Rainfall & Runoff Calculator - Ultimate User Guide

CivilWeb Spreadsheets - September 2018

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Rainfall & Runoff Methods

In the UK, there are many simple methods of estimating the rainfall and runoff requirements for drainage design. These are based on the Rational Method with the quantity of rainfall estimated from historical records, and the runoff coefficient estimated from studies of real catchment runoff measurements.

The Flood Studies Report was the first detailed attempt to produce a runoff estimation method which could be used anywhere in the UK. This method was updated many times in the 1970s and 1980s to better estimate runoff for particular situations such as small catchments. Then in the 1980s the Wallingford Procedure was produced as an improvement of the FSR, and this remains today as the pre-eminent runoff estimation model for most drainage design situations.

In general, it is recommended that for most drainage design situations the Wallingford Procedure is used to estimate runoff. However, in some cases other methodologies may be appropriate. For example;

- For very small simple cases, for example small new roads, car parks or buildings, BS EN 752 allows the use of the very simple constant rate method.
- For small rural catchments, for example calculating the greenfield runoff for comparison before a development is approved, the IH 124 model is used. If necessary these results can be checked using the ADAS method or the FSSR 6 method.

The Rainfall & Runoff Calculator spreadsheet allows the user to estimate runoff using the following methodologies;

- Constant Rate Method
- Wallingford Procedure
- IH 124 Method
- ADAS Method
- FSSR 6 Method

Constant Rate Runoff Calculator

Introduction

For small developments up to around 200ha, BS EN 16933-2 allows the use of simple constant rate rainfall methods to evaluate the runoff for drainage design. This simple method is a variant of the Rational Method which has been used all over the world since the 19th century as a quick and simple method for evaluating runoff. For major catchments and developments this method has been superseded by other more complex and accurate methodologies, but for preliminary or small scale drainage design it can still be useful.

The method consists simply of estimating the catchment area and the maximum rainfall intensity the system is required to handle, then multiplying by the Runoff Coefficient and the Climate Change Allowance coefficient.

Rainfall Intensity

The Rainfall Intensity can simply be taken as 0.014l/s/m² (50mm/hr) for small paved areas of up to 4,000m² according to BS EN 16933-2. This value corresponds roughly to a design storm of 5 minutes duration and a return period of 1 year. In this case ponding will occur for a few minutes after a heavy storm, which is acceptable for most small roads or car parks.

For small developments up to around 200ha or times of concentration less than 15 mins, historically derived constant rate rainfall intensities can be estimated for different return periods anywhere in the UK using the maps in BS EN 16933-2. These maps are reproduced here in Appendix A.

Runoff Coefficient

The Runoff Coefficient describes the percentage of rainfall which is runs off a particular surface during a storm event. The higher the value, the greater the quantity of water which will need to be dealt with by the drainage system.

This is not a very precise variable and as such attempts have been made to remove it using statistical analysis of historical events. However, for some simple applications or where better data is unavailable, an estimate of the runoff coefficient may be required. Obtaining an appropriate runoff coefficient requires considerable experience and judgement, and a number of factors must be considered.

The runoff coefficient chosen should include for the following factors;

- Surfacing materials – different man-made surfacing materials have different permeability values. Concrete and asphalt have low permeability values in a storm event, concrete block paving is relatively permeable. Typical values for common materials are given in the table below.
- Surfacing Age & Condition – New asphalt is considerably more permeable than old worn asphalt. Similarly old cracked concrete surfacing is more permeable than new uncracked concrete. This can increase/decrease the runoff coefficient by around 0.10 depending on the likely design life of the surfacing.
- Ground slope – The steeper the gradient, the more water will runoff the surface. This is one of the most important variables when calculating likely runoff. When using the below table it is advised that flat areas use the lower bound, areas with a slope greater than 6% should use the higher bound with intermediate slopes interpolated from the two values.
- Depressions – Any depressions in the ground will naturally attenuate the runoff, and can sometimes have a significant effect on the overall catchment runoff characteristics. This should be considered on a catchment by catchment basis, particularly for rural catchments.
- Underlying soils – This has a limited impact on man-made surfaces such as pavements, but has a very large effect on natural or agricultural surfaces. Common soil types are detailed in the table below.
- Vegetation – Dense vegetation on a rural surface can intercept and store a significant amount of rainfall, thereby reducing the catchment runoff.
- Antecedent wetness of the surface – for design purposes it is usually assumed that the surface is saturated or nearly saturated at the start of the storm event. When modeling summer rains or historical events, this may need to be considered in more detail.
- Rainfall depth – More intense rainfall events can lead to a higher percentage runoff as the surface becomes saturated while the storm is ongoing. For storm events with an intensity more than 50mm/hr, the upper bound value should be used from the table below.
- Burned Soil – Wildfires can cause calcification of the soil leading to a drop in permeability. This can be a factor in areas where wildfires are common.
- Frozen soil – Similarly in cold areas frozen soil in winter can reduce the permeability of the soil, increasing the runoff from a winter storm event.

In simple cases for new developments, it is often appropriate to assume 100% runoff from man-made or impermeable surfaces rather than spend a long time getting a value in the 90s which includes a lot of assumptions, simplifications and guesswork.

Typical Runoff Coefficients

Rural Land Use	Lower Bounds	Upper Bounds
Cultivated Land, Sand & Gravel Soils	0.25	0.35
Cultivated Land, Sandy Loam Soils	0.20	0.52
Cultivated Land, Clay & Silt Loam Soils	0.40	0.72
Cultivated Land, Tight Clay Soils	0.50	0.82
Pasture, Sandy Loam Soils	0.10	0.22
Pasture, Clay & Silt Loam Soils	0.30	0.42
Pasture, Tight Clay Soils	0.40	0.60
Meadow	0.10	0.50
Woodland, Sandy Loam Soils	0.10	0.30
Woodland, Clay & Silt Loam Soils	0.30	0.50
Woodland, Tight Clay Soils	0.40	0.60
Bare Rock	0.82	0.94
Desert	0.30	0.55

Urban Land Use	Lower Bounds	Upper Bounds
Parking	0.85	0.96
Commercial	0.71	0.89
Streets	0.70	0.91
Industrial	0.67	0.86
Residential Lots, High Density	0.25	0.54
Residential Lots, Medium Density	0.19	0.50
Residential Lots, Low Density	0.14	0.46
Railway Yards	0.20	0.35
Playgrounds	0.20	0.30
Sports Fields	0.20	0.35
Parks	0.10	0.25
Cemetaries	0.10	0.25

Man Made Surfaces	Lower Bounds	Upper Bounds
Roofs, Steeply Sloping	0.90	0.95
Roofs, Small Flat	0.90	0.95
Roofs, Large Flat	0.75	0.95
Asphalt	0.70	0.95
Pervious Asphalt	0.55	0.80
Concrete	0.70	0.95
Pervious Concrete	0.60	0.80
Concrete Blocks, Uncemeted Joints	0.50	0.70
Concrete Blocks, Cemeted Joints	0.70	0.85
Gravel	0.50	0.60
Earth	0.50	0.50
Grass, Poor Condition	0.32	0.62
Grass, Fair Condition	0.25	0.60
Grass, Good Condition	0.21	0.58
Turf Block	0.15	0.30

Wallingford Procedure

Introduction

The Wallingford Procedure was developed in the 1970s and 1980s to improve the estimation of rainfall runoff in the UK. It is based on the Rational Method, and is sometimes referred to as the Modified Rational Method. It expanded on previous work done in the Flood Studies Report on rainfall intensities in the UK and provided a more detailed calculation of the runoff coefficient calibrated to UK rainfall and soil characteristics.

For large catchments the Flood Estimation Handbook has largely replaced the Wallingford Procedure, though it is still widely used in the UK for small catchments and medium sized developments.

Rainfall Intensity

The Wallingford Procedure relies heavily on the Flood Studies Report published in 1975 for rainfall intensity information. This included a national scale study of data from hundreds of rain gauges to create a map of rainfall intensities and characteristics for the whole of the UK. This procedure is included in BS EN 16933-2 for catchments up to 200ha.

The Wallingford Procedure uses two main parameters to estimate the design Rainfall Intensity, the M5-60 value and the r Ratio value.

The M5-60 value corresponds to the quantity of rainfall expected for a particular location. The r Ratio relates to the type of rainfall expected. A low r value of 0.15 represents a light or drizzly rainfall, whereas a large r value of 0.40 represents the liklihood of a much more intense storm in this particluar location.

From these two location based values, the design rainfall intensity can be estimated for any storm duration and any return period for any site in the UK. The CivilWeb Rainfall & Runoff spreadsheet includes preset rainfall data for 250 towns and cities across the UK, or rainfall values can be obtained for any location in the UK using the maps taken from the Wallingford Procedure presented in Appendix B.

WRAP SOIL Index

The soil type of a site can have a big impact on the runoff of a catchment, particularly a large rural catchment. The Flood Studies Report used a theoretical model to classify soils according to their hydrological performance. The factors used where the soil types, depth to impermeable layers, how often the soils are waterlogged and the slope. These factors are considered most important in determining the soils likely response to rainfall.

This new classification was named the Winter Rainfall Acceptance Potential (WRAP) and a map was produced showing the distribution of the 5 WRAP classes across the whole of the UK. From this map the WRAP class of soil can be determined at any location in the UK. This map is reproduced in Appendix B. The CivilWeb Rainfall & Runoff spreadsheet also includes WRAP information for 250 towns and cities across the UK.

The WRAP classes are derived from the below table;

Water regime class	Depth to Impermeable horizon(cm)	Slope Classes								
		<2°			2-8°			>8°		
		Permeability class (above impermeable horizon)								
		Rapid	Medium	Slow	Rapid	Medium	Slow	Rapid	Medium	Slow
1	>80	1	1	2	1	1	2	1	2	3
1	80-40	1	1	2	2	2	3	3	3	4
1	<40	-	-	-	-	-	-	-	-	-
2	>80	2	2	3	3	3	4	-	4	5
2	80-40	2	3	3	3	4	4	4	4	5
2	<40	3	4	4	4	4	4	4	5	5
3	>80	4	4	5	5	5	5	-	5	5
3	80-40	4	5	5	5	5	5	-	5	5
3	<40	5	5	5	5	5	5	5	5	5

Each WRAP class has a Standard Percentage Runoff (SPR) value, which are shown below.

Class 1 – 0.15
Class 2 – 0.30
Class 3 – 0.40
Class 4 – 0.45
Class 5 – 0.50

Where a large catchment contains multiple soil types, the average value across the site is used.

HOST

The WRAP system of soil classification developed as part of the Flood Studies Report has some significant limitations, particularly the small number of classes and the low resolution of the distribution maps. A chance to improve the system came in the 1980s with the completion of national soil survey maps.

