

Article

# Stormwater Detention Ponds in Urban Catchments—Analysis and Validation of Performance of Ponds in the Ouseburn Catchment, Newcastle upon Tyne, UK

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**Abstract:** The impact of stormwater drainage and detention ponds on flooding is assessed using statistical analysis and physically based computer simulation of a 45-year case study for a peri-urban catchment. In 1978, the 54 km<sup>2</sup> Ouseburn catchment in Newcastle upon Tyne was impacted by the connection of a new 2.1 km<sup>2</sup> residential development, directly to the Ouseburn River, via a stormwater drain, which reduced the time to peak and increased flood risk. Further residential developments of 1.6 km<sup>2</sup> have been built since 2004, again with separated sewer systems, but this time linked to stormwater detention ponds before draining into the Ouseburn River. Detailed analysis of the data, confirmed with computer simulation, shows that in contrast with the 1978 intervention, these new developments had only a minimal effect on the flows in the Ouseburn River, in fact achieving a small reduction in peak flows for large events. This study assesses the post-construction efficiency of such systems, and we show that the stormwater detention ponds are working as designed.

**Keywords:** stormwater detention ponds; flooding; urban catchments; stormwater drainage; separated sewer systems; urban development



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## 1. Introduction

Urban expansion reduces the time to peak (increases flashiness), enhances peak flows and increases runoff volumes in urban and peri-urban river catchments [1–4]. It therefore increases the potential flood risk [5,6]. There are a number of methods used to negate this impact and a range of terms used to describe these methods, including Green Infrastructure (GI), Nature-Based solutions (NBS), Blue-Green Infrastructure (BGI) or Sustainable Drainage Systems (SuDS) [7–11]. Within the UK, GI or a SuDS feature are now required for any new development [12]. Stormwater detention ponds (also known as dry ponds or detention basins) are a type of GI or SuDS feature that are often incorporated into new housing developments in urban catchments [13,14]. Stormwater detention ponds are used to temporarily store water after a major rainfall event. The water then empties gradually to a downstream water body, attenuating the flood wave with potential to reduce downstream flooding. In addition to helping to reduce flooding, stormwater detention ponds are beneficial to the water quality in nearby rivers, as they trap pollutants and sediment [15–17].

There have been a number of case studies considering how effectively a single stormwater detention pond can attenuate flow from housing developments [18–20]. In addition, modelling studies have analysed the impacts of stormwater detention ponds [21–23], with an analytic solution evaluating the efficiency of a pond for flood risk reduction [24].

However, very few studies have analysed multiple stormwater detention ponds and other stormwater control methods (SCMs) in an urban or peri-urban river catchment and the effect of these features on the downstream discharges [25,26]. Li et al. [27] commented that there is “a distinct lack of monitoring studies that demonstrate the impact of SCMs applied across an entire catchment, on the resulting flow regime at the catchment outlet.”

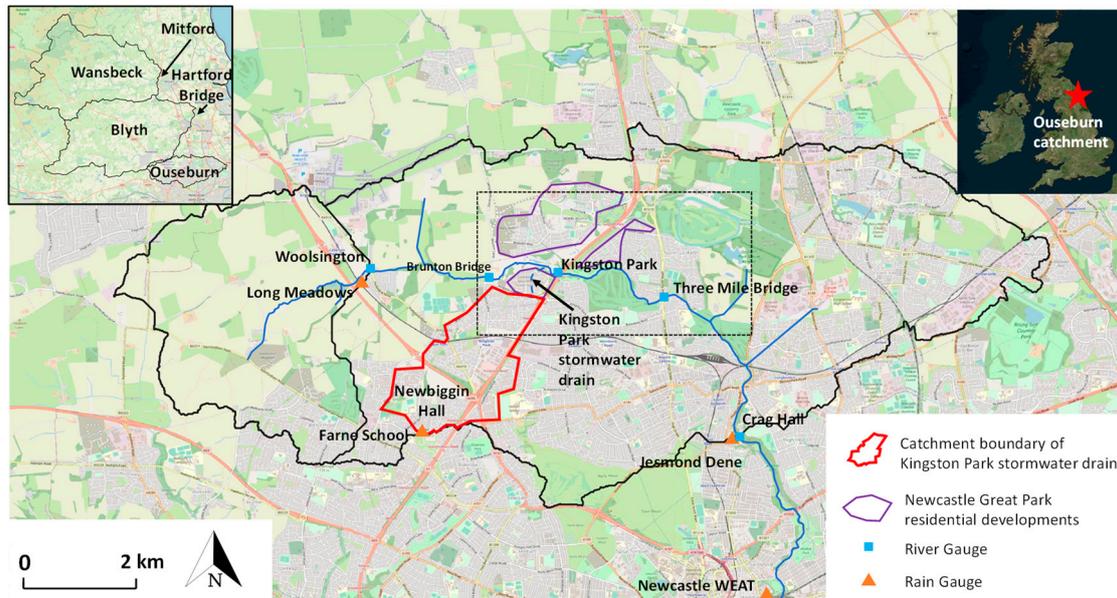
This work focuses on stormwater detention ponds in a peri-urban catchment and the effect of these ponds on downstream flooding. As in many peri-urban catchments, within this catchment, there have been a number of residential and business developments over the last 45 years and an increase in the urban fraction of the catchment. The aim of this work is to investigate whether this expansion, which occurred in two different periods (one without stormwater detention ponds and one with stormwater detention ponds), produced different responses in terms of flow in the catchment, and hence answer the following research question: “How well do stormwater detention ponds work in a real peri-urban catchment?”

## 2. Data and Methods

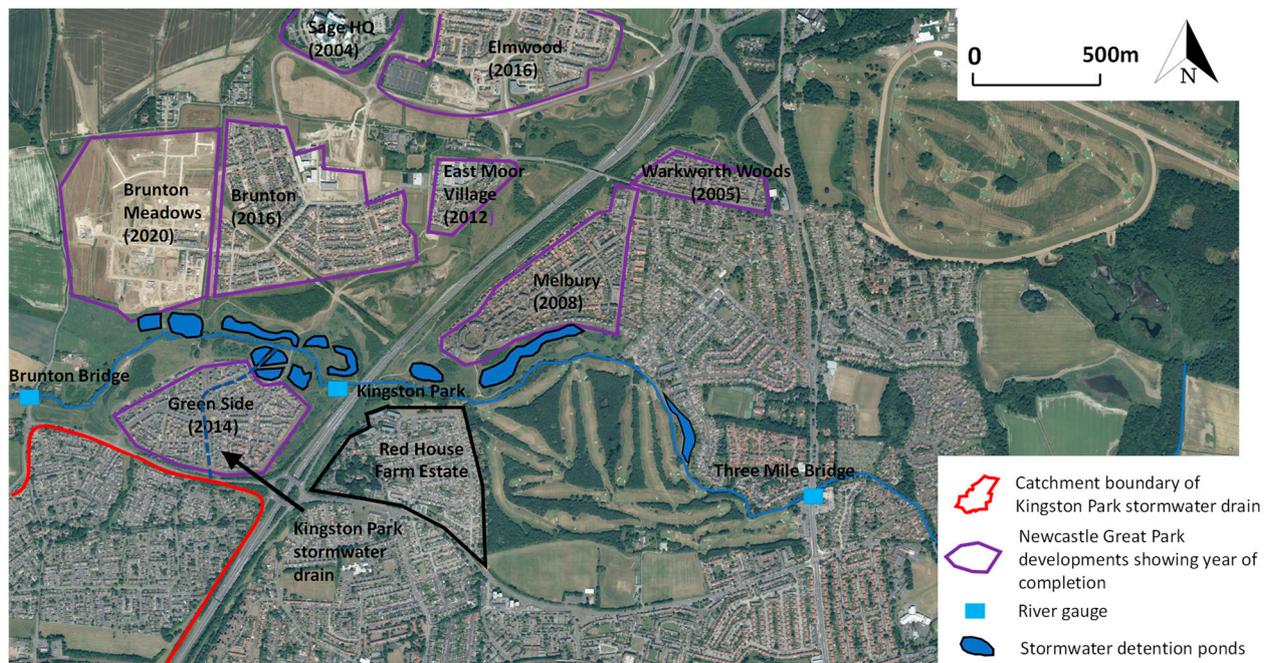
### 2.1. Case Study: Ouseburn Catchment

The Ouseburn catchment is located in the North-East of England and is a peri-urban catchment (Figure 1). The catchment is generally low lying with gentle slopes (elevation range: 35–144 m AOD). The higher part of the catchment in the north and west is predominantly rural and is used for agriculture (grassland and arable), while the lower part in the south and east is predominantly urban. There are loamy and clayey top soils above a 5–10 m deep glacial till of mixed permeability, with the geology consisting of Carboniferous Middle Coal Measures [28]. This work considers the 54 km<sup>2</sup> catchment to the gauging station at Crag Hall, which has a current urban fraction of 30%, with 11% of the catchment drained by a separated sewer system and 19% drained by a combined sewer system [29]. As the city of Newcastle upon Tyne has grown, more of the catchment has become urbanised. In the late 19th and early 20th centuries, the area towards the outlet was developed with high density terraced houses; after that, most of the development has consisted of lower density detached and semi-detached houses with gardens. In the last 45 years, this urbanisation has happened in two distinct phases. From 1976 to 1978, the Kingston Park residential development (often called a housing estate in the UK) was built (Figure 1), which involved the conversion of agricultural land to a residential development with some retail development. The residential development was mainly detached and semi-detached houses with gardens, built with a separated sewer system. Surface runoff drains into the Kingston Park stormwater drain, which feeds directly into the Ouseburn River between the Brunton Bridge and Kingston Park discharge stations, while wastewater is piped to a sewage treatment work in Howdon, 8 km east of the Ouseburn catchment outlet. Research suggests the Kingston Park stormwater drain was connected to the Ouseburn River at the start of 1978. This drain also takes water from part of the Newbiggin Hall residential development, which was designed with separated sewers but was previously connected to the combined sewer system. Overall, the Kingston Park stormwater system drains an urban area of 2.1 km<sup>2</sup>, which can be seen in the detailed sewer network map [30]. The boundary encloses a larger area (3.2 km<sup>2</sup>), but this includes arable land, grassland and some forested areas. Between 1978 and 2004, there was no major development of residential properties within the catchment, although the dual carriageway Newcastle Western Bypass road (designated the A1) was built from 1987 to 1990 with a surface area covering 0.02 km<sup>2</sup> draining directly into the Ouseburn River. From 2004 to the present, the Newcastle Great Park residential and business development has taken place (Figures 1 and 2). This is the largest housing and business development in North-East England encompassing 2500 residential dwellings, commercial premises and community facilities when complete [16]. Details of this development can be seen in Figure 2 and Table 1. The properties are mainly detached and semi-detached with gardens, all of the properties have separated sewers and the stormwater drains all feed into stormwater

detention ponds (Figure 2). The requirement for these new developments is that the risk of flooding downstream of the development is no higher than before the development. This has been achieved by carrying out local flood risk assessments for each new development and associated detention pond [31,32], considering rainfall events of different durations with return periods of at least 100 years. The water that does not infiltrate is then released through an outfall over the following days at a controlled discharge rate.



