QUICS: Quantifying Uncertainty in Integrated Catchment Studies

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Acronyms and Abbreviations

AARI	Areal Average Rainfall Intensity
IPCC	Intergovernmental Panel on Climate Change
KNMI	Dutch Meteorological Office (Koninklijk Nederlands Instituut Meteorologie)
RCP	Representative Concentration Pathway
TB	Tipping Bucket
UKCP09	UK Climate Predictions 2009
UK	United Kingdom

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Executive Summary

This report describes a brief overview of current predictions of the effect of climate change on precipitation. Although there is great regional variation on the predictions, there is a general consensus that there may be an increase in the occurrence of extreme events.

The current climate change predictions are generally made over large regions, and not urban scales. Downscaled predictions do exist, but they are generally still daily or hourly, and over several km^2 resolution. The wash-off of sediment from urban areas is a process that varies over small areas (e.g. streets, gardens, roofs, hence 10s and 100s meters) and over periods of minutes. Hence currently existing downscaled predictions of climate change are as yet not usable for prediction of effects of climate change on urban sediment wash-off.

Furthermore, questions remain in general about the relation between spatial and temporal variability of rainfall at urban scales (sub-km and minutes), sampling errors and uncertainty due to other sources, and uncertainty this may cause in simulating runoff and wash-off from urban areas.

Hence, to aid the study of potential effects of climate chance and localised high rainfall intensity peaks on urban sediment wash-off, this report described the effects of small scale rainfall variability on uncertainty in wash-off. A new dataset of uniquely high resolution rainfall (9 paired gauges over 200x400m at 1 minute resolution) was utilised, as well as an innovative set of laboratory wash-off experiments. The propagation of different sources of uncertainty, including rainfall uncertainty, in improved sediment wash-off modelling was investigated

Key findings were that: for a 400x200 m area, at 2 min temporal averaging interval the average coefficient of variation in the prediction of peak AARI is 6.6 % and the maximum coefficient of variation is 13 % and they are reduced to 1.5 % and 3.6 % respectively at 30 min averaging interval; and the maximum uncertainty in the prediction of peak wash-off load due to rainfall uncertainty within an 8-ha catchment was found to be ~15%.

CONTENTS

Executive Summary 3

1 Introduction 5

2 Predicted effects of climate change on precipitation 5

3 Relations between temporal and spatial rainfall variability, and importance for urban sediment wash-off 10

4 Impact of climate change and spatial rainfall variability on urban sediment wash-off processes 11

5 Conclusions 13

6 References 14

1 Introduction

Urban surface sediment is a major source of pollutants in the urban environment, mainly due to its ability to act as a transport medium for many contaminants (e.g. Brombach et al. 2005).

Climate change is generally accepted to influence rainfall patterns, but regional climate models only provide predictions of yearly or seasonally average precipitation patterns. There does appear to be a consensus on the expected increase of occurrence of extreme events (IPCC, 2014).

In order to estimate potential effects of climate change on urban sediment behaviour, climate predictions would need to be both spatially and temporally downscaled.

Recent studies on downscaling regional future precipitation scenario's provide future time series of daily or hourly precipitation, at several km^2 resolution (e.g. Met Office, 2012). Urban hydrological processes such as rainfall runoff and sediment wash-off, however, operate at sub-hourly and sub-kilometre spatio-temporal scales (e.g. Christiano et al., 2017).

Long-term historical precipitation records are often daily or at most hourly, with sub-hourly networks very limited and sub-km networks even more limited. Hence there have been very limited sub-hourly/sub kilometre precipitation records available for long-term trend analysis of rainfall or for testing of downscaling techniques.

It is furthermore known that at high temporal resolutions, the spatial correlation of rainfall reduces, (e.g. Villarini et al, 2008). Point measurements of rainfall have a limited spatial extent, hence for design purposed Areal Reduction Factors are generally used. However, these are generally for > 1km areas, those derived for <1km areas and timescales of 2-5 minutes are still based on very limited duration datasets (Svenson and Jones, 2010).

Questions thus still remain in general about the relation between spatial and temporal variability in rainfall, sampling errors and uncertainty in runoff and wash-off simulations on sub-kilometre urban street scales.

Hence, to aid the study of potential effects of climate chance and localised high rainfall intensity peaks on urban sediment wash-off, this report describes the effects of small scale rainfall variability on wash-off. A new dataset of uniquely high resolution rainfall (9 paired gauges over 200x400m at 1 minute resolution) was utilised.