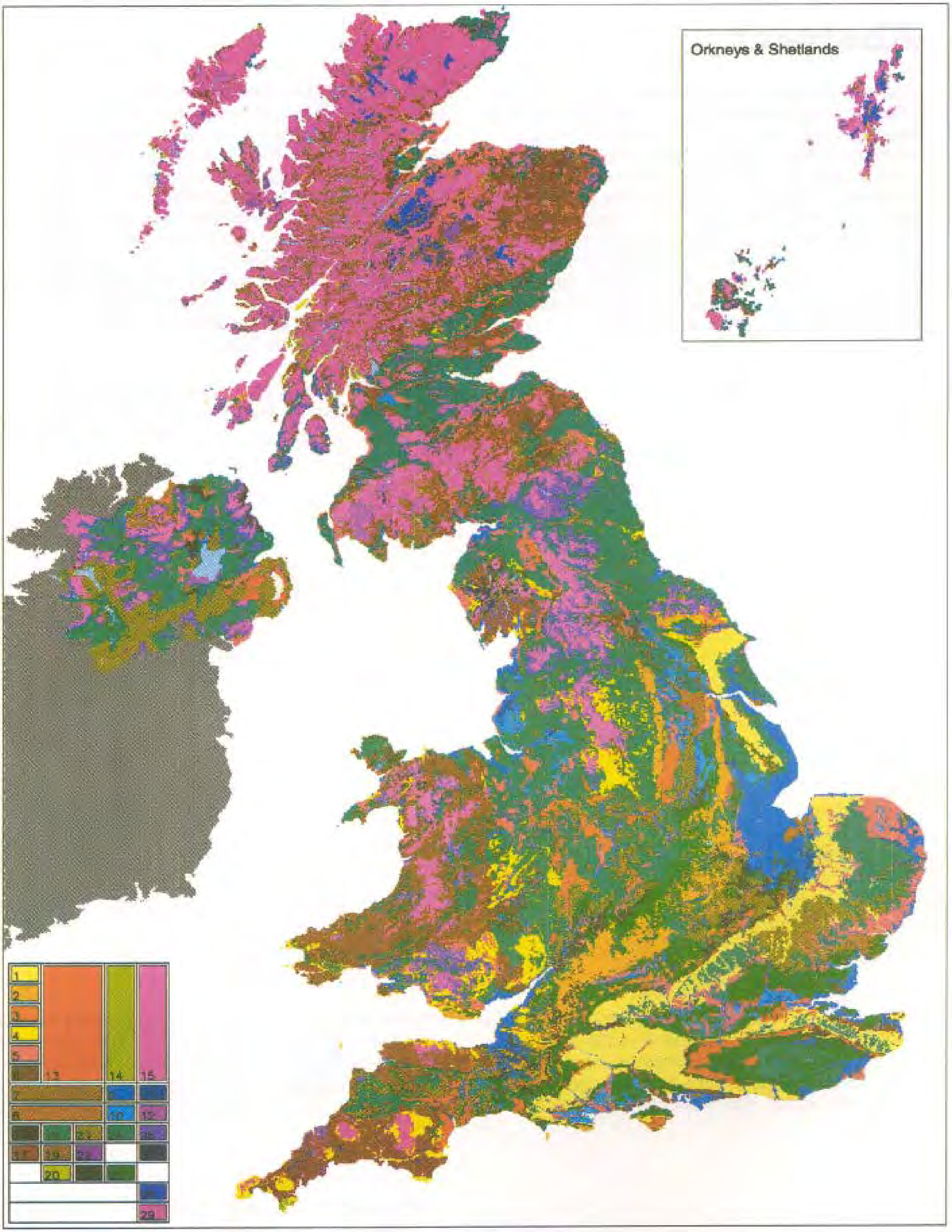
The Hydrology of Soil Types (HOST) project used the national soil maps to reclassify UK soils according to 29 different hydrological performance classes. The classification system is shown in the table below.

SUBSTRATE HYDROGEOLOGY	*MINERAL SOILS*						*PEAT SOILS*	
	Groundwater or aquifer	No impermeable or gleyed layer within 100cm	Impermeable layer within 100cm or gleyed layer at 40-100cm		Gleyed layer within 40cm			
Weakly consolidated, microporous, by-pass flow uncommon (Chalk)	Normally present and at >2m	[1] 4.31	[13] 0.87		[14] 0.66		[15] 9.93	
Weakly consolidated, microporous, by-pass flow uncommon (Limestone)		[2] 2.12						
Weakly consolidated, macroporous, by-pass flow uncommon		[3] 1.58						
Strongly consolidated, non or slightly porous. By-pass flow common		[4] 3.33						
Unconsolidated, macroporous, by-pass flow very uncommon		[5] 5.07						
Unconsolidated, microporous, by-pass flow common		[6] 2.61						
Unconsolidated, macroporous, by-pass flow very uncommon	Normally present and at ≤2m	[7] 1.01			IAC* < 12.5 [< 1m day^{-1}]	IAC* ≥ 12.5 [≥ 1m day^{-1}]	*Drained*	*Undrained*
Unconsolidated, microporous, by-pass flow common		[8] 1.62			[9] 3.68	[10] 2.21	[11] 0.55	[12] 2.94
			IAC# > 7.5	IAC# ≤ 7.5				
Slowly permeable	No significant groundwater or aquifer	[16] 0.43	[18] 5.40	[21] 4.02	[24] 13.85		[26] 2.49	
Impermeable (hard)		[17] 9.28	[19] 2.16	[22] 1.10			[27] 0.83	
Impermeable (soft)			[20] 0.69	[23] 1.31	[25] 3.64			
Eroded Peat							[28] 0.58	
Raw Peat							[29] 5.73	

Small numbers are HOST class number. Large numbers are percentage land cover in England, Wales and Scotland. Also unclassified (urban) areas (5.15%) and lakes (0.74%).
No extensive UK soil types exist outside the table or within the shaded portions of the diagram.
* IAC used to index lateral saturated hydraulic conductivity # IAC used to index soil water storage capacity

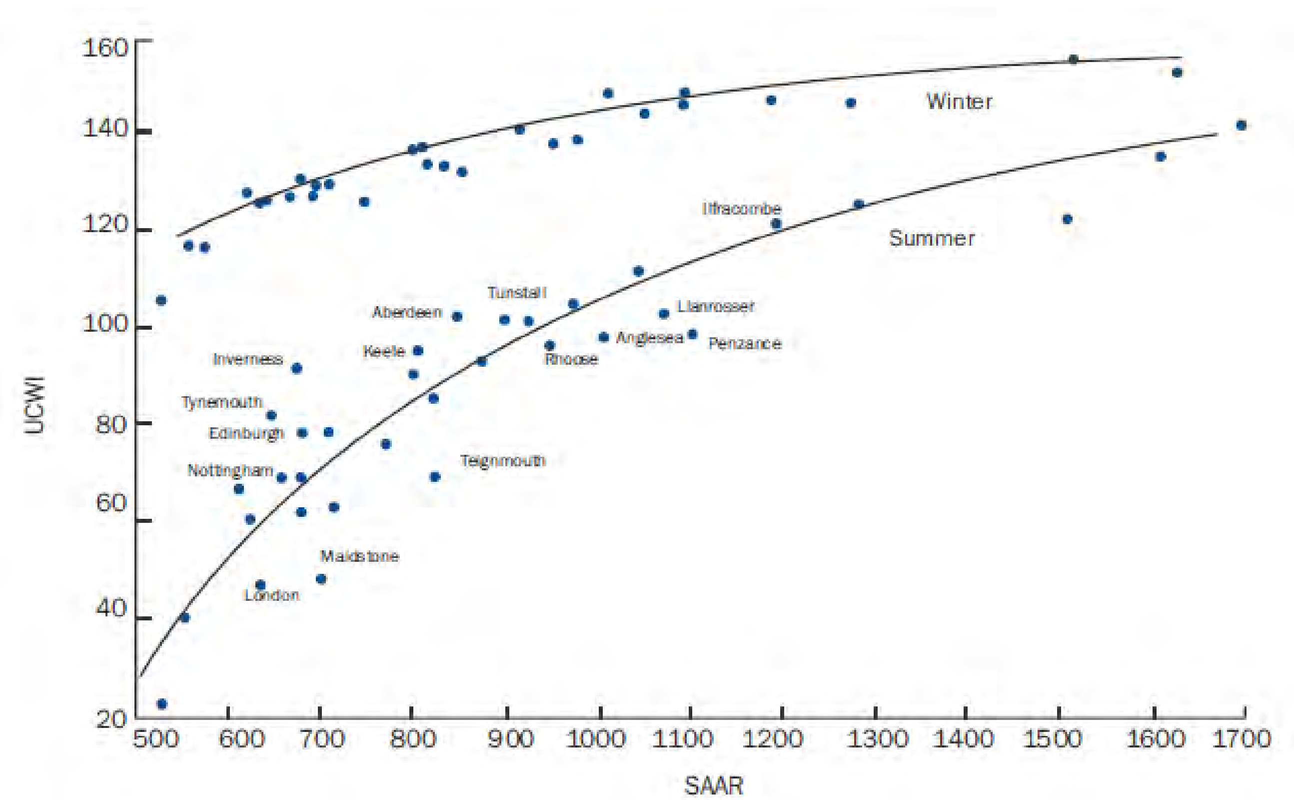
The HOST project subsequently published a map of the UK showing the 29 HOST classes and assigned a Standard Percentage Runoff (SPR) value for each class, which can be used in place of the WRAP SPR value included in the Flood Studies Report. These results are shown here;

HOST class	SPR value (%)	HOST class	SPR value (%)
1	2.0	16	29.2
2	2.0	17	29.2
3	14.5	18	47.2
4	2.0	19	60.0
5	14.5	20	60.0
6	33.8	21	47.2
7	44.3	22	60.0
8	44.3	23	60.0
9	25.3	24	39.7
10	25.3	25	49.6
11	2.0	26	58.7
12	60.0	27	60.0
13	2.0	28	60.0
14	25.3	29	60.0
15	48.4		


Orkneys & Shetlands
1
2
3
4
5
13
14
15
10
12
20
29

Urban Catchment Wetness Index (UCWI)
The Wallingford Procedure includes a factor called the Urban Catchment Wetness Index (UCWI) which is designed to allow for the likely saturation level of the soil before the storm event being considered. A higher UCWI value will lead to a higher runoff value as the soil will become saturated more quickly.

For design purposes, the spreadsheet uses a correlation between the Standard Annual Average Rainfall (SAAR) value and the UCWI value, which is shown in the graph below. The choice of winter or summer in the spreadsheet determines which curve is used to calculate the UCWI. Winter is always the worst case as can be seen from the graph below.



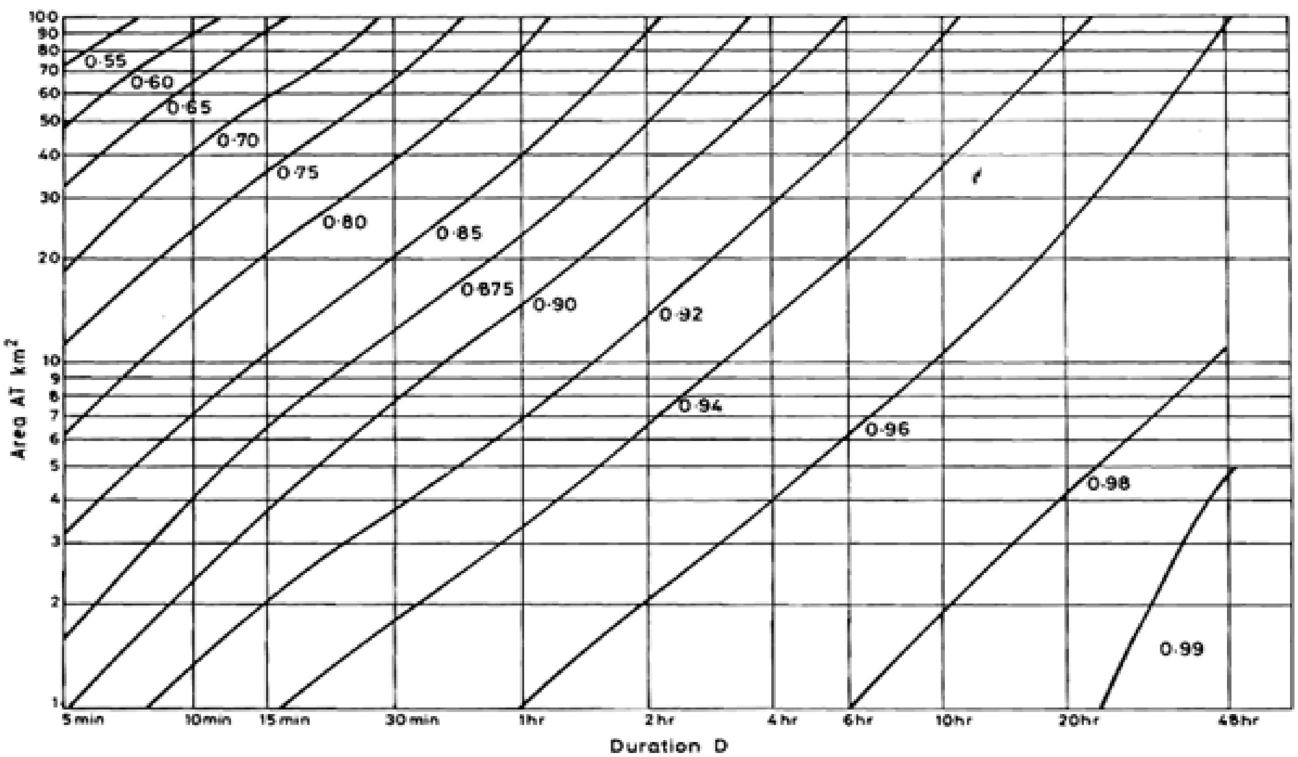
The CivilWeb Rainfall & Runoff spreadsheet also includes SAAR information for 250 towns and cities across the UK. Alternatively, the SAAR value for any location in the UK can be obtained from the map produced for the Wallingford Procedure. This map is reproduced here in Appendix B.