**Figure 1.** The Ouseburn at Crag Hall catchment (54 km<sup>2</sup>). The top-left insert shows the Ouseburn, Wansbeck and Blyth catchments, the top-right insert shows the location of the Ouseburn catchment in the UK. The area in the rectangle located near the centre of the Ouseburn catchment is shown in more detail in Figure 2 (©OpenStreetMap contributors).



**Figure 2.** Part of the Ouseburn catchment between the Brunton Bridge and Three Mile Bridge gauging stations. Google Earth image (©Google, Digital Globe).

**Table 1.** Newcastle Great Park Developments.

Development	Approximate Year Completion	Area (km <sup>2</sup> )	Cumulative Area (km <sup>2</sup> )
Sage HQ	2004	0.08	0.08
Warkworth Woods	2005	0.07	0.15
Melbury	2008	0.24	0.39
East Moor Village	2012	0.05	0.44
Green Side	2014	0.20	0.64
Brunton	2016	0.31	0.95
Elmwood	2016	0.29	1.24
Brunton Meadows	2020	0.34	1.58

There have been a number of recent flooding events within the Ouseburn catchment. This includes localised flooding on 30 June 2005 in the Red House Farm estate [33] and more extensive flooding on 28 June 2012 when a major rainfall event occurred, with up to 50 mm of rainfall in two hours, causing considerable damage [34].

## 2.2. Discharge and Precipitation Data

There are two long-term Environment Agency discharge gauging stations on the Ouseburn River at Woolsington and Crag Hall (Figure 1 and Table 2). The Crag Hall discharge data start in 1976 and, thus, include a two-year period before the Kingston Park stormwater drain was finished. There are also two long-term Environment Agency discharge gauging stations (Hartford Bridge and Mitford) in nearby catchments, which are used in some of the analyses. In addition to this Environment Agency data, there are short term records at three locations (Figures 1 and 2, Table 2), installed as part of the Making Space for Water (MS4W) project led by Newcastle University [33]. These are at Brunton Bridge, Kingston Park and Three Mile Bridge. These are not continuous records and the measured discharge data are of lower quality than the Environment Agency discharge measurements, as it was a short-term project with fewer resources. However, the ranking of discharges and the timing of events are reasonably accurate.

**Table 2.** Discharge gauges and data availability. EA gauges are long term flow records from the Environment Agency. The Woolsington and Crag Hall data have some gaps but are over 99% complete. MS4W is a research project led by Newcastle University, which installed additional river gauges (see Section 2.2 for details); these data are incomplete.

Gauging Station (Catchment)	Gauge Type (Number)	Area (km <sup>2</sup> )	Data Availability
Woolsington (Ouseburn)	EA (23018)	11.4	1984–1987 (daily), 1992–2018 (hourly and some 15 min)
Brunton Bridge (Ouseburn)	MS4W	17.6	2007–2013 (15 min)
Kingston Park (Ouseburn)	MS4W	22.6	2007–2013 (15 min)
Three Mile Bridge (Ouseburn)	MS4W	29.8	2007–2013 (15 min)
Crag Hall (Ouseburn)	EA (23016)	53.8	1976–1978 (daily), 1980–1981 (daily), 1983–1990 (daily), 1991–2018 (hourly and some 15 min)
Hartford Bridge (Blyth)	EA (22006)	269.4	1976–2018 (daily)
Mitford (Wansbeck)	EA (22007)	287.3	1976–2018 (daily)

There are four Environment Agency precipitation stations within or close to the Ouseburn catchment (Figure 1). Hourly data were obtained for these locations for 11 years, from 1 January 2004 to 31 December 2014, and used in the hydrological modelling. There is a small annual variation across the catchment with the highest annual total of 724 mm at Long Meadows rainfall station and the lowest annual total of 687 mm at Newcastle WEAT rainfall station. In addition, some 15 min interval rainfall data were obtained as part of the MS4W project.

### 2.3. Hydrological Modelling

Hydrological modelling of the Ouseburn catchment has been conducted to allow the effect of developments within the catchment on flows in the Ouseburn River to be considered in more detail. The Shetran hydrological model [35,36] was selected for use here as it is physically based and spatially distributed. The model allows for the explicit representation of the change in land use from rural to urban, the development of the Kingston Park stormwater drain and the addition of stormwater detention ponds. It includes components for vegetation interception and transpiration, overland flow, variably saturated subsurface flow and channel–aquifer interactions. Solutions to the governing, physics-based, partial differential equations of mass and momentum are solved on a three-dimensional grid using finite-difference equations (<https://research.ncl.ac.uk/shetran/>, accessed on 1 June 2010).

The model is usually applied to predominantly rural catchments [37,38] but a new method was developed in Birkinshaw et al. [29] to improve the hydrological modelling of urban catchment using runoff coefficients. This work showed that considering the fraction of separated sewer and combined sewers systems and incorporating them differently into the model produces much better hydrological simulations. This was achieved by removing the precipitation from urban areas with combined sewers (as the rainfall flows directly into combined sewers which drain to the Howdon treatment works located outside the catchment). To account for the separated sewers in urban areas, the saturated conductivity was set to zero with a high Strickler (low roughness) overland flow parameter to take into account the rapid flow of water to and within the pipe network. Full details can be seen in Birkinshaw et al. [29], which shows that the new method produces a much improved hydrological model of the Ouseburn catchment as opposed to not properly accounting for the separated and combined sewer networks.

The model was setup with a 200 m grid resolution and run for 11 years using hourly rainfall data from 1 January 2004 to 31 December 2014. The vegetation and overland flow parameter values were based on typical values obtained during previous calibrations [39,40]. Soil parameters were based on measured values [29] present in the catchment. The calibration was carried out in two parts, firstly for the Woosington sub-catchment where the parameters were calibrated for arable and grassland, then for the entire Crag Hall catchment where the parameters associated with urban areas were calibrated. In order to obtain the best hydrological model, the calibration was carried out for the entire period with a Nash–Sutcliffe efficiency of 0.86 obtained for hourly flows at Crag Hall. Considering the peak flows, the calibrated discharge is within 20% of the measured discharge for 80% of the 45 biggest discharge events.

A limitation of the modelling is that all the water from precipitation in urban areas with combined sewers is assumed to be removed from the model. During heavy rainfall events, the capacity of the combined sewer pipes can be exceeded and there are combined sewers overflows (CSO) flows into the Ouseburn River [30], thus increasing the peak discharge. Future work is planned, which will incorporate these CSO into the model, although this possibility is complicated by the actual flows being unknown. In this work, the modelling mainly considers changes in the flow from the urban developments with separated sewer systems, and most of the CSOs are unaffected by these developments.

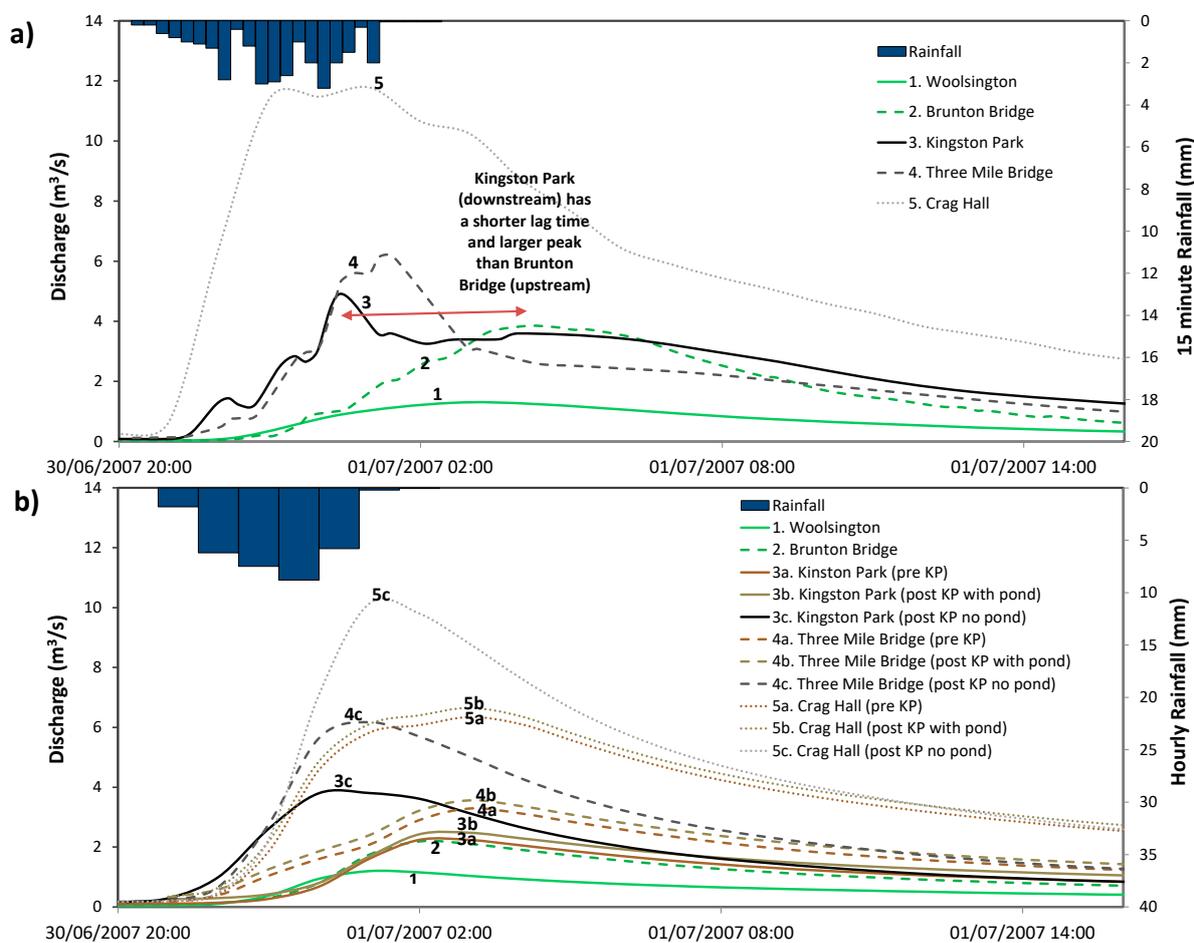
### 3. Kingston Park Developments 1976–1978

This section contains an analysis of the effect of the Kingston Park developments (Figure 1) on flows in the Ouseburn River. These developments include the building of the Kingston Park housing estate and the connection of the Kingston Park stormwater drain (which drains Kingston Park and parts of the Newbiggin Hall housing estate) directly into the Ouseburn River. As there are only daily discharge data until 1990, the analysis of the change in streamflow in the Ouseburn River as a result of these developments is limited in scope compared to more recent developments.

The analysis first looks in detail at the change in flows in five locations along the Ouseburn River in response to the 30 June 2007 rainfall event. This includes the sudden change in flow seen downstream of where the Kingston Park stormwater drains flows into the Ouseburn River. Then, the long-term changes in the daily discharge at Crag Hall are considered by looking at the base flow index (BFI) and the recessions.

