed, however the input parameters which affect the operation of the FL algorithm were adjusted. Initially the target maximum water depth at the downstream target site (LMS1) was set at 0.12 m, this was changed to 0.16 m on 23rd November. The reason for changing this parameter was that

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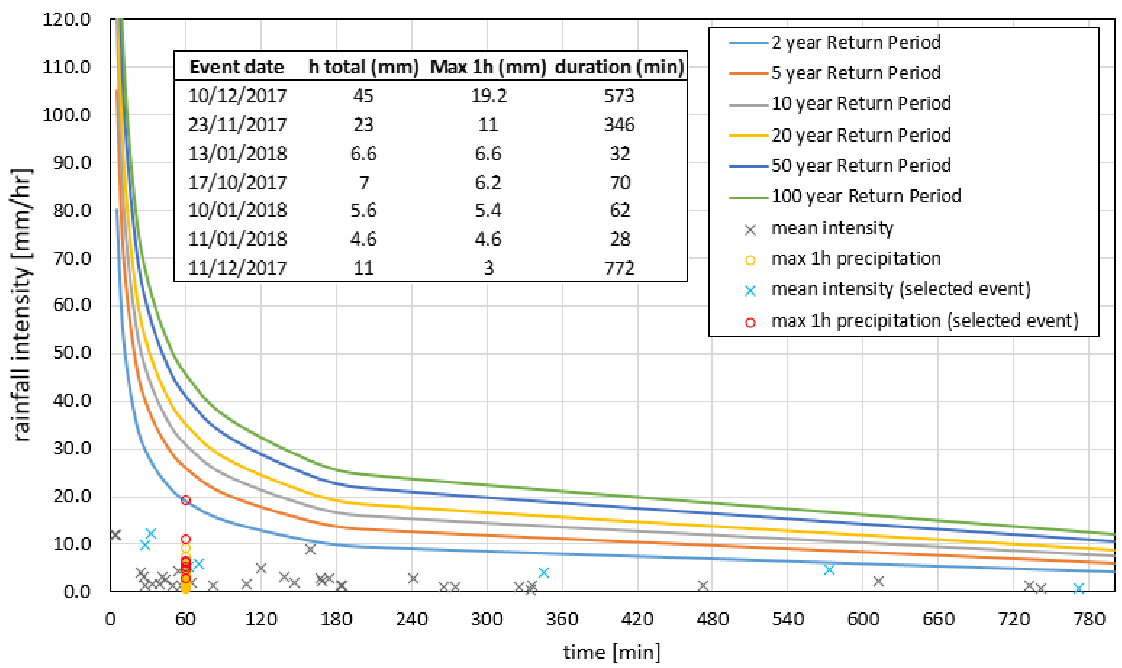
[1] Deliverable 2.1 Data driven control software architecture (Internal, confidential report)

the dry weather flow water depths at this location were higher than anticipated, possibly due to more infiltration into the drainage network during the autumn months. The higher than anticipated water depths resulted in premature operation of the FCD. The FCD was always set to have a minimum opening of 5% to maintain some pass forward flow and limit sedimentation immediately usptream of the FCD.

For the majority of 2017 Portugal was in an extreme drought situation, it is usually expected to have at least 100 mm of rainfall per month between October and February, however the measured rainfall was 28 mm in October 2017, 60 mm in November 2017, 107 mm in December 2017 and 95 mm in January 2018. In the first two months of operation there was therefore significantly less rainfall, and hence fewer large events, than originally anticipated. However there were 41 rainfall events that mobilised the FCD in the time period between October 2017 and February 2018.

To assess the benefit of the CENTAUR system installed in Coimbra, 7 events (with a range of rainfall depths and durations) from the 41 rainfall events were selected for detailed analysis with the use of the SWMM models described above.

The characteristics of these 7 rainfall events are presented on the Intensity-Duration-Frequency plot in Figure 2, along with a table of the rainfall event details. The Intensity-Duration-Frequency curves are based on the Portuguese legislation (RGSPPDADAR, 1995). It can be seen that the event on 10th December is the most significant, with the 1 hour mean rainfall intensity of 19.2 mm/hr exceeding a 2 year return period, while for the whole event it can be seen to also have the highest event return period with the average intensity of 4.7 mm/hr being a little under the 2 year value for the 9 hrs 33 minutes duration. The event on 11th December 2017 is the smallest presented with a 1 hour intensity of 3.0 mm/hr and a mean intensity of 0.93 mm/hr.



Event date	h total (mm)	Max 1h (mm)	duration (min)
10/12/2017	45	19.2	573
23/11/2017	23	11	346
13/01/2018	6.6	6.6	32
17/10/2017	7	6.2	70
10/01/2018	5.6	5.4	62
11/01/2018	4.6	4.6	28
11/12/2017	11	3	772

Figure 2 Intensity-Duration Curves and Data from 41 rainfall events that activated the FCD during the period of tests. Selected events, which were chosen to cover a range of rainfall depths and durations, are highlighted.

The seven events are analysed in the following three sub-sections, the events are presented in descending order of the maximum 1 hour rainfall depth. The first sub-section presents the recorded data and describes the event specific calibration of the SWMM model with the active FCD. The water depth at LMS1 and LMS2 and the FCD position are presented. To evaluate the performance of FCD in detail the second sub-section presents a comparison of the models with and without the CENTAUR system installed. Water depths at LMS1, LMS2 and at the first manhole downstream (DS) from the FCD are shown. Flow data is also presented, this is useful because flow is more sensitive than water depth until the urban drainage system becomes surcharged (i.e. water depths are above the pipe soffit (top of pipe)). When the system is surcharged the relationship between depth and flow changes significantly, hence the in-pipe difference in water depth seen in the pilot testing would be magnified in surcharged conditions. For example in surcharged conditions a unit change in flow can have 10 times more effect on water depths than when the pipe is not surcharged, as shown in Figure 3 for node B in a hypothetical 0.3 m diameter pipe. It should be noted that this head discharge relationship is site specific.

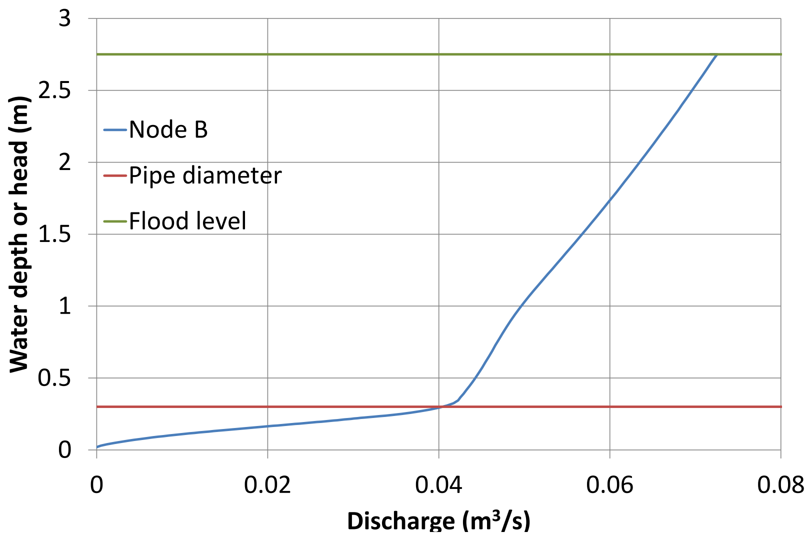


Figure 3 Indication of relationship between water depth and flow at a hypothetical location.

3.1 Data Analysis and Calibration of SWMM model with Centaur System

Here the observed data is described and then presented alongside the results from the SWMM model of the CENTAUR system. For each event a calibration was performed with the objective to better simulate the network flows and hence provide a more accurate representation of the modelled CENTAUR system. Ensuring a minimum difference between the modelled performance and the observed data provides a sound basis for the later analysis of the CENTAUR system performance. The calibrations were originally conducted to account for the local catchment runoff parameters. However, based on this it was found that the flows through the FCD orifice did not match the observations well. Further investigation showed that the reported FCD position was likely to have some error; hence the modelled FCD positions were also calibrated to provide a good match to the measured water depths. The flow through the valves and over the weir of the FCD did not require calibration.

The ideal model of the CENTAUR system would be able to replicate the movement of the FCD (opening and closing) exactly. This would allow the precise verification of the retention and release of water upstream and downstream of the FCD. However the control algorithm of CENTAUR is sensitive to water depths, meaning that in order for it to exactly replicate the FCD movements, the performance of the hydraulic model should be exactly the same as reality. As the model is an approximation of reality it contains slight differences in water depths compared to the observed data. These differences reflect directly on the operation of the FCD causing the model to demonstrate small divergences between the observed and the modelled FCD positions, inevitably producing discrepancies in water depth output.

3.1.1 Event 1 – Maximum of 19.2 mm in 1 hour on 10/12/2017

Observed data

Event 1 was the largest event in terms of both 1 hour and total event depths, it was also the second longest event at 9 hours 33 minutes. Figure 4, Figure 5 and Figure 6 show that the rainfall was almost constant but not high intensity for most of the event, however it included a short period of high intensity rainfall starting at around 6.5 hours from the beginning of the event. The highest intensity period results in 13 mm of rainfall in 10 minutes, which equates to a return period of almost 10 years. Figure 6 shows that the FCD closed early in the event and remained closed until the event ended with the aim of keeping water depths at LMS1 below 0.16 m, it can be seen that the water depths observed at LMS1 are close to or above this value, hence justifying the FCD closure at this time (Figure 6). The FCD was not able to keep the water depth at LMS1 below the 0.16 m target, this is due to the two other significant inflows to LMS1 in Praça da Republica which were sufficient to breach the target depth alone, even if the contribution from the catchment upstream of the FCD was nil. The length of the event also means that the available storage volume was filled, limiting the amount of attenuation that CENTAUR could provide in the later part of the event.

Calibration

The modelled water depths follow the shape of the observed water depths with, but with a higher peak water depth (Figure 4). The very high intensity recorded here could be expected to provide some discrepancies, not least because such a short burst of high intensity rainfall would have significant spatial variation, hence the rain gauge location most likely experienced a higher peak intensity than the catchment upstream of LMS2. Water depths at LMS1 are represented well in the model as shown in Figure 5. Operation of the FCD is also represented well in the model (Figure 6), apart from a short period after the main peak. This is caused by differences in the water depths shown in Figure 5, i.e. a sudden drop in the water depth after the peak at LMS2 in the modelled data. It should be noted that the FCD opening on the y-axis of Figure 6 and similar figures is presented as %/100, i.e. a value of 1 means the FCD is 100% open and the minimum opening of 5% is represented as 0.05 on the y-axis.