2 Predicted effects of climate change on precipitation

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014), describes climate change predictions based on different scenarios (termed Representative Concentration Pathways, or RCPs). Figure 1 shows predicted regional changes in precipitation for the stringent mitigation scenario (RCP2.6), and the scenario with very high Green House Gas emissions (RCP8.5). Figure 1 indicated that predicted changes in precipitation will not be uniform, as quoted from IPCC (2014): 'The high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent.'

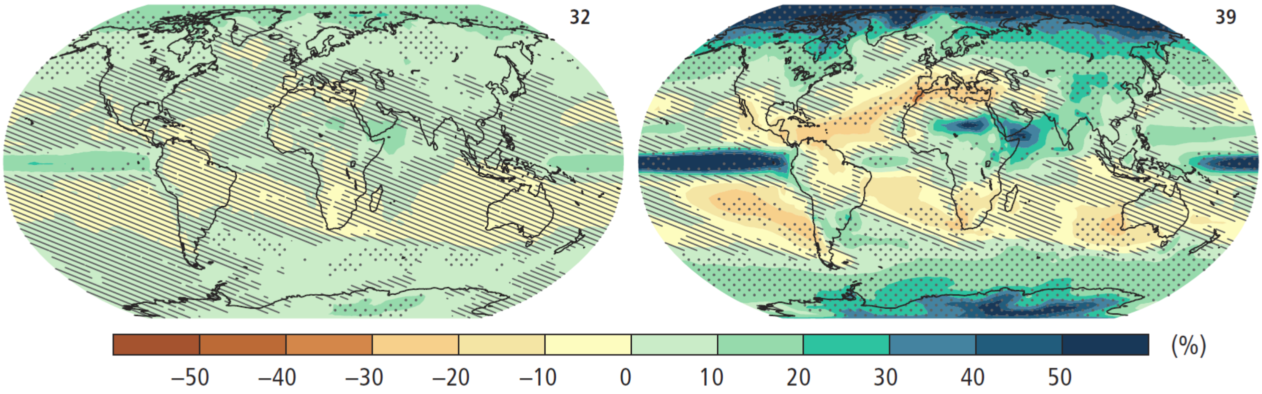

Figure 1. (Adapted from Figure SPM.7b in IPCC, 2014). Change in average precipitation based on multi-model mean projections for 2081-2100 relative to 1986-2005, following RCP2.6 scenario (left) and RCP8.5 scenario (right). Dotted areas indicate regions where projected change is large compared to natural internal variability and at least 90% of models agree on the sign of change, diagonally hatched areas show regions where projected change is less than 1 standard deviation of natural internal variability.

The IPCC (2014) predictions provide general indications of expected precipitation patterns, in order to translate these findings to urban sediment behaviour, more localised predictions would need to be studied.

Meteorological offices in different countries may provide more localised predictions of effects of climate change on precipitation. For example in the UK, the UK Met Office provides the UKCP09 climate predictions, which provides three prediction horizons (2020s, 2050s and 2080s), relative to the 1961-1990 period, for three scenarios (Low Emissions, Medium Emissions and High Emissions). For these scenarios and horizons, it provides UK Maps indicating %-age change in summer and winter mean precipitation, wettest day in winter and wettest day in summer, for a 10%, 50% and 90% probability level, for 25x25 km grid squares, see for example Figure 2.