### 3.1. Rainfall Event on 30 June 2007

The effect of the Kingston Park developments can be seen most clearly by considering individual events, making use of the MS4W (Table 2) discharge stations as well as those from the Environment Agency. Figure 3a shows the discharges at five locations on the Ouseburn River for an event on 30 June 2007, which was selected as there are discharge data for all the stations and 15 min rainfall data.



**Figure 3.** Discharge for a large rainfall event on 30 June 2007 at five discharge stations on the Ouseburn River, (a) measured and (b) simulated, where KP is the 1976–1978 Kingston Park development. Simulated values show the results for three scenarios, ‘pre KP’ before the Kingston Park development, ‘post KP with pond’ after the Kingston Park development with a detention pond included in the model and ‘post KP no pond’ after the Kingston Park development was built with stormwater drains connected directly to the Ouseburn River. ‘Post KP no pond’, i.e., 1, 2, 3c, 4c and 5c, corresponds to the current situation. Rainfall is the areal averaged value for the Crag Hall catchment with (a) 15 min data and (b) hourly data shown, as these were used in the simulation.

Woolsington and Brunton Bridge discharge stations show a typical rural response with a considerable time lag between the rainfall and the peak discharge. However, there was a significant change in response between Brunton Bridge discharge station and the one at Kingston Park, even though Kingston Park is located only 1 km downstream of Brunton Bridge. The Kingston Park flows had a higher peak and a shorter lag time, peaking about

four hours before Brunton Bridge. At around midnight on 30 June 2007, around 80% of the measured flow ( $\sim 4 \text{ m}^3/\text{s}$ ) at the Kingston Park discharge station came from inlets on the short section of river between Brunton Bridge and Kingston Park. In 2007, there were no other stormwater sewer inlets between the Brunton Bridge and Kingston Park discharge stations [30], so the vast majority of the flow at this time came from the Kingston Park stormwater drain. Downstream from Kingston Park discharge station, at both the Three Mile Bridge and Crag Hall discharge stations, the flows were still peaky with a short lag time. The flow at Crag Hall was affected by a number of stormwater inlets into the river from urban areas between Three Mile Bridge and Crag Hall.

As there are no hourly flow data from before 1978, hydrological modelling (Section 2.3) was carried out to understand the effect of the Kingston Park developments on the river flows (Figure 3b), with three scenarios considered. The first scenario corresponds to the situation before the Kingston Park developments were completed in 1978, called 'pre KP'. The second scenario corresponds to the period after the Kingston Park developments were completed but with the inclusion of a stormwater detention pond in the model, called 'post KP with pond'. This was a theoretical pond of  $150,000 \text{ m}^3$  designed to test the effect of capturing all the flow from the Kingston Park stormwater drain. The third scenario corresponds to the period after the Kingston Park developments were completed but were without a detention pond, and this is called 'post KP no pond', which corresponds to the current situation (note that the scenarios were run with hourly data, rather than 15 min data, as it is part of the longer simulation for which only hourly rainfall data are available). The modelling results show that in the 'pre KP' scenario, the Kingston Park simulated discharge data (line 3a in Figure 3b) correspond very closely to those of Brunton Bridge (line 2), with a similar lag time and a slightly higher peak. Downstream, at Three Mile Bridge (line 4a), there is again a similar shaped hydrograph and slightly longer lag time, whilst at the catchment outlet at Crag Hall (line 5a), there is flow into the river from older housing estates, so there are considerably larger flows than those at Kingston Park and Three Mile Bridge. The 'post KP with pond' scenario shows similar results to the 'pre KP' scenario although the discharges at Kingston Park, Three Mile Bridge and Crag Hall are all slightly larger. This is because in the 'pre KP' scenario, rain that fell on the Newbiggin Hall housing development was removed from the model as the housing development at that time had combined sewers with the water removed from the catchment to a treatment works, whereas in the 'post KP with pond' scenario, rain that fell on the Newbiggin Hall housing development is modelled as flowing through stormwater drains to the pond before being gradually released into the river. The 'post KP no pond' scenario, which corresponds to the current situation, produces a response that is much more similar to the measured discharge, but very different to the other two scenarios. In particular, the simulated Kingston Park discharge (line 3c) now has a much faster response with a shorter lag time and a larger peak than the other two scenarios (lines 3a and 3b). This change in response is also very obvious downstream at Three Mile Bridge (line 4c, compared with lines 4a and 4b) and Crag Hall (line 5c, compared with lines 5a and 5b). The difference in peak discharge at Crag Hall between the 'post KP no pond' scenario (line 5c) and the other two scenarios (lines 5a and 5b) is actually larger than the difference at Kingston Park (line 3c compared to lines 3a and 3b), despite the changes being confined to the area that drains through the Kingston Park stormwater sewer. This is because the higher flow at Kingston Park discharge station ('post KP no pond' scenario) is also increasing the river celerity and, thus, any additional flows into the river are reaching the outlet faster.

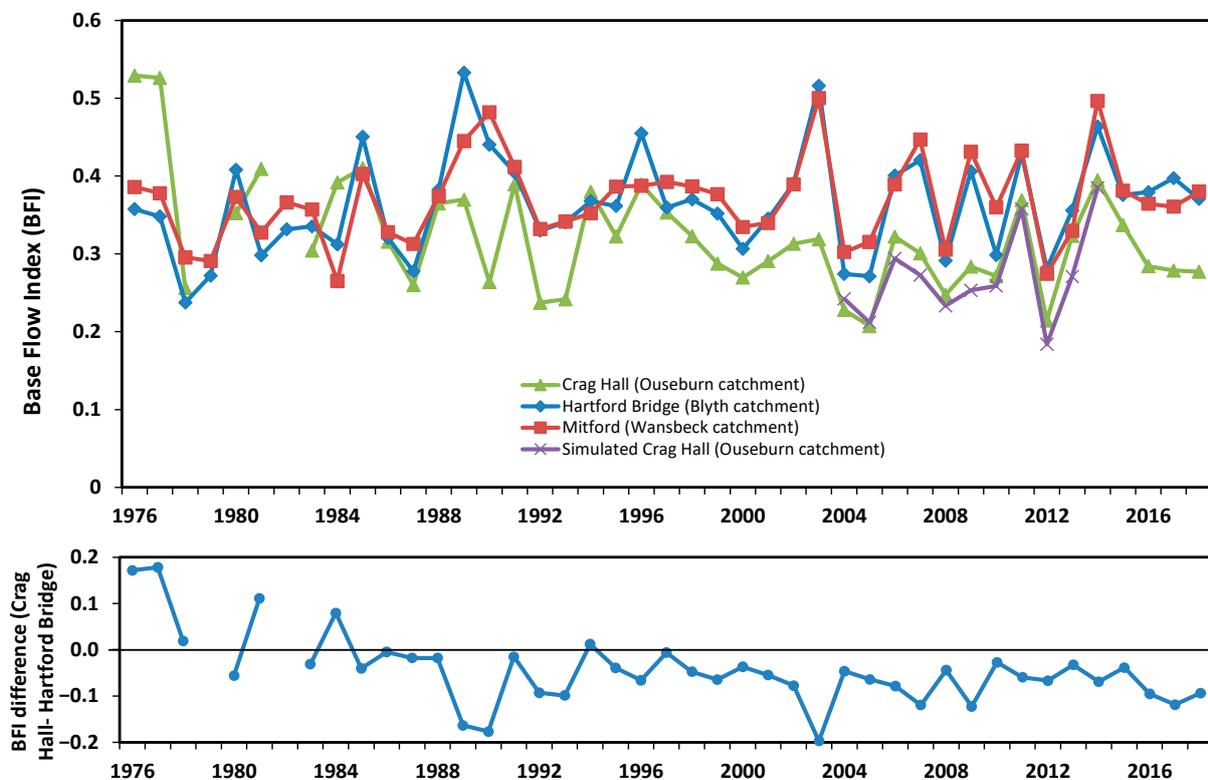
Figure A1 shows the measured and simulated discharges for an event on 6 August 2011. The measured data show a similar response to those for 30 June 2007 (considered in more detail in Section 4.1) The simulated discharges show the same significant change in response between the 'pre KP' and 'post KP no pond' scenarios, as shown in Figure 3b for the 30 June 2007 event.

### 3.2. Base Flow Index

The base flow index (BFI) is defined as the ratio of long-term baseflow to total streamflow [41]. Therefore, it is reasonable to expect a lower value of BFI in urban catchments as there is a faster runoff response with more surface flow and less baseflow. In this work, the method used to calculate BFI is the smoothed minima approach developed by Institute of Hydrology in the United Kingdom [42]. The calculation only requires daily flow data, so it is useful as for the Crag Hall discharge station only daily data are available up to 1990.

For each year, the BFI has been calculated for the Ouseburn at Crag Hall and at the nearby Blyth at Hartford Bridge and Wansbeck at Mitford catchments (Figure 1—inset). The Blyth and Wansbeck catchments at these locations are predominately rural, and thus provide a good baseline with which to see if there are any changes in the Ouseburn at the Crag Hall catchment.

Figure 4 shows that the BFI for the Blyth at Hartford Bridge and Wansbeck at Mitford catchments vary considerably from year to year but they are well correlated. The Ouseburn at Crag Hall also has high and low values in the same year as the other two catchments. However, as the lower panel in Figure 4 shows, there is a trend. The value at Crag Hall is considerably larger (0.16 and 0.18) than at Hartford Bridge in 1976 and 1977. There is a sudden drop, in 1978, of around 20–40% (the exact value is hard to quantify due to inter-annual variability). After 1978, there is some variation but, in general, there is a gradual decline in values at Crag Hall compared to those at Hartford Bridge. The Mann–Kendall test shows a downward trend from 1983 to the present at the 0.05 significance level but there is no trend from 1992 to the present, which is the period of the analysis in Section 4. The drop in 1978 corresponds to the completion of the Kingston Park stormwater drain. The trend of smaller values at Crag Hall after 1978 might be related to the building of the Newcastle Western Bypass road; there was also some industrial development and small housing estates built within the catchment in the 1980s.