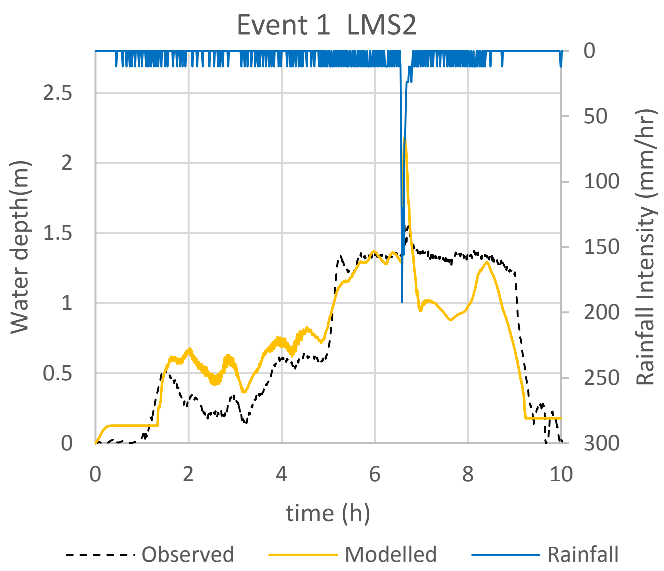


Figure 4 Comparison of water depth observed in LMS2 and modelled

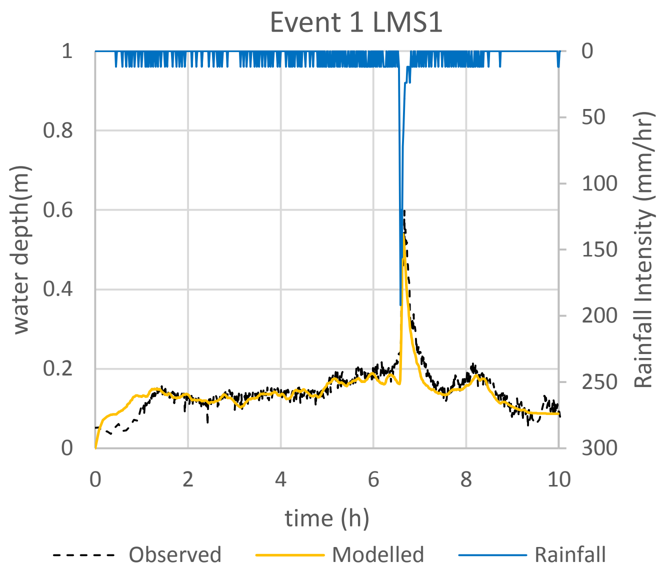


Figure 5 Comparison of water depth observed in LMS1 and modelled

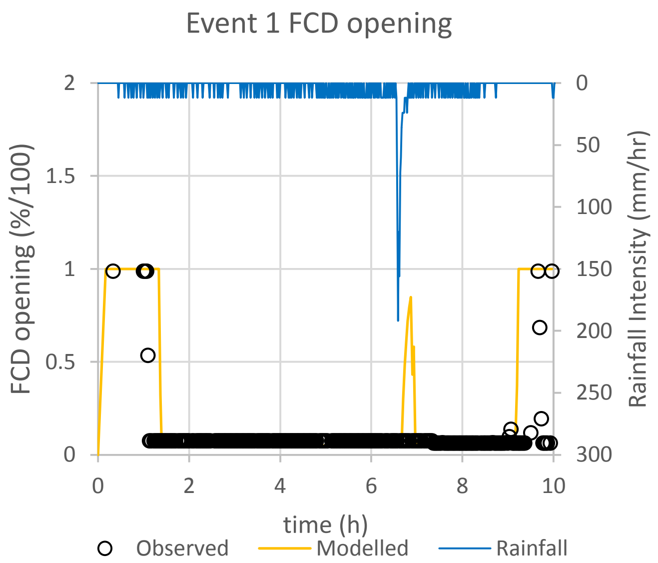


Figure 6 Comparison of modelled and observed FCD operation

3.1.2 Event 2 – Maximum of 11 mm in 1 hour on 23/11/2017

Observed data

The second event had both the second highest 1 hour depth and second largest total depth, while the duration at 5 hours 46 minutes is in the middle of the range of the seven selected events. There were two main rainfall peaks which result in two flow peaks as shown in Figure 7 and Figure 8. The rainfall peak intensities were 60 and 72 mm/hr respectively. The CENTAUR system responded independently to these peaks, being able to re-open the FCD (Figure 9) and fully drain the storage from the first peak before the second arrived. For both flow peaks, the magnitude of flows at LMS1 means that the target water depth of 0.12 m could be achieved by only controlling flows upstream of LMS2. It should be noted that while the FL control was active it recorded FCD position every 2 minutes, when the FL control became inactive at the end of the event the FCD returned to the fully open position but the position was not reported until the next scheduled communication, which was every 3 hours, or when the FCD switched back to being active. Hence at the start of this event the FCD positon was reported less frequently and in subsequent events there may not have been an observed FCD positon plotted after the FL control became inactive.

Calibration

The water depths at LMS2 and LMS1 (Figure 7 and Figure 8) are generally well represented by the model, as is the FCD position (Figure 9). The modelled peak depth at LMS1 is smaller than the observed water depth (Figure 8). The most likely explanation for this difference is spatial heterogeneity in the rainfall over the catchment, meaning the other catchments contributing to LMS1 had lower rainfall than the rain gauge and the catchments contributing to LMS2. The modelled FCD operation is a good approximation of the observed position (Figure 9), the differences are explained by the discrepancy in the water depth. Differences at LMS2 (Figure 7) during the periods when the water depths are decreasing are different for the two peaks. After the first peak the modelled water depths decrease at a similar rate, despite differences in FCD position when the FCD in the model re-opens at around 3.25 hours. When the modelled FCD re-closed again, the stored water depth increased, while the observed depth continued to decrease, despite the FCD positions being the same. This may indicate another case of spatial heterogeneity in the rainfall, where the rainfall at around 3.7 hours occurred at the rain gauge, but not at the catchments upstream of LMS2. For the second peak, the modelled water depths at LMS2 initially dropped more quickly than the observed, this is due the FCD reopening in the model. After the FCD in the model closed again the depth at LMS2 decreased, indicating, similarly to the depth increase in the model after the first peak, that the small later rainfall at 6 hours may have had significant spatial variability resulting in more flow at LMS2 in the model than actually occurred.

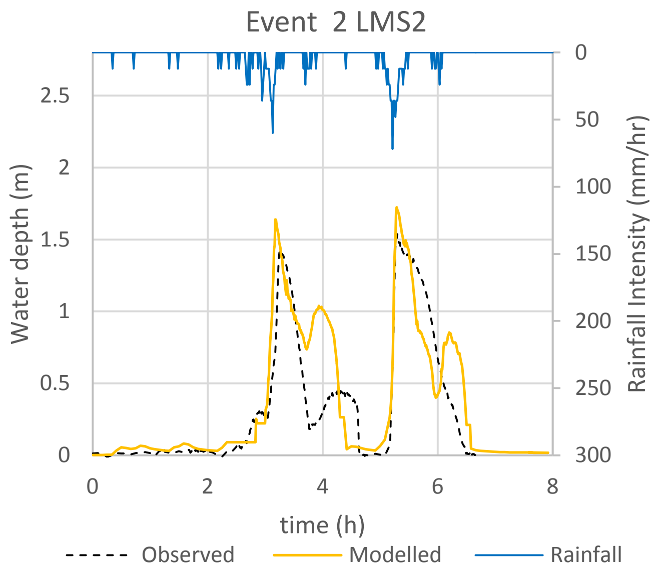


Figure 7 Comparison of water depth observed in LMS2 and modelled

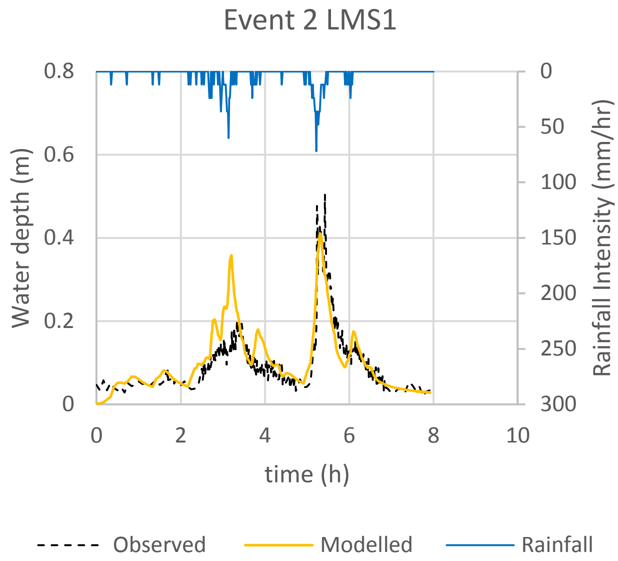


Figure 8 Comparison of water depth observed in LMS1 and modelled

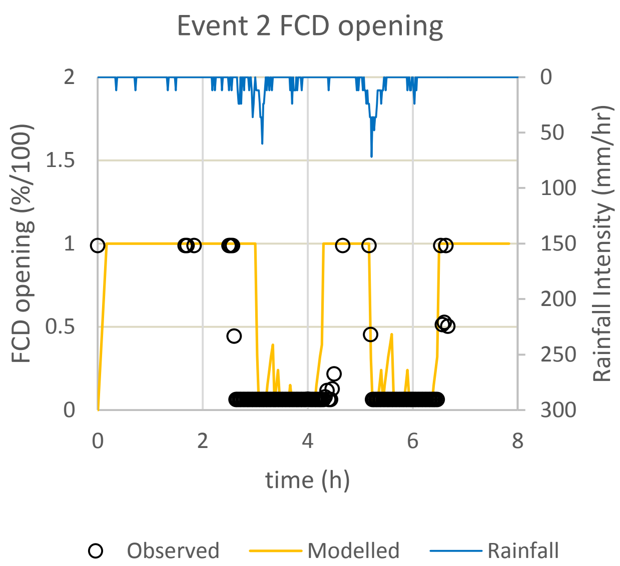


Figure 9 Comparison of modelled and observed FCD operation

3.1.3 Event 3 – Maximum of 6.6 mm in 1 hour on 13/01/2018

Observed data

This was the second shortest duration event with a single rainfall and flow peak, the total rainfall depth was 6.6 mm, with a peak intensity of 36 mm/hr. The rainfall event was large enough to activate the FCD and store water upstream (Figure 10). Although this was a small event, the flows from the uncontrolled catchments mean that the target depth of 0.16 m was not achieved.

Calibration

The hydro-dynamic model produces water depths that agree well with the observed values for LMS1, LMS2 and the opening of the FCD (Figure 10, Figure 11 and Figure *12*). The rise in depth at LMS2 (Figure 10) is slightly later in the model, caused by a slower closure of the FCD, in turn caused by differences in the water depths at LMS1.

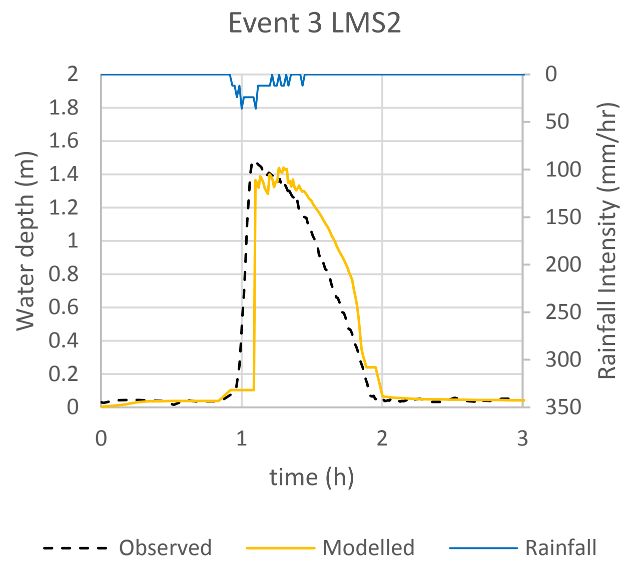


Figure 10 Comparison of water depth observed in LMS2 and modelled

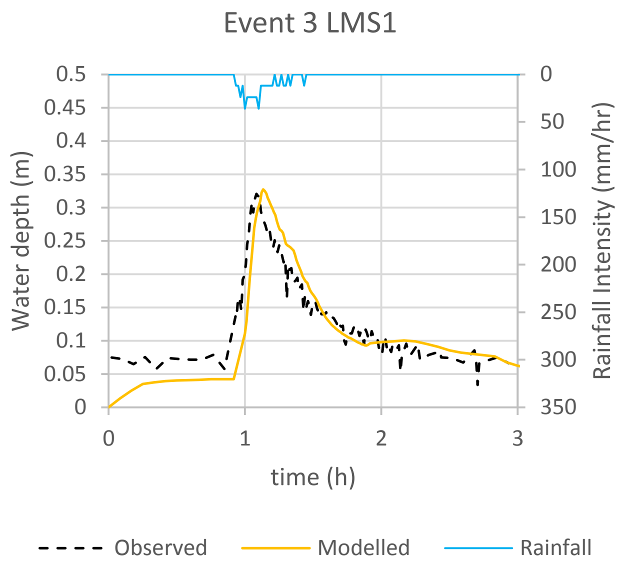


Figure 11 Comparison of water depth observed in LMS1 and modelled

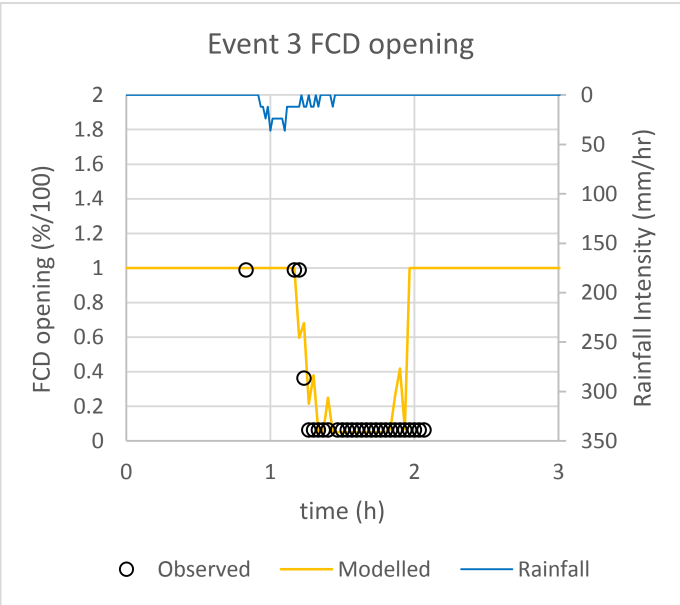


Figure 12 Comparison of modelled and observed gate operation

3.1.4 Event 4 – Maximum of 6.2 mm in 1 hour on 17/10/2017

Observed data

The fourth event had a duration of 70 minutes and is in the lower third of the recorded 1 hour intensities from the 41 events. The event comprised of two short periods of rainfall which resulted in two peaks in the sewer flow and depth. Figure 13 and Figure 14 show the observed water depth at LMS2 and LMS1 respectively. The observed data shows a small amount of rainfall in the first hour with a peak intensity of 24 mm/hr which caused the FCD to operate (Figure 15). The peak water depth corresponding to this first rainfall peak at LMS1 is 0.11 m, which is below the target depth of 0.12 m, after this rainfall the FCD re-opened. A second larger peak in the rainfall, with a maximum intensity of 48 mm/hr resulted in higher flows, this time the FCD was not able to keep the depth below the 0.12 m target as it is closed to the 5% limit while depths at LMS1 reached 0.29 m.

