Are rain gauges in the right place?

D. B. Haasnoot

Bachelor Thesis
Q3 2022

Are rain gauges in the right place?

by

D. B. Haasnoot

to obtain the degree of Bachelor of Science
at the Delft University of Technology

Student number:	4897900	
Project duration:	February 7, 2022 - March 28, 2022	
Thesis committee:	Dr. Ir. R. Hut	TU Delft, First supervisor
	Dr. Ir. R. Uijlenhoet	TU Delft
	Ir. J. Aerts	TU Delft

TU Delft

Preface

This thesis was written to conclude my Civil Engineering Bachelor of Science at Delft University of Technology. The research coincides with the work of Dr. Ir. R. Hut in hydrological modeling. The objective is to consider if the inputs used in these models are measured at the correct locations.

A simple geographic and hydrological understanding is useful however not required when reading this thesis. Readers interested in factors affecting rain gauges can find those in chapter 2. Those looking at the specific algorithms should turn to chapter 3. The finer details of these algorithms can be found in appendix B.3.

With thanks to Dr. Ir. R. Hut for the interesting discussions every week and the great supervision throughout the thesis. A thank you to Dr. Ir. R. Uijlenhoet and Ir. J. Aerts for the constructive feedback.

D. B. Haasnoot
Delft, March 2022

Summary

Rain gauges are a powerful tool to measure rain entering a watershed. When water flow through a watershed is modeled, these rainfall measurements are used as inputs. Hydrological models have become increasingly complex as they more accurately represent the physical processes occurring. This is mostly done by increasing the spatial and temporal resolution of the model. As this resolution is increased, the inputs also need to increase. This thesis looks into if rain gauges are in the right place when used as inputs for hydrological models. This has been done by analysing four factors which literature showed to have affect rain gauges.

The four considered factors are: the distribution of rain gauges, the steepness of the slope they are on, the location on that slope and their location within a watershed. For each of these factors algorithms have been developed in Python which compute relevant information on a given station. These algorithms have been applied to 368 gauges across the United Kingdom (UK), available from an open data source.

The rain gauges are well distributed across different altitudes matching the distribution of heights across the UK. Above 400 m there are no gauges and this area is therefore underrepresented. The spacing of stations is good, a few close together and some isolated gauges on islands. The steepness of slopes varies strongly, when a steepness of 25% is used as a threshold only around 3% are on too steep of a slope. A fair amount of gauges are on ridges. Especially those near the coast have steep seaward slopes and thus will suffer from underestimating the actual rainfall. Within watersheds gauges are often near rivers causing other areas of the watershed to be underrepresented, especially areas of higher elevation.

In future research it is recommended to use more gauges in the data set. Secondly focusing on a baseline comparison can help identify which stations are placed incorrectly. Lastly it is recommended to vary the resolution of elevation data and the spatial area considered, focusing on watersheds.

Contents

1 Introduction

Rain gauges are used throughout the world to measure precipitation. Traditionally, rain gauge funnels have been used to collect rainwater which was manually read and recorded, often daily (CIMO, 2017b). For remote areas storage gauges were used which kept water for a much longer period of time, often mountain or desert areas (WMO, 2020). These traditional gauges have been modernised to work automatically, recording the amount of water and sending in real time to a base station. With increasing spatial and temporal resolutions being used for hydrological modeling, the data we input into these models also needs to be of a higher resolution. Advances are being made in ground-based radar technologies, satellite remote sensing and microwave link attenuation to measure amounts and type of precipitation. These novel methods measure rain indirectly, for example through radar reflection or the attenuation of microwave signals. They are real time methods that can be quicker, however rain gauges measure the actual rainfall on the ground. This actual rainfall is then used to calibrate the other methods, such as done by Gyasi-Agyei, 2020. The calibration is therefore as good as the data collected from the gauges.

The aim of this research is looking into the location of current rain gauges and whether they are in the right place when used as inputs for hydrological models. The main research question to be answered is *"Are rain gauges in the right place when used as inputs for hydrological models?"*. To answer this the sub-question posed is *"What factors affect rain gauges? "*. Using these factors a spatial analysis will be conducted using Python and Geographic Information Systems (GIS). The current location of rain gauges in the UK will be considered and tested according to the factors whether they are correctly placed.

This thesis starts with a literature review found in chapter 2. The methodology used to explore the factors from the literature review are found in chapter 3. The results of these analyses are then presented in chapter 4. The conclusions can be found in chapter 5.1. These conclusions are then discussed and corresponding recommendations are given in chapter 5.2.

2
Literature Review

To answer the question ”are rain gauges in the right place?”, a literature review was conducted into the factors affecting rain gauges. This is done by looking at the regulations, then at the local factors and finally those affecting where water falls in a watershed.

2.1. Current requirements for placing rain gauges

The World Meteorological Organization (WMO) is a United Nations agency responsible for the exchange of atmospheric data between countries. They streamline the process of transferring data to allow accurate weather data and model predictions to be made available globally for various purposes (WMO, 2016). To ensure the data is consistent throughout the world, the CIMO (Commission for Instruments and Methods of Observation) create guidelines (CIMO, 2017b).

Chapter 6 of these guidelines concerns the measurement of precipitation and describes the current standards for instruments. Globally different approaches have been taken to account for local factors. The dimensions and height above ground of the gauges vary according to local standards (CIMO, 2017a). The Guide to Hydrological Practices expands on the CIMO guide citing 0.3 m above ground as a standard in most countries, but 1.0 m when splashing and snow effects are not applicable (WMO, 2020). The area of the orifice also varies per region, most using between 200 to 500 cm^2 (WMO, 2020). The use of upright cylinders with an orifice placed at a given height above the ground is used throughout the world (CIMO, 2017a).

In the 1970s and 1980s many studies were done into different precipitation gauges (Sevruk and Klemm, 1989). Studies covered 136 countries with 50 types of standards. Wind and bird protection screens are mentioned as being a difference across standards of gauges. In the modern CIMO guidelines the reference gauges are chosen due to their ability to deal with wind interference. This indicates wind to be a large contributor to errors (CIMO, 2017b). In the Guide to Hydrological Practices, the World Meteorological Organisation (WMO, 2020) further says air flow over the gauge should be horizontal with little turbulence and a low wind speed. To achieve this a site with uniform vegetation is preferred where possible. The height of this vegetation should be at least half of the distance from the gauge to the surroundings, but not more than that distance. This ensures that the gauge is sheltered, but the surroundings do not intercept rain (WMO, 2020). This is simplified in the CIMO (2017a) guide based on the height of the gauge. No objects should be within a radius around the gauge of twice the height of the gauge. When wind protection by vegetation is not possible the Guide to Hydrological Practices states that objects should be at a distance of four times the height of the gauge (WMO, 2020). Wind shields can effectively be used when little protection is offered by the surroundings. All shields still cause some error (WMO, 2020).

Aside from objects, the terrain slope is also a factor mentioned by Sevruk (1992), as often wind will effect how precipitation ends up in an upright gauge on a sloping surface. The CIMO guide for this reason regards sites on slopes and roofs as unsuitable (CIMO, 2017a). To conclude, it mentions that ground-level gauges are preferred due to low wind interference, but with a warning for in-splashing. For ground-level gauges a grid can be used to reduce splashing in. For raised gauges, hard surfaces should be avoided as rain splashes up more (WMO, 2020).

Aside from wind influences, evaporation can be of some influence, but is limited to models with removable funnels (Sevruk and Klemm, 1989). By adjusting the gauge design to limit ventilation and reduce external heating, evaporation losses can be minimised (CIMO, 2017a).

The bulk of the guide however is the description of how the gauges should be taken into account and what design considerations should be made for the gauge itself, rather than its placement.

In summary: for the purpose of this research we will focus mainly on rain gauges with their orifice at 0.3 m above ground level. The gauges should have a spacing from surrounding objects of at least twice the height of the gauge. The surroundings should be of uniform elevation and height.

2.2. Current placement factors concerning rain gauges

This section will explore what factors have been considered when looking at the optimal design of rain gauge networks, first highlighting the distance between gauges and then considering other spatial analyses.

Spacing and number of rain gauges in an area is a factor to consider. Using a statistical analysis, when using long-term averages, often only two gauges per watershed are needed if they are correctly placed according to Eagleson (1967). However, long-term averaging could be enough for simple models but more detailed hydrological models require more data points to accurately predict water levels. When considering thunderstorms in Arizona, Osborn et al. (1972) found that a spacing of 300 m between each gauge would be optimal. This however is often too expensive, and thus a middle ground between cost and density was found in that research in 1972. They found that watersheds up to around 50 hectares could for 1972 standards be serviced by a single gauge spaced centrally. Another factor is the shape of watershed, which affects where to place the gauges. This can be summarised to a spacing of 2 km between gauges or roughly 4 $km^2/gauge$ (Osborn et al., 1972). A similar modern study done in Queensland using radar technology yielded an average gauge density of 25 $km^2/gauge$ (Gyasi-Agyei, 2020). This however was a single area and still had daily variability which was left unaccounted for, citing more research is needed in order to account for local effects such as terrain and local variation in rainfall. This research was radar-based and statistically analyses to see how many gauges are needed to agree with radar rather than considering physical factors.

Aside from spacing other factors can also be considered when looking at the placement of rain gauges. A study using Geographical Information Systems (GIS) for Pakistan used elevation, slope, land use and the number of current gauges to investigate the new optimum (Sadiq et al., 2019). Another spatial analysis used a similar multi-criteria decision analysis to fit a GIS model to the Xicheng District of Beijing. Here distance from high-voltage wires, roads and buildings were used to find suitable sites. As starting point the vast number of public toilets and garbage houses were used. These sites were ranked according to the aforementioned factors to find the most suitable (Fu et al., 2016).

2.3. Variation of rain in watersheds

In order to obtain the best data for a given area, the location needs to be representative of that area. Local factors in a chosen site can effect this. Therefore the sub-question to explore is: *"How is rain distributed across a watershed?"* which will then lead to answer *"What is an optimal placement of rain gauges?"* to further explore the research question.

Rainfall has a high spatio-temporal variability by nature. Water droplets do not fall as one uniform curtain but instead can vary largely across a watershed. Rainfall is not constant with time either and varies daily, monthly and yearly. Orographic changes often also have effect on this. The essence for this research is to look into where we need to measure in order to get a representative sample of rainfall, therefore we must also take this into account. To do this a few case studies have been considered.

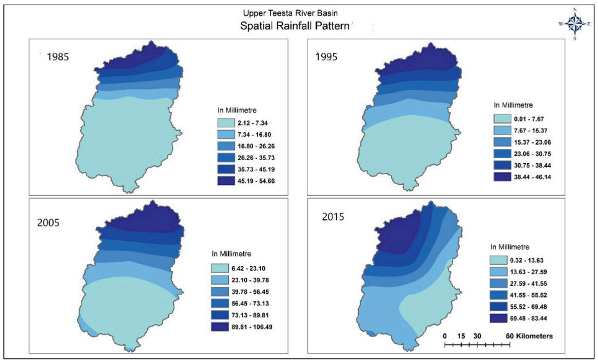
2.3.1. Spatio-temporal variations in India

Kumar (2021) showed past rainfall data gives an insight into spatio-temporal changes within the Sikkim watershed in India. The decadal variability in the area can be seen when looking at data between 1985 and 2015. A spatial variation can also be observed that stays fairly constant. Both can be seen in figure 2.1a (Kumar, 2021). This could imply that whilst data shows that currently an area is represented well by a network of gauges, changes in rainfall patterns could change that in decades to come.

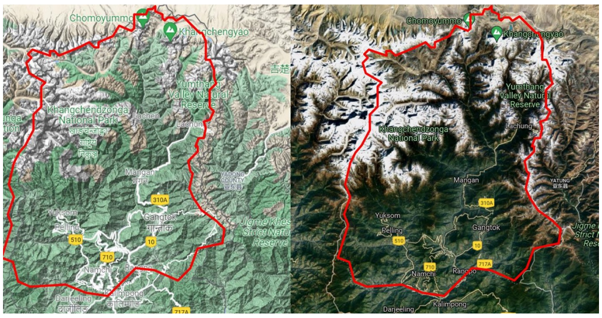
Comparing the rainfall pattern to the height and relief map in figure 2.1b we see a rough similarity between the increase in elevation and the amount of rain. As elevation increases, so does the rainfall.

The method used to create figure 2.1a uses interpolation so some detail will be lost. The reason for this mentioned by Kumar (2021) is the change in path which the thunderstorms take. These account for 70% of the annual rainfall. The combination of figures 2.1a and 2.1b could suggest that in this case the direction of prevailing wind can affect how thunderstorms progress and thus how they precipitate across a watershed. This shift in winds around India is somewhat explored by Sun et al. (2021) when looking at Regime shift in the decadal variability of the Indian Ocean subsurface temperature. More research into the impact of climate change and decadal variability on reliable rain gauge data could be interesting. However this falls outside of the scope of the research question.

In summary, literature shows clearly that elevation and prevailing wind affect where most of the rain falls within a catchment.



(a) Figure from Kumar, 2021, showing spatial rainfall distribution across the base of Himalaya mountains in Teesta watershed, India.



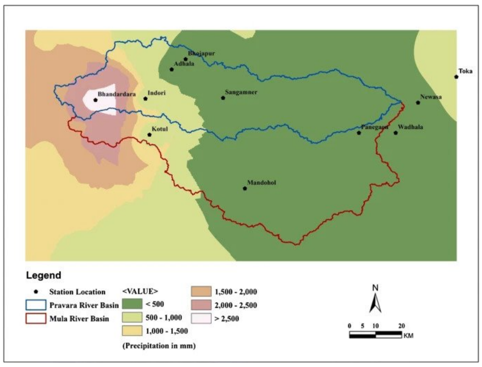
(b) Relief and satelite view of Upper Teesla River basin from "Google Maps", 2022 with highlighted watershed boundary.

Figure 2.1: Figures showing Upper Teesta watershed, India.

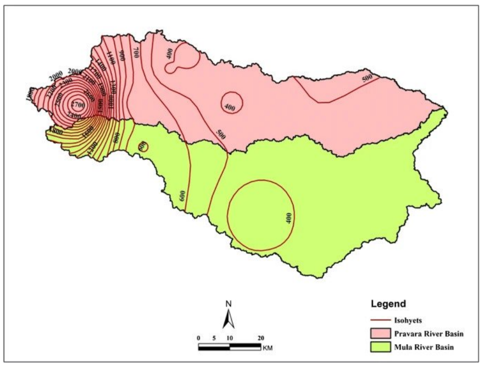
2.3.2. Spatio-temporal variations in Pravara-Mula River Basin, India

In a different part of India, closer to the east coast, a similar case study was conducted with 11 rain gauges for data between 1976 and 2006 (Kharake et al., 2021). The focus was mainly on the monsoon months which, as mentioned previously, accouns for most of India's rainfall. As seen in figure 2.2a and 2.2b a similar pattern emerges. The higher elevation areas seem to experience more rainfall and areas of similar elevation experience similar levels of rainfall. Both cases are however in the monsoon period and in a country where seasonal rainfall is dominant. This is known as relief or orographic rainfall and is a known hydrological concept (Rodrigo-Comino, 2021).

