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http://researchonline.ljmu.ac.uk/2343/

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Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Abdellatif, M, Atherton, W, Alkhaddar, R and Osman, Y (2014) Application of the UKCP09 WG Outputs to Assess Performance of Combined Sewers System in a Changing Climate. JOURNAL OF HYDROLOGIC ENGINEERING, 20 (9). ISSN 1084-0699

Application of the UKCP09 WG outputs to assess performance of combined sewers system in a changing climate

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Abstract

In many parts of the world old sewer systems have been designed without consideration for change in climate, so probabilities and risks of sewer surcharge and flooding are elevated due to increase in extreme rainfall events as a consequence of global warming. The current paper is aiming to assess how the climate change on interannual to multidecadal timescale (2020s, 2050s, 2080s) will affect design standards of waste water networks due to the presumed increase in rainfall intensity and frequency in the Northwest of England area (selected site). Design storms have been analysed for future rainfall obtained from the UK Climate Projection version 2009 (UKCP09) weather generator, which was applied to the existing urban drainage system to check the level of service in winter and summer seasons. Two emission scenarios (SRES) have been adopted to simulate the greenhouse gas concentration; high scenario (A1FI) and low scenario (B1). Results indicate that the impact of increase in the deign storm of the system in winter lead to a potential of increase flood volume from manholes and intern basements at risk of flooding with the worst condition associated with 24 hours storm in 2080s. Moreover, when this design storm depth increased by only 15%, the corresponding flood volume increase by 40%, this indicates that the relation between the cause of flooding and its consequences is non-linear. Summer season has an opposite picture and flood volume is projected to decrease with the increase in the storm duration causing low risk. Considering climate change in this study caused most of urban drainage models runs to be very slow with some interruption in the simulation due to the inflation in some parameters, so cautious should be taken.

Keywords: Urban drainage, Climate change, Combined Sewer System, Storm water, InfoWorks CS, UKCP09 WG

Introduction

Since the 1970s, average global temperature over land has increased by almost 0.7ºC. The Intergovernmental Panel on Climate Change (IPCC) projects a further rise of between 1ºC and 6ºC by the end of this Century IPCC, 2007). In recent years, on a local scale, the UK annual temperature has been generally between 0.5ºC and 0.7ºC warmer than the 1961-1990 average (Jenkins et al., 2009a). Moreover, most global climate modelling studies consistently suggest that increasing in the frequency and intensity of heavy precipitation are likely under enhanced greenhouse conditions (Tebaldi, 2006; Meehl, 2007) , even in regions that may experience a reduction in mean precipitation (Frei et al., 2006).

In the UK, large parts of the sewerage systems are combined systems, in which storm and sanitary flows are collected in one pipe. This accounts for 70% by total length of existing systems (Butler and Davies, 2004) and were designed to cope with weather conditions of a specific area. The age of the system The age of the system can vary and in some parts, it can be very old, more than 150 years as in London and Manchester and replacement/renewal rates are very low (Tait et al., 2008).

This means that the existing urban drainage systems have been designed for past climate conditions and may not be suitable for the situation occurring today or in the future. Currently, urban flooding due to failure in management of flood water by drainage systems is estimated to cost around £270 million a year in England and Wales; 80,000 homes are at risk (Parliamentary Office, 2008). The urban flooding impacts are expected to increase if no policy changes are made. Accordingly, the future design of urban drainage facilities needs to take into consideration impacts of climate change if the potential for flooding is to be addressed.

To assess the impact of potential climate change upon flood magnitude on urban drainage system, the output from climate models (which simulate the climate variables under different greenhouse emissions) must be converted to scales that are appropriate for input to those urban drainage catchments. The process of enhancing the spatial and temporal resolution of climate model outputs is commonly referred to as downscaling (Chandler et al., 2007).

There are numerous studies that have investigated the impact of climate change on urban flooding in the UK. However, most studies were focused on the impacts from rivers and coastal sources, as they are the most apparent and catastrophic in nature. A study by Houston et al., (2011) assess the future risk from ‘pluvial’ flooding – surface water accumulating from the result of intense rainfall in UK. They found almost 2 million people in urban areas face annual 0.5% probability of pluvial flooding. Most studies involving climate models report increased risk of flooding under a changed climate (Wilby et al., 2008; Kay and Jones, 2012; Ramsbottom et al., 2012). The latter typically apply one of two approaches: infer future flooding from changes in extreme precipitation (pluvial risks); or downscale climate scenarios to river basins for continuous river flow simulation and/or frequency estimation (fluvial risks). Fluvial studies show mixed results as a consequence of complex interactions between regional climate change signatures and local variations in catchment properties. Until relatively recently most fluvial flood risk assessments were based on a small number of catchments so generalizing to other sites was problematic. However, the Foresight Flood and Coastal Defence

Project (Evans, 2004), Defra's Regionalised Impacts of Climate Change on Flood Flows (Reynard et al., 2009; Prudhomme et al., 2010 a; b), the UK's first Climate Change Risk Assessment – Floods Sector Report (Ramsbottom et al., 2012), and Climate change – is the UK preparing for flooding and water scarcity? (ASC, 2012) have shaped national perspectives on flooding under climate change.

Few studies in the UK considered the urban flooding on combined sewer systems and most of these impact studies used projection of climate models. One of the recent studies, which did consider flooding on sewerage systems in England and Wales, was the work carried out by the UK Water Industry Research (UKWIR, 2011). They provide guidance to UK sewerage modellers on how to take account of climate change impacts when designing sewer systems or assessing performance of a sewer network model.

Some other notable climate change impact studies concerned with sewer systems carried out recently in the UK are briefly reviewed here. Hall et al. (2004) used outcomes of the UK Climate Impact Programmes, 2002 (UKCIP02), which assessed the risk of urban flooding in general, including sewers flooding as a result of different drivers including climate change. They found that climate change would be the main driver in changes in flood frequency. Tait et al. (2008) undertook a literature review about the current state and future of sewer systems to define the most important factors for the future of such systems. The study utilised the Drivers-Pressures-State-Impact-Response (DPSIR) approach, developed by the European Environment Agency (EEA) coupled with four socio-economic scenarios apparent in the UK. The DSPSIR approach reviews the current and future drivers for change, the resultant pressures and impacts and highlighted where there might be significant impact on sewer system performance. DSPSIR was used in the Foresight Future Flooding project in the UK (Evans, 2004). Other UKWIR studies include studies (UKWIR, 2003) to assess wastewater system performance as a result of climate change and (Ashley, 2006) in which the state and future pressure on sewer system planning, design, operation and maintenance in the UK up to 2020 and from 2020 to 2080 were studied. Moreover, Ryu et al. (2007) developed a model to quantify flood risk from sewers based on long-term continuous rainfall input using statistical analysis of the flow series. The model was developed under the assumptions that there is only one node in the flood catchment and the node is at the lowest level of the area. The model currently under development is to include more realistic features.

Moreover, there are intensive applications of hydroinformatic techniques in the literature eg., using Artificial Neural Network for simulation of groundwater aquifer (Taormina et al., 2012); modelling stream flow using data-driven models coupled with data processing techniques (Wu et al., 2009); long term prediction of reservoir discharges in with Artificial Neural Network (Cheng, 2005); Intelligent manipulation and calibration of parameters for hydrological models (Chen et al., 2006); Neural network and genetic programming for modelling coastal algal blooms (Muttil et al., 2006) and A split-step particle swarm optimization algorithm in river stage forecasting (Chau, 2007).

The study described in the present paper seeks to contribute to this important and timely area of research and tries to answer some questions relating to climate change impact on the risk of hydrological extremes on urban drainage systems for both short and long terms (to which extend climate change impact on extreme events and what potential risk to the buildings). It uses rainfall outputs of the weather generator developed by the UKCP09 project (the latest version of UKCP) and introduces a new methodology to assess potential risks of climate change on urban drainage systems. The potential risks of climate change are demonstrated by selecting the Windermere drainage area, situated in the Lakes District of North-western England, as case study. Results from the study can be used as warning signs for potential risks from climate change associated with urban drainage systems and can provide guidelines for good management of the systems until the end of 21st century. Some challenges were countered during running Infowork CS software which used for modelling urban drainage system, as it is not considered the inflation of some hydrological parameters due to climate change, so it important for users to be cautious and software developer to revise Infowork CS to make the models to be run more smoothly.

The novelty of this research and contribution to knowledge can be summarised mainly in the application of UKCP09 WG on Windermere catchment in North West of England and the risk methodology using GIS introduced in this work is additional contribution to existing knowledge, as most existing impact studies focus on the assessment of flood volume only without considering the risk to the properties for long future. There is another attempt by same authors (Abdellatif, 2012) to study the impact of climate change on extremes rainfall event on same location however it was using a deterministic model which is a combination of Generalised linear model and ANN while this one use the stochastic Weather Generator. Although each method is different in the structure but they are both indicating to climate change (wet winter and dry summer) with some disagree in the rate of increase or decrease.