Calibration

The model results presented in Figure 13 and Figure 14 show that the peak and shape of the water depth time series correspond well with the observed data. The model does not show an operation of the FCD during the first peak (Figure 15) as the control depth at LMS1 was not reached in the model. The observed data has a slightly higher peak which caused the FCD to operate and the water depths upstream of LMS2 to increase. The modelled FCD operation in the second rainfall peak matches the observed operation well and results in water depths at both LMS1 and LMS2 matching the observed values well.

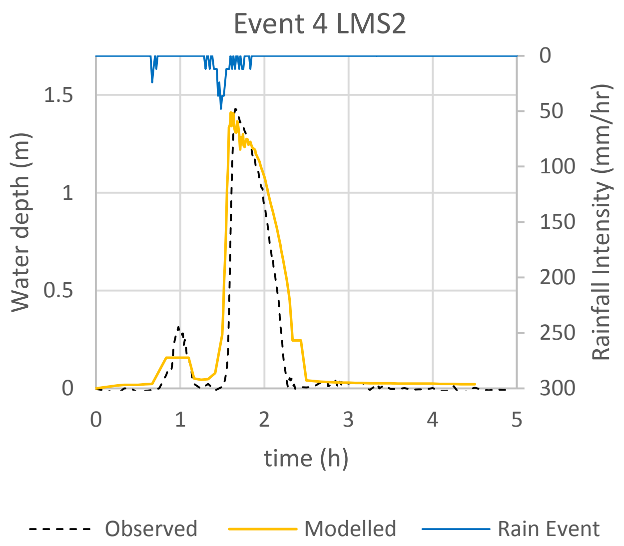


Figure 13 Comparison of water depth observed in LMS2 and modelled

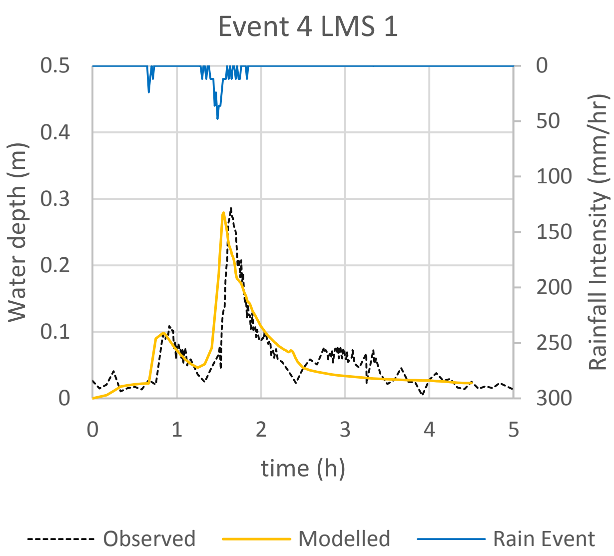


Figure 14 Comparison of water depth observed in LMS1 and modelled

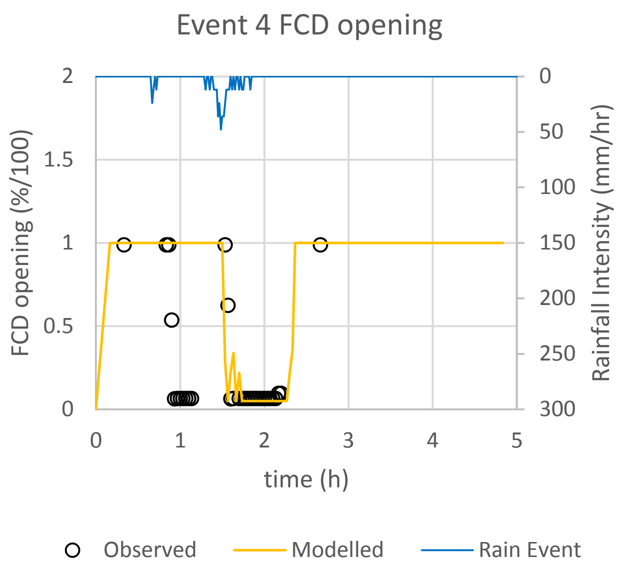


Figure 15 *Comparison of modelled and observed FCD operation*

3.1.5 Event 5 – Maximum of 5.4 mm in 1 hour on 10/01/2018

Observed data

Event 5 had a 1 hour intensity of 5.4 mm/hr, Figure 16 and Figure 17 show that the rainfall started with low intensity and had a short high intensity period, with a peak of 48 mm/hr towards the end of the event which produced the most significant flows. Figure 18 shows that the FCD closed just after 2 hours into the event and stayed closed for a little under 1.5 hours. In the initial part of the event water depths at LMS1 did not exceed 0.18 m, this is above the target of 0.16 m, but as previously discussed other inflows made meeting the target difficult. During the higher intensity period the water depths increased to 0.39 m.

Calibration

The model results for event 5 match the observed data at LMS1 and LMS2 well (Figure 16 and Figure 17). The modelled FCD reopens partially during the peak and closes again. This operation was different from the observed data (Figure 18). The peak depth at LMS1 was slightly later in the model than was observed. This could be due to the rainfall heterogeneity (e.g. the peak rainfall occurring later on the catchments upstream of LMS1 than at the rain gauge location and at LMS2.)

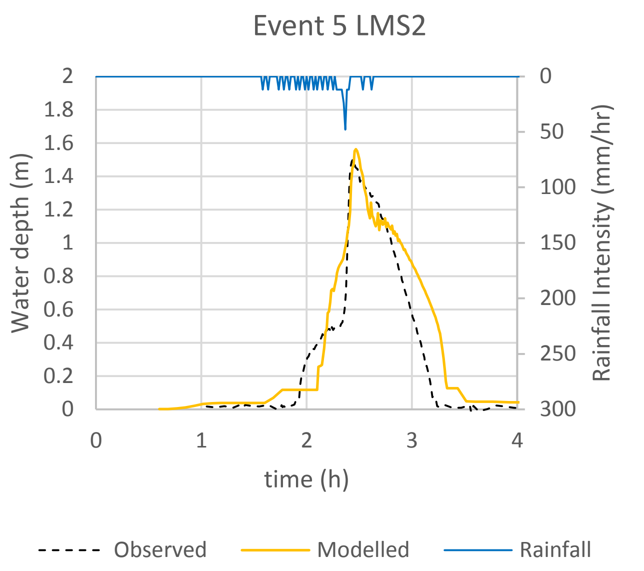


Figure 16 *Comparison of water depth observed in LMS2 and modelled*

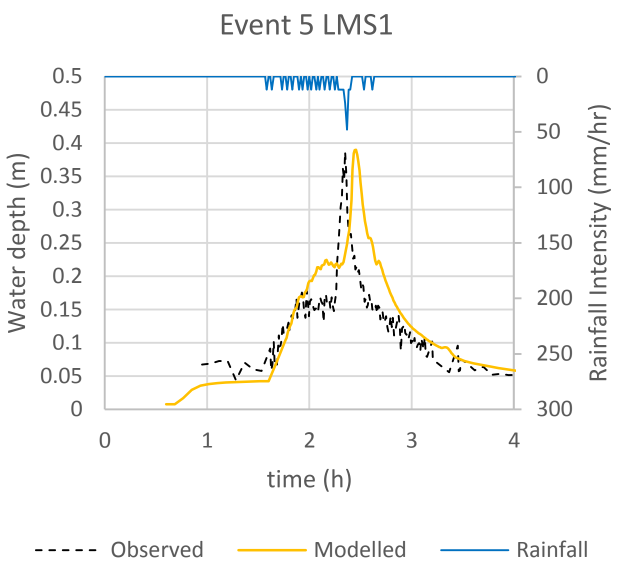


Figure 17 *Comparison of water depth observed in LMS1 and modelled*

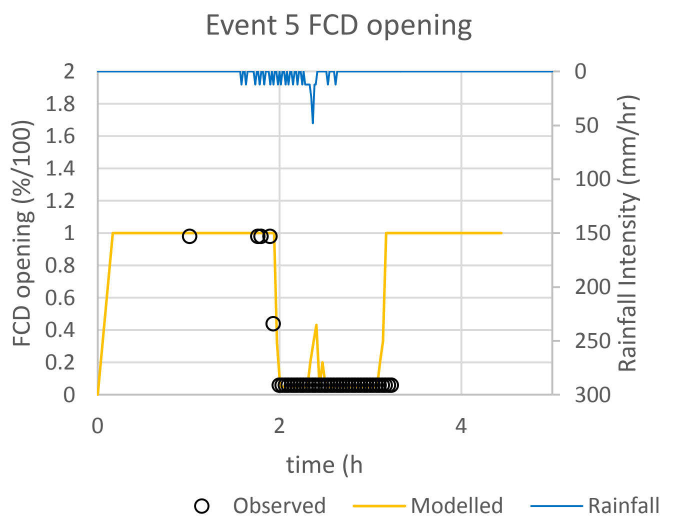


Figure 18 Comparison of modelled and observed FCD operation

3.1.6 Event 6 – Maximum of 4.6 mm in 1 hour on 11/01/2018

Observed data

This event had two peaks of low intensity (24 and 48 mm/hr respectively) which were close together. The FCD activated during the first rainfall peak and stayed closed until after the second peak (Figure *21*). The target water depth of 0.16 m at LMS1 was not met during either rainfall peak.

Calibration

The calibrated modelled water depths for this event are simulated well for both LMS1 and LMS2, but with some time shift at LMS1 during the initial rising limb. The double peak is easily visible at LMS1 (Figure 20) while LMS2 (Figure 19) shows a break in the water depth rise in the model results. As with other events, the modelled FCD position shows a small opening after the peak flow which was not seen in the observed data (Figure 21).

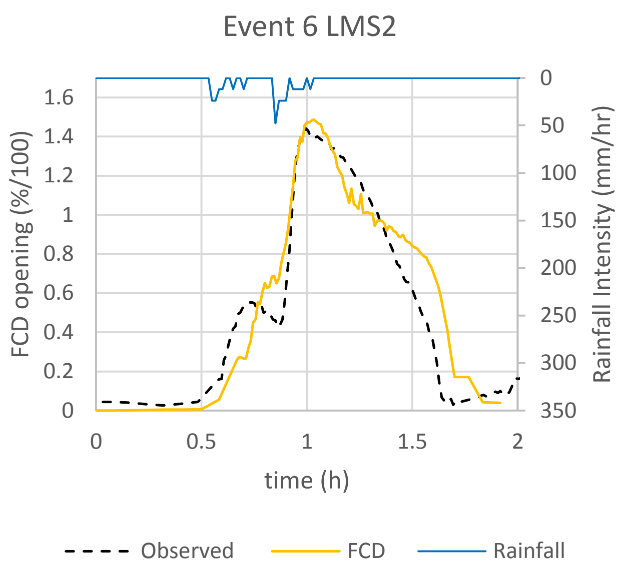


Figure 19 Comparison of water depth observed in LMS2 and modelled

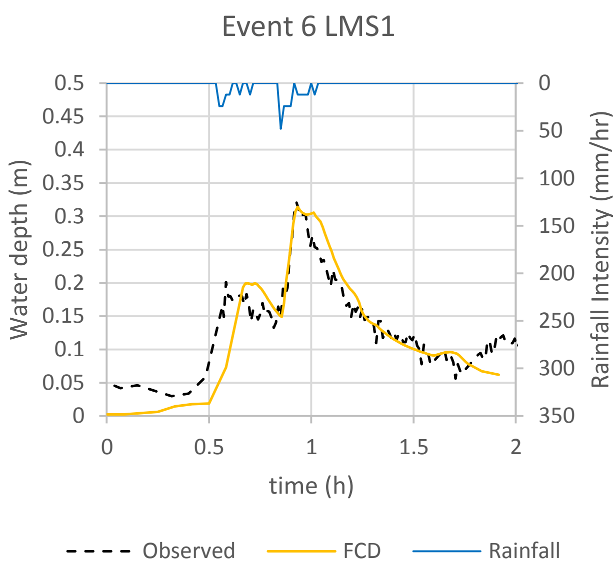


Figure 20 Comparison of water depth observed in LMS1 and modelled

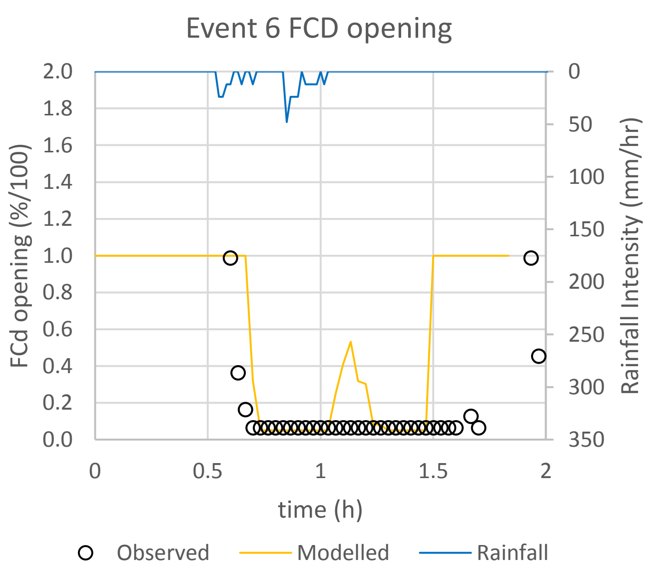


Figure 21 Comparison of modelled and observed gate operation

3.1.7 Event 7 – Maximum of 3 mm in 1hour on 11/12/2017

Observed data

Event 7 was the lowest intensity event with only 3 mm falling in 1 hour and a peak intensity of 24 mm/hr. The rainfall resulted in two distinct peaks in the water depths at LMS2 and LMS1 (Figure 22 and Figure 23). The observed FCD position in Figure 24 shows that the FCD re-opened between the sub-events. The target water depth at LMS1 of 0.16 m was not met for either peak.