In summary, this case study confirms that elevation has an effect on the spatial variations of rainfall.



(a) Average precipitation data (mm) during 5 months monsoonal period for Pravara and Mula watersheds

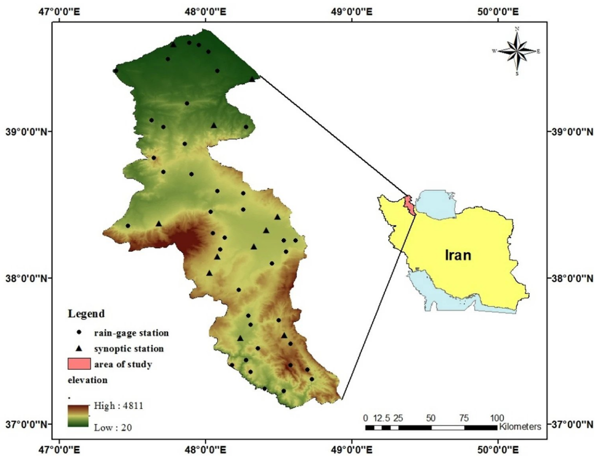


(b) Height above sea level (m) for Pravara and Mula watersheds

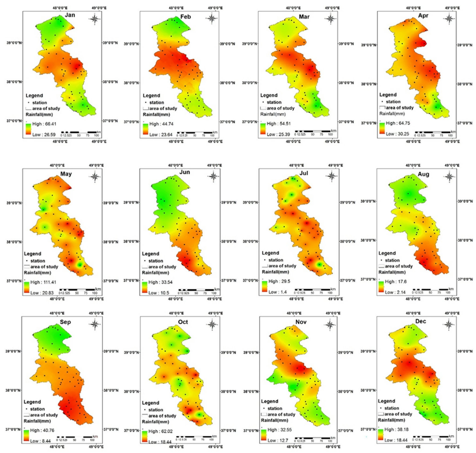
Figure 2.2: Both figures obtained from Kharake et al., 2021.

2.3.3. Spatio-temporal variations in Ardabil province, Iran

On a larger scale, a whole province can also be considered. In a study in Iran, 40 rain gauges were used to consider the variations in temperature and rainfall through the seasons (Ghorbani et al., 2021). Here temporal variations on a monthly scale were considered, showing seasonality had a strong effect as seen in figure 2.3b. Figure 2.3a shows all the stations which were used in generating the thematic maps. One observation is that we again see that areas of similar elevation tend to show similar readings. The upper part of the province experiences a uniform amount of rain and also had a lower constant elevation. An interesting observation is that in May, July and October we see circles of higher rainfall around a few observation points. This shows a break in the trend of otherwise medium to low amounts of rainfall, suggesting there are too few data points to fully capture the trend. The total land area of the province is 17 800 km^2 ("Iran National Census", 2011), averaging to only one gauge per 445 km^2, much more than discussed in chapter 2.1. The spatial trend indicates that altitude shows a relation with rainfall, although it is not the only factor at play. The scale on the facets is different, better visible in appendix A.1. The figure is showing only the relative difference per month rather than over all changes in the whole year.



(a) Location of Ardabil province within Iran and relief of the land



(b) Monthly rainfall distribution in mm for Ardabil province

Figure 2.3: Figure obtained from Ghorbani et al., 2021.

Comparing figure 2.3a and 2.4 information can be extracted about the current location. The province mainly has north to south spanning roads. With road access, often other infrastructure follows and the current gauges are clustered around these roads. With many near to the main roads and few branching off from them. Also higher concentrations near the province capital (also called Ardebil).

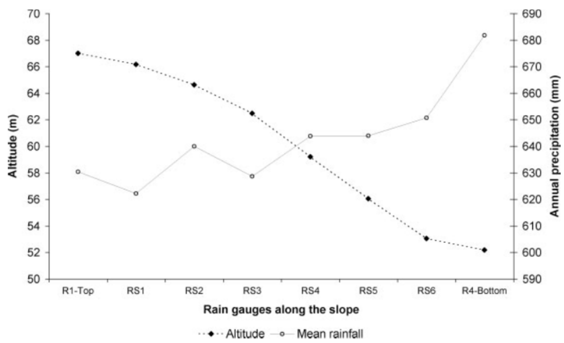
Figure 2.4: Map view of Ardabil province showing general layout of the provice, obtained from google maps "Ardebil · Iran", 2022.

In summary, in this case study we again see a relationship between elevation and rainfall, however more nuanced as we also introduce time as a variable. In some months there is more spatial variation whereas others have more uniform distributions of rainfall.

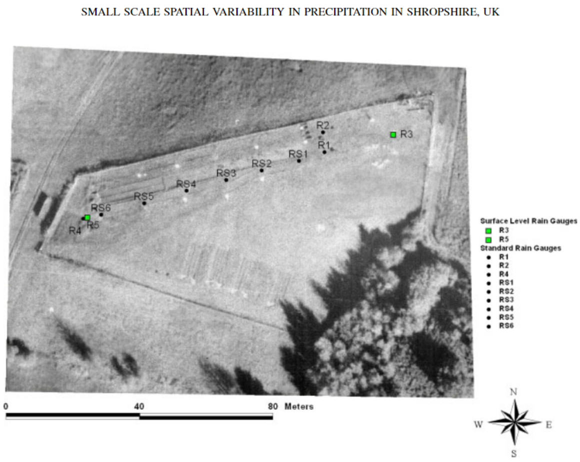
2.3.4. Spatio-temporal variations in Shropshire, UK

On a smaller scale, variation on a slope also occurs. Research between 1982 and 2006 across 12 gauges on a single slope in the UK, seen in figure 2.5b, found significant differences in measured precipitation. The gauges at the bottom receive more rain than those at the top as seen in figure 2.5a.The difference between surface-level and standard rain gauges was also measured. Surface-level gauges are more sophisticated and are less prone to interference due to wind. A significant difference at the hill top was observed, air turbulence being mentioned as the main reason for this. Whilst at the bottom the effect was not apparent: both the surface level and raised gauges measured the same amount of rainfall (Subedi and Fullen, 2009). The bottom of steep slopes, around 15° or 25%, had 2.5 - 8% more rain recorded.

In summary, even when considering larger areas, the local effects of slopes cannot be disregarded. Relatively uniform sites need to be chosen.



(a) Mean annual precipitation across 8 gauges on a slope, showing the difference between a ridge and a valley.



(b) Site plan of gauges used to collect rain data for 25 years in Shropshire, UK.

Figure 2.5: Both figure obtained from Subedi and Fullen, 2009.

3

Methodology

Based on the knowledge from the literature review in chapter 2 factors were identified. Subsequently the study area to study these factors is outlined and the algorithms used to explore the factors are explained.

3.1. Study area

The focus of the research needs to be defined geographically to limit complexity. The United Kingdom is a good location for this research, mainly due to the availability and length of data records.

The United Kingdom' meteorological organisation ('the MET Office') has a combination of hourly and daily rainfall records. Hourly records date back to 1915 and daily as far as 1853, both can be found on Centre for Environmental Data Analysis website ("The CEDA Archive", 2022). The data set contains current and past records,currently a total 368 gauges, which can be seen on figure 3.1.

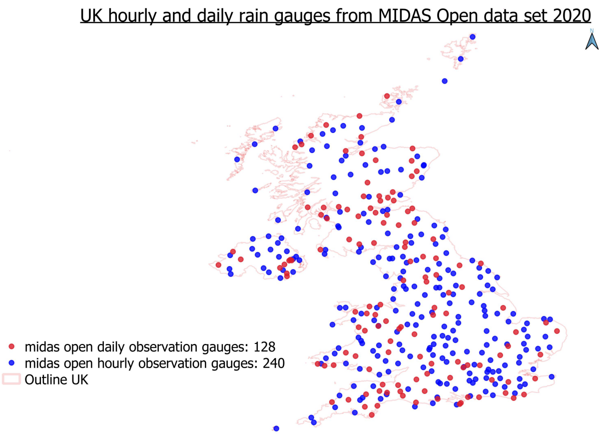


Figure 3.1: Hourly and daily rain gauges across the UK, made using data from "The CEDA Archive", 2022 in QGIS.

With the factors gathered from literature, the next steps are to then find the theoretical ideal location given a watershed. For these locations the literature needs to be converted into tangible requirements.

3.2. Choice of factors

Working through the literature review systematically, chapter 2.1 shows that gauges should be isolated from other objects to reduce interference from wind. Given the focus is mainly on rain gauges at a height of 0.3 m, a radius of 0.6 m should be kept free. Hard surfaces are to be avoided and the surroundings uniform in height and elevation. For this land use and height data can be used, available through the

Ordnance Survey ("OS Data Hub", 2022). In Summary: a site with a radius of 0.6 m free of obstructions and a surrounding of uniform height and elevation.

Chapter 2.2 considers factors used for optimum placement. When looking at spacing, in theory more data points is better for modeling. Estimates vary for an optimum, the UK currently had roughly between 1500 - 2000 daily gauges. The exact amount varies depending on the time series needed. 1524 have been recording for at least 30 years. When considering data from 2021, 2348 stations had recorded daily amounts of rainfall some time in history. This roughly means there has been one gauge per 100 km^2, given the UK has a surface area of 243 610 km^2 ("Worldbank Data", 2022).This would infer a spacing of 10 km between each gauge. Considering that spatially rain can very a lot, even across short distances, enforcing a minimum distance of 10 km might not be optimal. More gauges will always be more accurate, however if gauges are too close together we might over represent certain regions if others are spaced more. Roads and buildings can also be used when finding placements for gauges as done in some urban studies, which ties into the land use factor already mentioned.

In Summary: the spacing distribution should be investigated, and compared to a perfectly spaced grid.

Chapter 2.3 looks at four case studies considering spatial-temporal variability of rain in watersheds. Orographic effects and prevailing wind direction seem to be a large factor in India. This is seems to be further confirmed by the Iranian study where areas of similar elevation have similar rainfall amounts. Lastly the UK study into variations on a slope mention that over 25 years, the bottom of the slope had significantly more rain and was more consistent compared to a surface-level gauge. All sections consider a watershed or province as study area. This shows the scale which should be considered.

In Summary: Orographic effects have shown to contribute to rainfall distributions, where constant altitude often means constant rainfall over longer periods of time. The slope has a large effect on the amount of rain measured mainly due to the wind and air turbulence. Therefore slope angles should be considered. Locations within watersheds should also be taken into account.

These three sections can be summarised into figure 3.2. The factors to be considered are shown in the upper part of the figure. The lower, in italic front, are outside of the scope, namely due to the scales being very different. Distance to a building or roads looks at a small scale whilst the relative location on a slope is much larger. Another factor is the positions of rain gauges obtained from "The CEDA Archive", 2022 which only known to 3 decimal places. This is an accuracy of around 100 m. The contour line data from "OS Data Hub", 2022 is in increments of 50 m, thus on a similar scale to the position of the gauges. Land use could be interesting for further research but due to time restrictions fell out of the scope of the research.

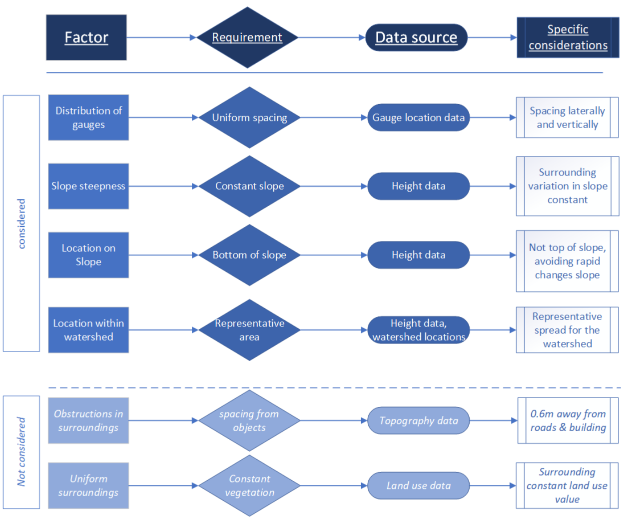


Figure 3.2: Flow chart showing factors from literature, at top those chosen to implement, and at the bottom those discarded.

3.3. Example of manual analysis

Given the factors in figure 3.2, these can then be investigated in several ways. Initially the analysis was first done in QGIS manually, as shown bellow. Python can be used to speed up the process. It could also be done manually, more human insight can be used to accurately consider every site. Once the algorithm has been developed and tested, it is much faster and can be applied in many more areas. The following sections of this chapter will outline the algorithms used.

The Ordnance Survey has many forms of maps available showing buildings and other features. This is all the data needed, however it is a lot of data to analyse at once. First a small segment was analysed, to then generalise the process. For this, the Lake District area was chosen arbitrarily, which falls in the county of Cumbria. Within Cumbria, Newton-Rigg was chosen randomly to analyse first.

Slope steepness and altitude can be found by measuring distances to the contours as shown in figure 3.3.The distance between two closest contours measures 429 m, meaning a slope of around 12%, as each contour represents 50 m of height variation. When considering the surrounding area, this seems an acceptable slope, anything more than a 25% could be considered too steep. The direction of slope can be measured, giving a bearing of 040°, thus facing north east.

A height map might be more useful compared to contours as the direction is inferred from the surroundings rather than from the contour data. Woodlands are far away so the land use surrounding it is acceptable. This would be an example of a site in a good location as all the requirements are met.

In summary, steps taken to analyse a site: Measure slope steepness, location on the slope and bearing. Check if these are all acceptable compared to the region and other sites.

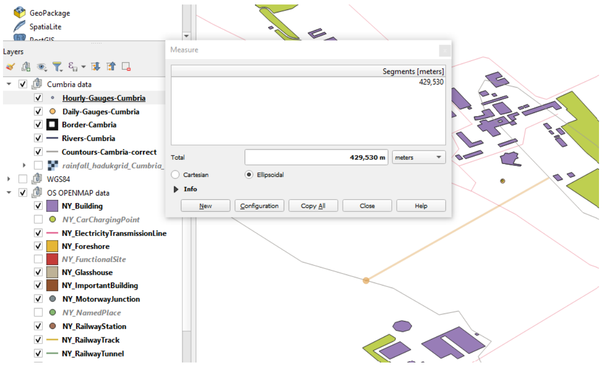


Figure 3.3: Screenshot showing process of manually measuring distances between contours in QGIS, data obtained from "OS Data Hub", 2022.