Areal Reduction Factor

The rainfall data used for the Wallingford procedure comes from rainfall gauges, which measure rainfall intensity at a single point. For large catchments the rainfall intensity is not constant across the whole of the catchment at all times during a storm. To account for this, an Areal Reduction Factor (ARF) is included to estimate the average rainfall over the whole of a large catchment. This factor was developed by comparing measured point rainfall intensities with the corresponding average catchment rainfall intensities for storms of the same return period.

The largest variations are seen for large catchments and short duration storms. Due to their relatively small areas, for most urban catchments the ARF is greater than 0.9 and does not have a large effect on the final design rainfall intensities.

The Wallingford Procedure uses the storm duration and the catchment area to calculate the ARF. It does not appear to vary greatly between regions and between different return periods, so these factors are ignored in the calculation. The Wallingford Procedure also included a graph which can be used to quickly estimate the ARF for different catchment areas and storm durations. This is shown below. The ARF calculated by the spreadsheet is appropriate for catchment areas up to 10,000km² and storm durations of between 5 minutes and 48 hours.



Percentage Runoff (Runoff Coefficient)
The Wallingford Procedure calculates the percentage runoff (effectively a runoff coefficient) using a regression equation derived from around 500 historical observed storm events. As the Wallingford Procedure focuses on mostly large rural catchments, this includes an estimate of the runoff from the soil as well as runoff from manmade impervious areas such as roofs and pavements.

Pr *(-)* = 0.829*PIMP + 25*SOIL + 0.078*UCWI – 20.7

PIMP
The impervious area is included in a simple percentage of impervious area factor (PIMP) which assumes 100% runoff from manmade areas. This can usually be taken as anything between 30% and 100%, though there may be some underestimation at the lower end of the scale.

SOIL
This is the Wrap soil index value as described on Page 7.

UCWI
This is the Urban Catchment Wetness Index value as described on Page 10.

This calculation has a number of limitations. It tends to underestimate the runoff from catchments with very small PIMP values. Long duration storms can also be underestimated as the increased wetting of the catchment during the event is not captured.

Routing Coefficient
The routing coefficient has not been found to vary significantly in observed storm events, therefore the recommendation is to use a value of 1.3 in the UK for design.

IH 124 Method

Introduction

The Institute of Hydrology Report 124 was published in 1994. The report was based on the flood data from 71 small rural catchments (less than 25km²). This data was used to produce a new regression equation to calculate the mean annual flood (Q_{BAR}). For practical purposes, this is an amended version of the Flood Studies Report equation, suitable for small rural catchments and greenfield development areas.

In the UK, BS 8582-2013 recommends that the IH 124 method is used to estimate the greenfield runoff rates. These rates are then used in the planning and design process to evaluate the hydrological impact of the development.

The method is very simple to use and is based data taken from a large number of small rural catchments. However, the definition of small being less than 25km² limits the equations use of most developments which are much smaller than this. Caution should be used for any sites smaller than 50ha. For very small areas the CivilWeb Rainfall & Runoff spreadsheet calculates the runoff value for a 50ha site, then scales this value down to suit the required catchment size. This is considered a better approximation than using the equation directly for very small sites.

The catchments studied are drained by a well-defined watercourse, so it is not entirely suitable for all greenfield sites. There is also a lack of a slope component to the equation (besides that implied in the SOIL and SAAR factors) so caution should be used on steeply sloped sites.

WRAP SOIL Index

The WRAP SOIL Index value used in the IH124 Method is the same as the Wallingford Procedure. Detailed guidance is included on Page 7.

Rainfall Intensity
The IH 124 Method does not include any new information regarding rainfall intensity. It uses the SAAR value and regional growth curves from the Flood Studies Report.

The spreadsheet includes preset rainfall data for 250 towns and cities across the UK, or rainfall values can be obtained for any location in the UK using the SAAR map in Appendix B.

The rainfall intensity for a particular return period can then be calculated from the Flood Studies report using the regional growth curves. The appropriate curve number is determined from the map below, then the graph can be used to determine the correction factor for the required return period. This is done automatically in the CivilWeb Rainfall & Runoff spreadsheet.

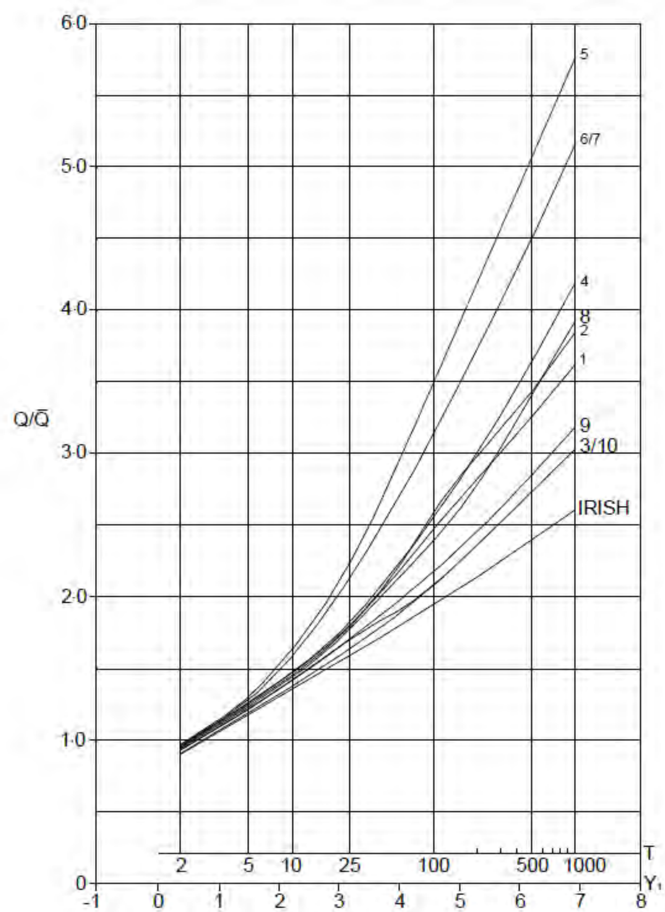


Figure A1.2 Peak flow growth curves of UK (from FSSR 14)

ADAS Method

Introduction

The Agricultural Development and Advisory Service (ADAS) Method originates from ADAS Report 345 completed in 1980. The report was primarily aimed at small rural catchments to aid field drainage design for agricultural land.

The method is based on a combination of other studies including the Flood Studies Report and the TRRL method. The results are suitable for small rural catchments, less than 30ha with little impervious areas. This is because the method does not include for any overland flow.

It remains the only runoff method based on very small rural catchments, and therefore it is sometimes used in the UK for estimating initial greenfield runoff for comparison when planning for development. Other uses are however very limited and the method can underestimate greenfield runoff on saturated catchments.

Rainfall Intensity

The ADAS Method computes the rainfall intensity in the same way as the IH 124 Method. Detailed guidance is included on Page 14.

WRAP SOIL Index

The WRAP SOIL Index value used in the IH124 Method is the same as the Wallingford Procedure. Detailed guidance is included on Page 7.

FSSR 6 Method

Introduction

The Flood Studies Supplementary Report 6 (FSSR 6) published in 1978 was an extension of the Flood Studies Report aimed to better predict runoff from small catchments.

The method is very simple to use, including only 3 parameters which can all be obtained from the maps published in the Flood Studies Report and included in this User Guide. The equation is valid for small catchments between 0.5km² and 20km². Caution should be used for any sites smaller than 50ha. For very small areas the spreadsheet calculates the runoff value for a 50ha site, then scales this value down to suit the required catchment size. This is considered a better approximation than using the equation directly for very small sites.

In practice it was found that the equation was over simplified and produced results no more accurate than the more complex Flood Studies Report equation for all catchments, though it does have the advantage of being much simpler and easier to use for small catchments.

Rainfall Intensity

The FSSR 6 Method computes the rainfall intensity in the same way as the IH 124 Method. Detailed guidance is included on Page 14.

WRAP SOIL Index

The WRAP SOIL Index value used in the FSSR 6 Method is the same as the Wallingford Procedure. Detailed guidance is included on Page 7.

General Design Parameters

Climate Change Allowance

The Climate Change Allowance (CCA) factor is a multiplier applied to rainfall intensities of all 5 methods to allow for the anticipated increase in the intensity of rainfall events over the next 100 years.

There are a number of different guidelines on appropriate CCA values for design, and these are of course changing regularly as new data on climate change is obtained. Selecting a suitable value depends on the type and design life of the structure.

PPS25 published in 2006 recommended a CCA of 1.3, and this recommendation was duplicated in many other documents such as Sewers for Adoption. In 2009 new climate change data was issued in UKCP09 and subsequent publications adopted a recommendation of 1.4 as an upper end projection.

BS EN 752:2017 advises that a CCA of 1.4 is applied in general circumstances for new storm drains. For short life developments or for analysis of existing systems, other CCAs are given in the table below.

Table NA.2 — Recommended values of Climate Change Allowance (CCA) Source Environment Agency [19])

End of design life	CCA (Central projection)	CCA (Upper end projection)
Up to 2039	1.05	1.1
2040-2069	1.1	1.2
2070-2115	1.2	1.4
Note: These recommendations are updated periodically in the light of new research. Users are advised to check for the most up to date guidance.		

Earlier guidance BS 8582:2013 advises that rainfall intensities should be given an uplift of 1.3 when designing for new developments. Again other CCAs are given in the table below.

Table B.1 **National precautionary sensitivity ranges for peak rainfall intensities and peak river flows**

Parameter	1990 to 2025	2025 to 2055	2055 to 2085	2085 to 2115
Peak rainfall intensity	+5%	+10%	+20%	+30%
Peak river flow	+10%	+20%		

NOTE This table was adapted from National Planning Policy Framework: Technical Guidance [46].

There is still some debate as to whether either of these values are appropriate for all new drainage design. Certainly storm drains tend to be among the longest lasting infrastructure elements, they tend to outlive their original purposes as they are difficult and expensive to upgrade. So a conservative approach would be appropriate in most cases. However, climate change will not affect the whole of the UK in the same way. This is illustrated in the below table taken from the UKCP09 data.