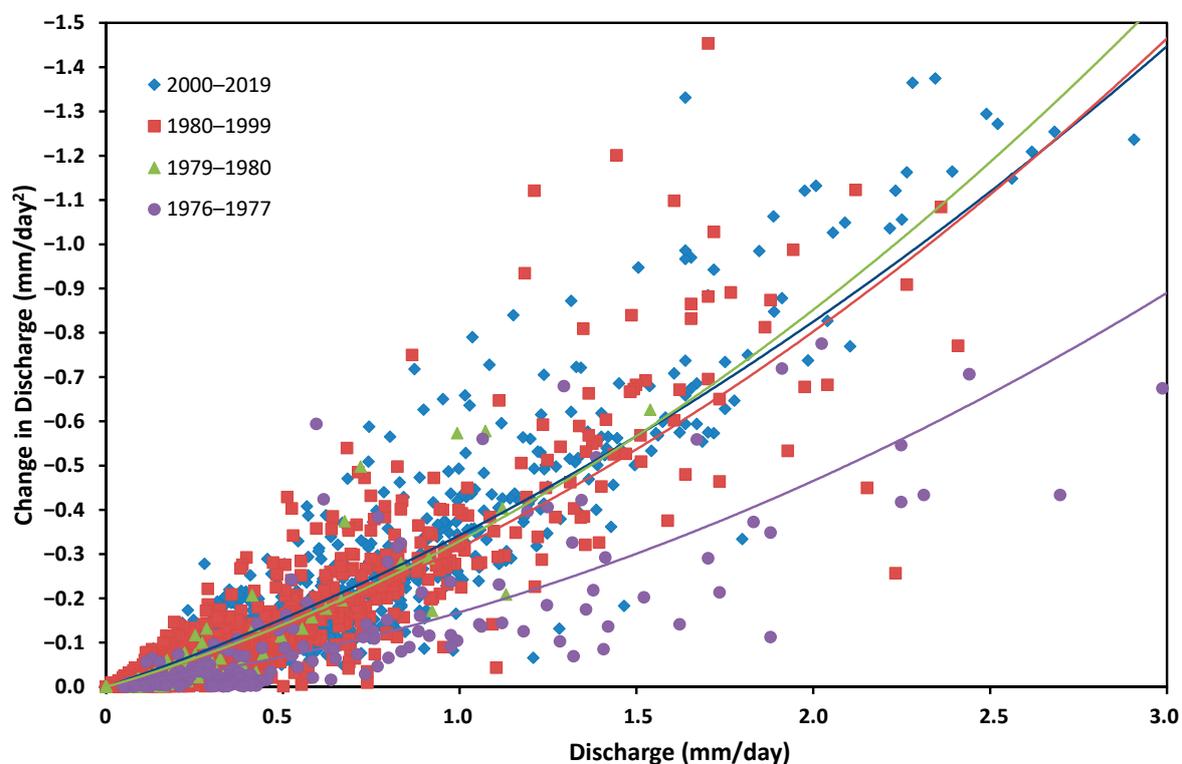


**Figure 4.** Base flow index (BFI) for the three catchments shown in the Figure 1 inset. The lower pane shows the difference in BFI values between the Ouseburn at Crag Hall and the Blyth at Hartford Bridge catchments. A positive value signifies that the BFI value is larger at Crag Hall than at Hartford Bridge.

The significant reduction in BFI in 1978 appears to be related to the commissioning of the Kingston Park stormwater drain, but the change is hard to quantify because of the annual variation in BFI values. Therefore, the Shetran hydrological model was used to see if it reproduces the same reduction in BFI between the ‘pre KP’ and ‘post KP no pond’ scenarios. The ‘post KP no pond’ scenario is the calibrated simulation from 2004 to 2014, i.e., the current situation, and the BFI values correspond extremely closely to the measured values (Figure 4), whereas the ‘pre KP’ scenario is the simulation from 2004 to 2014 but with the model altered to remove the Kingston Park developments and revert back to the original agricultural land. Incorporating the Kingston Park development produced a 24% reduction in BFI values, which confirms the statistical analysis results (20–40% reduction).

### 3.3. Recessions

There has been considerable research analysing hydrograph recessions (e.g., [43,44]) and it is useful here as another method of examining the effect of the Kingston Park development. In order to consider only the recessions, it was necessary to remove days with significant rainfall. This was achieved by calculating the areal averaged rainfall from a 1 km gridded daily rainfall dataset [45] and removing the days that had rainfall greater than 1 mm either on the day or on the previous day. The discharge was then plotted against the change in discharge between that day and the next (Figure 5). This shows a very different response in the 1976–1977 period compared to the other periods. For example, the fitted curve for a discharge of 1 mm/day has a reduction in discharge of 0.17 mm/day<sup>2</sup> for 1976–1977 and a reduction of 0.30 to 0.32 mm/day<sup>2</sup> for the other periods. Therefore, the 1976–1977 period has a much more gradual recession with a sudden change at the start of 1978.



**Figure 5.** Recession analysis for the Ouseburn at Crag Hall catchment showing the change in discharge for a particular discharge for non-rainfall days.

## 4. Newcastle Great Park Developments 2004–2019

This section contains an analysis of the effect of the Newcastle Great Park development on flows in the Ouseburn River. Unlike the Kingston Park development, the developments in this period have been built gradually (Table 1), so a sudden change in the flow at Crag

Hall discharge station is not expected. However, the flow data have a much better temporal resolution (Table 2 shows that they are hourly and sub-hourly from 1991 as opposed to daily data up to 1990) and long-term data from both Woosington and Crag Hall discharge stations are available, so smaller changes in flow as a result of the land-use change are possible to identify.

The analysis was achieved by first considering a rainfall event from 6 August 2011 and how both the water levels in the Melbury detention pond and flows in the Ouseburn River respond to this event. The hydrological simulations also show the simulated changes in flow as a result of building the Melbury detention pond. The BFI and recession analysis from Sections 3.2 and 3.3 are relevant here, as they include the time series data up to 2019, but they do not show any recent trends. Therefore, the rest of the analysis in this section focuses on the hourly data at Woosington and Crag Hall with statistical tests to see if there are any trends in this data.

One issue when considering changes in flow as a result of gradual changes in land-use is separating these changes from changes in the climate [37]. However, the Ouseburn catchment is an ideal location to analyse these changes as the Woosington nested sub-catchment has not undergone significant development, so comparing the flows at Woosington and Crag Hall allows for only the changes in land-use to be analysed. Therefore, using data from both Woosington and Crag Hall catchments can be considered as a paired catchment approach. From 1991 to the present, hourly data and some sub-hourly data are available for both sites, with the dataset over 99% complete.

#### 4.1. Rainfall Event on 6 August 2011

One of the first Newcastle Great Park developments was the Melbury housing estate (Figures 2 and 6). This was completed in approximately 2008 and has a surface area of 0.24 km<sup>2</sup>. The stormwater drains feed into a stormwater detention pond between the housing estate and the Ouseburn River at four different locations. The small upper pond (Figure 6) was designed to take water draining from a stretch of the Newcastle Western Bypass dual carriageway road with an area of 0.02 km<sup>2</sup>; however, this road still currently drains directly into the Ouseburn River. There is a culvert between the upper pond and the main pond; therefore, during major rainfall events, they effectively act as a single pond. The total surface area of both ponds is 25,000 m<sup>2</sup>, with an 'effective' volume of around 14,000 m<sup>3</sup> (the 'effective' volume is variable as there are sometimes elevated water levels in the pond at the start of a rainfall event due to groundwater flows, which reduce the potential storage capacity). The pond was built so that the water level remained below the level of the overflow weir for design storms with return periods of 100 years and durations from 4 h to 24 h, and also for a historic rainfall event with a return period of 136 years with 65 mm of rainfall over six hours. The outlet is controlled by a 0.225 m diameter pipe, which acts as a throttle with a maximum flow of about 0.073 m<sup>3</sup>/s [31]. Water from the pipe flows into the Ouseburn River between the Kingston Park and Three Mile Bridge discharge stations. As part of the MS4W project, water levels were measured in this pond. Figure 7a shows the measured flows in the Ouseburn River and the water level in the detention pond from an event on 6 August 2011. As with the event on 30 June 2007, there is a sudden change from the rural response at the Woosington and Brunton Bridge discharge stations (lines 1 and 2) to the more urban response downstream at the Kingston Park, Three Mile Bridge and Crag Hall discharge stations (lines 3, 4 and 5). The Kingston Park flows again have a higher peak and a shorter lag time than at Brunton Bridge. The water level in the stormwater detention pond shows that it captures all of the surface runoff from 28 mm of rainfall that fell in 10 h, with the water level rising from 0.22 m to 0.48 m and then gradually falling as a result of the controlled release. As a result of this development, there is no obvious change in flow response at Three Mile Bridge and Crag Hall.



**Figure 6.** The Melbury housing development and detention pond within the Ouseburn catchment. The inset shows a picture of the pond outlet. Google Earth image (©Google, Digital Globe).

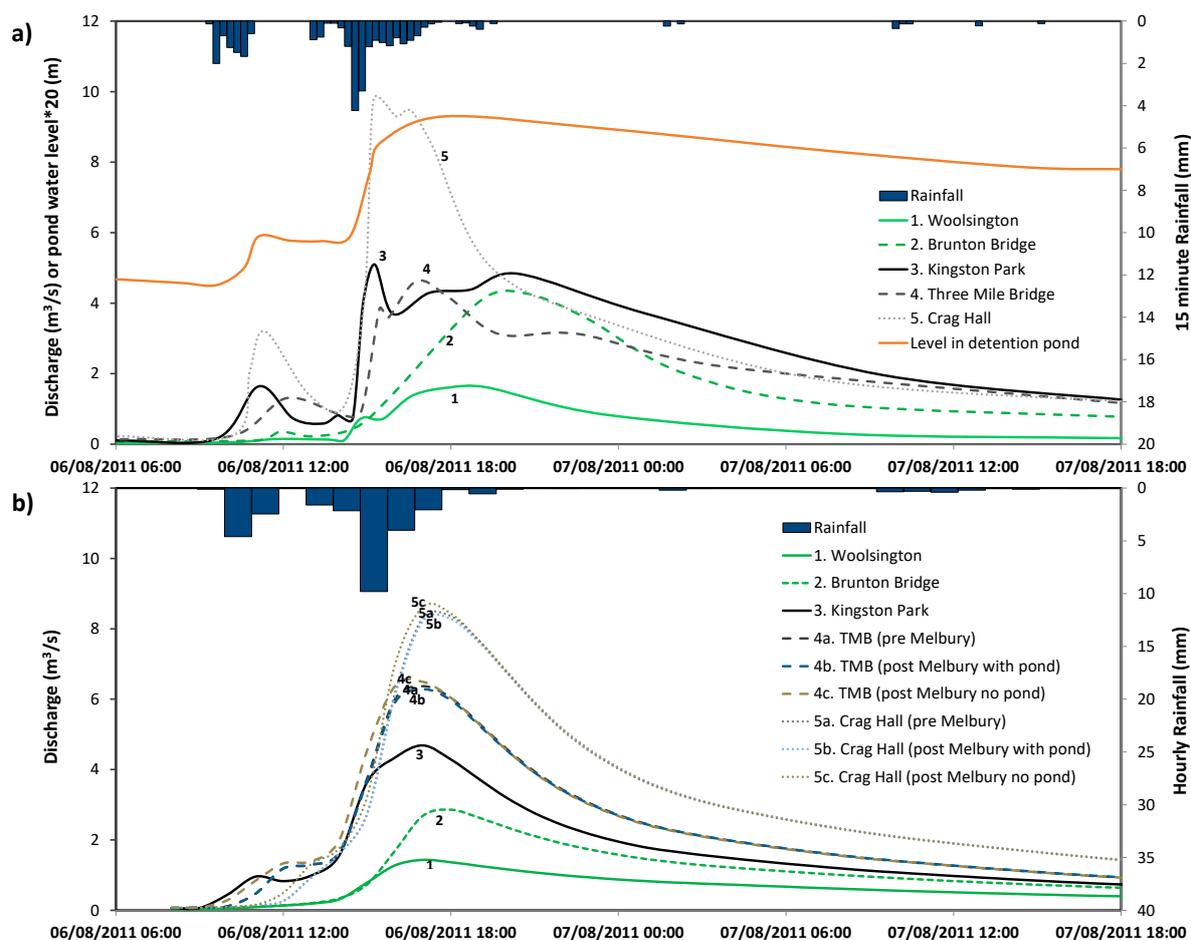
Three simulation scenarios were carried out to also consider the effect of the Melbury housing development on river flows. The first scenario includes the Melbury housing development as agricultural land ('pre Melbury'). The second scenario includes the period after the housing development had been completed and when the pond had been built ('post Melbury with pond'), which is the current situation. The third scenario includes the period after the housing development had been completed but when no pond had been built ('post Melbury no pond'). In second scenario, water storage of 14,000 m<sup>3</sup> was incorporated into the model on the land between the housing estate and the river, with a gradual release of this water back into the river after storm events. The 'post Melbury with pond' scenario reduces the peak flow by 1.4% at Three Mile Bridge and by 0.8% at Crag Hall compared to the 'pre Melbury' scenario, whereas the 'post Melbury no pond' scenario increases the peak flow by 1.8% at Three Mile Bridge and by 3.0% at Crag Hall compared to the 'pre Melbury' scenario (Figure 7b).