3.4. Rain gauge distribution

The relative placement of rain gauges has several implications when using rain gauge data in modeling. In this chapter methods used to obtain the elevation distribution and the spacing distribution are presented

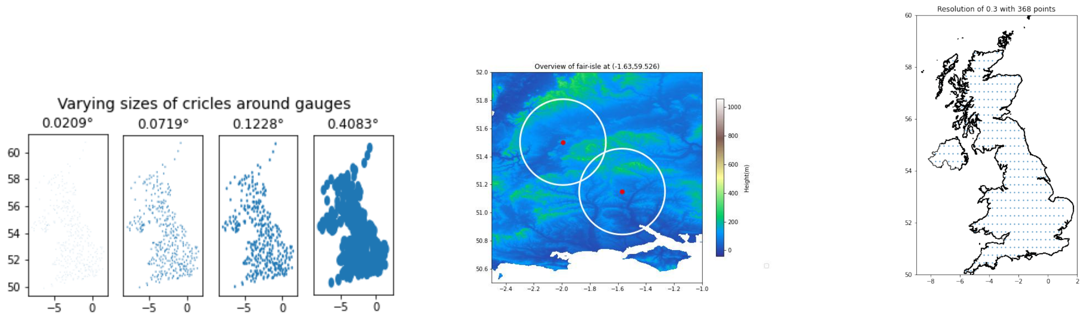
3.4.1. Elevation distribution

The stations from "The CEDA Archive", 2022 each contain meta data describing the location of the station. Among this is elevation data. This can be used to compare the elevation to that of the whole of the UK. A Digital Elevation model can be obtained from "HydroSHEDS", 2022 as described further in section 3.5.2. The distribution of total elevation and station elevation can then be compared.

3.4.2. Spatial distribution

Using the locations of the rain gauges we can also look at spacing between gauges. The distance between every rain gauge pair can be found using the GeoPy package with the geodesic function. These results can then be sorted to find the closest gauge and filtered according to the required threshold. To simplify programming, all the combinations were used between stations. This results in a fairly expensive computation, at time complexity $O(n^2)$. Although expensive, this was judged to be faster than optimising it to only select neighbouring gauges.

Another way is to use a buffer around the gauges. Here the Geopandas package is used to draw a radius around a point. The size of this radius can be increased as shown in figure 3.4a. This was done between 0 and 0.5 degrees. For every size radius the overlap between two drawn circles can be calculated. This is shown in figure 3.4b. This is a measure of how uniformly the gauges are distributed across the terrain. As a comparison, the same amount of points were spaced at 0.3° apart within the UK as show in figure 3.4c. The algorithm was then also run for this set of points.



(a) Variation of circle sizes drawn around all the rain gauges in the UK.

(b) Overlap between two neighbouring stations in the south of England.

(c) Base line comparison of fictional station spaced at 0.3°.

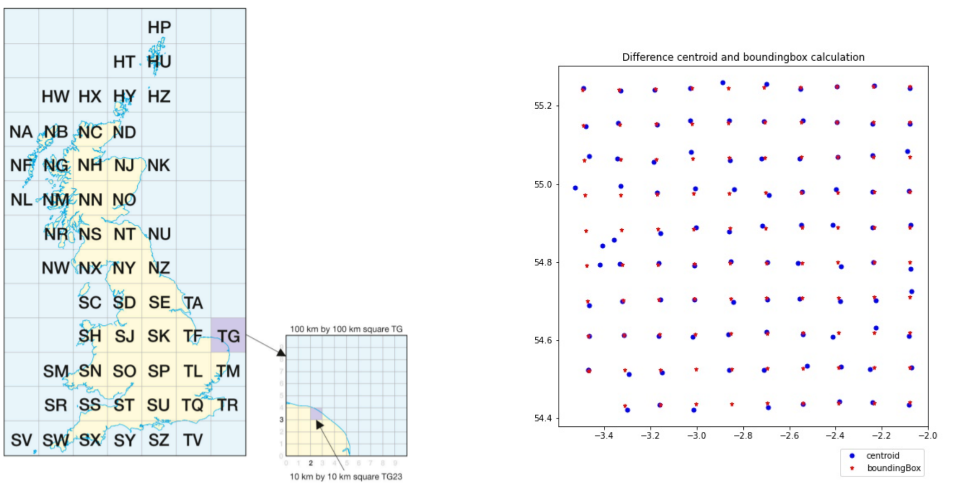
Figure 3.4: Created in Python with data obtained from “The CEDA Archive”, 2022 and “HydroSHEDS”, 2022.

3.5. Slope steepness

To consider how steep a slope is, topographic data is needed. Topographic data show three-dimensional relief data on a two-dimensional plane. This is achieved by the use of contours which shows the changes in height at a given interval or by the use of Digital Elevation Models (DEM) where every pixel has a given height.

3.5.1. Using contour maps to calculate slope steepness

Using open data from “OS Data Hub”, 2022 allows the use of a contour map with 50 m height intervals. 5 m intervals also exist however are not openly available and would make the data set even larger. The data is split into grid section as can be seen in figure 3.5a. The splitting of data means only the sections needed are loaded in at a given time, improving computing times. Figure 3.6a shows such a grid loaded into python and displayed.



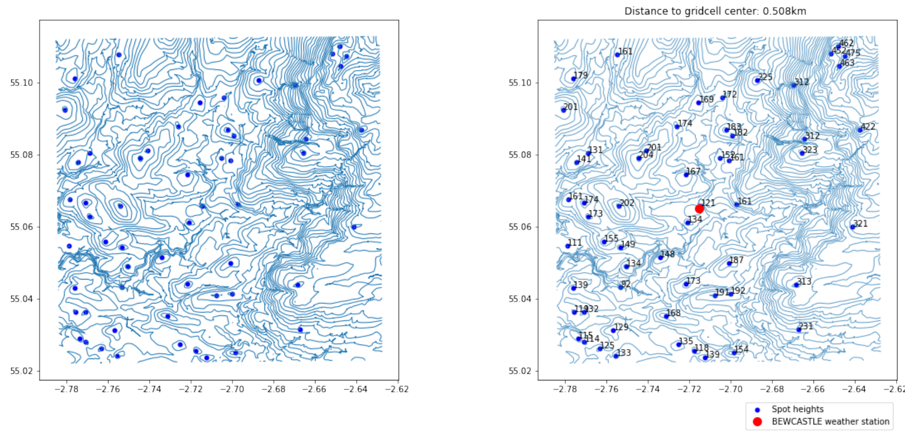
(a) Figure from OS Terrain 50 user guide showing the grid system used for mapping the United Kingdom

(b) Difference between using spotheights to determin the centers of grids and using contours to compute grid centers

Figure 3.5: Created in Python with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022.

In order to match a rain gauge to the corresponding grid, the centre point of the cell is calculated and stored. This was done using spot heights rather than the contours themselves as it took just 16 seconds, whilst the contours took 107 seconds for one 100x100km grid. As seen in figure 3.5b, on average the difference is not very large. Although using the bounding box of the contours is more accurate, the increased accuracy is not justified given the extra computation time. With the center of every grid cell, distances to each gauge can be calculated and the smallest distance used to pair a gauge to its grid cell. Figure 3.6b shows a gauge plotted with its corresponding contours surrounding it. One major downside was some gauges were on the border between grids. These were filtered out by removing gauges further than 5km from the center of a grid, given one grid cell is 10 km. Ideally two grid cells would be combined, however this optimisation was considered too costly given limited time and computing power.

Once the correct grid cell is selected, the data can then be narrowed down to the given slope. This was done by looking at the closest contours. Here the same computational choices are made as when selecting the center of a grid cell. Looking at all the points on a line segment would be too expensive. Instead the centers of the segments were used (green dots in figure 3.7a). With roughly 400 line segments per 10x10 km grid cell and 5500 grid cells across the UK, simplifying this search saves a lot of computational power. From testing on the Cumbria data set also used in section refsection:manualAnalysis, taking the 10 closest contours per rain gauge gave good representation of the surroundings of the slope as seen in figure 3.7a. Selecting more segments makes the operations more expensive and could mean different slopes are being considered. If too few are selected, vital information could be left out. Considering a total height difference of 500 m also gives a fair representation of the surrounding area.

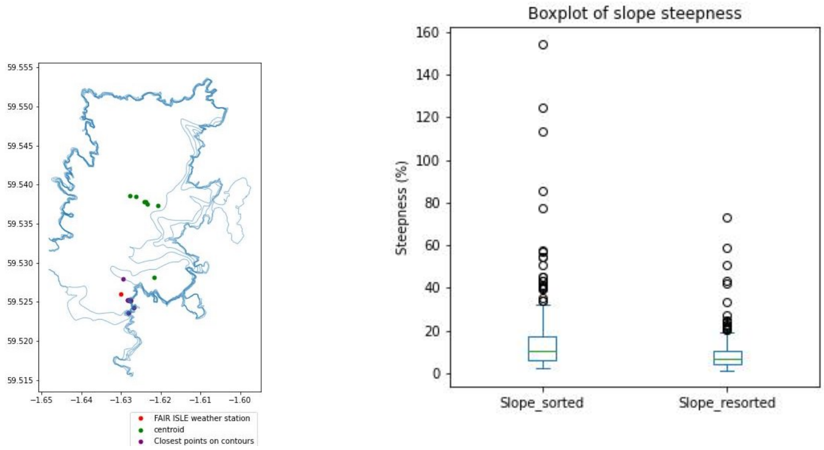


(a) One 10x10 km grid cell of contours and spot heights

(b) Same 10x10 km grid cell, but with the corresponding rain gauge and height labels added to the spot heights

Figure 3.6: Created in Python with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022.

With the selected contours, the closest point to the gauge on the line was projected (purple dots in figure 3.7a). These points give us information about the slope closest to the gauge itself, rather than other areas which the contour covers. The distance between each of the contours represents a change in height of 50m, meaning the distance apart allows the calculation of slope steepness. The points do need to be ordered, as the distances between neighboring contours needs to be considered. This was initially done by the sorting according to the distance from the contour to the gauge. More accurate is to sort the contours by distance apart. This was done by starting from the furthest contour and each time looking for the next closest contour. The difference between the initial sorting and the resorting can be seen in figure 3.7b. We see that resorting has less outliers and a smaller spread in results, thus the resorting method was used.



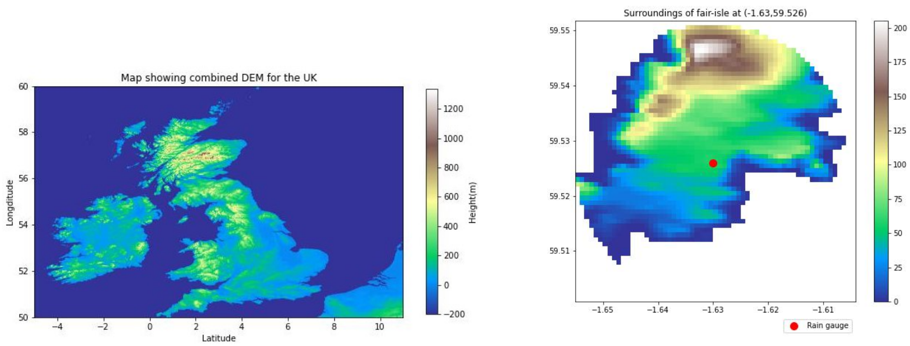
(a) The ten closest contours being selected with corresponding centers (green) and points closest to the gauge on each contour (purple)

(b) Difference between the two sorting methods. Left sorted by the distance to the contour, right when sorted by closest distance to neighboring contour.

Figure 3.7: created in Python with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022.

3.5.2. Using Digital Elevation Model to calculate slope steepness

Similar steps were used as in section 3.5.1, however a Digital Elevation Model (DEM) is raster data. This means every pixel on a map has a given value, in this case height. This data is available for the whole world in several resolutions from “HydroSHEDS”, 2022. The void-filled elevation is used, here water bodies are cut out of the model and set to a height of -3000 m. The DEM has a resolution of 3 arc-seconds, this translated to between 60 m for the lowest latitude of 50°N and and 45 m for highest of 59°N respectively. In some cases this causes issues when gauges are too close to water bodies as seen in figure 3.8b. When considering slopes this problem disappeared as the surroundings were considered, and any sections less than 0 m were discarded. From the Europe data set the grid cells containing the UK can be selected. This can be seen in figure 3.8a. Using the bounding box of the grid cells, each gauge can be matched to a grid cell. As every raster has its bounding box stored as a value, this can be done very efficiently. To select an area from a raster file, a mask is needed. Using the coordinates of each gauge, a circle or buffer can be drawn around the point of a given radius. 0.025° was chosen, this corresponds to 90 arc-seconds or 30 pixels. This gives enough data whilst keeping computing costs low. The mask can then be used to cut-out a section of the raster. Such a cut out can be seen in figure 3.8b. Three stations were above 60°N or below 50°N and not in the direct data set. These were omitted for simplicity and to keep the data set small.

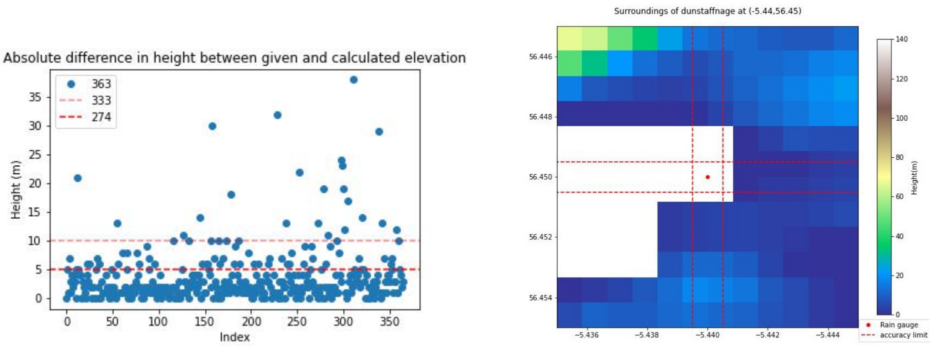


(a) Six DEM grids joined together to make up the of the the UK (limited between 50-60°N

(b) Example of a cut out of the raster data. Here showing the surrounding the rain gauge on Fair Isle in Scotland

Figure 3.8: Created in Python with data obtained from “HydroSHEDS”, 2022 and “The CEDA Archive”, 2022.