Calibration

The modelled water depths fit the observed peak and shape well for both LMS2 and LMS1 (Figure 22 and Figure 23 respectively), however there is a small time delay in LMS2 (Figure 22). The modelled FCD position agrees well with the observed data with small differences during the reopening when the model starts to move the FCD earlier than was observed (Figure 24).

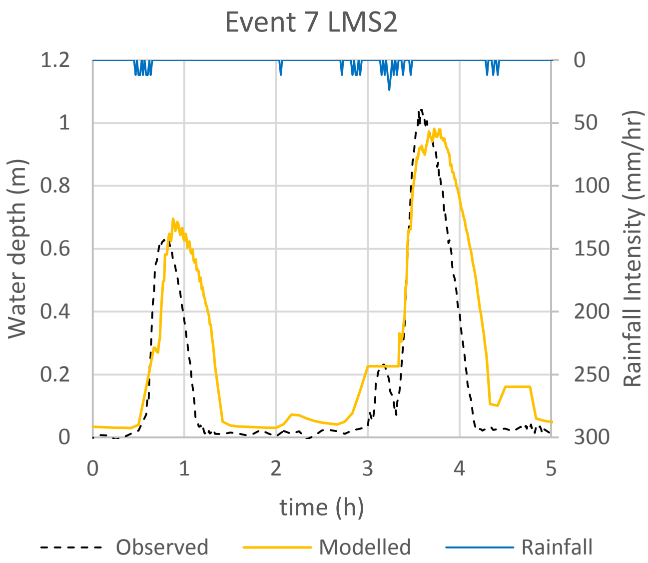


Figure 22 Comparison of water depth observed in LMS2 and modelled

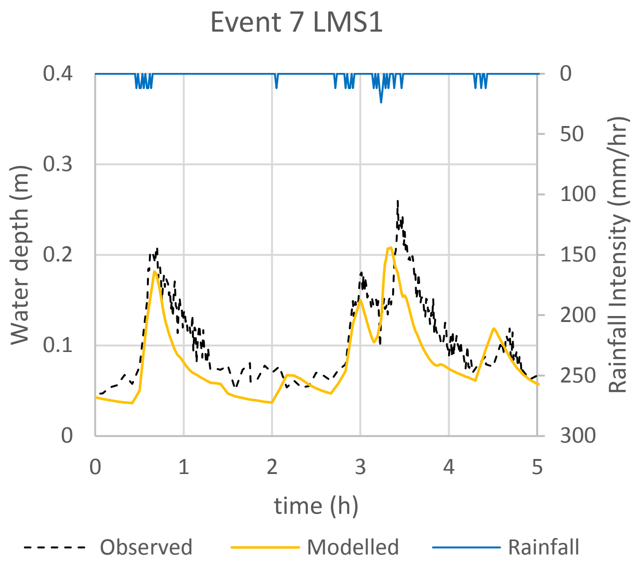


Figure 23 Comparison of water depth observed in LMS1 and modelled

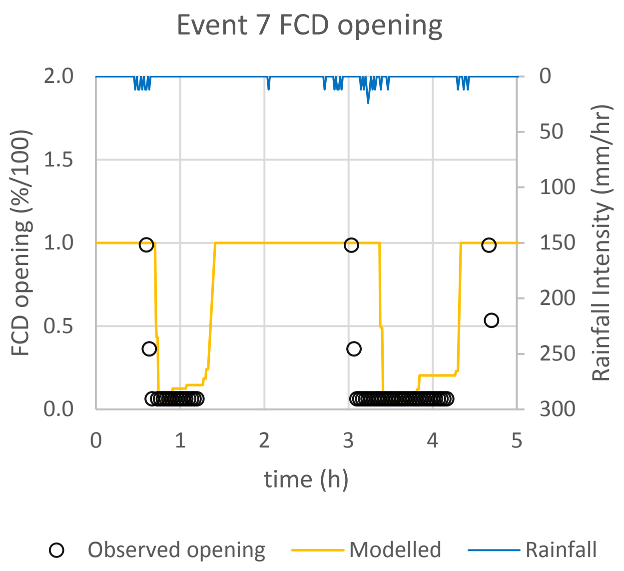


Figure 24 Comparison of modelled and observed FCD operation

3.2 CENTAUR FCD performance in the pilot installation

The second part of the evaluation process consisted of applying the calibrated SWMM models (one with the FCD incorporated and an earlier model in which there was no FCD) to objectively compare the response of the sewer system with and without the use of the CENTAUR system during the selected rainfall events. The goal is to demonstrate the impact that the CENTAUR system has when compared to the model without the FCD. This comparison is only possible through the use of a model because rainfall events and the associated catchment runoff response are effectively unique so it would be impossible to record the response of the system for identical rainfall events with and without the CENTAUR system to evaluate the performance.

3.2.1 Event 1 – Maximum of 19.2 mm in 1hour on 10/12/2017

Figure 25 to Figure 29 show a comparison between the modelled results when the CENTAUR system is installed and when it is not installed. Water depths are presented at LMS1, LMS2 and at the manhole immediately downstream of the FCD (DS). Flow rates are presented for LMS1 and at DS where the impact of the CENTAUR system can be better assessed. Table 1 presents the peak values and percentage differences in water depths and flows for LMS1 and DS with and without the FCD installed. Figure 25 shows that the depths at LMS2 do not rise significantly until the high intensity peak in the rainfall when the FCD is not installed. Figure 26 and Figure 28 show the benefit at the first manhole downstream of the FCD. Despite the high flow, there is a reduction in the peak flow depth of 13% and a 7% reduction in flow. At LMS1 the contributions from other catchments mean that the impact of the CENTAUR system is negligible. The benefit at DS is due to attenuation of the very short duration peak upstream of the FCD, although the storage was already almost full before this peak, the flows are still slowed sufficiently to have a benefit at DS.

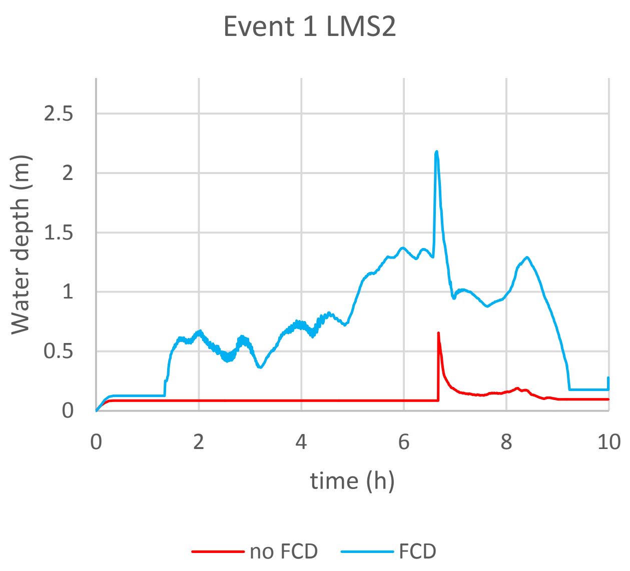


Figure 25 Event 1 water depth simulation with and without FCD at the LMS2

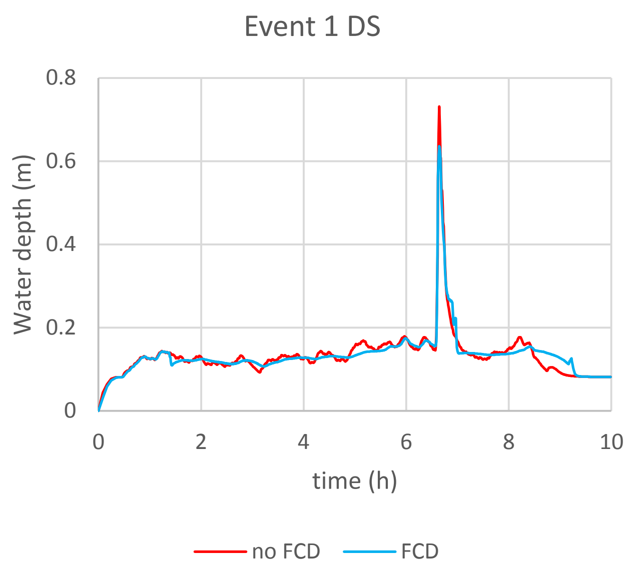


Figure 26 Event 1 water depth simulation with and without FCD at the first manhole downstream the FCD

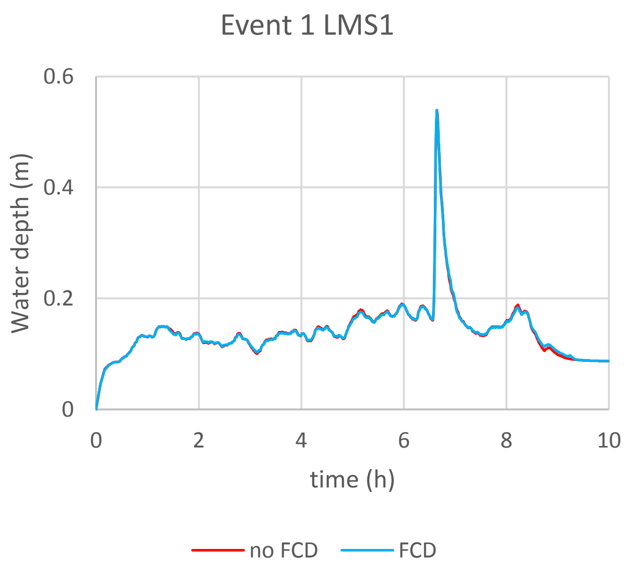


Figure 27 Event 1 water depth simulation with and without FCD at the LMS1

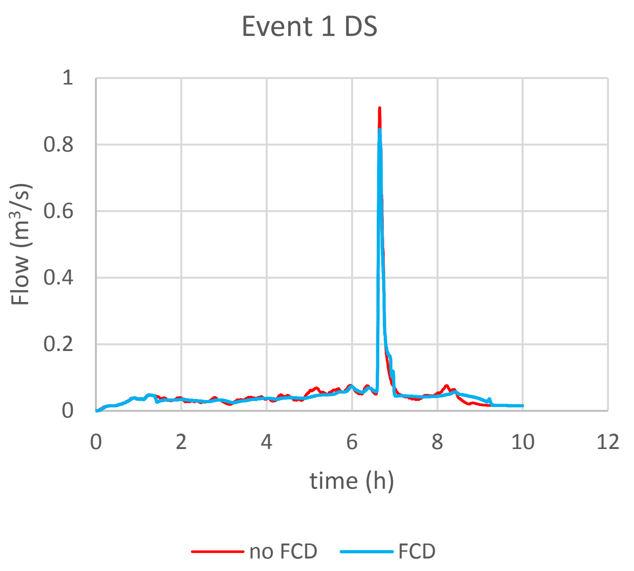


Figure 28 Event 1 flow simulation with and without FCD at the first manhole downstream the FCD

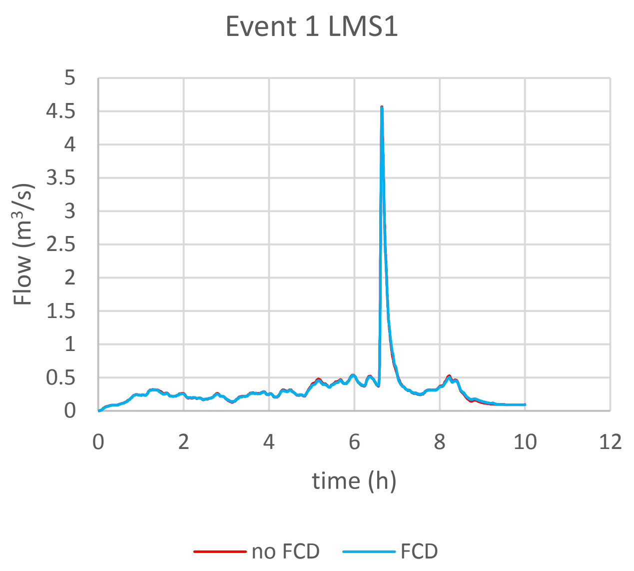


Figure 29 Event 1 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.539	0.538	0%
DS	0.731	0.636	-13%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	4.566	4.558	0%
DS	0.911	0.846	-7%

Table 1 Comparison of water flow and depths between simulations with FCD and without FCD for event 1

3.2.2 Event 2 – Maximum of 11 mm in 1 hour on 23/11/2017

Figure 30 to Figure 34 show the comparisons between the modelled results when the CENTAUR system is installed, and when it is not installed. In Figure 30 it is clear that storage is being utilised at LMS2 through operation of the FCD. Figure 31 and Figure 33 show the effects of the FCD when the storage is draining, but it is difficult to see the impact on the peaks. Table 2 shows that for the highest peak there is no benefit from the CENTAUR system, this is because the peak flow of around 0.350 m^3/s is significantly over the design control flow of the system. A more detailed investigation shows that although the absolute peak values with the FCD are slightly higher at DS, it is only greater than the values without the FCD for a single 2 minute time step. However, on the first peak, where the flow is less than 0.300 m^3/s, there is a reduction of around 7% in flow at DS, but the peak depths are almost identical (not shown in Table 2, but included in Figure 60).