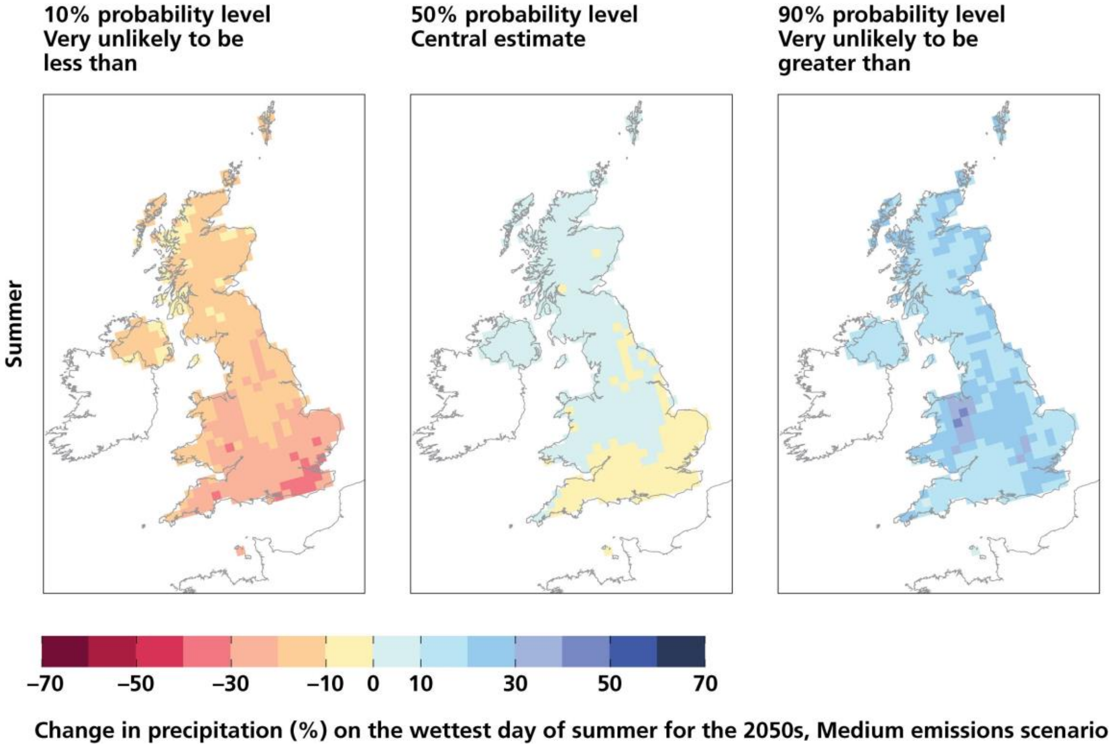

Figure 2. Figure from UKCP09, showing an example of the predicted change in summer precipitation, for the medium emissions scenario and 10%, 50% and 90% probability level.

Sanderson (2010) has used an 11 member ensemble of regional climate projections which was released alongside the UKCP09 climate projections to calculate the frequency (expressed as return period) of events with the same magnitude for the 2040s, 2060s and 2080s. This calculation was done for 40 towns and cities in the UK. The general conclusions are that all winter rainfall events are projected to become more frequent, but that there is no clear signal for the frequency of the summer rainfall events which could become either much less or much more frequent. There was also a wide variation in different UK regions, and for different return periods, see for example Fig 3.