The main benefit is that the cut outs of the raster files can be stored and later read individually. This reduces complexity and computing power needed. To check how accurate the DEM is we can compare it to the elevation data provided per station from "The CEDA Archive", 2022. Figure 3.9a shows the absolute difference between the two for the 363 stations. Two stations had a difference of more than 3000 m, these were omitted from this graph but still included as mentioned before. Figure 3.9b shows one of these stations where the DEM places it in the water. These inaccuracies are due to two known reasons. Firstly the inaccuracy of the station coordinates, shown by the red dotted lines as the coordinates of the stations are only accurate to three decimal places. Secondly the HydroSHEDS data itself is shifted to the north and east by 1.5 $arc - seconds$ caused the methods used to compile the data from the original sources which HydroSHEDS relies on (Lehner, 2008). If only one pixel either side was used, a shift of 1.5 $arc - seconds$ would be significant. As described later in this chapter more pixels were used and averaged to compute the slope. This accounted for these discrepancies in the data.

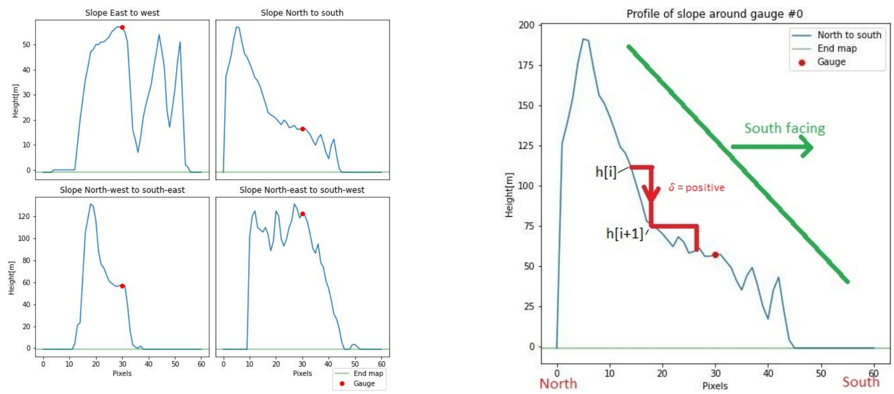


(a) Difference between height computed from DEM and height supplied by the Met Office.

(b) Zoomed in surrounding of Dunstaffnage gauge, showing that there is some error in the positioning. Red dotted lines showing the error in coordinates.

Figure 3.9: Created in Python with data obtained from "HydroSHEDS", 2022 and "The CEDA Archive", 2022.

Once the area is selected, an analysis of the slopes can be done. The raster data can be accessed as an array, making selection of subsections of the data easy. To limit the scope of the analysis of slope steepness, four directions were chosen. North to south, east to west, north-west to south-east and north-east to south-west. Plots these cross-sections can be seen in figure 3.10a for the same location as the DEM in figure 3.8b.



(a) Cross-sectional profiles of the land in the four directions considered

(b) North to south profile with annotations explaining the naming convention.

Figure 3.10: Created in Python with data obtained from "HydroSHEDS", 2022 and "The CEDA Archive", 2022.

To move from a given cross-section to a numerical value for slope steepness the difference between consecutive pixels needs to be considered.

$$\text{slope steepness is given by } \frac{rise}{run} * 100$$

The run is set to 3 arc-seconds, the resolution of pixels, and the rise can be calculated. Moving from one side to another,a pixel value is taken and the next value is then subtracted from it, i.e.

$$\delta = h[i] - h[i+1]$$

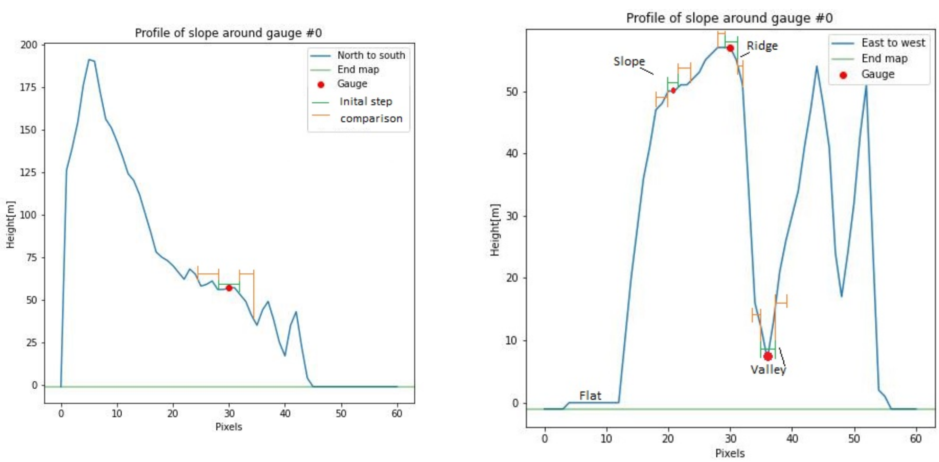
A positive difference implies a decrease in slope whilst a negative difference shows a increase in slope. Combining this with the four directions considered, means the direction the slope is facing can be found. For example, a positive difference when moving form north to south indicated the slope faces towards the south. This is illustrated in figure 3.10b. As wind directions are also given in the same format (i.e. southerly wind means wind approaching from the south), this allows for simple comparison when considering the effect of wind.

Looking at literature, often a whole watershed or province is analysed, spanning tens of kilometers, so in the order of 100 pixels. On the other had the study in the UK considering slopes looked at an area of roughly 100 m (Subedi and Fullen, 2009), so in the order of 2 pixels. Combining these two extremes, 5 pixels was used in the final computation of slopes.

3.6. Location on slope

For the reasons outlined in section 4.2.3, the Digital Elevation Map (DEM) was used for further computations. The algorithms in this section therefore build on the steps taken previously. The main difference is once the slope steepness is calculated, it is then further analysed.

The first analysis was location on the slope, looking at steepness either side of the gauge. This is similar to methods used to numerical find local maximum and minimum points in mathematics. A given step width of pixels is considered next to the interval used to compute the slope. The values on the left and on the right are then compared, as shown in figure 3.11a. The same convention for positive and negative slopes was used as in figure 3.10b. From this we can deduce if there is no change in sign, it must be a slope. If it changes from positive to negative, it must be a ridge. And oppositely if it changes from negative to positive it must be the opposite: a valley. This is summarised in figure 3.11b.



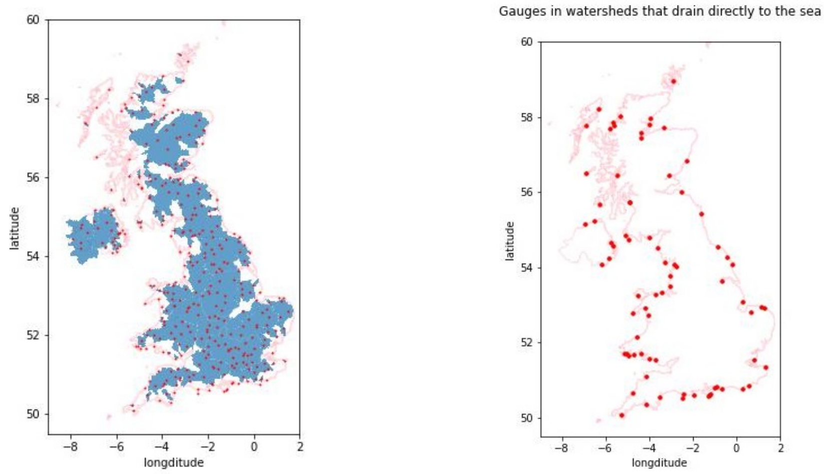
(a) North to south profile with annotations explaining the steps taken when considering location on the slope

(b) East to west profile with the different slope location names and their features

Figure 3.11: Created in Python with data obtained from “HydroSHEDS”, 2022.

3.7. Location in watershed

Placement of gauges within a watershed can effect hydrological modeling. If a gauge only represents a certain part of a watershed, the modelled discharge of a river using rain gauge measurements as input for the hydrological model might differ from observed (i.e. real) discharge. Similar steps were taken as in chapter 3.5.2 to localise an area around a gauge. Instead of taking a circle, the surrounding watershed was used. River data could then be matched in the same way to the catchment. Of all the 61 thousand river watersheds in the UK, only 200 have gauges in them, as seen in figure 3.12a. Only around two thousand are larger than 5 km^2. Majority of these watersheds are very small and have no rivers in them. These drain directly to the sea without passing through a river. 76 gauges are in watersheds like these as seen in figure 3.12b. The combined data can be plotted as seen in figure



(a) UK watersheds which have a gauges in them (blue), and the outline of the UK (pink)

(b) Gauges in watersheds that have no rivers, and thus drain direct to the sea without entering a river.

Figure 3.12: Created in Python with data obtained from “HydroSHEDS”, 2022 and “The CEDA Archive”, 2022.

3.13. This allows any height information to be deduced from any point within the watershed. Selecting the closest point on the river was done in the same way as selecting the contours in chapter 3.5.1. The height difference between the river and gauge can then be computed.

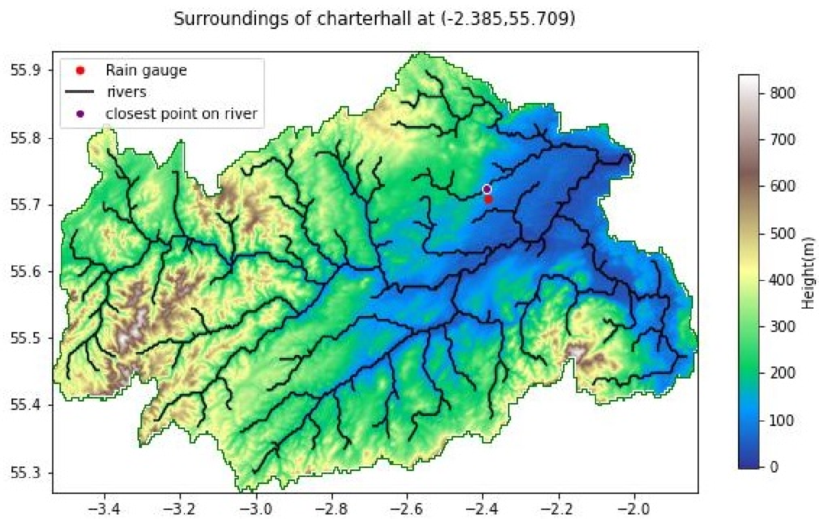


Figure 3.13: Watershed with accompanying DEM, river and closest point on the river.created in Python with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022.

4

Results

4.1. Distribution of gauges

4.1.1. Height distribution

Height distributions are fairly similar when comparing the 68 million pixels making up the united kingdom to the 368 rain gauges. This shows as a whole the gauges are fairly well distributed over the terrain heights. This is true up to 400m, the highest gauge is at 408m. The highest point on the Digital Elevation Map (DEM) is at 1335. This means higher altitudes are under-represented.

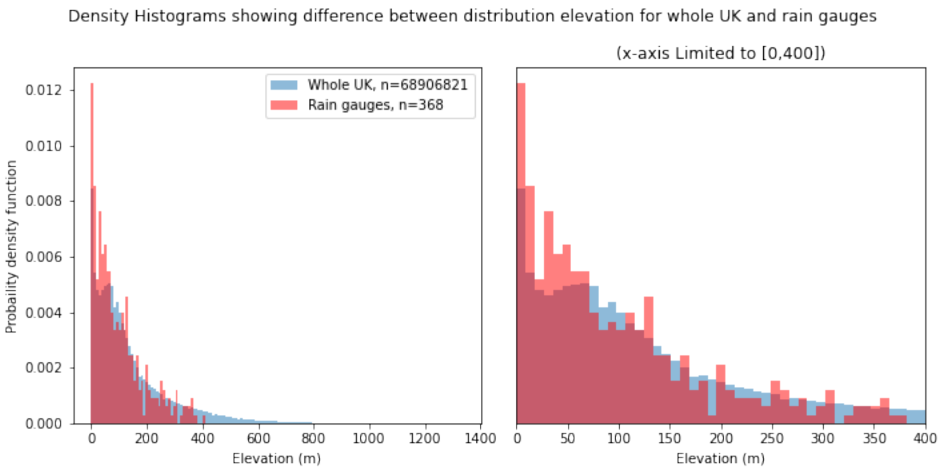


Figure 4.1: Density plot showing distribution of rain gauges elevation compared to total elevation across UK.

4.1.2. Spatial distribution

Figure 4.2 shows that the gauges are fairly well spaced. There is some variation compared to a similar amount of perfectly spaced points. Especially noticeable is that the gauges start to overlap first, meaning some are closer together, however the difference starts to decrease from 0.4 deg on. As a whole the gauges represent the land well.

Looking closer at distances between gauges, 16 gauges are within 5 km of one another. This can be seen in figure 4.3a. These tend to coincide with large cities, such as London. As mentioned in the literature review, stations closer together is not a bad sign, it can lead to an over-representation of a given area.

Figure 4.3b shows stations a distance of more than 40 km apart, highlighting the remoteness of Scotland and the Islands off the coast of the Great Britain. These are mot very new insights as remote areas tend to have less infrastructure and a lower population and also less rain gauges.

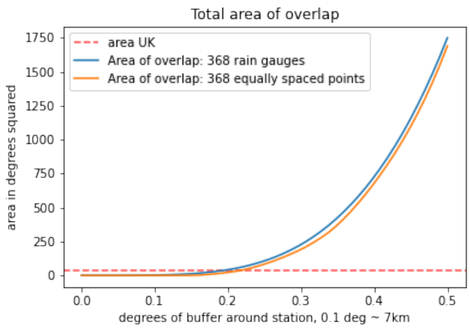
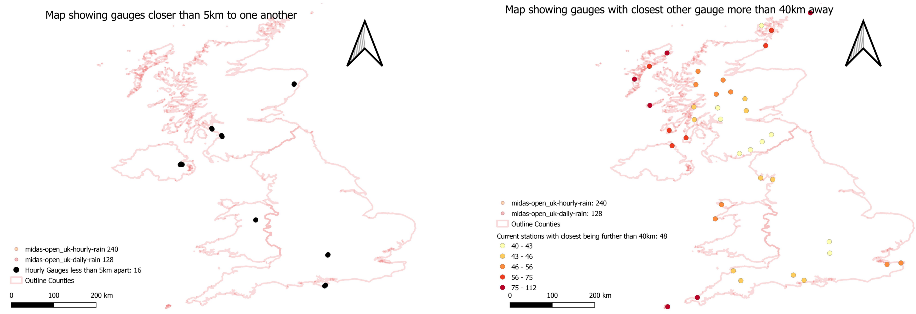


Figure 4.2: Area of overlap when increasing circle sizes drawn around gauges. This is compared with the area of the UK and the same algorithm run for a fictional equally spaced grid.