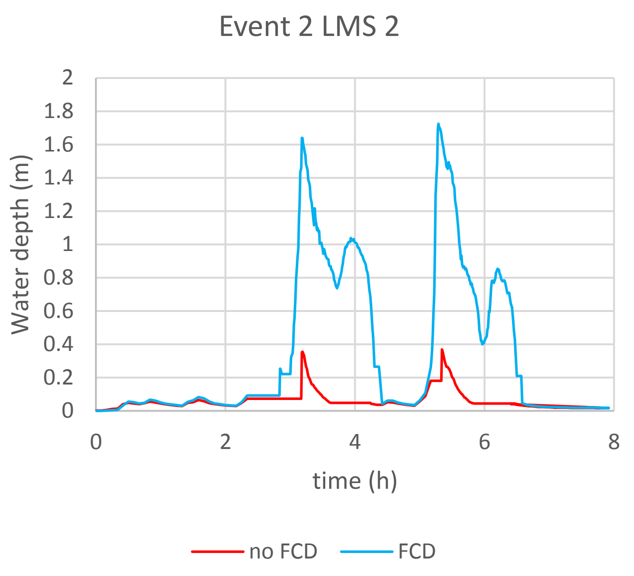


Figure 30 Event 2 water depth simulation with and without FCD at the LMS2

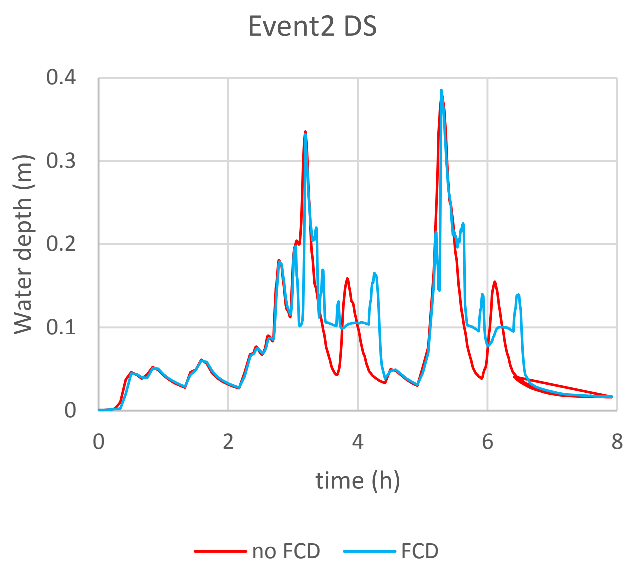


Figure 31 Event 2 water depth simulation with and without FCD at the first manhole downstream the FCD

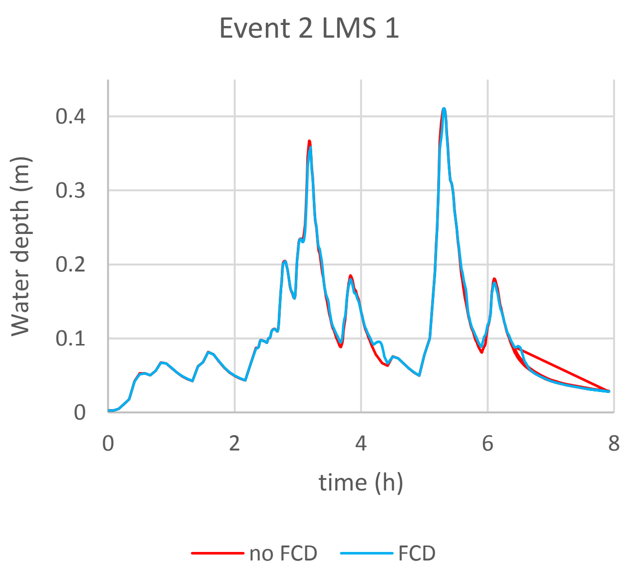


Figure 32 Event 2 water depth simulation with and without FCD at the LMS1

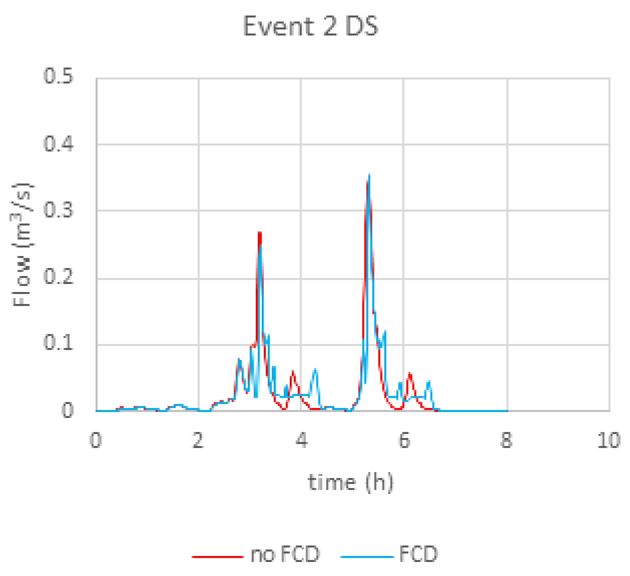


Figure 33 Event 2 flow simulation with and without FCD at the first manhole downstream the FCD

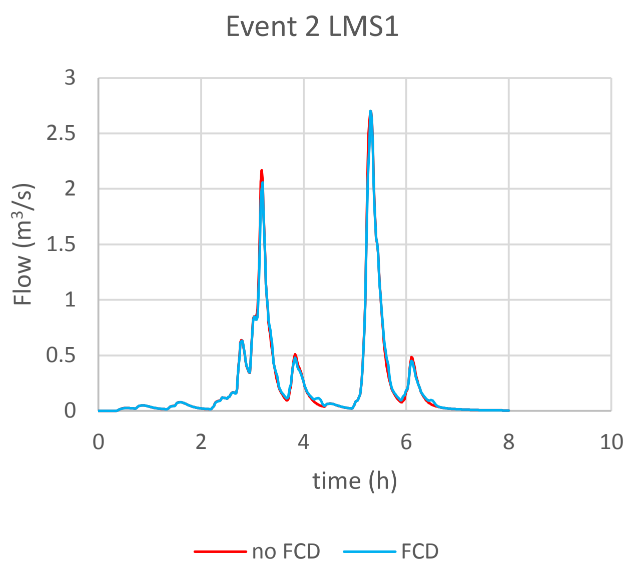


Figure 34 Event 2 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.410	0.410	0%
DS	0.378	0.385	2%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	2.700	2.701	0%
DS	0.349	0.354	1%

Table 2 Comparison of water flow and depths between simulations with FCD and without FCD for event 2

3.2.3 Event 3 – Maximum of 6.6 mm in 1 hour on 13/01/2018

Figure 35 to Figure 39 show a comparison between the modelled results when the CENTAUR system is installed, and when it is not installed. The event is significantly shorter than the first two events and the peak occurs close to the start of the event, hence although the peak depth and peak flow at DS are similar to event 2, the storage volume is able to attenuate the flows as can be seen in Figure 36 and Figure 38. It is also possible to see some benefit at LMS1 in Figure 37 and Figure 39. Table 3 confirms that there is a 17% reduction in flow and a 9% reduction in depth at DS, with smaller benefits at LMS1.

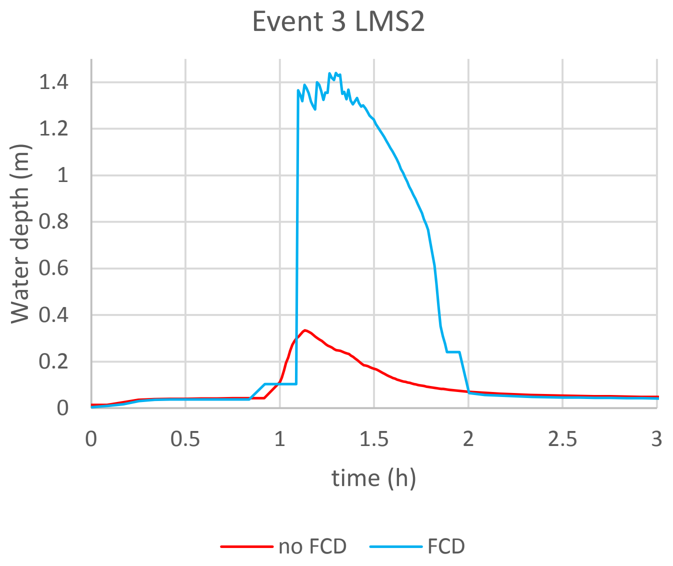


Figure 35 Event 3 water depth simulation with and without FCD at the LMS2

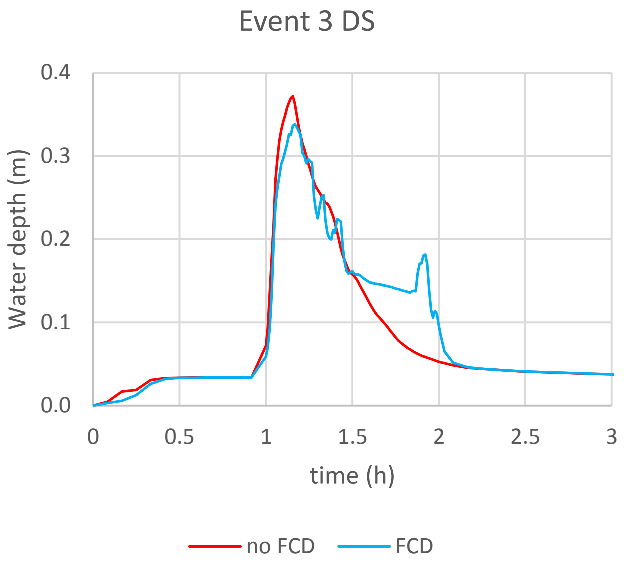


Figure 36 Event 3 water depth simulation with and without FCD at the first manhole downstream the FCD

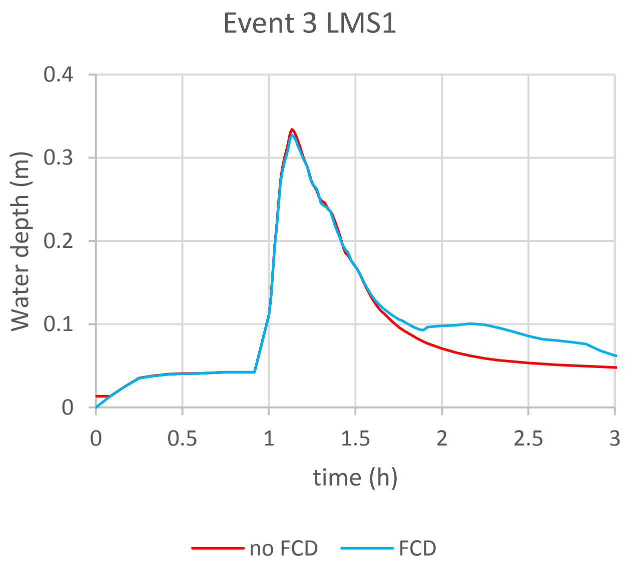


Figure 37 Event 3 water depth simulation with and without FCD at the LMS1

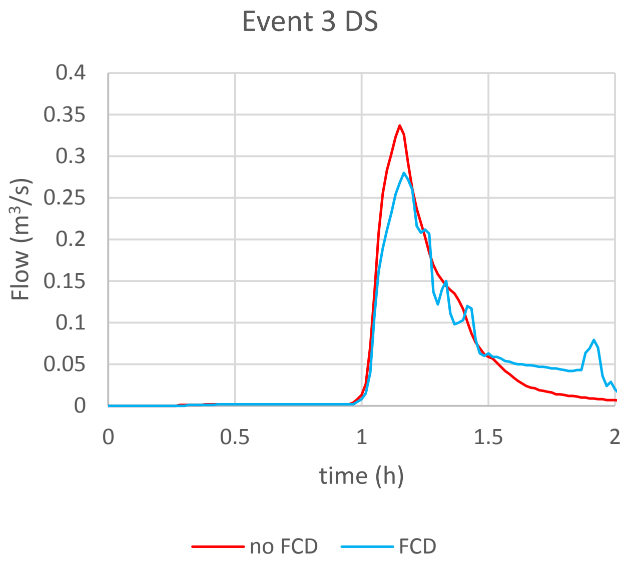


Figure 38 Event 3 flow simulation with and without FCD at the first manhole downstream the FCD

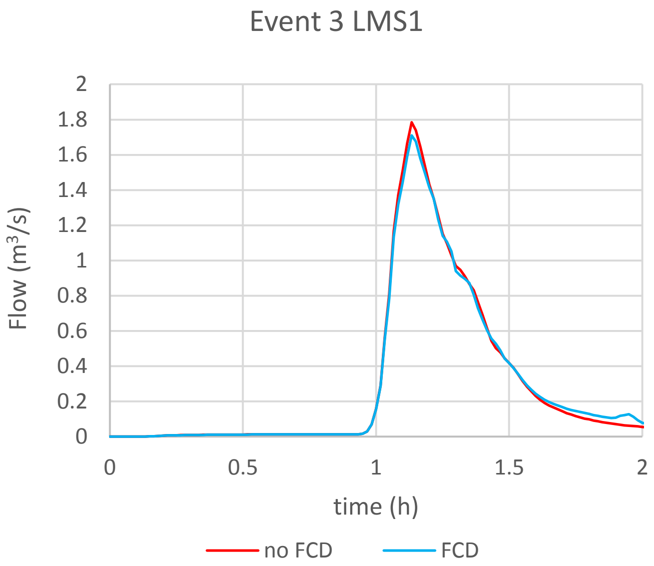


Figure 39 Event 3 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.334	0.327	-2%
DS	0.372	0.338	-9%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	1.784	1.711	-4%
DS	0.280	0.337	-17%

Table 3 Comparison of water flow and depths between simulations with FCD and without FCD for event 7

3.2.4 Event 4 – Maximum of 6.2 mm in 1hour on 17/10/2017

Figure 40 to Figure 44 show a comparison between the modelled results when the CENTAUR system is installed, and when it is not installed. Figure 41 and Figure 43 show that the benefit at the first manhole downstream the FCD is significant, it can also be seen that the draining of the storage volume causes water depths and flows to stay higher than without the FCD after the event, but below any critical depth. The benefit at LMS1 (Figure 42 and Figure 44) is smaller due to the contribution of other subcatchments between the FCD and the LMS1, again the draining down of the storage volume can be seen, but as might be expected the effect is much smaller. In this event, with a flow peak of approximately 0.250 m^3/s at the FCD location (without FCD), the FCD provided an excellent water depth and flow reduction, with a 19% reduction in depth and a 27% reduction in flow at DS.

