

Changing rate of urban creep and urban expansion over time and its impact upon the hydrologic response of a catchment

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ABSTRACT

Most previous quantitative research conducted on urban creep and urban expansion has focused on small areas, short time periods, case studies with fairly uniform housing stock and demographic makeup, and the characterisation of urban creep and expansion exclusively in terms of impervious area changes without quantification of the consequential hydrological impact, i.e., increase in surface runoff volume and peak flows in a catchment. This study, using satellite imagery, catchment characteristics data, geographic information system and hydrologic modelling, presents, for the first time, a long-term analysis of urban creep and expansion. The case study is the Ouseburn catchment in Newcastle upon Tyne, a wide-ranging catchment made up of rural, suburban and urban areas, over a period of seven decades. The rate of increase of impervious surfaces is found not to be constant in time; the significant impact of this variation on the catchment's hydrologic response is quantified. This has overall caused a substantial flow volume increase in the Ouseburn over the study period, e.g. 48% for a 1 in 5 years rainfall event. The conclusions obtained are likely representative of many large towns and cities across the United Kingdom and the methodology presented can be easily replicated in other study areas.

Key words: hydrological impact, hydrological modelling, urban change, urban creep, urban expansion

HIGHLIGHTS

- First long-term study into the changing rate of Urban Creep and Urban Expansion.
- Results facilitate the prediction of future levels of imperviousness in urban areas.
- Increased imperviousness has resulted in faster catchment hydrological response.
- Greater levels of imperviousness have also produced larger peak flows.
- Established links between socio-demographics and varying rates of urban creep.

1. INTRODUCTION

Urban creep is defined as the loss of pervious surfaces, through the progressive infilling of such surfaces in existing developments and the expansion of the impervious footprint of existing properties. This, together with urban expansion into previously undeveloped areas, leads to the increase of the fraction of surface area where runoff from rainfall directly contributes to sewer systems. Surface runoff from rainfall exceeding infiltration rates and drainage capacity in turn increases the risk of pluvial flooding (Wheater 2006), and this is only expected to get worse in the future where climate change will lead to an increase of precipitation both in frequency and intensity (Fischer *et al.* 2014).

Urban creep is of international concern with developed cities across the globe undergoing a progressive loss of pervious surfaces. A report by the European Environment Agency (2012) shows that cities of high levels of impervious surface occur throughout the continent and are not restricted to particular regions or countries. The potential negative impacts of increased imperviousness are recognised globally, with Frazer (2005) discussing the effects on rivers with increasing surface runoff and likelihood of pollutants being washed into watercourses; as well as rainfall runoff from paved surfaces on hot days threatening the ecology of rivers by increasing water temperatures.

Focusing on the United Kingdom (where this case study is located), one of the earliest studies on the quantification of urban creep (Cutting 2003) calculated an average percentage urban creep rate of 7.55% across the lifetime of the properties in their study area. (Cutting 2003) also analysed creep against variables such as area type and demographics to determine how they

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affect its magnitude. Previous research into the quantification of urban creep has largely been performed in localised studies produced for local authorities to assess urban creep in their area. One example is the report by [Newcastle City Council \(2008\)](#), which aimed to track the change in impervious areas by analysing two sets of aerial photographs taken nine years apart in $100\text{ m} \times 100\text{ m}$ sample square areas, and found that the nature and extent of urban creep was dependent upon the housing type and density in the sample squares, with lower density areas often experiencing higher levels of creep. A localised study conducted by [Wessex Water \(2008\)](#) built upon Newcastle City Council's 2008 use of aerial photography, incorporating historical mapping and site visits to provide a greater level of certainty. Wessex Water's 2008 study focused on urban sewer flood risk, from either combined or separate sewer systems, and found an average impermeable increase of $0.38\text{ m}^2/\text{property}/\text{year}$ for combined systems and 0.7 m^2 for separate systems. The study by [Allitt *et al.* \(2010\)](#) was the first robust investigation on the future levels of urban creep, based on a semi-automatic approach employing the use of image classification to detect changes in the satellite imagery, allowing for a large study area of 100 km^2 to be assessed. The study found an average increase between 0.38 and 1.094 m^2 per house per year, with an overall average of 0.737 m^2 per house per year from the five cities surveyed, a value that has been widely used to inform later studies, notably [Ofwat \(2011\)](#) and [Kennedy *et al.* \(2012\)](#). This valuable research, however, only provides a comparison between two points in time, therefore not analysing how the rate of urban creep is changing in time. Not accounting for this may lead to incorrect estimation of future urban creep levels, with consequent risk of insufficient or over engineered mitigations. [Allitt *et al.* \(2010\)](#) also focused on smaller subareas with the purpose of finding a correlation between urban creep and variables such as property density, property type, building footprint and Acorn social demographic data ([CACI International Inc 2020](#)). The results showed a clear correlation between the magnitude of urban creep and both property density and property types. Depth of front gardens similarly showed a correlation with urban creep in some of the study areas, with larger gardens typically seeing higher levels of creep. The study determined that urban creep could not be correlated with a single variable or a simple variable combination, with several factors contributing in different proportions within different socio-economic groups. [Haddock \(2015\)](#) work corroborates these findings, showing that the extent and location of urban creep varies depending upon property type and age.

Compared to urban creep quantification, the assessment of its hydrological impact of urban creep has been researched significantly less. [Kelly \(2016\)](#) performed a theoretical study upon the impact of paved front gardens on current and future urban flooding, using the United Kingdom mean front garden area of 50 m^2 , and found that a 10% covering of impervious area produces a runoff volume of 0.024 m^3 (9.9% of applied precipitation) and 0.035 m^3 (9.7% of applied precipitation) for 1 in 5 and 1 in 50 years rainfall events, respectively. [Kelly \(2016\)](#) also found that for a 50% impervious garden covering, corresponding to 25 m^2 , runoff increases to 0.12 m^3 (49.6%) and 0.18 m^3 (49.4%) for 1 in 5 and 1 in 50 years events, respectively. [Perry & Nawaz \(2008\)](#) studied a small 1.16 km^2 area of Leeds and showed that a 12.6% increase in impervious surfaces resulted in a 12% increase in annual runoff from the study area. [Haddock \(2015\)](#) examined a peri-urban catchment, with a housing stock varying across the study area creating a more diverse dataset, finding, like [Kelly \(2016\)](#) & [Perry & Nawaz \(2008\)](#), a direct correlation between urban creep and runoff, with a correlation coefficient of 0.57. A 2011 report by Ofwat on the future impacts on sewerage systems used the urban creep values that were produced by [Allitt *et al.* \(2010\)](#). The results showed that urban creep causes more water to enter the sewer network in storm events, leading to an increase in sewer flooding. The median increase in the predicted occurrence of sewer flooding for a 1 in 10 years event across 97 catchments was 11.5%.