(a) Stations with closest other station closer than 5km (b) Gauges further than 40 km from closest other station

Figure 4.3: Created in Python with data obtained from "The CEDA Archive", 2022.

4.2. Slope steepness

4.2.1. Slope steepness using contours

The algorithm described in section 3.5.1 was run for the whole United Kingdom. A box plot of the results of the 206 gauges can be found in figure 4.4. 162 stations had insufficient data available because they were on the edges of grids. This could be improved by adjusting on the algorithm to allow gauges on the edges of cells to be used. When looking at outliers, anything about 50% can be neglected. These are artifacts introduced by the nature of the algorithm, in particular averaging.

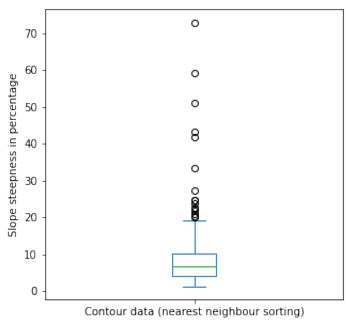
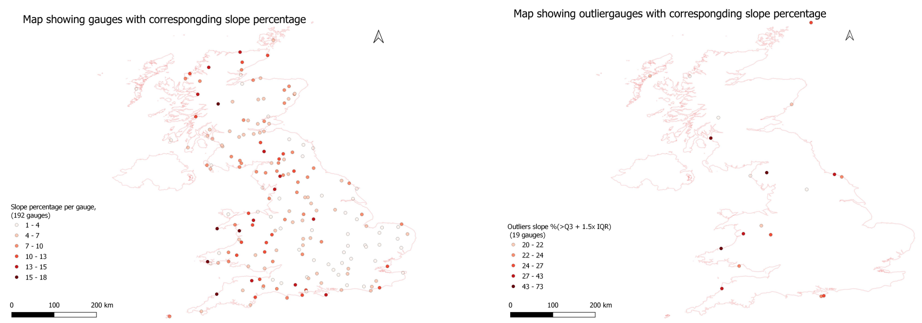


Figure 4.4: All slope steepness data,created in Python with data obtained from "OS Data Hub", 2022 and "The CEDA Archive", 2022.

When plotting these outliers on a map, all but one are near shorelines as seen in figure 4.5b. Looking at the contours here the shoreline in the UK often drops off due to cliffs. This shows that the algorithm effectively isolates cliffs and areas with steeps slopes surrounding the gauges. Removing these outliers in this case is not the best option, however investigating them is useful.

Looking at the map in figure 4.5a we see that the south-east of England has lower slope angles, whilst Wales and up north of England tend to have gauges placed on lower slope angles. This general pattern is not true in all cases, showing watersheds can differ locally. Larger versions of Maps can be found enlarged in appendix A.



(a) Slope steepness from contour data without outliers (genteler than 18%)

(b) Outliers of the slope steepness (steeper than 18%)

Figure 4.5: Created in QGIS with data obtained from "OS Data Hub", 2022 and "The CEDA Archive", 2022.

4.2.2. Slope steepness using DEM

The results from the DEM analysis shown in figure 4.6a follow a similar pattern to that of the contours. The north-west shows steeper sites whilst the south-east has flatter areas. The main difference is 365 sites were analysed as apposed to 206, due to the larger grid size making causing less issues with overlap. A more detailed comparison of the spread is done in section 4.2.3. When considering the locations of outliers, most are on the coast. Here the two stations in the centre of the UK show the Pennines hill range which runs up the UK.

(a) All slope steepness data (DEM)

(b) Map comparing outliers contours and DEM

Figure 4.6: Created in QGIS with data obtained from "HydroSHEDS", 2022 and "The CEDA Archive", 2022.

4.2.3. Comparing contours and DEM methods

Having completed slope steepness methods for both contour and DEM data for the same sites, the data can be compared. The differences in the data are summarised in the three plots in figure 4.7. Most stations are fairly close together with a mean difference around 2.5% and 150 of the 203 common stations had less than 5% difference between the two. The DEM data has been subtracted from the contour data in the unfiltered plot. On the positive end there tend to be more outliers when using contours, this is reiterated in the last plot where the spread is clearly more for contours.

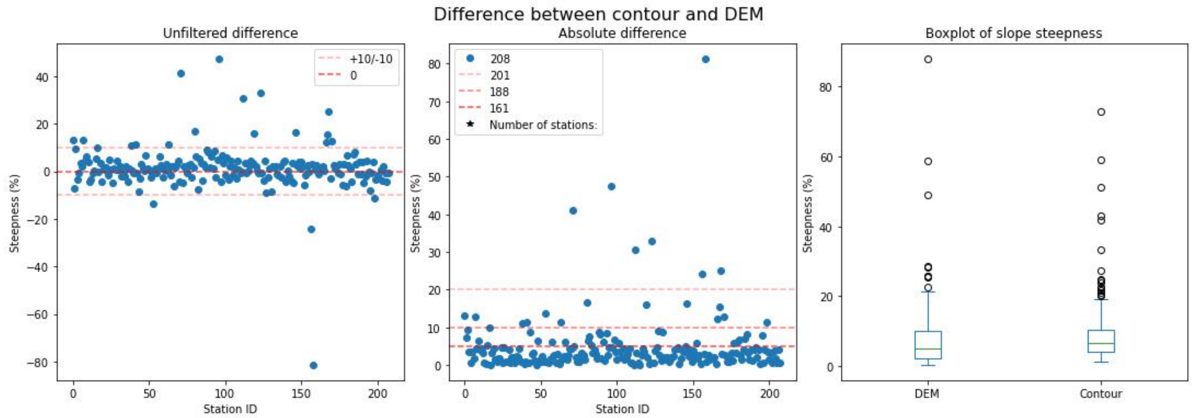


Figure 4.7: Three subplots of the difference (left) and absolute difference (middle) between contour and DEM data. Right shows box plots for both.

4.3. Location on slope

The location on slope, direction of the slope and steepness can all be summarised in figure 4.8. The logarithm of the steepness is represented by the length of the arrows, with the location of the gauge at the base of the arrow. Values less than 1% would result in a negative value when taking the logarithm, thus these have been set to an arbitrary value of 0.0001, which corresponds to just over 1%. In the figure these are just the arrowhead. Most locations are on slopes, which was expected as the maximum slope direction is taken. Some ridges, namely visible on the south coast, are very steep, suggesting the gauges are on the edge of cliffs. Areas near the coast tend to have arrows facing the sea, whilst those in land tend to point to one another. The gauges on ridges of steep slopes are likely to suffer from wind turbulence and thus underestimate the actual rainfall.

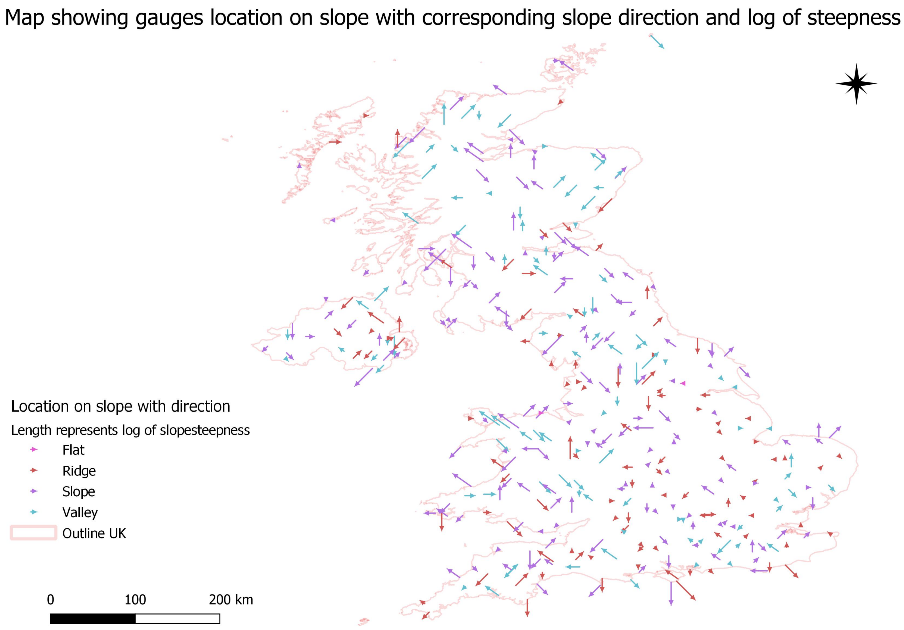
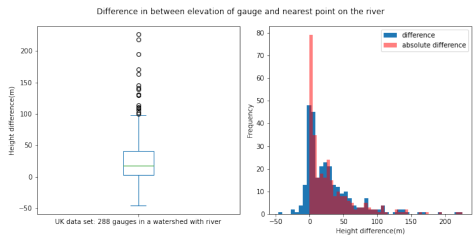


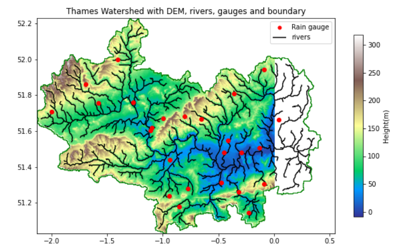
Figure 4.8: Direction of slope, position on slope and steepness of slope.

4.4. Location in watersheds

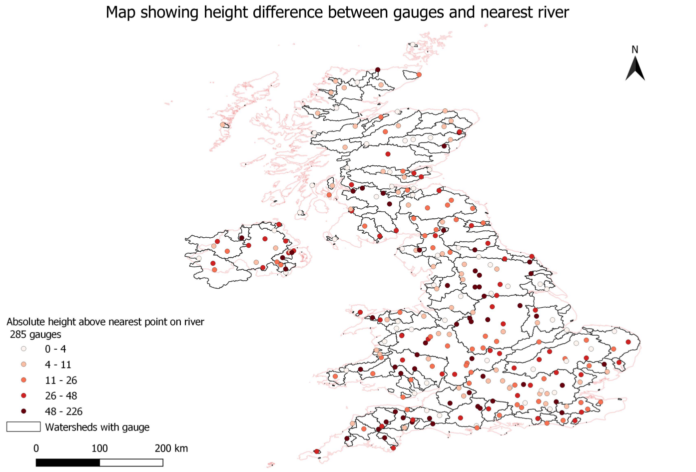
Figure 4.9a show the distribution of differences in height between gauges and their nearest point on rivers. Some points are negative, meaning the closest point is higher, which ideally this would be accounted for as we would expect water to flow down. In this case the absolute value of these 35 gauges is taken as a simplification, seen in red. In general the height difference is quite small, with most gauges being within 50 vertical meters of the river. Looking at the spatial distribution and comparing it to figure 3.8a showing the height distribution of the UK, some interesting conclusions can be drawn. We again see the Pennine hills running up the center of the UK, here a larger height difference is expected and useful as the terrain varies a lot. In Scotland we see very little height differences, whilst the terrain is hilly, meaning the gauges are all very close to the rivers. Figure 4.9b shows the largest watershed of the UK: the Thames with an area of 13 thousand km^2. Mainly the upper areas of the of the watershed are under represented. Especially the hills around 51.5°N,-1.5°E don't have any gauges, along with other large tributaries.



(a) Elevation difference between the gauge and closest point on the river in blue, in red the absolute value to get rid of negative values.



(b) Largest watershed in the UK: the Thames, covering 13 thousand km^2 with corresponding gauges



(c) Difference in height between gauge and the closest point to it on a river, all absolute.

Figure 4.9: Created in QGIS with data obtained from "HydroSHEDS", 2022 and "The CEDA Archive", 2022.

5

Conclusion, Discussion & Recommendations

5.1. Conclusion

From the distribution we can say the rain gauges are well spread out across the United Kingdom. Heights above 400 m could be better represented, especially considering the orographic rainfall. Spatial distribution does vary, mainly on the islands surrounding the UK and in Scotland. Comparing it to a homogeneously spaced alternative shows that it is overall sufficient. One downside is not all watersheds are covered, which should be improved upon.

Slope steepness calculated from both contours and Digital Elevation Model (DEM) shows that positioning could still be improved. Especially close to the coast some locations are at the top of steep slopes, where measurements are effected by wind. Comparing to the threshold of 25% from chapter 2.3.4, only 7 of 211 and 12 of 365 gauges are on steep slopes for the contours and DEM calculations respectively. Concluding, for this data set 97% of gauges are well placed.

The different locations on slope with their directions show no overall patterns. Ridges, valleys and slopes are all common and are spread out well. Scotland does show lack of representation with mainly gentle valleys whereas from the DEM we see most of the terrain is steep. While gauges in valleys measure rain more accurately due to less turbulence, it also suggests a false representation of the surroundings. The gauges on steep coastal ridges are wrongly placed as these will measure less rain than actually falls due to wind turbulence over the gauge.

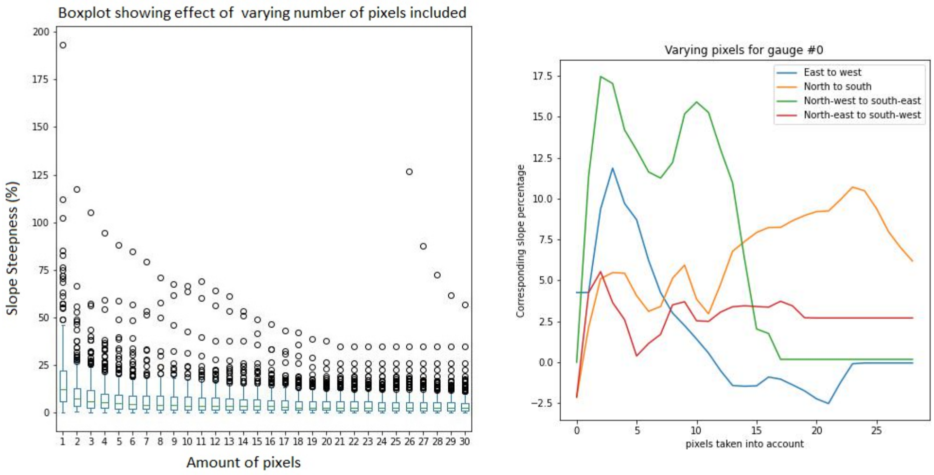
The location in watersheds shows that majority of gauges are very close to rivers both laterally and vertically. As the rivers make up the lower parts of a watershed, this leaves the higher terrain underrepresented. Given that orographic rainfall causes rainfall patterns to be correlated with elevation, within watersheds rain gauges are in the wrong place.