Windermere combined sewers network model

This study used the Windermere drainage area, in North West of England, as case study to demonstrate the potential impacts of climate change in this sector of hydrological systems. The InfoWorks CS model of the catchment was obtained from United Utilities Plc. (the water company which owns the assets in the region) for this purpose. InfoWorks CS Software from Innovyse Ltd is the standard software used by United Utilities and all UK water companies to model sewer networks systems. The Windermere drainage area is located in Cumbria in North West of England (see Figure 1). It covers an area of 425 hectares and has a residential population of 10,930. The InfoWorks CS model of the area contains 173 sub-catchments and a total number of 633 pipes, which connect 655 manholes and 4 outfalls. The main receiving water for effluent from the treatment works and spills from combined sewers overflows (CSOs) in the drainage area is Lake Windermere. The drainage network serves two main (and adjacent) settlements of Windermere and Bowness-on-Windermere together with small localised areas. In the Windermere area, the larger developments were judged to be redevelopments in existing developed areas and would contribute little additional area to the wastewater network United Utilities (2010).

Methodology

The methodology used to assess potential flood risk from climate change in future is described briefly in this section. This includes derivation of future rainfall using the UKCP09 weather generator Ltd to assess potential flood risk due to sewer surcharges.

UKCP09 WG

There are different downscaling methods in the literature used for projecting future rainfall such as dynamical downscale which (DD) which consider the physical relationship of the climate system. The main disadvantages of DD are that it requires significant computing resources, (Harun et al., 2008), imperfect modelling and numerical stability are also plaguing DD (e.g. Lenderink and van Meijgaard, 2008; Maraun et al., 2010). Weather typing and regression methods are also used as they are easy to apply however don't account for uncertainty of future projection (they generate one ensemble of projected rainfall). The main advantage of Stochastic Weather Generator employed in this study is that it can exactly reproduce many observed climate statistics and enable the efficient production of a large ensemble of scenarios for risk analysis(so uncertainty in climate systems have been considered) (Wilby et al., 2002).

Prediction of future rainfall is based on work carried out by the United Kingdom Climate Projection 2009 programme (UKCP09) which utilises the IPCC Special Report on Emissions Scenarios (SRES) and a weather generator to generate rainfall in the UK different regions based on the observed rainfall characteristics in each region or location. The IPCC emission scenarios have been developed based on different views of how the world might develop over the coming years.

UKCP09 is the fifth generation of climate information for the UK and is the most comprehensive package produced to date. It should supersede the projections from the UK projections 2002 (UKCP02), although many of the projected changes are of broadly similar nature. However, UKCP09 incorporates scientific advances that could have significant implications for the specifics of the projected climate change (UKCIP and Scottish Climate Change Impacts Partnership-SCCIP, 2009).

The UKCP09 gives probabilistic projections for a number of atmospheric variables with different temporal and spatial averaging, by utilising several future time periods with three future scenarios (Jenkins et al., 2009b). The future scenarios included in the UKCP09 are low, medium and high emissions scenarios which correspond to the IPCC's SRES B1, A1B and A1FI (IPCC, 2000).
Impact assessments of climate change on hydrologic systems often requires more detailed temporal and spatial rainfall than that which is provided by the UKCP09 (a grid of 25kmX25km). Outputs from the weather generator (the statistical downscaling tool used by the UKCP09) are better suited for the purposes of impacts assessment at these finer resolutions, as it provides daily and hourly rainfall at spatial resolutions of 5km x 5km.

The UKCP09 weather generator simulates a minimum of 100 rainfall series and up to 10,000, which allows full exploration for the range of uncertainty in the sampled data (Defra, 2009). These rainfall series can be downloaded from the Graphical User Interface on the Website of UKCP09. The series can be obtained for daily or hourly time scales with realistic extremes for present and future conditions for any location in the UK. The weather generator must be run for both the weather generator baseline climate (1961-1990) and for the future climate that consistent with (and using the same 30 year time periods as) the UKCP09 probabilistic climate projections themselves (Defra, 2009).

For the purpose of this study, potential climate impacts due to increased rainfall are discussed within three timeframes: the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099) under the high (A1FI) and low (B1) emission scenarios of HadCM3. Therefore, the rainfall time series corresponding to these timeframes and the location of the case study have been downloaded from the UKCP09 Website for winter and summer seasons. The observed rainfall time series, for the period 1961-1990, at the Windermere case study area (which was obtained from the Environment Agency) is used to represent the baseline climate.

Flood Risk Assessment Methodology

A specific methodology to assess potential flood risk from increased rainfall for a drainage area served by combined sewer systems has been used. The methodology assesses potential risk of flooding to properties in the area based on increase in sewer surcharge levels and surface flooding from manholes in the network system and the subsequent overland flow. It combines model run results from a 1D and 2D InfoWorks CS models of the drainage network with a ground model of the catchment and a MapInfo Geographical Information System (GIS) layer of the properties in the catchment; to calculate the potential flood risk. Specialist software (Data Manager) was the platform used to carry out all the tasks required to assess flood risk in the combined sewer network system. InfoWork CS is a popular software in the industry for modelling sewers network although there are others software such as MOUSE and SWMM, however InfoWork CS is the standard package used for modelling sewers in UK. It give more feature and compactable with the other software that has been used for modelling the overland flow.

Flood risk assessment due to sewer surcharge is assessed based on a comparison between the predicted top water level in the nearest assigned sewer and the individual property levels. In the present study, only potential flood risk to properties from increased sewer surcharge due to climate change is assessed. It is categorised as **VHI** (very high impact) when water level is greater than 200mm above the property level and as **MI** (medium impact) if it is less than 200mm.

Dry Weather Flow and Design Rainfall Used

Dry Weather Flow (DWF)

Combined sewer systems in urban areas are built to collect and transport foul flow (Dry Weather Flow) and storm runoff in the area to the treatment works and combined sewer overflow discharge points. The main constituents of DWF are population generated flows from residential properties within the network, trade and commercial flows together with infiltration from groundwater into the sewerage system networks.

For purposes of this study, the Windermere combined sewer model used a population generated flow of (123 l/h/d) which is based on the consumption; a total trade and commercial flow of 0.84l/s, and an infiltration flow of 20.39 l/s for winter and summer, which are measured and recorded on daily basis then average of each were considered in the model.

Design Rainfall

Design rainfalls or the rainfall extremes for certain return periods used were obtained from frequency analysis of the downscaled future rainfall from the UKCP09 weather generator for 100 ensembles employing peak over threshold method to check the level of serves (flooding) of the urban drainage system. The nominal distribution associated with the peak-over-threshold model is the Generalised Pareto Distribution (GPD) introduced by Pickands, (1975). The cumulative distributions function, $F(x)$, of the GPD, where $k \neq 0$ is given as

$$F(x) = 1 - \left(1 + \frac{k}{\sigma}(x-u)\right)^{-\frac{1}{k}} \tag{1}$$

where x is the random variable, $x > u$

u = a threshold

k = shape parameter (also called tail index or extreme index)

σ = scale parameter

Thresholds are determined by taking the 10 percentile value of the rainfall series as initial estimate and then refined to obtain the optimum threshold base on parameter stability and residual plots (for more information see (Abdellatif, 2012). Parameters of the model have been estimated using the Maximum Likelihood Estimator (MLE) method with Quasi Newton iteration alogarithm. The following is the MLE of the GPD used:

$$LL(x;\sigma,k) = -n\log\sigma - (1+1/k)\sum_{i=1}^{n}\log(1+k(\frac{x_i - u}{\sigma})) \qquad (2)$$

The extreme quantile (X_T) or the design storm that is exceeded once every T years is solution of Equation 1. Rearranging, this can be written as:

$$X_T = u + \frac{\sigma}{k}\left[(\lambda T)^k - 1\right] \qquad (3)$$

With λ = m/n, with m being the number of exceedance variables over the threshold u; and n is the total number of years. The frequency analysis computer package extReme (Gilleland, 2005) is used to perform the frequency analysis.

The frequency analysis was carried on each series of extreme peak over threshold rainfall extracted from the 100 ensembles of the future periods (2020s, 2050s and 2080s) hourly rainfall series obtained from the UKCP09 Website (UKCP09, 2009). For each run of the 100 ensembles rainfall series, the hourly and aggregated hourly rainfall data from weather generator winter and summer profiles design rainfall events were generated for a 5year event. Combinations of different durations (60, 120, 180, and 360, 480 and 1440 minutes) for the 5 years return period have been used in the frequency analysis.