2. AIMS OF THIS STUDY

Although very useful, previous studies on urban creep are typically characterized by the following limitations: (i) limited number of time periods considered, typically two ([Allitt *et al.* \(2010\)](#)), not allowing for estimating the temporal change of the rate of urban creep; (ii) focus on small areas, such as theoretical areas ([Kelly \(2016\)](#)) or small catchments ([Haddock \(2015\)](#)), although there are studies like [Ofwat \(2011\)](#) that look into the effect of urban creep upon the future sewer flooding risk across multiple cities; (iii) analysis of cases where the majority of the housing stock is the same age and type and the demographic makeup is relatively uniform ([Perry & Nawaz \(2008\)](#)); (iv) retrospective assessment of urban creep, with limited estimation of the projected (future) urban creep; and (v) characterisation of urban creep in terms of impervious area changes and not in terms of the consequent hydrological impact.

This study aims to perform a long-term analysis of the magnitude of urban creep and urban expansion, for the Ouseburn catchment in Newcastle upon Tyne, England. It is the first long-term study of this kind spanning over a period of seven

decades, allowing evaluation into change over time of the rate of increase in impervious surfaces and also make a prediction of the future levels of creep and urban expansion for proactive management of this phenomenon. In the authors' opinion this is a significant advancement in the way urban creep and urban expansion are accounted for, because the current practice is to consider a flat rate of annual increase of impervious surfaces, which may potentially lead to inaccurate estimates.

This study evaluates quantitatively the impact of the time variation of urban creep and urban expansion on the hydrologic response of the catchment (i.e., surface runoff volume, peak flows, time to peak). To the authors' knowledge, this is the first application on such a large and wide-ranging catchment, made up of rural, suburban and dense urban areas.

Although focusing on urban creep in Newcastle upon Tyne, the conclusions of this study on the changing rate of urban creep and expansion and its hydrologic impact are likely representative of many large towns and cities across the United Kingdom and the world at large. This study also outlines a methodology that can be easily replicated in other specific study areas.

3. METHODOLOGY

3.1. Case study

Newcastle upon Tyne's Ouseburn catchment was selected as the case study for this research because of its diverse makeup of urban, suburban and rural areas. Its catchment's boundary was obtained from the Environment Agency (Environment Agency 2020) and within it four 1-km² sample areas were chosen based upon attributes acquired from Acorn Demographics (CACI International Inc 2020), ensuring the data pool was diverse and provided a good representation of the catchment makeup. Specifically, two urban (Jesmond and Gosforth) and two suburban (Whorlton Grange and Great Park) sample areas were considered (Figure 1). Great Park was included in this research to evaluate differences between older and more modern suburban developments.

3.2. Digitisation and quantification of impervious areas over time

Impervious areas were digitised in the four sample areas considered. Satellite imagery acquired from the CEDA (Centre for Environmental Data Analysis) (CEDA 2020) was used to carry out the digitisation, after opportunely georeferencing the aerial images. Imagery relative to four years, 1945, 1995, 2001 and 2018, covering a 73-year timespan, was used. This is the largest timespan and number of sample years that research into urban creep has covered so far, with many studies, such as Allitt *et al.* (2010) and Perry & Nawaz (2008), only performing comparisons between two years' worth of data. The long time period considered in this study allowed for a meaningful evaluation of the change in time of the rate of urban creep.



Figure 1 | Ouseburn catchment boundary, sample areas and longest flow path.

For the digitisation this research opted for a manual process, drawing shapefiles in the ArcGIS software to represent impervious surfaces. Other investigations, such as Rowland *et al.* (2019), implemented a semi-automatic method. The manual process was adopted in this study because the semi-automatic method relies on high-resolution coloured satellite imagery to detect the type of surface covering; because this study covers a long period dating back to 1945, the resolution of the earlier satellite imagery used and the fact that the 1945 imagery was in black and white made the semi-automatic approach unfeasible. Rowland *et al.* (2019) also noted issues of the semi-automatic method in classifying areas of land covered in shadow or vegetation, leading to incorrect or unclassified land use; this would be problematic for this study area where gardens shrouded in shadow in terraced urban areas are widespread, and where vegetation cover (particularly around Jesmond Dene) may hide the ground surface in the imagery, thus requiring large scale checking and rectification. Based on these limitations, the manual method was implemented.

To optimise the digitisation process, the digitisation was undertaken taking the 1995 imagery as baseline, with a full digitisation within the four sample areas, with revisions taking place for the remaining study years. The impervious cover shapefiles produced were categorised into three types of impervious surface: roads, roofs and creep. The use of three separate impervious surface categories is due to the definition of urban creep that was adopted, where urban creep is the expansion of the impervious surfaces of an existing property, whilst the expansion of roads and roofs into previous undeveloped areas is classed as urban expansion; this allowed for separate analysis into each type of impervious surface.

Foliage produced some obstacles to the shapefile creation, with the likes of tree canopies covering the ground surface. To overcome the resulting challenges in determining the surface, the shapefiles were cross referenced against older and newer aerial imagery as well as Ordnance Survey maps.

Following the completion of the digitisation of the impervious areas, ArcMap's geometry calculation function was applied to calculate the area of each of the individual polygons. Using the polygon values, the total area of each of the three impervious surface types, and the overall area of impermeable surfaces were computed for each of the four sample zones. These values were used to compute a representative percentage of roads, roofs or creep impervious area for both urban and suburban areas, which could be applied to land use maps outside of the four sample zones to estimate the areas of impervious surfaces throughout the catchment considered.