Scenario	Medium						High					
Season	Summer			Winter			Summer			Winter		
Probability	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Leeds	-17.9	0.1	21.9	-4.3	6.7	19.2	-19.3	-1.7	19.6	-4.5	6.7	20.1
Manchester	-11.6	3.5	21.2	-5.5	5.9	19.0	-13.5	1.7	19.6	-5.7	6.1	19.4
Birmingham	-14.5	2.7	24.4	-6.9	6.4	22.2	-16.1	1.4	22.3	-9.0	4.6	20.6
London	-22.3	-0.2	27.9	-5.9	7.0	22.9	-24.1	-2.9	23.3	-5.7	7.0	22.8
Glasgow	-12.1	0.4	15.0	-3.9	4.7	14.9	-11.0	1.4	15.6	-6.0	3.5	13.9
Canterbury	-22.0	-0.4	27.3	-6.3	7.1	22.8	-24.2	-3.3	23.2	-6.9	6.8	22.4
Newcastle	-16.4	-0.2	18.9	-6.3	7.6	23.6	-17.8	-2.1	16.8	-6.2	7.6	24.2

Table 5.3: 2030's percentage changes in rainfall based on wettest day analysis

Scenario	Medium						High					
Season	Summer			Winter			Summer			Winter		
Probability	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
Leeds	-22.0	-3.9	18.0	-0.8	12.0	27.5	-21.9	-3.3	18.5	-0.3	13.1	29.6
Manchester	-16.9	0.6	21.3	-2.4	10.5	25.8	-16.9	0.9	22.5	-1.9	11.4	27.5
Birmingham	-18.4	0.4	23.2	-5.4	10.5	28.6	-18.6	0.7	24.4	-5.4	11.5	32.6
London	-28.6	-6.3	21.0	-2.7	12.2	31.4	-28.5	-6.1	22.5	-3.8	13.1	35.8
Glasgow	-13.4	0.1	15.1	-3.2	7.4	19.4	-12.9	1.0	16.2	-3.1	8.0	21.8
Canterbury	-29.3	-7.0	21.2	-2.6	11.5	28.5	-29.0	-6.8	22.2	-5.1	10.2	28.2
Newcastle	-20.9	-4.2	15.2	-2.0	13.6	32.3	-20.5	-3.8	15.5	-1.5	14.8	34.7

Table 5.4: 2050's percentage changes in rainfall based on wettest day analysis

In practice, an assessment must be made on a case by case basis to determine the most appropriate CCA value. Where it can be accommodated without significant expense, a value of 1.4 would usually be most appropriate. For some temporary systems or in areas expected to be less affected, a lower value may be appropriate.

Return Period

The design Return Period describes the likelihood that the design storm will be exceeded and the system overloaded with rainwater. This is typically given in years which describes on average how often the design storm will be exceeded. For example a Return Period of 10 years means that on average, the design storm will be exceeded once every 10 years. This does not mean that this will definitely occur once every decade, but that there is a 10% chance of the design storm being exceeded every year. It could happen two years in a row and then not again for 20 years, for example.

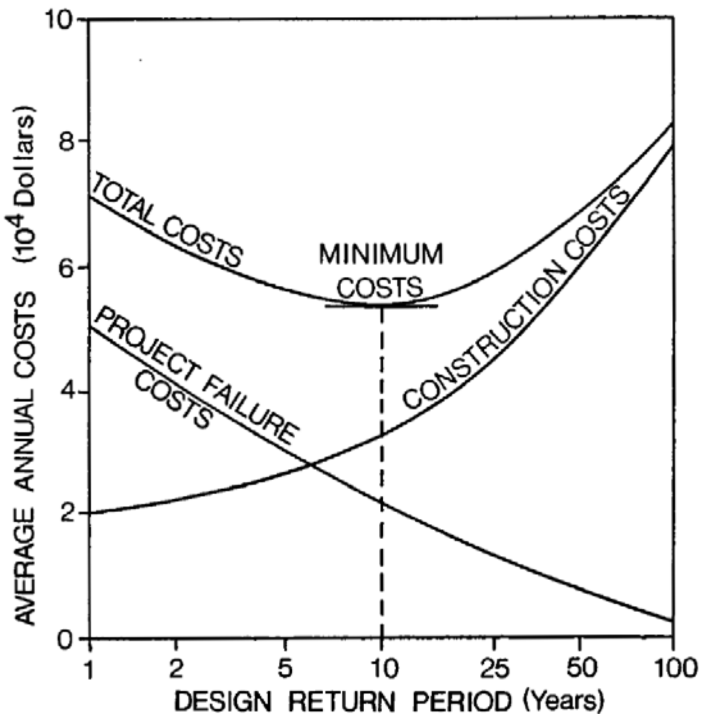
This parameter needs to be specified in all calculation methods other than the Constant Rate Method. For the Constant Rate Method the Return Period is implied by the chosen rainfall intensity.

When determining an appropriate design Return Period, a number of factors should be considered;

- The capabilities of neighbouring systems and structures, both upstream and downstream.
- Any other proposed or likely developments in the vicinity
- The consequences of the design storm event being exceeded, ie consequences of flooding. This will depend on the type, usage and robustness of the structures or facilities being served by the system, and on any contingency or back-up systems in place. For example the prevention of flooding of a hospital may be considered more important than a residential area, which in turn may be more important than an office block.
- Any historical or irreplaceable structures or facilities must be considered.
- Alternative roads or facilities which would alleviate the consequences of flooding of this system.
- The construction, operation and maintenance costs or practical implications of a higher Return Period, balanced with the benefits.
- The aesthetic implications of a higher Return Period may be considered in some cases.
- The effects on any combined foul and rainwater systems. Failure of a combined system being potentially more hazardous and disruptive, particularly in a residential area.

Most importantly the consequences of a failure must be investigated and the consequences mitigated wherever possible. This must avoid the possibility of a catastrophic failure of the system or dependant structures, for example the strength of a culvert structure must be assessed for if the culvert is overloaded with water. A flooding risk assessment would include any major safety consequences, particularly where overloaded bridges or culverts would force floodwaters through populated areas at sufficient velocities to cause structural damage to buildings or to risk the safety of people. It would also include an assessment of any likely erosion resulting from a flood event, particularly where this may affect the structural integrity of nearby structures.

As well as an assessment of the consequences of flooding, if this is combined with an assessment of the costs of construction this can result in a total cost curve similar to the example shown below.



It should also be noted that the recommendations for new drainage systems do not allow for the pipes to become surcharged. For a sewer laid perhaps 1m-2m beneath the ground, there is often considerable additional capacity than that allowed with the system running just full. This additional capacity is usually ignored and acts as an extra redundancy in the system.

There is a lot of general guidance on appropriate Return Periods for different kinds of drainage systems, below are a number of examples. In practice the design Return Period must be agreed with the client or local authority before the design is finalised.

New Developments in the UK
In the UK it is now standard practice that peak runoff rate from greenfield developments should not exceed the runoff from the original greenfield state for either the 1 year or the 100 year storm event. For re-development of a previously developed site, the peak runoff rate should be as close as reasonably practicable to the original greenfield runoff of the site for 1 year and 100 year storm events.

Similarly the runoff volume from a greenfield development should not exceed the original greenfield volume from the 100 year – 6 hour storm event. For re-development of a previously developed site, the runoff volume from the 100 year – 6 hour storm event should not exceed the original developed condition, and should be as close as reasonably practicable to the original greenfield runoff volume.

Within a new development the drainage should be designed so that no flooding of any part of the site should occur during a 30 year storm event, and no flooding should occur to any buildings during a 100 year event. Flows from an event exceeding the 100 year return period should be channelled through flood routes which minimise risk to people and the damage to buildings.

This usually leads to significant infiltration and attenuation systems being installed on large new developments.

Buildings & Facilities

For drainage systems serving typical buildings, the following guidance is taken from BS EN 752.

Risk category	Situation	Design rainfall frequency	
		Return period (1 in "n" years)	Probability of exceedence in any one year
Category 1	Normal situations where ponding can be tolerated during heavy rainfall and for a few minutes afterwards	1	1
Category 2	Ponding cannot be tolerated	5	0,2
Category 3 (see Note a)	Where a building or its contents require additional protection	1,5 × design life of building (see note b)	1/(1,5 × design life of the building) – (see note b)
Category 4 (see Note a)	Where a building or its contents require a higher degree of security than category 3	4,5 × design life of building (see note b)	1/(4,5 × design life of the building) – (see note b)

Notes:

a) Categories 3 and 4 should only be used in exceptional circumstances.

b) Design rainfall intensities for other frequencies and durations can be calculated using the method described in BS EN 16933-2.

Other typical Return Periods for used when designing drainage systems for common buildings, roads and dam projects are shown below.

Buildings	**Return Period (Years)**
Open spaces away from buildings	1
Agricultural land	2
Public open spaces	3
Open spaces adjacent to buildings	5
Commercial buildings	10
Residential buildings	10
Deep flooding to occupied buildings	30
Underpasses	30
Airports (Large)	50
Computer Server Rooms	200
Historical landmarks, musuems, libraries etc.	200
Police facilities	200
Hospitals & Emergency Services	500
Vital Infrastructure	35,000 or MPR

Roads	**Return Period (Years)**
Important Highways	100
Busy Rural Roads	50
Roads with no escape paths for water	50
Busy Urban Streets	25
Quiet Rural Roads	25
Longitudinal Overland Drainage	10
Quiet Urban Streets	10
Bridge Decks	10
Car Parks	5

Dams & Levees

Dam category	**Potential effect of a dam breach**	**Reservoir design flood inflow**	
		General	**Minimum standard if overtopping tolerable**
A	Where a breach could endanger lives in a community	Probable Maximum Flood (PMF)	10,000-year flood
B	Where a breach (i) could endanger lives not in a community (ii) could result in extensive damage	10,000-year flood	1,000-year flood
C	Where a breach would pose negligible risk to life and cause limited damage	1,000-year flood	150-year flood
D	Special cases where no loss of life can be foreseen as a result of a breach and very limited additional flood damage would be caused	150-year flood	Not applicable

Time of Concentration & Storm Duration

The Time of Concentration is the time between rainfall landing on the catchment and the water reaching the point of the drainage system being considered. It is used to evaluate the critical storm duration for each point in the drainage system. This is because the critical rainfall event must be long enough for rainfall from the whole catchment to be contributing to the flow in the system at the point being considered. A storm of shorter duration may be more intense, but the water from a large portion of the catchment may not have reached the point being considered yet.

For unusual shaped catchments or where multiple sub-catchments are being considered, it is sometimes necessary for several storm durations to be considered to find the critical one. Another example may be where a small impervious area may have a larger runoff potential than the rest of the permeable catchment. In this case the time of concentration and runoff for the impermeable area only should be checked as well as the whole catchment.

There are two main methods of calculating the Time of Concentration for a catchment. The simplest is to apply an empirical formula. Several empirical formulas have been derived from experimental data which takes account of all the different types of flow from rainfall landing on the catchment to the outfall. These formulas are typically based on larger rural catchments.

The second more complex method is to break down the flow into its component parts and calculate each separately. The three main flow types are;

1. Overland sheet flow. This is the flow that occurs immediately after the rain has landed as it heads towards a natural or man-made channel. This can be modelled using the kinematic wave formula.
2. Concentrated shallow flow. This is the flow within a small, shallow natural or man-made channel, before the water reaches an inlet. This can be calculated using the equations of shallow overland flow such as the Manning Equation.
3. Flow within a defined watercourse or drainage system. This is the flow from an inlet to the point of the system being considered. This can be calculated using the appropriate equations for open channel flow, pipe flow etc. As water is flowing through each part of the drainage system, each part has a slightly different time of concentration. This is often negligible but can b significant for very long or very shallow drainage runs.

A minimum time of concentration of 5 minutes is usually applied to prevent small catchments from using extremely high rainfall intensities associated with a 1 or 2 minute storm event. In practice it is usually acceptable to expect a few minutes of flooding during extreme short duration storm intensities. In the UK a design storm duration of 5 minutes is often used for general drainage design purposes.

Empirical Formulas

Kirpich Formula

The Kirpich Formula was developed in 1940 from a study of 7 small (1.25 acres – 112 acres) rural catchments in Tennessee with well-defined channels and steep slopes (3%-10%). A further study by Roussel et al. 2005 concluded that the method was suitable for catchment sizes between 0.25 and 150 square miles, for slopes between 0.002 and 0.1 m/m.

The Kirpich Method

For channel-flow component of runoff, the Kirpich equation is:

$$t_{ch} = KL^{0.770}S^{-0.385}$$

Equation 4-15.

Where:

t_{ch} = the time of concentration, in minutes

K = a units conversion coefficient, in which K = 0.0078 for traditional units and K = 0.0195 for *SI* units

L = the channel flow length, in feet or meters as dictated by K

S = the dimensionless main-channel slope

A correction factor has been proposed to extend the use of the formula outside the original studies catchment characteristics.