The 100 5 year event quantiles calculated for each duration in the frequency analysis stage give an opportunity to assess uncertainty across the 100 ensembles. By carrying out the same analyses for the control weather generator runs (i.e. the baseline period), the percentage uplift between control and scenario data can be calculated and hence the impacts of climate change can subsequently be assessed. The use of frequency distribution allows the user to make a specific selection from the range of uplifts (UKWIR, 2011). In this paper, the uplift percentage for a 5 year event has been selected for a 10, 50 and 90 percentile to project performance of the Windermere combined sewer model in future.

The reason for choosing a 5 year event is justified within the UKCP09 Weather Generator (WG) guidance. As urban drainage systems requires input rainfall to be at finer resolution (hourly or less), this is beyond the stated aims of the WG. The WG guidance documents (Defra, 2009) clearly states this “with a suggestion that for daily rainfall resolution data, up to a 10 year return period should be considered reasonably reliable, but that for hourly rainfall resolution, a 5 year return period should be the upper limit for reliability”.

Generation of future runoff in InfoWorks CS

The transformation of a rainfall hyetograph into a surface runoff which enters the drainage system involves two principal parts. Firstly, losses due to antecedent conditions (surface wetness of catchment and in depth wetness of catchment), areal reduction factor and evapotranspiration are deducted from the rainfall. In the current study the Antecedent Rainfall depth from surface wetness was set to 99mm to eliminate initial losses. Evaporation was considered to be 1mm/day and 3mm/day for winter and summer, respectively.

Secondly, the resulting net rainfall is used to estimate the effective rainfall and then runoff using the percentage runoff coefficient (C or PR) estimated from flow volume or runoff models. A simplified, but commonly used approach, which is usually applied to produce the effective rainfall from initial rainfall intensity, can be expressed as follows (Butler and Davies, 2007):

$$i_e = C\, i_n \qquad (4)$$

i_e is effective rainfall intensity (mm/h)

i_n is rainfall intensity (mm/h)

InfoWorks CS incorporates numerous runoff models for estimating the runoff coefficient. Generally there are three models used in the UK wastewater network modelling industry and were applied in the current study (Butler and Davies, 2007). These are:

- **Wallingford Procedure (fixed PR) Runoff Model:** The Wallingford model is applicable to typical urban catchments in the UK. It uses a regression equation to predict the runoff depending on the percentage impermeability, the soil type and antecedent wetness of each sub-catchment. The model predicts total runoff from all surfaces in the sub-catchment, both pervious and impervious. Therefore this model should not be mixed with another model within one catchment. It is used to represent continuing losses with an initial losses model. In this model, runoff losses are assumed to be constant throughout a rainfall event and are defined by the relationship:

  $$\mathrm{PR} = 0.829\mathrm{PIMP} + 25.0\ \mathrm{SOIL} + 0.078\mathrm{UCWI} - 20.7 \qquad (5)$$

  Where:

PR is the percentage runoff

PIMP is the percentage impermeability

UCWI is the Urban Catchment Wetness Index and represents the antecedent wetness of the catchment for the runoff model. It can be obtained from Wallingford Procedure which provides a curve of UCWI for winter and summer against annual average rainfall (SAAR) in the region.

SOIL is soil index based on five classes of the soil.

- **New UK (variable PR) Runoff Model:** This model is applicable to all catchments with all surface types, but particularly those which show significant delayed response from pervious areas. It calculates the runoff from paved and permeable surfaces separately and calculates the increase in runoff during an event as the catchment wetness increases. Percentage runoff is calculated using:

$$\mathrm{PR} = \mathrm{IF} * \mathrm{PIMP} + (100 - \mathrm{IF} * \mathrm{PIMP}) * \mathrm{API}_{30}/\mathrm{PF} \qquad (6)$$

PR is Percentage Runoff

IF is Effective impervious area factor

PF is soil storage depth (mm) default value is 0.2 m.

API30 is Derived from net rainfall after subtraction of running depression storage

API_{30} is defined as a 30-day API with evapotranspiration and initial losses subtracted from rainfall and can be continuously updated during the storm. It is calculated as:

$$API_{30}=\sum_{n=1,30} (P-E)_n \, C_p^{n-0.5} \qquad (7)$$

where

n is number of days prior to the event

$(P-E)_n$ is Net Rainfall on day n

P_n is total rainfall depth on day n

E_n is Effective evaporation on day n

C_p is Decay factor depending on the soil index

- **Fixed Percentage Runoff Model:** This is applied to one surface type in the sub-catchment (impervious) with the percentage of rainfall that actually runs off into the system.

InfoWorks CS software is deterministic model so all the output is sensitive with the inputs values and model calibration.

Calibration of the Windermere InfoWorks CS model

In order to use the urban drainage flow model for climate impact assessment the assumption of stationary in the model parameters which were calibrated based on the present flow survey data, is considered. These parameters were used to simulate the drainage system under future climate. The impact of change on these parameters has no significant affect eg. population is expected to decrease and change in evaporation is very minimal to be considered due to location of Windermere in cold region .

The Windermere drainage model used in the present work has been calibrated and validated against flow survey data commissioned by United Utilities. The flow monitoring described in this section was undertaken in order to re-verify parts of the hydraulic model of Windermere catchment, during dry weather and storm conditions. It has been carried in different parts across the catchment between September 2005 to February 2006 as there is no new development added in the catchment; moreover, the population in the studied area is forecasted to decrease in the future. So there no appreciable change in the network that requires a flow survey which is very expensive to be carried out.

The model includes commercial discharge of less than 1 l/s which added to the model as an equivalent population. No significant trade flows to apply to the model. Also 20.39l/s infiltration was assigned to the model and a total population of 10,023 is considered. Three rainfall events were monitored, during the flow survey, which were selected based on the company guidelines. Moreover, three dry periods were also recorded by the monitors. The survey used 5 standard flow monitors and 7 rain-gauges distributed throughout the catchment.

Samples of the verification results, for the flow monitor at the link at an inflow point to the treatment works, are reproduced here to confirm suitability of the model for the purpose of this study. The two survey periods used to reproduce these results are a wet weather event for 808 minutes (Figure 2a) and dry period for 1 day (Figure 2b). In the graphs of Figures 2, the filled graphs represent observed rainfall (in blue) and observed discharge, velocity, and depth (in turquoise); whereas the solid yellow line represents the corresponding simulated discharge, velocity and depth. In the dry period the pattern of the depth, velocity and discharge tend to be similar as there was no rainfall event and only the DWF contributes to the simulated results unlike the wet event where the pattern is more erratic (see Figure 2b). Both verification plots show reasonable match for the depth, velocity and discharge in the link, an indication for good representation and performance of the model during the two events. However there was a slight underestimation in the velocity and hence in the flow during the wet event simulation (Figure 2a). The model is slightly conservative during surcharge conditions. But this is not excessive, and therefore fit for purpose of flood prediction. The overall verification results were accepted by United Utilities and the Windermere calibrated model is approved for use to simulate flow in the catchment and permitted for use in this study.

Results & Discussion

Frequency Analysis

Two practical approaches for extreme value statistics are available which are the block maxima models, based on the generalised extreme value (GEV) or other distributions and the peaks-over-threshold method, and conventionally based on the exponential or Generalised Pareto (GP) distribution. For block maxima only one value is selected per epoch, this reduces the data available for analysis, such that the underlying data set from which the epochal extremes are drawn must be long. Cook (1985) suggests at least 20 years of data for reliable results (20 extremes for analysis), and states that the method should not be employed with fewer than 10 years, this why POT was introduced to increase the number of cases for analysis.

For this study the peaks over threshold extreme series have been adopted and extracted and fitted to GPD using maximum likelihood estimator (MLE) approach. Examples of how good the combined POT-GPD approach fits the extreme rainfall, gauged here by the diagnostic tests, have been given in Figure 3 for winter and summer daily observed rainfall series in Windermere during the base period (1961-1990). The probability, quantile-quantile, return level and PDF diagnostic plots in this Figure have clearly demonstrated that extreme rainfalls are reasonably representative by the combined POT-GPD approach which is best choice for fitting the extremes.

Before using the UKCP09 WG to produce the projected future design storms and hence their impacts on urban drainage system, the ability of the WG to reproduce the present extremes needs to be validated. Rainfall time series from the UKCP09 WG control period (1961-1990) has been used to compute design storms for a range of return periods (2, 3, 5 and 10 years) and durations (60, 120, 180, 360, 480 and 1440 min) and compared to design storms computed from an observed daily rainfall series in the catchment for the same control period (1961-1990) for the validation purposes. The quantile of 10, 50 and 90 percentile estimates from the UKCP09 WG are used for comparison with those from the observed rainfall and results are presented in Figures 4-9. As can be observed in these comparative plots, quantile estimates from the observed rainfall generally falls within the 10 and 90 percentiles estimates of the UKCP09 WG is closely matches the 50 percentile estimates; though there is one case where design storm estimates from the observed rainfall falls outside the UKCP09 ranges. These comparative plots give confidence on the use of the UKCP09 WG estimates for obtaining future design storms for durations less than 1440min.