The same three scenarios show a very similar response for the rainfall event on 30 June 2007, the results of which are shown in Figure A2.

#### 4.2. Trends in Flows

The analysis considers whether there are any trends in the flows on the Ouseburn River as a result of the Newcastle Great Park developments in Table 1. This is carried out by considering hourly measured data at Woolsington and Crag Hall.

From 1992 to 2019, the annual values of Q10 and Q50 (the flow exceeded 10% and 50% of the time) at Crag Hall and Woolsington were extracted from the hourly discharge data and are shown in Figure 8. The low flows, Q90, are not shown as, at Crag Hall, these are affected by effluent returns from industrial units and leaky combined sewer connections.



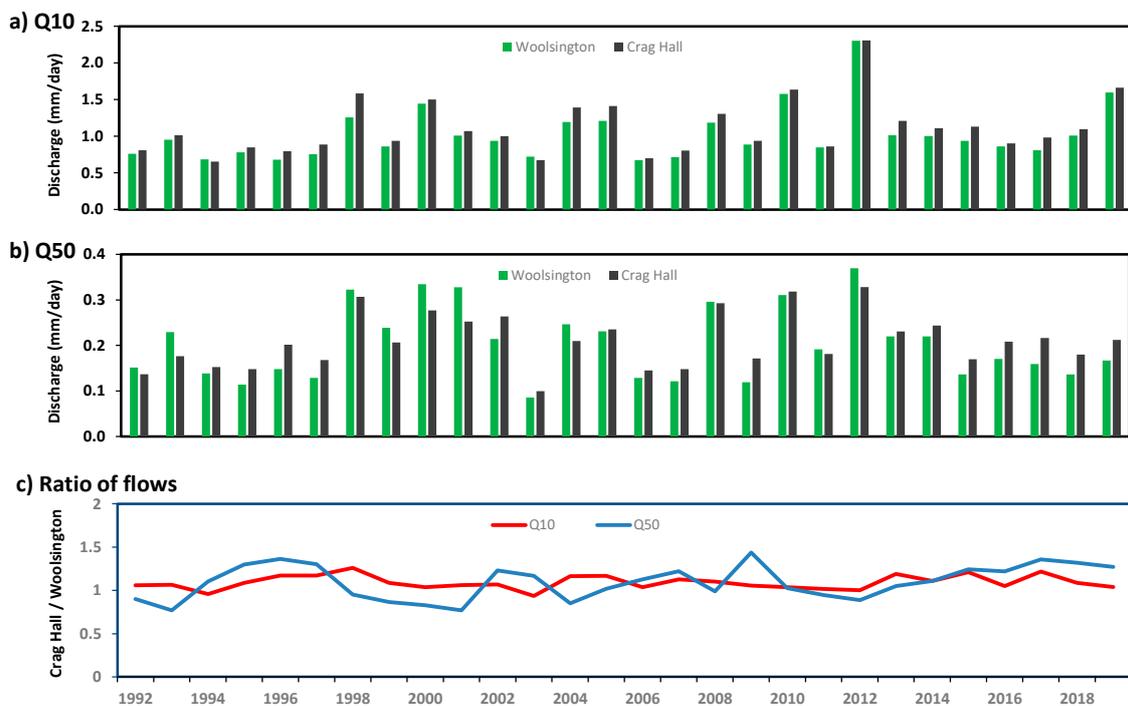
**Figure 7.** Discharges for a large rainfall event on 6 August 2011 at five discharge stations on the Ouseburn River: (a) measured and (b) simulated. Simulated values show the results for three scenarios, ‘pre Melbury’ before the Melbury housing estate was built, ‘post Melbury with pond’ after the Melbury housing estate was built with a detention pond included in the model and ‘post Melbury no pond’ after the Melbury housing estate was built with stormwater drains connected directly to the Ouseburn River. TMB is the Three Mile Bridge discharge station. Rainfall is the areal averaged value for the Crag Hall catchment with (a) 15 min data and (b) hourly data shown as these were used in the simulation.

The areal averaged flows (mm/day) at Crag Hall and Woolsington show a similar response, as annual precipitation varies little across the catchment (Section 2.2). Values range from 0.6 to 2.2 mm/day for Q10 values and from 0.08 to 0.37 mm/day for Q50 values. The Mann–Kendall test detected no trend in any of these series at a significance level of 0.05. In Figure 8c, the ratio of the areal averaged flows (Crag Hall/Woolsington) is shown for Q10 and Q50 values. At the significance level of 0.05, these also show no trend. The previous analysis of recessions (Figure 5) also shows that the fitted curve is almost the same for the two periods of 1980–1999 and 2000–2019. All these data suggest that the Newcastle Great Park developments have not had a significant effect on the flows at Crag Hall.

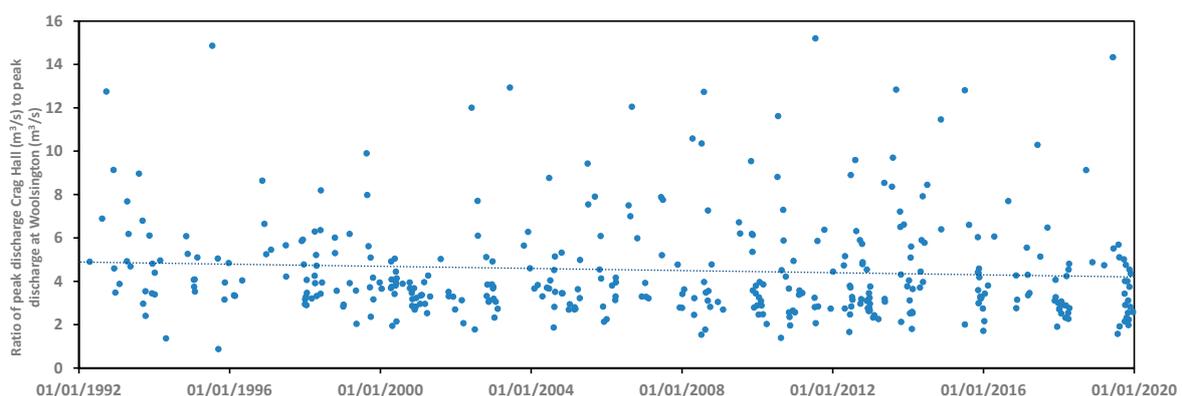
#### 4.3. Analysis of the Largest Events

Where hourly discharge data were available for both Woolsington and Crag Hall, rainfall events that produced the 400 largest discharges were extracted for the period from 1992 to 2019. Events needed to be at least 24 h apart to be considered as distinct. In Figure 9, the ratio of the peak flows at Crag Hall to those at Woolsington is shown. Due to the larger catchment area, the flows at Crag Hall are typically around four to five times bigger, although there is considerable variation, mainly due to the spatial variation in rainfall. There is a slight downward trend in the ratios with a value of 4.9 in 1992 reducing to 4.2 in 2019. The Mann–Kendall test shows that this is significant at the 0.01 level. This suggests

that more recent peak flows are reducing at Crag Hall compared to those at Woolsington. Potentially, this could be a result of the stormwater detention ponds built as part of the Newcastle Great Park development. However, there is no sudden change corresponding to this development and there is a downward trend from 1992 to 2004, in the period before any stormwater detention ponds were built. Another possible reason is the reduction in leaks in the water supply and sewage network, so there is less urban recharge [46], which, for large events, allows more infiltration and could reduce the peak flows at Crag Hall.



**Figure 8.** Areal averaged flows at Crag Hall and Woolsington. (a) is the Q10 annual discharge value, which is the flow exceeded 10% of the time. (b) is the Q50 annual discharge value, which is the flow exceeded 50% of the time. (c) The ratio of the flow at Crag Hall to the flow at Woolsington for Q10 and Q50 flows.

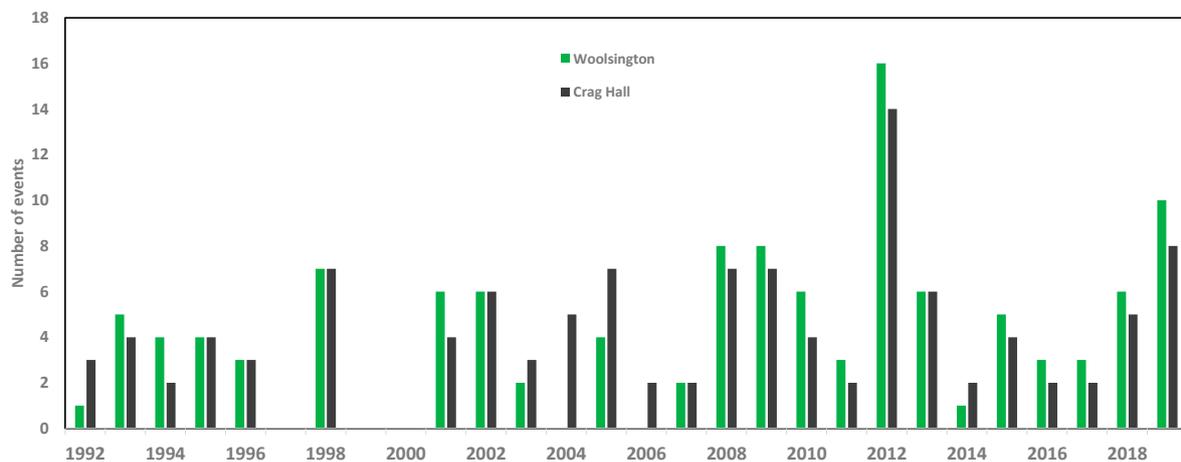


**Figure 9.** The ratio of the peak flow at Crag Hall to the peak flow at Woolsington for the largest 400 events for the period from 1992 to 2019. The trendline shows a slight downward trend.