Nationally, this set of open data rain gauges represent the UK well. They are spaced well and most are acceptably placed on gentle slopes. Locations on ridges should be reconsidered and within watersheds they should be spaced as to represent the watershed better.

5.2. Discussion & Recommendations

Throughout the analysis is of slopes, the parameter governing the scale used to analyse the slope was found to be the most difficult to determine. For the DEM model the cross-sections with radius of 30 pixels have been selected fairly arbitrarily. In order to depict the slope properly, the scale needs to be considered at which orographic effects start to affect rainfall. Using the data available, the procedure above can be done with varying amount of pixels, each time taking the maximum absolute slope steepness. Figure 5.1a shows box plots for all the stations and figure 5.1b shows the response of the four directions at fair-isle. At first glance we see that the more pixels we consider, the more it moves to an equilibrium. One important thing to note is in figure 5.1a the maximum is always taken, while in figure 5.1b we see that there is also variation within the directions. This is a very data-drive glance at the problem, wheras the actual amount should be come from physical principles rather than data analysis.

For the analysis in this research a width of 5 pixels either side of the gauge was used. This corresponds to a total horizontal distance of 30 arc-seconds or around 500m. The final contour amount used was 10, this represents a vertical change of 500m. Both were selected so as to remove any outliers and get the average slope of the surroundings.



(a) 30 runs of slope steepness algorithm varying the amount of pixels included in every run.

(b) Different responses varying number of pixels and directions

Figure 5.1: Created in Python with data obtained from “HydroSHEDS”, 2022 and “The CEDA Archive”, 2022.

When considering resolution of the DEM data, 3 arc-seconds is the smallest resolution globally available from open data sources. For this purpose, much smaller would not be much use, given averaging was used over a number of pixels. Repeating with a larger resolution might give better results if larger sections of slope are to be considered. Running a two-dimensional smoothing filter over the height profiles to remove local discrepancies might help. This was to some extent achieved in a single direction by averaging over 10 pixels in each direction. Contour data is available in 5m intervals rather than 50m. Aside from the computing power needed to process this, the scale mismatch would be too large. Currently the rounding on the coordinates of gauge sites was three decimal places, which could be drastically improved. Also considering more stations in the UK would be useful to draw final conclusions.

Currently most of the data has been compared to its own spread, a data driven approach. Where possible a baseline has been used, such as the distribution of gauges vertically and spatially. Repeating all the algorithms but for more points could give a better feel as there is not perfect location, only a best fit. If all slopes are steep in a watershed, the gauge has to be on a slope. To see if this is the case, data is needed for a given watershed. Taking points every couple kilometers and running the algorithms would give an interesting comparison.

Looking into wind data per station and taking the slope in the direction of the wind could also give interesting results, in this research only the maximum slope was selected.

A stronger focus on specifically the placement within watersheds also seems promising, whereas only a preliminary outlook has been done. Optimising the algorithm to find height above the nearest point on a river is recommended. Further analysing the watershed composition such as the slopes steepness at points in it would give a better idea as to if the gauge is placed optimally. This could be done by sampling a number of points and comparing the slope steepness, direction and location on the slope to that of the gauge(s).

A

Appendix A - Figures

Larger versions of selected figures to improve readability, in order of appearance in main body. All figures made in QGIS are in the WGS84 or EPSG:4326 projection, this mainly to keep different data sources working together well. Local projections may be more applicable in some cases.

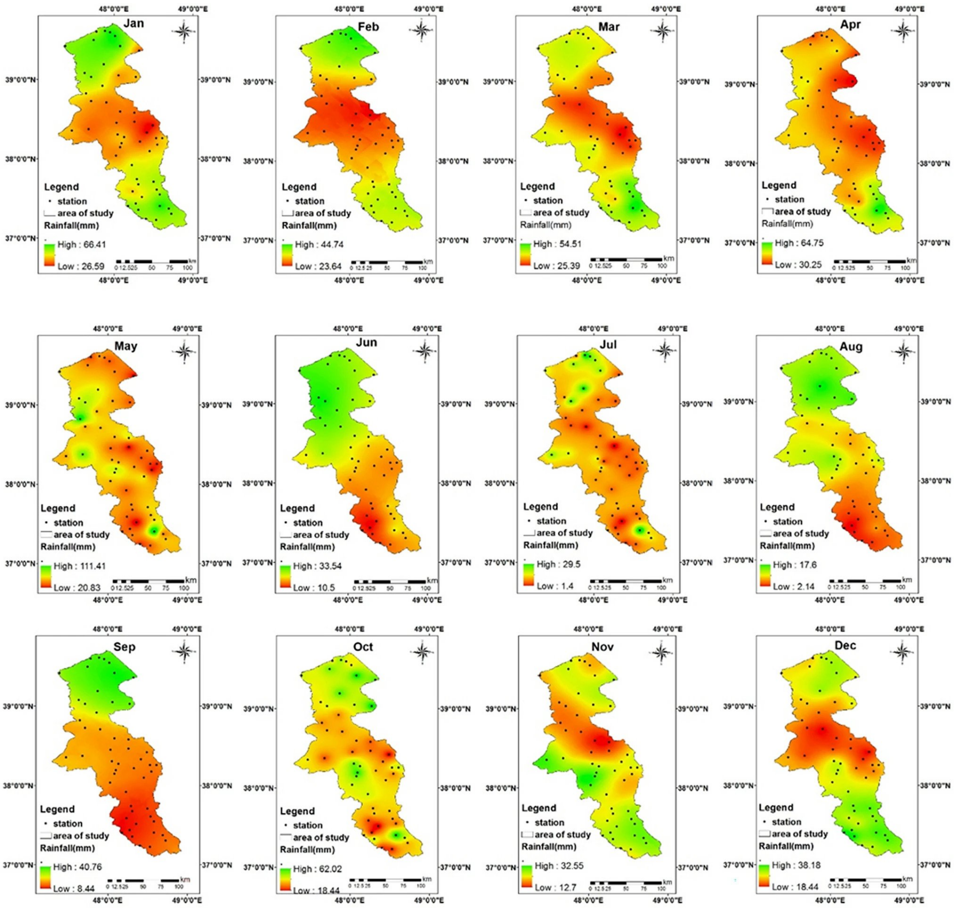


Figure A.1: Monthly rainfall distribution, from Singh et al., 2021

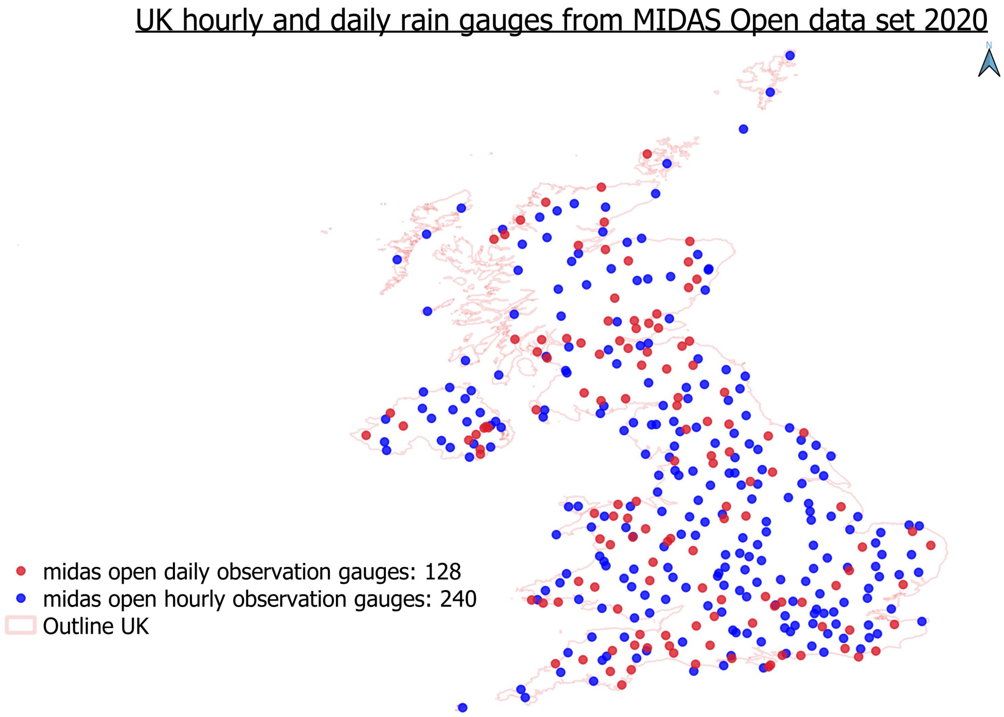


Figure A.2: Hourly and daily rain gauges across the UK, made using data from “The CEDA Archive”, 2022 in QGIS

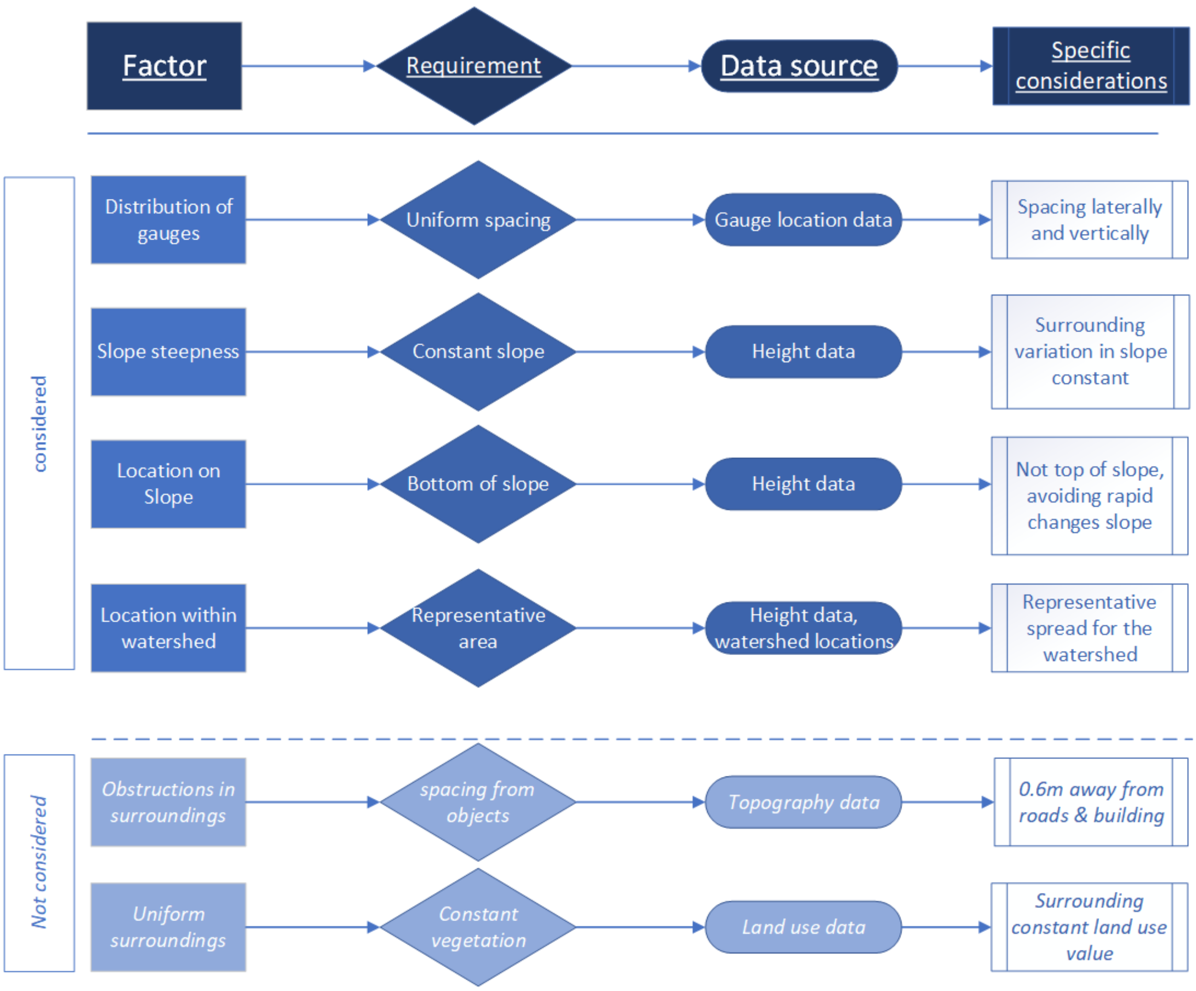


Figure A.3: Flow chart showing factors from literature, at top those chosen to implement, and at the bottom those discarded.

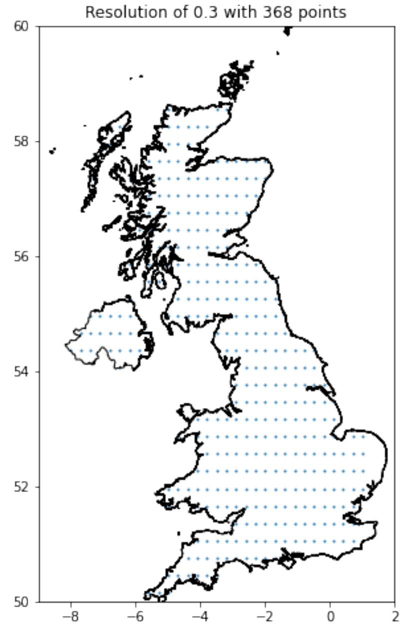


Figure A.4: Base line comparison of homogeneous station spaced at 0.3° would look like.