Figures 10 and 11 display comparative plots for percentage change in the future design storm relative to the base line design storm for the 10, 50 and 90 percentile estimates of a 5 year event for different durations. The plots show that for winter seasons an increase (of varying magnitude) in the percentage change of design storm magnitude is generally projected for all future design storms of different durations, with the same pattern of increase across the three percentile estimates, under both scenario emissions (this is attributed to the location of this station being in the wettest region in North-western England). For summer seasons, the picture is somewhat different. A general decrease (of varying magnitude) in the percentage change of design storm magnitude is projected for all future design storms of durations up to 360min, with the same pattern of increase across the three percentile estimates, under both emission scenarios. However, for storm durations greater than 360min, the picture is the opposite as an increase in the summer seasons percentage change of design storm magnitude is projected instead. Specifically, the percentage change increase or uplift, during future winter seasons, becomes pronounced with increase in the design storm duration and is projected to reach a value of 44% for a design storm of 1440min duration for a 90 percentile estimate in future period 2080s under emissions scenario

The plotted results in Figures 10 and 11 also show that for future summer seasons, the 10 percentile estimates are consistently associated with significant reduction in the design storms under both scenarios and is projected to reach up to 42% for a design storm of 60 min duration in future period 2080s under scenario A1FI.

These results also confirm that some agreement can be captured by the UKCP09 WG percentile estimates for the multi-ensemble design storm, but differences are there between the 10 and 90 percentiles estimates due to uncertainty in projection of future extremes rainfall. Therefore the 50 percentile estimate of the multi-ensemble design storm could be more appropriate to use when carrying out impact studies.

Future challenges for Urban Drainage Systems

Possible consequences caused by climate change in urban drainage systems include flooding (surface flooding), sewer surcharges which can cause internal flooding in house basements and additional spills from combined sewer overflows (CSOs). Three measures are used in this paper to represent the possible consequences: (1) number of flooding manholes and total volume of flood water spilling from the manholes; (2) number of surcharging sewers which have a pressure head above the top of the sewers (3) number of basements at risk of flooding.

In order to project a trend of possible consequences under different climate change scenarios, simulations for the high and the low emission scenarios for the three future periods are used to represent the near and distant future. The simulations are performed using seasonal (winter or summer) uplift or percentage change for the future design storm (which is obtained as ratio between the central estimate or 50 percentile design storm from the UKCP09 WG and the corresponding baseline design storm from the observed rainfall for period 1961-1990) as input to the InfoWorks CS model of Windermere drainage system. Each simulation is run for 7 days for the 5 years storm event for durations 60, 120, 180, 360, 480 and 1440min.

Damage from surface flooding actually depends on a combination of factors, including the depth of flooding, velocity of flood water, duration of flooding, sediment load and contamination of flood water [15]. Apart from the flood depth, few studies have considered the aforementioned factors in assessing damage from surface flooding, with no agreed method for reliable evolution to date. This mainly due to lack of relevant software that considers these entire factors when modelling the risk to properties (more efforts require in this area). Therefore, in the present study, flood depth and flood volume will only be used to assess the risk of surface flooding.

Figures 12 and 13 are representations of total flood volume from all manholes in the catchment, which includes stored flooding (which will return back to the system) or lost flooding, for different durations of 5 year storm event in the Windermere catchment. The flood volume is projected to increase significantly in the future with increase in the storm duration until it reaches a maximum value at one day duration in winter. In summer, the picture would be the opposite, as the flood volume is projected to decrease with the increase in the storm duration, which would in turn reduce the future risk from surface flooding in the summer.

The geographical distribution of flooding in the sewer system can vary from duration to duration or from one considered future period to another. The worst condition is projected to occur in the 2080s in winter for a storm of 1 day duration under scenario AFI (Figure 14). In this case, although the number of flooding manholes is projected to increase by only 26%, the corresponding flood volume from these manholes is significantly different from the baseline conditions. The total flood volume is increased by 40% when the design storm is projected to increase by only 15%. This indicates that the relation between the cause of flooding and its consequences is non-linear.

Figure 15 shows a longitudinal cross-section for sewers and manholes (for surface flooding locations in the catchment), where the water level or energy line (blue line) is above the ground level (the green line). The cross-sectional plot indicates that there is surcharge in the sewers as well as manhole surface flooding in the future for winter under scenario A1FI. The manholes in the long section, which are located in a significant area in the catchment surrounded with buildings, sustains considerable flood volume in the catchment amounts to 682.4m^3. This surface flood volume is more than 8% of that of the corresponding flood volume from the same manhole during the base period (1961-1990) for the same storm duration.

The increase in design storm intensity in winter, under the high and low emission scenarios, indicates that there might be more damage to properties due to expected sewers surcharge. Results in Table 1 show that the number of surcharged sewers and basements at risk of flooding in winter increases in the future. The worst condition is associated with storm of 60min duration in the 2080s under the high emission scenario, as the number of basements at risk of flooding is projected to increase by 16% due to an increase of 35% in the design storm. In the summer, under both emission scenarios, the number of basements at risk is projected to decrease as presented in Table 2. A significant drop in the number of basements at risk of flooding of 26% is projected to occur under the high scenario in the 2080s when a storm of 60min duration is decreased by 42% (cf. Table).

Figure 16 shows the distribution of basement properties at risk of internal flooding in the catchment due to sewer surcharge, as posed by the future change in climate. It can be noticed in Figure 16 that the very high flood risk impact (VHI in red) is distributed across the catchment as the drainage system is a fully combined one.

Generally the results for climate change assessment show that an increase in the frequency of extreme rainfall depends on the return period, season of the year, the future period considered and the emission scenario under which it will occur.

Conclusions

The primary effect of climate change on existing drainage infrastructure is that magnitude of rainfall associated with flows that were used in the hydraulic design is no longer constant with respect to time, and it is projected to increase gradually over time. The consequences of this effect are a decrease in level of service for drainage infrastructure, increasing risk of surface flooding, environmental damage resulting from channel destabilization, greater deterioration of sewers due to more frequent surcharging, poorer water quality in rivers due to extra CSO spills, and reduced base flows in summer.

From the results and analysis presented in this paper, it has been demonstrated that climate change (driven by the current global warming) is projected to have significant consequences and impacts on the Windermere sewers network system. In future winters, the severity of the impact is increase with increase in storm duration in terms of flood risk due to sewers surcharge and surface flooding. Conversely, in future summers, the risk of flooding is generally projected to decrease. The results also indicate that increase in future seasonal flood risk consequences, in terms of basement flooding, is not that significant compared to the percentage increase in the design storm (i.e. the relation is non-linear). This is clearly demonstrated by the winter results in Table 1, when the design storm is projected to increase by 35% and only projected to cause an increase of around 16% (at worst) in the number basements at risk of flooding. This is in contrast to projected increase in surface flooding due to increase in design storm, as a percentage increase in the design storm as little as 15% is projected to cause and an increase of about 40% in the flood volume.

As a final note, there are a lot of uncertainties associated with findings of climate impact studies in general. However, this does not mean that they are not totally un-useful. Therefore, the findings of the present study can be used by planning authorities and water companies as indicator to what can be expected in the future if proper storm water management is not followed. Although this study assessed the uncertainty using the ensamples of projected future rainfall, however only one GCM (HadCM3) has been employed, so more assessment for the issue of uncertainty can be quantified by using multiple GCMs to provide reliable hydrological projections. Moreover, soil moisture deficit and soil storage depth values in the Wallingford and New UK runoff equations should be changed with the global warming in the future. However, due to the location of the study area, these values have been taken in the future as in the present. So, for better assessment of climate change impacts, changes in values of these two parameters with time should be considered by developing a model to project their future values if the application of WG in a warm weather. Moreover, it is recommended to compare the results with more different methods of downscaling rainfall and asses the quality of the various methods to address the inherent uncertainty in the downscaling approaches and hence it would provide robust assessment tool for water management.