#### 4.4. Peaks over Threshold Analysis

An alternative way of testing to see if the Newcastle Great Park Development has changed the flow regime for big events is to consider the number of peak over threshold (POT) events. These were considered for both Woolsington and Crag Hall from 1992 to 2019. Events were extracted if the flow was greater than  $1 \text{ m}^3/\text{s}$  at Woolsington and  $5 \text{ m}^3/\text{s}$  at Crag Hall. This produced 144 events at Woolsington and 131 events at Crag Hall,

which are shown in Figure 10, although years where the discharge record is less than 99% complete have been removed. The number of events shows considerable variation over the time series but, at the 0.05 significance level, the Mann–Kendall test shows no trend in the number of events in terms of either time series or the differences in numbers of events between the two time series.



**Figure 10.** Number of peak over threshold events at Woolsington and Crag Hall discharge stations.

## 5. Discussion

The Ouseburn catchment (see Section 2.1 for details) provides an unusual and prime opportunity to assess the effect of housing developments and stormwater detention ponds for two reasons. Firstly, the housing developments were carried out in two distinct phases with little development between the phases: the Kingston Park development from 1976 to 1978 and the Newcastle Great Park development from 2004 to present. Both developments had separated sewer systems but the Newcastle Great Park developments were also built with stormwater detention ponds. Secondly, the Ouseburn River has two long-term river gauging stations and some short-term discharge records, which enables potential changes in the flow regime as a result of the developments to be seen.

### 5.1. Discussion of the 1976–1978 Kingston Park Developments

Both the analysis of the BFI and the recessions have shown a very different flow response at Crag Hall in 1976 and 1977 compared to the years from 1978 to the present. There was a larger base flow in 1976 and 1977 and more gradual recessions. The change corresponds to the completion of the Kingston Park development and the connection of the Kingston Park stormwater drain to the Ouseburn River. It is, perhaps, surprising that the flow from a 2.1 km<sup>2</sup> urban area can have such a large effect on the flows in a 54 km<sup>2</sup> catchment and the two-year record from before the completion of the Kingston Park developments is rather short. However, individual events with high resolution data from a larger number of discharge stations, such as from 30 June 2007, show a much earlier and larger peak downstream of where the Kingston Park stormwater sewer joins the Ouseburn River and this effect is still very obvious further downstream at the Crag Hall catchment outlet. Hydrological modelling shows a similar large response as a result of completion of the Kingston Park development and the connection of the stormwater sewer. Overall, we can have confidence that the development has had a major effect on flows in the Ouseburn River, increasing the ‘flashiness’ of the hydrograph and, thus, the flooding risk.

### 5.2. Discussion of 2004–2019 Newcastle Great Park Developments

The measured water levels at the Melbury stormwater detention pond suggest it is working as planned and the modelling work shows that the housing development with a

detention pond produces a small reduction in peak flows, and without a detention pond it produces a small increase in peak flows. The other detention ponds (Table 1) were designed in a similar way to be able to store the water that flows from the housing developments through the separated sewer system into the pond for design storms with a return period of at least 100 years of different durations.

The catchment data were analysed to see if the cumulative effect of a larger number of housing developments with detention ponds affects the flow regime in the Ouseburn River. The BFI and recession data, which include data from 1976 to 2019 (Figures 4 and 5), show no recent change in flows. The analysis of the data at Woolsington and Crag Hall shows that, from 1992 to 2019, there was little change in the flow regime at either location. There is no trend in the Q10 or Q50 flows or the number of POT events. The only trend seen is when the 400 biggest events are considered, where the ratio of the flows at Crag Hall to flows at Woolsington shows a slight downward trend (i.e., smaller flows at Crag Hall compared to Woolsington), although this trend cannot be attributed directly to the Newcastle Great Park developments. Overall, the Newcastle Great Park developments have been shown to not increase the downstream flows, as feared by the local population, and they may be having a small effect in terms of reducing them. With further Newcastle Great Park developments in progress and more ponds being utilised, further research is needed to check that the developments are continuing to not increase the flood risk.

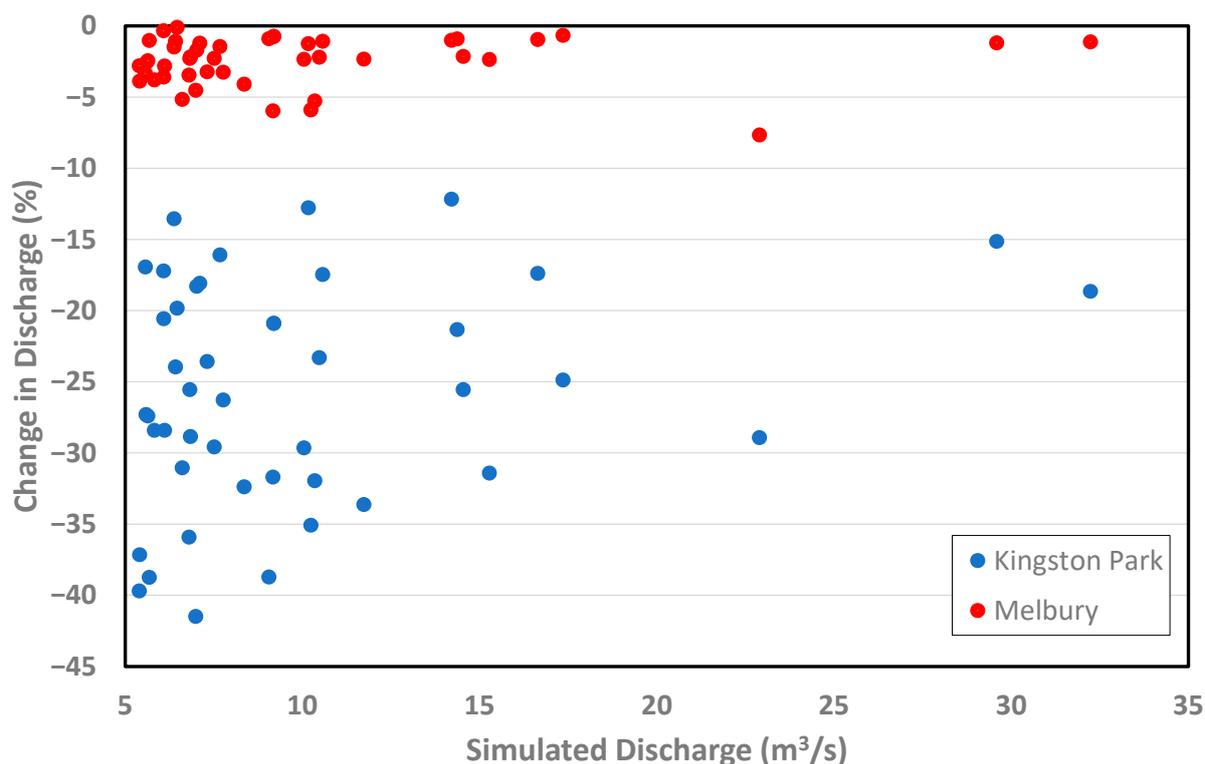
### 5.3. Discussion on the Location of Ponds and Their Effectiveness

In order to reduce the peak flow in a river and the potential for flooding, both the control of the outlet discharge from detention ponds [47] and the location of the ponds [48–50] are important. If the pond delays the peak from a new development and this new peak coincides with the upstream flood peak, then this can aggravate the downstream flooding issues. This effect depends on the rainfall duration, intensity and its distribution within the catchment, and also antecedent conditions throughout the catchment. To test these factors for flooding at Crag Hall, the calibrated hydrological model of the catchment was run for 45 events, with a simulated discharge greater than  $5 \text{ m}^3/\text{s}$ , considering the effect of the ponds on the peak flows (Figure 11). The results show variations for different events, but the simulations show that the Kingston Park pond would result in big reduction in peak discharge for every event, whilst the Melbury pond would also result in a reduction in peak discharge for every event, but with a much smaller reduction than for Kingston Park. Therefore, at Crag Hall, both detention ponds have a positive effect in terms of reducing flooding for all major events. Downstream of Crag Hall, the Ouseburn River flows through a narrow-wooded valley for 3 km and then for 1 km underground and, in this section, flooding issues are not considered to be important. Downstream of where the river reappears above ground, the tidal influence from the Tyne River is the most important aspect with respect to flooding.

### 5.4. Comparison with Other Studies

Jefferson et al. [26] and Li et al. [27] reviewed a number of studies that focus on the effect of SCMs, including GI and SuDS features, on flow regimes in urban and peri-urban catchments. The majority of the studies considered a modelling approach but some considered an empirical approach by carrying out a statistical analysis of the measured data. Jefferson et al. [26] highlight the potential of SCMs in delivering more natural flow regimes, although they note that the performance of SCMs in terms of reducing peak flows, predicted by models, seems to be much greater than that observed using the measured data.

This study uses both a modelling and empirical approach, and with the empirical approach it considers both the change in discharge over time as well as a paired catchment approach by utilising discharges at both Woolsington and Crag Hall. In this case, the results using both the modelling and empirical approach are in good agreement.



**Figure 11.** Change in the peak simulated discharge for detention ponds at Kingston Park and Melbury. The results from 45 events for a simulated discharge greater than 5 m<sup>3</sup>/s for the period from 1 January 2004 to 31 December 2014 are shown.

## 6. Conclusions

There have been a number of housing and business developments within the Ouseburn catchment, Newcastle upon Tyne, since the 1970s. This study considered the effect of these developments on flows in the Ouseburn River and assessed whether the stormwater detention ponds that were incorporated into the more recent developments work as they were designed to do.

The results clearly show that the older Kingston Park development led to a major change in the flow regime within the Ouseburn River. The data analysis and modelling demonstrate that it has made the catchment more 'flashy', increasing the downstream peak flows, reducing the time to peak and reducing the base flows. For example, for an event on 30 June 2007, the modelling shows that there is a 65% increase in peak flow and a three-hour reduction in time to peak as a consequence of an urban development and the connection of an urban area of 2.1 km<sup>2</sup>, directly to the Ouseburn River, via a stormwater drain. However, the newer Newcastle Great Park development has had a minimal effect on the downstream flow regime, possibly slightly reducing some of the peak flows for the big events. Both developments were predominantly housing developments built with separated sewer systems, the difference being that the Kingston Park development had no infrastructure built to attenuate the flows, whereas all the housing developments in the newer Newcastle Great Park have been built with stormwater detention ponds.

Each stormwater detention pond or group of ponds within the Ouseburn catchment was designed to capture the runoff from an individual housing development for rainfall events with return periods of at least 1 in 100 years. However, the ponds do not work in isolation, and it is necessary to consider how multiple ponds effect downstream flows and flooding issues. This work demonstrates, using both statistical analysis of the data and modelling, that, in this case, the ponds are achieving their intention at attenuating the flows and, thus, not increasing the peak flows. Without their presence, for more intense rainfall events, there would be larger peak flows and, thus, potentially more downstream flooding.