3.3. Curve number estimation for rainfall excess calculations

The Soil Conservation Service (SCS) method (USDA Soil Conservation Service 1986), based on Curve Number (CN) parameter, is widely used in hydrology to estimate the direct runoff depth (rainfall excess) from a rainfall event. The CN parameter is a function of land use, soil type and antecedent moisture condition, with a higher value being akin to a piece of land having low infiltration rates (Ponce & Hawkins 1996). The CN value is only as accurate as the data used to estimate it, and especially the quality of land use maps typically varies across the years. Particularly the early satellite imagery, used to produce land use maps, are very coarse and provide little definition around built areas, which can only be distinguished between urban and suburban. Specifically, for this study, which focuses over a period of a few decades between 1945 and 2018, there is a stark contrast between the urban and suburban environments in 1945 and 2018. The soil data distribution was obtained from Digi-Map (Digimap 2020) and each soil type was manually classified in four hydrologic soil groups (HSGs), ranging from 'A' to 'D', with 'A' being the soils with the highest infiltration capacity (sand and gravel) and 'D' being the soils with the lowest infiltration capacity (clay).

For each of the four sample areas (either suburban or urban) and for each of the four years considered, a weighted CN was computed. To obtain this weighted value, in each sample area, a constant value of 98 (close to the upper theoretical limit of 100, corresponding to perfectly impervious surface) was assigned to the impervious areas, while, for the pervious areas (taken as grassland covering) CN values were obtained from USDA Soil Conservation Service (1986) based on the hydrological soil group. Because two urban areas were considered (Jesmond and Gosforth), an average was taken of the two weighted CN values to represent urban areas for each year. The same was done for the two suburban areas (Whorlton Grange and Great Park). Due to the lack of representative suburban housing in the 1945 data, a weighted CN could not be produced, and the suburban CN value for 1995 was used in lieu. It should be noted the 1945 land use map has few areas designated as suburban within the research zone, limiting the impact that this assumption had on this study.

To compute a catchment-averaged value of CN for each of the four years considered, a large amount of data classification was conducted on the land use maps, originally containing an average of 25 different land use types. The land use types were consolidated under six main land types using ArcGIS, to simplify the assignment of CNs.

A lookup table was then created to assign a CN value to each combination of land use and soil group.

The ArcGIS tool HEC-GeoHMS was finally employed to combine the data from the catchment Digital Elevation Model (DEM), the lookup table and the soil and land use distribution maps, to produce a CN grid raster map, with each pixel corresponding to a CN value. From this, a mean, catchment-averaged CN was obtained for each year considered.

3.4. Hydrologic modelling

The hydrologic modelling of the Ouseburn catchment was carried out using the software HEC-HMS (US Army Corps of Engineers 2020), to simulate the transformation of rainfall into streamflow (flow in the river Ouseburn at the catchment outlet) for each focus year under several rainfall return periods.

The simulations were used to model different catchment hydrologic responses to the same design storm event throughout the history, as a result of the increasing imperviousness of the catchment. Runoff volumes were computed as the total volume from the respective hydrographs generated by the storm event. Note that the purpose of this study is not to quantify long-term increase of runoff volumes or increase of runoff volumes for specific historically observed rainfall events, neither to quantify how urban creep has changed the frequency of peak flows and runoff volumes throughout history. Instead, the focus is on the effect of urban creep on the runoff from single storm events that compare well with ‘flash floods’ occurred in the area, such as the flood event colloquially known as the ‘Toon Monsoon’ (BBC News 2013), which hit this particular catchment in 2012, with similar events occurring around the globe, most notably the European summer flash floods of 2021.

The use of the CN method implies that only infiltration losses are considered as continuous rainfall losses, with the initial loss accounting for other losses such as ponding and indirectly the losses associated with rainfall interception by vegetation. This approach does not consider other causes of rainfall loss, such as infiltration through cracks in impervious surfaces and drainage from impervious to pervious areas, as discussed for instance by Ball *et al.* (2019). These two types of loss may be important long term (e.g. in a year water balance) but are expected to not significantly affect results over the period of a single storm (our focus here); especially this is the case for the former type of loss because the infiltration through cracks typically occurs at a low rate.

3.4.1. Catchment characteristics

The Ouseburn catchment, when measured with respect to its outlet at the entrance to the Ouseburn Culvert in Heaton, has a drainage area of 61.58 km². The catchment-averaged CN was computed for each year considered in this analysis as illustrated in Section 3.3. The catchment lag time is defined as the delay between the time of the maximum rainfall amount and the time of the peak runoff rate at the catchment outlet (Woodward & Kent 2010). The SCS equation (United States Department of Agriculture 2010) for lag time in hours was used in this study and was applied for each year of study:

$$T_{lag} = \frac{L^{0.8}(S + 1)^{0.7}}{1900 \times \sqrt{Y}} \quad (1)$$

where L is the hydraulic length of the catchment in metres, S is the maximum retention in the catchment (computed in mm as $1000/CN-10$) and Y is the catchment percent slope. The time of concentration for the catchment, which is defined as the time it takes for water to flow from the farthest point of the catchment to the catchment outlet, was also calculated as $T_c = T_{lag}/0.6$ (United States Department of Agriculture 2010).

3.4.2. Rainfall

1-km² rainfall frequency spatial grids were obtained (UK Centre for Ecology and Hydrology 2020), giving rainfall depth values for different storm return periods in the catchment. Rainfall return periods of 1, 5, 10, 30, 50 and 100 years were considered for this analysis. Data are available for rainfall duration of 1 and 3 hours (Table 1).

Table 1 | Ouseburn catchment-averaged rainfall depth (units of mm)

	1 in 5 years	1 in 10 years	1 in 30 years	1 in 50 years	1 in 100 years
Rainfall duration = 1 hour	15.63	19.17	26.12	30.08	36.86
Rainfall duration = 3 hours	23.43	28.23	37.85	42.5	50.54

As regards the temporal distribution of rainfall (hyetograph), a centre-loaded hyetograph shape with a sharp peak intensity was selected for use in the simulations.