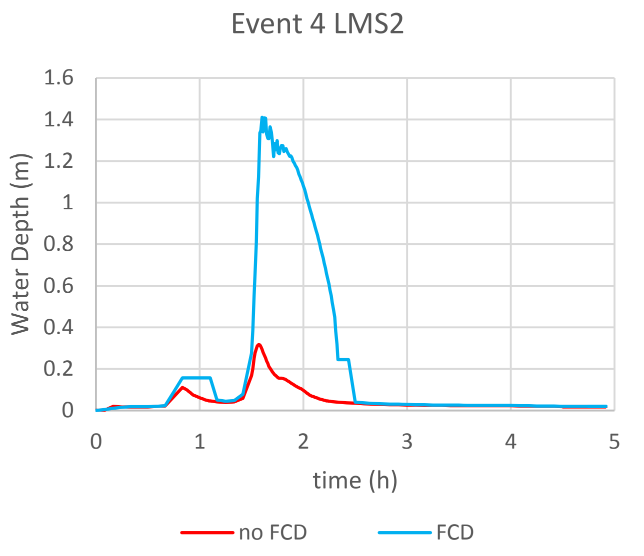


Figure 40 Event 4 water depth simulation with and without FCD at the LMS2

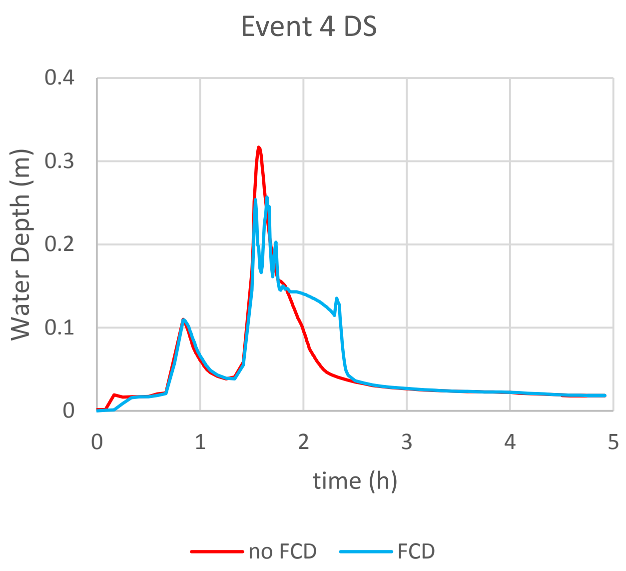


Figure 41 Event 4 water depth simulation with and without FCD at the first manhole downstream the FCD

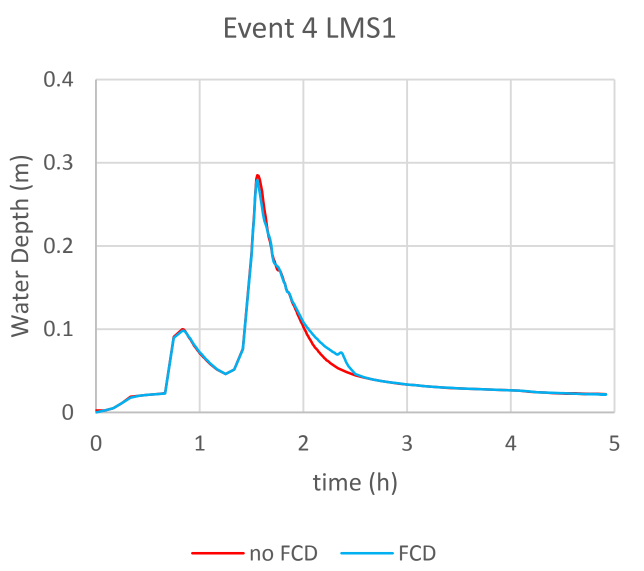


Figure 42 Event 4 water depth simulation with and without FCD at the LMS1

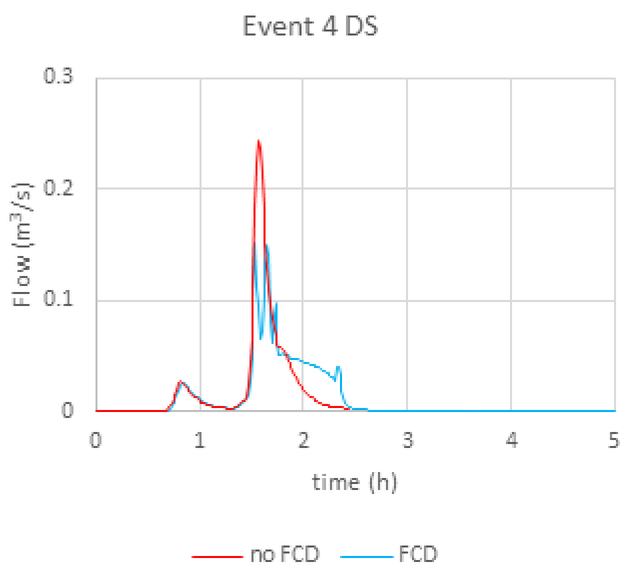


Figure 43 Event 4 flow simulation with and without FCD at the first manhole downstream the FCD

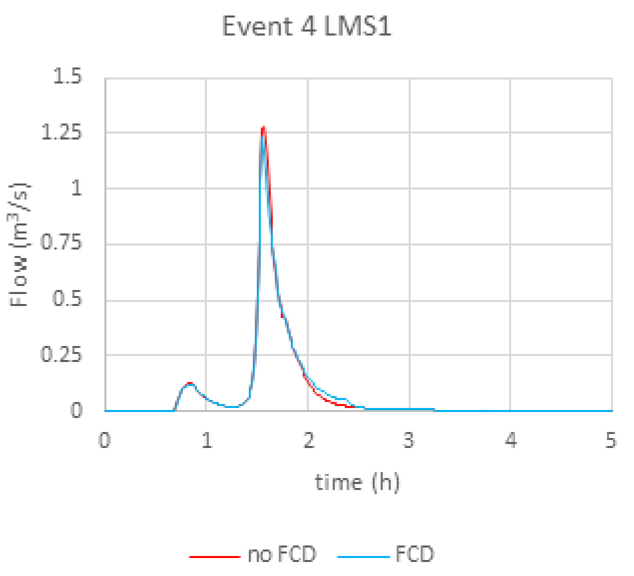


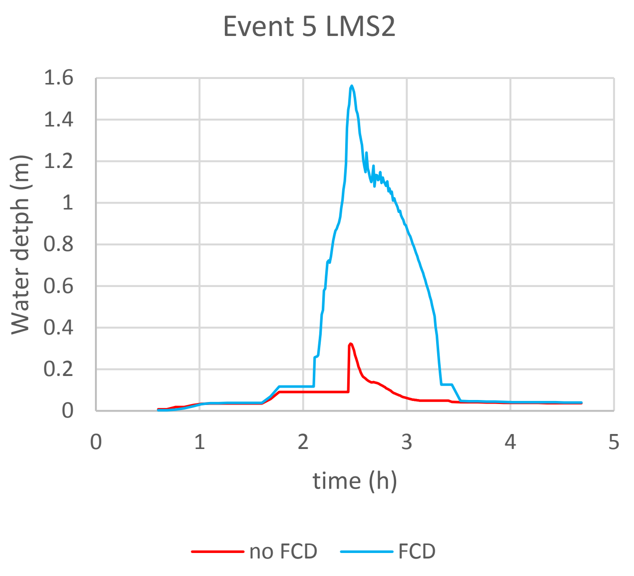
Figure 44 Event 4 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.284	0.279	-2%
DS	0.316	0.257	-19%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	1.279	1.235	-3%
DS	0.243	0.152	-37%

Table 4 Comparison of water flow and depths between simulations with FCD and without FCD for event 4

3.2.5 Event 5 – Maximum of 5.4 mm in 1hour on 10/01/2018

Figure 45 to Figure 49 show a comparison between the modelled results when the CENTAUR system is installed, and when it is not installed. Figure 46 and Figure 48 show the benefit at the first manhole downstream of the FCD, the difference in the peak values when the FCD is installed is less than for event 4 despite the peak values being similar. This is due to the peak occurring later in the rainfall event when the storage volume is already partially filled before the more intense rainfall occurs. As with other events, the benefit at LMS1 (Figure 47 and Figure 49) is smaller than at DS due to the contribution of other subcatchments between the FCD and the LMS1.



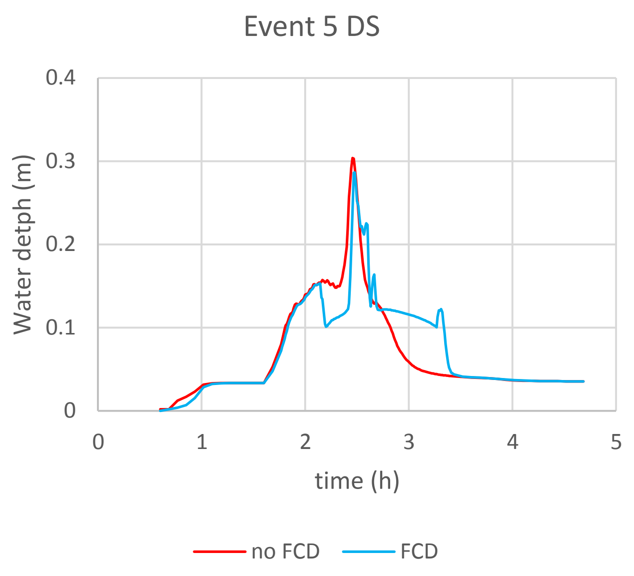


Figure 45 Event 5 water depth simulation with and without FCD at LMS2

Figure 46 Event 5 water depth simulation with and without FCD at the first manhole downstream the FCD

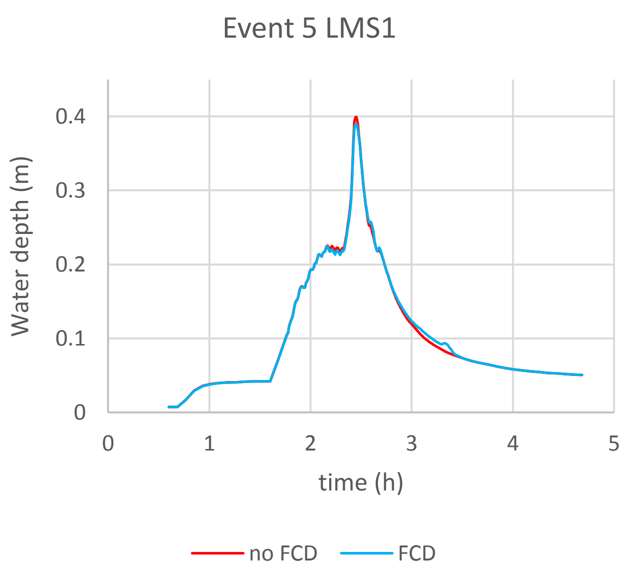


Figure 47 Event 5 water depth simulation with and without FCD at the LMS1

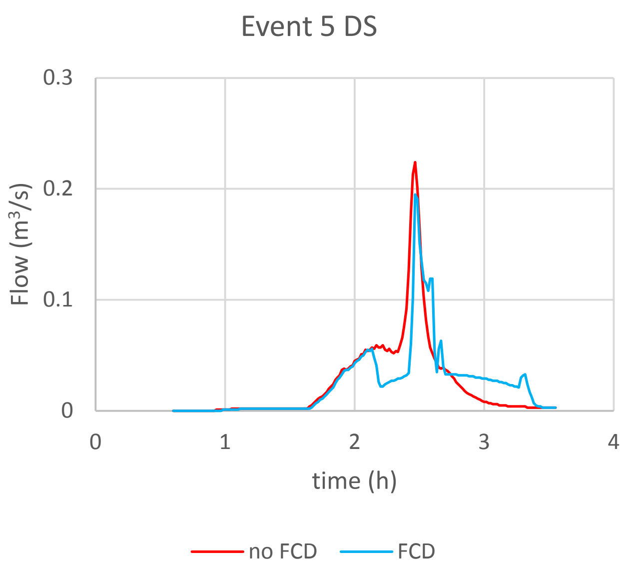


Figure 48 Event 5 flow simulation with and without FCD at the first manhole downstream the FCD