This case study is useful in providing more evidence of the catchment scale effect of stormwater detention ponds. It shows that stormwater detention ponds have the potential to avoid any increase and potentially reduce downstream flood risk during urban expansion, but there are still many uncertainties and challenges in the assessment of stormwater detention ponds and other GI or SuDS features at the catchment scale [27]. This includes limitations in the modelling of the ponds and the river catchment, and sufficiently detailed monitoring data that are able to capture the effect of the ponds on streamflow even with all of the other variability in meteorological data. Useful future research will include the use of long term datasets for other catchments and further analysis with different GI or SuDS features, including research into their locations within a catchment.

**Author Contributions:** Conceptualization, all authors; methodology, S.J.B., C.K. and G.O.; software, S.J.B.; validation, all authors; formal analysis, S.J.B., C.K., G.O. and R.A.; investigation, all authors; resources, S.J.B., P.Q. and M.E.W.; data curation, S.J.B., P.Q. and M.E.W.; writing—original draft preparation, S.J.B.; writing—review and editing, all authors; visualization, S.J.B.; project administration, C.K. and G.O.; funding acquisition, C.K. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

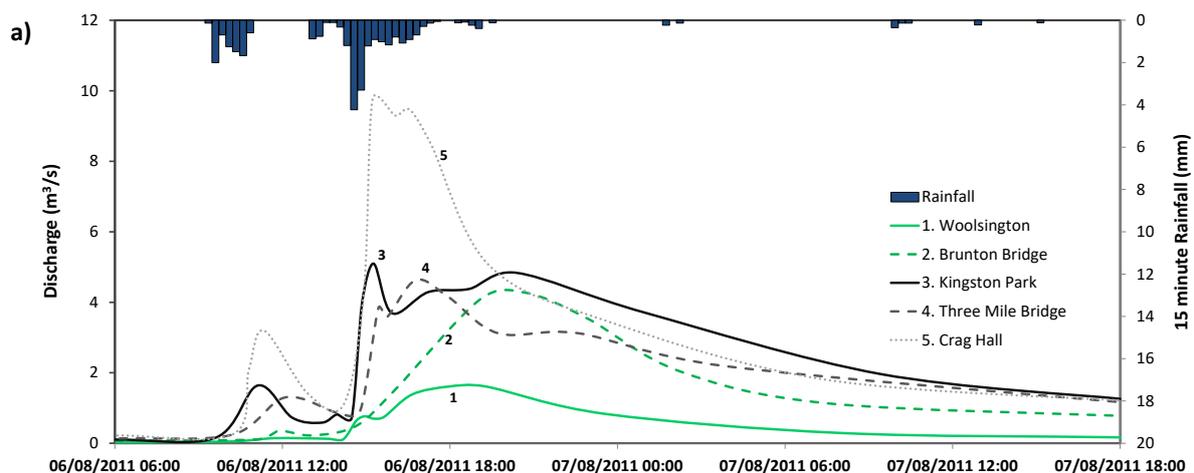
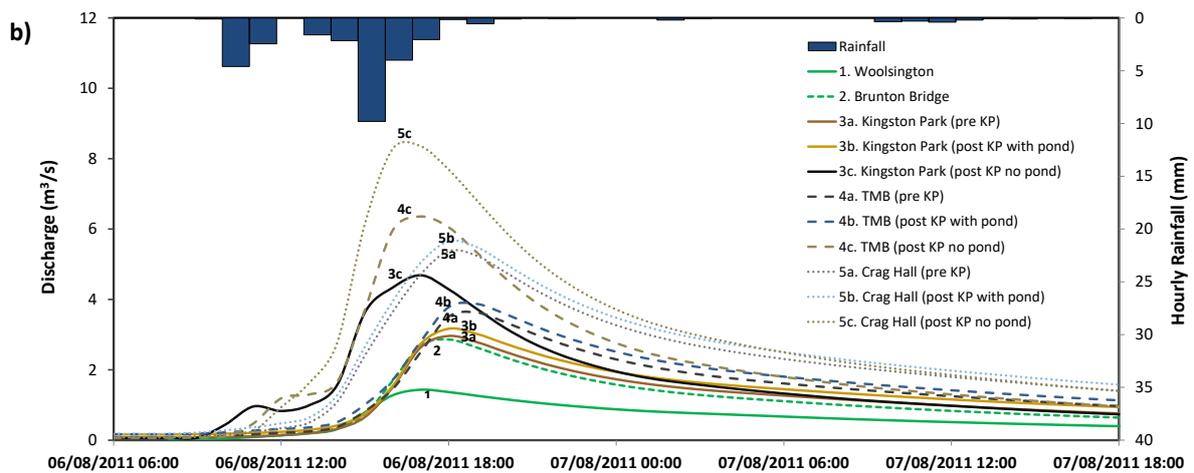
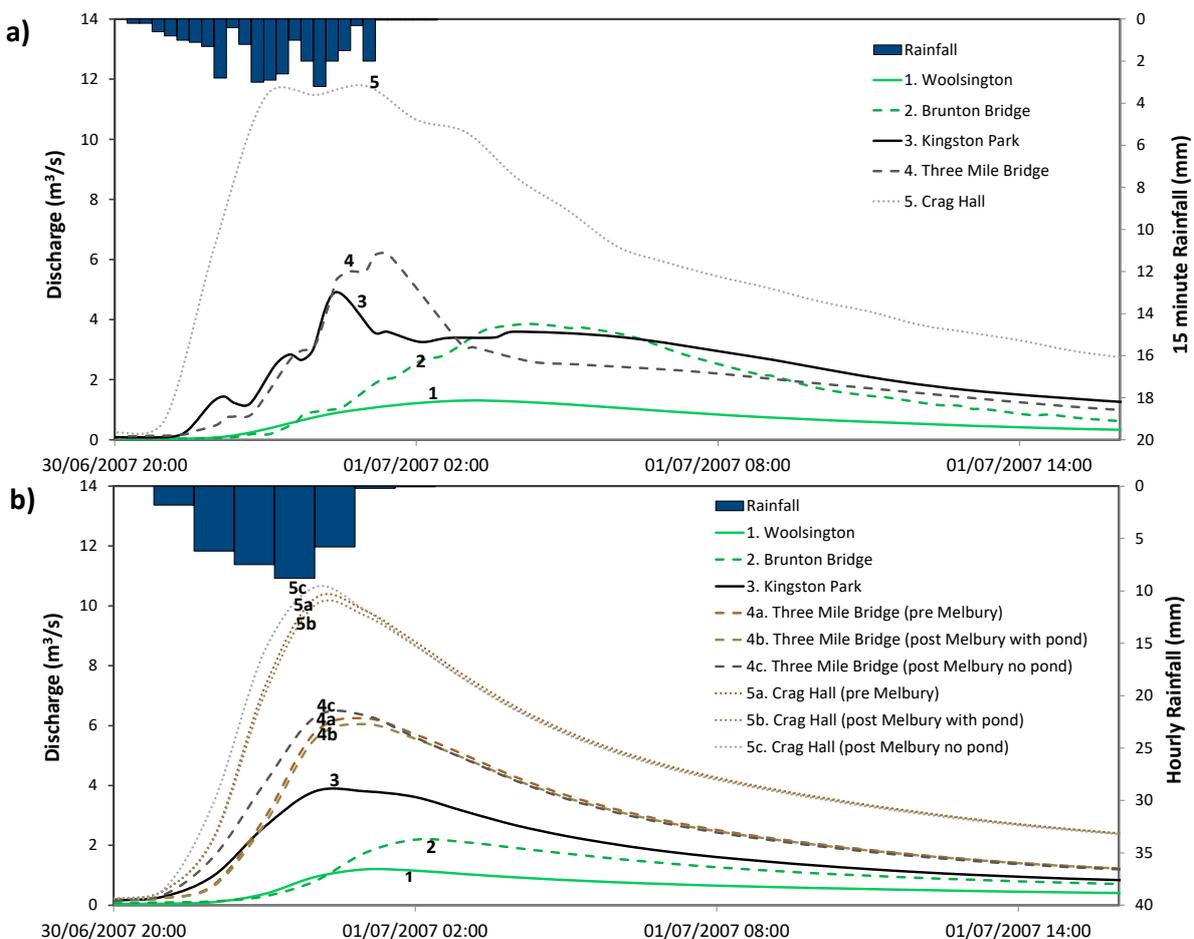


Figure A1. Cont.



**Figure A1.** Discharge for a large rainfall event on 6 August 2011 at five discharge stations on the Ouseburn River, (a) measured and (b) simulated, where KP is the 1976–1978 Kingston Park development. Simulated values show the results for three scenarios, ‘pre KP’ before the Kingston Park development, ‘post KP with pond’ after the Kingston Park development with a detention pond included in the model and ‘post KP no pond’ after the Kingston Park development was built with stormwater drains connected directly to the Ouseburn River. ‘Post KP no pond’, i.e., 1, 2, 3c, 4c and 5c, corresponds to the current situation. TMB is the Three Mile Bridge discharge station. Rainfall is the areal averaged value for the Crag Hall catchment with (a) 15 min data and (b) hourly data shown, as these were used in the simulation.



**Figure A2.** Discharge for a large rainfall event on 30 June 2007 at five discharge stations on the Ouseburn River: (a) measured and (b) simulated. Simulated values show the results for three scenarios, ‘pre Melbury’ before the Melbury housing estate was built, ‘post Melbury with pond’ after the Melbury housing estate was built with a detention pond included in the model

and ‘post Melbury no pond’ after the Melbury housing estate was built with stormwater drains connected directly to the Ouseburn River. Rainfall is the areal averaged value for the Crag Hall catchment with (a) 15 min data and (b) hourly data shown, as these were used in the simulation.