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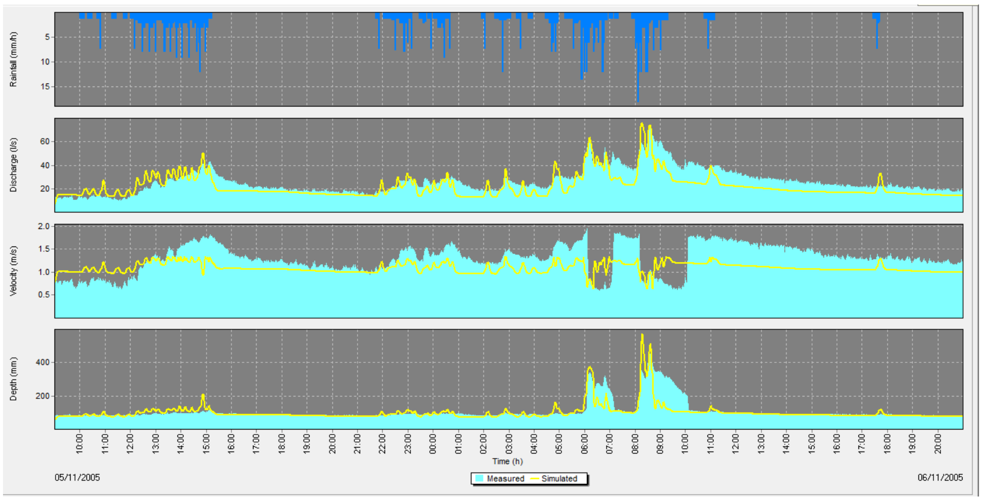
Table 1. Number of surcharged sewers and basements at risk of flooding in future due to surcharged sewers in winter seasons for a 5 year storm event

Duration (minutes)		Surcharged sewers (high scenario)			Surcharged sewers (Low scenario)				Basements at risk (high scenario)			Basements at risk (Low scenario)		
	Base period	20s	50s	80s	20s	50s	80s	Base period	20s	50s	80s	20s	50s	80s
60	189	195	200	216	196	198	200	414	428	454	480	437	446	460
120	187	186	188	204	188	189	195	366	372	405	442	376	389	415
180	184	186	189	199	188	190	189	360	360	376	387	363	363	377
360	183	188	188	196	191	188	189	357	363	364	375	363	364	370
480	176	181	186	189	185	181	185	363	368	363	365	362	362	365
1440	163	161	168	174	166	160	167	347	329	357	362	347	338	350

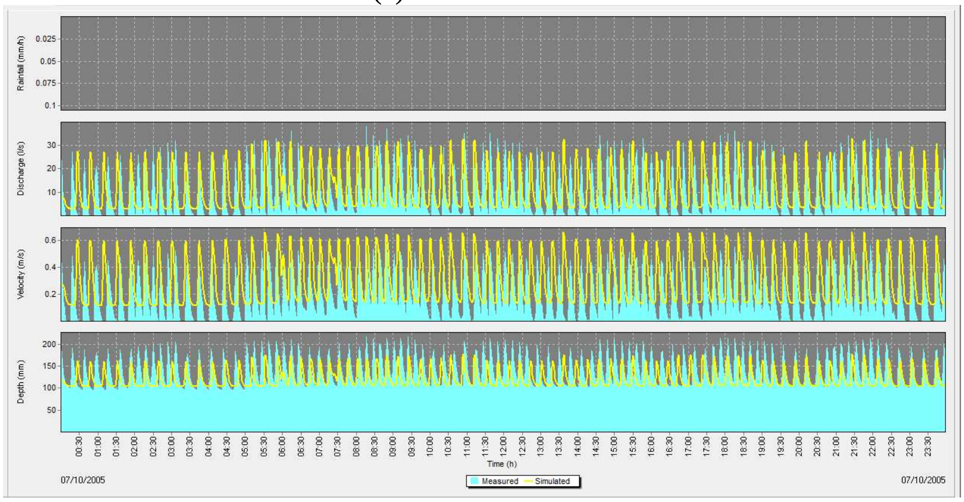
Table 2. Number of surcharged sewers and basements at risk of flooding in future due to surcharged sewers in summer seasons for a 5 year storm event

Duration (minutes)		Surcharged sewers (high scenario)			Surcharged sewers (Low scenario)				Basements at risk (high scenario)			Basements at risk (Low scenario)		
	Base period	20s	50s	80s	20s	50s	80s	Base period	20s	50s	80s	20s	50s	80s
60	193	195	182	160	191	181	173	457	427	389	338	439	395	366
120	199	182	174	165	182	181	174	436	383	354	339	386	365	351
180	190	177	175	170	179	178	175	404	352	346	343	352	352	344
360	188	176	175	168	175	177	176	362	343	342	341	343	352	342
480	182	175	177	167	175	177	177	363	342	353	342	346	353	351
1440	179	167	167	161	166	17	165	363	361	346	339	343	365	353

Fig1 Location of Windermere Drainage Area in the North West of England



(a) Wet weather event



(b) Dry weather event

Fig 2 Hydrograph comparisons for sewer flow model verification for a flow monitors in the Windermere catchment during rainfall event (a) and dry period (b)

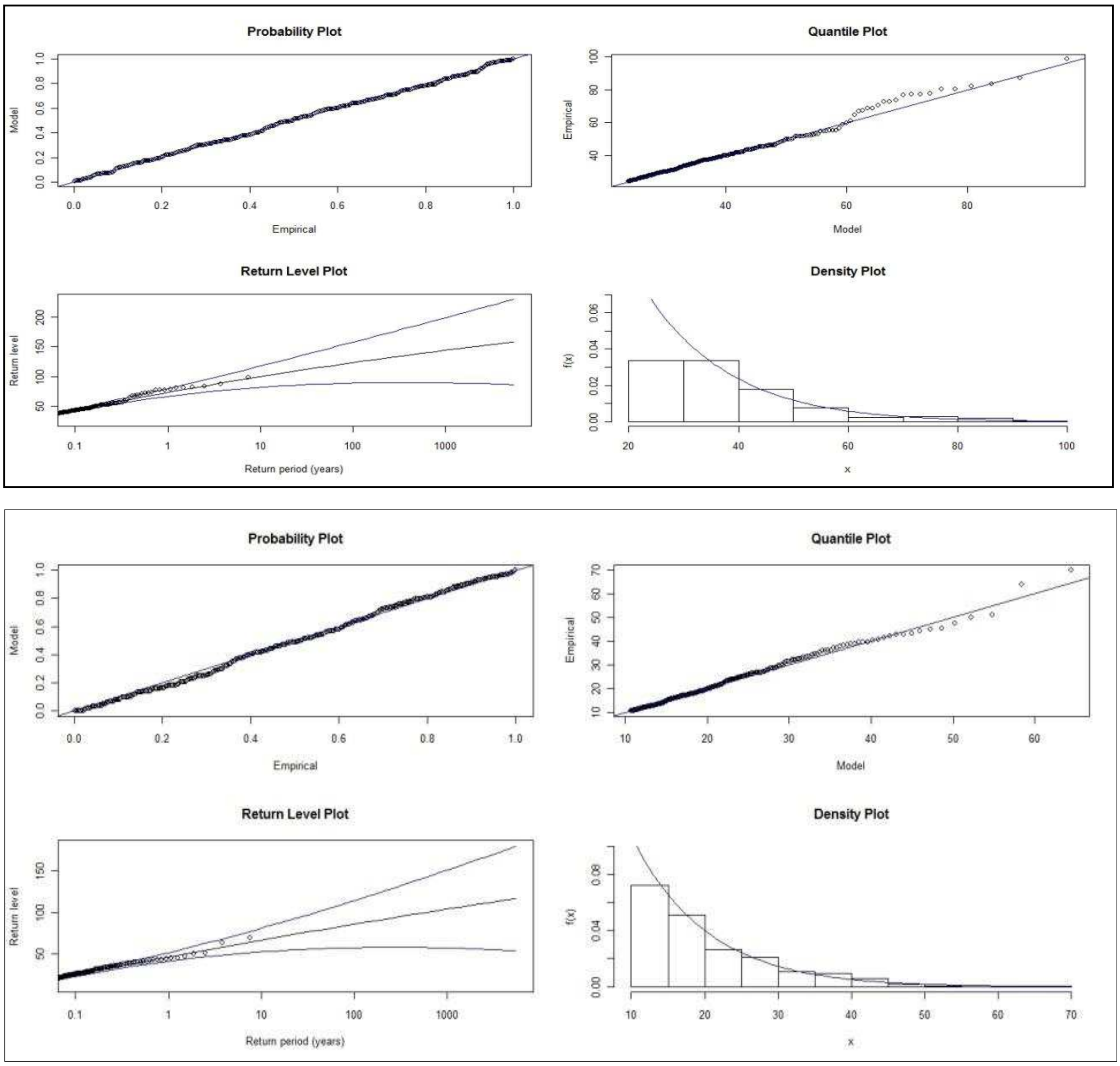
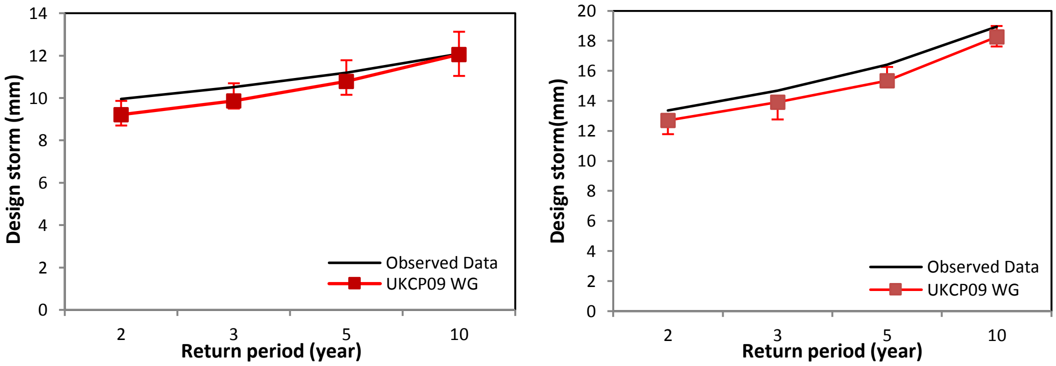
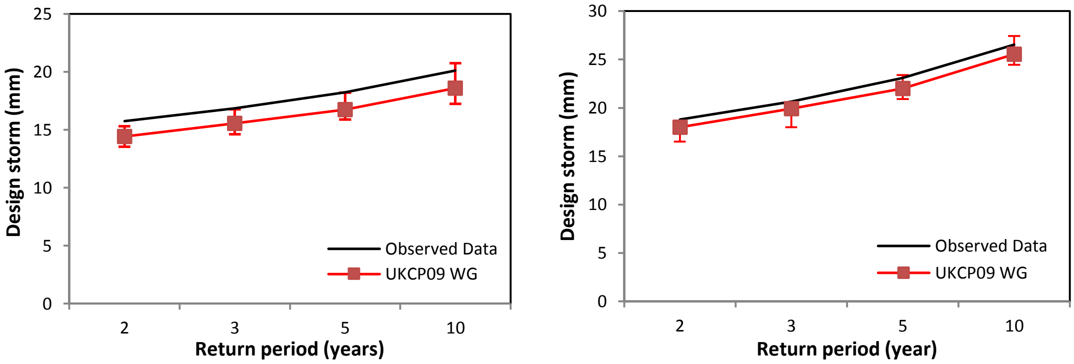