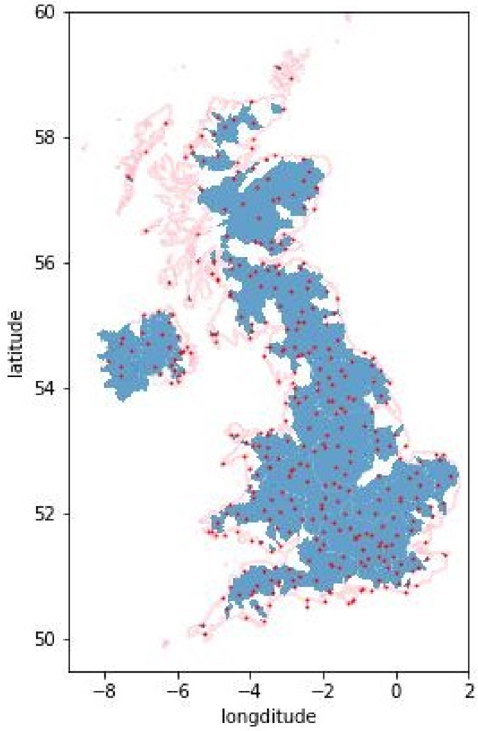


Figure A.5: UK watersheds which have a gauges in them (in blue), and the outline of the UK (in pink)

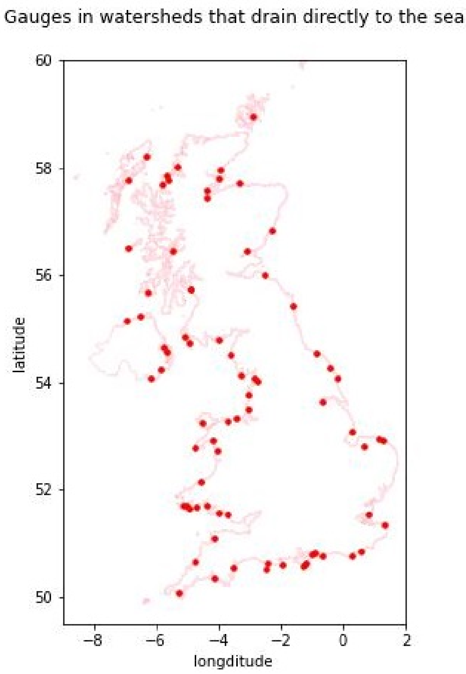


Figure A.6: Gauges in watersheds that have no rivers, and thus drain direct to the sea without entering a river.

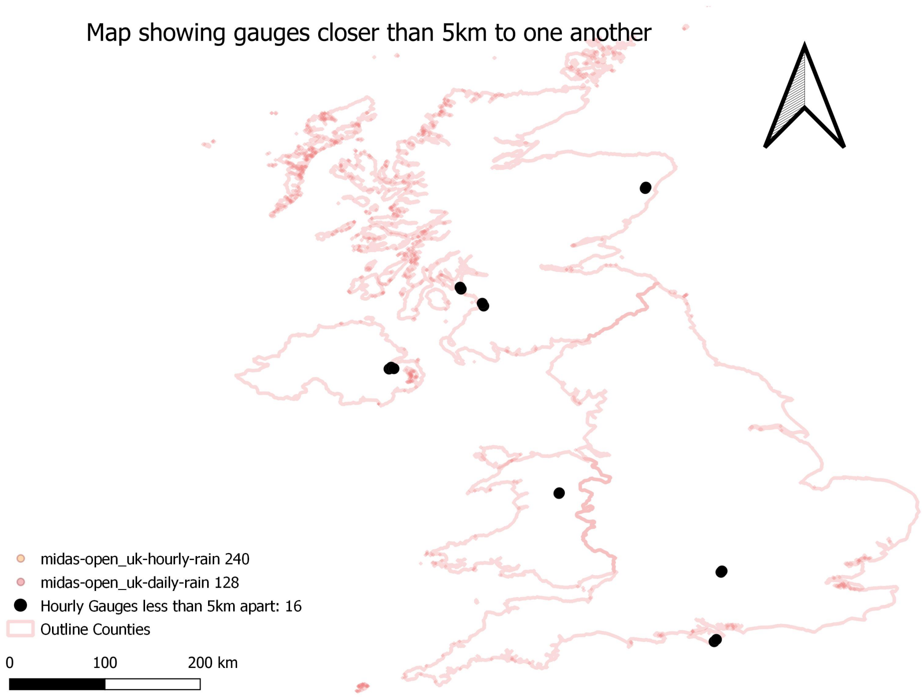


Figure A.7: Stations closer than 5km,created in QGIS with data obtained from “The CEDA Archive”, 2022

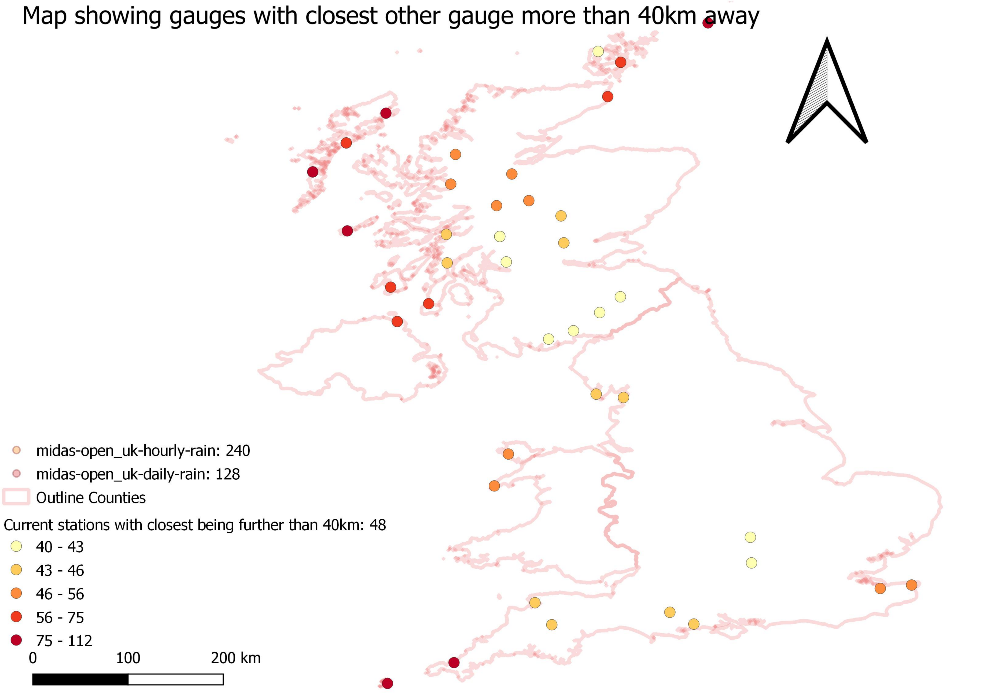


Figure A.8: Gauges further than 40km from another,created in QGIS with data obtained from “The CEDA Archive”, 2022

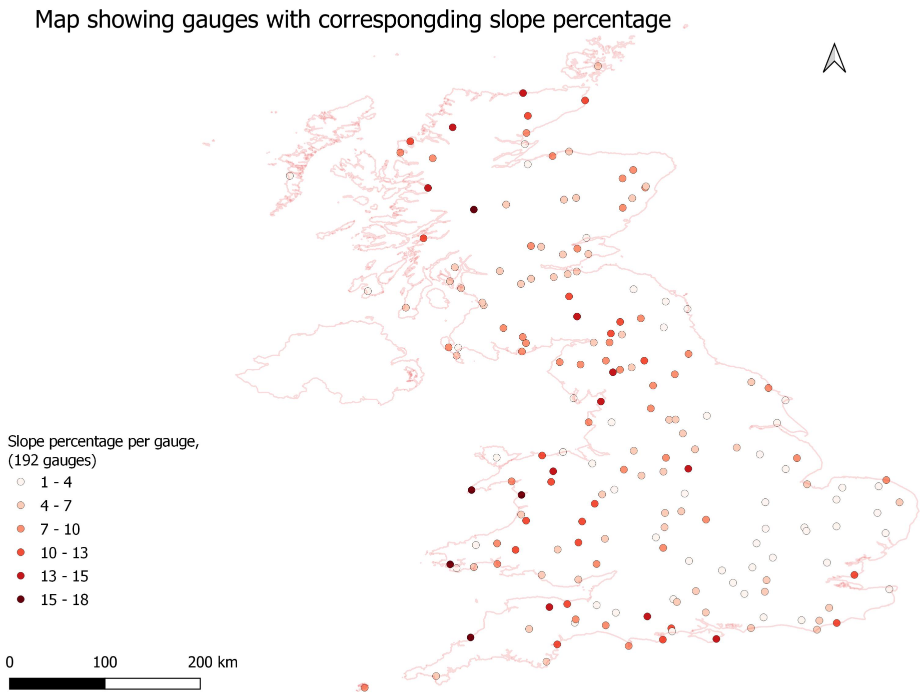


Figure A.9: Map showing all slope steepness data, created in QGIS with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022

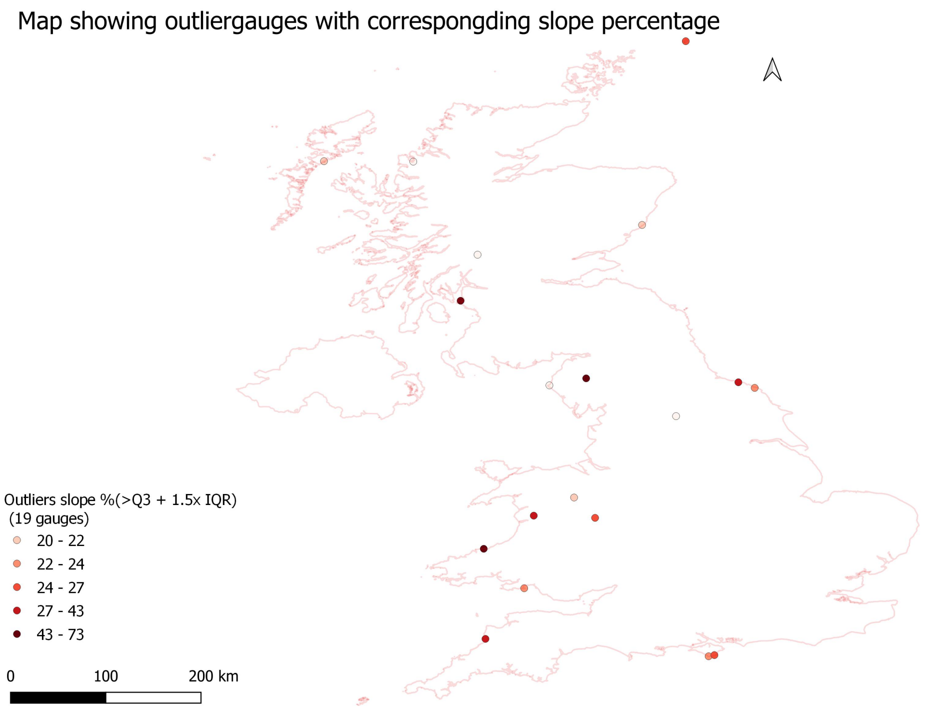


Figure A.10: Outliers were removed, created in QGIS with data obtained from “OS Data Hub”, 2022 and “The CEDA Archive”, 2022

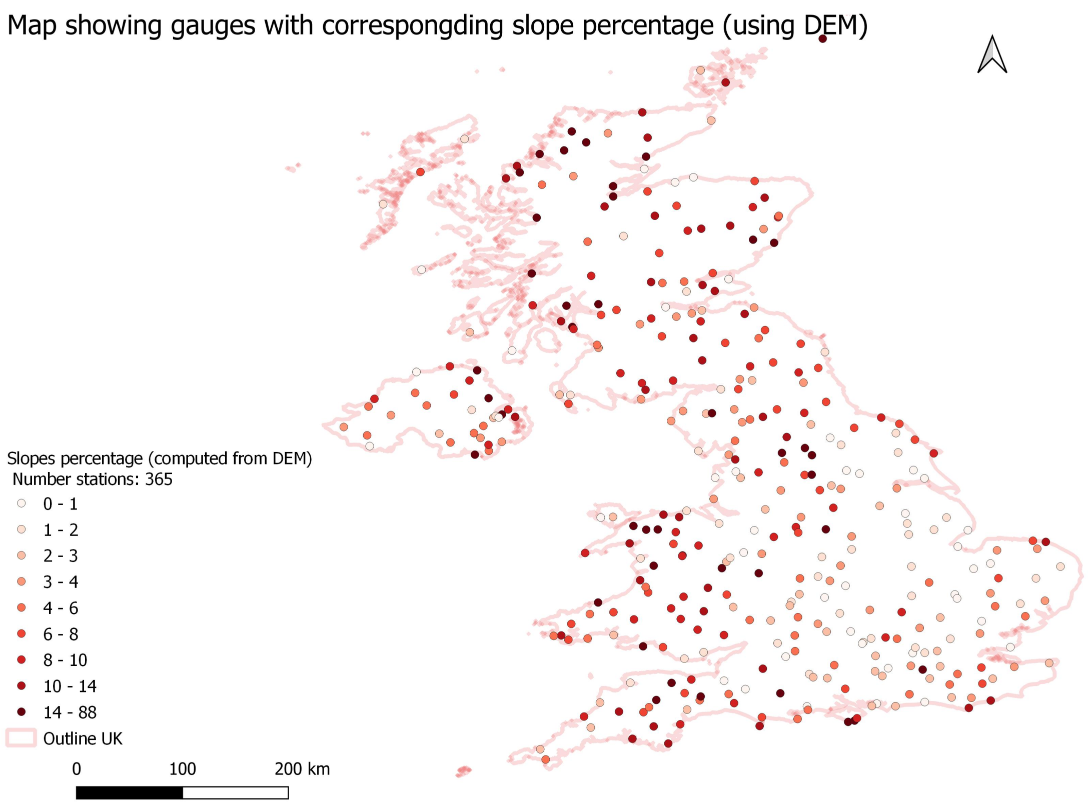


Figure A.11: All slope steepness data (DEM)

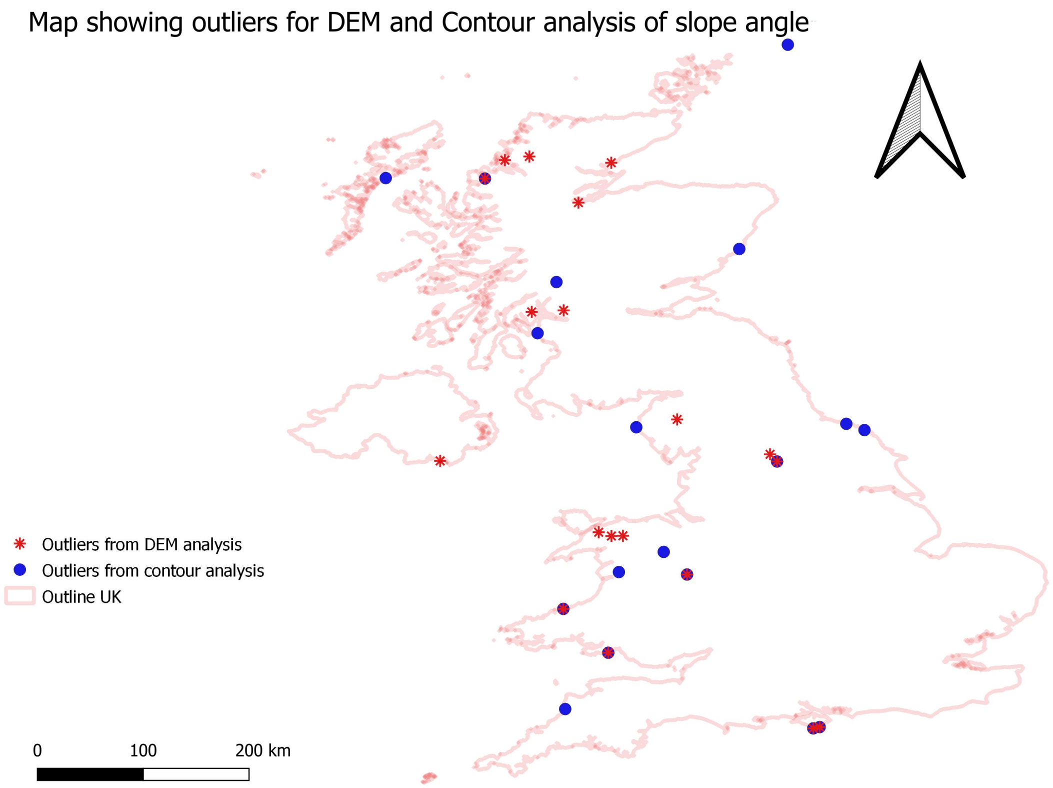


Figure A.12: Comparison of outliers contours and DEM,Created in QGIS with data obtained from “HydroSHEDS”, 2022 and “The CEDA Archive”, 2022