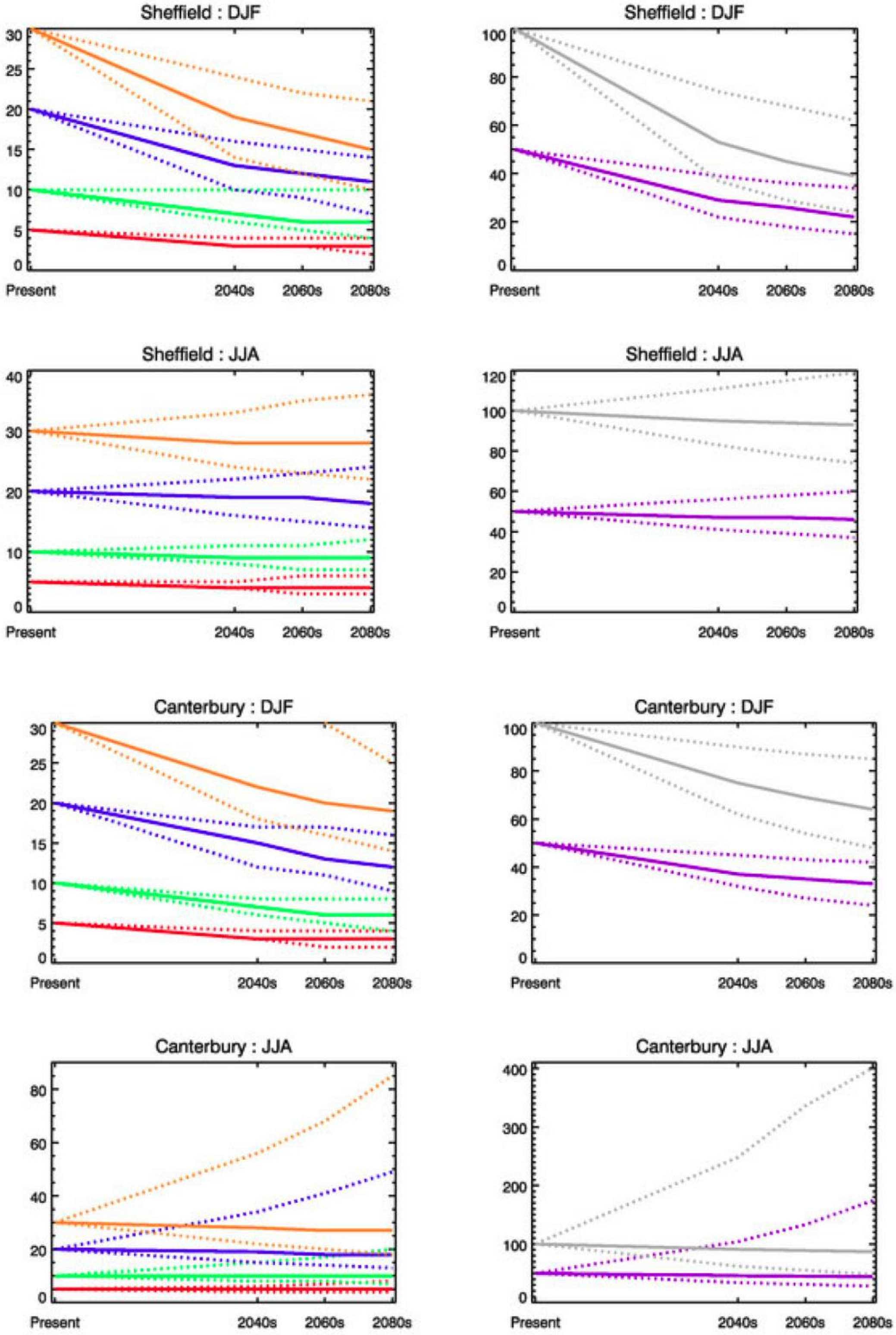

Figure 3. Figures from Sanderson (2010). Change in return period for rainfall events with present-day return periods of 1 in 5 (red), 1 in 10 (green), 1 in 20 (blue), 1 in 30 (orange) [left-hand panels] and 1 in 50 (purple) and 1 in 100 years (grey) [right-hand panels]. The return periods are shown on the y-axis. The central estimate (50th percentile) is indicated by a solid line, and the 10th and 90th percentiles, calculated using the full range of probabilistic projections from UKCP09, illustrate the possible range of return periods and are shown by dotted lines.

As another example, in the Netherlands the KNMI (the Dutch meteorological office) provides predictions for two 30 year periods (2036-2065 and 2071-2100) based on four scenarios (from medium to warn worldwide temperature increase, and from low to high change in air circulation patterns, in reference to the period of 1981-2010), (KNMI, 2014). Predictions on effects of climate change on precipitation are published on the KNMI website as average precipitation, or number of days per year with respectively 1, 10, 15, 20, 30 mm or more precipitation (e.g. Figure 4).

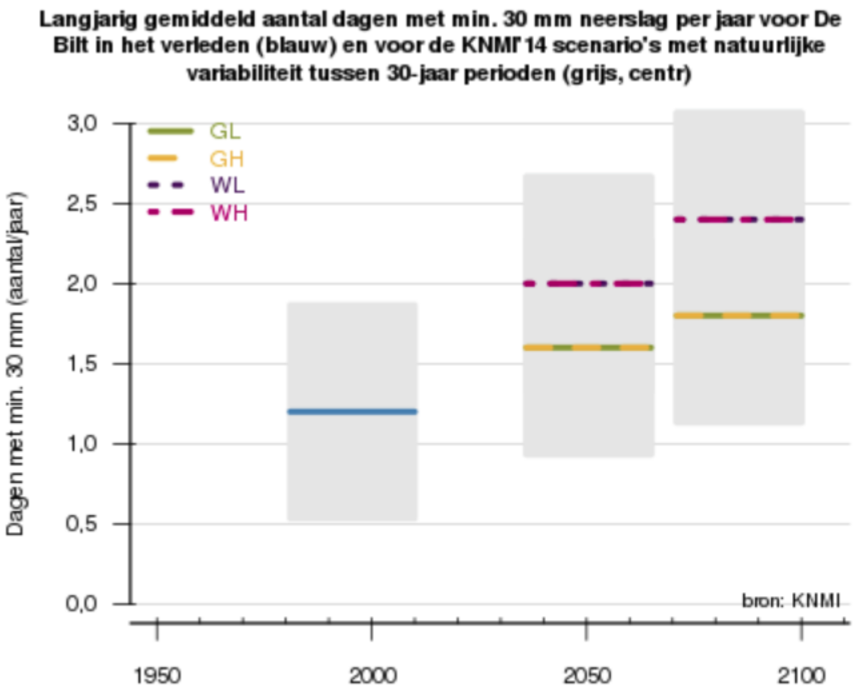

Figure 4. Long term average number of days with minimum 30 mm precipitation for De Bilt (The Netherlands) in blue, and for the KNMI (2014) scenarios including natural variability for 30-year periods (grey) (KNMI, 2014).