- 2.0 for natural grass surfaces
- 0.4 for flow over concrete or asphaltic surfaces
- 0.2 for flow in concrete channels

This method includes for both overland flow and channel flow, though an additional estimation of overland flow may be required where this is expected to be significant. As the formula is based on well-defined channels, the overland portion may be underestimated. This can lead to conservative high design rainfall intensities.

For this reason, this method is not widely used in the UK, though it can be useful as a check on a more modern method, or where the catchment parameters closely align with the original study.

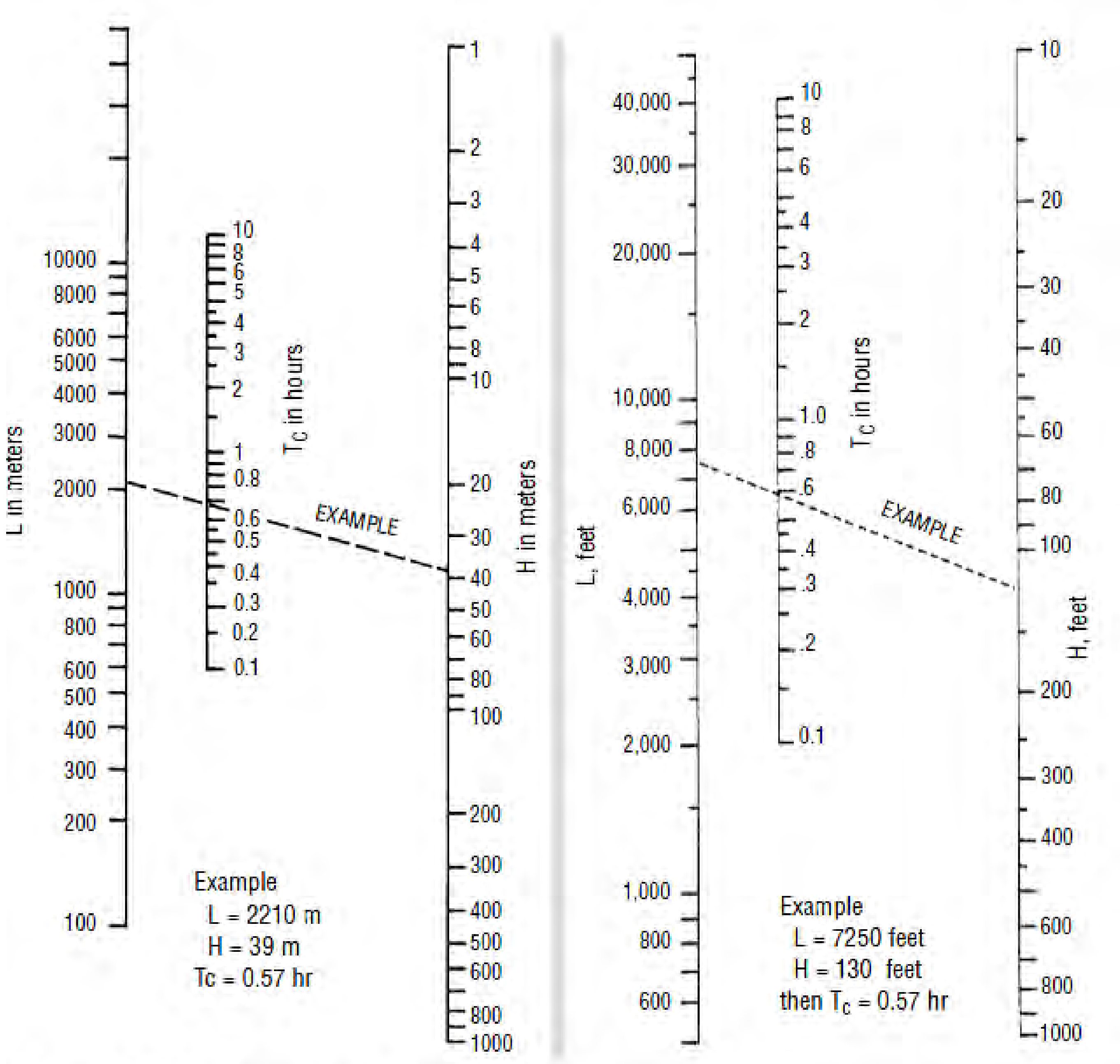


Figure 3.10 T_c nomograph using the Kirpich formula.

Bransby-Williams Equation

The Bransby-Williams equation was developed from studies done in India. It is better suited to small rural catchments without well-defined drainage channels, ie where overland flow is the dominant factor.

$$t_c = \frac{0.14465L}{H^{0.2}A^{0.1}} \qquad \text{-----------------------} \quad (2)$$

where t_c = time of concentration (min)

A = catchment area (m^2)

H = average slope (m/100m), measured along the line of natural flow, from the summit of the catchment to the point under consideration

L = distance (on plan) measured along the line of natural flow between the summit and the point under consideration (m)

Similar to the Kirpich Method, the Bransby-Williams method can tend to underestimate the Time of Concentration leading to conservative high design rainfall intensities. Where well-defined channels are present, it is recommended that the Time of Concentration of these channels is calculated separately then added to the Time of Concentration of the remote sub-catchment calculated using the Barnsby-Williams equation.

Kerby Equation

The Kerby equation is an empirical formula published in 1959 and relates to overland flows for small catchments and shallow slopes.

$$T_c = K(L \times N)^{0.467} S^{-0.235},$$

where T_c is the overland flow time of concentration, in minutes; K is a units conversion coefficient, in which $K = 0.828$ for traditional units and $K = 1.44$ for SI units; L is the overland-flow length, in feet or meters as dictated by K; N is a dimensionless retardance coefficient; and S is the dimensionless slope of terrain conveying the overland flow. In the development of the

For larger catchments where the flow length exceeds 350m or well-defined chaneels are present, the Kerby equation should be supplemented with an estimation of the channel flow. For this reason in the US a combination of the Kerby and Kirpich equations is often used.

Flow Formulas

Kinematic Wave Equation

The alternative to using an empirical formula is to calculate the runoff flow directly from flow formulas. The first part of runoff flow is the overland sheet flow which can be modeled using the kinematic wave equation. The equation is generally applicable for the first 100m or so of overland flow on shallow slopes. For steeper slopes or longer flow paths the flow should be modelled as shallow concentrated flow rather than overland sheet flow.

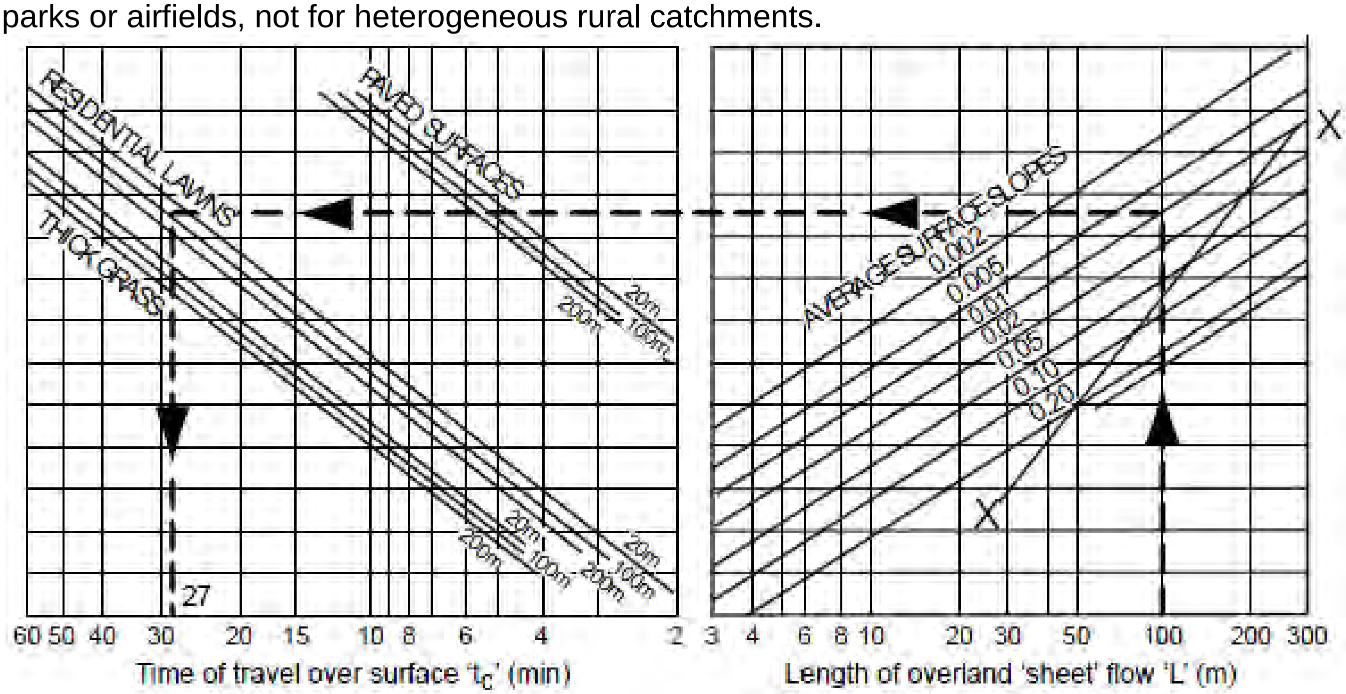
$$T_{ti} = \frac{K_u}{I^{0.4}}\left(\frac{n\,L}{\sqrt{S}}\right)^{0.6}$$

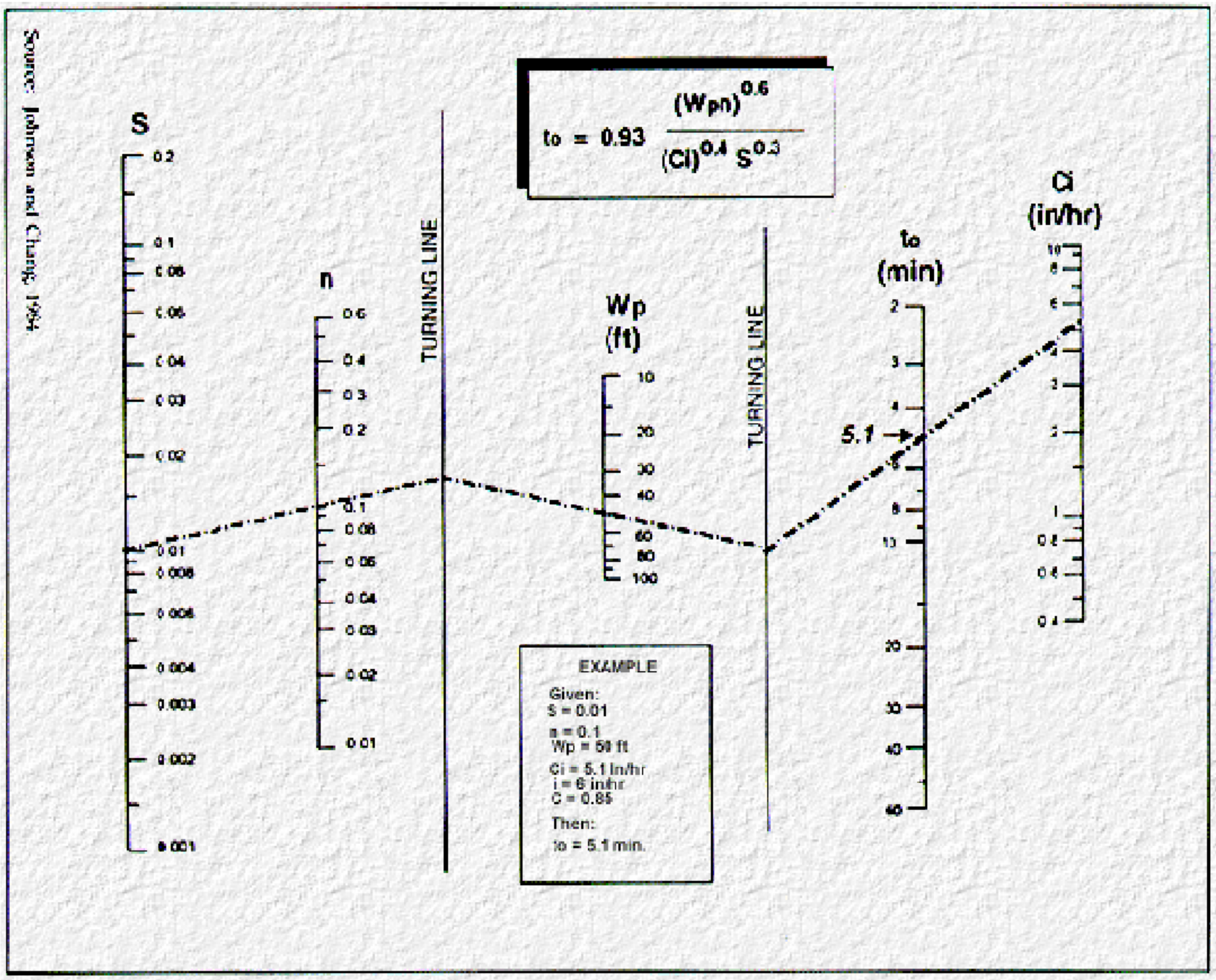
where:

T_{ti}	=	Sheet flow travel time, min
n	=	Roughness coefficient (see Table 3-2)
L	=	Flow length, m (ft)
I	=	Rainfall intensity, mm/hr (in/hr)
S	=	Surface slope, m/m (ft/ft)
K_u	=	Empirical coefficient equal to 6.92 (0.933 in English units)

As the wave equation requires the rainfall intensity, the determination of the time of concentration must be done via an iterative approach.

The equation has been shown to be applicable only for turbulent flow and where the product of rainfall intensity (mm/hr) and flow length (m) is greater than 750. It should also only be used on planes that are fairly homogenous in terms of slope and roughness. For these reasons the kinematic wave equation is most suitable for large paved areas such as car parks or airfields, not for heterogeneous rural catchments.




Source: Johnson and Chang, 1984
$t_o = 0.93 \frac{(W_p n)^{0.6}}{(Ci)^{0.4} S^{0.3}}$
S
n
TURNING LINE
Wp (ft)
TURNING LINE
to (min)
Ci (in/hr)
5.1
EXAMPLE
Given:
S = 0.01
n = 0.1
Wp = 50 ft
Ci = 5.1 in/hr
i = 6 in/hr
C = 0.85
Then:
to = 5.1 min.

TR-55 Alternative Wave Equation

In order to avoid having to solve the wave equation iteratively, an alternative equation has been developed which assumes an IDF curve from the M2-24hr rainfall value.

$$t_c = \frac{\alpha}{P_2^{0.5}} \left(\frac{nL}{\sqrt{S}}\right)^{0.8}$$

where,

P_2 = 2-year, 24-hour rainfall depth, mm (in)

α = unit conversion constant equal to 5.5 in SI units and 0.42 in CU units.

This equation should be used with caution due to the simplifying assumptions made regarding the rainfall intensity. It can however provide a good starting point for the iterative solution of the original kinematic wave equation, or as a preliminary estimate of the time of concentration for a catchment where more detailed rainfall intensity information is unavailable.

Manning Coefficient – Sheet Flow

The Manning Coefficient is used in the time of concentration formulas that attempt to model sheet flow.

The Manning Coefficient value for sheet flow is quite different to the equivalent value for open channel flow. As the assumed flow depth is very small, the sheet flow coefficient is dependent on the conditions on the surface and can be significantly affected by small changes, for example between lightly grassed surfaces and more densely grassed surfaces. Only the first 30mm need be considered as this will be the max height of the sheet flow.

The coefficient takes into account the effects of raindrop impact, the roughness of the surface, obstacles such as protruding rocks, leaf litter, crop ridges etc, and erosion and transportation of sediment. Where sediment may accumulate, for example on shallow sloped pavements or gutters, a value of 0.002 should be added to the coefficient.

Urban	Lower Bounds	Upper Bounds
Asphalt Pavement	0.010	0.015
Smooth Concrete (Float Finish)	0.012	0.015
Smooth Concrete (Brush Finish)	0.014	0.016
Gravel Areas	0.020	0.030
Bare Packed Soil	0.010	0.020
Packed Clay	0.030	0.040
Bare Sand	0.010	0.016
Short prairie grass and lawns	0.100	0.200
Dense grasses (weeping lovegrass, bluegrass, buffalo grass, blue grama grass, native grass mixtures, alfalfa, lespedeza)	0.200	0.240
Bermuda grass	0.300	0.480
Woods or forest with light underbrush	0.400	
Woods or forest with dense underbrush	0.800	

Pipes & Channels

Wood Lining	0.014
Blocks or Brisk with Cement Mortar	0.014
Vitrified Clay	0.015
Cast Iron	0.015
Corrugated Metal Pipe	0.024
Cement Rubble Surface	0.024

By Landuse

Parkland	0.350
Rural Residential	0.300
Urban Residential	0.210
Medium Density Urban Residential	0.110
Industrial	0.060
Commercial	0.040
Woods or forest with light underbrush	0.400
Woods or forest with dense underbrush	0.800

Agricultural Land

Fallow - no residue	0.008	0.012
Conventional tillage - no residue	0.060	0.120
Conventional tillage - with residue	0.160	0.220
Chisel plow - no residue	0.060	0.120
Chisel plow - with residue	0.100	0.160
Fall disking - with residue	0.300	0.500
No till - no residue	0.040	0.100
No till - 20-40% residue	0.070	0.170
No till - 60-100% residue	0.170	0.470
Sparse rangeland with debris - no cover	0.090	0.340
Sparse rangeland with debris - 20% cover	0.050	0.250
Moldboard Plow	0.020	0.100
Short prairie grass and lawns	0.100	0.200
Dense grasses (weeping lovegrass, bluegrass, buffalo grass, blue grama grass, native grass mixtures, alfalfa, lespedeza)	0.200	0.240
Bermuda grass	0.300	0.480
Woods or forest with light underbrush	0.400	
Woods or forest with dense underbrush	0.800	

Probablistic Methods

For some preliminary analyses there may be very little information on the characteristics of a catchment. For cases like this when an estimate is needed for the Time of Concentration, a probabilistic method can be used with only a catchment area.

For obvious reasons these formula should be used as a preliminary estimate and only where no further information is available.

Australian Methods

The below method is used in Australia to estimate Time of Concentration for catchments up to 250km².

$$t_c = 0.76A^{0.38}$$

US Methods

A number of similar methods have been derived from US studies. Details for some are given below.

Simas Equation;

$$T_c = 0.0481A^{0.324} \qquad \text{(eq. 15A–5)}$$

where:
T_c = time of concentration, h
A = the drainage area, acre

Regional Equations;

Region of applicability	Time of concentration equation	
Texas	$T_c = 2.4A^{0.6}$	(eq. 15A–3)
Ohio	$T_c = 0.9A^{0.6}$	(eq. 15A–4)

where:
T_c = time of concentration, h
A = drainage area, mi²

Appendix A

Constant Rate Rainfall Maps from BS 16933-2

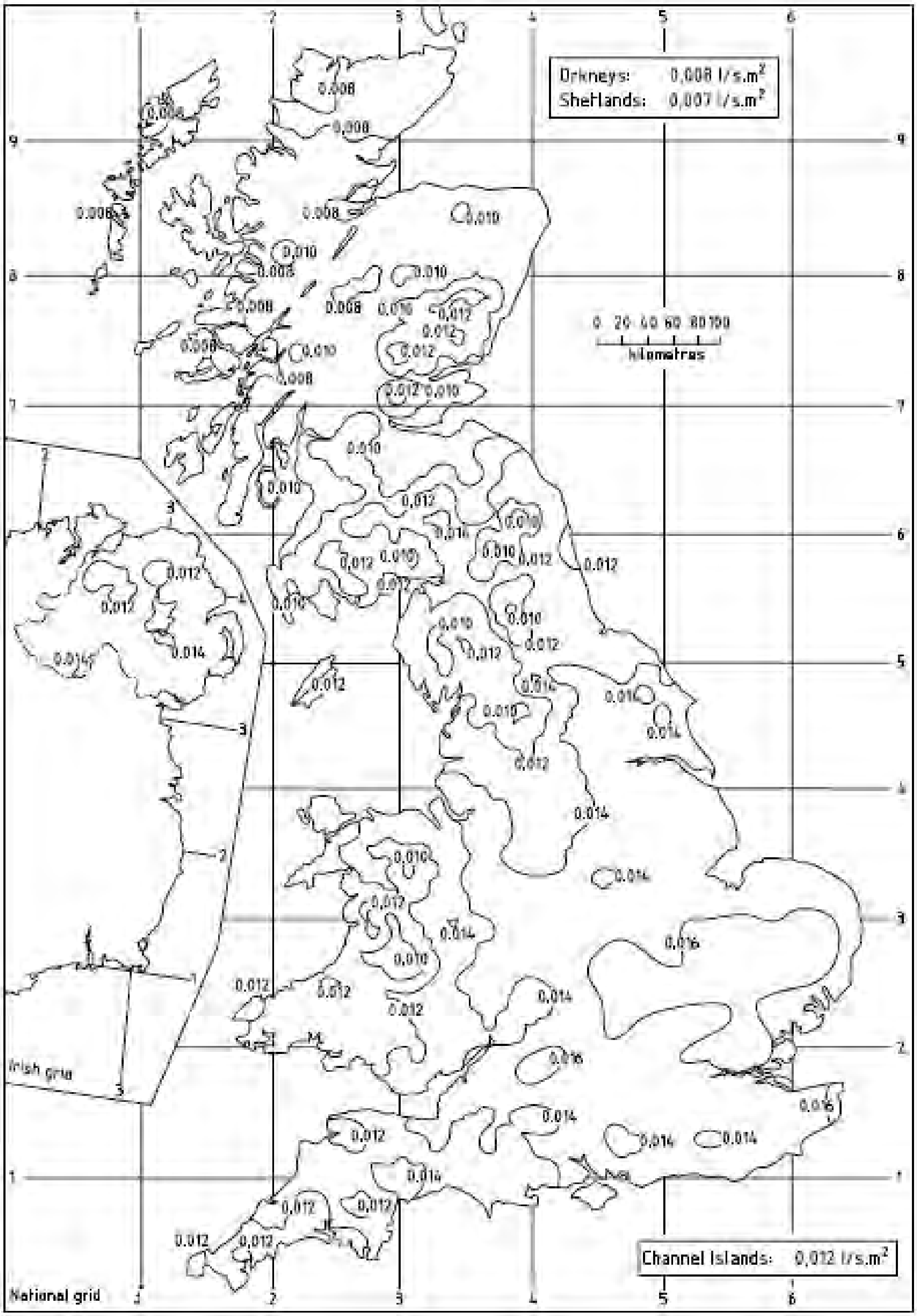


Figure NA.2 — Historically derived constant rate rainfall intensity for an event of 5 minutes' duration with a probability of exceedence of one in 1 year (a return period of 1 year)