3.4.3. Rainfall-streamflow simulations

The sewer network was not included in the simulation of the rainfall-streamflow simulation for the Ouseburn catchment. This was done because the purpose of this research is not to examine how well the network handles surface runoff, but to examine how increased impervious surface affects surface runoff, and because including a sewer network that has evolved and expanded over time would not allow for separating the effects of increased imperviousness from the effects of a changing sewer network. The length of the study period (going back to 1945) also raised accuracy concerns in relation to the reconstruction of the temporal evolution of the sewer network layout, due to the partial availability of historical sewer plans which would likely require a high number of assumptions; hence our decision to not include the sewer network in our modelling.

The Ouseburn catchment was simulated considering four different catchment scenarios, each representing one of the focus years, built around the differing characteristics for each year of catchment-averaged CN and catchment lag time. For each catchment scenario (focus year), different rainfall events corresponding to different return periods (frequencies) were simulated using the HEC-HMS model to obtain the resulting hydrograph (River Ouseburn flow rate vs time) at the catchment outlet.

A baseflow of $0.1 \text{ m}^3/\text{s}$ was applied to the Ouseburn in the model, calculated by multiplying the baseflow index (0.29) by the mean Ouseburn flow ($0.0936 \text{ m}^3/\text{s}$) (UK Centre for Ecology and Hydrology 2020).

4. RESULTS AND DISCUSSION

4.1. Rate of change of impervious areas

4.1.1. Total impervious areas

Across the study period of 73 years (1945–2018) the four 1-km^2 sample zones saw a percentage increase of 119.92% of total impervious area, corresponding to an increase of 1.05 km^2 . The detailed tabulated output of the digitisation of the impervious areas, either creep, roads or roofs, can be found in Tables 2 and 3.

A substantial portion of the impervious area increase is the product of the development of suburbs post 1945 as shown by the percentage of each sample area made up of impervious surfaces in Figure 2. There is no surface change recorded for Great Park between 1995 and 2001, though the area does see a decrease in impervious area post 1945 following the closure of industrial works in the area, producing a percentage imperviousness of only 0.18% for both 1995 and 2001. Great Park

Table 2 | Impervious areas for the different years considered

Area	1945					1995				
	Creep (m ²)	Roads (m ²)	Roofs (m ²)	Total (m ²)	Percentage impervious	Creep (m ²)	Roads (m ²)	Roofs (m ²)	Total (m ²)	Percentage impervious
Gosforth	39,498	151,682	197,229	388,409	39%	72,846	162,784	230,354	465,984	47%
Jesmond	64,754	187,941	210,055	462,750	46%	98,283	194,804	253,394	546,481	55%
Whorlton Grange	3,284	11,432	702	15,418	2%	23,419	205,616	141,096	370,131	37%
Great Park	344	10,663	0	11,007	1%	67	1,735	0	1,802	0.18%
Area	2001					2018				
	Creep (m ²)	Roads (m ²)	Roofs (m ²)	Total (m ²)	Percentage impervious	Creep (m ²)	Roads (m ²)	Roofs (m ²)	Total (m ²)	Percentage impervious
Gosforth	125,076	176,796	247,705	549,577	55%	146,222	177,514	250,253	573,989	57%
Jesmond	137,976	203,675	263,974	605,625	61%	161,486	204,591	260,232	626,309	63%
Whorlton Grange	67,062	220,944	149,359	437,365	44%	76,626	220,260	148,952	445,838	45%
Great Park	67	1,735	0	1,802	0.18%	59,334	138,652	85,849	283,835	28%

Table 3 | Impervious surface percentage change

	Impervious surface percentage change		
	1945–1995	1995–2001	2001–2018
Gosforth	20%	18%	4%
Jesmond	18%	11%	3%
Whorlton Grange	2,300%	18%	2%
Great Park	–83%	0.00%	15,651%

does see a dramatic increase of 15651% in impervious area between 2001 and 2018, due to the construction of large housing development.

The extent of the increase of impervious area can also be appreciated purely by visual comparison alone, with **Figure 3** showing an example comparison between Gosforth in 1945 and in 2018 with a clearly visible substantial reduction in pervious surfaces.

The creation of suburban areas accounted for 67% of the total increase of impervious surface from 1945 to 2018, with 33% being attributed to an increase in established urban areas. Analysis of the data from 1995 onwards, not considering the creation of new suburban areas to identify the impervious area change through normal occupation (e.g., houses being lived in) rather than from the construction of new areas, reveals that the urban environment makes up 45% of the total impervious

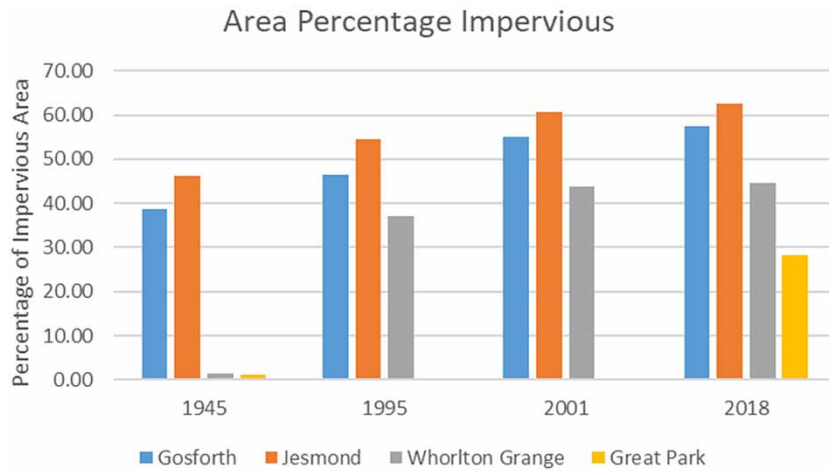


Figure 2 | Percentage of area that is impervious in the four sample areas across the years.



Figure 3 | Comparison of impervious surfaces in Gosforth between 1945 and 2018.

area increase; this shows that even though the urban environment is already densely packed with few green spaces, it is still undergoing a dramatic loss of pervious surface.

An estimated total percentage imperviousness of the Ouseburn catchment was calculated, extrapolating the percentage impervious values obtained from the digitisation of the four 1-km² sample zones to the land use distribution map for the whole catchment. The results show that the catchment consistently saw an increase in impervious surface, rising from 7% in 1945 to 23% in 2018. That is equivalent to a total increase of 14 km² of impervious surface within the catchment as of 2018.