What these examples of 'local' predictions of effect of climate change on precipitation all have in common is that they only provide seasonal or daily predictions of rainfall; and that the term 'local' means either countries or regions of several 10s of square km.

Various methods exist for spatial and temporal downscaling of climate change predictions, as well as publically available software that provides downscaled climate change predictions. For example the UKCP09 Weather Generator (Met Office, 2012) provides plausible daily or hourly time series of weather data for future time periods.

However, hourly time series are still too course for the majority of urban drainage hydrological, hydraulic and water quality model studies, see e.g. Schellart et al. (2012) for a specific case study illustration, and Christiano et al. (2017) for a review of the effect of spatial and temporal variability of rainfall on hydrological response in urban areas.

Goore Bi et al. (2017) provide an overview of the state of knowledge and recent work on downscaling of rainfall data for climate change impact studies in urban areas. The validity of many of the methods described has, however, not yet been tested in urban areas and there is little published information available on their effectiveness at smaller (1-10km^2) scales.

Egger and Maurer (2015) describe a case study on the effects of anthropogenic climate change impact, sampling error and urban development in sewer system design. Amongst others, they concluded that more research is needed to describe the role of different uncertainties when predicting impact, such as investigation of the influence of precipitation measuring errors, spatial variability of precipitation and the structural uncertainty of the runoff-precipitation models.

3 Relations between temporal and spatial rainfall variability, and importance for urban sediment wash-off

Chiach and Krajewski (2006) and Villarini et al. (2008) both studied the spatial correlation of rainfall in the range of 500 m – 15km, showing a considerable reduction in spatial correlation of rainfall at smaller temporal integration scales (e.g 1, 5 and 15 minutes). See Fig. 5 for an example.