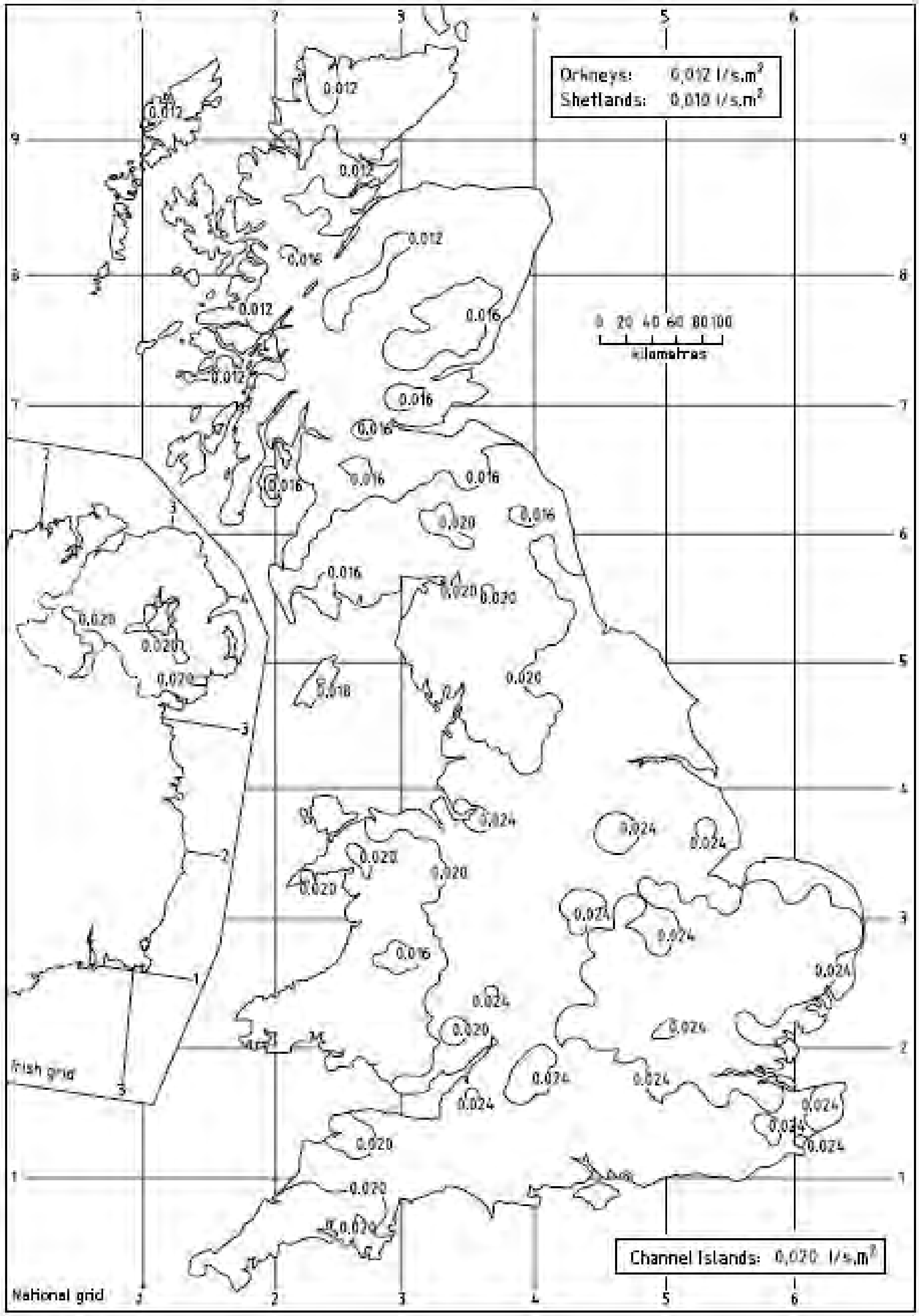


Figure NA.3 — Historically derived constant rate rainfall intensity for an event of 5 minutes' duration with a probability of exceedence of 0.2 in 1 year (a return period of 5 years)

Figure NA.4 — Historically derived constant rate rainfall intensity for an event of 5 minutes' duration with a probability of exceedence of 0,02 in 1 year (a return period of 50 years)

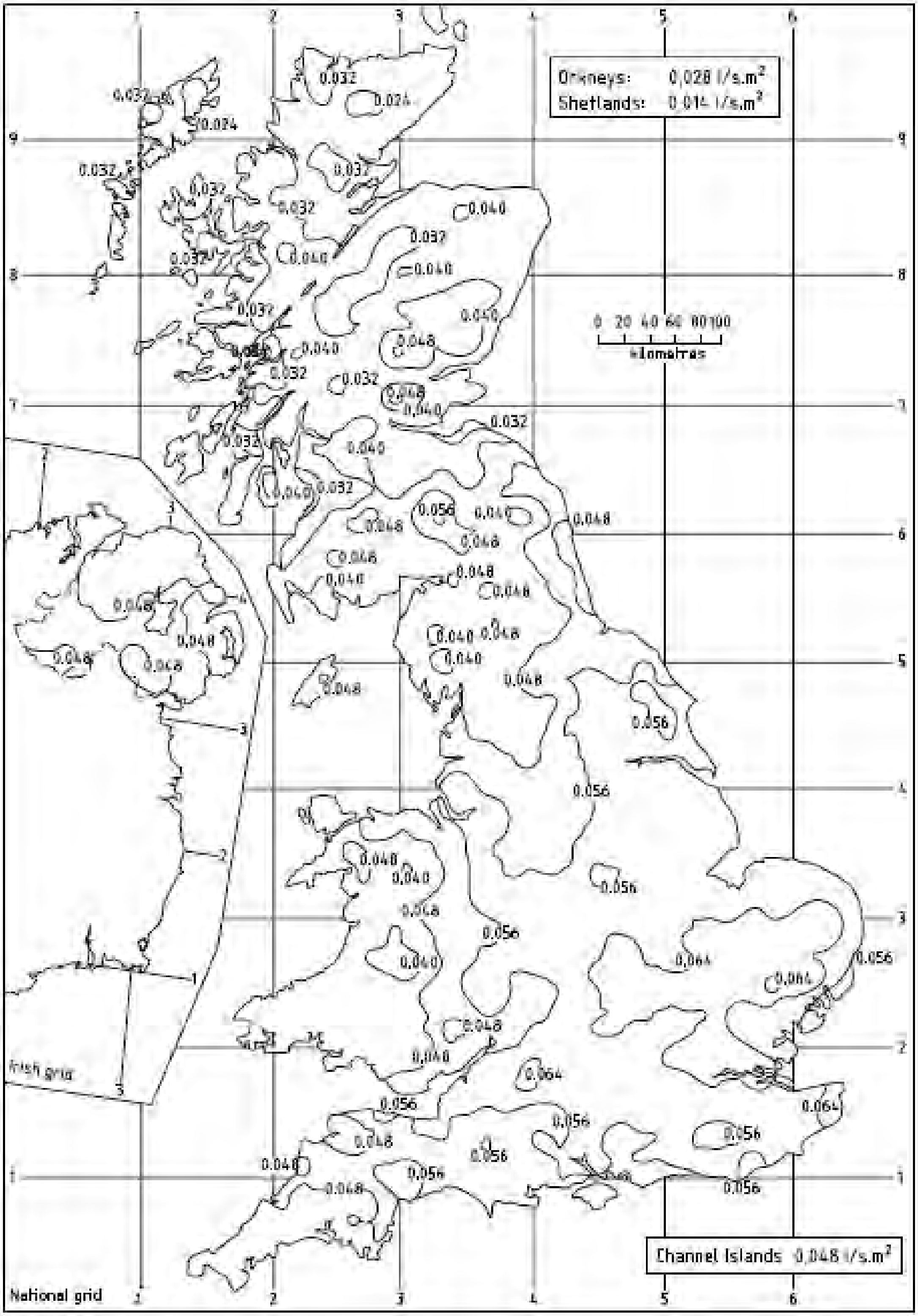


Figure NA.5 — Historically derived constant rate rainfall intensity for an event of 5 minutes' duration with a probability of exceedence of 0,002 in 1 year (a return period of 500 years)

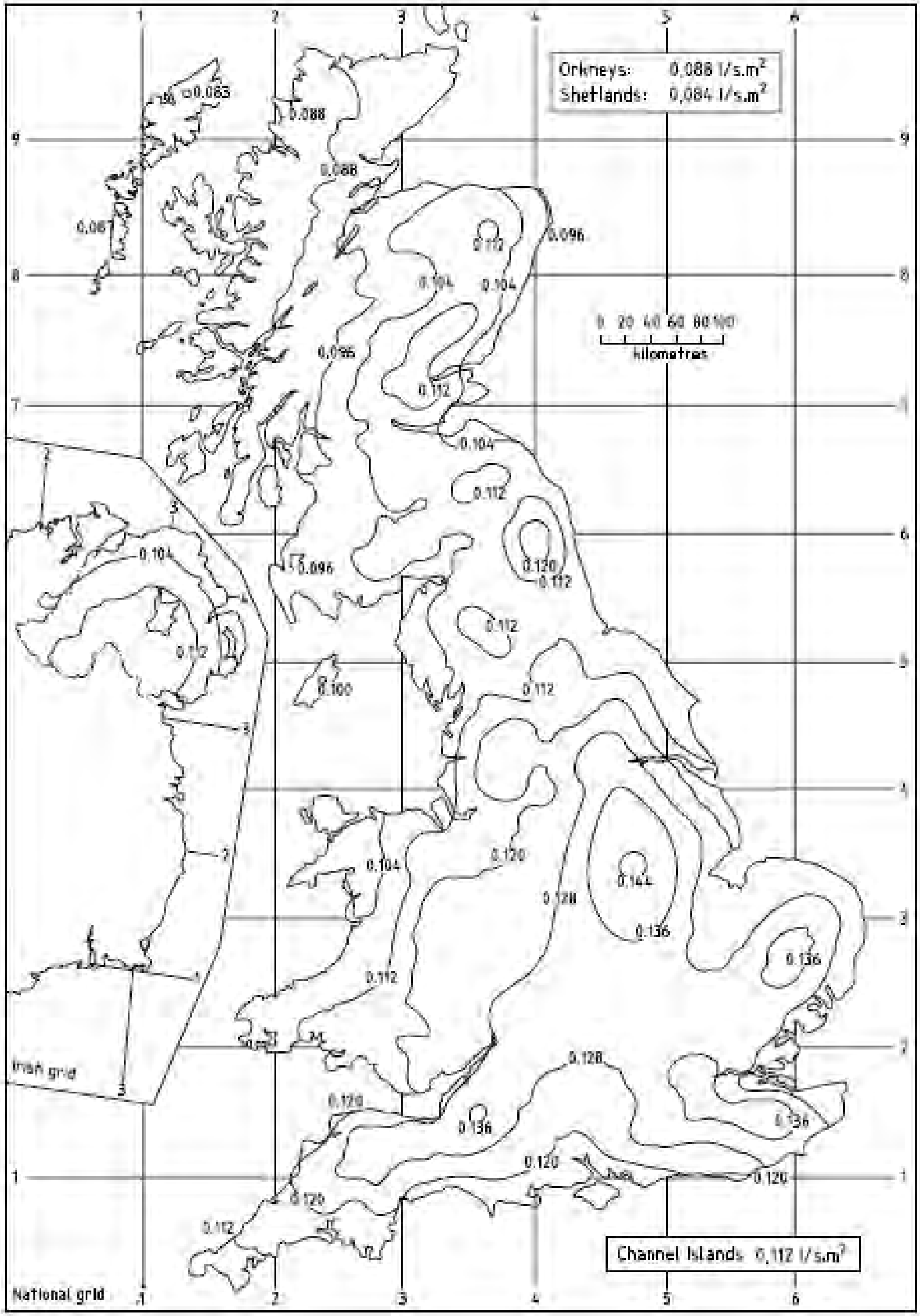
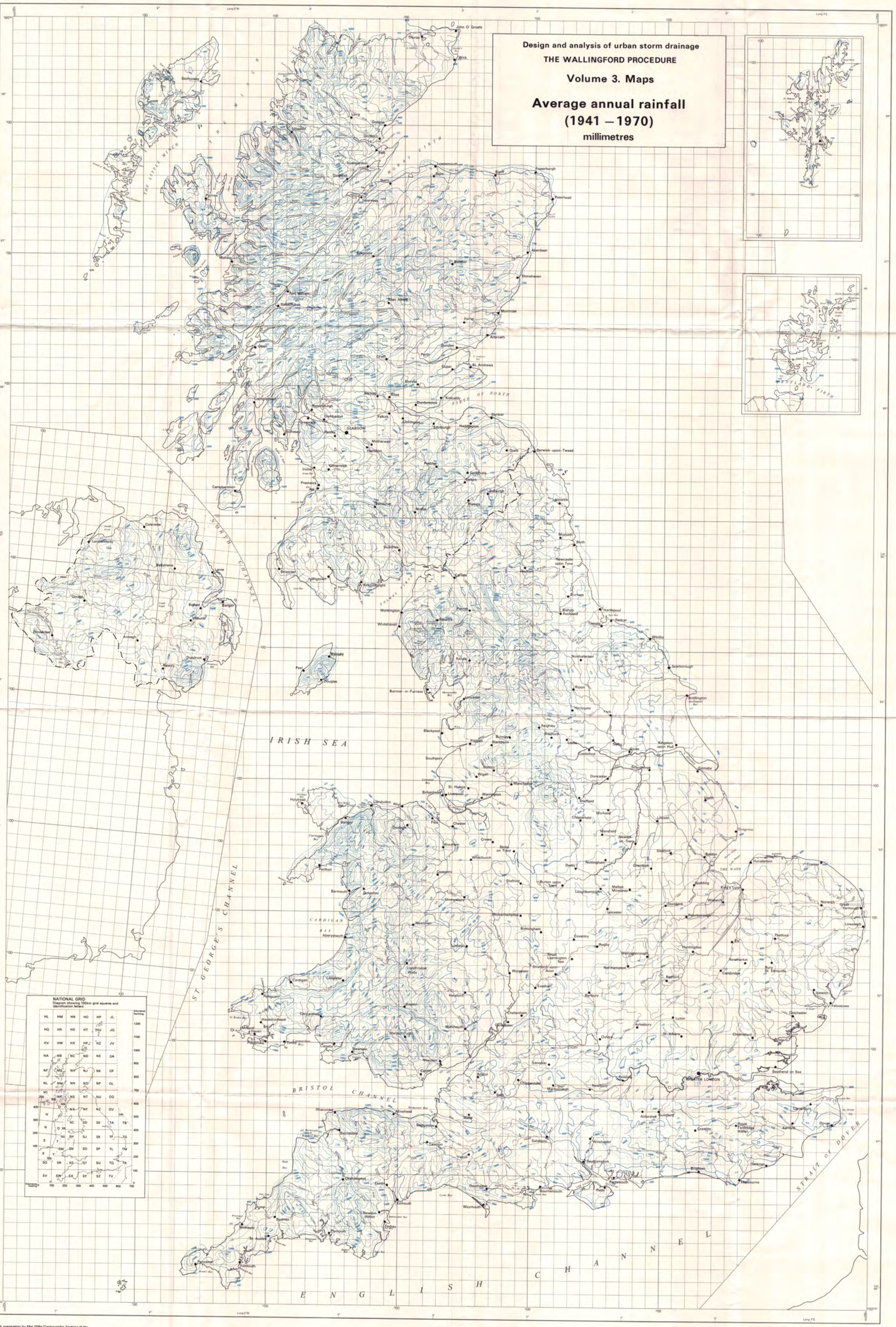