Fig 3 Diagnostic plots for goodness of fit of combined POT-GPD model for fitting the observed daily rainfall series in the baseline period for winter (top) and summer (bottom) control run



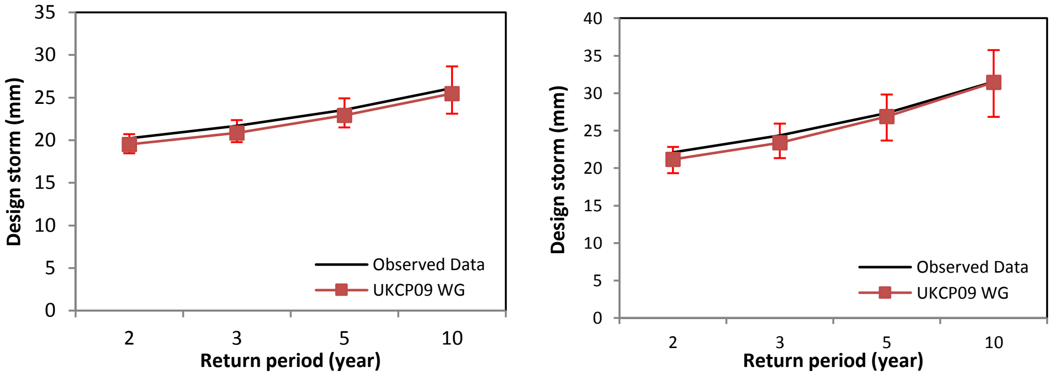
(Winter) (Summer)

Fig 4 Comparison of 60min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.



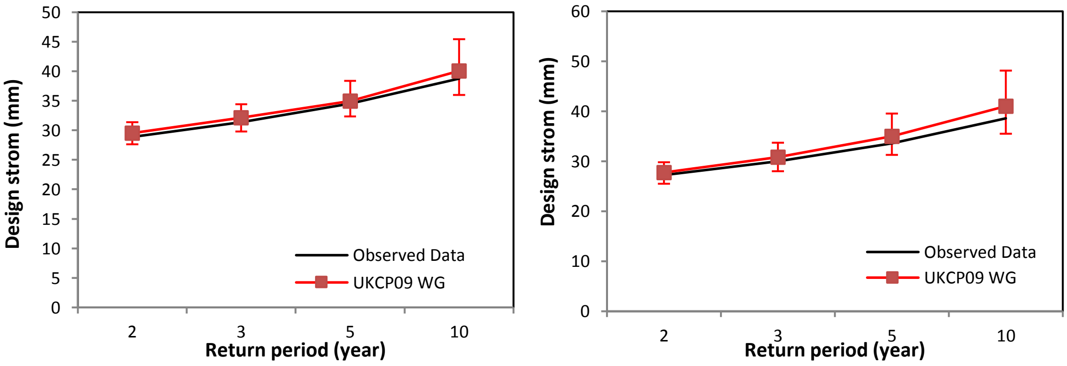
(Winter) (Summer)

Fig 5 Comparison of 120min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.



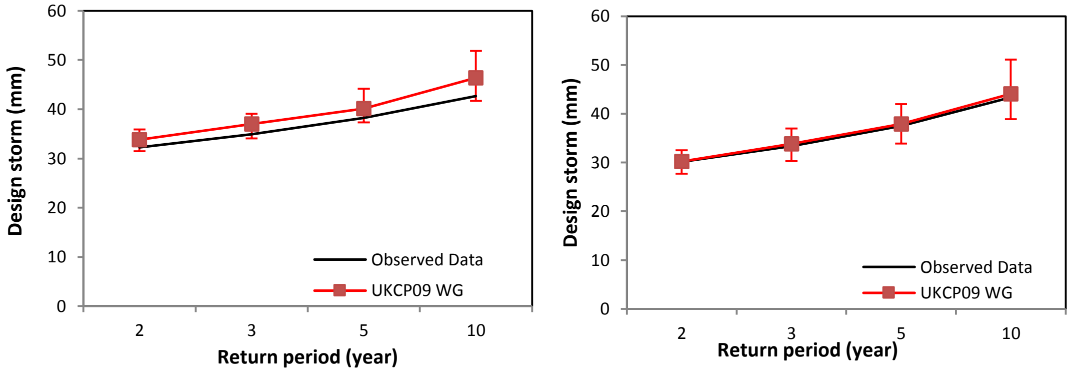
(Winter) (Summer)

Fig 6 Comparison of 180min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.



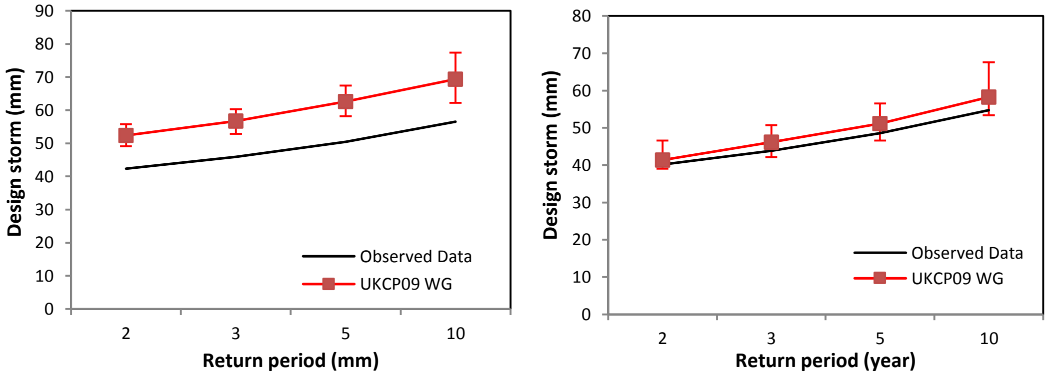
(Winter) (Summer)

Fig 7 Comparison of 360min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.



(Winter) (Summer)

Fig 8 Comparison of 480min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.



(Winter) (Summer)

Fig 9 Comparison of 1440min Design Storm from observed base period (1961-1990) and 50 percentile Design Storm from UKCP09 WG control run (1961-1990) in Windermere.10 and 90 percentiles Design Storms from UKCP09 WG are shown as error bars.