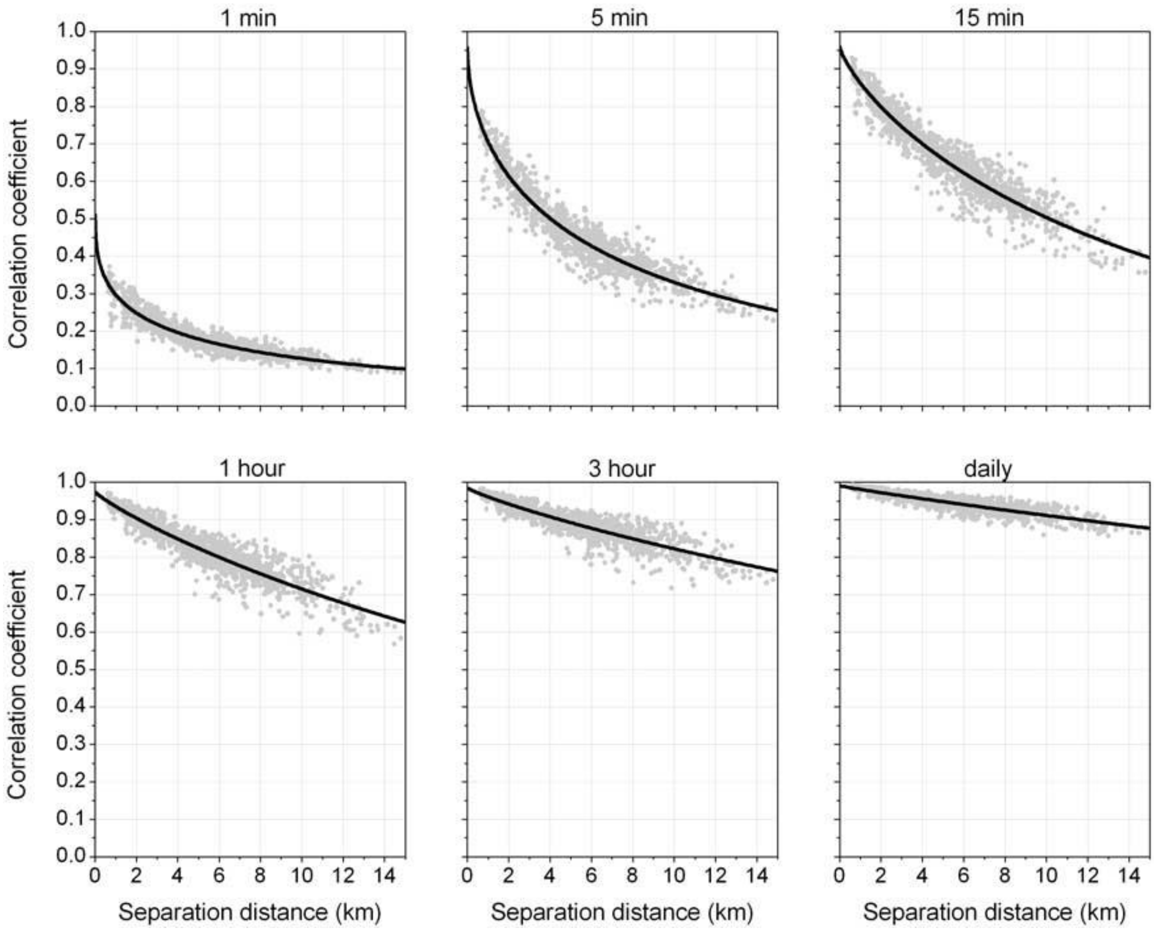

Figure 5. Figure from Villarini et al. (2008). Estimation of the spatial correlation for six accumulation times, based on more than six years of rain gauge data (from September 1993 to April 2000) from a dense network of 50 gauges deployed during the Hydrological Radar EXperiment (HYREX), within the 135 km^2 Brue basin in south-west England. The solid lines represent fitted exponential functions.

Several hydrological studies, as summarised by Christiano et al. (2017) describe urban drainage related processes occur on spatial scales of 0.01 and 1m and temporal scales of 10 to 1,000 seconds (approx. 17 minutes), and surface flow from 1 to 10,000m and 10 to 10,000 seconds (approx. 2 – 3 hours), Figure 6.

Urban areas have high spatial heterogeneity, and different types of urban sediments and associated pollutants can be washed-off from surfaces such as roofs, roads, pavements and green spaces, which are in the order of 10s – 100s of meters. Fabry et al. (1994) describes how rainfall spatial resolution needs to be smaller than the smallest runoff area component. However, rainfall data is generally not available at 10s or 100s of meters resolution in most places.

Interactions between rainfall variability, urban catchment heterogeneity, and hydrological response at multiple urban scales remains poorly understood; and uncertainty associated with rainfall spatial and temporal variability is one of the main sources of error in the simulation of hydrological processes in urban areas (Christiano et al. 2017).