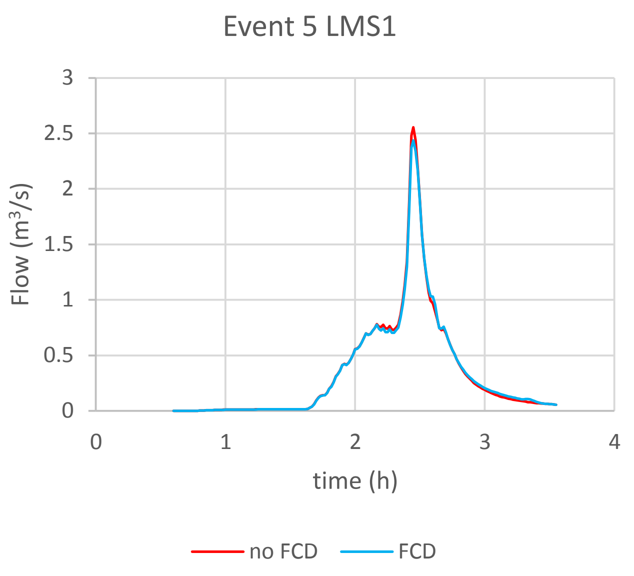


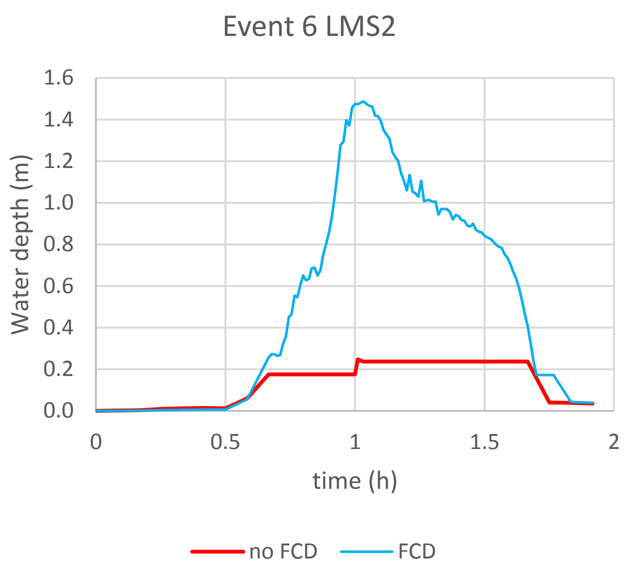
Figure 49 Event 5 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.399	0.389	-2%
DS	0.303	0.286	-6%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	2.555	2.438	-5%
DS	0.224	0.195	-13%

Table 5 Comparison of water flow and depths between simulations with FCD and without FCD for event 5

3.2.6 Event 6 – Maximum of 4.6 mm in 1hour on 11/01/2018

Figure 50 to Figure 54 show a comparison between the modelled results when the CENTAUR system is installed, and when it is not installed. It is possible to see the benefit at the node located downstream in the same branch of the FCD (Figure 51 and Figure 53) and a smaller effect, as with previous events at LMS1 (Figure 52 and Figure 54). The peak flow at DS without the FCD was 0.160 m^3/s, this well within the design flow range for this CENTAUR system and results in the highest benefits at the DS location from any of the events, with an 18% reduction in peak depth and a 29% reduction in peak flow.



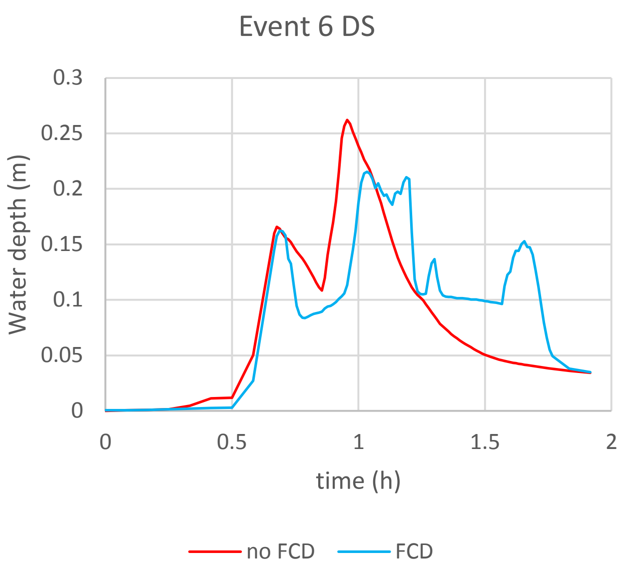


Figure 50 *Event 6 water depth simulation with and without FCD at the LMS2*

Figure 51 *Event 6 water depth simulation with and without FCD at the first manhole downstream the FCD*

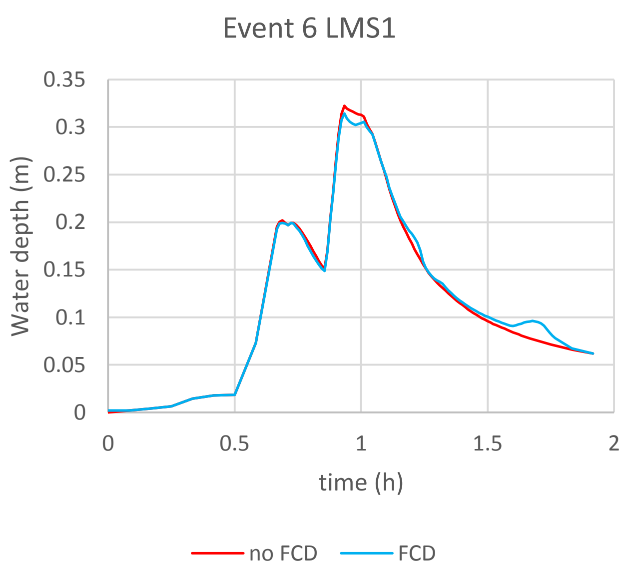


Figure 52 Event 6 water depth simulation with and without FCD at the LMS1

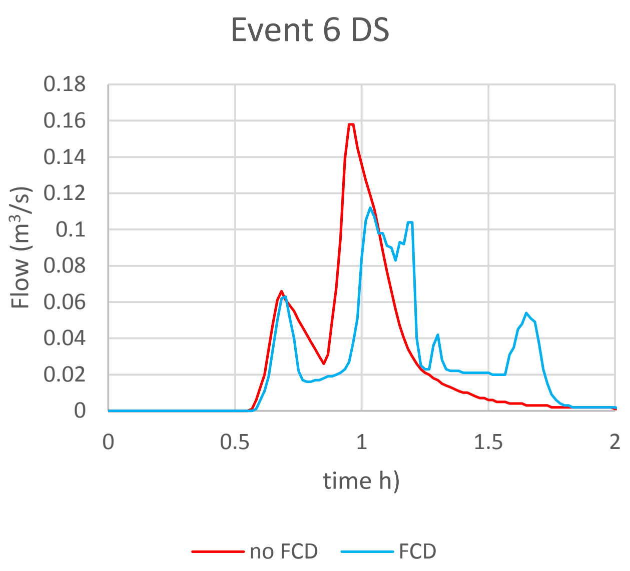


Figure 53 Event 6 flow simulation with and without FCD at the first manhole downstream the FCD

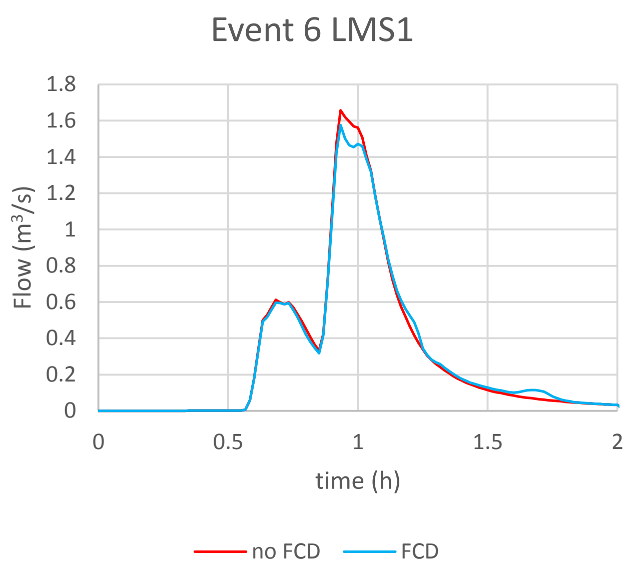


Figure 54 Event 6 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.322	0.314	-2%
DS	0.262	0.215	-18%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	1.658	1.579	-5%
DS	0.158	0.112	-29%

Table 6 Comparison of water flow and depths between simulations with FCD and without FCD for event 6

3.2.7 Event 7 – Maximum of 3 mm in 1 hour on 11/12/2017

Figure 55 to Figure 59 show a comparison between the modelled results when the CENTAUR system is installed, and when it is not installed. This is the smallest event with a peak flow at DS without the FCD of 0.07 m^3/s. There is no benefit seen with the CENTAUR system because the water depths at LMS1 do not enter the control range until the event is near its peak for both of the events, this means that the FCD was not able to close quickly enough to provide a benefit.

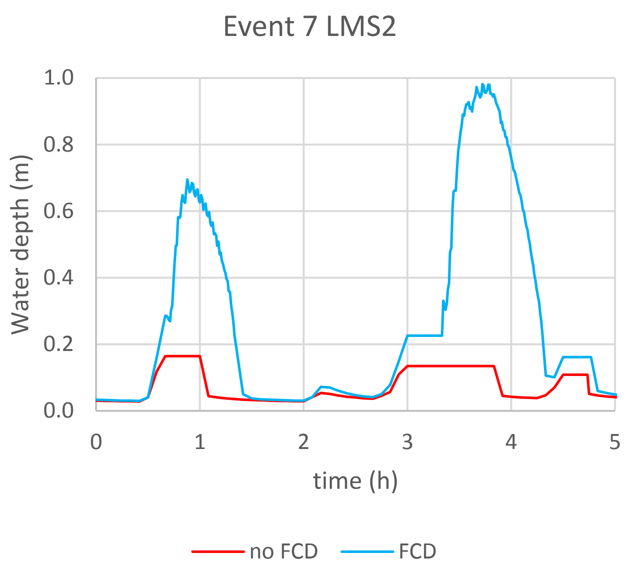


Figure 55 Event 7 water depth simulation with and without FCD at LMS2

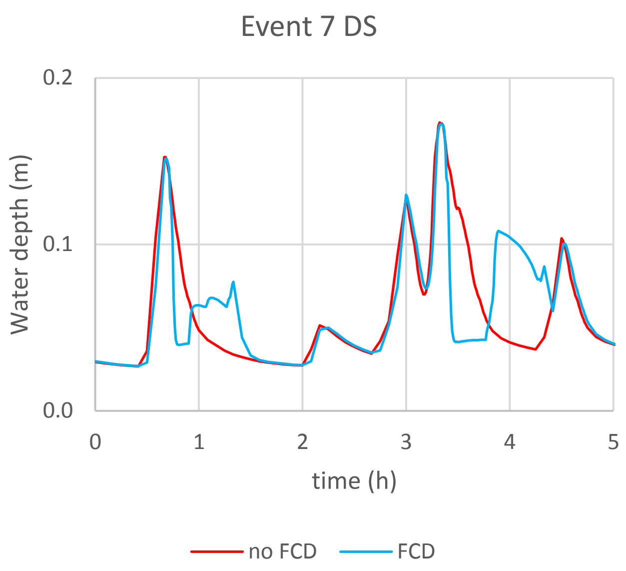


Figure 56 Event 7 water depth simulation with and without FCD at the first manhole downstream the FCD