4.1.2. Urban creep

In the two urban areas considered in this study (Gosforth and Jesmond) from 1945 to 2018 urban creep accounts for 58% of the total increase of impervious area alone. The urban increase in impervious surfaces could be attributed to the average number of cars per household having increased from 0.82 in 1985 to 1.12 in 2018 (Department for Transport 2019), thus providing a need to create additional parking spaces on what would be traditionally pervious surface in the back and sometimes in the front gardens.

The suburban environment showed a similar impervious increase distribution to the urban areas, with this time urban creep making up 70% of the total change between 1995 and 2018. The type of urban creep differs from that in the urban environment though, with the housing stock being newer builds, most of them built with parking facilities. Most creep identified in the suburban areas occurred in the rear of the property. This is likely to be a trend seen throughout the UK, but research into other catchments would be needed to validate this. The 1945 data was removed from the suburban areas analysis due to the undeveloped nature of the suburban environment, to avoid skewing the results.

4.1.3. Increase in roofed area

Roofed areas through the study period increased by 83%, with the majority of this increase coming from the period between 1945 and 1995, which saw a 53% increase. This dramatic growth in the early years of the study can be attributed to a post war housing boom, where growth continued right through till the mid-1970s (The Guardian 2014). Between 1995 and 2018 a total increase of 0.035 km² of roofed area to existing properties was observed, 77% of this being in the urban area.

4.1.4. Rate of impervious area expansion

Understanding how the rate of impervious area increase is changing over time is in general particularly important, to allow hydrology modellers to simulate future flood risk in a catchment by applying the latest rates alongside climate change effects. The annual rate of impervious area expansion for the Ouseburn catchment was estimated for three periods: 1945–95, 1995–2001 and 2001–18. The annual rate of impervious area expansion was calculated by dividing the total increase of impervious area over a certain period by the duration of that period in years.

The rate of overall impervious area increase, including all three types of impervious surface (roads, roofs and urban creep), was the largest, at 2.5% increase a year, between 1995 and 2001, rising from a rate of 1.2% for the period 1945–95 before falling back down to 1.2% again for the period 2001–18. As mentioned, the estimated overall rate of increase includes the addition of roads and buildings, both of which can be controlled and monitored through planning regulations and local authority housing plans. Urban creep, however, occurs more freely and sporadically, under the remit of permitted development (Portal Plan Quest 2020). When considering the urban creep contribution alone, the rate of increase shows the same trend of peaking in the period 1995 and 2001, with a rate of 11.61%, compared to a rate of 1.62% in the period 1945–95 and rate of 0.97% for the period 2001–2018. The peak and subsequent slowing of the rate can be linked to the increase of the percentage of households owning more than one car slowing post 2002 (Department for Transport 2019): this means that less households have the need to pave over gardens to create extra parking space. These results can also be linked to a 13% rise in households owning two cars between 1985 and 2002, compared to just a 5% rise in the subsequent 16 years (Department for Transport 2019).

For the above urban creep analysis, the large new development of Great Park was not considered to compute the rate, to avoid skewing the results. Whilst impervious area expansion in the large new development does add to the percentage impervious of the catchment, this type of impervious increase as stated before is regulated during the planning process, which details to what extent and when it will occur.

The slowing of the rate of urban creep highlights the approaching of a saturation point, because in highly dense areas once the majority of households have paved their property, there is limited pervious surface left to lose. Thus, established areas such as Gosforth and Jesmond will not experience such sharp increases as the likes of 1995–2001 again, reaching a plateau of low rates of urban creep. It is likely that the rate of creep in suburban areas will be greater than that of the urban areas as

this saturation point draws closer, because they generally have larger areas of pervious land at their disposal. This will be a reversal in the current standings, with urban areas currently having higher rates of urban creep compared with the suburban areas.

These findings raise some issues with the widely used urban creep rates produced by previous studies, such as *Allitt et al.* (2010), where changes are observed only for two points in time without considering the change in time of the rate of urban creep. Adopting a 'blanket' value of rate of urban creep computed for the start of the millennium may over predict its effects on the hydrologic response of catchments.

It can be seen from [Figure 4](#) that the percentage of impervious surface of the sample areas sharply increased between 1995 and 2001. Post 2001, the increase slowed and started to flatten. Great Park is an outlier in this regard, due to it being of newer construction.

4.1.5. Influencing factors

The findings show that urban creep affects different areas with different magnitude. The area type plays a significant role: there is a stark contrast between the rate of urban creep values for urban and suburban areas. The area type which saw the highest rate of urban creep changed throughout the study period, with the suburban areas showing the highest level of creep during the period 1994–2001, whilst currently urban areas are exhibiting the highest rate of creep. As previously mentioned, it is expected for the suburban environment to retake the lead with the higher rate of urban creep as the overall rate slows.

The demographics of an area has an influence upon the rate of increase of both roofed areas and urban creep. This can be seen through the comparison between Gosforth and Jesmond, two urban areas in close proximity to each other, with a similar housing stock yet seeing different rates of increase. Compared to Jesmond, Gosforth experiences consistently higher levels of percentage increase in impervious area. When comparing the geodemographic for both areas using data acquired from Acorn (*CACI International Inc 2020*), Gosforth is classed as being made up of predominantly couples with children with high income. Jesmond on the other hand is predominantly made up of students, and whilst this area is also classed as 'Living Comfortably' in household income term, it is not believed to be comparable with the household income of Gosforth. This is due to multiple occupancy houses inflating the average household income without being necessarily representative of the occupant's wealth. The differences between these demographic groups are believed to be a cause of the differing urban creep rates, with the high-income families of Gosforth more likely to invest in their own property thus causing urban creep. On the other hand, properties in Jesmond, which are predominantly student private lets, are less likely to see investment, especially in outdoor spaces, thus causing a lower level of creep.