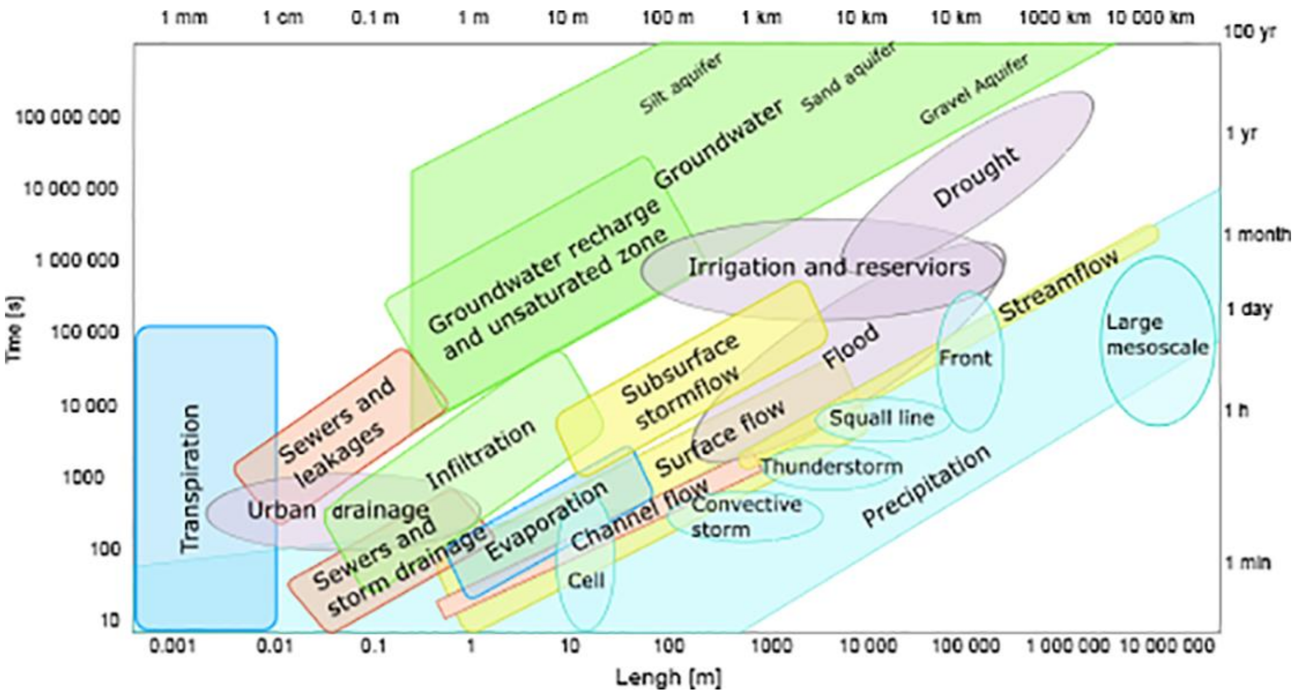

Figure 6. Figure by Christiano et al. 2017. Spatial and temporal scale variability of hydrological processes, adapted from Berndtsson and Niemczynowicz (1986), Blöschl and Sivapalan (1995), Stahl and Hisdal (2004), and Salvadore et al. (2015). The colours represent different groups of physical processes.

4 Impact of climate change and spatial rainfall variability on urban sediment wash-off processes

Given the overview described in Sections 2 and 3, questions remain as to how the impact of climate change on urban sediment wash-off processes can be best described.

Current downscaled climate change predictions are still too coarse both spatially and temporally, and even without the impact of climate change, questions remain as to what role small spatial and temporal variability of rainfall and sampling uncertainty plays in simulating urban sediment wash-off.

As part of the QUICS research therefore, the research of (Muthusamy, 2018) focussed on accounting for rainfall variability in sediment wash-off modelling using uncertainty propagation.

The aim of the first part of the study was to obtain a stochastic description of urban-scale spatial variability in rainfall in a way that can be used in lumped sediment wash-off models. Through literature review (Muthusamy, 2018), it was found that (1) uncertainty due to rainfall variability at a sub-kilometre scale is significant in the modelling of any hydrological process that is driven by rainfall and runoff such as sediment wash-off and (2) geostatistical methods, despite their challenging data requirements, can be modified and developed to study the spatial variability of rainfall. This is due to their capability to take into account the spatial correlation structure of rainfall data and their ability to provide quantification of uncertainty in upscaling. Taking into account these findings, a geostatistical method was developed to estimate the spatially averaged rainfall intensity together with the associated level of uncertainty (Muthusamy et al. 2017). High spatial resolution rainfall data collected from a cluster of eight paired rain gauges in a 400m × 200m urban catchment was used to develop this methodology. The spatial lag of the rain gauge network ranges from ~20 to ~400 m. As far as the authors are aware, this is the smallest spatial scale in which the variability in rainfall has been examined using high temporal resolution point rainfall measurements in urban hydrology. Unreliable data which were detected by making use of the paired rain gauge set up were omitted prior to geo-statistical analyses. Variogram, which is a widely accepted geo-statistical measure, was used to illustrate the spatial variability of rainfall for different combinations of the temporal averaging interval (2 min, 5 min, 15 min and 30 min) and different range of rainfall intensities (< 5 mm/h, 5-10 mm/hr and > 10 mm/h). As far as the authors are aware, this was the first time that geostatistical models such as variograms have been assigned to a combination of rainfall intensity ranges and temporal averaging intervals. These variograms were then used in spatial stochastic simulations to obtain spatially averaged rainfall intensities together with associated uncertainties for the same combinations. The two main challenges typically associated with rainfall data in an urban catchment addressed in this study were the scarcity of rainfall measurement locations and non-normality of rainfall data, both of which needed to be considered when adopting a geostatistical approach.

The results in Muthusamy et al. (2017) showed that (1) For small time and space scales the use of a single geostatistical model based on a single variogram is not appropriate and a distinction between rainfall intensity classes and length of temporal averaging intervals should be made, (2) At smaller temporal averaging intervals, the effect of both spatial variability and TB (Tipping Bucket rain gauge) error is high, resulting in higher uncertainty levels in the prediction of AARI (Areal average rainfall intensity). With increasing temporal averaging interval the uncertainty becomes smaller as the spatial correlation increases and the TB error reduces. At 2 min temporal averaging interval the average coefficient of variation in the prediction of peak AARI is 6.6 % and the maximum coefficient of variation is 13 % and they are reduced to 1.5 % and 3.6 % respectively at 30 min averaging interval.