## References

- Shuster, W.D.; Bonta, J.; Thurston, H.; Warnemuende, E.; Smith, D.R. Impacts of impervious surface on watershed hydrology: A review. *Urban Water J.* **2005**, *2*, 263–275. [[CrossRef](#)]
- Putro, B.; Kjeldsen, T.; Hutchins, M.; Miller, J. An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom. *Sci. Total Environ.* **2016**, *548–549*, 164–172. [[CrossRef](#)]
- Oudin, L.; Salavati, B.; Furusho, C.; Ribstein, P.; Saadi, M. Hydrological impacts of urbanization at the catchment scale. *J. Hydrol.* **2018**, *559*, 774–786. [[CrossRef](#)]
- Hu, S.; Fan, Y.; Zhang, T. Assessing the effect of land use change on surface runoff in a rapidly urbanized city: A case study of the central area of Beijing. *Land* **2020**, *9*, 17. [[CrossRef](#)]
- Miller, J.D.; Hutchins, M. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *J. Hydrol. Reg. Stud.* **2017**, *12*, 345–362. [[CrossRef](#)]
- Blum, A.G.; Ferraro, P.J.; Archfield, S.A.; Ryberg, K.R. Causal effect of impervious cover on annual flood magnitude for the United States. *Geophys. Res. Lett.* **2020**, *47*, e2019GL086480. [[CrossRef](#)]
- Ellis, J. Sustainable surface water management and green infrastructure in UK urban catchment planning. *J. Environ. Plan. Manag.* **2013**, *56*, 24–41. [[CrossRef](#)]
- Maes, J.; Jacobs, S. Nature-based solutions for Europe’s sustainable development. *Conserv. Lett.* **2017**, *10*, 121–124. [[CrossRef](#)]
- Nesshöver, C.; Assmuth, T.; Irvine, K.N.; Rusch, G.M.; Waylen, K.A.; Delbaere, B.; Haase, D.; Jones-Walters, L.; Keune, H.; Kovacs, E.; et al. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Sci. Total Environ.* **2017**, *579*, 1215–1227. [[CrossRef](#)] [[PubMed](#)]
- Pauleit, S.; Ambrose, B.; Endersson, E.; Anton Buijs, A.; Haase, D.; Elands, B.; Hansen, R.; Kowarik, I.; Kronenburg, J.; Mattijssen, T.; et al. Advancing urban green infrastructure in Europe: Outcomes and reflections from the GREEN SURGE project. *Urban For. Urban Green.* **2019**, *40*, 4–16. [[CrossRef](#)]
- O’Donnell, E.; Thorne, C.; Ahilan, S.; Arthur, S.; Birkinshaw, S.; Butler, D.; Dawson, D.; Everett, G.; Fenner, R.; Glenis, V.; et al. The blue-green path to ur-ban flood resilience. *Blue Green Syst.* **2020**, *2*, 28–45. [[CrossRef](#)]
- Melville-Shreeve, P.; Cotterill, S.; Grant, L.; Arahuetes, A.; Stovin, V.; Farmani, R.; Butler, D. State of SuDS delivery in the United Kingdom. *Water Environ. J.* **2017**, *32*, 9–16. [[CrossRef](#)]
- Guo, Y. Hydrologic Design of Urban Flood Control Detention Ponds. *J. Hydrol. Eng.* **2001**, *6*, 472–479. [[CrossRef](#)]
- Sahoo, S.N.; Pekkatt, S. Detention Ponds for Managing Flood Risk due to Increased Imperviousness: Case Study in an Urbanizing Catchment of India. *Nat. Hazards Rev.* **2018**, *19*, 05017008. [[CrossRef](#)]
- Wiest, L.; Baudot, R.; Lafay, F.; Bonjour, E.; Becouze-Lareure, C.; Aubin, J.-B.; Jame, P.; Barraud, S.; Kouyi, G.L.; Sébastien, C.; et al. Priority substances in accumulated sediments in a stormwater detention basin from an industrial area. *Environ. Pollut.* **2018**, *243*, 1669–1678. [[CrossRef](#)]
- Ahilan, S.; Guan, M.; Wright, N.; Sleight, A.; Allen, D.; Arthur, S.; Haynes, H.; Krivtsov, V. Modelling the long-term suspended sedimentological effects on stormwater pond performance in an urban catchment. *J. Hydrol.* **2019**, *571*, 805–818. [[CrossRef](#)]
- Sharior, S.; McDonald, W.; Parolari, A.J. Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. *J. Hydrol.* **2019**, *573*, 422–431. [[CrossRef](#)]
- Yao-Ming, H. Experimental evaluation of design methods for in-site detention ponds. *Int. J. Sediment Res.* **2010**, *25*, 52–63.
- Liew, Y.; Selamat, Z.; Ab Ghani, A.; Zakaria, N. Performance of a dry detention pond: Case study of Kota Damansara, Selangor, Malaysia. *Urban Water J.* **2012**, *9*, 129–136. [[CrossRef](#)]
- Wissler, A.D.; Hunt, W.F.; McLaughlin, R.A. Hydrologic and water quality performance of two aging and un-maintained dry detention basins receiving highway stormwater runoff. *J. Environ. Manag.* **2020**, *255*, 109853. [[CrossRef](#)]
- Ravazzani, G.; Gianoli, P.; Meucci, S.; Mancini, M. Assessing downstream impacts of detention basins in urbanized river basins using a distributed hydrological model. *Water Resour. Manag.* **2014**, *28*, 1033–1044. [[CrossRef](#)]
- Bilodeau, K.; Pelletier, G.; Duchesne, S. Real-time control of stormwater detention basins as an adaptation measure in mid-size cities. *Urban Water J.* **2018**, *15*, 858–867. [[CrossRef](#)]
- Ronalds, R.; Zhang, H. Assessing the impact of urban development and on-site stormwater detention on regional hydrology using monte carlo simulated rainfall. *Water Resour. Manag.* **2019**, *33*, 2517–2536. [[CrossRef](#)]
- Del Giudice, G.; Rasulo, G.; Siciliano, D.; Padulano, R. Combined Effects of Parallel and Series Detention Basins for Flood Peak Reduction. *Water Resour. Manag.* **2014**, *28*, 3193–3205. [[CrossRef](#)]
- Rhea, L.; Jarnagin, T.; Hogan, D.; Loperfido, J.V.; Shuster, W. Effects of urbanization and stormwater control measures on streamflows in the vicinity of Clarksburg, Maryland, USA. *Hydrol. Process.* **2015**, *29*, 4413–4426. [[CrossRef](#)]
- Jefferson, A.J.; Bhaskar, A.S.; Hopkins, K.G.; Fanelli, R.; Avellaneda, P.M.; McMillan, S.K. Stormwater management network effectiveness and implications for urban watershed function: A critical review. *Hydrol. Process.* **2017**, *31*, 4056–4080. [[CrossRef](#)]
- Li, C.; Fletcher, T.D.; Duncan, H.P.; Burns, M.J. Can stormwater control measures restore altered urban flow regimes at the catchment scale? *J. Hydrol.* **2017**, *549*, 631–653. [[CrossRef](#)]

28. British Geological Survey. Geology of Britain Viewer. 2020. Available online: <https://mapapps.bgs.ac.uk/geologyofbritain/home.html> (accessed on 15 October 2020).
29. Birkinshaw, S.J.; O'Donnell, G.; Glenis, V.; Kilsby, C. Improved hydrological modelling of urban catchments using runoff coefficients. *J. Hydrol.* **2021**, *594*, 125884. [[CrossRef](#)]
30. Newcastle City Council. Ouseburn Surface Water Management Plan. 2015. Available online: [https://www.newcastle.gov.uk/sites/default/files/Flooding/ouseburn\\_swmp\\_2015.pdf](https://www.newcastle.gov.uk/sites/default/files/Flooding/ouseburn_swmp_2015.pdf) (accessed on 20 September 2017).
31. Capita. Newcastle Great Park: Independent Review of SUDS Features Cell I. 2014; Unpublished report.
32. Fairhurst. Cell A, Newcastle Great Park, Newcastle upon Tyne. Flood Risk Assessment and Drainage strategy. 2017; Unpublished report.
33. Environment Agency. Ouseburn and North Gosforth Integrated Urban Drainage Study. *Making Space for Water Final Report*. 2008. Available online: <https://research.ncl.ac.uk/proactive/ouseburn/ms4wouseburnpilotstudy/MS4WFinalReportByEA.pdf> (accessed on 14 January 2021).
34. Smith, L.; Liang, Q.; James, P.; Lin, W. Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework. *J. Flood Risk Manag.* **2017**, *10*, 370–380. [[CrossRef](#)]
35. Ewen, J.; Parkin, G.; O'Connell, P.E. SHETRAN: Distributed River Basin Flow and Transport Modeling System. *J. Hydrol. Eng.* **2000**, *5*, 250–258. [[CrossRef](#)]
36. Birkinshaw, S.J.; James, P.; Ewen, J. Graphical user interface for rapid set-up of SHETRAN physically-based river catchment model. *Environ. Model. Softw.* **2010**, *25*, 609–610. [[CrossRef](#)]
37. Birkinshaw, S.J.; Bathurst, J.C.; Robinson, M. 45 years of non-stationary hydrology over a forest plantation growth cycle, Coalburn catchment, Northern England. *J. Hydrol.* **2014**, *519*, 559–573. [[CrossRef](#)]
38. Birkinshaw, S.J.; Guerreiro, S.B.; Nicholson, A.; Liang, Q.; Quinn, P.; Zhang, L.; He, B.; Yin, J.; Fowler, H.J. Climate change impacts on Yangtze River discharge at the Three Gorges Dam. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 1911–1927. [[CrossRef](#)]
39. De Hipt, F.O.; Diekkrüger, B.; Steup, G.; Yira, Y.; Hoffmann, T.; Rode, M. Applying SHETRAN in a tropical west african catchment (Dano, Burkina Faso)—Calibration, validation, uncertainty assessment. *Water* **2017**, *9*, 101. [[CrossRef](#)]
40. Sreedevi, S.; Eldho, T.I.; Madhusoodhanan, C.G.; Jayasankar, T. Multiobjective sensitivity analysis and model parameterization approach for coupled streamflow and groundwater table depth simulations using SHETRAN in a wet humid tropical catchment. *J. Hydrol.* **2019**, *579*, 124217. [[CrossRef](#)]
41. Santhi, C.; Allen, P.M.; Muttiah, R.S.; Arnold, J.G.; Tuppad, P. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. *J. Hydrol.* **2008**, *351*, 139–153. [[CrossRef](#)]
42. Gustard, A.; Bullock, A.; Dixon, J.M. *Low Flow Estimation in the United Kingdom*; Institute of Hydrology: Wallingford, Oxfordshire, UK, 1992.
43. Kirchner, J.W. Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resour. Res.* **2009**, *45*. [[CrossRef](#)]
44. Thomas, B.; Vogel, R.M.; Famiglietti, J. Objective hydrograph baseflow recession analysis. *J. Hydrol.* **2015**, *525*, 102–112. [[CrossRef](#)]
45. Keller, V.D.J.; Tanguy, M.; Prodocimi, I.; Terry, J.A.; Hitt, O.; Cole, S.J.; Fry, M.; Morris, D.G.; Dixon, H. CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications. *Earth Syst. Sci. Data* **2015**, *7*, 143–155. [[CrossRef](#)]
46. Lerner, D.N. Identifying and quantifying urban recharge: A review. *Hydrogeol. J.* **2002**, *10*, 143–152. [[CrossRef](#)]
47. Ngo, T.T.; Yoo, D.G.; Lee, Y.S.; Kim, J.H. Optimization of Upstream Detention Reservoir Facilities for Downstream Flood Mitigation in Urban Areas. *Water* **2016**, *8*, 290. [[CrossRef](#)]
48. Kaini, P.; Artita, K.; Nicklow, J.W. Evaluating optimal detention pond locations at a watershed scale. *World Environ. Water Resour. Congr.* **2007**, 1–8. [[CrossRef](#)]
49. Pereira Souza, F.; Leite Costa, M.E.; Koide, S. Hydrological modelling and evaluation of detention ponds to improve urban drainage system and water quality. *Water* **2019**, *11*, 1547. [[CrossRef](#)]
50. Saadatpour, M.; Delkhosh, F.; Afshar, A.; Solis, S.S. Developing a simulation-optimization approach to allocate low impact development practices for managing hydrological alterations in urban watershed. *Sustain. Cities Soc.* **2020**, *61*, 102334. [[CrossRef](#)]