4.2. Impact of impervious area increase on the rainfall excess calculations

4.2.1. Curve number in the sample areas and curve number look up tables

The CN value is only as accurate as the data used to estimate it. Land use maps, particularly the early satellite mapped ones (1995 and 2001), are coarse, providing little definition around built up areas, which only allows for defining them as either

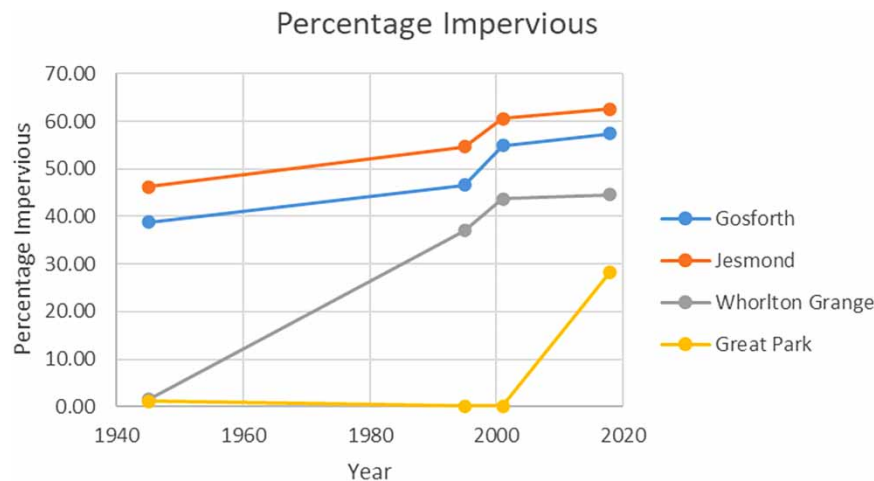


Figure 4 | Evolution in time of the percentage impervious area in the Ouseburn catchment sample areas.

urban or suburban. For all sample areas, the CN values were obtained from literature (USDA Soil Conservation Service 1986), for both impervious surfaces and pervious surfaces (assumed as grassland), for each of the four hydrological soil groups, as shown in Table 4.

Equation (2) was used in conjunction with Table 4 to calculate an area-weighted CN for each sample area, each year considered and each hydrologic soil group (Table 5).

$$\text{Weighted CN} = (\% \text{ Impervious Area} \times \text{Impervious Soil Group CN}) + (\% \text{ Pervious Area} \times \text{Pervious Soil Group CN}) \quad (2)$$

The results in Table 5 were then aggregated into area types (urban and suburban) with an average taken of the two areas for each area type and rounded to the nearest integer, producing a CN look-up table (Table 6) for urban and suburban areas. Note that the values for suburban areas in 1995 were also used for 1945; this is due to a lack of substantial suburban data for analysis in 1945. This may have caused some slight over estimation of the CN value, though the impact on the analysis is minimal due to the minor difference between what is classed as urban and suburban, with suburban areas in the catchment in 1945 tending to just be the fringes of urban areas, which would go on to become classed as urban areas later in the study, as seen in Figure 5. The use of the 1995 values reflects the close similarity between 1945 urban and suburban areas, with the suburban CN only being slightly lower.

Table 7 lists the remaining CN values that were used for the different land use and soil type combinations outside urban and suburban areas. These values were also taken from USDA Soil Conservation Service (1986).

The look-up tables (Tables 6 and 7) used in conjunction with the combined land use and soil maps in ArcMap to produce catchment curve number grids for each of the respective years. The curve number grids produced catchment averaged curve numbers for each of the study years.

Table 4 | Curve number values (USDA Soil Conservation Service 1986)

Hydrological soil group	A	B	C	D
Impervious	98	98	98	98
Pervious (Grassland)	49	69	74	84

Table 5 | Weighted curve number values

Hydrological soil groups	1945				1995				2001				2018			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Gosforth	68.1	80.3	83.3	89.4	71.8	82.5	85.2	90.5	75.9	84.9	87.2	91.7	77.1	85.7	87.8	92.1
Jesmond	71.7	82.4	85.1	90.5	75.9	84.9	87.1	91.7	78.7	86.6	88.5	92.5	79.7	87.7	89.1	92.8
Whorlton Grange	49.8	69.5	74.4	84.2	67.1	79.7	82.9	89.2	70.4	81.7	84.5	90.1	70.9	81.9	84.7	90.2
Great Park	49.5	69.3	74.3	84.2	49.1	69.1	74.1	84.1	49.1	69.1	74.1	84.1	62.9	77.2	80.8	87.9

Table 6 | Aggregated curve number values for urban and suburban areas

	1945				1995				2001				2018			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Urban	70	81	84	90	74	84	86	91	77	86	88	92	78	86	88	92
Suburban	67	80	83	89	67	80	83	89	70	82	84	90	71	82	85	90



Figure 5 | Comparison of 1945 suburban areas (in yellow) and urban areas (in blue) (Landmap; The GeoInformation Group (2007); Modern UK Aerial Photography. 2007) (Obtained from the CEDA Archive).

Table 7 | Curve number values for land uses other than urban and suburban areas

	A	B	C	D
Forest	36	60	73	79
Water	100	100	100	100
Grassland	49	69	79	84
Rocky gravel	76	85	89	91

4.2.2. Temporal evolution of the catchment-averaged curve number

The catchment-averaged CN value, which is an input parameter for the hydrologic model of the Ouseburn catchment, increases, as expected, over time, reflecting the effect of the loss of pervious surfaces. This means that, in time, the same precipitation produces a greater volume of surface runoff, ultimately resulting in larger flows in the River Ouseburn.

Through the study period an increase of 3 in the catchment-averaged CN value was estimated (Figure 6), with a sharp increase between 1995 and 2001 before levelling off (though it should be noted that the value is still increasing at this point, just at a slower rate of 0.021 per year).