A second aim was to improve the understanding of sediment wash-off from urban surfaces and to establish the correlation between calibration parameters and external drivers in the current wash-off model (Muthusamy et al. 2018). From the literature, it was understood that the current wash-off models still need to be improved in terms of representation of the interaction between the external drivers associated with rainfall, catchment surface and sediment characteristics. It was also noted that the current sediment wash-off model structure needs to be improved in order to be able to differentiate and quantify different sources of errors and their propagation, a feature that will be required when rainfall error propagation is investigated. Hence, before investigating the propagation of rainfall error quantified in the first part of the thesis, the widely used exponential wash-off model currently in practice was improved. Taking the research gaps identified through literature review into consideration, laboratory experiments were conducted to investigate the effect of three selected external drivers, rainfall intensity, surface slope and initial load on wash-off load, in an integrated and systematic way. The experimental set-up comprised of a rainfall simulator, a 1 m^2 bituminous road surface, and a continuous wash-off measuring system. Five rainfall intensities ranging from 33 to 155 mm/h, four slopes ranging from 2 to 16% and three initial loads ranging from 50 to 200 g/m^2 were selected based on values obtained from the literature. Fine sediment with a size range of 300–600 µm was used for all of the tests. As far as the authors are aware this was the first time where the effect of all the above three dominant parameters on wash-off load is investigated in an integrated and systematic way.

The results showed that the effect of initial load on wash-off fraction at any given time is negligible for most general combinations of rainfall intensity and surface slope. This essentially means that the washed off load at any given time is proportional to initial load for a given combination of a rainfall intensity and a surface slope. The negative-inverse-exponential trend due to the effect of the first flush was clearly observed at combinations of catchment slopes steeper than 8% and rainfall intensities higher than 75 mm/hr. It was also observed that a rainfall event has the capacity to mobilise only a fraction of sediment from the road surface and once it reaches that capacity wash-off becomes almost zero even though a significant fraction of sediment is still available on the surface. The maximum fraction that can be washed off from the surface increases with both rainfall intensity and the surface slope. Using the experimental results the original exponential equation which is still in practice was improved by establishing the correlation of two calibration parameters, capacity factor and wash-off coefficient, against rainfall intensity and catchment surface slope.

The final aim of the study was the propagation of different sources of uncertainty, including rainfall uncertainty, in sediment wash-off modelling (Muthusamy et al, *under review*). The level of uncertainty in predicted wash-off load due to rainfall uncertainty can be smaller, similar or higher than the rainfall uncertainty depending on the rainfall intensity range and the “first-flush” effect. The maximum uncertainty in the prediction of peak wash-off load due to rainfall uncertainty within an 8-ha catchment was found to be ~15%.

5 Conclusions

Although there are wide uncertainty bands and variations within regions, one general conclusion of climate change prediction literature is the possibility of more intense rainfall events.

Urban drainage processes and urban sediment wash-off processes tend to operate on sub-hourly and sub-kilometre scales, hence the currently existing climate change predictions and weather generators are not applicable for simulating impact of climate change on urban sediment wash-off.

Questions also remain in general about the relation between spatial and temporal variability in rainfall, sampling errors and uncertainty in runoff and wash-off simulations on urban street scales.

There is a distinct lack of long term datasets at a high spatial and temporal resolution, e.g. 1-5 minutes and sub-km scales. Therefore this deliverable focusses on accounting for uncertainty in sediment wash-off modelling due to current rainfall variability, using uncertainty propagation, for urban street scales (e.g. several 100s metres and minutes). This then provides statistics on very small scale rainfall variability, which may be utilised to aid development of downscaling tools.

Key findings were that: for a 400x200 m area, at 2 min temporal averaging interval the average coefficient of variation in the prediction of peak AARI is 6.6 % and the maximum coefficient of variation is 13 % and they are reduced to 1.5 % and 3.6 % respectively at 30 min averaging interval; and the maximum uncertainty in the prediction of peak wash-off load due to rainfall uncertainty within an 8-ha catchment was found to be ~15%.

Hence given that according to most of the current climate change predictions more high intensity rainfall events are expected, due care needs to be given to predicted rainfall input data for localised urban sediment simulations. As the spatial extent of high intensity rainfall peaks is limited, and also because urban surfaces exhibit large spatial heterogeneity, rainfall input data needs to be of high spatial and temporal resolution. If this is not possible or practical, then suitable statistical descriptions of rainfall variability should be included instead, to estimate the effects of rainfall sampling uncertainty on urban sediment wash-off simulations.

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