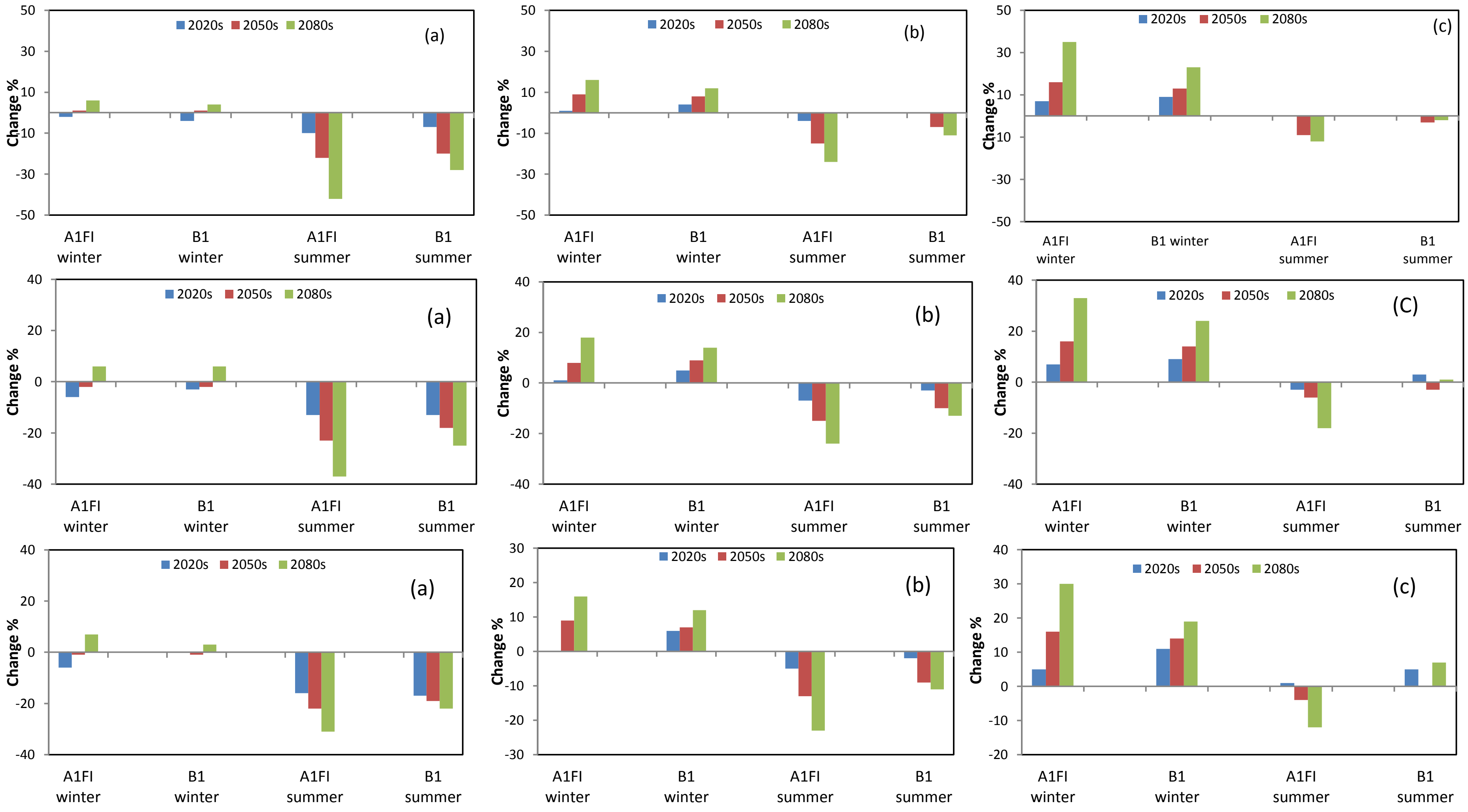


Fig 10 Percentage change of future 5 year event of duration 60 min (top), 120 min (middle) and 180 min (bottom) obtained from UKCP09 WG rainfall for (a) 10 (b) 50 (c) 90 percentile estimates in winter and summer under emission scenarios A1FI and B1

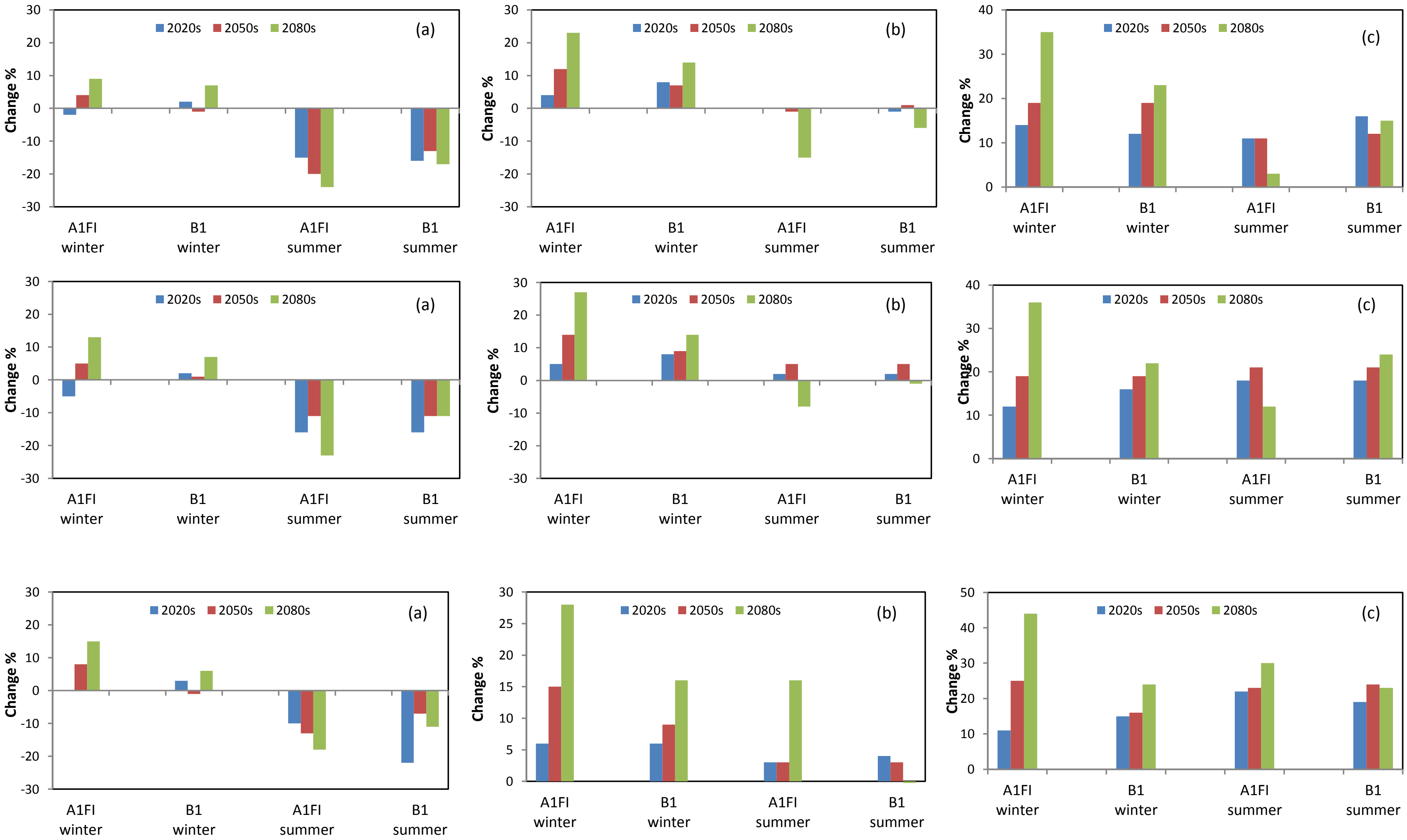


Fig 11 Percentage change of future 5 year event of duration 360 min (top), 480 min (middle) and 1440 min (bottom) obtained from UKCP09 WG rainfall for (a) 10 (b) 50 (c) 90 percentile estimates in winter and summer under emission scenarios A1FI and B1