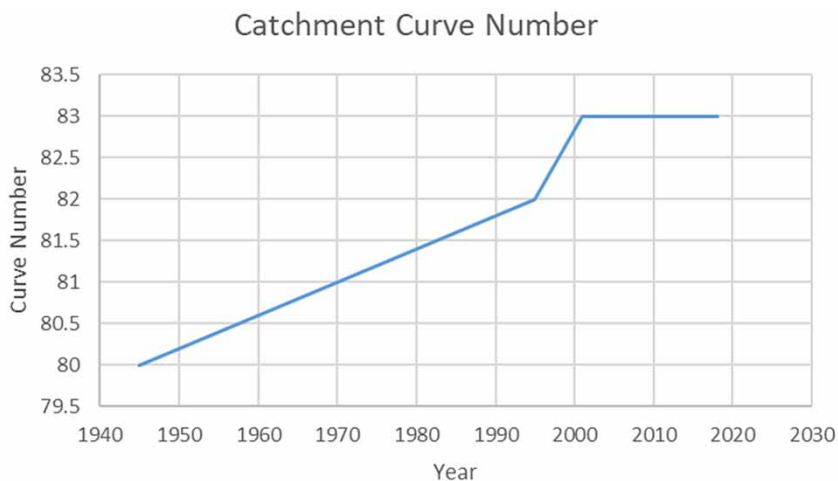


Figure 6 | Evolution in time of the catchment-averaged CN for the Ouseburn catchment.

4.3. Impact of the loss of pervious surfaces on surface runoff volume and temporal distribution

Using the DEM of the catchment, the hydraulic length (longest flow path) and the average slope of the Ouseburn catchment were calculated with the ArcHydro toolbox in ArcGIS, giving a length of 18 km and a slope of 7.49%. The resulting catchment lag times and time of concentrations, computed with Equation (1), are shown in Table 8. As the catchment surfaces change throughout the study period the catchment's response time to weather events is reducing.

The rainfall-streamflow modelling was conducted for rainfall duration of 3 hours, which is the value of duration, among the available rainfall data, closer to the catchment time of concentration and therefore producing the largest (most critical) flows in the River Ouseburn.

Five storm events, corresponding to the five different return periods considered, were simulated for the Ouseburn catchment for each of the four focus years considered in this analysis. As expected, river flow volume increases for larger return periods (lower frequency). The percentage increase in flow volume was calculated based on the difference between the total flow volume of 1945 and 2018. As can be seen in Table 9, the percentage increase in flow volume decreases as storm return periods increases; this is due to the soil during higher intensity events reaching its saturation point, and at that point the infiltration capacity of the soil does not affect runoff any more. For a larger return period, a larger portion of the total precipitation is converted into surface runoff: this is seen in 1945 with 32% of precipitation in a 1 in 5 years event becoming runoff, compared with 48% in a 1 in 100 years event for the same year of consideration. This highlights that the increase in impervious surfaces has the biggest impact upon more regular storm events, indicating that the catchment could potentially experience flooding more frequently under smaller storm events because of urban creep and generally increase of impervious areas, due to the higher percentage increase in flow.

The 1 in 100 years event simulation results are of particular interest, due to this specific catchment being subjected to a 1 in 100 years storm event in 2012 which brought widespread disruption, causing 8 million pounds worth of damage and becoming widely known as the 'Toon Monsoon' (BBC News 2013). The results highlight the dramatic effect that urban creep and urban expansion has had upon the hydrologic response of the catchment. When subjecting the catchment to the 1 in 100 years event the results for 1945 show only a 10% difference in peak flow with that of the results for a 1 in 30 years event in 2018, with the difference between 1 in 30 year and 1 in 100 year peak flow decreasing from 43% in 1945 to 38% in 2018. Note that a 1 in 30 years event is typically what urban sewer networks are designed for (South Gloucestershire Lead Local Authority n.d.). This serves as a testament to the effectiveness of pervious surface in the reduction of surface water flows, as well as a stark warning on the pressure increased imperviousness places upon a catchment.

It is possible to calculate future estimates for surface runoff by plotting a trend line against the percentage of precipitation that translates into surface runoff. A 1 in 30 years event is estimated to produce an increase of 3% in the amount of total precipitation becoming surface runoff by 2028 (Figure 7). It is also estimated that by 2028 a 1 in 100 years event would show 64% of precipitation becoming surface runoff; this is a 4% increase upon 2012 when this catchment experienced 'The Toon Monsoon'. The trend line used has a high coefficient of determination of 96%.

The increase in peak river flow year on year is clear to see from the plots of hydrograph at the catchment outlet (Figure 8), with each of the peak discharges greater than the last, when comparing for the same rainfall return period. The relationship between the increase of peak flow and urban creep and expansion is clear to see, with the hydrograph following the same

Table 8 | Time of concentrations and lag times

	1945	1995	2001	2018
Time of concentration (hrs)	1.939	1.819	1.760	1.760
Lag time (hrs)	1.16	1.09	1.06	1.06

Table 9 | River flow volume percentage increase from 1945 to 2018 for rainfall event with different frequency (return period)

	1 in 5 years	1 in 10 years	1 in 30 years	1 in 50 years	1 in 100 years
Percentage increase in flow volume	48%	42%	34%	31%	27%
Percentage increase in peak flow	54%	48%	40%	37%	33%

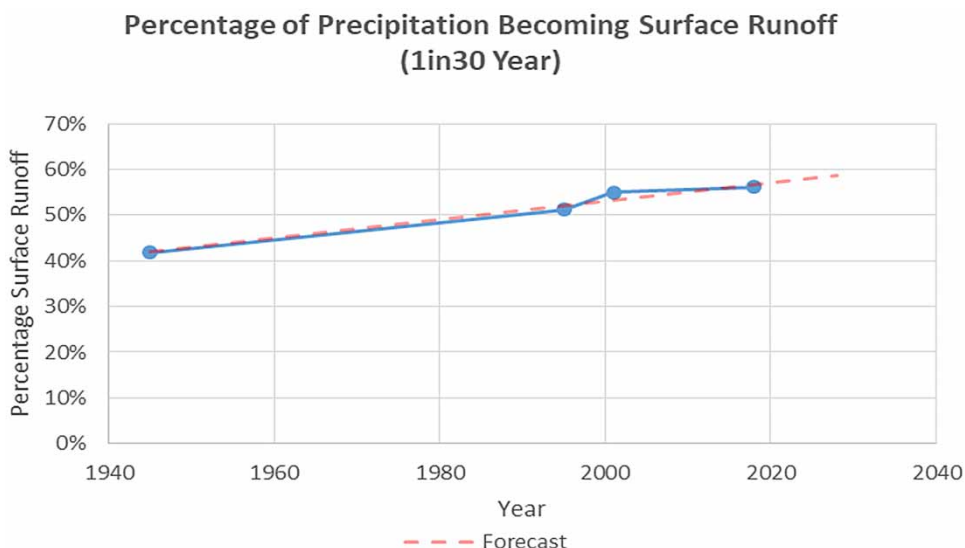


Figure 7 | Percentage of precipitation becoming runoff throughout the years, for 30-year return period rainfall events.