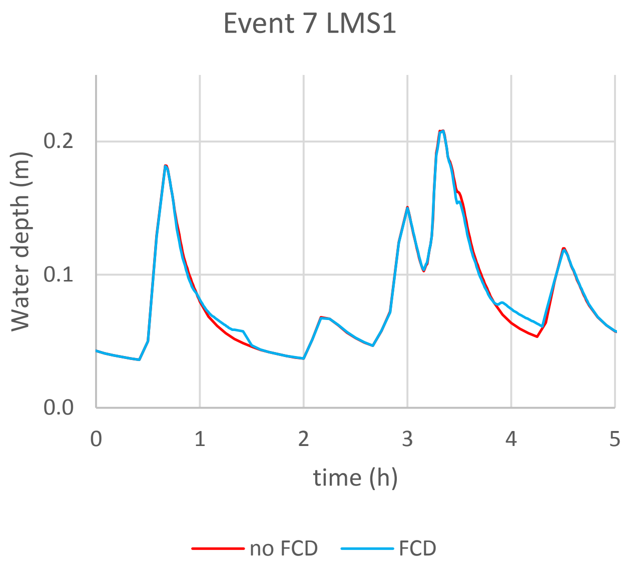


Figure 57 Event 7 water depth simulation with and without FCD at the LMS1

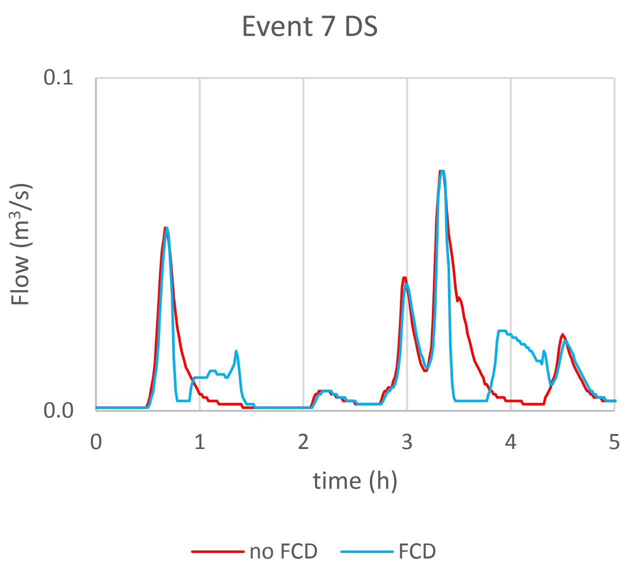


Figure 58 Event 7 flow simulation with and without FCD at the first manhole downstream the FCD

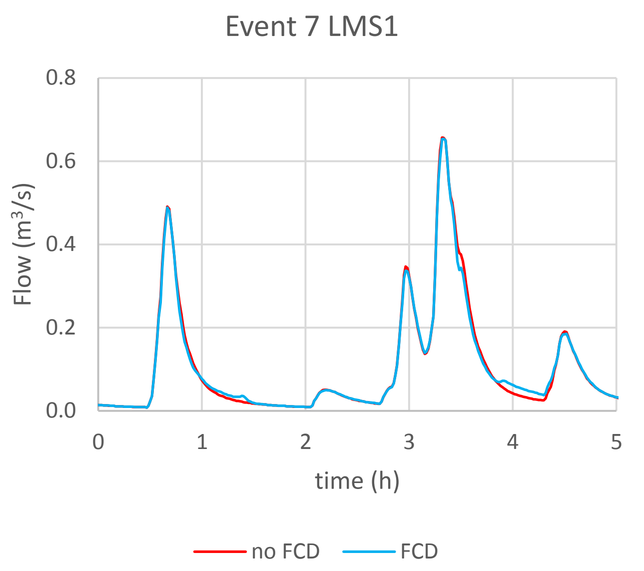


Figure 59 Event 7 flow simulation with and without FCD at the LMS1

	Maximum water depth (m)		
Location	No FCD	FCD	Percentage change
LMS1	0.208	0.207	0%
DS	0.173	0.172	0%
	Maximum flow (m^3/s)		
Location	No FCD	FCD	Percentage change
LMS1	0.657	0.654	0%
DS	0.072	0.072	0%

Table 7 Comparison of water flow and depths between simulations with FCD and without FCD for event 7

3.3 Summary of CENTAUR FCD performance in the pilot installation

It has been shown with the presented events that the CENTAUR system has performed reliably during wet weather, the FCD closes as water depths at LMS1 approach the target maximum and reopen as depths drop. Due to there being other flows contributing to the LMS1 target location which are capable of exceeding the target water depth on their own, it was often not possible to reduce depths to below the target, however it is possible to show benefit in terms of reductions in water depths and flow rate at the manhole immediately downstream of the FCD.

The modelled results generally show good agreement with the observed data at both LMS2 and LMS1 in terms of the time of the peak depths, the size of the peaks and the hydrograph shape. As the Fuzzy Logic control algorithm is data driven, small differences in the depth data can lead to different FCD operations and this can then further increase the differences between the observed and the modelled depth data.

The FCD was designed to control flows which would be expected to occur with sufficient frequency during the testing period to allow the CENTAUR system to be rigorously tested. The chosen FCD can provide good control of flows between 0.05 and 0.15 m3/s, although when fully open and with a high storage depth the FCD orifice can pass significantly higher flows. The parameters defining the target water depth at LMS1 were set with flows of this range in mind. The results presented in Section 3.2 show that the FCD works well for the smaller events it was designed for, for larger events the performance was generally lower. It is not possible to provide an exact flow range in which the system performs well because the performance also depends on the shape in the hydrograph. If the FCD was designed to control flows with a high return period (e.g. those which cause flooding), there would have been a high chance of the FCD not activating at all within the project period.

Figure 60 presents a summary of the performance evaluation for the seven events analysed at the DS location (both peaks for event 2 are plotted, so there are 8 data points). The CENTAUR system can be seen to provide a reductions in peak flow of up to 37% and in peak depth of up to 19%. It can be seen that the performance tends to reduce as the peak flow without the FCD increases. The performance for events which have high peak flows for longer periods is likely to be lower and it is expected that this pilot system will perform best for flows between 0.1 and 0.3 m^3/s. For larger and longer events the storage volume becomes full before the event peak and the flows are then passed forward with little or no restriction. Event 1 is an unusual case in having a very high but very short duration flow peak, the short duration means that even though the available storage is relatively full the peak can be still be attenuated by the storage provided by the CENTAUR system. Unfortunately there was a lack of events with peak flows at DS greater than 0.35 m^3/s to provide a better indication of the system performance in the higher range of flows. As previously mentioned, the CENTAUR system can easily be designed to control a different range of peak flow rates, depending on the downstream objective.

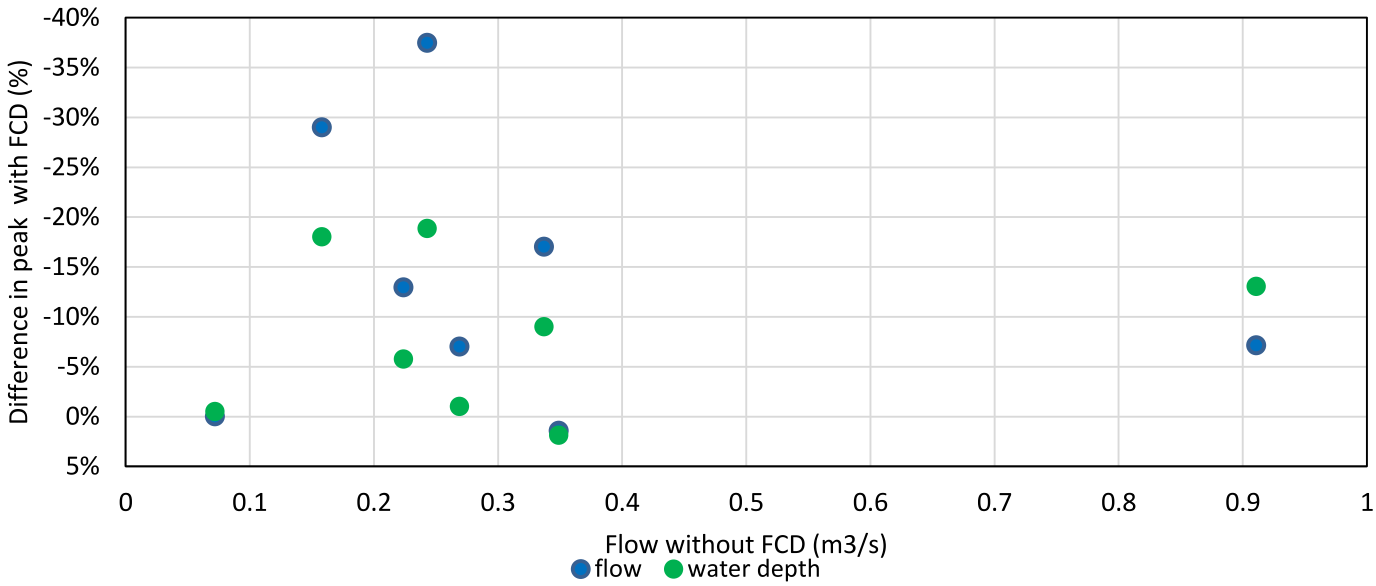


Figure 60 Change in peak flow and water depths through use of the CENTAUR system at the DS location in Coimbra.

4 Lessons learnt and recommended improvements in FCD operation

After the first period of installation in Coimbra, the operators made some comments and suggestions for potential improvements:

1- The FCD opening is controlled by an algorithm and its rules can control the passage of water through the FCD orifice from a 5% (15 mm) opening to a 100% (300 mm) opening. Within the design flow range the CENTAUR FCD proved to be an efficient device to reduce water depth and flow.

2- The water depth and flow reduction are more efficient near the FCD location. Downstream of this location additional flow contributions arrive in the network, reducing the effect of the CENTAUR system. In cases where the FCD cannot be located near to the flood control location, it would be beneficial to install FCDs in more of the pipe branches that contribute flows to the target location.

3- The testing proved that the use of high water depths in the system to provide storage can be done without causing any problems to upstream properties.

4- When the control target is an in-pipe depth (e.g. the target depth is 0.4 m, but the pipe diameter is 1.3 m), small water depth variations may represent large flow variations. In the future where the target depth is in-pipe it may be beneficial to include flow data in the algorithm. However, where the CENTAUR system is used for flooding the target depth will usually be above pipe full (i.e. surcharged conditions) where the relationship between flow and depth has changed so that a small change in flow gives a significant change in water depth, hence this would very rarely be required.

5 Problems and future improvements in FCD maintenance

In combined sewers, one of the crucial points should be the maintenance and cleaning of the device. All kinds of waste and rags can be found in these sewers.

It is crucial that a periodic visual observation of the FCD is made by operational staff. Water utility staff should also check the SCADA system for unexpected depths or FCD openings that may imply problems.

During the pilot testing a monthly visual observation was made and no problems were detected with rags or sediments collecting. Furthermore, daily observation of the dashboard containing depth data was also done and the depth data and FCD positions were always within the expected range. Consequently, the CENTAUR system is considered to be very robust.

Future improvements could be to include an automatic alert system and eventually an automatic flushing system. This could be useful in areas with problems due to sediments and rags.

6 Conclusions

The CENTAUR system was installed in Coimbra and became fully operational from 11th October 2017, this report covers the period up to 24th February 2018. During this period the CENTAUR system FCD activated for 41 rainfall events and has proved to be reliable. Seven of these events have been analysed in detail for this report, the events analysed were selected to provide a good representation of the range of observed rainfall depths and intensities.

The FCD was designed to control flows expected during the testing period, hence the return period of the events to be controlled during the pilot testing is under one year. It is not possible to accurately quantify the return periods of such rainfall as the Portuguese standards (RGSPPDADAR, 1995) only consider return periods of 2 years and above. The chosen FCD can provide good control of flows between 0.05 and 0.15 m^3/s, although when fully open and with a high storage depth the FCD orifice can pass significantly higher flows. Additionally the FCD incorporates an overflow weir and emergency valves which allow flows resulting from a 100 year design rainfall event to pass the FCD without causing additional upstream flood risk.

In order to control low return period flows, the CENTAUR control algorithm parameters were set at low values and the control range was defined as an in-pipe flow depth. The downstream target was selected in Praça Republica which provided good flow conditions (low slope) for monitoring water depths, however between the FCD on Av Júlio Henriques and Praça Republica there were several additional inflows. This meant that the CENTAUR system was often not able to keep water depths below the target value due to additional flow contributions from other areas.

A modelling study was carried out to provide an assessment on the performance of the CENTAUR system. Two versions of the model were run, one with the FCD installed and one without. The model was calibrated for each event to ensure an optimum representation and to therefore provide the best basis for performance assessment. Comparing the peak water depths and peak flows at both the downstream control point (LMS1) and a location immediately downstream of the FCD (DS) the CENTAUR system was found capable of reducing peak water depths by up to 19% and peak flows by up to 37%. For rainfall events which result in high flows for long periods, the performance of the system is reduced because the storage volume can become filled before the event peak occurs. Once the storage volume had been filled, the relief valves and overflow weir passed the flows as expected without causing any problems upstream and hence the system proved to be safe. This highlights the need to ensure the control parameters are set to ensure the FCD activates only when it is required, it also highlights the limitation of any storage based solution, in that it can only be effective up to the point where the storage is filled. Once storage is filled any flow attenuation benefits are very limited. This does not mean that the solutions are not useful, but they have a limited range of applicability which will be evident at the design stage.

During the evaluation period, the drainage network operator, AC, monitored the online dashboard and carried out regular visual checks, but no operational problems occurred, the FCD worked continuously without interruptions.

This report signifies the completion of Task 3.2 in the CENTAUR project.

7 References

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WaPUG, 2002. Code of practice for the hydraulic modelling of sewer systems, v3.001. Tech. rep., Waste Water Planning Users Group.