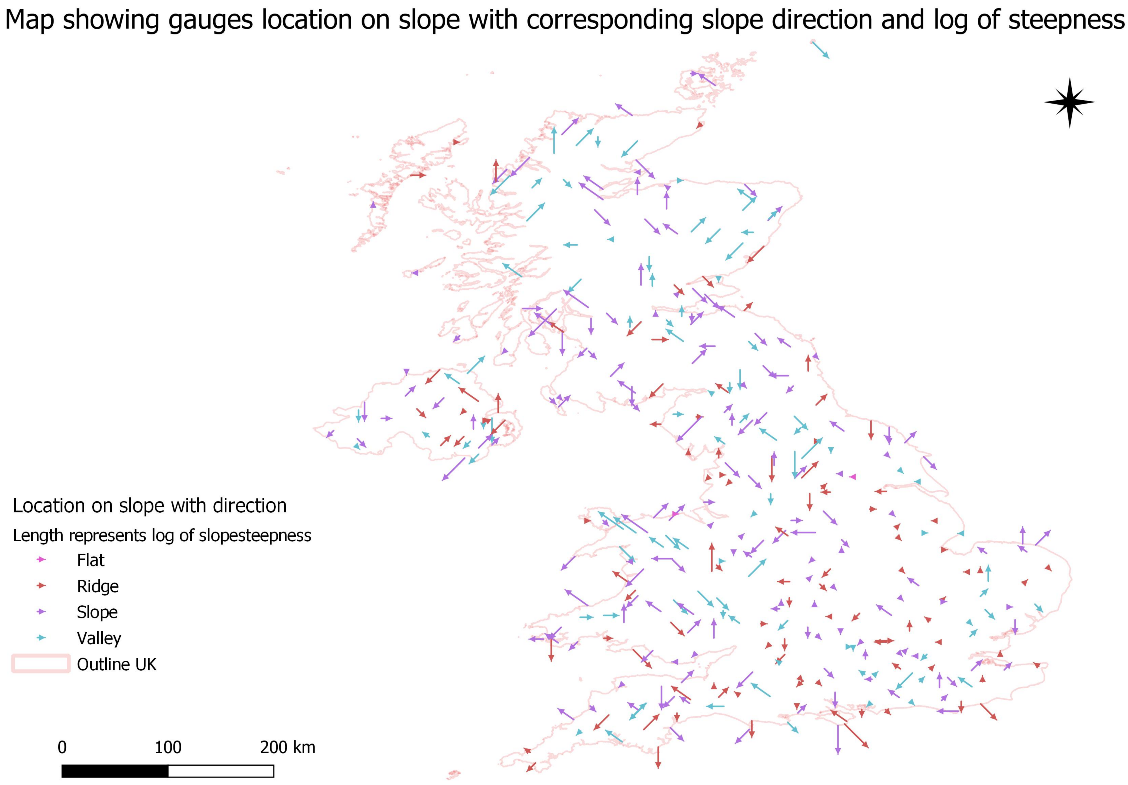


Figure A.13: The direction of slope, position on slope and steepness of slope

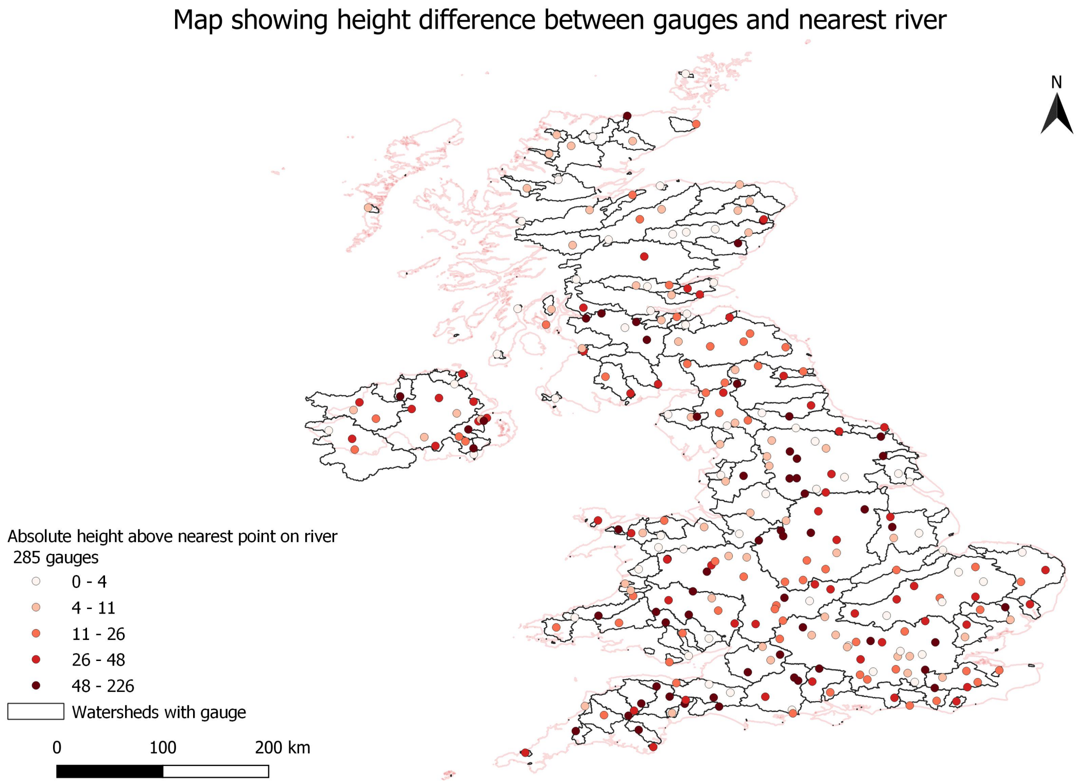


Figure A.14: Difference in height between gauge and the closest point to it on a river, all absolute.

B

Appendix B - Copyright and Data usage

In the writing of this thesis many sources have been used. All are documented throughout the report but some extra notes are added here to reiterate the usage.

B.1. Figures

All figure in chapter 2 are from journal articles, scientific sources or maps from "Google Maps", 2022.With regards to copyright:

- figure 2.1a, License Number: 5276450091383, on 26^{th} March.
- figure 2.2a and 2.2b, License Number 5276451076032 on 26^{th} March 2022.
- figure 2.3a and 2.3b are Open Access.
- figure 2.5a and 2.5b, License Number 5276461330199 on 26^{th} March 2022.

See SPRINGER NATURE LICENSE TERMS AND CONDITIONS under free academic use for more details.

All other figure have been created in Python using the Matplotlib package or have been exported from python and are made in QGIS.

B.2. Data

Meta data on the location of hourly and daily stations have been obtained through "The CEDA Archive", 2022 from the Met Office MIDAS Open: UK Land Surface Stations Data.

Contour data was obtained through "OS Data Hub", 2022.

Digital Elevation Map (DEM), Watersheds and river data was obtained through "HydroSHEDS", 2022.

B.3. Code

For this project quite a few packages were used extensively. Mainly GeoPandas to store geographical information, GeoPy to calculate some distances, Rasterio to deal with DEM data and the more common Numpy and Matplotlib. These are all openly accessible. A lot of information came from the documentation of the given packages and where needed the wide variety of Stackoverflow gave insights. These informal blog posts are too many to cite, and the amount used varied. When whole sections of code have been used, this has been cited along side the code, which can be found on **this GitHub page**. One explicit mention to Arribas-Bel, 2016 whose online course Geographic Data Science gave insights as to what was possible with geographic python packages.

Bibliography

Ardebil · Iran. (2022). Retrieved February 17, 2022, from https://www.google.com/maps/place/Ardebil,+Iran/@38.4086925,46.2140548,8z/data=!4m5!3m4!1s0x40187bd58365be6f:0xa184329c761eafd5!8m2!3d38.4853276!4d47.8911209

Arribas-Bel, D. (2016). Gds15: Geographic Data Science. https://doi.org/10.5281/zenodo.46313

The CEDA Archive. (2022). Retrieved February 16, 2022, from https://archive.ceda.ac.uk/

CIMO. (2017a). CIMO Chapter 6: Measurement of precipitation. Retrieved February 8, 2022, from https://library.wmo.int/doc_num.php?explnum_id=3152

CIMO. (2017b). CIMO Guide | World Meteorological Organization. Retrieved February 8, 2022, from https://community.wmo.int/activity-areas/imop/cimo-guide

Eagleson, P. S. (1967). Optimum density of rainfall networks. *Water Resources Research*, *3*(4), 1021–1033. https://doi.org/10.1029/WR003i004p01021

Fu, Y., Jing, C., & Du, M. (2016). URBAN RAIN GAUGE SITING SELECTION BASED ON GIS-MULTICRITERIA ANALYSIS. https://doi.org/10.5194/ISPRS-ARCHIVES-XLI-B2-185-2016

Ghorbani, M. A., Mahmoud Alilou, S., Javidan, S., & Naganna, S. R. (2021). Assessment of spatio-temporal variability of rainfall and mean air temperature over Ardabil province, Iran. *SN Applied Sciences*, *3*(8), 728. https://doi.org/10.1007/s42452-021-04698-y

Google Maps. (2022). Retrieved February 15, 2022, from https://www.google.nl/maps/@27.4544122,88.6016271,170978m/data=!3m1!1e3

Gyasi-Agyei, Y. (2020). Identification of the optimum rain gauge network density for hydrological modelling based on radar rainfall analysis. *Water (Switzerland)*, *12*(7). https://doi.org/10.3390/w12071906

HydroSHEDS. (2022). Retrieved March 15, 2022, from https://hydrosheds.org/

Iran National Census [page 28, tabel 13]. (2011). Retrieved February 17, 2022, from https://web.archive.org/web/20151116105123/http://iran.unfpa.org/Documents/Census2011/2011%20Census%20Selected%20Results%20-%20Eng.pdf

Kharake, A., Pathare, J., & Deshmukh, P. (2021). Spatio-temporal variability of intra-monsoonal rainfall in Pravara-Mula River Basin, India. *Arabian Journal of Geosciences*, *14*(10), 890. https://doi.org/10.1007/s12517-021-07268-z

Kumar, P. (2021). An Analysis of Spatio-Temporal Variability of Precipitation and Contours of Water Management in the Upper Teesta River Basin of Sikkim Himalaya, India. In M. Abrunhosa, A. Chambel, S. Peppoloni, & H. I. Chaminé (Eds.), *Advances in Geoethics and Groundwater Management : Theory and Practice for a Sustainable Development* (pp. 163–167). Springer International Publishing. https://doi.org/10.1007/978-3-030-59320-9_35

Lehner, B. (2008). HydroSHEDS Technical Documentation. https://hydrosheds.org/images/inpages/HydroSHEDS_TechDoc_v1_2.pdf

OS Data Hub. (2022). Retrieved February 22, 2022, from https://osdatahub.os.uk/

Osborn, H. B., Lane, L. J., & Hundley, J. F. (1972). Optimum gaging of thunderstorm rainfall in southeastern Arizona [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/WR008i001p00259]. *Water Resources Research*, *8*(1), 259–265. https://doi.org/10.1029/WR008i001p00259

Rodrigo-Comino, J. (2021). Precipitation: A regional geographic topic with numerous challenges. *Precipitation* (1st ed., p. 1). Elsevier. https://doi.org/10.1016/B978-0-12-822699-5.00001-X

Sadiq, S., Zahid Khalil, R., Malik, S., & Haque, S. (2019). Additional Rain Gauge Site Appropriation for Monitoring Precipitation in Sindh, Pakistan Using Geospatial Techniques and Multi-Criteria Decision Making, 4372–4374. https://doi.org/10.1109/IGARSS.2019.8898735

Sevruk, B. (1992). SNOW COVER MEASUREMENTS AND AREAL ASSESSMENT OF PRECIPITATION AND SOIL MOISTURE. (WMO-No. 749), 312.

Sevruk, B., & Klemm, S. (1989). CATALOGUE OF NATIONAL STANDARD PRECIPITATION GAUGES. *REPORT No. 39*, (WMO/TD-No. 313), 50. https://library.wmo.int/doc_num.php?explnum_id=9514

Singh, D. V., Jain, S., & Goyal, M. (2021). An assessment of snow-glacier melt runoff under climate change scenarios in the Himalayan basin. *Stochastic Environmental Research and Risk Assessment*, *35*. https://doi.org/10.1007/s00477-021-01987-1

Subedi, M., & Fullen, M. A. (2009). Spatial variability in precipitation within the Hilton Experimental Site, Shropshire, UK (1982–2006) [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/hyp.7133]. *Hydrological Processes*, *23*(2), 236–244. https://doi.org/10.1002/hyp.7133

Sun, S., Fang, Y., Liu, L., Wang, H., Liu, Y., & Zhang, M. (2021). Regime shift in the decadal variability of the Indian Ocean subsurface temperature. *Journal of Marine Systems*, *216*, 103511. https://doi.org/10.1016/j.jmarsys.2021.103511

WMO. (2016). What we do. Retrieved February 8, 2022, from https://public.wmo.int/en/our-mandate/what-we-do

WMO (Ed.). (2020). *Guide to hydrological practices* (6th ed). WMO.

Worldbank Data. (2022). Retrieved February 22, 2022, from https://data.worldbank.org/indicator/AG.SRF.TOTL.K2?locations=GB