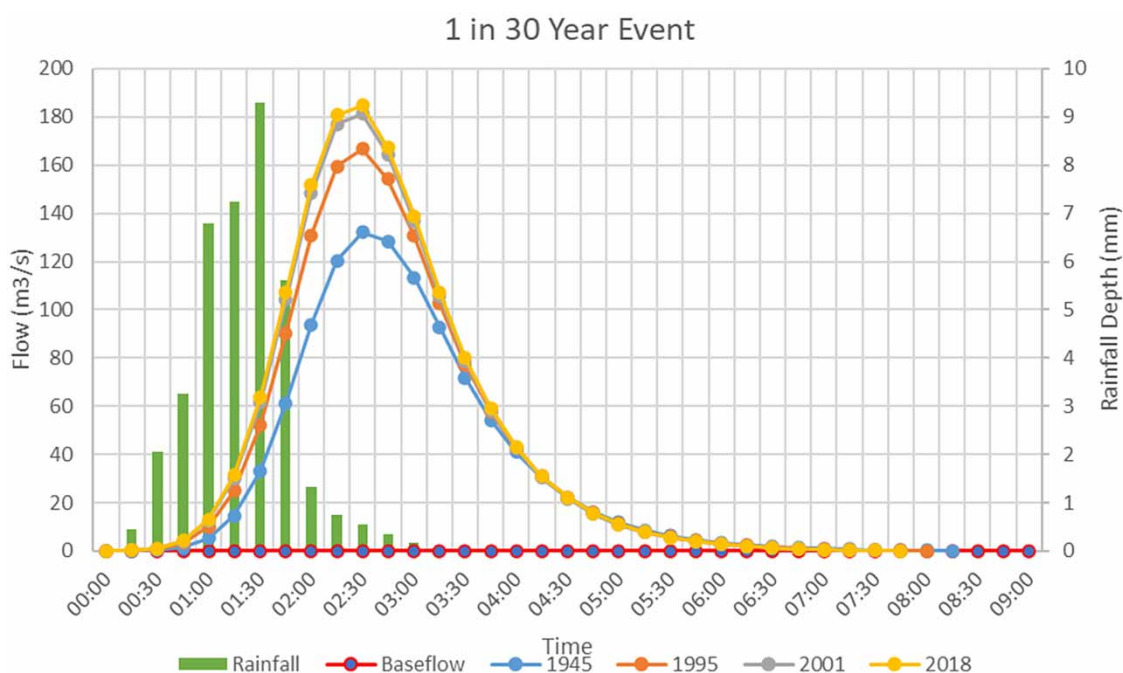


Figure 8 | 1 in 30 years hydrographs for the different years considered.

increasing trend as the increase in impervious areas in the catchment, with a substantial increase between 1995 and 2001 and with a smaller slower increase between 2001 and 2018. The percentage increase in peak flow for each of the rainfall event can be seen in [Table 9](#).

Increased urbanisation has also had a clear impact upon the delay between the maximum rainfall depth and the peak flow (lag time), with a distinct reduction in the lag time, falling by 9% between 1945 and 2018. This shows that the catchment is responding faster to rainfall events, through time, as it has become more impervious. The increased responsiveness of the catchment can also be seen through the time it takes for the river flow to return to baseflow level following a rainfall event; the time fell by 14% between 1945 and 2018.

This provides a flooding concern due to the total amount of flow for a rainfall event being concentrated into a shorter time period, creating greater depths within the channel, which increased likelihood of overbank flooding, as well as increasing the risk of sewer flooding due to the increased flow potentially preventing flap gates from opening, causing flow to back up and flood into streets and homes.

5. CONCLUSIONS

This is the first long-term study on the quantification of urban creep and urban expansion, analysing how the rate of change in impervious area in a catchment is evolving over time. Research into the hydrologic effect of urban creep were also limited, with studies previously focusing upon small catchments or sewerage networks. This study contributes to the understanding around the trend of urban creep providing insight into how the rate is changing, highlighting the effects this has on the prediction of urban creep. It also shows the effect urban creep has upon an entire river catchment, providing a good understanding of how runoff volumes, response times and peak flows are impacted.

This research found that between 1945 and 2018, the Ouseburn catchment experienced a 120% increase in total impervious area, leaving 23% of the catchment covered by impervious surface. Forty-five percent of the increase in impervious area was attributed to urban creep alone, with the rest of the growth being attributed to urban expansion (i.e., roads and roofs). Overall, urban creep is increasing, but the rate of increase is slowing over time after experiencing a peak in the mid-90s till the early 2000s. This study indicates that several factors influence the rate of creep, with the magnitude varying depending upon area type and socio-demographic influences.

Curve Numbers were calculated for the Ouseburn catchment based on results from this study that showed an average ratio of impervious to pervious surface for different area types. The overall catchment CN exhibited a year-on-year increase, showing that the catchment is becoming less able to infiltrate rainfall during storm events which will lead to a larger amount of precipitation translating into surface runoff. It was noted that the yearly increase in the overall catchment CN is slowing with a current annual increase of 0.021.

The study found that as impervious surfaces increased the catchment lag time decreased, showing that the catchments with higher levels of impervious surface exhibit faster hydrologic response times. As lag time decreases, it was also noted that the time it takes for the river to return to normal base flow after a rainfall event decreases, concentrating flow volume within a shorter time window. Peak flow following a rainfall event was found to increase as the catchment became more pervious, with the peak flow of the typical design return period (1 in 30 years) seeing an increase of 40% from 1945 to 2018. It was also noted that there is only a 10% difference in peak flow between a 1 in 100 years storm event in 1945 and a 1 in 30 years event in 2018, highlighting the significant impact that the increase in impervious surfaces has had upon the catchment.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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