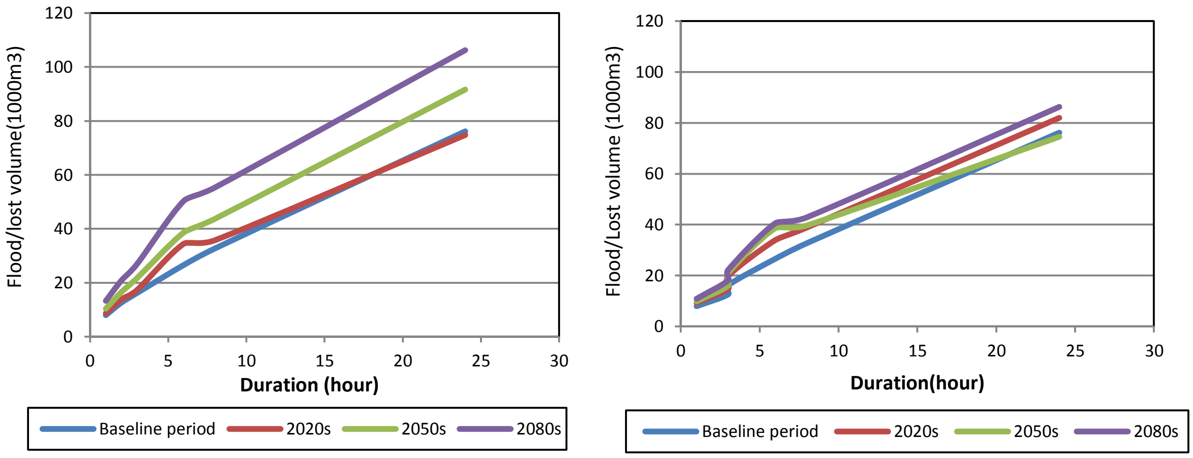


Fig. 12 Flood volume from manholes for different durations of 5year storm event in the future relative to present conditions in winter for high (left) and low (right) scenarios

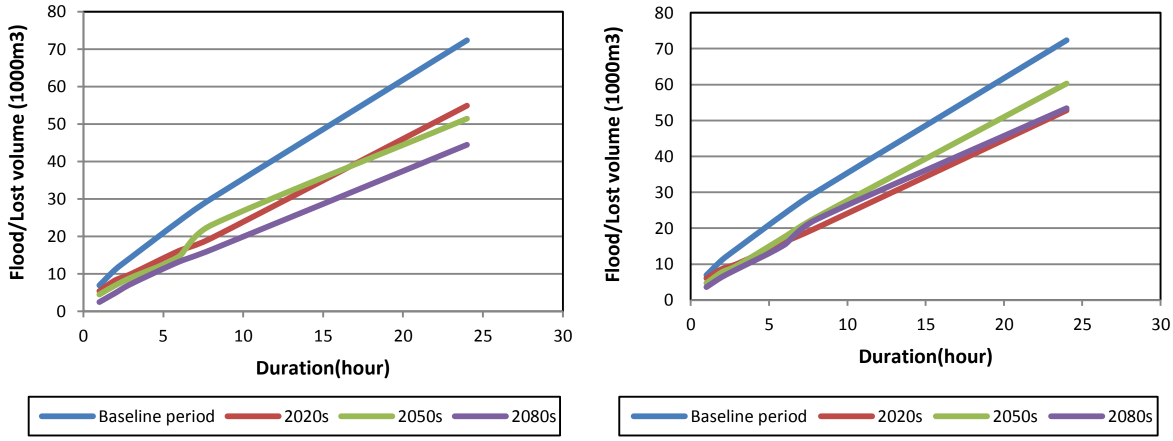


Fig. 13 Flood volume from manholes for different durations of 5year storm event in the future relative to present conditions in summer for high (left) and low (right) scenarios

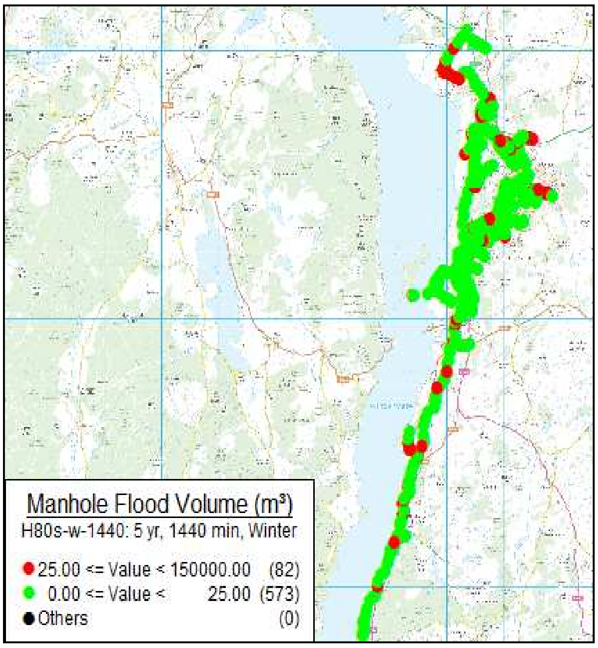


Fig.14 Location of manholes with different flood volumes in 2080s for high scenario for 5 year storm event of 1440 min duration

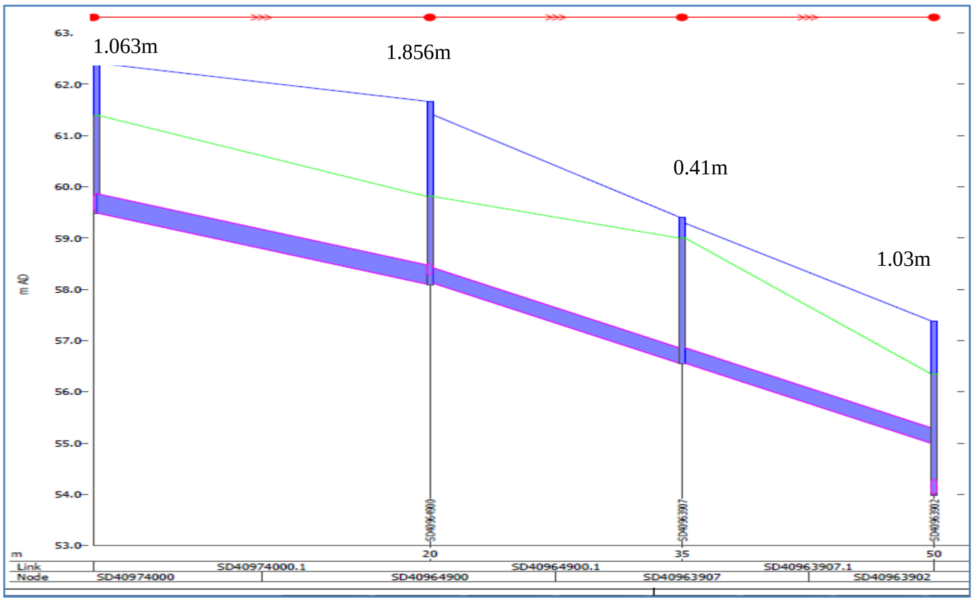


Fig. 15 Flood depth for selected manholes for event of 5y1440min of 50 percentile in winter of A1FI in 2080s

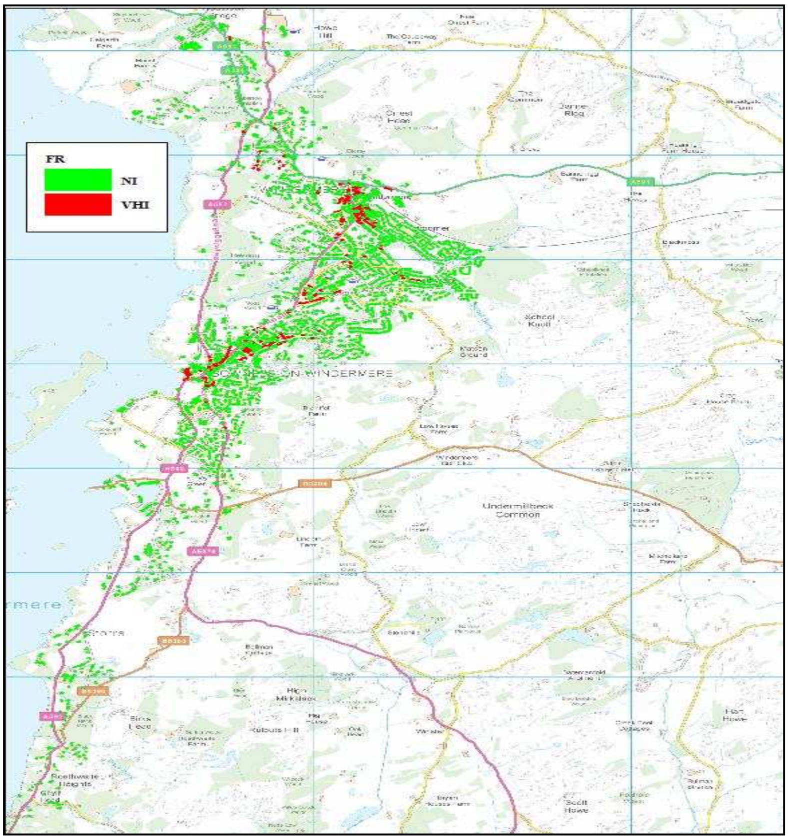


Fig. 16 Distribution of basements at risk of flooding due surcharged sewers for a 2080s winter 5 year storm event of 60min duration under scenario A1FI. Green indicates no impact and red indicates very high impact