Figure NA.6 — Historically derived maximum constant rate rainfall intensity for an event of 5 minutes' duration

Appendix B

Rainfall and Soil Maps from the Wallingford Procedure



Artwork preparation by Met 018d (Cartographic Section) of the Meteorological Office for the Working Party on the Hydraulic Design of Storm Sewers.

Published by National Water Council (1 Queen Anne's Gate, London SW1H 9BT) for the NWC/DoE Standing Technical Committee on Sewers and Water Mains. October 1981

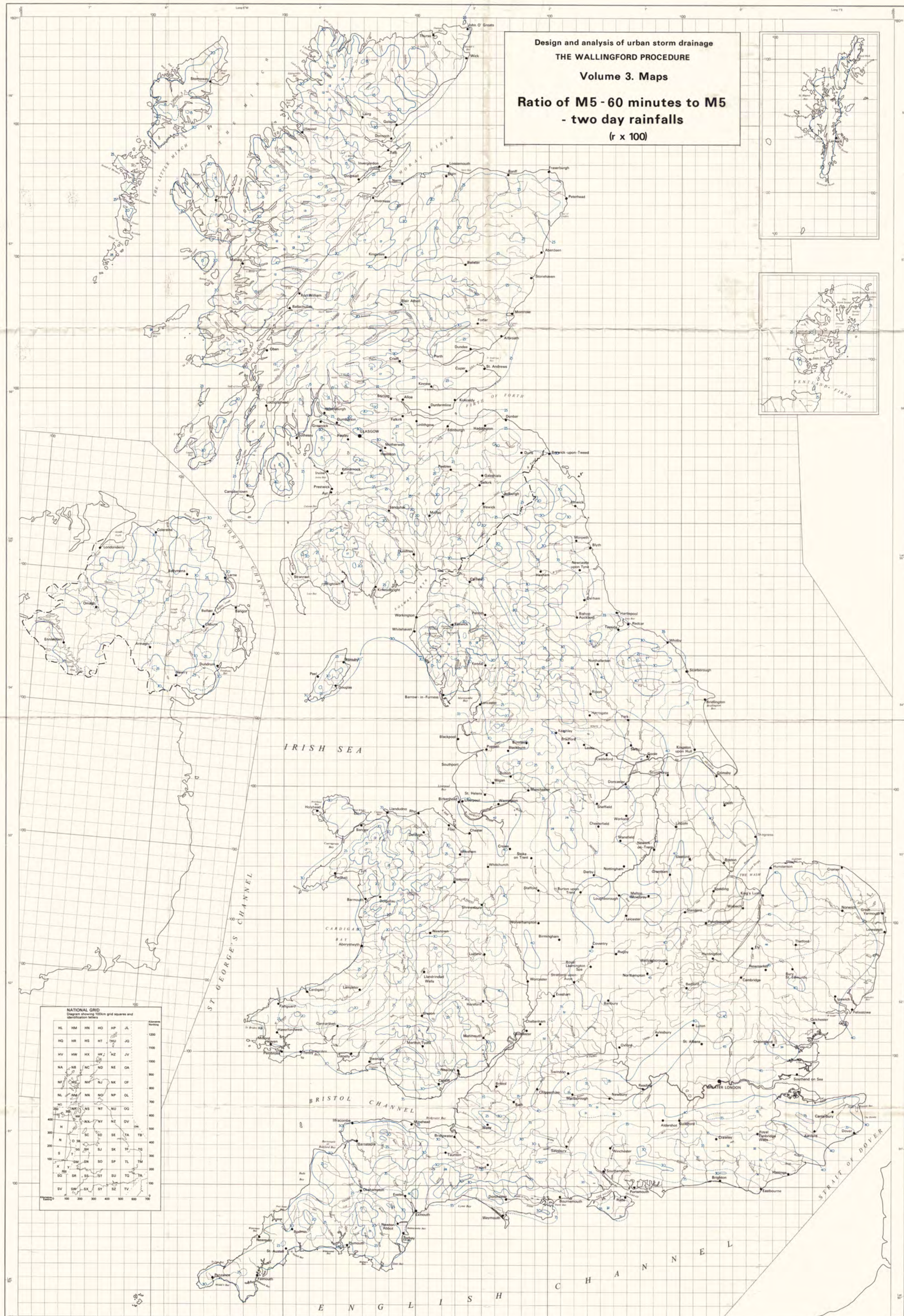
SCALE 1:1 000 000

Kilometres 10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 Kilometres

Miles 10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 Miles

Based on the International Map of the World 1 : 1000 000 sheet NN-30 1965, with the permission of the Director General of the Ordnance Survey.
Printed and Prepared by Cook Hammond and Kell Ltd. London.

Design and analysis of urban storm drainage
THE WALLINGFORD PROCEDURE
Volume 3. Maps
Ratio of M5 - 60 minutes to M5 - two day rainfalls
(r x 100)



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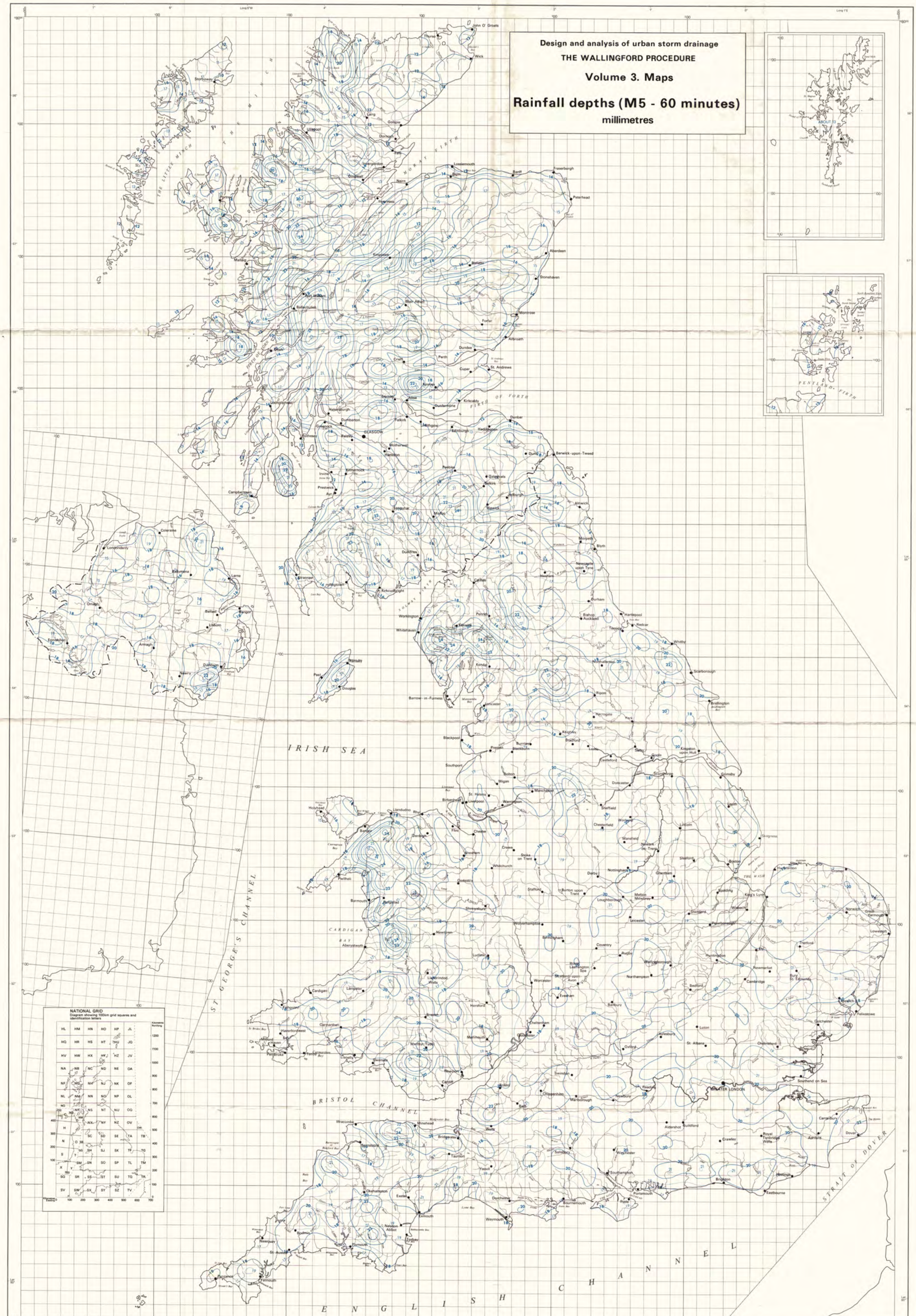

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Miles 10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 Miles

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Map drawn by the Cartography Department Soil Survey of England and Wales 1980 for the Working Party on the Hydraulic Design of Storm Sewers

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